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Economic Viability of Extracting High Value Metals from End of Life Vehicles

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Abstract: Electronics containing growing quantities of high value and critical metals are increasingly used in automobiles. The conventional treatment practice for end-of-life vehicles (ELV) is shredding after de-pollution and partial separation of spare parts. Despite opportunities for resource recovery, the selective separation of components containing relevant amounts of critical metals for the purpose of material recycling is not commonly implemented. This article is aimed to contribute to recycling strategies for future critical metal quantities and the role of extended material recovery from ELVs. The study examines the economic feasibility of dismantling electronic components from ELVs for high value metal recycling. The results illustrate the effects of factors as dismantling time, labour costs and logistics on the economic potential of resource recovery from ELVs. Manual dismantling is profitable for only a few components at the higher labour costs in western/northern parts of Europe and applicable material prices, including the inverter for hybrid vehicles, oxygen sensor, side assistant sensor, distance and near distance sensors. Depending on the vehicle model, labour costs and current material prices, manual dismantling can also be cost-efficient for also some other such as the heating blower, generator, starter, engine and transmission control, start/stop motor, drive control, infotainment and chassis control.

Keywords: end of life vehicle; metals recovery; WEEE; recycling

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1. Introduction

Besides catalytic converters, electronic components containing noteworthy amounts of high-value metals (e.g., gold, silver, palladium, indium, neodymium and other rare earth metals) are increasingly used in modern vehicles. Although technologies are available for the recovery of such metals from end of life products, this is not currently common practice in the case of automobiles. Most of high value metals are lost in current end of life vehicle (ELV) recycling practices, which are focused on shredding and recovery of bulk metals, steel, aluminium and copper [1,2]. Electronics make up a minute part of the overall vehicle volume and thus, after shredding the full ELV, higher value metals occur only in non-noteworthy concentrations. Selective separation of components with a greater content of high value metals (e.g., printed circuit boards (PCB) for separate material recovery is seldom implemented, although it would enable the recovery and re-use of these strategic materials.

In a typical ELV with a mass of 1050 kg, the mass of critical or precious metals might amount to 50 kg [3,4]. Steel, aluminium, copper, glass and plastics make up the largest portion of the mass of a vehicle and yield the main revenues for authorised treatment facilities (ATFs). According to Ortego et al. [5], Fe, Al, and Cu account for more than 90% of the car's metal content. Electronic components with precious or critical raw materials can offer additional material value by linking the recycling segments for ELV more closely to waste electronic and electric equipment (WEEE) management assuming that the effort required to dismantle the ELV is less than the revenues gained by selling the electronic components to a WEEE recycler.

The European ELV directive states that as of 1 January 2015, 95 wt% of the ELV must be recovered. Recovery is defined as the final productive use of the parts and materials embedded in ELVs. The EU sets the current recycling target in terms of the mass-% of the entire vehicle. In practice, this incentivises the recycling of heavy materials, although these materials are not necessarily the most important to recycle from a resource and environmental point of view.

A study of German ATFs in 2014 identified a number of relevant car components that contain strategic raw materials in ELVs, which could be subject to dismantling with potential economic gain [4]. Many of the raw materials in the identified components have a substantial environmental impact, such as a high carbon footprint.

Groke et al. [4] compared the time required to dismantle the selected components in different car types with the relative quantity of precious metals and other valuable materials contained in the components. Comparison between the cost of dismantling the components and the potential revenues from sales of the components to WEEE recycling facilities indicates the economic viability of dismantling ELV electronic components. Metal prices in 2014 in Germany provided the basis for economic viability calculations by Groke et al. [4]. Using these calculations as a starting point, this paper will provide a broader overview of the economic potential for recovering critical and/or precious raw materials from ELV components in different EU regions, taking into account the volume and nature of local ELV markets as well as relevant costs and recent raw material prices. Moreover, the specific information regarding recovery of valuable and /or critical metals occurring in lower quantities in the complex end-of life matrix is missing. Increased understanding of the factors affecting the economic potential of recovering materials with a low-weight contribution is crucial to enhance specific material recovery. The aim of this study is therefore to answer to the need for objective assessment of the recovery. The countries selected and the respective European regions represented in the present analysis were Germany and the Netherlands (western Europe), Finland (northern Europe), the Czech Republic (central Europe and a former country of the Eastern bloc) and Spain (southern Europe).

Circa 5.3 million cars with an average age of 15 years were officially scrapped in 2017 in the European Union [6,7]. These End-of-life vehicles generate 7–8 Mtons of waste annually in the EU [8]. Hereof, 94% of parts and materials were reused and recovered, 88% again reused and recycled. In general, the market structure of vehicle recycling in most European countries is characterized by numerous small companies that also provide other services such as towing, repairs, used car trading, scrap trading, etc. A few large companies in each country typically dismantle up to 10,000 ELVs per annum [9,10]. Some electronic components, such as the starter, generator, steering servo unit, are regularly dismantled for reuse as spare parts, remanufacturing or for export purposes. The scrap market is a regional market and prices depend on supply volume, prevailing local economic conditions and season. Generally, the market prices for scrap are highly volatile, indicated e.g., by the German raw material database EUWID 2020 [11].

Generally, dismantling of ELV components for reuse as spare parts is more common for vehicles less than 10 years old, whilst the main economic benefit of old ELVs is in their material content [10].

2. Methodology

2.1. Analysis Principle and Input Data

The economic viability of dismantling was evaluated for 18 electronic components, for which the content of metals and other valuable materials had previously been determined [4,12,13] and for which the expected economic revenues from material price via WEEE recycling are or have potential to be greater than the cost of dismantling the additional components.

The present evaluation of economic viability was carried out by measuring the time required to dismantle the priority components from 11 different demolished vehicles built between 2009 and 2014, representing nine different vehicle classes (large-capacity limousine, leisure activity vehicle (LAV), minivan, large, medium and small off-road vehicle, lower mid-range, small and very small vehicle). The dismantling time for the separate components varied for different vehicle types as explained by Groke et al. [4]. Details on the dismantling times are found in [4].

The economic valuation was carried out by comparing the operational component dismantling costs at the ATF with the potential revenues that ELV recyclers can generate by selling the components to a WEEE recycler. In addition to the labour costs for the time of the dismantling of the parts, other running costs like logistics costs and costs for processing at the electrical scrap recycler were added to the costs of dismantling each component. Possible investment costs were not considered, as some dismantling takes place at most ATFs and thus, extra investments would in most cases not likely be necessary. Moreover, these costs depend very much on the company size and are more difficult to nominate. The revenues were estimated using market information obtained from the ELV recyclers and publicly available scrap prices or prices for secondary materials. These price estimates were then multiplied by the quantity of these materials in the individual components. Based on personal communication with a WEEE-recycler, the recycling efficiency 80% was applied [4]. This allows a ratio of costs to revenues to be determined for each component and vehicle type. If the ratio is >1, the revenues are higher than the costs. If the ratio is <1, dismantling does not deliver economic benefit.

The 18 priority components examined herein can be categorized in three groups according to their functions:

- Engines: heating blower, servomotor, starter, fan motor, generator, wiper motor, and servomotor gear
- Controls: engine and transmission control, drive control, infotainment, CD-changer, TV-tuner and radio controls, chassis control, start/stop controls, and inverter for the hybrid vehicle
- Sensors: oxygen sensor, side assistant sensor, and distance/near distance sensors.

Table 1 lists these 18 priority vehicle components, the primary materials of which the components are comprised, and the average mass of the recycle materials in different model vehicles.

Equal dismantling times and material contents were applied for all countries assessed (Germany, the Netherlands, Finland, the Czech Republic and Spain). A comparison between different countries was then performed with respect to current local labour costs, logistics costs, material prices/scrap prices and costs for WEEE recycling.

2.2. Calculations

2.2.1. Input Data for Cost Efficiency Assessment

Data from Groke et al. [4] concerning the different types of cars analysed and the time required to dismantle each of the 18 priority components were used as input data. The costs of WEEE recycling were based on values from Groke et al. [4] and Magalini and Huisman [14].

Labour cost were defined based on labour market statistic from Eurostat and National statistics bureaus [15–17] and the Dutch car recycling organization ARN [18].

Eurostat labour market statistics show that the cost of labour in the Czech Republic is roughly 30% of that in western and northern Europe [19]. Czech ATFs are primarily very small companies with only 3–5 employees and largely without a trade union collective agreement. Based on personal communication [9] and Eurostat data [19], the hourly labour cost for component dismantling in the Czech Republic was estimated as 10.00 €/h. As logistical and WEEE treatment costs are to a significant extent also driven by labour costs, the logistics and WEEE treatment cost in the Czech Republic were estimated to be 30% of equivalent costs in Germany.

Table 1. Analysed components that are most likely to be economically viable for dismantling.

Component	Main Materials Involved in the Component	Weight per ELV in kg
(1) Heating blower	Fe, plastics, Cu (Al, PCB)	1.15–1.87
(2) Servomotor	Fe, plastics, Cu (Al, PCB)	1.7–5.1
(3) Starter	Fe, Al, Cu (plastics, brass)	2.5–4.3
(4) Fan motor	Fe, plastics, Cu (Al, brass)	1.6–3.9
(5) Generators	Fe, Cu, Al, plastics	5.4–7.6
(6) Wiper Motor	Fe, Al, Cu, plastics (PCB)	2.2–3
(7) Engine & Transmission control	Al, plastics, Fe, PCB (Cu, brass)	0.4–1.2
(8) Drive control	Fe, Al, plastics, Cu, PCB (brass)	2.0–3.1
(9) Infotainment	Fe, PCB, Al, plastics, (Cu)	1.65–1.9
(10) Chassis control	Al, PCB, Fe, plastics, (Cu)	0.4
(11) CD charger	Fe, PCB, Al, plastics (brass)	1.7 [1]
TV turner	Fe, PCB	1.2
Radio control	Fe, PCB, Al	0.7
(12) Inverter	Al, Fe, Cu, PCB, plastics, brass	14 [1]
(13) Start/Stop motor	Fe, Al, PCB, plastics, (Cu)	0.4–0.5
(14) Side assistant	PCB, Cu, plastics, Fe	0.3
(15) Distance sensor	PCB, Cu, plastics, Al	0.3
(16) Near-distance radar	PCB, Cu, Al, Fe, plastics	0.3
(17) Oxygen sensor	sensor contains Pt, Pd	0.1–2.7
(18) Servomotor gear	Fe, Cu, plastics, brass	0.5–0.6

[1] Large vehicle.

Average hourly labour costs in Spain for the whole economy, excluding agriculture and public administration, in enterprises with 10 or more employees were 21.40 €/h in 2018 [19]. Labour costs per hour in NACE-09 division "Waste collection, treatment and disposal activities; materials recovery" varied between 18.2 and 22.2 €/h in 2017–2020 [17]. Labour costs in Spain are 62.5% in comparison with labour costs in western and northern Europe. Logistics and WEEE treatment costs in Spain were therefore estimated as 62.5% of equivalent costs in Germany.

Scrap prices for Germany were obtained from EUWID databases [11]. The values for the 18 priority components which were listed in Table 1 are weighted prices representative of the specific types of these components likely to be found in ELVs. The German data were compared with online scrap prices in the Netherlands and Finland, and the price ranges were found to be consistent with EUWID data [11].

The price for printed circuit boards (PCBs), where most of the critical raw materials and precious metals in car components are located varies widely depending on the PCB quality. The lower end of the range—2.80 €/kg—represents PCBs with less metal content whereas the upper end of the range—ca. 26.00 €/kg—is valid for, e.g., PCBs from mobile phones and notebook computers. The PCB components of ELVs can be considered similar to low quality PCBs rather than the high-quality PCBs found in mobile phones.

Based on communication with Czech ATFs, 2019 steel scrap prices were 140 €/t, or 76% of the price in Germany (185 €/t). To reach those prices, ATFs need a consistent volume of material. The prices of other scrap metals and secondary materials in the Czech Republic were estimated from German data using the same proportionate value as that for scrap steel (76%).

There are very few public data on logistics costs and material prices for the Spanish ELV sector. Thus, EUWID data and data from Groke et al. [4] on material prices were applied for these calculations.

2.2.2. Sensitivity Analyses

Scrap prices are volatile; for example, on the European market, the price of aluminium and iron scrap decreased almost 30% from 2018 to 2019 [11] and that the price of brass scrap decreased by 10% during the same period. Thus, a robust sensitivity analysis with respect to the scrap prices was performed, assuming a 50% increase in material prices, which is considered a realistic near-term maximum price fluctuation range based on historical market data [11]. This partial sensitivity analysis was performed for all cases, where material prices (Table 3) were changed (50% increase) and the effect on profitability was monitored.

The impact of transportation logistics costs was also assessed in the Finnish case. The population density in Finland is one of the lowest in Europe and vehicle dismantling facilities in Finland are typically small companies. Logistics costs for the collection of consumer electronics are nearly 30.00 €/t in Finland. However, 30.00 €/t can be only achieved in case of high-volume transportation and full containers. For smaller volumes, which is a realistic option in the case of dismantled electronic components from vehicle dismantling facilities the logistics costs were estimated at approximately 60.00 €/t [20,21]. Thus, the calculations were performed using both 30.00 and 60.00 €/t for logistics costs to test the sensitivity of economic profitability to logistics costs.

Tables 2 and 3 give the input data.

Table 2. Input data for the calculation of costs of dismantling and of life vehicle electronic components.

Costs	Germany	The Netherlands	Finland	Czechia	Spain
Labour Cost ATF in €/hour	32.00 €	32.00 €	31.00 €	10.00 €	20.00 €
Transport Cost ATF in €/ton	30.00 €	30.00 €	30.00 or 60.00 €	9.38 €	18.75 €
Transport Cost WEEE in €/ton	30.00 €	30.00 €	30.00 €	9.38 €	18.75 €
WEEE Treatment cost in €/ton	200.00 €	200.00 €	200.00 €	62.50 €	125.00 €

Table 3. Input data for the calculation of revenues from dismantling and of life vehicle electronic components.

Revenues	DE; FI, NL, ES 2019	CZ 2019
Printed Circuit Board in €/kg	2.80 €	2.12 €
Fe/Steel Scrap in €/kg	0.19 €	0.14 €
AL Scrap in €/kg	0.40 €	0.30 €
Cu Scrap in €/kg	4.50 €	3.41 €
Plastic (old) in €/kg	0.40 €	0.30 €
Brass scrap in €/kg	3.50 €	2.65 €
Oxygen Sensor €/kg	6.50 €	4.92 €

3. Results

The results of calculations of revenues versus costs for the selected priority components from ELVs are presented in Tables S1–S5 in the Supplementary Material and summarized in Table 4. For most of the components examined, material revenues are so small (less than 2€ in most cases) that the dismantling can be only economically beneficial when the dismantling times are less than or equal to 2 min. For this reason, we have carried out a sensitivity analysis and analysed how the result will change assuming a 50% increase in material prices. The economic feasibility is slightly improved at 50% higher scrap material prices; however, dismantling of ELVs for WEEE recycling remained non-economically feasible in most cases, with the exception of Czechia where significantly lower labour costs yield relatively greater economic opportunity for WEEE recycling under the 50% higher scrap price scenario.

3.1. Potential in Northern and Western Europe—Germany, The Netherlands and Finland Cases

Components for which dismantling is clearly beneficial (for examined vehicle types) are the inverter for hybrid vehicles, and the side assistant sensor, distance sensor and oxygen sensor for all vehicles. Generally, components with larger masses such as the generator and inverter, rendering higher material revenues were found economical viable to dismantle (Tables S1–S3 Supplementary Material).

Table 4. Analysed components that are most likely to be economically viable for dismantling.

Component	Profitable to Separate for Material Recycling	European Potential (−−—++)	Sensitivity Analysis
(1) Heating blower	profitable for some car types	+/−	50% higher material prices have minor effect on the economic result
(2) Servomotor	not profitable	−−	50% higher material costs minor effect only with low labour cost
(3) Starter	generally profitable with labour cost <20 €	+/−	50% higher material costs will not render profit in central and northern ATFs
(4) Fan motor	profitable with labour cost level 10 €/h	−	50% higher material costs will render profit in ATFs with labour costs <20 €/h
(5) Generators	profitable for some car types in central and northern Europe, profitable with labour cost <20 €/h	+	50% higher material costs will turn material recovery profitable with transport costs 30 €/t
(6) Wiper Motor	profitable only with labour costs <10 €/h	−	
(7) Engine & Transmission control	profitable for some car types	+/−	50% increase in material prices makes material recycling feasible for additional car types (not all)
(8) Drive control	profitable for some car types with labour costs <20 €/h. Not profitable in central and northern Europe	0/−	50% increase in material prices makes material recycling feasible for additional car types with labour costs >20 €/h
(9) Infotainment	partly profitable with labour cost <20€/h, profitable when labour costs <10 €/h	0/−	50% increase in material prices renders profitability, provided logistics costs are 30 €/t.
(10) Chassis control	profitable for some car types only with labour costs <10 €/h	-	+50% material price will not make recovery more profitable
(11) CD charger	not profitable	−−	not profitable
TV turner	not profitable	−−	not profitable
Radio control	not profitable	−−	not profitable
(12) Inverter	recovery profitable	++	profitable
(13) Start/Stop motor	profitable for some car types with labour costs >30 €/h		
(14) Side assistant	profitable with labour cost <20 €/h	+/0	50% material increase makes material recovery profitable provided logistics cost 30 €/t
(15) Distance sensor	profitable	++	profitable
(16) Near-distance radar	profitable	++	profitable
(17) Oxygen sensor	profitable	++	profitable
(18) Servomotor gear	profitable	++	profitable

The benefit of dismantling was uncertain for five components, where profitability depends on the vehicle type and dismantling time. These components are the heating blower and generators in the group of engine components, and engine control, transmission control, infotainment and start/stop motor in the group of control components.

For the remaining components, dismantling is not profitable at current labour costs and material prices. These components identified as uneconomic for WEEE recycling include the servomotor, starter, fan motor, and wiper motor in the group of engine components, and drive control, chassis control, and CD changer, TV tuner and radio control in the group of control components.

For most of the components examined, material revenues are so small (less than 2€ in most cases) that the dismantling can be only economically beneficial when the dismantling times are less than or equal to 2 min. For several components (servomotor, starter, fan motor, wiper motor, drive control and CD-changer/TV tuner/radio control), the material revenues in comparison with ATF and WEEE costs are such that that not even a 50% increase in scrap metal prices is sufficient for ELV component dismantling to be profitable (Tables S1–S3 Supplementary Material).

The impact of transportation costs is less significant than dismantling costs. Calculations using both 30.00 €/t and 60.00 €/t transport costs (ATF) showed that doubling of transport costs causes only a minor change in the ratio of revenue/cost associated with ELV component dismantling and WEEE recycling. The transportation costs are in most cases clearly less than 10% of the total ATF costs, and >10% only when dismantling times are very rapid or component mass high. Thus, doubling of transportation costs typically results in an increase of 1–6% of the total costs of ATF.

3.2. Southern Europe—The Spain Case

The components for which the dismantling is clearly positive (for all examined vehicle types) are the generator in the group of engine components, inverter for hybrid vehicles, start/stop motor in the group of control components and the side assistant, distance sensor and oxygen sensor in the group of sensor components.

For five components, the present analysis could not indicate a clear benefit or disadvantage of dismantling, but the profitability would depend on the vehicle type and dismantling time. Those components include the heating blower and starter in the group of engine components, and engine control, transmission control, drive control, infotainment and chassis control in the group of control components.

For the other components investigated, dismantling is not profitable with the Spanish labour cost of 20.00 €/h and current material prices. These components include the servomotor, fan motor, wiper motor, and servomotor gear in the group of engine components, and CD changer, TV tuner and radio control in the group of control components.

For components with an original ratio of revenue/cost >0.7, the increase of 50% in scrap metal prices shifts the revenue from dismantling to positive. These were some starters, heating blower, engine and transmission control, drive control and servomotor gear. However, for many of the components, the ratio for revenue/costs remained <1.

3.3. Central Europe—The Czech Republic Case

The components for which the dismantling is clearly positive (for all examined vehicle types) are the fan motor, generator and servomotor gear in the group of engine components, the inverter for hybrid vehicles, infotainment and start/stop motor in the group of control components and the side assistant, distance sensor and oxygen sensor in the group of sensor components.

For the following components, the present analysis could not indicate a clear benefit or disadvantage of dismantling, as the profitability depends on the vehicle type and dismantling time: the heating blower and starter in the group of engine components, and engine control, transmission control, drive control and chassis control in the group of control components.

For the other ELV components, dismantling is not profitable with the Czech labour cost of 10.00 €/h and current material prices. These include the servomotor and wiper motor in the group of engine components, and CD changer, TV tuner and radio control in the group of control components. An increase of 50% in material prices may shift the dismantling revenue from negative to positive for the servomotor and wiper motor of some vehicle models.

4. Summary and Discussion

The economic viability of dismantling electronic components for material recycling was evaluated for Germany, the Netherlands, Finland, the Czech Republic and Spain. The countries selected for the analysis represent different parts of the EU and differ with respect to the size and density of the population, average labour costs and ELV fleet, etc.

Metal scrap prices depend on several factors including, e.g., the quality of the obtained scrap and the transportation distance. The volatility of scrap prices substantially impacts material revenues. Between 2011 and 2019, the price of steel scrap on the German market fluctuated between 150 and 370 €/t while the price of aluminium scrap decreased from 1000 €/t in 2017 to 400 €/t in 2019 [11]. The price range for PCBs, which typically contain the highest quantity of precious metals (Au, Ag, Pd), depend on the quality of the PCB. In the present analysis it is assumed that PCB quality is closer to the lower end of the range of values according to previous analyses by, e.g., [22].

Material revenues from the dismantled components is primarily based upon the value of Cu, Al and PCBs. Copper is the most valuable material in most components in the engine group, whereas Al and PCBs are the most valuable materials in the group of control components. Printed circuit boards are found in nearly all electronic components, especially those in the control group. Printed circuit boards contain numerous precious metals/critical raw materials, of which the most valuable are gold, silver and palladium.

Critical raw materials (CRMs) also exist in other ELV components. For example, neodymium (Nd) and dysprosium (Dy) are used in permanent magnets, and various rare earth elements (REE) are used in liquid crystal display (LCD) and light-emitting diode (LED) displays as well as other components. The CRM content in different ELV components typically varies from milligrams to grams and is typically low with respect to the total mass of the component [22]. As the recoverable amounts of CRMs in the almost all ATFs with moderate throughput is economically insignificant and commercial recovery plants remain rare, CRMs such as Nd and REEs have not been taken into account in the present analysis. Research and development on recycling processes for, e.g., Nd magnets and REEs is progressing and these elements could provide additional value if economic recovery processes are available in the future. Furthermore, recovering scarce metals from ELVs could contribute to the EU's resource resilience. However, economic extraction of CRMs, which are present in very low concentrations within electronic components, remains challenging and public economic incentives for recovering scarce elements from ELVs may be required to promote CRM recovery from ELVs. Neither the current ELV directive nor the WEEE directive provide incentives, as these do not target scarce metals specifically but focus on total recycling rates.

There are significant differences in labour costs across Europe, with hourly labour costs ranging from 5.40 to 43.50 €/h [8]. In countries where labour costs are lower, manual dismantling and thus also material recovery from electronic components is profitable for a wider range of components. The higher labour costs in western and northern European countries (31.00–32.00 €/h estimated for ATFs) prohibits wider material recovery from electronic components. Where labour costs are high, manual dismantling of components is economical for relatively few components, such as the inverter, oxygen sensor, side assistant sensor, distance and near distance sensors. For some vehicle models, component dismantling can be also profitable for the heating blower, generator, engine and transmission control and start/stop motor.

Spain and the Czech Republic represent the southern and central/eastern regions of Europe where labour costs are on average 30–60% of those in western and northern Europe. Lower labour costs are beneficial for manual component dismantling and thus, more components can be profitably dismantled. In addition to the aforementioned components, dismantling of the drive control, infotainment and chassis control can be profitable depending on the vehicle model and applicable scrap metal prices. If scrap metal prices are higher, even more components can be dismantled in a profitable way.

For many ELV components, the material revenues are so minimal that dismantling yields little to no profit at locally appropriate labour costs without a significant increase in material prices or significantly reduced dismantling times. The components for which significant increases in material prices or reductions in dismantling times would be required include the servomotor, fan motor, wiper motor, CD changer/TV tuner/radio control, and servomotor gear. These particular components are associated with relatively lengthy dismantling times and are largely composed of materials with low scrap value, such as iron/steel and plastics.

In contrast, components for which dismantling is profitable are primarily those with the shortest dismantling times (typically less than two minutes). Rapid dismantling presumes that the ATF knows the location and accessibility of the valuable components. However, information about the content of precious metals and REE in car components are not easily available for ATFs at present. For example, the International Material Data System (IMDS) database that would in principle contain these data is designed for car producers and their suppliers and is currently not available to ATFs. Instead, ATFs use the International dismantling information system (IDIS) database, which provides information about the location of some components in a vehicle and how best to dismantle them but does not contain material compositions of components. One possibility in the future could be to implement an interface between IMDS and IDIS and make information available for ATFs.

The dismantling times and components were assessed for relatively new vehicles (2009–2014) in the present study, representing a future ELV flow. The average scrapping age of ELVs in studied countries are countries is ca. 17–21 years [3,10,23,24]. To avoid underestimation of required labour, the measured dismantling of components from each vehicle type, performed under good conditions, was multiplied with the factor 1.5 [4]. The dismantling time measurements did not per se take into account factors such as different skill levels of employees or learning curves that enable faster dismantling, which causes some uncertainty. All the same, as the profit margin is small for almost all the components, longer dismantling times can easily shift the profitability of component dismantling from positive to negative. Furthermore, the dismantling times vary for the same components in different vehicle models and thus the profitability of dismantling of electronic components needs to be considered on a case by case basis. On average, older ELVs also contain fewer electronics.

A market demand for the dismantled components is a prerequisite for the dismantling of electronic components to be economically viable. From both the waste hierarchy and the ELV directive point of view, reuse of the components has higher priority than material recycling. Because the material values related to most of the ELV components are so minor with respect to the dismantling cost, reuse is typically more profitable if there is a market for the dismantled components. The average scrapping age of ELVs is rather high in the countries evaluated in this report, however, in which case there is a lower demand to reuse dismantled components as spare parts. Thus, the utilization of components from older ELVs typically focus on the material recycling rather than reuse. The economic viability of dismantling requires that there is a market for the components and the price is higher when compared to the vehicle body.

Collection and recycling logistics for dismantled components is also economically challenging. The majority of ATFs are small companies and only a few ATFs dismantle more than 10,000 ELVs/year. Estimated logistics costs of 30.00 €/t assume fully a loaded truck with 10 t of transported weight [4]. However, full load truck transportations may be difficult to achieve in a typical vehicle dismantling facility where material flows are generally small. Thus, it is important to find logistic solutions for small masses of electronic components, such as integration into existing collection systems. Often the recycling of ELVs and WEEE is carried out by the same operators which may also result in synergies in the logistics chain. Logistics costs are also affected by average transportation distances, which vary across Europe.

Changes in the European vehicle fleet and the increasing market share of electric vehicles (EVs) are not considered in detail in the present analysis. The quantities of critical and scarce metals have increased substantially in recent years and vehicles also now include many new metals such as neodymium. Ljunggren Söderman [25] estimated that by 2020 there will be nearly 18,000 t of neodymium in the active vehicle fleet—nine times the amount present in 2000. While the content of neodymium has been assessed to 27–43 g/unit for conventional vehicles registered from 2003 onwards, the neodymium content is 200–661 g/vehicle for EVs [26]. Moreover, the volumes of EVs approaching their end-of-life will increase rapidly in the near future [7] as global EV stock has increased from 17 000 in 2010 to 7.2 million in 2019 [27]. It has been estimated that the amount of EVs requiring end-of-life processing will increase to 200,000 by 2027 in the EU [28]. Electric vehicle batteries contain critical raw materials, most importantly cobalt, and they constitute a significant part of the value of the EV. Separate collection and recycling systems are currently being established for the end-of-life EV batteries.

The fast development of the vehicle fleet has been associated with several material risks Ortego et al. [5] pointed out that this will probably lead to a future supply risk that may hinder the very development of the electric vehicle. At the same time, the recovery of the rare earths does not play a role in the steps of the end-of-life chain of vehicles due to economic viability issues.

Our paper adds to the literature as it is the first detailed analysis of some economic factors which can impede a shift towards more circular practices in this sector.

5. Conclusions

The present analysis considered the material recycling potential of 18 electronic components from ELVs across different European regions, taking into account average local labour costs and recent raw material prices.

The profitability of dismantling different ELV components varies, as it depends on a number of factors and differs depending upon vehicle model. The profit margin is very small for most of the components evaluated here, thus small changes in labour costs and/or material revenues can shift ELV component dismantling from profitable to non-profitable or vice versa. Manual dismantling is generally more beneficial in countries with lower labour costs. The volatility of scrap metal prices also affects the revenues obtained from the recovered materials. Manual dismantling is profitable for only a few components at the higher labour costs in western/northern parts of Europe and current material prices, including the inverter for hybrid vehicles, oxygen sensor, side assistant sensor, distance and near distance sensors. Depending on the vehicle model, labour costs and current material prices, manual dismantling can also be positive for also some other such as the heating blower, generator, starter, engine and transmission control, start/stop motor, drive control, infotainment and chassis control.

The collection and recycling logistics for the dismantled components is challenging as the volumes from typical ATFs are typically low. Thus, close collaboration between ATF and WEEE recyclers is crucial in order to optimize the logistics for dismantled components.

The quantity of electronic components and thus the potential for recovering CRMs from ELVs will increase in the future. Currently, the bottleneck for recovering CRMs such as Nd magnets or REEs from dismantled components is the availability of economical recycling processes for these elements, which are present in very low concentrations. Thus, technological solutions are needed in order to recover critical elements from the electronic components in ELVs. Considering the criticality, i.e., their wider economic importance and high supply risks, such improvements should get a much higher attention in the future.

Supplementary Materials: Country analysis: Ratio of revenues vs. cost of dismantling for focal car parts are available online at https://www.mdpi.com/2071-1050/13/4/1902/s1. Table S1. Ratio of revenues versus cost of dismantling end of life vehicle components. Numbers in green indicate economic benefit, red no economic gain. Germany; Table S2. Ratio of revenues versus cost of dismantling end of life vehicle components. Numbers in green indicate economic benefit, red no economic gain. The Netherlands; Table S3. Ratio of revenues versus cost of dismantling end of life vehicle components. Numbers in green indicate economic benefit, red no economic gain. Finland; Table S4. Ratio of revenues versus cost of dismantling end of life vehicle components. Numbers in green indicate economic benefit, red no economic gain. Czech Republic; Table S5. Ratio of revenues versus s cost of dismantling end of life vehicle components. Numbers in green indicate economic benefit, red no economic gain Spain.

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