European Commission

JRC TECHNICAL REPORT

Material composition trends in vehicles: critical raw materials and other relevant metals

Preparing a dataset on secondary raw materials for the Raw Materials Information System

Amund N. Løvik, Charles Marmy, Maria Ljunggren, Duncan Kushnir, Jaco Huisman, Silvia Bobba, Thibaut Maury, Theodor Ciuta, Elisa Garbossa, Fabrice Mathieux, Patrick Wäger

2021

Joint Research Centre

EUR 30916 EN

Contact information
Name: Fabrice Mathieux
Address: Joint Research Centre
Directorate D – Sustainable Resources
Unit D3 – Land Resources
Via E. Fermi 2749, Building 100, TP 122, I-21027 Ispra (VA) - Italy
Email: Fabrice.MATHIEUX@ec.europa.eu
Tel.: +39 0332 78 92 38

EU Science Hub
https://ec.europa.eu/jrc

JRC126564

EUR 30916 EN

PDF	ISBN 978-92-76-45213-3	ISSN 1831-9424	doi:10.2760/351825

Luxembourg: Publications Office of the European Union, 2021

How to cite this report: Amund N. Løvik, Charles Marmy, Maria Ljunggren, Duncan Kushnir, Jaco Huisman, Silvia Bobba, Thibaut Maury, Theodor Ciuta, Elisa Garbossa, Fabrice Mathieux, Patrick Wäger, *Material composition trends in vehicles: critical raw materials and other relevant metals. Preparing a dataset on secondary raw materials for the Raw Materials Information System*, EUR 30916 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-45213-3, doi:10.2760/351825, JRC126564.

Contents

Acknowledgements

This report and the associated datasets were produced with financial support from the European Commission - Joint Research Centre (service contract number 722515).

Authors

Amund N. Løvik[1], Charles Marmy[1], Maria Ljunggren[2], Duncan Kushnir[2], Jaco Huisman[3], Silvia Bobba[3], Thibaut Maury[3], Theodor Ciuta[3], Elisa Garbossa[3], Fabrice Mathieux[3], Patrick Wäger[1]

[1]Empa, Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, St. Gallen, Switzerland

[2]Chalmers University of Technology, Environmental systems analysis, DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS, 412 96 Göteborg, Sweden

[3]Joint Research Centre, Sustainable Resources Directorate, Via E. Fermi 2749, Building 100, TP 122, I-21027 Ispra (VA) - Italy

Abstract

Previous research efforts have focused on the development of comprehensive and robust datasets on Secondary Raw Materials, as requested in particular in the EU Circular Economy Action Plan (2015). For example, the Horizon 2020 project ProSUM (Prospecting Secondary raw materials in the Urban mine and Mining wastes, 2015-2017) resulted in the creation of the Urban Mine Platform (UMP)[1]. The UMP displays comprehensive data from the RMIS on the European stocks and flows of batteries, electrical and electronic equipment (EEE) and vehicles, as well as the materials, components and chemical elements contained in these stocks and flows. The battery dataset has been updated in 2019 in the Raw Materials Information System (RMIS)[2]

This report presents the approach, the background data and the key results of the update of the UMP data concerning vehicle composition. It discusses in particular the improvement of existing data using recent information and knowledge that has become available since the realisation of ProSUM, and the extension of time series until the year 2023 through extrapolation. New components were also added to the existing dataset. The considered materials in the dataset are: cast and wrought aluminium, mild and high strength steel, cast iron and magnesium alloys. The considered components are: catalytic converter, electrics and electronics, power electronics, battery management systems, induction and permanent magnets electric drive motors. The average mass of each of those materials and components is estimated in vehicles, categorized by vehicle type, fuel type, engine size and mass class, for each year between until 2023. Moreover, the average mass fractions of 16 elements (Ag, Al, Au, Cu, Dy, Fe, La, Mg, Mn, Mo, Nb, Nd, Pd, Pt, Rh, Si) in the materials and components are estimated. This composition data, when combined with data on the fleet of vehicles in the EU, is the basis for datasets on secondary raw materials in vehicles, to be soon featured in an interactive data viewer in the RMIS. The vehicle dataset will not address battery active materials and will have therefore to be looked at in combination with the battery datasets already available on the RMIS[2].

Such updated dataset can be extremely useful to support EU policies, since vehicles and mobility are key products and sectors in the transition towards a low carbon and circular economy.

[1] www.urbanmineplatform.eu [accessed on 20/09/2021]
[2] https://rmis.jrc.ec.europa.eu/apps/bvc/#/v/apps [accessed on 20/09/2021]

1 Introduction

The 'Raw Material Initiative' COM(2008)699 (European Commission, 2008) already identified back in 2008 end-of-life products as being very important sources of secondary raw materials for the EU, including for high-tech metals. The Circular Economy Action Plan COM(2015)614 (European Commission 2015) stated in 2015 that the "*Raw Material Information System will be further developed to improve the availability of data on secondary raw materials and support EU-wide research on raw material flows*". The 2020 Circular Economy Action Plan COM/2020/98 (European Commission 2020) reiterated this policy agenda to establish more circular business models and emphasise more high quality recycling, while focusing special efforts on priority product value chain such as vehicles. The Action Plan in particular established that provisions concerning recycled content for certain materials of components and improving recycling efficiency will be considered during the revision of the end-of-life vehicle Directive planned in 2021-2022 (European Commission 2021). A recent JRC report (European Commission. Joint Research Centre. 2021) has also demonstrated that circular economy strategies have the potential to significantly improve material efficiency of (critical) raw materials contained in vehicles. The current report aims at establishing robust and up-to-date data concerning selected metals and (critical) raw materials contained in vehicles that is the basis of a dataset on secondary raw materials in vehicles. This work was carried out in the context of the JRC 2021-2022 institutional work-programme, through its project "SUstainable and secure sourcing of Raw materials for future competitive and low carbon European strategic VALue chains (SureVAL)". The work was supported by the service contract number 722515.

The Horizon 2020 project ProSUM (2015-2017) resulted in the creation of the Urban Mine Platform (UMP) (www.urbanmineplatform.eu), which displays comprehensive data on the European stocks and flows of batteries, electrical and electronic equipment (EEE) and vehicles[3], as well as the materials, components and chemical elements contained in these stocks and flows. The data on vehicles displayed in the Urban Mine Platform were generated through a combination of data on the number and mass of vehicles (placed on the market, in stock and in waste flows) with data on the composition of vehicles, e.g. the average content of aluminium in each vehicle type. This report summarises work undertaken to update and expand the data on composition of vehicles. This data is now being combined with data on fleets of vehicles in the EU, for the purpose of disseminating data on (secondary) raw materials in vehicles in the Raw Materials Information System (RMIS), developed and maintained by the Joint Research Centre (JRC) of the European Commission.

The main goals of the work were to extend time series data until the year 2023 and to update the data with new information that has become available since the launch of the UMP. For example, in

[3] *Vehicles* here refers to passenger cars (M1) and vans (N1).

the past few years, several studies have been undertaken to sample and analyse electrical and electronic devices contained in cars (Yano et al. 2019; Nguyen et al. 2019; 2020; Groke et al. 2017). In the process of updating and expanding the data, substantial changes were also made to further harmonise the structure of the data and add more information on specific components, including the battery management system (BMS) and power electronics (PE) of hybrid (HEV), plug-in hybrid (PHEV) and full electric vehicles (BEV)[4]. In the following chapters, we describe the general approach for obtaining and estimating data on the composition of vehicles, the data sources, the main findings compared to what was known when the Urban Mine Platform was launched. Visualisations of some example data are also included in an Annex.

[4] HEVs, PHEVs and BEVs will be collectively referred to as xEVs.

2 Approach and data sources

2.1 General approach

2.1.1 Vehicle keys

Vehicles were categorised using the vehicle keys defined in ProSUM, which are defined by four categories of characteristics, stemming from Eurostat vehicle statistics, listed below.

- ***Type***: unknown, car or van
- ***fuel type***: unknown, petrol, diesel, LPG (Liquified Petroleum Gas), NG (Natural gas), HEV, PHEV, BEV/fuel cell and other
- ***engine size***: unknown, <1400 cm3, 1400-2000 cm3, >2000 cm3, no cylinder
- ***mass***: unknown, <1000 kg, 1000-1249 kg, 1250-1500 kg, >1500 kg.

All possible combinations of those characteristics gives 675 different possible vehicle keys. The majority of these vehicle keys represent unlikely or in some cases impossible combinations of characteristics (e.g. *no cylinder* is only relevant for BEV). However, for consistency in the structure of the data, they are all included in the final dataset.

As an additional characteristic, vehicles are categorised based on their ***cohort***, which is defined as the year they were placed on the market (approximately the model year of the vehicle). It ranges between 1980 and 2023. In total, this gives 675*44 = 29700 different categories of vehicles, which in principle have different material compositions that we may attempt to quantify.

2.1.2 Parameters to quantify

In ProSUM, the composition data for vehicles were prepared in a flexible structure, with a different set of parameters for each component and material. For example, while for aluminium alloys we quantified their mass per vehicle and mass fractions of elements in the alloys, for catalytic converters we quantified the number of catalytic converters per vehicle (effectively the share of vehicles that have a catalytic converter) and the mass of each element per catalytic converter. This flexible approach led to a somewhat complicated data structure that was not straight-forward to convert into a single dataset[5].

To facilitate further work with the data and comparisons between different materials and components, we have now harmonised the approach between all materials and components to follow the same structure. For each component and material, we now quantify two parameters:

- The mass of the component or the material per vehicle, $M_{c,v,t}$

[5] In ProSUM this was nevertheless achieved through the use of a unified data model.

- The mass fraction of each element in each material and component, $w_{e,c,v,t}$

The subscripts specify the material or component (*c*), the vehicle type (*v*), the cohort (*t*) and the element (*e*). With these two parameters, we can easily calculate the following:

- The mass of each element contained in material or component *m* per vehicle:

$$m_{e,c,v,t} = M_{c,v,t}\, w_{e,c,v,t}$$

- The total mass of each element per vehicle

$$m_{e,v,t} = \sum_{c} m_{e,c,v,t}$$

These four parameters are provided in the attached dataset.

2.1.3 Selection of materials, components and elements

In addition to the nine components and material that were included in ProSUM, we also included here the battery management system, induction drive motor and power electronics for xEVs as three separate components[6]. Power electronics here includes the inverter, DC-DC converter, on-board charger and related controllers. We included 16 different chemical elements; all of them were also included in ProSUM. The following table presents the full lists of materials, components and elements as well as which elements were quantified in each material/component.

Table 1. Materials, components and elements included in the dataset.

	MATERIALS/COMPONENTS: **mass/kg**	ELEMENTS: **mass fraction/ppm**															
		Ag	Al	Au	Cu	Dy	Fe	La	Mg	Mn	Mo	Nb	Nd	Pd	Pt	Rh	Si
VEHICLE (675 keys, 1980-2023)	Cast aluminium		x		x		x		x	x							x
	Wrought aluminium		x		x		x		x	x							x
	Mild steel				x		x			x							x
	High strength steel				x		x			x	x	x					x
	Cast iron				x		x			x							x
	Magnesium alloys		x						x	x							
	Catalytic converter							x						x	x	x	
	Electrics and electronics	x		x	x	x		x					x	x			
	Power electronics (xEV)	x		x	x									x			
	Battery management system (xEV)	x		x	x									x			
	Drive motor, induction (xEV)				x												
	Drive motor, PM (xEV)				x	x							x				

2.1.4 Data extrapolations to all vehicle keys

It is obviously not possible to quantify the composition of 29700 different categories of vehicles individually, especially considering that comprehensive, public data sources on vehicle composition

[6] Batteries contained in vehicles are excluded from the dataset as they are already well characterised in another RMIS dataset : https://rmis.jrc.ec.europa.eu/apps/bvc/#/v/apps

are limited to a small number of scientific papers and market reports that focus on selected materials, elements or components, and usually do not include any temporal analysis. Our approach is therefore based on quantifying relevant parameters (e.g. the total mass of electrics and electronics) for an average or example vehicle, and then extrapolate this to other vehicle categories using information about key differences that depend on selected characteristics of the vehicles. For example, it is often relevant to scale the mass of materials or components per vehicle by the vehicle mass category.

For each parameter, the level of differentiation between different vehicle keys and cohorts depends on its relevance and data availability. The most detailed data (e.g. mass of aluminium alloys per vehicle) were differentiated by three characteristics: vehicle fuel type, vehicle mass or engine size, and vehicle cohort. The least detailed data (e.g. mass fractions of elements in aluminium alloys) were not differentiated between different vehicle types at all.

The extrapolation process used to populate the entire dataset means that many values are repeated for different categories of vehicles, e.g. when no data on time dependency or fuel type dependency were identified. In these cases, the supplied dataset includes an artificial level of detail, which can be easily identified as repetition of identical data. In general, when data for two vehicle categories are identical, it means that we have no reason to believe that there is a systematic difference between these vehicle categories for that particular parameter, or insufficient knowledge of the difference. In some cases, it is not meaningful to present results at the full level of detail. Particularly, we have not included any distinction between cars and vans other than what is captured by their respective mass/engine size/fuel type categories, and we have not included any differentiation between petrol, LPG, NG, unknown and *other* fuel types. When presenting results, it therefore makes sense to aggregate these categories. Despite these limitations, we assert that for the quantified parameters, the most significant and important differences are indeed captured in the dataset. In Table 2, we present an overview of the vehicle characteristics that the data depend on for each material and component. An *x* in this table indicates that for the given material or component and variable, there is a differentiation between at least two categories of the indicated vehicle characteristic. For example, the element mass fractions in catalytic converters are different for different fuel types.

Table 2. Dependencies of variables on vehicle characteristics (x: at least one category is different from the rest)

	Dependencies							
	material or component mass				element mass fractions			
	cohort	fuel type	engine size	vehicle mass	cohort	fuel type	engine size	vehicle mass
Cast aluminium	x	x	x	x*				
Wrought aluminium	x	x	x	x*				
Mild steel	x	x		x				
High strength steel	x			x				
Cast iron	x	x		x				
Magnesium alloys		x						
Catalytic converter	x	x	x			x		
Electrics and electronics	x	x		x	x	x		
Power electronics (xEV)		x						
Battery management system (xEV)		x		x				
Drive motor, induction (xEV)		x		x				
Drive motor, PM (xEV)		x		x				

* Only for xEVs

2.2 Approach and data sources for individual materials and components

2.2.1 Steel and iron

Data on the content of steel and iron were in ProSUM based on a scientific publication with data obtained through market reports (Modaresi et al. 2014). For the updated RMIS data, ProSUM data were changed from 2011 onwards based on a recent market study that includes forecasts (DuckerFrontier 2019). Relative changes in content of standard steel, high strength steel and cast iron were calculated based on data on North American light vehicles. Data specifically for the European market are not available, but it can be assumed that the general technological trends are similar. Both standard steel and high strength steel (HSS) have been decreasing in recent years due to the increased use of advanced high strength steel (AHSS) and ultra-high strength steel (UHSS) that fulfil the same demands with smaller mass, as well as increasing use of aluminium alloys. This trend is expected to continue. The increasing use of AHSS and UHSS are not visible in the data, since they are included among HSS and the net effect is an overall decrease of HSS. Using data from Modaresi et al. on the steel and iron content in different subsystems of vehicles (Modaresi et al. 2014), we estimated that BEVs contain 14% less mild steel and 85% less cast iron than Internal Combustion Engine Vehicle (ICEVs), due to the absence of the combustion engine. The average composition (element mass fractions) of standard steel, HSS and cast iron was not changed compared to ProSUM data.

2.2.2 Aluminium alloys

Data on aluminium content in vehicles were in ProSUM estimated until 2015 from a scientific publication and two market reports (Modaresi, Løvik, and Müller 2014; Ducker Worldwide 2012; 2014). Here, an addition was made to include the battery casing for HEVs, PHEVs and BEVs (this was excluded from vehicles data in ProSUM). Increased resolution between different size categories of HEVs, PHEVs and BEVs was also included. Finally, the projections until 2023 were made based on the latest available market report (European Aluminium and DuckerFrontier 2019). In general, aluminium content is expected to continue increasing for all vehicle types due to more use of wrought aluminium in body and closures. However, the largest overall increase is expected to come from an increased penetration of PHEVs and BEVs, which in general contain substantially more aluminium due to the relatively heavy battery casing. The average composition of cast and wrought aluminium was not changed compared to ProSUM.

2.2.3 Magnesium alloys

The content of magnesium alloys in vehicles was included in the scope of some studies that focus on aluminium content (DuckerFrontier, The Aluminum Association 2020). However, the average content of magnesium alloys was found to be so low that it is not visible in the results. One study that attempted to calculate a recycling rate for magnesium in the EU collected data on magnesium use in cars and performed an independent estimate using top-down data on production of magnesium castings in the EU (Bell et al., 2017), estimating 2.7 kg per vehicle on average. Other estimates for individual vehicles lie in the range 2-10 kg per vehicle (Field et al. 2017; Ortego et al. 2018; Bell et al., 2017). As an average, we estimate 5.2 kg magnesium alloys per vehicle with internal combustion engine (including HEVs and PHEVs). For BEV, we assumed a magnesium alloy content equal to 20% of the magnesium alloy content in ICEVs, due to the fact that magnesium castings are typically used in components that are specific to internal combustion engines (Field et al. 2017).

2.2.4 Catalytic converter

In ProSUM, catalytic converters were included with two parameters: 1. the number of catalytic converters per vehicle (between 0 and 1), by fuel type and cohort, and 2. the mass of Pt, Pd, Rh, Ce and La per catalytic converter, by engine size and fuel type. The data were obtained from a small number of studies (Hagelüken 2008; Cullbrand and Magnusson 2011; Johnson Matthey 2013; Ministry of Environment Japan 2009; Alonso, Field, and Kirchain 2012; Xu, Yano, and Sakai 2016). In the present study we have refined the approach in the following way. Catalytic converters are now represented with two different parameters: 1. the average mass of catalytic converters per vehicle, by fuel type and cohort, and 2. the mass fractions of Pt, Pd, Rh, Ce and La in catalytic converters, by fuel type. New compared to the ProSUM approach is that now also the total mass of catalytic converters can be computed. In addition, the data now takes into account the historical increase in average mass of catalytic converters to comply with increasingly strict emissions standards. The estimates of average mass of catalytic converters and mass fractions of the elements are based on newly obtained data sources (Zhang et al. 2020; Trinh et al. 2020; Paraskevas, Papoutsi, and Ochsenkühn-Petropoulou 2012; Seo and Morimoto 2017; Walker Emissions Control 2018) as well as the sources used in ProSUM.

2.2.5 Electrical and electronic components (excluding electric drive motor, batteries and power electronics for xEV)

In ProSUM, the mass of selected elements occurring in electrical and electronic components was estimated. Here, we have added an estimate of the total mass of all electrical and electronic components per vehicle using data from studies that were published after the ProSUM work was finished (Groke et al. 2017; Field et al. 2017; Ortego et al. 2018), which together provide data on 12 different common ICEV models. Two of the vehicles are described with data from the International Materials Data System (IMDS) and the remaining 10 were characterised through comprehensive dismantling. The total mass of electrics and electronics is in the range 25 to 82 kg per vehicle, with most observations in the range 29 to 67 kg. The average model year of the vehicles was 2013. Building on work done as part of the EVA project (Restrepo et al. 2019; 2020), we estimated the historical change in total mass of electrical and electronic components per vehicle. These estimates are based on historical data on the market penetration rate (Auto-i-Dat AG 2018; Deutsche Automobil Treuhand GmbH 2016) and average mass (Groke et al. 2017; Restrepo et al. 2020; Nguyen et al. 2019; Yano et al. 2019) of automotive electrics and electronics that emerged in the past three decades.

The mass fractions of Ag, Cu, Pd, La, Nd and Dy in the total electrics and electronics mass were quantified. The approach is different from the approach used in ProSUM, where only the mass of each element per vehicle was quantified and copper was not included (only the total mass of copper per vehicle). Since ProSUM, new research has been published that helps quantify the mass or mass fractions of these elements in vehicle electronics. This includes studies based on sampling and chemical analysis of vehicle components (Groke et al. 2017; Nguyen et al. 2019; Yano et al. 2019; Nguyen et al. 2020) as well as studies based on data from manufacturers (Field et al. 2017; Ortego et al. 2018; Iglesias-Émbil et al. 2020). Additional data sources include the studies that formed the basis for the ProSUM data (Cullbrand and Magnusson 2011; Ministry of Environment Japan 2009; Xu, Yano, and Sakai 2016; Alonso et al. 2012; R. Widmer et al. 2015; Du et al. 2015; Restrepo et al. 2017) as well as other newly identified information (The Martec Group 2017; Zur-Lage 2014).

Compared to the ProSUM approach, the availability of additional data has made it possible to better distinguish between different vehicle types (higher mass of electrics and electronics in heavier cars that are often more luxurious), and to improve the confidence about the data. The new information that has become available since ProSUM has led us to adjust down the estimate of Nd and Dy content in conventional cars. Sampling and analysis of magnets in cars (Nguyen et al. 2019; Yano et al. 2019) has indicated that neodymium magnets are less frequently used than previously assumed.

2.2.6 Electric drive motor/generator

Electric drive motors were not included in ProSUM. The current study distinguishes between permanent magnets motors (PM motors) and induction motors[7] as components. The mass ratio of the elements Nd, Dy and Cu for the former category of motors, and only Cu for the latter are considered.

Electric drive motors are used in HEV, PHEV and BEV in various sizes and characteristics. Electric cars can still be considered as an emerging trend in individual mobility, although its growth is very rapid. As such currently available xEVs display a vast diversity in electric drive motors types. Another consequence of this fact is that there are very few published data on the subject. In order to take this aspect into consideration, the approach used in this study was to consider the 10 most sold models in the first half of 2020 of BEV, HEV and PHEV in EU as representative samples of their respective market segment, whose total size is also known (Bart Demandt 2020b; 2020a; Thomas Gersdorf et al. 2020; Jose Pontes 2020). Those models represent at least half of their market segment. It can thus be assumed that those samples are representative of their overall segment.

Those models were individually studied and sorted by vehicle mass. The characteristics of their electric drive motors were collected, such as torque, power or type, either through technical documentation ('Technical Specs, Dimensions, Fuel Consumption of Cars' n.d.; 'EVSpecifications - Electric Vehicle Specifications, Electric Car News, EV Comparisons' n.d.) or inferred from the mass of the vehicle (Marvin, Helenbrook, and Visser 2017). However, motor mass was not directly available and had to be extrapolated from the torque of PM motors (Nordelöf A et al. 2017; Nordelöf et al. 2018; Bhatt, Mehar, and Sahajwani 2019). The mass of induction motors was estimated using its approximately linear relationship to the mass of a PM motor developing an equivalent torque (Schultz and Huard 2013; J. D. Widmer, Martin, and Kimiabeigi 2015).

HEV and PHEV are using exclusively PM motors. Induction motors are present in some BEVs only. The ratio of induction motors to PM motors is represented through the mass ponderation of each, that could be estimated with the market segment-based approach described above. However, there is not necessarily only one motor per BEV, some models even having one motor of each type (Adams 2020; Marc Amblard 2019). This was taken into account to ponder the mass of each type per vehicle. In

[7] In this study, all "magnetless" electric motors were considered as "induction" motors, since the sense of this distinction is to study the presence of Nd and Dy, present in magnets. An example of magnetless motor that is not *stricto sensu* an induction motor, but considered as such in this study is the brushed synchronous motor of the Renault Zoe, the most sold BEV in the first half of 2020.

other words, the motor mass indicated in the data does not represent an actual motor, but the mass of a motor of a certain type multiplied by the proportion of motors that are of this type in this particular weight category.

The mass ratio of magnets in PM motors as well as the mass ratio of Dy and Nd in rare earths permanent magnets used in the automotive sector have been explored through several studies, whose results were used directly here. The mass ratio of copper in PM motors and induction motors could be retrieved thanks to dismantling data and teardown videos (Groke et al. 2017; Nordelöf et al. 2018; Schultz and Huard 2013; Elwert et al. 2016; Zepf 2013; Yano, Muroi, and Sakai 2015).

BEV and especially PHEV are typically heavier than traditional ICEV. Due to this fact, the sampled models did not populate the lighter weight categories. A linear relation between vehicle mass and total torque was used to interpolate or extrapolate the data. It is moreover assumed that the parameters considered regarding electric drive motors remain constant in time.

2.2.7 Power electronics for HEVs, PHEVs and BEVs

Power electronics for HEVs, PHEVs and BEVs were not included as a separate component group in ProSUM (elemental contents were implicitly accounted for in the Electric and electronic system (EES) component group). Due to their importance for material content, power electronics are here included separately from other electrical and electronic components. Power electronics here means collectively the inverter, DC-DC (high to low voltage) converter, on-board charger (in PHEVs and BEVs only) and related controllers. These devices and the functions they provide are, in different xEV models, integrated to variable degrees with each other and the electric drive motor. Therefore, it makes sense to group them into one component. Data on the mass of some power electronics modules as well as on-board chargers were found from several sources, including research publications with data from samples or from manufacturers, manufacturer web sites and teardown videos (Groke et al. 2017; Elwert et al. 2015; Bulach et al. 2018; Reimers et al. 2019; jehugarcia 2015; Innoelectric 2020; Ficosa 2020). Power electronics modules mass (including inverter, controllers and usually DC-DC converter) ranged from 6 to 17 kg (average 13 kg), while on-board charger mass ranged from 4.5 to 18 kg (average 10 kg). No systematic difference between the mass of HEV, PHEV and BEV power electronics modules was found. Although there is probably a trend of increasing integration, amongst others to reduce the total mass and volume, it was not possible to obtain a quantitative estimate of this trend.

Three publications providing data on inverter composition were found, including overall breakdown into main materials and components (Yano et al. 2019; Elwert et al. 2015; Bulach et al. 2018), as well as detailed chemical analysis of element content in the printed circuit boards (Yano et al. 2019; Bulach et al. 2018). All examples of power electronics modules that were identified included a relatively heavy aluminium casing (around 50% of the mass on average). Printed wiring boards constituted around 5% of the total mass, and copper constituted around 11% of the mass. Printed circuit boards from inverters were found to contain moderate amounts of Ag (700 ppm), Au (110 ppm) and Pd (70 ppm). Separate composition data for on-board chargers were not identified.

Based on the collected data, it was estimated that HEVs contain on average 14 kg of power electronics modules, while PHEVs and BEVs contain on average 24 kg of power electronics modules. On average, these components were estimated to contain 11 % Cu, 35 ppm Ag, 5 ppm Au and 4 ppm Pd.

2.2.8 Battery management system (BMS) for traction batteries

Battery management system (BMS) for traction batteries in HEVs, PHEVs and BEVs was not included as a separate component in ProSUM (element contents such as Ag and Au were implicitly accounted for in the EES component group). Here, the BMS is included as a separate component group that includes printed circuit boards, cables and connectors inside the battery pack. A small amount of data on typical BMS mass and composition was identified. Estimates of BMS mass range from around 1.5% up to 9% of total battery pack mass, with most values in the range 2-4% (Elwert et al. 2015; Buchert et al. 2011; Majeau-Bettez, Hawkins, and Strømman 2011; Kushnir 2015; Yuan et al. 2017). Comparison between different sources is difficult, since it is often not clearly specified what is accounted for under the relevant category (e.g. "BMS", "electronics"). Here, it was estimated that the BMS (including cables, connectors and printed circuit boards (PCBs)) accounts for 3.6% of the battery pack mass on average. The BMS mass was then estimated for different mass categories of HEVs, PHEVs and BEVs using estimates of the total battery pack mass in these different vehicle types (Wagner et al. 2019).

According to the few data that were identified on BMS composition, the PCBs constitute around 17% of the BMS mass and contain a substantial amount of Ag (2000 ppm) and smaller amounts of Au (24 ppm) and Pd (36 ppm)(Yano et al. 2019; Buchert et al. 2011). Also accounting for cables and connectors that contain a large amount of copper, we estimated here that the BMS overall contains 74% Cu, 340 ppm Ag, 4 ppm Au, and 6 ppm Pd, by mass.

2.3 Elements that were excluded due to lack of data

The present vehicle dataset does not address battery active materials and should therefore be looked at in combination with the battery datasets already available on the RMIS (Joint Research Centre, 2021). The following two elements are also excluded.

2.3.1 Gallium

We identified six studies that provide information on gallium content in vehicles, either through sampling and analysis of electrical and electronic components (R. Widmer et al. 2015; Nguyen et al. 2020; Yano et al. 2019), or through extraction of data from the materials databases of car manufacturers using the International Materials Data System (IMDS) (Cullbrand and Magnusson 2011; Ortego et al. 2018; Iglesias-Émbil et al. 2020). The observed mass of gallium per vehicle ranges from 0.001 g to 0.6 g. Due to the wide variability, leading to high uncertainty for an average estimate of gallium content in cars, it was decided to not include gallium in the final dataset.

2.3.2 Titanium

Very little information on titanium metal use in automobiles was found. The use of titanium alloys in automobiles has generally been restricted to niche applications due to its high costs compared to competing materials like stainless steel (Sachdev et al. 2012). Since no quantitative data on the use of titanium alloys in cars were identified, it was decided to not include titanium in the data for the RMIS.

3 Uncertainties

The data prepared in this project have variable degrees of uncertainty due to differences in data availability. Due to the diversity of the primary data (e.g. collected using very different methods) and the small amount of data available, statistical analysis to estimate uncertainties is not feasible.

In general, the relative uncertainty is higher for components, materials or elements with lower mass per vehicle. This is both due to the quantity of data available to inform our estimates as well as the inherent uncertainties of primary data collection. For example, chemical analysis is more challenging for metals that occur in low mass fractions (e.g. Au and Ag) compared to metals that occur at higher mass fractions (e.g. Cu). We consider data on steel and aluminium content the most reliable data, since it is ultimately based on a comprehensive analysis of many different representative vehicle models. The least reliable data are the mass fractions of rare metals, such as precious metals and rare earth elements, due to the small amount of primary data, and potentially high variability between different vehicle models. For example, observations of gold content range from around 0.2g per vehicle (R. Widmer et al. 2015) up to 7g per vehicle (Cullbrand and Magnusson 2011). The lower end estimates almost certainly include some underestimation due to not capturing all relevant components, while the higher end estimates might be high-end vehicles with much higher content than the average car. This range gives an indication of the variability between different vehicle models. However, the uncertainty for the dataset presented here, which represents *average* values for the entire vehicle fleet, is considered lower.

In Table 3, we present a qualitative indication of the uncertainty for each element and some additional comments about interpretation of the final results.

Table 3 Qualitative indication of uncertainty and considerations when interpreting results.

element	*uncertainty*	*considerations when interpreting results*
Ag	high	Ag is often underestimated in chemical analyses due to difficulties in measurement. This effect may have propagated to the data presented here. There is little information about changes in Ag content in electronics over time, although it is reasonable to expect that there have been changes.
Al	low	Aluminium content in battery cell casings and cathodes is not included in the data. Aluminium in electric drive motor casings is not included either. Battery pack casings and content in module periphery are included.
Au	high	There is little information about changes in Au content in electronics over time, although it is reasonable to expect that there have been substantial changes.
Cu	medium	Copper content in steel alloys and iron is impurities.
Dy	medium	The quantification of dysprosium content is often dependant on the neodymium content, because both elements are usually used concurrently in permanent magnets and are estimated at the same time, with the dysprosium content being considered as a fraction of the neodymium content.
Fe	low	
La	medium	
Mg	medium	No temporal changes in magnesium alloy content per vehicle is included in the data, although there is probably an upward trend.
Mn	medium	
Mo	high	Data on typical Mo content in vehicles is very limited. The downward trend in Mo content per vehicle is caused by the estimated decrease of high-strength steels. However, within this trend there is an increased use of advanced high strength steel, which may contain more Mo. This is not captured in the data.
Nb	high	Data on typical Nb content in vehicles is very limited. The downward trend in Nb content per vehicle is caused by the estimated decrease of high-strength steels. However, within this trend there is an increased use of advanced high strength steel, which may contain more Nb. This is not captured in the data.
Nd	medium	
Pd	medium	
Pt	medium	
Rh	medium	
Si	medium	

4 Results and conclusions

The main result of the data updates is the new dataset that is to be published as secondary raw material dataset on the Raw Material Information System. Due to the large amount of data, we do not present the results in detail here. However, some figures presenting the mass of each element for 5 example vehicles types, showing the contribution from different materials and components, are included in the Annex. The new dataset has provided better insights into the differences between conventional vehicles and xEVs. Changes in the material flows related to the European vehicle fleet will be driven mainly by the trend of increased electrification, rather than changes in the composition of individual vehicle types. In particular, electrification will lead to substantial increases in the use of Al, Ag, Cu, Nd and Dy (in addition to battery cell elements such as Li and Co), and substantial reductions in the use of Fe, La, Pd, Pt and Rh.

Aluminium alloys

The trend of increasing aluminium use is expected to continue at a moderate pace for all vehicle types, due to substitution for steel especially in body and closures. This mainly affects the use of wrought aluminium. HEVs, PHEVs and BEVs on average contain substantially more aluminium than pure ICEVs, the largest contribution coming from the casing of the traction batteries, which is usually made out of wrought aluminium. The lack of aluminium engine components in BEVs represents a reduction of cast aluminium compared to ICEVs, however, this is more than compensated for by other cast components in BEVs, such as the housing of the power electronics, the electric drive motors and the on-board charger.

Steel and iron

It is expected that the mass of mild steel and high-strength steel in cars continues to decline until 2023, the main reason being that steel alloys are substituted by lighter options, including aluminium alloys and advanced high strength steel (AHSS). BEVs in general contain less steel, as a large portion of the steel in internal combustion engine vehicles (ICEVs) is used in powertrain components.

Magnesium alloys

No quantitative information on trends in magnesium use were identified. Compared to the ProSUM data, the main difference is that we now make a differentiation between BEVs and other vehicle types, since magnesium alloys seem to primarily be used in engine components. In general, the identification of additional data that matches with former estimates (around 5 kg magnesium alloys per car on average), improves our confidence in these data.

Catalytic converter

New compared to ProSUM is that the mass of catalytic converters is now also included, considering also the historical progressive increase in catalytic converter mass to comply with increasingly strict emissions regulations. In general however, no important current trends were identified, as the regulations have not changed substantially since 2006. Electrification and the recently declining market share of diesel will have a huge impact on the material flows of platinum group metals.

Electrics and electronics

In the new dataset we also quantify the total mass of electrics and electronics per vehicle (this was not included in ProSUM), differentiating between different fuel types and different mass categories. Several new studies on the content of precious metals and rare earth elements in car electronics have been published since ProSUM. In general, this led to a reduced estimate of the content of these elements in car electronics. For example, for a 2015 vehicle with all characteristics unknown, we now estimate 1.5 g Au per vehicle, while in ProSUM we estimated 2.1 g per vehicle. The largest reduction was made for Nd, which was estimated at 107 g in a 2015 vehicle with all characteristics unknown, while now we estimate 44 g.

Electric drive motors

Electric drive motors were not included in ProSUM. PHEV and HEV use exclusively Permanent Magnets Motors, as well as the majority of BEV on the market. The rest of the BEV use Induction Motors. PM motors contain Nd and Dy in their magnets, as well as significant amounts of copper for their wiring. Induction motors do not use permanent magnets, and thus contain no Nd and Dy, but more copper for their additional electromagnets. Induction motors are heavier than PM motors for a given torque or car weight. Since xEVs are still very new on the market, no significant change in time of the parameters have been considered.

Power electronics

Power electronics (inverters, DC-DC converters, on-board chargers and related controllers) were not included as a separate component in ProSUM. Power electronics were found to contain substantial amounts of Ag, which was accounted for under electrics and electronics in ProSUM. However, in ProSUM we estimated a bigger difference in Ag content between ICEVs and xEVs compared to what can be accounted for by power electronics and the BMS, leading to a lower total Ag content estimate for xEVs compared to ProSUM data.

Battery management system

The battery management system was not included as a separate component in ProSUM. The BMS contains a large amount of Cu, which was simply accounted for under Cu total in ProSUM. Considering the amounts of Cu in each component (including power electronics and BMS), we ended up with a somewhat lower total Cu mass per vehicle compared to ProSUM, e.g. 48 kg in total for a BEV, compared to 58 kg in ProSUM. This may also be due to an ongoing trend of component integration and reduction in the amounts of copper cables and connectors (The Martec Group 2017).

A dataset on vehicle compositions was prepared as MS Excel files and it is being combined with EU data on vehicle fleets so that data on raw materials in vehicles put on the market, in stocks and as waste flows (i.e. secondary raw materials) can be visualised into a specific “vehicle” data viewer of the Raw Material Information System. The present vehicle dataset does not address battery active materials and should therefore be looked at in combination with the battery datasets already available on the RMIS (Joint Research Centre, 2021). This dataset improves the knowledge on secondary raw materials in the EU, and hence contributes to the development of the knowledge pillars of the Circular Economy Action Plans. Such updated dataset can be extremely useful to support policies since vehicles and mobility are key products and sectors in the transition towards a low carbon and circular economy.

References

Adams, Eric. 2020. 'The Secrets of Electric Cars and Their Motors: It's Not All About the Battery, Folks'. The Drive. 17 September 2020. https://www.thedrive.com/tech/17505/the-secrets-of-electric-cars-and-their-motors-its-not-all-about-the-battery-folks.

Alonso, Elisa, Frank R. Field, and Randolph E. Kirchain. 2012. 'Platinum Availability for Future Automotive Technologies'. *Environmental Science & Technology* 46 (23): 12986–93. https://doi.org/10.1021/es301110e.

Alonso, Elisa, Timothy Wallington, Andrew Sherman, Mark Everson, Frank Field, Richard Roth, and Randolph Kirchain. 2012. 'An Assessment of the Rare Earth Element Content of Conventional and Electric Vehicles'. *SAE Int. J. Mater. Manuf.* 5 (2): 473–77. https://doi.org/10.4271/2012-01-1061 saematman.saejournals.org.

Auto-i-Dat AG. 2018. 'Autohandel'. Produkte. 2018. https://www.auto-i-dat.ch/produkte/autohandel.

Bell, N., Waugh, R., Parker, D.aker, Katie, and Peter Lee. 2017 'Magnesium Recycling in the EU: Material Flow Analysis of Magnesium (Metal) in the EU and Derivation of the Recycling Rate', 87p, https://cdn.ymaws.com/www.intlmag.org/resource/resmgr/sustainability/FullRprt_EU-Mg-recycling_201.pdf [accessed on 29/11/2021].

Bart Demandt. 2020a. 'European Sales 2019 EV and PHEV'. *Carsalesbase.Com* (blog). 12 February 2020. https://carsalesbase.com/european-sales-2019-ev-phev/.

Bart Demandt.. 2020b. 'European Sales 2020 First Half EV and PHEV'. *Carsalesbase.Com* (blog). 27 August 2020. https://carsalesbase.com/european-sales-2020-first-half-ev-phev/.

Bhatt, Pooja, Hemant Mehar, and Manish Sahajwani. 2019. 'Electrical Motors for Electric Vehicle – A Comparative Study'. SSRN Scholarly Paper ID 3364887. Rochester, NY: Social Science Research Network. https://doi.org/10.2139/ssrn.3364887.

Buchert, Matthias, Wolfgang Jenseit, Cornelia Merz, and Doris Schüler. 2011. 'Ökobilanz Zum "Recycling von Lithium-Ionen-Batterien" (LithoRec)'. https://www.oeko.de/oekodoc/1500/2011-068-de.pdf.

Bulach, Winfried, Doris Schüler, Guido Sellin, Tobias Elwert, Dieter Schmid, Daniel Goldmann, Matthias Buchert, and Ulrich Kammer. 2018. 'Electric Vehicle Recycling 2020: Key Component Power Electronics,Electric Vehicle Recycling 2020: Key Component Power Electronics'. *Waste Management & Research* 36 (4): 311–20. https://doi.org/10.1177/0734242X18759191.

Cullbrand, Klas, and Olof Magnusson. 2011. 'The Use of Potentially Critical Materials in Passenger Cars'. Master's Thesis, Gothenburg, Sweden: Chalmers University of Technology.

Deutsche Automobil Treuhand GmbH. 2016. 'DAT Reports 2002-2016'. Ostfildern, Germany. https://www.autokiste.de/service/dat-report/.

Du, Xiaoyue, Eliette Restrepo, Rolf Widmer, and Patrick Wäger. 2015. 'Quantifying the Distribution of Critical Metals in Conventional Passenger Vehicles Using Input-Driven and Output-Driven Approaches: A Comparative Study'. *Journal of Material Cycles and Waste Management* 17 (2): 218–28. https://doi.org/10.1007/s10163-015-0353-3.

Ducker Worldwide. 2012. 'EAA Aluminium Penetration in Cars: Final Report. Public Version'. http://www.european-aluminium.eu/wp-content/uploads/2012/04/EAA-Aluminium-Penetration-in-cars_Final-Report-Public-version.pdf.

Ducker Worldwide.2014. ‘2015 North American Light Vehicle Aluminum Content Study’. https://www.autonews.com/assets/PDF/CA95065611.PDF.

DuckerFrontier. 2019. ‘The Evolution and Outlook for Steel in North American Light Vehicles’.

DuckerFrontier, The Aluminum Association. 2020. ‘2020 North America Light Vehicle Aluminum Content and Outlook: Final Report Summary: July 2020’. https://1pp2jy1h0dtm6dg8i11qjfb1-wpengine.netdna-ssl.com/wp-content/uploads/2020/08/DuckerFrontier-Aluminum-Association-2020-Content-Study-Summary-Report-FINAL.pdf.

Elwert, Tobias, Daniel Goldmann, Felix Roemer, and Sabrina Schwarz. 2016. ‘Recycling of NdFeB Magnets from Electric Drive Motors of (Hybrid) Electric Vehicles’. *Journal of Sustainable Metallurgy*. https://doi.org/10.1007/s40831-016-0085-1.

Elwert, Tobias, Daniel Goldmann, Felix Römer, Matthias Buchert, Cornelia Merz, Doris Schueler, and Juergen Sutter. 2015. ‘Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles’. *Recycling* 1 (1): 25–60. https://doi.org/10.3390/recycling1010025.

European Aluminium and DuckerFrontier. 2019. ‘Aluminium Content in European Passenger Cars - Public Summary’. https://www.european-aluminium.eu/media/2802/aluminum-content-in-european-cars_european-aluminium_public-summary_101019-1.pdf.

European Commission. 2008. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL The Raw Materials Initiative — Meeting Our Critical Needs for Growth and Jobs in Europe*. *COM(2008)699*. https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2008)699&lang=en.

European Commission. 2015. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Closing the Loop - An EU Action Plan for the Circular Economy*. *COM(2015)614*. https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2015)614&lang=en.

European Commission, 2020. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A New Circular Economy Action Plan For a Cleaner and More Competitive Europe*. *COM(2020) 98*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

European Commission, 2021. *COMMISSION STAFF WORKING DOCUMENT EVALUATION of Directive (EC) 2000/53 of 18 September 2000 on End-of-Life Vehicles*. *SWD(2021) 60*. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/1912-End-of-life-vehicles-evaluating-the-EU-rules_en.

European Commission. Joint Research Centre. 2021. *Sustainable Use of Materials through Automotive Remanufacturing to Boost Resource Efficiency in the Road Transport System (SMART).* LU: Publications Office. https://data.europa.eu/doi/10.2760/84767.

‘EVSpecifications - Electric Vehicle Specifications, Electric Car News, EV Comparisons’. n.d. EVSpecifications. Accessed 12 January 2021. https://www.evspecifications.com.

Ficosa. 2020. ‘On Board Charger’. Ficosa. 2020. https://www.ficosa.com/products/emobility/on-board-charger/.

Field, Frank R., Timothy J. Wallington, Mark Everson, and Randolph E. Kirchain. 2017. ‘Strategic Materials in the Automobile: A Comprehensive Assessment of Strategic and Minor Metals Use in Passenger Cars and Light Trucks’. *Environmental Science & Technology* 51 (24): 14436–44. https://doi.org/10.1021/acs.est.6b06063.

Groke, Matthias, Wolfgang Kaerger, Knut Sander, and Maik Bergamos. 2017. 'Optimierung Der Separation von Bauteilen Und Materialien Aus Altfahrzeugen Zur Rückgewinnung Kritischer Metalle (ORKAM)'. Dessau-Rosslau, Germany: Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/1/publikationen/2017-01-11_texte_02-2017_orkam_endbericht.pdf.

Hagelüken, Christian. 2008. 'Recycling von Autoabgaskatalysatoren'. In *NE-Metall-Recycling - Grundlagen Und Aktuelle Entwicklungen*, 1st ed. Clausthal-Zellerfeld: GDMB Medienverlag.

Iglesias-Émbil, Marta, Alicia Valero, Abel Ortego, Mar Villacampa, Josep Vilaró, and Gara Villalba. 2020. 'Raw Material Use in a Battery Electric Car – a Thermodynamic Rarity Assessment'. *Resources, Conservation and Recycling* 158 (July): 104820. https://doi.org/10.1016/j.resconrec.2020.104820.

Innoelectric. 2020. 'On-Board Charger'. *Innolectric* (blog). 2020. https://innolectric.ag/on-board-charger-2-2/?lang=en.

jehugarcia. 2015. 'Delta Energy Systems 3.3kw Ev Charger Teardown'. 5 December 2015. https://www.youtube.com/watch?v=kzpDVhljQmk.

Johnson Matthey. 2013. 'Platinum 2013 - Interim Review'. http://www.platinum.matthey.com/documents/market-review/2013-interim/full-review/english.pdf.

Joint Research Centre. 2021. 'RMIS – Raw Materials in the Battery Value Chain'. Accessed 31 August 2021. https://rmis.jrc.ec.europa.eu/apps/bvc/#/v/apps.

Jose Pontes. 2020. 'Record EV Sales In Europe'. CleanTechnica. 30 July 2020. https://cleantechnica.com/2020/07/29/record-ev-sales-in-europe/.

Kushnir, Duncan. 2015. 'Lithium Ion Battery Recycling Technology 2015: Current State and Future Prospects'. http://publications.lib.chalmers.se/records/fulltext/230991/local_230991.pdf.

Majeau-Bettez, Guillaume, Troy R. Hawkins, and Anders Hammer Strømman. 2011. 'Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles'. *Environmental Science & Technology* 45 (10): 4548–54. https://doi.org/10.1021/es103607c.

Marc Amblard. 2019. 'Tesla Leads in Energy Efficiency by 10 to 30%'. The Urban Mobility Blog. 26 November 2019. https://urbanmobilitydaily.com/tesla-leads-in-energy-efficiency-by-10-to-30/.

Marvin, Russel H., Brian T. Helenbrook, and Kenneth D. Visser. 2017. 'Predicting Motor and Generator Maximum Torque as a Function of Mass'. In *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, 1–6. https://doi.org/10.1109/IEMDC.2017.8002164.

Ministry of Environment Japan. 2009. 'Report on FY2009 Survey to Promote Streamlining of End-of-Life Vehicle Recycling (使用済み自動車再資源化の効率化及び合理化推進調査)'.

Modaresi, Roja, Amund N. Løvik, and Daniel B. Müller. 2014. 'Component- and Alloy-Specific Modeling for Evaluating Aluminum Recycling Strategies for Vehicles'. *JOM* 66 (11): 2262–71. https://doi.org/10.1007/s11837-014-0900-8.

Modaresi, Roja, Stefan Pauliuk, Amund N. Løvik, and Daniel B. Müller. 2014. 'Global Carbon Benefits of Material Substitution in Passenger Cars until 2050 and the Impact on the Steel and Aluminum Industries'. *Environmental Science & Technology* 48 (18): 10776–84. https://doi.org/10.1021/es502930w.

Nguyen, Ruby T., Donna L. Baek, Bryna J. Haile, Mary E. Case, Carson C. Cole, Mike H. Severson, and Liam N. Carlson. 2020. 'Critical Material Content in Modern Conventional U.S. Vehicle Electronics'. *Waste Management* 109 (May): 10–18. https://doi.org/10.1016/j.wasman.2020.04.040.

Nguyen, Ruby T., D. Devin Imholte, Austin C. Matthews, and W. David Swank. 2019. 'NdFeB Content in Ancillary Motors of U.S. Conventional Passenger Cars and Light Trucks: Results from the Field'. *Waste Management* 83 (January): 209–17. https://doi.org/10.1016/j.wasman.2018.11.017.

Nordelöf A, Grunditz E, Tillman A-M, Thiringer T, and Alatalo M. 2017. 'A Scalable Life Cycle Inventory of an Electrical Automotive Traction Machine - Technical and Methodological Description, Version 1.01'. LCI documentation Report No. 2016:4 (1.01). Gothenburg, Sweden: Environmental Systems Analysis & Electric Power Engineering, Chalmers University of Technology.

Nordelöf, Anders, Emma Grunditz, Anne-Marie Tillman, Torbjörn Thiringer, and Mikael Alatalo. 2018. 'A Scalable Life Cycle Inventory of an Electrical Automotive Traction Machine—Part I: Design and Composition'. *The International Journal of Life Cycle Assessment* 23 (1): 55–69. https://doi.org/10.1007/s11367-017-1308-9.

Ortego, Abel, Alicia Valero, Antonio Valero, and Marta Iglesias. 2018. 'Downcycling in Automobile Recycling Process: A Thermodynamic Assessment'. *Resources, Conservation and Recycling* 136 (September): 24–32. https://doi.org/10.1016/j.resconrec.2018.04.006.

Paraskevas, M., K. Papoutsi, and M. Ochsenkühn-Petropoulou. 2012. 'A Novel Way of Sampling Particles Containing Platinum Group Elements from Automobile Catalysts'. *Analytical Letters*. https://www.researchgate.net/profile/Michael_Paraskevas/post/Why_do_automotive_catalytic_converters_contain_three_PGM_metals/attachment/59d61dd879197b807797abb6/AS%3A273674916040730%401442260594861/download/Analytical+letters+2012.pdf.

Reimers, John, Lea Dorn-Gomba, Christopher Mak, and Ali Emadi. 2019. 'Automotive Traction Inverters: Current Status and Future Trends'. *IEEE Transactions on Vehicular Technology* 68 (4): 3337–50. https://doi.org/10.1109/TVT.2019.2897899.

Restrepo, Eliette, Amund N. Løvik, Patrick Wäger, Rolf Widmer, Radek Lonka, and Daniel B. Müller. 2017. 'Stocks, Flows and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles'. *Environmental Science & Technology* 51 (3): 1129–39. https://doi.org/10.1021/acs.est.6b05743.

Restrepo, Eliette, Amund N. Løvik, Rolf Widmer, Patrick Wäger, and Daniel B. Müller. 2019. 'Historical Penetration Patterns of Automobile Electronic Control Systems and Implications for Critical Raw Materials Recycling'. *Resources* 8 (2): 58. https://doi.org/10.3390/resources8020058.

Restrepo, Eliette, Amund N. Løvik, Rolf Widmer, Patrick Wäger, and Daniel B. Müller. 2020. 'Effects of Car Electronics Penetration, Integration and Downsizing on Their Recycling Potentials'. *Resources, Conservation & Recycling: X*, February, 100032. https://doi.org/10.1016/j.rcrx.2020.100032.

Sachdev, Anil K., Kaustubh Kulkarni, Zhigang Zak Fang, Rui Yang, and Vladimir Girshov. 2012. 'Titanium for Automotive Applications: Challenges and Opportunities in Materials and Processing'. *JOM* 64 (5): 553–65. https://doi.org/10.1007/s11837-012-0310-8.

Schultz, Jay W, and Steve Huard. 2013. 'Comparing AC Induction with Permanent Magnet Motors in Hybrid Vehicles and the Impact on the Value Proposition', 15.

Seo, Yuna, and Shinichirou Morimoto. 2017. 'Analyzing Platinum and Palladium Consumption and Demand Forecast in Japan'. *Resources* 6 (4): 61. https://doi.org/10.3390/resources6040061.

'Technical Specs, Dimensions, Fuel Consumption of Cars'. n.d. Accessed 12 January 2021. https://www.ultimatespecs.com/.

The Martec Group. 2017. 'The Reality of Copper Substitution in Automotive Wire Harnesses'. https://copperalliance.org/wp-content/uploads/2017/03/Keith-Miller-Automotive-Wire-Harness.pdf.

Thomas Gersdorf, Patrick Hertzke, Patrick Schaufuss, and Stephanie Schenk. 2020. 'McKinsey Electric Vehicle Index: Electric Vehicle Trends | McKinsey'. 16 September 2020. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/mckinsey-electric-vehicle-index-europe-cushions-a-global-plunge-in-ev-sales.

Trinh, Ha Bich, Jae-chun Lee, Yong-jae Suh, and Jaeryeong Lee. 2020. 'A Review on the Recycling Processes of Spent Auto-Catalysts: Towards the Development of Sustainable Metallurgy'. *Waste Management* 114 (August): 148–65. https://doi.org/10.1016/j.wasman.2020.06.030.

Wagner, Michelle, Špela Bavec, Jaco Huisman, Lucía Herreras, Amund N. Løvik, Maria Ljunggren Söderman, Johanna Emmerich, et al. 2019. 'ORAMA Deliverable Report D2.3: Draft Good Practice Guidelines for the Collection of SRM Data, Improvement Potential, Definition and Execution of Case Studies'. https://orama-h2020.eu/wp-content/uploads/ORAMA_WP2_DEL2.3_20192905_v1.0.pdf.

Walker Emissions Control. 2018. 'New Items 2018 Q3'. https://www.walker-eu.com/en-uk/support/coverage/.

Widmer, James D., Richard Martin, and Mohammed Kimiabeigi. 2015. 'Electric Vehicle Traction Motors without Rare Earth Magnets'. *Sustainable Materials and Technologies* 3 (April): 7–13. https://doi.org/10.1016/j.susmat.2015.02.001.

Widmer, Rolf, Xiaoyue Du, Olaf Haag, Eliette Restrepo, and Patrick A. Wäger. 2015. 'Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output'. *Environmental Science & Technology* 49 (7): 4591–99. https://doi.org/10.1021/es505415d.

Xu, Guochang, Junya Yano, and Shin-ichi Sakai. 2016. 'Scenario Analysis for Recovery of Rare Earth Elements from End-of-Life Vehicles'. *Journal of Material Cycles and Waste Management*, March, 1–14. https://doi.org/10.1007/s10163-016-0487-y.

Yano, Junya, Takanori Muroi, and Shin-ichi Sakai. 2015. 'Rare Earth Element Recovery Potentials from End-of-Life Hybrid Electric Vehicle Components in 2010–2030'. *Journal of Material Cycles and Waste Management*, February, 1–10. https://doi.org/10.1007/s10163-015-0360-4.

Yano, Junya, Guochang Xu, Heping Liu, Toshiyuki Toyoguchi, Hisao Iwasawa, and Shin-ichi Sakai. 2019. 'Resource and Toxic Characterization in End-of-Life Vehicles through Dismantling Survey'. *Journal of Material Cycles and Waste Management*, August. https://doi.org/10.1007/s10163-019-00902-9.

Yuan, Chris, Yelin Deng, Tonghui Li, and Fan Yang. 2017. 'Manufacturing Energy Analysis of Lithium Ion Battery Pack for Electric Vehicles'. *CIRP Annals* 66 (1): 53–56. https://doi.org/10.1016/j.cirp.2017.04.109.

Zepf, Volker. 2013. 'Scales and Relations: Analysis of REPM Use with Emphasis on the Years from 2000 to 2010'. In *Rare Earth Elements: A New Approach to the Nexus of Supply, Demand and Use: Exemplified along the Use of Neodymium in Permanent Magnets*, edited by Volker Zepf, 73–122. Springer Theses. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-35458-8_6.

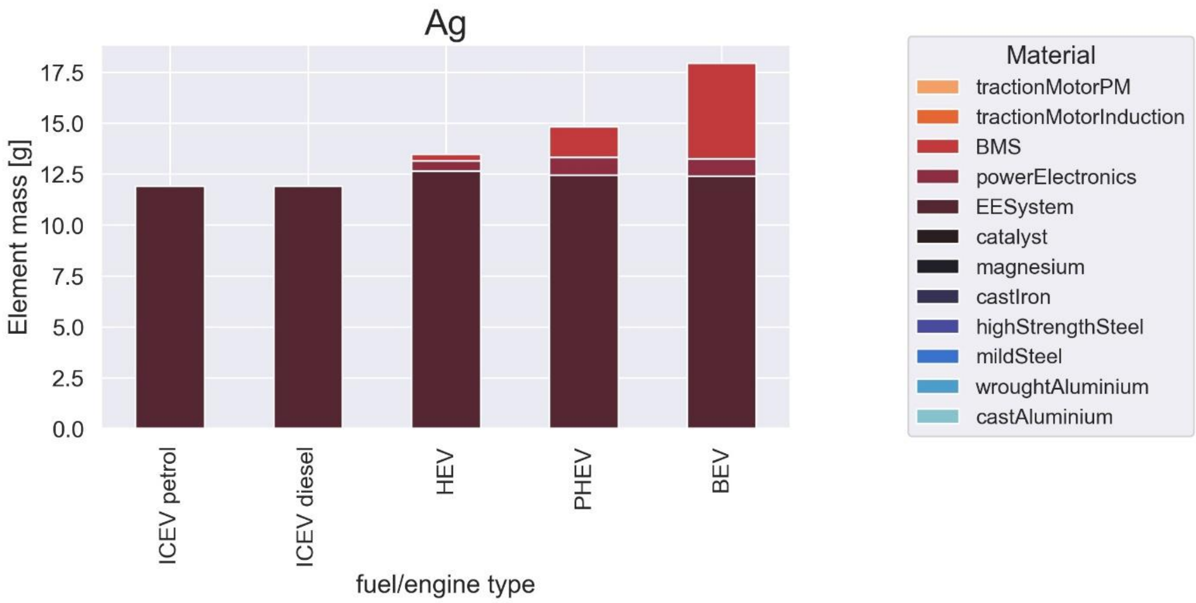
Zhang, Lingen, Qingming Song, Ya Liu, and Zhenming Xu. 2020. 'An Integrated Capture of Copper Scrap and Electrodeposition Process to Enrich and Prepare Pure Palladium for Recycling of Spent Catalyst from Automobile'. *Waste Management* 108 (May): 172–82. https://doi.org/10.1016/j.wasman.2020.04.013.

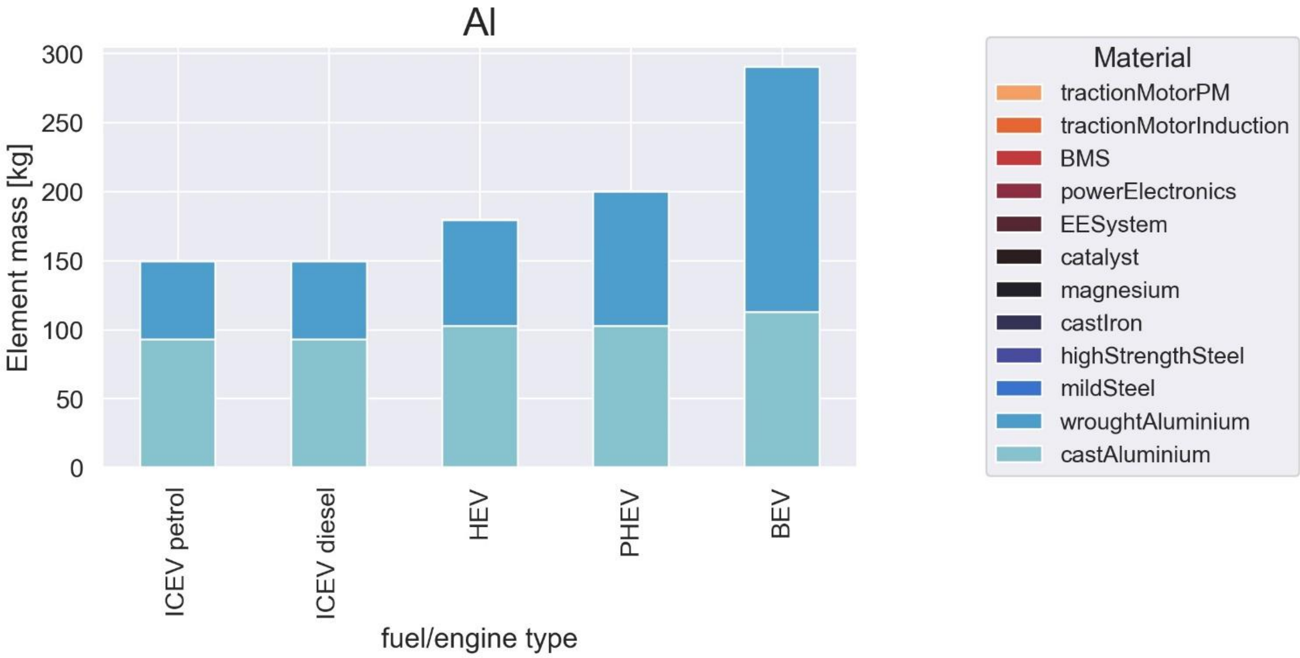
Zur-Lage, Lutz. 2014. 'Modern Cars and Adapted Recycling-Technologies: Outlook on ELV-Recycling'. Presented at the International Automobile Recycling Congress, Brussels, Belgium.

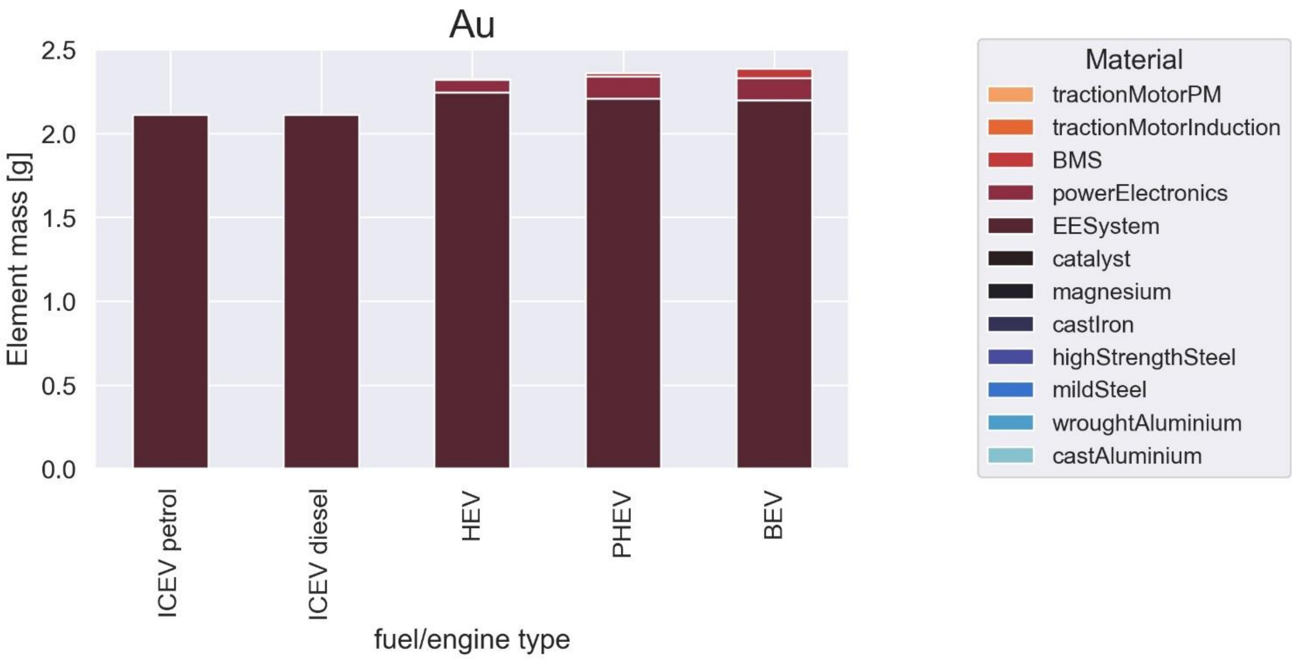
Annex I. Visualisations of data

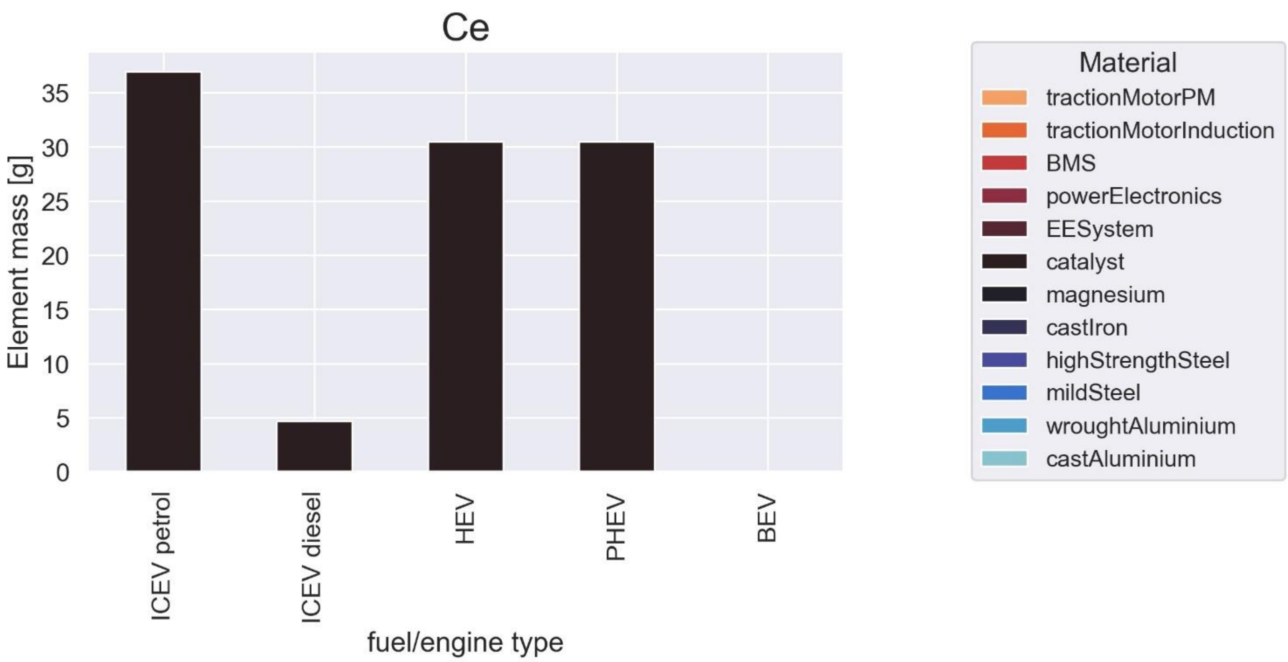
Mass of elements per vehicle

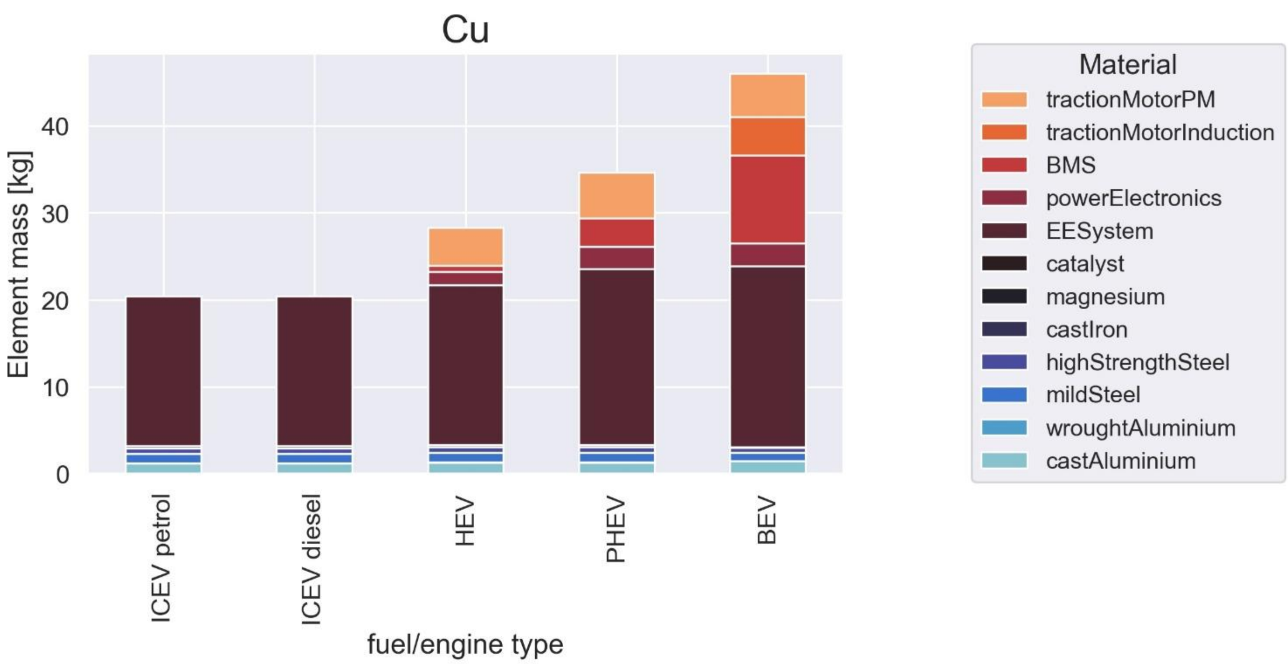
As an illustration of the data, the following figures show the estimated total mass per vehicle of each element for cars of the cohort 2020, with mass larger than 1500 kg and unknown engine size (the only category that is applicable to all fuel types), by fuel / engine type. Only petrol, diesel, HEV, PHEV and BEV are shown, since the remaining fuel types (LPG, NG, unknown and other) were assumed to have the same composition as petrol vehicles (due to a lack of specific data).

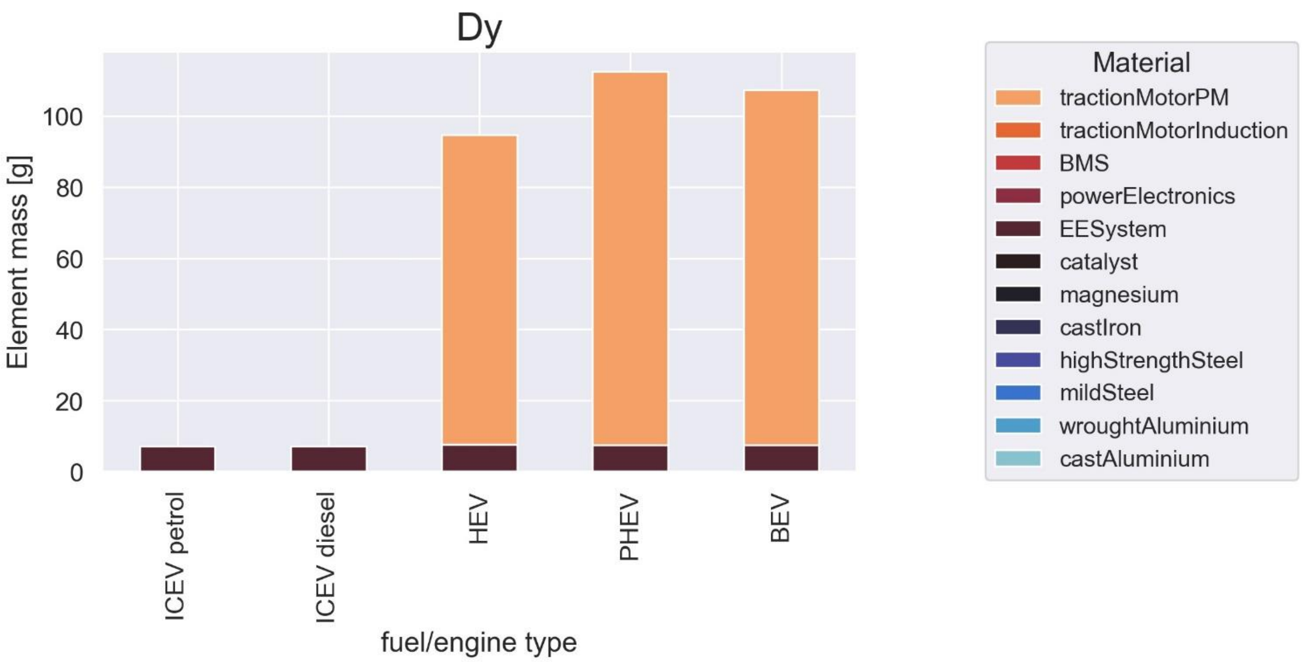


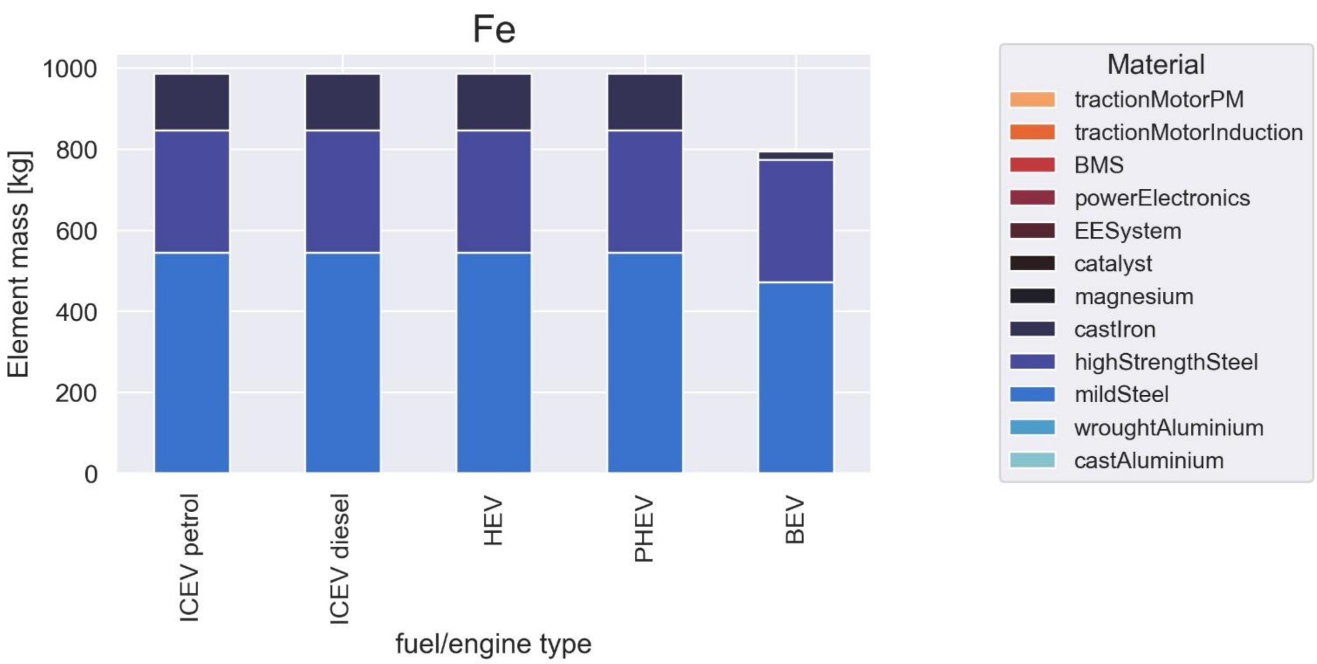

Al
300
250
200
150
100
50
0
Element mass [kg]
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

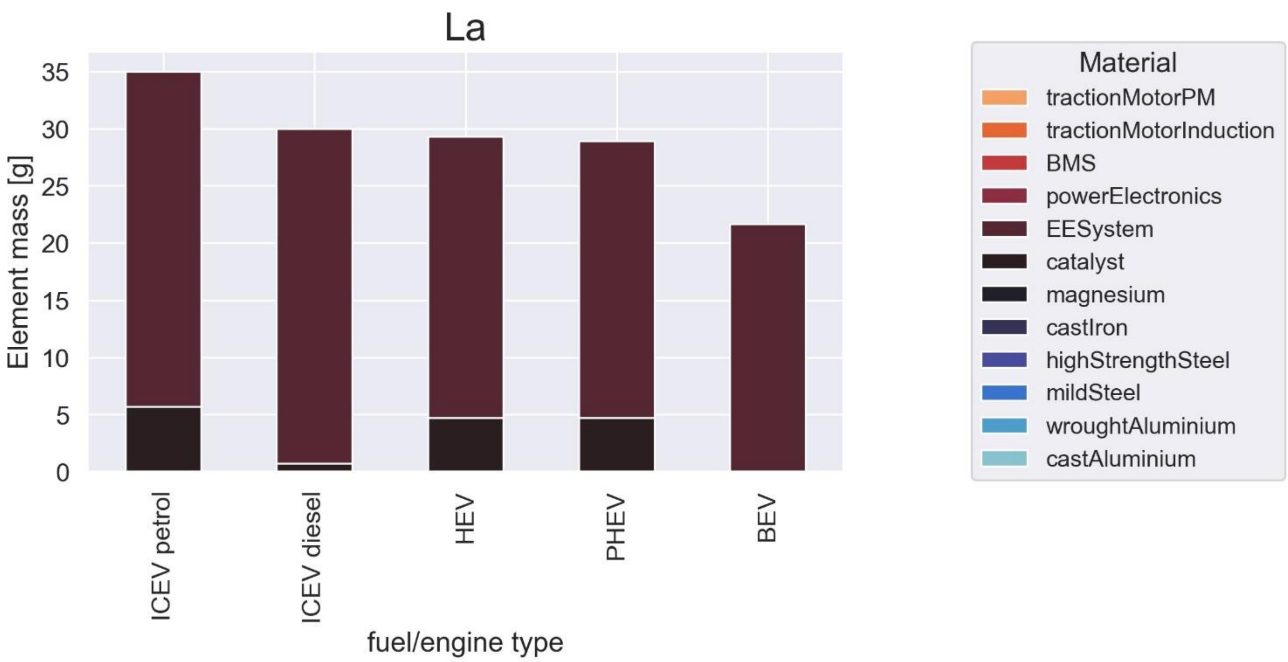

Au
2.5
2.0
1.5
1.0
0.5
0.0
Element mass [g]
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

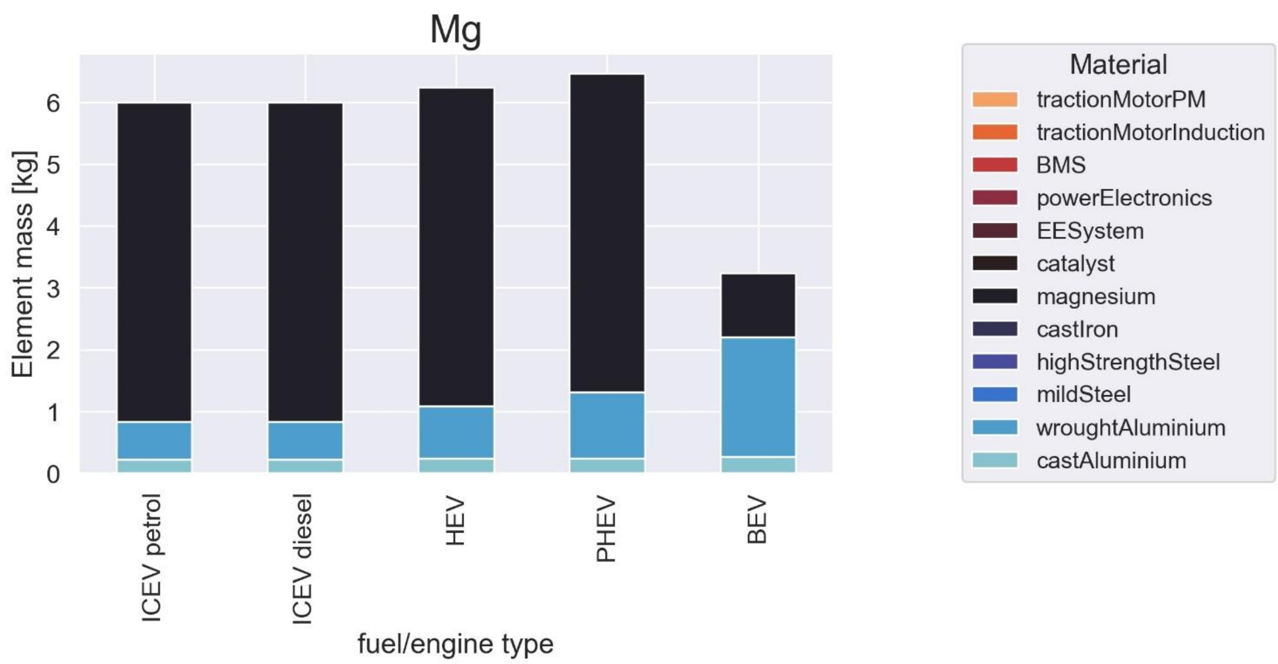

Ce
Element mass [g]
35
30
25
20
15
10
5
0
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

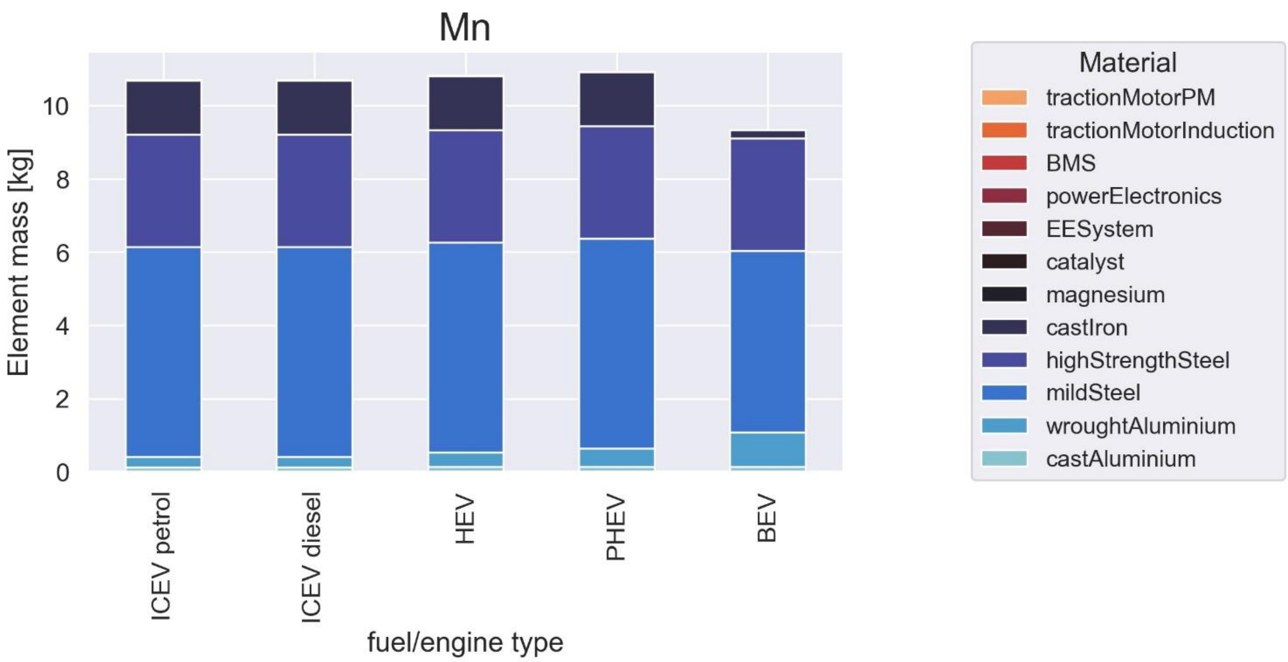

Cu
Element mass [kg]
40
30
20
10
0
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

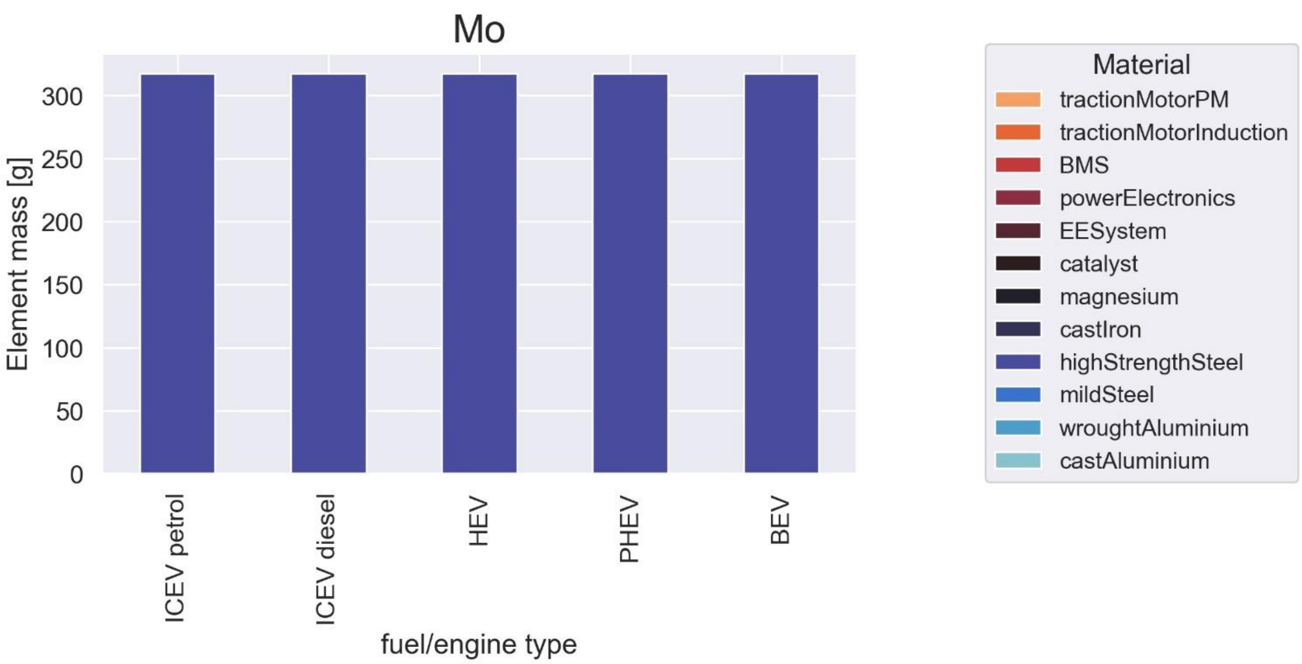

Dy
Element mass [g]
0
20
40
60
80
100
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

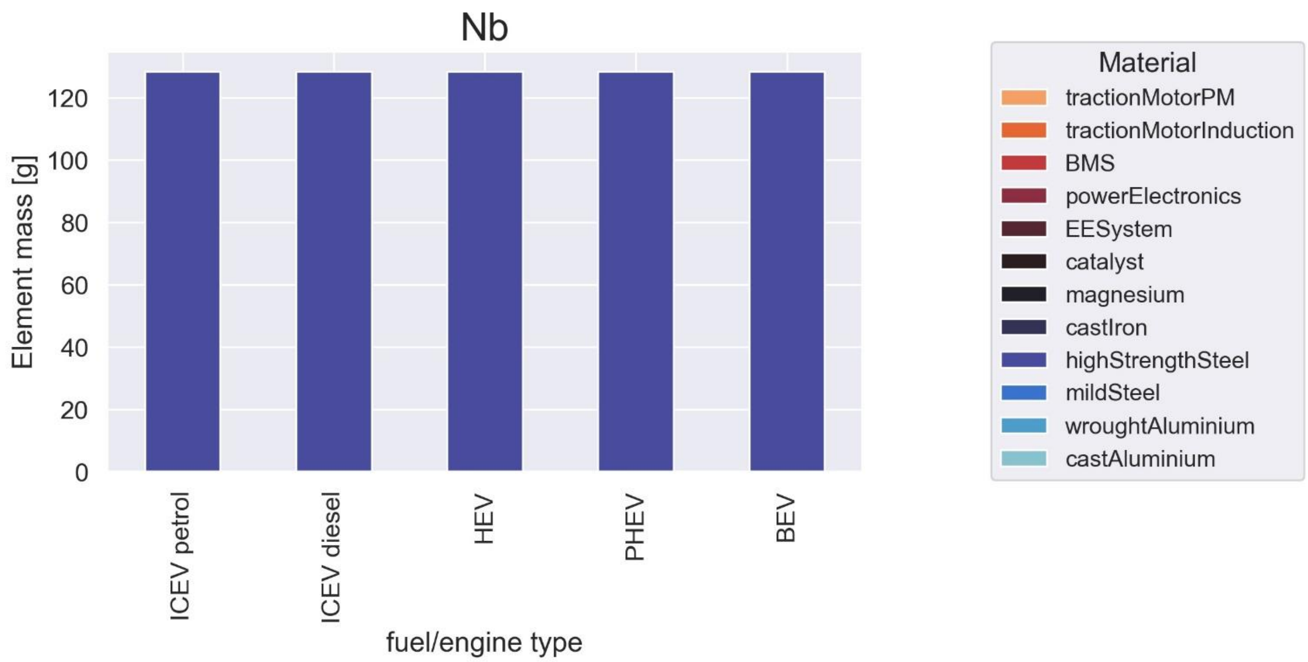

Fe
Element mass [kg]
0
200
400
600
800
1000
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

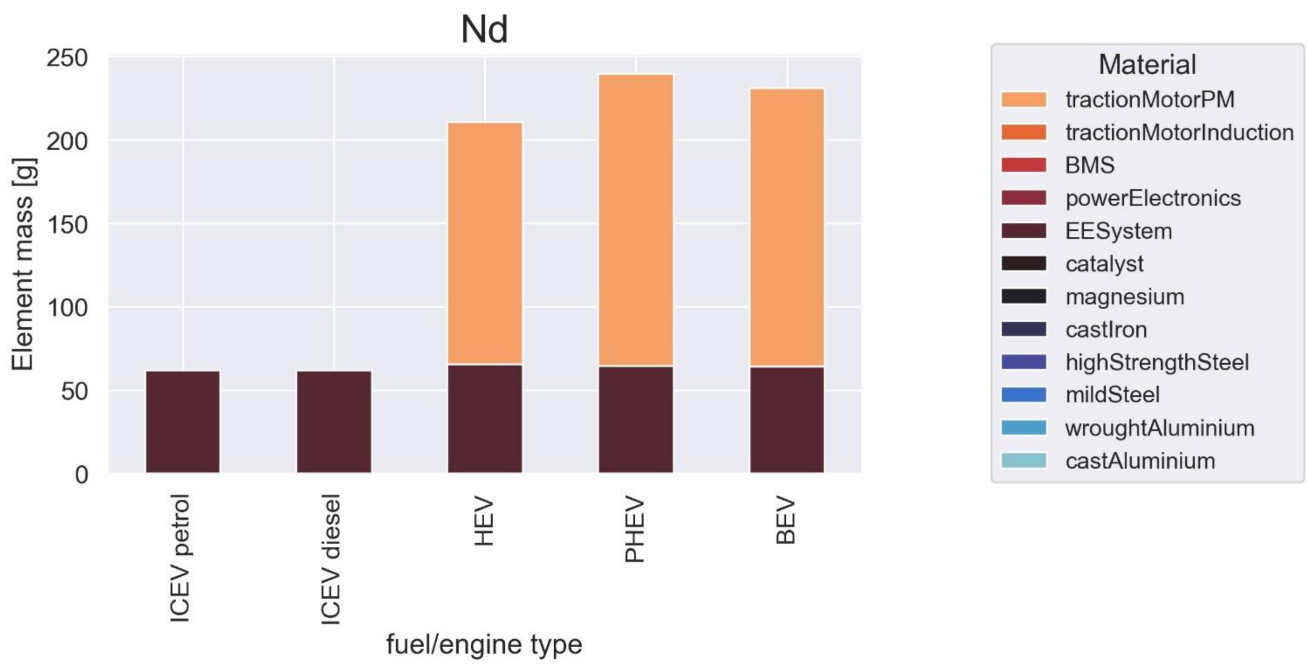

La
Element mass [g]
35
30
25
20
15
10
5
0
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

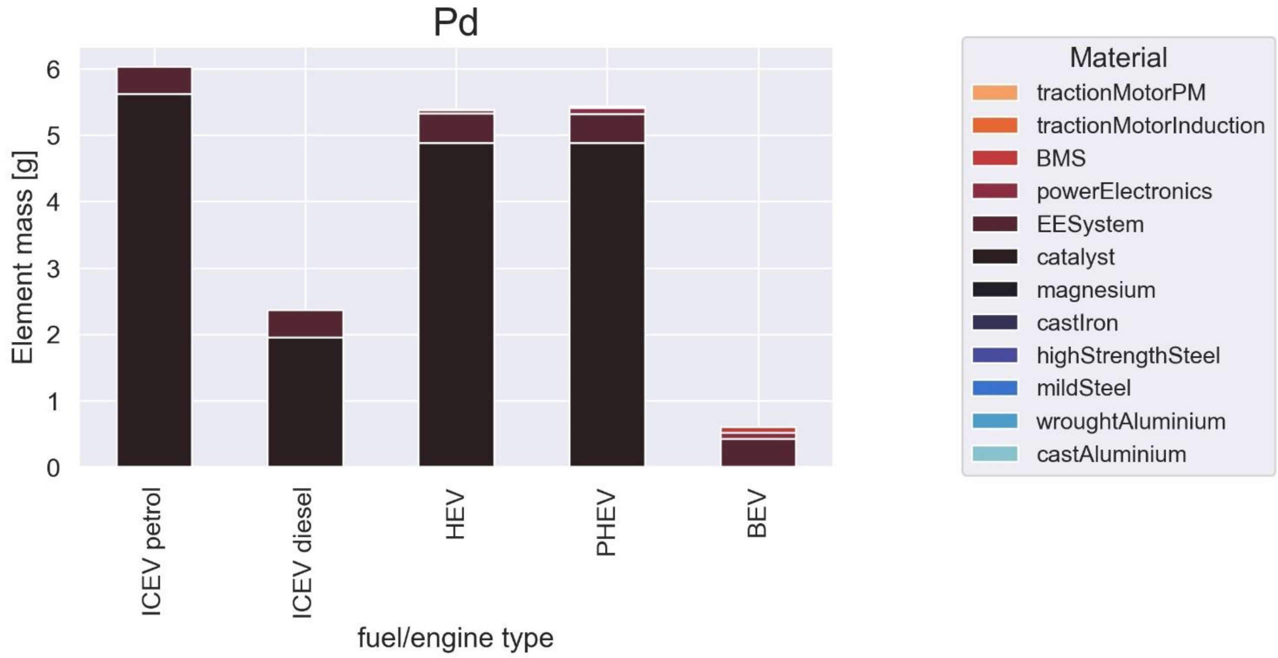

Mg
Element mass [kg]
6
5
4
3
2
1
0
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

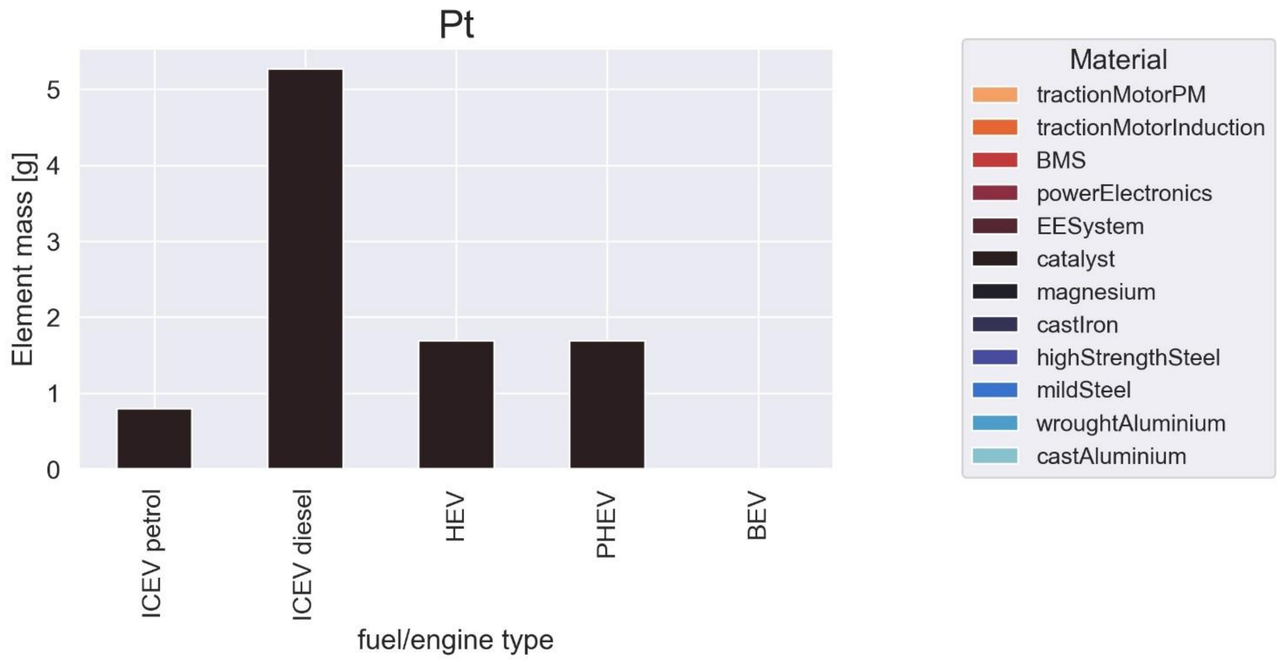

Mn
Element mass [kg]
0
2
4
6
8
10
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium


Mo
Element mass [g]
0
50
100
150
200
250
300
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium


Nb
Element mass [g]
0
20
40
60
80
100
120
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium


Nd
Element mass [g]
0
50
100
150
200
250
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium


Pd
Element mass [g]
0
1
2
3
4
5
6
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium


Pt
Element mass [g]
0
1
2
3
4
5
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
fuel/engine type
Material
tractionMotorPM
tractionMotorInduction
BMS
powerElectronics
EESystem
catalyst
magnesium
castIron
highStrengthSteel
mildSteel
wroughtAluminium
castAluminium

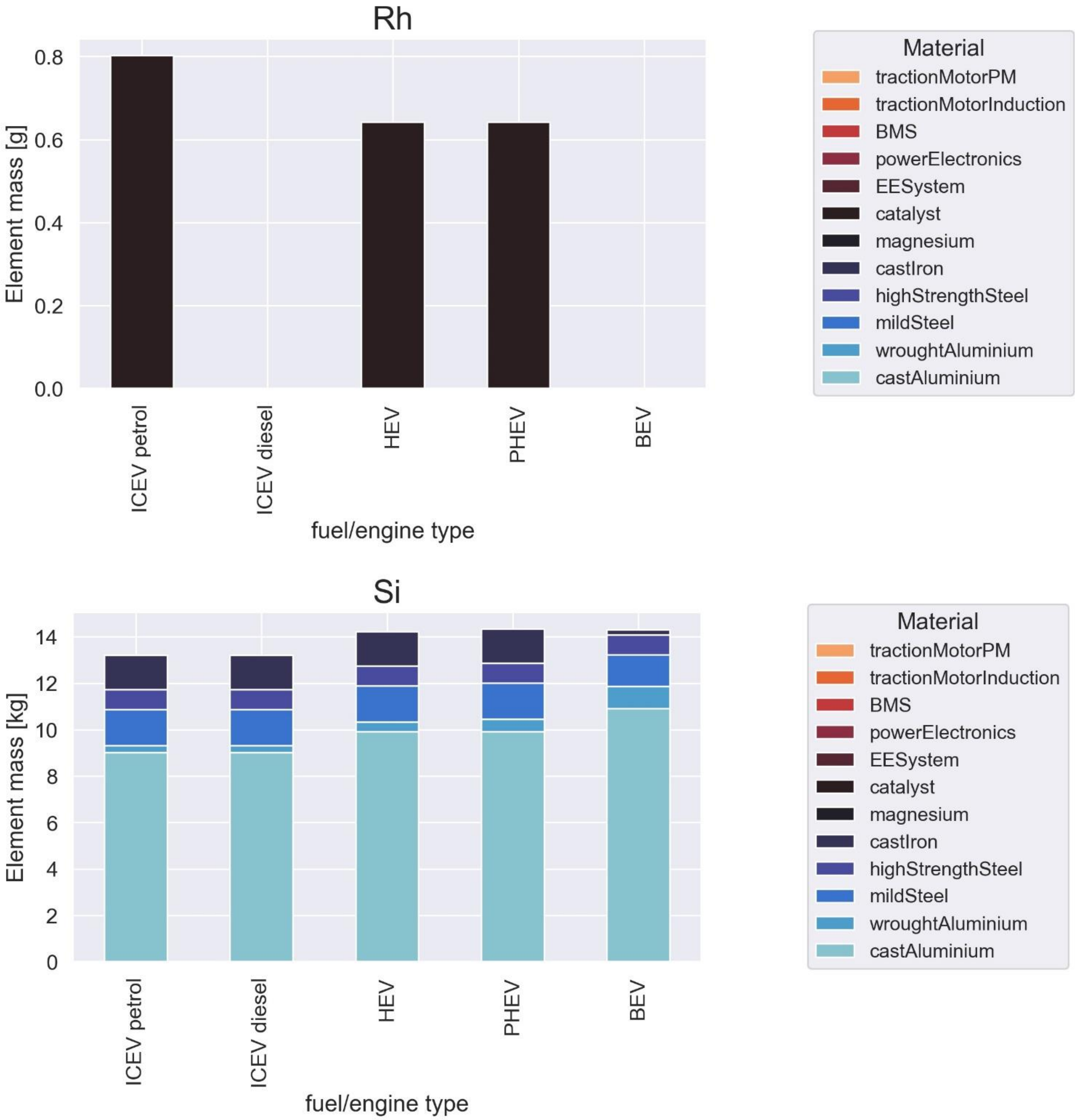
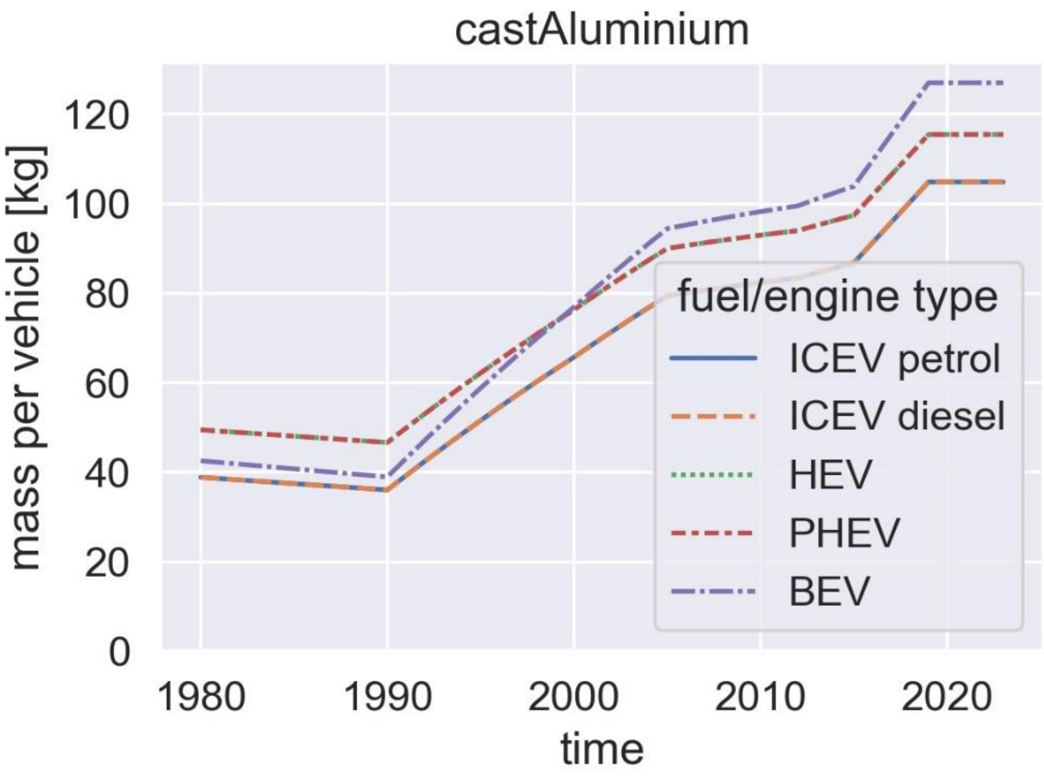
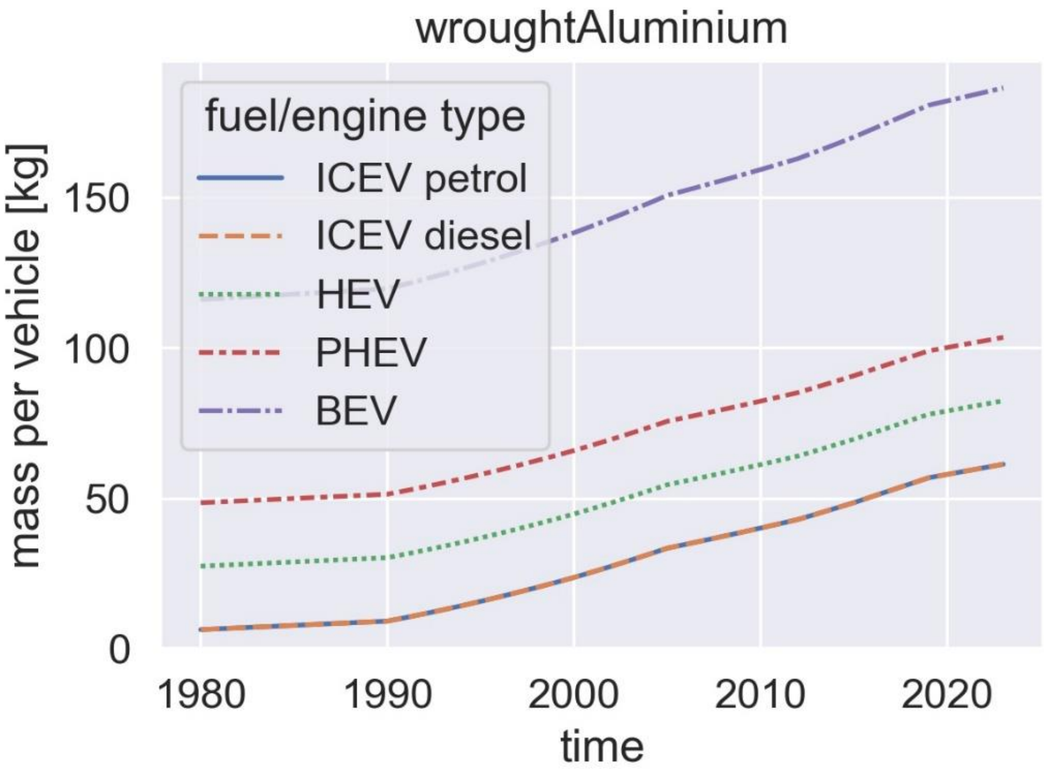


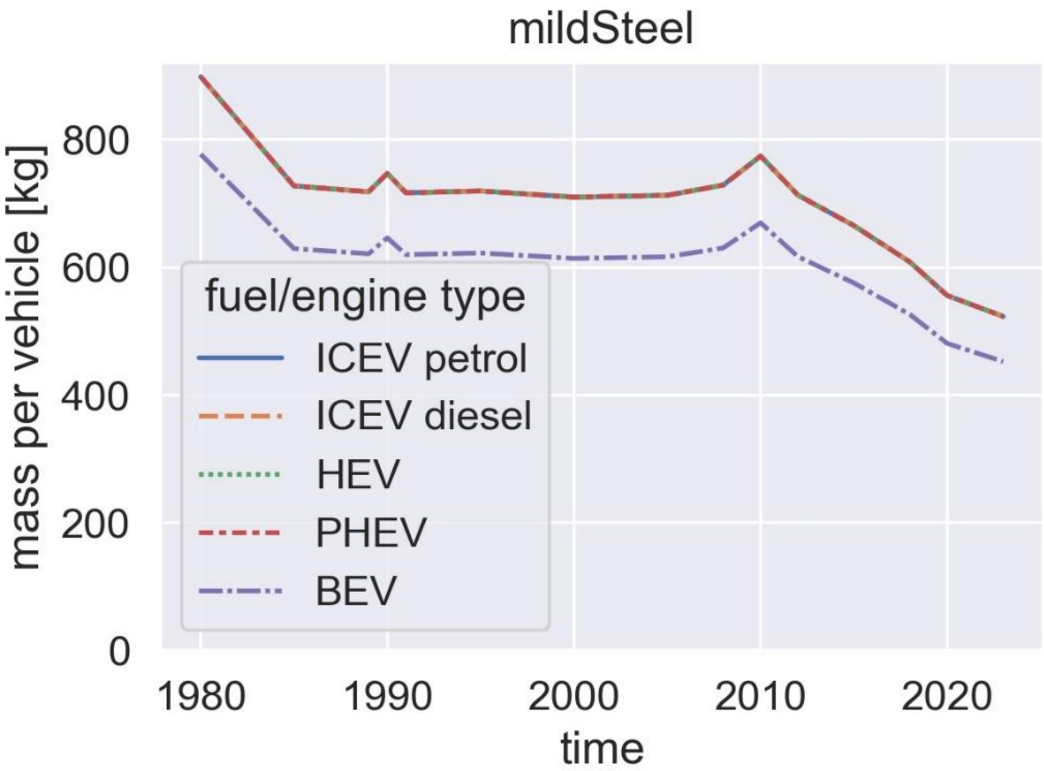
Figure 1. Estimated total mass per vehicle of selected elements for cars with mass larger than 1500 kg and unknown engine size of the cohort 2020 (please note that some y-axis values are expressed in kg, some others in g).

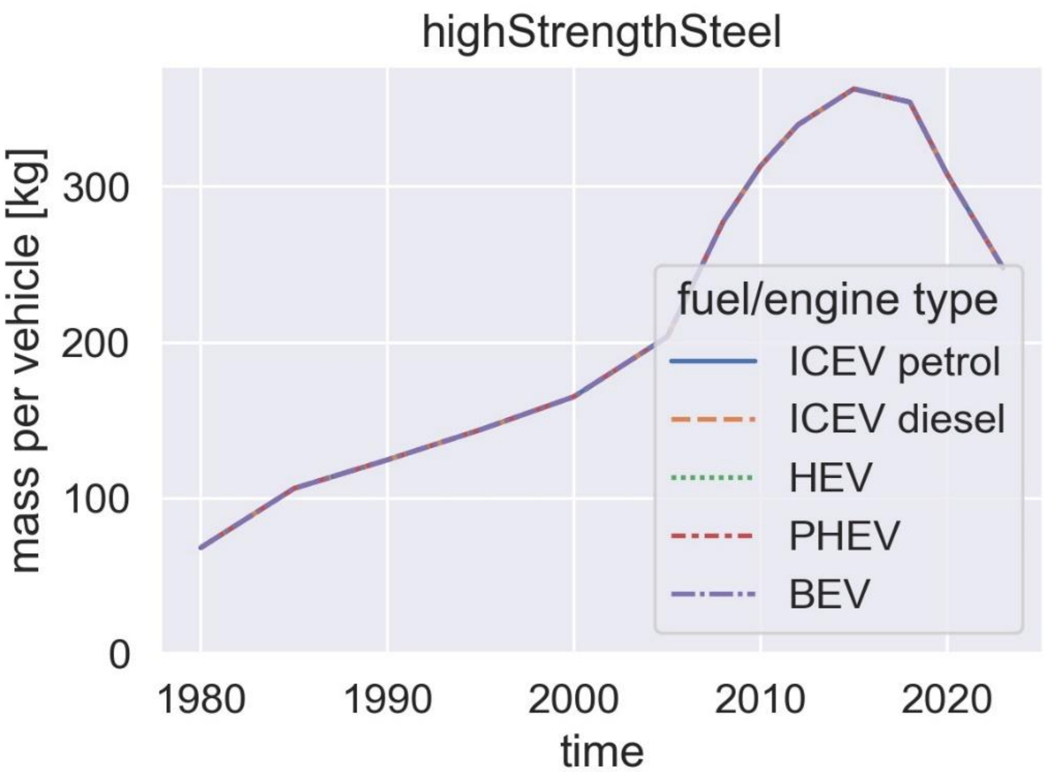
Mass of components and materials per vehicle by cohort

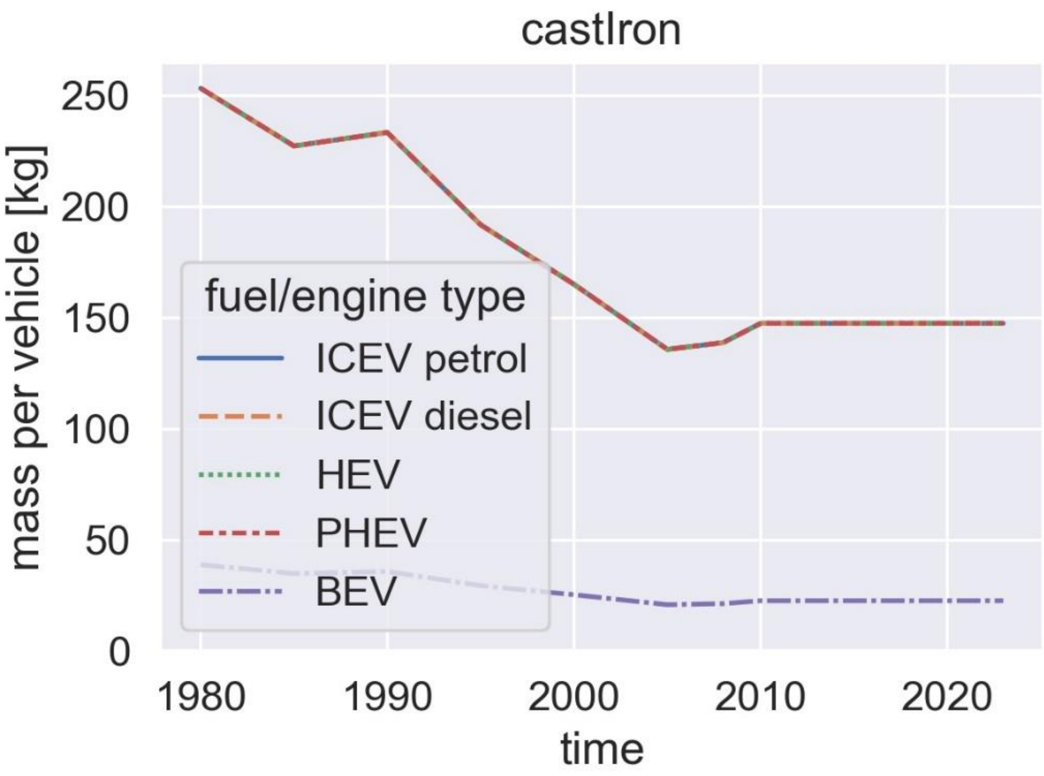
The following figures show the estimated total mass per vehicle of each material and component for cars with mass larger than 1500 kg and unknown engine size (the only category that is applicable to all fuel types), by fuel type and as a function of cohort. Only petrol, diesel, HEV, PHEV and BEV are shown, since the remaining fuel types (LPG, NG, unknown and other) were assumed to have the same composition as petrol vehicles (due to a lack of specific data). When no change over time is seen, it means that there is insufficient data to estimate the trend, and it should not be interpreted as "there is no trend".

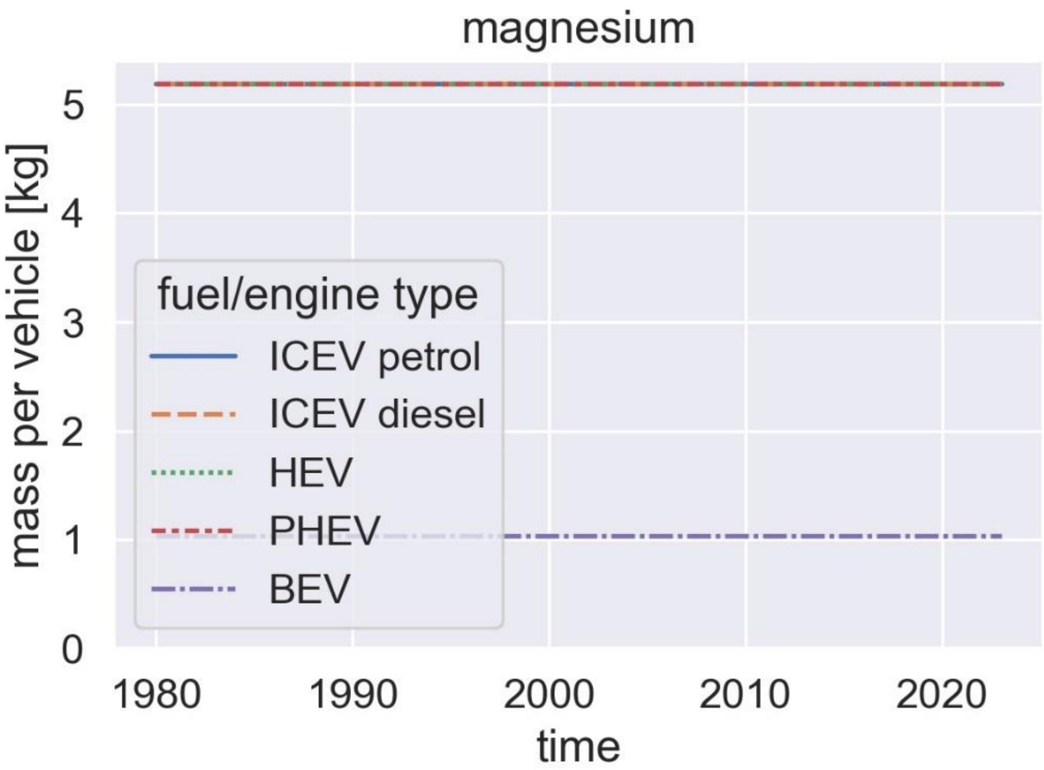

castAluminium
mass per vehicle [kg]
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV

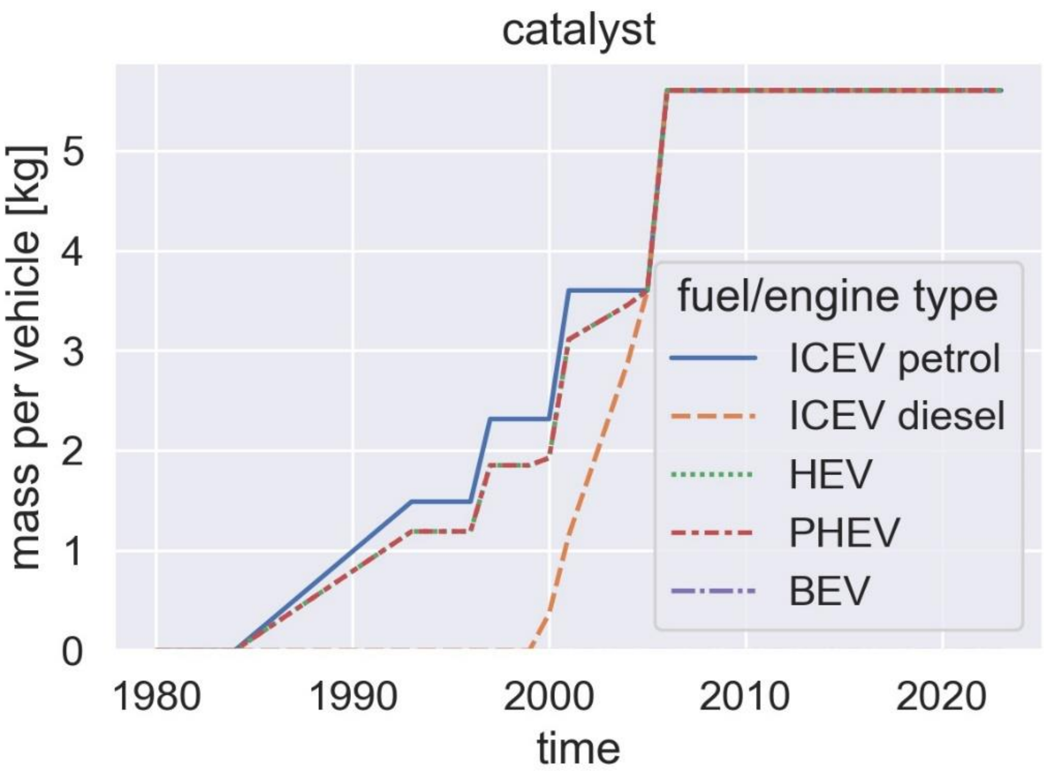

wroughtAluminium
mass per vehicle [kg]
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV

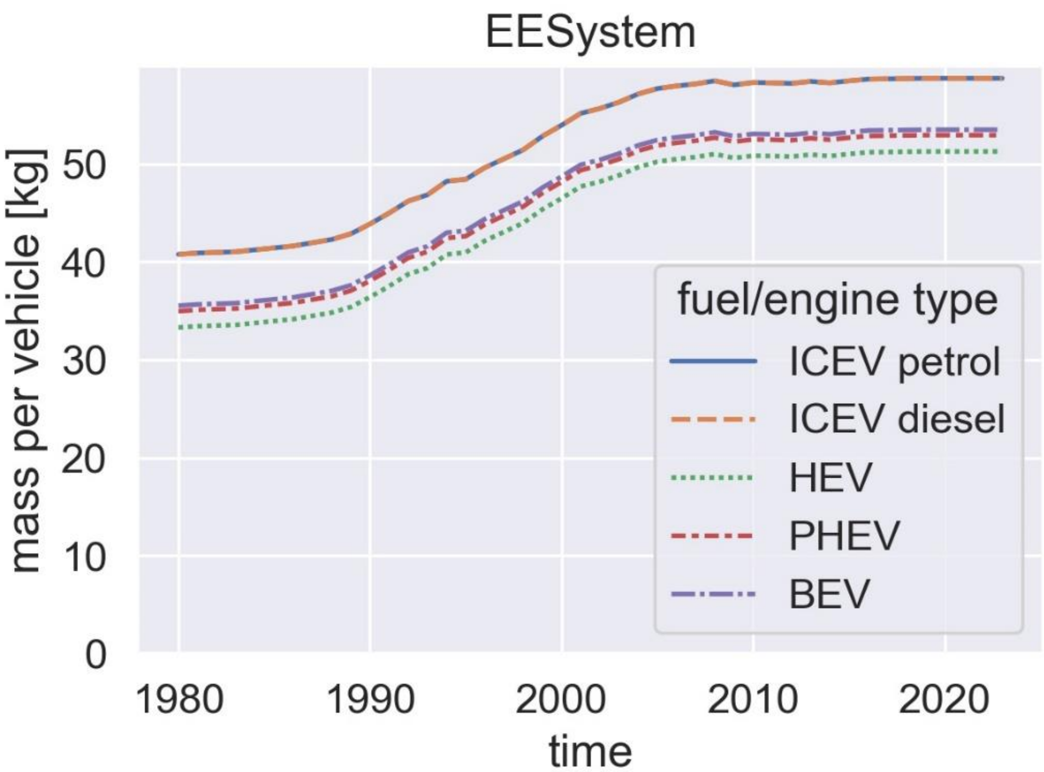

mildSteel
mass per vehicle [kg]
0
200
400
600
800
1980
1990
2000
2010
2020
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV

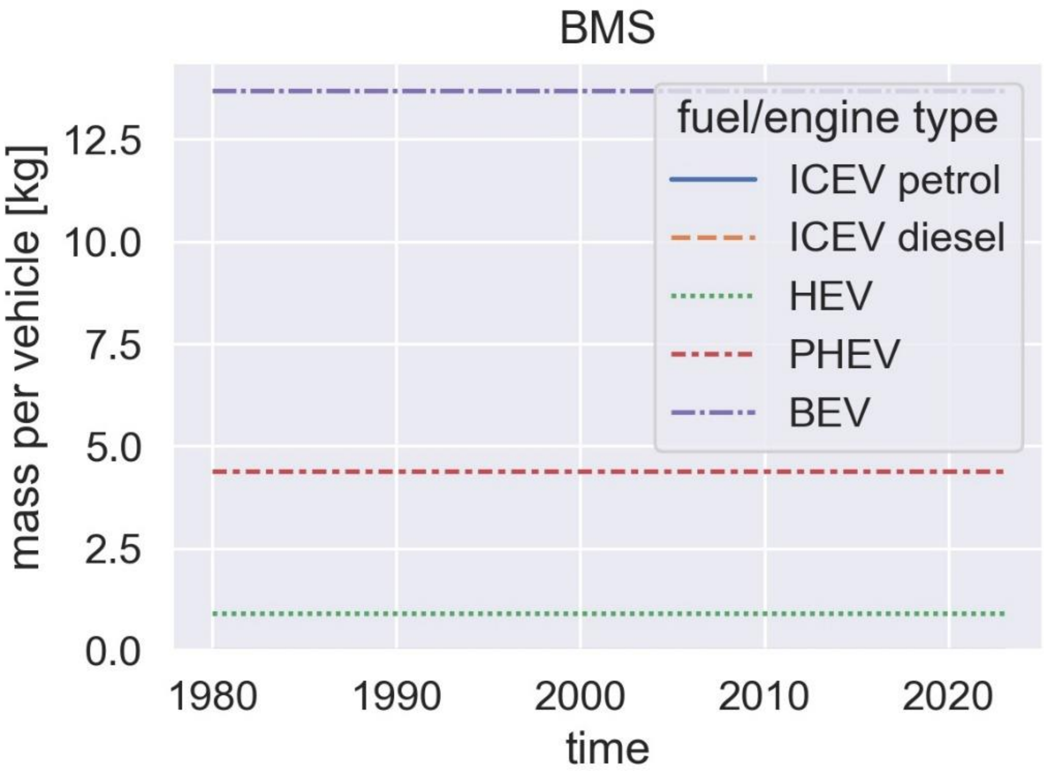

highStrengthSteel
mass per vehicle [kg]
0
100
200
300
1980
1990
2000
2010
2020
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV

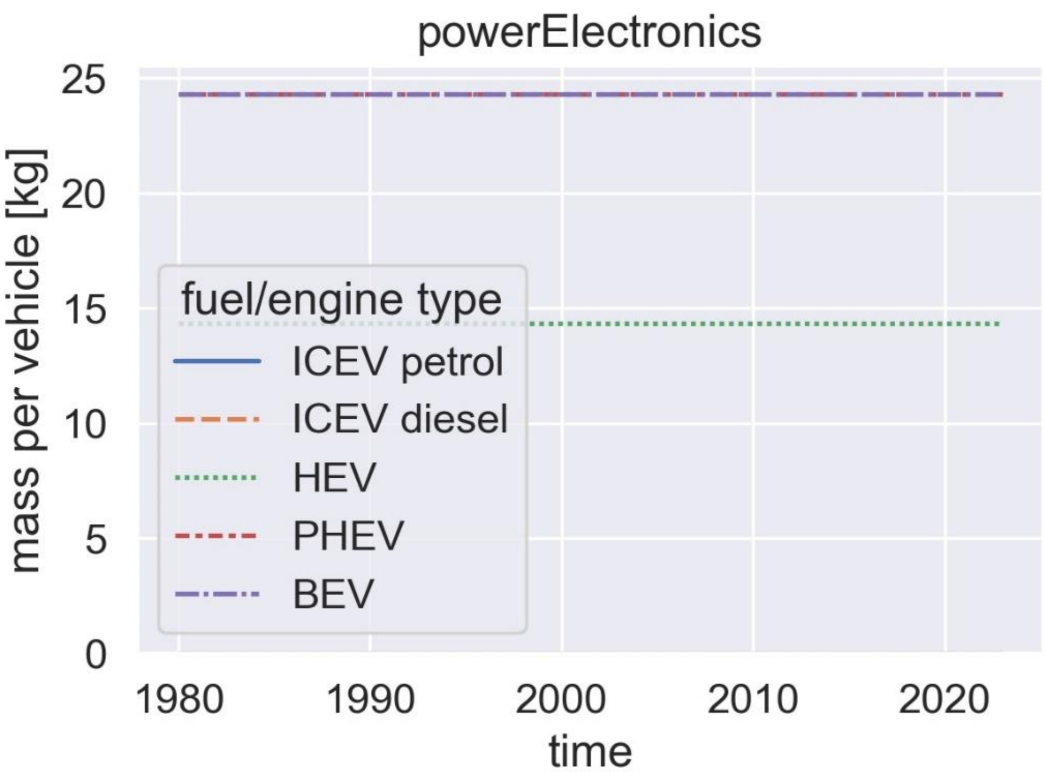

castIron
250
200
150
100
50
0
mass per vehicle [kg]
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
1980
1990
2000
2010
2020
time


magnesium
5
4
3
2
1
0
mass per vehicle [kg]
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
1980
1990
2000
2010
2020
time


catalyst
mass per vehicle [kg]
0
1
2
3
4
5
1980
1990
2000
2010
2020
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV


EESystem
mass per vehicle [kg]
0
10
20
30
40
50
1980
1990
2000
2010
2020
time
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV


BMS
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
12.5
10.0
7.5
5.0
2.5
0.0
mass per vehicle [kg]
1980
1990
2000
2010
2020
time


powerElectronics
fuel/engine type
ICEV petrol
ICEV diesel
HEV
PHEV
BEV
25
20
15
10
5
0
mass per vehicle [kg]
1980
1990
2000
2010
2020
time

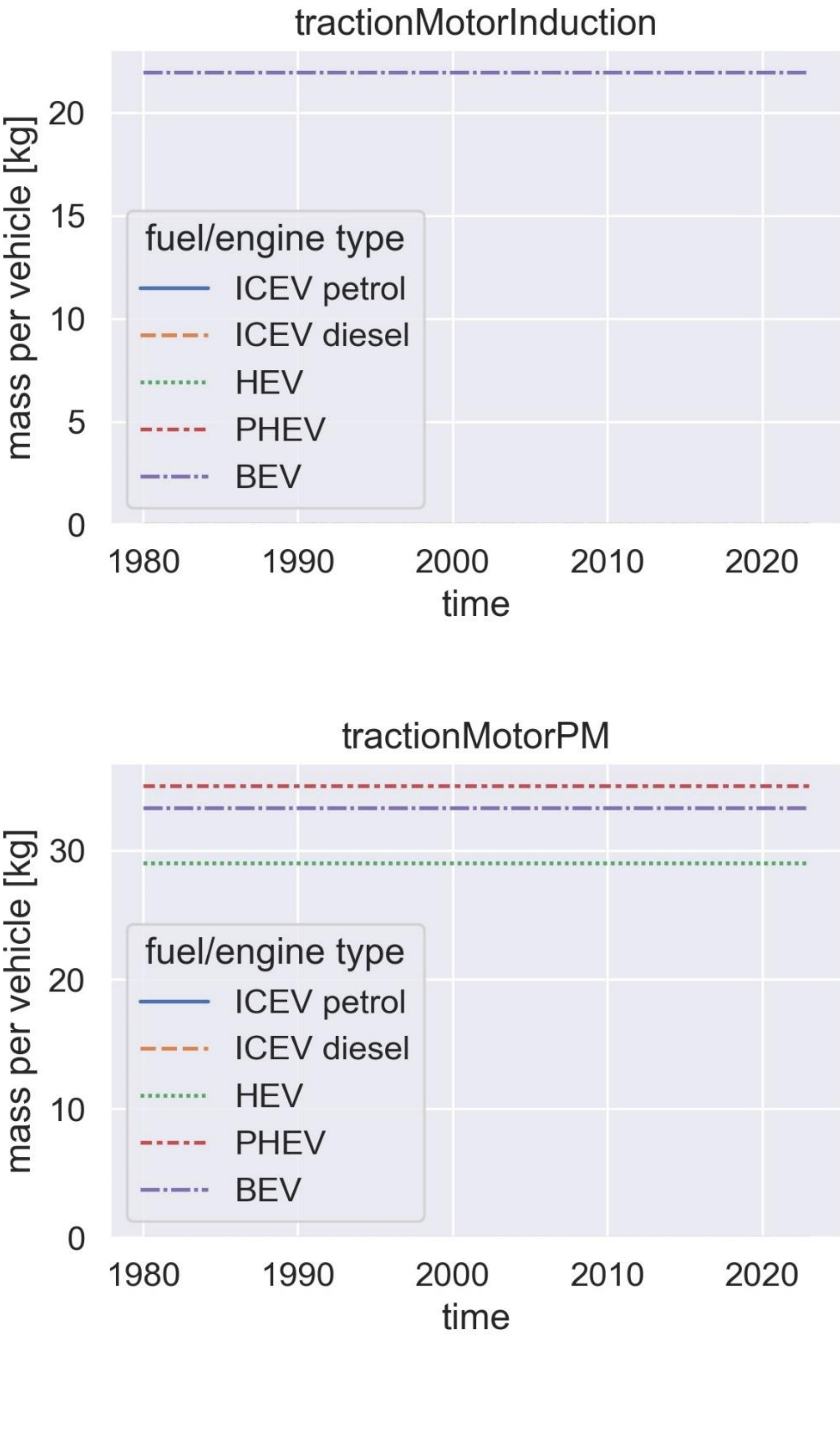


Figure 2. Estimated total mass per vehicle of each material and component for cars with mass larger than 1500 kg and unknown engine size by fuel type and as a function of cohort.

List of abbreviations

Ag	Silver
AHSS	Advanced high strength steel
Al	Aluminium
Au	Gold
BEV	Full electric vehicle
BMS	battery management system
Cu	Copper
DC	Direct current
Dy	Dysprosium
EEE	electrical and electronic equipment
EES	Electric and electronic system
EMPA	Swiss Federal Laboratories for Materials Science and Technology
Fe	Iron
HEV	Hybrid vehicle
HSS	High strength steel
ICEV	Internal Combustion Engine Vehicle
IMDS	International Materials Data System (IMDS)
La	Lanthanum
LPG	Liquefied Petroleum Gas
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Nb	Niobium
Nd	Neodymium
NG	Natural gas
PCB	Printed circuit board
Pd	Palladium
PE	Power electronics
PHEV	Plug-in hybrid vehicle
PM	Permanent magnet
ProSUM	Prospecting Secondary raw materials in the Urban mine and Mining wastes
Pt	Platinum
Rh	Rhodium
RMIS	Raw Materials Information System
Si	Silicon
UHSS	Ultra-high strength steel ()
UMP	Urban Mine Platform
xEV	Electric vehicle

List of figures

List of tables

KJ-NA-30916-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

doi:10.2760/351825

ISBN 978-92-76-45213-3

Publications Office
of the European Union