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Metals for Fuels? The Raw Material Shift by Energy-Efficient Transport Systems in Europe

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Abstract: The long-term transition towards a low-carbon transport sector is a key strategy in Europe. This includes the replacement of fossil fuels, modal shifts towards public transport as well as higher energy efficiency in the transport sector overall. While these energy savings are likely to reduce the direct greenhouse gas emissions of transport, they also require the production of new and different vehicles. This study analyses in detail whether final energy savings in the transport sector also induce savings for material resources from nature if the production of future vehicles is considered. The results for 28 member states in 2030 indicate that energy efficiency in the transport sector leads to lower carbon emissions as well as resource use savings. However, energy-efficient transport sectors can have a significant impact on the demand for metals in Europe. An additional annual demand for 28.4 Mt of metal ores was calculated from the personal transport sector in 2030 alone. The additional metal ores from semiprecious metals (e.g., copper) amount to 12.0 Mt, from precious metals (e.g., gold) to 9.1 Mt and from other metals (e.g., lithium) to 11.7 Mt, with small savings for ferrous metal ores (−4.6 Mt).

1. Introduction

The transport sector in Europe is responsible for one quarter of the region's greenhouse gas (GHG) emissions. A transition towards low-carbon transport alone would enable a 60% reduction until 2050 compared to 1990 [1]. Existing policies work towards this goal. They promote, for example, low- and zero-emission vehicles or a switch to alternative energy for transport.

From a technical point of view, this translates into fewer and other vehicles (modal shift). These vehicles are either more fuel efficient or powered by alternative sources of mechanical energy. While these steps help to reduce the direct GHG emissions in Europe, there are some indications for additional indirect emissions (e.g., from electricity supply and battery production) as well as unintended side or rebound effects from this transition strategy. The study at hand intends to shed light on some of these effects and to assess their criticality in regard to future material use in Europe and abroad.

One major concern of researchers is the additional indirect GHG emissions from non-operational infrastructures, fuel provision and vehicle manufacture. Chester and Horvath (2009), for example, found that GHG emissions and energy use are influenced by non-operational aspects. The overall GHG emissions are 1.4–1.6 times higher for road transport and 1.8 to 2.5 times higher for rail transport in the US [2]. Renewable electricity and lower material intensities of transport infrastructure and manufacturing could reduce GHG emissions and emissions from air pollutants such as SO_2 and NO_X. Other authors (Williams et al., 2012) emphasize that low carbon transitions require a logical

deployment sequence in order to be successful. Energy efficiency is followed by decarbonization of energy supply and the electrification of fossil energy use [3].

These findings go hand in hand with research on effects from the production of electrified vehicles and their infrastructure. A recent study on behalf of the European Environment Agency [4] analyzed the interactions of electric vehicles and the power sector in Europe. The authors quantified the net emissions from an increased number of electric vehicles. They conclude that with an increased share of electric vehicles, the electricity demand of these cars becomes a relevant factor in the energy system. The positive GHG effects are partially offset by the additional demand.

The affected systems and impacts of low-carbon mobility are widely discussed in the literature. Bohnes et al. (2017), for example, found that environmental burden shifting can take place if electric vehicles are deployed to a large degree. The electrification of passenger transport can also have unintended side effects in cold countries. Additional energy for car heating might be required, as vehicles with an internal combustion engine are more energy-efficient in this regard [5]. It is also possible that direct and indirect price effects lead to a rebound effect from a microeconomic point of view. Vivanco et al. (2014) analyzed the price elasticity of transport demand and marginal consumption models. They showed that some technologies for electric vehicles can lead to partial or over-compensation for some environmental impacts [6].

In regard to natural resources, raw materials and the economic effects of low-carbon transport, several studies focus on metals (e.g., lithium). Tagliaferri et al. (2016) analyzed the environmental impacts of conventional and electric vehicles in a cradle-to-grave life-cycle assessment (LCA) [7]. They found that higher toxicology impacts for electric vehicles are linked to the use of precious metals and chemicals in the battery-manufacturing phase (GHG emissions and abiotic depletion are reduced with the help of battery electric vehicles, but are more influential during the production phase). Olivetti et al. (2017) put their research focus on the future material requirement for lithium-ion batteries. They conclude that manganese and nickel supply is sufficient to meet these requirements [8]. For lithium itself, it is not the quantity of reserves that poses a challenge, but the slow increase in production compared to the high increase in demand. The authors are confident that this is only a bottleneck in the short term. Another potential bottleneck is the material requirement for cobalt. The mining and refining of cobalt is currently highly concentrated in certain regions (Democratic Republic of the Congo (DRC) and China).

The metal availability for future low-carbon transport also depends on similar transitions in other sectors. In this context, several studies analyzed the future demand of metals such as lithium or neodymium [9–13]. It is assumed that these issues can be overcome with an upscaling in metal production. However, there is a need for further analysis of the trade-off between reducing GHG emissions on the one hand and the additional material demand from technologies towards electrification.

The authors of this study follow up on this question by analyzing the results of a multiple-impact analysis of future energy efficiency improvement actions in Europe in 2030 (Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe (COMBI)). With respect to the transport sector, it is investigated whether future transport systems require additional metal ores to be produced and which metals might be needed in particular. Are we required to trade metals for fuels?

The consequences of such a trade could affect different aspects of more sustainable economies. Further increasing the extraction rates of metals would increase the associated environmental burden itself and the burden shift towards developing countries (which often provide the metal ores). Bottlenecks in particular could amplify these effects, as metal costs increase and less favorable reserves (lower ore grades) are tapped in order to meet the demand. This could, in turn, lessen the positive effect of many sustainable policies on a global scale. However, it could also be an additional incentive for countries to promote higher material efficiency and material recovery rates in their economies (including the development of cost-effective recycling technologies).

The study is subdivided into 6 sections. The introduction in Section 1 is followed by a description of the scope of the study in Section 2. Section 3 covers impact-indicators, methods, data, models and limitations. Section 4 describes the results and Section 5 discusses the implications for metal demand and supply. Section 6 concludes the study with an aggregation of the findings and the need for future research.

2. Scope

The core results in this paper are part of the Horizon 2020-project COMBI. COMBI aims at calculating the energy and non-energy impacts 21 energy efficiency improvement (EEIs) in the 28 European Union members (EU-28) in 2030. The analyzed impacts cover the areas of air pollution, social welfare, macro economy, energy systems/security and resources (further information such as reports and a tool to visualize the effects, can be found at https://combi-project.eu or [14–16]). They are calculated from a snapshot view. The final energy use in 2030 after implementing EEIs is compared to its equivalent without these measures. The base-case scenario includes activities that are already in motion (extrapolated towards 2030).

For resources, the authors created several bottom-up models to quantify the annual net impacts in terms of raw material extraction and greenhouse gas emissions. These models cover the so-called use-phase of all 21 actions in five sectors. The use-phase represents the difference in resource impacts from two different scenarios: base-case and energy-efficiency. They are based on final energy savings, but also the necessary material and energy flows to provide the energy services. This includes, for example, the construction of power plants and grids for electricity in the member states (see pp. 37–54 in [17]). The calculation method uses the input data (final energy per energy carrier and EEI) and relates this energy consumption to the material and energy flows necessary to provide the energy service. The differences in the flows of both scenarios are then used to calculate the resource impacts (see also section on methods).

In addition to the net effects during the use-phase, several actions were also considered in the context of their production-phase. The production-phase represents the material and energy flows that stem from differences in the product stocks and product types. For passenger and freight transport, production-phase models consider the production of cars, busses, duty trucks and trains (see pp. 55–63 in [17]).

This study focuses on EEIs in the transport sector, which were modeled by the University of Antwerp (see [18,19] for further details). For passenger transport, a modal shift (action 9), future car (action 11) and bus stocks (action 12) were considered. The freight transport activities cover a modal shift (action 13), light duty trucks (action 14) and heavy-duty trucks (action 15). Table 1 shows the list of actions considered, as well as the resulting differences in the final energy use between base-case and EEI scenarios in 2030.

Table 1. List of energy efficiency improvements (EEIs) in the transport sector considered for the study at hand.

Actions [a] (EEIs)	Final Energy Saving in EU-28 in 2030 (Baseline vs. EEI)
9—Transport (passenger) modal shift	40 TWh
11—Transport (passenger) cars	284 TWh
12—Transport (passenger) public road/bus transport	3 TWh
13—Transport (freight) modal shift	90 TWh

Table 1. *Cont.*

Actions [a] (EEIs)	Final Energy Saving in EU-28 in 2030 (Baseline vs. EEI)
14—Transport (freight) light duty truck	13 TWh
15—Transport (freight) heavy duty trucks [b]	32 TWh
Total [c] (Actions 9,11,12,13,14,15)	460 TWh (rounded value)

Source: Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe (COMBI) input data [18,19] based on the models: PRIMES [20]; JRC TIMES [21]; TREMOVE [22]; iTREN [23]; ASTRA-EC [24]; SULTAN [25]. [a] The numbering of actions might deviate from other COMBI sources, because it has been changed over the course of the project; all numberings in this paper refer to this table. [b] There are no differences in the product stocks for action 15 in the COMBI input data (the same types of heavy duty trucks are produced in both scenarios). However, changes in the overall amount of heavy duty trucks are also reflected in the data on modal shift. [c] The "missing" action 10 considers energy savings from passenger transport with two-wheelers. As the production of two-wheelers could not be incorporated into a production phase model, it is omitted from the selection of actions for impact quantification (use phase and production phase).

The actions themselves can be differentiated into measures towards structural changes in the mode of transport (modal shift in actions 9 and 13) and changes in the transport systems (road transport in actions 11,12,14,15) [18,19]. Modal shifts in the personal transport sector include a shift towards public transport and to non-motorized transport (cycling, walking). For freight transport, a shift towards rail and waterborne transport is assumed. The actions for road transport address changes in drive train technologies (fewer conventional vehicles with an internal combustion engine). They also cover higher fuel efficiency (eco-driving, increased occupancy levels/load factors, higher fuel efficiency for vehicles) and the use of "green" fuels (more environmentally friendly). Avoiding or reducing the number of trips or trip lengths is not considered.

The two modal-shift EEIs represent growth rates for the different modes of transport (all vehicles including walking and cycling). They are based on PRIMES data. While activity levels (e.g., passenger-km) change between 2015 (base year) and 2030 (both scenarios), they are not different between both scenarios. The same holds true for occupancy levels and loading factors. All of these parameters would affect energy consumption and thus distort the direct impacts of EEIs.

The vehicle-specific EEIs rely on fuel-efficiency improvements and changes in drive-train technologies. Fuel efficiency and fuel share values are based on EU scenarios and models (TIMES by the Joint Research Centre), TREMOVE, iTREN, ASTRA-EC and SULTAN). Changes in the vehicle stocks are based on country-specific shares for all different technologies. They are modeled according to annual new sales for each drive-train technology and transportation mode. Basis for the stock-model are JRC TIMES, TREMOVE, iTREN, ASTRA-EC and SULTAN as well.

The quantified net impacts (see methodology) originate in the EU (see Figure 1). Measures within European countries are the source for a reduction of the country-specific energy consumption. The impacts of providing the energy services and producing necessary technologies are not restricted to the European borders (with exception of direct GHG emissions). Because many energy services require materials from outside of the EU, final energy savings also affect material extraction and emissions on a global scale.
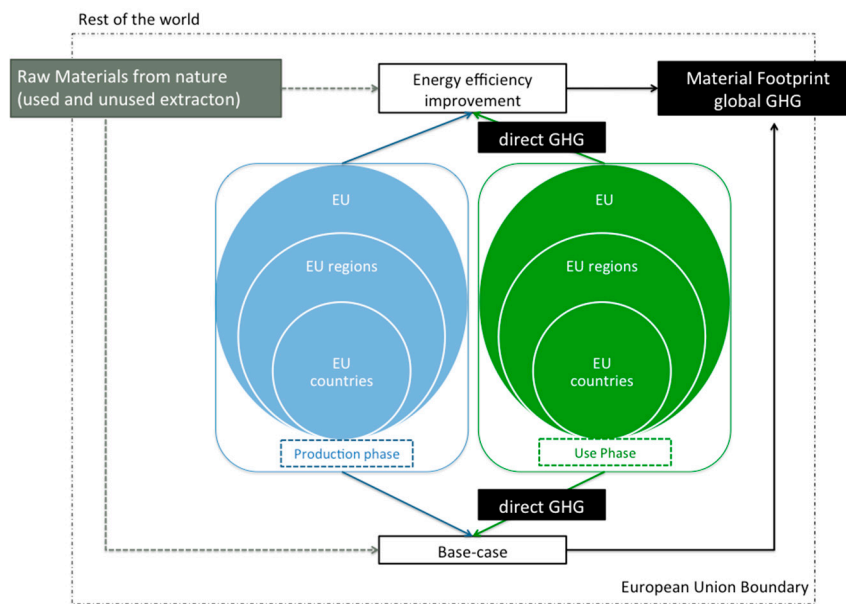
Figure 1. System boundaries for resource impacts material footprint, global greenhouse gases (GHG) and direct GHG (own compilation).

3. Methodology

The quantification required the definition of resource impacts, the selection of methods and the generation of models. A thorough description can be found on the COMBI website (see scope). It contains a literature review [26] as well as a report on methodology (see pp. 14–36 in [17]) and results (see pp. 64–91 in [17]).

3.1. Impact Indicators for Natural Resources

There are several definitions of natural resources and their sustainable use. Most definitions revolve around the usefulness of resources to humans. It is also commonly agreed upon that their depletion affects the environment as well as the needs of future generations. According to the Flagship Initiative under the Europe 2020 Strategy, natural "resources underpin the functioning of the European and global economy and our quality of life. These resources include raw materials such as fuels, minerals and metals but also food, soil, water, air, biomass and ecosystems" [27].

The study at hand restricts natural resource use to raw materials (in tons) and GHG emissions (in tons of CO_2 equivalents or CO2e). The wide variety of environmental and economic effects of resource use cannot be merged into a single indicator [28]. However, the extraction of raw materials on the input side of the techno sphere allow for a rough estimation of resource use effects. Less use of material resources is likely to be accompanied by less pressure on soil, water and ecosystems. A lower global warming potential also indicates a lower environmental footprint in most cases. Functioning as a proxy for a much more complex issue, both impact categories are strongly linked to the EEIs. A more detailed description of advantages and limitations of material flow accounting (MFA) and similar methods (e.g., primary energy demand) can be found in the literature [29–32].

Other potential impact-indicators have been omitted for various reasons. First, any resource indicator for COMBI needed to be applicable to single EEIs within countries and the sum of all EEIs in a country. Second, any resource indicator should have no direct relation to other impacts in the study on multiple benefits of energy efficiency in order to avoid double counting. Third, resource indicators should be able to cover mining aspects as well as biotic raw materials.

Methods based on multi-criteria analysis were ruled out, because they are either non-quantitative assessments or rely on weighting by experts. Energy-related resource indicators were not used for

risk of double counting. Methods based on input-output tables on the other hand (e.g., economy-wide material flow accounting) were ruled out due to their high level of aggregation. Many suitable LCA impact categories for resource depletion (such as abiotic depletion potential) are restricted to a selected group of materials and do not cover the mining process or raw materials without economic use. However, future assessments of multiple impacts might benefit from the current work of the task force on natural resources. This expert group is expected to classify and evaluate several resource indicators and relate them to their area of protection (see [33] for present findings).

Table 2 lists the impact indicators. The indicator dGHG refers to the GHG emissions from both scenarios, caused by the combustion of fossil fuels in the transport sector. It is restricted to the use phase of EEIs and the direct consumption of energy carriers. The carbon footprint also includes the life-cycle wide, but annual GHG emissions from energy services and the production of vehicles (use and production phase). It refers to globally induced GHG emissions.

Table 2. Impact indicators for EEIs in the European transport sector.

Impact Indicators [Unit]	Description
Material Footprint [tons]	Biotic and abiotic raw materials from used extraction in use- and production-phases unused extraction of biotic and abiotic materials without economic use in use- and production-phases
Biotic Raw Materials [tons]	Biotic raw material demand from used extraction in use- and production-phases
Abiotic Raw Materials [tons]	Fossil fuel demand from used extraction in use- and production-phases Metal ore demand from used extraction in use- and production-phases Mineral demand from used extraction in use- and production-phases
Carbon Footprint [tons]	Global Warming Potential (GWP 100a) within and outside of Europe in use- and production-phases
dGHG [tons]	Global Warming Potential (GWP 100a) from fossil fuel combustion in Europe in use-phase

Source: [17].

The material footprint (in kg or tons) includes the life-cycle wide amount of extracted raw materials. These materials are either put to an economic use (used extraction) or not (unused extraction from e.g., excavation). It can be further divided into abiotic raw material demands for fossil fuels, minerals and metal ores. This includes for example ore waste after processing as well as the biotic raw material demand. The material footprint is a sum-indicator of material accounting. It adds up the life-cycle wide inputs of specific materials and connects them to their natural occurrence (e.g., in form of a ore) as well as any additional material needed for their provision:

$$\text{Material Footprint (MF) = Fossil Fuel Demand + Metal Ore Demand} \atop \text{+ Mineral Demand + Biotic Raw Material Demand + Unused Extraction} \tag{1}$$

The final results or net effects are quantified as the difference between both scenarios (see 3.4 models) with help of characterization factors (e.g., the fossil fuel demand of electricity from soft coal in a certain country). This means that sub-impacts can partially compensate each other, such as trading fossil fuels for metal ores.

3.2. Methods

Impact indicators refer to different base-lines throughout EU member states or European markets. Energy-efficiency improvements take place in the same spatial and temporal boundaries. The methods for calculation are based on the material flow accounting and life-cycle assessment methodology.

A additional advantage of these two methods lies in their compatibility. All impacts can be calculated by using characterization factors in the same models from the same input and generic data.

For material footprint the material-input-per-service (MIPS) is chosen (see also [29,34–36]). The necessary impact factors (raw material extraction and unused extraction from nature) are mostly based on Wiesen et al. (2014) [37]. Additional factors are found in an expertise on behalf of the German Environment Agency [38].

The carbon footprint represents the Global Warming Potential for 100 years (GWP 100a) by the International Panel on Climate Change [39]. Direct GHG emissions are calculated by multiplying the direct fossil fuel use in both scenarios with their characterization for GWP 100a. Emission factors stem from a guideline for GHG monitoring by the European Commission [40]. Renewable energy carriers have no direct emissions (dGHG), but can have global GHG emissions for provision and utilization.

Apart from these direct emissions, all impact indicators cover the life cycle phase from extraction to production or cradle-to-gate over the lifetime. They represent a current set of technologies for energy supply and, in case of EE's during the production-phase, for average vehicles and lighting systems in Europe. The functional unit is 1 MWh of net energy or 1000 products.

The phase of decomposition or end-of-life (EoL) is excluded from the analysis. Including the EoL stage would have required data or assumptions for at least the state-of-art, costs and capacities of utilization technologies. It would also require reliable information on secondary material prices and regulatory requirements.

The use-phase, on the other hand, is directly represented by the final energy use in the input data.

3.3. Data

The following data is included in the COMBI input data (not all of which were used to model EEI's in the transport sector):

Final energy use per energy carrier, EEI and country

- Gross energy production in 2030 per country (aggregated data based on PRIMES);
- Stocks of cars, busses, duty trucks, lighting systems per EEI (if relevant) and country;
- Share of ambient heat sources per country;
- V-% of blend for biofuels in 2030;
- loading factors for freight transport vehicles;
- number of lighting points per building in residential and non-residential buildings;
- lighting efficiency of lighting types.

The upstream material and energy flows, including parameters for energy conversion, stem from the Life Cycle Inventory (LCI) database ecoinvent in version 3.1 (The first models were generated as early as 2015. At this point, only ecoinvent 3.1. data was available for the calculation of impact factors for resource use.). Additional data was drawn from EUROSTAT and literature (see section on models).

3.4. Models

The researcher chose a static bottom-up model approach in light of the project's restrictions. Those restrictions required the compilation of input data during impact quantification. The input data itself focused on the effects of energy-efficiency improvements alone. Many surrounding systems were assumed to be the same between scenarios. Dynamic modelling (e.g., feedback loops between sectors) was therefore not possible. The models also exclude the export and imports of energy or products. Each model consists of a set of characterization factors for a country, a region, Europe or one type of product. These factors are then multiplied with the final energy use per energy carrier in the input data or the amount of product type stocks in both scenarios.

The basis for the electricity model is a top-down disaggregation of the gross electricity production in Europe in 2030 (generated within the PRIMES model). The electricity supply by power plants and

grids is then further disaggregated bottom-up. Each country is represented by one characterization factor for each impact indicator. However, power plants are, in many cases, representatives of a European region rather than a European country. The same holds true for electric grids, which represent a European average. Additional data stems from ecoinvent 3.1. [41], Eurostat [42], the PRIS database on nuclear reactors [43], wind energy statistics [44], solar power statistics [45] as well as a study on hydropower in Europe [46].

The (transport) fuel model is somewhat simpler, as there are not many differences between European countries in terms of fuel production. This led to the compilation of a European model for fuel provision. Each of the 8 different fuel types in the input data is represented by one average characterization factor for each impact indicator. Additional data for model generation was drawn from ecoinvent 3.1, the JRC well-to-tank/well-to-wheel analysis [47] and the SULTAN model on biofuel substitution of the future [48]. Feedstock data stems a study on biofuel sustainability [49] and information on the natural gas supply in Europe [50].

Additional models were required to represent the production of vehicles in the European market. The COMBI input data provides information on the stocks of 14 different car types (with 3 different sizes each) in both scenarios. A recent study provided the LCIs of 8 different car types [51], which had to be matched to that input data and scaled according to three different sizes (see Tables 3 and 4). The LCI data in [51] is based on several LCAs of vehicles [52–55]. In light of these sources, data on the car body and to lesser extent electrical engines might be outdated.

Additional characterization factors were generated for light-duty trucks (based on the car data), busses (based on a MAN Lion's City M in [56]) and heavy-duty trucks (based on the ecoinvent 3.1. process "production of lorry, 28 tons"). Trains were modeled according to ecoinvent data as well ("goods wagon production" and "locomotive production" for the Rest-of-Europe). All data on vehicles for freight transport was scaled to the country-specific COMBI input data on average load factors (see supplementary materials for detailed information).

Table 3. Matching of drivetrains in the COMBI input data with data from a project on "key technologies for electro mobility" (STROM).

Passenger Car Type in COMBI	Used Drive Train Based on STROM
Internal combustion engine (ICE) gasoline baseline	ICE gasoline
ICE gasoline advanced	ICE gasoline
ICE diesel baseline	ICE diesel
ICE diesel advanced	ICE diesel
ICE liquefied petroleum gas (LPG) retrofit	ICE CNG
ICE compressed natural gas (CNG) retrofit	ICE CNG
ICE ethanol	ICE gasoline
ICE hydrogen	ICE gasoline
Hybrid electric vehicle (HEV) gasoline	Hybrid gasoline
HEV diesel	Hybrid gasoline
Plug-in Hybrid (PHEV) gasoline	Plug-In Hybrid gasoline
Plug-in Hybrid (PHEV) diesel	Plug-in Hybrid gasoline
Battery electric vehicle (BEV)	Battery electric
Fuel cell (FC) hydrogen	Fuel cell electric

Source: [17] based on [51].

Table 4. Scaling of vehicle weight for personal transport.

Type	Weight Class	Weight	Lifetime
Passenger Car	Small	1200 kg	12 years
	Medium	1600 kg	12 years
	Large	2000 kg	12 years
Bus	Standard	11,000 kg	13 years

Source: own compilation.

3.5. Limitations

The chosen approach as well as data availability and matching to the input data resulted in numerous simplifications, assumptions and cut-offs for the models (see Table 5).

Table 5. Key assumptions and cut-offs of models in the study.

Model	Key Assumptions	Cut-Off
Electricity Supply-Use Phase	• All countries use the same network specific (per unit of energy) length and technology for their electrical grid • Power plan technologies of single countries may represent countries within one market • One European process was used to process natural gas into heat and electricity • Country-specific processes do not include upstreams for waste provision, therefore an appropriate process for Switzerland was used for all countries	• Imports and exports of electricity in Europe or between Europe and Rest-of-World • No SF_6 for switching gear
Fuel Supply- Use Phase	• EU-28 average for fuel provision • Direct CO_2 emission factors for each fuel are average in Europe (assuming total combustion) • Share of biofuel in biofuel blends is the same throughout Europe	• No bioethanol from wheat, barley, triticale, wine, cassava • No biodiesel from sunflower, tallow • No natural gas from Turkey, Poland, Romania
Passenger Vehicles-Production Phase	• One product represents one vehicle type in EU-28 • Small, medium, large vehicles are scaled by mass • Standard and advanced cars with internal combustion engine share the same production recipes • Vehicle types differ by types of drive train, not auto body (glider)	
Freight Vehicles-Production Phase	• Light-duty trucks based on large car types in passenger transport model • Heavy duty trucks only represented by one type with different loading capacities per country • Trains represented by one type with different loading capacities per country	• Different production mix for heavy duty trucks in efficiency and base-case scenario (only stock differences by modal shift relate to impacts)

The researchers used current production recipes to generate models of a future use of resources. They neglected potential higher rates of secondary materials in the European economies in the future. This results in the following major limitations in regard to the study itself and their use in another context:

- the generated characterization factors are not a robust basis for a comparison of impacts between countries or technologies by themselves;
- the resulting impact indicators (e.g., net material footprint) depend on the size of final energy use in both scenarios as well as product stocks and the assumption on the share of certain energy carriers (e.g., electricity from soft coal in 2030);
- differences in the LCIs within one product type (e.g., for different battery electric vehicles) can be larger than differences between average product types;
- static bottom-up models cannot account for the fact that changes in the product stocks and final energy use are likely to have an impact on the systems (e.g., the electricity system) themselves as well as extraction and recycling rates of material in a economy.

Other (minor) limitations are inherent to LCA and MFA methods in general (e.g., uncertainty from actuality of data and the use of generic process data), but would also affect other models.

4. Results

The energy efficiency improvements in the transport sector scenarios result in final energy savings in the European Union of 460 TWh in 2030. This results in savings for the overall material demand (material footprint) of 67 Mt (56 Mt for passenger transport alone); 52 Mt stem from a lower raw material demand for fossil fuels; and 12 Mt from a lower demand for materials from unused extraction. There is also the possibility for a small negative trade-off for the extraction of biotic materials. Changes in the provision of final energy lead to an additional demand of 0.4 Mt of biotic raw materials in the use phase. On the emission side, greenhouse gas emissions of 159 Mt CO_2e could be saved globally. 135 Mt CO_2e could be saved directly from a lower combustion of fossil fuels within the EU.

4.1. Use vs. Production in the European Union (EU)

The changes in the production systems for vehicles attributes to additional global Carbon Footprint savings. 8 Mt CO_2e are not emitted globally, resulting in a net carbon footprint of 168 Mt CO_2e. However, additional 12 Mt of material have to be extracted during this production phase, decreasing the net material footprint down to 54 Mt. While additional savings could be realized for minerals (1.2 Mt of savings), fossil fuels (1.1 Mt of savings) and materials from unused extraction (5 Mt of savings), the extra demand for 19.9 Mt of metal ores is largely responsible for this effect (see Figure 2). There is also evidence that these transitions lead to an additional demand for biotic raw materials: additional demands of 0.4 Mt are required during use with a net effect of 0.33 Mt.
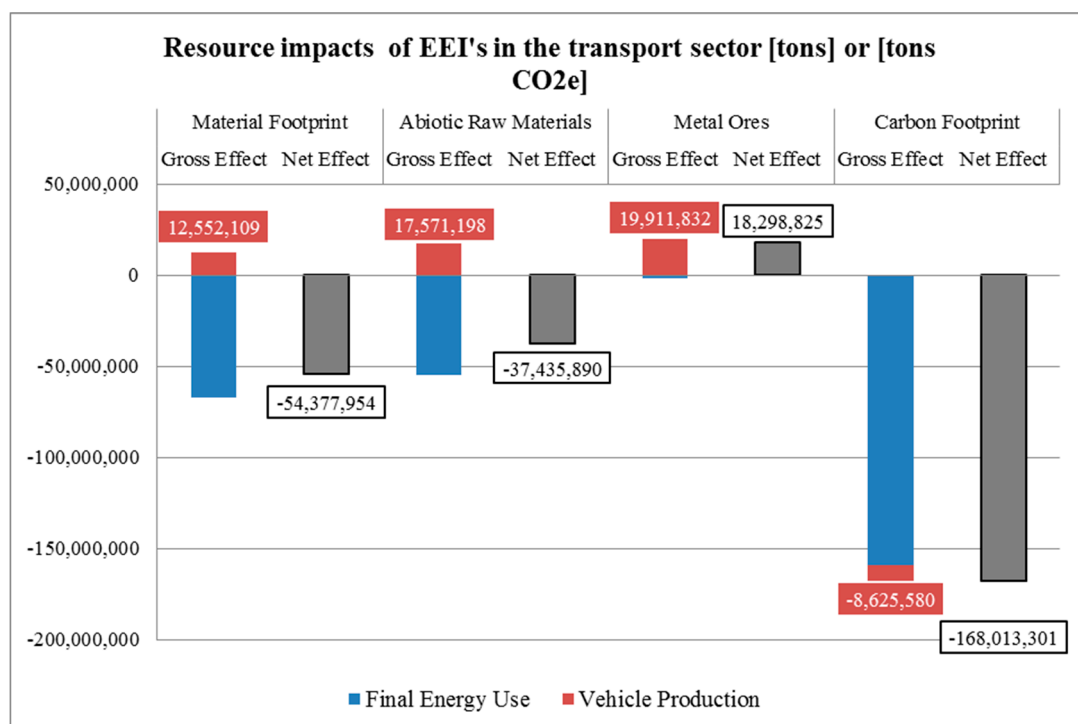

Figure 2. Gross and net impacts of resource impacts in the transport sector (negative values indicate savings). By calculating the differences between both scenarios, single sub-impacts (e.g., metal ores) can be higher than the sum of all sub-impacts combined (see also Section 3.1).

4.2. Material Demand for Modal Shift and Differences in Vehicle Types

The modal shift improvements (action 9 and 13) have a rather small effect on the material requirements of the use-phase. Additional 0.7 Mt are required in the personal transport sector, while 1.2 Mt are saved in the freight transport sector. The overall smaller product stocks from modal shift

rather affect the production-phase. The study found additional savings of 53 Mt for personal transport and 61 Mt for freight transport.

Changes from differences in the produced vehicle stocks (actions 11, 12, 14) are mainly responsible for additional material requirements. For personal transport, 56 Mt are saved during use-phase compared to an extra of 106 Mt during the production phase. Light-duty vehicles on the other hand require an additional 18 Mt during the production-phase, but reduce the material demand during the use-phase by 61 Mt.

Looking at the net effect of both sectors (savings of 54 Mt), personal transport only contributes 7% of the savings.

4.3. Metal Ore and Metal Demand

Metal ores are the only material resources that are required additionally in relevant amounts. While EEIs from freight transport induce metal ore savings of 9.8 Mt, an extra of 28.2 Mt of metal ores are needed to provide energy savings in the passenger transport sector in 2030 (resulting in a net effect of an extra 18.3 Mt).

The following sub-sections focus on the metal demand for cars in the passenger transport sector, as this sector alone is responsible for an additional net metal ore demand of 28.4 Mt.

4.3.1. Differences in Car Types and Stocks

Two actions are responsible for metal ore savings and additional metal ore demand from passenger transport in the scenario. Action 9 compares the car stocks in the reference scenario with reduced car stocks from modal shift. Action 11 is compiled from changes in car stocks towards more fuel-efficient vehicles. The total of both actions results in the total net effect. Large differences can only be found for diesel cars (46 million advanced cars in exchange for 57 million baseline cars) and gasoline cars (64 million advanced cars in exchange for 72 million baseline cars). Fewer than 10 million hybrid cars have to be produced additionally. Stocks for full battery vehicles are even negative: 0.2 million cars do not have to be produced as a net effect (although their share in the production mix is significantly higher compared to a reference scenario).

4.3.2. Metal Ore Demand by Metal Type

Despite low differences in car stocks for non-conventional cars, additional metal ores are required to provide energy savings during the use-phase. According to Table 6, additional 28.4 Mt of metal ores are required with savings only for iron ores (4.6 Mt). The additional metal ores from semiprecious metals amount to 12.0 Mt, from precious metals 9.1 Mt and from other metals 11.7 Mt. While the modal shift effect itself saves up to 20.0 Mt of metal ores, an additional 48.6 Mt are required to produce the cars for action 11.

Table 6. Material and metal ore demand (net effects of actions 9, 11 and 9 + 11; negative values indicate savings).

Indicators for Metal Ores	Modal Shift for Cars (A 9)	Production of Cars (A 11)	SUM of A 9 & A 11
Material Footprint	−55.49 Mt	104.81 Mt	49.33 Mt
Unused Extraction	−32.49 Mt	53.07 Mt	20.58 Mt
Metal Ores—TOTAL	−20.17 Mt	48.56 Mt	28.39 Mt
Metal Ores—Iron	−4.96 Mt	0.39 Mt	−4.57 Mt
Metal Ores—semiprecious metals	−5.30 Mt	17.29 Mt	11.99 Mt
Metal Ores—precious metals	−1.90 Mt	11.04 Mt	9.14 Mt
Metal Ores—rare earth metals	−0.01 Mt	0.10 Mt	0.08 Mt
Metal Ores—minor & other metals	−8.00 Mt	19.73 Mt	11.74 Mt

4.3.3. Direct Metal Input

The production of fuel-efficient cars is the cause of the additional metal ore demand in the scenario. The main drivers for the additional requirement of 48.6 Mt in action 11 are hybrid cars (58.1%), fuel cell cars (39.4%) and plug-in hybrids (38.2%), while the reduction in conventional car stocks saves metal ores of up to 17.8 Mt.

The demand for semi-precious metals (12.0 Mt for both actions) is dominated by copper. Copper ores alone contribute 80.3% of this demand. This corresponds to a direct input of 148,000 tons of copper metal and equals 1.0% of the global copper production in 2012 (but 3.6% of Europe's demand in 2014 according to [57]).

For precious metals, an additional metal ore demand of 9.1 Mt would be required. The majority (73.1%) stems from gold ores (coupled production). The corresponding annual direct input for gold only amounts to 11.6 tons of gold, which is 0.5% of the global gold production in 2012 [58], and only 0.4% of the mined gold supply in 2015 [59].

The metal ore demand for minor and other metals (11.7 Mt) is driven by the demand for lithium brines (13.0 Mt). Nickel derivate savings of 2.1 Mt only partially compensate for that. The direct input for lithium amounts to 19,550 tons or 103,000 tons of lithium carbonate or LCE (it is assumed that 1 kg of LCE is equal to 0.1895 kg of pure Li), which is roughly 51% of the worldwide lithium production in 2012. While it seems likely that lithium production will increase of the next decades, demand is likely to increase as well, as more and more lithium-dependent applications evolving (see also [60]).

Cobalt and rare-earth elements are both popular research objects in related literature. Unfortunately, the researchers of this study could not quantify robust results for these metals. The uncertainties from data, methodology and the potential technological development were too high.

4.3.4. Metal Ore Demand for Drive Trains

Many factors in the scenario data were kept on the same level for both scenarios in order to focus on EEIs (e.g., energy mix or activity levels). Additionally, modal shift improvements played a crucial role in reducing the overall demand for cars in the personal transport sector. Only replacing current car technologies with future car technologies would, therefore, have a larger impact on the overall metal demand. Using data in this study on the production of medium-sized cars allows for a rough estimation of these effects. Table 7 shows the comparison between the metal ore demand for a petrol car and the additional demand of other drive trains. However, this risk can be mitigated, if metal recovery and material efficiency are improved.

Table 7. Additional annual metal ore demand per car type compared to a medium-sized petrol car (production of car).

Material Demand	Hybrid, Medium	Fuel Cell, Medium	Battery, Medium
Metal ores (all)	3.1 tons	5.4 tons	6.1 tons
Semi-precious metal ores	1.1 tons	2.0 tons	2.5 tons
Precious metal ores	0.8 tons	0.9 tons	1.0 tons

5. Discussion of Metal Demand and Supply

Table 8 lists the direct metal input results in the study for copper, gold and lithium. It compares them to maximum global production rates in Sverdrup et al. (2017) [58]. Even without considering the uncertainty of the scenario and LCI data, possible technological development as well as higher recycling and more efficient extraction rates, most additional demands for metals are not critical from the perspective of supply.

Trading "metals for fuels" is clearly a possible consequence of low-carbon transport policies, however; in particular, if electrical drive trains (hybrid and battery vehicles) are advocated and lithium remains the most important raw materials for their production. Looking at the literature (e.g., [8,11,61]),

it is likely that the future demand for lithium in electrical vehicles exceeds its current production. These additional supply needs can likely be met by an increase in production (also in regard to a comparable large availability). However, lithium is not only required for future vehicles, but also electronic products, thus further tightening the supply in the future.

Table 8. Net direct input for modal shift and car production in the study.

Metal	Net Demand (Direct Input) in This Study in 2030 in [Tons/Year]	Current Production in Sverdrup et al. (2017) in 2012 in [Tons/Year]	Maximum Production Rate in Sverdrup et al. (2017) in [Tons/Year]	Share of Net Demand in the Study Compared to Maximum Production
Copper	148,000	16,000,000	28,000,000	0.7%
Gold	11.6	2600	3200	0.3%
Lithium (LCE)	103,166	200,000	350,000	29.5%

Source: Own compilation based on [58].

Koning et al. (2018), for example, analyzed the demand, production and supply of various metals. They looked at four different scenarios for a low-carbon economy in 2050 (not restricted to the transport sector) [11]. The authors found that the high demand for most analyzed metals (such as aluminum) can be met by the known economic reserves (not without further development of mines, however). In opposition, the demand for lithium and copper (among other metals) cannot be met by current reserves. It was calculated that the global annual demand for electricity production, construction works and land vehicles in 2050 amounts to 18 million tons of copper and 414,000 tons of lithium (supplementary material in [11]); 37 million tons of copper and 1.6 million tons of lithium are required, if also other products such as electronics are considered (data stems from the Blue Map electricity supply (BMES) scenario in the study, which not only considers technological development, but also changes in the electricity supply systems with high shares for renewables and nuclear energy).

Another study by Olivetti et al. (2017) looked closely at the future supply chains of lithium-ion batteries [8]. They emphasized that comparing the demand for lithium to its future supply is not sufficient to determine its criticality. Potential bottlenecks are, rather, likely to stem from an imbalance in production of lithium carbonates in comparison to the demand for battery-grade material. Recycling batteries at the end of life might mitigate the challenges in the lithium supply in the long run, but this is currently economically not feasible.

6. Conclusions

This study quantified the annual final energy and GHG emission reductions from low-carbon transport in Europe in 2030. It compared these reductions to the savings and additional requirements for materials and metals in particular. In regard to the research question (metals for fuels?), additional metal ores are required to allow for energy and GHG savings in Europe and worldwide. The net effect from energy-efficiency improvements in freight and personal transport, amount to an additional demand of ca. 18 million tons for metal ores per year (compared to savings of 54 million tons of fossil fuels). In turn, large global GHG savings of more than 168 million tons of CO_2 equivalent and a lower final energy use of 460 TWh are realized. However, the overall material bill is positive: despite negative net effects for metals and biotic materials (0.3 Mt), more than 54 million tons of material would not have to be extracted due to transport modal shift and low-carbon vehicle stocks. This amount is likely to increase, if technological development and recycling lead to better material efficiency.

For metal ores, the negative impact is dominated by EEIs in the personal transport sector. Considering both use and production of vehicles, an extra of 28 million tons of metal ores are required to be extracted in 2030 alone. This demand mainly stems from car production, which is only partially compensated for by their use and a modal shift. The resulting extra annual net demand for metal ores (28.4 million tons) is divided into the following ore types: an extra of 12.0 Mt for semi-precious metals, 9.1 Mt for precious metals, 11.7 Mt for other metals (mainly lithium) and savings of 4.6 Mt for

ferrous metals. The direct input (metal) for copper amounts to 150,000 tons, for lithium carbonates to 103,000 tons, and for gold to 12 tons per annum. With the exception of lithium, none of this demand is deemed crucial on its own or from a low-carbon transport sector alone. Nonetheless, the occurrence of future supply bottlenecks for these metals in particular also depend on the metal ore demand in other areas, as a short literature review showed.

The authors applied a bottom-up approach by calculating the effects of over 20 different energy efficiency actions in different sectors all over Europe and summing these effects up. The models did not account for the fact that recycling rates for metals might increase due to policies for recovery. They also exclude assumptions on technological developments leading to higher material efficiency. Positive synergies can also be created by developing different sectors together, reducing environmental impacts as a consequence (e.g., by power-to-x technologies). Due to the focus on material resources, many environmental effects could not be accounted for. Deep and large structural changes for an energy-efficient Europe might harm water resources, induce land-use change, decrease biodiversity as well as generate additional waste or emit additional harmful substances into water, air and land. It is up to further research to determine whether all of these effects are going to be negative or whether positive effects occur in Europe alone.

The perspective applied in this study is driven from a technological and economic point of view. Societies invest in energy-efficiency products in Europe in order to meet the goals of a low-carbon society. It is recommended to validate these and similar findings by applying a more transdisciplinary approach which also takes into account the needs of future societies or the cultural drivers of transformation (e.g., as shown by [62]).

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References

1. European Commission. A European Strategy for Low-Emission Mobility (SWD (2016) 244 final). Staff Working Document. 2016. Available online: https://ec.europa.eu/transport/sites/transport/files/themes/strategies/news/doc/2016-07-20-decarbonisation/swd%282016%29244.pdf (accessed on 20 July 2016).
2. Chester, M.V.; Horvath, A. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environ. Res. Lett.* **2009**, *4*, 024008. [CrossRef]
3. Williams, J.H.; DeBenedictis, A.; Ghanadan, R.; Mahone, A.; Moore, J.; Morrow, W.R.; Price, S.; Torn, M.S. The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science* **2012**, *335*, 53–59. [CrossRef] [PubMed]
4. Kasten, P.; Bracker, J.; Haller, M.; Purwanto, J. *Electric Mobility in Europe—Future Impact on the Emissions and the Energy Systems*; Final Report of Task 2—Assessing the Status of Electrification of Road Transport Passenger Vehicles and Potential Future Implications for the Environment and European Energy System; Öko-Institut e.V. on Behalf of European Environment Agency: Berlin, Germany, 2016.
5. Bohnes, F.A.; Gregg, J.S.; Laurent, A. Environmental Impacts of Future Urban Deployment of Electric Vehicles: Assessment Framework and Case Study of Copenhagen for 2016–2030. *Environ. Sci. Technol.* **2017**, *51*, 13995–14005. [CrossRef] [PubMed]
6. Vivanco, D.F.; Freire-González, J.; Kemp, R.; van der Voet, E. The remarkable environmental rebound effect of electric cars: A microeconomic approach. *Environ. Sci. Technol.* **2014**, *48*, 12063–12072. [CrossRef] [PubMed]
7. Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins, P.; Barletta, D.; Lettieri, P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chem. Eng. Res. Des.* **2016**, *112*, 298–309. [CrossRef]

8. Olivetti, E.A.; Ceder, G.; Gaustad, G.G.; Fu, X. Lithium-ion battery supply chain considerations: Analysis of potential bottlenecks in critical metals. *Joule* **2017**, *1*, 229–243. [CrossRef]

9. Busch, J.; Dawson, D.; Roelich, K. Closing the low-carbon material loop using a dynamic whole system approach. *J. Clean. Prod.* **2017**, *149*, 751–761. [CrossRef]

10. Kleijn, R.; Van der Voet, E.; Kramer, G.J.; Van Oers, L.; Van der Giesen, C. Metal requirements of low-carbon power generation. *Energy* **2011**, *36*, 5640–5648. [CrossRef]

11. De Koning, A.; Kleijn, R.; Huppes, G.; Sprecher, B.; van Engelen, G.; Tukker, A. Metal supply constraints for a low-carbon economy? *Resour. Conserv. Recycl.* **2018**, *129*, 202–208. [CrossRef]

12. Pavel, C.C.; Thiel, C.; Degreif, S.; Blagoeva, D.; Buchert, M.; Schüler, D.; Tzimas, E. Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. *Sustain. Mater. Technol.* **2017**, *12*, 62–72. [CrossRef]

13. Roelich, K.; Dawson, D.A.; Purnell, P.; Knoeri, C.; Revell, R.; Busch, J.; Steinberger, J.K. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Appl. Energy* **2014**, *123*, 378–386. [CrossRef]

14. Thema, J.; Suerkemper, F.; Thomas, S.; Teubler, J.; Couder, J.; Chatterjee, S.; Ürge-Vorsatz, D.; Bouzarovski, S.; Mzavanadze, N.; Below, D.V. More than energy savings: Quantifying the multiple impacts of energy efficiency in Europe. In Proceedings of the Consumption, Efficiency and Limits: ECEEE 2017 Summer Study, Presqu'ile de Giens, France, 29 May–3 June 2017; Council for an Energy Efficient Economy: Stockholm, Sweden, 2017; pp. 1727–1736.

15. Thema, J.; Suerkemper, F.; Thomas, S.; Teubler, J.; Couder, J.; Mzavanadze, N.; Bouzarovski, S.; Ürge-Vorsatz, D.; Chatterjee, S.; Below, D.V. Widening the perspective: An approach to evaluating the multiple benefits of the 2030 EU energy efficiency potential. In Proceedings of the 2016 International Energy Policies & Programmes Evaluation Conference, Amsterdam, The Netherlands, 7–9 June 2016.

16. Ürge-Vorsatz, D.; Kelemen, A.; Tirado-Herrero, S.; Thomas, S.; Thema, J.; Mzavanadze, N.; Hauptstock, D.; Suerkemper, F.; Teubler, J.; Gupta, M.; et al. Measuring multiple impacts of low-carbon energy options in a green economy context. *Appl. Energy* **2016**, *179*, 1409–1426. [CrossRef]

17. Teubler, J.; Kiefer, S.; Bienge, K. *Methodology and Quantification of Resource Impacts from Energy Efficiency in Europe (D4.4); COMBI—Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe*; Wuppertal Institute: Wuppertal, Germany, 2018; p. 109.

18. University of Antwerp. *Description of End-Use Energy Efficiency Improvement Actions in the Residential*; Tertiary, Transport and Industry Sectors D2.2 Report, Updated March 2018; University of Antwerp: Antwerp, Belgium, 2018.

19. University of Antwerp. *Overview of COMBI Scenarios and How They Were Constructed D2.2 Annex*; University of Antwerp: Antwerp, Belgium, 2018.

20. *E3MLab/ICCS PRIMES MODEL 2013–2014 Detailed Model Description*; National Technical University of Athens: Athens, Greece, 2014.

21. Simoes, S.; Nijs, W.; Ruiz, P.; Sgobbi, A.; Radu, D.; Bolat, P.; Thiel, C.; Peteves, S. *The JRC-EU-TIMES Model—Assess—Long-Term Role SET Plan Energy Technologies*; Publications Office of the European Union: Luxembourg, 2013. [CrossRef]

22. De Ceuster, G.; van Herbruggen, B.; Ivanova, O.; Carlier, K.; Martino, A.; Fiorello, D. *TREMOVE Version 2.3 Simulation Model for European Environmental Transport Policy Analysis*; Transport & Mobility Leuven: Leuven, Belgium, 2007.

23. Schade, W.; Krail, M. *The iTREN-2030 Integrated Scenario Until 2030*; Fraunhofer Institute for Systems and Innovation Research: Karlsruhe, Germany, 2010.

24. Fermi, F.; Fiorello, D.; Krail, M.; Schade, W. *Description of the ASTRA-EC Model and of the User Interface*; Fraunhofer-ISI: Karlsruhe, Germany, 2014.

25. Nikolas, H.; Matthew, M. EU Transport GHG: Routes to 2050 II. SULTAN Illustrative Scenario Tool—User Guide: 2012 Update. 2012. Available online: http://www.eutransportghg2050.eu/cms/reports/ (accessed on 5 September 2016).

26. Teubler, J.; Bienge, K.; Wiesen, K. *WP4 Resources: Literature Review on Resource Benefits D4. 1 Report*; Wuppertal Institute: Wuppertal, Germany, 2015.

27. European Commission. A Resource-Efficient Europe-Flagship Initiative under the Europe 2020 Strategy. Available online: https://uk.practicallaw.thomsonreuters.com/6-504-6764?transitionType=Default&contextData=%28sc.Default%29&firstPage=true&comp=pluk&bhcp=1 (accessed on 26 January 2011).

28. Fischer-Kowalski, M.; Swilling, M. *Decoupling: Natural Resource Use and Environmental Impacts from Economic Growth*; United Nations Environment Programme: Nairobi, Kenya, 2011.

29. Liedtke, C.; Bienge, K.; Wiesen, K.; Teubler, J.; Greiff, K.; Lettenmeier, M.; Rohn, H. Resource use in the production and consumption system: The MIPS approach. *Resources* **2014**, *3*, 544–574. [CrossRef]

30. Haberl, H.; Fischer-Kowalski, M.; Krausmann, F.; Weisz, H.; Winiwarter, V. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy* **2004**, *21*, 199–213. [CrossRef]

31. Huijbregts, M.A.; Rombouts, L.J.; Hellweg, S.; Frischknecht, R.; Hendriks, A.J.; van de Meent, D.; Ragas, A.M.; Reijnders, L.; Struijs, J. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? *ACS Publ.* **2006**, *40*, 641–648. [CrossRef]

32. Wiedmann, T.O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci. USA* **2013**, *29*, 201220362. [CrossRef] [PubMed]

33. Sonderegger, T.; Dewulf, J.; Fantke, P.; de Souza, D.M.; Pfister, S.; Stoessel, F.; Verones, F.; Vieira, M.; Weidema, B.; Hellweg, S. Towards harmonizing natural resources as an area of protection in Life Cycle Impact Assessment. *Int. J. Life Cycle Assess.* **2017**, *22*, 1912–1917. [CrossRef]

34. Saurat, M.; Ritthoff, M. Calculating MIPS 2.0. *Resources* **2013**, *2*, 581–607. [CrossRef]

35. Schmidt-Bleek, F.; Bringezu, S.; Hinterberger, F.; Liedtke, C.; Spangenberg, J.H.; Stiller, H.; Welfens, M.J. *MAIA: Einführung in Die Material-Intensitäts—Analyse Nach Dem MIPS-Konzept*; Wuppertal Texte; Birkhäuser: Berlin, Germany, 1998; ISBN 978-3-7643-5949-2.

36. Schmidt-Bleek, F. *Das MIPS-Konzept. Weniger Naturverbrauch–Mehr Leb. Durch Fakt*; Droemer Knaur: Munich, Germany, 1998; Volume 10.

37. Wiesen, K.; Mathieu, S.; Michael, L. Calculating the Material Input per Service Unit using the Ecoinvent Database. *Int. J. Perform. Eng.* **2014**, *10*, 357–366.

38. Wiesen, K.; Teubler, J.; Saurat, M.; Suski, P.; Samadi, S.; Kiefer, S.; Soukup, O. *Analyse des Rohstoffaufwandes der Energieinfrastruktur in Deutschland (Expertise)*; German Environment Agency (UBA): Wuppertal, Germany, 2017.

39. Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.; Tignor, M.; Miller, H. *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*; Cambridge University Press: Cambridge, UK, 2007.

40. European Commission. *Establishing Guidelines for the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament and of the Council*; European Commission: Luxembourg, 2007; Volume 3416.

41. Ecoinvent Centre. *Ecoinvent Datenbank Version 3.1*; Ecoinvent Centre: Zürich, Switzerland, 2015.

42. Eurostat. *Energy Statistics*; Eurostat: Brussels, Belgium, 2016.

43. IAEA PRIS Home. Available online: https://www.iaea.org/pris/ (accessed on 21 March 2018).

44. *EWEA Wind in Power 2015*; European Statistics: Brussels, Belgium, 2016.

45. SolarPower Europe. *Verteilung Der Neu Installlierten Photovoltaikleistung in Europa Nach Segment im Jahr 2013*; SolarPower Europe: Brussels, Belgium, 2016.

46. Mennel, T.; Ziegler, H.; Ebert, M. *The Hydropower Sector's Contribution to A Sustainable and Prosperous Europe*; Main Report; A European Hydropower Initiative of Hydropower Companies and Associations: Wien, Austria, 2015.

47. Edwards, R.; Larivé, J.-F.; Rickeard, D.; Weindorf, W. *Well–to–Tank Report Version 4. A. JC Well–to–Wheels Analysis*; Publications Office of the European Union: Luxembourg, 2014.

48. Hill, N. *SULTAN Modelling to Explore the Potential Contribution of Bioethanol to EU Transport GHG Reduction in 2030*; Ricardo Energy & Environment: Didcot, UK, 2016.

49. Hamelinck, C.; De Loveinfosse, I.; Koper, M. *Renewable Energy Progress and Biofuels Sustainability*; Ecofys: London, UK, 2012; Volume 450.

50. Honoré, A. *The Outlook for Natural Gas Demand in Europe*; Oxford Institute for Energy Studies: Oxford, UK, 2014.

51. Frieske, B.; Klötzke, M.; Kreyenberg, D.; Bienge, K.; Hillebrand, P.; Hüging, H.; Koska, T.; Monscheidt, J.; Ritthoff, M.; Soukup, O.; et al. *Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität: STROMbegleitung; Abschlussbericht des Verbundvorhabens*; Dt. Zentrum für Luft- und Raumfahrt: Stuttgart, Germany, 2015; p. 433.

52. Buchert, M.; Jenseit, W.; Merz, C.; Schüler, D. *Ökobilanz zum Recycling von Lithium-Ionen-Batterien "(LithoRec)*; Öko-Institute: Freiburg, Germany, 2011.

53. Gerboni, R.; Pehnt, M.; Viebahn, P.; Lavagno, E. Final Report on Technical Data, Costs and Life Cycle Inventories of Fuel Cells. New Energy Externalities Developments for Sustainability NEEDS. 2008. Available online: http://www.needs-project.org/2009/Deliverables/RS1a%20D9.2%20Final%20report%20on%20fuel%20cells.pdf (accessed on 13 June 2008).

54. Renault Fluence and Fluence Z.E. Life Cycle Assessment. 2011. Available online: https://group.renault.com/wp-content/uploads/2014/09/fluence-acv-2011.pdf (accessed on 31 July 2008).

55. Schweimer, G.W.; Levin, M. *Sachbilanz Des Golf a4*; Forschung, Umwelt und Verkehr; Volkswagen AG: Wolfsburg, Germany, 2005.

56. Dominique Nadelhofer; MAN SE the Specialist for the Inner City: MAN Lion's City M. Available online: https://www.corporate.man.eu/en/press-and-media/presscenter/The-specialist-for-the-inner-city_-MAN-Lion_s-City-M-26432.html (accessed on 18 September 2017).

57. European Copper Institute Copper Market. Available online: http://copperalliance.eu/industry/market (accessed on 20 April 2018).

58. Sverdrup, H.U.; Ragnarsdottir, K.V.; Koca, D. An assessment of metal supply sustainability as an input to policy: Security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. *J. Clean. Prod.* **2017**, *140*, 359–372. [CrossRef]

59. Tan, Q.; Dong, Q.; Liu, L.; Song, Q.; Liang, Y.; Li, J. Potential recycling availability and capacity assessment on typical metals in waste mobile phones: A current research study in China. *J. Clean. Prod.* **2017**, *148*, 509–517. [CrossRef]

60. Lebedeva, N.; De Periso, F.; Boon-Brett, L. *Lithium Ion Battery Value Chain and Related Opportunities for Europe*; European Commission: Petten, Netherlands, 2016.

61. Speirs, J.; Contestabile, M.; Houari, Y.; Gross, R. The future of lithium availability for electric vehicle batteries. *Renew. Sustain. Energy Rev.* **2014**, *35*, 183–193. [CrossRef]

62. Kirby, P.; O'Mahony, T. Planning Future Pathways: Implications and Outcomes of Scenario Studies. In *The Political Economy of the Low-Carbon Transition*; Springer: Berlin, Germany, 2018; pp. 115–141.