energies

MDPI

Article

Environmental and Economic Performance of an Li-Ion Battery Pack: A Multiregional Input-Output Approach

Javier Sanfélix [1,*], Cristina de la Rúa [2], Jannick Hoejrup Schmidt [3], Maarten Messagie [1] and Joeri Van Mierlo [1]

1 Electrotechnical Engineering and Energy Technology, Mobility and Automotive Technology Research Group (MOBI), Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium; maarten.messagie@vub.ac.be (M.M.); joeri.van.mierlo@vub.ac.be (J.V.M.)

2 Research Centre on Energy, Environment and Technologies (CIEMAT), Energy Department, Energy Systems Analysis Unit, Av. Complutense 40, 28040 Madrid, Spain; cristina.delarua@ciemat.es

3 Department of Development and Planning, Aalborg University, Skibbrogade 5 1, 9000 Aalborg, Denmark; jannick@plan.aau.dk

* Correspondence: jsanfeli@vub.ac.be; Tel.: +32-2629-2838

Academic Editor: Haolin Tang

Received: 16 March 2016; Accepted: 13 July 2016; Published: 27 July 2016

Abstract: In this paper, the environmental and economic impacts of the life cycle of an advanced lithium based energy storage system (ESS) for a battery electric vehicle are assessed. The methodology followed to perform the study is a Multiregional Input–Output (MRIO) analysis, with a world IO table that combines detailed information on national production activities and international trade data for 40 countries and a region called Rest of the World. The life cycle stages considered in the study are manufacturing, use and recycling. The functional unit is one ESS with a 150,000 km lifetime. The results of the MRIO analysis show the stimulation that the life cycle of the EES has in the economy, in terms of production of goods and services. The manufacturing is the life cycle stage with the highest environmental load for all the impact categories assessed. The geographical resolution of the results show the relevance that some countries may have in the environmental performance of the assessed product even if they are not directly involved in any of the stages of the life cycle, proving the significance of the indirect effects.

Keywords: multiregional input-output analysis; life cycle assessment; batteries; electric vehicles

1. Introduction

The implementation of electric vehicles (EVs) as a mean of transport, both private and public, is an imminent fact that can be noticed in big urban areas. This implementation is due to two main benefits to society of transport electrification: emissions reduction (no tailpipe emissions compared to internal combustion engines) and energy security. EVs have a significant potential to reduce dependence on foreign oil for oil-importing nations, as they can rely on domestically produced electricity. Governmental entities around the world have provided incentives, plans and strategies for the introduction of EVs [1], including national targets for EV adoption.

Electric drivetrains also have the capability to increase vehicle performance [2]. They are more efficient than conventional cars and emit less CO_2 per kilometer driven, depending on the electricity production mix and the efficiency of the drivetrain [3]. The batteries needed for those cars must fulfil specific power and energy requirements. Since the available energy on board is limited, the overall system efficiency is important. The requirements depend on the purpose and the size of the vehicle; for full electric vehicles, high energy storage ability is essential in addition to the capability to meet power demands of the vehicle required for acceleration, recuperation and sustain fast charging. Many researchers [4–8] have analyzed different topologies of energy storage systems (ESS) on their applicability regarding electric mobility in terms of driving range, charging time and lifetime (which are the three major concerns within this topic). The mentioned studies are focused on models that optimize the energy management of the ESSs; their findings agree that the hybrid energy/power systems is crucial for saving energy, reaching high overall efficiency and enhancing system dynamics. Therefore, advanced energy storage systems are needed to provide both high power and reasonable energy density. Li-ion batteries have been perceived as one of the most promising options among the different battery chemistries because of its significant advantage in energy density [9], but they are required to be controlled during their charging/discharging operations to avoid harmful operative conditions, such as overcharge/discharge and cell voltage unbalancing [10]. A dual-cell battery comprising high power and high energy cells seems to be a promising option to fulfil the requirements of EVs [11].

Production processes are characterized by international fragmentation leading to an interdependent structure, which has to be accounted for. The data that provide a description of such an interdependent production structure are given in supply and use tables (SUTs) and/or input–output tables (IOTs) [12]. Input–output (IO) analysis appeared as a tool able to analyze the interdependency of the different industries of an economy, at a national or regional level [13], developed by Leontief in 1936 [14]. From the beginning, the IO method has been developed and extended by many authors, to the point that not only economic information of the interdependency of the industries can be obtained, but also employment data, social aspects, international exchanges, energy consumption and environmental pollution. For the last one, IO analysis has been combined with life cycle assessment (LCA) to estimate the environmental impact of emissions along the supply and demand chain of related industries [15]. LCA addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life (EoL) treatment, recycling and final disposal [16]. Traditional life cycle inventory databases require extensive data, which is time consuming and expensive, and does not account for all the direct and indirect economic interactions, since these databases typically apply a cut-off that means that services and, to some extent, capital goods are excluded. The so called Environmentally Extended IO analysis (EEIO) calculates both the direct and indirect environmental implications of producing commodities, based on coupled national economic and environmental accounts. In 1996, Cobas-Flores et al. [17] implemented an EEIO analysis for lead acid battery manufacturing using the information of the IO table of the U.S. economy; in their work, they show the benefits of that methodology for a specific product besides its application for industrial sector, and thereby expanding the use of such a tool. Other authors [18] have combined the life cycle environmental impact of an EV with the total cost of ownership, using two different methodologies to assess the environmental impact with a financial study. The IO analysis has the advantage of combining environmental and economic impacts applying the same methodology at a macro-economic level (IO analysis does not estimate the benefit of a company, industry or sector. To do that, there are other methodologies, e.g., cost-benefit analyses.), and one only inventory.

The present work documents a comprehensive LCA of an advanced battery system for EV applications. The study is conducted according to the ISO 14040 [16] and 14044 [19] standards and using the IO tables from the world input–output database (WIOD) [12]. The WIOD allows addressing issues related to fragmentation of production, economic and environmental aspects of the assessed product. With the present study, we provide, for the first time, a global geographical resolution of the environmental and economic impacts of an EES for EVs. The results of the study do contribute to a better understanding of where and what occurs during the life cycle of the product taking into account the current global economy. The study could be characterized as a hybrid LCA since the foreground system makes use of detailed inter-connected physical flows (following a traditional bottom-up LCA approach), which are then linked to the corresponding industry sectors included in the WIOD.

The sections of the paper have been structured according to the above mentioned ISO standards: in Section 2—goal, scope and methodology—the purpose, system boundaries and methodological approach of the study are described; Section 3—Life Cycle Inventory Analysis—describes the particularities of the case study together with the inventory collected; Section 4—Results and Discussion—includes the environmental and economic impact assessment results and its interpretation, and in Section 5—Conclusions—we describe the conclusions obtained from the research developed in the study.

2. Goal, Scope and Methodology

The purpose of the present study is to perform a life cycle environmental and economic assessment of an advanced ESS for EV applications within a Belgian context, meaning that some components of the ESS are manufactured around Europe but final assembly, use stage and end-of-life (EoL) take place in Belgium. The main questions to be addressed are: (a) which are the environmental impacts during the life cycle of the ESS? (b) how many goods and services will be produced, directly and indirectly, to satisfy the demand during the life cycle of the ESS? (c) where are those impacts located following the supply chain of the life cycle of the ESS? The defined functional unit (FU) is 1 ESS of a 150,000 km lifetime for EV applications. Figure 1 describes in a flow diagram the life cycle stages considered in the present study: manufacturing, use and EoL (recycling) together with its location.

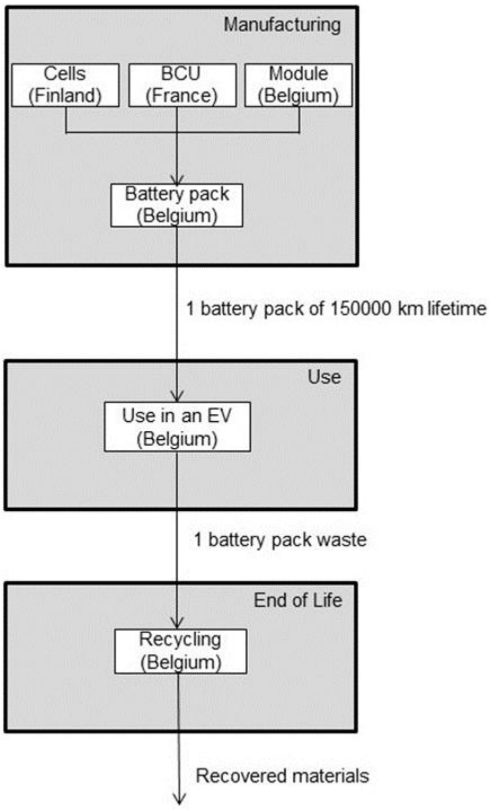

Figure 1. Life cycle stages of the studied system and location.

Multiregional Input–Output Analysis

In the present study, an Multiregional Input-Output (MRIO) table has been used instead of national IO tables. As of today, several MRIO models are available to conduct global analysis. Some of them are listed here:

- The Organisation for Economic Co-operation and Development (OECD) Input–Output Tables comprise 48 countries and cover 37 sectors. The reference year varies from 2002 to 2006 depending on the country [20].
- Eora is a multi-regional Input–Output database, working in native classification of individual countries, which consists of 187 countries and offers data for 25 sectors. This database covers the period 1970–2011 [21].
- EXIOBASE is a global, detailed Multi-Regional Environmentally Extended Supply and Use/Input–Output (MR EE SUT/IOT) database. It comprises 43 countries, five Rest of the World (RoW) regions (and is 10% of the global GDP), and it uses a resolution at 200 products and 163 industries, based on year 2007 [22].
- World Input–Output Database (WIOD) provides time-series of world input–output tables for 40 countries worldwide and a model for the rest-of-the-world, with 35 sectors. It covers a period from 1995 to 2011 [23].

As previously mentioned, the database chosen for this study was the WIOD, developed in a 7th Framework Programme project. This database contains detailed information on national production activities for 27 EU countries, 13 major non-EU countries and one region referred to the rest of the world and covers 35 activity sectors. All data used in the WIOD have been obtained from official national statistics, mainly from National Accounts published by the National Statistical Institutes. At the time when this study was designed, WIOD appeared as the best option among the others with more recent data. The choice of one database over any other can have influence on the final results. Moran and Wood [24] analyzed the reliability of different global MRIO databases, comparing the results of four of them, showing that the degree of disagreement varies by country and by model.

The tables of the WIOD show the distribution of goods and services along different activity sectors and countries, as well as final users, providing a summary of all transactions in the global economy [23]. In other words, it allows for understanding the origin of the imported goods and services of a certain country, providing a geographical resolution of the results. The database combines detailed information on national production activities and international trade data, turning the WIOD into a powerful tool for the global production network. Table S1 in the Supporting Information includes the list of the activity sectors included in the WIOD.

IO analysis has been widely used to estimate macro-economic impacts of industries within the national or regional economy. This analysis was developed by Leontief and describes, through the use of symmetrical tables, the interdependencies between activity sectors within an economy [13]. The IO tables represent the production cost components in columns, accounting for the resources consumed from other sectors to obtain a certain production in each sector, while, in rows, the distribution of one sector's production among the other sectors is described.

According to Leontief, the IO analysis estimates the total output in monetary terms that will be produced by the different sectors in the economy in order to satisfy the intermediate and final demand of goods and services, using as a base the A matrix or technical coefficient matrix, which represents the monetary amount required from one sector to another sector in order to produce one monetary unit. The analysis is conducted using Equation (1) (a detailed description of the IO model to obtain this equation is included in the Supplementary Information.):

$$X = (I - A)^{-1} Y \tag{1}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix and describes the direct and indirect requirements per unit of final demand and Y is the required final demand, object of the study.

This equation can also be represented as follows:

$$X = (I + A + AA + AAA + ... + A^n) Y \tag{2}$$

In order to calculate the economic impacts associated with our system, it is necessary to define the final demand vector Y. This vector is described for each life cycle stage of the ESS, and it is based on the inventory, which will be detailed later. The final demand vectors will account for the goods and services required by each stage in monetary units.

Environmental impacts can be estimated by adding to the equation a new matrix or vector describing the emissions of pollutants per monetary output unit for each economic activity sector considered in the table. The EEIO analysis will be defined as follows:

$$E_t = R_i X = R_i \left(I - A\right)^{-1} Y \tag{3}$$

where E_t are the total emissions.

Results from the EEIO analysis estimate total impacts that can be separated into direct and indirect impacts. Direct impacts are those caused by the direct demand of goods and services (Y) related to the analyzed system, while indirect impacts are due to the upstream economic activities needed to supply the direct goods and services. Based on this definition and taking into account that the EEIO analysis assesses total impacts, direct (ED) and indirect (ID) impacts can be calculated by:

$$ED_t = R_i Y \tag{4}$$

$$ID_t = E_t - ED_t = R_i X - R_i Y \tag{5}$$

EEIO analysis is a powerful tool for decision making support; however, the methodology also has some limitations that need to be considered when applying it and during the interpretation of the results. The input–output analysis simplifies the reality of an economy in order to facilitate its application and comprehension and due to the complexity of national economic data collection. For example, the methodology considers homogeneity within the different industry sectors, assuming that all outputs from a specific sector are equally produced/manufactured. Another limitation is the linearity of the input–output model, meaning that the effect of a 1000 € purchase from a sector will be ten times bigger than the effects of a 100 € purchase from the same sector. Furthermore, the technical coefficients are constant, thus they do not consider the effect of prices or the possibility of substitute goods. This linearity limitation appears as well in LCA. The methodology considers as well that the capacity to stimulate the economy is unlimited [24], thus it does not have any constraints regarding resources in the production chain.

The methodology chosen to perform the LCIA is ReCiPe version 1.11 [25] (Manufacturer, City, US State if applicable, Country), the characterization factors used are at midpoint level and no normalization or weighting has been applied. Considering the air emissions provided by sector and country in the environmental accounts of the WIOD [23], four impact categories from the ReCiPe method are assessed: Global Warming Potential (GWP) (ReCiPe v1.11 uses the CO_2 equivalency factors from IPCC 2007 to calculate GWP impact.), Terrestrial Acidification (TA), Photochemical Oxidation Formation (POF) and Particulate Matter Formation (PMF).

3. Life Cycle Inventory Analysis

In this section, the description of the assessed product and the life cycle stages analyzed in the study are documented.

3.1. Hybrid Energy Storage System

The hybrid system assessed includes two types of battery cells, high energy (HE) and high power (HP), for a better electrical performance, higher efficiencies and longer lifetime—when compared to the battery packs available in current EVs. The chemistry of the HE cell is lithium iron phosphate (LFP) with nominal capacity of 45 Ah. The HP storage component has a nominal capacity of 7 Ah with the same positive electrode chemistry as the HE but with significant higher specific power. The battery layout concept is a parallel connection composed of seven HE modules connected in one string and seven HP modules connected to the other string. The total weight of the ESS is 318 kg, with an energy content of 20 kWh and expected 2000 cycles.

The manufacturing of the ESS is divided into three main components: battery cells, battery control units (BCUs) and modules. The manufacturing of the cells, both HE and HP, is located in Finland, the BCUs are produced in France and the modules and assembly of the final product take place in Belgium. The transport of materials and intermediate products is also considered in the study.

3.2. Use

The use stage is modeled with a driving cycle simulation that estimates the power demand of a vehicle with the assessed battery pack. The parameters of the ESS are based on characterization tests performed in the SuperLIB project (Smart Battery Control System based on a Charge-equalization Circuit for an advanced Dual-Cell Battery for Electric Vehicles). The input parameters considered are: vehicle mass, gravity, coefficient of rolling resistance, air density, aerodynamic drag coefficient, frontal area, power auxiliary and the efficiencies of the transmission, electric motor, power electronics and battery pack. The driving cycle implemented in the simulation is the NEDC (New European Driving Cycle). The equations and more details about the simulation model implemented in the study can be found in our previous publication [11]. The calculated energy demand during the lifetime of the battery pack is 27,228 kWh.

3.3. End-of-Life

The EoL scenario for the ESS is a hydrometallurgical recycling process. The process takes place at room temperature and it involves a series of mechanical and chemical steps. Figure 2 illustrates a simplified diagram of the hydrometallurgical recycling process. To address the benefits of the material recovery, the recycling process is modeled as a new stage, extending the limits of the system to follow a substitution approach and open-loop recycling scheme. Thus, the materials recovered in the recycling process will enter into another product system, avoiding the use of primary raw materials. Due to this modeling approach of the EoL, the environmental and economic impacts of that life cycle stage have a negative value. In the environmental assessment, the negative sign represents the credit that the studied system receives from the avoided impacts of the manufacturing of the recovered products. In the economic assessment, the negative sign has the same meaning, indicating that the recycling process avoids the production of goods and services that the recovered materials would have produced in another system where they are manufactured in their common industrial process.

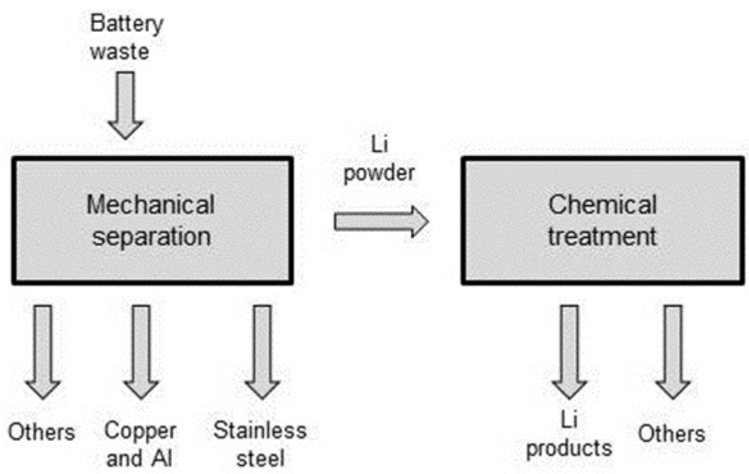

Figure 2. Hydrometallurgical recycling process.

3.4. Economic Performance of the System

As described previously, the life cycle inventory, used to describe the final demand vectors to conduct the MRIO analysis, is based on the process based inventory implemented in [11]. The process based inventory, in physical mass and energy units has been converted into monetary units (M€2010) and then the different components have been assigned to the most closely matching industrial sector of the WIOD, creating, this way, the final demand vector. Tables S2–S5 in the Supporting Information include the assignation to the industry sectors, for the manufacturing of the cells, BCUs, modules and recycling. The manufacturing costs of all the components included in the ESS were collected mainly from manufacturers of the specific product. Cost estimators were used when the manufacturers could not provide the cost. That cost inventory data represents the purchaser's price of the components of the battery pack. However, the WIOD refers to production costs (basic prices), normally inferior to the purchaser's price. Given the difficulty to estimate the percentage of the transport and commercial margins, and the taxes of each product, sector and country, the prices collected have been assumed to be basic prices. The transport costs of the materials to the manufacturing plants, and the transport cost of the cells and BCU to the assembly plant in Belgium are estimated with the euro terminal model [26]. To quantify the energy cost in the study, the levelised cost of producing electricity (LCOE) from [27] has been used. The year of the input–output tables chosen from the WIOD is 2010; therefore, the cost inventory compiled has been converted to the year 2010 (€2010), applying the consumer price index of the corresponding countries (Belgium, Finland and France). The complete list of costs can be find in [28]. The calculated manufacturing cost of the battery pack is 241.71 €/kWh, which is among the range of the latest published data [29] on battery packs for EVs.

4. Results and Discussion

In this section, the results obtained in the MRIO analysis are discussed. First, the environmental life cycle impact assessment is presented followed by the economic life cycle impact.

4.1. Environmental Life Cycle Impact Assessment

The calculated results of the total, direct and indirect impacts of the four impact categories mentioned above per FU and for each of the life cycle stages of the EES are included in Figures 3–6. Focusing on the results of the total impacts, the manufacturing is the highest contributor to all the categories assessed in the three life cycle stages, followed by the use stage. This correlation is in line with the results obtained in similar process based LCA studies [11,30,31], except for GWP impact; in a process based LCA, normally the use stage has higher impact than the manufacturing.

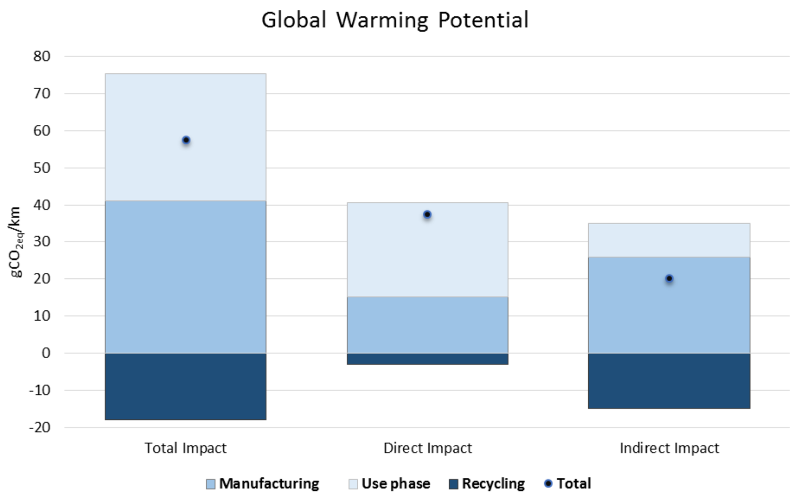

Figure 3. Global Warming Potential impact per km.

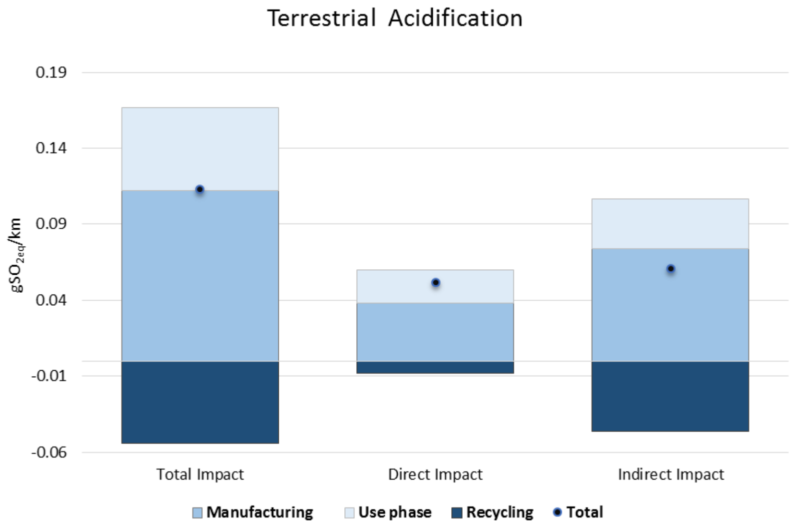

Figure 4. Terrestrial Acidification impact per km.

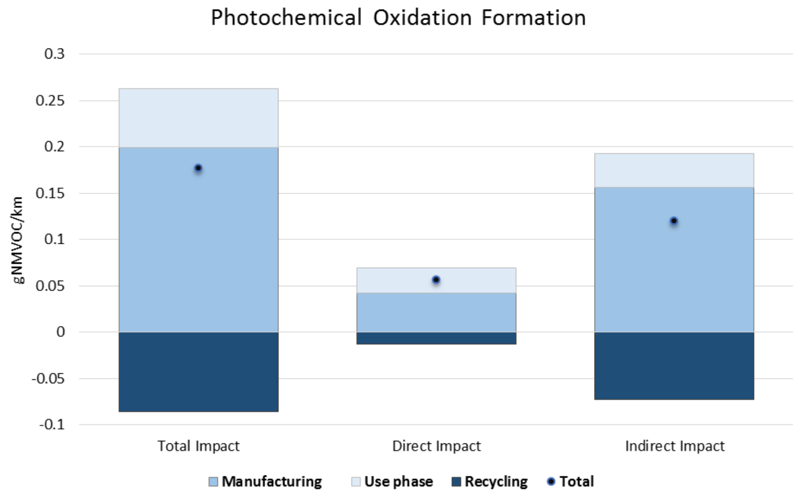

Figure 5. Photochemical Oxidation Formation impact per km.

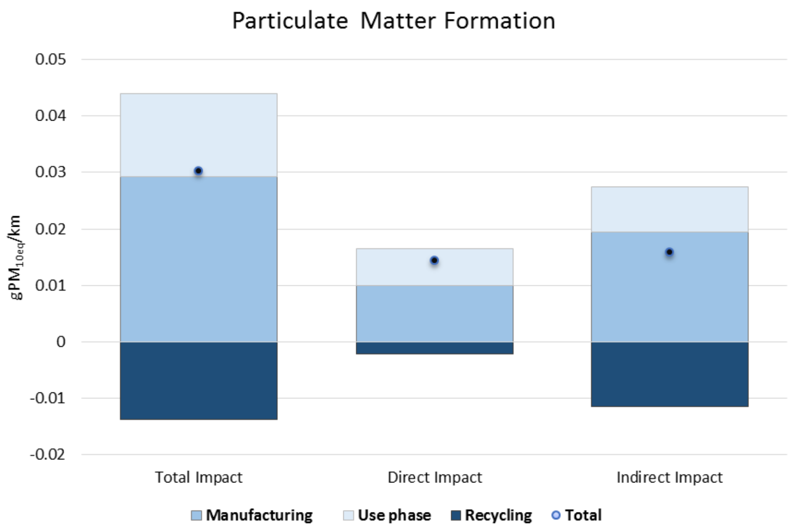

Figure 6. Particulate Matter Formation impact per km.

The ESS has impact during its whole life cycle, and, from an MRIO perspective, this is translated to 57.54 g of CO_2 euivalent per km. Analyzing in detail the results obtained for GWP, greenhouse gas (GHG) emissions in manufacturing represent 71% of the total emitted, reaching 41 g of CO_2 eq. per km, while the use stage is responsible for around 60% of the total. It must be highlighted again that negative figures from the EoL stage result from the substitution approach due to materials recovery.

Through the MRIO analysis, it is possible to identify not only the regions in which the emissions occur but also the activity sectors that are responsible. Figure 7 shows the percentage contribution of the top 10 countries and regions to the total impact of GWP (the percentage contribution of the rest of the countries and regions below the top 10 is aggregated in "others"). The geographical resolution of the impact categories: Terrestrial Acidification, Photochemical Oxidation Formation and Particulate Matter can be seen in the Supporting Information. A summary of those results is presented in Table 1. Figure 7 shows that 42% of the overall impact to GWP during the life cycle of the ESS take place in Belgium. Next, we will analyze in detail each stage of the life cycle.

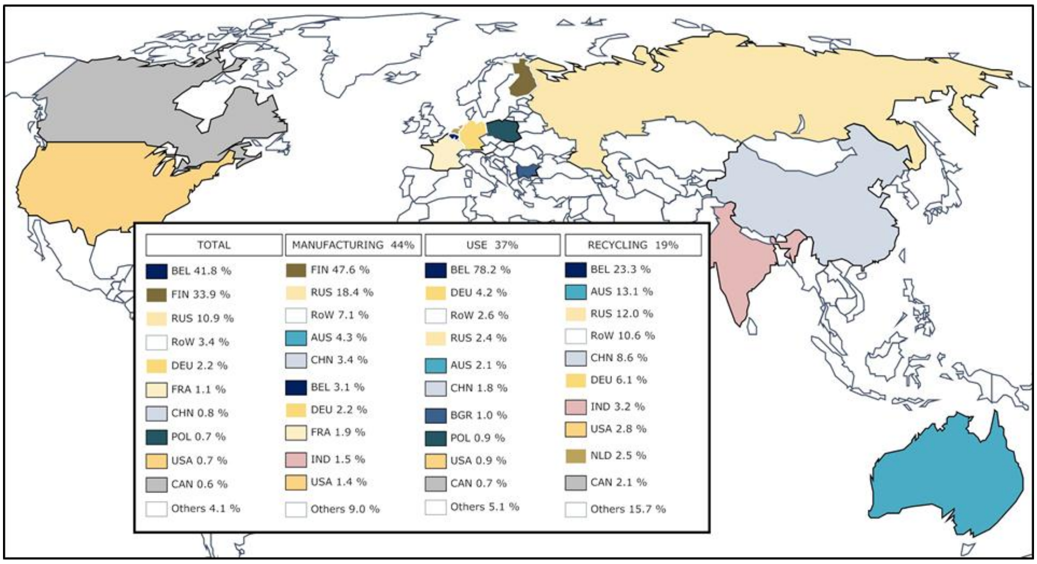

Figure 7. Geographical resolution and country contribution to Global Warming Potential.

Table 1. Contribution of the top 3 countries and regions to the total impacts of Terrestrial Acidification, Photochemical Ozone Formation and Particulate Matter Formation.

Impact Category	Country and Percentage Contribution		
Terrestrial Acidification	BEL 44.91%	FIN 14.85%	RoW 9.88%
Photochemical Oxidation Formation	FIN 31.02%	RoW 27.72%	RUS 17.94%
Particulate Matter Formation	FIN 43.90%	BEL 17.61%	RUS 8.89%

Focusing on the activity sectors, one finds out that roughly 37% of the total GHG emissions come from the electricity needed for the manufacturing. The production of the battery cells has the highest environmental load among the three components of the EES. The main economic activity sectors contributing to GWP due to the battery cells manufacturing are "electricity, gas and water supply", "chemicals and chemical products" and "basic metals and fabricated metals". Impact on materials processing and raw material extraction are reduced by the credit given with the recycling, thus, in the total results, is electricity generation the main contributor in the manufacturing stage. This pattern applies to all the impact categories except in Photochemical Oxidation Formation, where the main contributor to those emissions is the sector "coke, refine petroleum and nuclear fuel", due to the coke needed to supply the coke power plants.

During manufacturing, most of the GHG emissions are generated within the Finnish boundaries (48%) and especially due to the "electricity, gas and water supply" activity sector followed by the "chemicals and chemical industry". Russia contributes with 18% to the total GHG emissions from manufacturing, basically due to three activity sectors: "electricity, gas and water supply" "mining and quarrying" and "basic metals and fabricated metals". These sectors are directly related to the materials required to produce the battery cells—carbon, lithium, copper and aluminium. Although Russia does not participate directly in the manufacturing stage, as Belgium and France do, this result shows the importance of indirect effects. Russia, as a neighboring country for Finland, is the main supplier of goods and services to Finland, playing a relevant role in the embodied emissions. The economic sectors that gather the materials needed in the manufacturing of the battery cells generate a high percentage of indirect impacts, almost three times higher than the indirect impact generated in the use stage, as it can be noticed in Figure 3. These indirect impacts include emissions from economic activities that in a traditional process based LCA are cut off due to their holistic nature, as it is unavoidable to select the system limits and omit details and aspects to simplify the process based LCA.

The contribution of Belgium and France to the GWP associated with the manufacturing process are not as high as in Finland, reaching 1.29 and 0.78 g of CO_2 eq. per FU, respectively. The final demand of goods required in Finland is ten times higher in monetary terms than in France and five times higher than in Belgium. Therefore, the total production in order to satisfy this demand shall be higher than in the other countries and thus, it will result in higher emissions, as it is the case. However, some differences might be due to differences in the environmental accounts provided by the WIOD. The use of process-based specific emission factors for sectors like "electricity, gas and water supply" within a hybrid input–output approach could improve the precision for this sector, as Wiedmann et al. describe in their work [32].

During the use stage, the economic sector with the highest contribution to all impact categories is "electricity, gas and water supply", as expected since the use stage covers the energy demanded by the EV. For the recycling stage, the economic sectors benefited by the credit from the avoided impacts is more distributed than in the other life cycle stages; for the domestic recycling impacts (in Belgium), the economic sectors with highest credits are "basic and fabricated metals" and "chemicals and chemical products". These two sectors comprise the steel, aluminum, copper and lithium salt that are recovered in the recycling. On the other hand, the credits for the imported economic activities due to recycling are mainly associated with "electricity, gas and water supply", "mining and quarrying" and "agriculture, hunting, forestry and fishing", which are the sectors supplying the intermediate demand to produce the materials in the avoided system of the substitution approach (in the supporting info, see the top 5 activity sectors contributing to each impact category, Table S6). After Belgium, the countries benefitting due to the recycling credit are those that would have supplied to Belgium the goods now avoided with the substitution approach. Those are: Austria ("mining and quarrying"), Russia ("basic and fabricated metals" and "electricity, gas and water supply"), RoW ("electricity, gas and water supply", "mining and quarrying", "basic and fabricated metals" and "chemicals and chemical products"), China ("electricity, gas and water supply", "basic and fabricated metals" and "mining and quarrying") and Germany ("electricity, gas and water supply", "basic and fabricated metals" and "chemicals and chemical products").

4.2. Economic Effects

Figure 8 includes the results of the economic impacts during the life cycle of the ESS, measured as the production of goods and services in (€) from the industry sectors of the WIOD. The figure shows that the life cycle of the ESS generates an impact of 0.068 €/km.

The calculated multiplying effect is 2.09, which means that when the demand of battery packs, considering the entire life cycle, is increased by 1 €, a total of 1.09 € are generated in the economy in terms of goods and services. Looking at the manufacturing and use stages individually, the manufacturing of the battery pack stimulates the economy more. This is due to the fact that manufacturing has a higher direct impact (see Figure 8), which furthermore encompasses several economic sectors: chemicals, metals, plastics and electricity, which are involved in the manufacturing process. On the other hand, the use stage, although it has a high demand of energy, only stimulates the sectors related to the electricity production.

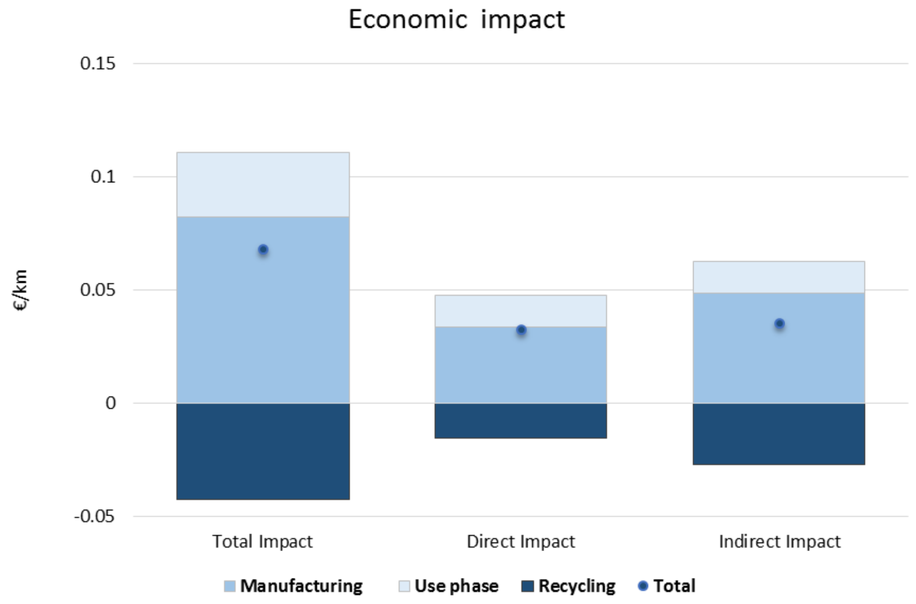

Figure 8. Impact on the production of goods and services during the life cycle of the Energy Storage System in €/km.

The economic activity sectors that are more stimulated during the life cycle of the ESS are included in Table 2, which shows the results in % of the total production of goods and services. The most stimulated economic sector during the life cycle of the ESS is "electricity, gas and water supply" due to the intense demand of electricity during the use stage and during the manufacturing. Other stimulated sectors, especially during the manufacturing stage, are "chemicals and chemicals production" and "mining and quarrying" influenced by the demand of the materials needed to produce the ESS. Figure 9 shows the contribution of the countries and regions included in the WIOD to the total production of goods and services during the life cycle of the ESS.

Table 2. Top ten economic activity sectors stimulated by the life cycle of the Energy Storage System, expressed in percentage of the total M€ generated.

Economic Activity Sector	%
Electricity, Gas and Water Supply	30.34
Chemicals and Chemical Products	21.28
Mining and Quarrying	11.19
Renting of Machinery and Equipment and Other Business Activities	7.87
Rubber and Plastics	4.13
Electrical and Optical Equipment	3.69
Coke, Refined Petroleum and Nuclear Fuel	3.30
Inland Transport	2.86
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	2.45
Construction	1.97
Financial Intermediation	1.68

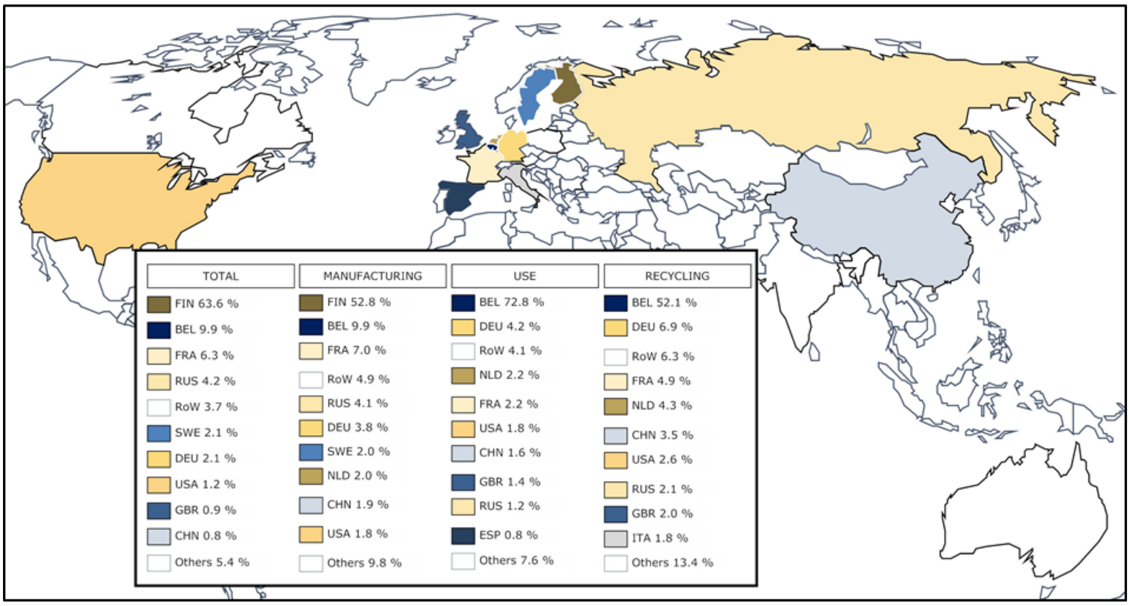

Figure 9. Geographical resolution and country contribution to the economic impact measured in production of goods and services in €.

The largest generation of goods and services happens during the manufacturing of the ESS, where 60% of the impact is indirect. In this stage, the highest production is located in Finland, where the battery cells are produced, followed by Belgium and France (manufacturing of modules and BCUs, respectively). During the use stage, the main contributor is Belgium, followed by the countries and regions that supply goods and services for the electricity generation in Belgium.

The negative values during the recycling stage, as mentioned before, result from the substitution approach considered in this study. Recovery and recycling of materials will avoid the production of raw materials that provide the same services. This means that the economic stimulation that would happen with these raw materials new demands is being avoided. Thus, it gives a negative credit to the total economic input of recycling. As the hydrometallurgical recycling plant is based in Belgium, it is Belgium who receives more credit from the recycling followed by the countries that supply goods and services to the production of the avoided materials. Thus, the total Belgium production of goods and services is cut to a 9.93% of the $1.02 \times 10^{-02} M€$ generated during the life cycle of the ESS, even though Belgium produces a total of $3.12 \times 10^{-03} M€$ in goods and services during the use stage. The largest producer of goods and services along the life cycle of the ESS is Finland, as it is not influenced by the recycling.

5. Conclusions

The present study shows the environmental and economic impacts of an MRIO analysis during the life cycle of an advanced ESS. The characterized results of the environmental impact assessment show that the manufacturing of the ESS is the life cycle stage with the highest environmental load, more precisely the manufacturing of the battery cells. The main economic activity sector generating emissions is "electricity, gas and water supply" due to the amount of energy required during the use stage. Thanks to the WIOD, the emissions can be localized geographically and the results help to understand the global interconnections among the supply chain to meet the demand of the studied system. The geographical resolution of the results has shown that countries that are not directly involved in the manufacturing stage can have an important role regarding the emissions, i.e., Russia and its implications in the supply chain of Finland.

Regarding the economic impact assessment, the results show that the life cycle of ESS generates a total of 0.068 €/km produced in terms of goods and services. The largest contributor is the manufacturing of the ESS, and again, the battery cells are the principal component in this impact. The use stage also has a relevant role in the total input generated in the economy, which occurs mainly in Belgium. When assessing the economic impact of the recycling stage with the system expansion approach implemented in the model, this life cycle stage has a negative impact in the economy. Other EoL scenarios of the battery pack should be analyzed in order to find a better compromise with the environment and the economy stimulation, e.g., remanufacturing of the battery cells for a second life use [33].

The results obtained give an international picture of the environmental and economic impact of the ESS. Since the study is based on an IO analysis, these results need to be treated while understanding the methodology and its limitations. The IO tables used have the economy represented in aggregated industrial sectors, where each sector is assumed as homogeneous and therefore the output of each sector generates the same impact. As discussed previously, the sectorial aggregation of the WIOD tables has a special influence on the emissions due to electricity generation. In such cases, process based emissions could be included in order to improve the precision of the sector emissions, applying then a hybrid IO approach. As described in Section 3.4, the cost data collected for some materials and components are at the purchaser's price (it includes the trades and transport margins and taxes on the final product, excluding any subsidy), while the IO tables used are developed at the basic price. This implies that the calculated impacts might be slightly overestimated, given the fact that purchaser's prices are higher than basic prices. For this reason, we recommend the use of basic prices when available. On the other hand, this MRIO analysis provides, in a relatively fast and economic way, the environmental and economic impacts, addressing the issues of the fragmentation of the current global production, converting this type of analysis into a very useful tool for decision and policy-making, e.g., providing scientific support in the Green Cars Initiative of the European Commission [34].

Supplementary Materials: The following are available online at www.mdpi.com/1996-1073/9/8/584/s1.

Acknowledgments: We acknowledge Flanders Make for the support to our team. We also acknowledge SuperLIB and Opera4FEV projects funded under the 7th Framework program of the European Commission. We gratefully thank Ignacio Martin from Research Centre on Energy, Environment and Technologies for the design of the Table of Contents graphic and Luis M. Oliveira from Vrije Universiteit Brussel for reviewing and editing the text.

Author Contributions: Javier Sanfélix performed the overall study. Cristina de la Rúa provided input with the introduction, modeling and interpretation of the results. Jannick Hoejrup Schmidt, Maarten Messagie and Joeri Van Mierlo contributed by scientifically validating the different iterations of this research with consecutive reviews.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BCU	Battery Control Unit
BEL	Belgium
ED	Direct Impacts
EEIO	Environmental Extended Input-Output
EoL	End-of-Life
ESS	Energy Storage System
EVs	Electric Vehicles
FIN	Finland
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential

HE	High Energy
HP	High Power
ID	Indirect Impacts
IO	Input–Output
IOTs	Input–Output Tables
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Producing Electricity
LFP	Lithium Iron Phosphate
MRIO	Multiregional Input-Output
NEDC	New European Driving Cycle
OECD	Organisation for Economic Co-operation and Development
PMF	Particulate Matter Formation
POF	Photochemical Oxidation Formation
RoW	Rest of the World
RUS	Russia
SUTs	Supply and Use Tables
TA	Terrestrial Acidification
WIOD	World Input–Output Database

References

1. Bradley, M.J. *Electric Vehicle Grid Integration in the US, Europe and China*; Technical Reprot, International Council on Clean Transportation: Washington, DC, USA, 2013.
2. Al-Alawi, B.M.; Bradley, T.H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. *Renew. Sustain. Energy Rev.* **2013**, *21*, 190–203. [CrossRef]
3. Messagie, M.; Boureima, F.-S.; Coosemans, T.; Macharis, C.; Mierlo, J. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. *Energies* **2014**, *7*, 1467–1482. [CrossRef]
4. Omar, N.; Daowd, M.; van den Bossche, P.; Hegazy, O.; Smekens, J.; Coosemans, T.; van Mierlo, J. Rechargeable energy storage systems for plug-in hybrid electric vehicles-assessment of electrical characteristics. *Energies* **2012**, *8*, 2952–2988. [CrossRef]
5. Katrašnik, T. Analytical method to evaluate fuel consumption of hybrid electric vehicles at balanced energy content of the electric storage devices. *Appl. Energy* **2010**, *87*, 3330–3339. [CrossRef]
6. Trovão, J.P.; Pereirinha, P.G.; Jorge, H.M.; Antunes, C.H. A multi-level energy management system for multi-source electric vehicles—An integrated rule-based meta-heuristic approach. *Appl. Energy* **2013**, *105*, 304–318. [CrossRef]
7. Hung, Y.-H.; Wu, C.-H. An integrated optimization approach for a hybrid energy system in electric vehicles. *Appl. Energy* **2012**, *98*, 479–490. [CrossRef]
8. He, H.; Xiong, R.; Zhao, K.; Liu, Z. Energy management strategy research on a hybrid power system by hardware-in-loop experiments. *Appl. Energy* **2013**, *112*, 1311–1317. [CrossRef]
9. Hu, X.; Murgovski, N.; Johannesson, L.M.; Egardt, B. Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous optimal sizing and energy management. *IEEE Trans. Intell. Transp. Syst.* **2014**, *15*, 1–13. [CrossRef]
10. Capasso, C.; Veneri, O. Experimental analysis on the performance of lithium based batteries for road full electric and hybrid vehicles. *Appl. Energy* **2014**, *136*, 921–930. [CrossRef]
11. Sanfélix, J.; Messagie, M.; Omar, N.; Van Mierlo, J.; Hennige, V. Environmental performance of advanced hybrid energy storage systems for electric vehicle applications. *Appl. Energy* **2015**, *137*, 925–930. [CrossRef]
12. Dietzenbacher, E.; Los, B.; Stehrer, R.; Timmer, M.; de Vries, G. The construction of world input-output tables in the wiod project. *Econ. Syst. Res.* **2013**, *25*, 71–98. [CrossRef]
13. Miller, R.E.; Blair, P.D. *Input-Output Analysis: Foundations and Extensions*; Cambridge University Press: New York, NY, USA, 2009.
14. Leontief, W.W. Quantitative input and output relations in the economic systems of the United States. *Rev. Econ. Stat.* **1936**, *18*, 105–125. [CrossRef]

15. Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L. Economic input–output models for environmental life-cycle assessment. *Environ. Sci. Technol.* **1998**, *32*, 184a–191a. [CrossRef]
16. Environmental Management—Life Cycle Assessment—Principles and Frameworks. ISO 14040:2006, International Organization for Standardization (ISO), Geneva, Switzerland.
17. Cobas-flores, E.; Hendrickson, C.T.; Lave, L.B.; Mcmichael, F.C. Life Cycle Analysis of Batteries Using Economic Input-Output Analysis. In Proceedings of the IEEE International Symposium on Electronics and the Environment, Dallas, TX, USA, 6–8 May 1996; pp. 130–134.
18. Messagie, M.; Lebeau, K.; Coosemans, T.; Macharis, C.; van Mierlo, J. Environmental and financial evaluation of passenger vehicle technologies in Belgium. *Sustainability* **2013**, *5*, 5020–5033. [CrossRef]
19. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO 14044:2006, International Organization for Standardization (ISO), Geneva, Switzerland.
20. OECD Input-Output Tables. Available online: www.oecd.org/sti/inputoutput (accessed on 6 October 2015).
21. Lenzen, M.; Moran, D.; Kanemoto, K.; Geschke, A. Building Eora: A Global Multi-Region Input-Output Database At High Country and Sector Resolution. *Econ. Syst. Res.* **2013**, *25*, 20–49. [CrossRef]
22. Wood, R.; Stadler, K.; Bulavskaya, T.; Lutter, S.; Giljum, S.; de Koning, A.; Kuenen, J.; Schütz, H.; Acosta-Fernández, J.; Usubiaga, A.; et al. Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability* **2014**, *7*, 138–163. [CrossRef]
23. Timmer, M.P.; Dietzenbacher, E.; Los, B.; Stehrer, R.; de Vries, G.J. An illustrated user guide to the world input-output database: The case of global automotive production. *Rev. Int. Econ.* **2015**, *23*, 575–605. [CrossRef]
24. Caldés, N.; Varela, M.; Santamaría, M.; Sáez, R. Economic impact of solar thermal electricity deployment in Spain. *Energy Policy* **2009**, *37*, 1628–1636. [CrossRef]
25. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; van Zelm, R. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Available online: http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf (accessed on 6 October 2015).
26. Pekin, E.; Macharis, C. The Euro terminal model: An analysis of intermodal rail freight transport in Europe. In Proceedings of the 13th World Conference on Transport Research, Rio de Janeiro, Brazil, 15–18 July 2013; pp. 1–17.
27. Alberici, B.S.; Boeve, S.; Van Breevoort, P.; Deng, Y.; Förster, S. *Subsidies and Costs of EU Energy*; European Commission: Brussels, Belgium, 2014.
28. Sanfelix, J. *Multiregional Input-Output Life Cycle Analysis of a Battery Pack for Electric Vehicle Applications*; Mobility, Logistics and Automotive Technology Research Centre: Brussels, Belgium, 2016.
29. Nykvist, B.; Nilsson, M. Rapidly falling costs of battery packs for electric vehicles. *Nat. Clim. Chang.* **2015**, *5*, 329–332. [CrossRef]
30. Notter, D.A.; Gauch, M.; Widmer, R.; Wäger, P.; Stamp, A.; Zah, R.; Althaus, H.-J. Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environ. Sci. Technol.* **2010**, *44*, 6550–6556. [CrossRef] [PubMed]
31. Majeau-Bettez, G.; Hawkins, T.R.; Strømman, A.H. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ. Sci. Technol.* **2011**, *45*, 4548–4554. [CrossRef] [PubMed]
32. Wiedmann, T.O.; Suh, S.; Feng, K.; Lenzen, M.; Acquaye, A.; Scott, K.; Barrett, J.R. Application of hybrid life cycle approaches to emerging energy technologies—The case of wind power in the UK. *Environ. Sci. Technol.* **2011**, *45*, 5900–5907. [CrossRef] [PubMed]
33. Ramoni, M.O.; Zhang, H.-C. End-of-life (EOL) issues and options for electric vehicle batteries. *Clean Technol. Environ. Policy* **2013**, *15*, 881–891. [CrossRef]
34. DG Research and Innovation—European Commission. Green Cars Initiative. Available online: http://ec.europa.eu/research/transport/road/green_cars/index_en.htm (accessed on 14 September 2015).