JUST2CE

A Just Transition to Circular Economy

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CHAPTER 5

Energy and material costs of electric caroriented Li-ion battery industry chains, within a perspective of social and environmental shared responsibility

Chapter 5. Energy and material costs of electric car-oriented Li-ion battery industry chains, within a perspective of social and environmental shared responsibility

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Abstract

Demand for carbon emission reduction is promoting the development of the electric vehicle industry, within which Li-ion batteries play an important role as the main source of power storage. From the perspective of the Li-ion battery industry chain, the environmental impacts of 5 kinds of minerals and Li-ion batteries within the production process have been assessed by means of the Life Cycle Assessment (LCA) approach. The environmental impacts of 8 kinds of traditional and renewable energy sources were also analysed and compared. The extraction and use of crucial minerals as well as fossil energy resources bears huge environmental and social consequences, in that it affects large areas and large amounts of water for production processes and most often involves employees without sufficient care of their health problems and young age. From the perspective of global worldwide trade, this study puts forward the producers and users shared responsibility, emphasizing that importing countries also have the responsibility to bear the environmental impacts caused in producing countries, with special focus on mining and treating crucial minerals. The results show that: (i) nickel, cobalt and other rare metals have more significant impacts on carbon emission and ecotoxicity; (ii) Li-ion battery production has the most significant impact on freshwater and marine ecotoxicity; (iii) process energy use (mainly electricity) heavily affects the overall impacts, with hydroelectricity still showing the best environmental performance, in spite of its small availability and competition with other uses, followed by wind power, characterized by fast spreading worldwide, and photovoltaic, which still has to solve some toxicity problems in the production chain. Improvement are expected from several steps of the production process, starting from the extraction of minerals, the selection of less impacting minerals, the increased efficiency of produced batteries, and finally the end-of-life recycling of component minerals and metals. Based on the evaluation results, some policy suggestions are put forward from the perspectives of production, import and trade cooperation, shared responsibility of environmental and social consequences.

Keywords: Li-ion battery industry chain; Environmental impacts; Life cycle assessment; Circular Economy; Global shared responsibility

Although EV and Li-ion batteries are very promising for carbon emission reduction, they have large environmental and social impacts associated to extraction and production patterns. To promote a socially and environmentally sustainable low-carbon economy, it is necessary to first identify the key environmental impacts of the Li-ion battery industry and then promote increased awareness about the shared responsibility of producers and consumers, within a perspective of global worldwide trade.

5.1 Introduction

With the development of the global low-carbon economy, electric vehicles are expected to play an increasingly environmental role. According to Global EV Outlook, the number of electric vehicles in the world was less than 1.5 million in 2015, growing to about 16.5 million in 2022. In a seven-year period, EVs have increased by more than ten times, as a consequence of increased global people's and Governments´ attention to energy conservation and emissions reduction. Although electric vehicles are developing very quickly, they are still a minority, not void of challenges, compared to internal combustion engine cars. The number of internal combustion engine vehicles in the world in 2022 was about 1.446 billion, 87.6 times the number of presently running electric vehicles, with an unequal distribution of cars per capita in the different regions of the world as follows: North America 0.71 cars per capita, Europe 0.52, South America 0.22, Middle East 0.18, Asia-Pacific 0.14, Africa 0.05, Antarctica 0.05. Should electric vehicles replace the present number of combustion engine cars, the challenge is not only to replace the large number of presently running combustion engine cars in wealthy countries, but also to provide the large number of electric vehicles needed to bring the less developed countries to the same level of mobility per person as the industrialized and wealthy countries. The challenge therefore is to replace a large fraction of combustion engine vehicles by means of electricity powered mass transportation networks (railways, subways, buses) and a larger number of electric vehicles (at least for intensive users, such as taxi, health and emergency services, police, shared cars). For this to happen, a large number of components (batteries, electric engines, other components for electric engine control) is needed, which translates into mining or recycling an unbelievable amount of minerals and crucial metals. While railways and subways generally do not need to store electricity for their functioning, buses and cars are not connected to the electric grid and therefore require charge a battery to allow a sufficient number of kms. Such requirement translates into large weight of batteries (between 200 and 900 kg, depending on the car) and therefore requires the extraction of crucial minerals from worldwide mines. Extraction and refining of minerals and metals is not an easy task nor an environmentally friendly process. As a consequence, large areas and large amounts of process water (affecting the availability of drinking water) as well as large amounts of workforce (among which large fractions of child labor) are needed, so that "*The unprecedented increase in demand for the raw materials needed to produce the batteries to propel these vehicles poses serious human rights and environmental risks and begs the question how sustainable and fair a mobility transition based on the mass uptake of electric vehicles really is.*" (González and de Haan, 2020). Special focus on children rights violation has been investigated by SOMO-Centre for Research on Multinational Corporations and Terres des Hommes, two Netherland Organizations, releasing an alarming report (Schipper and Cowan, 2018) concerning mica mining (including

Lithium mica), where global responsibilities of several Governments and Companies and the urgent need to address the problem emerge. “Mica” is the name given to a group of minerals that are physically and chemically similar. The mica group of minerals contains a total of 37 different types of mica. The main types of mica are: (i) muscovite or white mica (potassium mica); (ii) phlogopite or amber mica (magnesium mica); (iii) biotite or black mica (ferro-magnesium mica); and (iv) and lepidolite (lithium mica). Magnesium and lithium mica are used for two different types of electric car batteries. Li-ion batteries are the most advanced typology presently available in the global market and will be the main focus of the present research. However, other very interesting research activities are being developed, among which magnesium batteries, still at a laboratory stage, but claimed and expected to bear lower environmental impacts and economic costs. Just as an example, the AIT (Austrian Institute of Technology) and the ISTA (Institute of Science and Technology Austria have launched a research project about magnesium batteries in the hope to develop “another step towards the implementation of a sustainable, climate-friendly and efficient energy system in stationery and mobility sectors” (Emove360, 2023; Romio et al., 2023).
Among the main goals of this study are, therefore, the evaluation of the environmental consequences and associated social problems of the transition from combustion engine to electric vehicles powered by Li-ion batteries and the available improvement options. For this to be done, the environmental impacts of Lithium mining, Li-ion battery production and electricity production from different sources to provide large scale charging have been investigated through LCA in order to identify the main challenges and solutions.

5.2 The Li-ion batteries. Production and material demand

Li-ion batteries are considered the core components of electric vehicles. There are four main types of Li-ion batteries, namely LMO, NMC (111), NMC (811) and NCA. The code numbers 111 and 811 indicate approximate different proportions among main component metals, according to the different battery composition (Alejandro & Esther., 2020), as shown in **Figure 5.1**. LMO is the Lithium-Manganese-Oxide composition ($LiMn_2O_4$), of which 94% is Manganese and 6% is Lithium. NMC is Lithium-Nickel-Cobalt-Manganese Oxide ($LiNiCoMnO_2$), where NMC (111) and NMC (811) are respectively the content of Cobalt, Nickel and Manganese: NMC (111) has 30% cobalt, 30% nickel, 29% manganese (and 11% lithium), while NMC (811) has 9% cobalt, 72% nickel, 8% manganese (and 11% lithium). NCA is Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$), with 2% aluminium, 14% cobalt, 73% nickel, and 11% lithium. Lithium is a crucial component of all four types of batteries, indicating that its role is, at present, irreplaceable. Battery manufacturing has become a priority and strategic goal in many world regions, especially China and European Union. The EU recently adopted the Battery Strategic Action Plan to accelerate the construction of a European battery value chain.

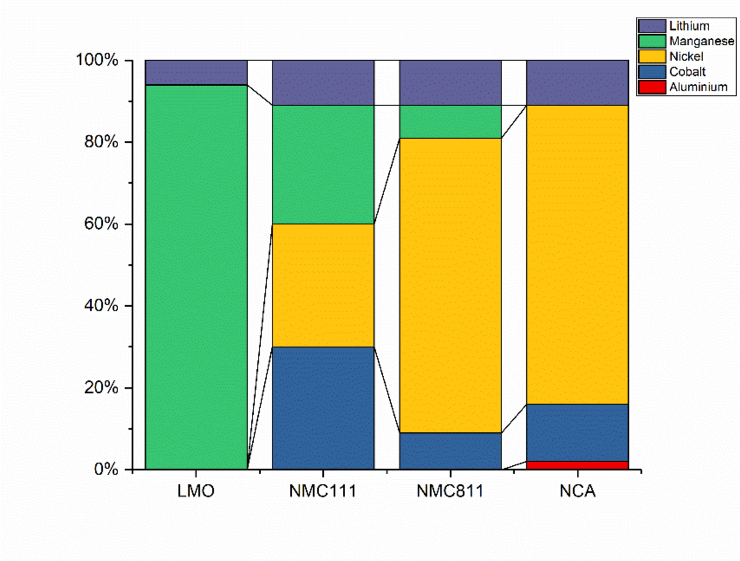

Figure 5.1 Composition of different Li-ion batteries (source: modified after Alejandro & Esther., 2020)

As demand for electric vehicles and batteries continues to rise, production for the minerals needed to produce them - lithium, cobalt, nickel, graphite, manganese - is also soaring. According to Statista (2022), the global lithium production in 2011 was only 0.34E+5 tons, while the global lithium production in 2021 was as high as 1.0E+5 tons, three times that of 2011. At the current rate of mining (assuming no electric car increase occurs), it could be expected that the world's lithium resources would be depleted in less than 220 years. Instead, if Lithium consumption increases due to the much larger demand for EVs (e.g., from the present 16.5 million vehicles up to very likely 10 times more in the near future), the present world Lithium resources would only last 22 years and additional Lithium discoveries may not be enough to meet future demand. This poses real challenges of replacement of metals and demand for smaller, more efficient and less impacting batteries and increased

recycling. In addition to lithium, large amounts of cobalt, nickel and manganese, respectively 1.7E+5, 2.7E+6, 2.0E+7 tons, were mined globally in 2021. These minerals are, as well known, non-renewable resources, and most of them are rare metals. Long-term large-scale mining may not only cause the degradation of large environmental areas, but also irreversibly deplete mineral resources, which is not conducive to sustainable development. Due to resource distribution and economic development, minerals are unevenly exploited in the world. Taking Lithium reserves as an example, according to the United States Geological Survey (USGS, 2022), 22 million tons of lithium reserves are available worldwide, but they are not evenly distributed. About 9.2 million tons are estimated to be available in Chile, 5.7 million in Australia, 2.2 million in Argentina, 1.5 million in China, and a small number are distributed in Zimbabwe, Brazil, Portugal and other countries. Much larger estimates of Lithium availability have been made, just considering both discovered and undiscovered deposits worldwide - i.e. by definition a "best guess" of resources to become reserves. Of course, depending on depth and other physical factors, extraction prices vary significantly, which makes difficult to estimate their real availability to technological processes of battery production.

The "lithium triangle" countries of Argentina, Chile and Bolivia, which hold 75 percent of the world's lithium known reserves, jointly with the Democratic Republic of Congo (DRC) produce about two-thirds of the world's cobalt and already feel the economic pressure due to the so-called "battery boom". With the development of trade integration, the mineral reserves required for batteries are flowing over a large scale around the world, and the environmental impact caused by mineral mining, transporting and processing as well as battery production is also transferred to a larger scale worldwide.

Of course, the possibility that larger amounts of resources are discovered and become available reserves (maybe at higher market cost) cannot be denied, but this would bear the consequence of increased environmental degradation in the mining locations, around the processing plants and all over the transport and storage chain. In a like manner, the limited availability of the above-mentioned minerals and metals may also push towards technological discoveries to allow the use of different metals, e.g., magnesium for use in a different kind of batteries competing with Lithium (AIT, 2023).

5.3 Environmental impacts of mineral resource exploitation for Li-ion battery production

As mentioned above, electric vehicle batteries contain a variety of mineral resources, and the environmental impacts of the mining process is also different. Taking lithium, cobalt, nickel, manganese and iron as examples, we used the life cycle assessment approach to analyse the impact of key raw minerals on water, air, soil and human toxicity over 18 environmental impact categories of the mining process. Of course, identifying these impacts is not just a technological achievement, but allows to understand the consequences on human health and ecosystem integrity. The data used in the mining process are from the Ecoinvent database, by means of the openLCA analysis tool. Table 1 shows the final results.

By comparing the impact categories of Table 1, with reference to a Functional Unit (FU) of 1 kg, it clearly appears, just as an example, that the carbon dioxide emissions of the five minerals (Global warming potential, GWP) are quite different. The largest amount of carbon dioxide emissions are associated to 1 kg of nickel and 1 kg of cobalt, with 13.9 kg and 10.4 kg of CO_2 eq emissions respectively, while iron mining released the least carbon emissions, only 0.006 kg CO_2 eq. In terms of contribution to "Human carcinogenic toxicity" and "Human non-carcinogenic toxicity", nickel mining has the most significant effect, releasing about 2.2 kg 1,4-DCB and 288.9 kg 1,4-DCB, respectively. The non-carcinogenic toxicity of nickel ore is really surprising, 18 times that of cobalt ore and 144 times that of lithium! In terms of "Terrestrial ecotoxicity", 1 kg of nickel mining can release 917.2 kg 1,4-DCB, suggesting that the impact of nickel mining on land is higher than on human health. The effect of iron ore and manganese ore is less than 1 kg 1,4-DCB. The results in **Table 5.1** suggest that nickel ore is the mineral with the largest environmental impact in electric vehicle batteries, which is particularly detrimental to the sustainable development of human and terrestrial health, followed by cobalt, lithium, iron and manganese. Considering the proportions of these metals in the composition of electric vehicles batteries (see Figure 1 above), it clearly appears that availability of minerals and their environmental impacts are crucial factors towards accurate use and recycling of exhaust batteries as well as towards design of less impacting devices based on different minerals and metals.

Table 5.1 LCA impacts of different metals used in the battery industrial chain (FU: 1 kg)

Impact category	Unit	Lithium	Iron	Manganese	Nickel	Cobalt
Fine particulate matter formation	kg PM2.5 eq	5.01E-03	1.73E-04	7.3E-05	4.28E-01	3.07E-02
Fossil resource scarcity	kg oil eq	6.03E-01	1.63E-03	4.54E-03	2.86E+00	2.45E+00
Freshwater ecotoxicity	kg 1,4-DCB	8.53E-02	7.05E-05	1.02E-03	8.49E+00	2.89E-01
Freshwater eutrophication	kg P eq	1.92E-03	8.06E-07	6.35E-06	4.67E-02	2.98E-03
Global warming	kg CO_2 eq	2.23E+00	6.01E-03	1.73E-02	1.39E+01	1.04E+01
Human carcinogenic toxicity	kg 1,4-DCB	3.03E-01	1.70E-04	1.98E-03	2.18E+00	3.12E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	2.01E+00	1.67E-03	2.99E-02	2.89E+02	1.66E+01
Ionizing radiation	kBq Co-60 eq	2.12E-01	3.50E-04	1.09E-03	1.11E+00	1.14E+00
Land use	m^2a crop eq	9.48E-02	9.97E-05	1.62E-02	1.75E-01	5.39E-01
Marine ecotoxicity	kg 1,4-DCB	1.19E-01	1.00E-04	1.46E-03	1.22E+01	4.11E-01
Marine eutrophication	kg N eq	2.07E-03	2.22E-06	5.49E-06	3.96E-03	4.93E-03
Mineral resource scarcity	kg Cu eq	1.37E+00	2.86E-02	5.15E-02	3.78E+00	8.74E+00
Ozone formation, Human health	kg NO_x eq	8.83E-03	1.38E-04	2.69E-04	8.83E-02	9.25E-02
Ozone formation, Terrestrial ecosystems	kg NO_x eq	8.96E-03	1.41E-04	2.74E-04	8.98E-02	9.41E-02
Stratospheric ozone depletion	kg CFC11 eq	9.68E-07	2.47E-08	4.45E-08	1.72E-05	1.87E-05
Terrestrial acidification	kg SO_2 eq	1.43E-02	9.53E-05	2.07E-04	1.40E+00	8.67E-02
Terrestrial ecotoxicity	kg 1,4-DCB	9.78E+00	8.25E-03	1.56E-01	9.17E+02	3.19E+01
Water use	m^3	4.06E-02	2.64E-05	3.06E-04	1.57E-01	1.60E-01

Source: Ecoinvent 3.1 database (Ecoinvent 3.1, 2020) through OpenLCA software (GreenDelta, 2020)

Once the impacts of battery minerals are identified, it may be useful to "locate" these impacts starting from the countries where these minerals come from.

For example, the main 2021 producers of Lithium have been Australia (61,000 ton/yr), Chile (39,000 ton/yr), China (19,000 ton/yr) and Argentina (6,200 ton/yr), while the countries with the 2021 largest known (although not yet exploited) reserves are Bolivia (21Mt), Argentina (20 Mt), USA (12 Mt), Chile (11 Mt), Australia (7.9 Mt) and China (6.8 Mt) (Source: USGS, 2022).

In a like manner, the main 2021 Iron ore producers have been: Australia (900 Mt/yr), Brazil (380 Mt/yr), China (360 Mt/yr), India (240 Mt/yr), Russia (100 Mt/yr), Ukraine (81 Mt/yr), out of a total world production of 2,537 Mt/yr, while the main 2021 iron ore known reserves were in Australia (51 Gt), Brazil (34 Gt), Russia (25 Gt), China (20 Gt) Ukraine and Canada (both 6.5 Gt) (source: Canada, 2023).

Similar location of impacts and potential social and environmental risk related to the existence of large reserves can be performed for all the crucial minerals from Table 1 as well as others largely used in electronic and vehicle industry and may provide very useful suggestions for mining and trade policy making, within a circular economy and shared responsibility policy. Liu et al. (2021) investigated the 2020 worldwide trade of iron and steel, with special focus on mining, exports & imports, and steel making processes, identifying a significant transfer of embodied impacts (emissions, toxicity, land and water use) within the import/export dynamics, calling for urgent collaborative links to decrease the environmental damages in resource exporting countries and, to a different extent, in importing countries and suggesting compensation policies based on technology support and more appropriate economic return from importing to exporting countries.

5.4 Environmental impacts of electric vehicle battery production

Once impacts of crucial minerals mining have been assessed, it should not be disregarded that they are processed within the mining country and then further exported to more industrialized countries for processing to batteries (in this study, Li-ion batteries). This additional step is likely to generate further environmental and health impacts which add up to the mining phase. We therefore evaluated the whole environmental impacts of the production process of Li-ion batteries for electric vehicles, by using again the life cycle assessment method. The specific results are shown in Table 2. For each kg of rechargeable Li-ion battery produced, 6 kg of carbon dioxide, 95 kg 1,4-DCB contributing to carcinogenic and non-carcinogenic toxicity, and 4 kg 1,4-DCB contributing to marine toxicity, among other impacts. In fact, 0.075 m^2 of land and 0.18 m^3 of water are also consumed. Considering that the weight of Li-ion batteries for average electric vehicles is generally 300 kg and the annual production of electric vehicles in the world exceeds 10 million, it is easy to assess that the carbon emissions caused by the production of lithium batteries for electric vehicles in the world are about 1.8E10 kg CO_2 eq per year. In addition, it can be found from the normalized results in **Table 5.2** that Li-ion battery production has the biggest impact on freshwater ecotoxicity and seawater ecotoxicity. With the promotion of the global dual-carbon goal, the development of electric vehicles will become more and more rapid, and the production will be larger. If the production process will not be improved (in both design and recycling), being Li-ion batteries among the most important components of electric vehicles, their impact on the in the long-term will seriously affect human and ecosystem health.

Table 5.2 LCA impacts of Li-ion battery production (F.U.: 1 kg of Li-ion battery produced)

Impact category	Reference unit	Characterized	Normalized
Fine particulate matter formation	kg PM2.5 eq	2.54E-02	9.93E-04
Fossil resource scarcity	kg oil eq	1.62E+00	1.66E-03
Freshwater ecotoxicity	kg 1,4-DCB	2.78E+00	2.27E+00
Freshwater eutrophication	kg P eq	1.56E-02	2.40E-02
Global warming	kg CO2 eq	6.03E+00	7.55E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.06E+00	3.82E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	9.49E+01	6.37E-01
Ionizing radiation	kBq Co-60 eq	7.65E-01	1.59E-03
Land use	m2a crop eq	7.54E-02	1.22E-05
Marine ecotoxicity	kg 1,4-DCB	3.98E+00	3.85E+00

Marine eutrophication	kg N eq	3.49E-03	7.56E-04
Mineral resource scarcity	kg Cu eq	3.83E-01	3.19E-06
Ozone formation, Human health	kg NOx eq	1.97E-02	9.58E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.02E-02	1.14E-03
Stratospheric ozone depletion	kg CFC11 eq	4.16E-06	6.95E-05
Terrestrial acidification	kg SO2 eq	6.98E-02	1.70E-03
Terrestrial ecotoxicity	kg 1,4-DCB	2.95E+02	2.85E-01
Water consumption	m3	1.81E-01	6.78E-04

Source: Ecoinvent 3.1 database (Ecoinvent 3.1, 2020) through OpenLCA software (GreenDelta, 2020)

The take-home lesson is that in addition to the impacts associated to extraction of minerals in primary exporting countries, other impacts are generated in industrial countries, where batteries are produced and then sold to car producing companies. Considering that the weight of a battery to store electricity for an electric vehicle is between 300 and 1000 kg, the above unit LCA impacts should be multiplied by the weight of the battery in order to calculate the extent a Li-ion battery affects terrestrial and human health categories. Let´s just consider the 1.81E-01 m^3 of water per kg of battery: in the case of an average battery whose weight is about 500 kg, the total water demand for battery production (mining, transporting and processing) is around 500 kg x 1.81E-01 m^3/kg= 90 m^3, i.e. 90,000 kg of water, for a device which will more or less last 10 years. In a like manner, Global Warming impacts of a 500 kg battery would be around 3,000 kg CO_2 eq, Human Carcinogenic and Non-carcinogenic Toxicity would amount around 47,980 kg 1,4-DCB, and finally Terrestrial Ecotoxicity would be in the order of 147,500 kg 1,4-DCB, all of which to be divided by 10 in order to calculate the yearly impacts. Impacts will have to be multiplied by the expected number of electric vehicles in Europe and worldwide. As mentioned in the Introduction, the challenge to replace the presently existing 1.45 billion combustion engine cars worldwide compared to the about 20 million electric cars, is not as easy to address as it is most often shown in the media and literature. The available amounts of crucial

minerals do not seem enough to spread electric vehicles worldwide, so that the near future of electric cars seems to be limited to the wealthy fraction of industrialized countries, leaving the large fraction of world population still without a car at all or still using combustion engine cars, due to both the insufficient amounts of resources and the environmental and social problems associated to resource mining, as mentioned in the previous sections. The potential increase of electric car number provides an alarming signal also concerning the impacts of batteries production for electric cars (let´s just think of the impacts from Table 2 expanded to hundreds of millions of potentially circulating electric vehicles), unless smaller and more efficient batteries are designed and less impacting minerals are used, in addition to increased recycling ability within a circular economy perspective (US DOE, 2023).

5.5 Environmental impacts of energy sources to support electric vehicles

The development of electric vehicles will also require that presently used fossil fuels are replaced by electricity to charge the batteries, worldwide. It does not deal with small amounts but instead very large fractions of present fossil fuel use. The needed electricity may be generated from fossil fuels, or nuclear and renewable sources. Large, energy-intensive plants will have to be built rapidly to meet the growing demand for electricity by household as well as to charge the increasing number of batteries for electric vehicles. In order to understand the environmental impacts of the electricity from different sources needed for electric cars, we may refer to a LCA study based on data from Ecoinvent database 3.1, published by one of the co-Authors of the present study in Ghisellini et al. (2023), partially shown in **Table 5.3**. The latter focuses on the environmental impact of generating 1 kWh of electricity from traditional and renewable energy sources, such as nuclear, wind, hydroelectric, geothermal, PV solar, natural gas, coal and oil. It is important to note that 1 kWh is able to support an average distance of 5 km in an electric car. None of the sources from **Table 5.3** is capable to offer a performance completely void of impacts. Mining and processing resources to build and operate an electric power plant generate unavoidable life cycle impacts as water and land use, energy and material resource consumption, emissions). Among these sources, hydroelectricity generates the least carbon emissions, only 7.49E-3 kg CO_2 eq, followed by nuclear energy, which releases 1.64E-2 kg CO_2 eq, while conventional coal and oil release the most carbon emissions, 1.14 kg CO_2 eq and 0.90 kg CO_2 eq respectively, as they require more fossil heat when generating electricity. Focusing on a different kind of impact, namely ionizing radiations, hydroelectricity and wind still have the smallest impacts, only 4.62E-4 kBq Co-60 eq and 1.87E-3 kBq Co-60 eq, while nuclear energy has the largest impact, about 1.19 kBq Co-60 eq. Moving to the human toxicity category, traditional coal shows the largest effect, about 2.6E-2 kg 1,4-DCB, while the smallest impact comes from hydro-power generation, only 7.70E-4 kg 1,4-DCB. In terms of water use (a resource depletion that cannot be disregarded due to its role in other aspects of human life and other species survival), the impact of these energy sources can be identified, with wind energy consuming the smallest amount of water resources, and geothermal and hydroelectricity the largest, in so affecting other, not negligible, water uses. In terms of Terrestrial acidification, the sulphur dioxide impact of traditional energy sources such as coal, oil and natural gas is generally very large, about 5.28E-3 kg SO_2 eq, 7.67E-3 kg SO_2 eq and 1.67E-3 kg SO_2 eq, respectively, while hydroelectricity and nuclear energy show the least impact, only 2.16E-5 kg SO_2 eq and 8.18E-5 kg SO_2 eq.

Although each electricity source has different impacts for the environment, yet wind energy and solar energy seem to be a real alternative to traditional fossil fuels. They are renewable, large-scale applicable, and their cost is acceptable at present. In addition, wind energy has little impact on water resources consumption and negligible Ionizing radiation, while solar energy has little impact on atmospheric ozone and land use. In order to maximize sustainable development, it is necessary to use a combination of energy sources to ensure that the environmental impact of different dimensions is minimized. Anyway, even if these renewable sources are quickly developing, they may not be a sufficient energy support to a fast development and increase of electric car number, so that charging ability may become another limiting factor to the spread of electric cars worldwide to a large extent.

Table 5.3 LCA impacts per 1 kWh of the production of electricity from different sources (from Ghisellini et al., 2023)

Impact category	Nuclear	Nat. gas	Coal	Oil	PV	Deep heat (*)	Wind	Hydro-power

Fine particulate matter (kg PM2.5 eq)	4.83E-5	5.61E-4	1.81E-3	2.37E-3	1.59E-4	1,57E-4	5.53E-5	1.13E-5
Fossil resource scarcity (kg oil eq)	4.09E-3	2.60E-1	2.26E-1	2.81E-1	1.67E-2	1.76E-2	6.45E-3	1.19E-3
Freshwater ecotoxicity (kg 1,4-DCB)	1.18E-3	1.93E-3	1.29E-2	1.80E-3	1.75E-2	2.42E-3	1.95E-2	1.22E-3
Freshwater eutrophic. (kg P eq)	6.18E-6	2.86E-5	4.16E-4	1.56E-5	5.48E-5	1.43E-5	1.55E-5	1.43E-6
Global warming (kg CO_2 eq)	1.64E-2	6.84E-1	1.14E+0	9.02E-1	6.57E-2	6.27E-2	2.58E-2	7.49E-3
Human carcinogenic toxicity (kg 1,4-DCB)	2.24E-3	3.94E-3	2.60E-2	4.36E-3	6.06E-3	7.59E-3	8.47E-3	7.70E-4
Human non-carcinog. toxicity (kg 1,4-DCB)	3.14E-2	5.20E-2	3.91E-1	6.32E-2	2.47E-1	5.68E-2	8.63E-2	6.47E-3
Ionizing radiation (kBq Co-60 eq)	1.19E+0	1.23E-2	8.25E-3	1.44E-2	1.02E-2	2.76E-3	1.87E-3	4.62E-4
Land use (m^2a crop eq)	1.49E-4	2.68E-4	5.79E-3	4.26E-4	3.90E-4	2.69E-4	9.12E-4	6.04E-5
Marine ecotoxicity (kg 1,4-DCB)	1.74E-3	2.86E-3	1.80E-2	4.82E-3	2.30E-2	3.23E-3	2.39E-2	1.50E-3
Marine eutrophication (kg N eq)	8.28E-6	1.76E-5	4.45E-5	5.00E-5	5.34E-5	6.89E-6	1.06E-5	1.80E-6
Mineral resource scarcity (kg Cu eq)	8.94E-4	4.44E-4	3.75E-4	4.02E-4	1.37E-3	1.62E-3	1.48E-3	2.18E-4
O_3, Human health (kg NO_x eq) (#)	5.11E-5	1.03E-3	2.20E-3	2.86E-3	1.74E-4	4.48E-4	7.58E-5	2.04E-5
O_3, Ecosystems health (kg NO_x eq) (#)	5.21E-5	1.08E-3	2.20E-3	2.90E-3	1.81E-4	4.57E-4	7.88E-5	2.08E-5
Stratospheric ozone depletion (kg CFC11 eq)	4.17E-8	3.26E-7	2.77E-7	6.21E-7	3.63E-8	7.05E-8	1.08E-8	4.11E-9

Terrestrial acidification (kg SO_2 eq)	8.18E-5	1.67E-3	5.28E-3	7.67E-3	4.04E-4	3.09E-4	1.19E-4	2.16E-5
Terrestrial ecotoxicity (kg 1,4-DCB)	3.28E-1	1.13E-1	3.25E-1	3.13E+0	1.43E+0	1.35E-1	2.44E-1	2.08E-2
Water use (m^3)	3.15E-3	1.05E-3	1.88E-3	2.30E-3	1.84E-3	1.32E-2	3.29E-4	2.93E-2

(*) Geothermal energy; (#) Impacts generated on human and ecosystems health by generation of tropospheric ozone (O_3)

5.6 Shared responsibility for environmental costs of electric car-oriented Li-ion battery industry chain

It clearly appears from the previous sections that mineral mining, battery production and power plants for charging are three unavoidable phases of the transition from conventional combustion engine vehicles to electric vehicles, and that these phases bear significant environmental, technological and social consequences in primary minerals exporting countries as well as in battery and electricity production countries within an international minerals and fuels trade framework. Each phase and related impacts require very carefully management and innovative policies for global mobility design, efficient technologies, just workforce use to prevent human rights disregarding (especially child work in mining countries and impacts on human health, water depletion and land demand). Therefore, the likely unavoidable transition to electric vehicles is not an easy task, but instead a challenge that requires the aware convergence of environmental and technology researchers, industry operators (for both production and recycling phases), mobility and urban planners (for appropriate implementation of mass transportation networks and individual mobility tools) and economic policy makers.

With the development of the global low-carbon economy, the demand for electric vehicles and lithium-ion batteries is increasing rapidly. But because of factors such as resource endowments, social development and technology, many countries need to trade to get the products they need. At the same time, with the deepening of global trade integration, the scale of international trade is also expanding (Liu et al., 2020). At present, global trade is largely determined by the market price of products. The impacts that the exporting countries face in minerals mining and manufacturing are most often disregarded by the importing countries, which generally only focus on the price and quality of the products. Most often, countries that mine and export minerals or import and process them into Li-ion batteries and other electronic devices for market export have also come under international criticism for the pollution they produce (**Tables 5.1** to **5.3**). Further, mining producing countries export resources and goods abroad to support internal and external economies and suffer from large environmental impacts, but the economic return

they receive from trade is barely enough to compensate for the environmental impacts they must suffer. From the perspective of demand, the environmental impact should not only strictly associated to the producing countries: also, the countries which import the products should bear some responsibility. Selling goods at the lowest possible price determined by international competition is not the best way to promote or reward cleaner production efforts.

Very few (if not none) importing countries choose trading partners based on their environmental performance in order to encourage exporting countries to adopt environmentally sound methods of producing goods. Trade must be a win-win effort for shared well-being and sustainable development, and it may be time for the international community to "share their environmental responsibility." For the importing country, the cost of import benefits is lower in the absence of social responsibility for pollution problems. Sharing responsibility may mean additional costs for importing countries, but it will also help producing countries develop better products with less impacts. Given the complexity of market prices, importing countries can be held liable in other ways besides paying additional costs. For example, (i) working with producing countries to develop more rational joint pollution management agreements and terms of trade; (ii) or sharing advanced technology and expertise with exporting countries. When it comes, for example, to the global steel trade, it is critical that governments and businesses recognize that the environmental burden should not be borne by just one player in the trading system (exporters), but other trading partners (importers) as well. This means that producing countries should be committed to improvement and exporting countries should also be aware that a large part of the impacts is due to their demand for low-cost primary or refined commodities and should therefore lead to joint efforts to prevent environmental impacts by promoting investment for better extraction and processing.

5.7 Conclusions

The rapid development of the global electric vehicle industry has made Li-ion batteries a crucial device as a power source (and storage) for electric vehicles. However, lithium batteries and electric vehicles need large amounts of minerals, energy and water in the production process, while releasing carbon and toxic emissions. Given that trade demand is also one of the main reasons for production, importing countries also have a responsibility to help improve the battery technology and mitigate environmental impacts. Therefore, this entails nonnegligible policy implications.

In producing countries, first of all, more recycling is necessary. Considering the stock of mineral resources is limited compared to the worldwide demand, in order to promote circular economy and sustainable development, producing countries should maximize technologies that minimize the use of resources and that promote the implementation of recycling to new production. Through the recovery of Li-ion battery and electric vehicle, the reuse of resources is strengthened. Secondly, optimizing power sources is crucial. There are many types of energy sources to provide electricity, and some of them (PV solar, wind, deep heat, etc.) have lower impacts on the environment than others (fossil, nuclear). Appropriate energy mixes depending on each country´s availability and technological factors, may help minimize environmental impact of electricity for charging, i.e. of the transition from

fossil fuels for combustion engines to electricity for electric car batteries. Third, improve production efficiency. Increasing production capacity through technological innovation and other means may help improve the utilization of mineral resources, thereby reducing the high demand for raw materials and energy.

In wealthy countries, the present large number of circulating cars as well as electric cars can be reduced through car sharing and mobility networks such as subways and other forms of electrified public transport. Providing the same service by using fewer cars will require fewer batteries, thereby reducing mineral and energy demand and its associated negative environmental impacts such as carbon emissions and mining-related pollution. This would leave the available electric cars to more intensive uses, such as taxi, security and health services. Secondly, long-distance commuting demand between living and working places should be reduced, in order to decrease the need for car mobility by improving urban planning. It should be clear to mobility policy makers that increasing traffic will make mobility harder, no matter cars are combustion or electric engines powered.

For trading partners, strengthening shared environmentally responsibility for global trade and resource availability is urgently needed. While some countries have applied the “polluter pays principle” to greenhouse gas emissions and responsible waste disposal, the United Nations Environment Program, and other international decision makers can still push countries that import large amounts of Li-ion batteries (as well as other electronic devices not dealt with in this study) and related minerals to pay a price that includes the cost of pollution. The related tax income could be used to help producing countries invest in cleaner production technologies and improve recycling, thereby protecting local and global ecosystems. Incentives can also be helpful as an alternative to taxes, perhaps easier to implement within market mechanisms. Importing countries can also help their trading partners decrease their environmental impact by exchanging technology and developing sensible joint pollution management agreements.

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