Follow-up feasibility study on sustainable batteries under FWC ENER/C3/2015-619-Lot 1

Task 1 Report

Feasibility of Scope Extension to Electric Scooter, Bicycles, Mopeds and Motorcycles

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PREPRINT(version 10/04/2020)

December 2019

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Luxembourg: Publications Office of the European Union, 2019

ISBN number 978-92-76-16375-6

doi:number 10.2873/685441

Printed in Belgium

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List of abbreviations and acronyms

Abbreviations	Descriptions
AS	Application service energy
BMS	Battery Management System
CBA	Cost-benefit-analysis
DC	Direct current
EOL	End-of-life
EPAC	Electrically power assisted bicycle
ESS	Elecrical energy storage system
EV	Electric vehicle
FU	Functional unit
GHG	Greenhouse gas
LEV	Light electric vehicles
LFP	Lithium-iron-phosphate
LIB	Lithium ion battery
NiMH	Nickel metal hydride
NMC	Lithium-manganese-nickel-cobalt
SLA	Sealed lead acid batteries
SOC	State of charge
SOH	State of health

1. Task 1: Feasibility of Scope Extension to Electric Scooter, Bicycles, Mopeds and Motorcycles

1.0. General introduction to Task 1

The original study defined a scope, which included electro-mobility applications for passenger electric vehicles and trucks, both hybrid and full electric. Batteries for lighter mobility applications (scooters, pedelecs, mopeds and motorcycles) were not in the original study scope. Though the batteries may have different design constraints, they still share many common characteristics, including battery chemistry.

The objective of this task is to consider to what extent, if any, requirements identified in the original study on performance, durability, carbon footprint, responsible sourcing, reuse/repurpose, recycle and so on, are applicable to lighter e-mobility applications (light electric vehicles - LEV) mentioned above.

This task should also analyse the implications of extending the scope of a possible regulation to LEV, including a cost/benefit analysis, as well as analysis of potential enforcement and verification issues.

Task 1 consists of the following subtasks:

- **Subtask 1.1 – Definition and specification of applications**

  This subtask gives definitions on LEVs considered within this study. The definitions are based on international standards, where possible. Furthermore, the batteries used in these applications will be specified (cell chemistries, technical parameters, battery system design etc.) and test standards will be outlined. Finally, typical use profiles of the LEV applications will be described.

- **Subtask 1.2 – Market**

  This subtask reviews historical market data on sales and stocks of light e-mobility applications. Based on historical data and further assumptions, forecasts on the potential future development of sales and stocks will be made.

- **Subtask 1.3 – Analysis of requirements**

  Based on the previous subtasks, this task analyses all requirements discussed in Task 7 "Policy Scenario Analysis" in the original study according to their applicability to light e-mobility applications. This includes analyses of requirements for battery lifetime, battery management systems, information provision about batteries, traceability of batteries, carbon footprint information and for battery design and construction.

- **Subtask 1.4 – Impact assessment and cost-benefit-analysis**

  This task analyses the implications of extending the scope and conducts a qualitative cost-benefit-analysis.

1.1. Subtask 1.1 – Definition and specification of applications

AIM OF SUBTASK 1.1:

The aim of this subtask is to give definitions on LEVs considered within this study. Furthermore, the batteries used in these applications will be specified (cell chemistries, battery system components, technical parameters) and test standards will be outlined. Finally, typical use profiles of the LEV applications will be described.

1.1.1. Definitions

As far as possible, the definitions follow the EU categorization of L-category vehicles (2- and 3-wheel vehicles and quadricycles).[1] Hence, in the following the categorization is described and it is explained which vehicle types are explicitly meant by which term within this study and which vehicle types are beyond the scope of this study. If the vehicle is considered within this study, a detailed definition is given on the following pages. If the vehicle category is not considered within this study, it is referred to the official categorization document which can be found within the regulation (EU) No 168/2013 of the European Parliament and of the Council as of 15.01.2013.

Table 1: Categorization of studied vehicles based on the EU L-categorization

Category	Sub-category	Category name	This study
L1e Light two-wheel powered vehicle	L1e-A	Powered cycle	Pedelec
	L1e-B	Two-wheel moped	E-moped (and Pedelec)
L2e Three-wheel moped	L2e-P	Three-wheel moped for passenger transport	E-moped
	L2e-U	Three-wheel moped for utility purposes	
L3e Two-wheel motorcycle	L3e-A1	Low-performance motorcycle	E-motorcycle
	L3e-A2	Medium-performance motorcycle	
	L3e-A3	High-performance motorcycle	

[1] Based on regulation (EU) No 168/2013 of the European Parliament and of the Council as of 15.01.2013

	L3e-AxE	Enduro motorcycles	
	L3e-AxT	Trial motorcycles	
L4e Two-wheel motorcycle with side-car			E-motorcycle
L5e Powered tricycle	L5e-A	Tricycle	E-motorcycle
	L5e-B	Commercial tricycle	
L6e Light quadricycle			Not considered due to low market volumes
L7e Heavy quadricycle			Not considered due to low market volumes

In order to determine use profiles, battery-specific characteristics or market forecasts, it is necessary for this study to aggregate the vehicle (sub-) categories to clusters, which can be explored further with regards to the aim of this study. Therefore, categories L6e and L7e are excluded since they currently do not show market-relevant sales figures, which makes defining use profiles and calculate market forecasts too uncertain.

E-scooter

As can be seen from Table 1, e-scooters are not directly within the scope of the L-vehicle categorization. However, they are electrically driven two-wheelers. Furthermore, the process of defining a standardization for these types of vehicles is still ongoing at the time of this study (IEC 2019). Moreover, several EU member states are currently dealing with regulating e-scooters but have not defined a law or regulation yet. There are also countries such as the United Kingdom or Ireland banning e-scooters. This is why we draw on recent national laws, within the EU, regulating this vehicle type (Austria, Belgium, Czech Republic, Denmark, France, Germany, Netherlands, Norway, Spain, and Sweden). As the national laws sometimes even differentiate from city to city within a certain country and laws differentiate between countries, the definition aims to bring the main regulation factors together, which are of relevance for this study (AHK 2019, BBC 2019, Bicle 2019, BMJV 2019, El País 2019, ePilot 2019, ETSC 2019, Euronews 2019, Grayling 2019).

The maximum speed allowed ranges from 20 to 25 km/h. Regarding the lanes where e-scooters are allowed to drive, there is a clear trend to cycling lanes if available. If these are not available, pavements are mostly forbidden and roads are recommended for e-scooters. In some countries such as Sweden or Norway, the regulations have been adapted to those of bicycles. This also holds for the Czech Republic and Austria with the addition that e-scooters qualify as (e-) bikes as long as they do not exceed a maximum speed of 25 km/h and an electrical power of 600 W or 1 kW. Moreover, taking passengers on e-scooters is usually forbidden such that e-scooters are single-occupancy vehicles. In countries like Germany or the Netherlands, the e-scooters have to be insured.

There are further vehicles that might fall into the category of e-scooters such as monowheels, segways or other self-balancing[2] vehicle types. However, e-scooters have been showing tremendous growth rates in sales and usage (via shared services), which has not been the case for other vehicle types, potentially being part of this category. Moreover, current sales figures for other vehicle types, related to e-scooters (vehicles with seating, self-balancing vehicles), are relatively small and it is assumed that these vehicles do not show very different technical characteristics, with regards to their batteries, and usage or user profile than e-scooters. This is why we focused on e-scooters within this category in order to calculate use profiles and market forecasts.

A tentative definition can be given as follows:

- electrically power driven two-wheelers with a maximum speed between 20 and 25 km/h (depending on country-specific regulation)
- without seat, but with handlebars
- max. continuous power of 500 to 1,400 W

[2] Self-balancing if equipped with integrated electronic balance-, engine-, steering- and deceleration technology, which enables the vehicle to balance itself.

Pedelec (Electrically power assisted bicycle: EPAC)

The pedelec or electrically power-assisted bicycle is a powered cycle as defined in the L1e-A sub-category. For the definition, this classification as well as the European Standard EN 15194:2017 is applied.

- Cycle[3], equipped with pedals and an auxiliary electric motor, which cannot be propelled exclusively by means of this auxiliary electric motor, except in the start-up assistance mode
- Maximum continuous rated power of 250 kW
- Output progressively reduced and finally cut off as EPAC reaches speed of 25 km/h or sooner if the cyclist stops pedalling
- Cut off speed is the speed reached at the moment the current has dropped to zero or to the no load current value (current for which there is no torque on the driving wheel)

Beyond the L1e-A category, there are so-called speed pedelecs, which can realize velocities of up to 45 km/h. These vehicles are, within this report, also referred to as mopeds and are therefore categorized as L1e-B vehicles. This also means that they must be driven on streets rather than bicycle lanes (which is however not the case in all EU countries, see Denmark[4]). Yet, these vehicles exhibit only small sales numbers compared to usual pedelecs (Guy 2019). Nevertheless, due to their potentially different use profiles from pedelecs, speed pedelecs are taken into account for the e-moped market calculations.

[3] Cycle: Vehicle with min. two wheels and propelled solely or mainly by muscular energy of the person on that vehicle, in particular by means of pedals.

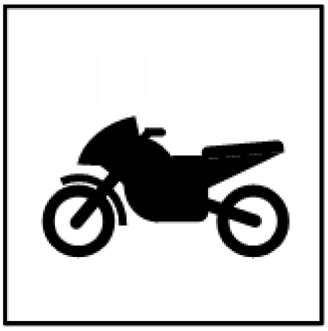
[4] https://www.sikkertrafik.dk/raad-og-viden/paa-cykel/speed-pedelecs

E-moped

For the e-moped, the Regulation No 168/2013 of the European Parliament and of the Council is applied:

- Two-wheel vehicles (L1e-B[5]) or three-wheel vehicles with mass in running order of less than 270 kg and max. two seating positions (L2e-P)
- Max. design speed of not more than 45 km/h
- Max. continuous rated power is no more than 4 kW

E-motorcycle



For the e-motorcycle, as for the e-moped, the Regulation No 168/2013 of the European Parliament and of the Council is applied.

- Two-wheel vehicle without sidecar (L3e) or with sidecar (L4e)
- Powered tricycles with three symmetrically arranged wheels (L5e-A)
- Max. continuous rated or net power of more than 4 kW
- Max. design speed of more than 45 km/h

[5] Vehicle classification following Annex I of Regulation No 168/2013 of the European Parliament and of the Council.

1.1.2. Battery specifications

Battery types / cell chemistries

In general, the following battery types have been used for e-scooters and in some early pedelecs, e-mopeds or e-motorcycles:

- nickel metal hydride (NiMH)
- sealed lead acid batteries (SLA)
- lithium ion battery (LIB)

Mainly, the first two types have been used so far, but they are replaced almost entirely by LIB, since the latter have more adequate battery performance for traction applications (higher energy and power density, no memory effect).

The most used cell chemistry of the latest e-scooter, pedelec, e-moped and e-motorcycle models are lithium-manganese-nickel-cobalt (NMC) or in some cases lithium-iron-phosphate (LFP). These are the same cell chemistries that have been discussed in the original study for the use in electric vehicles (EV) and electrical energy storage systems (ESS).

Components of battery system

Battery Management System

All LIB batteries need a battery management system (BMS), for that reason, also light electric vehicles (LEV) such as e-scooters, pedelecs, e-mopeds and e-motorcycles have a BMS to monitor the battery pack (e.g. temperature, voltage) and control charging and discharging. For most e-scooters the BMS is kept very simple, with mechanisms for preventing overheating and overcharging only. Some pedelecs and e-mopeds and e-motorcycles, however, have a quite advanced BMS,[6] with several sensors and processors ensuring optimum battery utilisation (e.g. state of charge (SOC) between 20 and 80%). Still for all LEV applications, the majority of BMS seems to allow firmware updates. In general, the existence of a BMS is in line with the battery systems discussed in the original study

Figure 1 shows the wiring and BMS of a Samsung SDI battery pack for e-mopeds and Figure 2 shows the functionalities of a smart BMS for Super SOCO e-motorcycles.

[6] https://www.samsungsdi.com/lithium-ion-battery/trans-devices/e-bike.html
https://www.samsungsdi.com/lithium-ion-battery/trans-devices/e-scooter.html
http://www.supersoco.com/second-phase/en/details-ts-technology.php

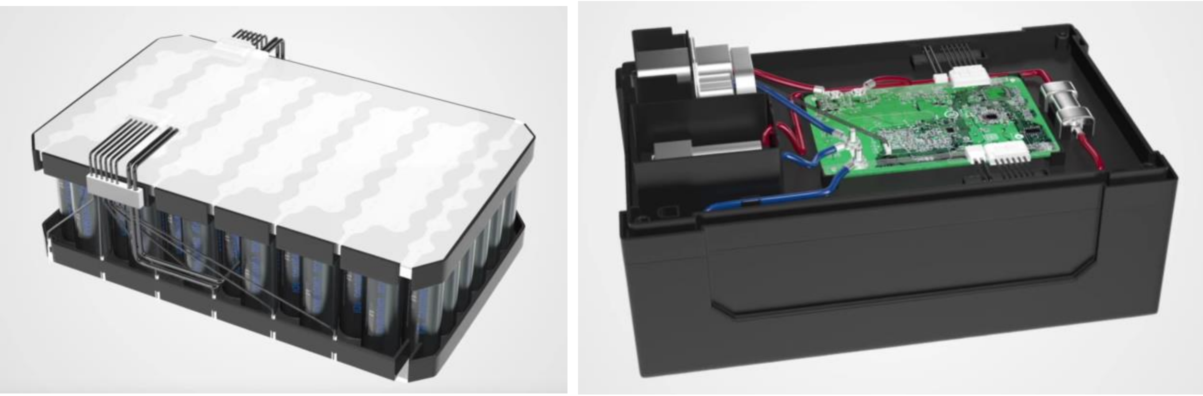


Figure 1: Wiring and BMS of Samsung SDI battery pack for e-mopeds Source: https://www.samsungsdi.com/lithium-ion-battery/trans-devices/e-scooter.html

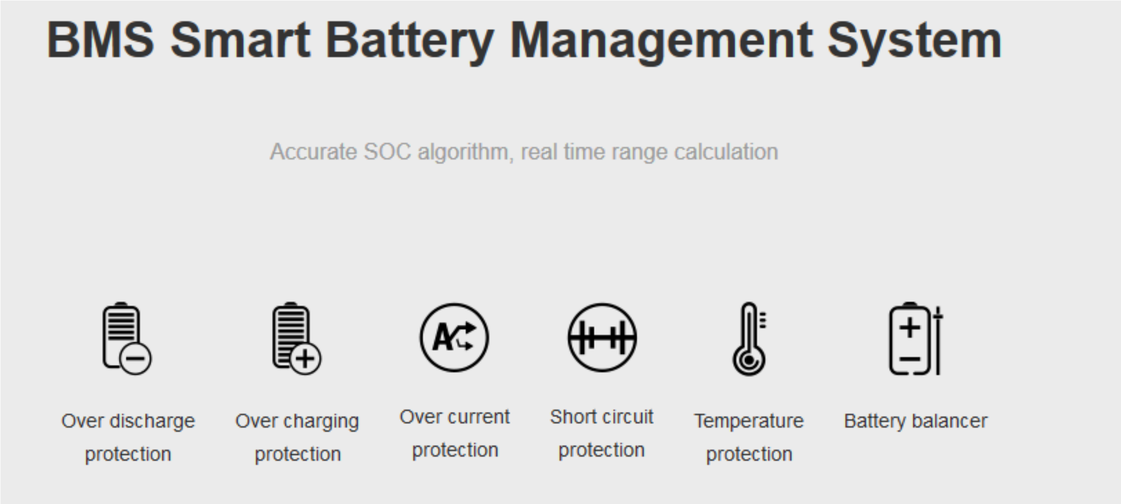


Figure 2: Functionalities of smart BMS of Super SOCO e-motorcycles Source: http://www.supersoco.com/second-phase/en/details-ts-technology.php

Thermal Management System

Most LEVs do not have active thermal management systems except for cut-off mechanisms in case of over-heating. Even batteries used in e-motorcycles (e.g. Harley Davidson LiveWire, Super SOCO models) generally only have passive cooling with aluminium ribs and special heat-conducting materials, but without fans. Here, the battery systems of LEVs and EVs or ESS discussed in the original study differ, since the latter have active thermal management systems with fans or even cooling pipes and heating. For that reason in LEVs, outside temperature and weather conditions have a higher impact on the battery than in EVs. Considering, that LEVs will be used all throughout the year, especially by commuters, and that LEVs are mostly parked outside, the susceptibility to temperature and weather is a very critical point.

Further Components

Battery packs of LEVs usually consist of one module, which is made up of several cells (for most e-mopeds and e-motorcycles, however, modular battery systems/packs are offered). This is in contrast to the battery system defined in the original study, which usually comprises several modules. High power DC charging (with more than 3.8 kW) is only possible with some e-mopeds and e-motorcycles. Most power electronics of LEVs do not allow higher charging power. EV and ESS, however, allow charging power of up to 350 kW.[7] For most e-mopeds and e-motorcycles exchangeable and modularly expandable batteries are available, while for most EV and ESS, as defined in the original study, that was not the case. Some e-scooter sharing companies want to work with exchangeable batteries as well.[8]

Technical specifications

Technical specifications of the LEV applications and the batteries used are outlined in Table 2, as well as calculations of Application Service Energy (AS), Functional Unit (FU) and energy losses.

The numbers for battery energy efficiency, self-discharge rate, average state of charge and charger efficiency are assumed to be identical to the parameters used in the original study. While the economic lifetime was defined after consultations with stakeholders, while the annual vehicle kilometres were derived from various sources (see section 1.1.3). The energy consumption and typical battery capacity was defined as average of various currently existing LEV models. Braking energy recovery is only offered in few e-scooters and pedelecs,[9] while it is offered in most e-mopeds and e-motorcycles. Still, we included braking energy recovery for all applications, thus representing a very conservative value when calculating the application service energy (AS).[10] The calendar and cycle life of batteries, as well as the state of health (SOH) at end-of-life (EOL) were derived from consultations with stakeholders. The underlying assumption is that the lifetime of LEV batteries is lower compared to EV batteries, since LEVs have a shorter economic lifetime and thus, lower lifetime requirements regarding batteries.

Table 2: Technical specifications of LEV applications and respective batteries as well as calculation of Application Service Energy, Functional Unit and energy losses. Values in bold are calculated values.

	Unit	**E-scooter**	**Pedelec**	**E-moped**	**E-motorcycle**
Economic life time of the *application*	a	1.5	10	10	10
Annual vehicle kilometres	km/a	2,360	1,392	2,959	7,800
Energy consumption	kWh/100km	1.0	0.8	4.0	10.0
Braking energy recovery in AS	% fuel consumption	20%	20%	20%	20%
All-electric range [km]	**km/a**	**32**	**60**	**80**	**112**
Maximum DOD (stroke)	%	80%	80%	80%	80%

[7] https://newsroom.porsche.com/en/2019/technology/porsche-engineering-dc-energy-meter-high-power-charging-measuring-technology-electromobility-18140.html

[8] https://www.businessinsider.de/tier-und-co-stellen-e-scooter-mit-austauschbaren-akkus-vor-2019-10

[9] https://electrek.co/2018/04/24/regenerative-braking-how-it-works/
https://electric-scooter.guide/guides/electric-scooter-regenerative-brakes/

[10] For details on the consideration and impact of braking energy recovery and on all calculations carried out within Table 2, see Task 3 report of the original study

Typical capacity of the application	kWh	0.4	0.6	4.0	14.0
Min capacity of the application	kWh	0.2	0.3	1.5	4.0
Max capacity of the application	kWh	1.2	1.3	4.8	18.0
Battery calendar life (no cycling)	a	10	10	10	10
Battery cycle life (no calendar aging)	FC	1,000	1,000	1,500	1,500
SOH @ EOL	%	70%	70%	70%	70%
Application Service Energy (AS)	**kWh**	**42**	**134**	**1,420**	**9,360**
Maximum quantity of functional units (FU) over battery service life	**kWh**	**320**	**480**	**4,800**	**16,800**
Calculated batteries per economic service life (according to cycles/FU)	**-**	***0.1***	***0.3***	***0.3***	***0.6***
Battery energy efficiency	%	92%	92%	92%	92%
Energy consumption battery energy efficiency	**kWh**	**26**	**38**	**384**	**1,344**
Self discharge rate	%/month	2%	2%	2%	2%
Average SOC	%	50%	50%	50%	50%
Energy consumption self-discharge	**kWh**	**0.5**	**0.7**	**4.8**	**16.8**
Charger efficiency AC	%	92%	92%	92%	92%
Charge power AC	kW	3.8	3.8	3.8	3.8
Charger efficiency DC	%			93%	93%
Charge power DC	kW			50	50
Share AC charge	%	100%	100%	95%	80%
Energy consumption charger energy efficiency	**kWh**	**28**	**42**	**415**	**1,424**

1.1.3. Use profiles

Data about use profiles is obtained by combining different sources specifically outlined per vehicle type in Table 3. For the remainder of this report, these numbers are used as assumptions, which are calculated as average numbers in order not to skew the calculations to an extreme. This also means that there might be e-mopeds for example, which show annual mileages of 14,600 or even 21,900 km. However, these do not match the estimated lifetime of 10 years for this vehicle as stated in Table 2 but the lifetime will be below this value. This holds for maximum and minimum values depicted in Table 3. As there are many providers offering sharing services for the vehicles discussed in this study, these utilisation figures are included into the annual mileage where possible. However, the shared use applications are usually well above average, since service providers need to bring them into use as often as possible in order to generate revenue. This is why the numbers from shared use should be seen as upper boundary. On the contrary, privately used vehicles can be interpreted as lower boundary since these vehicles are in usage for the owner only. It has to be mentioned, that (internal combustion engine) motorcycles are mainly used for two purposes, which are leisure and commuting or daily transport. This leads to entirely different user profiles and requirements regarding range, charging (power) and battery cycle and calendar life. Motorcycles that are mainly used for leisure ride less kilometres per year, but more per ride. As described above, however, we cannot account for both use profiles, and use the European average values.

Table 3: Use profiles of studied vehicles

Vehicle	**Annual mileage [km]**	**Source of data**	**Assumptions made**
E-scooter	Average: 2,360 Shared use: 3,326 Private use: 1,395	Tack et al. (2019)	Private use: 3.1 trips per day (as in Nobis and Kuhnimhof 2018), 2 km per trip (as in shared use), 5 days per week and 45 weeks per year
Pedelec	1,392 [min 1,004; max 1,804]	Castro et al. (2019)	
E-moped	2,959	Papadimitriou et al. (2013)	
E-motorcycle	7,800	Williams et al. (2017); Delhaye and Marot (2015a/b)	

1.2. Subtask 1.2 – Market

AIM OF SUBTASK 1.2:

The aim of this subtask is a review of historical market data on sales and stocks of LEVs. Based on historical data and further assumptions, forecasts on the potential future development of sales will be made.

1.2.1. E-scooter market

E-scooters are transport vehicles that just recently found their way into European markets. The majority of e-scooters is provided by sharing services such as Lime, Voi, Bird etc. that equip an increasing number of cities with the scooters for shared use. The firms do not provide complete information about the amount of distributed scooters and the regulating institutions have not yet established a registration system that provides comprehensive data on the amount of scooter-registration in Europe.

Data basis

In order retrieve market figures and to develop a projection of future e-scooter sales we build on the following base:

- E-scooters are considered a new phenomenon with scarce availability of historical and current data
- Only some data on status-quo in some major and smaller European cities is available
- We selected countries with differences in geographical region, cultural patterns etc., shown in Table 4, to account for possible differences in diffusion characteristics:
    - Germany, Sweden, Spain, Switzerland, Region Eastern Europe
    - Data for biggest cities or capitals as well for a sample medium size city of ~ 300,000

From the analyzed data, there is no clear trend observable to which extent the density of e-scooters per 1,000 inhabitants is related to the city-size. Furthermore, the observed cities show a large variance in e-scooter density per 1,000 inhabitants.

Table 4: E-scooter density in variety of European cities, 2019

Country	City	Inhabitants	E-scooters total	E-scooters / 1000 inhabitants	Source
Germany	Berlin	3,600,000	4,425	1.23	http://scooters.civity.de/
Germany	Münster	300,000	378	1.26	http://scooters.civity.de/
Sweden	Stockholm	950,000	1,500	1.58	https://www.thelocal.se/20190531/swedish-transport-agency-calls-for-ban-on-electric-scooters-after-fatal-crash
Sweden	Malmö	300,000	700	2.33	https://www.thelocal.se/20190531/swedish-transport-agency-calls-for-ban-on-electric-scooters-after-fatal-crash

Switzerland	Zürich	409,000	1,500	3.67	https://nzzas.nzz.ch/schweiz/tier-bird-circ-e-scooter-sind-erst-der-anfang-ld.1497280?reduced=true
Switzerland	Basel	172,000	400	2.33	https://nzzas.nzz.ch/schweiz/tier-bird-circ-e-scooter-sind-erst-der-anfang-ld.1497280?reduced=true
Spain	Madrid	3,260,000	10,000	3.07	City of Madrid
Eastern Europe	Sofia	1,240,000	150	0.12	https://www.trendingtopics.at/bulgaria/lime-escooters-just-launched-in-sofia-heres-how-they-work/

Forecast

Without the official registration numbers, there is hardly any possibility to track private scooter registration / sales right now. The main focus lies on the given data from the sharing service providers, since assumptions on private sales lack any basis. Thus, the market development for private e-scooters is not explicitly projected. Within the scope of this study, the estimation remains a rough projection of possible amounts of scooters. The market is expected to be very volatile and deviation is likely to occur.

Projection approach:

- The actual e-scooter stock in supplied cities varies around 2.5 e-scooters per 1,000 inhabitants. In the projection, a quick dissemination is expected for most bigger European cities until 2030, finally all supplied cities will converge to 2.5 e-scooters per 1,000 inhabitants until 2050. Due to a possible slower uptake in some countries, until 2030, an average of 2 e-scooters is projected for supplied cities.
- Some cities show higher numbers of e-scooter density right now. However due to the below mentioned suggestion of actual oversupply by the sharing service providers and increasing reservations of the population towards the e-scooters, a saturation at 2.5 is expected, which is below the maximum density observable right now. Due to the scarce data sources, any further distinction would also build on hypothetical assumptions.
- Estimation of number of e-scooter via inhabitants and density of 2 / 2.5 e-scooters per 1,000 inhabitants, where the dissemination of shared scooters is only considered for cities with more than 200 000 inhabitants
- ~ 290 European cities of more than 200,000 inhabitants identified. Multiplication of the latest available inhabitant numbers for the selected cities by 2 / 2.5 e-scooters per 1000 inhabitants.
- The calculation leads to an estimate of 380,000 e-scooters in stock in 2030 and 475,000 e-scooters in stock in 2050
- Considering the quick death rate and thus replacement rate according to estimated lifetime of 15 months leads to around 300,000 yearly e-scooter in 2030 and 380,000 yearly e-scooter sales in the year 2050

Assumptions:

- E-scooters are only used in urban areas

- Saturation at actual density rate of pilot cities, thus no increase in the density of e-scooters per 1,000 inhabitants over 2.5 e-scooters per 1,000 inhabitants in 2050
- Lower value of average of 2 e-scooters per 1,000 inhabitants in 2030, due to lower rise in especially Eastern European countries
- Service providers are fighting over market shares right now, which might result in oversupply of targeted cities. Actual numbers might overestimate long-term supply
- Increases in numbers of e-scooters driven by an increasing number of cities that are supplied by the sharing service providers
- Projected dissemination across all cities > of 200,000 inhabitants (or cities that had 200,000 within in the past 5 years) (Source: Eurostat database, urb_cgc, “Population on 1 January by age groups and sex - cities and greater cities”)

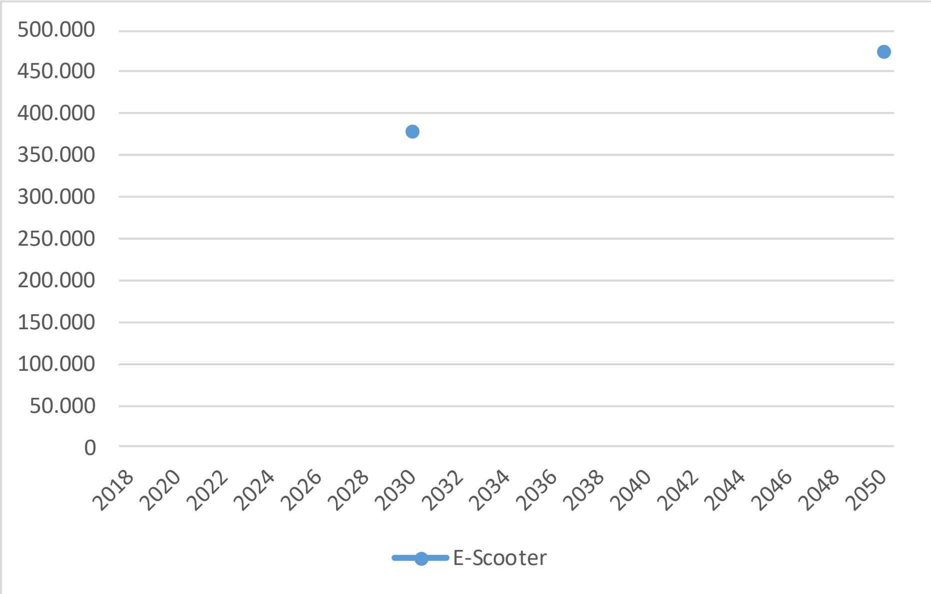


Figure 3: E-scooter sales for 2030 and 2050 EU-28

1.2.2. Pedelec market

The pedelec market has been growing quickly over the past 10 years. The strong positive trend for total European pedelec sales has recently been driven by early adopters, mainly in central Europe. Due to the higher speed and longer range, compared to conventional bikes, as well as the possibility e.g. for elderly Europeans to use pedelecs, when conventional bikes would no longer be an option, sales are likely to increase in other countries as well.

Data basis

- CONEBI, the Confederation of the European Bicycle Industry, publishes numbers on pedelec sales for EU-28 countries
- Upward trend in total pedelec sales, especially in central Europe

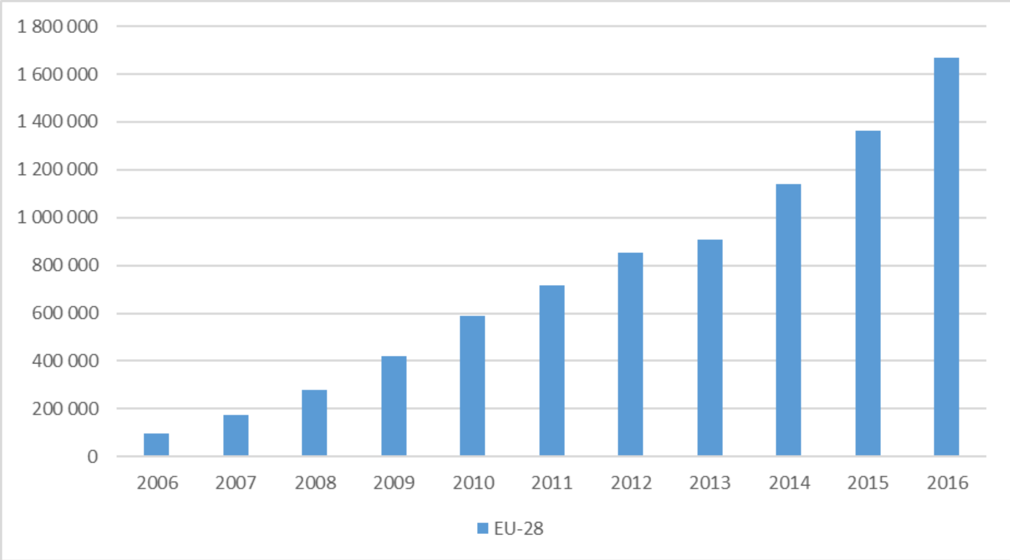


Figure 4: Development of pedelec sales EU-28 (CONEBI, 2017)

Forecast

According to the ECF, the European Cycling Federation, there is large potential in cycling, if cycling was prioritized in traffic regulations (ECF, 2019). Especially pedelecs would profit while the number of conventional bike sales are expected to remain at a constant level. Pedelecs are considered rather an additional vehicle than a replacement of conventional bikes due to partly different application fields.

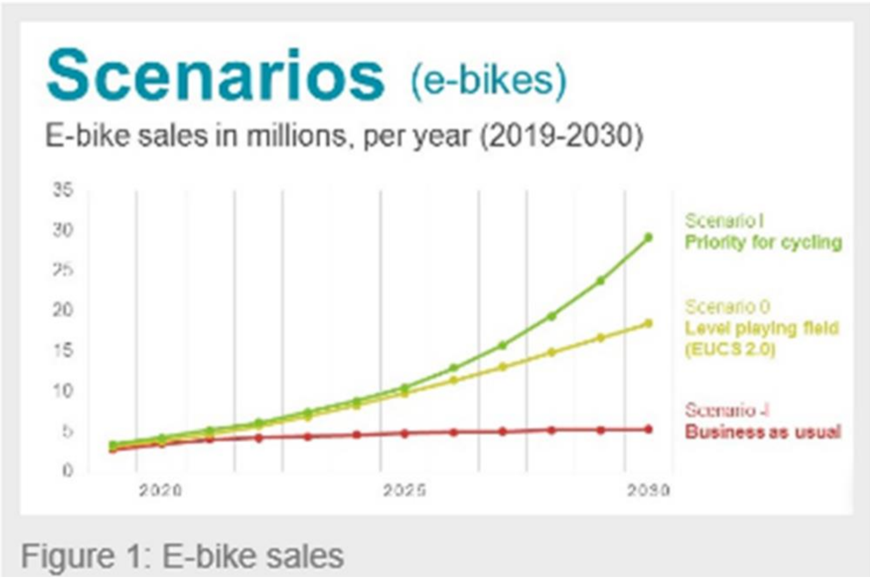


Figure 5: ECF e-bike sales scenarios (equivalent to pedelecs in this study) (ECF, 2019)

Projection Approach

- Since a direct shift to prioritizing cycling might not be reached, an estimation of future pedelec sales between Scenario 1 and Scenario 0 of the ECF until 2030 is expected: sales increase to 20 mio. pedelecs in 2030
- This means continuing trends from the observed development

- Constant yearly sales of 20 mio. pedelecs would come along with a long-term saturation at about 30% pedelec ownership rate (~200 mio. pedelecs in Europe) among the 740 mio. Europeans from 2040 on, considering an upper limit economic lifetime of 10 years
- This might be a rather optimistic long-term projection of pedelec ownership rates. A continuous increase can be projected for the upcoming years until 2030 in order for the ownership stock to grow and due to higher exchange rates due to occurring technical weaknesses of a fairly new product. However, afterwards sales numbers are likely to stagnate and even to decrease, to reach a long term saturation of about 20 % maximum. This would mean yearly sales around 14 mio. pedelecs, considering an economic lifetime of 10 years.

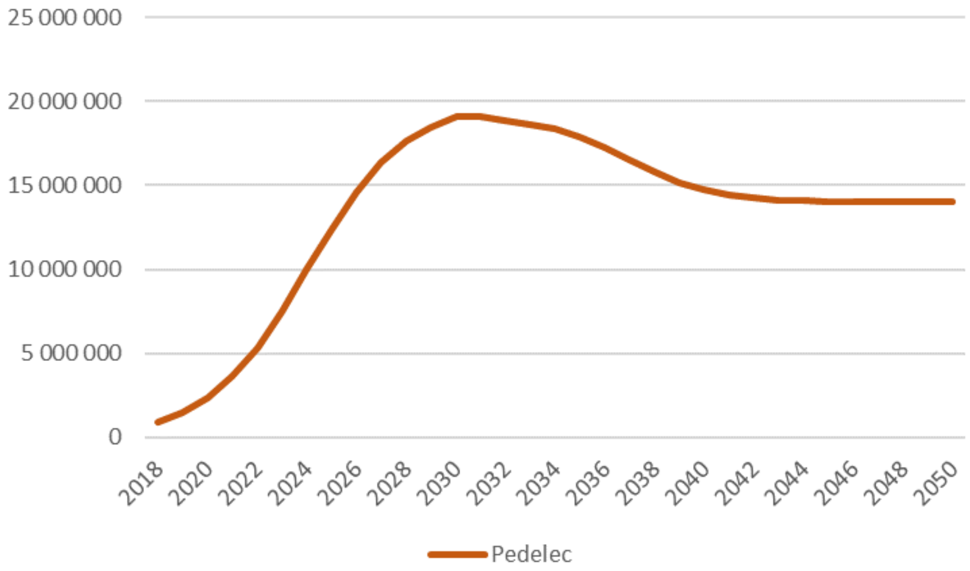


Figure 6: Forecast pedelec sales 2050 EU-28 (own calculation)

1.2.3. E-moped market

Mopeds are well known motorized vehicles that are used in rural as well as urban areas. Considering their range as well as the maximum speed, they have always been applied for shorter distances. The characteristics of electrified mopeds, e-mopeds, do not differ much from conventional mopeds and can easily be substituted. In the past years, an increasing number of shared moped providers has launched e-moped fleets in European cities. Right now, the price for the electrified version of a moped is high, compared to the alternative equipped with an internal combustion engine. The application field of e-mopeds includes longer distances compared to pedelecs that favor or require higher travel speeds. Consequently, these distances can also be traveled with speed pedelecs. The degree of potential substitution between speed pedelecs and e-mopeds is hardly predictable. However, due to comparable use profiles and battery capacities, the distinction must not necessarily be made within the scope of the study.

Data basis

- Eurostat database with many blank spots on countries' registration numbers

- ACEM, the European Association of Motorcycle Manufacturers, publishes numbers on two-wheeler registrations
- Past years: Falling registration numbers
    - Young adults shift from mopeds to cars as first vehicle or use bikes
- Rising numbers of e-mopeds

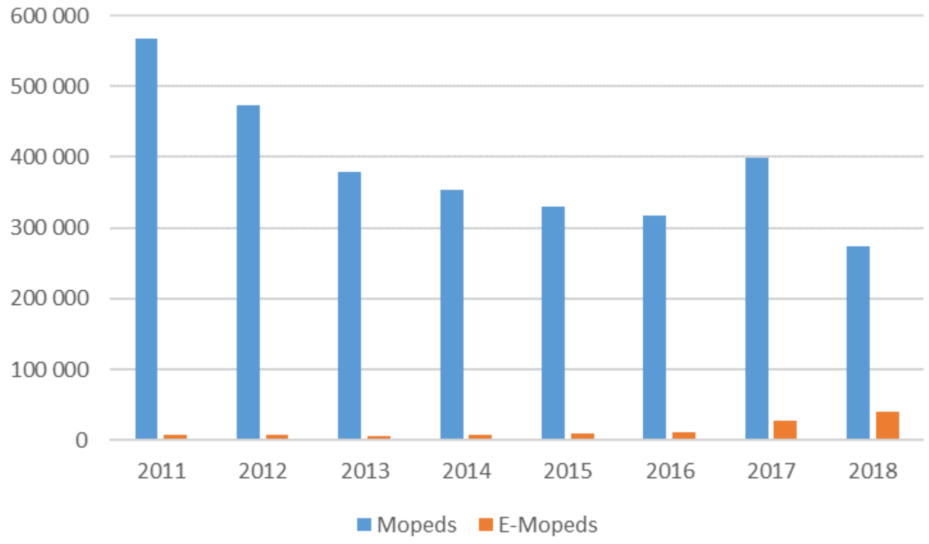


Figure 7: Development of moped and e-moped sales EU-28 (ACEM CIACEM database, 2019)

Forecast

The potentially rising relevance of e-mopeds as a transport mode, especially in urban areas as a substitute for cars, drives the high expectation towards e-mopeds to retrieve historic registration numbers. Urbanization is strengthening this trend and it is also supported by potential bans of conventional mopeds from urban areas, which are for example planned in Amsterdam and in other Dutch cities. Due to the small changes in driving patterns, e-mopeds are expected to quickly substitute conventional moped sales.

Projection approach

- Rising trend in moped sales: back to 500,000 mopeds per year in 2030, up to 600,000 in 2050 (EC, 2017)
- Quick diffusion of e-mopeds: ~90 % of registrations electrified in 2030, ~100 % of registrations electrified by 2050

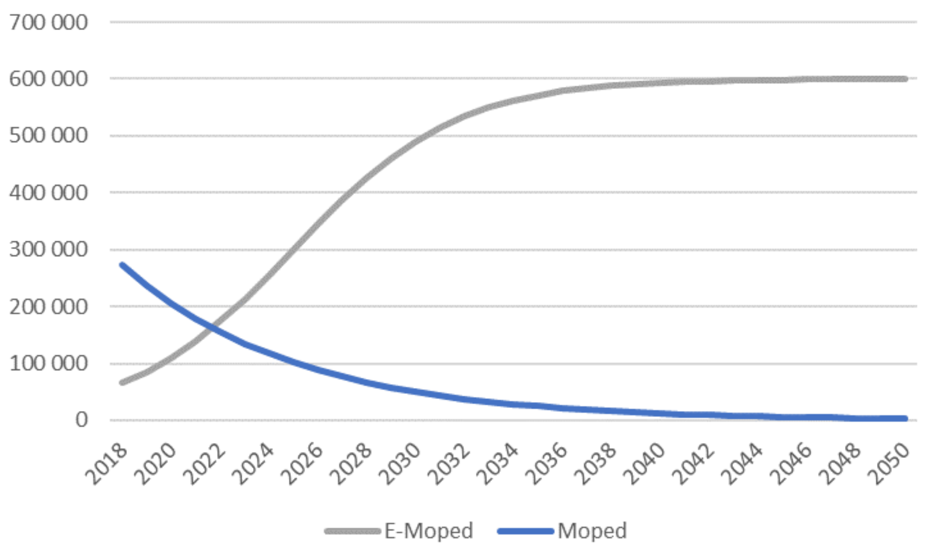


Figure 8: Forecast moped and e-moped sales 2050 EU-28 (own calculation)

1.2.4. E-motorcycle market

Motorcycling plays big role as a hobby, fascination driving, but also as means of daily transportation (Delhaye and Marot, 2015a). The share of cyclists, using motorbikes in leisure/hobby/sport is comparably high. These rides are usually short ride, thus the share of vehicle kilometres in that category might be smaller. However, hobby-cyclists might react differently to alternative powertrains, compared to commuting cyclists. One has to weigh characteristics as the motor sound of a combustion engine against e.g. the immediate torque but limited range of an electric drive. This question of personal preferences is hard to answer regarding long-term developments. Motorcycles have not yet been provided on a shared base, in the following only privately owned motorcycles are considered.

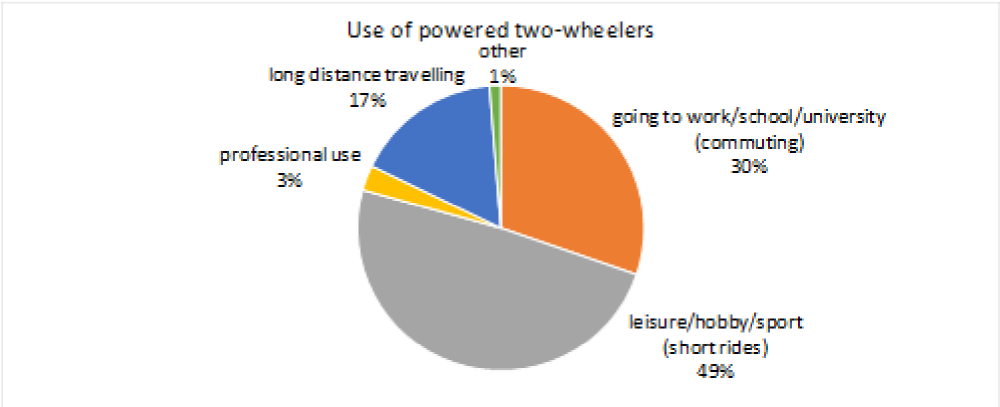


Figure 9: Use of motorcycles (own graph adapted from Delhaye and Marot, 2015a)

Data basis

- Eurostat database with many blank spots on countries' registration numbers
- ACEM, the European Association of Motorcycle Manufacturers, publishes numbers on two-wheeler registrations
- During the past years, registration numbers have been fluctuating, no trend observable

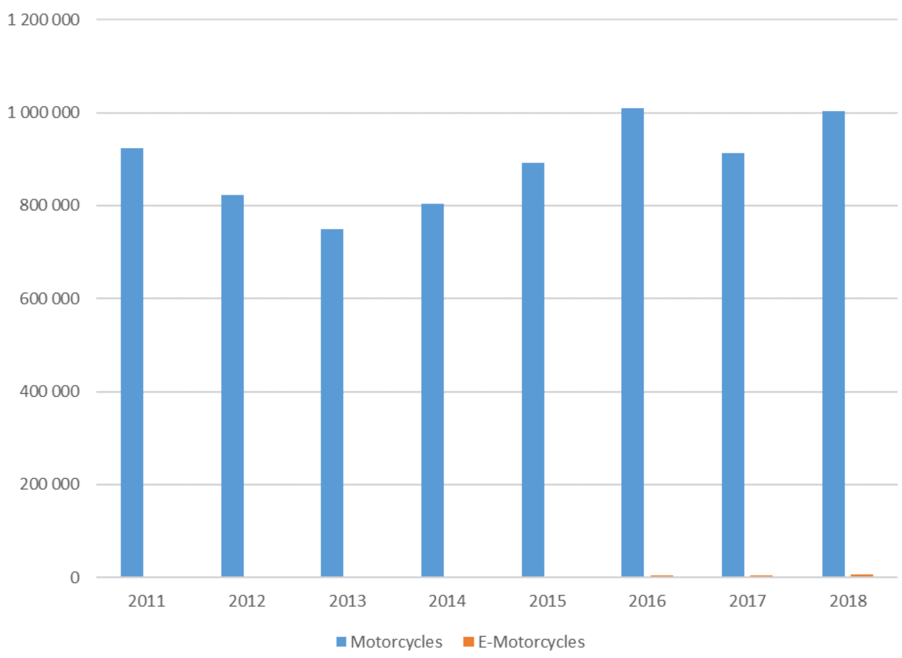


Figure 10: Motorcycle and e-motorcycle registrations EU-28 (ACEM, 2019)

Forecast

Electrified motorcycles represent a suitable alternative choice for motorcyclists. Compared to e-mopeds, the price difference between conventional motorcycles and the electrified versions is relatively smaller. This might encourage motorcyclists to quickly adopt the new technology. In the visions for future cities, two-wheelers play an important role. This might also positively influence the total sales of motorcycles. However, especially hobby motorcyclists might not change their preferences and remain buying motorcycles with combustion engines, also because of the limited range of e-motorcycles.

Projection approach

- Yearly sales of motorcycles constant at around 1,000,000 in total until 2030 (upper limit of recent yearly sales), considering a 55 % share of e-motorcycles in sales
- Further rise to a total of 1,250,000 until 2050 (baseline in EC, 2017): around 1,100,000 e-motorcycles are sold, while a remainder of 150,000 motorcycles (~10 %) is still sold with combustion engines for fascination driving users

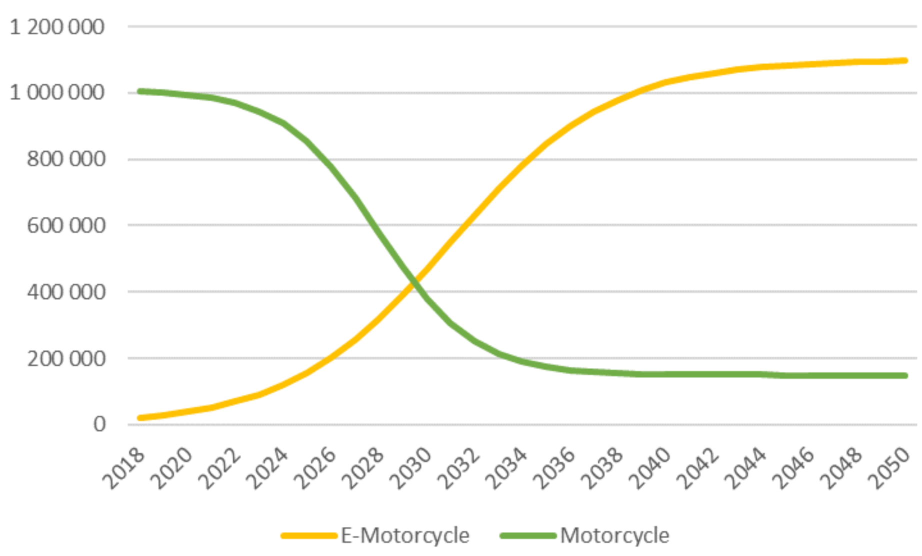


Figure 11: Forecast motorcycle and e-motorcycle sales 2050 EU-28 (own calculation)

1.2.5. Total battery demand

Projections of LEV sales for 2020, 2030, 2040 and 2050 were multiplied by typical battery capacity of application (see Table 2) in order to derive total battery capacity demand. The results can be seen in Figure 12. In the years 2020 and 2030 battery capacity demand from pedelecs play the most important role, while after then demand is dominated by e-motorcycles. Battery demand from e-scooters and e-mopeds only plays a subordinate role, due to their low sales but also low battery capacity per vehicle.

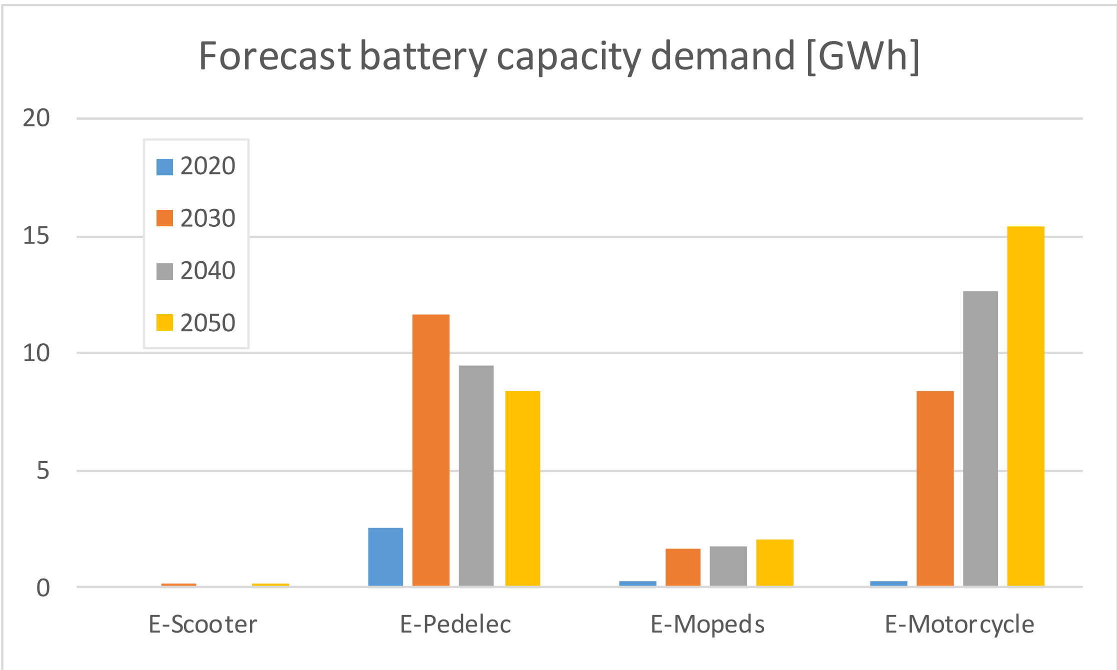


Figure 12: Forecast of battery demand from LEV, EV and ESS in GWh.

Figure 13 shows the forecasted battery capacity demand from EV and ESS in GWh until 2050 according to Task 2 report of the preparatory study. It is important to note, that maximum battery capacity demand from LEVs adds to 26 GWh in 2050, while demand for ESS alone in 2050 is at 260 GWh. Thus, in terms of battery capacity demand, LEVs mainly play a certain role within the next decade.

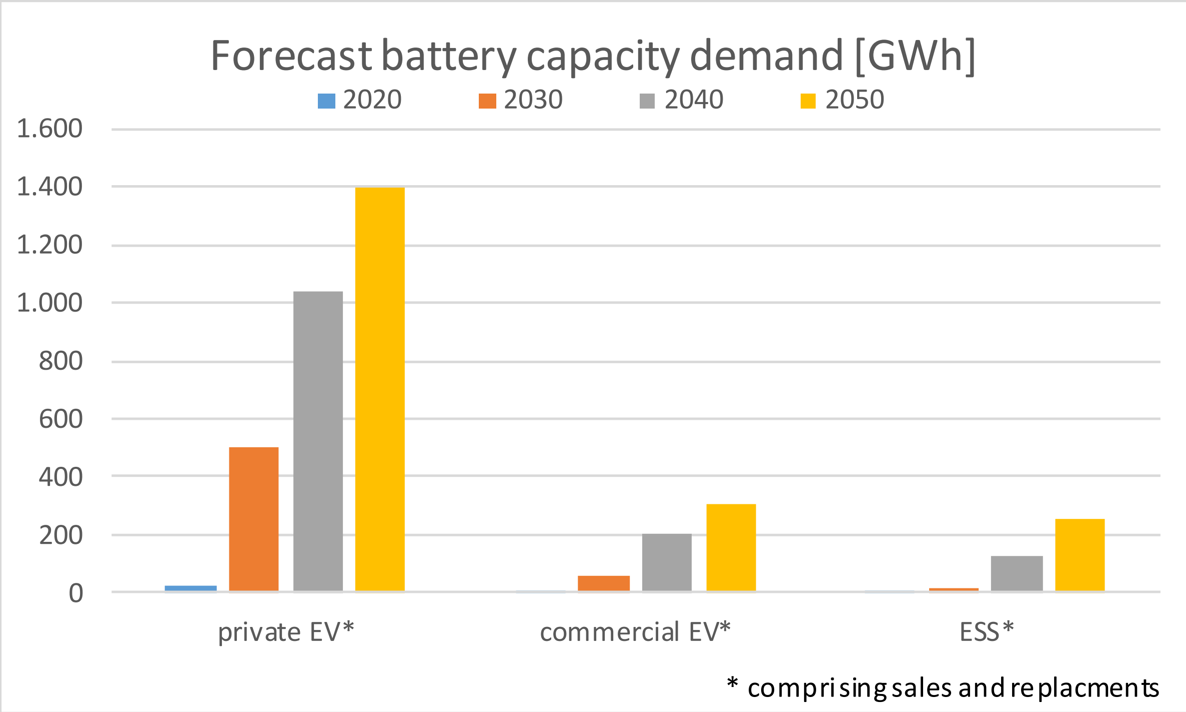


Figure 13: Forecast of battery demand from EV and ESS in GWh until 2050. Source: Task 2 report of preparatory study.

1.3. Subtask 1.3 – Analysis of requirements

AIM OF SUBTASK 1.3:

The aim of this subtask is to analyse all requirements discussed in the preparatory study Task 7 "Policy Scenario Analysis" according to their applicability to LEV, based on the previous subtasks. This includes analyses of requirements for battery lifetime, battery management systems, information provision about batteries, traceability of batteries, carbon footprint information and for battery design and construction.

1.3.1. Requirements for lifetime of battery packs and battery systems

In order to win the trust of the European public and end users a long service life and a minimisation of energy waste are important factors. This could be achieved by minimum battery pack and battery system requirements regarding lifetime and efficiency, possibly assured by warranties. Thus, the carbon footprint per functional unit can be reduced.

This could lead to a proposal for maximum capacity fade, maximum internal resistance increase and minimum round-trip efficiency for battery systems/modules/packs brought on the market for the intended applications

In order to ensure acceptable test durations, thresholds can be stated for half of the battery's service life (in cycles). As a consequence not a full lifecycle test is needed, but a half-life test is sufficient. Examples from the original study's Task 7 are given in Table 5.

Table 5: Examples of minimum performance and durability requirements after half of the service life for battery electric passenger vehicles (BEV)

Application	**Remaining capacity** (relative to the declared value)	**Maximum internal resistance increase**	**Minimum round-trip energy efficiency**	**Standards** (provisional -see notes on review)
PC BEV	90 % @ 750 cycles	30 % @ 750 cycles	90 % @ 750 cycles	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application

Discussion of requirements

- According to chapter 1.1.2 cycle life and EOL of LEV batteries is lower compared to EV and ESS (according to original study) since the applications have different requirements. Consequently, performance requirements and test duration for LEVs should be set lower.
- The test duration, even for a half-life test, is very long. Especially when adding it to the typical engineering development process needed for a LEV, which is shorter compared to EVs.
- Efficiency of batteries for LEV is expected to be similar to EV and ESS since same cell chemistries are used.
- However, test standards for LEV test / drive cycles are only partially available (see Table 6)

- Furthermore, no representative data on actual user behaviour and drive cycles is available, since LEVs are a quite new phenomenon
- Also, user behaviour is very unpredictable, especially for e-scooters and pedelecs.
- Finally, there are entirely different use profiles for LEVs. For e-scooters, pedelecs and e-mopeds in shared use the annual kilometres are much higher than those in private use. Also, there are different use profiles of leisure versus commuting e-motorcycle riders.

Table 6: Test standards for LEV

	Battery level & type	**LEV type**	**Cyclelife**	**Drive cycle**
		Performance		
ISO 18243 (2017)	Li-ion: battery system	Mopeds, motorcycles	x	
ISO 13064-1 (2012)	Li-ion: battery application system	Mopeds, motorcycles		x
IEC 63193 (in prep.)	Lead-acid: modules	Two-wheelers (mopeds), three-wheelers (e-rickshaws & delivery vehicles), golf cars & similar light utility vehicles, similar multi-passenger vehicles	x	x
IEC 62620 (2016)	Li-ion: cell to battery system	Fork-lift truck, golf cart, AGV, industrial	x	
EN 50604-1:2016	Secondary lithium batteries for LEV			
		Safety		
ANSI-CAN-UL2271 (2018)	All battery types: modules to battery system	Bicycles, scooters and motorcycles, wheel chairs, Golf carts, All-terrain vehicles, Non-ride-on industrial material handling equipment, Ride-on floor care machines and lawnmowers, personal mobility devices		
EN 15194 (2017)	All battery types: battery application system	Electrically power assisted cycles (EPAC)		

IEC 62619 (2016)	(see IEC 62620)			
Other				
IEC 61851-3-4 (in prep.)	All battery types: battery application system	Electrical bicycle, motor-bike, scooter, wheelchair, robot, EV		

It has to be mentioned, that for vehicles outside the L-categories (see section 1.1.1), other and further technical regulations and (test) standards apply, such as the EU battery directive (2006/66/EC), machinery directive (2006/42/EC), restriction of hazardous substances directive (2002/95/EC) or the standard for secondary lithium batteries for light EV (EN 50604-1:2016), for secondary cells and batteries containing alkaline or other non-acid electrolytes (EN62133-2) and many more.

Conclusion

- In general requirements applicable to all LEV
- Thresholds have to be adapted
- Test standards not available for all LEVs and not all parameters are covered
- Data on actual drive cycles required

Furthermore, a proposal for a minimum battery pack/system warranty per product could be introduced, including calendar life, energy that can be stored over lifetime, remaining capacity, internal resistance increase, energy efficiency (see Table 7).

Table 7: Examples of warranties

Application	**Warranty period**	**Minimum warranty**				**Methods**
	Calendar life warranty	Minimum **energy that can be stored over life-time in** kWh	**Remaining capacity** (relative to the declared value)	Maximum **internal resistance** increase	Minimum round-trip **energy efficiency**	Standards (provisional -see notes on review)
PC BEV	10 years	Declared capacity [kWh]x750	80%	60%	80%	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application

Discussion of requirements

- Outside temperature / weather conditions have higher impact on LEV batteries, because they have no thermal management and less "mass" (vehicle) and packaging around them. Thermal influences heavily impact ageing of batteries, thus warranties might be hard to fulfil

- Warranties can only be assessed under laboratory / benchmark conditions, since no data on real drive cycles are available
- Warranty period exceeds assumed lifetime of e-scooters and matches lifetime of other LEV applications, thus, for e-scooters a warranty period of 2 years and for the other LEV applications of 5 years seems more reasonable

Conclusion

- Influence of outside conditions too high for warranties
- Because of lack of active thermal management LEV manufacturer would have little opportunities to safeguard compliance with warranties
- Testing if warranty is fulfilled or not might be very costly in relation to LEV product value (battery cost between 200€ and 2000€), especially for e-scooter, pedelecs and e-scooters

1.3.2. Requirements for battery management system

A BMS with partially open data has multiple benefits. It would increase consumer confidence to invest in such applications, as feedback on battery status and ageing would be available. Furthermore, the resale of applications would be eased, since information on the use history would be available. In addition, it could help to support warranty claims, reduce repair costs and facilitate second life applications.

BMS allowing firmware updates would especially facilitate second use of batteries, since for the new applications manual effort such as exchanging the BMS and re-attaching cables for voltage measurements could be avoided.

Discussion of requirements

- BMS is available for all LEV and firmware updates are possible for most LEV, however, a potential firmware update, as the original firmware, has to comply with existing regulation, thus it requires a certain effort.
- Information for determination of state of health, lifetime information by statistics, general battery information etc. are hard to determine and probably not available for all LEV, since they have less sensors than EV BMS. This is especially true for e-scooters and pedelecs, while e-mopeds and e-motorcycles have several sensors.
- BMS open data diagnostics connector for second life use requires additional space, however space is very limited, especially in small LEVs. Adaptors for the existing connectors in LEVs might be a solution.
- Second life / repurposing of e-scooter and pedelec batteries might not be economically viable, due to their low battery capacities. For e-mopeds and e-motorcycles, however, there might be second life potential. With 1.5 to 16 kWh their battery capacities cover the range of residential ESS' capacities and they might also be aggregated to the dimensions of commercial ESS.
- Battery pack capacities of e-scooters and pedelecs might be too low to justify the high effort of repurposing. For some e-mopeds (e.g. $\geq$ 2 kWh) and for e-motorcycles, however, repurposing can make sense

Conclusion

- Requirements mostly applicable, but only useful for LEVs with high battery capacities of $\geq$ 2 kWh, such as most e-mopeds and e-motorcycles in general, since the battery capacity of other LEVs might be too low for second life / repurposing
- Requirements should be applied to e-mopeds and e-motorcycles

1.3.3. Requirements for information provision

To allow repair, reuse, repurposing and especially recycling of batteries, information about the battery is required. Not all of that information necessarily has to be stored per individual battery, but rather per battery model or type. The information especially concerns the material composition of batteries and thus, recycling of batteries. Batteries can be recycled more easily and with less material waste, when information on their cell chemistry (cathode and anode chemistry, electrolyte chemistry) is available. Beyond that, information on the content of recycled material including critical raw materials would be helpful. Additionally, the information is helpful, when sorting cell or modules for second life applications. That requirement could be implemented with a bar code, QR code or similar on each battery system, packs and module, with an EAN number and serial number. These numbers would be listed in a central database.

Conclusion

- Requirements applicable
- Information might be also interesting for end-user (specifications / compatibility of third-party batteries, repair in a specialized repair shop)

1.3.4. Requirements on traceability

One important aspect in the public debate on lithium-ion batteries are labour conditions and environmental impact of the extraction of raw materials for batteries. Thus, the traceability of raw materials can be set further to tracing battery modules and packs. The idea is to have serial numbers on each battery module and pack that is linked to a database tracking them. Furthermore, this database has to be linked to a material database for ethical mining.

Discussion of requirements

- Batteries of e-scooters and pedelecs have low capacities and thus, only account for a very small amount of material demand.
- The effort for tracing materials might consequently be too high

Conclusion

- Requirements applicable
- Information might be also interesting for end-user (sustainability)

1.3.5. Requirements on carbon footprint

The previous study showed that manufacturing of a battery consumes much more energy compared to its storage capacity. For some applications, that amount of energy is even bigger than the energy stored over the battery's lifetime (number of functional units). Thus, a "capacity Energy Efficiency Index" (cEEI), ratio of declared storage capacity relative to the embodied primary or gross energy requirement for manufacturing or a "functional Energy Efficiency

Index" (fEEI) as ratio between functional unit or kWh stored over its lifetime relative to the embodied primary or gross energy requirement for manufacturing could be introduced. Beyond that, information requirements on the energy sources used during battery production could be set, enabling the determination of the carbon footprint. Embodied energy and carbon footprint cannot be neglected.

Conclusion

- So far, use phase cannot be modelled accurately, due to missing data
- Only few standards for LEVs are available
- Requirements hardly applicable at the moment

1.3.6. Requirements on battery design and construction

Harmonized battery design would simplify repair, replacement, reuse and recycling of batteries. Mandatory addition of dismantling information to an open access database, an R-R-R-R index (repair, re-use, repurpose, recycle) and a mandatory DC charging/discharging interface that supports vehicle-to-grid mode (V2G) and a vehicle-to-test mode (V2test) to verify the performance and information criteria would be measures to implement these requirements. This could lead to easy assembly and disassembly standards, standardized interfaces for hardware and software, thermal interfaces, dimensions and connections etc.

Discussion of requirements

- E-scooter and pedelec battery capacities are most probably too small for V2G applications. Beyond that, DC charging is only possible for few e-motorcycles
- Especially e-scooter and pedelec batteries are already repaired, not by the OEM though, but by specialized repair work shops, thus warranty is lost.
- Due to warranty losses and feared safety risks, most end-users buy new batteries.
- Beyond that, a major problem is that decommissioned pedelec batteries, for example are currently not returned to manufacturers by customers, but kept in their possession
- Often not the battery modules but other electronics (e.g. BMS) is damaged, thus a modular design of the battery system would be favourable
- E-scooter batteries are not very maintenance friendly and at the moment, especially e-scooters in shared use, are treated as use-and-throw things with short lifetimes, which makes eased recycling necessary
- Some e-mopeds and e-motorcycles already have exchangeable batteries, thus repurposing is easier
- Already now, 50 to 70 percent of pedelec battery materials can be recovered.[11]

Conclusion

- Requirements are applicable with benefits for end-users

[11] https://www.velototal.de/2019/08/27/second-life-f%C3%BCr-batteriezellen/

1.4. Subtask 1.4 – Qualitative impact assessment and cost-benefit-analysis

AIM OF SUBTASK 1.4:

The aim of this subtask is to analyse the implications of extending the scope and to conduct a cost-benefit-analysis (CBA), both in a qualitative manner.

1.4.1. Qualitative impact assessment

1.4.1.1. Environmental impacts

Usually, the energy consumption during the use phase of products is the most important environmental impact for products covered within the ecodesign regulative framework. However, the original study showed that for battery systems the situation is more complex. Therefore, in addition to the electricity consumption and the GHG emissions, the demand of critical raw materials will be discussed in a qualitative manner.

In accordance with the original study, the three main phases of the product will be differentiated when discussing the impacts:

- Production (raw materials use and manufacturing)
- Use phase
- End of Life

Electricity consumption

Due to the much lower battery capacity demand resulting from LEVs in comparison to EVs or ESS also the total electricity consumption of LEVs will be much lower.

This study showed lower relative electricity consumption (application service energy and resulting losses) of LEVs during the use phase in relation to the battery capacity, than EVs or ESS. Consequently, the electricity consumption during the production phase of batteries for LEVs might outweigh the electricity consumption during the use phase of LEVs. Thus, especially requirements addressing a longer utilisation of batteries, potentially in a second-life application, are promising, since they allow a better ratio of utilisation to production electricity consumption and a higher yield of the electricity employed during production. That mainly applies to BMS and battery design and construction requirements, since they enable easier repurposing.

Furthermore, because of the lower impact of the use phase, requirements such as information provision, traceability and battery design and construction, enabling easier recycling seems also more beneficial for LEVs in comparison to EVs or ESS

Greenhouse gases

Regarding the production phase, the best option to reduce greenhouse gas (GHG) emissions, as described in task 7 of the original study, is the electricity mix. Shifting to electricity from renewable energy sources can significantly decrease the GHG emissions during the production phase. A reduction of up to 99 % seems to be feasible.

A slight reduction of GHG during the use phase might be achieved with requirements for lifetime, which focus on a low internal resistance or a high round-trip energy efficiency. Warranties related to that, might also support slight GHG emissions reductions.

Material demand

Requirements that increase the recycling rates of batteries and percentage of recoverable materials, such as information provision, traceability and battery design and construction requirements have the potential to decrease the material demand.

Additionally, as already discussed, requirements extending the lifetime with regards to a second-life, result in a better yield of material effort to employable functional unit.

1.4.1.2. Socio-economic impacts

Socio-economic impacts refer to:

- Purchase costs: they are driven by the market sales and the purchase price of the battery systems.
- Running costs: only the electricity costs in the use phase are considered
- EOL costs: including the replacement costs and the decommissioning costs

The relative cost impacts of the requirements are expected to similar to those calculated in task 7 of the original study.

Lifetime requirements require extensive testing and thus, are quite cost-intensive. While information provision or carbon footprint requirements might only have minor impact on the costs, traceability requirements require a bigger effort resulting in higher costs. The latter is also true for requirements on batter design and construction.

1.4.1.3. General impacts

Regarding the impacts of a potential regulation, it has to be noted, that the LEV manufacturing industry has a different industry structure than for example the automotive industry has. While car manufacturers are big, multi-national companies, LEV manufacturers are usually small or medium-sized enterprises (SME). For the latter it is very difficult to implement a comprehensive regulation, because of limited human and financial resources. While car manufacturers and big suppliers can quite easily procure the resources for finding adequate new suppliers, reengineering a specific product or component or fulfilling new information requirements in order to be compliant with new regulations, for SMEs in LEV manufacturing that might consume a substantial amount of their resources. Furthermore, one-time costs for the implementation of a regulation can be attributed to a lot more produced units (in value but also in numbers) in the automotive than in the LEV industry.

On the other hand, one could assume, that big automotive OEM having long-term relationships with their (battery) suppliers, have more difficulties to make a quick shift to other, regulation-conform batteries more difficult than for small SMEs in the LEV industry, who can easily change suppliers.

1.4.2. Qualitative cost-benefit-analysis

In Table 8 a brief qualitative cost-benefit-analysis is carried out, summarizing the insights of this study.

It is assumed, that the costs will be added to the purchase price and thus, be paid by the customer/end-user

Table 8: Qualitative cost-benefit-analysis

	CBA LEV	
Requirements	**End-user**	**Manufacturer**
Minimum requirements for lifetime	- higher battery price - life-time and other performance criteria with lower criticality for LEVs because of lower economic lifetime and low impact of use phase - performance criteria hard to understand for end-customer + longer battery durability or fewer replacements required + beneficial for second-life utilisation, thus leading to lower impacts	- costs hard to determine, but will be noteworthy, since special meters, standards, data etc. are required - verifying minimum life cycle requirements will also entail costs - engineering and research required - high costs and duration for tests + increased end-customer trust and thus, more sales from OEM + competitive advantage with well performing batteries
Warranties	- higher battery price + longer battery durability or fewer replacements required + warranty is a known tool to the consumer, would provide the necessary trust in the product and would equally contribute to increasing lifetime of poor products + warranty also gives direct control to the consumer, empowering him further to select the right products.	- testing if warranty is fulfilled or not is very costly in relation to product value (battery cost between 200€ and 2000€) + increased end-customer trust and more sales from OEM + competitive advantage with well performing batteries
Requirements for battery management system	- higher battery price - space required for connector + warranty claims might be assessed with BMS + firmware updates improve battery performance + easier resale	- costs <5€ per battery - firmware updates also have to comply with regulation, leading to increased effort - critical information might be accessible by competitors - might lead to compliance issues + increased end-customer trust + potential improvements from big community + reduced effort for second-life application

Requirements for information provision	- higher battery price + information might be interesting for end-user (specifications, compatibility of third party batteries, own repair)	- high costs of setting up and updating database + easy distribution of data sheets and repair information
Requirements on traceability	- higher battery price + information might be interesting for end-user (sustainability and environmental concerncs) + promotion of ethically mined materials	- high costs of setting up and updating database + improved image
Requirements on carbon footprint	- higher battery price + better conscience + lower carbon footprint	o data availability is similar to initial scope
Requirements on battery design and construction	- higher battery price - new batteries might still be preferred (battery exchange for smart phones not frequently used) + repair instead of replacement is likely to cheaper + also leads to lower battery waste and new capacity demand	- high engineering effort, but quite low operational effort (screws instead of glue, sealing issues) - since battery design is closely aligned to specific application, requirements could decrease performance of batteries

1.5. Concluding remarks

There are aspects that have not be discussed in the previous section, but that are relevant for a potential regulation:

- Customers of e-scooters and pedelecs tend to keep the vehicles as well as the batteries even after their end of life, thus a regulation should address that issue, by ensuring recycling streams.
- Furthermore, safety issues are more important for LEVs, especially for e-scooters and pedelecs, since their batteries are usually charged indoor, where fire would have severe consequences

1.6. References

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Follow-up feasibility study on sustainable batteries under FWC ENER/C3/2015-619-Lot 1

Task 2 Report

CHARACTERISATION OF PERFORMANCE AND SUSTAINABILITY REQUIREMENTS FOR RECHARGEABLE BATTERIES WITH INTERNAL STORAGE FOR CHEMISTRIES OTHER THAN LITHIUM-ION FOR BOTH ELECTRO-MOBILITY AND STATIONARY APPLICATIONS

DRAFT FINAL PREPRINT

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December 2019

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EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

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Luxembourg: Publications Office of the European Union, 2019

ISBN number 978-92-76-16376-3

Doi: number 10.2873/780284

Printed in Belgium

Use of number format

“space” as thousand separator

. “dot” as decimal point

Contents

2. Task 2 – Characterisation of performance and sustainability requirements for rechargeable batteries with internal storage for chemistries other than lithium-ion for both electro-mobility and stationary applications

2.0. General introduction to Task 2

The original study has focused primarily on lithium-ion batteries, which is likely to remain as the predominant technology in the market in the near future. However, any potential regulation that is proposed, after the analytical phase has concluded, should be as technology neutral as possible.

Therefore, there is a need to verify that the performance and sustainability requirements suggested in the original study are applicable for battery technologies and chemistries other than lithium ion, and what adjustments might be necessary to make an possible regulation and technology and chemistry neutral as possible. This should include an analysis of existing and prospective battery chemistries, including lithium metal, sodium-sulphur and nickel metal hydride.

2.1. Key Challenges

Key challenges are:

- Considering the current state of the proposed requirements on sustainability, for example carbon footprint information, can be easily applied to other chemistries and is relatively straightforward.
- The extension of the proposed performance requirements on battery lifetime is considered a much larger challenge, because standards are missing and here again a reliable set of public available data to set thresholds.
- In general, for ESS a technology agnostic test standard exists, but seems especially written for lead-acid batteries. Specific standards for ESS application exist for lithium, lead-acid, nickel metal hydride and high temperature sodium batteries. Standards on EVs mainly focus on the Li-ion chemistry.

2.2. Scope considerations

2.2.1. Existing scope definition for Lithium Chemistries

In line with Task 1 of the preparatory study the proposed scope is 'high energy rechargeable batteries of high specific energy with solid lithium cathode chemistries for e-mobility and stationary energy storage (if any)'.

High specific energy is hereby defined by a gravimetric energy density 'typically' above 100 Wh/kg at cell level.

High capacity means that a total battery system capacity between 2 and 1000 kWh.

See Task 1 for more details.

This does not include power electronics neither heat nor cool supply systems for thermal management, which can be part of what the study defined as a battery *application* system.

Further on in Task 7 of the original study the applications EV and stationary energy storage was proposed for the regulation.

2.2.2. New scope definition including other than lithium chemistries

The scope of Task 2 is the original scope extended to all rechargeable battery chemistries with internal storage, covering the original applications (EV & ESS).

The scope becomes therefore:

'rechargeable batteries of high capacity with internal storage for e-mobility and stationary energy storage (if any)'. High capacity means that a total battery system capacity between 2 and 1000 kWh.'

2.3. Example of chemistries

2.3.1. For electric vehicles applications

We do not consider that other than lithium chemistries will play a significant role in near future. This has been underpinned recently by attributing the Noble prize for the development of lithium chemistries. Lithium chemistries have the highest energy density of all rechargeable battery types.

Lithium chemistries include besides Li-ion, also lithium alloys, lithium metal and lithium sulphur batteries. The international standardisation committee IEC SC21A includes those types in their scope of lithium batteries. Nevertheless, their prescribed test methods and rules, including battery marking, are skewed to the lithium ion industry as that is the most dominant.

2.3.2. For stationary energy storage applications

For electric vehicle applications only lithium chemistries are envisaged due to their high specific energy density. In case of stationary energy storage this is not a decisive parameter and therefore other chemistries can remain and/or enter the market. Hence the remainder of this report will focus on these chemistries for ESS. The following chemistries are taken into the evaluation:

- Li-ion
- Li-metal
- Lead-acid
- Advanced lead
- NiMH
- NiFe
- $NaNiCl_2$
- NaS
- hybrid-ion
- LiS
- Na-ion

Recent market data from Germany showed that for residential grid energy storage applications the market converges to lithium chemistries, despite above mentioned argument for investigating other chemistries. Consequently, it will also be difficult to obtain representative market data for other chemistries than Li-ion and much in the study will be based on assumptions.

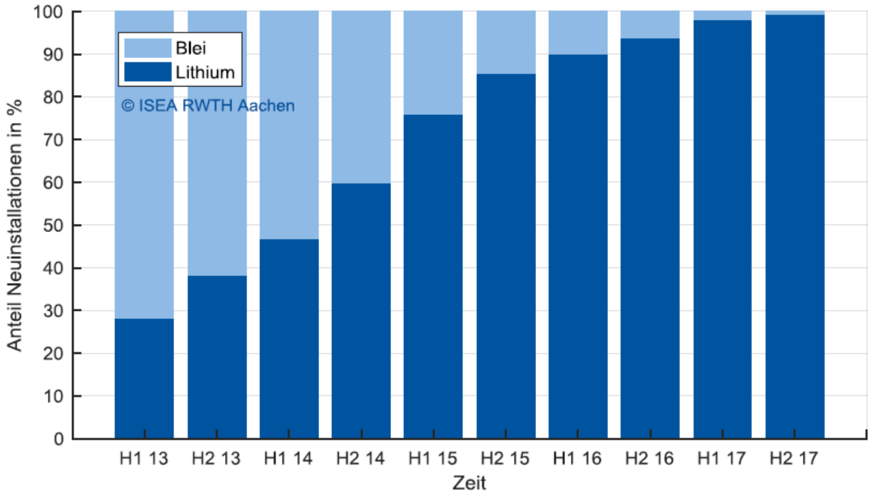

Figure 2-1: Evolution of market share between lead-acid batteries ('Blei') and Li-ion batteries ('Lithium') on the German market for PV energy storage. Source: Speichermonitoring Jahresbericht 2018, RWTH Aachen.

2.3.3. Battery standards

The extended scope requires also an augmentation of the inventory on battery standards. For performance related standards this is given in the annex, Table 2-8.

2.4. Screening of the originally proposed scope versus proposed policy in follow-up study

In task 7 of the preparatory study for ecodesign batteries policy propositions were given on 6 topics:

1. Minimum battery pack/system lifetime requirements
2. Requirements for battery management systems
3. Requirements for providing information about batteries and cells
4. Requirements on the traceability of battery modules and packs
5. Carbon footprint information and the option for a threshold
6. Minimum battery pack design and construction requirements

Hereafter it is evaluated how well they fit for the other battery chemistries in the case of stationary energy storage (this case has been selected in the previous section as the only case where other batteries are considered than lithium chemistries).

2.4.1. Minimum battery pack/system lifetime requirements

The original lifetime requirements from the preparatory study, task 7, for stationary energy storage are reproduced here. The requirements were split into requirements at mid-life that are tested according to a cycle-life test (see Table 2-1) and into warranty requirements (see

Table 2-2). **Error! Reference source not found.**. These requirements are for new batteries. Storage systems made of second life batteries cannot be re-submitted to the original requirements.

The evaluation of the requirements is performed with help of three subsequent tables:

- Coverage of performance criteria in standards (Table 2-3);
- Possible performance of the selected chemistries for ESS application (Table 2-4);
- Evaluation against currently proposed criteria, including conclusion and standardisation need per chemistry (Table 2-5).

Of each battery chemistry many battery types are produced with a different set of design requirements. Even for stationary energy storage, one brand can produce several battery types with difference in predicted lifetime, maintenance need and certainly in price. The possible performances shown in the Table 2-4 is therefore not valid for all battery types. They have been assumed as plausible and the source is mentioned. Hardly, data on efficiency exists. In some case data from the battery testing lab is given as an indication. This is clearly documented in the table.

After the tables (2-1 to 2-5) conclusions are derived.

Table 2-1: Summary of minimum battery system lifetime compliance requirements as tested before bringing on the market for the ESS application. This test represents a mid-life condition (copied from Table 7-2 in the previous task 7 report).

Application	**Remaining capacity** (relative to the declared value)	**Maximum internal resistance increase**	**Minimum round-trip energy efficiency**	**Standards** (provisional -see notes on review)
ESS	90 % @ 2000 cycles	NA	94 % @ 2000 cycles	IEC 61427-2 Cycle-life test according to declared application(s)

Table 2-2: Summary of minimum battery system lifetime minimum warranty requirements (copied from Table 7-3 in the previous task 7 report).

Appli-cation	**Warranty period**	(whatever reached first)	**Minimum warranty**				**Methods**
	Calendar life[1] warranty	Exceedance of minimum warranted amount of stored energy during the lifetime	Minimum energy that can be stored over life time in kWh	Remaining capacity (relative to the declared value)	Maximum internal resistance increase	Minimum round-trip energy efficiency	Standards (provisional -see notes on review)
ESS	12 years	See prescription at the right	Declared capacity [kWh]x2000	80%	NA	88%	IEC 61427-2 Cycle-life test according to declared application(s)

[1] Measured from the manufacturing time (see information proposal in previous Task 7 report).

Table 2-3: Evaluation of standards for the needed performance characteristics. (Resistance test is given. It is important for EV application, but no threshold was given for this in case of ESS. Therefore, this column is in grey colour).

Chemistry	Standard	Cycle-life test	Description test	(Remaining) capacity test	Energy determination	Efficiency test	Resistance test	Conclusion (standardisation need)
Agnostic	IEC 61427-2	yes	Cycles for 4 applications, mostly 1 cycle per 24h. No EOL criteria.	no	no	no	no	Insufficient (see previous task 7 for details).
Li-ion	IEC 62620	yes	500 cycles with 1/5I_t. 1I_t allowed. The capacity must remain above 60% of initial capacity. The cycle test can be repeated several times until the EOL criterion.	yes	no	no	yes	Sufficient, but officially only for industrial applications.
	BVES Effizienzleitfaden	no	–	no	no	yes	no	Insufficient, focusses on performance of application system instead of battery life.
	White Paper on Test methods for improved battery cell understanding	yes	Large dataset of many conditions	yes	yes	yes	yes	Insufficient: cell level only; not application oriented.
	Summary		IEC 62620 can be sufficient if it is allowed to be used for residential storage too. The test cycle is not application dependent but with a C/5-rate representative for ESS. Other standards are insufficient.					IEC 62620 can be sufficient if it is allowed to be used for residential storage too. The test cycle is not application dependent but with a C/5-rate representative for ESS. Other standards are insufficient.
Li metal	IEC 62620	see above						See for Li-ion.
Lead-acid	IEC 61427-2	see above						The cyclelife tests in IEC 61427-2 are designed for lead batteries, but take too long for being applicable.
	IEC 60896 series	yes	Float service (daily a 40% DOD (2h) at C_{10}, until 80% of initial capacity).	yes	no	no	yes	The cyclelife test is hardly representative and slow procedure. It is more applicable for UPS service.
	IEC 61056-1	yes	2 test cycles: float service and for cycle service endurance (daily a 50% DOD(C_{10}) (4 to 6h) until 50% of initial capacity).	yes	no	no	no	The discharge time in the cycle service endurance test is representative. Charge does not reflect solar energy charging. A slow procedure.
	Summary							Cycle life tests in standards take too long, performance indicators not all covered. Charge is not representative in the standards

Chemistry	Standard	Cycle-life test	Description test	(Remai-ning) capacity test	Energy deter-mination	Efficiency test	Resistance test	Conclusion (standardisation need)
Advanced lead	like lead-acid	see above	see above					See for lead-acid
NiMH	IEC 63115-1	yes	Cycle life consists of 2h20' discharges at $I_t/4$ and charge with same rate, until 70% of initial capacity.	yes	no	no	no	Performance indicators are mostly not covered.
	IEC 62675	yes	Cycle life consists of 3h discharges $I_t/5$ and charge with same rate, until 70% of initial capacity.	yes	no	no	no	Performance indicators are mostly not covered.
	Summary							Performance indicators lacking, cycle life tests not representative for ESS applications (more for UPS).
NiFe	lacking	-	-	-	-	-	-	No standard
$NaNiCl_2$	IEC 62984-3	yes	Cycle life test is a 8h discharge at 80% DOD, repeated 300 times, with a max. energy contents loss of 5%.	yes	yes	yes	no	Cycle life test seems representative, but shorter in cycles than envisaged with the policy proposition.
NaS	IEC 62984-3	see above	,,					,,
Hybrid ion	lacking	-	-	-	-	-	-	No standard
LiS	lacking	-	-	-	-	-	-	No standard
Na-ion	lacking	-	-	-	-	-	-	No standard

Table 2-4: Possibilities of the chemistries for ESS

Chemistry	Reasonable # cycles	Reasonable # calendar years	DOD per cycle	Capacity retention at EOL	Lifetime energy (equivalent cycles: correction for DOD and avg. SOH)>	Lifetime estimation (min. of calendar life and cycle life)	Characteristic efficiency	Source
Proposed	*2000 at midlife (4000 in total)*	*12 at midlife (25 in total)*	*80%*	*90% at midlife (80% at EOL)*	*2880 (80% DOD, 90% SOH on avg., 200 cycles/yr)*	*20*	*94% (at midlife)*	*From task 7*
Li-ion	4000	20	80%	80%	2880	20	94%	From task 7
Li metal	unknown	unknown	unknown	unknown	unknown	unknown	unknown	Not found
Lead-acid	3000	8	40%	80%	576	8	90%[2]	http://www.sonnenschein.org/PDF%20files/GelHandbookPart2.pdf
Advanced lead	2400	10	60%	80%	1080	10	unknown	http://lead-crystalbatteries.co.uk/images/docs/Data/2V/BLC-CNFJ-300.pdf
NiMH	8000	20	50%	80%	1800	20	90%[3] /unknown	https://www.nilar.com/wp-content/uploads/2019/05/Product-catalogue-Nilar-EC-Series-EN.pdf
NiFe	4000	20	50%	70%[3]	1700[4]	20	70%[5]/ unknown	https://batterysupplies.be/wp-content/uploads/docs/catalog/BSCataloogENG_web_nife.pdf
$NaNiCl_2$	3000	15	80%	70%[5]	2040[6]/ unknown	15	84% [7]	https://www.electrilabs.co.za/Electrilabs%20-%20Sodium%20Nickel%20batteries.pdf
NaS	4500	20	50%	80%	1800	20	75%	http://ease-storage.eu/wp-content/uploads/2018/09/2018.07_EASE_Technology-Description_NaS.pdf
Hybrid ion	3000	15	50%	70%	1275	15	85%	http://www.eventhorizonsolar.com/pdf/Batteries/aquion_energy_aspen_48m_25_9_product_specification_sheet__1_.pdf

[2] Not in datasheet; based on solar cycle tests at VITO with a multitude of lead-acid batteries.

[3] Based on measurement at VITO with NiMH for LEV it is 90% with a 50% SOC window. The datasheet in the source does not provide it.

[4] Remaining capacity as EOL criterion is not given in datasheet: 70% is assumed.

[5] Not in the datasheet. 70% is found in internet sources.

[6] EOL capacity not given. Based on extrapolation of the standard (cat.A) it can be 70%.

[7] Communication from ENEL as answer on the question in this study for data, communicated as 83 to 85%.

Chemistry	Reasonable # cycles	Reasonable # calendar years	DOD per cycle	Capacity retention at EOL	Lifetime energy (equivalent cycles: correction for DOD and avg. SOH)>	Lifetime estimation (min. of calendar life and cycle life)	Characteristic efficiency	Source
LiS (Laboratory scale)	1500	unknown	80%	80%[8]/ unknown	1080/ unknown	unknown	unknown	https://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Ultra-Light-Cell-v4.01.pdf
Na-ion (Laboratory scale)	2000[9]	unknown	100%	80%	1800	unknown	90% [9]	https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00640j (Peters, Jens, et al. "Life cycle assessment of sodium-ion batteries." Energy & Environmental Science 9.5 (2016): 1744-1751)

[8] Assumption: like Li-ion.

[9] Based on the assumption mentioned in the source.

Table 2-5: Evaluation of currently proposed policy propositions

Chemistry	Performance: # cycles	Performance: remaining capacity	Performance: min. efficiency	Warranty: period	Warranty: # cycles	Warranty: remaining capacity	Warranty: min. efficiency	Conclusion	Standardisation need
Li-ion	OK	OK	OK	OK	OK	OK	OK	Proposition is executable	IEC 62620 is proposed.
Li metal	Unknown							Unknown if proposition is feasible due to lack of performance data. Inclusion needed of energy consumption to keep battery at elevated temperature	See above. Heating energy must be included however: extension needed.
Lead-acid	For most lead batteries, proposition is too much.	OK (in line with IEC 60896 series)	Not attainable.	too long	too much.	Correct.	Too high	Adaptation of requirements is needed.	Need to cover energy and efficiency determination. A quicker test procedure is needed too.
Advanced lead	Requirement is higher than possible	OK	Unknown	should be half.	too much.	Correct.	unknown	See lead-acid	See lead-acid
NiMH	Good	good	unknown	good	good	good	unknown	This chemistry can fulfil lifetime criteria, but at slightly lower efficiency.	Need for performance indicators in test regime. Shorter test cycle is needed.
NiFe	Good	unknown	Not attainable. it has low efficiency.	good	good	unknown	unknown	This chemistry can fulfil lifetime criteria, but at low efficiency.	Standard is necessary.
$NaNiCl_2$	Requirement is higher than possible	unknown	unknown.	too long	too high	unknown	Too high	A suitable standard exists. Little data available. The proposed requirements are too high for this chemistry.	Correct.
NaS	Good	unknown	Not attained.	good	good	unknown	Too high	For lifetime the criteria are good. For efficiency too high.	Correct.
Hybrid ion	Requirement is higher than possible	Too high	Not attained.	too long	too high	too high	too high	The proposed criteria are for lifetime and efficiency too high.	Standard is necessary.
LiS	Too high in the short term.	unknown	unknown	unknown	too high	unknown	unknown	It is a future type, little information available. Progress possible on cycles.	Covered by lithium standards, but methods may be too much dedicated at Li-ion currently.
Na-ion	Probably good	Probably good	Probably good	Probably good	Probably good	Probably good	Probably good	It is a future type, it seems close to Li-ion and therefore the propositions are OK.	Probably this chemistry can fall under Lithium(-ion) standardisation.

2.4.1.1. Conclusion on policy measure

The current policy propositions appear only feasible with Li-ion batteries. This is mainly due to a lower efficiency for all other battery chemistries (as far as information was found).

The best batteries after Li-ion regarding efficiency are NiMH and lead-acid, under the condition that they are not often fully charged since most energy loss occurs at almost fully charged batteries for NiMH and lead-acid batteries. For NiMH it is not problematic to avoid full charges, even in the contrary (their lifetime increases if they are not fully charged regularly). For lead-acid abstaining from frequent full charges is only possible for batteries that are dedicated for so-called “partial SOC” (pSOC) operation.

A lifetime of 20 years is for several chemistries possible: Li-ion, NiMH, NiFe and NaS. If this criterion is decreased to 15 years also $NaNiCl_2$ and hybrid-ion are possible.

2.4.1.2. Conclusion on the standards analysis

The analysis of the standards in Table 2-3 shows that standards are lacking for NiFe, hybrid-ion, LiS and Na-ion. Only for $NaNiCl_2$ and NaS all needed information is covered by a standard, being a representative cycle life test and measurement methods of the needed performance indicators, being the (remaining) energy contents and the efficiency. Of the other batteries, the standards do not cover the performance indicators and the cycle life tests are sufficiently useful: they are not representative enough or too time consuming.

2.4.2. Requirements for battery management systems

In task 7 of the preceding study requirements have been proposed for battery management systems. This covers several topics:

- Provision of partially open data covering:
    - State of *BMS update possibilities* Coupling to the information about traceability of battery modules and packs
- Diagnostics connector
- BMS update possibilities

The evaluation of the BMS requirements is given in the subsequent table (Table 2-6).

2.4.2.1. Conclusion on policy measure

Half of the chemistries use a BMS, i.e. Li-ion, Li-metal, sometimes NiMH, $NaNiCl_2$, NaS and Na-ion. They are probably of the advanced type, that is capable to perform analytics on the remaining capacity and the change in resistance (for ESS resistance was not seen as an issue). Currently only the Li-ion battery type is used for repurposing means, creating a necessity of partial open data on the remaining battery quality. This need is less existing for other batteries, but still sustaining a long first life operation possibility, by the means of being able to follow up the battery degradation.

For the battery types that would be able to fulfil the (adapted) policy requirements for system lifetime, it is recommended that they also fulfil the BMS requirement, at least to enable the degradation awareness. If a battery does not need a BMS for safety reasons, the ageing diagnostics can be added by an external analysing and logging device.

Table 2-6: Evaluation of battery management system requirement

Chemistry	Availability BMS	Repurpo-sing[10]	Communication method	BMS: partially open data					Diagnostics connector	BMS update possibility	Conclusion	Standardisation need
				SOH info	SOH definition	Lifetime info	Traceability info	Conclusion				
Proposed	advanced BMS	yes	CAN	necessary	capacity, power, resistance, other	necessary	necessary	Partial open data is possible	necessary	possible		
Li-ion	yes, advanced BMS	yes	mostly CAN	possible	capacity, power, resistance	possible	possible	Partial open data is possible	Possible	In potential	The proposition is feasible.	Yes, as proposed.
Li metal	yes, advanced BMS	no	unknown	possible	unknown	possible	possible	Partial open data is possible	Possible	In potential	The proposition is feasible.	Yes, as proposed.
Lead-acid	no	no	n.a.	no	n.a.	no	no	Not possible without external analysing& logging device	n.a.	n.a.	n.a.	n.a.
Advanced lead	no	no	n.a.	no	n.a.	no	no	Not possible without external analysing& logging device	n.a.	n.a.	n.a.	n.a.
NiMH	sometimes, unknown whether a simple BMS or advanced.	maybe from HEV	unknown	sometimes possible	capacity	sometimes possible, but unknown if BMS advanced enough.	sometimes possible	Sometimes possible	Possible	Unknown	Unknown	Yes, as proposed.
NiFe	no	no	n.a.	no	n.a.	no	no	Not possible without external analysing& logging device	n.a.	n.a.	n.a.	n.a.
$NaNiCl_2$	yes, advanced BMS	no	unknown	possible	capacity	possible	possible	Partial open data is possible	Possible	In potential	The proposition is feasible.	Yes, as proposed.
NaS	yes, advanced BMS	no	unknown	possible	capacity	possible	possible	Partial open data is possible	Possible	In potential (these systems are not used for second life applications).	The proposition is feasible.	Yes, as proposed.
Hybrid ion	no	no	n.a.	no	n.a.	no	no	Not possible without external analysing& logging device	n.a.	n.a.	n.a.	n.a.
LiS	unknown	no: research	unknown	no	n.a.	no	no	Not possible without external analysing& logging device	unknown	Unknown	Unknown	Yes, as proposed.

[10] Used for 2nd hand & 2nd life application or can come from first life application

Chemistry	Availability BMS	Repurpo-sing[10]	Communication method	BMS: partially open data					Diagnostics connector	BMS update possibility	Conclusion	Standardisation need
Na-ion	yes, advanced BMS	no: research	unknown	possible	unknown	possible	possible	Partial open data is possible	Possible	In potential	The proposition is feasible.	Yes, as proposed.

2.4.3. Requirements for providing information about batteries and cells

To allow repair, reuse, remanufacturing and repurposing but also recycling of batteries data and information about the battery is required. In task 7 of the preceding study an information proposal is given for battery systems, packs and modules. A similar proposal exists for cell level.

The proposal is that the individual battery should carry at all levels (battery system, battery pack and module) a bar code, QR code or similar with an EAN number and serial number. This code provides access to a European database with information on batteries and cells, which the manufacturer or supplier bears the responsibility of updating, e.g. similar to the European Product Database for Energy Labelling (EPREL[11]), in three levels of:

- Level 1: Public part (no access restriction) covering:
  - Carbon footprint information in CO_2eq
  - Battery manufacturer
  - Battery type, and chemistry
  - Percentage of recycled materials used in the cathode and anode material
  - A reference to a recycling method that can be used.
- Level 2: Data available to third party accredited professionals:
  - Performance data
  - BMS related data
  - Repair & dismantling information
- Level 3: Compliance part (Information available for market surveillance authorities only, protected access for intellectual property reasons).

In the subsequent table (Table 2-7) the requirements for providing information about batteries are given. To allow this evaluation the following topics are added to the table:

- Minimum traded unit
- Possibility to carry a code
- Current possibility recycling

The level 3 data (compliance) has been left out. This mainly depends whether standards are available. That analysis was performed in Table 2-3.

No evaluation for the information on cell level has been carried out. This would be identical to the analysis on battery level, except that cells must be freely on the market, from which another manufacturer makes batteries. For NiMH, $NaNiCl_2$, NaS and Hybrid-ion this is not the case.

[11] https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/european-product-database-energy-labelling_en

2.4.3.1. Conclusion on policy measure

Since not for all battery types an PEFCR exists, the carbon footprint cannot be given for all types.

Note that only marking symbols exist for Lithium, Li-ion, lead-acid and NiMH in IEC standards. The following chemistries lack an official marking:

- NiFe
- NaNiCl2
- NaS
- Hybrid-ion
- Na-ion

The $NaNiCl_2$ and NaS have nevertheless an UN number for transportation as sodium battery (UN 3292).

For recycling Li-ion chemistries it is helpful to know not only the family (such as Li-ion) but also subclass information like cobalt-based or iron phosphate based. This is included in standards with marking for Li-ion batteries. For most chemistries only the family name is important since there is hardly variation in materials, except Li-ion, Li-metal, Na-ion and advanced lead.

The previously proposed information requirement (preceding task 7) covers the percentage of recycled materials in the battery and also the recycling method that can be used. Currently, not for all battery types specific information on the recycling method seems to exist. To include information on the recycled material contents, recycling up to battery must exist in the first place. For e.g. sodium and sulphur this seems not the case currently. For Ni, Co but also Li this is already possible.

Table 2-7: Evaluation of the requirements for providing information about batteries

Chemistry	Minimum traded unit	Possibility to carry a code	Current possibility recycling	Level 1 data (public)				Level 2 data (professionals)				Conclusion
				Carbon footprint	Manufac-turer	Battery	Recycling	Performance	BMS related	Chemistry identification	Repair & dismantling	
Li-ion	Cell	yes, better at higher level such as module level since many cells involved.	yes	PEFCR exists	yes	yes	yes	yes	yes	yes	yes	Correct
Li metal	Battery system	yes	yes, like Li-ion	no	yes	yes	yes	yes	yes	yes	yes	PEFCR lacking
Lead-acid	Cell	yes	yes, best example	PEFCR exists	yes	yes	yes	not all, lack of suitable standard	yes	family, not necessary for subclass	yes	Correct, but performance must be standardised better.
Advanced lead	Cell	yes	yes, best example	no	yes	yes	yes	not all, lack of suitable standard	no: no BMS	yes	yes	PEFCR lacking but performance must be standardised better.
NiMH	Cell	yes	yes	PEFCR exists	yes	yes	yes	yes	no: mostly no BMS	family, not necessary for subclass	yes	Correct
NiFe	Cell	yes	yes	no	yes	yes	yes	no, no standard	no: no BMS	family, not necessary for subclass	yes	PEFCR lacking but performance must be standardised better. No family marking symbol.
$NaNiCl_2$	Battery system	yes	unknown	no	yes	yes	unknown	yes	yes	family, not necessary for subclass		PEFCR lacking. No family marking symbol.
NaS	Battery application system	yes, better at lower level, although not traded as such.	unknown	no	yes	yes	unknown	yes	yes	family, not necessary for subclass		PEFCR lacking. No family marking symbol.
Hybrid ion	Battery system	yes	yes, cradle to cradle certified.	no	yes	yes	unknown	no, no standard	no: no BMS	family, not necessary for subclass		PEFCR lacking. No family marking symbol.
LiS	Research only	yes, better at higher level such as module level since many cells involved..	no	no	yes	yes	unknown	no, research currently	currently not: research	family, not necessary for subclass		PEFCR lacking

Chemistry	Minimum traded unit	Possibility to carry a code	Current possibility recycling	Level 1 data (public)				Level 2 data (professionals)			Conclusion
Na-ion	Research only	yes, better at higher level such as module.	yes, like Li-ion	no	yes	yes	unknown	no, research currently	currently not: research	yes	No family marking symbol.

2.4.4. Requirements on the remaining three topics

The remaining three topics are:

- The traceability of battery modules and packs
- Carbon footprint information and the option for a threshold
- Minimum battery pack design and construction requirements

For these criteria no specific issues are supposed for the proposed requirements. There is no difference between Li-ion modules and other battery modules for the possibility to add identification like a QR code. Module and pack design differ from Li-ion counterparts especially if gas release is possible (lead-acid) or increased internal temperature is used (NaS, $NaNiCl_2$). Nevertheless, other battery modules and packs than Li-ion ones have no additional constraints in pack design that would hinder repair, re-use and recyclability.

Carbon footprint information can only be given if a PEFCR exists. This is given in Table 2-7.

2.5. Conclusion on technology neutral policy

2.5.1. The potential need and rational for performance concessions for other chemistries

Hereafter we will focus on grid energy storage applications (ESS) because for these applications there were new chemistries identified.

New chemistries can potentially not meet those requirements (see conclusions per policy requirement in section 2.4) and hereafter are two rationales and methods discussed for granting concessions. The idea would be that concessions can be granted to particular chemistries because the carbon footprint (GWP([CO_2eq]) is lower and/or fewer gross energy (GER[MJ]) is required. Note: GER is a parameter that stems from the MEErP but not included in the PEF CR.

2.5.1.1. A correction factor based on carbon footprint

A first rationale for a concession could be a lower carbon footprint of the particular battery chemistry. Usually such an ESS is used in conjunction with renewable energy to reduce the carbon footprint of electricity generation. However, for example, battery systems with a lower efficiency can still provide a similar service over its full life cycle when their manufacturing carbon footprint is relatively lower. Therefore, a concession can be granted on efficiency, based on their carbon footprint for manufacturing.

The preparatory study did found a GWP for production and distribution of 61 gCO_2eq per kWh functional unit (GWP_{FU}) or 155 kgCO_2eq per kWh declared storage capacity(GWP_{CAP}) for the residential ESS base case, see Table 7-5.

2.5.1.2. A correction factor based on Gross Energy Requirements

A second rationale to consider is the Gross Energy Requirements (GER) for manufacturing batteries which is related to the Primary Energy; this parameter is available from the MEErP. Therefore, the preparatory study proposed the newly defined capacity Energy Efficiency Index (cEEI). This capacity Energy Efficiency Index (cEEI) refers to the ratio of declared storage capacity relative to the embodied primary or gross energy requirement (GER) for manufacturing. It was defined in Task 7 of the preparatory study, section 7.1.2.5. It is a metric that shows how much energy the manufacturing a battery system requires compared to its storage capacity. A cEEI value of 890 was calculated for the residential base case ESS, see Table 7-5 in the Task 7 report of the preparatory study. Using the cEEI as a rationale can also be justified by the idea that the lifetime of a battery product must be sufficiently longer otherwise the embodied energy in the battery manufacturing is the primary energy supply to the system.

Note: the GER and the primary energy are currently not included in the PEF CR. Therefore, the MEErP is needed to calculate the cEEI. The GER is e.g. used in the Ecodesign study on PV systems[12]. The energy needed to produce substances from raw materials are not given in the PEF CR, but in the MEErP.

This capacity Energy Efficiency Index (cEEI) is defined as:

$$\mathrm{cEEI} = \frac{\text{Gross Energy Requirement (GER) according to the MEErP[MJ]}}{\text{declared storage capacity [MJ]} \times \frac{\text{DOD from cycle life test [\%]}}{100}}$$

GER: the discussion on how to calculate the Gross Energy Requirement (GER) for the cEEI is part of WP3 and eventually later standardization work.

Declared capacity: the declared capacity was defined in section 7.1.2.1 in task7 of the preparatory study. This capacity is not necessarily the initial capacity of the battery. In this way the effect of a possible quick initial capacity fade before entering a steady capacity reduction over time can be taken into account by setting the declared capacity lower than the initial capacity.

DOD from cycle life test: the DOD that is used for the cycle life test and reported in the level 2 data (data available to third party accredited professionals) of the proposed European database (section 7.1.2.3 in the preparatory study). Almost no battery types are allowed to be discharged 100% to reach a long cycle life. This is shown in Table 2-4. For Li-ion batteries this DOD is in general 80%. However, most of the battery types accept only a 50% DOD for a long life. This means that double the capacity must be installed. This must thus be taken into account in the cEEI.

The preparatory study did find a typical cEEI of 890 for a lithium battery used for the residential ESS base case, see Table 7.5. Including the DOD from cycle life test, and assuming that it is 80% for a Li-ion battery, then it becomes now 1110 MJ.

2.5.2. Rationale and method for potential concessions on remaining capacity versus lifetime in policy requirements

The current LiB policy proposal for LiB required for ESS a remaining capacity of 90 % after 2000 test cycles before the product can brought on the market.

12 https://susproc.jrc.ec.europa.eu/solar_photovoltaics/docs/20191220%20Solar%20PV%20Preparatory%20Study_Task%207_Final%20following%20consultation.pdf

Furthermore, it required a warranty of 12 years minimum calendar life or 2000x (Declared Capacity) in kWh functional unit. Herein the functional unit is the total measured delivered energy at the output of the battery over its lifetime.

In general, we believe that whichever cEEI, a minimum functional lifetime on capacity fade might be needed before such a storage is useful, in our opinion 1000 test cycles or 50 % and 6 years of warranty.

We recommend not to propose stronger requirements (2000 cycles) for new chemistries, preventing them from the market, which could justify to cap the requirements at the current proposal.

Therefore, it is proposed to apply the following correction factor (Kcycle) on the 2000 proposed cycles and on the warranty period of 12 years:

K_{cycle}[%] = 100 x cEEI/1110 [%] when 1110/2< cEEI < 1100

K_{cycle}[%] = 50 % when 1110/2< cEEI

K_{cycle}[%] = 100 % when cEEI ≥ 1110

For example, in the best case if renewable energy is used during manufacturing then the cEEI is below 445. In that case a 50% reduce factor can be used, i.e. 1000 cycles at midlife and 6 years warranty period.

According to Table 2-4, 2000 cycles at full life can be satisfied by all chemistries, except LiS up to our knowledge. The minimum warranty period of 6 years is for most chemistries possible. For lithium metal and lithium sulphur data lacks currently. For most lead-acid batteries this period is challenging, but there are solar type lead-acid batteries for which it is feasible.

Note that alternatively GWP_{CAP} [$kgCO_2eq/kWh$] / 155 [$kgCO_2eq/kWh$], this approach is applied in the subsequent section.

2.5.3. Rationale and method for remaining round trip efficiency versus lifetime in policy requirements

The current LiB policy proposal a minimum remaining round trip efficiency versus lifetime for LiB, however here those thresholds cannot be met for other chemistries used in ESS (see Table 2-4).

A rationale for a concession can be found in the lower carbon footprint of the battery system involved. Usually such an ESS is used in conjunction with renewable energy to address Global Warming and reduce the carbon footprint of electricity. Battery systems with a lower efficiency can still provide a similar service to store renewables over its lifetime when the manufacturing carbon footprint is lower and therefore a concession can be granted on efficiency based on their carbon footprint. The study found GWP for production and distribution of 61 gCO_2eq per kWh functional unit (GWP_{FU}) or 155 $kgCO_2eq$ per kWh declared storage capacity (GWP_{CAP}) for the residential ESS base case, see Table 7-5.

In general, we believe that an efficiency below 80% mid-life is unacceptable, therefore the corrections can be capped.

Therefore, it is proposed to apply the following correction factor (K_{eff}) on the 2000 proposed cycles:

$$K_{eff}[\%] = \max(100 \times GWP_{CAP}[kgCO_2eq/kWh]/155[kgCO_2eq/kWh], 75)\ [\%]$$

$$\text{when } GWP_{CAP} < 155\ kgCO_2eq/kWh$$

$$K_{eff}[\%] = 100\ \% \quad \text{when } GWP_{CAP} \geq 155\ kgCO_2eq/kWh$$

Note: the discussion on how to calculate the carbon footprint of production and distribution is part of WP3 and possible later standardization work.

As example, Na-ion batteries have GWP_{CAP} of 140 $kgCO_2eq$ per kWh[13]. The decreased roundtrip efficiency therefore can be 140/155x94% = 85% (at mid-life). For new batteries, which have always better efficiency than at mid-life, 85% seems not reachable for: NiFe and NaS. For the hybrid ion type the characteristic efficiency is 85% at the beginning of life, and therefore 85% at midlife is not possible currently without changing the battery design. For LMP, $NaNiCl_2$, and LiS characteristic efficiencies are unknown.

If the excluded batteries are manufactured with help of renewable energy, GWP_{CAP} decreases, resulting in a lower efficiency threshold, creating a possibility.

[13] Fig. 3 in https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00640j

ANNEX:OVERVIEW OF STANDARDS ON BATTERY PERFORMANCE

Table 2-8: Identification of battery standards related to performance and classified per application and battery chemistry.

Performance tests

Application	Battery type											
	Agnostic	Li-ion	Li-metal	Pb	NiMH	NiFe	NaNiCl2	NaS	Flow battery	hybrid-ion	LiS	Na-ion
Stationary												
Stationary in general	IEC 62933-2-1 *Batt. appl. system*			IEC 60896 series *Cell &Module*	IEC 63115-1 *Cell to battery system*		IEC 62984-3 *Battery system*	IEC 62984-3 *Battery system*	IEC 62932-2-1 *Battery system& Batt.appl.system*			
residential ESS (BC6)	IEC 61427-2 *Battery system*	BVES Effizienzleitfaden für PV Speichersysteme *Batt. appl. system*										
Grid ESS (BC7)	„ „	IEC 62620 *cell to battery system*	IEC 62620 *cell to battery system*									
Other	IEC 61427-1 *Battery system*											
Light EV												
LEV in general												
scooters												
bicycles												
mopeds & motorcycles	ISO 13064-1& 2 *Batt. appl. system*	ISO/DIS 18243 *Battery system*		IEC 63193 *Modules& packs*								
Industrial LEV		IEC 62620 *Cell to battery system*	IEC 62620 *Cell to battery system*	IEC 63193 *Modules& packs*								
Industrial												
mobility to stationary		IEC 62620 *cell to battery system*	IEC 62620 *Cell to battery system*		IEC 63115-1 *Cell to battery system* IEC 62675 *Cells*							
Portable												
Portable		IEC 61960-3& 4 *Cell to battery system* ANSI C.18.2M-1 *Cell to battery system*	IEC 61960-3& 4 *Cell to battery system*		IEC 61951-2 *Cell to battery system* ANSI C.18.2M-1 *Cell to battery system*							

Performance tests

Application	Battery type											
	Agnostic	Li-ion	Li-metal	Pb	NiMH	NiFe	NaNiCl2	NaS	Flow battery	hybrid-ion	LiS	Na-ion
EV												
Mobility in general	SAE 2288 *Modules* SAE J1798 *Modules*			IEC 60254-1 *Cell & module*			IEC 62984-3 *Battery system*	IEC 62984-2 *Battery system*				
cars	DOE-INL/EXT-15-34184 *all levels* DOE-INL/EXT-07-12536 *all levels* DOE-INL/EXT-12-27920 *Battery system*	IEC 62660-1 *Cells* ISO 12405-4 *Packs to battery system*		IEC 61982 *Cells to battery system*	IEC 61982 *Cells to battery system*		IEC 61982 *Cells to battery system*					
Trucks												
Busses	UITP E-SORT *vehicle*											
Off road (incl. industrial& ships)												
Other												
Vehicle auxiliary power		IEC 63118 *Modules to battery system*	IEC 63118 *Modules to battery system*	EN 50342 series *Modules*								
Aircraft				IEC 60952-1 *Modules*								
Ships		IEC 62620 *Cell to battery system*	IEC 62620 *Cell to battery system*									
Light electric rail		IEC 62620 *Cell to battery system*	IEC 62620 *Cell to battery system*									
Repurposing	ANSI/CAN/UL 1974 *Cells to pack*											
General (not application dependent)		White Paper on Test methods for improved battery cell understanding *Cells*		IEC 61056 series *Cells to modules*								

Levels:
- Cell
- Module (monobloc)
- Pack
- Battery system
- Batt.appl.system (ESS)
- Vehicle

Follow-up feasibility study on sustainable batteries under FWC ENER/C3/2015-619-Lot 1

Final Report for Task 3

Development of models for rechargeable battery chemistries and technologies beyond lithium-ion, in compliance with the existing product environmental footprint category rules

DRAFT FINAL PREPRINT

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Project website: https://ecodesignbatteries.eu/

January 2020

Version history:

Version 1: first draft for discussion in the stakeholder meeting

Version 2: draft final report with the results of the sodium-ion and sodium nickel chloride batteries.

EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

Directorate C – Industrial Transformation and Advanced Value Chains

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More information on the European Union is available on the Internet (http://www.europa.eu).

Luxembourg: Publications Office of the European Union, 2019

ISBN number 978-92-76-16377-0

doi:number 10.2873/453640

Printed in Belgium

Use of number format

"space" as thousand separator

. "dot" as decimal point

CONTENTS

LIST OF TABLES

List of abbreviations and acronyms

Abbreviations	Descriptions
EF	Environmental Footprint
EFTA	European Free Trade Association
EOL	End-of-Life
eq.	equivalent
ESS	Energy Storage System
EU	European Union
EU-28	28 Member States of the European Union
FU	Functional Unit
GHG	Greenhous Gases
GLO	Global
GWP	Global Warming Potential
ICT	Information and Communications Technology
ILCD	International reference Life Cycle Data system
ILCD-EL	ILCD Entry Level
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCO	Lithium Cobalt Oxide
Li	Lithium
LiS	Lithium Sulfur
LMO	Lithium Manganese Oxide
Na	Sodium
$NaNiCl_2$	Sodium Nickel Chloride
NaS	Sodium Sulfur
NCM	Lithium Nickel Manganese Cobalt Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
NiMh	Nickel-Metal hydride
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
UPS	Uninterruptible Power Supply
WP	Work Package

1. Task 3: Development of models for rechargeable battery chemistries and technologies beyond lithium-ion, in compliance with the existing Product Environment Footprint (PEF) Category Rules

1.1. General introduction to Task 3

This report is a final report with the results of two batteries analysed for this task.

The aim of Task 3 is to develop life cycle assessment (LCA) models of additional battery technologies and chemistries beyond Li-ion in compliance with the PEF Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications.

The PEFCR were published in December 2018[1]. Mobile Applications refers to three application fields:

- e-mobility (from e-bikes up to trucks)
- ICT
- cordless power tools.

The battery technologies and chemistries covered in the PEFCR for batteries included:

- Li-ion: LCO (LiCoO2), NMC (LiNixMnyCozO2), LMO (LiMnO2) and LFP (LiFePO4)
- NiMH.

These battery types will tend to dominate the mobile market in coming years and are likely to be at the core of the scope of any possible regulatory intervention being proposed by the Commission.

The follow-up feasibility study on sustainable batteries focusses partly on different application fields from the above mentioned PEFCR and also on a broader field of battery types i.e. chemistries.

The idea of setting mandatory information requirements on the carbon footprint associated with the manufacturing of batteries is gaining ground and the availability of PEFCR will be instrumental to make this possible. However, there is a need to ensure that PEFCR are available for all battery chemistries and technologies that fall in the scope of a possible regulatory intervention.

The development of PEF Category Rules for a specific product group is a well-defined process. The PEFCR development process is complex, as it is comprehensive and requires a number of technical steps followed by consultations of all the relevant stakeholders[2]. Therefore, starting from the existing PEFCR, the purpose of this task is to:

- Identify other battery technologies and chemistries with a significant presence in the market, including a possible grouping or categorization;
- Identify, for each battery technology and chemistry, their system boundary and the processes included in each life cycle stage;

[1] Available at: http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

[2] See https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf

- Identify the activity data to be used for each process, based on best available information;
- Develop a model[3] for each battery technology and chemistry identified, implementing –where possible and relevant – the rules and requirements as included in the High Specific Energy Rechargeable Batteries for Mobile Applications PEF Category Rules [1];
- Identify the best available secondary datasets (Environmental Footprint (EF) compliant or at least International reference Life Cycle Data system Entry Level (ILCD-EL) compliant using EF nomenclature) to be used to populate the models developed and also to identify and list missing secondary datasets;
- Perform a hotspot analysis according to the method elaborated by JRC[2], focusing on the climate change impact category; this analysis should also identify the most relevant processes for climate change impact category that should be looked at as a priority;

Hence, the objective of Task 3 is to develop life cycle assessment (LCA) models of other battery technologies and chemistries beyond Li-ion in compliance with the PEFCR for High Specific Energy Rechargeable Batteries for Mobile Applications[1], hereinafter 'PEFCR for batteries'.

The purpose of Task 3 is not to review or change the existing PEFCR on batteries, but to develop proof of concepts of the PEF profiles for other chemistries, if possible. All phases from raw materials production and manufacturing of battery to end of life recycling will be included in analysis. The exception is the use phase, which will be excluded for all batteries analysed in this study. Due to uncertainties arising in the use phase energy consumption and losses, this phase is not considered within the scope of this study.

The success of this task is however highly dependent on the availability of primary data that will allow the development of these PEF profiles. Public availability of such data is very limited and insufficient for the purpose of this study, reason for which the contribution of manufacturers is absolutely necessary for obtaining data with an acceptable quality level from reliable sources.

2. Analysis of batteries using the PEF Approach

2.1. Battery chemistries selected

For electric vehicles, any other chemistries apart from Li-ion will not play a significant role (also mentioned in Task 2 report). For stationary applications, low specific weight is not the only decisive parameter in case of stationary energy storage and therefore other chemistries can remain and/or enter the market. The following chemistries were considered within the scope:

- Li-ion Data available in PEF for batteries, already covered in a PEF data set
- Li-metal Data unavailable, no agreement reached in the supply of data.
- Lead-acid Data available in PEF for UPS study, already covered in PEF data set

[3] The model should be developed according to the ILCD format or eILCD if available.

- NiMH Data available in PEF for batteries, already covered
- $NaNiCl_2$ Data available in publicly available study[4]
- NaS Large scale energy storage system (ESS) - data not available
- Hybrid-ion Residential ESS - data not available
- LiS Residential ESS - under development - data not available
- Na-ion Residential ESS - data available[5] in publicly available study

The aim of this task was to analyse three to five additional chemistries. After a preliminary analysis of data availability, the battery chemistries selected for analysis in Task 3 include existing battery types not yet included in the PEFCR for batteries are:

- sodium nickel chloride,
- future battery type - sodium-ion batteries.

Both selected batteries are considered for residential storage application. Sodium-ion is chosen as a first example case to apply the PEF method using publicly available data[5] followed by sodium nickel chloride[4].

2.2. Application of PEFCR for batteries

The PEFCR for batteries is applied to the two battery types selected. The following sections will detail the procedure of application of PEFCR for batteries for sodium-ion and the sodium nickel chloride battery.

2.3. Sodium-ion battery

This subsection describes how the PEFCR for batteries is applied to the sodium-ion battery.

2.3.1. Functional unit

The functional unit in the PEFCR[1] for rechargeable batteries is defined as **1 kWh of total energy provided over the service life by the battery**. The service life is dictated by the application service. The application service parameter is not available in the PEFCR. For this study, we used the value for the Ecodesign Batteries Preparatory Study [6]. The functional unit for sodium-ion is calculated using the method provided in the PEFCR and with information gathered from the Peters et al (2016)[5] study. Based on the functional unit, the number of batteries required per functional unit and the reference flow is calculated (Table 1).

The functional unit calculation makes some assumption regarding the parameters such as depth of discharge, the number of cycles, weight of the battery and others. These assumptions are carried over to the calculation of number of batteries required for the service lifetime.

---

[4] Galloway & Dustmann (2003) ZEBRA Battery

[5] Peters, Jens, et al. "Life cycle assessment of sodium-ion batteries." *Energy & Environmental Science* 9.5 (2016): 1744-1751 (https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00640j).

Table 1: Parameters used to calculate the functional unit, reference flow and the number of sodium-ion batteries applied within a residential ESS based on the PEFCR for batteries.

Parameter	Unit	Value	Reference
Nominal battery system capacity	kWh	10	Ecodesign Batteries - Preparatory Study - Base Case 6-Residential ESS (see Task 5 report)[6]
Economic lifetime of application (Tapp) note: this is not a parameter within the PEFCR	y	20	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Depth of discharge (DoD)	%	80	Assumption
Energy delivered per cycle (Edc)	kWh/cycle	8	Calculated (nominal capacity*DoD)
Number of cycles for battery system over its service life (Nc)	-	2 000	Peters et al (2016) Life cycle assessment of sodium-ion batteries-laboratory test data Note: The author made three assumptions for a kind of sensitivity analysis (1000/2000/3000) cycles and this is the average. Because this is still a prototype real data is still missing.
Average capacity per cycle (Acc)	%	90	Based on standards and data from Peters et al (2016) initial capacity retention of 80%
Total weight of battery system	kg	128	Assumption - based on Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Average net capacity per cycle until EoL	kWh/cycle	7.2	Calculated (Edc*Acc)
Functional unit over service life (QUa) per battery	kWh/service life	14 400	Calculated (Edc*Nc*Acc; as per PEFCR)
Application Service (AS) (as defined in the preparatory study)	kWh	40 000	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Coulombic Efficiency (ɳcoul)	%	-	Not considered for this analysis
Voltage Efficiency (ɳv = Vp/Vc)	%	-	Not considered for this analysis
Energy efficiency (ɳcd = ɳcoul x ɳv)	%	-	Not considered for this analysis (see WP 2 for discussion)
Charger Efficiency (ɳcharger)	%	-	Not considered for this analysis

[6] https://ecodesignbatteries.eu/welcome

Parameter	Unit	Value	Reference
No. of battery systems per economic service life (Nb batt)	-	2.78	Calculated (AS/Qua; as per PEFCR)
Reference flow (Rf)	kg battery/kWh	0.0089	Calculated (Nb batt*mass/AS; as per PEFCR)

2.3.2. System boundary

The following life cycle stages (Table 2) are included in the study.

Table 2: Life cycle stages modelled for sodium-ion batteries as per PEFCR for batteries

Life Cycle Stage	Description
Raw materials acquisition	Included. Data sourced from Peters et al (2016)[5]
Main product production	Included. Data sourced from Peters et al (2016)[5]
Distribution	Included. Data sourced from Peters et al (2016)[5]
Use	Not included. Deviation from PEFCR
End of life recycling	Included. Data sourced from PEFCR for batteries[1]. Modified to suit material quantities in Na-ion batteries.

2.3.3. Raw materials acquisition and main product production stage

The battery manufacturing and assembly stages of a sodium-ion battery are organized as:

- Manufacturing of active materials for cathode and anode
- Manufacturing of cathode, anode and electrolyte
- Manufacturing of battery cell
- Assembly and manufacturing of battery pack

The details are shown in Figure 1.

A life cycle inventory for the production of the battery is provided in Table 3.

Where possible, EF datasets were used. New datasets were created for certain materials using data from Peters et al (2016)[5] study. The activity data (i.e. amounts) for the new datasets was obtained from the study while the input and output life cycle data was from EF database (where available) or ecoinvent database[7], version 3.5.

[7] Frischknecht, Rolf, et al. "The ecoinvent database: Overview and methodological framework (7 pp)." *The international journal of life cycle assessment* 10.1 (2005): 3-9.

Note that for manufacturing sodium-ion battery anodes hard carbon was used as opposed to graphite in lithium-ion anodes for technical reasons[8]. The manufacturing of hard carbon is significantly different from graphite and is assumed to use sugar beets which will have a strong impact on the obtained LCA results.

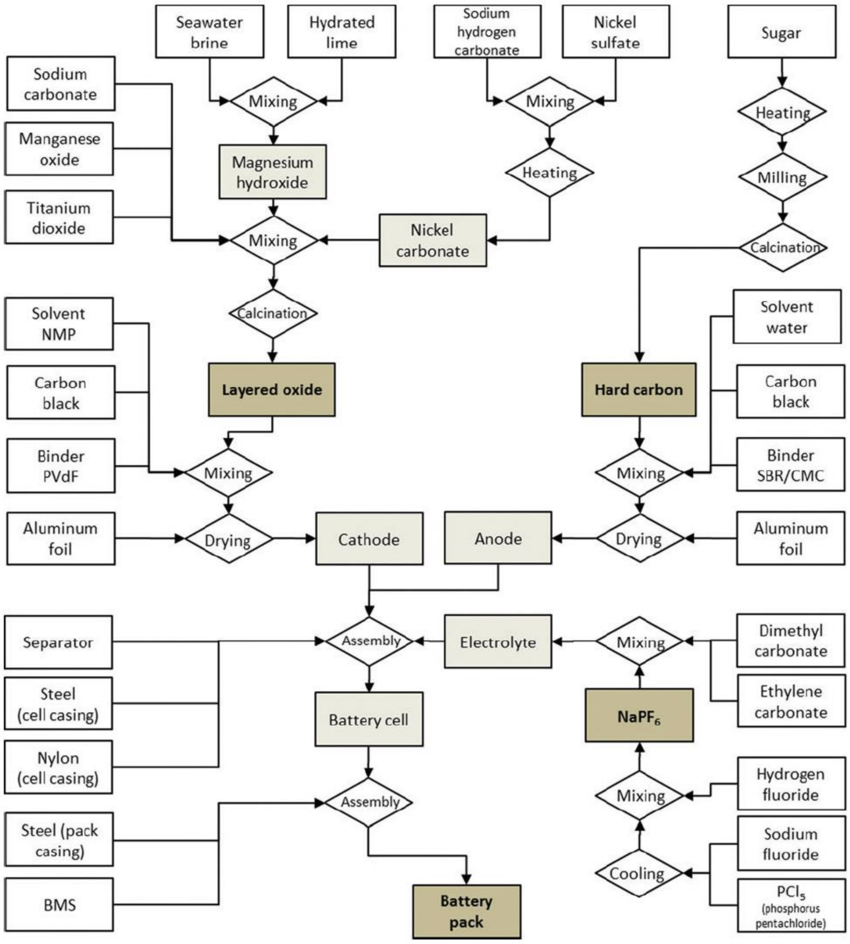

Figure 1: Cradle to gate diagram of sodium-ion production processes (Source: Peters et al (2016)[5])

8 Xinwei Dou, " Hard Carbon Anode Materials for Sodium-ion Battery", PhD dissertation, December 2018, Karlsruher Instituts für Technologie (KIT), Germany

Table 3: Life cycle inventory for the production of Na-ion battery. Data from Peters et al (2016)[5]

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Power_electrode	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.00E-03
Power_cell forming	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.91E+00
Power_battery assembly	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	3.53E+00
Heat	EU-28+3	Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency		MJ/kg battery	2.10E+01
Anode					
Hard carbon, anode from sugar			Hard carbon, anode, from sugar - created based on Peters et al (2016)[5] data	kg/kg battery	2.34E-01
Carbon black	RER	Carbon black, general purposes production, 100% active substance		kg/kg battery	7.56E-03
Carboxymethyl cellulose	RER	Carboxymethyl cellulose production		kg/kg battery	1.01E-02
Aluminium foil	EU-28+3	Aluminium foil| primary production| single route, at plant| 2.7 g/cm3		kg/kg battery	4.03E-02
Cathode					
Layered oxide			NMMT active material, layered oxide, for Na-ion batteries - created based on Peters et al (2016)[5] data	kg/kg battery	1.84E-01

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Carbon black	RER	Carbon black, general purposes production, 100% active substance		kg/kg battery	3.92E-03
PVDF	World	Polyvinylidene fluoride (PVDF)| polymerisation of vinyl fluoride| production mix, at plant| 1.76 g/cm3		kg/kg battery	7.84E-03
Aluminium foil	EU-28+3	Aluminium foil| primary production| single route, at plant| 2.7 g/cm3		kg/kg battery	1.96E-02
Electrolyte					
Sodium hexafluorophosphate			Sodium hexafluorophosphate, at plant -created based on Peters et al (2016)[5] data	kg/kg battery	8.30E-04
Separator					
Battery Separator	GLO		Battery separator - ecoinvent database	kg/kg battery	1.73E-05
Cell casing					
Steel sheet part	EU-28+EFTA	Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel		kg/kg battery	1.93E-01
Nylon 6	EU-28+EFTA	Nylon 6 fiber| extrusion into fiber| production mix, at plant| 5% loss, 3,5 MJ electricity		kg/kg battery	7.06E-01
Battery casing					
Steel sheet part	DE	Steel sheet cold rolling - thickness 2.5mm | steel cold rolling process | single route, at plant | thickness 2.5 mm		kg/kg battery	1.45E-01
Battery Management System					

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Data cable	EU-28+EFTA	Cable, high current| technology mix| production mix, at plant| high current, 1m		m/kg battery	3.73E-01
Three-phase cable	EU-28+EFTA	Cable, three-conductor cable| technology mix| production mix, at plant| three-conductor cable, 1m		m/kg battery	2.50E-02
Printed wiring board, Pb containing	GLO		Printed wiring board, for surface mounting, Pb containing surface, ecoinvent database	kg/kg battery	1.01E-03
Printed wiring board, Pb free	GLO		Printed wiring board, for surface mounting, Pb free surface, ecoinvent database	kg/kg battery	2.37E-03

2.3.4. Distribution stage

The distribution stage for Na-ion was modelled based on data from Peters et al (2016). The life cycle inventory is presented in Table 4.

Table 4: Life cycle inventory of the distribution of battery pack

Material/Process	Geographical Reference	EF compliant dataset name	Unit	Amount per kg battery
Distribution				
Truck-trailer	GLO	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel)	tkm	1.00E-01
Diesel mix at refinery	EU-27	Diesel mix at refinery	kg	1.00E-01
Rail transport cargo - average	GLO	Freight train, average (without fuel)	tkm	5.42E-01
Diesel mix at refinery	EU-27	Diesel mix at refinery	kg	5.42E-01

2.3.5. Use stage impact from losses

Due to uncertainties arising in the use phase energy consumption and losses, the resulting impact on the use phase is not considered within the scope of this study. If batteries have efficiencies similar to Li-ion then use phase impacts will be similar and will be a fraction of the production phase.

Note however that the functional unit depends on the life time assumptions which depend on the use stage and therefore this impact is taken into account (see Table 1).

2.3.6. End of life stage

There is no established market for sodium-ion batteries cell recycling and hence no information available on end of life recycling of sodium battery cells. To overcome this lack of data the lithium-ion EOL e-mobility scenario (95% collection for recycling and 5% unidentified stream) and model for recycling was used as a baseline to model this phase for sodium-ion batteries. The battery recycling processes was used as-is from the PEFCR for batteries except for the dataset for the passive components recycling. That dataset was modified for the Na-ion batteries passive components based on inventory mass balance from Peters et al[5]. The steel, copper and plastic amounts in the passive components parts were changed in accordance with the amounts available in the production of the battery part. When no amount data was available assumptions were made. In the EOL stage that was only the case for the data cable inventory which is in m cable/kg battery, therefore estimations were made on the metal and plastic components per m cable. The data cables were assumed to have 0.01555 kg of copper and 0.0342 kg of polyethylene per m cable. The aluminium data was removed as there is no aluminium in the battery casing system for Na-ion but steel and plastic data were modified according to mass balance from Peters et al.

The circular footprint formula (CFF) was applied to the amounts and default parameters as described in the PEFCR for batteries were used. The formula and parameters used are presented below. Since there is no incineration or landfill component, the energy recovery and landfill parameters are not shown in the formula.

$$(1 - R_1)E_V + R_1 \times \left(AE_{recycled} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_p}\right) + (1 - A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$$

In which:

R_1 = Recycled content (of raw materials at production) recycled from previous system.

E_v = Environmental impacts of virgin content (of raw materials in production).

A = Allocation factor of burdens and credits between supplier and user of recycle materials; in PEF studies A can be 0.2, 0.5, or 0.8.

$E_{recycled}$ = Environmental impacts of recycling/reuse process of R_1 (incl. collection, sorting, transport).

Q_{Sin} = Quality of the ingoing secondary material.

Q_p = Quality of the primary material.

R_2 = Recycling fraction (at EOL) for a subsequent system.

$E_{recyclingEoL}$ = Environmental impacts of recycling process at EOL.

E^*_v = Environmental impacts of substituted virgin materials after recycling ("avoided virgin materials"); there is no E^*_v if R_1 equals 0.

Q_{Sout} = Quality of the outgoing secondary material.

The assumption is that the steel, copper and plastic are recycled and with no materials going to landfill. In addition Based on the default parameters applied, the formula for calculating the environmental impact of the EOL stage reduces to:

$(1-A)R_2 \times E_{recyclingEoL}$

The default parameters as per the PEFCR for batteries used for the CFF calculation are:

- Parameter A= 0.5 for plastics and 0.2 for metals
- Parameter B= 0
- Parameter R_1 = 0
- Parameter R_2[9] = 1
- Parameter Q_{Sout}/Q_P= 1

A complete life cycle inventory for the end of life phase is provided in Table 5.

[9] As per Annex C, Values in the R2 cells refer to the collection rate, and they refer to the whole product. The conversion to the recycling output rate (R2) for the different materials is included in the EF-compliant dataset.

Table 5: Life cycle inventory of end of life of Na-ion battery (based on PEFCR for batteries). The in green highlighted processes have different amounts when compared with the PEFCR for batteries as they have been modified based on Na-ion battery contents

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery	Proxy Y/N
Battery cell recycling	EU-27	Electricity grid mix	MJ/kg battery	6.90E-01	N
	EU-27	Thermal energy from natural gas	MJ/kg battery	2.07E+00	N
	EU-27	Process steam from natural gas	MJ/kg battery	6.48E+00	N
	EU-27	Tap water	kg/kg battery	7.63E+00	N
	DE	Lime production	kg/kg battery	4.00E-02	Y
	EU-27	Hard coal mix	kg/kg battery	3.00E-02	N
	EU-27	Sodium hydroxide production	kg/kg battery	1.90E-01	N
	EU-27	Sulphuric acid production (100%)	kg/kg battery	6.60E-01	N
	EU-27	Landfill of inert (steel)	kg/kg battery	9.00E-02	N
	EU-27	Treatment of residential wastewater, large plant	kg/kg battery	8.27E+00	N
Battery cell recycling credits (depending on cell composition)	EU-27	Process steam from natural gas	kg/kg battery	1.46E+00	N
	DE	Manganese	kg/kg battery	2.00E-01	N
	DE	Nickel (updated)	kg/kg battery	4.00E-02	N
	GLO	Cobalt	kg/kg battery	5.00E-02	Y
	EU-27	Steel cold rolled coil / Steel cast part alloyed	kg/kg battery	0.00E+00	N
Passive parts recycling	**EU-28+EFTA**	**Recycling of steel into steel scrap: Steel billet (St)**	**kg/kg battery**	**1.93E-01**	**N**
	EU-28+EFTA	Landfill of inert (steel)	kg/kg battery	n.a.	N

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery	Proxy Y/N
	EU-28+EFTA	**Recycling of aluminium into aluminium scrap - from post-consumer**	**kg/kg battery**	**0.00E+00**	**N**
	EU-28+EFTA	Landfill of inert material (other materials)	kg/kg battery	n.a.	N
	EU-28+EFTA	Recycling of steel into steel scrap: Steel billet (St)	kg/kg battery	0.00E+00	Y
	EU-28+EFTA	**Recycling of copper from electronic and electric waste**	**kg/kg battery**	**6.19E-03**	**N**
	EU-28	Plastic granulate secondary (low metal contamination)	kg/kg battery	1.00E-01	N
Passive parts credits	**EU-28+EFTA**	**Aluminium ingot mix (high purity)**	**kg/kg battery**	**0.00E+00**	**N**
	EU-28+EFTA	**Recycling of steel into steel scrap: Steel billet (St)**	**kg/kg battery**	**0.00E+00**	**N**
	n.a.	n.a.	kg/kg battery	n.a.	N
	EU-28+EFTA	**Copper cathode**	**kg/kg battery**	**9.00E-03**	**N**
	EU-28+EFTA	**LDPE granulates**	**kg/kg battery**	**1.36E-02**	**N**
	EU-28+EFTA	**Steel cast part alloyed**	**kg/kg battery**	**1.93E-01**	**N**

2.3.7. LCA modelling using the PEFCR method

The primary activity data was sourced from the Peters et al (2016)[5] study and modelled in SimaPro[10]. To develop the sodium-ion battery models the best available secondary datasets to populate the models were identified. At first a dataset was matched as much as possible with the default datasets specified in the PEFCR for batteries. Whenever a dataset needed to calculate the PEF-profile was not in the PEFCR for batteries, we chose between the following options (in hierarchical order):

- Use an EF-compliant dataset available in a free or commercial source.
- Use another EF-compliant dataset considered to be a good proxy.
- Use an ILCD-entry level-compliant dataset.
- Use existing databases in commercially available software that are not EF or ILCD compliant. For sodium-ion battery modelling, ecoinvent[11] background datasets were used. The original LCA was also conducted using ecoinvent datasets.
- If none of the above is available, the process shall be excluded and also be mentioned in the project report as data gap. This situation was not encountered in the modelling of sodium-ion batteries.

A list of processes that were not available as EF compliant datasets were also created during this step (Table 6). Another list was created which contains the specific to Na-ion battery datasets that were created using activity data from the Peters et al (2016) study (Table 7). These are not currently available as EF compliant datasets and are listed to highlight the newly modelled data that can be made available to a user of this PEF study.

Table 6: List of processes not available as EF compliant datasets for Na-ion PEF modelling and for which ecoinvent datasets were used

No.	Name of process
1	Soda ash, dense
2	Sodium chloride, brine solution
3	Lime, hydrated, loose
4	Transformation, unknown to mineral extraction site
5	Occupation, mineral extraction site
6	Manganese dioxide production
7	Chemical factory, organics
8	Chemicals, inorganic
9	Wastewater treatment, average
10	N-methyl-2-pyrrolidone production
11	Sodium fluoride production
12	Phosphorous pentachloride production
13	Hydrogen fluoride
14	Battery Separator
15	Used Lithium ion

[10] PRé Consultants, "SimaPro software." SimaPro Version 9.0.0.48 (2019).

[11] Frischknecht, R., et al. "Overview and methodology. Data v2. 0 (2007). Ecoinvent report No." (2007). For this project we used ecoinvent version 3.5.

No.	Name of process
16	Printed wiring board, unspecified, Pb containing
17	Printed wiring board, unspecified, Pb free
18	Reinforcing steel
19	Sheet rolling, steel

Table 7: List of newly modelled processes that were created using data from Peters et al (2016)[5] for Na-ion batteries that are currently not available as EF compliant datasets

No.	Name of process
1	Anode, hard carbon-Al, for Na-ion battery
2	Cathode, NMMT layered oxide, for Na-ion battery
3	Hard carbon, anode, from sugar
4	NMMT active material, layered oxide
5	Magnesium hydroxide production
6	Nickel carbonate, anhydrous, production
7	Sodium hexafluorophosphate production
8	Electrolyte, sodium hexafluorophosphate based
9	Cell container, 18650 battery type
10	Battery cell, Na-ion, NMMT-HC, 18650, at plant
11	Battery management system for Na-ion battery
12	Battery pack, Na-ion, NMMT-HC, 18650, at plant

2.3.8. PEF results for sodium-ion battery

2.3.8.1. Characterized results for Na-ion battery

The characterized result per functional unit of 1 kWh provided by the Na-ion battery is shown in Table 8. The impact assessment method used is: EF Method 2.0 (adapted version from SimaPro) V1/Global 2010) with tox categories.

Table 8: Characterized results of 1 kWh of the total energy provided over the service life by the Na-ion battery

Impact category	Unit	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_ Battery Dismantlin g	Total	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLi fe_Batte ry Dismant ling
Climate change	kg CO2 eq	1,30E-01	2,54E-02	1,55E-01	84%	16%
Ozone depletion	kg CFC11 eq	1,92E-09	2,25E-09	4,16E-09	46%	54%
Ionising radiation, HH	kBq U-235 eq	1,83E-02	2,35E-03	2,06E-02	89%	11%

Impact category	Unit	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_Battery Dismantling	Total	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_Battery Dismantling
Photochemical ozone formation, HH	kg NMVOC eq	4,07E-04	1,17E-04	5,24E-04	78%	22%
Respiratory inorganics	disease inc.	9,27E-09	5,94E-09	1,52E-08	61%	39%
Non-cancer human health effects	CTUh	7,85E-08	1,20E-08	9,05E-08	87%	13%
Cancer human health effects	CTUh	1,83E-09	1,13E-09	2,96E-09	62%	38%
Acidification terrestrial and freshwater	mol H+ eq	1,88E-03	7,76E-04	2,65E-03	71%	29%
Eutrophication freshwater	kg P eq	1,80E-05	9,84E-06	2,79E-05	65%	35%
Eutrophication marine	kg N eq	4,63E-04	2,85E-05	4,92E-04	94%	6%
Eutrophication terrestrial	mol N eq	2,88E-03	3,03E-04	3,19E-03	91%	9%
Ecotoxicity freshwater	CTUe	4,92E-01	4,10E-02	5,33E-01	92%	8%
Land use	Pt	6,43E+00	1,29E-01	6,55E+00	98%	2%
Water scarcity	m3 depriv.	7,51E-02	1,72E-02	9,23E-02	81%	19%
Resource use, energy carriers	MJ	1,64E+00	4,29E-01	2,07E+00	79%	21%
Resource use, mineral and metals	kg Sb eq	6,81E-07	1,58E-06	2,26E-06	30%	70%

2.3.8.2. Normalized and weighted results for sodium-ion battery

The normalized and weighted results for Na-ion battery are shown in Table 9. The EF Method (adapted) V1/Global (2010) with the toxicity categories is used to highlight the most relevant impact categories which have a cumulative contribution of greater than 80% to the total impact.

Table 9: Normalized and weighted results for Na-ion battery. The highlighted impact categories are the most relevant impact categories that contribute >80% cumulatively to the total impact

Impact category	**EF method (adapted)V1.00 Global (2010) with tox categories**	
	Na-ion battery pack manufacturing + EOL	**Contribution to total impact (%)**
Total	**4.27E+01**	
Climate change	4.19E+00	10%
Ozone depletion	1.20E-02	0%
Ionising radiation, HH	2.42E-01	1%
Photochemical ozone formation, HH	6.13E-01	1%
Respiratory inorganics	2.08E+00	5%
Non-cancer human health effects	3.48E+00	8%
Cancer human health effects	1.62E+00	4%
Acidification terrestrial and freshwater	2.95E+00	7%
Eutrophication freshwater	2.98E-01	1%
Eutrophication marine	5.14E-01	1%
Eutrophication terrestrial	6.66E-01	2%
Ecotoxicity freshwater	8.85E-01	2%
Land use	3.90E-01	1%
Water scarcity	1.85E+01	43%
Resource use, energy carriers	2.88E+00	7%
Resource use, mineral and metals	3.37E+00	8%

2.3.8.3. Hotspots Analysis

The most relevant life cycle stages based on the characterized results for each of the highlighted relevant impact categories is shown in Table 10. The most relevant process based on characterized results for each relevant impact category is shown in Table 11.

Table 10: Most relevant life cycle stages based on characterized results for the most relevant impact categories

Impact category	Production of the main product	End-of-Life
Climate Change (fossil) [kg CO2 eq.]	84%	16%
Acidification terrestrial & freshwater [mol H+ eq.]	71%	29%
Water scarcity [m3 depriv.]	81%	19%
Resource use, energy carriers [MJ]	79%	21%
Resource use, mineral and metals [kg Sb eq.]	30%	70%
Respiratory inorganics [kg PM2.5 eq.]	61%	39%

Table 11: Most relevant processes during the life cycle of the Na-ion battery characterized for the most relevant impact categories

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Climate Change	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	28%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	18%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	12%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	7%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	3%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	3%
Process steam from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 90% efficiency {EU-28+3} [LCI result]	3%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	2%

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Manganese dioxide| Semisynthetic route from high-grade oxidic manganese ore| at plant| per kg {EU-28+3} [LCI result]	1%
Acidification terrestrial and freshwater	
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	40%
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	18%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	15%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	7%
Non-cancer human health effects	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	78%
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	8%
Water scarcity	
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	41%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	15%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	8%
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	7%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	5%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	5%
Resource use, energy carriers	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	26%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	23%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	15%

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	8%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	4%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	3%
Resource use, minerals and metals	
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	44%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	15%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	14%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	10%

2.4. Sodium nickel chloride battery

2.4.1. Functional unit

Similar to sodium-ion, the PEFCR for batteries functional unit of 1 kWh of total energy provided by the battery over its service life was used. The functional unit for sodium nickel chloride or ZEBRA battery from hereon, is calculated using the method provided in the PEFCR and with information gathered from Galloway et al (2003)[4] . Table 12 shows the parameters used to model the ZEBRA battery.

Table 12: Parameters used to calculate the functional unit, reference flow and the number of ZEBRA batteries applied within a residential ESS based on PEFCR for batteries[1] method and data from Galloway et al (2003)[4]

Parameter	Unit	Value	Reference
Nominal battery system capacity	kWh	21	Galloway et al (2003)
Economic lifetime of application (Tapp)	y	20	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Depth of discharge (DoD)	%	-	
Energy delivered per cycle (Edc)	kWh/cycle	16.8	Galloway et al (2003)
Number of cycles for battery system over its service life (Nc)	-	3 000	Galloway et al (2003)
Average capacity per cycle (Acc)	%	0.8	Galloway et al (2003)
Total weight of battery system	kg	37	Galloway et al (2003)
Average net capacity per cycle until EoL	kWh/cycle	-	
Functional unit over service life (QUa)	kWh/service life	40 320	Calculated (Edc*Nc*Acc; as per PEFCR)
Application Service (AS) (as defined in the preparatory study)	kWh	40 000	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
No. of battery systems per economic service life (Nb batt)	-	0.99	Calculated (AS/Qua; as per PEFCR)
Reference flow (Rf)	kg battery/kWh	9.180E-04	Calculated (Nb batt*mass/AS; as per PEFCR)

2.4.2. System boundary

The system boundary includes the raw materials acquisition and manufacturing, and the end of life stages based on the availability of data.

Life Cycle Stage	Description
Raw materials acquisition	Included. Data sourced from Galloway et al (2003) [4]
Main product production	Included. Data sourced from Galloway et al (2003) [4]
Distribution	Not included. No data available
Use	Not included. Deviation from PEFCR for batteries
End of life recycling	Included. Data sourced from PEFCR for batteries[1]. Modified to suit data for ZEBRA batteries recycling[4]

2.4.3. Raw materials acquisition and main product production stage

The manufacturing of the ZEBRA battery was modelled by ecoinvent mainly based on Galloway et al (2003) and the dataset is available in SimaPro. This dataset was recreated using EF compliant datasets and activity data from Galloway et al (2003)[4]. The life cycle inventory used for modelling the raw materials acquisition and manufacturing ZEBRA battery is shown in Table 13.

Table 13: Life cycle inventory for manufacturing of ZEBRA battery. Activity data from Galloway et al (2003)[4]

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery	Proxy: Y/N
Manufacturing (production of main product)						
Power_battery	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.34E+00	
Active components per cell						
Anode						
Sodium chloride powder production	RER	Sodium chloride powder production| technology mix| production mix, at plant| 100% active substance		kg/kg battery	2.61E-01	
Helium	GLO		Helium - ecoinvent database	kg/kg battery	5.57E-05	
Cathode						
Nickel	GLO	Nickel| mining and processing| production mix, at plant| 8.9 g/cm3		kg/kg battery	1.78E-01	
Copper	EU-28+3	Copper cathode		kg/kg battery	3.56E-02	
Pig Iron	GLO		Pig Iron - ecoinvent database	kg/kg battery	1.66E-01	
Electrolyte						
Aluminium oxide production	GLO	Aluminium oxide production| technology mix| production mix, at plant| 100% active substance		kg/kg battery	1.66E-01	
Separator						

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery	Proxy: Y/N
Polyethylene terephthalate	EU-28	Polyethylene terephthalate (PET) granulate secondary no metal fraction | from post-consumer plastic waste, via grinding, metal separation, washing, pelletization | single route, at consumer | plastic waste without metal fraction		kg/kg battery	2.20E-02	
Passive components per cell						
Battery casing						
Steel part	EU-28+EFTA	Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel		kg/kg battery	4.12E-02	
Cooling system	EU-28+EFTA	Tin plated chromium steel sheet| steel sheet tin plating| single route, at plant| chromium steel		kg/kg battery	9.89E-02	
Silicone foam insulation	GLO	Silicone resins		kg/kg battery	4.12E-02	
Battery Management System						
BMS	World	Capacitor, electrolyte| technology mix| production mix, at plant| electrolyte, height <2 cm		p/kg battery	8.72E-03	

2.4.4. Distribution stage

Due to lack of data, this phase is not included within this assessment.

2.4.5. Use stage impact from energy losses

Due to uncertainties arising in the use phase energy consumption and losses, this phase is not considered within the scope of this study. Related to this it is important to know that a major drawback of the ZEBRA battery is that it is a high temperature technology but as we do not model the losses this drawback is not considered and taken into account.

Note however that the functional unit depends on the life time assumptions which depend on the use stage and therefore this impact is taken into account.

2.4.6. End of Life stage

The ZEBRA battery recycling is modelled based on data from Galloway et al (2003) and supplemented with the PEFCR for batteries end of life model. The first step in the recycling process is the dismantling of the ZEBRA battery system including cell and box. The box material of steel and silicon dioxide is recycled. The cells contain nickel, iron, salts and ceramic which are recycled by adding to the steel melting process of stainless steel production[4].

To model the end of life of the ZEBRA battery, the battery recycling process used in the PEFCR batteries is used as a baseline. Additionally, the passive components materials (steel) are recycled as per Galloway et al (2003). The stainless steel production is modified with additions of nickel and iron. The salt from the cell collects as the slag and is sold as replacement for lime in road construction. The CFF formula and the parameters remain the same as applied for sodium-ion.

The CFF formula for calculating the environmental impact of the EOL stage reduces to :

$(1-A)R_2 \times E_{recyclingEoL}$ for recycling of materials and

$(1-A)R_2 \times (-E^*_v \times Q_{Sout}/Q_p)$ for lime replacement

The life cycle inventory used for modelling the end of life of ZEBRA battery is provided in Table 14.

Table 14: Life cycle inventory of the end of life modelling for ZEBRA battery (based on data from Galloway et al (2003) and supplemented with the PEFCR for batteries end of life model)

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery
Battery cell recycling	EU-27	Electricity grid mix	MJ/kg battery	6.90E-01
	EU-27	Thermal energy from natural gas	MJ/kg battery	2.07E+00
	EU-27	Process steam from natural gas	MJ/kg battery	6.48E+00
	EU-27	Tap water	kg/kg battery	7.63E+00
	DE	Lime production	kg/kg battery	4.00E-02
	EU-27	Hard coal mix	kg/kg battery	3.00E-02
	EU-27	Sodium hydroxide production	kg/kg battery	1.90E-01
	EU-27	Sulphuric acid production (100%)	kg/kg battery	6.60E-01
	EU-27	Landfill of inert (steel)	kg/kg battery	9.00E-02
	EU-27	Treatment of residential wastewater, large plant	kg/kg battery	8.27E+00
Battery cell recycling credits (depending on cell composition)	EU-27	Process steam from natural gas	kg/kg battery	1.46E+00
	DE	Manganese	kg/kg battery	2.00E-01
	DE	Nickel (updated)	kg/kg battery	4.00E-02
	GLO	Cobalt	kg/kg battery	5.00E-02
	GLO	Copper cathode	kg/kg battery	3.00E-02
	EU-27	Steel cold rolled coil / Steel cast part alloyed	kg/kg battery	0.00E+00
	EU-28+EFTA	Recycling of steel into steel scrap: Steel billet (St)	kg/kg battery	4.70E-01

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery
Passive parts recycling	EU-28+EFTA	Landfill of inert (steel)	kg/kg battery	n.a.
	EU-28+EFTA	Recycling of aluminium into aluminium scrap - from post-consumer	kg/kg battery	1.66E-01
	EU-28+EFTA	Landfill of inert material (other materials)	kg/kg battery	n.a.
	EU-28+EFTA	Recycling of copper from electronic and electric waste	kg/kg battery	3.56E-02
	DE	Lime (CaO finelime) | technology mix | production mix, at plant | CaO finelime, density of CaO: 3,37 g·cm-3 (20 °C), molar mass of CaO: 56,08 g·mol-1	kg/kg battery	-1.31E-02
Passive parts credits	EU-28+EFTA	Aluminium ingot mix (high purity)	kg/kg battery	6.00E-02
	EU-28+EFTA	Copper cathode	kg/kg battery	9.00E-03
	EU-28+EFTA	LDPE granulates	kg/kg battery	2.20E-02
	EU-28+EFTA	Steel cast part alloyed	kg/kg battery	5.00E-02

2.4.7. LCA modelling using the PEFCR method

The similar hierarchical way of selecting the type of dataset as described in section 2.3.7 was applied for the ZEBRA battery. The processes that were not available for modelling the ZEBRA batteries is listed. Since the ZEBRA battery model exists in ecoinvent, processes that were not available as EF compliant datasets were replaced with ecoinvent 3.5 data (Table 15).

Table 15: List of processes not available as EF compliant datasets for ZEBRA battery PEF modelling and for which ecoinvent datasets were used

No.	Name of process
1	Helium production
2	Metal working, average for metal product manufacturing processing
3	Pig iron
4	Electronics, for control units

2.4.8. PEF results for ZEBRA battery

2.4.8.1. Characterized results for ZEBRA battery

The characterized results for ZEBRA battery are shown in Table 16. The impact assessment method used is: EF method (adapted) V1.00 Global (2010) with tox categories.

Table 16: Characterized results per 1 kWh functional unit of ZEBRA battery

Impact category	Unit	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_ Battery Cell Dismantling	Total	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_ Battery Cell Dismantling
Climate change	kg CO2 eq	5.59E-03	1.48E-03	7,07E-03	79%	21%
Ozone depletion	kg CFC11 eq	6.99E-10	1.18E-10	8,17E-10	86%	14%
Ionising radiation, HH	kBq U-235 eq	7.01E-04	1.11E-04	8,12E-04	86%	14%
Photochemical ozone formation, HH	kg NMVOC eq	3.68E-05	3.02E-06	3,98E-05	92%	8%
Respiratory inorganics	disease inc.	2.02E-09	8.41E-11	2,10E-09	96%	4%
Non-cancer human health effects	CTUh	3.82E-09	9.57E-11	3,92E-09	98%	2%
Cancer human health effects	CTUh	3.21E-10	1.25E-11	3,33E-10	96%	4%
Acidification terrestrial and freshwater	mol H+ eq	3.17E-04	9.47E-06	3,26E-04	97%	3%

Impact category	Unit	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_Battery Cell Dismantling	Total	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_Battery Cell Dismantling
Eutrophication freshwater	kg P eq	2.51E-06	3.10E-08	2,54E-06	99%	1%
Eutrophication marine	kg N eq	6.45E-06	8.61E-07	7,31E-06	88%	12%
Eutrophication terrestrial	mol N eq	8.08E-05	9.24E-06	9,00E-05	90%	10%
Ecotoxicity freshwater	CTUe	1.33E-02	4.66E-04	1,37E-02	97%	3%
Land use	Pt	3.83E-02	3.03E-03	4,14E-02	93%	7%
Water scarcity	m3 depriv.	1.13E-03	7.45E-04	1,87E-03	60%	40%
Resource use, energy carriers	MJ	6.27E-02	2.52E-02	8,79E-02	71%	29%
Resource use, mineral and metals	kg Sb eq	3.22E-07	1.37E-08	3,36E-07	96%	4%

2.4.8.2. Normalized and weighted Results for ZEBRA battery

The normalized and weighted results are shown in Table 17. The most relevant impact categories based on a cumulative contribution of greater than 80% to the total impact are highlighted in the table. The EF methodV1.0.6 without toxic categories is used for calculating the contribution to the total impact.

Table 17: Normalized and Weighted impacts of 1kWh of ZEBRA battery. The impact categories with a total cumulative contribution of >80% are highlighted as the most relevant impact categories

Impact category	EF method (adapted) V1,00 Global (2010) with tox categories	
	Battery production + EOL, NaCl, rechargeable, 38Ah/2,58V	Contribution to total impact (%)
Total	**3.09E+00**	
Climate change	1.89E-01	6.1%
Ozone depletion	2.21E-03	0.1%

Impact category	EF method (adapted) V1,00 Global (2010) with tox categories	
	Battery production + EOL, NaCl, rechargeable, 38Ah/2,58V	Contribution to total impact (%)
Ionising radiation, HH	9.63E-03	0.3%
Photochemical ozone formation, HH	4.66E-02	1.5%
Respiratory inorganics	2.95E-01	9.5%
Non-cancer human health effects	1.52E-01	4.9%
Cancer human health effects	1.84E-01	5.9%
Acidification terrestrial and freshwater	3.63E-01	11.7%
Eutrophication freshwater	2.79E-02	0.9%
Eutrophication marine	7.57E-03	0.2%
Eutrophication terrestrial	1.87E-02	0.6%
Ecotoxicity freshwater	2.22E-02	0.7%
Land use	2.45E-03	0.1%
Water scarcity	1.13E+00	36.6%
Resource use, energy carriers	1.46E-01	4.7%
Resource use, mineral and metals	4.95E-01	16.0%

2.4.8.3. Hotspot Analysis

Based on the most relevant impact categories, the life cycle stages which have the most relevant contributions are calculated (Table 18). These calculations are made based on the characterized results shown in Table 16.

Table 18: Most relevant life cycle stages based on most relevant impact categories

Impact category	Production of the main product	End-of-Life
Climate Change [kg CO2 eq.]	80%	20%
Respiratory inorganics [kg PM2.5 eq.]	96%	4%

Acidification terrestrial & freshwater [mol H+ eq.]	97%	3%
Water scarcity [m3 depriv.]	92%	8%
Resource use, mineral and metals [kg Sb eq.]	96%	4%

The most relevant processes for each of the most relevant impact categories is also calculated based on the characterized results. The cumulative contribution of the processes >80% to each of the relevant impact categories is shown in Table 19.

Table 19: Most relevant processes contributing >80% cumulative impacts to the relevant impact categories

Process Contribution (>80% contribution cumulative)	**ZEBRA Battery manufacturing + EOL**
Climate Change	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	25%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	14%
Process steam from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 90% efficiency {EU-28+3} [LCI result]	8%
Silicone resins| Technology mix| Production mix, at plant| {GLO} [LCI result]	4%
Pig iron {GLO}| production | Cut-off, U	3%
Stainless steel hot rolled| hot rolling| production mix, at plant| stainless steel {ROW} [LCI result]	3%
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	3%
Aluminium oxide production| technology mix| production mix, at plant| 100% active substance {GLO} [LCI result]	3%
Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	3%
Sodium hydroxide production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	2%

Process Contribution (>80% contribution cumulative)	ZEBRA Battery manufacturing + EOL
Sulphuric acid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	1%
Capacitor, electrolyte| technology mix| production mix, at plant| electrolyte, hight <2 cm {World} [LCI result]	1%
Recycling of aluminium into aluminium scrap - from post-consumer| collection, transport, pretreatment, remelting| production mix, at plant| aluminium waste, efficiency 90% {EU-28+EFTA} [LCI result]	1%
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	1%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	1%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	1%
Sinter, iron {GLO}| production | Cut-off, U	1%
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	1%
Recycling of steel into steel scrap| collection, transport, pretreatment, remelting| production mix, at plant| steel waste, efficiency 95% {EU-28+EFTA} [LCI result]	1%
Acidification terrestrial and freshwater	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	83%
Respiratory inorganics	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	82%
Water scarcity	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	59%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	24%

Process Contribution (>80% contribution cumulative)	ZEBRA Battery manufacturing + EOL
Resource use, minerals and metals	
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	49%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	44%

3. Conclusion for implementing PEFCR for batteries

This study shows the application of the PEFCR for batteries to two stationary battery types: sodium-ion and sodium nickel chloride.

In principle, the PEFCR for Batteries can be applied for the current and emerging technologies in its current form. But there needs to be deviations to applying the PEFCR as the use phase is currently included in the PEFCR while this study has explicitly not included the use phase in the calculations.

There were some underlying issues identified in applying the PEFCR for batteries for the two battery types selected for this study. The following paragraphs detail the missing details.

3.0. Functional Unit

The functional unit calculations in this study are based on assumptions about stationary battery systems and data from publicly available data sources for particular battery types. Some of the assumptions such as mass of battery, number of cycles and depth of discharge have an impact on the functional unit and need to be reported for the calculation of the functional unit. The formula as is used in the PEFCR for batteries requires additional values to calculate the parameters used in the functional unit. For example, the energy delivered per cycle (Edc) for the Na-ion battery was not available. A calculation was made in this study based on the nominal battery system capacity and the depth of discharge which were parameters based on the preparatory study for stationary application case. But such information might not be readily available for emerging battery solutions which hinders the functional unit calculation. The PEFCR for batteries does not include a calculation for any of the battery types included. An example of functional unit calculation for the relevant battery types of the PEFCR will be a useful addition to model other battery types.

3.1. Lifetime calculation

The Economic lifetime of application (Tapp) was expressed in a Number of cycles for battery system over its service life (Nc). This value was used to calculate the amount of needed batteries. However, batteries age also over time. This is expressed as Calendar life. In the Ecodesign Batteries - Preparatory Study (see Task 5 report) both the Cycle life and the Calendar life were taken into account by taking the inverse proportional value of both lives. This is a hypothetical construction since in reality not a clear split can be made between calendar life and cycle life. Still both ageing mechanisms exist and using only Cycle life leads to an under-estimation of the needed amount of batteries.

3.2. Availability of primary data

The study is dependent on primary activity data from manufacturers to model the different battery chemistries. In addition, datasets used to model different battery chemistries beyond Li-ion are also necessary. This study highlighted some of the EF datasets that are currently unavailable to model the studied batteries. The more datasets that are available, the less the proxy data or datasets from other databases will be used for LCA modelling of different batteries. The data collection process is the most time consuming process and this study emphasised the need for more EF compliant datasets to model batteries.

3.3. End of Life Modelling

The end of life modelling of batteries is dependent on each battery technology and its recycling method in place. This can be a challenge for emerging technologies. The PEFCR for batteries has information for modelling the end of life for Li-ion batteries. However, the PEFCR Excel output is not uidetailed enough to model a battery type accurately. The blocks for battery cell, passive parts, OEM recycling and credits are not represented intuitively for a LCA modeler. The screenshots for the Gabi model do not match with all the blocks for battery cell and other parts recycling and credits in the EoL phase in the PEFCR Excel. This can be a challenge for a modeler relying only on the PEFCR Excel for guidance and also to use any LCA software tool other than Gabi.

The battery cell recycling process is specific to battery types. Emerging and new battery types that do not have an established recycling process will not be able to accurately model this phase and will have to rely on lithium ion recycling processes.

The activity data along with the default parameters can be used to apply the Circular Footprint Formula when there is lack of data available. The parameters are material specific and should be applied as is material and region specific to the manufacture. The more specific activity data a manufacturer provides, the better the PEF profile will be for a particular battery type.

The application of the Circular Footprint Formula (CFF) method as is currently in the PEFCR to implement the method for modelling is not sufficiently explained. A more detailed description of the mass balance and an example of how the parameters are applied for an example material will be useful to clearly understand how to use the PEFCR for batteries for other battery types. Currently, the PEFCR for batteries Excel does not clearly show the application of the CFF, which will be a challenge to modelers.

The results shown in this study are not a PEF benchmark as they represent only one data point for each battery type. This study is an example application for batteries that are currently not in the PEFCR for batteries.

Follow-up feasibility study on sustainable batteries under FWC ENER/C3/2015-619-Lot 1

TASK 4 Report

Sustainable sourcing

DRAFT FINAL PREPRINT

Viegand Maagøe, Fraunhofer

November 2019

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EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

Directorate Directorate C – Industrial Transformation and Advanced Value Chains

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LEGAL NOTICE

Luxembourg: Publications Office of the European Union, 2019

ISBN number 978-92-76-16378-7

doi:number 10.2873/59461

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ABBREVIATIONS

Abbreviations	Descriptions
APAC	Asia Pacific
ASM	Artisinal and Small Scale Mining
BEB	Battery Electric Busses
BEPV	Battery Electric Passenger Vehicles
BEV	Battery Electric Vehicle
BGS	British Geoligical Survey
BMS	Battery Management System
BOM	Bill of Materials
Cd	Cadmium
CRM	Critical Raw Materials
DRC	Democratic Republic of Congo
EC	European Commission
ED	Ecodesign Directive
ELR	Energy Labelling Regulation
EMEA	Europe, Middle-East and Africa
EPI	Environmental Performance Index
EU	European Union
EV	Electric Vehicle
FTE	Full Time Employee
Hg	Mercury
ILO	International Labour Organisation
IRMA	Initiative for Responsible Mining Assurance
LCE	lithium carbonate equivalent
LCO	Lithium-ion Cobalt Oxide
LFP	Lithium-Ion Phosphate
LIB	Lithium ion battery
Li-Cap	Lithium-ion Capacitor
LiPF	lithium hexafluorophosphate
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium-Ion Manganese Oxide
LTO	Lithium-Ion Titanate Oxide
MEErP	Methodology for Ecodesign of Energy related Products
NCA	Lithium Nickel Cobalt Aluminium
NiCd	Nickel-Cadmium
NiMh	Nickel-Metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
OECD DDG CAHRA	The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High Risk Areas
OECD DDG for RBC	OECD Due Diligence Guidance for Responsible Business Conduct
OPC	Open Public Consultation
Pb	Lead
PHEB	Plug-in Hybrid Electric Busses
PHEPV	Plug-in Hybrid Electric Passenger Vehicles
SME	Small and Medium sized Companies

UBA	The German Environment Agency
UN	United Nations
USGS	US Geological Survey
WGI	Worldwide Governance Indicators

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1. Aim of Work package 4

The aim of Task 4 is to identify and assess high risk raw materials used in batteries, by analysing their supply chains. Specifically risks to environment and people.

The general aim of this study is to support developing of a new internal market Regulation for batteries[1], which means; to set the performance and sustainability criteria that batteries will have to comply to be placed on the EU market. This may eventually be combined with the revision of the battery directive.

Task 4 investigates the possibility to set requirements related to the sustainable sourcing of some raw materials for the production of batteries.

Some precedents exist in the EU to regulate social, ethical and legal aspects of raw materials being imported in the internal market, such as the EU Timber Regulation and the Conflict Minerals Regulation.

The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High Risk Areas describes how companies can identify and better manage risks throughout the entire mineral supply chain.

The purpose of this task is to analyse the feasibility of applying the regulatory principles laid out in the regulations and guidance documents mentioned above to the sustainable and responsible sourcing of the raw materials that are used in the production of batteries. Other relevant non-regulatory initiatives and approaches are considered as well.

This task provides an indication of which raw materials used in the manufacturing of rechargeable batteries with internal storage may conflict with widely accepted social and environmental standards in their extraction and supply. All main raw materials for batteries (cobalt, lithium, nickel, manganese, natural graphite and others) are looked at but with special focus on cobalt. The analysis is backed by figures on market volumes and geographic origin, where possible.

An analysis of all possible associated costs (e.g., administrative burden due to reporting or cost of monitoring by national authorities), as well as the possible benefits for society, will be included.

Key challenges:

- To assess the future needs of the raw materials, which may have issues to comply with social, ethical and legal aspects, because battery technologies are continuously in development and the market as well.
- To assess the costs and impacts of regulatory measures including the enforcement for a supply chain often starting in countries far away from EU, which effect therefore may be more uncertain compared to requirements being able to enforce and verify in EU.

[1] http://europa.eu/rapid/press-release_IP-18-6114_en.htm, D. Linden and T. Reddy, “Handbook of batteries,” 1865, D. Linden, *Lithium-Ion Batteries*. 2002

2. Definition of sustainable sourcing

Sustainability as a term is used in many different contexts, and often with different meanings. For a long time, sustainability has been viewed as solutions that consider both people, planet and profit. In other words, it needs to protect the environment and people and their living conditions without being at an excessive cost that renders the solution uneconomic or impossible to sell in case of products.

However, with the adoption of the 17 sustainable development goals (shown in Figure 1) and 169 targets[2] this approach became more nuanced and specific. As written in the preambles of the decision the goals are “are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental.”

Figure 1: The 17 sustainable development goals

Hence instead of seeing the three (where social, economic, and ecological development) as separate, economies and societies are seen as embedded parts of the biosphere, and ”the economy serves society so that it evolves within the safe operating space of the planet”[3].

For the purpose of this study the meaning of sustainable sourcing therefore builds on the sustainable development goals. Based on this, the following specific focus areas have been identified as important to ensure sustainable sourcing of materials for batteries:

- Political stability and avoidance of corruption
- Regulatory compliance
- Human health and human rights including

[2] https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf
[3] https://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.htm

    - Fair remuneration and benefit sharing
    - Local land rights and land grabbing
- Working conditions including
    - Child labour
    - Labour rights and social risks
- local and global environmental protection including
    - Climate change
    - Any negative impacts on air, water or soil ecosystems
- avoidance of child labour

3. Identification of the relevant raw materials

The starting point for identifying relevant raw materials in battery supply chains is the raw materials listed in the BOM (Bill Of Materials) for batteries listed in the preparatory study. Data was collected for the markets and sustainability risks of each material. Based on this data the raw materials with the highest risks related to the focus areas listed in section 2, was short-listed.

3.1 Methodology

Nine raw materials have been identified in the preparatory study to be important in the production of Li-ion batteries for EVs:

- Cobalt
- Nickel
- Lithium
- Manganese
- Aluminium
- Iron
- Copper
- Phosphorus
- Graphite

The following sections provide a brief introduction to each raw material and present quantitative and qualitative data covering production, end-use, forecast and reserves, governance, environment, human health and working conditions. The methodology behind each theme and why they are relevant will be described below.

3.1.1 World production

The production data corresponds to the average global yearly production in the period 2013-2017. Data is primarily covering the initial sourcing country where the raw material has been mined. It should be noted that official data doesn't include sources from artisanal and small-scale mining (ASM). ASM is only relevant for some raw materials, for which it will be highlighted under each, where relevant. For raw materials where locations of refining and further processing are particularly relevant this have been included. Data are primarily acquired from British Geological Survey (BGS) and their World Mineral Production publication for 2013-2017[4]. Data for some minerals has been supplemented by data from World Mining Data[5]. The actual source of production data has been stated under each mineral.

3.1.2 End-use

In this section a general overview of the typical end-uses for the specific raw material is given. However, the overall purpose is to determine how large a share of the global production is consumed by the EV battery industry. Most statistics covering end-use do not distinguish

[4] https://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html
[5] https://www.world-mining-data.info/

between the different battery types and whether they are used for EVs or other purposes. Table 1 gives an overview of the five dominant battery types, its prevailing applications and its overall market share. The three battery types used for EVs (LMO, LFP and NMC) constitute 70% of the market. For cobalt specifically, data has been adjusted according to the cobalt content for each battery. For the other four metals it has been assumed equal.

Table 1: Types of lithium ion battery chemistries with a description of their properties and applications (source: JRC (2018) Cobalt demand-supply balances in the transition to electric mobility)

Name	Abb.	Cobalt content	Market share	Properties and applications
Lithium Cobalt Oxide	LCO	60%	21%	High capacity. Mobile phones, tablets, laptops, cameras
Lithium Manganese Oxide	LMO	no Co	8%	Safest; lower capacity than LCO but specific power and long life. Power tools, e-bikes, EVs, medical devices.
Lithium Iron Phosphate	LFP	no Co	36%	
Lithium Nickel Manganese Cobalt Oxide	NMC	10-30%	26%	
Lithium Nickel Cobalt Aluminium Oxide	NCA	10-15%	9%	High capacity; gaining importance in electric powertrain and grid storage; industrial applications, medical devices

3.1.3 Forecast and reserves

This section is intended to give a brief overview of the trend in supply and demand for each raw material. It is based on desktop research and comes primarily from market reports and industry insights.

3.1.4 Governance

The Worldwide Governance Indicators (WGI) project constructs aggregate indicators of six broad dimensions of governance[6]:

1. Voice and Accountability
2. Political Stability and Absence of Violence/Terrorism
3. Government Effectiveness
4. Regulatory Quality
5. Rule of Law
6. Control of Corruption

The six aggregate indicators are based on over 30 underlying data sources reporting the perceptions of governance of a large number of survey respondents and expert assessments

[6] https://info.worldbank.org/governance/wgi/Home/Reports

worldwide. Details on the underlying data sources, the aggregation method, and the interpretation of the indicators, can be found in the WGI methodology paper[7].

A score for each indicator between -2.5 and +2.5 has been applied to every country in the World. The lower the number, the weaker (poorer) the level of governance in the specific country and conversely the higher the number, the stronger (better) the level of governance.

This assessment provides a weighted score for each mineral for each indicator based on each country's share of World production. Furthermore, it only covers the sourcing countries where the metal has been mined – it does not include countries where the metal has been refined or further processed.

Another index presented for each raw material is the Environmental Performance Index (EPI) which ranks 180 countries on 24 performance indicators across ten issue categories covering environmental health and ecosystem vitality[8]. The German Environment Agency (UBA) has weighted the EPI score according to each country's share of global mine production and classified each raw material into three groups of environmental hazard potential – low (best), medium and high (worst)[9].

3.1.5 Environment, human health and working conditions

Each raw material has been rated using a qualitative approach determining the risk of problematic working conditions and impact to environment and human health. The scale has four levels: Low, Moderate, high and very high. The rating is based on a study on material sourcing produced by Drive Sustainability, the Responsible Minerals Initiative and The Dragonfly Initiative[10].

A study by the German Environment Agency has analysed a wide range of raw materials according to 8 environmental indicators from pollution risk to water stress and aggregated them into one results on a 5-level scale: low (best); low to medium; medium; medium to high; high (worst).

The final ratings can be seen in the summarizing table (Table 11) for each of these two indicators.

Information about GHG emissions related to the life cycle of each raw material has been included the environment sections. The life cycle covers the supply chain from extraction of the ore to refined material also referred to as cradle to gate. The data in GHG emissions are given in an interval based on different datasets such as Ecoinvent 3.1,Thinkstep GaBi and GREET 2016.

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[7] Daniel Kaufmann, Aart Kraay and Massimo Mastruzzi (2010). "The Worldwide Governance Indicators : A Summary of Methodology, Data and Analytical Issues". World Bank Policy Research Working Paper No. 5430

[8] Wendling, Z. A., Emerson, J. W., Esty, D. C., Levy, M. A., de Sherbinin, A., et al. (2018). 2018 Environmental Performance Index. New Haven, CT: Yale Center for Environmental Law & Policy. https://epi.yale.edu/

[9] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

[10] https://drivesustainability.org/wp-content/uploads/2018/07/Material-Change_VF.pdf

3.1.6 Critical Raw Material rating

EUs Critical Raw Material List was first published in 2011 and is updated every three years most recently in 2017. It evaluates a number of materials on two parameters: Supply risk and economic importance. Each parameter is rated on a numerical scale based on quantitative and qualitative analyses. Materials that has supply risk ≥ 1 AND economic importance ≥ 2.8 are categorised as Critical Raw Materials and are subject to increased attention[11].

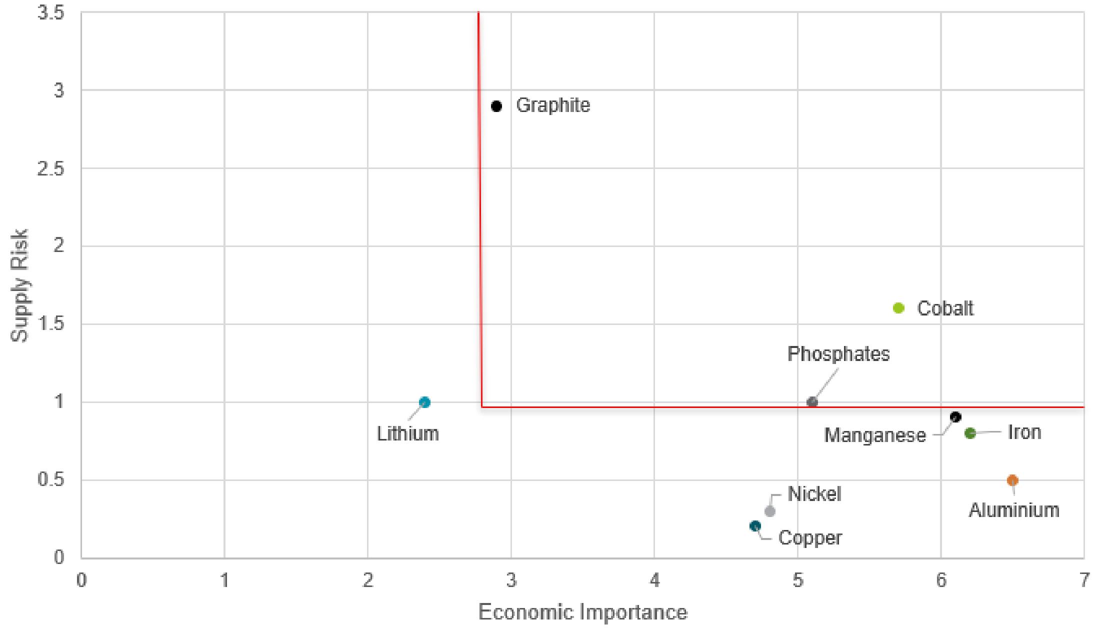

Figure 2: EU Critical Raw Materials

The list of critical raw materials is an important tool for the European Commission that always needs to be considered when considering any product regulation on resources. Some stakeholders have argued that this is not an important criteriar to include in the assessment because battery producers inside Europe do not buy raw materials, but rather component finished cells, and the material is not critical to cell manufacturers in for example China. However, as it is done in any Ecodesign regulation, any critical raw material that is part of a final product (where this might be produced) needs to be considered. The critical raw materials do not loose their economic importance for Europe because they are part of a product, especially of they can be recycled. Hence presence of critical raw materials in a product, will increase the benefits of a good recycling procedure within Europe. Furthermore, it is expected that a continuously larger share of batteries will be produced in Europe in the future, and therefore this criterion is important for the discussion.

[11] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

3.2 Cobalt

Besides lithium, cobalt is an essential component of the cathode for most types of lithium-ion batteries (LIB). Cobalt helps to stabilize the cell structure without compromising the capacity and is critical in increasing the rate performance – the rate at which the power is delivered – which is especially important for batteries used in electric vehicles.[12]

However, cobalt is suffering from a range of issues related to limited supply concentrated to only a few countries and social and environmental problems associated with the mining activities. Furthermore, it has been added to the EUs critical raw materials list with a high level of economic importance and a medium level of supply risk (see Figure 2)[13].

3.2.1 World cobalt production

Cobalt is mined in 22 different countries around the world, where the far majority at 55% is mined in the Democratic Republic of Congo (DRC) The second largest producer of Cobalt is New Caledonia (French territory in the Pacific) with only 8% of the world total. Finland is the only EU country with commercial cobalt mining production, but only constitutes less than 2% of the world total (see Figure 3).

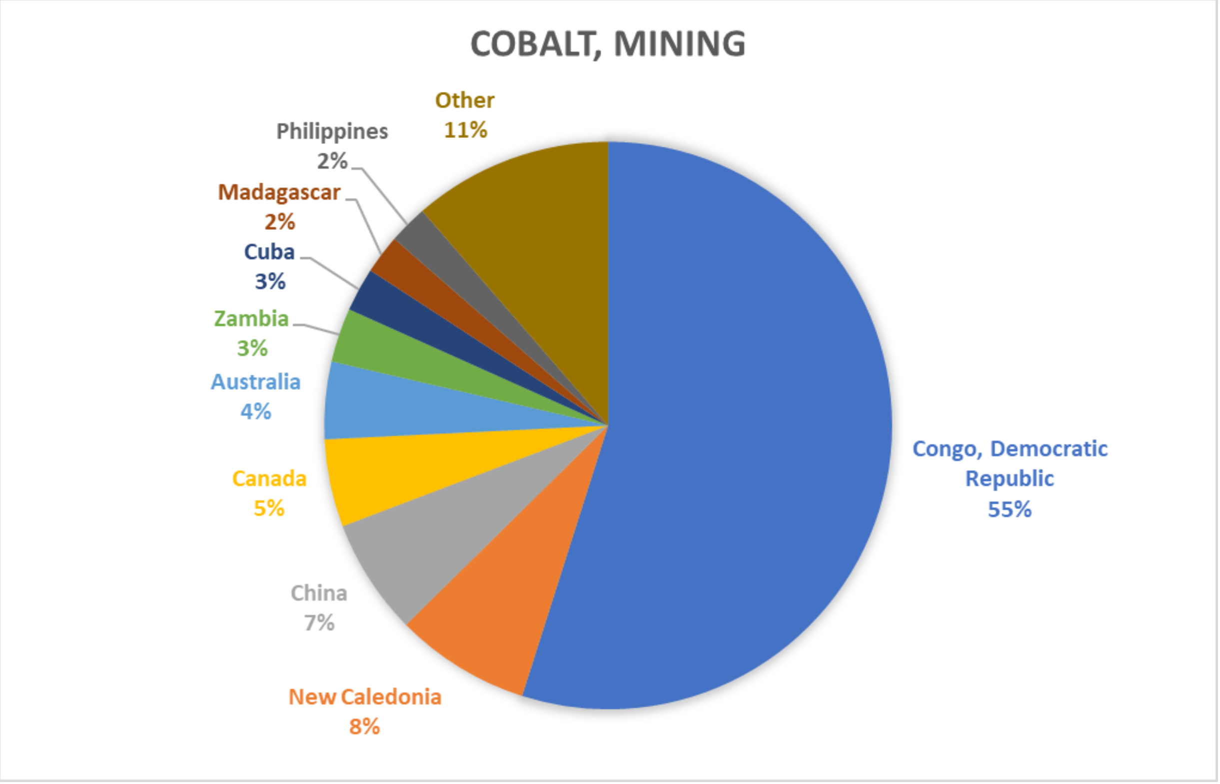

Figure 3: Global cobalt mine production in percentage of global total based on average production in the period 2013-2017 (Source: BGS).

[12] https://www.designnews.com/electronics-test/understanding-role-cobalt-batteries/63068579258429
[13] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

The global annual production of cobalt has on average been 141,000 metric tons in the period 2013-2017. The largest producer D.R.C. mined 82,000 metric tons of cobalt in 2017. It should be noted that ASM mining of cobalt is widespread in D.R.C. but are not included in the national statistics. According to a report by German UBA, 10-30% of cobalt is produced from ASM[14].

Cobalt is primarily mined as by- or co-product of nickel or copper mining. It is estimated that approximately 50% of global supplies of cobalt come from the nickel mining industry and 44% come from copper mining, whilst only 6% come from mining operations with cobalt as the principal commodity[15].

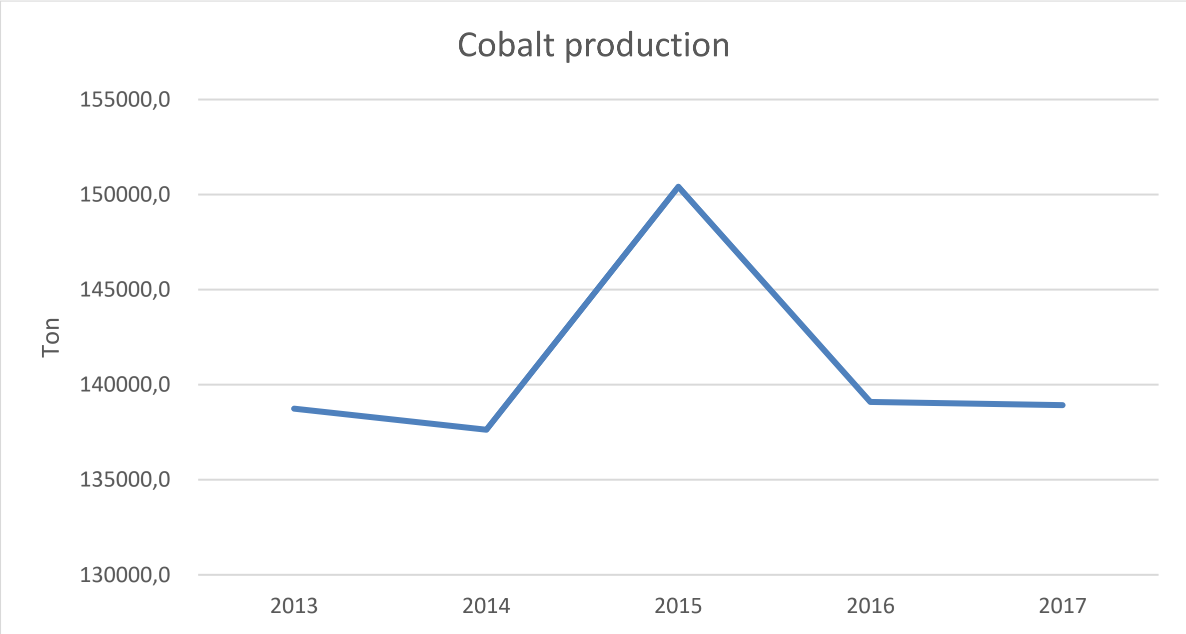

Figure 4: Global production of Cobalt in metric tons in the period 2013 to 2017 (Source: BGS).

3.2.2 End-use of Cobalt

The primary use of cobalt globally is for manufacturing of rechargeable batteries for consumer electronics and EVs at a share of 49% in 2015. The share going to EV batteries alone constitutes 9%[16]. Other uses of cobalt are in superalloys and composite materials for e.g. turbine engines and cutting tools that require high strength and resistance to high temperatures.

[14] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[15] https://publications.europa.eu/en/publication-detail/-/publication/7345e3e8-98fc-11e7-b92d-01aa75ed71a1/language-en
[16] JRC (2018) Cobalt demand-supply balances in the transition to electric mobility

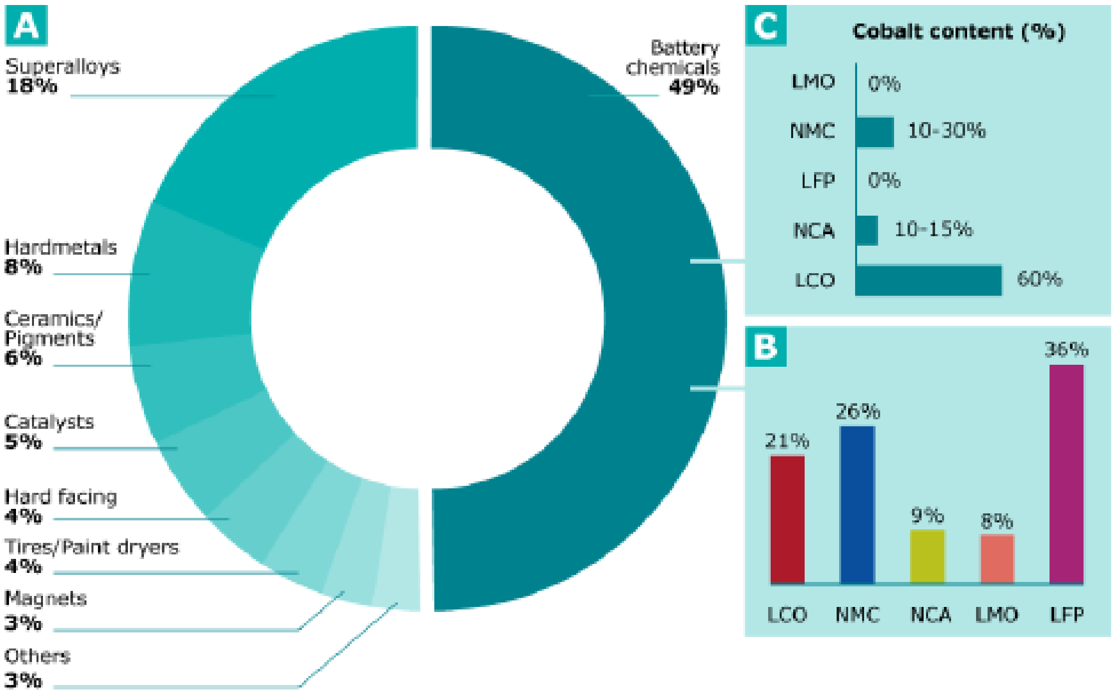

Figure 5: End-use of global cobalt production (Source: JRC)

3.2.3 Forecast and reserves

If there are no technological developments in reducing or limiting the cobalt content in EV batteries it is estimated that the global demand will increase from under 20,000 tons annually to between 300,000 and 400,000 tons in 2030[17]. 60,000 tons is estimated to be demanded by the EU in 2030[18]. Put in perspective, the annual production of cobalt is currently 134,000 tons. The global reserves have been estimated to about 12 million tons at current active mining operations. A further 5.9 million tons have been identified in exploration projects. Reserves are primarily found in D.R.C. and Australia. Since cobalt is primarily mined as a by-product of copper and nickel, its production has therefore been determined by the demand of these metals in the past and is likely to remain so for the foreseeable future. Recycling rates are also relatively low due to the complexity and low yields of recycling of raw materials from batteries[19].

3.2.4 Governance

The Democratic Republic of Congo, where most of the Worlds cobalt is sourced from, generally scores low on all 6 WGI indicators, thereby influencing the average weighted score on cobalt negatively (see Table 2). Cobalt producing countries scores lowest on Political Stability (-1.12) and highest on Government Effectiveness (-0.69). The average score for all 6 indicators is -0.82 and suggest poor to very poor governance.

[17] JRC (2018) Cobalt demand-supply balances in the transition to electric mobility
[18] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 Task 7
[19] https://batteryuniversity.com/learn/article/battery_recycling_as_a_business

Table 2: Worldwide Governance Indicator scores for cobalt producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	-0.82
Political Stability and Absence of Violence/Terrorism	-1.12
Government Effectiveness	-0.69
Regulatory Quality	-0.70
Rule of Law	-0.88
Control of Corruption	-0.72
Average score	**-0.82**

The weighted environmental performance index (EPI) classifies cobalt as having a high environmental hazard potential, thereby supporting the WGI score. Furthermore, ASM mining is of importance, which also influences the governance. The share of cobalt sourced from ASMs is estimated to be 10-30%[20].

3.2.5 Environment

Cobalt is an essential nutrient for most life, since it is part of the vitamin B-12 and is therefore common in the natural environment at varying levels. However, cobalt can become toxic to plant and animal life at elevated concentrations.

Mining, refining and processing of cobalt can lead to leakage of cobalt into the environment with the risk of reaching toxic levels. The risk of environmental contamination varies greatly depending on the type of mining and the level of measures implemented. All types of mining produce large quantities of solid and liquid waste (tailings) that need to be managed in order to avoid it being a source of contamination. Specifically, for cobalt ores, which are sulphidic (which is the majority), there is a high risk of creation of acid and potential drainage into water bodies[21]. Since small-scale artisanal mining is widespread in the DRC the risk of contamination is high for both health and environment, due absence of adequate chemical management, waste management and controlled mine closure and rehabilitation.

A more severe problem than leakage of cobalt is the leakage of several other materials found in the same deposits that are more toxic to the environment such as lead, cadmium, arsenic or radioactive metals like uranium[22]. While production in developed countries are clearly regulated regarding which chemicals can be released to waters and many chemicals are recovered and reused in the production processes, the mining operations in Africa often rely on “pollution prone technologies and the controls on the discharge of pollutants from African mines and smelters are lax or non-existent. The net result is that the air, water, soils and

[20] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[21] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[22] https://phys.org/news/2018-09-scientists-reveal-hidden-cobalt-dr.html

vegetation near the mining centres of Africa tend to be severely contaminated with toxic metals"[23].

Life cycle GHG emissions from ore to refined metal is estimated to between 1.45 and 10 kg CO2/kg cobalt[24].

3.2.6 Human health and working conditions

Small-scale artisanal mining is widespread in the DRC and it is estimated that about 10-30% of the cobalt exported from DRC is coming from artisanal mining. There are approximately 110,000 to 150,000 artisanal miners in the region also referred to as 'creuseurs'. Their approach to mining is very primitive compared to the larger commercial mines. Most of the work is done by hand with primitive tools and with no or limited protection gear such as head gear, eye and face protection, respiratory protection, hearing protection, skin and foot protection.

Mining is done by children as young as seven years old who scavenge for rocks containing cobalt and is involved in washing and sorting the ore before it is being sold. It is estimated that approximately 40,000 children work in mines across southern DRC[25].

Mines are open-pit or primitively dug tunnels often located in or close to urban areas. The primitive mining operations result in release of dust containing cobalt and other metals that disperse and settle in the urban areas, thereby exposing not only the miners to toxic metals, but also their families and other residents. Research from artisanal mining regions have shown urine concentrations of cobalt and other metals 10 times higher than concentrations from a normal population.

All health effects from exposure to the toxic dust are not yet clear, but there are signs of DNA damage to the children living close to the mines and an increased risk of birth defects. Inhalation of dust containing cobalt over a long time period can result in fatal lung disease or other respiratory problems such as asthma and exposure to skin can evolve to dermatitis[26].

Also, a large share of the miners carries sacks that contain up to 50 kg of ore which result in strain and risk of long-term injury such as back problems or other physical disabilities. Lastly, miners are exposed to severe or fatal accidents due to lack of access to proper equipment, e.g. collapse of tunnels that are not supported properly. Nonetheless, there are no official statistics that provide an overview to the extent of human health effects and accidents.

3.3 Nickel

Nickel Cobalt Aluminium (NCA) and Nickel Manganese Cobalt (NMC) are the most widely used Li-ion batteries on the market and use 80% and 33% nickel in the cathode, respectively[27]. The advantage of nickel in battery chemistry is that it provides a higher energy density thereby increasing the storage capacity[28]. However, nickel is primarily used

[23] Dunn, J.B; Gaines, L.; Kelly, J.C.; James, C.; Gallagher, K.G. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy and Environmental Science 8, 158–168.

[24] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

[25] https://www.amnesty.org/download/Documents/AFR6231832016ENGLISH.PDF

[26] https://phys.org/news/2018-09-scientists-reveal-hidden-cobalt-dr.html

[27] https://www.nickelinstitute.org/media/2318/nickel_battery_infographic-finalen2.pdf

[28] https://www.nickelinstitute.org/about-nickel/nickel-in-batteries/

for stainless steel production where it provides strength, toughness and corrosion resistance at high temperatures[29].

3.3.1 World nickel production

Nickel is mined in 31 countries around the world, where 66% comes from five countries: Philippines, Indonesia, Russia, Australia and Canada. Nickel must undergo a comprehensive refining and smelting process before becoming pure nickel. The nickel ore is not necessarily refined in the country of origin and the largest producer of refined nickel is China with 31%[30] despite its mining share being only 4%.

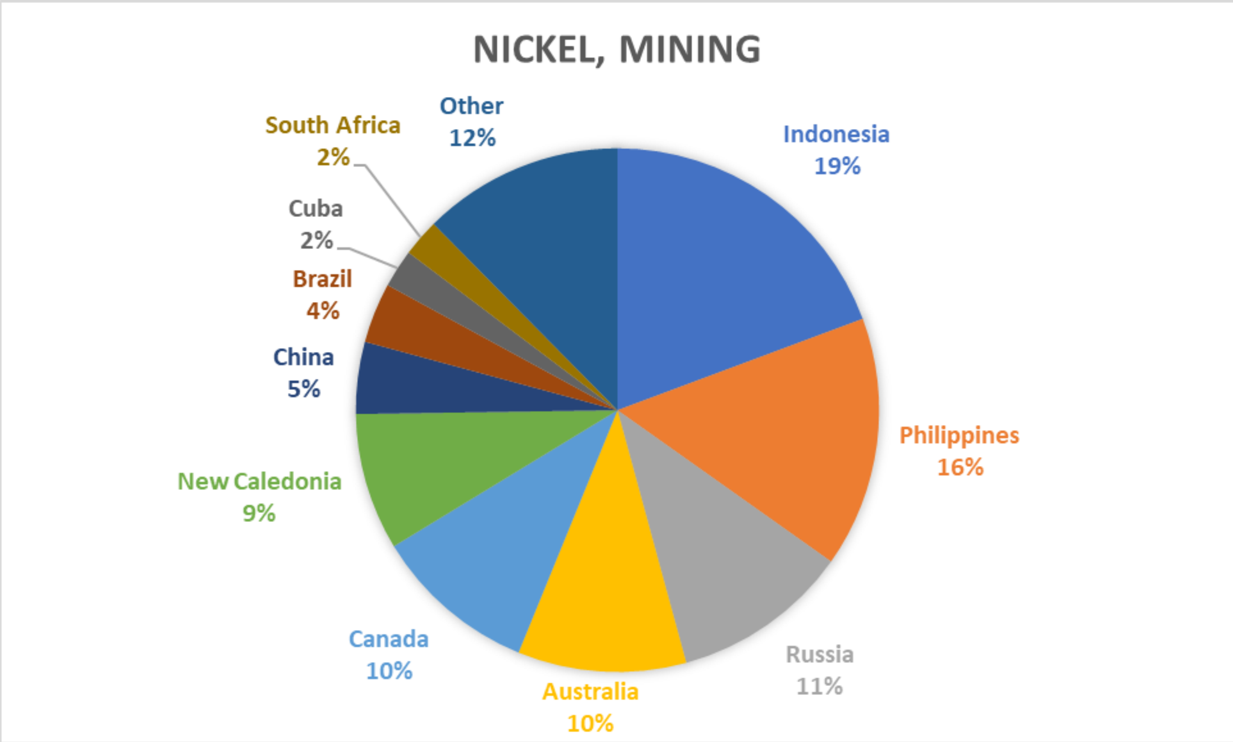

Figure 6: World mining production of nickel (Source: BGS)

The global annual production of nickel has on average been 2.3 million tons in the period 2013-2017. The global production has decreased 32% in the same period (see Figure 7).

[29] JRC (2018) Cobalt demand-supply balances in the transition to electric mobility
[30] EC (2017) Non Critical Raw Material Factsheet

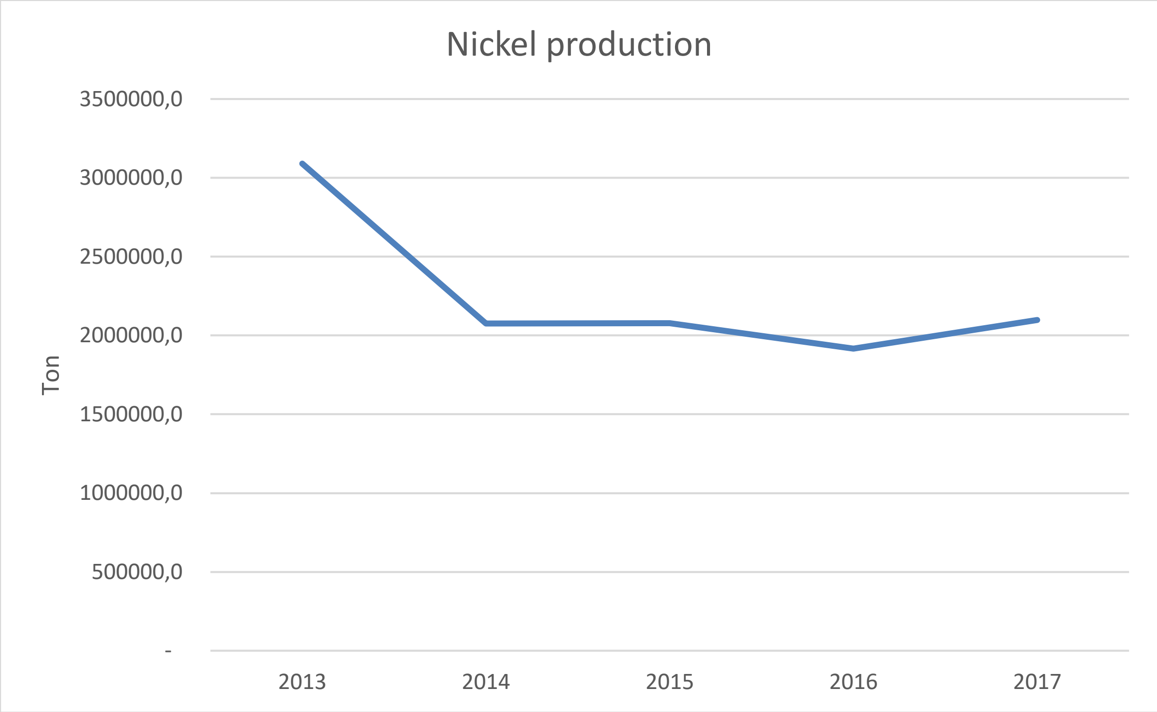

Figure 7: Development in global nickel production

3.3.2 End-use of nickel

70% of global nickel supply is used for stainless steel production where it provides strength, toughness and corrosion resistance at high temperatures. Other uses include other metal alloys and as thin layer plating on materials and equipment to increase corrosion and wear resistance[31].

Nickel consumption for batteries constitutes 6% of the global demand (see Figure 8). This primarily includes the li-ion batteries NMC and NCA. Other nickel-based batteries such as the Nickel - metal hydride battery (NiMH) constitutes a marginal market share. NMC has a market share of 26% of the li-ion battery market and is primarily used for EVs. NCA has a market share of 9% but is primarily used in industrial applications. However, the NCA contains 80% nickel whereas the NMC only contains 33%. A fair estimate of nickel demand going to EVs is therefore 3% or 66,000 tons.

[31] EC (2017) Non Critical Raw Material Factsheet

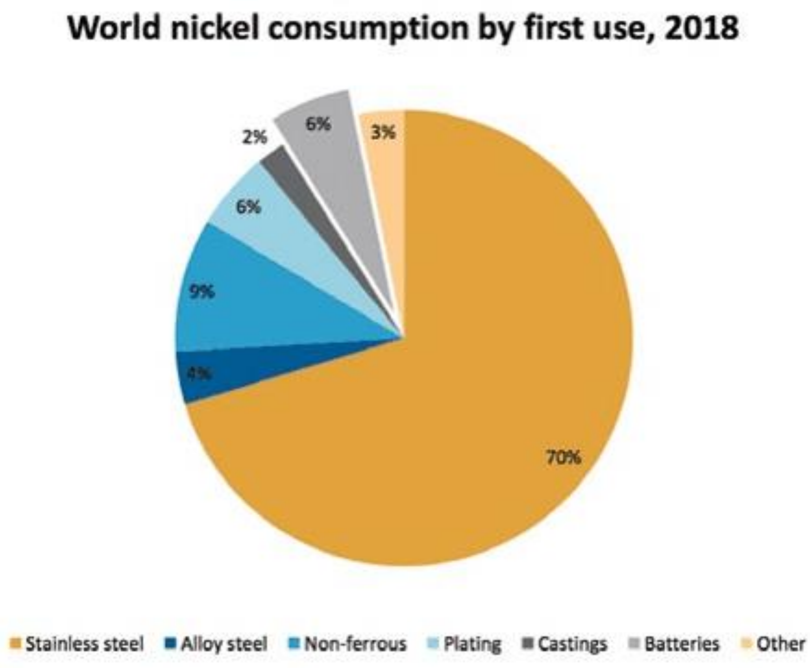

Figure 8: End use of global nickel supply[32]

3.3.3 Forecast and reserves

Global nickel reserves are estimated to 79 million ton with 27% located in Australia and Brazil, which is about 40 years of the current production rate. The demand for nickel from li-ion batteries is forecasted to increase by 16 times by 2030 to 1.8 million tons. This is 80% of the current annual production. 210,000 tons is estimated to be demanded by the EU in 2030[33]. EV battery suppliers are concerned of future nickel supply deficit mainly caused by lack of investments in new mines[34]. The timeline from exploration to a fully functioning mine can take at least a decade.

3.3.4 Governance

Five out of six governance indicators are positive with Government Effectiveness being the best at 0.36, as seen in Table 3. The only negative indicator is Political Stability at -0.19. This indicator is primarily influenced by the Philippines which has a score of -1.12 and is the second largest producer of nickel.

[32] https://www.theassay.com/base-metals-insight/nickels-chance-to-shine-again/

[33] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 Task 7

[34] https://www.bloomberg.com/news/articles/2019-08-05/there-s-one-metal-worrying-tesla-and-the-ev-battery-supply-chain

Table 3: Worldwide Governance Indicator scores for nickel producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	0.17
Political Stability and Absence of Violence/Terrorism	-0.19
Government Effectiveness	0.36
Regulatory Quality	0.26
Rule of Law	0.07
Control of Corruption	0.10
Average score	**0.13**

An average WGI score of 0.13 is considered to be an intermediate level of governance, whereas the weighted environmental performance index (EPI) classifies nickel as having a low environmental hazard potential, implying a better level of governance.

3.3.5 Environment

Mining and refining of nickel have been associated with a range of environmental problems from leakage of mining waste into local waterways and emissions of sulphur dioxide to the air from nickel refining and smelting, which is the cause of acid rain and linked to heavy-metal contamination of water systems.

Environmental Impacts associated with nickel extraction and refining are heavily dependent on the type of extracted ore (sulfidic or lateritic), and on the type of process used (pyrometallurgy or hydrometallurgy). Lateritic ores are mainly extracted in areas which are considered hotspots of terrestrial and marine biodiversity (Indonesia, Philippines, New-Caledonia), and which are prone to erosion due to heavy rainfalls. Sulfidic ores may lead to acid mine drainage in the mining stage, and to large sulphur dioxide emissions in the smelting phase. Pyrometallurgical plants are associated with large energy needs and large $C0_2$ emissions. For hydrometallurgical plants, the tailings management is the main environmental issue. The highly controversial “deep-sea tailings placement” method is used by a small number of plants, or projected new plants.

The largest producer of nickel is the Philippines, which in 2017 closed or suspended 17 nickel mines because of environmental concerns. Also, Norilsk in Russia, one of the world’s largest sites for nickel mining and refining, have experienced leakage of mining waste to the local river and heavy emissions of sulphur dioxide[35]. Environmental concerns related to Nickel mining often arise because a considerable percentage of nickel is mined within or near to protected areas[36].

Life cycle GHG emissions from ore to refined metal is estimated to between 5.25 and 10 kg CO2/kg nickel[37].

[35] Drive Sustainability – Material Change
[36] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[37] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

3.3.6 Human health and Working conditions

Sulphur dioxide air pollution, primarily related to sulphidic nickel ores, not only causes acid rain but also affects human health when breathed in. It can be fatal at very high concentrations and at lower concentrations cause breathing problems and eye irritation and lead to respiratory diseases such as asthma[38]. This affects both the local population living near mines and refining plants but also the workers if they don't wear proper protection gear[39]. This is especially a risk in countries with weak laws on worker rights.

3.4 Lithium

Lithium is a highly reactive mineral and therefore only becomes stable in compound with other elements. Lithium carbonate is the most widely used but also lithium hydroxide is becoming more common in battery production. Lithium is mined from two sources, either from hard rock which resembles mining of other metals, or extracted from brine, which is pumped from underground. Both sources of lithium can be transformed into the needed compound[40].

3.4.1 World lithium production

There are 9 countries in the world producing lithium. Australia, Zimbabwe, Portugal and Brazil are extracting from hard rocks, whereas Chile, Argentina, Bolivia and USA extract from brines. China is extracting from both sources. Chile and Australia produce the far majority of all lithium (76%), followed by Argentina (13%) and the remaining countries have a marginal share (see Figure 9). The specific compounds used in the battery chemistry are mainly produced in the same country where the lithium ore has been mined. However, China stands out with and increased share of lithium compounds production compared to its mining production, which means they import lithium ore for refining[41].

[38] https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects
[39] http://stop-mad-mining.org/wp-content/uploads/2015/10/2017_philipppinenbuero_Nickel__ENG__web.pdf
[40] EC (2017) Non Critical Raw Material Factsheet
[41] EC (2017) Non Critical Raw Material Factsheet

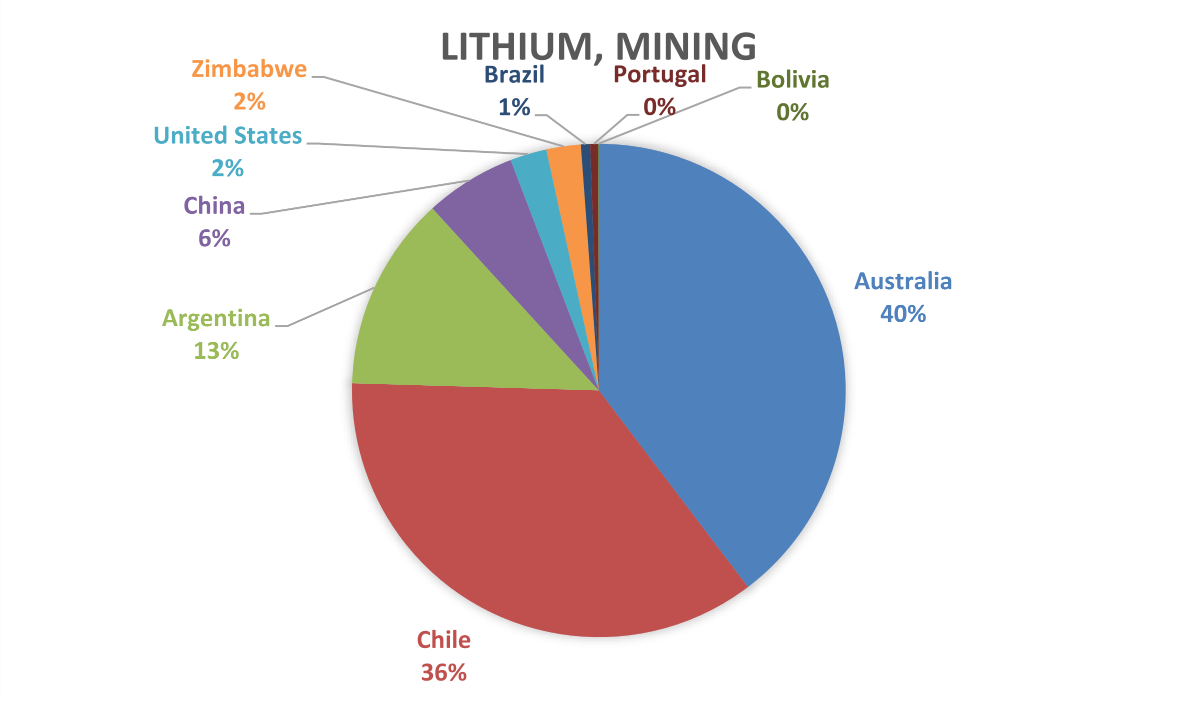

Figure 9: World lithium mining (Li2O equivalents) (Source: World Mining Data).

The average annual production of lithium was 76,000 ton in the period 2013-2017. However, is has seen a dramatic increase and almost doubled from 60,000 tons to 107,000 tons in the same period (see Figure 10).

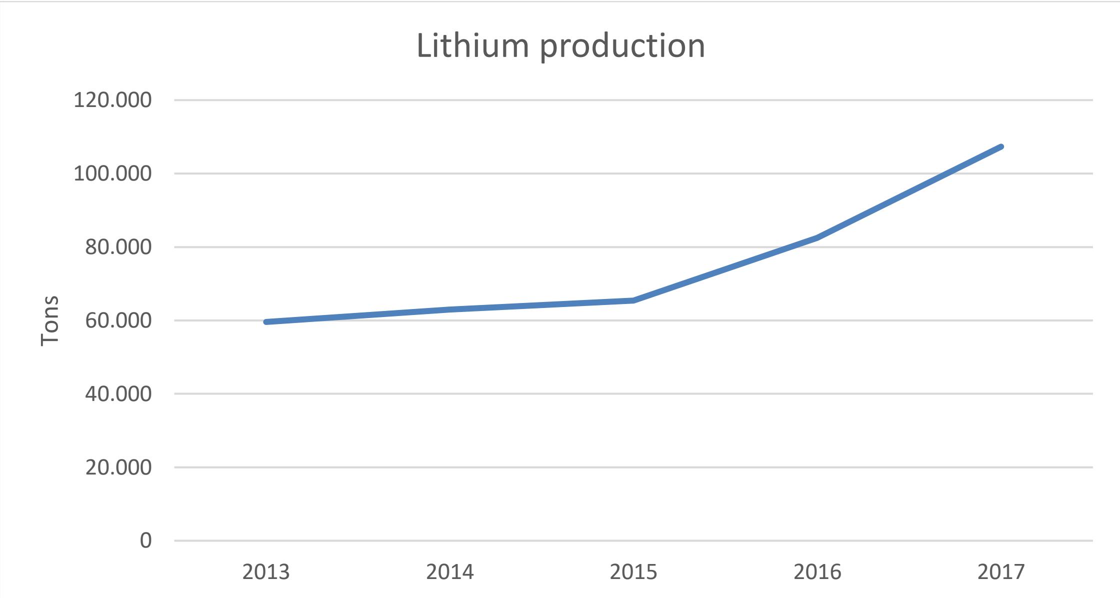

Figure 10: Development of lithium production in the period 2013-2017.

3.4.2 End-use

Globally, lithium is mainly used for rechargeable batteries (56%), where other primary uses are within the glass- and ceramics industry and for one of the most widely used types of lubricating greases. The most widely used batteries for EVs (LMO, LFP, NMC) constitute 70%

of the li-ion battery market. Consequently, a fair estimate of EV batteries' demand of the global lithium production is 39% equivalent to 42,000 tons in 2017.

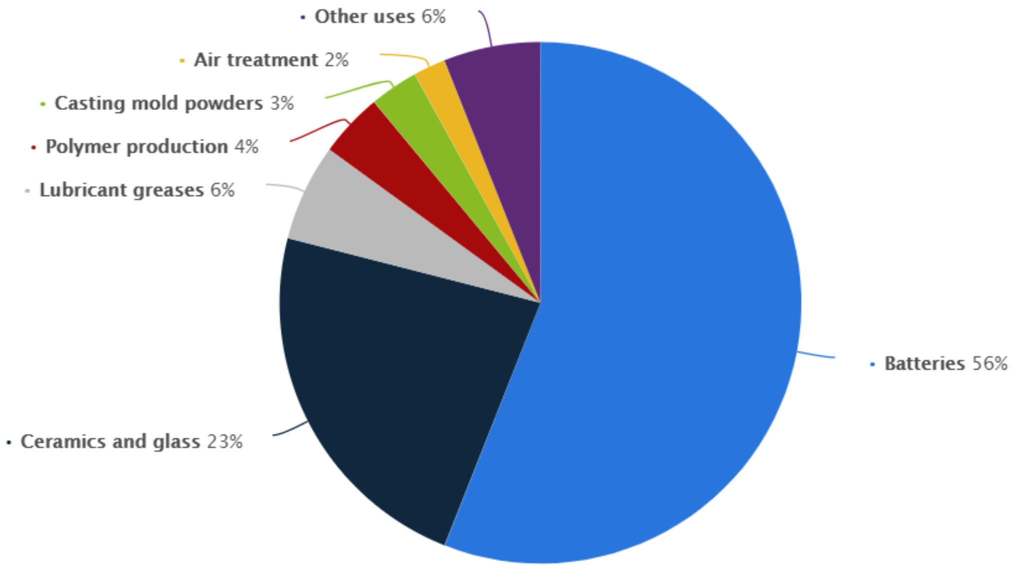

Figure 11: World lithium end-use[42]

3.4.3 Forecast and reserves

Global reserves of lithium are estimated to about 41 million tons with the most significant shares held by the already top producing countries – Chile (7.5 million tons), China (3.2 million tons), Argentina (2.0 million tons) and Australia (1.5 million tons). However, Chiles neighbouring country Bolivia are believed to hold the largest reserves of all at up to 9 million tons[43]. These reserves are practically untouched, and Bolivia only produced 120 tons of lithium in 2017. Bolivia is well aware of its major potential as a large lithium producer and has invested large sums into kickstarting mining developments[44]. 90,000 tons is expected to be demanded by the EU in 2030[45].

3.4.4 Governance

All six indicators are positive for lithium with an average of 0.97 suggesting a good level of governance for the lithium sourcing countries. Regulatory Quality has the highest score of 1.21 and Political Stability has the lowest score of 0.53 (see Table 4).

[42] https://www.statista.com/statistics/268787/lithium-usage-in-the-world-market/
[43] EC (2017) Non Critical Raw Material Factsheet
[44] https://www.mining.com/web/bolivia-revolutionaries-lithium-miners-go-die/
[45] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 Task 7

Table 4: Worldwide Governance Indicator scores for lithium producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	0.94
Political Stability and Absence of Violence/Terrorism	0.53
Government Effectiveness	1.07
Regulatory Quality	1.21
Rule of Law	1.05
Control of Corruption	1.06
Average score	**0.97**

The weighted environmental performance index (EPI) classifies lithium as having a low environmental hazard potential, thereby supporting the WGI score.

3.4.5 Environment

Regarding life cycle GHG emissions from ore to refined metal, brine extraction process is in general less intensive. On average it emits 2 kg CO_2 per kg lithium. However, there are examples from brine extraction where the brine is heated up in order to increase evaporation and thereby speeding up the process. This is very energy intensive and leads to higher GHG emissions[46]. In comparison, GHG emissions related to extraction from hard rock is as high as 27 kg CO_2 per kg lithium[47].

The main concern from brine extraction is the high water consumption in the already very dry region impacting both local farmers and the ecosystem[48]. The industry benchmark for water consumption in brine extraction operation is between 150-1000 m3/ton of lithium according to industry stakeholders. Both Argentina and Chile have experienced problems with the high water consumption from brine extraction of lithium[49].

There are also examples of leakage of toxic chemicals, used in the processing of lithium, into the local environment in Australia, United States and China[50].

3.4.6 Human health and Working conditions

Leakage of toxic chemicals from lithium mining can have adverse effects on human health, but the risk is considered low and only few examples have been identified. The toxicity of lithium itself is not very high but chronic exposure leading to lithium accumulation in the human body can lead to adverse health effects[51].

Brine extraction is a relatively less labour-intensive form of mining with little exposure to dust, fallen rocks and explosives. Lithium extraction from hard rock is dominantly occurring in Australia, where there is strong law on working conditions. The risk of poor working conditions is therefore considered low.

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[46] https://www.wired.co.uk/article/lithium-batteries-environment-impact
[47] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf
[48] Drive Sustainability – Material Change
[49] https://www.lexology.com/library/detail.aspx?g=7a3d0fa2-d817-4667-9315-92edbf36920d
And: https://eandt.theiet.org/content/articles/2019/08/lithium-firms-are-depleting-vital-water-supplies-in-chile-according-to-et-analysis/
[50] https://www.wired.co.uk/article/lithium-batteries-environment-impact
[51] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3918183/

3.5 Manganese

Manganese is a relative abundant element in the earth's crust and is typically found together with iron but is normally mined as a primary product. Manganese is a critical and irreplaceable metal used in steel production but is also an important part of many Li-ion battery types.

3.5.1 World manganese production

Manganese production is currently occurring in 34 countries in the World but is dominated by four countries: South Africa (27%), Australia (17%), China (16%) and Gabon (11%) with a combined share of 71% (see Figure 12).

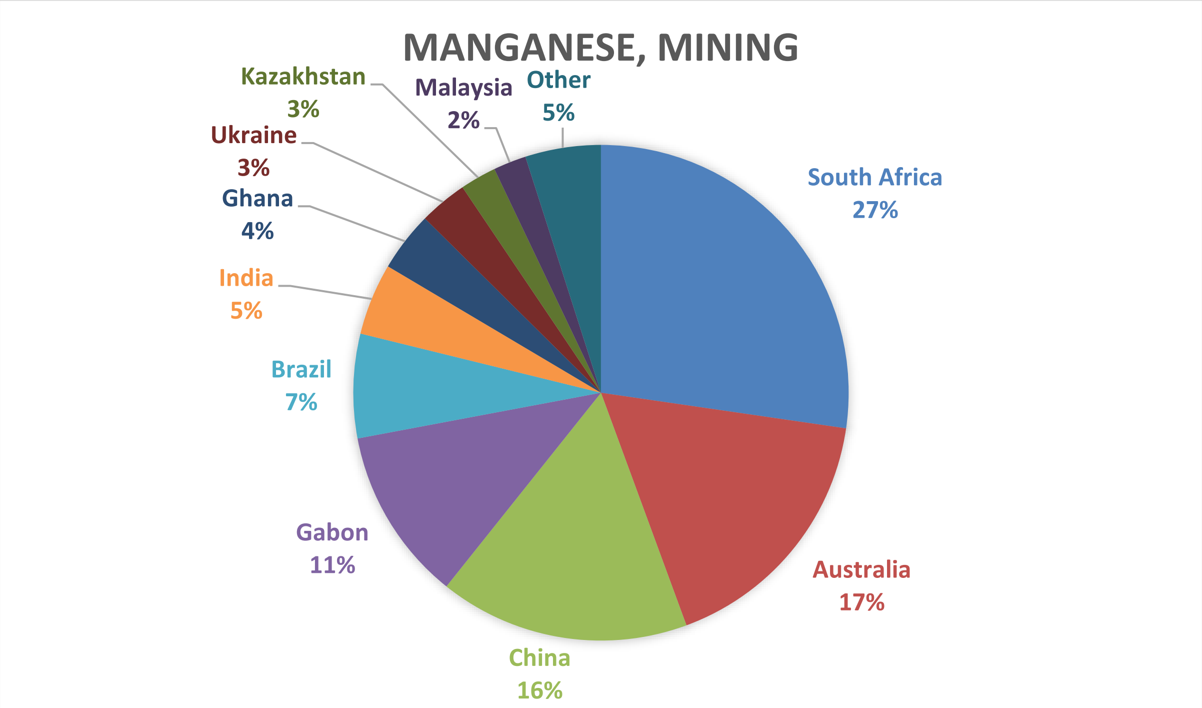

Figure 12: World production of manganese (Source: World Mining Data).

The average annual global production of manganese ore is 17.4 million tons in the period 2013-2017. The development in annual production has been fairly stable in the same period. It should be noted that ASM mining is occurring in a number of manganese producing countries, such as South Africa, China, Gabon, Brazil, India and Ghana. This production is not included in the national statistics[52] and it has not been possible to quantify the share of world manganese production from ASMs.

[52] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

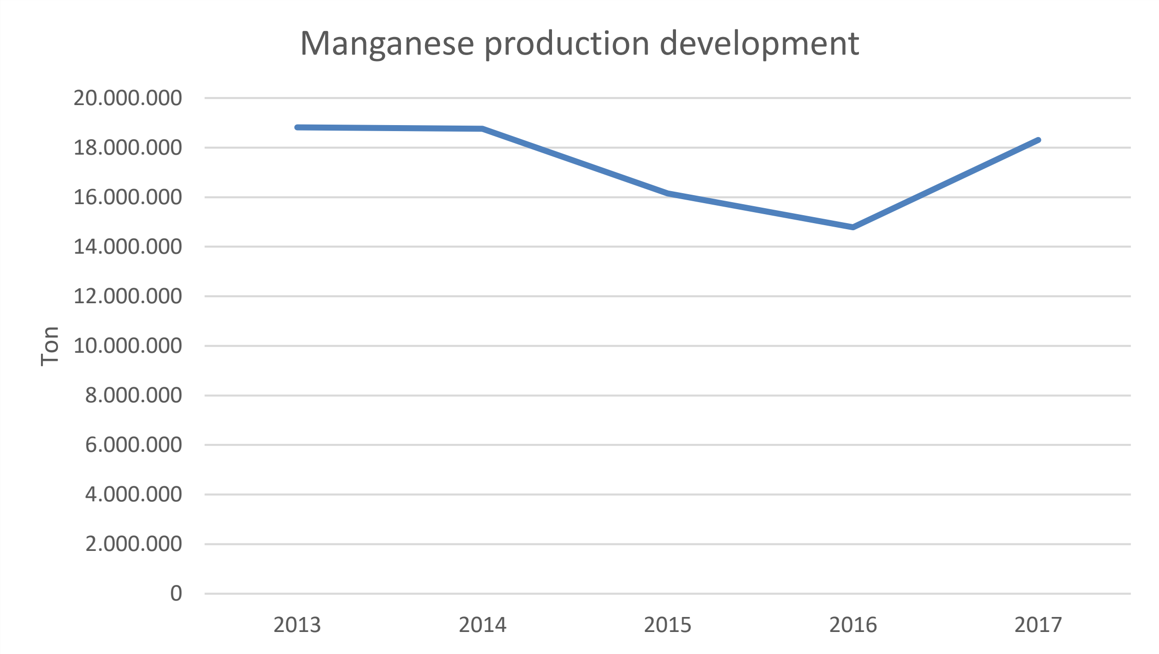

Figure 13: Manganese production development in the period 2013-2017

3.5.2 End-use

Manganese is a critical and irreplaceable metal in steel production because of its de-sulphurizing and deoxidizing properties that strengthens steel. Consequently, the dominant end-use of manganese is in steel production at 87% of total supply. Manganese is also used in other metal alloys and about 2% of the global production goes to batteries. Manganese share some of the same qualities as cobalt but is considerably cheaper, which is therefore replaced to some extent without compromising performance[53]. Manganese is an essential element in the Li-ion battery types LMO and NMC which are predominantly used for EVs. A fair assumption is therefore that the far majority of manganese used for battery production goes to EV batteries.

[53] http://www.manganesexenergycorp.com/single-post/2017/07/20/Manganese-Critical-Metal-for-Battery-and-Electric-Vehicle-Markets

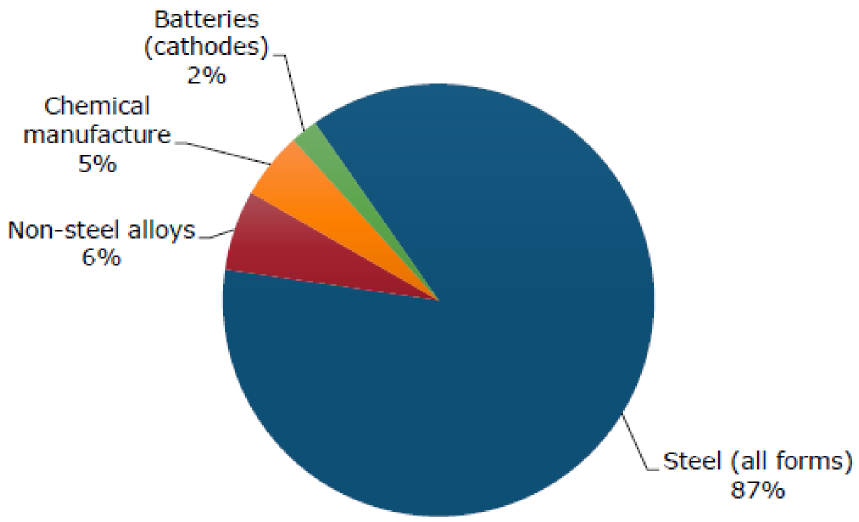

Figure 14: End-use of manganese[54]

3.5.3 Forecast and reserves

Manganese is a relatively abundant element in the Earth's crust and the global reserves are therefore large – estimated to 620 million tons. Almost 85% are located on South Africa and Ukraine. However, the manganese content in most minerals are quite small and therefore not economically viable to extract. Consequently, Ukraine's share of global production is a mere 3% despite their large resources[55]. Steel production is expected to increase by about 2% annually and will therefore continue to drive the manganese supply. However, manganese for battery production is expected to increase exponentially, since manufacturers are continuously researching in increasing the manganese content of batteries in order to limit the use of other more controversial metals[56]. 105,000 tons is expected to be demanded by the EU in 2030[57].

3.5.4 Governance

The average indicator score is slightly above zero at 0.11 suggesting an intermediate level of governance with the only negative indicator being Political Stability at -0.13. The highest scoring indicator is Government Effectiveness at 0.32 (see Table 5).

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[54] EC (2017) Non Critical Raw Material Factsheet
[55] EC (2017) Non Critical Raw Material Factsheet
[56] https://www.mining.com/web/manganese-the-third-electric-vehicle-metal-no-one-is-talking-about-it-heres-how-to-take-advantage/
[57] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 Task 7

Table 5: Worldwide Governance Indicator scores for manganese producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	0.10
Political Stability and Absence of Violence/Terrorism	-0.13
Government Effectiveness	0.32
Regulatory Quality	0.23
Rule of Law	0.10
Control of Corruption	0.06
Average score	**0.11**

The weighted environmental performance index (EPI) classifies manganese as having a high environmental hazard potential, implying a very poor level of governance, which to some degree is contradicting the WGI score.

3.5.5 Environment

Release of manganese to the environment will at lower levels not harm wildlife or animals. However, it will have a toxic effect at higher levels and has a tendency to accumulate in some plants and animals and potentially increase risks further up the food chain[58].

In general manganese mining possess the same risks as for other mining activities, including risk of releasing geogenic radioactive substances. The risk is more profound in countries with poor legislation and/or weak law enforcement and with ASM, which is likely the case for the countries where most of global manganese is sourced – such as South Africa, Gabon and China. Mining in or close to protected areas increases the environmental risks to ecosystems.

Life cycle GHG emissions from ore to refined metal is estimated to 6 kg CO2/kg manganese[59]. This estimate is based on a pyrometallurgical route. Manganese for EV batteries will most likely be in the form of electrolytic manganese dioxide, which follows a very different industrial route, probably with less GHG emissions, but no data has been found for this route[60].

3.5.6 Human health and Working conditions

Manganese is essential to development and metabolism in humans. However, overexposure to manganese from e.g. dust or water contamination typically occurring from mining activities has been observed to cause a Parkinson's disease-like neurological condition called manganism[61]. Some manganese ore deposits show high concentrations of radioactive nuclides, from which workers might get exposed if not handled properly[62].

[58] http://apps.sepa.org.uk/spripa/Pages/SubstanceInformation.aspx?pid=106
[59] https://link.springer.com/article/10.1007/s11367-015-0995-3
[60] Stakeholder comment
[61] https://www.sciencedirect.com/topics/engineering/manganese
[62] https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/099/45099894.pdf

3.6 Aluminium

Aluminium is the most abundant metal in the Earth's crust (8.1%) and is the third most abundant element after oxygen and silicon.

Bauxite is the main ore of aluminium. Approximately 90% of bauxite mined in the world is converted to alumina (aluminium oxide). 80–90% of the world's alumina is smelted to aluminium. Almost all aluminium production is from bauxite[63].

3.6.1 World aluminium production

The first step of aluminium production is the mining of bauxite ore. It is currently occurring in 33 countries worldwide. The far majority (80%) of bauxite comes from five countries: Australia (29%), China (21%), Brazil (13%), Guinea (9%) and India (8%). The total production has on average been 288 million tons in the period 2013-2017.

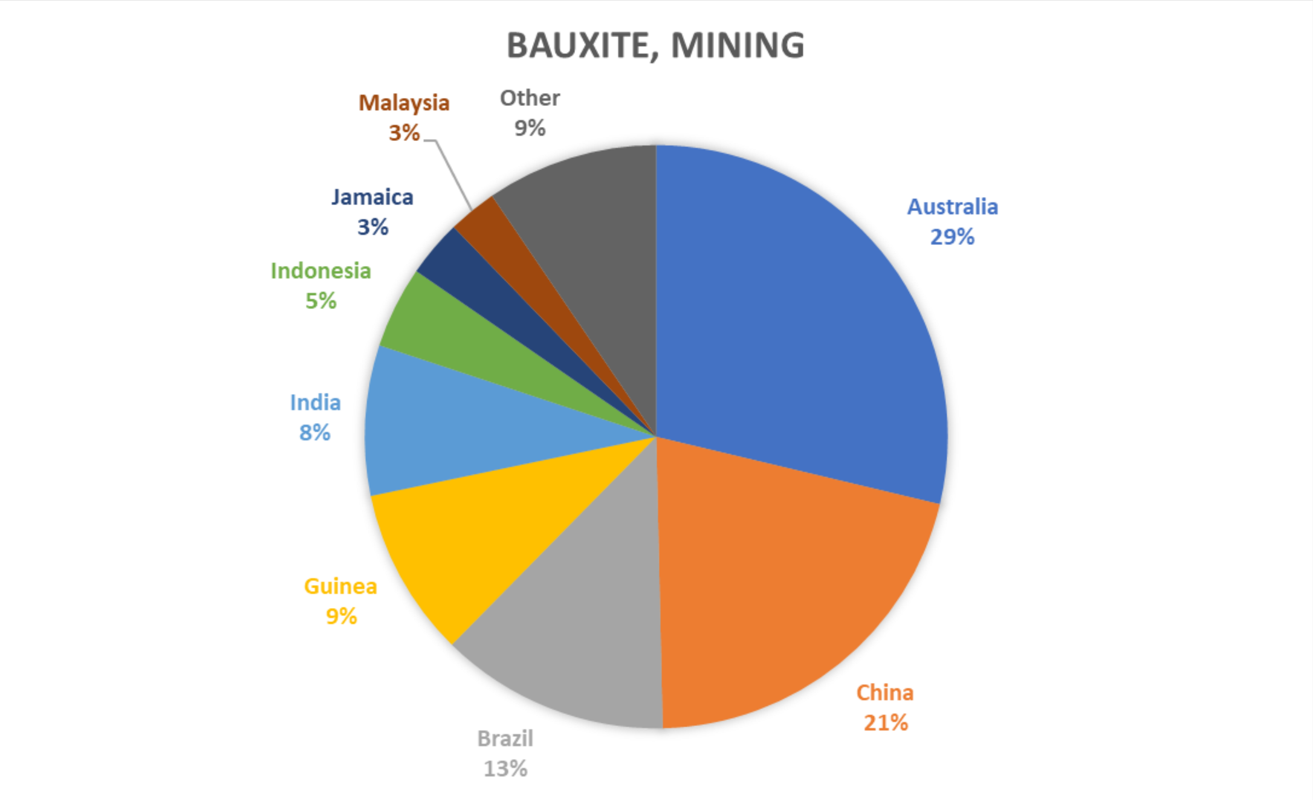

Figure 15: World production of bauxite (Source: BGS).

85% of all bauxite is further converted into aluminium oxide which can finally be processed into aluminium metal. The processing is not necessarily taking place in the mining country but is shipped to other countries. Australia which is mining the largest share of bauxite (29%) is only processing 3% of aluminium metal, as shown in Figure 16. China is by far the largest producer of aluminium at 53% of the world total. The remaining production is spread to 42 countries.

[63] EC (2017) Non Critical Raw Material Factsheet

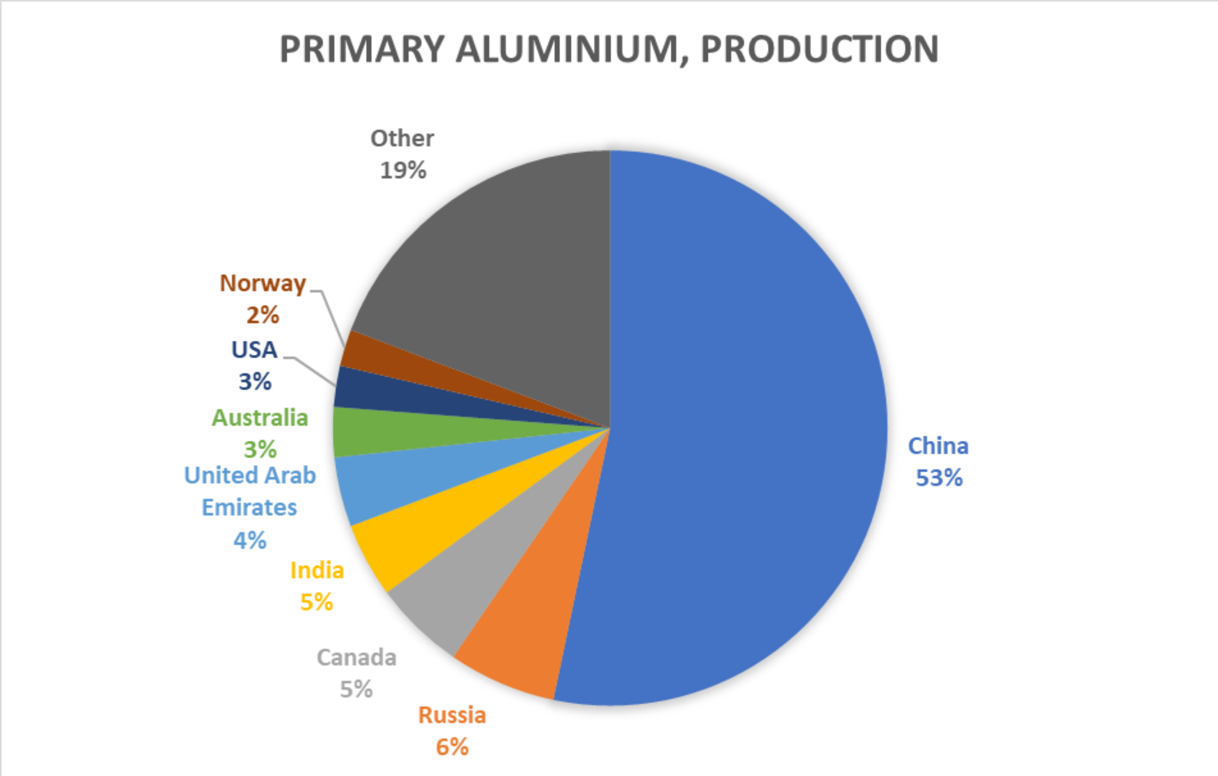

Figure 16: World primary aluminium production (Source: BGS)

Around 4-6 tons of bauxite is required to produce one ton of aluminium. The average annual global production was 57 million tons in the period 2013-2017. There has been a considerable increase in production in the same period at about 20% (see Figure 17).

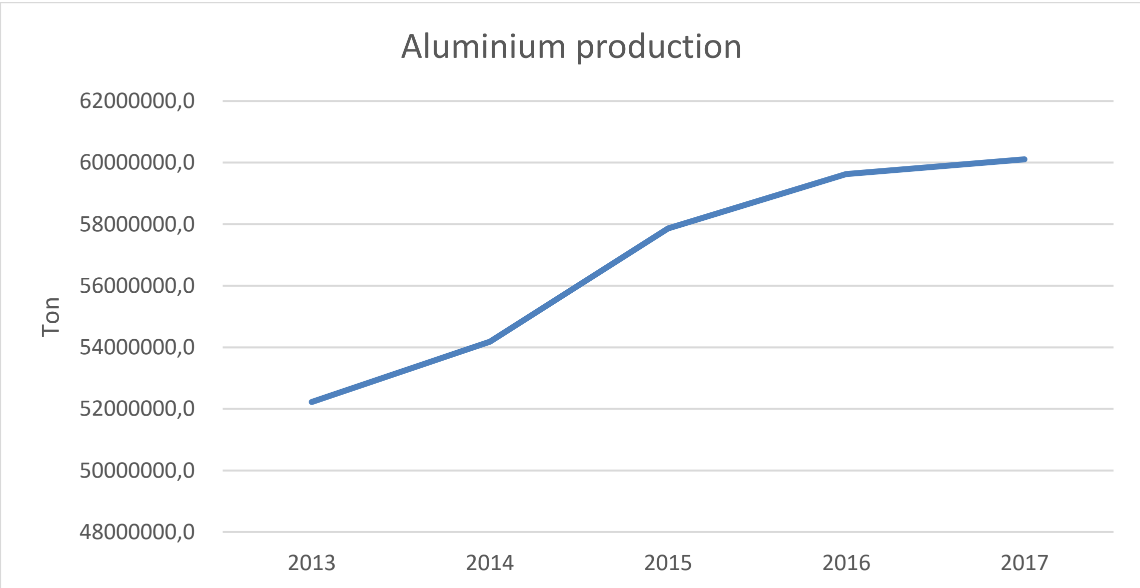

Figure 17: Development in aluminium production in the period 2013-2017

3.6.2 End-use

Due to its qualities as light, strong and flexible, aluminium is widely used in the transportation industry for cars, trains, aircrafts and bicycles instead of steel, which is significantly heavier but otherwise share the same qualities. For the same reasons it is also widely used in construction and equipment. Other uses include packaging, such as beverage cans and aluminium foils, and consumer durables such as cooking ware, phones and laptops.

The only Li-ion battery to include aluminium in its battery chemistry is the NCA type. It is similar to NMC and has a higher capacity. However, it is less safe and has higher cost and therefore not suitable for EVs[64]. Batteries have been developed where lithium is replaced by aluminium proving to have significantly higher capacities. However, these are still at an experimental level and not yet ready for upscaling[65].

The main use of aluminium in EV batteries is instead for peripheral use such as the casing of the battery system. Despite aluminium constituting a relatively large share of a battery systems weight it is considered as having an insignificant share of the overall global consumption.

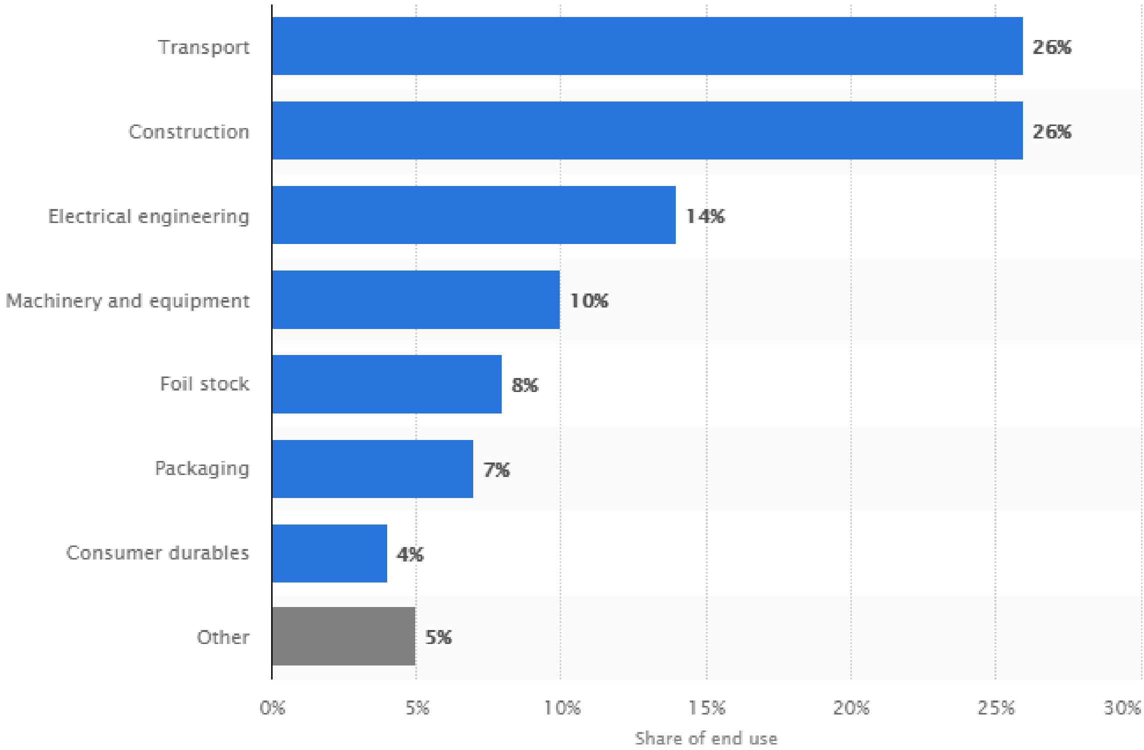

Figure 18: End-use of aluminium[66]

3.6.3 Forecast and reserves

The reserves of bauxite have been estimated to be about 28 billion tons globally with the largest reserves in Guinea, Australia and Brazil. Nonetheless, aluminium is termed an almost inexhaustible resource due to its abundance the Earth's crust also in other minerals besides bauxite. However, these resources are not yet economically viable to extract[67]. Furthermore, in many of the end-uses aluminium is not mixed with other metals, which makes the recycling

[64] https://batteryuniversity.com/index.php/learn/article/types_of_lithium_ion
[65] https://www.designnews.com/electronics-test/can-aluminum-take-us-beyond-lithium/44692193958697
[66] https://www.statista.com/statistics/280983/share-of-aluminum-consumption-by-sector/
[67] EC (2017) Non Critical Raw Material Factsheet

of aluminium easier and thus cheaper, especially compared to the energy intensive mining process.

A constant growth in the demand for aluminium is expected, particularly driven by the auto and aerospace industries. Ironically, it is the expected increase in EVs, requiring lightweight materials to decrease energy consumption, that is one of the primary drivers. An annual growth of 2.8% is expected towards 2028 creating a demand of about 80 million tons compared to the current 60 million tons[68].

3.6.4 Governance

The average score across all 6 indicators is just above zero at 0.05 suggestion an intermediate level of governance (see Table 5). One indicator standing out is Voice and Accountability with a low score of -0.70 which is mainly influenced by the large share of World production in China.

Table 6: Worldwide Governance Indicator scores for aluminium producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	-0.70
Political Stability and Absence of Violence/Terrorism	-0.07
Government Effectiveness	0.61
Regulatory Quality	0.20
Rule of Law	0.16
Control of Corruption	0.12
Average score	**0.05**

The weighted environmental performance index (EPI) classifies aluminium as having a medium environmental hazard potential, thereby supporting the WGI score.

3.6.5 Environment

Since it takes 4-6 tons of bauxite to produce one ton of aluminium there a very large amount of waste material which needs to be handled. The resulting bauxite residue is referred to as 'red mud' which are stored in open holding ponds. This creates a risk of sudden collapses that will release 'red mud' to its surroundings contaminating large areas and waterways. This happened in Hungary in 2010 exterminating all life in the nearby river and killing 10 people[69].

Another concern from aluminium production is the very high energy consumption compared to other metals. Consequently, the life cycle GHG emissions from ore to refined metal from one kg of aluminium is 12 kg CO2eq compared to steel of 1 kg CO2eq.

Furthermore, bauxite is mostly mined from open pit mines which have a significant impact on local wildlife and vegetation[70]. This is especially important since many bauxite deposits are located in tropical rainforest areas[71]. Land and soil degradation, biodiversity and proper rehabilitation practice are therefore major environmental concerns for aluminium production.

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[68] https://www.mining.com/global-aluminium-market-remain-undersupplied-coming-years-report/
[69] http://www.greenspec.co.uk/building-design/aluminium-production-environmental-impact/
[70] https://recyclenation.com/2010/11/aluminum-extraction-recycling-environment/
[71] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

3.6.6 Human health and Working conditions

Bauxite contains aluminium hydroxide, iron oxide and titanium oxide which all are damaging to human health to varying degrees. Local people and miners can be exposed to these substances through dust occurring from the mining operations and transportation of bauxite. Several regions in Malaysia have experienced problems with air pollution from nearby bauxite mines[72].

3.7 Iron

Iron is an abundant element in the Earth's crust and most widely used metal. Approximately 98% of mined iron ore in the world is used in iron and steel manufacturing. Pure iron is rarely used because it is soft and oxidises rapidly in air, instead it is combined with other elements into different types of steel to increase strength and durability. These elements are for example carbon, chromium, nickel, molybdenum, tungsten, copper, manganese, silicon, niobium and vanadium[73].

3.7.1 World iron production

Iron ore is currently mined in 54 countries around the world, but five countries supply 78%: Australia (31%), China (24%), Brazil (16%) and India (7%). Not all iron is processed locally but instead exported for steel production. China produces approximately half the World's steel[74].

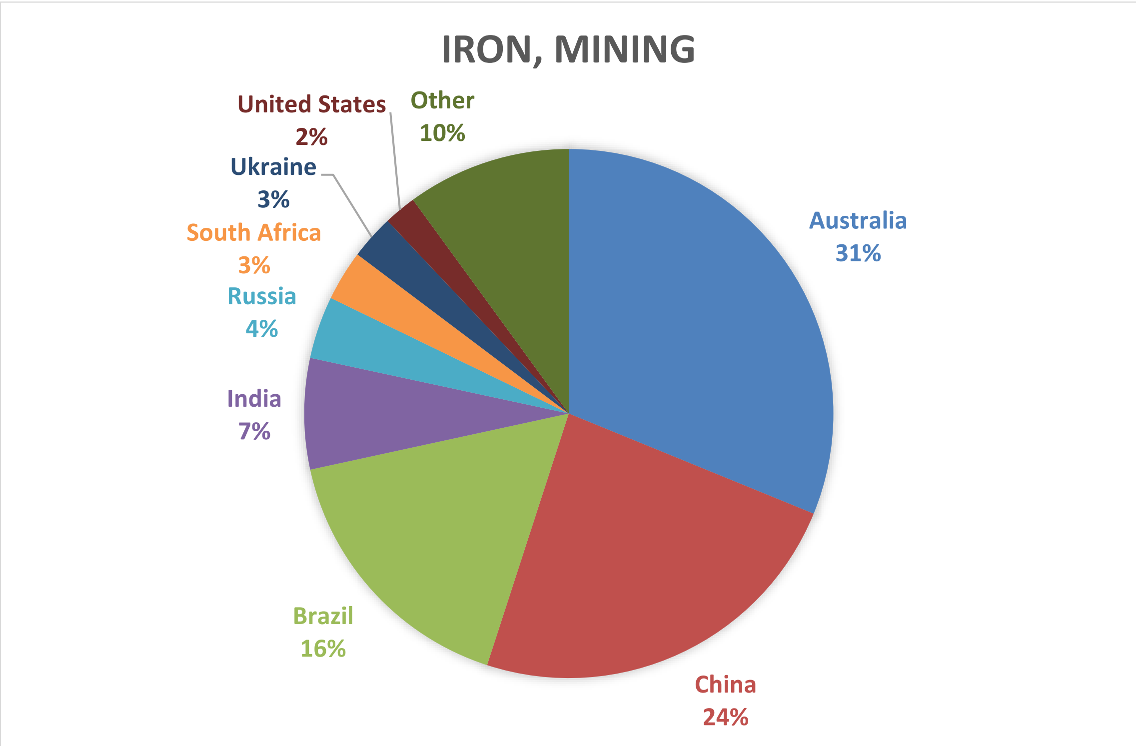

Figure 19: Annual World mining of iron (Source: World Mining Data).

[72] https://www.malaysiakini.com/letters/326807
[73] EC (2017) Non Critical Raw Material Factsheet
[74] EC (2017) Non Critical Raw Material Factsheet

The annual average production globally was 1.5 billion tons in the period 2013-2017. The production has seen a steady increase at about 8% in the same period (see Figure 20).

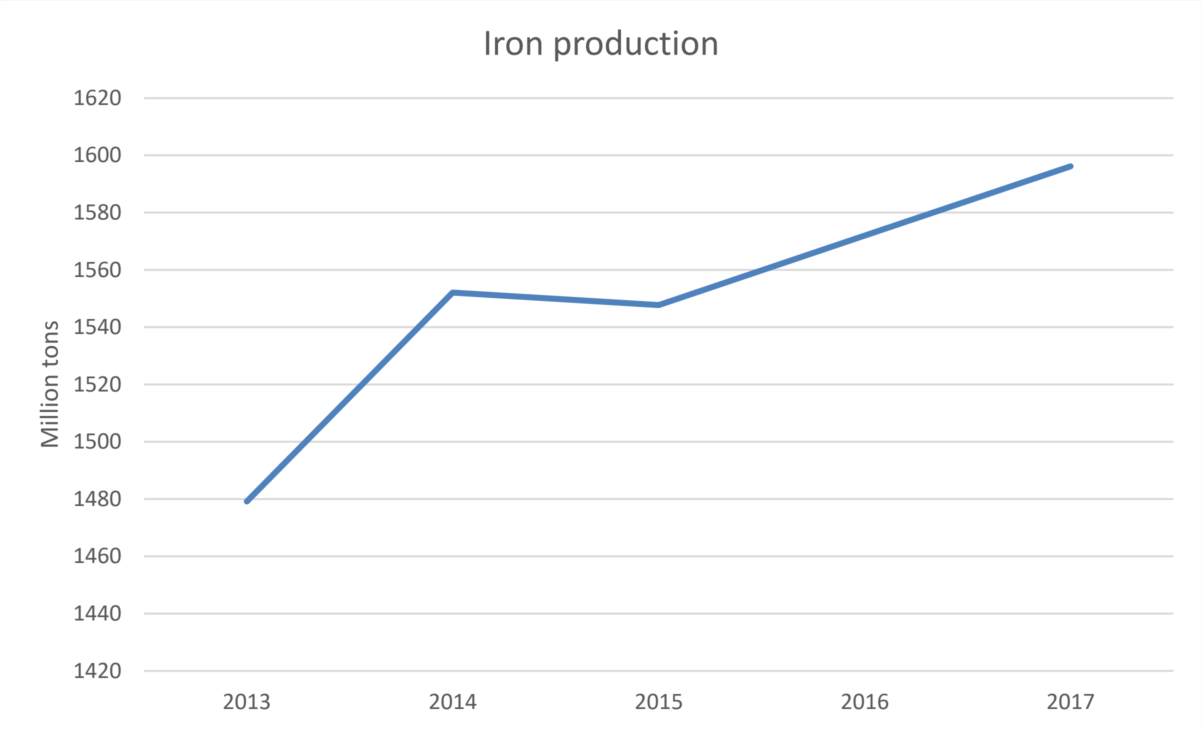

Figure 20: Development in iron production in the period 2013-2017

3.7.2 End-use (steel)

Iron is predominantly used for steel production, which has an array of different uses. The largest share (49%) is used in the construction sector, e.g. as structural material in buildings. Other uses include production of motor vehicles and in mechanical engineering for tools and machinery (see Figure 21).

Just like with aluminium, iron is not part of the battery chemistry but instead used at varying degrees for the housing and casing of the battery system. Despite iron/steel constituting a relatively large share of a battery systems weight it is considered as having an insignificant share of the overall global consumption.

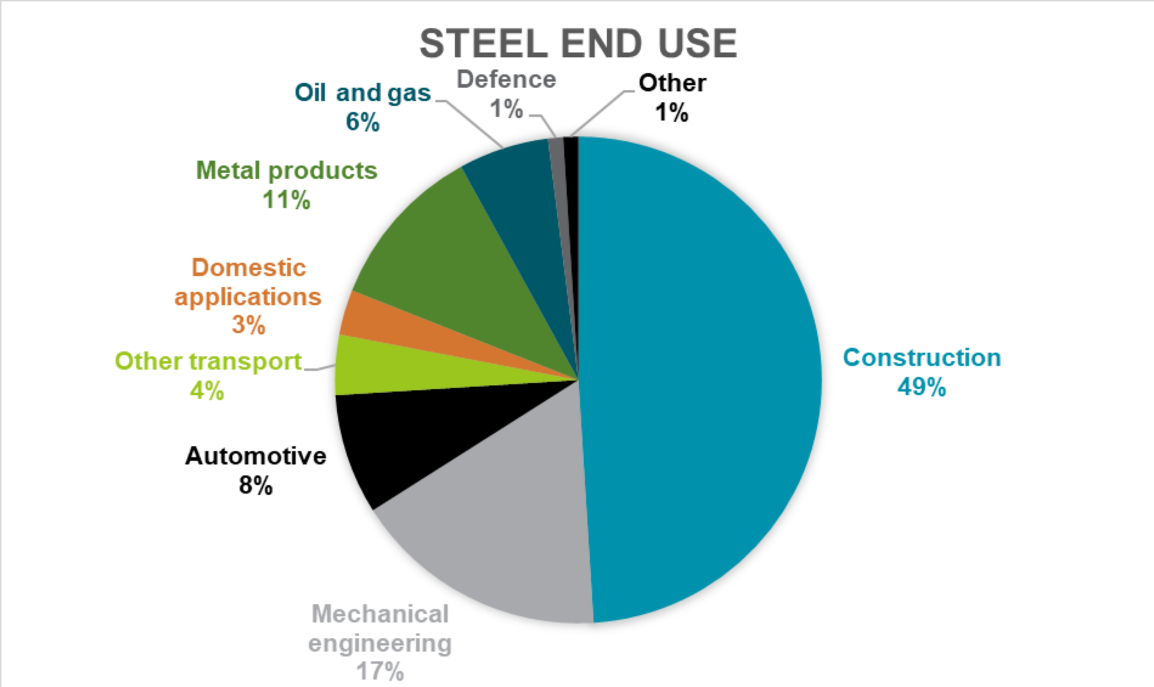

Figure 21: End use of steel globally[75]

3.7.3 Forecast and reserves

The global reserves of iron have been estimated to about 230 billion tons, primarily found in Australia, Russia, Brazil and China.

The global demand for steel is expected to increase at an annual rate of about 1.1% towards 2035 and reach 1.9 billion tons[76]. This trend is primarily driven by emerging economies requiring steel for buildings and infrastructure developments.

3.7.4 Governance

All six indicators are positive suggesting a good level of governance for the iron sourcing countries. Government Effectiveness has the highest score of 0.62 and Political Stability has the lowest at 0.05 (see Table 7).

Table 7: Worldwide Governance Indicator scores for iron producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	0.20
Political Stability and Absence of Violence/Terrorism	0.05
Government Effectiveness	0.62
Regulatory Quality	0.54
Rule of Law	0.44
Control of Corruption	0.41
Average score	**0.38**

[75] https://www.steelonthenet.com/consumption.html
[76] https://www.oecd.org/industry/ind/Item_4b_Accenture_Timothy_van_Audenaerde.pdf

The weighted environmental performance index (EPI) classifies iron as having a low environmental hazard potential, thereby supporting the WGI score.

3.7.5 Environment

Most environmental impacts from steel production are related to the production and use of coke. Coke is made of coal and used as a fuel and reactive reduction agent when melting iron ore. It is preferred over other fuels because it is cheap and produce high heat and little smoke. However, the production of coke is a major air pollution source where toxic gasses and dust is released. Large quantities of water are used in cooling the coke after use which then becomes contaminated. If not handled properly this possess a risk of leaking into the local environment[77].

Due to the very large volumes of iron ore processed globally there is an enormous amount of mining waste that needs to be stored in so-called tailing dams. There are several examples of tailing dam failures which can have grave consequences for the local environment and be fatal for nearby communities[78].Furthermore, an analysis by the German Environment Agency indicate that a considerable number of iron ore mines are located within protected areas[79]. Hence, while handling of mine tailings is an important issue for all mining, it needs additional focus for iron mining.

Life cycle GHG emissions from ore to refined metal related to steel production is fairly limited compared to other metals with an emission factor of between 1.7 -1.9 kg CO2 per kg steel[80]. Despite the low specific carbon footprint, the large amounts produced means that around 75% of all CO2 released from metals production is from steel.

3.7.6 Human health and Working conditions

Most health problems related to steel production are caused by air pollution from emissions of sulphur dioxide and dust. Especially in countries with weak environmental regulations such as China. In recent years the problems have reach a level that can no longer be ignored, and steel companies have started to implement various forms of environmental initiatives[81].

A large share of the World's iron and steel comes from China, where working conditions for miners are notoriously dangerous and many accidents and deaths have been reported through the years[82].

Failure of tailing dams which is mentioned above, can apart from being immediately fatal on the local communities also have long lasting indirect impacts from the contaminated tailings affecting local agriculture and fisheries and health of local communities.

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[77] http://www.greenspec.co.uk/building-design/steel-products-and-environmental-impact/
[78] Stakeholder comment
[79] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[80] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf
[81] http://www.seaisi.org/News/662/Dealing+with+Environmental+Pollution+in+the+Iron+and+Steel+Industry:+The+China+Case+Study
[82] https://www.mining-technology.com/features/featurechina-mine-death-rate-coal-safety/

3.8 Copper

Copper is the best electrical conductor (after silver) and is therefore widely used in all kinds of wiring and electrical equipment. It is also corrosion resistant and antibacterial and ideal for waterpipes and fittings[83]. It is mined all over the World primarily from open pit mines[84].

3.8.1 World copper production

Copper is found worldwide and is currently mined in 57 countries where four countries stands for 55% of the total production: Chile (29%), Peru (10%), China (9%) and USA (7%).

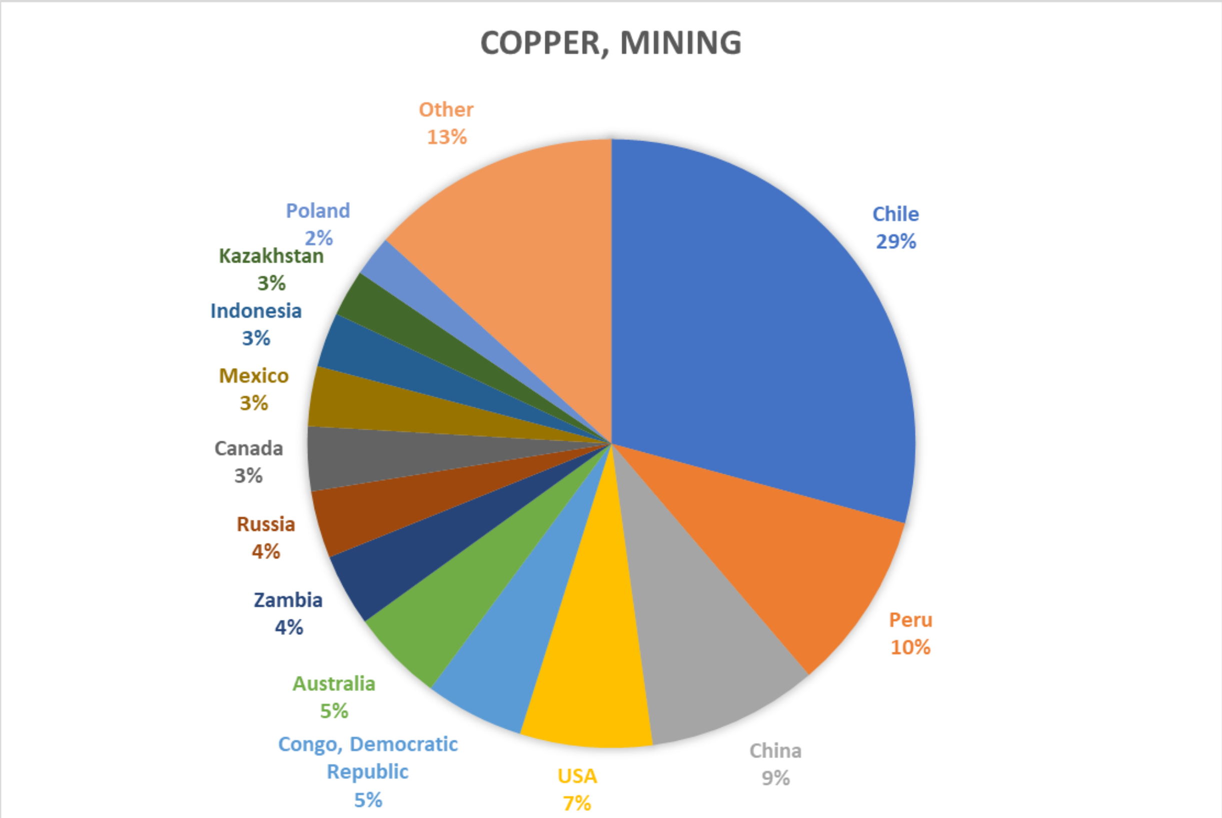

Figure 22: Sources of world production of copper in the period 2013-2017 (Source: BGS).

The annual average production of copper was globally 19 million tons in the period 2013-2017. It has seen a steady increase at about 9% in the same period, as shown in Figure 23 .

[83] EC (2017) Non Critical Raw Material Factsheet
[84] https://www.globalxetfs.com/copper-explained/

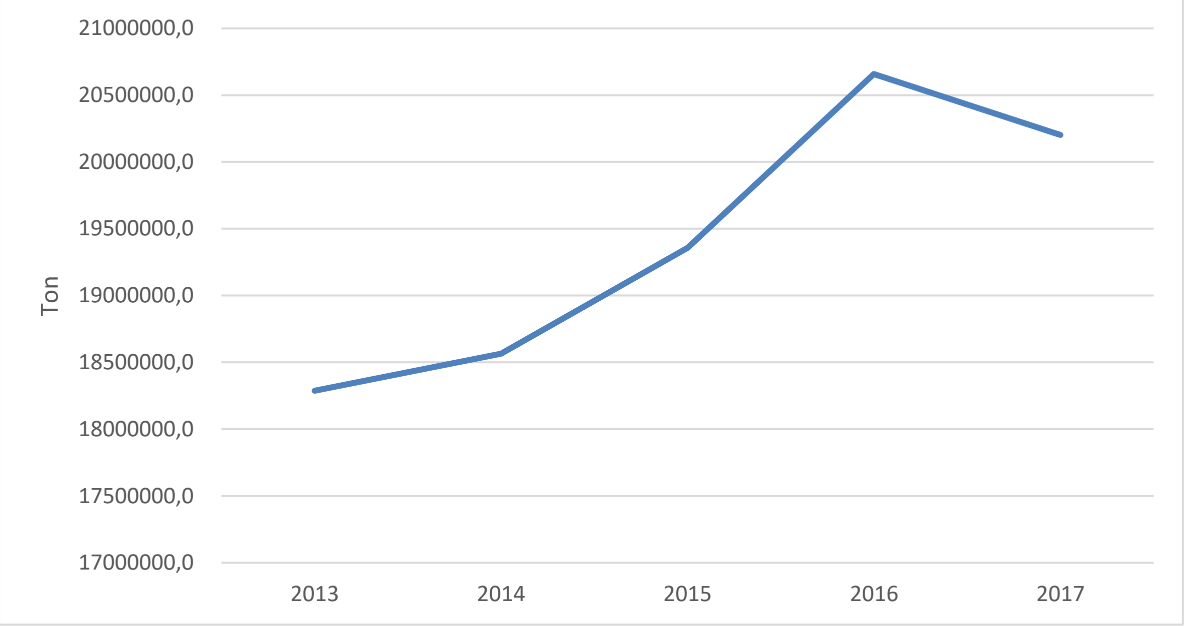

Figure 23: Copper production in the period 2013-2017 (Source: BGS)

3.8.2 End-use

Copper and its alloys (e.g. bronze and brass) have a wide range of applications due to their unique properties as a good conductor of electricity and heat, corrosion resistance, anti-bacterial, ductile and alloys easily.

Copper is used in all types of electronic equipment from computers, mobile phones and televisions to household wiring and large transmission systems and telecommunications. Due to its high thermal conductivity it is also widely used as heat exchangers in air conditioners and refrigerators. Its antibacterial properties and corrosion resistance make it useful in plumbing and other water systems[85].

For Li-ion batteries, copper is primarily used in combination with graphite to make up the anode of the battery. Copper is preferred over other metals due to its high electric conductivity, thermal conductivity to drain heat out of the battery cell and heat resistance. Furthermore copper is used in the wiring for batteries in EVs.

The global share of copper demanded by EV batteries and Li-ion batteries in general is estimated to be marginal given the relatively small volumes of material used per battery compared to other applications.

[85] https://www.globalxetfs.com/copper-explained/

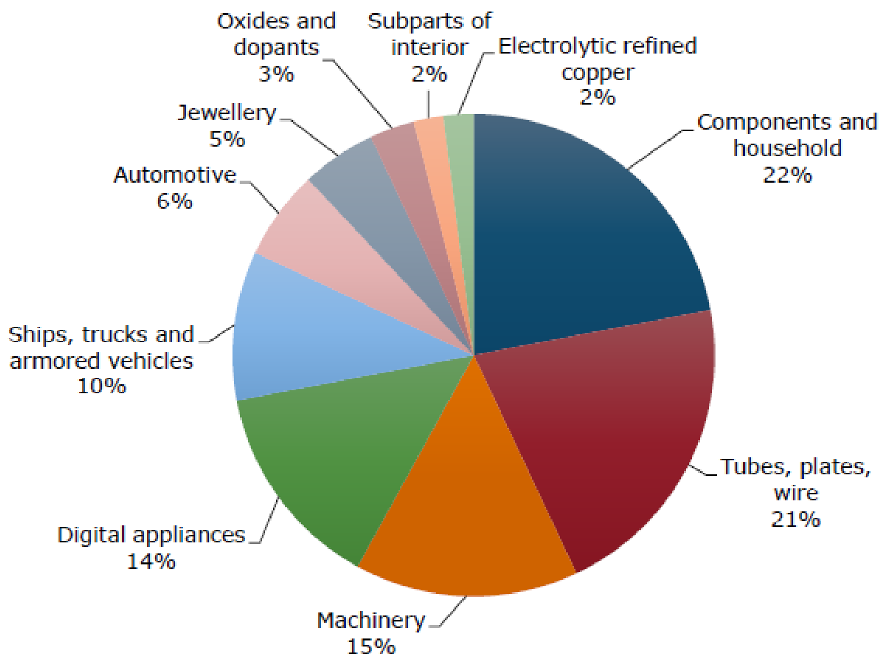

Figure 24: End-use of copper[86]

3.8.3 Forecast and reserves

The global known reserves of copper are estimated to about 720 million tons with about half located in Chile, Australia and Peru[87].

The global copper demand has seen an increase of about 2.5% annually in the last decade primarily driven by high growth in emerging economies, primarily China. Growth means demand for wiring and plumbing, transmission wires, consumer electronics and auto vehicles all using large volumes of copper. The growth in especially China is expected to decline which will consequently impact on copper demand and continue with a lower growth towards 2025 at about 1.9%. Copper plays an important part in renewable energy systems and EVs and hybrid vehicles, however it is not expected to impact the global copper demand significantly before the late 2020s[88]. Some analysts expect copper demand to increase by 43% by 2035 primarily driven by green technologies[89].

3.8.4 Governance

All indicator scores are positive with an overall average of 0.32 suggesting an intermediate to good level of governance. The lowest scoring indicator is Political Stability at 0.02 (see Table 8).

[86] EC (2017) Non Critical Raw Material Factsheet
[87] EC (2017) Non Critical Raw Material Factsheet
[88] https://www.ft.com/content/2d2eef1e-5187-11e9-9c76-bf4a0ce37d49
[89] https://copperalliance.eu/about-us/europes-copper-industry/

Table 8: Worldwide Governance Indicator scores for copper producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	0.24
Political Stability and Absence of Violence/Terrorism	0.02
Government Effectiveness	0.48
Regulatory Quality	0.58
Rule of Law	0.31
Control of Corruption	0.26
Average score	**0.32**

The weighted environmental performance index (EPI) classifies copper as having a medium environmental hazard potential, thereby largely supporting the WGI score.

3.8.5 Environment

Copper is an essential metal for normal plant growth and development, but it is characterized as a heavy metal, however of the less-toxic kind. Excess copper levels are inhibiting plant growth and impair important cellular processes[90].

Copper is primarily found in sulphidic ores, thereby potentially leading to acid mine drainage in the mining stage. When sulphidic ores are exposed and react with air and water it forms sulphuric acid, which potentially precipitates to the surrounding environment causing acid rain.

Large open pit mines are common in copper extractions which are potentially destructive to the local ecosystem removing animal habitats and involving deforestation. Furthermore copper mines are often located in regions with high earthquake risks, making tailing handling more prone to leakage accidents.

An analysis from the German Environment Agency shows that a large number of copper mines are located in regions with high water stress. Since copper is commonly extracted from low ore grades, there is a high water demand for ore beneficiation putting additional stress on water resources[91].

Sulphuric acid is a primary by-product from the smelting process of copper concentrate which is normally collected and stored on-site and usually resold. Hence, not imposing any environmental concerns if handled properly[92].

Life cycle GHG emissions from ore to refined metal is estimated to between 1 and 5 kg CO2/kg copper[93]. In Europe, the copper industry has seen large efficiency gains in the period 1990-2015. The CO_2-intensity of copper has in that period dropped 40% from 2.67 to 1.62 kg CO2/kg copper. This is mainly cause by a shift to 'flash-melting'[94]. This is likely not the case for all

[90] http://www.scielo.br/pdf/bjpp/v17n1/a12v17n1.pdf
[91] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[92] https://www.eurometaux.eu/media/2005/full-report-8-56-17.pdf
[93] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf
[94] https://www.eurometaux.eu/media/2005/full-report-8-56-17.pdf

smelters in the world, as investment costs are high for advanced environmental technologies[95].

3.8.6 Human health and Working conditions

Copper is essential to human health and therefore needed in small quantities. However, excessive exposure to copper can be toxic to human health, e.g. inhaling of fumes, dusts or mists containing copper[96]. Industry stakeholders have underlined that there is no evidence showing that workplace dusts and fumes have an effect on worker health. Nonetheless, the main health concerns are related to release of sulphuric acid and other chemicals, used in the extraction and treatment of copper, into rivers and aquifers therefore contaminating local drinking water in case no state-of-the-art manufacturing technologies are applied. Grave examples have been reported from the largest copper mine in Africa in Zambia[97]. Hence, the broader copper industry decided to engage in a voluntary programme to demonstrate and improve the industry's contribution to sustainable development over time by assessing the performance of copper mines and refiners against responsible production criteria and verifying performance through the Copper Mark Assurance Process[98].

3.9 Phosphorus

Phosphorus is highly reactive and is therefore never found as a free element on Earth, but only in its oxidized compound as phosphate. Phosphorus is an essential nutrient for all life and is often the limiting nutrient in agriculture. Therefore 96% of global phosphate production goes to fertilizers and animal feed. It is critical to current agriculture practices and there are indications that we are close to peak phosphorus production. It is therefore included on EU's critical raw material list[99].

3.9.1 World phosphate production

Phosphate is currently mined in 39 countries in the World where the far majority (70%) comes from only three countries: China (49%), Morocco (11%) and USA (10%) as shown in Figure 25.

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95 Stakeholder comment
96 https://www.lenntech.com/periodic/elements/cu.htm
97 https://old.danwatch.dk/undersogelseskapitel/impacts-of-copper-mining-on-people-and-nature/
98 https://sustainablecopper.org/rmi-and-ica-partner-to-advance-responsible-copper-production-and-trade/
99 EC (2017) Critical Raw Material Factsheet

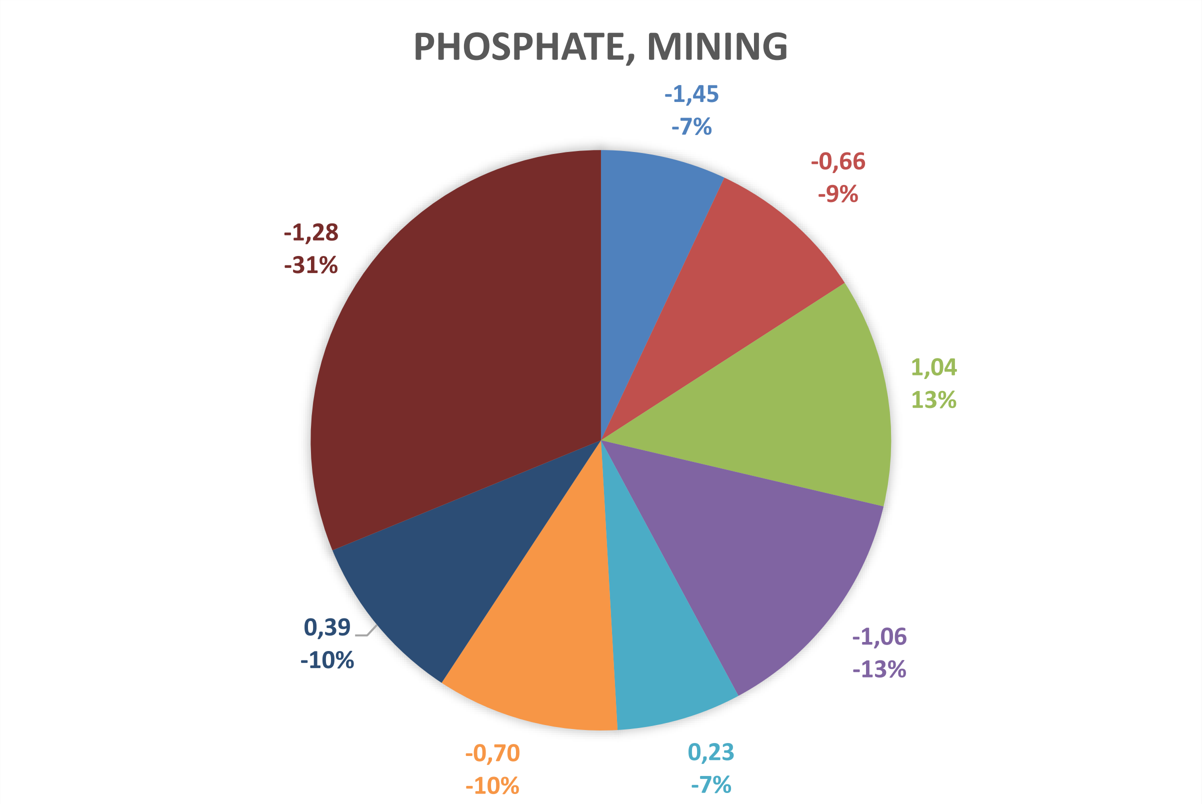

Figure 25: Source of world phosphate (Source: World Mining Data).

The average annual production of phosphate was globally 80 million tons in the period 2013-2017. The production has seen a steady growth of more than 13% in the same period as shown in Figure 26.

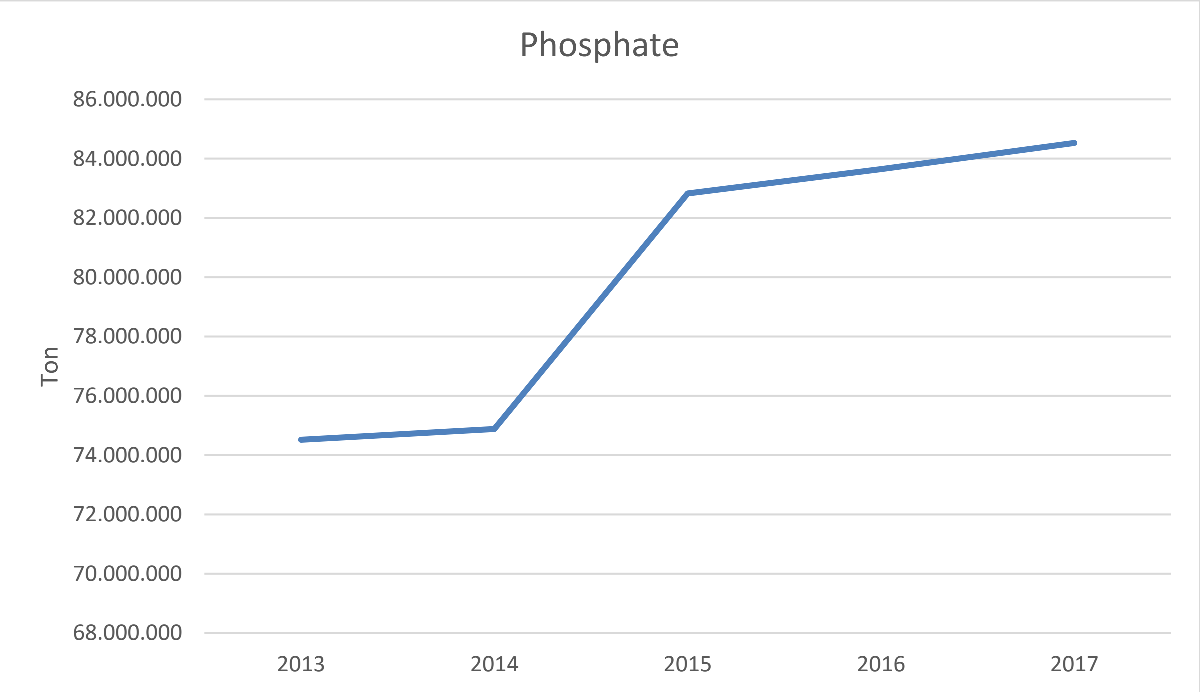

Figure 26: Development of phosphate production in the period 2013-2017

3.9.2 End-use

The main application of phosphate is as mineral fertilizer and as animal feed in the agricultural sector. Only 4% of the global phosphate production has other uses. Other uses mainly cover chemical industry applications where pure forms of phosphorus (white and red phosphorus) are used for lubricant additives, pharmaceuticals, detergents, matches and pyrotechnics among others (see Figure 27).

A purified form of phosphoric acid is used for the lithium iron phosphate (LFP) battery type where it acts as a replacement of cobalt in the cathode. LFP is most widely used for EVs and energy storage due to its higher safety and longer lifetime[100].

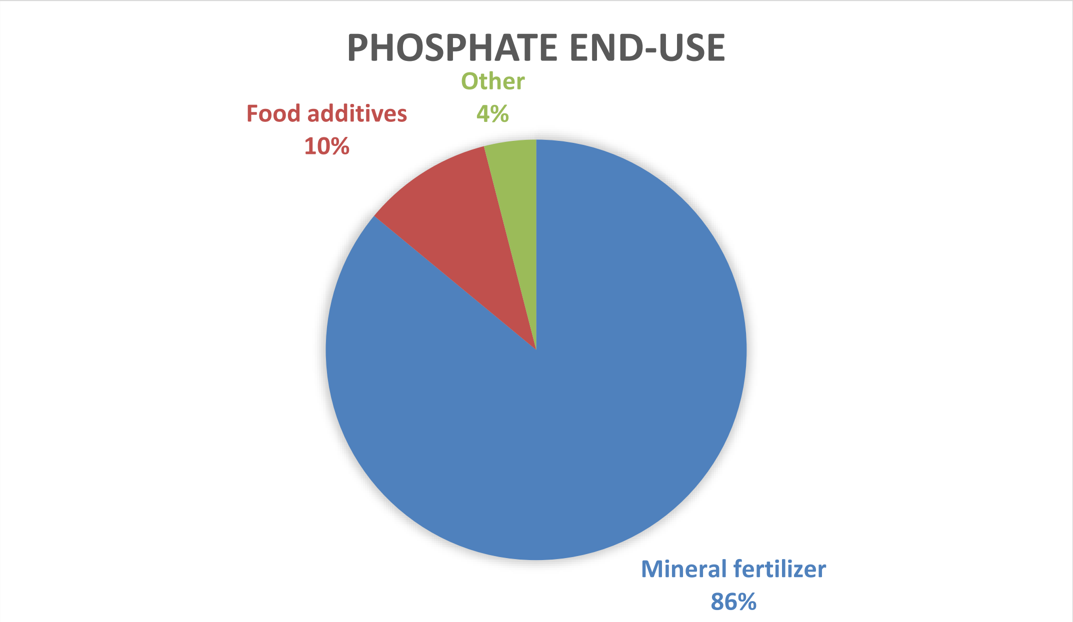

Figure 27: Global end-use of phosphate

3.9.3 Forecast and reserves

The global known reserves of phosphate rock are estimated to about 60 billion tons, but only between 4% and 20% of phosphate rock is actual phosphate mineral. By far the largest reserves (73%) are located in Morocco, other large deposits are found in China, Middle East and USA. Phosphate rock is relatively abundant in the Earth's crust; however, many deposits are not yet economically viable to extract[101].

There is a growing concern that the World might hit a peak phosphorus in the next 30 to 60 years if current practices are continued and no new large reserved are discovered. Phosphate mining is and will continue to be driven by demand from the agricultural sector for fertilizer because there exists no substitute. Furthermore, phosphorus is not retrieved or recycled to any significant degree. When reserves are also isolated to a few countries then there is a large risk to future supplies of phosphate[102]. Consequently, phosphate has been included in the EU list of critical raw materials.

[100] http://www.prayon.com/en/news/2012/05/umicore-and-prayon-join-forces-to-develop-and-produce-phosphate-based-cathode-materials-for-lithium-ion-batteries
[101] EC (2017) Critical Raw Material Factsheet
[102] http://phosphorusfutures.net/the-phosphorus-challenge/peak-phosphorus-the-sequel-to-peak-oil/

3.9.4 Governance

Four out of six indicators score negatively with the worst being Voice and Accountability at -0.79. The average score is also negative at -0.14 suggesting a poor level of governance. It should be noted that phosphate mines in Morocco are located in Western Sahara, annexed by Morocco contrary to international law[103]. If this was taken into account, it might affect some of the indicators negatively.

Table 9: Worldwide Governance Indicator scores for phosphate producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	-0.79
Political Stability and Absence of Violence/Terrorism	-0.26
Government Effectiveness	0.35
Regulatory Quality	0.04
Rule of Law	-0.05
Control of Corruption	-0.13
Average score	**-0.14**

The weighted environmental performance index (EPI) classifies phosphate as having a medium environmental hazard potential, thereby presenting a slightly better level of governance than the WGI score.

3.9.5 Environment

As with mining for many other minerals open-pit or surface mining is also very typical with mining of phosphate rock. This results in severe land degradation such as rock desertification, loss of vegetation and habitats and ground erosion. Not only where the mine is located but also for the surrounding areas where surplus soil and waste is placed. Several studies have documented environmental impacts from phosphate mining such as local depletion of water resources and contamination of surface and ground water by discharge of mining wastewater.

In order to produce soluble phosphate products from the phosphate rock, large quantities of sulfuric acid are used. Acidic wastewater has in some locations drained into the local surface and ground water sources. Leakage of phosphate rich material into local surface waters has in some cases resulted in algal bloom and eutrophic conditions with increased fish mortality as a consequence[104].

Another concern is that phosphate rock is often associated with radioactive substances (e.g. uranium) which can be mobilized in the environment during mining and processing[105].

[103] Comment from stakeholder
[104] http://medcraveonline.com/IJH/IJH-02-00106.pdf
[105] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

3.9.6 Human health and Working conditions

The major airborne emissions occur in the form of fine rock dust from drying and grinding operations of phosphate rock. At least 57 of the trace elements in phosphate rock have been reported to possess toxicity to varying degrees, and Be, As, Cd, Hg, Tl, and Ra are generally designated as extremely toxic. Fluoride is also associated with phosphate mining and can be released to air or water sources and is in higher concentrations toxic to human health[106].

It is especially the mining workers that are exposed to severe health effects from air pollution if they do not wear proper respiratory protection gear. There are examples of workers from Moroccan mines that only wear thin disposable face masks. As a result, many workers contract illnesses directly related to severe air pollution[107].

3.10 Graphite

Graphite is a naturally occurring form of crystalline carbon arranged in sheets formed under high temperature and pressure. Graphite is extremely soft, cleaves with very light pressure, and has a very low specific gravity. In contrast, it is extremely resistant to heat and nearly inert in contact with almost any other material. These unique properties give it a wide range of uses in metallurgy and manufacturing. It is possible to produce synthetic graphite by heating up carbon rich materials to a temperature of about 3,000 degrees; resulting in a very high purity[108]. Graphite is mainly used in steel production but is also an important material in Li-ion battery production. Due to limited resources in the EU and its economic importance it is listed as a critical raw material.

3.10.1 World graphite production

Graphite is currently mined in 19 countries worldwide and the far majority (89%) comes from only three countries: China (73%), India (9%) and Brazil (7%) (see Figure 28).

106 http://medcraveonline.com/IJH/IJH-02-00106.pdf
107 https://www.theguardian.com/global-development/2015/dec/16/toxic-shadow-phosphate-miners-morocco-fear-they-pay-high-price
108 https://geology.com/minerals/graphite.shtml

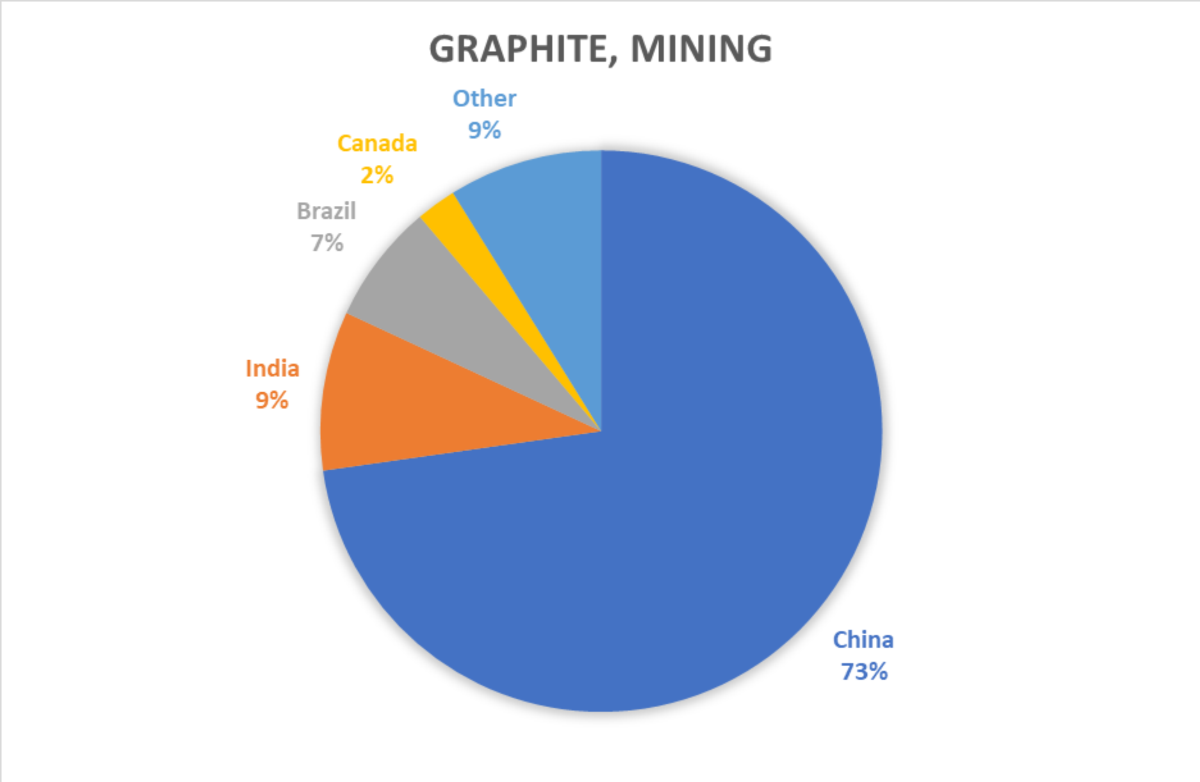

Figure 28: Sources of World graphite production (Source: BGS).

The annual average production of graphite was globally 1.2 million tons in the period 2013-2017. The production has been relatively stable in the same period; however, a sudden drop is seen in 2017 of about 6% (see Figure 29). Reportedly, this was due to capacity shutdowns in China as a consequence of environmental inspections[109]. It should be noted that ASM mining is occurring in a number of graphite producing countries, such as China, India and Brazil[110]. This production is not included in the national statistics

[109]https://investingnews.com/daily/resource-investing/battery-metals-investing/graphite-investing/graphite-outlook/
[110] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

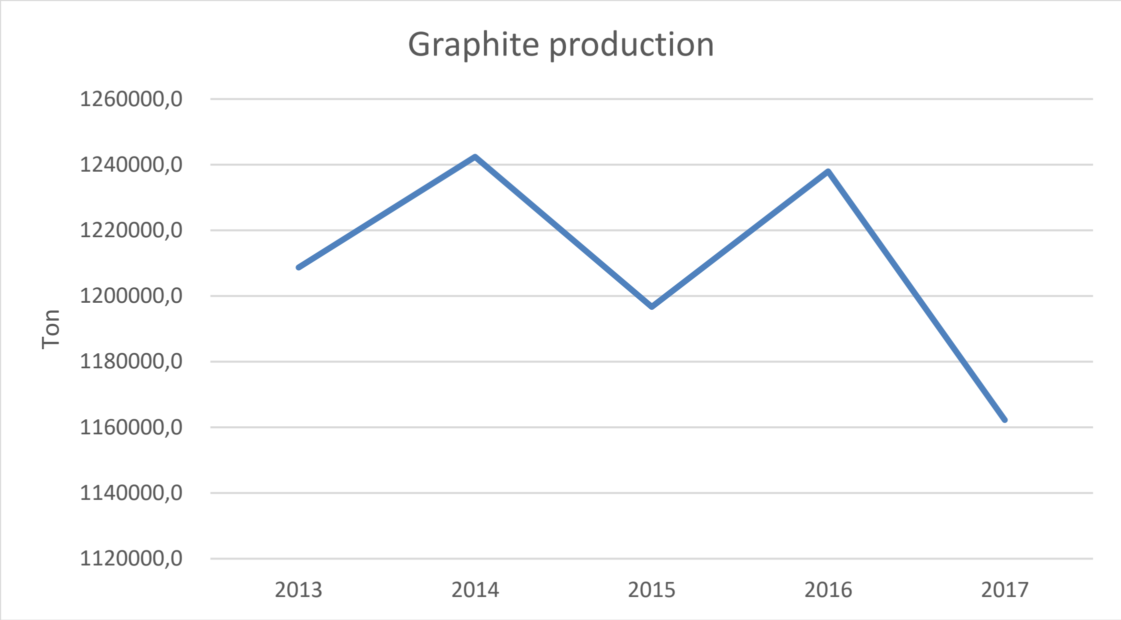

Figure 29: Development in World graphite production in the period 2013-2017.

3.10.2 End-use

More than half (66%) of globally produced graphite is used in refractory materials, which are used for very high temperature (>500 °C) applications such as in incinerators and ovens. Other applications include components in lubricants, lining of high friction products and pencils[111], as seen in Figure 30.

Graphite is an important component in Li-ion batteries used for the anode where it is typically coated onto copper foil. About 8% of the World's graphite production is used for batteries. Li-ion battery types used EVs constitute about 70% of the battery market and the share of graphite going to EV batteries is therefore estimated to about 6%.

[111] EC (2017) Critical Raw Material Factsheet

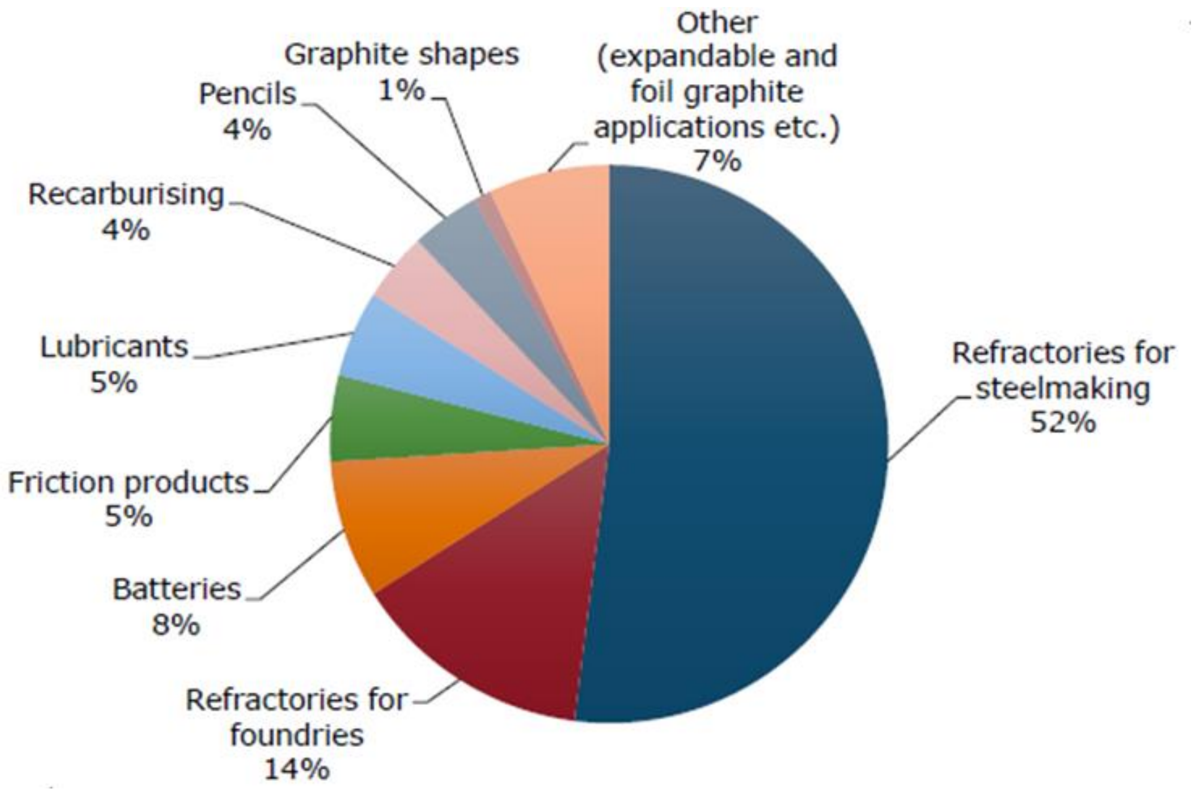

Figure 30: End-use of global graphite demand (2014)[112]

3.10.3 Forecast and reserves

The global reserves of natural graphite are estimated to be 230 million tons with the majority located in Turkey, Brazil and China. The supply of synthetic graphite is essentially unlimited since it is made from coal. Currently, China is the dominating power in graphite production, but projects are started outside China[113].

Despite synthetic graphite being perfectly applicable to Li-ion batteries it is more expensive than natural graphite and cannot acquire the same level of purity. Therefore, a future increase in demand for natural graphite will come from the Li-ion battery industry and is estimated to increase between 17 o 23% per year over the next decade[114]. 550,000 tons is expected to be demanded by the EU in 2030[115].

3.10.4 Governance

Five out of six governance indicators are negative with Voice and Accountability being the poorest at -0.97. The only positive indicator is Government Effectiveness at 0.39. Overall, indicator scores resemble that of China, since most of World graphite is source from here (see Table 10).

[112] EC (2017) Critical Raw Material Factsheet
[113] https://roskill.com/market-report/natural-synthetic-graphite/
[114] https://roskill.com/market-report/natural-synthetic-graphite/
[115] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 Task 7

Table 10: Worldwide Governance Indicator scores for graphite producing countries. The results have been weighted by the share of World production.

Worldwide Governance Indicator	Weighted score
Voice and Accountability	-0.97
Political Stability and Absence of Violence/Terrorism	-0.31
Government Effectiveness	0.39
Regulatory Quality	-0.10
Rule of Law	-0.13
Control of Corruption	-0.21
Average score	**-0.22**

The weighted environmental performance index (EPI) classifies graphite as having a high environmental hazard potential, thereby largely supporting the WGI score. It should be noted that ASM plays a role in mining of natural graphite, and around 92% of natural graphite originates from countries known to have ASM mines such as China, india, Brazil and Mexico. However, even though 90% of graphite comes from small producers due to the geological conditions, most of the small mines are mechanised[116].

3.10.5 Environment

The majority of graphite is sourced from China, where there are numerous reports of environmental problems related to graphite production. A major concern is the dispersal of fine graphite dust from the mining activities that settle on the vegetation essentially killing it. In order to be utilized in Li-ion batteries the purity of the graphite needs to be very high. The purification process typically uses large quantities of strong acids. If not handled properly, the acid waste can leak into and contaminate local ground and surface waters[117].

Synthetic graphite can eliminate many of these issues, however they require a large amount of energy and the purity level is lower than what can be reached for natural graphite.

Life cycle GHG emissions from ore to refined material is estimated to between 1 and 4.4 kg CO2/kg graphite[118].

3.10.6 Human health and working conditions

Human health aspects of graphite mining are primarily related to the air pollution from graphite dust than can cause severe health effects such as heart attacks and respiratory diseases[119].

Due to the geological nature of graphite deposits the extraction of graphite is mostly done at a small scale in countries with a high degree of ASM[120]. Working conditions for mining workers

[116] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.
[117] https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/
[118] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf
[119] https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/
[120] Dehoust, G. et al. (manuscript submitted for publication) (2020). Environmental Criticality of Raw Materials - An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy (ÖkoRess II). Commissioned by German Environment Agency (UBA). Texte xx/2020. Dessau-Roßlau.

in China are generally described as poor with limited access to protective gear which is assumed to be the same with graphite mining.

Besides China a smaller producer of graphite is North Korea (1%), however some sources estimate its share of World production as high as 4%[121]. North Korea is associated with a number of human rights violations and mining specifically is connected to forced labour. Therefore, the UN has introduced a full ban on all minerals exported from North Korea. However, there have been reports on North Korea successfully circumventing some of these sanctions[122].

3.11 Shortlisting

The findings from the previous sections have been summarized in Table 11 below. Based on this data the raw materials with the highest social and environmental risks will be short-listed. However, the first criteria the selection will be based on is the current share of the global production utilised in the EV battery sector. The findings show that aluminium, iron, copper and phosphorus are all important elements of a battery; either as casing material (Al, Fe) or part of the battery chemistry (Cu, P, Mn). Nonetheless, their primary use is dominated by other sectors making their share of global production going to EV batteries negligible. It is therefore not considered meaningful to apply any regulatory or voluntary measures to these raw materials and they have then not been shortlisted.

- Al, Fe, CU, P and Mn are not shortlisted

On the other end of the scale, a large share of the global production of lithium is going into EV batteries (and batteries in general) and is only expected to increase further in the future. Even though lithium is neither on the list on of critical raw materials nor has any "high" ratings on risks related to environment or human health (see Table 11) it cannot be said to be without any risk at all, and increased demand in the future is likely to increase the risks. Lithium is therefore shortlisted based on in its extraction to a large degree being affected by the EV and ESS production.

- Lithium is shortlisted

The remaining three materials (Ni, Co and natural graphite) have medium to high shares of global production being used in batteries. The highest being cobalt and graphite with current EV battery share consumption of 9% and 6%, respectively, but both expected to increase to above 40% in the 2030 forecast. The share of global production of nickel utilised for EV batteries is currently small (3%) but expected to grow significantly in the coming decade.

Both cobalt and nickel mining and refining is related to a large range of social and environmental issues, especially cobalt which is already in the industry's focus. While the social and environmental impacts are rated low to moderate for graphite, mining of natural graphite has high shares of ASM, which mostly takes place in informal settings, which can lead to serious health and environmental impacts despite the otherwise low scores, for example no regular mine closure and no rehabilitation means destruction of ecosystems and soils.

- Nickel, cobalt and natural graphite are shortlisted.

[121] World Mining Data
[122] https://drivesustainability.org/wp-content/uploads/2018/07/Material-Change_VF.pdf

Hence, in total four key materials have been shortlisted for further in-depth supply chain assessment based on the screening: lithium, nickel, cobalt and natural graphite.

Table 11: Summarizing table of section 3 on screening of materials

	Lithium	Nickel	Manganese	Cobalt	Aluminium	Iron	Copper	Phosphorus	Graphite
Symbol	Li	Ni	Mn	Co	Al	Fe	Cu	P	C
Compounds	Li carbonate Li hydroxide					Steel		Phosphate	
Global annual production (metric ton)	76,000	2,252,000	17,366,000	141,000	56,801,000	1,549,452,000	19,414,000	80,079,000	1,210,000
EU 2020 demand for EV batteries (metric ton)	5,000	5,000	5,000	5,000	n/a	n/a	n/a	n/a	25,000
EU 2030 demand for EV batteries (metric ton)	90,000	210,000	105,000	60,000	n/a	n/a	n/a	n/a	550,000
Price (EUR/ton)	9,900€ 11,700€	15,400€	1,800€	32,500€	1,600€	460€ (steel)	5,200€	n/a	2,700€
All batteries share% (2019)	56%	6%	2%	49%	n/a	n/a	<0.1%	n/a	8%
EV battery share% (2019)	39%	3%	2%	9%	n/a	n/a	<0.1%	n/a	6%
Battery types (Li-ion)	All	NMC, NCA	LMO, NMC	LCO, NMC, NCA	All	All	All	LFP	All
Governance - WGI 2.5(Best); -2.5(Worst)	0.97	0.13	0.11	-0.82	0.05	0.38	0.32	-0.14	-0.22
Env. Governance Low (Best); High (Worst)	Low	Low	High	High	Medium	Low	Medium	Medium	High
Critical Raw Material (EU)	Non-critical	Non-critical	Non-critical	Critical	Non-critical	Non-critical	Non-critical	Critical	Critical
EU Economic importance	2.4	4.8	6.1	5.7	6.5	6.2	4.7	5.1	2.9
EU Supply Risk	1.0	0.3	0.9	1.6	0.5	0.8	0.2	1.0	2.9
CO2-emission (kgCO2/kg)	2 (brine) 27 (hard rock)	5.25-10	6	1.45-10	12	1.7-1.9 (steel)	1-5	n/a	1-4.4
Env. Hazard Potential	Medium	High	Medium	High	Medium-high	Medium	High	High	Low
Environment	Low	Very high	High	Very high	High	High	Very high	Moderate	Low
Working conditions	Low	Low	Moderate	Very high	Low	Low	Low	Moderate	Low
Human health	Low	High	Moderate	Moderate	High	High	Very high	High	Moderate
ASM relevance	No	No	Yes	Yes	No	No	No	No	Yes

4. Supply chain analysis

In this section the supply chains for the short-listed materials will be detailed further. The supply chain means all the processes of these metals from mining until they are part of a battery that is placed in the market. This is important, because the possible regulation is intended to apply to batteries placed on the EU market, and hence all risks along the supply chain of the selected materials will need to be accounted for in the due diligence procedure for the battery, not only risks related to mining.

For each of the shortlisted materials, the supply chains are detailed from the mining to the refining step, after which the material is usually in a form that can be traded as a commodity.

The process after refining involves mixing of different compounds and is therefore described below, before the material-specific sections. The refined materials need to be further processed into active materials specifically suited for batteries. This process is often done by specialised companies, before it is sold to cell manufacturers, and includes mixing of different compounds (e.g. nickel, cobalt and manganese are mixed for the cathode active material for NMC batteries) and can involve energy consuming processes such as burning in furnaces.

The cell manufacturers then further prepare the active materials by mixing them with binder, carbon and a solvent into a slurry, which is then coated onto copper foil (for anodes) or aluminium foil (for cathodes), see Figure 31. The coated foils are then compressed to control the electrode density (a process called calendaring), and then dried with heat to evaporate the solvent. Finally, the electrodes are cut into the correct shape and size for the specific cell[123]. After that comes that assembly of the battery cells[124], where the current carrying electronics are added, and when cells are then assembled into modules and then packs, the battery management system (BMS), heating and cooling etc. is added. This final assembly into packs are usually performed by the ESS or EV manufacturer (to make it fit the specific car/ESS system).

[123] https://www.batterypoweronline.com/articles/optimal-rheology-better-electrodes-understanding-the-links-between-battery-slurry-properties-and-electrode-performance/
[124] https://www.mpoweruk.com/battery_manufacturing.htm

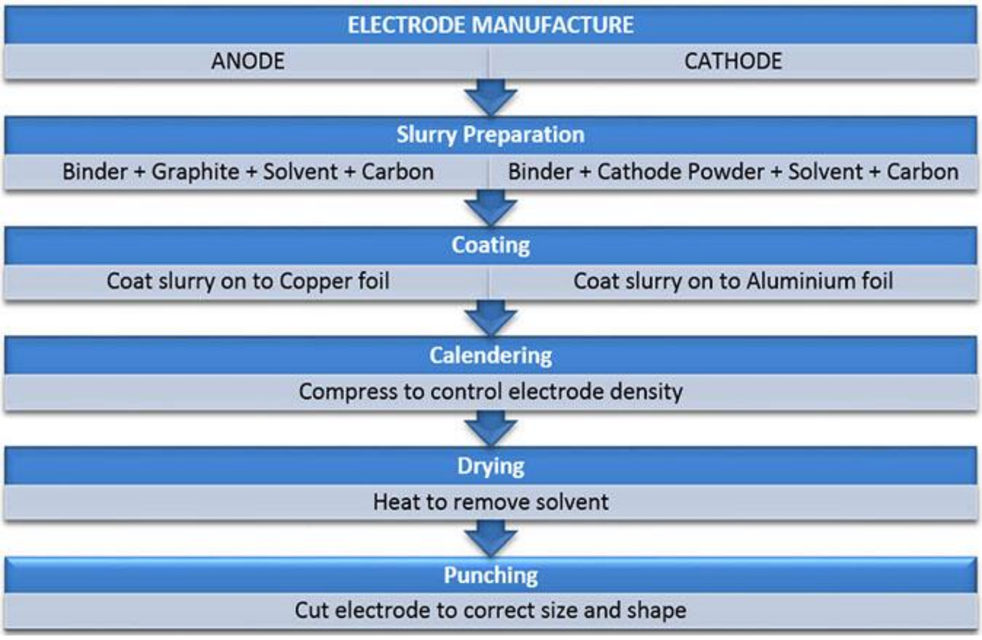

Figure 31: General process of electrode manufacturing for batteries[125].

Hence, the materials are traded several times throughout the supply chain, also after they have been integrated into battery parts (e.g. electrodes, cells). Regarding geographical location of these processes, China plays a major role on the global battery market.

Table 12 shows the production data for the components of lithium-ion batteries and the market shares (based on GWh) in different countries[126]. As seen from the table the major manufacturers of lithium-ion batteries (around 85% of the manufacturing capability) are China, Japan and Korea[127].

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[125] https://www.batterypoweronline.com/articles/optimal-rheology-better-electrodes-understanding-the-links-between-battery-slurry-properties-and-electrode-performance/
[126] Thielmann, Axel; Neef, Christoph (2019): Lithium-ion battery industry structure - Global value-creation chains and market structure. Internal Presentation, Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany.
[127] Olivetti, Elsa A.; Ceder, Gerbrand; Gaustad, Gabrielle G.; Fu, Xinkai (2017): Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule 1, pp. 229-243.
And: Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61.
And: Mercator Institute for China Studies (merics) (2018): China's battery industry is powering up for global competition. Link: https://www.merics.org/en/blog/chinas-battery-industry-powering-global-competition

Table 12: Geographical distribution of market shares for lithium-ion battery component production

Material	Application	Market shares	
Cathode active materials	NMC, LCO and NCA for the greatest part	China (50%) Japan (20%) Korea (15%)	Belgium (10%) Others (5%)
Anode active materials	Mainly, synthetic and natural graphite	China (65%) Japan (29%)	Korea (3%) Others (3%)
Electrolytes	Mostly based on $LiPF_6$ salt and carbonate solvents	China (72%) Japan (23%)	Korea (3%) Germany (2%)
Separators	Among others polyethylene or polypropylene based	Japan (58%) China (33%)	Korea (7%) US (2%)
Lithium-ion battery cells	Cell assembly	China (65%) Japan (15%) Korea 13%	US (3%) EU (1%) Others (6%)

4.1 Cobalt

The flow of cobalt from the natural deposits to its use in batteries can be described by the process chain depicted in Figure 32. This process chain is a highly stylized representation of the different types of cobalt production techniques/processes that are employed at different production sites (depending among others on the type of cobalt ore processed) and differ significantly from each other regarding the chemical and energetic process requirements. All major types of ores can be used for production of class-I cobalt (i.e. cobalt metal) and cobalt chemicals, which are used for battery production[128].

Many of the chemicals involved in the production of cobalt (e.g., nickel tetracarbonyl[129]) are highly toxic and environmentally hazardous. In the following, the technical aspects of each of the steps of the process chain depicted in Figure 32 are described.

[128] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122
[129] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.

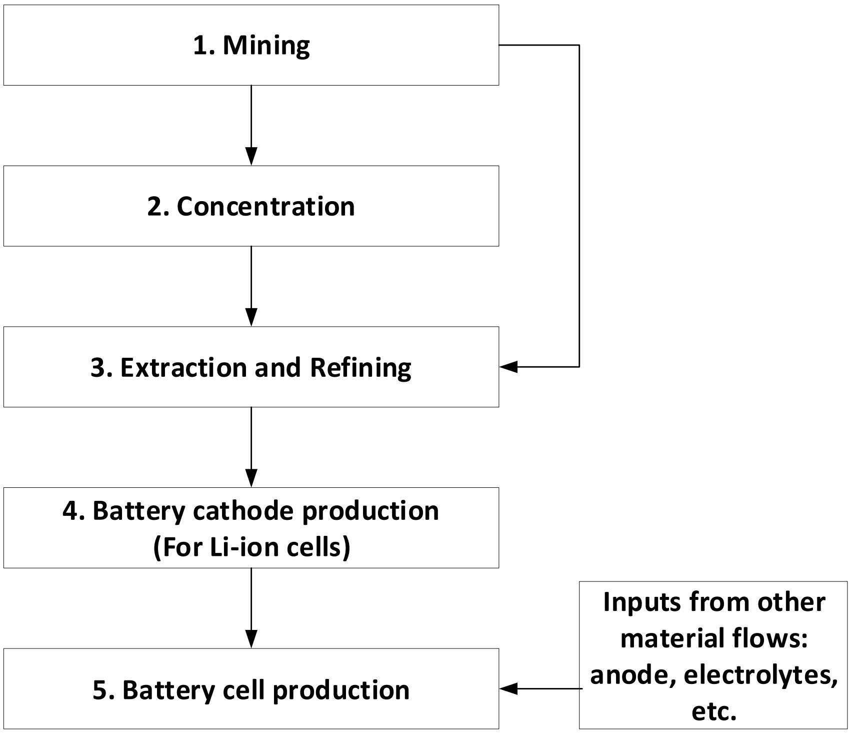

Figure 32: Stylized representation of the Cobalt supply chain for Li-ion batteries.

The main battery types containing cobalt are[130]:

- Lithium-ion batteries:
  - lithium cobalt oxide (LCO) batteries (used in the portable electronics market)
  - lithium nickel cobalt aluminium oxide (NCA) batteries (used in the automobile industry)
  - lithium nickel manganese cobalt oxide (NMC) batteries (used in the automobile industry and in cutting tools).
- Nickel metal hydride (NiMH) batteries (used in hybrid vehicles and power tools)
- Nickel cadmium (NiCd) batteries (industrial batteries and in power tools)

Cobalt has many different uses in various final products, other than batteries[131]:

a) bonding agent in cemented carbides (used as cutting tools),
b) uses of cobalt alloys (numerous applications; e.g., surgical implants, magnets, springs, and blades in aircraft engines)

[130] Olivetti, Elsa A.; Ceder, Gerbrand; Gaustad, Gabrielle G.; Fu, Xinkai (2017): Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule 1, pp. 229-243.
And: Cobalt Institute (2019): Cobalt in Batteries. Link: https://www.cobaltinstitute.org/assets/files/Pages%20PDFs/Infographic-Cobalt-Batteries.pdf
[131] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.

c) uses of cobalt compounds/chemicals (in glasses, ceramics, refractories, driers, paints, varnishes, dressings[132], electronics, solid-state devices, and batteries; in electroplating, agriculture, nutrition and medicine; as catalyst).

For battery production specifically, the following compounds have been identified to be used: Cobalt powder and certain cobalt compounds/chemicals (cobalt sulphates, hydroxides and oxides) are used for battery production[133] cathode and anodes. For lithium-ion batteries cobalt is used in cathodes, whereas it can also be used in the anodes of other types of rechargeable batteries such as nickel-metal hydride rechargeable batteries[134].

It should be noted that metallic cobalt is thus not used directly in the cell, but that various steps take place as part of the cathode production step. One article state that different cobalt chemicals (sulphates, oxides, and cobalt powder) are all used on battery production[135], while one cell manufacturer stated in relation to the study that predominantly cobalt sulphates are used in battery cathode production for Li-ion batteries.

However, none of these compounds are used directly in batteries, but they are used to produce complex chemicals, such as:

- lithium cobalt oxide (LCO)
- lithium nickel cobalt aluminium oxide (NCA)
- lithium nickel manganese cobalt oxide (NMC)
- As well as other chemicals that are used in nickel metal hydride (NiMH) and nickel cadmium (NiCd) batteries.

4.1.1 Mining

Cobalt can be regarded as a by-product of the production processes of copper, nickel, silver and other metals[136], and therefore, the estimated losses of cobalt in mining are relatively high; for example the loss rate in China is estimated to 50%[137]. Losses here means that because the cobalt is seen as a by-product, it ends up in the mining waste, but it might potentially be available for future “re-mining” from heaps or ponds where mining waste is deposited.

The main types of cobalt ores are arsenide ores, sulfoarsenide ores, sulphide ores and oxide ores138. The ores of major importance for battery production are nickel sulphides, nickel

[132] This refers to the treatment of soils to correct cobalt deficiencies in soils
[133] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
And: Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.
And: Olivetti, Elsa A.; Ceder, Gerbrand; Gaustad, Gabrielle G.; Fu, Xinkai (2017): Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule 1, pp. 229-243.
[134] Berndt, D. (2014). Batteries, 3. Secondary Batteries. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.o03_o12 . P41
[135] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122
[136] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.
[137] Harper, E.M.; Kavlak, G.; Graedel, T.E. (2012): Tracking the Metal of the Goblins: Cobalt’s Cycle of Use. Environmental Science & Technology 46, 1079−1086.
[138] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465

limonite, copper-cobalt sulphides and copper cobalt oxides[139]. The ores come from both artisanal and small-scale as well as industrial large-scale mines in for example DRC[140]. The global cobalt production share from ASM is between 10-30%, whereas in some countries, cobalt the target of ASM, especially in DRC. Here the numbers on the ASM production share vary between 35 and 90% of the national production. Besides DRC, other cobalt producing countries have prominent ASM production, for example China, Zambia, Philippines, Brazil and Madagascar. In total 84 % of cobalt is produced in countries with ASM[141]. Table 13 shows the cobalt world production by country from 2012-2016, including cobalt used for both class-I cobalt and for the chemicals that are used in battery production.

Table 13: Cobalt World Mine Production, by Country or Locality[1, 2] (Source: USGS (2016)).in Metric tons,

Country or locality[3]	2012		2013		2014		2015		2016	
Australia[4]	5.870		6.410		5.978		6.000	e	5.500	e
Botswana[5]	195		248		196		316		281	
Brazil	2.900		3.500		3.828		3.800	e	300	e
Canada[6]	3.698	r	4.005	r	3.907	r	4.339	r	4.245	p
China[e]	2.200	r	2.600	r	2.800	r	3.000	r	3.100	
Congo, (Kinshasa)[e, 7]	52.000		56.000		62.000	r	66.000	r	64.000	
Cuba[e, 8]	4.700	r	4.000	r	3.700		4.300		5.100	
Finland[e]	635		750		770		440		690	
Indonesia[e, 9]	1.700		1.700		1.300		1.300		1.200	
Madagascar[e, 10]	600	r	2.400	r	3.400	r	4.000	r	3.800	
Mexico[e]	--		--		--		--		980	
Morocco[e, 11]	2.000		2.000		2.150		2.250	r	2.400	
New Caledonia[e, 12]	2.670		3.190		4.040		3.690	r	3.390	
Papua New Guinea[13]	469		1.013		2.134		2.505		2.191	
Philippines[e, 14]	2.700		2.800		4.600		4.300		4.100	
Russia[e, 15]	6.300		6.300		6.300		6.200		5.500	
South Africa[e]	2.500		3.000		3.000		2.900	r	2.300	
United States[e, 15, 16]	--		--		120		760		690	
Vietnam[15]	--		25	e	223		277		134	
Zambia[17]	5.435		5.919		4.600	e	4.000	r, e	3.000	e
Zimbabwe[18]	195		319		358		355	r	409	
Total	96.800	r	106.000	r	115.000	r	121.000	r	113.000	

[e]Estimated. [p]Preliminary. [r]Revised. -- Zero.

1 Includes data available through February 8, 2018. All data are reported unless otherwise noted. Totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.
2 Figures represent recoverable cobalt content of ores, concentrates, or intermediate products from cobalt, copper, nickel, platinum, or zinc operations.
3 In addition to the countries and (or) localities listed, Spain and Turkey are known to produce ores that contain cobalt, but information was inadequate to make reliable estimates of production. Poland produced copper ore containing 1,500 to 5,000

[139] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122
[140] Resourcing Consulting Services Limited (RCS Global) (2016): The Battery Revolution: Balancing Progress with Supply Chain Risks. RCS Global Industry Briefing Paper. Link: https://www.rcsglobal.com/the-battery-revolution-balancing-progress-with-supply-chain-risks/
141 https://www.ifeu.de/en/project/oekoress-ii/ commissioned by German Environment Agency (UBA)

metric tons per year of cobalt, which was not recovered. Other copper-, nickel-, platinum-, or zinc-producing nations may also produce ores containing cobalt as a byproduct component, but recovery is small or nil.
4 Cobalt content of lateritic nickel ore and nickel concentrate reported by the government of Western Australia.
5 Reported cobalt content of pelletized nickel-copper matte.
6 Recoverable cobalt in ores and concentrates shipped.
7 Determined from estimated cobalt content of ores, concentrates, refined cobalt metal, and intermediate products such as crude cobalt alloys, crude cobalt hydroxide, and crude cobalt carbonate, produced from cobalt ores and concentrates, tailings, and slags sourced from Congo (Kinshasa).
8 Determined from estimated cobalt content of nickel-cobalt sulfide production and estimated cobalt content of ammoniacal liquor production.
9 Cobalt content of nickel matte plus estimated cobalt in lateritic ore processed in Australia.
10 Data are estimated cobalt content of ore production based on reported cobalt metal powder production and nickel recovery rates.
11 Cobalt content of concentrate estimated from reported gross weight.
12 Cobalt contained in the following materials: cobalt chloride produced in France from New Caledonian matte, cobalt carbonate and nickel hydroxide produced in New Caledonia, and lateritic nickel ore exported to Australia.
13 Cobalt content of nickel-cobalt hydroxide.
14 Cobalt contained in the following materials: nickel-cobalt sulfide produced in the Philippines and lateritic nickel ore exported to Australia.
15 Cobalt content of concentrates.
16 Negligible production prior to 2014.
17 Data for 2012−13 were reported by the Bank of Zambia.
18 Production reported by the Zimbabwe National Statistics Agency.

4.1.2 Concentration

The concentration is the separation of cobalt-bearing minerals from other minerals and gangue. In the mined ores cobalt content can be as low as around 2% of the volume. The concentration step is therefore usually done in the mining country to avoid transporting large amounts of ore. The concentration step is primarily taken in the case of sulphide ores. In the case of nickel limonite and copper-cobalt oxide ores, the typical concentration step is not taken. Rather, the ores are sent directly (after some screening and upgrading) to the extraction step[142]. Since artisanal mines primarily deals with copper-cobalt oxide ores[143], and they are not involved on the concentration of nickel-bearing ores, this step is often not taken for artisanal mined cobalt ore. In general, concentrates are produced in order to be traded internationally (see section 4.1.5).

The main method used for concentration of cobalt ores is froth flotation, while gravity separation can also be used. The methods used for concentration and, in particular, the chemicals used for froth flotation (lime, xanthate, hydrolyzed palm oil, gas oil, sodium cyanide etc.) differ across production sites and depend on the type of ore that is concentrated. Cobalt content of cobalt concentrates obtained by these concentration methods is up to 15% but in general much lower, down to a few percent[144].

4.1.3 Extraction and refining of cobalt

The extraction and refining of cobalt can be from cobalt concentrates or sometimes directly from cobalt ores that are not concentrated (see above). The main methods used for extraction and refining are hydrometallurgical methods, pyrometallurgical methods, electrometallurgical methods and vapometallurgical methods.

[142] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.115.
[143] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.115.
[144] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.

In the hydrometallurgical methods the main steps are[145]:

i. Preparation of cobalt concentrates
ii. Leaching of cobalt concentrates (i.e., creation of a solution containing cobalt ions)
iii. Separation of cobalt ions from other metal ions contained in the solution
iv. Reduction of cobalt ions to metal.

The details of this process differ across cobalt production sites depending on the type of the ore/concentrate that is extracted/refined. In particular, there are differences in the type of the preparatory process (roasting[146]/smelting), leaching media (acidic/alkaline), required pressure and heat, etc.

The pyrometallurgical methods involve, e.g., mixing of cobalt concentrates with lime and coal, melting of the mixture and further processing of the resulting cobalt alloys for cobalt (and other metals).

Electrometallurgic method is the electrolysis of sulphate or chloride solutions for electro-winning and refining of cobalt, whereas vapometallurgical[147] method is the chemical vaporisation of the metal in the ore by using gases (carbon monoxide among others) and subsequent collection.

These different processes are all energy consuming, because heat and pressure is applied at the different steps of the processes. For example the Sherritt Gordon process (used at Fort Saskatschewan in Canada), which is a hydrometallurgical process that involves the following steps[148]:

- pressure leaching at 83°C and 7 bar
- pressure oxidation hydrolysis reaction at 65 bar
- sulfuric acid leaching at 140°C and 64 bar
- hydrogen treatment at 120°C and 46 bar

Falconbridge in Canada and Norway leach sulphide concentrates at 70°C and ambient pressure, while Laterite ores are typically acid leached at 250°C. Cobalt is more energy intensive that production of nickel and lithium, in terms of lifecycle energy[149].

Since cobalt for batteries can be produced in many different ways150 and from many different intermediate products (concentrates, matte, sulphides and hydroxides) using many different processes (froth flotation, smelting, roasting, leaching, pressure leaching, electrowinning...), it

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[145] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.
[146] Roasting means heating of the ore/concentrate (below melting point). For example, cobalt containing arsenide ores are roasted at 600-700°C.
[147] British Geological Survey (BGS) (2009): Mineral Profile. Cobalt. August 2009. Link: https://www.bgs.ac.uk/mineralsUK/statistics/mineralProfiles.html
[148] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465
[149] Dunn, J.B; Gaines, L.; Kelly, J.C.; James, C.; Gallagher, K.G. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy and Environmental Science 8, 158–168.
[150] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.1115f.

has not been possible to separate cobalt-for-batteries production from cobalt-for-other-uses production at the extraction stage.

During the extraction/refining-process, different types of intermediate products arise, e.g., matte or cobalt hydroxide[151]. Some of these intermediates (in particular, cobalt hydroxide) are not only further transformed into refined cobalt (chemicals), but also put on the market for other uses than batteries and exported[152].

Table 14 and Table 15 gives an overview of the geographical location of the global cobalt refinery production, based on company and country/locality, respectively.

Table 14: Refined Cobalt Production (Tonnes) of Cobalt Institute Member and Non-Member Companies[153]

MEMBER COMPANIES	2011	2012	2013	2014	2015	2016	2017	2018
Ambatovy, Madagascar	0	0	2,083	2,915	3,464	3,273	3,053	2,852
BHPB/QNPL, Australia(1)	2,631	2,369	0	0	0	0	0	0
CTT, Morocco	1,788	1,314	1,353	1,391	1,722	1,568	1,428	1,619
Eramet, France	354	326	308	219	133	119	277	48
Gecamines, DRC(2)	650	870	700	500	400	400	400	400
Glencore(3): Katanga, DRC				2,800	2,900	0	0	0
Minara, Australia				2,900	3,300	3,200	3,000	3,200
Mopani, Zambia				0	0	0	0	0
Nikkelverk/Raglan/Sudbury(4)	3,067	2,969	3,400	3,600	3,100	3,500	3,500	4,200
NPMC, Canada (was ICCI)	3,853	3,792	3,319	3,210	3,733	3,693	3,601	3,234
Freeport Cobalt, Finland (was OMG)	10,441	10,547	10,010	11,452	8,582	11,187	12,221	12,874
Rubamin, India (Left CI 2012)(5)	579	200	45	0	0	0	0	0
Sumitomo, Japan	2,007	2,542	2,747	3,654	4,259	4,305	4,159	3,669
Umicore, Belgium (6)	3,187	4,200	5,415	5,850	6,306	6,329	6,987	6,360
Vale, Canada	2,070	1,890	2,240	2,051	1,858	1,851	2,906	2,918
Chambishi, Zambia (7)	4,856	5,435	5,000	4,317	2,997	4,725	2,520	1,613
TOTAL	**35,483**	**36,454**	**36,620**	**44,859**	**42,754**	**44,150**	**44,052**	**42,987**

[151] Donaldson, John Dallas; Beyersmann, Detmar (2011): Cobalt and Cobalt Compounds. In: Fritz Ullmann (ed.): Ullmann's Encyclopedia of Industrial Chemistry, Bd. 9. 7th. Edition. Weinheim, Germany: Wiley-VCH, pp. 430-465.
And Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
And Farjana, Shahjadi Hisan; Huda, Nazmul; Mahmud, M.A. Parvez (2019): Life cycle assessment of cobalt extraction process. Journal of Sustainable Mining 18, pp.150-161
[152] Farjana, Shahjadi Hisan; Huda, Nazmul; Mahmud, M.A. Parvez (2019): Life cycle assessment of cobalt extraction process. Journal of Sustainable Mining 18, pp.150-161
and Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
[153] Source: https://www.cobaltinstitute.org/statistics.html

Non-Member companies	2011	2012	2013	2014	2015	2016	2017	2018
China (8)	34,969	29,784	36,062	39,292	48,719	45,046	69,600	78,360
India (9)	720	600	250	100	150	100	100	100
Kasese, Uganda	661	556	376	0	0	0	0	0
Katanga, DRC (See Glencore)(10)	2,433	2,129	2,300	0	0	0	0	0
Minara, Australia (See Glencore)(10)	2,091	2,400	2,700	0	0	0	0	0
Mopani, Zambia (See Glencore)(10)	1,100	230	0	0	0	0	0	0
Norilsk, Russia(11)	2,337	2,186	2,368	2,302	2,040	3,092	2,077	1,800
QNPL, Australia(12)	0	0	2,281	2,519	1,850	0	0	0
South Africa	840	1,100	1,294	1,332	1,300	1,101	1,062	1,089
Votorantim, Brazil	1,613	1,750	1,653	1,350	1,300	400	46	8
TOTAL	46,764	40,735	49,284	46,895	55,359	49,739	72,885	81,357
DLA Deliveries	0	0	0	0	0	0	0	0
TOTAL SUPPLY	**46,764**	**40,735**	**49,284**	**46,895**	**55,359**	**49,739**	**72,885**	**81,357**

1. 2009: BHPB 700mt Jan - Jul and Queensland Nickel Pty (QNPL) 1000mt Aug-Dec. (See also Note 12).
2. Estimated production after 2012.
3. Glencore joined CI 2014.
4. Previously reported as Xstrata, Norway.
5. Rubamin joined CI in 2009 and left in 2013.
6. Includes Umicore's global refined production.
7. Chambishi Metals plc Zambia (ERG).
8. Excludes Umicore's refined production in China.
9. Excludes Rubamin between 09 and 13 & est thereafter.
10. From 2014 this reports as Glencore in Table 1.
11. Norilsk ceased to be a CI member in 2009.
12. QNPL ceased to be a CI Member from 2014. Ceased trading 2016.

Table 15: Cobalt World Refinery Production, by Country or Locality[1, 2] (Metric tons, cobalt content)[154]

Country or locality and form	2012	2013	2014	2015	2016
Australia, metal powder and oxide hydroxide[3]	4.859 [4]	4.981	5.419	5.150	3.350 [e]
Belgium, metal powder, oxide, hydroxide[3, 5]	4.200	5.415	5.850	6.306	6.329
Brazil, metal	1.750	1.871	1.350	1.300 [3]	400 [3]
Canada, metal, metal powder, oxide	5.775 [r]	5.602	5.491	6.126 [r]	6.355 [p]
China, metal, metal powder, oxide, salts[e, 3, 6]	29.800	36.100	39.300	48.700	45.000
Congo, (Kinshasa), metal[7]	3.021	2.777	2.859	3.141	82
Finland, metal powder and salts[8]	10.562 [*]	10.798	12.551	9.615	12.393
France, chloride[3]	326	308	219	133	119
India, metal and salts[3]	800	295	100	150	100
Japan, metal[3]	2.542	2.747	3.654	4.259	4.305
Madagascar, metal powder	493	2.083	2.915	3.464	3.273
Mexico, metal	--	--	--	--	419
Morocco, metal	1.314	1.353	1.391	1.982 [r]	2.081
Norway, metal[9]	2.969	3.348	3.600	3.100	3.500
Russia, metal[3]	2.186	2.368	2.302	2.040	3.092
South Africa, metal powder and sulfate	1.102	1.294	1.332	1.300	1.101
Uganda, metal[3]	556	376	--	--	--
Zambia, metal[3]	5.669 [10]	5.000	4.317	2.997	4.725
Total	77.900 [r]	86.700	92.700	99.800 [r]	96.600

[e]Estimated. [p]Preliminary. [r]Revised. -- Zero.

[154] U.S. Geological Survey (USGS) (2016): Minerals Yearbook, Cobalt, 2016 tables-only release. Link: https://www.usgs.gov/centers/nmic/cobalt-statistics-and-information

1 Includes data available through February 8, 2018. All data are reported unless otherwise noted. Totals and estimated data are rounded to no more than three significant digits; may not add to totals shown.
2 Figures represent cobalt refined from ores, concentrates, or intermediate products and do not include productionfd of downstream products from refined cobalt.
3 Production reported by the Cobalt Development Institute, except as noted.
4 Production reported by the Cobalt Development Institute and Glencore plc.
5 Production from n.v. Umicore s.a.; includes production from China that is not otherwise included in this table.
6 Production from domestic and imported ores, concentrates, and intermediate materials; excludes production by n.v. Umicore s.a. that is included under Belgium.
7 Does not include production of cobalt in alloys, carbonate, hydroxide, and other materials that would require further refining.
8 Production reported by the Geological Survey of Finland.
9 Data were reported by Xstrata plc for 2012, the Geological Survey of Norway for 2013, and Glencore plc for 2014–16*
10 Includes production reported by Zambian Chamber of Mines.

4.1.4 Further processing and cell manufacturing

After the refining step, the cobalt has been transformed into forms that are traded as commodities for different uses. However, in order to be used in batteries the cobalt compounds need to be further processed into active materials specifically suited for batteries (see section 4 introduction). This can involve mixing of different compounds for the electrode to create the active cathode materials needed for batteries.

4.1.5 Geographic routes of cobalt for batteries

A 2016 article investigated the primary production routes of cobalt (and nickel) used for Li-ion batteries155. Figure 33 and Figure 34 show the trade flows of cobalt metal and cobalt chemicals, respectively, as well as the relevant intermediate products. Both cobalt (metal) powder and cobalt chemicals (sulphates, hydroxides and oxides) are used in battery production, but unfortunately, the available trade data is not specific enough to include only the cobalt used in batteries. Thus, the cobalt flows depicted in Figure 33 and Figure 34 do not only depict the cobalt products that are relevant for battery production (powder, sulphates, hydroxides and oxides) but also other products:

- Figure 33 depicts the flow of "cobalt class I". This category does not only include cobalt (metal) powder but also other forms of cobalt metal (e.g. briquettes and cathodes).
- Figure 34 depicts the flow of "cobalt chemicals". This category does not only include sulphates, hydroxides and oxides, but also possibly carbonates and other cobalt chemicals, which are not used in batteries.

It is, however, the most comprehensive source of trade flow data that the study team was able to find, and it does give a proxy for the global trade flows of cobalt specifically for batteries.

[155] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.

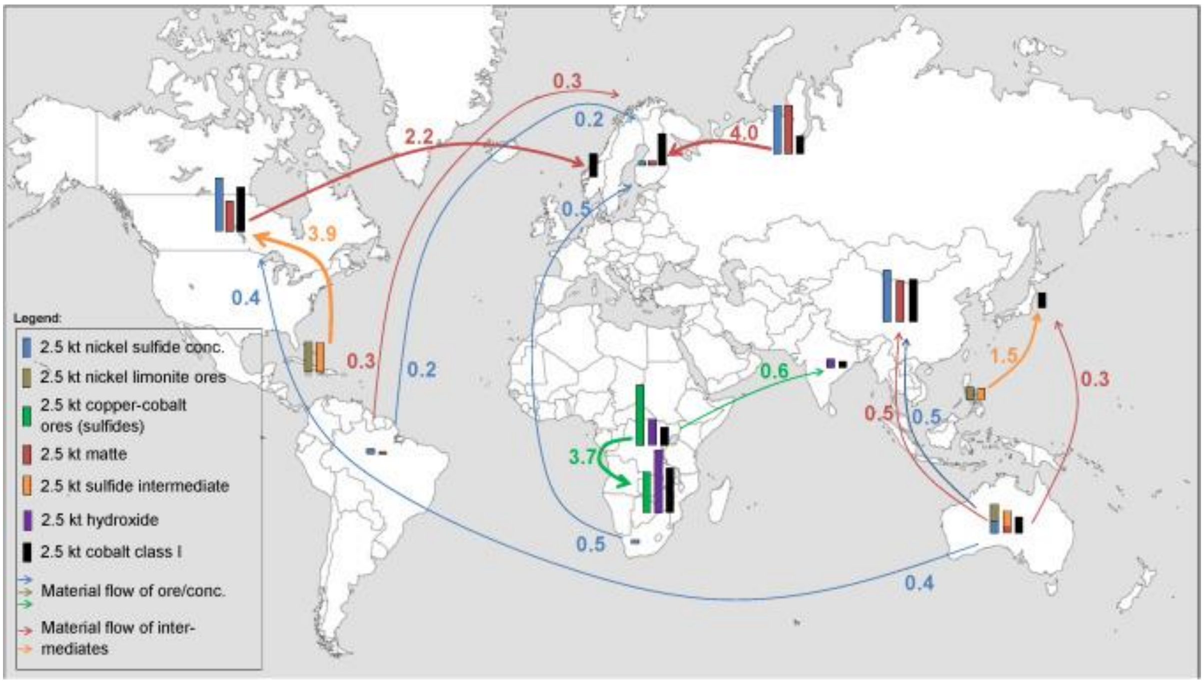

Figure 33: Primary production and global trade flows of "cobalt metal"/"cobalt class I" (year 2011; kt cobalt content). Red: flow of matte. Matte is an intermediate product that is obtained after roasting/smelting. Orange: flows of sulphide intermediates. They are obtained by leaching of (nickel limonite) ores. Blue: flow of nickel sulphide concentrate, which is obtained after concentration of (nickel sulphide) ores. Brown: nickel limonite ores. Green: copper-cobalt sulphide ores.

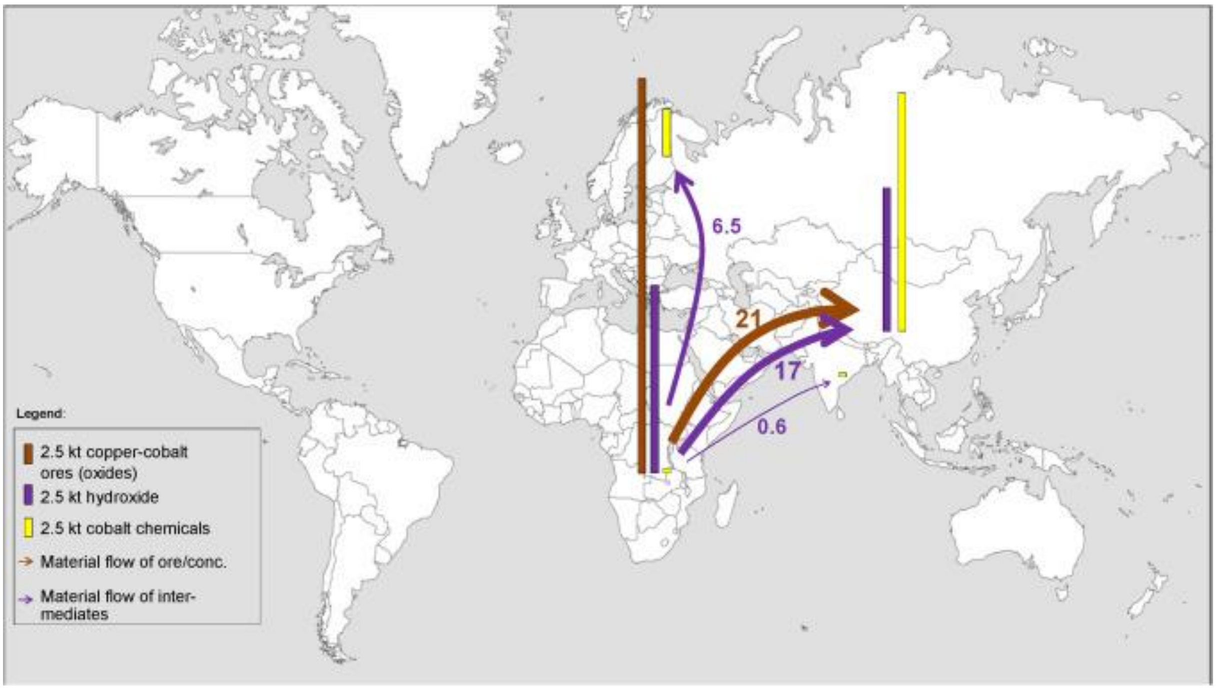

Figure 34: Primary production and global trade flows of "cobalt chemicals" (year 2011; kt cobalt content). Brown: flow of copper-cobalt oxide ores. Purple: flow of hydroxide intermediates. They are obtained after leaching of copper-cobalt oxide ores.

The article[156] identified three major primary production routes for cobalt metal/cobalt class I, and one for cobalt chemicals. The cobalt metal/ class I routes include:

- the nickel sulphide route (sulphide concentrate is transformed into matte and then into cobalt metal)
- nickel limonite route (limonite ores are transformed into sulphide/hydroxide intermediates and then into cobalt metal)
- copper-cobalt sulphide route (copper-cobalt sulphide ores are transformed into hydroxide intermediates and then into cobalt metal).

These are the routes depicted in Figure 33. All these ores, concentrates and intermediates are used in the production of cobalt metal/powder.

The "cobalt chemicals" route identified by Schmidt et al. (2016) is the copper-cobalt oxide route, along which copper-cobalt oxide ores are transformed into hydroxide intermediates and then into cobalt chemicals. This route is depicted in Figure 34. These ores and intermediates are used in the production of cobalt chemicals.

The figures show that DRC and China are major players in the worldwide supply chains of cobalt, and Finland also plays a role for both. It is also possible to see that the majority of cobalt chemical production (Transformation from ore to chemicals) happens in China, and to a smaller extent Finland. For the cobalt metal trade flows also Canada, Australia, Russia, Cuba and Brazil play a role in production of intermediates and cobalt metal.

According to this model, the cobalt metal and cobalt chemicals are produced through different routes, and there might thus be some mixing of the flows. However, it is also possible to produce cobalt chemicals from cobalt class I, but there is only little information available on the exact production processes of cobalt chemicals in the context of battery production specifically. This is true for all/most studies that try to identify the flows of metals from extraction to its uses in batteries.

4.1.6 Cobalt price fluctuations

Cobalt prices have fluctuated considerably in the past decades due to a variety of factors including geopolitical unrest, recessions, stockpiling and de-stocking and joint price setting from major producers.

The most recent development is shown in Figure 35, which shows that prices have been increasing dramatically for a two-year period from 2016 to 2018. This can be explained by higher demand from EV manufacturers and future expectations of exponential growth has resulted in investors stockpiling cobalt. However, the pace of the EV industry was lower than expected and resulted in a price crash in July 2018 dropping from almost 100,000 UDS per ton to 25,000 USD per ton one year later. Nonetheless, prices are expected to rise again when the EV market picks up momentum[157].

[156] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
[157] https://oilprice.com/Energy/Energy-General/Whats-Behind-The-Cobalt-Price-Crash.html

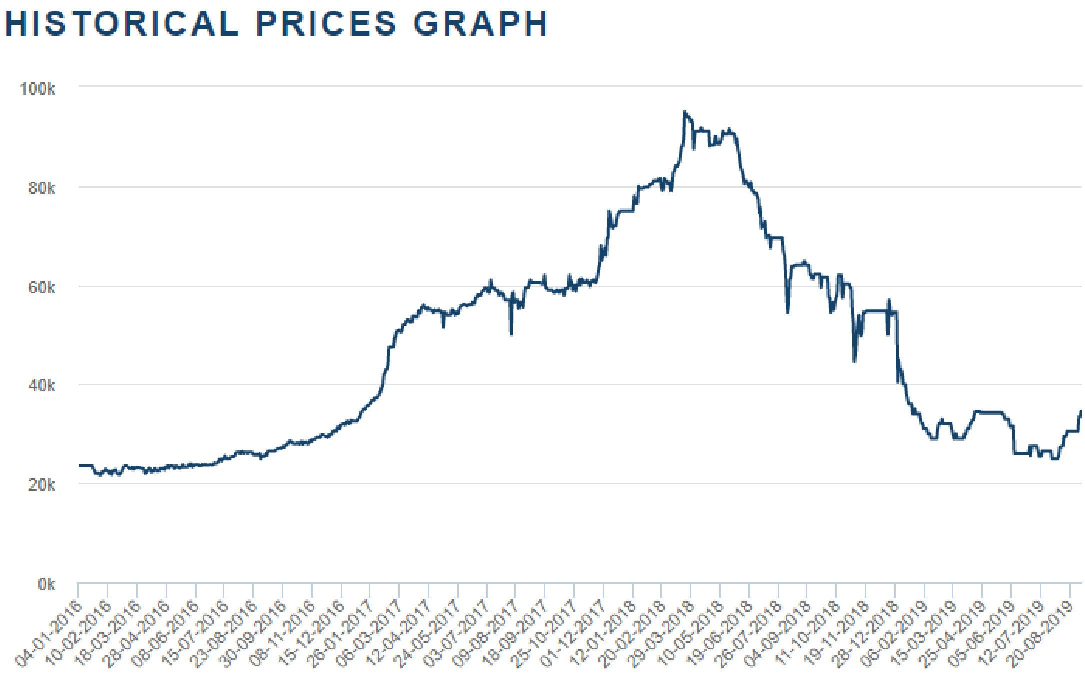

Figure 35: Price development of Cobalt from January 2016 until now[158]

4.2 Nickel

The flow of nickel from its natural deposits to its uses in batteries can be described by the process chain depicted in Figure 36. This is a stylized representation of the different types of nickel production techniques/processes that are employed at different production sites (depending among others on the deposit type) and differ significantly from each other regarding the chemical and energetic process requirements.

Figure 36 depicts the aspects of the nickel production process that are important for battery production (and, therefore, neglects the production of e.g., ferronickel and nickel pig iron). In the following sections the technical aspects of each of the links of the process chain are explained further.

[158] https://www.lme.com/Metals/Minor-metals/Cobalt#tabIndex=0

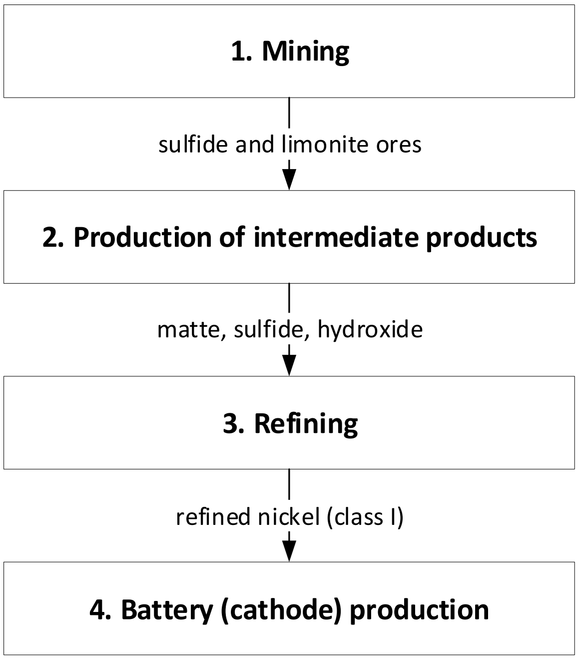

Figure 36: Stylized representation of the nickel supply chain for Li-ion batteries.

4.2.1 Mining

Nickel used in batteries is primarily won from sulphide and laterite ores, and among the laterites, limonite is primarily used for battery production [159]. The world nickel mine production is more spread out than for cobalt, as seen in Table 16, with Indonesia as the largest producer, followed by the Phillipines, Russia and New Caledonia.

Table 16: Nickel - World Mine Production and Reserves (metric tons of nickel content) in 2017 and 2018

	Mine production		Reserves[8]
	2017	2018[e]	
United States	22,100	19,000	110,000
Australia	179,000	170,000	[9]19,000,000
Brazil	78,600	80,000	11,000,000
Canada	214,000	160,000	2,700,000
China	103,000	110,000	2,800,000
Colombia	45,500	43,000	440,000
Cuba	52,800	53,000	5,500,000
Finland	34,600	46,000	NA
Guatemala	53,700	49,000	1,800,000
Indonesia	345,000	560,000	21,000,000
Madagascar	41,700	39,000	1,600,000
New Caledonia[10]	215,000	210,000	—
Philippines	366,000	340,000	4,800,000
Russia	214,000	210,000	7,600,000
South Africa	48,400	44,000	3,700,000
Other countries	146,000	180,000	6,500,000
World total (rounded)	2,160,000	2,300,000	89,000,000

[e]Estimated. NA Not available. W Withheld to avoid disclosing company proprietary data. — Zero.

[159] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
And: Kerfoot, D.G.E. (2012). Nickel. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a17_157
And: Elshkaki, A.; Reck, B.K.; Graedel, T.E. (2017). Anthropogenic nickel supply, demand, and associated energy and water use. Resources, Conservation & Recycling 125, 300–307.

[9]For Australia, Joint Ore Reserves Committee-compliant reserves were about 6.0 million tons.
[10]Overseas territory of France. Although nickel-cobalt mining and processing continued, the leading producing company reported zero reserves owing to recent nickel prices.

More detailed an historical data on worldwide nickel production is given in Table 17.

Table 17: Nickel - World Mine Production by Country or Locality[1,2] and Ore Type (metric tons, contained nickel)[160]

Country or locality[3]	2012	2013	2014	2015	2016
Albania, laterite ore[e]	1,000	2,100	4,900	6,500 [r]	3,960
Australia, undifferentiated or other	282,067 [r]	290,986 [r]	266,181 [r]	225,227 [r]	204,356
Botswana, sulfide ore, content of matte produced	17,942 [r]	22,848	14,958	16,789	16,878
Brazil, undifferentiated or other	109,000 [r]	108,000 [r]	102,000 [r]	89,302 [r]	77,000 [e]
Burma, laterite ore	5,000 [e]	6,100 [r]	21,000	26,400	22,800
Canada, sulfide ore, concentrate	211,701	227,743	228,867	234,519 [r]	235,707
China, undifferentiated or other	93,300 [r]	93,200 [r]	101,100 [r]	101,400 [r]	98,000 [e]
Colombia, laterite ore:[4]					
Mined	77,900 [r]	74,400 [r]	NA	NA	NA
Dry	NA	NA	47,400 [r]	43,900 [r]	41,600
Cuba, laterite ore	68,007 [r]	55,620 [r]	51,587 [r]	56,400	51,600
Dominican Republic, laterite ore	25,590	15,825	--	4,000 [r]	19,900
Finland, undifferentiated or other	19,590	19,440	18,730	9,383 [r]	20,654
Greece, laterite ore	21,980	19,100	21,405	19,610	19,431
Guatemala, laterite ore	2,400	10,200 [r, e]	46,800	56,400 [r]	45,900
Indonesia, laterite ore	648,400	834,200	177,100	129,600 [r]	198,900
Kazakhstan, laterite ore	450 [e]	--	--	--	--
Kosovo, laterite ore	4,436	7,606	6,724	7,418	4,300
Macedonia, laterite ore	1,680	-- [r]	-- [r]	--	--
Madagascar, laterite ore, nickel-cobalt sulfide[e]	8,300	29,000 [r]	43,000 [r]	55,000 [r]	49,000
Morocco, undifferentiated or other	288	160 [r]	-- [r]	-- [r]	--
New Caledonia, laterite ore	131,693	164,406	175,174 [r]	193,199 [r]	204,207
Norway, undifferentiated or other	352 [r]	335 [r]	400 [r]	285 [r]	220
Papua New Guinea, laterite ore, nickel-cobalt hydroxide[5]	5,283	11,369	20,987	25,582	22,269
Philippines, laterite ore	322,424 [r]	315,633 [r]	443,909 [r]	470,042 [r]	347,423
Russia:					
Laterite ore	26,620	10,400 [r, e]	11,200 [e]	7,400 [r]	7,000 [e]
Sulfide ore, concentrate	270,030	270,700	271,950	269,310	245,520
South Africa, sulfide ore, concentrate	45,945	51,208	54,956	56,689	48,994
Spain, sulfide ore, concentrate	2,398	7,574	8,631	7,213	--

[160] *US Geological Survey (USGS), Minerals Yearbook 2016, tables-only-release:* https://www.usgs.gov/centers/nmic/nickel-statistics-and-information

Country or locality[3]	2012		2013		2014		2015		2016
Turkey, laterite ore	4,400	r	1,200		3,223	r	9,600		10,200
United States, sulfide ore, concentrate	--		--		4,300		27,200		24,100
Venezuela, laterite ore[e]	8,100		--		5,000	r	4,800	r	--
Vietnam, sulfide ore, concentrate	--		1,166		6,854		8,607		4,272
Zimbabwe, sulfide ore, concentrate	7,899		12,962		16,633		16,109	r	17,743
Total	2,420,000	r	2,660,000	r	2,170,000	r	2,180,000	r	2,040,000
Of which:[6]									
Laterite ore	1,360,000	r	1,560,000	r	1,080,000	r	1,120,000	r	1,050,000
Sulfide ore	556,000		594,000		607,000		636,000	r	593,000
Undifferentiated or other	505,000	r	512,000	r	488,000	r	426,000	r	400,000

[e]Estimated. [r]Revised. NA Not available. -- Zero.

[1]Includes data available through March 1, 2018. All data are reported unless otherwise noted. Totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.

[2]Insofar as possible, this table represents recoverable mine production of nickel. Where actual mine output is not available, data related to a more highly processed form have been used to provide an indication of the magnitude of mine output, and this was noted.

[3]North Korea may have had an active nickel mine, but information was inadequate to make reliable estimates of output.

[4] Prior to 2013, mine production was as reported by the International Study Group. From 2014 onward, mine production data were estimated using data from South32 Company.

[5]Often called mixed hydroxide product or MHP by industry.

[6]An effort has been made to characterize each country's mine production by ore type (laterite, sulfide, undifferentiated and other), but the data may include a small amount of production from other ore types.

4.2.2 Concentration and conversion

The intermediate processing of nickel ores depends on the type of ore. Here only the types of ores relevant for battery production (sulphide ore and limonite) are included, and the focus is on processes that are applied in the production of class-I nickel, which is what is relevant for batteries.

For nickel sulphite ore, the processing includes firstly a concentration step, where the ore is crushed, ground, and concentrated by froth flotation (as described in section 4.1.2 for cobalt). This produces nickel concentrate, which is then roasted, smelted and converted. Nickel-copper converting is a type of metallurgical smelting that includes treatment of molten metal sulphides to produce crude metal and slag / matte.

In case of limonite ores the processing instead involves pressure leaching of the prepared ore with sulfuric acid, followed by neutralization and precipitation. The output from this process is sulphites and hydroxides[161].

[161] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
And: Kerfoot, D.G.E. (2012). Nickel. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a17_157

4.2.3 Refining

In the process of refining, the intermediates (matte, sulphides and hydroxides) are transformed into refined nickel. In the case of class I nickel production, refining involves the following three main alternatives[162]:

- (re-)leaching, solvent extraction and hydrogen reduction or electro-winning
- direct electrorefining of matte, or
- the application of the carbonyl process (in the case of matte).

The final product of these refining processes is nickel class I, or simply nickel metal, meaning the nickel content is more than 99%. The nickel metal is used for battery production but also has other uses (e.g., in the alloy steel and nickel compounds/chemicals production).

Besides class-I nickel, there are other nickel products, such as oxide sinter, ferronickel, nickel pig iron and nickel compounds/ chemicals, which are used in for example the production of stainless steel and alloys, electroplating, and as catalysts. Nickel compounds/chemicals that are not produced from class-I nickel can also be used in production of batteries, however, this production route is not common. Table 18 gives an overview of where the different nickel products are produced in the world.

Table 18: Nickel - World Plant Production by Country or Locality and Product[1,2] (metric tons, contained nickel)[163]

Country or locality	2014		2015		2016	
Australia:						
Metal	129.862	r	132.074	r	117.920	
Unspecified	7.901		20.904	r	2.600	
Total	137.763	r	152.978	r	120.520	
Austria, ferronickel, including ferronickel molybdenum	1.000		1.000	r	1.000	
Brazil:						
Ferronickel	37.237		54.700	r,e	68.600	
Metal	21.000		21.900	r,e	--	
Total	58.237		76.600	r	68.600	
Burma, ferronickel[e, 3]	16.000	r	16.000	r	8.800	
Canada, unspecified	149.486		149.717	r	158.381	
China:[4]						
Chemicals, including unspecified	20.000	r	18.891	r	28.400	
Ferronickel, high-nickel pig iron	471.500	r	385.035	r	375.645	
Metal	247.000		236.700	r	216.200	
Total	738.500	r	640.626	r	620.245	
Colombia, ferronickel	41.221		36.671		37.091	
Cuba, oxide sinter, including oxides[5]	13.251	r	13.300	r,e	13.300	e
Dominican Republic, ferronickel	--		--		9.913	
Finland:[e]						
Chemicals, including powder, salts, solutions, and other	5.960	r	7.130	r	8.050	
Metal, electrolytic, including cathode and briquets	36.600	r	36.400	r	45.600	

[162] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.
And: Kerfoot, D.G.E. (2012). Nickel. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a17_157

[163] US Geological Survey (USGS), Minerals Yearbook 2016, tables-only-release (https://www.usgs.gov/centers/nmic/nickel-statistics-and-information).

Country or locality	2014	2015	2016
Total	42.600	43.500 r	53.700
France:[e]			
Chemicals	1.260 r	980 r	696
Metal	7.140 r	5.550 r	3.940
Total	8.400 r	6.530 r	4.640
Greece, ferronickel	18.481	17.114	17.070
Guatemala, ferronickel	5.040 r	10.826	8.688
Indonesia, ferronickel	16.851	17.211	20.293
Japan:			
Chemicals	5.673	10.045 r	11.152
Ferronickel[e]	70.100 r	71.200 r	70.300
Metal	56.129	64.068 r	63.442
Oxide sinter[e]	45.900	47.500 r	46.900
Total[e]	178.000 r	193.000 r	192.000
Korea, Republic of:			
Ferronickel	22.799	39.005 r	45.600
Metal	(6)	(6)	(6)
Total	22.799	39.005 r	45.600
Kosovo, ferronickel	7.700 r	11.300 r	1.200
Macedonia, ferronickel	18.054	17.699	10.603
Madagascar, metal	37.053	47.271	42.105
Morocco, chemicals, nickel hydroxide[7]	-- r	-- r	--
New Caledonia:			
Ferronickel	54.863	56.486	67.518
Oxide sinter	7.366	21.044	28.465
Total	62.229	77.530	95.983
Norway, metal	90.500	91.220 r	92.700
Russia:			
Chemicals[e]	2.700	2.900	2.400
Ferronickel, high nickel	--	--	--
Ferronickel, other	--	--	--
Metal	234.700 r	231.200 r	192.000
Total	237.000 r	234.000 r	194.000
South Africa:			
Chemicals[e, 8]	3.500	5.200 r	4.800
Metal	34.100	41.910 r	42.100
Total	37.600	47.100 r	46.900
Taiwan, metal	(6)	(6)	(6)
Ukraine, ferronickel[9]	18.615	17.952 r	18.100
United Kingdom, metal[10]	39.100	38.804 r	45.194
Venezuela, ferronickel	5.000 r	4.000	--
Zimbabwe, metal, toll refined from imported nickel feed[11]	2.915	617	--
Grand total	2.000.000	2.000.000 r	1.930.000
Of which:			
Chemicals	39.100 r	45.100 r	55.500
Ferronickel	804.000 r	756.000 r	760.000
Metal	936.000 r	948.000 r	861.000
Oxide Sinter	66.500 r	81.800 r	88.700
Unspecified	157.000 r	171.000 r	161.000

[e]Estimated. [r]Revised. -- Zero.

[1]Includes data available through November 23, 2017. All data are reported unless otherwise noted. Grand totals and estimated data are rounded to no more than three significant digits; may not add to totals shown.

Country or locality	2014	2015	2016

[2]North Korea was thought to have produced metallic nickel and (or) ferronickel, but information was inadequate to make reliable estimates of output levels. Several countries produced nickel-containing matte and other intermediate nickel products, but output of nickel in such materials has been excluded from this table to avoid double counting. Countries that produced matte for export are listed in table 11.
[3]Imports to other countries of ferronickel from Burma, assumed 26% nickel content.
[4]Figures for ferronickel and chemicals were derived from data published by Beijing Antaike Information Development Co. Ltd. Figures for electrolytic and other class I nickel are based on data provided by the China Nonferrous Metals Industry Association and the International Nickel Study Group. China also produced nickeliferous pig iron from lateritic ores imported from Indonesia, New Caledonia, and the Philippines.
[5]An estimated 1% of reported production is unrecovered cobalt. Cuba also produces nickel sulfide and ammoniacal liquor precipitate, but because they are used as feed material elsewhere, they are not included in this table to avoid double counting.
[6]Utility® Nickel production figures for the Republic of Korea and Taiwan were not included because the production was derived wholly from imported metallurgical-grade oxides and to include them would result in double counting.
[7]Most of the nickel hydroxide was a byproduct of the concentrating, smelting, and refining of domestically mined copper ores. Some production, however, may have been derived from imported nickeliferous raw materials that were blended with the domestic copper concentrates.
[8]Primarily in the form of crystalline nickel sulfate. Estimates include nickel sulfate plus exported metal in concentrate.
[9]May include nickel in remelt alloys derived from scrap.
[10]Includes nickel content of chemicals.
[11]Data represent production from matte imported from Botswana and nickel sulfate imported from South Africa.

4.2.4 Further processing and cell manufacturing

The main battery types containing nickel are shown in Table 19. Nickel is an essential component of the cathode of these battery types, and Most Li-ion batteries now rely on nickel. Two of the most commonly-used types of batteries, Nickel Cobalt Aluminium (NCA) and Nickel Manganese Cobalt (NMC) use 80% and 33% nickel respectively. Newer formulations of NMC are also approaching 80% nickel[164].

[164] https://www.nickelinstitute.org/about-nickel/nickel-in-batteries/

Table 19: Nickel content in different types of batteries where nickel is used[165].

<table>
<tr><th>BATTERY TYPE</th><th></th><th>CATHODE</th><th>ANODE</th><th>ELECTROLYTE</th></tr>
<tr><td>Alkaline</td><td>Single use</td><td>Manganese dioxide (MnO_2)</td><td>Zinc</td><td>Aqueous alkaline</td></tr>
<tr><td>Lead acid (secondary)</td><td>Rechargeable</td><td>Lead dioxide (PbO_2)</td><td>Lead</td><td>Sulphuric acid</td></tr>
<tr><td>Nickel Cadmium (NiCd) (secondary)</td><td>Rechargeable</td><td rowspan="2">Nickel oxyhydroxide (NiOOH)</td><td>Cadmium</td><td rowspan="2">Potassium hydroxide</td></tr>
<tr><td>Nickel Metal Hydride (NiMH) (secondary)</td><td>Rechargeable</td><td>Hydrogen-absorbing alloy</td></tr>
<tr><td>Lithium Ion (LCO) (secondary)</td><td>Rechargeable</td><td>Lithium cobalt oxide ($LiCoO_2$)</td><td rowspan="3">Carbon-based, typically graphite</td><td></td></tr>
<tr><td>Lithium Ion (NMC) (secondary)</td><td>Rechargeable</td><td>Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$)</td><td rowspan="2">Lithium salt in an organic solvent</td></tr>
<tr><td>Lithium Ion (NCA) (secondary)</td><td>Rechargeable</td><td>Lithium nickel cobalt aluminium ($LiNiCoAlO_2$)</td></tr>
</table>

The most important of the battery types containing nickel for the EV industry are the NCA and NMC batteries (used in EVs) as well as the NiMH (used in hybrid vehicles). NiMH batteries are also used in power tools, and NiCd batteries are used in both power tools and industrial batteries[166].

4.2.5 Geographic routes of nickel for batteries

The primary production levels and trade flows for nickel are shown in Figure 37. As for cobalt (section 4.1.5) the figure shows the stages of nickel from mining to battery production and the trade of the intermediates. These have been separated into the following stages:

- nickel sulfide/limonite ores
- nickel intermediate products:
  - nickel sulfide concentrates
  - matte
  - sulfide/hydroxide
- nickel end-products (class-I nickel).

[165] https://www.nickelinstitute.org/about-nickel/nickel-in-batteries/

[166] Dunn, J.B; Gaines, L.; Kelly, J.C.; James, C.; Gallagher, K.G. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy and Environmental Science 8, 158–168,
And: Olivetti, Elsa A.; Ceder, Gerbrand; Gaustad, Gabrielle G.; Fu, Xinkai (2017): Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule 1, pp. 229-243.

As seen from Figure 37, Russia, Canada, Australia and China play important roles for the nickel supply chain for batteries.

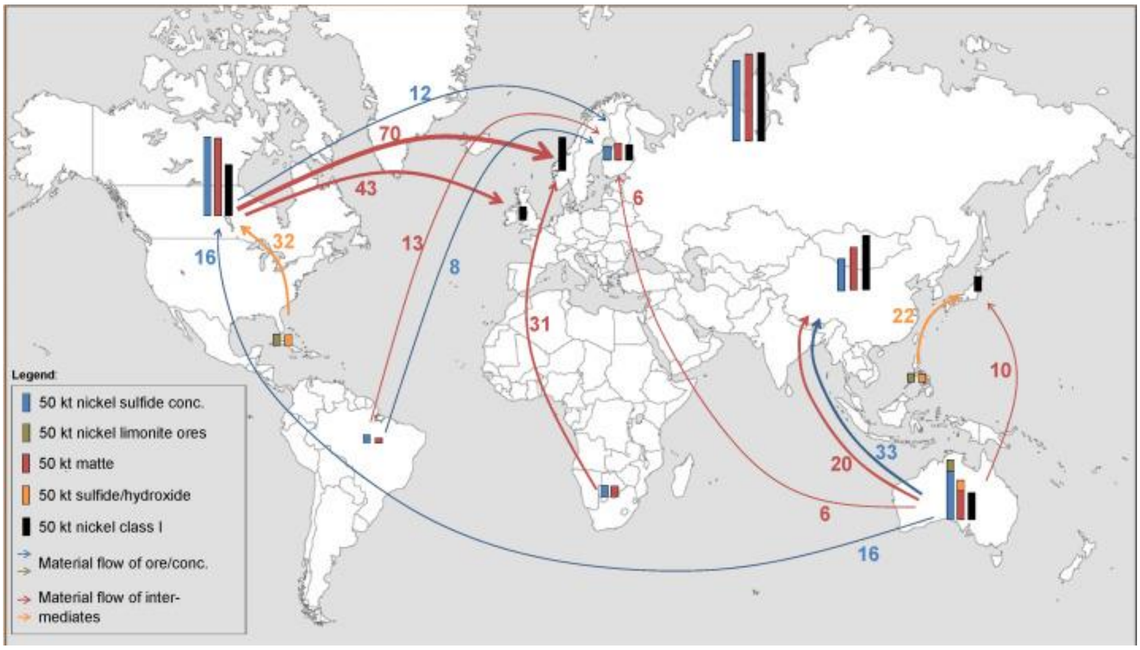

Figure 37: Primary production and global trade flows of different nickel products/commodities (year 2011; kt nickel content). Blue: flow of nickel sulphide concentrate. Red: flow of matte. Orange: flow of sulphide/hydroxide. [167]

4.3 Lithium

The flow of lithium from its natural deposits to its uses in batteries can be described by the process chain depicted in Figure 38. This is a stylized representation of the different types of lithium production techniques/processes that are employed at different production sites (depending among others on the deposit type) and differ significantly from each other regarding the chemical and energetic process requirements.

In the following sections the technical aspects of each of the links of the process chain for lithium will be described, focusing on the aspects of the lithium production process that are important for (lithium ion) battery production and, therefore, neglecting the production of e.g., lithium metal and lithium alloys.

[167] Schmidt, Tobias; Buchert, Matthias; Schebek, Liselotte (2016): Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling 112, pp.107-122.

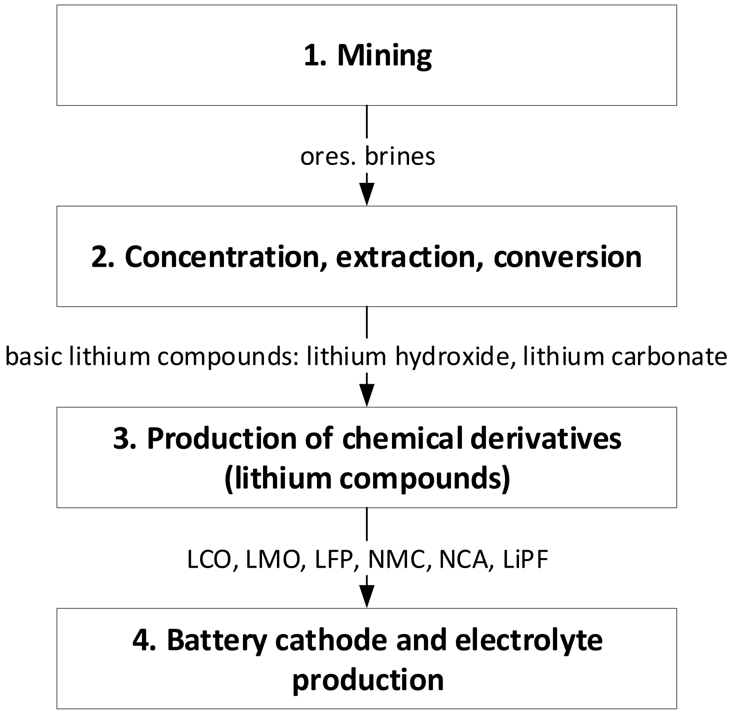

Figure 38: Stylized representation of the lithium supply chain for Li-ion batteries.

4.3.1 Mining

Lithium is contained in the hard rock mineral pegmatite, in clay (in particular, hectorite), brines (fluids containing dissolved solids) and seawater. Currently, the major sources of lithium are spodumene, which is a mineral contained in pegmatite and brines. To a much lesser extent, petalite, amblygonite and eucryptite (minerals contained in pegmatite) are used as a source for lithium[168]. In the past, lepidolite (a mineral contained in pegmatite) was among the most important sources of lithium. Pegmatite (ore) is extracted from the deposits by quarrying, open-pit mining and underground mining. Brines are extracted (i.e. pumped) from boreholes drilled into the brine aquifer. Table 20 gives an overview of where in the world lithium is extracted and the potential reserves.

Potential sources of lithium, which are currently explored, are geothermal and oilfield brines as well as clay. Also seawater has been investigated but since it has a relatively low content of lithium it is not an economically relevant source of lithium (currently).

Table 20: Lithium - World Mine Production and Reserves (metric tons of lithium content)[169]

[168] Wietelman, U.; Steinbild, M. (2013). Lithium and Lithium Compounds. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a15_393.pub2
[169] U.S. Geological Survey (USGS), Mineral Commodity Summaries, February 2019, p.99.

	Mine production		Reserves[6]
	2017	2018[e]	
United States	W	W	35,000
Argentina	5,700	6,200	2,000,000
Australia	40,000	51,000	[7]2,700,000
Brazil	200	600	54,000
Chile	14,200	16,000	8,000,000
China	6,800	8,000	1,000,000
Portugal	800	800	60,000
Namibia	—	500	NA
Zimbabwe	800	1,600	70,000
World total (rounded)	[8]69,000	[8]85,000	14,000,000

[e]Estimated. W Withheld to avoid disclosing company proprietary data. NA Not available. — Zero.
[7]For Australia, Joint Ore Reserves Committee-compliant reserves were about 1.4 million tons.
[8]Excludes U.S. production.

4.3.2 Concentration and conversion

The further processing of lithium depends on whether it is mined from ores (hard rock minerals) or extracted from brines

The processing of lithium from hard rock mineral ores, involves the following steps[170]:

1. Concentrate production
   - Preparatory steps: crushing, milling sieving of the ore and desliming by a hydro-cyclone (electrodynamic and optical sorting processes are also possible).
   - Flotation by using anionic fatty acids in alkaline medium and sulfonated oils in acidic medium and several follow-up treatments (washing/cleaning, magnetic separation, filtration, drying).
   - In this process, the lithium-bearing mineral is separated from other substances/minerals (e.g., spodumene is separated from quartz, feldspar, mica, iron).

The result of these processes is a mineral concentrate, for example spodumene concentrate, which contains around 7% lithium oxide.

2. Conversion ("digestion of lithium")
   - In this production step, lithium ores/concentrates are transformed into lithium carbonate and lithium hydroxide (and lithium chloride).
   - Three major types of conversion in the case of lithium: (i) acid-roast conversion, (ii) lime-roast conversion and (iii) ion-exchange processes.
     i. The acid-roast conversion (in particular, the sulfuric acid digestion process) generates lithium carbonate from lithium mineral concentrates or (crushed) lithium ores. This is a multi-stage procedure, which involves the use of sulfuric acid (in roasting of the prepared ores/concentrates), leaching with hot water, neutralization with lime and soda, and precipitation of lithium carbonate (by

[170] Wietelman, U.; Steinbild, M. (2013). Lithium and Lithium Compounds. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a15_393.pub2

concentrated sodium carbonate solution). It is applicable to all lithium ores (e.g., spodumene and petalite) and has a relatively low energy requirement and relatively high lithium yield in comparison to the alternatives ((ii) and (iii))

ii. In lime-roast conversion, spodumene (or lepidolite) are mixed with lime and heated to 900°C-1000°C. Several further process steps follow including crushing, milling, and leaching with hot water. The output from this process is lithium hydroxide.

iii. In the Ion-exchange processes, the lithium ore is heated with a sodium or potassium salt followed by several further steps, such as leaching. The output from this process is either lithium carbonate or in some cases lithium chloride.

The processing of brine also contains both a concentration and a further step:

1. Concentration of the brine:
   - The brine is concentrated by solar evaporation in large pond systems.
   - During the evaporation, different chemicals (salts) crystalize and are separated from the brine.
   - Depending on the brine type/production site, a preparation of the brine may be necessary before it is sent to the ponds (e.g. treatment with slaked lime).
   - The concentration processes last up to 18 months
   - The result of the processes is concentrated, lithium-rich brine (brine concentrate).

2. Production ("extraction") of lithium carbonate from brine concentrate:
   - In a multistep procedure, the brine concentrate is treated with different chemicals (alcohol-kerosene, sodium hydroxide, soda ash, lime), filtered, centrifuged, washed, dried and milled. The output after this step is lithium carbonate.

In summary, the lithium-bearing ores and brines are transformed into the following basic lithium compounds or, "basic chemicals" for short:

a) (lithium) mineral concentrate (e.g. spodumene concentrate). These mineral concentrates can be used for production of lithium carbonate (point b), lithium hydroxide (point c) and lithium chloride (point d), but also for production of other/end products,
b) lithium carbonate. This is used for production of lithium hydroxide (point c) and lithium chloride (point d).
c) lithium hydroxide and
d) lithium chloride.

Table 21 shows the world production of these basic chemicals from 2012 to 2016.

Table 21: Lithium Minerals and Brine: World Production, by Country or Locality[1] (metric tons, gross weight)[171]

Country or locality[2]	2012	2013	2014	2015	2016
Argentina, subsurface brine:					
Lithium carbonate	10,535	9,248	11,698	14,137	25,500
Lithium chloride	4,297	5,156	7,370	5,848	6,000
Australia, spodumene	456,921	415,000	463,000	490,000	560,000
Brazil, concentrates	7,084	7,982	8,519	8,500	8,500
Chile, subsurface brine:					
Lithium carbonate	62,002	52,358	55,074	50,418	67,300
Lithium chloride	4,145	4,091	2,985	2,069	1,600
Lithium hydroxide	5,447	4,197	4,194	3,888	6,000
China, lithium carbonate equivalent[e, 3]	10,000	11,200	10,100	10,700	12,200
Portugal, lepidolite	20,698	19,940	17,459	17,120	25,800
United States, lithium carbonate	W	4,600 [4]	W	W	W
Zimbabwe, amblygonite, eucryptite, lepidolite, and petalite	53,000	50,000 [e]	50,000 [e]	50,000 [e]	50,000

[e]Estimated. W Withehld to avoid disclosing proprietary data.
[1]Includes data available through May 2, 2017. All data are reported unless otherwise noted. U.S. data and estimated data are rounded to no more than three significant digits.
[2]In addition to the countries listed, other nations may have produced small quantities of lithium minerals, but available information was inadequate to make reliable estimates of output.
[3]Produced from subsurface brine and concentrates.
[4]Source: Rockwood Holdings, Inc., 2014, 2013 annual report: Rockwood Holdings, Inc., p. 16.

4.3.3 Further processing

The basic lithium compounds (lithium mineral concentrate and lithium carbonate, hydroxide and chloride) are used in the production of chemical (lithium) derivatives, lithium metal and final goods[172]:

- lithium mineral concentrates are used in the production of ceramics and glasses,
- lithium carbonate is used in the production of lithium hydroxide/chloride, in rechargeable batteries and in glazing
- lithium hydroxide is used in lubricating greases
- lithium chloride is used in the production of lithium metal, which is used in primary (i.e., non-rechargeable) batteries among others

Among all basic lithium compounds, lithium carbonate is the most important. It accounts for more than 90% of consumption.

Different types of lithium derivatives are produced from lithium carbonate for use in rechargeable li-ion batteries. These include[173]:

a) lithium manganese oxide (LMO),
b) lithium nickel manganese cobalt oxide (NMC),
c) lithium cobalt oxide (LCO),

[171] U.S. Geological Survey (USGS) 2016 Minerals Yearbook - LITHIUM [ADVANCE RELEASE]
[172] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61
And: British Geological Survey (BGS) (2016). Lithium. https://www.bgs.ac.uk/downloads/start.cfm?id=310
[173] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61
And: British Geological Survey (BGS) (2016). Lithium. https://www.bgs.ac.uk/downloads/start.cfm?id=310
And: Wietelman, U.; Steinbild, M. (2013). Lithium and Lithium Compounds. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. doi: 10.1002/14356007.a15_393.pub2

d) lithium iron phosphate (LFP) and
e) lithium hexafluorophosphate (LiPF)

Lithium hydroxide, which is also produced from lithium carbonate, is used in the production of NMC and LFP (lithium ferrophosphate) batteries.

Lithium can be used both as cathode material and as electrolyte in lithium-ion batteries. For electrolytes, the compound used is LiPF, while for cathodes it is LMO, NMC, LCO, LFP and NCA (Lithium nickel cobalt aluminium oxide).

4.3.4 Geographic routes of lithium for batteries

Since lithium carbonate is the base compound that all of the lithium battery compounds can be derived from, the trade flows in this section are expressed as tones lithium carbonate equivalent (t LCE). Figure 39 gives a detailed overview of lithium production and trade, including lithium ion batteries production and trade[174].

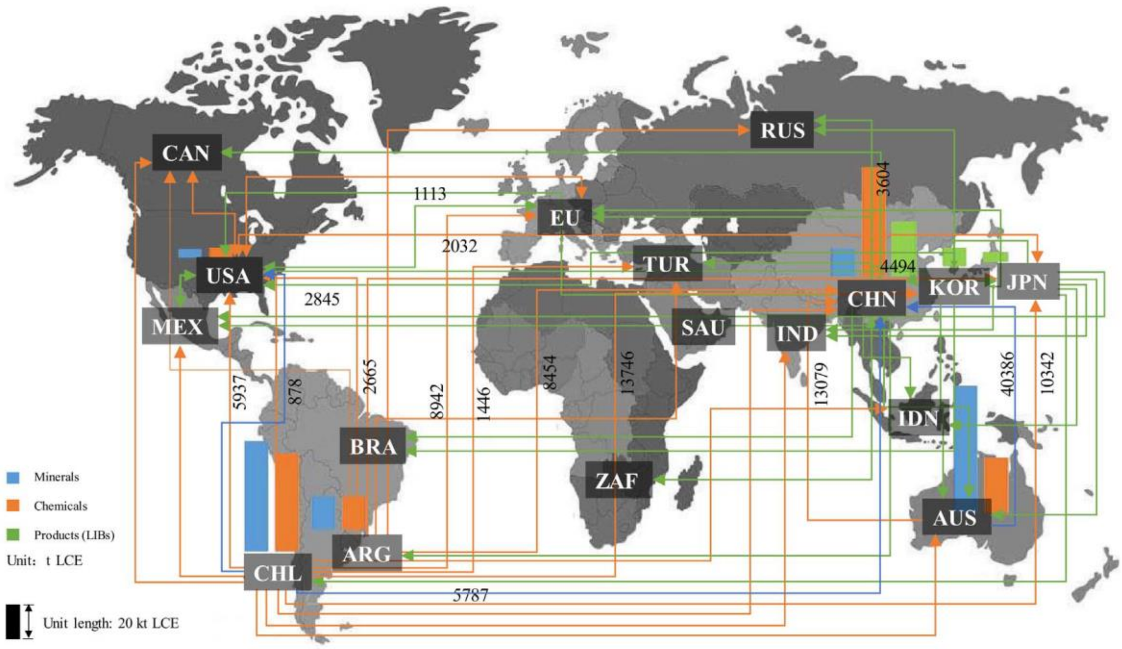

Figure 39: Global production and trade of lithium "minerals", "chemicals" and "products" (only LIB) in 2014 (t LCE)[175]. Blue: flow of lithium minerals. Orange: flow of lithium chemicals. Green: flow of final products (lithium-ion cells/batteries).

The trade flows shown in Figure 39 are divided into three categories: minerals chemicals and products. The minerals category includes lithium ores and brines. Chemicals include both basic lithium chemicals (lithium mineral concentrate, lithium carbonate, lithium hydroxide, lithium chloride) and chemical derivatives (lithium hydroxide and lithium chloride as well as

[174] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61
[175] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61

derivatives used in batteries (LMO. LCO, LFP, NMC and LiPF). The products included in the figure is only lithium-ion batteries (LIB).

Figure 40 and Figure 41 detail the flows further, by subdividing the categories and including LIB derivates/products. This category includes the products that use LIBs, including:

1. consumer electronics
    - mobile phones
    - portable computers
2. electric vehicles (EV)
    - battery electric busses (BEB)
    - battery electric passenger vehicles (BEPV)
    - plug-in hybrid electric busses (PHEB)
    - plug-in hybrid electric passenger vehicles (PHEPV)
    - electric bicycles
3. energy storage systems

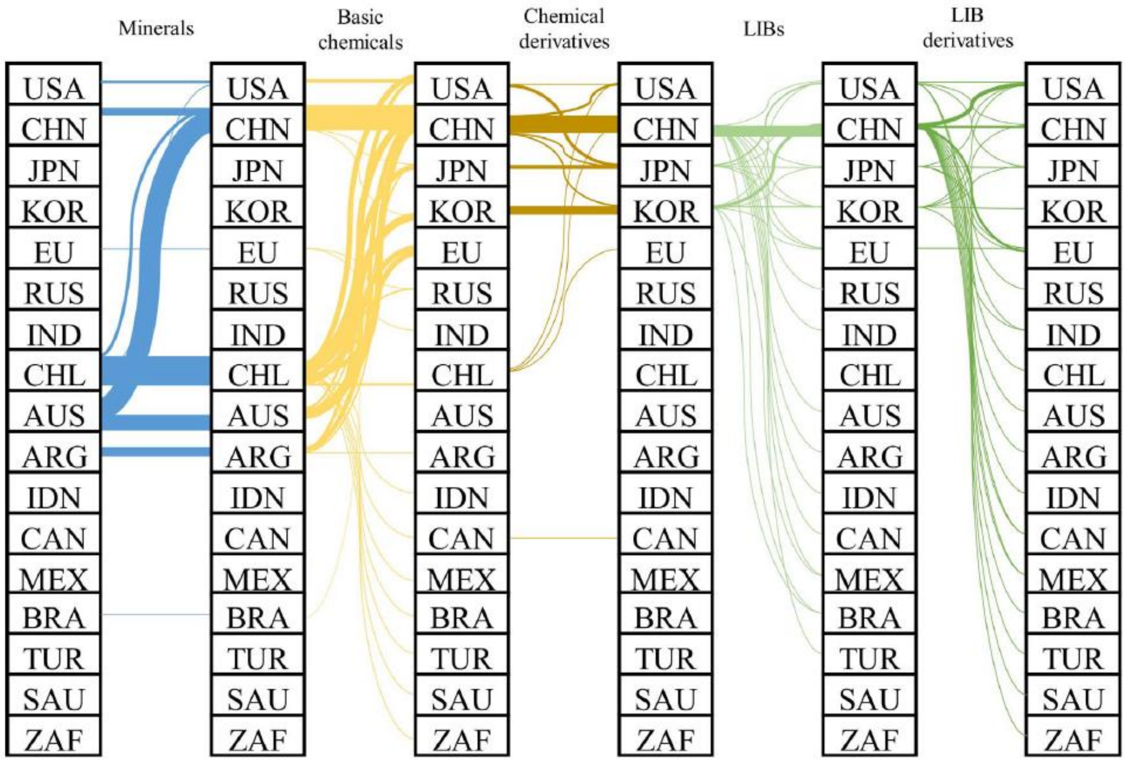

Figure 40: *Global production and trade of (lithium) minerals, basic (lithium) chemicals, chemical (lithium) derivatives, lithium ion batteries (LIBs) and LIB derivatives in 2014 (t LCE)*[176].

[176] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61

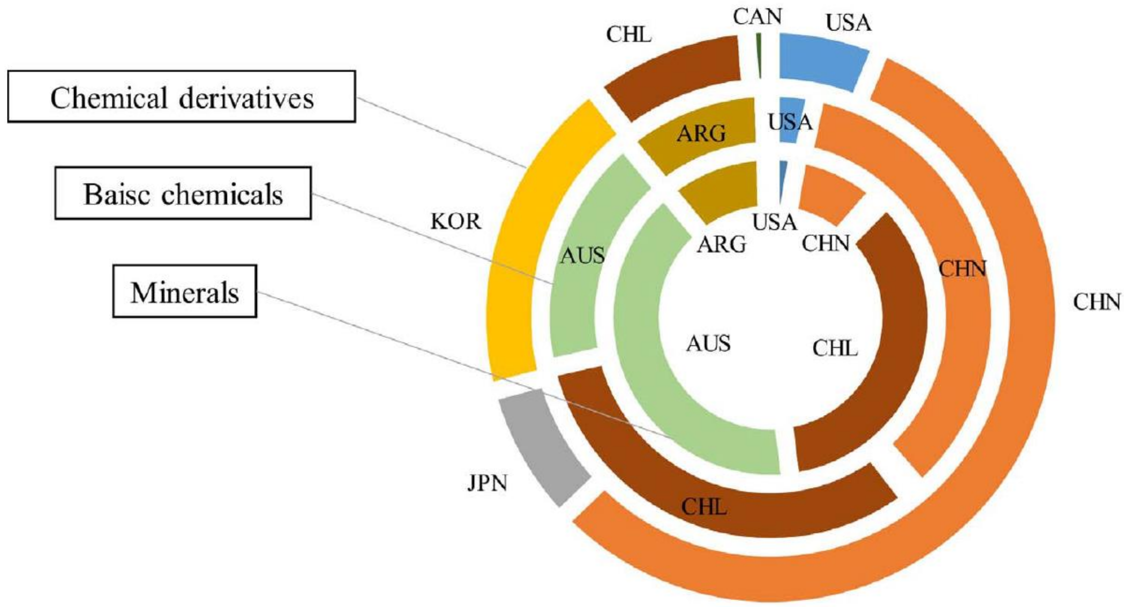

Figure 41: Global production of lithium "minerals" and "chemicals" (in particular, "basic chemicals" and "chemical derivatives") in 2014 (t LCE) - country shares[177].

The production and trade of lithium minerals (i.e. ores and brines containing lithium) happens primarily in Chile and Australia where the minerals are extracted. Moreover, Argentina, China and USA contribute significantly to world lithium mineral production (measured by t LCE). Australia exports the major part of its lithium minerals output to China for processing, while Chile exports only a small parts of its lithium mineral output (also to China). The other production countries of lithium minerals do not export to any significant extent. Hence, China is the only major importer of these minerals.

The next step, the production of basic lithium chemicals (lithium mineral concentrate, lithium carbonate, lithium hydroxide and lithium chloride) is dominated by China and Chile, while also Australia, Argentina and USA have significant shares in world basic lithium chemicals production. Chile, Australia and Argentina are the major exporters of these chemicals, while China do not export significant shares of their production, but on the other hand imports further amounts. EU, Korea, Japan and USA are also major importers of the basic lithium chemicals.

The further refined chemicals, the chemical lithium derivatives (LCO, LMO, NMC, LFP, LiPF, lithium hydroxide and lithium chloride) is primarily produced in China, based on their imports of both minerals and basic chemicals. Moreover, Korea, Japan, Chile and USA (and Canada) have significant shares in world chemical lithium derivative production. The chemical derivatives are for a large part kept in the countries where they are produced, but some are exported, mainly from USA, China and Chile. The major importers of these flows are oJapan, USA, Korea, China and EU.

For the production of batteries themselves, China is the major producer, followed by Korea and Japan. These countries produce nearly all LIBs and are therefore also the major

[177] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61

exporters. The finished LIBs are traded to most of the world, but with the most significant trade flow being from Korea to China, followed by the flow from Japan to USA.

For the final products wherein the LIBs are included (i.e. consumer electronics, electric vehicles and energy storage systems), the major trade flow is from China to USA and EU.

Figure 42 gives a breakdown on the different sub-types of minerals, basic chemicals, derivatives and products produced worldwide, rather than on geographical location. In this diagram it is seen that brine is a slightly larger source of lithium than ores. Also, as mentioned previously, lithium carbonate is the most important basic lithium chemical followed by lithium hydroxide and lithium mineral concentrate; lithium chloride has a rather small share in world output of basic chemicals. Regarding end uses in products, LIBs and Ceramics are the most important uses, but with an equally large share of "other" uses.

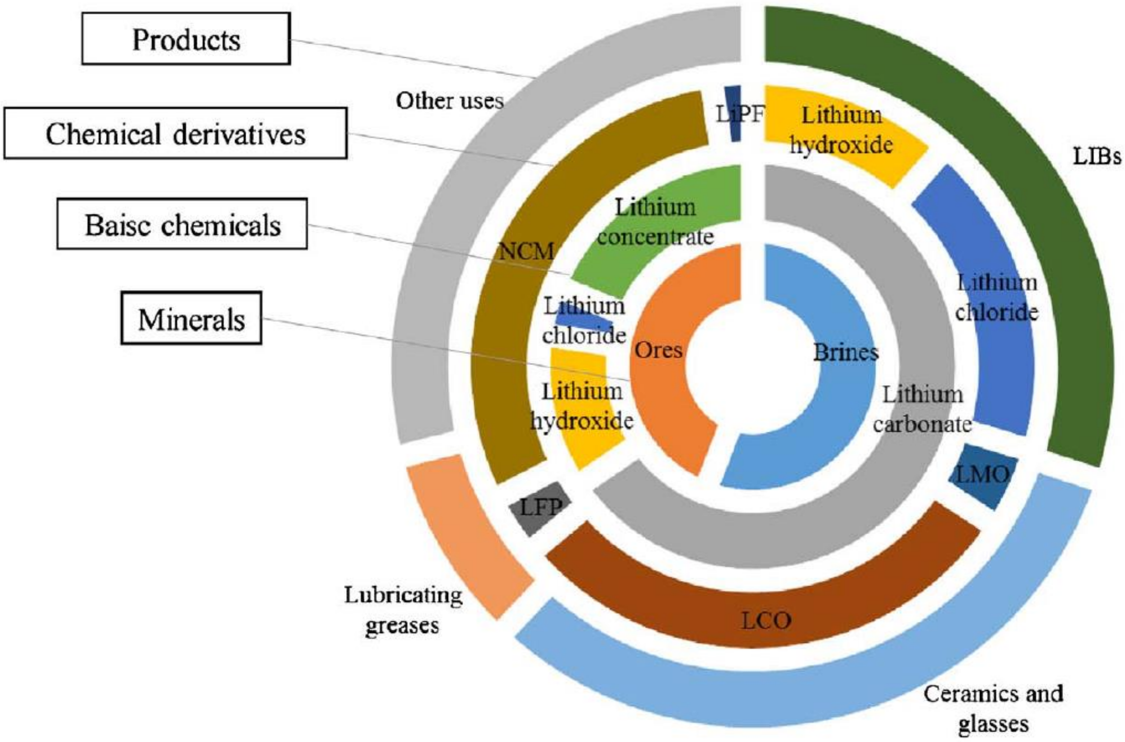

Figure 42: Inner-circle: Global production of lithium minerals (ores and brines), 2nd circle: basic chemicals (lithium mineral concentrate, carbonate, hydroxide and chloride), 3rd circle: chemical derivatives (LCO, LMO, NMC, LFP, LiPF, lithium hydroxide and lithium chloride), outer-circle: products (LIB, ceramics and glasses, lubricating greases and other uses) in 2014 (t LCE) - sub-category shares[178].

4.4 Natural Graphite

The flow of graphite from its natural deposits to its uses in batteries can be described by the process chain depicted in Figure 43. This is a stylized representation of the crystalline flake graphite production techniques/processes that are usually employed. Figure 43 depicts the aspects of the graphite production process that are important for battery production (and,

[178] Sun, Xin; Hao, Han; Zhao, Fuquan; Liu, Zongwei (2017): Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling 124, pp. 50-61

therefore, neglects the production from lump and amorphous graphite). In the following sections the technical aspects of each of the links of the process chain are explained further.

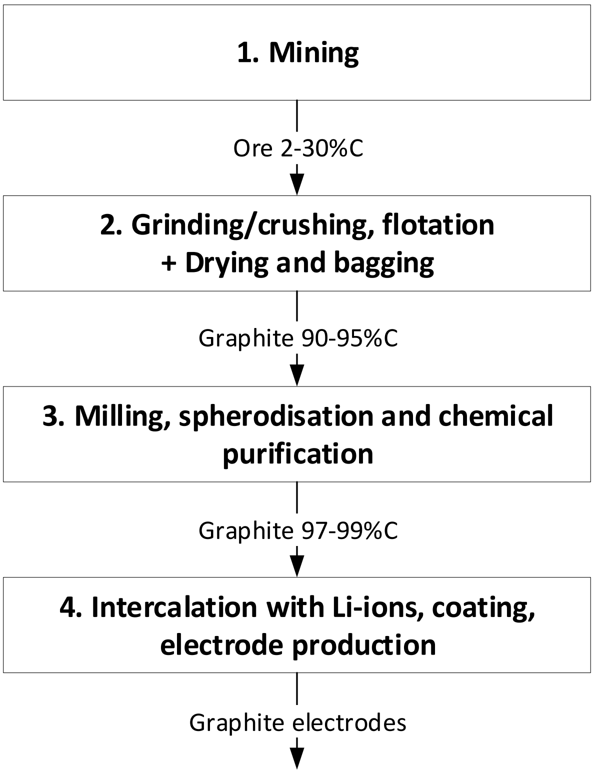

Figure 43: Stylized representation of the natural graphite supply chain for Li-ion batteries[179].

The battery sector uses both synthetic and natural graphite flake in a ratio of about 60:40[180], however, this section will concentrate only on natural graphite as a raw material for batteries, While both lump and flake graphite can be used as raw materials for anodes, the lump graphite is very limited in amount and comparatively expensive[181].

4.4.1 Mining

Natural graphite can be classified into three principle types: crystalline flake graphite, crystalline vein or lump graphite, and amorphous graphite. Only the flake graphite is used in batteries[182]. Crystalline flake graphite is usually mined in open pit mines with bulldozers, and ripper. Since it is usually near the surface and highly weathered drilling and blasting is rarely necessary[183]. Graphite is embedded in different rocks, often shales and limestones (calcareous sedimentary or metamorphic rocks)[184]. The concentration of flake graphite

[179] https://www.indmin.com/Article/3238613/Spherical-graphite-how-is-it-made.html
[180] https://www.metalbulletin.com/Article/3896232/BATTERY-MATERIALS-EUROPE-Anode-grade-graphite-poses-reputational-risk-to-buyers-RHO-Motion-says.html
[181] Jara, A. D., Betemariam, A., Woldetinsae, G., Kim, J. Y. (2018). Purification, application and current market trend of natural graphite: A review. In: International Journal of Mining Science and Technology 29 (2019) 671–689
[182] Jara, A. D., Betemariam, A., Woldetinsae, G., Kim, J. Y. (2018). Purification, application and current market trend of natural graphite: A review. In: International Journal of Mining Science and Technology 29 (2019) 671–689.
[183] Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. By U.S. Geological Survey, Harold A. Taylor Jr.
[184] Weis PL, Friedman I, Gleason JP. The origin of epigenetic graphite: evidence from isotopes. Geochim Cosmochim Acta 1981;45(12):2325–32.

(measured as % Carbon, C) is typically between 2-30% and thus varies significantly between regions. For example in Brazil the ore grade is between 10-23%, in Norway it is 26%, I Mexico it is 4% and in Madagascar it is 5-9%[185]. Table 22 shows the world mining production of graphite from 2013 to 2017, for all graphite forms. Most of these countries produce flake graphite, with exemption of Sri Lanka producing lump graphite, and Mexico and North Korea producing both flake and amorph graphite.

Table 22: Natural graphite - World Mine Production and Reserves (metric tons of graphite content) [186]

	Mine production		Reserves[2]
	2017	2018[e]	
United States	—	—	(3)
Brazil	90,000	95,000	72,000,000
Canada	40,000	40,000	(3)
China	625,000	630,000	73,000,000
India	35,000	35,000	8,000,000
Korea, North	5,500	6,000	2,000,000
Madagascar	9,000	9,000	1,600,000
Mexico	9,000	9,000	3,100,000
Mozambique	300	20,000	17,000,000
Namibia	2,220	2,200	(3)
Norway	15,500	16,000	600,000
Pakistan	14,000	14,000	(3)
Russia	17,000	17,000	(3)
Sri Lanka	3,500	4,000	(3)
Tanzania	—	—	17,000,000
Turkey	2,300	2,000	90,000,000
Ukraine	20,000	20,000	(3)
Vietnam	5,000	5,000	7,600,000
Zimbabwe	1,580	2,000	(3)
Other	1,900	4,000	(3)
World total (rounded)	897,000	930,000	300,000,000

e Estimated. — Zero.
1 Defined as imports – exports.
3 Included with "World total."

4.4.2 Concentration

Since natural graphite is embedded in the host rock, this needs to be crushed in order to release the graphite flakes. Several steps are taken in order to upgrade the carbon content and remove impurities from the graphite flakes. The most common method for concentration is multiple grinding/crushing and flotation cycles, most commonly using froth flotation. After three to six cycles, a carbon content of 85-96% is typically achieved, depending on the specific methods, ore grade and number of cycles[187].

The crushing and grinding is carefully monitored in order to prevent breaking of the flakes, since larger flakes are more valuable (from 4000-6000 USD/ton for Super-Jumbo flakes to

[185] Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. By U.S. Geological Survey, Harold A. Taylor Jr
[186] U.S. Geological Survey, Mineral Commodity Summaries, February 2019. Link: https://www.usgs.gov/centers/nmic/mineral-commodity-summaries.
[187] Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. By U.S. Geological Survey, Harold A. Taylor Jr

500-800 USD/ton for small flakes[188]). After passing the crude ore through a primary crusher, ball mills are usually used for the regrinding between flotation cycles in order to liberate more gangue minerals[189]. After flotation, the graphite is dried and bagged for transportation.

4.4.3 Refining

To achieve the graphite necessary for batteries the purified flake graphite needs to be modified into spherical graphite morphology. This is done through physical milling to manipulate the graphite layers to bend in on themselves and form spheres as seen in Figure 44. This step often increases the graphite prices greatly since the spherical graphite production has yield of around 30%[190]-50%[191].

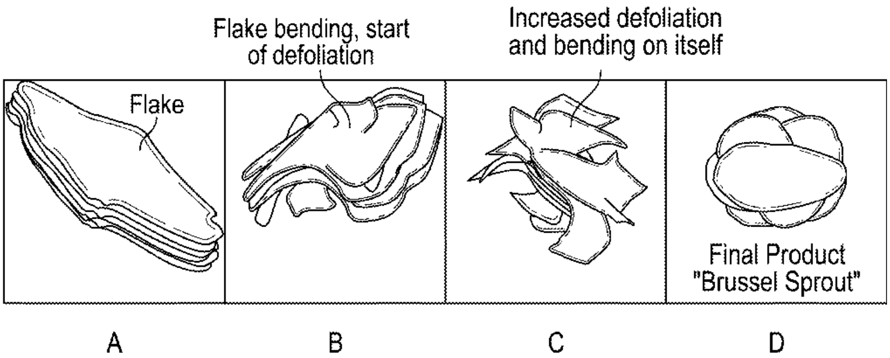

Figure 44: illustration of flake re-shaping transformation process. A: pure graphite flake, B: After substantial impacts with the processing equipment, the flake starts to bend and partially disintegrate at the edges, C: After further processing more substantial defoliation and dislocation of the flake occurs and more substantial bending of these defoliated layers, D: final product, the approximately spherical, rounded particle[192].

After spheroidization, the graphite needs to be further purified in order to be suitable for battery electrodes. This is usually done by roasting and acid leaching of the graphite. If the graphite concentrates have carbonate gangue, hydrochloric acid is used for the leaching, resulting in chloride acid waste. If the graphite concentrate has silica or silicate gangue, which is more common, it is leached with hydrofluoric acid. The fluoride acid waste is reactive and poisonous is usually treated to make it less hazardous (e.g. by neutralisation with lime), before being disposed of. The largest acid leaching plants are found in China and Brazil, while very little of this refining step takes place in Europe[193]. The heating and chemical treatment processes of

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[188] Jara, A. D., Betemariam, A., Woldetinsae, G., Kim, J. Y. (2018). Purification, application and current market trend of natural graphite: A review. In: International Journal of Mining Science and Technology 29 (2019) 671–689
[189] Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. By U.S. Geological Survey, Harold A. Taylor Jr
[190] Jara, A. D., Betemariam, A., Woldetinsae, G., Kim, J. Y. (2018). Purification, application and current market trend of natural graphite: A review. In: International Journal of Mining Science and Technology 29 (2019) 671–689
[191] https://ecs.confex.com/ecs/imlb2016/webprogram/Paper76389.html
[192] United States Patent Application Publication, Pub . No . : US 2017 / 0333913 A1, Nov . 23 , 2017, method and system for precision spheroidisation of graphite https://patents.google.com/patent/US20170333913A1/en
[193] Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. By U.S. Geological Survey, Harold A. Taylor Jr

graphite can increase the concentration to more than 99.9% C, which is necessary for batteries[194].

4.4.4 Further processing and cell manufacturing

In batteries, specifically lithium-ion batteries graphite is used in the anode, which are made of highly purified graphite (>99%) into which lithium ions are intercalated. The spherical graphite is coated with various materials, e.g. AlF3 coating[195], other forms of carbon[196], or AlPO4[197] to improve the anode properties of graphite.

In most batteries a blend of natural and synthetic graphite is used in the anodes to with market shares around 65-70% for natural and 30-35% for synthetic graphite[198]. The purified natural flake graphite has slightly better electrical and thermal conductivity[199] than synthetic material, as seen in Table 23.

Table 23: Properties of Graphite Anode Active Battery Materials for natural and synthetic graphite, based on information from producer's portfolio[200]

Product Series	Characteristics	Discharge Capacity	First Efficiency	Design Capacity/Full Cell	D_{50}	BET	Tap Density	Compressed Density
		mAh/g	%	mAh/g	um	m^2/g	g/cm^3	g/cm^3
High performance anode material	Compound natural graphite, high capacity, high first efficiency, good machinability	365.2	95.1	345-355	18-21	1.68	≥1.15	1.60-1.65
	High performance artificial graphite, high capacity, high rate capability, good cycle/ safety performance	338.52	94.5	325-335	23-27	0.92	≥1.08	1.55-1.60
		340.3	94.5	325-335	13-17	2	≥0.95	1.45-1.55

4.4.5 Geographic routes of graphite for batteries

Even though mining of graphite happens in various places on the globe, China mines around 68% of the World's natural graphite, and regarding spherical graphite (specifically for use in batteries), China is the only commercial scale producer. They produced more than 100 kt in 2018, all which was almost exclusively used for anodes for lithium-ion batteries[201]. This is also true for production of anode material, where China is both the largest producer and consumer and produces most lithium-ion battery cells as well. Also, China's market share of synthetic graphite is around 50%[202].

[194] Jara, A. D., Betemariam, A., Woldetinsae, G., Kim, J. Y. (2018). Purification, application and current market trend of natural graphite: A review. In: International Journal of Mining Science and Technology 29 (2019) 671–689

[195] https://www.researchgate.net/publication/234094664_Enhanced_performance_of_graphite_anode_materials_by_AlF3_coating_for_lithium-ion_batteries

[196] https://www.researchgate.net/publication/245108279_Carbon-coated_graphite_for_anode_of_lithium_ion_rechargeable_batteries_Carbon_coating_conditions_and_precursors

[197] https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.201801078

[198] https://batteryuniversity.com/learn/article/bu_309_graphite

[199] https://batteryuniversity.com/learn/article/bu_309_graphite

[200] http://www.indmin.com/events/download.ashx/document/speaker/6562/a0ID000000X0jaHMAR/Presentation

[201] https://www.kitco.com/commentaries/2019-04-29/Graphite-The-race-for-non-Chinese-spherical-graphite-heats-up.html

[202] https://www.slideshare.net/MorganAdvancedMaterials/2016-international-lithium-graphite-conference

However, with the increasing demand for graphite for batteries, a number of companies are aiming at developing a commercial-scale spherical graphite production outside China[203]. This is an attractive business due to the higher return on investments and prospects of a growing market. However, the barriers for market entry to spherical graphite production are high, especially due to China's low cost of labour and energy and its less stringent environmental restrictions, which is especially relevant when using hydrofluoric and other strong acids. Producers outside China therefore also look to develop different purification methods[204].

4.5 Risks related to the supply chains

The risks related to the first steps of the supply chains for each of the shortlisted materials, specifically in the originating countries and mining sector, are described in the sections 3.2, 3.2., 3.3., and 3.4. for cobalt, nickel, lithium, and natural graphite. For the risks in the further processing of the materials, it is much more difficult to find detailed information. However, the trade flows show the majority of the materials are processed and traded in the following countries: DRC, Indonesia, Philippines, Russia, Australia, Canada, Chile, Argentina, China, Cuba, Brazil, Japan and Korea.

When looking as far as the production and assembly of li-ion battery cells, the far majority of production takes place in China, with around 55% of the global manufacturing capacity in 2018. Japan, Korea and America have around 10% of the world production capacity each, and the rest is shared between other APAC and EMEA regions[205].

Many of the risks related to low governance, human rights and occupational health and safety are also present in several of these countries and the production processes undertaken in the later steps of the supply chain. The WI scores are shown for these production countries in Table 24. Environmental impacts are also an issue for several of these processes, both in terms of energy consumption and the use of various chemicals that can be hazard to natural ecosystems if not handled correctly.

Table 24: WGI government indicators on cell producing countries

Parameter	China	Japan	Korea	USA
Market share, 2018	**55%**	**10%**	**10%**	**10%**
Voice and Accountability	-1.45	1.02	0.80	1.04
Political Stability and Absence of Violence/Terrorism	-0.26	1.06	0.54	0.48
Government Effectiveness	0.48	1.68	1.18	1.58
Regulatory Quality	-0.14	1.33	1.09	1.58
Rule of Law	-0.20	1.53	1.24	1.45
Control of Corruption	-0.27	1.42	0.60	1.32
Average	**-0.31**	**1.34**	**0.91**	**1.24**

203 https://roskill.com/news/graphite-the-race-for-non-chinese-spherical-graphite-heats-up/
204 https://roskill.com/news/graphite-the-race-for-non-chinese-spherical-graphite-heats-up/
205 https://www.sustainable-bus.com/news/lithium-ion-battery-market-asian-players-to-support-european-growth/

5. Regulatory measures and impacts

In this section the different regulatory measures are identified, and their impacts estimated. The policy measures aim at increasing the share of responsibly sourced materials for batteries, specifically aiming at the four shortlisted materials: cobalt, nickel, natural graphite and lithium. The identified measures can be applied either as voluntary schemes or mandatory requirements. The identified options are described in the first part of this section, and their impacts will be elaborated further the second part.

In order to identify the best possible policy measures, a screening was made on other examples of due diligence and supply chain traceability regulations in different areas, as well as voluntary schemes evolving in the battery and mineral industries specifically. Due to the large number of standards, initiatives and frameworks for different areas affecting the sourcing of materials for batteries (including mining, environment, human rights and due diligence of supply chains), it has not been possible within the scope of this study to create a full list describing each. However, several studies already exist that describe and compare these frameworks within different areas of interest[206].

5.1 Possible regulatory measures

The possible policy measures identified and described in this section are:

- Due diligence throughout supply chain of shortlisted materials and batteries, related to human rights, environment and occupational health and safety
- Requirement on applying certain standards in the companies involved in the supply chains
- Minimum requirements for practices related to human rights, environment and occupational health and safety, focusing on shortlisted materials and batteries.
- A combination of the above

5.1.1 Due diligence requirements

Risk-based due diligence procedures have become an accepted way of moving towards more responsible sourcing, especially within the metal and mining industries. Due diligence in short terms involves identifying the supply chain, assess the risks, take mitigating actions, and disclose a report of the steps.

[206] Karoline Kickler, Jan Kosmol, Gudrun Franken, Christine Schol, Renzo Mori Junior, Lukas Rüttinger, Kathryn Sturman (2018): Mapping sustainability standards systems for mining and mineral supply chains, Commodity TopNews 59. Link: https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Rohstoffwirtschaft/59_sustainability_standards.html
And: Umwelt Bundesamt (2019): Verantwortung für Mensch und Umwelt: Unternehmen und ihre Sorgfaltspflichten: Hintergrundpapier aus dem Forschungsvorhaben des Umweltbundesamtes. Link: https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/hintergrundpapier_unternehmerische_sorgfaltspflichten.pdf
And: ISSD (2018): State of Sustainability Initiatives Review: Standards and the Extractive Economy, International Institute for Sustainable Development ISBN: 978-1-894784-79-5 https://www.iisd.org/sites/default/files/publications/igf-ssi-review-extractive-economy.pdf
And: Transport & environment (2019): Cobalt from Congo: how to source it better: Comparative analysis of existing supply chain certification schemes and artisanal practices https://www.transportenvironment.org/sites/te/files/publications/Cobalt%20from%20Congo_how%20to%20source%20it%20better_Final.pdf
And: Federal Environment Agency, UBA (2019): International Governance for Environmentally Sound Supply of Raw Materials - Policy options and recommendations (InGoRo) FKZ 3716 32 103 0. https://www.ecologic.eu/14297

Due diligence of the supply chain is seen as an important tool to achieve responsible sourcing for batteries and is therefore suggested as the basis for any regulatory requirement or voluntary scheme in this context. It is imperative, however, that the due diligence approach chosen for this purpose lives up to the following four criteria:

1. Covers the following parameters in the risk assessment: human rights, environment, occupational health and safety
2. Covers the entire supply chain from mining of a material until a battery is placed on the market in the EU
3. Has a robust verification system to ensure risks in the supply chain are indeed identified and responded to
4. Ensure that the results of the due diligence are reported upon annually and made publicly available

In this context risk should not be understood as risks to the company in terms of financial risk, market risk, operational risk, reputational risk, etc. Instead, risk is understood here as the likelihood of adverse impacts on people, the environment and society that enterprises cause, contribute to, or to which they are directly linked. In other words, it is an outward-facing approach to risk.

5.1.1.1 Which due diligence framework should be used?

The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas[207] (OECD DDG CAHRA) has been discussed as a possible framework for the implementation of due diligence in the supply chain for batteries. This is also the guidance on which the EU Conflict Minerals Regulation is based[208] and many of the due diligence frameworks developed by industry, that was screened for this study, are based on this guidance as well.

One of the disadvantages of using the OECD DDG CAHRA alone as basis for a requirement, is that this framework does not explicitly include environmental issues and occupational health and safety as part of their “red flags”, as is also highlighted by the fact that many of the voluntary schemes developed by the industry includes these as additional parameters.

One possibility that has therefore been discussed is to follow the requirements in the Conflict Minerals Regulation, where industry certification frameworks can be approved as compliant with the regulation, and in order to proof regulatory compliance, a company need a certification from one of these frameworks. This approach has been discarded, however, because the industry certification frameworks often consist of a simple report, where companies evaluate themselves and do not include any certification, third-party audits or verification[209], and selecting only one or few of these specific frameworks might favour some parts of the industry unintentionally. Hence, it was agreed among several stakeholders that compliance with such industry certification schemes cannot replace due diligence at EU level.

[207] https://www.oecd.org/corporate/mne/mining.htm
[208] https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/
[209] https://www.transportenvironment.org/sites/te/files/publications/Cobalt%20from%20Congo_how%20to%20source%20it%20better_Final.pdf

Another solution to ensure inclusion of all relevant risk areas in the due diligence (human rights, environment, occupational health and safety) is to instead use the OECD Due Diligence Guidelines for Responsible Business conduct[210] (RBC). These guidelines explicitly address adverse impacts related to workers, human rights, the environment, bribery, consumers and corporate governance that may be associated with their operations, supply chains and other business relationships. The guidelines on RBC build on a framework very similar to that of the guidelines for responsible supply chains of minerals, and consists of the following six steps for companies to implement:

- Embed responsible business conduct into policies and management systems
- Identify and assess actual and potential adverse impacts associated with the enterprise's operations, products or services
- Cease, prevent and mitigate adverse impacts
- Track implementation and results
- Communicate how impacts are addressed
- Provide for or cooperate in remediation when appropriate

In order to ensure that all relevant criteria are covered in the due diligence and that it can be applied to all parts of the supply chain (the two first criteria listed in section 5.1.1), it is thus recommended to use the OECD Due Diligence Guidance for Responsible Business Conduct as basis for any regulatory requirements or voluntary schemes implemented for batteries.

5.1.1.2 Who should perform due diligence?

The intention of the policy measure is that it should apply to all batteries for EVs and ESS placed on the market in the EU. Hence, the actor placing the battery on the market need to make sure the due diligence is performed for the battery components and materials (cobalt, nickel, lithium) that comprise the battery. However, in order for the final actor in the supply chain to be able to perform due diligence, all the companies involved in the supply chain needs to perform due diligence to provide the necessary information.

While the EU cannot set requirement for companies operating solely outside the EU, they can set requirements for any material, component or product imported into the EU. Hence, for the due diligence requirement/voluntary scheme to be effective, it should apply to all the following materials / products imported to the EU:

- Any ore or refined product used for production of cobalt, nickel, lithium or their derivatives necessary for battery production
- Any battery cell, electrode or electrolyte
- Any battery modules, packs and systems

Any company trading these materials to the EU would need to ensure their due diligence reports living up to the regulatory requirements/voluntary schemes. Especially where metals are purchased from different sources, due diligence of all materials need to be ensured before mixing or processing the materials together.

The advantages of this approach as well as the impacts would therefore also be much in line with those of the Conflict Minerals Regulation, except that the regulation for batteries would

[210] http://www.oecd.org/investment/due-diligence-guidance-for-responsible-business-conduct.htm

set material specific due diligence obligations on the downstream sector producing finished battery cells. This would be an advantage in the case of batteries as most of the short-listed high-risk metals is imported to Europe in batteries and not as metal or minerals. In addition, the metals and their minerals short-listed in section 3.11 could be included in the Conflict Minerals Regulation to cover this part of the supply chain. This should not stand alone, however, as the majority of these metals enters the EU as part of batteries.

5.1.1.3 How should the option be implemented?

The due diligence can be implemented either as voluntary scheme or mandatory requirement. Whichever approach is chosen by the Commission, in order to claim to adhere to the scheme or comply with the regulation, the following factors should be included:

- Disclosing information on the results of the due diligence process
- Verification of the results by 3rd party audits

The results of the due diligence process each year, should be disclosed as part in the companies' annual report for shareholders. This is to ensure that the information is easily available for any interested party, and that it would have direct consequences for companies if risks are not treated adequately, in terms of reputational drawbacks. The report should there for include a specific focus on risk mitigation measures.

The information disclosed regarding the due diligence results, should be audited by an independent third party through audits of the company procedures (e.g. audits of the mines, the refineries, the battery cell production sites etc.). Independent third-party audits are crucial to ensure compliance. Audits should tackle specific requirements on how to respond to risks and be performed at least annually. This will eliminate the drawback of due diligence, which is that it is up to each independent importer of batteries to assess whether identified risks should be responded to, and how exactly to respond.

In case of mandatory requirements, a notification system for conformity assessment bodies could be set up, in accordance with decision 768/2008/EC, who would then be qualified to perform the audits. If a voluntary scheme is chosen, there should likewise be strong authorisation procedures for third party actors to undertake audits, probably using a similar notification system. Since no system currently exist for these types of third-party audits its competences and requirements would need to be developed from the bottom, no matter if a voluntary or mandatory approach is chosen. However, experience might be drawn from auditing schemes like the EU Ecolabel[211] or existing voluntary mining due diligence audit systems.

For recycled materials, specific considerations should be made, to ensure that they should be traced back to the first use, but that due diligence should start from the recycling facility until part of new battery.

5.1.2 Standards as support to requirements

In order to strengthen the due diligence approach described above, standards on environment and occupational health and safety could be included for supporting voluntary or mandatory measures in a regulation for batteries.

[211] https://ec.europa.eu/environment/ecolabel/

5.1.2.1 Which are the relevant standards?

Relevant standards to support due diligence could for example be:

- ISO 140001 on environmental management
- ISO 45001 (replacing OHSAS 18001) on occupational health and safety
- ISO 22095 on Chain of custody - General terminology and models (under development)
- ILO Convention No.87: Freedom of Association and Protection of the Right to Organize, 1948;
- ILO Convention No.98: Right to Organize and Collective Bargaining, 1949;
- ILO Convention No.29: Forced Labour, 1930;
- ILO Convention No.105: Abolition of Forced Labour, 1957;
- ILO Convention No.138: Minimum Age Convention, 1973;
- ILO Convention No.182: Worst Forms of Child Labour, 1999;
- ILO Convention No.111: Discrimination (Employment and Occupation), 1958;
- ILO Convention No.100: Equal Remuneration, 1951

In order to set clear expectations for these aspects in a possible regulation, and to live up to all of the aspects of "sustainable sourcing", elevating these standards or equivalent to be a regulatory requirement could be considered as a solution, however taking into account the complexity of compliance for smaller companies (SMEs[212]).

ISO 14001 sets specific requirements for the company to identify and understand the environmental impacts of their activities, products and services. ISO 14001 requires the company to comply with all relevant environmental laws, establish an environmental policy and goals for reducing environmental impacts. The standards explicitly refer to upstream and downstream supply chain in doing this assessment[213]. Furthermore, a risk assessment related to negative environmental impacts is required, as well as a plan for how to prevent these risks.

ISO 45001 is based on OHSAS 18001, but with some changes[214]. The goal with ISO 45001 is to ensure a safe and healthy working environment. Besides complying with all legal requirements on work environment and safety, ISO 45001 also requires the company to build a structure for improving employee safety, reduce risks at the workplace and create better and more safe working conditions worldwide. As with ISO 14001, ISO 45001 also requires a risk assessment procedure assessing how employees' working environment and safety is potentially negatively affected by the company's activities, products and services, as well as a plan to solve any issues. ISO 45001 requires employee participation.

Both of these ISO standards are thus a systematised way to work with the environmental and occupational health and safety aspects in an organisation, to identify risks and prevent them.

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[212] https://ec.europa.eu/growth/smes/business-friendly-environment/sme-definition_en
[213] https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/background_paper_duediligence.pdf
[214] https://www.dnvgl.com/assurance/Management-Systems/new-iso/transition/key-changes-in-iso-45001-vs-ohsas-18001.html

For both standards an ISO auditor inspects the company premises and management systems and issues a certification as proof of compliance.

The ISO 22095[215] is under development (recently been on public hearing), and is intended to provide:

- a consistent generic approach to the design, implementation and management of Chains of Custody;
- harmonized terminology;
- the requirements for different Chain of Custody models;
- general guidance on the application of the defined Chain of Custody models, including initial guidance on the circumstances under which each Chain of Custody model might be appropriate;

Chain of custody systems enable information associated with a product and/or production characteristic to be shared among various organizations active in the supply chain. Hence a chain of custody system could be used to ensure transparency in the battery supply chain.

Any chain of custody system should benefit the interests of all relevant actors in the value chain so that it does not benefit special interest. This means that end manufacturers, recycling industries, interest groups and small and medium-sized enterprises must be encouraged to participate in the standardization process. Any Chain of Custody system developed must promote recycled metals.

The ILO conventions mentioned above are the eight essential core ILO conventions that cover the “fundamental principles and rights at work, which are universal and applicable to all human beings in all States, regardless of the level of economic development.”[216] The conventions express in detail and in a formal legal structure the scope and content of the fundamental principles, which are:

- freedom of association and the effective recognition of the right to collective bargaining;
- the elimination of all forms of forced or compulsory labour;
- the effective abolition of child labour; and
- the elimination of discrimination in respect of employment and occupation.

5.1.2.2 Who should adhere to the standards?

As for the due diligence option, all actors in the supply chain should adhere to the standards, however, the complexity of the standards and the nature of some of the first steps of the mineral supply chains, might make it near impossible. This could for example be the case for artisanal mines regarding the ISO standards. It is therefore suggested that the ISO standards described above should not be mandatory. However for middle and down-stream actors in the supply chains, the standards could be useful tool to manage environmental and occupational health and safety aspects of the companies, and it should be possible to provide information about adherence to standards in the due diligence report.

For the ILO conventions, these are in principles intended to be respected by States, however, companies could adhere to the principles therein as well. In order to ensure that the materials

[215] https://dgn.isolutions.iso.org/obp/ui#iso:std:iso:22095:dis:ed-1:v1:en
[216] http://www.claiminghumanrights.org/_ilo.html

that end up in the batteries placed on the market in the EU, all companies along the supply chains should adhere to the principles in order to avoid forced labour, child labour, discrimination etc.

5.1.2.3 How should the option be implemented?

As for the due diligence option, the standards can be implemented either as mandatory requirement or on a voluntary basis. For ISO standards, which have a build-in certification scheme, obtaining and maintain a certification within an ISO standard would be the legal requirement if these standards were elevated to legislation. Caution should be kept, however, as to who is required to adhere to which standards.

For ILO conventions, there is no certification scheme. The conventions are aimed at states, and not directly at companies. However, the conventions in question are regarded as human rights by all other parts of the United Nations system and are incorporated into other international law. It would therefore be reasonable to ensure that all companies in the battery supply chains adhere to these conventions, and to verify this as part of the due diligence procedure as part of the human rights and occupational health and safety aspects. Hence, it is suggested that compliance with all ILO conventions is mandatory.

5.1.3 Specific sustainability requirements

Specific requirements for the materials (cobalt, nickel and lithium) and the production processes throughout the supply chain could also be considered. This could for example be avoidance of certain worst practices, or adherence to certain best practices.

5.1.3.1 What could be the requirements?

An example of avoidance of worst practices was suggested by one stakeholder during the study, which regarded the mining stage. The requirement suggested was:

- Metals cannot be sourced from mines practicing deep-sea tailing placement (marine disposal of mine tailings)

No other specific requirements were suggested, but one stakeholder suggested looking to the IRMA framework (Initiative for Responsible Mining Assurance[217]), because they have an elaborate a complete definition of “clean production” in the mining sector. This could for example help to establish a differentiation between “clean” and “dirty” cobalt, lithium and nickel. These definitions also apply the mining stage.

For the middle and downstream steps in the supply chain, no suggestions have been raised by stakeholders.

5.1.3.2 Who should comply to the requirements?

Specific sustainability requirements could be implemented for all steps of the supply chains, in order to set a higher standard for sustainability of raw materials that can be obtained through due diligence alone. However, the specific options considered are thus far related solely to the mining of metals and therefore only the mining step would be affected by such requirements. Middle and downstream actors of the supply chain would however need to

[217] https://responsiblemining.net/

ensure that the metals/compounds/semi-manufacture they source does not contain metals not adhering to the specific requirements.

5.1.3.3 How should requirements be implemented?

The requirements should be part of the due diligence procedure as one of the parameters that should be checked at the mining stage (and other stages in case of elaboration with more requirements for these steps). They could be either voluntary or mandatory. In regard to the two specific requirements suggested above, it is recommended that avoidance of deep-sea tailing placement is made a mandatory requirement. For the IRMA certification however, it is recommended to make this a voluntary certification such as is the case for other industry frameworks.

It should also be ensured that any specific requirements do not have the unintended consequence of eliminating the livelihood of people. This is a consideration that has been made for conflict minerals in general, since many of the adverse impacts in the supply chains is often related to poverty issues.

5.1.4 Combination of the options

These presented policy options are not mutually exclusive but should be understood as complementary multi-level governance system. The due diligence procedure should be used as backbone and underpinned by standards and specific requirements, which in turn are made part of the checklist for due diligence audits.

In such a combination option, the following requirements would be made:

- General Supply Chain Due Diligence according to OECD Guidance for Responsible Business Conduct should be mandatory for up- and downstream users for the entire supply chain of the materials cobalt, nickel and lithium. For batteries not containing any of these metals, the due diligence should apply from the step in the supply chain where electrodes and electrolytes are produced.
- Adhering to ILO conventions should be mandatory for all actors of the supply chain
- Avoidance of deep-sea tailing placement should be mandatory for all mines mining or co-mining cobalt, Nickel and Lithium.
- Adherence to ISO standards should be voluntary
- Adherence to IRMA or other industry frameworks standards should be voluntary

The evaluation of a regulation implementing these factors, should specifically consider whether the scope should be expanded to include further specific metals the cobalt, nickel and lithium, and whether further specific requirements should be added.

5.2 Impacts of options

The impact of introducing the policy options described above will be a mitigation of risks to environment and people in the supply chain of batteries. Since at least one of the four shortlisted materials are expected to be used in every EV and ESS battery placed on the market in the EU, it is assumed that all battery cells will have been subject to the requirements in their supply chain. Hence, even though only some materials are covered all the way from the mining stage, as soon as they enter the battery supply chain (often at conversion stage), the battery cells or cell component they are incorporated into, are subject to due diligence.

5.2.1 Effectiveness of the option

The effectiveness of the regulation is quantified by the share of each selected metal (cobalt, nickel, lithium and natural graphite) contained in the batteries put on the market in the EU, that has been sourced responsibly. Responsible sourcing in this context is defined as adhering to the requirements defined in the policy options. Table 25 shows the expected share of metals sourced according to the responsible sourcing criteria in case of a voluntary or a mandatory reporting requirement by 2025, compared to no requirements (no action). The numbers are a forecast of the current market trends, where more and more companies already perform due diligence for cobalt, and is based on the assumption that around 30% of battery purchasers will also choose batteries with sustainably sourced nickel, lithium and graphite, if the information is available to them. In case of a mandatory requirement, it is assumed that all batteries put on the market will have had a due diligence process for the selected materials.

Table 25: Effect of voluntary and mandatory reporting on sustainable sourcing compared to BAU

Metal	Option	2020	2025	2030	2035	2040	2045	2050
Cobalt	No action	50%	60%	70%	80%	90%	95%	95%
	Voluntary	50%	70%	80%	85%	90%	95%	95%
	Mandatory	50%	100%	100%	100%	100%	100%	100%
Nickel	No action	0%	0%	5%	5%	10%	10%	15%
	Voluntary	0%	5%	10%	15%	20%	25%	30%
	Mandatory	0%	100%	100%	100%	100%	100%	100%
Lithium	No action	0%	0%	0%	0%	0%	0%	0%
	Voluntary	0%	5%	10%	15%	20%	25%	30%
	Mandatory	0%	100%	100%	100%	100%	100%	100%
Graphite	No action	0%	0%	0%	0%	0%	0%	0%
	Voluntary	0%	5%	10%	15%	20%	25%	30%
	Mandatory	0%	100%	100%	100%	100%	100%	100%

5.2.2 Economic impacts

Economic impacts of implementing due diligence happens to each link in the supply chain needing to perform due diligence and is thus expected to be transferred to end-users through increasing product prices. In case of a voluntary scheme this applies only to the manufacturers and supply chains adhering to the voluntary due diligence requirements, while for mandatory requirements it will apply to all.

For supply chain actors, the costs are estimated based on stakeholder inputs, which were, however, quite limited. The indications given was that around one Full Time Employee (FTE) would be needed for managing due diligence procedures for each 50-100 million € turnover. This number is averaged and very uncertain, however, and also depends on the number of sub-suppliers that are overseen and the quality of their due diligence. Sub-suppliers could be mines, refineries, cell producers etc., as the entire supply chain needs to be covered. Furthermore there might be some costs related to improving the practices used in the supply chain, i.e. minimising the risks identified in the due diligence. However, this will depend on the individual company and supply chain, and cannot be quantified in general.

A more tangible cost is the cost of third party independent audits, which was estimated to be around 20 consultant hours, once a year at each supply chain step. At a cost of around 150 EUR/hour, this amounts to 3000 EUR per year for each third party audit necessary. These costs are thus quite insignificant for the single supplier.

One of the major economic impacts is expected to be on the raw material prices, if some are in higher demand because they live up to the regulatory requirements. However, with time the price increase initiated by the voluntary scheme or regulatory requirements, is likely to level out and become closer to the average market price of non-compliant material. Approximate data was only available for cobalt, and one supplier estimated a 1USD increase per kg cobalt. Based on a high-grade cobalt price of around 30 USD/kg[218], this would correspond to an increase in material prices of around 3.5%, which is quite significant. This is the material price itself and thus comes in addition to the direct costs of managing the due diligence procedure.

The increase in material prices are likely to be conveyed to the end-user through increased battery prices. However, there are many other costs of a battery than the raw materials, and the price increase is therefore not assumed to be significant for the end-user in comparison with the cost of the EV.

The economic benefit is difficult to quantify but the expected impact of voluntary scheme or mandatory requirement is a reduction of the risks in supply chain, which can be worth a premium due to the improved market reputation for manufacturers. If due diligence is not performed, or performed poorly, manufacturers have a risk of a public scandal, which could be a large risk to future sales. Furthermore, there will be an economic benefit in the countries where environmental and health risks have been mitigated. This benefit has not been quantified due to lack of data.

5.2.3 Social and environmental impact

The main social and environmental benefit of this policy option will be the improvement of political and social stability for local operators and communities in conflict regions and the strengthening of environmental aspects, reducing contamination and health issues. However, in order to not further risk impoverishment and unemployment of local operators and communities through reduced economic activity in the regions concerned, it is important to ensure improvement of the small and artisanal mines, e.g. through formalisation processes[219], rather than avoid them completely in the supply chains.

Due to the uncertainty of the economic impacts described above, it is not possible to estimate the number of jobs created in the EU, but due to additional activities within the battery manufacturing companies, market surveillance etc., there is no doubt additional jobs are created. The share of these jobs inside and outside EU also depends on the specific supply chains and how much of them lies outside the EU.

[218] https://www.metalbulletin.com/Article/3314661/Cobalt-prices-hit-two-year-highs.html
[219] https://www.africaportal.org/documents/18664/IMPACT_ASM-Best-Practices_May-2018-EN-web.pdf

5.2.4 Administrative impact for European Commission and Member State authorities

Depending on how the requirements are implemented, the costs for the European Commission will vary. If the Commission needs to develop an implementing guidance, detailing how manufacturers should implement the requirement or voluntary scheme, previous experience from the conflict mineral regulation show that an estimated 200,000 EUR will be needed for one external study to make this guidance. As well as one Commission staff FTE is assumed to be needed for this work[220].

Furthermore, if the Commission chooses to publish a list of sustainable suppliers to show who adhere to the voluntary scheme, the costs for keeping this up to date, is estimated at 120,000 EUR annually[221].

In case of a mandatory requirement, there will be no need to keep a list of manufacturers adhering to a voluntary scheme, but instead the scheme would require up to 1.5 FTEs in designated control bodies per Member State to handle market surveillance and coordination of compliance control.

5.2.5 Stakeholders' views of the option

When asked about the most relevant social and environmental impacts in battery production, almost 60% of respondents of the Open Public Consultation (OPC) (carried out in relation to the Impact Assessment) were in favour of setting reporting obligations on the responsible sourcing of raw materials.

When asked about the type of policy and regulatory interventions most appropriate for the promotion of battery manufacturing in Europe, requirements on the ethical sourcing of raw materials was favoured by 47% of the OPC respondents.

When consulting stakeholders involved in the preparatory study, the general replies were positive towards due diligence, but most favoured mandatory requirements rather than voluntary, even though transparency of the supply chain was raised as a concern.

Mandatory requirements

Arguments for implementing mandatory rather than voluntary requirements included ensuring a level playing field for all battery manufacturers selling their products in the EU. This was especially a concern for some industry members, with regard to the minimum requirement on “worst” practices used for mining and transforming materials. It will often require substantial investments to improve production above the worst practices and avoid techniques and processes that are especially harmful to people and the environment. For the producers it is important the EU ensures legislation will not hamper the competitiveness of businesses making these investments and not using these practices. Therefore, they argue that some of these worst practices should be banned through a specific hard requirement, as is suggested for the deep-sea tailings placement (only worst-practice identified).

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[220] commission staff working document - Part 1 (Impact Assessment) Accompanying the document
Proposal for a Regulation of the European Parliament and of the Council setting up a Union system for supply chain due diligence self-certification of responsible importers of tin, tantalum and tungsten, their ores, and gold originating in conflict-affected and high-risk areas. COM(2014) 111 final, Brussels, 5.3.2014, SWD(2014) 53 final

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Type of requirements

This recommendation of a specific ban of certain practices also related to the statement from several stakeholders that due diligence alone is not enough, but that they recommend the EU to opt for the combination option, as recommended in this report. Such statement was made by Member States as well as NGOs and industry stakeholders. While including information on potential compliance to ISO standards (e.g. ISO 14001) would ensure that an environmental management system is in place to improve the environmental performance, it would not ensure that some practices are not used, or that certain worker rights are not violated. Therefore stakeholders from both industry and Member States recommended to make a combination option and argued that as long as there is no global UN convention on responsible mining, national or supranational due diligence regulations in combination with voluntary standards seem to be the best governance model for global responsible supply chains.

A specific concern was raised by several stakeholders that the OECD DDG for Responsible Supply Chains of Minerals from CAHRA were mainly focused on human rights and governance issues and would not help to tackle relevant environmental issues such as CO2 emissions, tailings management, erosion prevention, dust and chemical contamination and other environmental problems. The OECD DDG on Responsible Business Conduct was therefore raised as a better alternative by especially Member States. Furthermore, stakeholders supported that a regulation should encourage the industry to source from supply chains that have fully implemented the 8 ILO conventions and truly implement them within their facilities.

Scope of the regulation

The broad scope of including both human rights, worker rights and environment was agreed by all stakeholders with whom the study team has been in contact during the study. Another issue agreed upon by all was that the regulation should cover the entire value chain, from raw materials extraction and materials refining, to cell and battery/battery pack manufacturing. Again this was related to ensuring a level playing field, and stakeholders argued that without requirements on the entire supply chain there is a risk that European subcontractors for battery production will be disadvantaged.

Also, it was mentioned by stakeholders that to ensure batteries placed on the market in Europe are sustainably sourced, the materials need to be traced all the way from mining to finished battery system, and that level of transparency in the supply chain requires each actor along the chain to take action for due diligence. It was suggested that for each step of the supply chain, operational performance should be evaluated towards due diligence criteria and mandatory minimum sustainability requirements. Third party audits at each level of the supply chain was mentioned as an important tool, as well as sharing the conclusions of the audit along the supply chain.

Transparency

In terms of transparency different options were mentioned by stakeholders, for example the idea of a battery passport was raised, which should then be a digital record that tracks information about the battery along its entire life cycle, starting with raw material extraction to the stage of end-of-life where batteries are de-registered. In each step of the battery's life, essential information should be registered on the passport, in accordance with proposals from the Global Battery Alliance.

Other stakeholders mentioned block chain technology solutions, which are under development, to ensure supply chain traceability.

5.3 Conclusion and recommendation

Based on the findings of the report, it is clear that a regulation is necessary to ensure the sustainability of sourcing of battery materials over the entire supply chain and to avoid a trade-off between EV low-carbon transport and environmentally and socially harmful extraction and production processes for batteries. Such a regulation is recommended, based on this study, to consider the following:

- A mandatory due diligence requirement for the entire supply chain as a backbone of the regulation, from mining of the selected raw materials until the battery is placed on the European market
    - Preferably the due diligence should be required to be made according to the OECD DDG for RBC guidelines to ensure that environment and occupational health aspects are included in the due diligence process
    - If instead the OECD DGG on CAHRA is chosen as framework for the regulation, it should be explicitly mentioned that these aspects are mandatory to include in line with human rights issues highlighted in this guidance
- A mandatory, annual report on due diligence activities including results, risks identified, and mitigation actions taken. Should be published as part of the company's annual report to shareholders.
- Independent third-party auditing should be mandatory for all due diligence procedures
- Make it voluntary to comply with ISO or other environmental standards, and to report on it in the annual due diligence report
- Mandatory minimum requirements to environmental performance in the form of a blacklist of specific worst-practice mining and production methods
- Evaluate the regulation to make sure sustainability requirements increase over time by regularly assessing:
    - The effectiveness of a due diligence-based approach
    - Further worst-practices to be blacklisted