Supplementary Information of

LAYERS: A Decision-Support Tool to Illustrate and Assess the Supply and Value Chain for the Energy Transition

Oliver Heidrich [1,2,*], Alistair C. Ford [1,2], Richard J. Dawson [1,2], David A. C. Manning [3], Eugene Mohareb [4], Marco Raugei [5], Joris Baars [1] and Mohammad Ali Rajaeifar [1,2]

[1] School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK; alistair.ford@newcastle.ac.uk (A.C.F.); richard.dawson@newcastle.ac.uk (R.J.D.); j.baars2@newcastle.ac.uk (J.B.); mohammad.rajaeifar@newcastle.ac.uk (M.A.R.)
[2] Tyndall Centre for Climate Change Research, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[3] School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK; david.manning@newcastle.ac.uk
[4] School of Construction Management and Engineering, University of Reading, Reading RG6 6DF, UK; e.mohareb@reading.ac.uk
[5] School of Engineering, Computing and Mathematics, Oxford Brookes University, Oxford OX33 1HX, UK; marco.raugei@brookes.ac.uk
* Correspondence: oliver.heidrich@newcastle.ac.uk; Tel.: +44-1912086563

S1. Mitigation strategies

S1.1. International, national and local carbon reduction targets

The provision of new technologies on the required scale carries a significant risk of failure to secure the raw materials needed to deliver the politically-agreed targets. As a result, decision makers should consider global resources and supply chains in understanding the barriers and risks to meeting these goals. Thus, the complexity of the supply and consequence chain for various technologies needs be better understood and visualised. This will allow more realistic and achievable climate change strategies to be proposed and increase the likelihood of meaningful local action to achieve carbon emission reduction. It will also allow an understanding of the risk to such targets from global events, and the points of vulnerability in the global supply network underpinning mitigation targets.

S1.2. Mineral Scarcity and Implications for Sustainable Development

The concern about exhaustion of raw materials is not new; the geologist Nathaniel Shaler discussed the exhaustible nature of mineral resources in his book *Man and the Earth* in 1905 [1,2]. The

book evaluated long time series and observed that since the coming of the Iron Age, the consumption of mineral resources had increased dramatically and to an unsustainable degree. Government action to manage resources includes the introduction by the US government of the Materials Policy Commission-National Security Resources Board (1952) and the Materials Preservation Act (1974). Indeed, the report to the Club of Rome "Limits of Growth" [3] showed boundaries of physical expansion of the human economy are flexible, dynamic and interconnected [4]. In a similar vein, arguments of population growth and resource shortages were presented by [5]. This resulted in the infamous Paul Ehrlich and Julian Simon scientific wager; in 1980 Ehrlich bet that material prices would increase by 1990, due to resource scarcity and increased consumption, whereas Simon bet that prices would decrease. They mutually agreed on five commodity metals: copper, chromium, nickel, tin, and tungsten. Although Simon did win the bet, he would have lost if the bet had instead considered a longer timeframe, i.e. until 2011 [6].

It has been estimated that between 1980 and 2009 global extraction of mineral raw materials increased on average by 2.4% per annum, from 35 billion tonnes in 1980 to 67.7 billion tonnes extracted in 2009 and some 9.4 billion tonnes, of which 1.9 billion tonnes are metal ores, were physically traded in the same year [7]. Increasing raw material consumption is one driver of environmental problems [8] that can be directly or indirectly responsible for problems such as climate change, desertification, ecosystem degradation, water scarcity, and loss of biodiversity [9]. The interdependencies of people, nations and nature span across time and space and are greater than previously imagined [4].

S1.3. Electric Vehicles and Cobalt Demand

EVs are seen as an important means to help achieve the GHG reduction targets in many countries [10,11], including the UK [12,13]. The high share of EV use in cities implies the fact that cities are often at the forefront of innovation for climate change mitigation strategies [14]. It is reported that the light duty EV market surpassed 2.7 million vehicle sales in 2014 and the global EV market will grow to reach nearly 5.8 million EV vehicles in a conservative scenario and nearly 7.0 million in an aggressive scenario by 2023 [15]. Technically, EVs would absolutely be of help in reducing the demand for non-

renewable energy throughout their entire life cycle [16]. Nevertheless, the level of EV technology deployment severely depends on source of electricity and/or consumer behaviour [17].

As mitigation technologies such as EVs are adopted at a large scale across the globe, an unprecedented transformation in natural resource extraction has to occur, moving away from hydrocarbons to focus on other raw materials such as rare earths, cobalt, copper and lithium, which are needed for magnets, cables, gear shafts and batteries. As previously mentioned, due to many advantages brought by LIBs [18], many EVs are fitted with these batteries as a means of storing electrical power. These batteries encompass different designs, technologies and chemical compositions which based on different materials could be include in cathode and anode structure such as lithium, cobalt, graphite, aluminium, iron, manganese, nickel, etc. Among these materials cobalt, nickel, lithium and graphite are the critical materials that face supply constraints, while this issue is not a problem for other metals due to diversity of supply [19,20]. The problem is more severe for cobalt due to many reasons including competitive market, availability and high cost.

Cobalt is a technology-enabling metal that can be used in various applications in addition to rechargeable batteries, including use as a catalyst enabling clean fuel technology in other applications such as hard metals, the aerospace and defence industries. However a deep knowledge of the supply chain does not currently exist for Cobalt and an analysis and visualisation is needed [21]; the U.S. Geological Survey [22,23] reported that nearly half of estimated global reserves are in the Democratic Republic of Congo, a country with ongoing human/workers rights abuses associated with mineral extraction. Thus, the supply of minerals such as cobalt is strategically important to support the manufacture of batteries in order to support national governments to meet the ambitious targets set in climate change mitigation policies. However, the mass deployment of EVs will require manufacturing, raw material providers and the transportation system as a whole to consider and integrate the supply and value chain for the rapid deployment of this technology. There is no doubt the call for more efficient and sustainable battery systems will inevitably result in different battery designs and raw material requirements [24] or indeed that, at present, higher quantities of cobalt and other minerals are consumed by other applications and that EVs might not be the limiting technology for its supplies [25]. However,

there are number of other elements (rather than cobalt) that need to be considered for further assessment of supply risk. These elements mainly encompass manganese, silicon, germanium, magnesium, tin (all used in cathodes or anodes materials) as well as rare earth elements (used in high performance neodymium-iron-boron magnets for EV electric motors/ Hybrid Electric Vehicles (HEVs) and also used in nickel metal hydride batteries [26]. This paper describes the methodology that can be used to illustrate supply and value chains of all these materials and also all the other materials used in mitigation technologies.

Only a handful of studies in the literature have been focused on supply chain of cobalt. For example, the global flow of cobalt into the LIB sector (for phones and laptops) was estimated using chemical analysis and questionnaire survey, and the process flow using a Sankey diagram for the year 2002 and 2010 has been illustrated [27]. Harper *et al.* [21] developed a cycle diagram for Cobalt (worldwide and for Japan, USA and China specifically), using Cobalt Development Institute and Comtrade data in 2005 (and sometimes 2007). They considered the production, fabrication and manufacture, use and waste, proposing conversion factors to standardise the data into tonnages in order to make assumptions on the life time of 27 products they investigated. Peiró *et al.* [28] conducted a simple material flow analysis (MFA) to illustrate the industrial metabolism from source to product using U.S.G.S. and British Geological Survey data and industry reports for cobalt (amongst other scare metals) in terms of mineral ore, attractor and hitchhiker metal flows for the year 2010. Nansai *et al.* [29] identified top flows (import-export) between countries by converting data from World Database of International Trade at the Product-level (Base pour l'Analyze du Commerce International: BACI), i.e., prices into tonnages, estimated metal contents within commodities, adjusted material balances within each country, to illustrate flows of neodymium, cobalt and platinum in the year 2005. They considered 160 products containing cobalt, and estimated that 1,072,000 tonnes were mined, of which only 154,000 tonnes were moved on international markets. The biggest flow (with 64,500 tonnes) was cobalt mattes and other scrap; powders (HS 810510[1]); 21,700 tonnes cobalt ores and concentrates (HS 260500) and

[1] HS code is short for Harmonized Commodity Description and Coding System. This system provides a list of numbers used by customs to classify a product, more specifically the material, its category

20,100t electric accumulators (HS 850780). More recently, Schmidt *et al.* [30] utilised literature reviews, expert interviews and statistical data for the year 2011 to investigate the production systems for nickel and cobalt. They also collected information regarding the process chains for the most frequent technology routes, from which production sites and interconnecting product flows have been identified. Finally, the authors derived global flow charts for the respective nickel and cobalt products [30]. The worldwide extraction and supply of cobalt is well documented by the USGS and a detailed study conducted by Wilburn [31] provided an overview of the cobalt extraction industry between 2002 and 2013, which described factors that can affect mineral supply [31]. Over the last decades, global cobalt extraction increased from 18,530 metric tonnes per annum in 1994 to some 89,450 metric tonnes in the 2010, and reached over 120,000 metric tonnes in 2017. Prices have been volatile since 1990s, fluctuating between $15,000 and $86,000, and experienced a particularly large fluctuation between 2006 and 2009 (Figure S1).

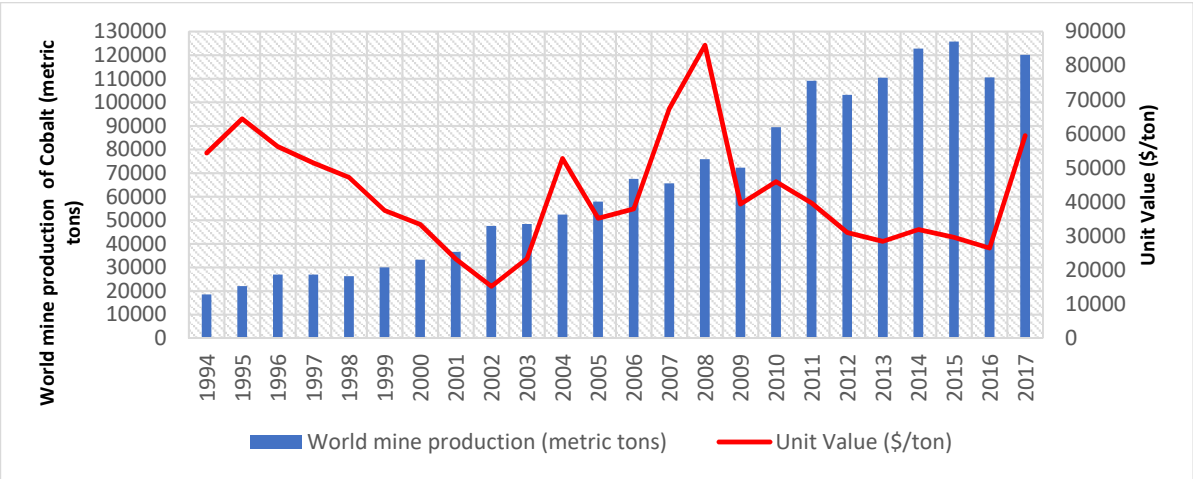

Figure S1. World production and unit price of cobalt from 1994 to 2017; Source: Authors, based on USGS data [39].

and subcategories.

S2. Material flow analysis and database architecture

Given the scarcity and complexity of materials critical to climate mitigation technologies, techniques are needed for better understanding the flows of material in their supply chains/production processes. One of these techniques is material flow analysis (MFA), which is related to the chemical engineering mass balance approach, with its basis in the first law of thermodynamics; in layman terms it means what goes in has to come out. Material MFA quantifies and tracks the physical inputs, outputs, and stocks within a system. Using monetary accounts, treatment of inputs and outputs was proposed by Leontief [32], and Ayres and Kneese [33] argued that the externalities such as waste or natural resource required in the production chain need to be included, which can be done by using tonnages rather than solely monetary terms.

MFA uses a systems-oriented approach and does not focus on a specific problem within a system or provide detailed results that can assist in tactical decision and implementation of programmes. It focuses on the relationships among energy and material flows, economic and trade developments and environmental changes [34]. Many different types of MFA studies at meso-/macro-, and micro- level are used in order solve different problems [35]. In industry, it is a tool that quantifies flows and stocks of materials in processes or production lines in physical terms [36]. MFA can also be used to model whole economies, so called Economy-Wide (EW) MFA [37], economic sectors e.g. National Accounting Matrix with Environmental Accounts; [38]; individual materials, products, or substances [36]; or determination of environmental impacts [39]. Thus, it can be used to track the movement of materials from extraction to manufacturing, and their use in cradle to grave cycles, i.e., from product, use, reuse, recycling to final disposal as well as stockpiling. Literature studies have estimated material extraction, production and consumption using Comtrade, BACI, OECD data for various elements and goods mapping the temporal and spatial flows [7,40-42].

Both MFA and EW-MFA utilise data about the movements of materials and resources between spatial locations on the Earth's surface. The activities in an MFA process (e.g. businesses or sources of material) almost always occur at a given location, be that a mine, a factory, or a consuming household,

although they are often reported at an aggregate level. Each of these locations of activity also has a number of attributes that describe its condition or status, such as its total production. The inherent spatiality of these material movements means that geographical information systems (GIS) are well-suited to helping to organise, manipulate and analyse material flow data at a range of spatial scales [43].

A key concept of GIS is the notion of layers; a layer is a discrete set of spatially related locations, and are represented in a common way. Tomlinson [44] described the use of layers in the first commercially-operational GIS system. This built on a practice used by earlier analogue map-makers and geographers of overlaying disparate map layers onto each other in order to gain an insight into spatial relationships. The layers of a GIS contain information about similar or related geographic features which are described using a common database table or similar spatial representation.

There has been much work on visualising flows and movements using GIS, where associated attributes tied to coordinate information are displayed via visual cues such as varied flow colour and width, or via multiple combinations of different cues to communicate more dimensions of the underlying data [45-49]. Both spatial economics and economic geography are also concerned with the location of economic activity, utilising techniques such as location theory to describe the basis for the siting of particular activities and to understand their interactions (or flows between them). These fields often consider single or coupled systems, e.g. the land-use and transport system and associated flows, modelling the movements of people, goods, or monetary transactions between locations.

Data visualisation techniques have been utilised in a multitude of applications, and operate as an effective mechanism for interacting with complex, multivariate datasets [50,51]. Visual presentation of complex data, coupled with the capability for data visualisation consumers to interact and interrogate presented data, gives the power of the knowledge discovery process to the consumer themselves. This ownership of the process allows users to explore and discover new insights based on their own interests [50,52]. Further, in the case of mineral flows, it enables the exploration of geopolitical implications that may have otherwise been uncertain.

Visualisation in GIS has been employed in this paper to link the concepts of MFA to a spatial

visualisation of global activities for a given material. In this case, each layer is a set of locations pertaining to a given activity within the MFA, relating to a particular stage in the life cycle of a product or material and the locations where the activities in that stage take place are mapped in that layer. It can be assumed that at the locations within each layer a process takes place where a material is changed (e.g. combined, refined, extracted etc). Between the layers are flows which represent physical movements of materials from one stage of the lifecycle to another. This process is summarised in Figure S2, in which the schematic principles of Comtrade, country data and operator (mining) sites and flows are illustrated.

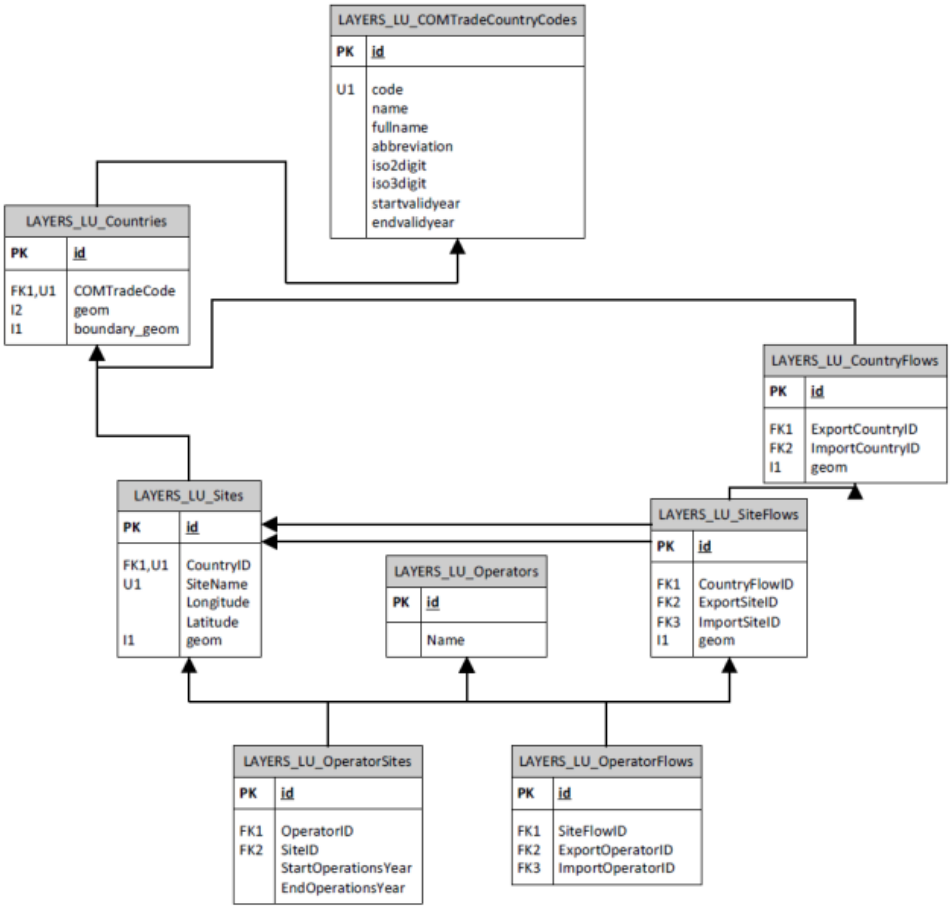

Figure S2. Schematic principles of Comtrade, country data and operator (mining) sites and flows. (PK = Primary Key, FK = Foreign Key (e.g. primary key from another table used to define a relationship), U1 = Unique Identifier, I1 = Spatial location).

The conversion of Comtrade data into this scheme requires a number of steps:

Initially, Comtrade countries are read into the 'LAYERS_LU_COMTradeCountryCodes' table from the list of official country codes. This gives a cross-reference between country codes in the Comtrade database and the spatial locations of those countries.

The location of each country is generated from a set of national polygons to give geographic locations for national-level activities. These are stored as point locations with latitude and longitude coordinates.

The network links between each country location, stored in the 'LU_LAYERS_CountryFlows' table, is constructed using the country centroid locations as the start and end point of the link. The flow quantity and other information from Comtrade is assigned to the link.

Table S1. Database functions interacting with lookup and data tables.

Table	Add New Record Function	Get Data Function(s)
LAYERS_LU_COMTradeCountryCodes	LAYERS_LU_Add_COMTradeCountryCode	LAYERS_LU_Get_COMTradeCountryCode_ByCode LAYERS_LU_Get_COMTradeCountryCodes_ByName
LAYERS_LU_Countries	LAYERS_LU_Add_Country	LAYERS_LU_Get_Country_ByCode LAYERS_LU_Get_Country_ByName
LAYERS_LU_CountryFlows	LAYERS_LU_Add_CountryFlow	LAYERS_LU_Get_CountryFlow_ByIDS LAYERS_LU_Get_CountryFlow_ByCodes LAYERS_LU_Get_CountryFlow_ByNames LAYERS_LU_Get_CountryFlowGeometry LAYERS_LU_PopulateCountryFlows
LAYERS_LU_DataLevels	LAYERS_LU_Add_DataLevel	LAYERS_LU_Get_DataLevel_ByName
LAYERS_LU_DataSources	LAYERS_LU_Add_DataSource	LAYERS_LU_Get_DataSource_ByName
LAYERS_LU_ElementType	LAYERS_LU_Add_ElementType	LAYERS_LU_Get_ElementType_ByName
LAYERS_LU_Elements	LAYERS_LU_Add_Elements	LAYERS_LU_Get_Elements_ByName LAYERS_LU_Get_Elements_BySymbol
LAYERS_LU_LayerConnections	LAYERS_LU_Add_LayerConnection	LAYERS_LU_Get_LayerConnection_ByLayerNames
LAYERS_LU_Layers	LAYERS_LU_Add_Layer	LAYERS_LU_Get_Layer_ByName
LAYERS_LU_OperatorFlows	LAYERS_LU_Add_OperatorFlow	LAYERS_LU_Get_OperatorFlow_ByCountryNames_SiteNames_OperatorNames
LAYERS_LU_OperatorSites	LAYERS_LU_Add_OperatorSite	LAYERS_LU_Get_OperatorSites_BySiteName_OperatorName
LAYERS_LU_Operators	LAYERS_LU_Add_Operator	LAYERS_LU_Get_Operator_ByName
LAYERS_LU_SiteFlows	LAYERS_LU_Add_SiteFlow	LAYERS_LU_Get_SiteFlowGeometry LAYERS_LU_Get_SiteFlow_BySiteIDS LAYERS_LU_Get_SiteFlow_BySiteNames_CountryCodes
LAYERS_LU_Sites	LAYERS_LU_Add_Site	LAYERS_LU_Get_Site_BySiteName_CountryCodes

LAYERS_LU_Units	LAYERS_LU_Add_Units	LAYERS_LU_Get_Units_ByName
LAYERS_Flows	LAYERS_DATA_Add_Flow_ Data	LAYERS_Data_Get_Flow_Data_ByIds
LAYERS_Deposits LAYERS_...	LAYERS_DATA_Add_Layer _Data	LAYERS_Data_Get_Layer_Data_ByIds LAYERS_Data_Get_Layer_Data_ByNames

This table illustrates an example entity-relationship diagram for the scheme, using example LAYERS data tables and associated lookup tables. To facilitate the use of the database scheme, a series of stored procedures or functions has been created. These can be categorized into those adding data to specific tables (add), and those used to retrieve data (get). These functions are outlined in Table S1 including an indication of the table(s) (i.e., relations) with which they interact.

S3. Cobalt trade-network data collection

The cobalt trade-network was based on Baars*, et al.* [53] and the corresponding data can be obtained from that study. Following is a repetition from Baars, Domenech, Bleischwitz, Melin and Heidrich [53] on the construction of the trade-network.

S3.1. Cobalt mine production

Primary production data of cobalt producing mines in 2017 was obtained from a wide variety of company reports, literature and government reports. Total national production was compared with data mineral commodities summaries from the USGS [54] and BGS [55], and the more detailed mineral yearbook from 2016 by the USGS [56]. For many countries there are discrepancies between national estimates and mine specific estimates. For the DRC and Morocco, more detailed calculation and assumptions were required to estimate primary cobalt production and are described below.

Morocco:

The Bou Azzer mine is the only operating mine in Morocco, operated by Compagnie de Tifnout Tighanimine (CTT), part of Managem Group. This is the only mine in the world where cobalt is produced as the main product [57]. The Bou Azzer facility includes a mine processing plant producing cobalt metals, producing a total of 1,924 tonne of refined cobalt metals in 2017 [58]. According to the USGS, total mine production in Morocco in 2017 was 2,200 tonne. Trade statistics suggest that Morocco exported a total of 1,973 tonne of cobalt metals, while it imported a total of 760 tonne of cobalt

ores and intermediates primarily from the DRC. Third party feed stock is used [56], but the company does not highlight how much of their production was derived from the Bou Azzer mine and how much from third party feed. Based on reported refined production minus cobalt import, the total primary production was assumed to be 1,140 tonne.

DRC:

Mine production from the DRC was derived from [59] which was derived from the Congomines, an online documentation portal for information on the industrial mining sector in the Democratic Republic of the Congo. This data was cross checked with a recent cobalt report from the German geological survey (BGR) [60], which is based on S&P metals and mining database. In two cases the reported mine production by [59] (Tenke Fungurume and CDM) differentiated significantly with the data by BGR. In both cases the data from the BGR was used. In addition, the Big Hill operation by Gécamines (3,568 tonne of cobalt) was listed in the data by the BGR but not listed in the source from Congomines. A reason could be that this is mined from a slag pile and not accounted for primary production. We included the Big Hill operation in our dataset.

S3.2. Cobalt ore trade

Cobalt ore trade was based on HS code 260500 'cobalt ores and concentrates', assuming a 7% cobalt content based on Gulley et al. [61].

S3.3. Intermediate cobalt production

Refiners rely on either intermediate cobalt products or ore to produce refined cobalt. Intermediate refining is a step in between mining and final product refining, often taking place near or at the same country as the mine. Intermediate production is calculated based on domestic cobalt production minus ore export.

S3.4. Intermediate trade

Here we only included intermediate imports by countries with cobalt refining capacity (only the facilities producing battery suitable refined cobalt). Estimating intermediate cobalt trade is difficult due

to the wide range of cobalt content in different products. To reduce uncertainty, we include the following intermediate cobalt products that have a corresponding HS trade code based on Schmidt, Buchert and Schebek [30]: cobalt hydroxides, nickel matte and nickel hydroxides.

Cobalt intermediates (HS 810520):

HS 810520 'Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders' was used to capture cobalt hydroxide intermediates. This trade flow also contains refined products such as powders and metals. Intermediate cobalt flows where therefore identified by economic value of the trade flow based on [62], where flows with an average value of 11$ per kilogram are assumed to be intermediates, between 11$ and 22$ it is assumed to be 50% intermediates and 50% pure metal or powder, and above 22$ it was pure metal. Data was derived from the UNComtrade database[63] and, assuming a cobalt content for intermediates of 27% based on Gulley, McCullough and Shedd [61]. The Chinese trade customs database [64] provides more detailed trade codes for intermediate cobalt trade for China. Due to the significant intermediate imported by China, this database was used to obtain more detailed information on Chinese imports. Trade code HS 81052010 (Cobalt hydrometallurgy intermediate) and 81052090 (Cobalt mattes and other intermediate products of cobalt metallurgy) where used, assuming a cobalt content of 27% and 22% as done Gulley et al [61].

Nickel-cobalt intermediates (HS750110 and 750120):

Some countries trade nickel-cobalt intermediate products that are further refined. The USGS Mineral Yearbook highlights where intermediate Ni is produced [56]. Ni-Co sulphides are produced in Cuba and the Philippines and Ni-Co hydroxide (also referred to as MHP) in New Caledonia and Papua New Guinea. Furthermore, production of Ni matte by cobalt producing countries takes place in Australia, Canada, Finland, Indonesia, New Caledonia and South Africa. Based on this information, we included several nickel-cobalt trade flows.

Philippines-Japan (Ni-Co sulphide): Ni-Co sulphide imports by Japan from the Philippines and Australia. Sumitomo is the only cobalt refiner in Japan, producing 4.2 kt of electrolytic cobalt in 2017 (see below for more detail on refining). The company reports that feedstock for the Harima and Niihama

smelter are imported from the Coral Bay and Taganito refineries (Sumitomo has majority of ownership in both) in the Philippines [65]. HS code 75.01.20 - 'Nickel; oxide sinters and other intermediate products of nickel metallurgy' [30]was used for nickel-cobalt sulphide, assuming a 4.2 % cobalt content as reported by the Coral Bay Nickel Corporation [66].

Australia-Japan and China (Ni matte): Ni-Co matte imports by Japan and China from Australia. Here a cobalt content of 0.9 % in Ni matte was based on information on Ni matte from the BHP Kalgoorlie smelter by BHP [30].

Russia-Finland (Ni matte): Ni-Co intermediate trade flow was from Russia to Finland. The Kokkola refinery, owned by Freeport Cobalt, produced 7kt cobalt chemical and 5.6 cobalt powder. The Harjavalta Refinery in Finland, owned by Nornickel, produced 0.9 cobalt chemical in form of cobalt sulphate and sold the rest of its cobalt solutions to the Kokkola refinery [38]. Total nickel production at the Harjavalta refinery in 2017 was 59.7 kt, of which 55 kt came from Russian feedstock in form of nickel matte. This is equal to the total nickel matte imports from Russia in 2017, which was 102 kt of Ni matte, suggesting a Ni content of 55% in matte which is similar as reported in the literature by [16]. Cobalt content in Ni matte was assumed to be 1.5% (literature reported between 0.9 and 2% [16]), resulting in a total cobalt import of 1.5kt from Russia to the Harjavalta refinery.

PNG-China (Ni-Co hydroxide): The Ramu nickel-cobalt mine, was operating on the north coast of PNG and owned by the Metallurgical Corp. of China, other Chinese companies and the government of PNG [25]. Nickel-cobalt ore is transported by pipeline and leached with sulphuric acid under pressure and high temperature (HPAL) to recover an Ni and Co hydroxide (known as mixed hydroxide product or MHP) [42]. Trade flows indicate that all intermediate Ni-Co from Papua New Guinea where was exported to China. It was therefore assumed that all cobalt contained in the MHP produced in 2017 (3.3kt) was exported to China in 2017.

Cuba-Japan and China (Ni-Co hydroxide): According to the UNComtrade data, total Ni-Co hydroxide exports in 2017 from Cuba where 21,742 kt, of which 21,427 kt was imported by China and 315 tonne by Japan. Sherrit reports that its Ni-Co hydroxide is exported to Canada [67]. No information production

data can be found on the second Ni operation, the Che Guevara plant in Punta Gorda. However, it is reported that most of its output is shipped to China[68]. The Che Guevara plant uses the Caron process to recover nickel and cobalt[69]. The output of a Caron process is a Ni oxide sinter[30]. Taylor [70] reports on four operating Caron installations (Nicaro in Cuba, Yabula in Australia, Tocantins in Brazil and Punta Gorda in Cuba), of which currently only the Punta Gorda still operates. Nicaro seized operations in 2012 and Yabula and Tocantis in 2016. Limited recent information is available on cobalt content in Ni oxides. As we estimated that the Punta Gorda had a total cobalt mine production of 1,399 tonne in 2017, we assumed that all of this was exported in 2017. This results in a cobalt content of 6.5% in the Ni-Co trade flows to China and Japan.

Missing trade flows

We also included three large missing trade flows. The first gap is the large discrepancy between imports and exports by Zambia. Zambia imported a total of 16.9kt (5.4 kt of ore and 11 kt of intermediate cobalt) from the DRC. However, its total exports accounted for 5.2 kt (2.3 cobalt intermediate and 2.8 kt cobalt metal), indicating a total 10.4 kt missing from the trade statistics.

The second data gap is the missing trade flow between the DRC and Finland. The Freeport Cobalt Kokkola refinery (production in 2017: 13.5 kt cobalt) is supplied with cobalt hydroxide from the Tenke Fungurume Mine (TFM) in the DRC, as highlighted by China Molybdenum in their annual report of 2017 [39, 40]. Trade statistics for 2017 do not show any large import flow of cobalt (cobalt/copper ores, intermediates or oxides) into Finland. However, there is a supply agreement in place between China Molybdenum and Freeport Cobalt [25], and 2014 did illustrate significant imports from the DRC (roughly 13.2 kt). We assumed that the missing export values for Zambia and import values for Finland are the same. Taking into account that 1.4 kt of cobalt intermediate from Zambia was reported to be exported to the EU, total exports from Zambia to Europe would be 11.8kt, roughly matching the missing flow. As this is a re-imported flow from the DRC to Zambia, it is counted for the DRC.

The last missing flows are from Cuba to Canada. Cuba produces primary cobalt but no refined materials. Sherritt produced cobalt briquettes (2 kt) and powder (1.6kt) at its Fort Saskatchewan refinery. The

company reports that this happens with feedstock from its nickel mine in Moa, Cuba, where a nickel-cobalt intermediate sulphide product is produced[69]. Under the Moa Joint Venture, Sherrit (50% ownership) and the General Nickel Company S.A. of Cuba (50% ownership), nickel is mined and shipped to Canada [67]. Although no trade statistics can be found for nickel or cobalt intermediates exports from Cuba, it is assumed that the mixed sulphide containing 3.6 kt of cobalt for the Sherrit refinery is all derived from Cuba.

S3.5. Cobalt refining

Different refined cobalt products exist and not all are used to produce batteries [71].The cobalt products used for the cathode market include chemicals, powders, briquette, ingots/rounds and broken cathode [30,72]. The Cobalt Institute provides company and locations specific data on annual refined cobalt production but does not make a distinction in the type of products [73]. Data from Darton Commodities, as reported by Bloomberg, was used to obtain product specific refined cobalt production in 2017 [74]. Here final refined cobalt is subdivided into three product forms: chemical, powder and metal. However, broken cathode, briquette and ingots/rounds are 'hidden' in cobalt metals in this dataset and some additional steps had to be taken to filter these out.

First, according to the product range of the Minor Metals Trade Association, Norilsk Nickel, Russia was the only producer of cobalt ingots [75], but seized the production of cobalt ingot in 2016 and is no longer traded on the London Metal Exchange (LME) [76]. However, cobalt rounds and ingot are considered under the same product group by industry [77], and Vale in Canada, the only producer of LME traded cobalt rounds, highlights that its products are used in the battery industry [78]. Second, cobalt round production in Canada is therefore included in the analysis. In terms of broken cathodes, there are currently two producers of LME products, CTT in Morocco and Chambishi in Zambia [75], both included in the analysis. Third, it was found that briquettes where only produced in Madagascar and Australia. Lastly, cobalt briquettes and powders are combined as they can be considered the same product group [77] and are therefore combined as one group.

Japan:

- Sumitomo in Japan produced 4.2 kt of cobalt metal and is one of the main supplier of NCA cathode material to Panasonic [79]. The Sumitomo refining process in Japan produces cobalt chloride, which is then turned into pure cobalt metal through electrowinning [71]. According to the USGS, some of this cobalt chloride in 2015 was used as feedstock in the Sumitomo Isoura battery plant. Although the company reports that it uses Ni sulphate from its own refinery to produce cathode materials, the company does not report on the production of any cobalt products other than electrolytic cobalt and highlights that most of its battery raw materials came from external inputs [80].

Australia:

According to the Bloomberg refining data, 6.3 kt of cobalt metal was refined by Glencore. This consists of 2.7 kt refined production at the Murrin Murrin nickel-cobalt mine in Australia and 3.5 kt from the Nikkelverk refining in Norway [81]. The Murrin Murrin refinery produces cobalt briquette and powders [82].

S3.6. Refined cobalt trade

Imports and production of refined cobalt by South Korea, Japan, USA and China was obtained to understand the potential origin of primary cobalt sources embedded in European EVs. Without any or limited refining capacity, Japan, USA and South Korea where all depended on imports. To estimate total imports, the UNComtrade database and the six digit Harmonised System codes where used. For imports of cobalt chemicals, the HS code 282200 'Cobalt oxides and hydroxides; commercial cobalt oxides' was used. The cobalt content for HS 282200 was assumed to be 72%, based on the EU Critical Material Factsheets [62] and similar as the 70-78% for oxides cobalt content reported by Donaldson [71]. While oxides and hydroxides could be further refined to other products, without any domestic refining capacity for Japan, US, and Korea it was assumed that imports of chemicals were a refined cobalt chemical product. For China, some chemicals where imported from Belgium and Finland, which were assumed to be refined final products derived from the Freeport refinery in Finland and the Umicore refinery in Belgium.

To account for imports of cobalt powder and briquette, HS 810520 'Cobalt; mattes and other

intermediate products of cobalt metallurgy, unwrought cobalt, powders' needs to be used. This trade flow however, also includes intermediate cobalt products for further refining, as well as cobalt metals used in the alloy industry. While mattes and intermediates could contain a cobalt content of 20%, all other cobalt metal products have a content of around 100% [62]. Similar as the EC Critical Raw Material Factsheet, the value of a trade was used as an indicator to decide on the cobalt product and total content [62]. Trade flows with a value of €10 per kg or less where assumed to be only intermediate products and containing 27% cobalt (content based on [61]), trade flows between €10-23 per kg where 50% intermediates and 50% cobalt powder and pure metal, and flows of more than €23 per kg where assumed to consist entirely of cobalt metal (100% cobalt content). €23 was chosen as the upper limit as it was the average price of €23 for pure cobalt metal on the London Metal Exchange in 2017 [83].

After accounting for the price, the HS810520 flows contains several cobalt metal products and powders. The decision whether the trade flows from HS810520 was either pure metal, cobalt powder and briquette or broken cathode and rounds is based upon the refinery based in the country of the trade partner. For instance, the HS810520 trade flow from Madagascar to the USA is either cobalt powder or briquettes as Ambatovy is the only refinery in Madagascar and only produces powders or briquettes. Similar, exports from country only producing cobalt metals are excluded. This for instances includes exports from Norway (only producing cobalt metals) to Japan. Some uncertainties exist where a distinction between cobalt metals cannot be made. These trade flows are indicated as powder/metal in the dataset. The origin of refined cobalt from countries without any cobalt refining where double checked to avoid double counting. For instance, the UK exports a large amount of cobalt oxides to the US but imports these primarily from Belgium and Finland (two cobalt producers). Several additional sources of information are used and country specific data of all refiners of cobalt is available upon request.

S3.7. Battery suitable cobalt consumption Japan, China, USA and South Korea

Consumption of cobalt suitable for battery production is calculated by apparent consumption: total import + production - export. Exports refers to cobalt chemicals (HS282200) and powders, briquette,

ingots/rounds, and broken cathode (HS810520). China produces primarily cobalt chemicals and a small amount of metals (8.35 kt in 2017). All Chinese HS810520 exports (roughly 3.7kt) are therefore in form of cobalt metals and not considered in the analysis. Japanese exports of HS810520 are primarily cobalt metals from Sumitomo. However, as we included the cobalt metal production by Sumitomo in Japan, the HS810520 exports flows from Japan are included in the analysis. Imports of HS810520 from Japan by the USA and China are not included. Exports of HS810520 are not included for the USA and South Korea as both countries had no cobalt powder, broken cathode/rounds, or briquette production in 2017.

S3.8. Cathode and cathode material production

Due to the lack of data on which company supplies cathode or cathode material to which battery cell producer and a lack of detailed cathode specific trade codes, it is assumed that all cathodes were produced in the same country as the cell, with the exception of the UK. This assumption is based on data from Bloomberg highlighting that all NCM and NCA electrode production is based in China, South Korea, Japan and the USA [74]. Cathodes for the AESC/Envision plant in the UK where imported from Japan as reported by [84].

S3.9. Cell assembly

The battery cell supplier was included for each vehicle model to track the origin of cell production and the flows of cobalt. AESC/Envision, LG Chem and Samsung SDI have several production facilities for LIB used in EVs. For AESC/envision, only used by Nissan, it was assumed that all batteries for the EU market were manufactured in the UK. For Samsung SDI, it was assumed that cells were produced equally in each country based on the location specific capacity. For LG Chem, the US plant only produces for GM, Ford and Chrysler, all other cells come from China and Korea

S3.10. Cobalt embedded in electric vehicles in 2017

To obtain detailed registration data based on vehicle models from non-commercial sources, the European Environmental Agency [85] passenger vehicle CO_2 monitoring database was used. This

database includes 26 fields of information of each passenger vehicle registered in the EU, including fuel type, $C0_2$ emissions, weight, wheelbase, energy efficiency (kwh/km) and full manufacturer name and car model, making it a rich data source to analyse the current European car fleet. The database however contains a number of errors and misreporting, in particular related to the fuel type. Thiel, *et al.* [86] highlight a methodology that allows identifying the fuel type for each car based on its emissions. This methodology has been adopted and BEV and PHEV has been identified based on their $C0_2$ levels. All cars with a C02 of zero where labelled as BEV or fuel cell vehicles (FCEV) and those with 20-80 as PHEV. HEV where not included as they generally have a higher emission level which makes it difficult to filter out of the EEA database and distinguish from conventional vehicles. The HEV has therefore been completely excluded from the study.

Table S2. Identification of the correct fuel type based on C02 emissions per km (Thiel et al. 2015).

Powertrain	E (g/km)	Fuel type
BEV	0	Electric
FCEV	0	Hydrogen
PHEV	20-80	Petrol/diesel-Electric

Table S3. Comparison between total BEV and PHEV found in this study, European Automobile Manufacturers Association [87] and European Alternative Fuels Observatory [88].

	This study	ACEA	EAFO
BEV	97,370	97,571	96,351
PHEV	121,483	115,405	121,113

Based on a wide range of publicly available sources, the battery size, chemistry, energy density and cell producer for each EV model where included. Most public sources, however, do not differentiate between the type of NCM_{xyz} (where $_{xyz}$ determines the amount of Ni, Mn and Co) chemistry. The NCM type is therefore based on the specific energy (Wh/kg) on the pack level for each car as reported by the in the EPA's Transportation and Air Quality Document Index System. Vehicles with a high specific energy where assumed to have either a 622 or 523 NCM mix. For most PHEV, obtaining information on chemistry type from public sources was difficult. Energy density for all PHEV was found to be much

lower than all BEV models, which reflects on the fact that this less important in comparison to BEV. Due to the lack of data, it is assumed that most PHEV used an NCM-111 cathode. Based on the chemistry type and the capacity of each vehicle, the cobalt content was calculated. Average metal content per kWh of battery was derived from the literature and multiplied by the battery capacity to obtain total cobalt content per vehicle.

Table S4. Metal content per kWh in different chemistries derived from [89]. Values for NCM-811 where derived from [90] and the NCM blend in the LMO chemistry from [91].

	NCA	**NCM-111**	**NCM-622**	**NCM-811**	**LMO-NCM (52%/48%)**	**LFP**
Cobalt	0.13	0.37	0.19	0.09	0.14	X
Lithium	0.1	0.15	0.13	0.11	0.14	0.10
Nickel	0.67	0.37	0.56	0.75	0.25	X
Manganese	0	0.34	0.17	0.09	0.46	x

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