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

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Abstract: Climate change mitigation strategies are developed at international, national, and local authority levels. Technological solutions such as renewable energies (RE) and electric vehicles (EV) have geographically widespread knock-on effects on raw materials. In this paper, a decision-support and data-visualization tool named "LAYERS" is presented, which applies a material flow analysis to illustrate the complex connections along supply chains for carbon technologies. A case study focuses on cobalt for lithium-ion batteries (LIB) required for EVs. It relates real business data from mining and manufacturing to actual EV registrations in the UK to visualize the intended and unintended consequences of the demand for cobalt. LAYERS integrates a geographic information systems (GIS) architecture, database scheme, and whole series of stored procedures and functions. By means of a 3D visualization based on GIS, LAYERS conveys a clear understanding of the location of raw materials (from reserves, to mining, refining, manufacturing, and use) across the globe. This highlights to decision makers the often hidden but far-reaching geo-political implications of the growing demands for a range of raw materials that are needed to meet long-term carbon-reduction targets.

Keywords: climate change; mitigation; material flows; electric vehicles; raw materials; cobalt; GIS; decision support

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1. Introduction

Dealing with climate change is becoming one of the main challenges facing societies and governments around the world. It is well-known that direct effects of climate change can lead to increased extreme weather events such as heatwaves, intense rainfall, and prolonged droughts [1]. Based on The Lancet Countdown on health and climate change reports, climate-related extreme events happened between 2017–2019, resulting in an absolute economic loss of almost USD (United States dollar) 624 billion [2–4]. In addition, the indirect effects of climate change could be even more devastating, causing different types of damage to human health and ecosystems [5]. These threats have collectively created momentum throughout the international community, driving decision makers to further focus on climate change mitigation as well as adaptation [6,7]. Therefore, strategies for climate change mitigation have been and are being developed at and across different levels of governance, i.e., international [8], national, or local (including city-level strategies) [9–12]. This is also further described in the Supplementary Information (Section S1, Mitigation strategies).

The Paris Agreement is a prime example at the international level, which reiterated the need to set global economy-wide emission-reductions targets [13]. This leads to national or multinational climate change reduction strategies to reach a set of targets [8]. For instance, the European Union (EU) has set ambitious legally binding carbon emissions reduction targets, reducing GHG (greenhouse gas) emissions by at least 55% by 2030 compared to 1990 levels and aiming to become climate neutral by 2050 [14]. Similarly, in the United Kingdom (UK), the 2050 Target Amendment of the Climate Change Act commits the country to a legally binding net zero reduction target of at least 100% by 2050 compared to 1990 levels [15].

Such climate change mitigation strategies promote heavily technological solutions, such as renewable energies (RE) and nuclear energy, to reduce GHG emissions [16,17]. However, exploiting RE resources on a large scale entails a range of specific actions, including, e.g., transport electrification [18], phasing out of coal-fired power plants [19], using biofuels [20], and establishing biorefineries [21], etc. Transport electrification has been widely considered as a promising strategy to reduce the dependency on fossil fuels and lower the environmental impacts of road transportation (See SI Section S1). Thus, in recent years, electric vehicles (EVs) have been at the center of attention [22,23].

Indeed, the number of EVs has increased from a negligible amount before 2010 to 11.3 million EVs in 2020 [24], and it is projected to dramatically increase to more than 142 million EVs by 2030 [25]. A key component of EV powertrains is the battery pack, whereby the lithium-ion battery (LIB) has emerged as the dominant and preferred battery technology and is expected to remain so for the years to come [26,27]. However, while beneficial in terms of reducing GHG emissions, a massive shift to EVs could have an indirect negative impact up and down the supply chain. A key concern is the need for large amounts of critical raw materials (CRM) for LIB production [24,28,29]. Despite difference in definitions and assessment methods [30], CRM can be largely understood as materials that have (1) a high supply risk and (2) a high vulnerability to supply disruption [31,32]. As such, these materials are prone to market disruptions and could quickly result in material shortages and corresponding price increases. Key LIB materials, including cobalt, natural graphite, lithium, manganese, and nickel, are considered critical by several governments, such as Australia, Canada, the EU, Japan, and the U.S. [33]. Among these, cobalt is considered as a particular raw material of concern due to its wide industrial applications and vulnerable supply chain (See SI Figure S1). Although the battery market accounts for about 57% of global cobalt consumption [34], it also has strategic importance for industrial and military applications [35,36]. Cobalt is mainly obtained as a by-product in nickel and copper mining activities, and thus, its availability is contingent upon on the dynamics of nickel and copper markets [37]. Furthermore, over 46% of global cobalt reserves are located in the Democratic Republic of Congo (DRC) [38]. This poses a potential socio-political risk of supply chain disruption. In terms of production, the DRC supplies approximately 70% of all cobalt on the global market in 2021, while no other single country produces more than 5% thereof [38]. Furthermore, with an average price of USD 53,827 per ton and price fluctuation of 36.2% between 2017 to 2021 [39], cobalt has a high impact on the cost of some LIB chemistries [40]. Thus, the rapid electrification of road transportation and promotion of EVs as part of a climate change mitigation strategy may result in supply chain disruptions and impact shifting.

The problem is that to manage low-carbon technological transitions, these potential implications need to be understood by policymakers. Other low-carbon technologies (e.g., solar photovoltaics, wind turbines, etc.) also require critical elements for their manufacturing (e.g., rare earths, cobalt, indium, and others) [41], likewise potentially leading to supply chain problems that need to be addressed carefully.

Material system analyses of CRM are increasingly established to understand the complexity of CRM across the supply and value chain. Several studies utilize this approach to trace the national, regional, or global flows of a single material such as cobalt [42–44] or several materials [45,46] to map out the origin of raw materials, trade relations, and potentials for secondary recovery. Such an approach could therefore be useful as a decision-support tool, which aims to offer a mechanism through which interested stakeholders can interact with different models and datasets in many complicated decision-making situations [47]. By being presented with multiple options, possibly representing different decision pathways due to changes in the regulatory landscape or alternative investment decisions as a result of likely shifting future markets, a decision maker is thus able to explore the virtual space in which a given phenomenon may arise or operate. More specifically, a coupled system linking data repositories of materials, resources, or elements, to a visualization dashboard containing graphical user interface (GUI) elements allows a user to interact with underlying data and provide a tool for user-centric knowledge discovery. Such interaction is important to improve the communication of complex data sets of material systems but is not widely used [48,49].

In this paper, a decision-support and data-visualization tool named "LAYERS" is presented, which is capable of visualizing the origins of CRMs and thus allows a better understanding of the implications (and unintended consequences) of technologies embedded within well-meaning climate change mitigation strategies. The visualization tool is demonstrated using an example focused on the raw materials required for EVs and, more specifically, on cobalt for LIBs. LAYERS benefits from visual information systems and combines different layers of publicly available data sources within the scope of a decision (e.g., using EVs as a climate change mitigation strategy) to provide relevant and contextual information in a format that can be use efficiently by decision makers. In this study, for the first time, the linkages between an emissions mitigation strategy (in this case based on EVs) and a key related supply and value chain (in this case, those of cobalt) are fully visualized using geographic information systems (GIS).

To demonstrate this technique, the following objectives are addressed in this paper: We provide a background on key issues related to mineral extraction, future drivers, and associated risks as well as approaches to quantifying and communicating these demands. Then, a research methodology was developed using publicly available data to link GHG-emissions-reduction strategies to global supply chains, specifically examining the supply of cobalt for LIBs as part of climate change mitigation strategy (i.e., EV promotion) in the UK. The final objective is to visualize the global flow of cobalt and the source of materials used that are essential to deliver climate change mitigation strategies was mapped. Whilst in this example, the focus is on cobalt supplies for EVs, the research method can be used for any other technology and any other raw material that could be linked to climate change mitigation targets or other sustainability strategies. Our approach perhaps does allow the effects of disruption due to events such as the 2022 war in Ukraine to be better managed.

2. Materials and Methods

Given the supply chain complexity of materials critical to climate change mitigation technologies, techniques are needed for better understanding the flows of such materials in their supply chains and production processes. One of these techniques is material flow analysis (MFA), which quantifies and tracks the physical inputs, outputs, and stocks within a system. MFA is related to the chemical engineering mass balance approach, with its basis in the first law of thermodynamics. Performing such accounting using monetary input-output tables was proposed by Leontief [50], and Ayres and Kneese [51] argued that externalities such as waste flows and natural resources required in the production chain must also be included, which can be done by using physical units of mass rather than solely monetary units.

LAYERS uses a network concept based on global mineral supply chains to map the locations and flows of materials. In the first case-study application illustrated in this paper, these locations are the positions of activity in the cobalt supply chain, such as known reserves, mining locations, refining locations, manufacturers using cobalt products, and locations of consumption. These can be at local, regional, or national scale. Figure 1 shows the flowchart of data and insights that can link local strategies for climate change mitigation to remote parts of the globe where there are implications of these decisions in terms of material extraction or further environmental emissions.

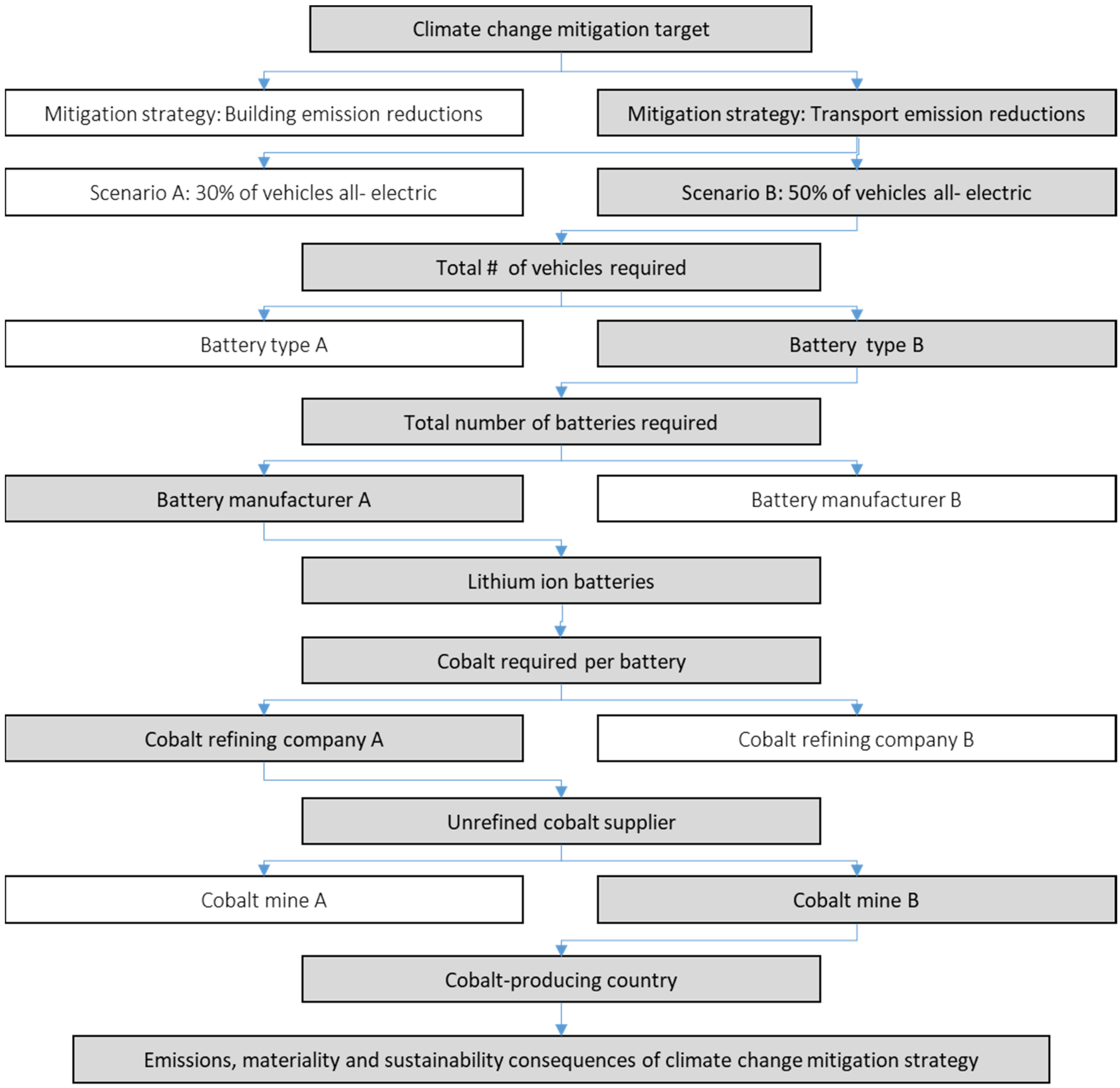

Figure 1. Conceptual route through LAYERS process from climate change mitigation targets to sustainability consequences.

In order to map the various activities using the LAYERS methodology, information must first be gathered that links each part of the material supply chain to a position on the Earth's surface. Hence, 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. For this purpose, a basic form of MFA was applied, whereby patterns of material stocks and flows are identified by setting boundaries of space and time using a mass balance approach. Whilst the data required by LAYERS may be freely available for some activities (e.g., mining operations or location of EV production plants), other information may be more difficult to obtain (e.g., specific manufacturers of car batteries).

The collected data were organized to fit into the following layers:

1. Reserves;
2. Mining;
3. Refining;
4. Manufacturing;
5. Use (e.g., in EVs).

The datasets used in LAYERS can be broadly divided into two types:

1. Activity locations—these are spatial locations on the Earth where a process takes place within the MFA. These could be seen as locations of stocks, such as mining reserves, or locations of conversion processes, such as refinement of cobalt ore into cobalt products.
2. Spatial flows—the movement of materials between activity locations. These are essentially imports and exports at trans-national scale or transport of materials within a country.

Spatial flows are provided by the United Nations Commodity Trade Statistics Database [52], whilst activity locations must be inferred from the grey literature, mapped from national or corporate data, or translated from existing datasets. UN Comtrade data are searchable by commodity type (e.g., cobalt ore), by year, and by country, and it is possible to download complete statistics for all reported trade for a given commodity between all countries. The Comtrade database includes several fields which are useful for the generation of spatial flows of data, which are:

1. Origin country code;
2. Destination country code;
3. Nature of the trade for that entry (e.g., import or export);
4. Size of the flow (either number of items or mass);
5. Value of the flow in USD.

These values are used to construct the flows between the various layers of the material lifecycle: Input material flows from the Mining layer to the Refining layer, intermediate substances flow from Refining to Manufacturing, and End-use commodities flow from Manufacturing to Use. Since these flows are reported at a national level, the centroid of each country is used as the origin or destination of the flow. Higher-resolution geographical data, however, can be inferred using a variety of online resources and data mining techniques, which gives an approximate location of most activities in the LAYERS "stack". Where possible, national or international standard datasets have been used, ensuring the transferability of the approach to other materials as much as possible.

The data contained in the database are subject to various routines of quality assurance, such as checks for consistency among different data sources and for plausibility within time series. However, international MFA data quality varies for the different types of elements, and some uncertainty is unavoidable [53]. However, in many cases, informed estimates must be made regarding the concentration and quantities of metals involved in ore extraction. Data quality becomes less accurate and reliable along the supply chain (i.e., through processing, manufacturing, and use).

Disposal has also an added complexity of its own, as the goods manufactured and used are disposed of not just within the same reference year but potentially many years later, as products may last, e.g., 7–12 years before disposal is needed, and therefore, this stage has not been considered in the current work.

In terms of data storage and usage, this study employed relational database technology for the MFA data. A relational database is a digital database that is based on relational theory [54]. It stores data as a set of formally described tables and facilitates data acquisition/reassembling in many ways without having to reorganize the database tables. In other words, relational database technology provides a robust and relatively flexible data storage mechanism to help store and manage many domain-specific datasets. Essentially, these consist of *relationships*, more commonly known as *tables*, with each table having a formally defined schema [55]. They have been extensively used to store spatial, non-spatial, and evolving datasets since their inception and uptake in the 1970s [56]. Although recent development of non-relational databases, such as graph databases, are becoming more prevalent and could also be used, this paper adopted relational databases for MFA. By considering the different stages through which a particular element or material passes, a simple set of common attributes that exist at or between each stage can be discovered. For example, this could include the different stocks themselves, from deposits or mines to flows from manufacturing to use and end-of-life.

By abstracting from the specific domain in which a stock or a flow is being considered, it has been possible to develop a simple relational database scheme to help manage information, particularly, in this instance, with respect to specific elements, where they are mined and what quantities exist at different stages of their processing from extraction to finished product and use. This process is summarized in the SI in which the schematic principles of Comtrade, country data and operator (mining) sites, and flows are described and illustrated in more detail (Figure S2).

Database Design and Presentation

The flexibility of the scheme developed to date (shown in Figure 2) allows additional layers to be created as new tables and the connections between layers defined through adding records to the *LayerConnections* table. Furthermore, additional sites and operators can also be added, for example, to denote new mining operations by a particular company in a particular country for a given year. Each record in one of the LAYERS *Data* tables, currently named *Deposits*, *Mining*, *Refining*, *Manufacturing*, and *Use*, contains information about a specific activity of the same name. For example, the *Deposits* table records all deposit information for multiple sites, countries, and operators. The *CountryFlows*, *SiteFlows*, and *OperatorFlows* tables define linkages that exist between countries, sites within countries, and operators at specific sites within countries.

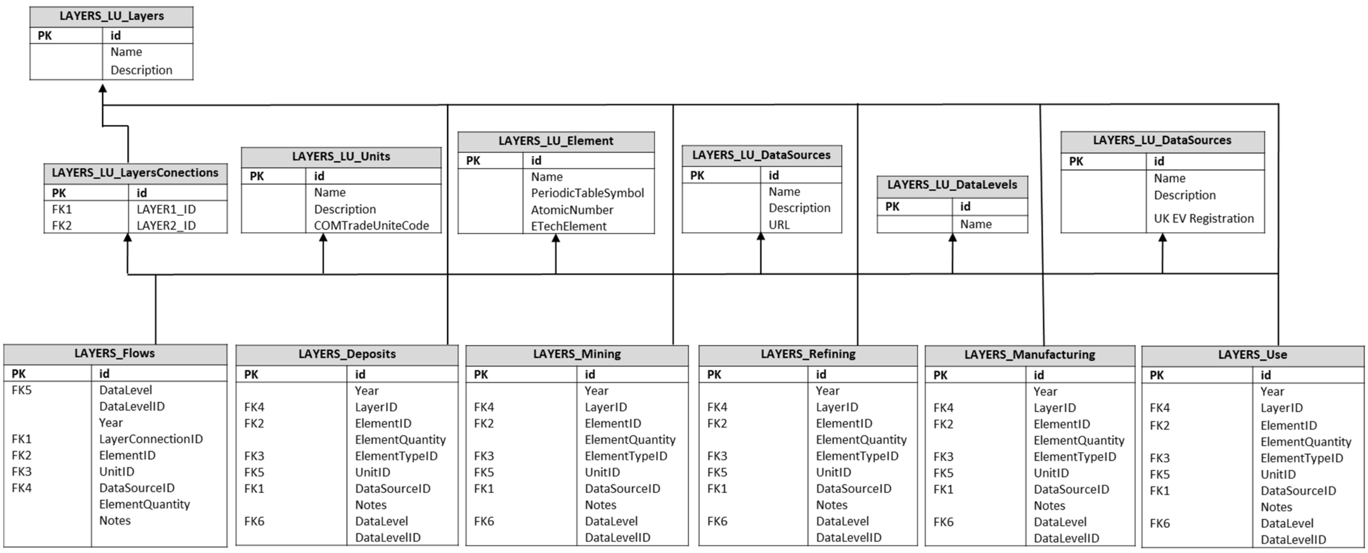

Figure 2. Example entity-relationship diagram for LAYERS data storage.

The quantity of a particular element moving between different layers (i.e., a flow) is stored within the *LAYERS_Flows* table. The LAYERS *Data* tables, previously identified, and the *LAYERS_Flows* table both contain two attributes, *DataLevel* and *DataLevelID*. These attributes indicate at what spatial resolution a particular quantity, whether flow or stock, for example, is meant to be represented. *DataLevel 1* represents a country-level quantity, *DataLevel 2* represents a site-level quantity, whilst *DataLevel 3* represents an operator-level quantity. By storing this information, it is possible to perform checks on input data, for example, to preserve conservation of mass such that the aggregation of operator and site-level quantities does not exceed country-level values. The *DataLevelID* value stores a reference to the spatial location itself for the matched *DataLevel*. For example, country-level quantities refer to locations in the *LAYERS_LU_Countries* table via the *DataLevelID* attribute.

The structure described here allows the storage of spatial data of varying resolutions (sub-national to global) within the same relational database, helping to address the general difficulty in accessing high-quality complete data of this nature, as mentioned in other studies [57–60]. It must be noted that the ability to represent flows or stocks at any level of spatial resolution is ultimately dependent upon the available data; however, the LAYERS approach offers some flexibility in this regard. To facilitate understanding the provenance of particular records, which is especially important when multiple sparse and disparate datasets are combined, the scheme allows a reference or link to the original data source to be stored. Furthermore, the units of a particular quantity can also be stored with each element at each site or flow between sites. The differences between units can then be resolved by appropriate conversions when extracting and aggregating data from the database as part of a specific analysis. Figure 3 illustrates an example of the entity-relationship diagram for the scheme, using example *LAYERS_* data tables and associated lookup tables, which are outlined in more detail in the Supplementary Information (Table S2).

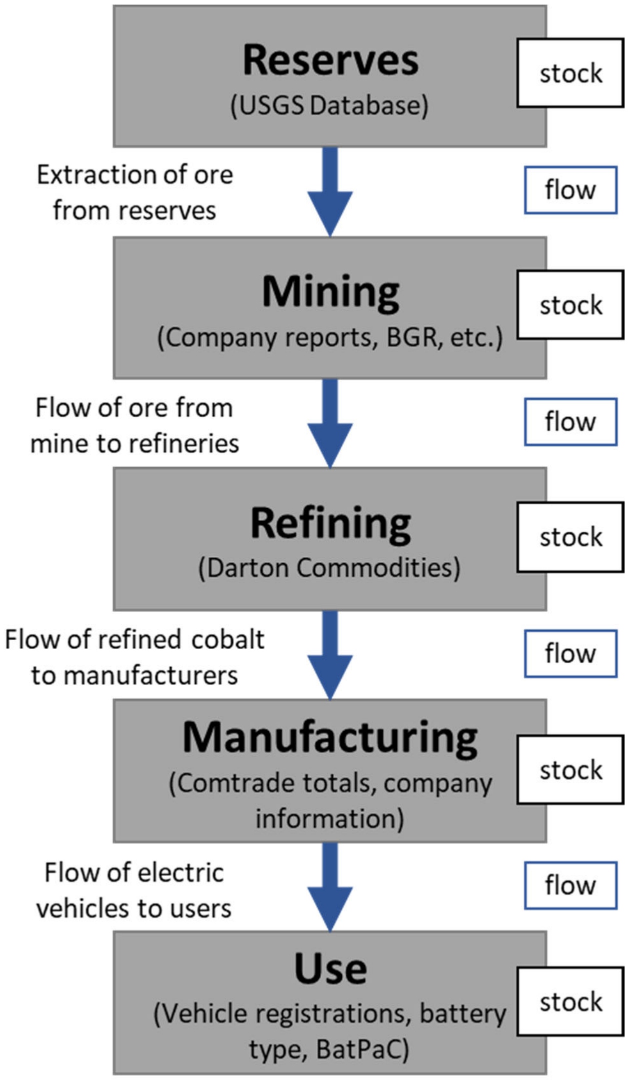

Figure 3. Data flow through LAYERS for Cobalt, including sources of key data.

The list of available chemical elements is populated from a current list of elements found within the periodic table. By extending the *Elements* table further by adding columns or by the introduction of new status tables listing the considered status of a particular element, such as those as identified as critical by the EU, it is possible to retrieve information about particularly topical elements at the time of analysis. For example, this could be taken from the current list of CRMs for the [29] as a starting position and then adjusted as other elements migrate into or out of focus depending upon the level of interest from relevant stakeholders.

The database is constructed from a series of structured query language (SQL) scripts. The following tables are created and populated when the scripts are executed:

1. *LAYERS_LU_DataSources*—five initial data sources are loaded, representing the references to:
    a. UN COMTrade Country Codes;
    b. UN COMTrade Supplementary Unit Reference List;
    c. Periodic Table;
    d. World Political Boundaries—used for country boundaries;
    e. World Cities—used for capital cities.
2. *LAYERS_LU_COMTradeCountryCodes*—293 country codes are loaded from the UN COMTrade Country Code Listings (see http://unstats.un.org/unsd/tradekb/Attachment392.aspx (accessed on 1 May 2022), UN COMTrade Country Codes);
3. *LAYERS_LU_Countries*—249 countries are matched from the *LAYERS_LU_COMTradeCountryCodes* table and the reference World Political Boundaries dataset used as reference for country boundaries;
4. *LAYERS_LU_DataLevels*—three data levels are defined (1 = country level, 2 = site level, 3 = operator level);
5. *LAYERS_LU_ElementTypes*—two types are loaded; namely *Primary* and *Companion* (also known as "hitch-hiker");
6. *LAYERS_LU_Elements*—118 elements are loaded, including their symbol and atomic number;
7. *LAYERS_LU_Layers*—five layers are loaded (*Deposits*, *Mining*, *Manufacturing*, *Refining*, *Use*);
8. *LAYERS_LU_LayerConnections*—five connections are loaded, representing links between different layers, e.g., *Deposits* -> *Mining; Mining* -> *Manufacturing; Manufacturing* -> *Refining; Refining* -> *Use*;
9. *LAYERS_LU_Units*—13 units and their respective COMTrade unit codes are loaded (see http://unstats.un.org/unsd/tradekb/Knowledgebase/UN-Comtrade-Reference-Tables (accessed on 01 May 2022)).

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 in the Supplementary Information (SI), including an indication of the table(s) (i.e., relationships) with which they interact.

Functions of particular interest include *LAYERS_DATA_Add_Flow_Data* and *LAYERS_DATA_Add_Layer_Data*, as these are used to add specific quantity information to a particular layer or flow. Within each function, a check is performed to ensure that the value specified for *DataLevelID*, i.e., the spatiality of the quantity, matches a value in the corresponding table based on the value for *DataLevel* supplied. Table 1 shows against which tables the *DataLevelID* value is compared, using the *DataLevel* value. Furthermore, specifically at the operator level, a check is performed to ascertain whether the year to which a new record for either flow or layer data relates is within the operations window of an operator at a specific site. This is to prevent erroneous operator-level quantities being added to the database, which do not match the defined operations window given by the *StartOperationsYear* and *EndOperationsYear* attributes of the *LAYERS_LU_OperatorSites* table.

Table 1. *DataLevel* lookups performed when adding data to flows or LAYERS.

Data Level	Tables to Match against for Flow Data	Tables to Match against for LAYER Data
1	*LAYERS_LU_CountryFlows*	*LAYERS_LU_Countries*
2	*LAYERS_LU_SiteFlows*	*LAYERS_LU_Sites*
3	*LAYERS_LU_OperatorFlows*	*LAYERS_LU_OperatorSites*

3. Results and Visualization

3.1. LAYERS Application Example: Global Cobalt Supply Chain for UK Electric Vehicles

Using the method described in Section 2, an MFA and spatial model was developed that represents the different layers and global flows of the supply and demand chain of cobalt for UK electric vehicles in 2017. Visualizations of the flows of materials from reserves to EV use were created to understand the implications of carbon-reduction strategies. These visualizations build on the spatial data gathered during earlier stages of the methodology and serve as a data-exploration and decision-support tool to allow interactive interrogation of the LAYERS database for the commodity of interest. The deployment of the various spatial data in constructing visualizations of the cobalt flows is shown in Figure 3 and is described in more detail below.

The *Stocks* for each activity layer of the database, gathered from a number of sources, are established with varying degree of accuracy. The use of Comtrade data helps to construct the network elements (nodes) of the LAYERS approach to define the spatial connections between those stock locations and establishing a network of flows across the globe. Such a network allows the analysis of the sources of materials for carbon mitigation technologies and thus the implications for climate strategies adopted at various levels from cities, to nations, to international communities. The network also allows the analysis of potential disruptions to supply since the route of such materials can be traced across the globe.

A search of the Comtrade database for cobalt-related entries yielded 22 records where cobalt was mentioned in the description of the commodity. Due to the focus on electric vehicle batteries, only the commodity flows of cobalt products relevant for battery production were included. These commodities were then sorted into input materials (materials that are extracted from the Mining layer and sent to the Refining layer) and Intermediate substances (items that are produced during Refining and used in later processes such as Manufacturing). The commodity codes from the Comtrade database are given in Table 2 and map to the layers that are used to describe the flow of materials during geographic visualization. Many data gaps, however, exist within the Comtrade database. Each trade-flow was therefore carefully evaluated by cross checking import–export statistics and mass balancing of trade flows and production statistics. Several assumptions were made to include missing trade flows, which inherently will have some uncertainty. The cobalt trade network is based on Baars et al. [61] and is described in more detail in the Supplementary Materials (Section S3).

Table 2. The commodity codes from the Comtrade database (HS codes).

Input Materials		Intermediate Substances	
260500	Cobalt ores and concentrates	282200	Cobalt oxides and hydroxides; commercial cobalt oxides
		810520	Cobalt mattes and other intermediate products
		750110	Nickel mattes
		750120	Nickel oxide sinters

3.1.1. Reserves

The Reserves layer stores the location of all cobalt containing reserves. A database of 214 explored global deposits presented by the USGS in 2017 was used to map out the global reserves [62]. Once extracted, the data were used to create a spatial data layer with information about each deposit, including:

1. Spatial location (latitude, longitude) and country;
2. Deposit name;
3. Deposit type and ore grade;
4. Main and other commodities present (all those deposits where cobalt was present were recorded).

Figure 4 shows the global cobalt deposits as mapped in the corresponding LAYER.

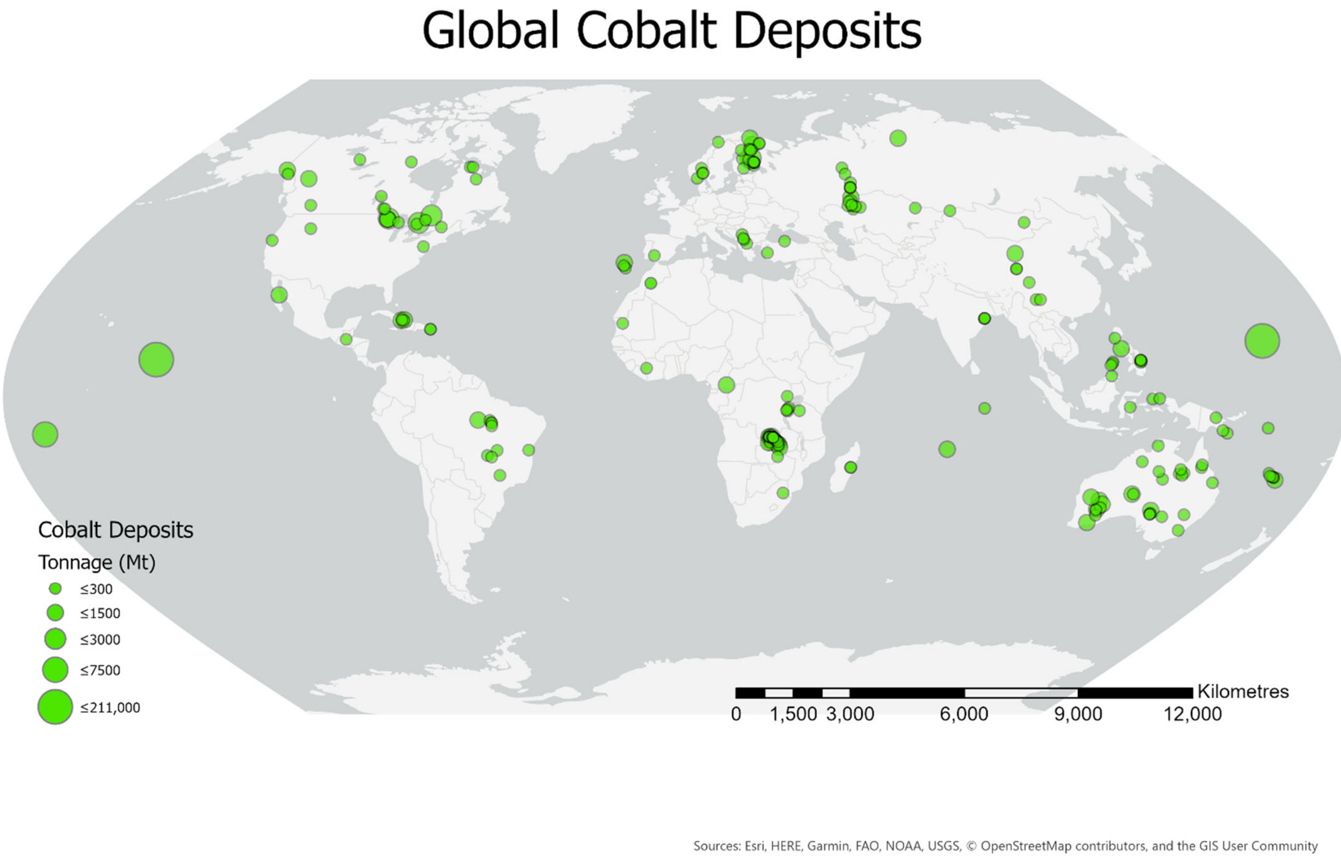

Figure 4. Global deposits of cobalt showing total estimated tonnage in tons.

3.1.2. Mining

The Mining layer stores the locations of active mines where the mineral of interest is extracted, and the raw ore or other base materials are produced. Once active cobalt mining facilities were identified, their spatial coordinates were required to establish locations of activity for this layer. For all mines with current cobalt production, a search was conducted primarily based on company reports. Locations can be updated if they are found to be erroneous (i.e., as a result of visual interpretation from the Google Earth imagery). As outlined below, the information about mining operations was stored in the mining table of the LAYERS database. Once extracted, the data were used to create a spatial data layer with information about each mining operation, including:

1. Spatial location (latitude, longitude) and country of mine;
2. Name of mine;
3. Deposit type;
4. Total production in 2017.

Figure 5 shows the global cobalt mining output as mapped in the corresponding LAYER.

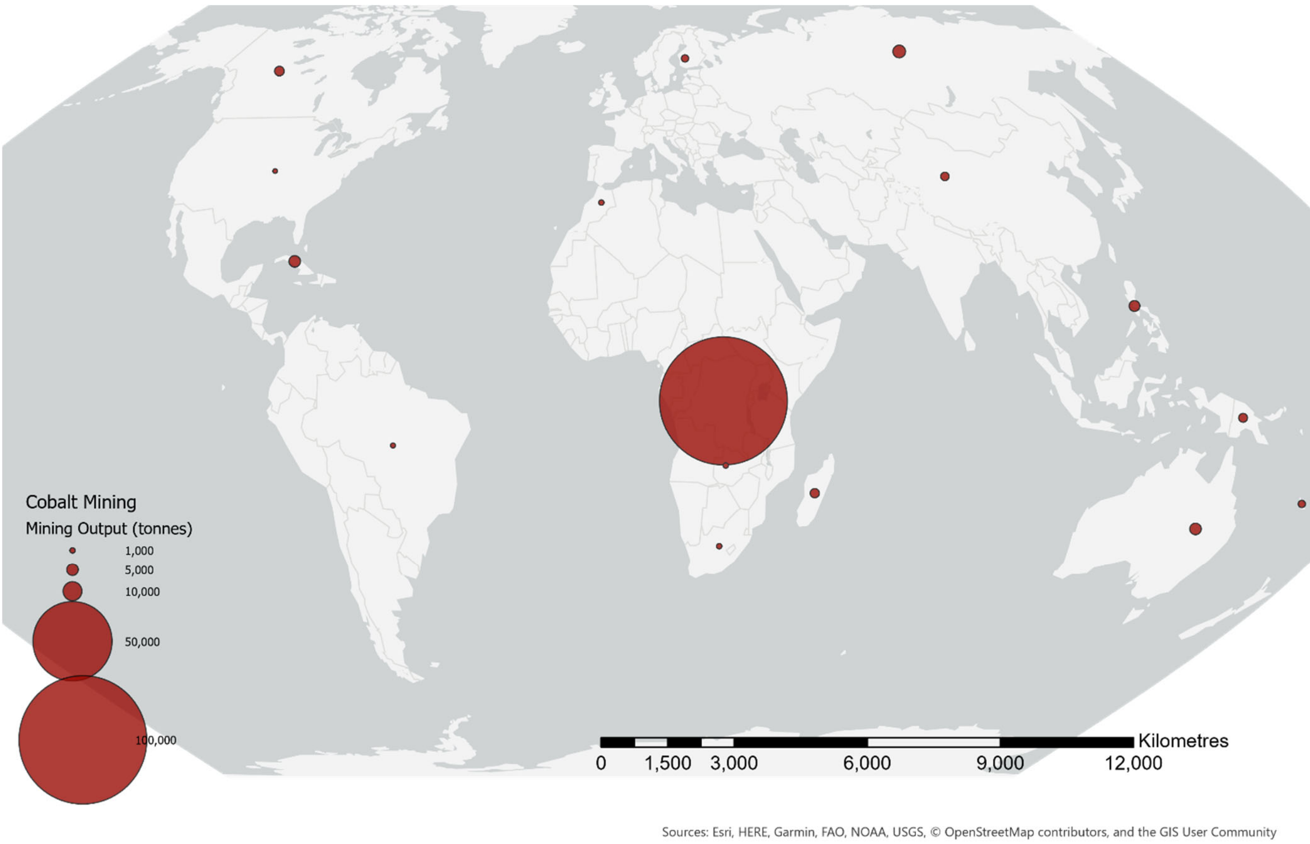

Figure 5. Cobalt mining output aggregated to each producing country.

3.1.3. Refining

Cobalt can be recovered after a separation by solvent extraction and/or from the refining of copper—cobalt ores or from copper or nickel processing. Different techniques and technologies can be applied [63], and cobalt can be recovered as a by-product from copper, as it is contained in and smelted with copper concentrate being oxidized along with iron during the final conversion to blister copper. If the copper and cobalt ores are in the oxidized state, copper can be removed by electrolysis in sulfuric acid solution and the cobalt precipitated from the spent electrolyte by adjustment of the pH of the solution. Cobalt concentrates from arsenide ores may be roasted in the same manner as sulfide concentrates in order to remove the arsenic as impure arsenic trioxide. Alternatively, they can be leached and cobalt precipitated with hydrogen, as with nickel sulfide concentrates. The final refined cobalt products include chemicals, powder, and several metal products (pure metals, briquettes, rounds, and broken cathode).

Actual refining processes are typically commercially confidential and both site- and company-specific and difficult to obtain. For LAYERS, the refining data from Darton Commodities as reported by Bloomberg were used to obtain company and product-specific refined cobalt production in 2017 [64]. The flow of these products from the refining layer to the manufacturing layer is calculated as an aggregation of the Comtrade commodities listed under the Intermediate Substances column in Table 2. The spatial data for the refining layer therefore are limited to:

1. Spatial location (latitude, longitude) of each country's centroid;
2. Name of refining company;
3. Type of refined cobalt product;
4. Tonnage of refined cobalt produced per year.

Figure 6 shows the refined cobalt output as mapped in the corresponding LAYER.

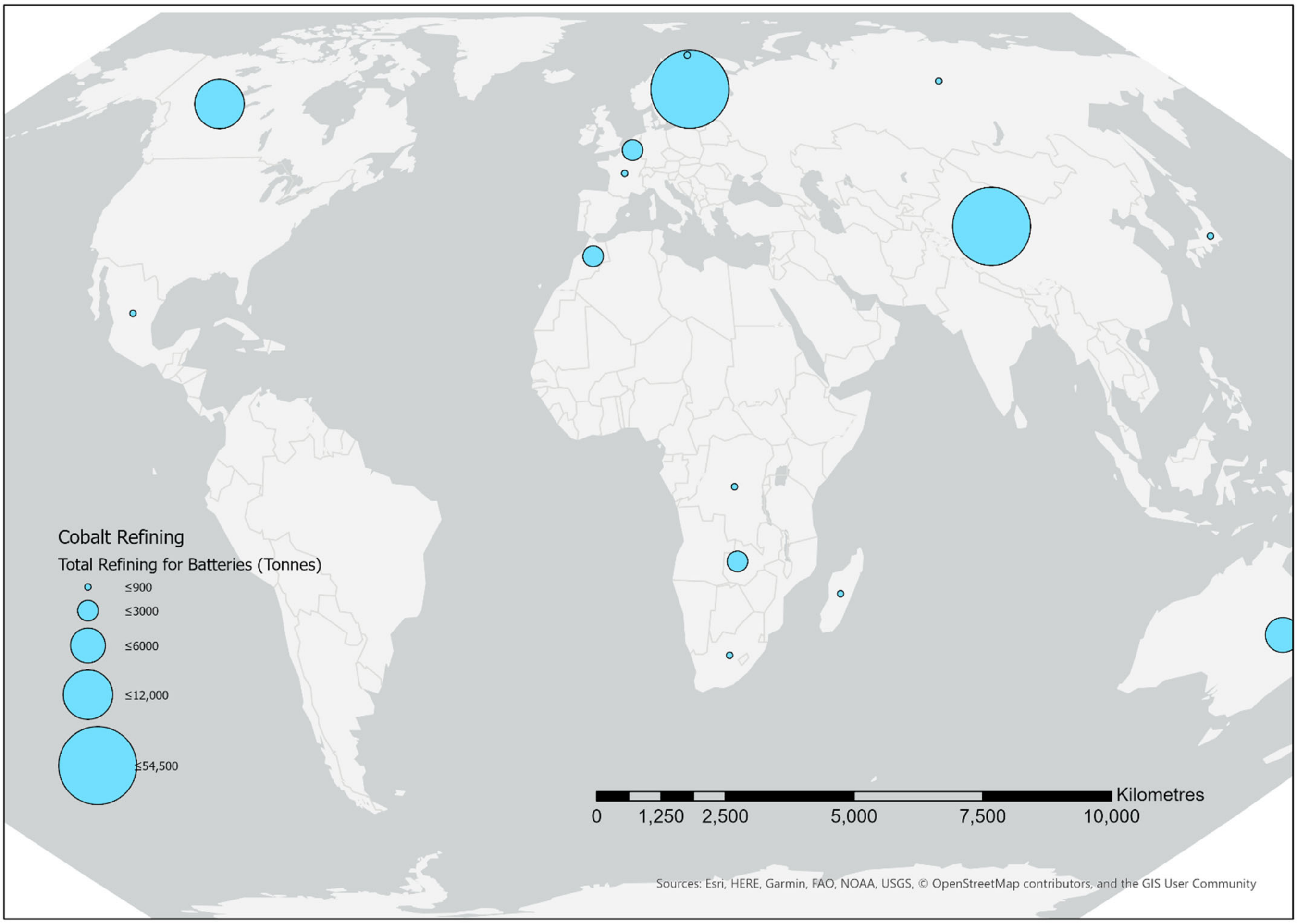

Figure 6. Refined cobalt (in tonnes) for use in batteries by country.

3.1.4. Manufacturing

The locations of the manufacturing plants for cobalt containing EV battery cells are difficult to estimate. Here, we used the names of the cell supplier for each registered vehicle model in the UK in 2017 to track the origin of cell production and the flow of cobalt. Based on this, the production facilities of these battery producers (AESC, LG Chem, Panasonic, Samsung SDI, SK Innovation, and GS Yuasa) were used to obtain the location of battery cell manufacturing. AESC/Envision, LG Chem, and Samsung SDI have several production facilities for LIB used in EVs. To estimate which factory supplied batteries for UK vehicles, the following assumptions were made. For Envision-AESC batteries, only used in Nissan vehicles, it was assumed that all batteries for the UK market were produced in Sunderland, UK, which is the only operating production plant of Envision-AESC in Europe in 2017. For Samsung SDI, it was assumed that cells were produced equally in each country based on the location-specific capacity. For LG Chem cells, the U.S. plant only produces for GM, Ford, and Chrysler; all other cells were assumed to come from China and Korea. Based on this, the battery cell location was estimated, and the production locations of cell suppliers were established. The total cobalt consumption for each factory was based on the total cobalt in each vehicle (see below); losses in cell production are not included. These totals are mapped to the centroid of the country in question by stating (a) spatial location (latitude, longitude) and country of manufacturing and (b) total cobalt imports per year.

3.1.5. Use

The battery chemistry type and vehicle size have a large impact on the total cobalt content of EVs, and using aggregated averages might provide an inaccurate picture of the actual material content in vehicles. To obtain detailed registration data based on vehicle models from non-commercial sources, the European Environmental Agency passenger vehicle CO_2 monitoring database was used [65]. This database includes 26 fields of information of each passenger vehicle registered in the EU, including fuel type, CO_2 emissions, weight, wheelbase, energy efficiency (kWh/km), and full manufacturer name and car model, making it a rich data source to analyze the European car fleet. The database however contains several errors and misreporting, in particular, related to the fuel type. The calculation approach as highlighted by Thiel et al. [66] was therefore used to filter out battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV). Based on all registered BEV and PHEV models in the UK, the battery size, chemistry, energy density, and cell producer for each model was obtained from a wide range of public sources. The result includes a detailed database of all BEVs and PHEVs registered in the UK in 2017, including all battery information. Based on this, the cobalt content for all BEV and PHEV models has been calculated based on the battery capacity, the cathode chemistry, and the cobalt content for the different LIB chemistries obtained from the BatPaC model (see Figure 7). Information in this layer therefore includes:

1. Spatial location (latitude, longitude) and country of use (UK);
2. Total quantities of cobalt imported;
3. Estimated proportion of cobalt per unit.

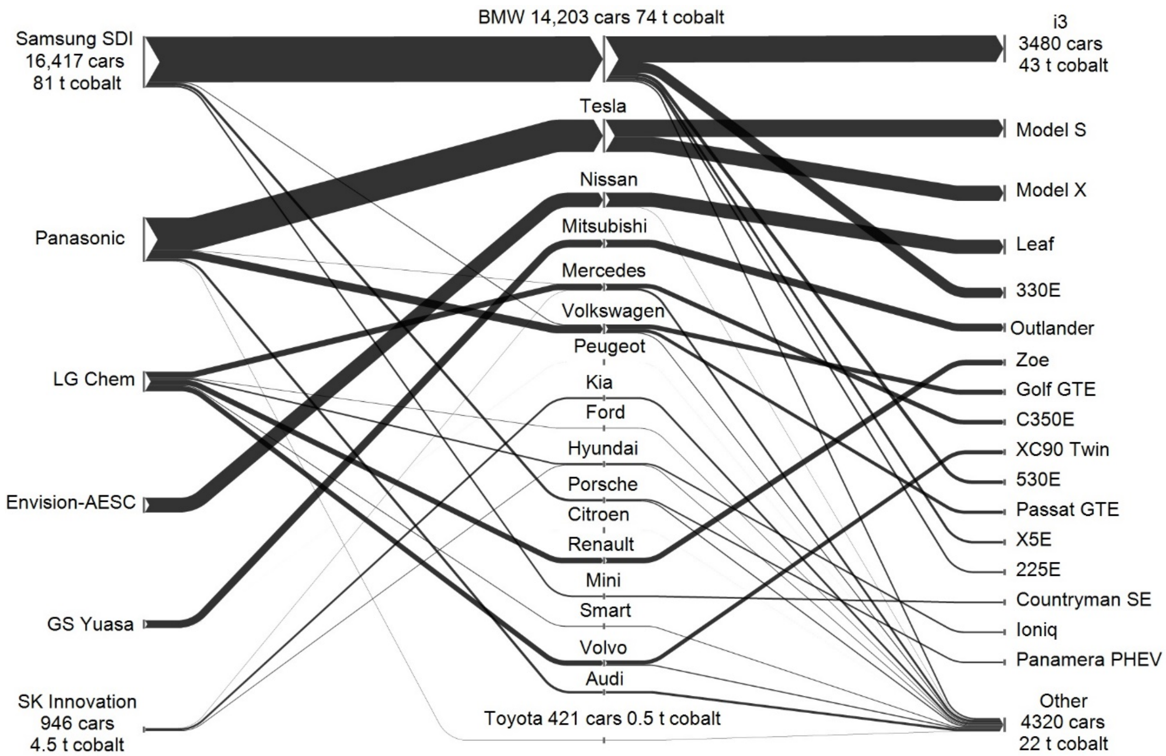

Figure 7. Cobalt flows from cell producers to batteries for electric and plug-in hybrid vehicles registered in the UK (2017).

Due to the significant time lag between production, use, and specifically, disposal, there is lack of reliable data for the disposal stage. Therefore, the stock of cobalt that might be in disposed LIBs in 2017 is not considered here (Figure 7).

3.2. D Visualization and Presentation of Integrated Data

The database scheme outlined in Section 2 allows the storage and management of the data obtained from various sources for each layer in an integrated manner. In addition to providing the basis for analysis, the integrated database also allows for interactive visualization of the datasets in a number of ways. The simplest visualization is through the plotting of locations of activity and flows between them on a standard 2D map. Through the flexibility of the LAYERS approach, such maps can be custom generated for any given material or element at the desired temporal and spatial resolution. It is also possible to examine multiple layers of activity concurrently to identify spatial hotspots of activity throughout the supply chain. Since these interactive visualizations are generated in a GIS environment, it is also possible to combine them with other spatial data of interest in order to examine the possible impact of other geo-spatial phenomena on the supply chain of the material of interest.

The second, more advanced method of interactive data display employs 3D visualization, where the 2D maps for each layer are displayed in a 3D stack, where the stages through the material life cycle, from deposits to use, are arranged along the vertical dimension. In this manner, it is possible to display multiple layers of activity for a given material over a specified time period without the visual clutter of a conventional 2D map. Flows between layers, for example, from Mining to Refining, are displayed as three-dimensional links between activity points or country centroids for each layer. Using queries, it is possible to filter and customize the data that are displayed in the 3D view to examine flows in particular years, for particular, material types, or from specific sources or destination locations. Data for different years can then be collated to show long-term patterns of trade for given materials or to examine changes to flows between activity locations over time (Figure 8).

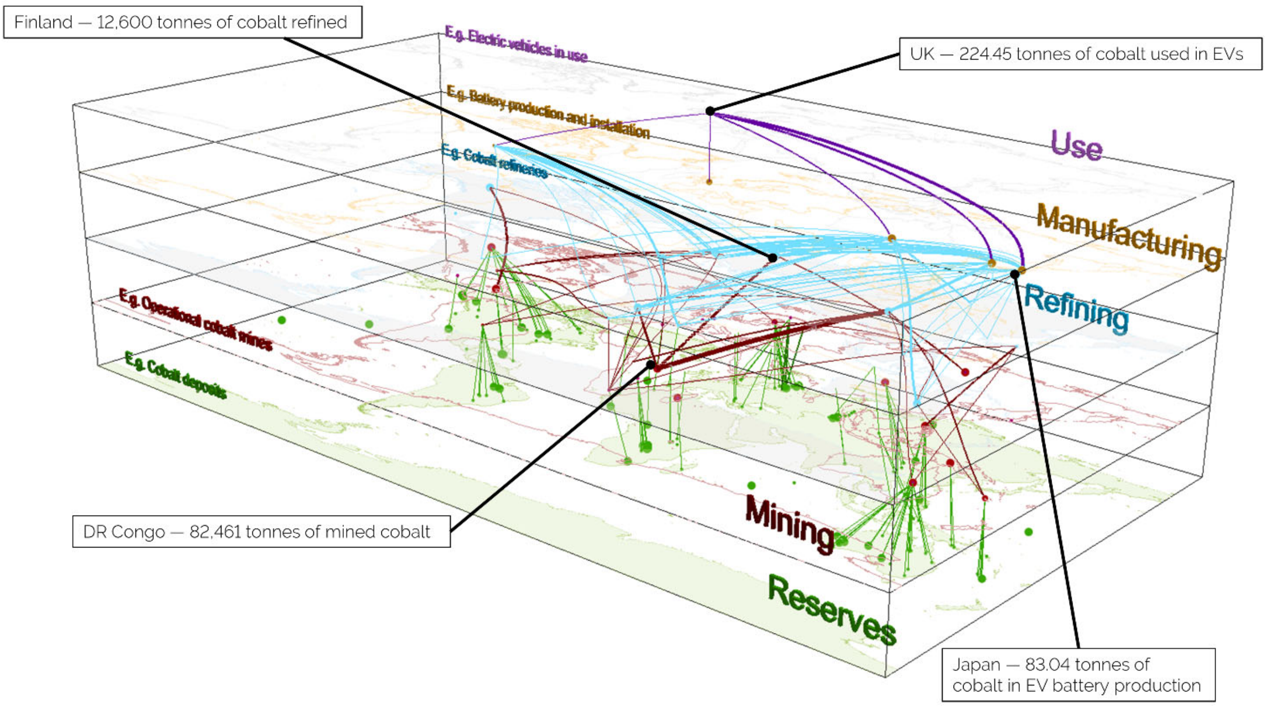

Figure 8. Example of LAYERS 3D visualization, stocks, and flows of cobalt from one layer to the next layer across the globe (2017) by considering the UK market.

In addressing the final objective, LAYERS gathered and visualized the data for different years. However, a major limitation is represented by the fact that many datasets are incomplete and are only infrequently updated. Therefore, for the sake of consistency, this first case-study was limited to data for one year only. For example, some 83,000 tonnes of cobalt were mined in the DRC, some 12,600 tonnes were refined in Finland, and only 224 tonnes of cobalt were actually in the EV batteries that were used in the UK in 2017. Figure 8 illustrates the resulting sample 3D stack, visualizing the cobalt flows that feed the UK EV market in the year 2017. By tracing all cobalt inputs and outputs across world regions and activity levels, this 3D visualization allows a clear understanding of the location of the major cobalt-related activities (from Reserves, to Mining, Refining, Manufacturing, and Use) taking place across the globe in that year. The model and the data behind it as well as a brief validation of the model is further described in the Supplementary Information (Section S3—Cobalt trade network data collection).

4. Discussion and Conclusions

LAYERS tackles the problems of illustrating resource availability and potential impacts of the low-carbon transition on the global material flows. Other studies have estimated the impact of the expansion of low-carbon energy technologies on future metal demands to highlight the energy metal nexus [67,68] to policy makers. Determining the potential impacts metal shortage can have on delivering Chinas EV strategies have recently been reported [69], and others have presented physical and monetary methods for estimating the hidden trade of materials [70]. However, the geographical relationships and potential bottlenecks are not that well-illustrated or indeed explored. Apart from the work presented by Nansai et al. [49], who showed the global trade flows of neodymium, cobalt, and platinum for low-carbon technologies. However, they did not illustrate the supply and value chain of the minerals in such detail, as the data might have not been available.

Indeed, improving data quality is of key importance to utilize the LAYERS approach or any other tool that might be used to illustrate material flows. Official trade and production statistics are too aggregated, with many data gaps resulting in incomplete maps of trade networks. In the case study, this was largely avoided by relying on public company reports and detailed vehicle registration statistics. However, this is a time-consuming approach. Improving data availability, accessibility, and collection methods are therefore an import future research direction to enable the inclusion of many more mineral flows and to regularly update maps. Such illustrations are not only relevant to cobalt or CRM but also other more common materials such as copper [71] or nickel [72], which also have important roles to play in meeting carbon-reduction targets. Furthermore, while this first paper focuses on minerals required for climate change mitigation strategies, the LAYERS approach can be used to visualize virtually any global material trade flow, for example, the 3D LAYERS visualization of global fertilizer or grain flows [73], which will help policy makers to understand the implications of unforeseen circumstance on the supply disruptions on the global food system [74].

To conclude, a novel decision-support method and visualization tool named LAYERS is thus presented. It combines practical application to cobalt as a key CRM for LIBs used in EVs using data from numerous global data sources (EU ProMine, UN Comtrade) and mining industry sources (USGS, CDI, Roskill, Idaho Cobalt). LAYERS has shown to enable a clear and comprehensive 3D visualization of the intricate network of material flows along the supply chains of any chemical element of interest. Using detailed data on resource and trade flows, LAYERS can be used to accurately trace the movement of each element across the globe as it progresses through its supply and value chain and to present the results in a visually engaging way by leveraging geographical information systems (GIS) and its architecture.

The method and model presented are very dependent on the quality of the data that is used to carry out the MFA that underpins LAYERS. For the future, it is desirable that the "observed" situation is improved. With better data quality, the management of CRM resources would be better understood and subsequently better managed. However, as these data are frequently commercially confidential, it is unlikely that key data will be provided or accessed easily. Nevertheless, the value of LAYERS could reinforce the monitoring of statistics collected by bodies such as the British Geological Survey and the United States Geological Survey, who compile mineral production statistics to inform government and public policy, presenting commercially confidential material in an aggregate form that is acceptable to the industry.

LAYERS is well-placed to inform future models and tools that might be used to highlight the often hidden but far-reaching implications of the growing demand for a range of critical raw materials. In particular, consideration is needed for raw materials associated with the increasing reliance on low-carbon technologies (including RE electricity generators and battery-based technologies) that are being promoted in virtually all climate change mitigation strategies. This will pinpoint future bottlenecks and informs decision makers on the geopolitical and resource consequences of their decisions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14127120/s1, Figure S1: World production and unit price of cobalt from 1994 to 2017; Figure S2: Schematic principles of Comtrade, country data, and operator; Table S1: Database functions interacting with lookup and data tables; Table S2: Identification of the correct fuel type based on CO_2 emissions per km; Table S3: Comparison between total BEV and PHEV found in this study; Table S4: Metal content per kWh in different chemistries.

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Abbreviations

BEV	Battery electric vehicles
CDI	Cobalt Development Institute
CRM	Critical raw materials
DRC	Democratic Republic of Congo
EPSRC	Engineering and Physical Sciences Research Council
EV	Electric vehicle
GIS	Geographical information systems
GUI	Graphical user interface
LIB	Lithium ion batteries
EU	European Union
GHG	Greenhouse gas
MFA	Material flow analysis
NERC	National Environmental Research Council
PHEV	Plug-in hybrid vehicles
RE	Renewable energy
ReLiB	Recycling of Li-ion batteries
SQL	Structured query language
UK	United Kingdom
UN	United Nations
USGS	United States Geological Survey

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