The Development of GTAP-CM version 11: Incorporating Critical Minerals and Renewable Energy Technologies in Multi-Region Input-Output Tables

By

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Research Memorandum No. 41
June 2026

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We thank Antoine Vagneur-Jones and colleagues (Bloomberg/BNEF) for sharing data inputs. The opinions expressed in this paper are those of the authors. They do not represent the positions or opinions of the WTO or its Members and are without prejudice to Members' rights and obligations under the WTO. Any errors are attributable to the authors.
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Abstract

In this paper we introduce the Global Trade Analysis Project Critical Minerals (GTAP-CM) Data Base which is an extension of the GTAP Circular Economy (GTAP-CE) Data Base with 35 additional sectors. The additional sectors are related to the renewable energy value chain, including electric vehicles, solar panels, wind turbines, batteries and permanent magnets, as well as mining and refining products used in these sectors. Data reconciliation is implemented using the MSplitCom utility and RAS balancing method, utilizing data inputs on bilateral trade, production, cost and supply structures. We describe how a range of data inputs from various sources are combined, processed and reconciled to generate these data inputs. Trade data at the HS6 level are sourced from the BACI international trade database compiled by CEPII, production data for mining goods are from United States Geological Survey (USGS), data for downstream activities are derived from BloombergNEF, International Energy Agency (IEA) and several other complementary data sources, cost and supply structures are compiled using inputs from the academic literature and technical information. Data processing and reconciliation includes harmonizing units of trade and production data, adjusting the cases of exports exceeding domestic production, and estimating unavailable production values using constrained optimization procedures, among other steps.

JEL Codes: C67, D57, L72, Q54.
Keywords: Critical minerals, GTAP, CGE modelling, input-output tables, renewable energy.

Contents

INTRODUCTION

Decarbonization and digitalization will change the structure of the global economy. Decarbonization leads to a shift in demand away from fossil fuels and towards more sustainable energy sources with renewable energy equipment heavily relying on critical minerals as inputs (Comincioli et al., 2025). Digitalization and the growth of artificial intelligence (AI) generate increased demand for semiconductors and other equipment also fostering demand for critical minerals (Reich and Simon, 2025).

Global Computable General Equilibrium (CGE) models are well-suited for developing the long run projections of the impacts of decarbonization, digitalization and the growth of AI on critical mineral supply chains. Providing the economy-wide coverage and representing various stages of the global supply chain, this class of models can evaluate the role of trade policies related to critical minerals and energy equipment, such as subsidies, export restrictions and local content requirements; quantify the impacts of the energy transition and climate policies on critical minerals supply and demand; and analyse the impact of the growth of AI on emissions, demand for semiconductors and critical minerals, as well as associated trade pattern and the concentration of trade and production. However, global CGE models, while being widely used to support the decision-making process in the area of mineral mining and downstream activities, still lack essential details to facilitate the granular analysis of these essential policy issues.

Building on the GTAP-CE (circular economy) database (Chepeliev et al., 2026), this paper describes the extension of the GTAP Data Base with critical minerals and downstream products with equipment used to generate renewable energy, thus constructing the GTAP-CM (critical minerals) database, further extending previous developments in this area (Chepeliev et al., 2025). The disaggregated database is constructed for 2017 reference year of the GTAP Data Base Version 11. The extended database adds 35 new activities compared to GTAP-CE (7 GTAP-CE parent sectors are disaggregated into 42 new sectors), covering four stages of the mineral supply chains: (i) mining of critical minerals; (ii) refining of critical minerals; (iii) intermediate sectors such as batteries and magnets; (iv) downstream sectors such as solar panels, wind turbines and electric vehicles. Output is available both in value and volumes whereas the other variables such as trade are only available in values.

The paper contains a detailed description of the data sources employed and the methods used to reconcile different data inputs. In addition, the paper discusses a number of ongoing data developments, related to further updates and extensions of the GTAP-CM database and related modelling capacity.

Section 2 includes a description of the GTAP-CE database – a core input and starting point of the GTAP-CM development, as well as a discussion of the selection of new sectors. In Section 3 we turn to a detailed exposition of the methodology employed, mapping out the MSplitCom routines and RAS balancing procedures, the data sources, and the methodology to reconcile the different data sources. Since both the nature of the sectors in terms of technologies and production structures and the data sources available are heterogeneous, the data reconciliation approach varies across sectors. The general approach is described in the main text, while the annex contains details on the tailored approach for various sectors. Section 4 concludes and discusses directions for future research.

THE BASIS: GTAP-CE AND DATA SOURCES FOR GTAP-CM

This section starts with a short description of GTAP-CE which serves as the basis for the extension with critical minerals and associated downstream sectors. Then we turn to the selection of sectors and products included in GTAP-CM.

2.1 GTAP Circular Economy (GTAP-CE)

The starting point for developing the GTAP critical minerals (GTAP-CM) Data Base splits is the GTAP Circular Economy (GTAP-CE) Data Base version 11 (Chepeliev, 2026). The GTAP-CE Data Base introduces an additional disaggregation of sectors in the GTAP-Power 11 Data Base containing 76 sectors, 160 regions with 2017 as reference year (Chepeliev, 2023). Six sectors of the original GTAP-Power 11 Data Base are further split into 29 sub-sectors, providing a more detailed representation of categories like metallic and non-metallic minerals mining, rubber and plastic products, iron and steel, non-ferrous metals, fertilizers and cement (Figure 1). Corresponding sectoral splits are developed for all 160 regions reported in the GTAP-Power 11 Data Base. The sectoral splits introduced are designed to facilitate the assessment of circular economy policies, climate mitigation, as well as Carbon Border Adjustment Mechanism (CBAM) measures. As a result, the GTAP-CE Data Base includes both the electricity generation details part of GTAP-Power, i.e. 11 generation activities, as well as transmission and distribution, as well as additional material-related details. Table 1 provides an overview of the 76 GTAP-Power sectors split up to generate 99 sectors in the GTAP-CE Data Base.

Some of the sectors disaggregated in GTAP-CE are also relevant for the critical minerals supply chain disaggregation in GTAP-CM. For example, it includes ore mining activities (e.g. mining of iron, bauxite, copper and other ores), as well as metal-producing sectors (production of steel, aluminum, copper and other metals).

Table 1: An overview of the sectoral splits introduced in the GTAP-CE Data Base based on the sectors in the GTAP-Power 11 Data Base

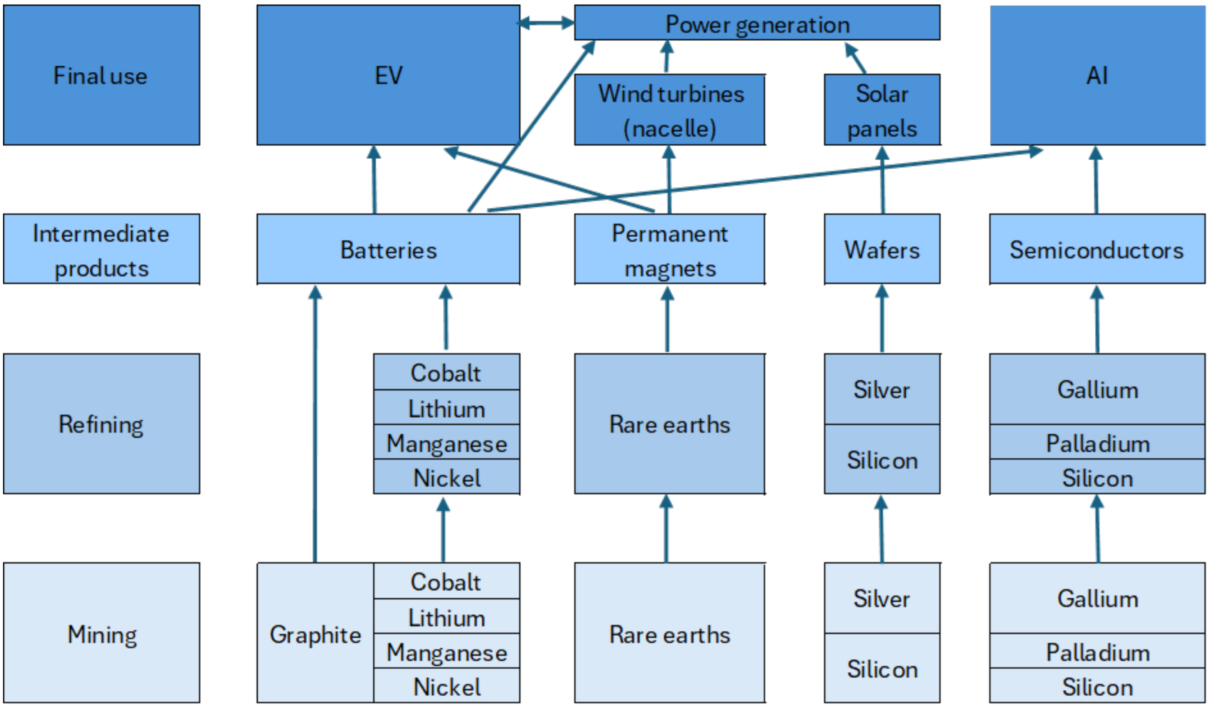
No.	GTAP	New sector	Description
1	oxt	nmn	Non-metallic minerals mining
2		mio	Mining of iron ores
3		mao	Mining of aluminum ores
4		mco	Mining of copper ores
5		moo	Mining of other ores
6	rpp	rbr	Rubber products
7		plp	Plastic products – primary
8		pls	Plastic products – secondary
9		plr	Recycling - plastics
10	nmm	cem	Cement
11		nmx	Other mineral products
12	i_s	isp	Iron and steel – primary
13		iss	Iron and steel – secondary
14		ris	Recycling - iron and steel
15		isc	Iron and steel casting
16	nfm	app	Aluminum – primary
17		aps	Aluminum – secondary
18		ral	Recycling - aluminum
19		cpp	Copper – primary
20		cps	Copper – secondary
21		rcp	Recycling - copper
22		mpp	Other metals – primary
23		mps	Other metals – secondary
24		rom	Recycling - other metals
25		nfc	Non-ferrous metals casting
26	chm	nfr	Nitrogen fertilizer
27		pfr	Phosphorus fertilizer
28		kfr	Potassium fertilizer
29		xch	Other chemicals

Source: Chepeliev (2026).

2.2 Selection of sectors: criteria and overview of sectors

The GTAP Critical Minerals (GTAP-CM) database extends the GTAP-CE database to enhance the representation of the global value chains of a selected set of critical minerals, from upstream mineral extraction to the downstream production of selected technologies. To select the sectors, we first identified four key stages of the renewable energy and artificial intelligence supply chains (Table 2): (i) mining; (ii) refining; (iii) intermediate production; and (iv) final use.

Table 2: Renewable energy and AI supply chains



Notes: the AI supply chain will be developed in future work.
Source: own elaboration by authors based on sources described in the main text.

The four supply chains associated with electric vehicles (EVs), wind turbines, solar panels, and AI-related goods are interlinked. In the current paper we focus only on the first three with the AI value chain left for further work. We split out the sectors corresponding to the mining and refining of the selected critical minerals required for these applications, as well as intermediate sectors such as batteries (disaggregated into different types), permanent magnets, and downstream sectors such as nacelles, solar panels, and EVs.

To select the critical minerals, we relied on an extensive literature review, as well as on existing lists developed by international organizations and criticality indices from IRENA, the IEA, USGS and the EU, as displayed in Table A.1 in the Annex.

To select the sectors, we used three main criteria. First, the importance of critical minerals for each selected technology. For instance, in the wind turbine supply chain, we include rare earths as a separate sector since it is crucial to produce permanent magnets. Even though other minerals are also used in wind turbines they are less critical. Rare earths are considered particularly critical because of their limited substitutability and concentrated geographic availability relative to other inputs. Second, the relative scarcity of the minerals. Minerals that are not considered scarce are therefore excluded from the analysis. Third, the value of production and trade of minerals, thus omitting minerals with tiny production values.

Selected minerals are combined into groups for reasons of trade and production data availability. For example, platinum group metals and rare earth elements are one category. Furthermore, we omit two products represented in Table 2 from the analysis: silicon and wafers, associated which are part of the solar panels supply chain. Silicon is omitted because it is not clear to what extent it is critical and to what extent it is actually abundantly available. Wafers are omitted because of the lack of data on both wafer production and the cost share of wafers in the production of solar panels.

Importantly, six minerals selected based on those criteria have explicit refining sectors, which map into further intermediate and downstream sectors. For some of the remaining critical minerals (e.g., zinc, chromium, niobium), we made use of the mining production data available and included these minerals as new mining sectors in the database. Those mining sectors link into the residual refining sector (mppR), with the exception of phosphorus which links to the sector phosphorus fertilizer (*pfr)* sector.

Table 3 provides an overview of the sectoral splits introduced in the GTAP-CM Data Base on top of the GTAP-CE sectoral disaggregation. Within this development, seven original GTAP-CE sectors are further disaggregated into 42 sectors. Panel (a) contains the mining and refining activities and panel (b) the downstream sectors (intermediate products and final use). In addition to mining and refining activities, selected downstream uses (intermediate products and final use) are disaggregated in the GTAP-CM Data Base. As a result, 7 original GTAP-CE sectors are further disaggregated into 42 activities. Table 3 makes clear that GTAP-CE has two mining sectors, Non-metallic minerals mining (nmn) and Mining of other ores (moo) which are both split into a range of minerals. Two refining sectors, Other chemicals (xch) and Other metals (mpp) are both split into a range of refined products. More of the new disaggregated refining sectors belong to Other chemicals because the intermediate technologies we are interested in (batteries, magnets) use refined minerals processed chemically. The HS codes representing these refined minerals are part of Other chemicals (xch) in the GTAP Data Base. Electrical equipment (eeq) is split into Permanent magnets, various batteries (intermediate products) and nacelles, whereas Solar panels are part of Electronics (ele). Finally, Motor vehicles and parts (mvh) are split into different types of electric vehicles (EVs), combustion engine vehicles and motor vehicle parts. The latter split enables the modelling of substitution between combustion engine cars and EVs.

Table 3: Overview of new GTAP sectors in GTAP-CM based on GTAP-CE sectors

No.	GTAP-CE sector	GTAP-CM sector	
		Code	Description
1	Mining of other ores ("moo")	man	Manganese
2		nik	Nickel
3		cob	Cobalt
4		zin	Zink
5		chr	Chromium
6		tit	Titanium
7		nio	Niobium
8		sil	Silver
9		gal	Gallium
10		pgm	Platinum group metals
11		mooR	Rest of other ores mining
12	Non-metallic minerals mining ("nmn")	lit	Lithium
13		gra	Graphite
14		rre	Rare earth elements
15		pho	Phosphorus
16		mgm	Magnesium
17		nmnR	Rest of non-metallic minerals mining
18	Other chemicals ("xch")	coR	Refined cobalt
19		mnR	Refined manganese
20		liR	Refined lithium
21		reR	Refined rare earths
22		niR	Refined nickel
23		agp	Artificial graphite

24		xchR	Rest of other chemicals
25	Other metals ("mpp")	siR	Refined silver
26		mppR	Rest of other metals
27	Electrical equipment ("eeq")	mag	Permanent magnets
28		LCO	Lithium Cobalt Oxide batteries
29		LFP	Lithium Iron Phosphate batteries
30		NCM	Nickel Manganese Cobalt Oxide batteries
31		NCA	Lithium Nickel Cobalt Aluminum Oxide batteries
32		LMO	Lithium Manganese Oxide batteries
33		egs	Nacelle
34		eeqR	Rest of electrical equipment
35	Electronics ("ele")	sop	Solar panels
36		eleR	Other electronics
37	Motor vehicles and parts ("mvh")	evl	Private electric vehicles EV
38		pvl	Private hybrid vehicles PHEV
39		cbl	Private combustion engine vehicles
40		evb	Electric buses
41		vpr	Motor vehicle parts
42		otv	Other transport vehicles

Source: own elaboration by authors based on sources described in the main text.

Table 4 displays the key intersectoral linkages between the new disaggregated sectors in GTAP-CM. The fourth column contains all 42 new sectors whereas the second row contains a selected set of the purchasing sectors to keep the table readable.[3] The table shows that most mined minerals serve as inputs into separate refined minerals sectors (such as Lithium and Rare Earths) although a range of mined minerals such as Chromium and Gallium are sold to the refining sector Rest of other metals (mppR).

[3] Phosphorous fertilizer (pfr) is one of the purchasing sectors although it is not a new sector, since it is the only sector absorbing phosphorous.

Table 4: Key intersectoral linkages in the GTAP Critical Minerals Data base

				xch							mpp		ele		eeq								mvh						
	Parent sector	New sector	New sector's name	cor	mnr	lir	rer	nir	agp	xchR	sir	mppR	sop	eleR	mag	LCO	LMO	NCM	NCA	LFP	egs	eeqR	cbl	evl	pvl	evb	vpr	otv	pfr
1	nmn	lit	Lithium			x																							
2		gra	Natural graphite													x	x	x	x	x									
3		rre	Rare earths				x																						
4		pho	Phosporous																										x
5		mgm	Magnesium									x																	
6		nmnR	Other non metallic minerals																										
7	moo	man	Manganese		x																								
8		nik	Nickel					x																					
9		cob	Cobalt	x																									
10		zin	Zinc									x																	
11		chr	Chromium									x																	
12		tit	Titanium									x																	
13		nio	Niobium									x																	
14		sil	Silver								x																		
15		gal	Gallium									x																	
16		pgm	Platinium group metals									x																	
17		mooR	Other metallic minerals																										
18	xch	cor	Refined cobalt (chemical)													x		x	x										
19		mnr	Refined manganese (chemical)														x	x	x										
20		lir	Refined lithium													x	x	x	x	x									
21		rer	Refined rare earths												x														
22		nir	Refined nickel (chemical)															x	x										
23		agp	Artificial graphite													x	x	x	x	x									
24		xchR	Other chemicals																										
25	mpp	sir	Refined silver										x																
26		mppR	Other																										
27	ele	sop	Solar panels																										
28		eleR	Other electronics																										
29	eeq	mag	Permanent magnets																		x			x	x	x			
30		LCO	LCO																			x							
31		LMO	LMO																			x							
32		NCM	NCM																					x	x	x			
33		NCA	NCA																					x	x	x			
34		LFP	LFP																					x	x	x			
35		egs	electric generator sets																										
36		eeqR	Other elecronic equipment																										
37	mvh	cbl	Combustion private cars																										
38		evl	Electric private cars																										
39		pvl	Plug- in hybrid private cars																										
40		evb	Electric buses																										
41		vpr	Vehicle parts																										
42		otv	Other vehilcles																										

Notes: intermediate linkages displayed as not present in the figure (white) contain small nuisance values in the final data base for modelling purposes.
Source: own elaboration based on various data sources described in the text.

Most refined minerals are used in the five types of batteries, LCO, LMO, NCM, NCA and LFP, although refined rare earths (rer) serve as inputs for permanent magnets (mag) and refined silver (sir) for solar panels (sop). Permanent magnets in turn serve as inputs for nacelles (egs) and different types of electric vehicles (evl, pvl and evb). The different types of batteries are also used in electric vehicles but also serve as investment inputs directly in the generation of renewable energy (for battery type LFP). Finally, phosphorus serves as input for phosphorus fertilizer.

DATA SOURCES AND DISAGGREGATION METHODOLOGY

This section provides an overview of the methodology employed to split up the GTAP-CE sectors. We start with a description of the MSplitCom routines and RAS procedures, followed by a discussion of data sources. Then we turn to the most technical part requiring extensive discussion, the reconciliation methodology. In the main text we describe the generic approach employed for most mining and refining sectors, whereas the annex outlines the approach for the different intermediate and final use sectors which differs across sectors because of differences in data availability.

In constructing the database, we faced a set of problems. First, there were inconsistencies between the production data of critical minerals from USGS and the trade data from CEPII BACI. More specifically, the HS code for trade could contain more commodities than explicit minerals in USGS. To address this issue, we worked with assumptions on shares since more detailed trade codes are only available (e.g. HS8, HS10) for a small set of countries. Furthermore, USGS reports extraction of 'mineral content', whereas trade data are reported in 'gross quantities'. To address this issue, we applied an adjustment factor to convert from gross quantities into metal content. Regarding inconsistencies between production and trade data, there are countries with exports but no production or exports exceeding production, thus implying negative use. To tackle this issue, production data are given preference and trade data adjusted accordingly. Hence, for country-sector combinations with no output reported, trade flows are discarded.

Second, trade prices (based on unit values) for selected country-commodity cases are unrealistically high/low. This was addressed by using regional-average prices and/or cap price variations. Third, data on supply and cost structures were sometimes lacking. To address this issue US IOT or GTAP parent sector structures were employed, as well as information from selected data sources, in particular academic papers on cost structures. Fourth and finally, data on values of output for some downstream sectors are difficult to obtain from public sources, so they were obtained from BloombergNEF (2024) and complemented by constrained optimization routines we developed for this work.

3.1 MSplitCom routines and RAS procedures

The database disaggregation and balancing procedure is implemented using the MSplitCom utility (Horridge, 2008). MSplitCom is a GEMPACK-based utility specifically designed for disaggregating sectors in the GTAP Data Base. The routing utilizes the RAS bi-proportional method, which iteratively adjusts the entries of an initial matrix until they match pre-defined row and column totals (Lahr and Mesnard, 2004). By design, the implemented balancing procedure preserves the original flows of the underlying GTAP-CE Data Base, with the latter serving as the starting point for the development of GTAP-CM. To conduct the RAS procedure, MSplitCom employs data on trade shares and production shares of the new sectors as well as their cost structure and their supply structure.

We modify the MSplitCom procedure splitting the selected sectors in four separate blocks (using GEMPACK's RAS_MATRIX function), including domestic supply shares, bilateral trade, imported supply shares and cost structure. This approach is chosen because it adds robustness and is better able to more closely replicate targeted output values.

The disaggregation procedure itself is implemented in a sequence of steps, as splits are first introduced for mining sectors, then refining, then intermediate activities, and finally, the remaining downstream sectors. Such a sequential implementation allows us to refine targets across the critical minerals supply-chain stages during the database construction process. For instance, we first run the split for mining sectors and obtain a balanced database with disaggregated mining activities. Then the corresponding mineral mining flows (production and trade) are used to refine the targets for the refining sectors based on the availability of minerals (mineral supply) by countries. This ensures better alignment across data inputs for various supply chain stages.

3.2 Data sources and data processing

Data collection for this project followed four stages—mining, refining, intermediate, and downstream sectors—corresponding to the selected clean energy and transportation supply chains. In this section, we present the inventory of the raw data inputs used in the analysis, discussing in turn the four sets of data needed, on trade, production, cost structure and supply structure. In the next section, we discuss in detail how these raw data are reconciled to ensure internal balance and consistency, and how they are prepared for use as inputs to the MSplitCom utility.

3.2.1 Trade

The main data source for bilateral trade flows underlying the GTAP CM database is the CEPII- BACI database (Gaulier et al., 2010), which reports bilateral trade in minerals in both value and volume terms.

The CEPII-BACI database covers bilateral trade in commodities at the HS 6-digit level for 238 countries and political entities. It reports trade values in millions of dollars and trade volumes in tons. Volumes are reported in gross weight, that is, the actual weight of the trade flow in metric tonnes. CEPII-BACI converts quantities reported in other units into tons by estimating conversion factors. Data are not reported when quantities are expressed in an unknown unit or in kWh.

The HS codes used to determine the volume and value of trade of the 42 new sectors, based on the 2017 revision, are identified through a review of the literature and bilateral consultations with trade experts. The full list of HS codes employed with the mapping to the 42 new sectors is presented in Annex 3. A key challenge is that some products, particularly certain raw ores, do not have dedicated six-digit HS codes. For example, HS code 253090 includes both raw lithium and raw rare earths, which prevents the direct identification of mineral-specific trade flows. In such cases, we made country-specific assumptions to assign each trade flow to a particular mineral, based on available information on mineral production.

A similar issue arises for the individual battery types that we disaggregate. Specifically, the CEPII-BACI database contains only aggregate trade flows for lithium batteries, without distinguishing among different lithium battery types. We therefore use a simple constrained optimization model (Annex 2.5) to disaggregate these flows into specific lithium battery types.

3.2.2 Production

For mined minerals, we use data from United States Geological Survey (USGS) (2017). The USGS database provides information on the quantities of minerals extracted worldwide, measured in metric tons. In most cases, quantities are reported in terms of metal content, that is, the weight of the pure mineral. In some cases, however, data are reported in gross weight, referring to the weight of the ore, only a fraction of which consists of the pure mineral.

Other sources of mineral production data are also available. For example, Fally and Sayre (2019) use data from the British Geological Survey (BGS). These data do not differ substantially from those of the USGS. As noted by Fally and Sayre, where comparisons are possible, the USGS and BGS production data generally coincide, and any differences tend to be small.

For artificial graphite, data on global and Chinese production based on USGS are used, because country-specific production data are not available except for China[4]. Global production is allocated to China and rest of the world based on shares available at the USGS. The remaining amount is allocated to different countries based on export shares.

Production data for refined minerals are limited. The USGS reports refinery production only for a small number of cases. We therefore assume that the production of refined minerals (in volumes) is equal to the domestic use of mined minerals, calculated as domestic production plus imports minus exports (see Section 3.3). This assumption is supported by the fact that global totals for mineral extraction and refinery production are very similar for the few minerals (cobalt, nickel, manganese) for which USGS refinery production data are available. Hence, refinery production data are reported in metal content terms by USGS and the refined quantities correspond to pure metal.

Importantly, some minerals—namely cobalt, manganese, and nickel—are part of two types of refining sectors, one falling under the chemical sector (Other chemicals, xch) and the other under the metallurgy sector (Other metals primary, mpp). For the purposes of this database, only the chemically refined products are relevant for batteries. We therefore do not model metallurgical refining explicitly. Instead, we allocate the domestic use of mined minerals between the production of chemically refined minerals and a residual refining sector (falling under the sector *mpp*). To determine production in the chemical refining sector for these minerals with dual end uses, we assume that the share of domestic use of the mined mineral allocated to the chemical refining sector is equal to the share of exports (of all HS6 level products) associated with the chemical refining in total exports of both the chemical and metallurgical refining.

For the production data on intermediate and final use products, we rely on a wide range of sources which vary in their coverage and detail. Therefore, for intermediate and final stages of the supply chain we apply a sector-specific approach to process and reconcile the data collected. Annex 2 describes these sector-specific approaches in detail, together with the data available for each new sector. There are three main sources of the production data for intermediate and final use products. First, information about the factory capacity for batteries, wind turbines and solar panels for a list of regions including China, US, EU, South Korea and Japan is sourced from BNEF (2024). Second, we rely on reports from research institutions for estimates on aggregate production of batteries (Tsiropoulos et al., 2018) and permanent magnets (Alves Dias et al., 2020). Third, the production of passenger cars is based on data from OICA[5].

[4] Graphite 2017
[5] Production Statistics - International Organization of Motor Vehicle Manufacturers

3.2.3 Cost structures

Cost structures of the mining sectors follow the cost structures of their respective GTAP parent sector. For the cost structures of refining, intermediate, and downstream sectors, available information is limited and is drawn primarily from technical and engineering studies. We combine these sources with a set of technical assumptions and the pre-existing cost structures of the parent sectors in the GTAP-CE database. We describe the approach sequentially, moving from mining to refining to intermediate and final use sectors.

To construct the cost structure of the refining sector for a given mineral, we assume that the cost share of the mined mineral is equal to the ratio of the value of production of the mined mineral (see the reconciliation of production volumes into values in Section 3.3) to the value of production of the refined mineral. Once this share is obtained, the remaining cost shares are in line with the cost structure of the GTAP parent sector of the refined mineral, either the chemicals (xch) or metallurgy (mpp) sector.

For intermediate sectors—magnets and batteries—we rely on the literature on the quantity of refined minerals required per unit of magnets and batteries. Using insights from this literature, we compute the share of refined minerals in the total value of intermediate goods produced (see the computation of unit prices and values in Section 3.3). Once this share is obtained, the remaining cost share is allocated proportionally according to the cost structure of the GTAP parent sector of the intermediate product.

Analogously, for downstream sectors, we rely on the literature on the quantities of intermediate inputs required (see the discussion below). Based on assumptions on material requirements drawn from this literature, we compute the value share of intermediate goods in the total value of downstream products produced (see the computation of unit prices and values in Section 3.3). Once this share is obtained, the remaining cost share is allocated proportionally according to the cost structure of the GTAP parent sector of the downstream product.

For batteries and vehicles, both electric and internal combustion, additional information on cost structures is available. For these sectors, we reconcile the approach described above with this supplementary information by making additional adjustments. For batteries, we rely on Orangi et al. (2022), using China as a representative benchmark for cost structures across all regions. Specifically, suppose that for a given battery type the refined lithium share is estimated at 15 percent using the approach described above, while Orangi et al. (2022) estimate the total material share at 40 percent. In this case, the additional 25 percent associated with materials is allocated across the GTAP sectors classified as material inputs (e.g., rom, nfc, fmp, ele among other sectors). The remaining 60 percent of costs is allocated to the sectors identified in Orangi et al. (2022), rather than according to the GTAP parent sector for batteries. For electric and combustion vehicles, we have used cost structures based on Tamba et al. (2022).

Annex 2 describes the sector-specific approach to obtain cost structures.

3.2.4 Supply structures

Information on the supply structure of the products we disaggregate is limited. As described earlier, raw minerals are used primarily as inputs into refining. We nevertheless assume that a small share—5% of total supply—is used also by other sectors.

For the supply structure of refined minerals (and their use in intermediate and downstream technologies), we rely on data from Barry et al. (2015) and Fally and Sayre (2019). Barry et al. (2015) document the supply structure of minerals across different intermediate sectors in the U.S. economy. We map these sectors to GTAP sectors and assume that the same supply structure applies across all GTAP regions. These sources are reconciled with our own estimates of domestic supply of refined minerals, calculated as production plus imports minus exports (see Section 3.3).

For some downstream technologies, data on sales are more readily available than data on production. First, we use data from IRENA on installed capacity for wind turbines and solar panels. IRENA reports stocks of wind turbines and solar panels. To transform these stock measures into newly installed capacity, which corresponds to production at the global level, we apply a capital accumulation formula. Second, we use data from the IEA on regional sales of electric vehicles (EVs) and plug-in hybrid vehicles. Annex 2 describes these procedures for each sector in detail.

We make further assumptions based on our understanding of the current technology as displayed also in Figure 1. As an example, we assume that batteries are used either in the transport sector, in electricity storage (investment) or in computer, electronic and optical products. Similarly, permanent magnets are used in EVs, electric generating sets (nacelles) and other electronic equipment. Finally, we assume that solar panels and nacelles are used as investment goods, also based on the fact that most of the costs in electricity generated with solar and wind energy consist of purchases of investment goods. Supply of permanent magnets to electric generation sets and vehicles has been calculated given production of those products and their material intensity (demand for magnets per product). The remaining supply has been allocated to (residual) electric equipment sector.

3.3 Six data reconciliation steps

The initial production and trade data must be reconciled before they can be used as inputs for the RAS procedure in MSplitCom. We follow six main steps to construct balanced and internally consistent datasets suitable for MSplitCom. These steps are as follows:

Step 1 – Harmonization of units for trade and production volumes
Step 2 – Adjustment of exports exceeding domestic production
Step 3 – Removal of re-exports from bilateral trade flows
Step 4 – Adjustment of imports to ensure consistency with supply
Step 5 – Harmonization of export unit prices and adjustment of export volumes
Step 6 – Estimation of supply

We now revisit these steps in turn. Importantly, this procedure is applied to calculate balanced flows for mined minerals, refined products, and private combustion vehicles. For these products, relatively detailed data are available on both trade and production. For other sectors, available data are more limited and are allocated across countries and sectors partially based on modelling such as quadratic optimization procedures employing assumptions on cost and supply structures based on academic literature. The calculation of flows for these remaining products is presented in Annex 2, on a product-by-product basis. Annex 2 also describes the method used to estimate trade flows for minerals for which HS6 trade data are not available, including lithium, rare earths, gallium, and platinum group metals (PGMs).

3.3.1 Harmonization of the units for trade and production volumes

The first step aims at harmonizing the units of different data sources. The trade volumes of mining goods are harmonized to reflect metal content rather than gross weight. We scale trade flows, originally measured in gross weight, using adjustment factors taken from Alvarez et al. (2023). For example, for nickel we assume that only 1.5% of nickel ore is pure mineral.

Trade volumes for solar panels, EVs, and magnets are further converted from tons into Gigawatt-hour (GWh), numbers of cars, and rare-earth content, respectively. This is necessary because we need to compute product-specific prices which are multiplied by production data in volumes (reported in GWh) to obtain production values. The adjustment factors used to harmonize units are presented in Table 5 below.

Table 5: Adjustment factors used to convert trade data volumes into the same units as production/supply

a. Mining

Lithium	lit	x
Graphite	gra	1
Rare earths	rre	x
Phosphorus	pho	1
Magnesium	mgm	0.285 [a]
Manganese	man	1
Nickel	nik	0.015[a]
Cobalt	cob	0.07 [a]
Zinc	zin	0.65 [a]
Chromium	chr	0.68 [a]
Titanium	tit	Own estimates
Niobium	nio	1
Silver	sil	0.017 [a]
Gallium	gal	x
Platinum group metals	pgm	x

b. Refining

Lithium refining	lir	0.2[b]
Cobalt refining	cor	0.72 [e]
Rare earths refining	rer	1
Manganese chemical refining	mnr	0.77 [b]
Nickel chemical refining	nir	0.78 [b]
Artificial graphite	agp	1
Silver refined	sir	1

c. Intermediate goods

Permanent magnets	mag	x
LCO	LCO	x
LMO	LMO	x
NMC	NMC	x
NCA	NCA	x
LFP	LFP	x

d. Final goods

Solar panels	sop	10 W/kg[c]
Electric generation sets	egs	x
Private vehicles EV	evl	2 tonnes/unit[d]
Private vehicles PHEV	pvl	2 tonnes/unit[d]
Private combustion vehicles	cbl	1.5 tonnes/unit[d]
Electric buses	evb	10 tonnes/unit[d]
Vehicle parts	vpr	x
Other transport vehicles	otv	x

a – Based on Alvarez et al. (2026).
b – Estimated as the share of mineral content in chemical mass of the refined products of nickel oxide and manganese oxide (assumed to be NiO and MnO).
c – Based on IRENA (2018).
d – Based on US EPA (2024). For three countries (USA, Canada and Germany) we assume that the weight of private combustion vehicles is 1.8 tonnes instead of 1.5 tonnes. This is to reflect that North American cars are larger and for Germany we scaled down the number of exported cars to obtain a better match with the combustion car production data from OICA.
e – Based on Gulley (2024).
Notes:
- For products with an "x" trade data are not available at a sufficient level of detail or trade volumes are not comparable with production/sales volumes. The treatment of the trade flows for those sectors is implemented on a product-by-product basis as described in Annex 2.
- For some of the export flows of mined minerals, we skip this step as it is inappropriate to apply the conversion factor in Table 5. These are the cases where the product is already exported in a purified manner, which we infer from the (implicit) unit export price. Specifically, if the price is significantly above the global average, we conclude

that the product is already exported in pure metal content and thus don't apply the adjustment factors to the export volumes. One example of such cases is the nickel exports from Canada.

Importantly, it should be noted that having production and trade in the same units, does not necessarily make them consistent with each other. For example, because production and trade data come from different sources, this can sometimes result in negative values for the supply (e.g., when production plus imports is lower than exports). In other cases, exports alone may exceed production. Both situations are not allowed in the GTAP framework and require adjustments.

3.3.2 Adjustment of exports exceeding domestic production

In the second step we adjust exports exceeding domestic production which would imply negative domestic supply. This occurs in countries reporting both exports and production volumes and addresses cases where, despite harmonized volumes, the reported export volume still exceeds the domestic production volume. In such cases, we scale down the export flows so that the export-to-production ratio does not exceed that of the corresponding parent GTAP sector, except for cases where the export to production ratio is less than 0.5 in the GTAP parent sector in which case we set the ratio at 0.5 in the disaggregated new sector.

3.3.3 Removal of re-exports from bilateral trade flows

In this step we remove trade flows for countries which report exports in CEPII but do not display any mining of minerals according to USGS data. These flows are implicitly treated as re-exports. Since the GTAP structure does not allow for re-exports, the bilateral flow is adjusted changing values in both the exporter and the importer country. For example, assume that according to trade data country B exports 10 units to country C, but according to the production data country B is not a producer. Then we treat these 10 units as re-exports and remove the bilateral trade flow from B to C.[6]

3.3.4 Adjustment of imports to ensure consistency with supply

The adjustment from Step 3 reduced imports of countries buying goods from re-exporters, thus possibly distorting the value for domestic supply of the mineral. The supply within the country is now lower than what it should be. This step addresses those cases to re-adjust the affected flows. We eliminate exports of countries not producing in a certain sector and then employ a RAS procedure to rebalance the data. The elimination and RAS procedure can be illustrated with the following example (Tables 6a-6c). We have three countries, A, B, and C; among whom A is the only producer. We observe from the trade data that A exports 50 units to B and 10 units to C; and that B exports 10 units to C. In this initial case, the total imports of B from the rest of the world are 50; and the total imports of C from the rest of the world are 20 units.

Table 6a: Initial trade structure (selling country in rows and purchasing country in column)

Production	Country	A	B	C
yes	A		50	10
no	B			10
no	C			

Given that B is a non-producer, we have treated in Step 3 the exports of 10 units from B to C as re-exports. When we remove exports of the non-producer, country B, we get the following adjusted bilateral flows.

[6] An alternative interpretation of the case where there is no production with positive exports is that for production a different classification is employed or the production data are wrong. However, we decided to give preference to the production data (as for the adjustment f exports exceeding domestic production in the previous subsection).

Table 6b: Trade structure after removing trade for non-producing countries

Production	Country	A	B	C
yes	A		50	10
no	B			
no	C			

In this new case, the total imports of B from the rest of the world is 50; and the total imports of C from the rest of the world is 10 units. The adjustment reduced the imports of C, hence the supply of the mineral inside C. The supply within the country is now lower than what it should be. In order to re-balance these bilateral flows, we apply the initial shares of countries B and C in the total world imports (respectively 5/7 and 2/7) to the new total imports of 60 units. Therefore, the adjusted bilateral flows upscales the imports of C to approximately 17 as represented in Table 6c:

Table 6c: Trade structure after adjusting trade shares related to re-exports

Production	Country	A	B	C
yes	A		~43	~17
no	B			
no	C			

We need to proceed in this way, since it is unknown what share of the exports from B to C which are reallocated comes from A or another region.

As a result of this procedure, re-exports are handled while import shares are closer to initial import shares.

3.3.5 Harmonization of export unit prices and adjustment of export volumes

To obtain production values and convert production data in volumes, we need price data. Employing trade data, the implicit export price of a product for each exporting region is calculated based on the total value of exports divided by the total quantity of exports. For each exporter-sector combination we compute a single price which is applied to each destination market, calculated as the value of exports divided by the volume of exports. Furthermore, for each sector, the variation in exporter prices are bounded between 50% and 200% of the world average price of exporter prices in the specific sector. With this assumption we are in line with the theoretical structure of Armington based models which do not have pricing-to-the-market and thus variation in export prices by destination.

Then, the volumes of trade for each exporting country are obtained by assuming a uniform export price to all destinations. To do so, bilateral trade flows in values are divided by the average export price. This procedure yields a new set of volume flows. An illustrative example is provided below:

Table 7a: Initial trade flows

	Total	A	B	C
V	60	10	20	30
Q	13	2	3	8
P	4.6	5	6.7	3.8

Table 7b: Trade flows after unification of prices

	Total	A	B	C
V	60	10	20	30
Q	13	2.2	4.3	6.5
P	4.6	4.6	4.6	4.6

The exporter and product specific prices are applied to the production volumes.

3.3.6 Estimation of supply

We can now combine the modified data inputs to obtain estimates for the supply in each region-sector combination in values. The supply of a product can be calculated as Supply = Production + Import - Export.

In this formula the value of production is obtained by multiplying the volume of production in the data collected from different sources, such as USGS, with exporter-sector generic trade prices from CEPII. Trade values (both exports and imports) are obtained from the trade values from CEPII adjusted based on the steps described previously (e.g., removal of re-exports, imposing exporter-sector generic trade prices). The approach is summarized in Table 8:

Table 8: Approach to calculate production and supply of minerals in mining.

	production	import	export	supply
Value (V)	USGS Q * CEPII V/Q (adjusted)	CEPII V (adjusted)	CEPII V (adjusted)	estimate
Quantity (Q)	USGS Q	CEPII Q (adjusted)	CEPII Q (adjusted)	estimate
Price (P)	CEPII V/Q (adjusted)	CEPII V/Q (adjusted)	CEPII V/Q (adjusted)	estimate

CONCLUDING REMARKS

In this paper we describe how to extend the GTAP-CE Data Base with critical minerals sectors and downstream renewable energy sectors to generate the GTAP-CM Data Base with base year 2017. Future work can be extended in various directions, related to further updates and extensions of the GTAP-CM database and related modelling capacity. More specifically, the data collection and modelling work can be extended in four directions.

First, the construction of the GTAP Critical Minerals Data base can be done as well for 2023. Due to the rapid changes in the renewable energy and digital sectors, it is important to construct GTAP-CM for 2023, allowing for a more up-to-date and realistic starting point for modelling assessments.

Second, GTAP-CM can be further extended by including semiconductors and other AI related products. So far, the data work has focused on renewable energy sectors and critical minerals essential for their production. To study the upstream effects of digitalization and AI, semiconductors should be explicitly included in the database representation, together with the critical minerals employed in the production of semiconductors. Incorporating these supply chains in GTAP-CM would be an important development, allowing for the analysis of semiconductor-related policies. In addition to the rich trade data (ITC, 2025) and industry information provided by UNIDO (2025), selected national input-output (IO) tables for economies that provide detailed information to identify semiconductors could facilitate the parametrization of the semiconductor supply chains on the demand side. Corresponding IO tables include South Korea, Japan, Malaysia, Taiwan, and the United States (OECD, 2023).

Third, the representation of the link between electricity generated with renewable energy and renewable energy equipment can be improved by including an investment matrix. To comprehensively study the emission effects of trade and other policies impacting the costs of renewable energy equipment (batteries, solar panels, wind turbines) the existing database and model have to be extended with sector specific investments. Given that about 80% of inputs in the renewable energy sectors (solar and wind energy) consist of capital, most of the renewable energy equipment used by these sectors is capital. At the same time, the conventional GTAP approach works with a capital accumulation equation at the national level, implying that there is no direct impact of the price of renewable energy equipment on costs to produce solar and wind energy and that the composition of capital inputs is uniform across all sectors of economy. By developing an investment matrix, distinguishing the sourcing of investments by sector, and including a sectoral capital accumulation equation into the GTAP-based modelling framework, this omission can be addressed. Such development would allow for a more realistic assessment of the energy transition and mineral-related policies. A number of available data sources could facilitate the development of such investment matrix.

Fourth and finally, data can be collected on critical mineral reserves and the costs of extracting these with extraction curves. The database constructed for 2017 (and later for 2023) only contains information about current production structures. However, production can expand and shift depending on demand and policies. To study this, we need to incorporate a database of reserves of critical minerals combined with extraction curves indicating how responsive supply is to changes in prices. Several groups in research institutions and universities around the world have been collecting such data and estimating supply curves.

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ANNEX 1: LISTS OF CRITICAL MINERALS

Table A.1: Lists of critical minerals in GTAP-CM compared to lists from IRENA, the EU, USGS and WTO-ADB

GTAP CM	EC	USGS	IRENA		WTO-ADB
REE	Heavy Rare Earth Elements	Gadolinium	Gadolinium	0.24	Rare Earth Elements
		Ytterbium			
		Yttrium	Yttrium	0.39	
		Erbium			
		Dysprosium	Dysprosium	0.65	
		Scandium			
		Terbium	Terbium	0.38	
		Thulium			
		Lutetium			
		Holmium			
	Light Rare Earth Elements	Praseodymium	Praseodymium	0.57	
		Neodymium	Neodymium	0.68	
		Cerium	Cerium	0.41	
		Lanthanum	Lanthanum	0.45	
		Europium	Europium	0.31	
		Samarium			
Aluminum	Bauxite	Aluminum	Aluminum	0.44	Aluminium
	Antimony	Antimony			
	Arsenic				Arsenic
	Baryte	Barite			
	Beryllium	Beryllium	Beryllium	0.33	
	Bismuth	Bismuth	Bismuth		
	Boron		Boron	0.43	Borates
			Cadmium	0.38	Cadmium
		Cesium			
Chromium		Chromium	Chromium	0.47	Chromium
Cobalt	Cobalt	Cobalt	Cobalt	0.81	Cobalt
	Coking Coal				
Copper	Copper	Copper	Copper	0.52	Copper
	Feldspar				
	Fluorspar	Fluorspar			Fluorspar
Gallium	Gallium	Gallium	Gallium	0.73	Gallium
	Germanium	Germanium	Germanium	0.51	
Natural Graphite	Natural Graphite	Graphite	Natural Graphite	0.57	Graphite
					Gold
	Hafnium	Hafnium			
	Helium				
		Indium	Indium	**0.68**	
			Iron/steel	**0.32**	
		Lead	Lead	**0.24**	Lead
Lithium	Lithium	Lithium	Lithium	**0.81**	Lithium
Magnesium	Magnesium	Magnesium	Magnesium	**0.39**	Magnesium
Manganese	Manganese	Manganese	Manganese	**0.54**	Manganese
			Molybedenum	**0.39**	Molybedenum
Nickel	Nickel	Nickel	Nickel	**0.63**	Nickel
Niobium	Niobium	Niobium	Niobium	**0.29**	Niobium

	Phosphate				
Phosphorus	Phosphorus		Phosphorus	**0.47**	
			Potasium	**0.31**	
Platinum Group Metals	Platinum Group Metals	Iridium	Iridium	**0.36**	Platinum Group Metals (PGMs)
		Rhodium	Rhodium	**0.45**	Rhodium
		Platinum	Platinum	**0.47**	Platinum Group Metals (PGMs)
		Ruthenium	Ruthenium	**0.44**	
		Palladium	Palladium	**0.42**	
		Potash			
		Rhenium	Rhenium	**0.22**	
		Rubidium			
			Samarium	**0.35**	
			Selenium	**0.43**	Selenium
	Silicon	Silicon	Silicon	**0.4**	Silicon
Silver		Silver	Silver	**0.49**	Silver
	Strontium		Strontium	**0.48**	
	Tantalum	Tantalum	Tantalum	**0.27**	
			Tellurium	**0.61**	Tellerium (Tellurium boron)
		Tin	Tin	**0.32**	Tin
Titanium	Titanium	Titanium	Titanium	**0.4**	Titanium
	Tungsten	Tungsten	Tungsten	**0.34**	
	Vanadium	Vanadium	Vanadium	**0.41**	Vanadium
Zinc		Zinc	Zinc	**0.36**	Zinc
		Zirconium	Zirconium	**0.35**	Zirconium

Color legend:
GTAP-CM

mining and refining stage
only mining
GTAP CE

USGS risk classification

High
Elevated
Moderate

IRENA

Criticality Index

ANNEX 2: PRODUCT SPECIFIC TREATMENTS AND ASSUMPTIONS

A.2.1: Lithium and REEs

For the mining of lithium and rare earths, additional steps are needed to obtain trade flows. The reason is that these products fall under a single aggregated HS6 code (253090 *Mineral substances; n.e.c. in chapter 25*), also containing other products. To obtain trade flows for lithium only, we proceed as follows. First, we calculate the unit price of lithium by dividing the value of exports of HS 253090 from Australia to China by the quantity of exports of HS 253090 from Australia to China. This is based on the assumption that flows under this HS line from Australia to China are associated only with lithium. This unit price is then applied to the production volume reported by the USGS in order to obtain the value of production. At this stage, we have the value of lithium production (for example, 100) and the value of exports of lithium and REEs jointly (for example, 120). To calculate trade flows in lithium, we multiply the export-to-production ratio in the parent sector of lithium with the production of lithium to obtain lithium exports.

To obtain trade flows for REEs only, we follow a different approach. We first compute the unit values for refined rare earth elements. We then assume that the unit price of mined REEs is equal to half of the unit price of refined REEs. We apply this price to the mining production volume in order to obtain the value of mining production.

Next, we assume that 90 percent of global production of mined REE is used domestically in China (BNEF, 2024). The remaining 10 percent of total global REE production is allocated to other countries according to their export shares in refined REEs.

At this point, we know the production and supply values of mined REEs at the country level, implying values for total net trade (exports minus imports) of each country. To convert these net flows into bilateral flows, we run a simple model. We optimize bilateral flows of mined REEs under three constraints. The first constraint is that, at the country level, the sum of production and exports must be equal to the sum of supply and imports. The second constraint is that, for non-producers, supply must be equal to imports. The third constraint is that production must be greater than exports. The objective function minimizes the distance between observed bilateral HS6 trade under the aggregate mining code for lithium and REEs (253090) and the variables representing bilateral flows in the model. Once the bilateral flows are calculated, we follow Steps 1 to 5 described in Section 3.3.

A.2.2: Gallium

There is no dedicated HS line for raw gallium ore, and USGS data indicate that the production is entirely concentrated in China. We therefore assume that there is no international trade in raw gallium ore. Instead, domestic gallium production is assumed to be used by the domestic residual refining sector, Other chemicals (xch). Gallium refining is not modelled explicitly, because it does not play a role in the intermediate and downstream sectors modelled.

In terms of modelling including gallium mining as a separate sector might be difficult to justify, since gallium is generally obtained as a by-product of bauxite (aluminium) extraction. Therefore, gallium could be embedded within aluminium activity with the two minerals (gallium and bauxite) jointly produced, for instance through a CET-type function.

A.2.3: PGMs

Raw platinum group metals are classified under HS 261690, *Precious metal ores and concentrates; (excluding silver)*. This HS category also includes gold, which is another major mineral within the same code. To estimate the share of PGMs (platinum and palladium) within this HS line, we assume that each country's exports under HS 261690 are proportional to its domestic extraction of PGMs among the total of PGMs and gold. The prices of palladium, platinum and gold are similar which allows us to use this rudimentary approach. The resulting adjusted trade flows are then used to construct balanced flows of production, trade, and supply, following the steps in Section 3.3.

A.2.4: Artificial graphite

Artificial graphite is a product that can be used as a substitute for natural graphite. It is not extracted but produced from petroleum coke. In the USGS Data Base only global production as well as China's share in global production is available. Combining this information with the trade data for artificial graphite, we calculate production (volumes) through the following steps.

First, we apply step 5 in section 3.3 thus estimating export prices for each country and putting upper and lower caps on prices and adjusted export volumes. Second, we estimate production volumes in each country using $prod_{reg} = {export_{reg}}/{EXPRAT_{reg}}$, based on updated export volumes and the exportability ratio of the parent sector (which is chemicals) for EXPRAT. Third, we adjust the estimated production volumes from step 2 in each country such that the sum over all regions is equal to global production applying a common scaling factor to all regions.[7] Finally, the value of production is calculated as volume times the price.

For the cost structures, we assumed that this sector follows the cost structure of its parent sector.

A.2.5: Permanent Magnets

For permanent magnets, we have two pieces of information: bilateral trade flows for the HS6 code 850511, *Magnets; permanent magnets and articles intended to become permanent magnets after magnetisation, of metal*; and estimates of the global value ($) and tonnes of permanent magnets produced from Alves Dias et al. (2020). Table A.2 reports the information retrieved from Alves Dias et al. (2020).

Table A.2: Global data used for permanent magnets for the year 2017 (Alves Dias et al., 2020)

Global production (tonnes)	160 000
China's share in global production	90%
Global value of the market	10 billion USD

The value of permanent magnet production in China can be directly inferred from Table A.2. To calculate the production and supply of magnets in other countries, we set up a constrained optimization model to minimize the distance between the variation in regional prices for the product. Table A.3 lists the variables to be solved by this model (indicated with lower-case letters) and parameters given (indicated with upper-case letters):

Table A.3: Variables and parameters needed for the constrained optimization model to get production and supply of permanent magnets

Variables (to be solved)	Parameters (taken as given)
$price_{reg}$ (regional permanent magnet prices)	EXP_{reg} (regional exports from CEPI)
$prod_{reg}$ (regional permanent magnet production)	*PROD* (global production of permanent magnets in tonnes from Alves Dias et al. (2020))
	EXPRAT (share of export in production for parent GTAP sector eeq) [8]

[7] For China production is known and so this country is excluded from the procedure.
[8] We apply a lower bound of 50% to this variable which allows for a higher exportability than 50% thus preserving regional differences.

	PRICE (average price of permanent magnet calculated as the global production value over volume)

Using the parameter values in Table A.3, we minimize $price_{reg} \cdot \ln(price_{reg}/PRICE)$ under two constraints:

1) $price_{reg} * prod_{reg} * EXPRAT_{reg} \geq EXP_{reg}$
2) $\sum prod_{reg} = PROD$

The first constraint imposes that the export-to-production ratio does not exceed the export-to-production ratio of the corresponding GTAP parent sector (in this case, *eeq*). The second constraint imposes that the sum of regional production volumes (in tonnes) equals global production reported in Table A.2. Under these constraints, minimizing the objective function solves for regional prices as close as possible to the average world price, (calculated as the ratio of global output value to global production volume). It also solves for regional permanent magnet production values.

To determine the cost structure, our starting point is that the most important inputs in permanent magnet production are refined REEs. We assume that refined REEs (specifically neodymium) account for 30% of the weight of a permanent magnet.[9] By using the unit price of refined REEs based on the trade data, we calculate the corresponding material cost in magnet production[10]. The remaining production costs (i.e., the cost structure) are taken from the GTAP parent sector (*eeq*).

On the supply structure, we know that permanent magnets are widely used in different sectors of the economy. However, we are interested in their supply in two sectors, namely electric vehicles and electric generating sets for wind turbines (nacelles). Demand for permanent magnets in those sectors is calculated using technological assumptions about material intensity per vehicle and per MW of installed wind turbines (see section 2.6 for the cost structure of electric generating sets). The remaining supply has been allocated to different sectors based on the supply structure of the parent GTAP sector.

A.2.6: Batteries

Data on production, trade, supply structure, and costs of different types of lithium-ion batteries for 2017 come from different sources and are limited thus requiring further calculations. First, we have data on global production for all battery types combined from JRC. Second, we have bilateral trade data aggregated across all battery types from CEPII. Third, we have battery price information from the literature. Fourth, we have shares of factory capacity from BNEF (2024). Fifth, we have estimates on the demand for materials in battery technologies from Sun et al. (2022).

We choose to model five battery types, since the supply of batteries across different end-use applications, such as transportation and electricity storage, depend on the battery type. These five types are lithium cobalt oxide (LCO) batteries, lithium manganese oxide (LMO) batteries, lithium iron phosphate (LFP) batteries, lithium nickel manganese cobalt oxide (NMC) batteries, and lithium nickel cobalt aluminum oxide (NCA) batteries. We follow several steps to obtain the required inputs on these battery types to be able to estimate their production, trade, supply and costs.

Step 1: Collect information on the global production of batteries as an aggregate product, and split this total global production across five use categories

First, we have information on the global production and supply of batteries as an aggregate product, not differentiated by type. Specifically, we rely on Tsiropoulos et al. (2018) reporting that the global estimate of batteries production was around 120 GwH in 2017, for all battery types combined. We also rely on IEA (2023) to infer the supply of batteries as an aggregate group to different end-use applications including light-duty electric and hybrid vehicles (associated with the new sectors evl and pvl), electric buses (associated with the new sector evb), other transport vehicles (associated

[9] The Production of NdFeB Magnets | Stanford Magnets

[10] Although the technology is the same for all regions, the cost share can differ because rare earth price and the price of permanent magnet are different across regions.

with the new sector otv) and electricity storage.[11] We assume that the residual amount is used in other sectors. Table A.5 summarizes the information collected in this step.

Table A.5: Global production and supply of lithium-ion batteries in 2017

a. Information collected in step 1

	Value (GwH)
Total global production	120
Other supply	38
Storage supply	1.3
Supply to LDV (evl,pvl)	36.7
Supply to electic bus (evb)	12.8
Supply to other transp. (otv)	31.2

b. Information collected in step 2

GWh	All batteries	LCO	LMO	LFP	NMC	NCA
Total global production (GwH)	120	30	8	34	40	8
Other supply (GwH)	38	30	8			
Storage supply (GwH)	1.3			1.3		
Supply to LDV (evl,pvl) (GwH)	36.7					
Supply to electic bus (evb) (GwH)	12.8					
Supply to other transp. (otv) (GwH)	31.2					

c. Information collected in step 3

GWh	All batteries	LCO	LMO	LFP	NMC	NCA
Total global production (GwH)	120	30	8	34	40	8
Other supply (GwH)	38	30	8			
Storage supply (GwH)	1.3			1.3		
Supply to LDV (evl,pvl) (GwH)	36.7			10.7	21.6	4.3
Supply to electic bus (evb) (GwH)	12.8			12.8		
Supply to other transp. (otv) (GwH)	31.2			9.1	18.4	3.7

[11] Https://Www.Nortonrosefulbright.Com/En-Gb/Knowledge/Publications/7efd5ecd/Energy-Storage-Updater---June-2018, 'Energy Storage Updater - June 2018 | Global Law Firm | Norton Rose Fulbright'.

Step 2: Estimate the global production per differentiated battery type

To allocate total battery production across different battery types, we make the following assumptions. First, we assume that the battery types used in transportation sectors (light-duty vehicles, buses, and other vehicles) are LFP, NMC, and NCA. Of total supply to transport, taken to be approximately 80 GWh, NMC holds a share of 50%, LFP holds a share of 40%, and NCA holds a share of 10%.[12] Second, we assume that only LFP-type batteries can be used to store electricity.[13] These assumptions allow us to infer the global production of LFP, NMC, and NCA batteries, as indicated in the first row of Table A.5b. Assuming that LCO and LMO are used in all other applications, mainly electronic equipment, we allocate the remaining global production to LCO and LMO as 30 and 8 GWh, respectively. Table A.5b summarizes the information collected in this step.

Step 3: Estimate the global supply per battery type and user sector

In order to allocate total global supply by sector across different battery types, we make the following assumptions. First, we assume that electric buses use only LFP batteries. Therefore, the amount of batteries supplied to buses is associated entirely with LFP batteries. The remaining production of LFP is allocated between light-duty vehicles and other transportation. The allocation followed the following method. The residual amounts to be allocated for LFP, NMC and NCA are 19.9, 40 and 8 respectively. Furthermore, the share of batteries in light-duty vehicles is equal to 36.7/(19.9+40+8). We apply this share to the residual amounts to get the amount of LFP, NMC and NCA used in light duties. Similarly, the share of batteries in other transportation is equal to 31.2/((19.9+40+8). We apply this share to the residual amounts to get the amount of LFP, NMC and NCA used in other transportation. The information collected in this step is summarized in Table A.5c.

Step 4: Collect information on prices of different battery types

We rely on Wentker et al.(2019) for prices of batteries, measured as dollars per kWh. Wentker et al. (2019) doesn’t show the price of LCO batteries. We assume that the price is higher than for other batteries and set it at 250 $kWh.[14] Importantly, these prices reflect production costs in China. For other regions, prices are obtained by multiplying initial prices by 1.16, which is the relative cost of NMC batteries in China versus Germany in BNEF(2024).[15] Table A.6 displays the assumptions on battery prices of different types.

Table A.6: Price assumptions for lithium-ion batteries

LMO	188 $/kWh
LFP	210 $/kWh
NMC	198 $/kWh
NCA	183 $/kWh
LCO	250 $/kWh

Step 5: Determining the production and supply of batteries at the regional level

Until now we collected the following pieces of information. First, we have data on global production of different types of batteries. Second, we have bilateral trade data aggregated for all types of batteries. Third, we have the supply of different types of batteries in each region. Fourth, we have the prices of batteries from the academic literature. Lastly, we also have the shares of factory capacity from BNEF (2024).

Based on those inputs, we set up a constrained optimization model to minimize the distance between the calculated and observed bilateral value of batteries trade generating production and

[12] The shares are based on IEA (2023) but adjusted to accommodate the information collected in step 3 on the amount of batteries in GwH needed for different modes of transport.

[13] This is a good assumption based on for example IRENA (2025) arguing that in 2024 85% of storage was based on LFP batteries. BloombergNEF (2025a) argues that LFP batteries completely dominate the market for storage.

[14] See for example Sharmili (2023) or BNEF (2025b) who show that LCO based batteries are more expensive because of their reliance on cobalt.

[15] BNEF prices are lower than the prices used in Table A.6. The BNEF price data are for 2024 in which unit costs were lower than in 2017, given the falling costs of batteries production (). However, we only use the BNEF data here to calculate the relative price of batteries in China compared to other economies.

bilateral trade of different battery types per region. Table A.7 lists the variables to be solved by this model (indicated with lower-case letters) and parameters given (indicated with upper-case letters).

Importantly, the model is solved only for batteries used in transport. For LCO and LMO we assume that all production takes place in China and that 25% of Chinese production is exported based on export shares from CEPII on total batteries trade.[16] Those flows have been removed from the trade data for China when used in the model above.

Table A.7: Variables and parameters needed for the constrained optimization model to get production and trade of batteries

Variables (to be solved)	Parameters (taken as given)
$prod_{bat,reg}$ (production by battery type LFP, NMC, NCA by each region)	$SUPPLY_{bat,reg}$ (supply to battery type LFP, NMC, NCA by each region[17])
$trd_{bat,rge,reg}$ (bilateral trade flows from the first region into the second for each battery type)	$PROD_{bat}$ (global production by battery type LFP, NMC, NCA)
	$EXPRAT_{bat,reg}$ (exportability ratio of a region calculated as exports over production in the parent sector of each battery type LFP, NMC, NCA by each region) [18]
	$PROD\_EU$ (total battery factory capacity in the EU, from BNEF)
	$PROD\_R_{reg}$ (total battery factory capacity of a region, from BNEF)
	$TRD_{reg,reg}$ (bilateral trade flows from the first region into the second)

Using the parameter values in Table A.7, we minimize $\sum_{reg,rge}(\sum_{bat}(PRICE_{bat,reg} * trd_{bat,reg,rge}) - TRD_{reg,reg})^2 / TRD_{reg,reg}$ with respect to the variables in Table A.7 subject to five constraints:

1) $prod_{bat,reg} + \sum_{rge} trd_{bat,rge,reg} = \sum_{rge} trd_{bat,reg,rge} + SUPPLY_{bat,reg}$
2) $\sum_{reg} prod_{bat,reg} = PROD_{bat}$
3) $prod_{bat,reg} * EXPRAT_{bat,reg} \geq \sum_{rge} trd_{bat,reg,rge}$
4) $\sum_{bat} prod_{bat,reg} = PROD\_R_{reg}$
5) $\sum_{bat,eu(reg)} prod_{bat,eu(reg)} = PROD\_EU$

The constrained minimization procedure generates production and trade volumes in each region consistent with the constraints. The first constraint states that the global sum of production and exports of each battery type should equal the global sum of imports and supply of each battery. The second constraint states that regional production of each battery type should equal global production of that battery type. The third constraint states that the value of exports, calculated using production and the parent sector's exportability ratio, should be at least as large as the exports of a battery type originating from a region, based on bilateral trade flows generated by the constrained minimization procedure. The fourth and fifth constraints ensure consistency with the additional information shared by BNEF on battery factory capacity for certain regions (China, the US, Europe,

[16] See IEA (2024).

[17] The calculation of the use structure of batteries in production of electric vehicles and buses by region is discussed in section 2.8 below, detailing the cost structures of those vehicles. The remaining part of batteries are used either in the eeq sector (for various uses in electronics) or the investment sector (for the use in battery storage).

[18] We apply a lower bound of 50% to this variable which allows for higher export share preserving at the same time regional differences

Japan, South Korea, and ROW). The fourth constraint states that the total production in a region solved by the model for all battery types should equal the value implied by BNEF for China, the US, Japan, and South Korea. The fifth constraint similarly states that the total production in all European regions together generated by the model for each battery type should equal the value for the EU from BNEF. The objective function minimizes a measure of the distance between the value of bilateral trade in all batteries, as solved by the model separately for each battery type, and the aggregate bilateral trade data observed. Thus, the variable that can be adjusted in the procedure is the value of trade.

Step 6: Determining the cost and supply structure

To determine the cost share of critical minerals for different battery types, we rely on Sun et al. (2022) to obtain the demand for materials in battery technologies. The study distinguishes between the types of batteries in our model and also different types of NMC batteries (specifically NMC532, NMC622 and NMC811) which we average. Table A.8 reports the value of demand for minerals from Sun et al. (2022).

Table A.8: Demand for materials in battery technologies (kg/kWh)

Material\battery type	LCO	NMC	NCA	LFP	LMO
Lir	0.11	0.13	0.1	0.1	0.11
Cor	0.96	0.19	0.13	0	0
Nir	0	0.64	0.68	0	0
Mnr	0	0.19	0	0	1.4
Gra/Agp	0.94	0.98	0.97	1.09	0.92

The outcomes of the constrained minimization procedure in Step 5 have generated estimates of the volumes of production of each battery type in each region (variable $prod_{bat,reg}$). Using the material needs from Table A.8, we can compute the tons of minerals used to produce a battery type in a region. We then split those material needs into batteries sourced domestically and imported based on the domestic and imported shares of the refined minerals in the region. This is then transformed into values by using domestic and imported mineral prices.

To determine the cost shares of batteries from the non-mineral sectors, we rely on cost shares reported in Orangi et al. (2022) for China for non-material sectors.

A.2.7: Electric generating sets / nacelles (egs)

The component of wind turbines dependent on rare-earth permanent magnets is called nacelle, which is the electric generating engine of the wind turbine. The new sector egs corresponds to this product.

For this product, we have the following pieces of information. First, we have bilateral trade data associated with the HS code 850231, *Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)*. Second, we have information on installed cumulative wind energy capacity at the regional level from IRENA. Third, we have information on the factory production capacity for wind turbines from BNEF for certain regions (China, US, Europe, Japan, South Korea, ROW). Fourth, we have information on the total supply of rare earths (neodymium) to different wind turbine technologies globally from Carrara et al. (2020). Based on those inputs, we take the following steps to get the regional estimates for production, trade, costs and use.

Step 1: Compute the supply at the regional level

We convert the installed cumulative capacity information into regional values for the supply of wind turbines, so we compute the newly installed capacity by subtracting the 2016 value from the 2017 value, using a depreciation rate of 0.01:

$$WIND_{reg} = IRENA_{reg}^{2017} - (1 - 0.01) \cdot IRENA_{reg}^{2016}$$

The value share of nacelle (electric generation set) is assumed to be 30% of wind turbine costs (Semken et. al, 2012). We thus calculate the used (purchased) value of nacelles in each region as follows, assuming moreover that the price of wind turbines is 1000:[19]

$$NAC_{reg} = 0.3 * 1000 * WIND_{reg}$$

Step 2: Estimate the regional production and supply

Based on the inputs from the previous steps and the collected data, to calculate the production at the regional level, we set up a constrained optimization model to minimize the distance between the supply as computed by the model and as computed by step 1 above. Table A.9 lists the variables to be solved by this model (indicated with lower case letters) and parameters that are given (indicated with lower case letters):

Table A.9: Variables and parameters needed for the constrained optimization model to get production and supply of electric generating sets

Variables (to be solved)	Parameters (taken as given)
$prod_{reg}$ (production of electric generating sets by each region)	IMP_{reg} (imports of electric generating sets at the regional level)
$supply_{reg}$ (use of electric generating sets at by each region)	EXP_{reg} (exports of electric generating sets at the regional level)
$prod_{reg(EU)}$ (production of electric generating sets by each European sub-region)	$EXPRAT_{reg}$ (exportability ratio calculated as exports over production in the parent sector of electric generating sets) [20]
	BSH_{reg} (BNEF factory capacity share of the region in producing electric generating sets)
	BSH_{EU} (BNEF factory capacity share of EU in producing electric generating sets)
	NAC_{reg} *(*purchased value of the nacelles in each region*)*

Using the parameter values in Table A.9, we minimize the objective function $\sum_{reg}(supply_{reg} - NAC_{reg})^2$ with respect to the variables in Table A.9 under four constraints:[21]

1) $prod_{reg} = use_{reg} + IMP_{reg} - EXP_{reg}$
2) $prod_{reg} * EXPRAT_{reg} \geq EXP_{reg}$
3) $prod_{reg} = BSH_{reg} * \sum_{reg} prod_{reg}$
4) $prod_{reg(EU)} = \sum_{reg(EU)} prod_{reg(EU)} * BSH_{EU}$

The model generates production and supply values in each region consistent with the constraints. The first constraint states that global production and exports of the electric generating sets should equal global imports and use. The second constraint states that the estimated production value is not lower than the reported export data (from CEPII). The third and fourth constraints state that for the regions with available BNEF data on factory capacity (China, the US, Europe, Japan, South Korea and ROW), their share in global production reflects the nacelle factory capacity shares from BNEF.

[19] See US Department of Energy (2017).

[20] We apply a lower bound of 0.5 for this variable thus imposing a higher export share for nacelles compared to the parent sector based on the observation that exportability in parent sectors tends to be (much) lower than in the sector of interest (for mining). At the same time with a lower bound, this approach preserves regional differences.

[21] We cannot impose that regional use is equal to NAC_{reg}, since we are targeting production output shares from BNEF for the largest producers. Therefore, we set this as the minimization objective.

The objective function minimizes the sum of squared differences of the supply of electric generating sets as computed by the model and the supply values calculated from the IRENA data.

Importantly, the model generates production and supply in value terms. Due to limited data availability, we can only trace the volumes of the electric generating sets in rare-earth content terms, instead of a unit of electric generating sets. To do so, we estimate the total supply of rare earths to wind turbines relying on the information provided by Carrara et al.(2020).

Step 3: Determining the cost structure

Given that we trace the volumes of electric generating sets in terms of the rare-earth content, this approach by construction informs us about the cost share of rare earths in electric generating sets. Furthermore, we calculate the cost share of permanent magnets in nacelles production by relying on the supply of rare earths to wind turbines (kg/GW), prices of wind turbines, the cost share of nacelles in wind turbines (to be 30% following Semken et al., 2012) and the price of permanent magnets (measured as $/rare earth content). The cost shares of the other sectors in electric generating sets follow the cost structure of the parent sector.

A.2.8: Solar Panels

For this product, we use the following pieces of information. First, we use bilateral trade flows for HS6 code 854140, *Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED),* from CEPII. Second, we use information on the installed capacity of solar panels from the IRENA database, which serves as a proxy for regional supply. Third, we have information on the factory production capacity for solar panels from BNEF for certain regions (China, US, Europe, Japan, South Korea, ROW). Based on these inputs, we take the following steps to obtain regional estimates for production, trade, costs and supply.

Step 1: Compute supply at the regional level

We convert cumulative installed capacity into regional values for the supply of solar panels by calculating newly installed capacity. Using the same depreciation rate as for wind turbines, we define the supply of solar panels in a region as:

$$SUPPLY_{reg}^{2017} = IRENA_{reg}^{2017} - (1 - 0.01) \cdot IRENA_{reg}^{2016}$$

Step 2: Harmonize the units for supply and trade

Before estimating production at the regional level, we harmonize the IRENA and CEPII data. Since the trade data are reported in weight units, while the IRENA data are reported in capacity units, we first transform trade flows from tonnes into MW using a power-to-weight ratio of 10 W/kg (IRENA,2018). We then calculate export prices for each country by dividing export values by export volumes, now measured in MW. Finally, we impose lower and upper bounds on these prices and overwrite trade volumes where necessary following the approach described in Section 3.3. The last two steps mirror the procedure described in detail in the main text.

Step 3: Calculate production by region

Based on the inputs from the previous steps and the collected data, we calculate production at the regional level. Assuming that the global supply of solar panels is equal to the global production of solar panels, we employ the shares provided by BNEF on regions' solar panel factory capacities. Those shares were available for China, the US, Europe, Japan, South Korea. For China, South Korea, the US and Japan we directly calculate production by applying the BNEF share to global supply. For the individual EU countries and the other countries, we allocated the remaining amount of global production (supply) based on these countries' respective installed solar panel capacity shares.

Importantly, there were large differences between the trade patterns and the production structures. For example, China's share in total exports is much lower than its share in global production. In the approach employed we adjust trade and target production data from BNEF (2024) for China, so we address this concern.

Step 4: Adjust trade flows

Now that we have information on the production, supply and trade, we proceed by letting the trade flows adjust to make all these inputs consistent. For this purpose, we set up a constrained optimization model to minimize the distance between trade computed by the model and trade in the data. In other words, the adjustment comes from reconciling trade with all the other inputs. Table A.10 lists the variables to be solved by this model (indicated with lower-case letters) and given parameters (indicated with upper-case letters):

Table A.10: Variables and parameters needed for the constrained optimization model to get production and supply of solar panels

Variables (to be solved)	**Parameters (taken as given)**
$trd_{rge,reg}$ (bilateral trade flows from the first region into the second)	$PROD_{reg}$ (production of solar panels by region)
	$SUPPLY_{reg}$ (supply of solar panels by region)
	$EXPRAT_{reg}$ (exportability ratio calculated as exports over production in the parent sector of solar panels) [22]

Using the parameter values in Table A.10, we minimize the objective function $\sum_{reg,rge}(trd_{reg,reg} - TRD_{reg,reg})^2 / TRD_{reg,reg}$ with respect to the variables in Table A.10 under two constraints:

1) $PROD_{reg} + \sum_{rge} trd_{rge,reg} = \sum_{reg} trd_{rge,reg} + SUPPLY_{reg}$
2) $PROD_{reg} * EXPRAT_{reg} \geq \sum_{rge} trd_{rge,reg}$

The model gives us trade flows consistent with the constraints. The first constraint states that production and imports of solar panels should equal exports and (domestic) supply. The second constraint imposes an upper bound on exports, calculated as production of solar panels multiplied by the exports-to-production ratio in the parent GTAP-sector ("ele").

Step 5: Determine cost and supply structure

The critical mineral used in the production of solar panels is silver. We assume that 15 tonnes of refined silver are needed per 1 GW of PVs.[23] Based on this assumption and on the prices of refined silver, we calculate the cost share of this material in solar panel production.

The price of refined silver is calculated as the weighted average of the domestic price, measured as the value of production divided by the volume of production, and the imported price, measured as the value of imports divided by the volume of imports from all sources, where the weights are the respective volumes of domestic production and imports.

Total costs are allocated between domestic and imported sources based on total availability at the country level. At this stage, we have not been able to include costs of other important material inputs in solar panel production separately, such as polysilicon and wafers, because of the lack of trade and production data on these products.

The remaining cost shares are taken from the GTAP parent sector. That is, once the value cost of refined silver is determined, the residual costs are allocated according to the cost structure of the parent sector.

We assume that solar panels are purchased by the investment sector and households are not purchasing solar panels, something that could be modified later.

[22] We apply a lower bound of 0.5 for this variable
[23] See Carrara (2020) , Table 3, mid range for 2020.

A.2.9: Private electric vehicles (evl)

For private electric vehicles, we have the following pieces of information. First, we have bilateral trade flows from CEPII. Second, we have data on electric vehicle sales from the IEA. Third, we have information on the amount of batteries and other intermediates needed to produce these vehicles, from IEA and Tamba et al.(2022). Based on these inputs, we take the following steps to obtain regional estimates for production, trade, costs and supply.

Step 1: Harmonize trade and sales data

To harmonize trade data from CEPII and sales data from IEA, we proceed as follows.
First, we assume that the average weight of an electric car is 2 tonnes.[24] This allows us to transform trade data reported in tonnes into trade flows measured in numbers of cars. Second, for each country, we calculate the average price of an exported car as the total value of exports divided by the number of exported cars. Third, we impose upper and lower bounds on the price of a car. For cases falling outside these bounds, trade flows in numbers of cars are adjusted by dividing trade flows in value terms by the minimum or maximum price.

At this stage, we have data on car sales, that is, supply, as well as exports and imports, all measured in volume units. Although these data allow us to estimate car production using the identity production + imports = supply + exports, the resulting values for production are not necessarily positive, which occurs in several cases.

Step 2: Reconcile the negative production values

To calculate supply and production at the regional level while ensuring that production is not negative, we set up a constrained optimization model to minimize the distance between the supply computed by the model and the supply reported in the IEA data. Table A.11 lists the variables to be solved by the model and the parameters taken as given.

Table A.11: Variables and parameters needed for the constrained optimization model to obtain use and production of electric cars

Variables (to be solved)	**Parameters (taken as given)**
$supply_{reg}$ (number of private electric vehicles sold by region)	NT_{reg} (net trade of private electric vehicles by region)
	EXP_{reg} (exports of private electric vehicles by region)
	$EXPRAT_{reg}$ (exportability ratio calculated as exports over production in the parent sector of private electric vehicles) [25]
	IEA_{reg} (sales of private electric vehicles by the IEA)

Using the parameter values in Table A.11, we minimize the objective function $\sum_{reg} supply_{reg} * \ln\left({supply_{reg}}/{IEA_{reg}}\right)$ subject to two constraints:

1) $(supply_{reg} + NT_{reg}) * EXPRAT_{reg} \geq EXP_{reg}$ the first term is production; and we multiply it with the parent sector exportability
2) $\sum_{reg} use_{reg} = 760000$ total global sales

The model gives us supply values in each region consistent with the constraints. The first constraint states that production, defined as supply plus net trade, multiplied by the exportability ratio of the

[24] US EPA (2024).
[25] We apply a lower bound of 0.5 for this variable

parent sector, should be at least as large as exports of electric vehicles. The second constraint states that total global sales should be consistent with the IEA data.

The objective function minimizes the deviation of the estimated use values from the initial IEA data on sales. In this way, the model overwrites the IEA sales data such that production is positive, total sales remain consistent with the global total reported by the IEA, while the adjustments to supply are as small as possible.

The model is solved for flows in quantity terms, that is, numbers of cars. To construct flows in value terms, previously calculated export unit prices of cars are used.

Step 3: Determine the cost structure

Next, we calculate two important elements of costs: batteries and permanent magnets. Permanent magnets are essential inputs for electric motors which are inputs to private electric vehicles. We assume that electric motors relying on permanent magnets are produced within the private electric vehicles sector, which purchases permanent magnets as a material inputs.

For the cost share of batteries, Table A.5a informs us on the total supply of batteries in light-duty vehicles (which correspond to the new sectors private electric vehicles and plug-in-hybrid electric vehicles). In section 2.9, we calculate the supply of batteries to plug-in hybdrid vehicles as 5.9 GWh and assume that the remaining supply is allocated to private electric vehicles. Dividing this value by the global number of cars (from IEA), we calculate the average amount of batteries used per private electric car as follows:

$$\frac{(36.7\ GWh - 5.9\ GWh)}{760000} \approx 41kWh$$

This amount is used in the optimization model in section 2.5 for the parameter $USE_{bat,reg}$ (in Table A.7). We calculate the cost of batteries in private electric vehicles production by multiplying the average battery price with the average amount of batteries used per vehicle to obtain a cost price per private electric car.[26] This in turn is multiplied by the number of vehicles produced in each region to obtain total battery costs.

For the cost share of permanent magnets, we assume that the demand for rare earths is 0.464 kg per car.[27] Given that we track the flows of permanent magnets in terms of rare-earth content, we calculate the value of permanent magnets purchased by private electric vehicles by region using the assumptions on the share of rare earths in permanent magnets (Section 2.4). The cost share of permanent magnets is then the value of permanent magnets purchased by private electric vehicles in the total production of private electric vehicles.

With the cost shares for batteries and permanent magnets calculated as described, we determine the cost shares of the remaining sectors based on Tamba et al (2022).

A.2.10: Plug-in hybrid electric vehicles (pvl)

For plug-in hybrid vehicles, we have the following pieces of information. First, we have bilateral trade flows from CEPII. Second, we have data on electric vehicles sales from the IEA. Third, we have information on the amount of batteries and other intermediates needed to produce these vehicles, from DOE (2023) and Tamba et al.(2022). We follow the procedure described in Steps 1 and 2 in Section 2.8 to obtain the production by region based on sales and trade data.

On the cost side, we need to calculate two important elements of costs: batteries and permanent magnets. Permanent magnets are essential inputs for electric motors which are inputs to vehicles.

To determine the cost share of batteries, we first assume that the average amount of batteries in kWh in plug-in hybrids is 14 kWh.[28] To determine the cost of batteries in the production of plug-in hybrid electric vehicle per vehicle we multiply the average battery price with the average amount of

[26] Recall that the price of batteries is assumed to be the same across all regions, except for China, where it is lower (based on BNEF, 2024).
[27] *2023 Critical Materials Assessment*.
[28] Internet search (using AI) gave us a range between 7 and 18 kWh.

batteries used per plug-in hybrid vehicle. Total battery costs per region are then calculated by multiplying the costs per vehicle with the number of cars produced.

Furthermore, the average value of 14kWh per plug-in hybrid is also used to determine the battery per electric vehicle in Section 2.8 (as residual). Specifically, we multiply the average value by the number of plug-in hybrid electric vehicles sold (and produced) globally from the IEA to obtain the total amount of batteries used globally in plug-in hybrid electric vehicles:

$$14\ kWh * 420000 = 5.9\ GWh$$

To determine the cost share of permanent magnets, we assume that 0.232kg of rare earths (neodymium) is needed for each car based on DOE (2023)[29]. Given that we track the flows of permanent magnets in terms of rare-earth content, we calculate the value of permanent magnets purchased by plug-in hybrid electric vehicles by region using the assumptions on the share of rare earths in permanent magnets (See Section 2.4). The cost share of permanent magnets is then the value of permanent magnets purchased by plug-in-hybrid electric vehicles divided by the total value of production of plug-in-hybrid electric vehicles.

With the cost shares for batteries and permanent magnets calculated as described, we determine the cost shares of the remaining sectors based on Tamba et al (2022). Unlike the approach for private electric vehicles, we employ the cost shares of conventional cars for the plug-in-hybrid hybrid vehicles.

A.2.11: Electric buses (evb)

For electric buses, we have the following pieces of information. First, we have information on the sales of electric buses in China and in Europe, as an aggregate region from IEA (2025).[30] Second, we have information on bilateral trade flows of electric buses from CEPII. Third, we have information on the amount of batteries and other intermediates needed to produce these vehicles, from DOE (2023) and Tamba et al. (2022).

To calculate the sales (supply) of electric buses in countries other than China, we assume that the sales by other regions are equal to the number of imported buses. To convert the quantity of buses in tons into units, we assume that the weight of an electric bus is 10 tons.[31] By applying this procedure, we impute the supply by region which was available by the IEA for private electric and plug-in-hybrid vehicles. We then follow the procedure described in Steps 1 and 2 in Section 2.8 to obtain the production by region based on sales and trade data.

On the cost side, we need to calculate cost shares for batteries and permanent magnets like for EVs and plug-in hybrid cars. To determine the cost share of batteries, we first calculate the average amount of a battery in electric buses by dividing the total volume of batteries used in electric buses (Table A.5) by the total number of buses sold globally:

$$\frac{12.8\ GWh}{88000} = 145\ kWh$$

To determine the cost of batteries in the production of electric buses we multiply the average battery price with the average amount of batteries used per electric bus. Total battery costs per region are then calculated by multiplying the costs per bus with the number of buses produced.

To determine the cost share of permanent magnets, we rely on DOE (2023) and assume that 0.928 kg of rare earths (neodymium) are needed for each bus. Given that we track the flows of permanent magnets in terms of rare-earth content, we calculate the value of permanent magnets purchased by electric buses by region using the assumptions on the share of rare earths in permanent magnets (Section 2.4). The cost share of permanent magnets is then the value of permanent magnets purchased by electric buses divided by the total value of production of electric buses.

[29] *2023 Critical Materials Assessment*.
[30] https://www.iea.org/reports/global-ev-outlook-2025/trends-in-heavy-duty-electric-vehicles
[31] See Dallmann et al. (2021).

ANNEX 3: CONCORDANCE BETWEEN HS 6 CODES AND NEWLY DISAGGREGATED GTAP SECTORS

Category	GTAP sector name	Description	HS2017	HS Code Description
Mining	man	manganese mining	260200	Manganese ores and concentrates, including ferruginous manganese ores and concentrates with a manganese content of 20% or more, calculated on the dry weight
	nik	nickel mining	260400	Nickel ores and concentrates
	cob	cobalt mining	260500	Cobalt ores and concentrates
	zin	zinc mining	260800	Zinc ores and concentrates
	chr	chromium mining	261000	Chromium ores and concentrates
	tit	titanium mining	261400	Titanium ores and concentrates
	nio	niobium mining	261590	Niobium, tantalum, vanadium ores and concentrates
	sil	silver mining	261610	Silver ores and concentrates
	gra	graphite mining	250410	Graphite; natural, in powder or in flakes
	gra	graphite mining	250490	Graphite; natural, in other forms, excluding powder or flakes
	mgm	magnesium mining	251910	Magnesium carbonate (magnesite); natural
	mgm	magnesium mining	251990	Magnesia, fused or dead-burned (sintered); whether or not containing small quantities of other oxides added before sintering, other magnesium oxide, whether or not pure, (not natural magnesium carbonate)
	lit	lithium mining	253090	Mineral substances; n.e.c. in chapter 25
	rre	rare earths mining	253090	Mineral substances; n.e.c. in chapter 25
	pgm	platinum group metals mining	261690	Precious metal ores and concentrates; (excluding silver)
	pho	phosphorus mining	251010	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk; unground
	pho	phosphorus mining	251020	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk; ground
Refining	mnr	manganese chemical refining	282010	Manganese dioxide
	mnr	manganese chemical refining	282090	Manganese oxides; excluding manganese dioxide
	cor	cobalt chemical refining	282200	Cobalt oxides and hydroxides; commercial cobalt oxides
	lir	lithium refining	282520	Lithium oxide and hydroxide

Category	GTAP sector name	Description	HS2017	HS Code Description
	lir	lithium refining	283691	Carbonates; lithium carbonate
	rer	rare earths refining	280530	Earth-metals, rare; scandium and yttrium, whether or not intermixed or interalloyed
	rer	rare earths refining	284610	Cerium compounds
	rer	rare earths refining	284690	Compounds, inorganic or organic (excluding cerium), of rare-earth metals, of yttrium, scandium or of mixtures of these metals
	nir	nickel refining	282540	Nickel oxides and hydroxides
	nir	nickel refining	282735	Chlorides; of nickel
	nir	Nickel refining	381511	Catalysts, supported: reaction initiators, reaction accelerators and catalytic preparations, with nickel or nickel compounds as the active substance, n.e.c. or included
	agp	artfical graphite	380110	Graphite; artificial
	sir	silver refining	710610	Metals; silver powder
Intermediate	mag	permanent magnets	850511	Magnets; permanent magnets and articles intended to become permanent magnets after magnetisation, of metal
	LCO, LMO, NCM, NCA, LFP	batteries	850760	Electric accumulators; lithium-ion, including separators, whether or not rectangular (including square)
Final	cbl	combustion vehicles	870321	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only spark-ignition internal combustion reciprocating piston engine of a cylinder capacity <= 1.000 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870322	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 1.000 cm^3 but <= 1.500 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870323	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 1.500 cm^3 but <= 3.000 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)

Category	GTAP sector name	Description	HS2017	HS Code Description
	cbl	combustion vehicles	870324	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 3.000 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870331	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only diesel engine of a cylinder capacity <= 1.500 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870332	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only diesel engine of a cylinder capacity > 1.500 cm^3 but <= 2.500 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870333	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only diesel engine of a cylinder capacity > 2.500 cm^3 (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	cbl	combustion vehicles	870340	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with both spark-ignition internal combustion reciprocating piston engine and electric motor as motors for propulsion (excl. vehicles for travelling on snow, other specially designed vehicles of subheading 8703.10 and plug-in hybrids)
	cbl	combustion vehicles	870350	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with both diesel engine and electric motor as motors for propulsion (excl. vehicles for travelling on snow, other specially designed vehicles of subheading 8703.10 and plug-in hybrids)
	vpr	vehicle parts	840731	Spark-ignition reciprocating piston engine, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity <= 50 cm^3

Category	GTAP sector name	Description	HS2017	HS Code Description
	vpr	vehicle parts	840732	Spark-ignition reciprocating piston engine, of a kind used for the propulsion of vehicles of chapter 87, of a cylinder capacity > 50 cm^3 but <= 250 cm^3
	vpr	vehicle parts	840733	Spark-ignition reciprocating piston engine, of a kind used for vehicles of chapter 87, of a cylinder capacity > 250 cm^3 but <= 1.000 cm^3
	vpr	vehicle parts	840734	Spark-ignition reciprocating piston engine, of a kind used for vehicles of chapter 87, of a cylinder capacity > 1.000 cm^3
	vpr	vehicle parts	840820	Compression-ignition internal combustion piston engine "diesel or semi-diesel engine", for the propulsion of vehicles of chapter 87
	vpr	vehicle parts	840991	Parts suitable for use solely or principally with spark-ignition internal combustion piston engine, n.e.s.
	vpr	vehicle parts	840999	Parts suitable for use solely or principally with compression-ignition internal combustion piston engine "diesel or semi-diesel engine", n.e.s.
	vpr	vehicle parts	870600	Chassis fitted with engines, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles of heading 8701 to 8705 (excl. those with engines and cabs)
	vpr	vehicle parts	870710	Bodies for motor cars and other motor vehicles principally designed for the transport of persons
	vpr	vehicle parts	870790	Bodies for tractors, motor vehicles for the transport of ten or more persons, motor vehicles for the transport of goods and special purpose motor vehicles of heading 8705
	vpr	vehicle parts	870810	Bumpers and parts thereof for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870821	Safety seat belts for motor vehicles

Category	GTAP sector name	Description	HS2017	HS Code Description
	vpr	vehicle parts	870829	Parts and accessories of bodies for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles (excl. bumpers and parts thereof and safety seat belts)
	vpr	vehicle parts	870830	Brakes and servo-brakes and their parts, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870840	Gear boxes and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870850	Drive-axles with differential, whether or not provided with other transmission components, and non-driving axles, and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870870	Road wheels and parts and accessories thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870880	Suspension systems and parts thereof, incl. shock-absorbers, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.

Category	GTAP sector name	Description	HS2017	HS Code Description
	vpr	vehicle parts	870891	Radiators and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870892	Silencers "mufflers" and exhaust pipes, and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870893	Clutches and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870894	Steering wheels, steering columns and steering boxes, and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870895	Safety airbags with inflator system and parts thereof, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.
	vpr	vehicle parts	870899	Parts and accessories, for tractors, motor vehicles for the transport of ten or more persons, motor cars and other motor vehicles principally designed for the transport of persons, motor vehicles for the transport of goods and special purpose motor vehicles, n.e.s.

Category	GTAP sector name	Description	HS2017	HS Code Description
	vpr	vehicle parts	870990	Parts of self-propelled works trucks, not fitted with lifting or handling equipment, of the type used in factories, warehouses, dock areas or airports for short distance transport of goods, incl. tractors for railways station platforms, n.e.s.
	vpr	vehicle parts	871690	Parts of trailers and semi-trailers and other vehicles not mechanically propelled, n.e.s.
	vpr	vehicle parts	940120	Seats for motor vehicles
	evl	electric vehicles	870380	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only electric motor for propulsion (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	pvl	plug in hybrid vehicles	870360	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with both spark-ignition internal combustion reciprocating piston engine and electric motor as motors for propulsion, capable of being charged by plugging to external source of electric power (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	pvl	plug in hybrid vehicles	870370	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with both diesel engine and electric motor as motors for propulsion, capable of being charged by plugging to external source of electric power (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)
	evb	electric busses	870240	Motor vehicles for the transport of >= 10 persons, incl. driver, with only electric motor for propulsion
	egs	nacelle electric generating sets	850231	Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)
	sop	solar panels	854140	Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED)