Supplemental Information – Critical Mineral and Material Supply Availability and Energy System Development: A Multisector Analysis and Implications

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Supplementary Note 1 – Expanding the demand representation of critical minerals and materials to multiple energy system sectors.

We build on our previous work and expand the capability of the Global Change Analysis Model (GCAM) to represent material demands across key end-use sectors, including electricity (both electricity generation and transmission & distribution (T&D)), transport, hydrogen production. A total of 13 materials are considered in this study. These include 3 bulk materials—steel, aluminum (Al), and copper (Cu)—which are industrial metals with broad cross-sectoral applications and high production volume. The remaining 10 are specialty materials: silicon (Si), lithium (Li), graphite, cobalt (Co), nickel (Ni), manganese (Mn), neodymium (Nd), tellurium (Te), vanadium (V), and platinum (Pt). These specialty materials generally have more specialized technological uses and lower global production volumes compared with bulk materials.

To quantify the material demand, we apply a bottom-up approach to quantify material demand based on detailed technology representation for the energy system sectors in GCAM. We have also further enhanced the technology representation in GCAM by considering some subtype technologies in electricity generation and battery electric vehicles in the transport sector. A detailed technology representation of electricity, transport and hydrogen production has been provided in **SI-Table 1-3,** respectively.

SI-Table 1 Electricity sector technology representation in GCAM. GCAM represents a wide range of technologies in the electricity sector, as shown in this table. To better capture critical mineral material (CMM) demand, we further disaggregated selected technologies—specifically solar PV, wind, and battery storage—into additional subtypes to reflect differences in material use across technology configurations. These additional subtype technologies are highlighted in light blue in the table.

Fuel type	Technology	Technology explanation
Biomass	biomass (conv)	Conventional biomass-fired power plant.
	biomass (conv CCS)	Conventional biomass-fired power plant equipped with carbon capture and storage (CCS).
	biomass (IGCC)	Biomass Integrated Gasification Combined Cycle power plant.
	biomass (IGCC CCS)	Biomass Integrated Gasification Combined Cycle power plant equipped with carbon capture and storage (CCS).
Coal	coal (conv pul)	Conventional pulverized coal power plant.
	coal (conv pul CCS)	Conventional pulverized coal power plant equipped with carbon capture and storage (CCS).
	coal (IGCC)	Integrated Gasification Combined Cycle coal power plant.
	coal (IGCC CCS)	Integrated Gasification Combined Cycle coal power plant equipped with carbon capture and storage (CCS).
Gas	gas (CC)	Natural gas combined-cycle power plant.
	gas (CC CCS)	Natural gas combined-cycle power plant equipped with carbon capture and storage (CCS).
	gas (steam/CT)	Natural gas steam turbine or combustion turbine plant.
Geothermal	geothermal	Geothermal electricity generation plant.
Hydro	hydro	Hydropower electricity generation.
Nuclear	Gen_II_LWR	Generation II Light Water Reactor nuclear power plant.
	Gen_III	Generation III advanced nuclear power plant with enhanced safety systems and improved efficiency.
Refined liquids	refined liquids (CC)	Oil-fired combined-cycle power plant.
	refined liquids (CC CCS)	Oil-fired combined-cycle power plant equipped with carbon capture and storage (CCS).
	refined liquids (steam/CT)	Oil-fired steam turbine or combustion turbine plant.
Solar	CSP	Concentrated Solar Power without thermal storage.
	CSP_storage	Concentrated Solar Power with thermal energy storage.
	pv (a-Si)	Amorphous silicon thin-film solar photovoltaic panels.
	pv (CdTe)	Cadmium telluride thin-film solar photovoltaic panels.
	pv (c-Si)	Crystalline silicon photovoltaic solar panels.
	pv (CIGS)	Copper indium gallium selenide thin-film solar photovoltaic panels.
	pv_storage (LFP)	Utility-scale solar photovoltaic power paired with Lithium Iron Phosphate (LFP) battery energy storage.

	pv_storage (NMC111)	Utility-scale solar photovoltaic power paired with Nickel Manganese Cobalt (1:1:1) lithium-ion batteries.
	pv_storage (NMC532)	Utility-scale solar photovoltaic power paired with Nickel Manganese Cobalt (5:3:2) lithium-ion batteries.
	pv_storage (NMC622)	Utility-scale solar photovoltaic power paired with Nickel Manganese Cobalt (6:2:2) lithium-ion batteries.
	pv_storage (NMC811)	Utility-scale solar photovoltaic power paired with Nickel Manganese Cobalt (8:1:1) lithium-ion batteries.
	pv_storage (VRFB)	Utility-scale solar photovoltaic power paired with Vanadium Redox Flow Batteries (VRFB).
	rooftop_pv_mineral (a-Si)	Distributed rooftop solar photovoltaic systems using amorphous silicon thin-film panels.
	rooftop_pv_mineral (CdTe)	Distributed rooftop solar photovoltaic systems using cadmium telluride thin-film panels.
	rooftop_pv_mineral (c-Si)	Distributed rooftop solar photovoltaic systems using crystalline silicon panels.
	rooftop_pv_mineral (CIGS)	Distributed rooftop solar photovoltaic systems using copper indium gallium selenide thin-film panels.
Wind	wind (DD-EESG)	Onshore wind turbine using Direct Drive (DD) with an Electrically Excited Synchronous Generator (EESG).
	wind (DD-PMSG)	Onshore wind turbine using Direct Drive (DD) architecture with a Permanent Magnet Synchronous Generator (PMSG).
	wind (GB-DFIG)	Onshore wind turbine using a Gearbox (GB) with a Doubly Fed Induction Generator (DFIG).
	wind (GB-PMSG)	Onshore wind turbine using a Gearbox (GB) with a Permanent Magnet Synchronous Generator (PMSG).
	wind_offshore (DD-EESG)	Offshore wind turbine using Direct Drive (DD) and Electrically Excited Synchronous Generator (EESG).
	wind_offshore (DD-PMSG)	Offshore wind turbine using Direct Drive (DD) and Permanent Magnet Synchronous Generator (PMSG).
	wind_offshore (GB-PMSG)	Offshore wind turbine using a Gearbox (GB) and Permanent Magnet Synchronous Generator (PMSG).
	wind_storage (LFP)	Wind power generation paired with Lithium Iron Phosphate (LFP) battery energy storage.
	wind_storage (NMC111)	Wind power generation paired with Nickel Manganese Cobalt (1:1:1) lithium-ion batteries.
	wind_storage (NMC532)	Wind power generation paired with Nickel Manganese Cobalt (5:3:2) lithium-ion batteries.
	wind_storage (NMC622)	Wind power generation paired with Nickel Manganese Cobalt (6:2:2) lithium-ion batteries.
	wind_storage (NMC811)	Wind power generation paired with Nickel Manganese Cobalt (8:1:1) lithium-ion batteries.
	wind_storage (VRFB)	Wind power generation paired with Vanadium Redox Flow Batteries (VRFB).

SI-Table 2 Transport sector technology representation in GCAM. GCAM represents a wide range of modes and technologies in the transport sector, as shown in this table. To better capture critical mineral material (CMM) demand, we further disaggregated selected technologies—specifically battery electric vehicles (BEV) in Bus, Truck (with different sizes) and light-duty vehicles (with different sizes)—into additional subtypes to reflect battery technologies. These additional subtype technologies are highlighted in light blue in the table.

Transport mode	**Fuel type**	**Technology explanation**
International Aviation	BEV	Battery electric aircraft for international passenger aviation (advanced long-term concept).
	Hydrogen	Hydrogen-powered aircraft using combustion or fuel cells for propulsion.
	Liquids	Conventional liquid hydrocarbon jet fuel aircraft.
Domestic Aviation	BEV	Battery electric aircraft for short-haul domestic routes.
	Hydrogen	Hydrogen-powered domestic aircraft (combustion or fuel cell-based).
	Liquids	Conventional jet fuel-powered domestic aircraft.
International Shipping	BEV	Battery electric vessels for international maritime transport.
	FCEV	Hydrogen fuel-cell powered ships.
	Hybrid Liquids	Ships using hybrid propulsion combining liquid fuels and electric systems.
	Liquids	Conventional heavy fuel oil or marine diesel-powered ships.
Domestic Shipping	BEV	Battery electric vessels for domestic maritime transport.
	FCEV	Hydrogen fuel-cell powered domestic ships.
	Hybrid Liquids	Hybrid marine propulsion using liquid fuels and electric systems.
	Liquids	Conventional marine liquid fuel-powered ships.
Freight Rail	Electric	Electrified rail powered by grid electricity.
	BEV	Battery electric freight locomotives.
	FCEV	Hydrogen fuel-cell freight locomotives.
	Coal	Coal-powered steam or coal-derived fuel rail systems (legacy technology).
	Liquids	Diesel-powered freight locomotives.
Passenger Rail	Electric	Electrified passenger rail powered by overhead lines or third rail.
	Liquids	Diesel-powered passenger trains.
High-Speed Rail (HSR)	Electric	Electrified high-speed passenger rail systems.
Bus (Passenger Road)	BEV	Battery electric buses (various lithium-ion chemistries including LFP, NMC, Na-ion, solid-state, silicon-anode variants).

	FCEV	Hydrogen fuel-cell electric buses.
	NG	Natural gas-powered buses (CNG/LNG).
	Liquids	Conventional diesel or gasoline buses.
Heavy Truck (Freight Road)	BEV	Battery electric heavy-duty trucks (multiple lithium-ion chemistries including LFP, NMC, NCA, Na-ion, SSB variants).
	FCEV	Hydrogen fuel-cell heavy-duty trucks.
	NG	Natural gas-powered heavy trucks (CNG/LNG).
	Liquids	Diesel-powered heavy trucks.
Medium Truck (Freight Road)	BEV	Battery electric medium-duty trucks (multiple lithium-ion chemistries).
	FCEV	Hydrogen fuel-cell medium-duty trucks.
	NG	Natural gas-powered medium trucks.
	Liquids	Diesel-powered medium trucks.
Light Truck (Freight Road)	BEV	Battery electric light-duty trucks (multiple lithium-ion chemistries).
	FCEV	Hydrogen fuel-cell light-duty trucks.
	NG	Natural gas-powered light trucks.
	Liquids	Gasoline or diesel light trucks.
Car (Mid-size LDV)	BEV	Battery electric passenger cars (various lithium-ion chemistries including LFP, NMC, NCA, Na-ion, SSB variants).
	FCEV	Hydrogen fuel-cell passenger cars.
	Hybrid Liquids	Hybrid electric vehicles using liquid fuels plus electric drivetrain.
	NG	Natural gas passenger cars.
	Liquids	Conventional gasoline or diesel passenger cars.
Large Car / SUV / Pickup (LDV)	BEV	Battery electric large passenger vehicles (SUVs, pickups).
	FCEV	Hydrogen fuel-cell large passenger vehicles.
	Hybrid Liquids	Hybrid large passenger vehicles.
	NG	Natural gas large passenger vehicles.
	Liquids	Gasoline or diesel large passenger vehicles.
Mini Car (LDV)	BEV	Battery electric mini or compact cars (various chemistries).
	FCEV	Hydrogen fuel-cell mini cars.
	Hybrid Liquids	Hybrid mini cars using liquid fuels.

	NG	Natural gas mini cars.
	Liquids	Gasoline or diesel mini cars.
2W and 3W	BEV	Battery electric two- and three-wheelers.
	LA-BEV	Lead-acid battery electric two- and three-wheelers.
	NG	Natural gas-powered two- and three-wheelers.
	Liquids	Gasoline-powered motorcycles and three-wheelers.
Cycle	Human-powered	Non-motorized bicycle transport.
Walk	Human-powered	Non-motorized pedestrian transport.
Additional level of technology details for BEV of: Bus (Passenger Road) Heavy Truck (Freight Road) Medium Truck (Freight Road) Light Truck (Freight Road) Car (Mid-size LDV) Large Car / SUV / Pickup (LDV) Mini Car (LDV)	BEV (LFP)	Battery electric vehicle using Lithium Iron Phosphate (LFP) batteries
	BEV (LFP Si-substitute)	Battery electric vehicle using LFP batteries with silicon-doped graphite anodes (10%)
	BEV (LFP Solid-state)	Battery electric vehicle using LFP-based solid-state batteries
	BEV (NCA)	Battery electric vehicle using Nickel Cobalt Aluminum (NCA) lithium-ion batteries
	BEV (NMC111)	Battery electric vehicle using Nickel Manganese Cobalt (1:1:1) lithium-ion batteries
	BEV (NMC622)	Battery electric vehicle using Nickel Manganese Cobalt (6:2:2) lithium-ion batteries
	BEV (NMC811)	Battery electric vehicle using Nickel Manganese Cobalt (8:1:1) lithium-ion batteries
	BEV (NMC811 Si-substitute)	Battery electric vehicle using NMC811 batteries with silicon-doped anodes (10%)
	BEV (NMC811 Solid-state)	Battery electric vehicle using NMC811 solid-state batteries
	BEV (Na-ion)	Battery electric vehicle using sodium-ion batteries

SI-Table 3. Hydrogen sector technology representation in GCAM. GCAM represents a wide range of hydrogen production technologies, as shown in this table. No additional subtype technologies were added in the hydrogen sector.

Fuel type	**Technology**	**Technology explanation**
Biomass	Biomass to H_2	Hydrogen production via biomass gasification followed by syngas reforming and purification.
Biomass	Biomass to H_2 + CCS	Biomass gasification-based hydrogen production with carbon capture and storage (BECCS configuration).
Coal	Coal to H_2 (Chemical Process)	Hydrogen production from coal gasification
Coal	Coal to H_2 (Chemical Process + CCS)	Coal gasification-based hydrogen production with carbon capture and storage.
Electricity (Grid)	Electrolysis (Grid-powered)	Water electrolysis using grid electricity to produce hydrogen and oxygen.
Gas	Natural Gas Steam Reforming (SMR)	Hydrogen production via steam methane reforming without carbon capture.
Gas	Autothermal Reforming (ATR) + CCS	Hydrogen production using autothermal reforming of natural gas with integrated carbon capture.
Solar	Solar-powered Electrolysis	Hydrogen production via water electrolysis powered by solar PV electricity (PV).
Wind	Wind-powered Electrolysis	Hydrogen production via water electrolysis powered by wind electricity.
Onsite Production	Onsite Electrolysis	Distributed hydrogen production via electrolysis at point-of-use (e.g., refueling stations or industrial facilities).

Supplementary Note 2 – Material intensity of technologies across different sectors

We have collected material intensity data of technologies across different sectors from peer-reviewed research papers or highly reputable reports. The material intensity data of electricity generation and storage technologies are based on our previous study[1]. We also collect material intensity data of technologies for electricity T&D, transport, and hydrogen production. Detailed information about the material intensity data of technologies in these sectors can be found in **Supplementary Dataset**.

The material intensity data varies in units, so we did unit conversion for the material intensity data to be consistent and suitable for GCAM inputs. Detailed unit conversion for electricity generation and storage technologies are documented in our previous study[1]. Here we provided additional details on unit conversion and assumptions being made for material intensity data in transport, electricity T&D, and hydrogen production.

Transport

For all transport technologies, the collected material intensity data are expressed either as mass per unit service output (kg/passenger-km travel or kg/ton freight-km travel) or as mass per vehicle (kg/vehicle). GCAM does not directly calculate the annual transport fleet additions of different transport modes and technologies. Instead, the model calculates service outputs (passenger-km travel or ton freight-km travel) for deployed technologies and tracks technology vintages based on their year of initial deployment and retirement. Therefore, material intensity data reported in unit of mass per service output (kg/passenger-km travel or kg/ton freight-km travel) can be directly used as inputs in GCAM. For material intensity data reported in mass per vehicle, we convert them to mass per unit service output using the following equation 1 to align with the GCAM input format.

$$Material\ intensity\ (GCAM\ input)_{\ i,j} \left(\frac{Mt-year}{passenger-km}\right) = \frac{Material\ intensity\ (data)_{i,j} \left(\frac{kg}{vehicle}\right) * \frac{Mt}{kg} conversion}{load\ factor\ (passenger/vehicle) * vehicle\ annual\ travel\ (km/year)} \qquad (1)$$

Here the $Material\ intensity\ (data)_{i,j}$ represents the material intensity of material i in technology j collected from literature (unit: kg/vehicle). $Material\ intensity\ (GCAM\ input)_{i,j}$ denotes the converted material intensity used as input in value of material i in technology j that is used as GCAM input (with the unit being Mt/passenger-km) after unit conversion. defined as the average number of passengers per vehicle (passenger/vehicle), and vehicle annual travel represents the total distance traveled by a vehicle fleet in one year (km/year).

In GCAM modelling, the total material demand $Material\ demand\ _{i,k}(Mt)$ for material i in year k is calculated by multiplying the $Material\ intensity\ (GCAM\ input)_{i,j}$ by the $service\ output\ of\ new\ fleet_{j,\,k}$, of the technology j in year k, and them summing across all the technologies that consumes material i. (Equation 2 below).

$$Material\ demand\ _{i,k}(Mt) =$$

$$\sum_j (Service\ output\ of\ new\ fleet_{j,\,k}(passenger - km/year) \times Material\ intensity\ (GCAM\ input)_{i,j}\left(\frac{Mt-year}{passenger-km}\right)) \qquad (2)$$

Electricity T&D

In GCAM, the electricity T&D sector is modeled simply as a “pass through sector” to allow generated electricity to flow to each of the end-use demand sectors (buildings, industry, and transportation). Thus, explicit T&D infrastructure build out is not considered, and T&D electricity demands simply scale with the level of total electrification. In reality, future T&D infrastructural (material) demands are not likely to scale linearly with total electrification, therefore we make additional assumptions about how T&D material intensities vary across regions and change over time to correct for this simplified approach.

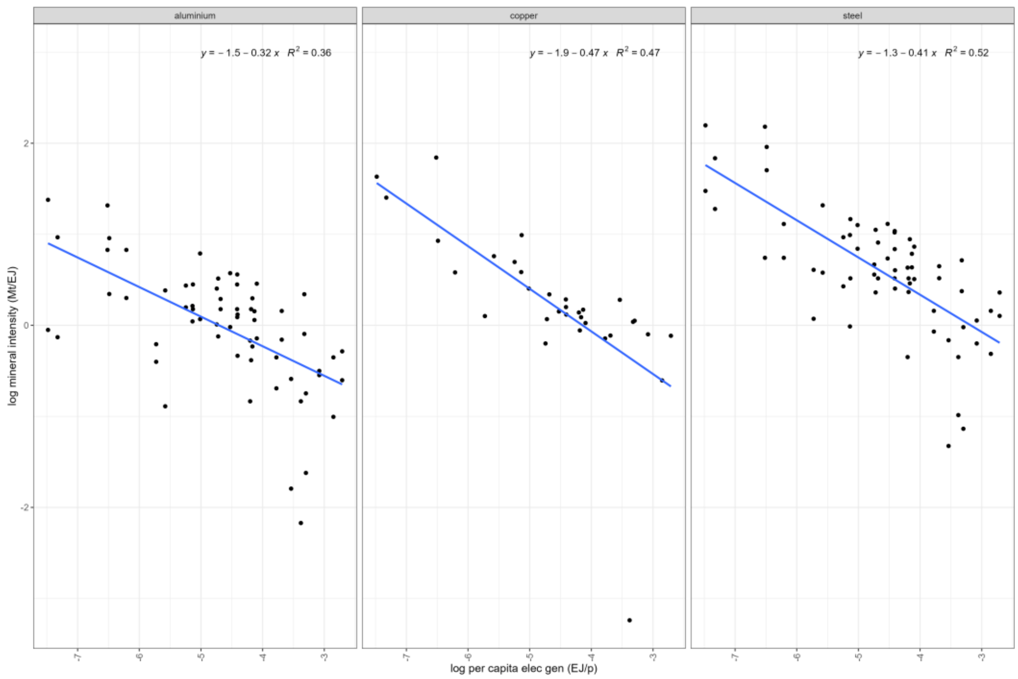
We have added T&D material intensity information for steel, aluminum, and copper. We collected input data on: historical transmission and distribution length (km) across voltage levels *v* by region *r*, transformer/substation unit data (unit/km) across voltage levels (v), material intensity data for transmission and distribution lines (kg/km) and transformer units (kg/unit) for each material *i* and voltage level *v*, as well as historical electricity capacity (kW) by region *r*. This input data was collected and synthesized from two key data sources: Kalt et al.[2–4] and Deetman et al.[5] Input files and a script for processing and synthesizing this data are provided in a stand-alone repository at: https://github.com/brinday/GCAM-TD-CMM[6]

For GCAM's T&D technologies, material intensities are based on a mass per energy unit. Thus, we convert T&D material intensities using the following equation to suit GCAM data input format.

$$Material\ intensity\ (GCAM\ input)_{i,r}\left(\frac{Mt}{EJ}\right) = \frac{\begin{array}{c}(TD\ line\ length\ (km)_{v,r} \times TD\ line\ material\ intensity(data)\left(\frac{kg}{km}\right)_{i,v} + \\ TD\ line\ length(km)_{v,r} \times transformer\left(\frac{unit}{km}\right) \times transformer\ materials\ intensity\ (data)\left(\frac{kg}{unit}\right)_{i,v})\end{array}}{electricity\ capacity\ [kW]_r/8760h} \times \left(\frac{Mt}{kg}, \frac{kWh}{EJ}\ conversion\right) \quad (3)$$

The above equation, which utilizes data on historical grid size (T&D lengths, electricity capacity), was used to obtain material intensities for the base year. Material intensity in historical years varies significantly across GCAM regions due to differences in grid sizes and electrification rates. In particular, very low-income regions with low electrification rates have high material intensity in the base year. We expect this to decrease over time as electrification increases and there is diminishing marginal cost of expanding the grid. Thus, to project future mineral intensities, we use a GCAM reference scenario projection to calculate the evolution of per capita electricity generation in each GCAM region in 2050. We use regression to calculate 2050 material intensities **(SI-Figure 1)**, and then linearly converge material intensities from the base year to this 2050 value over time. If the base year value is already lower than the 2050 value, we just use the base year value in all future years, assuming no change in material intensity for that region and material over time.

The following additional changes were made to the existing GCAM T&D technologies. In this effort, we have now added lifetime and retirement information for T&D, to more accurately track T&D material demands. We assume a 40-year lifetime for all T&D technologies in all regions, following assumptions in Deetman et al[5]. We have updated T&D non-energy cost information, accounting for the variation in T&D costs across regions (where they were previously uniform across regions), which are scaled based on the variation in T&D mineral costs across regions.



SI-Figure 1. Linear regression of log material intensity (Mt/EJ) versus log per capita electricity generation (EJ/p) in the base year for copper, lithium, and nickel across GCAM regions. This figure highlights a correlation between current electrification and material intensities across regions. This relationship is used to project 2050 material intensities based on 2050 levels of electrification by region.

Hydrogen production

Deriving material intensities for hydrogen production technologies follow a similar format to that of electricity generation technologies, as documented in our previous study[1], in which material intensity assumptions are collected from the literature and input into GCAM in units of kg/kW. In a few cases, where no suitable assumptions for hydrogen production technologies were used, assumptions were copied from comparable electricity generation technologies (see **Supplementary Dataset** for details).

Supplementary Note 3 – Material demand results comparison

In this section, we compare GCAM's material demand estimates with those reported by the International Energy Agency (IEA) to assess whether our projections fall within a reasonable range. We selected the IEA estimates because they provide multi-sector material demand projections derived under internally consistent scenario assumptions, making them a useful point of comparison. It is worth noting that the GCAM and IEA analyses differ in scenario design, sectoral definitions, system boundaries, and material coverage. These structural differences naturally lead to variation in projected material demands. Therefore, the objective of this comparison is not to demonstrate precise agreement, but rather to evaluate whether GCAM produces estimates of comparable magnitude and broadly consistent sectoral patterns.

The comparison shows that GCAM and IEA estimates are broadly aligned in magnitude for the electricity and transportation sectors. However, relatively larger discrepancies arise in the hydrogen production sector. Several factors are likely to contribute to these differences. First, the scenario assumptions differ. The IEA estimates are based on a stated-policies scenario, whereas the GCAM results presented here reflect a reference (no-new-policy) case. As a result, GCAM projects lower deployment of electrolysis technologies, which contributes to lower platinum (Pt) demand relative to the IEA estimates. Second, differences in technology representation and system boundaries also affect the comparison. In GCAM, hydrogen electrolysis can be coupled with different electricity supply configurations, including dedicated on-site solar or wind generation. In such cases, the material intensity of hydrogen production reflects both the electrolyzer infrastructure and the associated renewable power capacity. By contrast, if the IEA estimates account only for the electrolyzer unit itself, this narrower system boundary would result in lower associated demand for bulk materials such as copper (Cu). These differences in modeling scope explain the higher Cu demand for hydrogen observed in GCAM.

SI-Table 4. Comparison of GCAM electricity generation material demand with results from other sources.

Material	Year	Unit	GCAM estimates	IEA estimates
aluminium	2025	Mt	2.540	
aluminium	2050	Mt	3.767	
cobalt	2025	Mt	0.009	0.004
cobalt	2050	Mt	0.017	0.000
copper	2025	Mt	0.940	2.400
copper	2050	Mt	1.833	3.950
graphite	2025	Mt	0.006	0.163
graphite	2050	Mt	0.239	0.786
lithium	2025	Mt	0.001	0.019
lithium	2050	Mt	0.024	0.089
manganese	2025	Mt	0.080	0.110
manganese	2050	Mt	0.156	0.700
neodymium	2025	Mt	0.002	0.008
neodymium	2050	Mt	0.010	0.013
nickel	2025	Mt	0.470	0.220
nickel	2050	Mt	0.653	0.640
silicon	2025	Mt	0.309	1.480
silicon	2050	Mt	0.425	1.370
steel	2025	Mt	26.890	
steel	2050	Mt	51.409	
tellurium	2025	Mt	0.0007	0.0010
tellurium	2050	Mt	0.0011	0.0010
vanadium	2025	Mt	0.001	0
vanadium	2050	Mt	0.065	0.500

Note: IEA estimates are based on Stated Policies Scenario. Technologies includes renewable energy (i.e. solar, wind), grid battery storage, and other low emission power generation technologies. Shaded cells represent no data are provided.

SI-Table 5. Comparison of GCAM electricity T&D material demand with results from other sources.

Material	Year	Unit	GCAM estimate	IEA estimate
steel	2025	Mt	7.15	
steel	2050	Mt	11.20	
aluminum	2025	Mt	3.82	
aluminum	2050	Mt	6.70	
copper	2025	Mt	5.44	4.9
copper	2050	Mt	7.70	5.6

Note: IEA estimates are based on Stated Policies Scenario. Shaded cells represent no data are provided.

SI-Table 6. Comparison of GCAM transport sector material demand with results from other sources.

Material	Year	Unit	GCAM estimates (BEV)	IEA estimates
aluminium	2025	Mt	3.52	
aluminium	2050	Mt	20.78	
cobalt	2025	Mt	0.13	0.067
cobalt	2050	Mt	0.356	0.17
copper	2025	Mt	1.65	0.5
copper	2050	Mt	6.95	3.5
graphite	2025	Mt	1.24	0.84
graphite	2050	Mt	3.51	2.1
lithium	2025	Mt	0.15	0.11
lithium	2050	Mt	0.84	0.93
manganese	2025	Mt	0.38	0.06
manganese	2050	Mt	1.41	2.7
neodymium	2025	Mt	0.009	0.006
neodymium	2050	Mt	0.032	0.03
nickel	2025	Mt	0.62	0.3
nickel	2050	Mt	2.475	2.1
platinum	2025	Mt		
platinum	2050	Mt		
silicon	2025	Mt	0.01	0.018
silicon	2050	Mt	0.127	0.745
steel	2025	Mt	17.77	
steel	2050	Mt	69.2	
tellurium	2025	Mt	0.00058	
tellurium	2050	Mt	0.026	
vanadium	2025	Mt	0.001	
vanadium	2050	Mt	0.0068	

Note: IEA estimates are based on Stated Policies Scenario. IEA transport sector results only include electric vehicles. Therefore, to make consistent comparison, the GCAM material demand here only represent electric vehicles from passenger and freight transport modes (i.e. passenger 4-wheel light-duty vehicles, bus, and freight trucks). Shaded cells represent no data are provided.

SI-Table 7. Comparison of GCAM hydrogen production sector material demand with results from other sources.

Material	Year	Unit	**GCAM estimates (**hydrogen production relying on electrolysis**)**	IEA estimates
aluminium	2025	kt	0.9	
aluminium	2050	kt	43	
cobalt	2025	kt	0	0.004
cobalt	2050	kt	0	0.005
copper	2025	kt	0.43	0.003
copper	2050	kt	15.3	0.014
manganese	2025	kt	0.07	
manganese	2050	kt	1.42	
neodymium	2025	kt	0.001	
neodymium	2050	kt	0.02	
nickel	2025	kt	0.04	1.4
nickel	2050	kt	0.82	5.37
platinum	2025	kt	0	0.001
platinum	2050	kt	0.002	0.02
silicon	2025	kt	0.12	
silicon	2050	kt	6.2	
steel	2025	kt	14.6	
steel	2050	kt	402	

Note: IEA estimates are based on Stated Policies Scenario. IEA hydrogen sector results only include electrolysers. Therefore, to make consistent comparison, the GCAM material demand here represents hydrogen production relying on electrolysis. Shaded cells represent no data are provided.

Supplementary Note 4 – Order-of-magnitude calculation on material intensity

We performed an order-of-magnitude calculation to compare material intensity across key electricity generation technologies and other energy transformation sectors. For electricity generation, we focused on coal, gas, solar PV, and wind, using steel intensity data previously employed in GCAM[1]. These values were converted to million tonne of steel per exajoule (Mt/EJ) of annual electricity output using representative capacity factors (20% for solar, 35% for wind, 70% for coal, and 50% for gas) based on GCAM inputs[7] (**SI-Table 8**). On this basis, fossil-fired power plants exhibit steel intensities of approximately 2.5–2.8 Mt/EJ, whereas wind and solar PV require roughly 12–13 Mt/EJ. The higher intensities for renewables reflect both lower capacity factors and greater structural material requirements per unit of annual electricity output.

SI-Table 8: Steel requirement for different technologies.

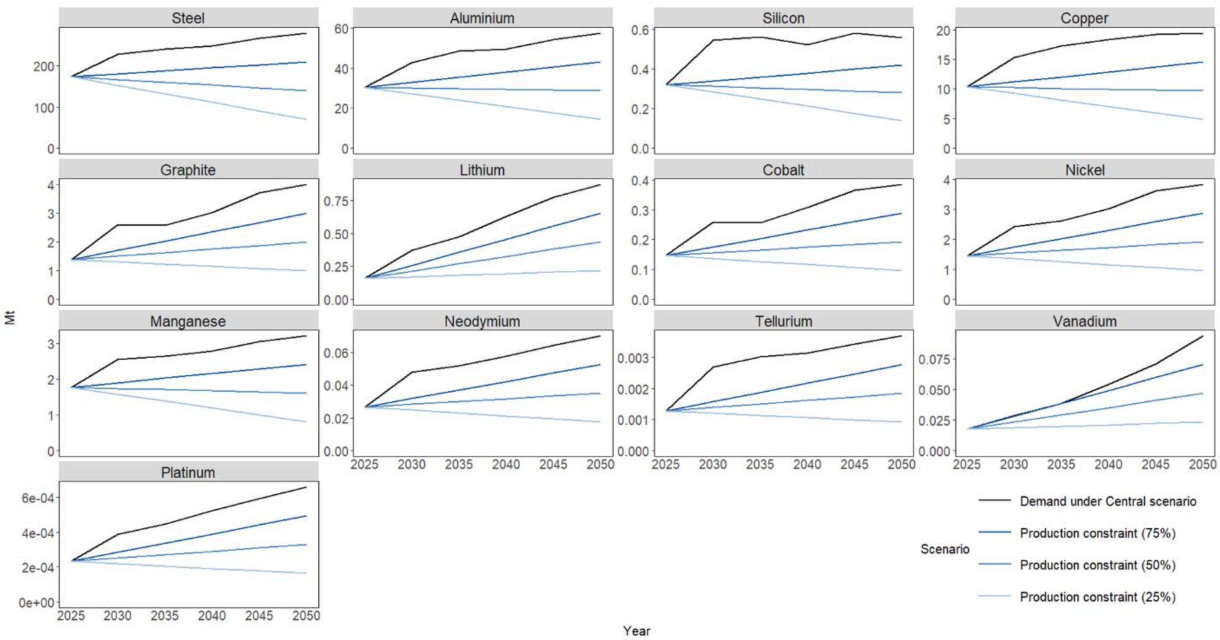
Technology	**Reported Steel Metric**	**Steel Intensity (Mt/EJ annual output)**
Solar PV	78 kg/kW	12.5 Mt/EJ
Wind	140 kg/kW	12.8 Mt/EJ
Coal Power	60 kg/kW	2.8 Mt/EJ
Gas Power	40 kg/kW	2.5 Mt/EJ

In addition, we evaluated oil refining and gas processing, which are other key energy transformation sectors represented in GCAM. Because plant-level material data are limited in the open literature, we derived order-of-magnitude steel intensities. These estimates reflect the authors' synthesis of prior life-cycle inventory experience, including consultation of proprietary data sources to which the authors had legitimate access. No proprietary data are reported, and the values are provided solely as approximate contextual benchmarks. Based on our estimation, oil refining exhibits a steel intensity on the order of 10^{-1} Mt/EJ—one to two orders of magnitude lower than electricity generation—reflecting the high energy density of crude oil and the role of refineries as processing rather than energy-conversion infrastructure. Gas processing has an intensity on the order of 10^{0} Mt/EJ, comparable to fossil power generation but roughly an order of magnitude lower than renewables. When normalized by annual energy output, the resulting hierarchy of steel intensity is:

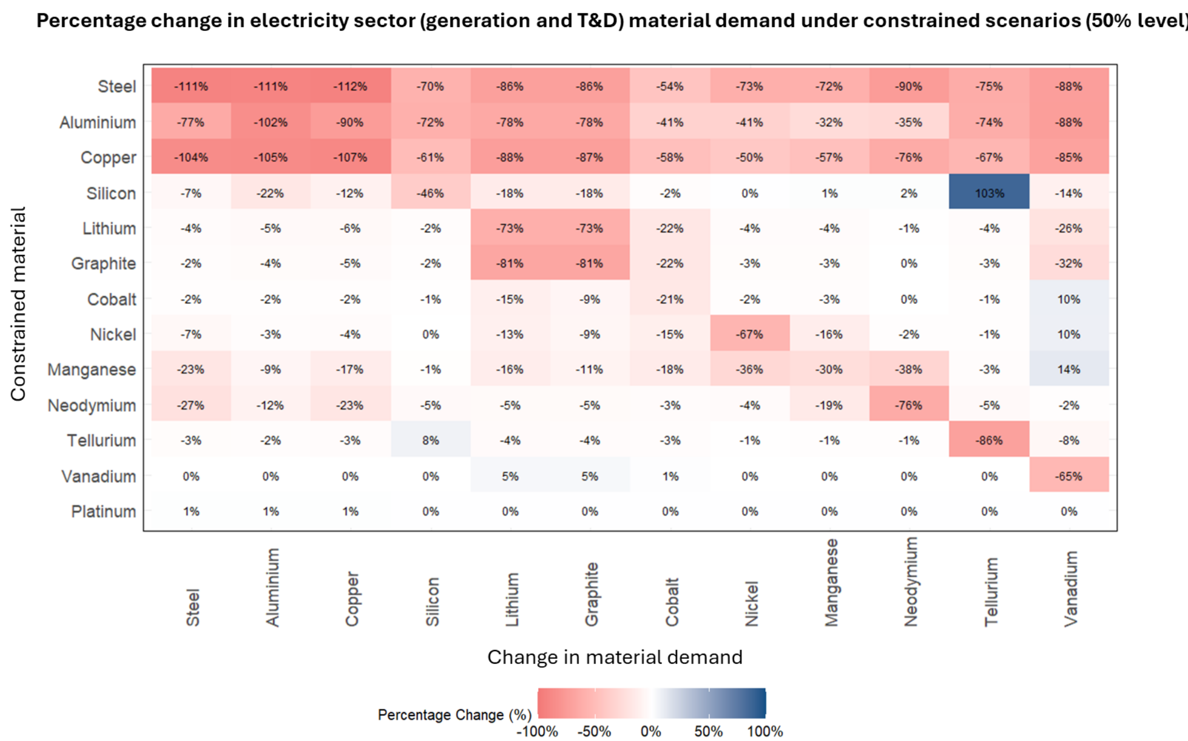
Oil refining<Gas processing≈Coal & Gas power<Wind & Solar PV

This order-of-magnitude comparison supports the argument in the main text: although the current GCAM configuration explicitly represents material demand only for a subset of energy-related sectors, engineering estimates indicate that oil refining and gas processing systems are less material-intensive than electricity generation, particularly renewable technologies. Consequently, while the model's reallocation of energy away from electricity may be slightly amplified due to incomplete material representation, the qualitative mechanism remains robust: material constraints disproportionately affect more material-intensive electricity technologies, favoring less material-intensive transformation pathways.

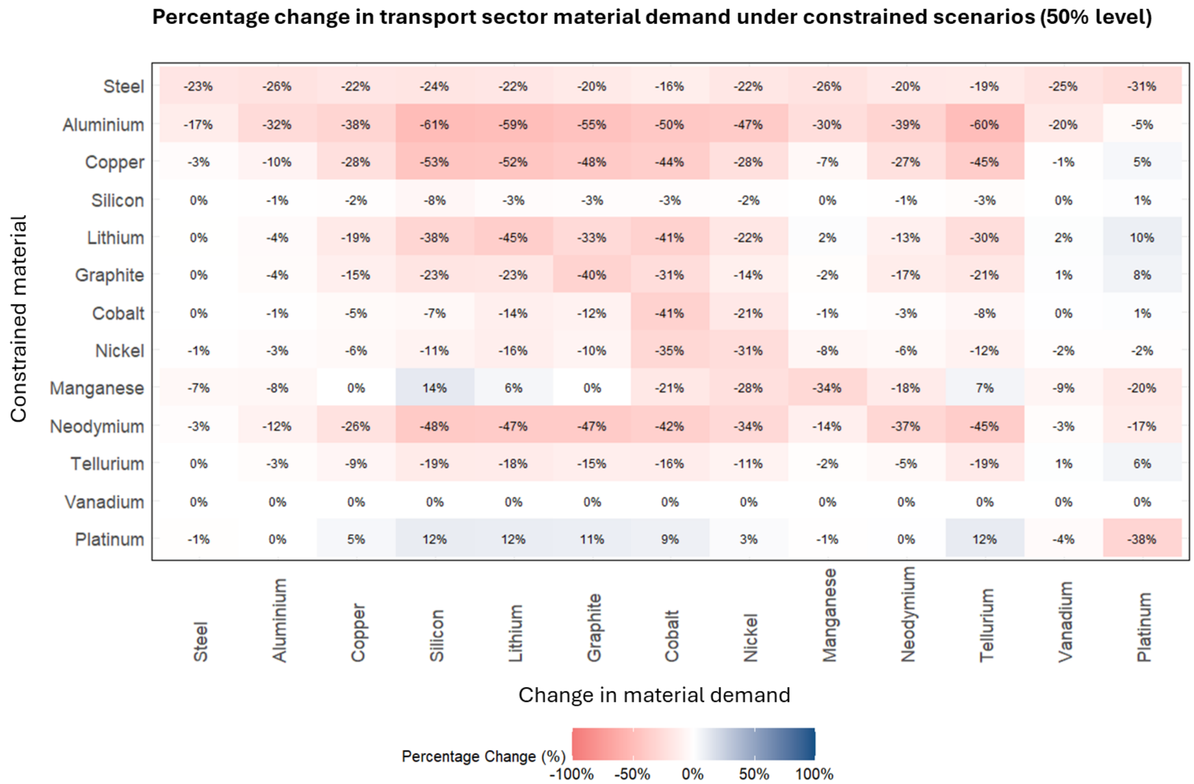
Note 5 – Supplementary results



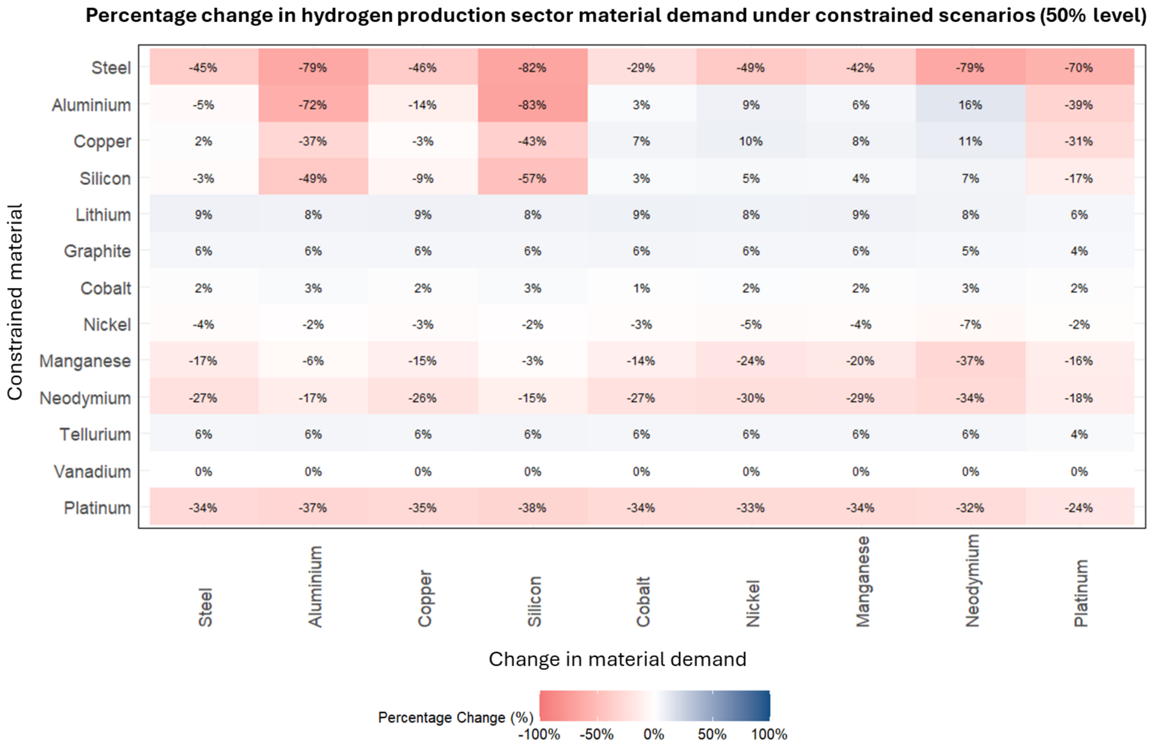
SI-Figure 2. Estimated material demand projections under *Central scenario* and production constraint trajectories used in this study.



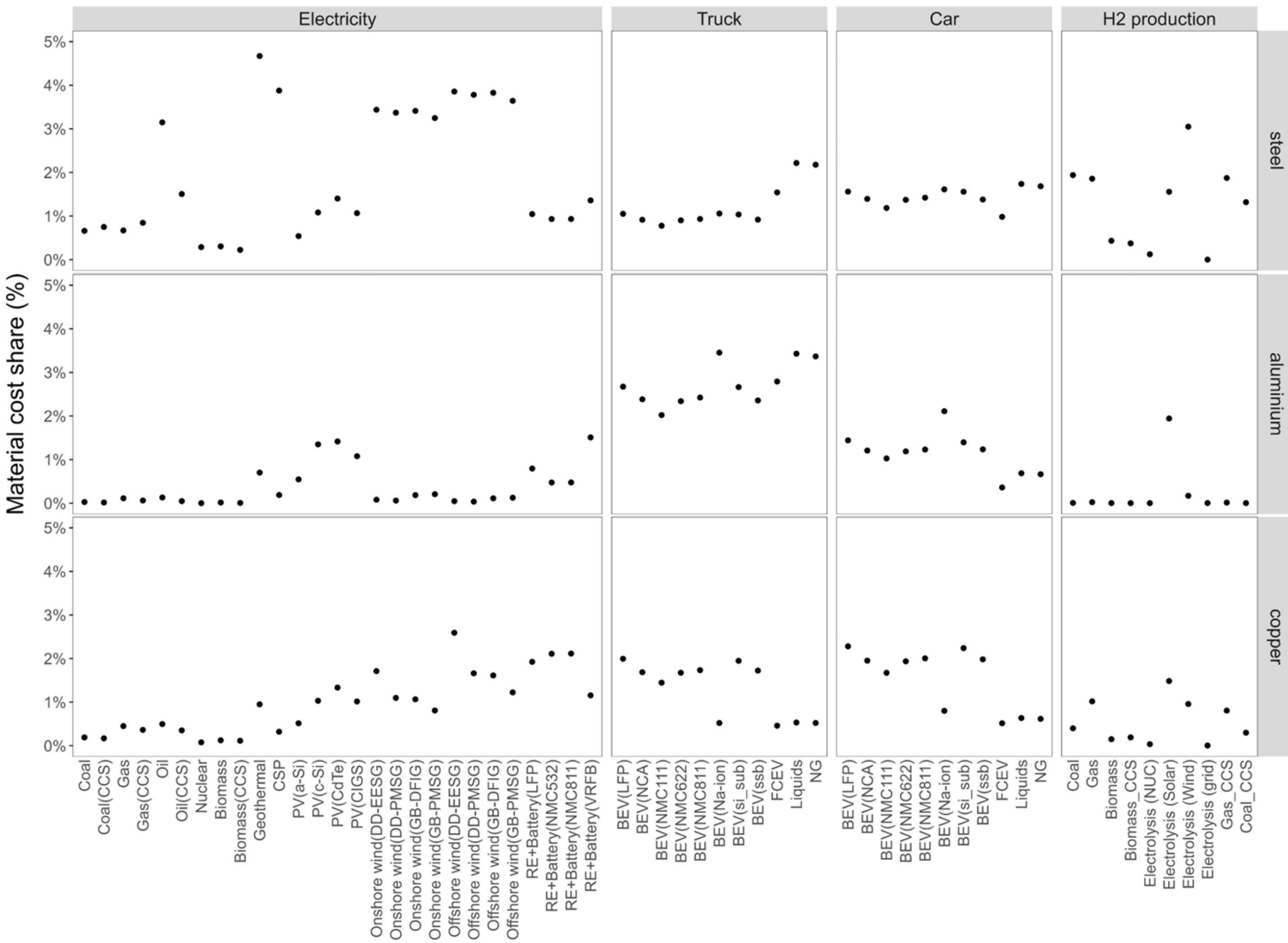
SI-Figure 3. Percentage change of material demand in the electricity sector (generation and T&D) under *Constraint scenarios* at 50% level. Each row represents a constrained scenario, where the row label indicates the material subject to the production constraint. Value > 0 implies an increase in demand relative to the *Central scenario*, while value < 0 implies a decrease in demand relative to the *Central scenario*.



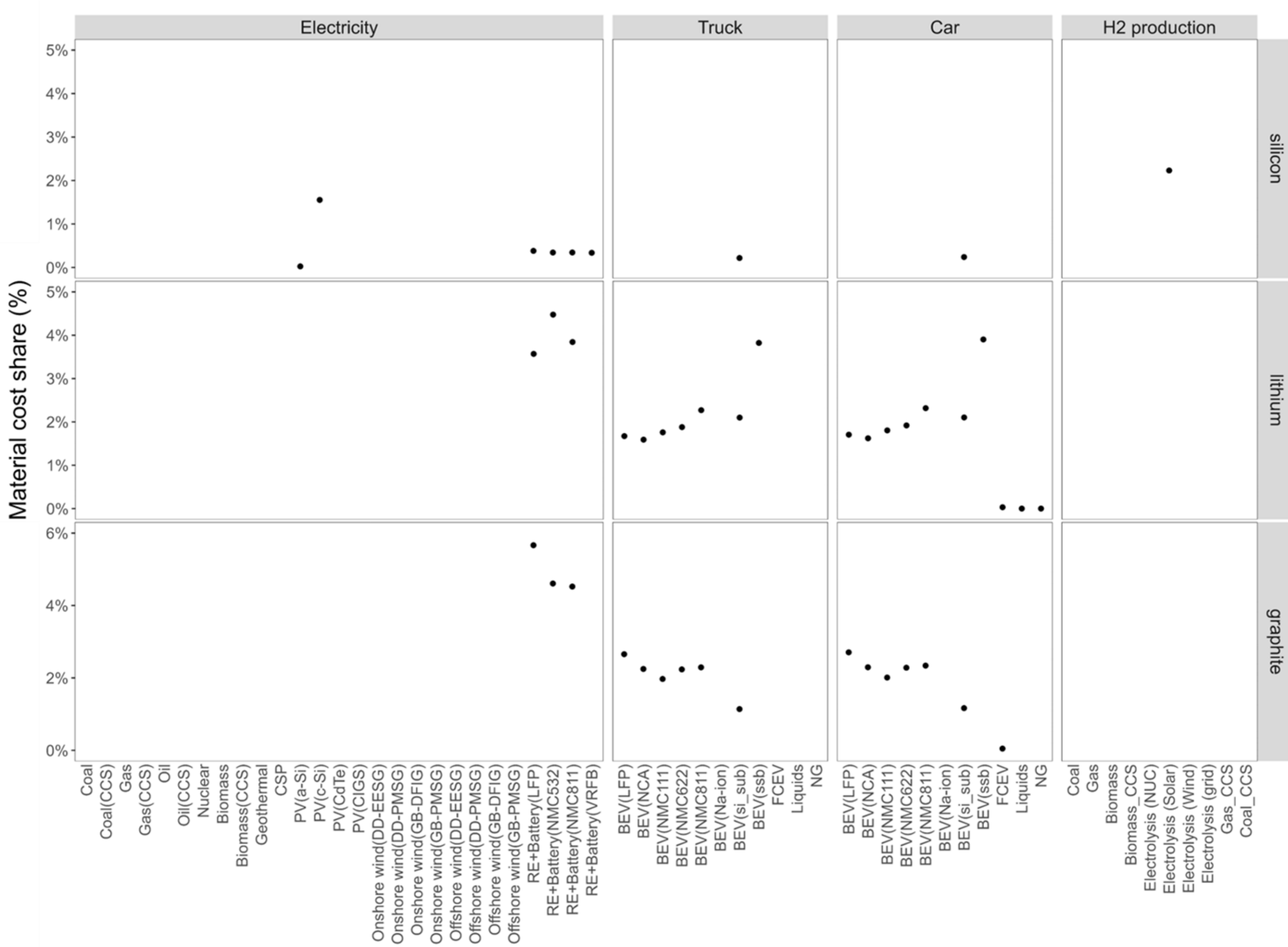
SI-Figure 4. Percentage change of material demand in the transport sector (including all transport modes and fuel types) under *Constraint scenarios* at 50% level. Each row represents a constrained scenario, where the row label indicates the material subject to the production constraint. Value > 0 implies an increase in demand relative to the *Central scenario*, while value < 0 implies a decrease in demand relative to the *Central scenario*.



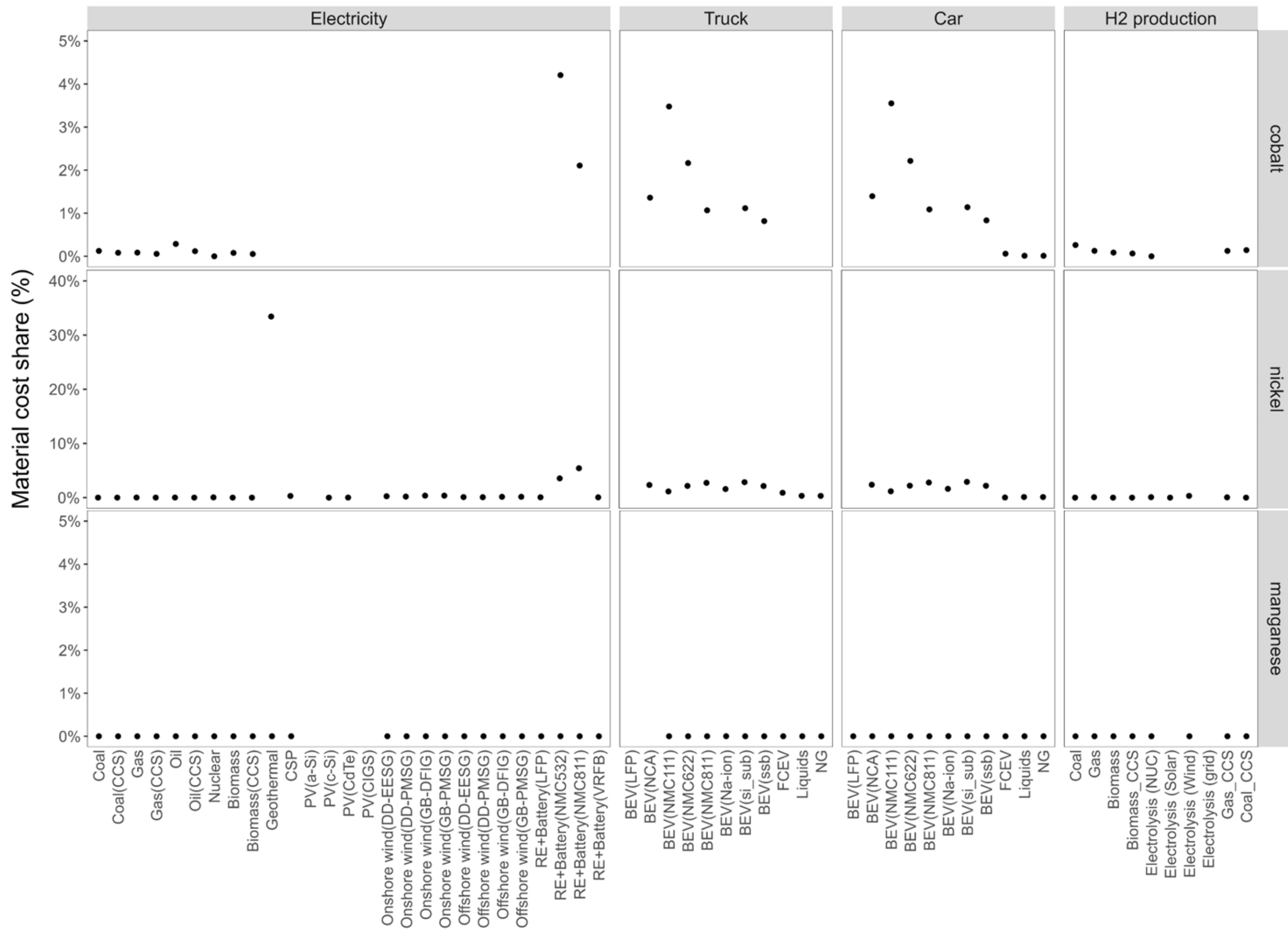
SI-Figure 5. Percentage change of material demand in the hydrogen production sector under *Constraint scenarios* at 50% level. Each row represents a constrained scenario, where the row label indicates the material subject to the production constraint. Value > 0 implies an increase in demand relative to the *Central scenario*, while value < 0 implies a decrease in demand relative to the *Central scenario*.



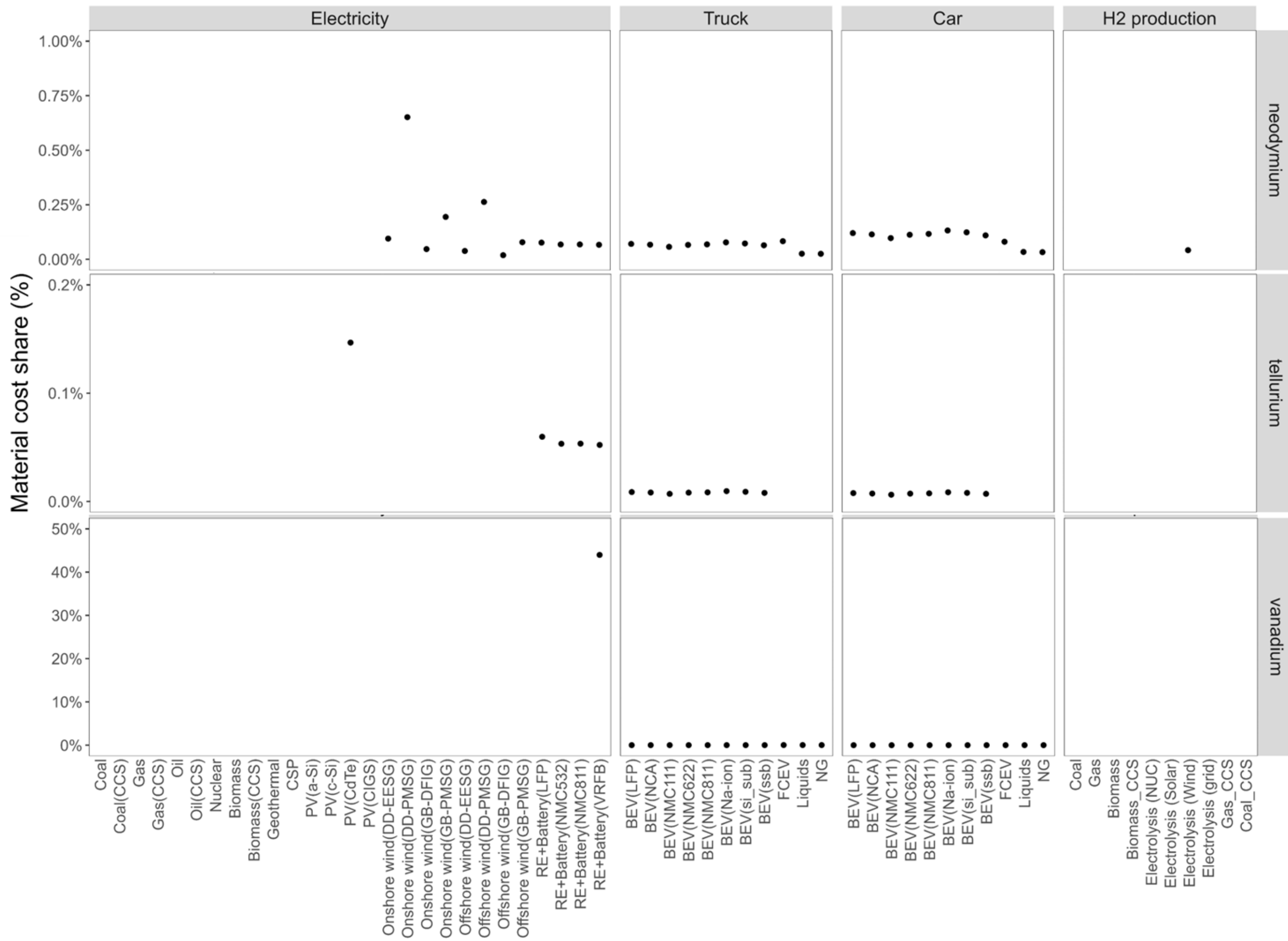
SI-Figure 6. Percentage share of material cost in total technology capital cost (or non-energy cost). Each row corresponds to a specific material. Each dot represents the cost share of that material in the capital (or non-energy) cost of the technology indicated on the x-axis. The material cost is calculated as the product of the input material price and its intensity in the corresponding technology. This page shows material cost shares of steel, aluminum and copper. Figure continues to the next page.



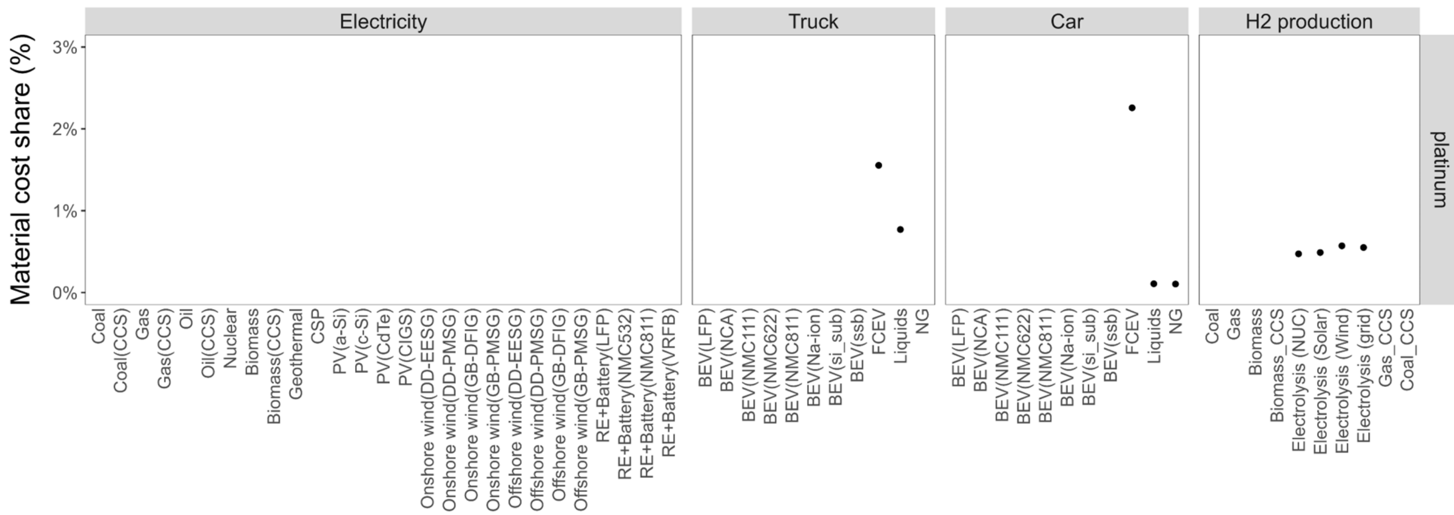
SI-Figure 6. Percentage share of material cost in total technology capital cost (or non-energy cost). Each row corresponds to a specific material. Each dot represents the cost share of that material in the capital (or non-energy) cost of the technology indicated on the x-axis. The material cost is calculated as the product of the input material price and its intensity in the corresponding technology. This page shows material cost shares of silicon, lithium and graphite. Figure continues to the next page.



SI-Figure 6. Percentage share of material cost in total technology capital cost (or non-energy cost). Each row corresponds to a specific material. Each dot represents the cost share of that material in the capital (or non-energy) cost of the technology indicated on the x-axis. The material cost is calculated as the product of the input material price and its intensity in the corresponding technology. This page shows material cost shares of cobalt, nickel and manganese. Figure continues to the next page.



SI-Figure 6. Percentage share of material cost in total technology capital cost (or non-energy cost). Each row corresponds to a specific material. Each dot represents the cost share of that material in the capital (or non-energy) cost of the technology indicated on the x-axis. The material cost is calculated as the product of the input material price and its intensity in the corresponding technology. This page shows material cost shares of neodymium, tellurium, and vanadium. Figure continues to the next page.



SI-Figure 6. Percentage share of material cost in total technology capital cost (or non-energy cost). Each row corresponds to a specific material. Each dot represents the cost share of that material in the capital (or non-energy) cost of the technology indicated on the x-axis. The material cost is calculated as the product of the input material price and its intensity in the corresponding technology. This page shows material cost shares of platinum. Figure continues to the next page.

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