Modeling critical mineral and materials in GCAM

Gokul Iyer, Yang Qiu,
Neal Graham, and Brinda Yarlagadda

on behalf of the GCAM CMM team

June 3, 2026

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CMM Research Outlook and MSD Implications

Gokul Iyer

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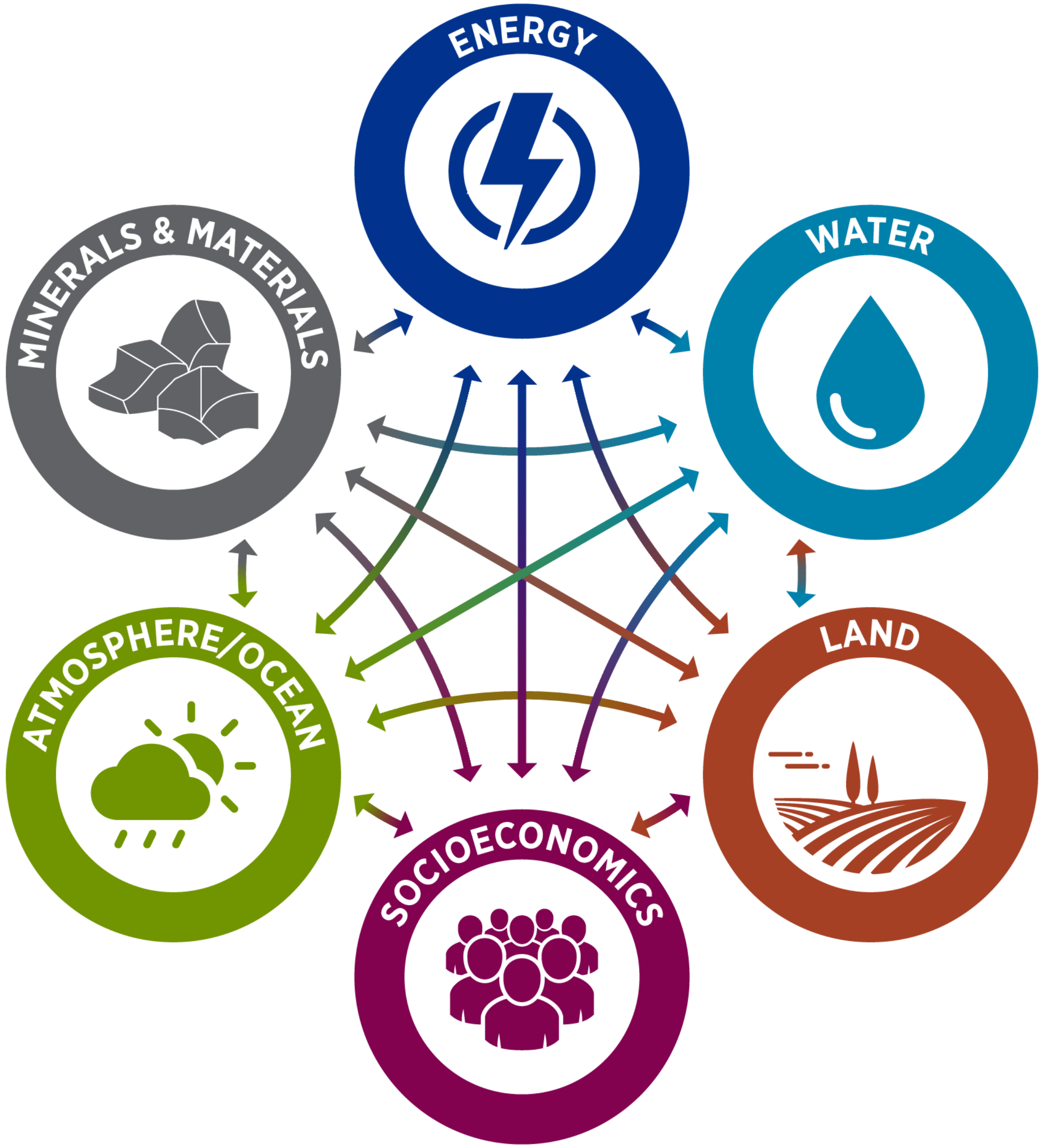
CMMs play an important role in multisectoral interactions

- ***Critical minerals and materials (CMMs) are used extensively*** in energy technologies, manufacturing, critical infrastructure, and rest of the economy
    - For example, lithium, nickel, cobalt, manganese, and graphite are used in batteries
    - Rare earth elements are essential for the permanent magnets used in electric vehicle motors
- CMMs also have ***geographically concentrated deposits***, and complex supply chains
- CMM availability, trade patterns, and supply chain dynamics could affect ***how various systems respond to stressors*** and disruptions
- In addition, ***CMM supply chains could themselves be important sources of stressors*** that could affect energy investments and broader multisectoral interactions



Source: https://elements.visualcapitalist.com/charted-americas-reliance-on-foreign-minerals/

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We are developing capabilities within GCAM to model multisectoral interactions across CMM markets, the energy system and other systems

SUPPLY	PROCESSING AND TRADE	DEMAND
Economic competition across different supply streams	Geographic distributions: raw/processed minerals/materials/components	Multisectoral demands, technology and mineral/material substitution

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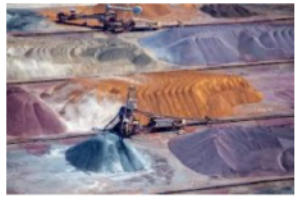
SUPPLY

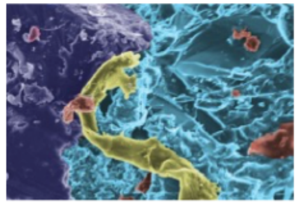
Economic competition across different supply streams

Broad range of materials/minerals
(e.g. Li, Ni, Co, Cu, Si, graphite, rare earth elements)

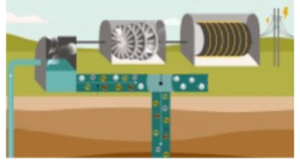
Traditional mining



Biomining



Geothermal brines



Wastewater

Other unconventional sources and recovery methods

PROCESSING AND TRADE

Geographic distributions: raw/processed minerals/materials/components

DEMAND

Multisectoral demands, technology and mineral/material substitution

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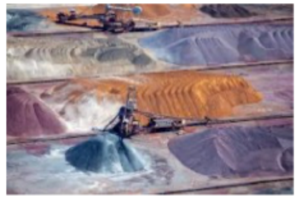

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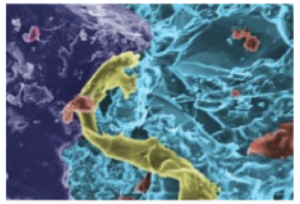

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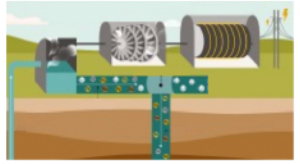

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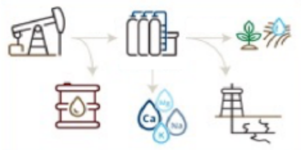
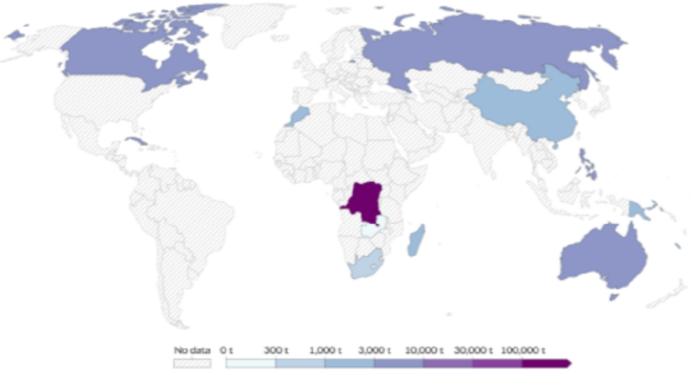


Other unconventional sources and recovery methods

PROCESSING AND TRADE

Geographic distributions: raw/processed minerals/materials/components

Production by country (e.g. Cobalt)



Refining and component production by country

DEMAND

Multisectoral demands, technology and mineral/material substitution

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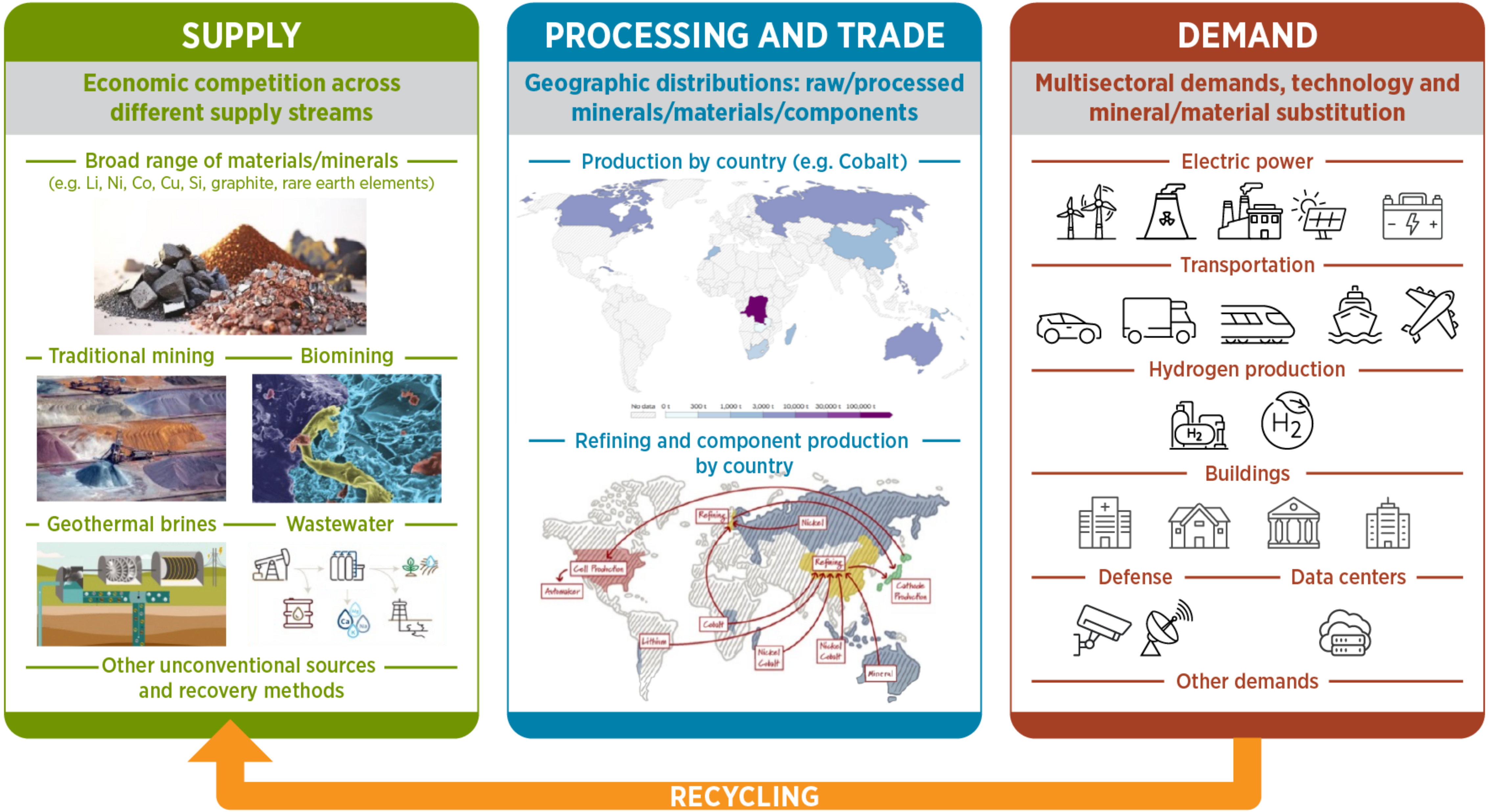
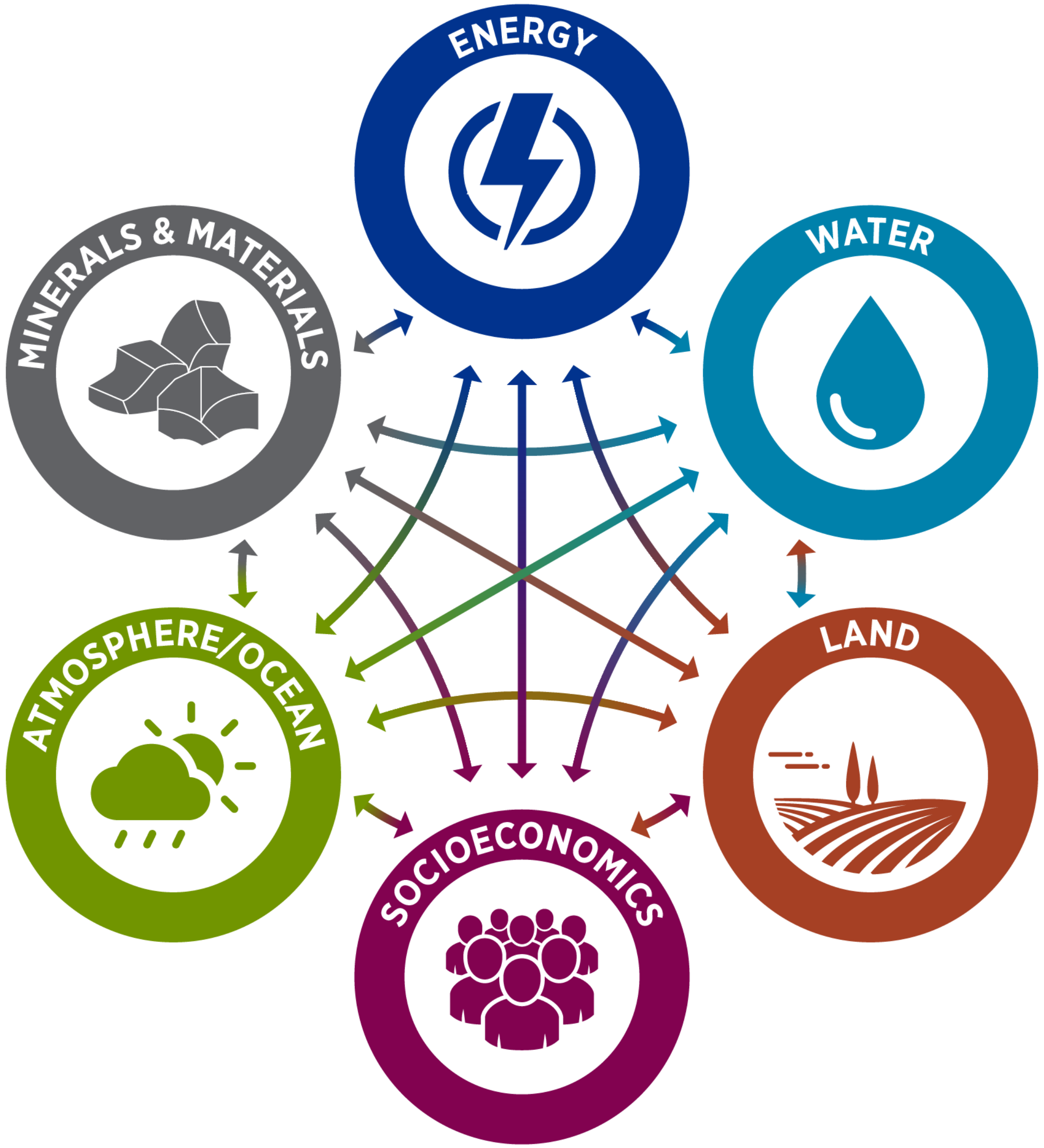


GCAM modeling of CMMs offers a multisectoral perspective

- ***Dynamic and internally consistent*** resource prices, supplies, demands, and trade patterns (as opposed to externally-forced assumptions)
- ***Competition across technologies*** and sectors for scarce resources
- ***Substitution*** across materials
- ***Competition across regions*** to meet global demands
- We welcome collaborations in additional capability developments
  - Implications of short-term disruptions & modeling at finer scales (AI/ML)
  - Rapid scenario evaluation (AI/ML)
  - Implications of CMMs for the macroeconomy



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Agenda for this session

- Multisectoral CMM demands (Yang Qiu)
- CMM demands in datacenters (Neal Graham)
- Modeling of CMM supplies (Brinda Yarlagadda)
- Recycling, unconventional sources, and trade (Gokul Iyer, Yang Qiu, Brinda Yarlagadda)

https://epsci.stanford.edu/critical-minerals

Multisectoral CMM Demands

Yang Qiu, Brinda Yarlagadda, Neal Graham, Matthew Binsted, Pralit Patel, Marshall Wise, Allen Fawcett, Maggie Liu, Siddarth Durga, Nathan Wiens, Anastasiia Zagoruichyk, Gokul Iyer

June 3, 2026

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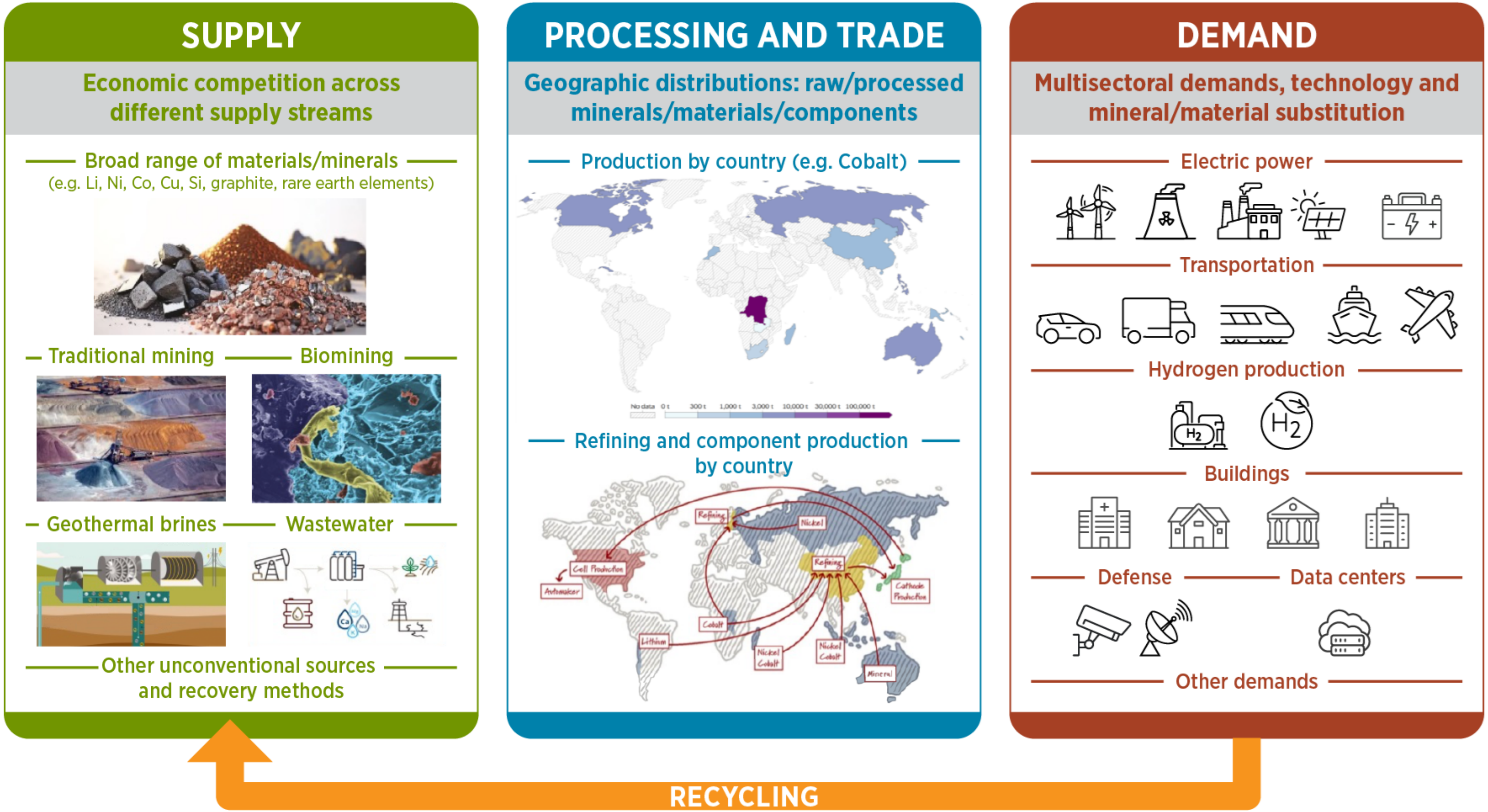
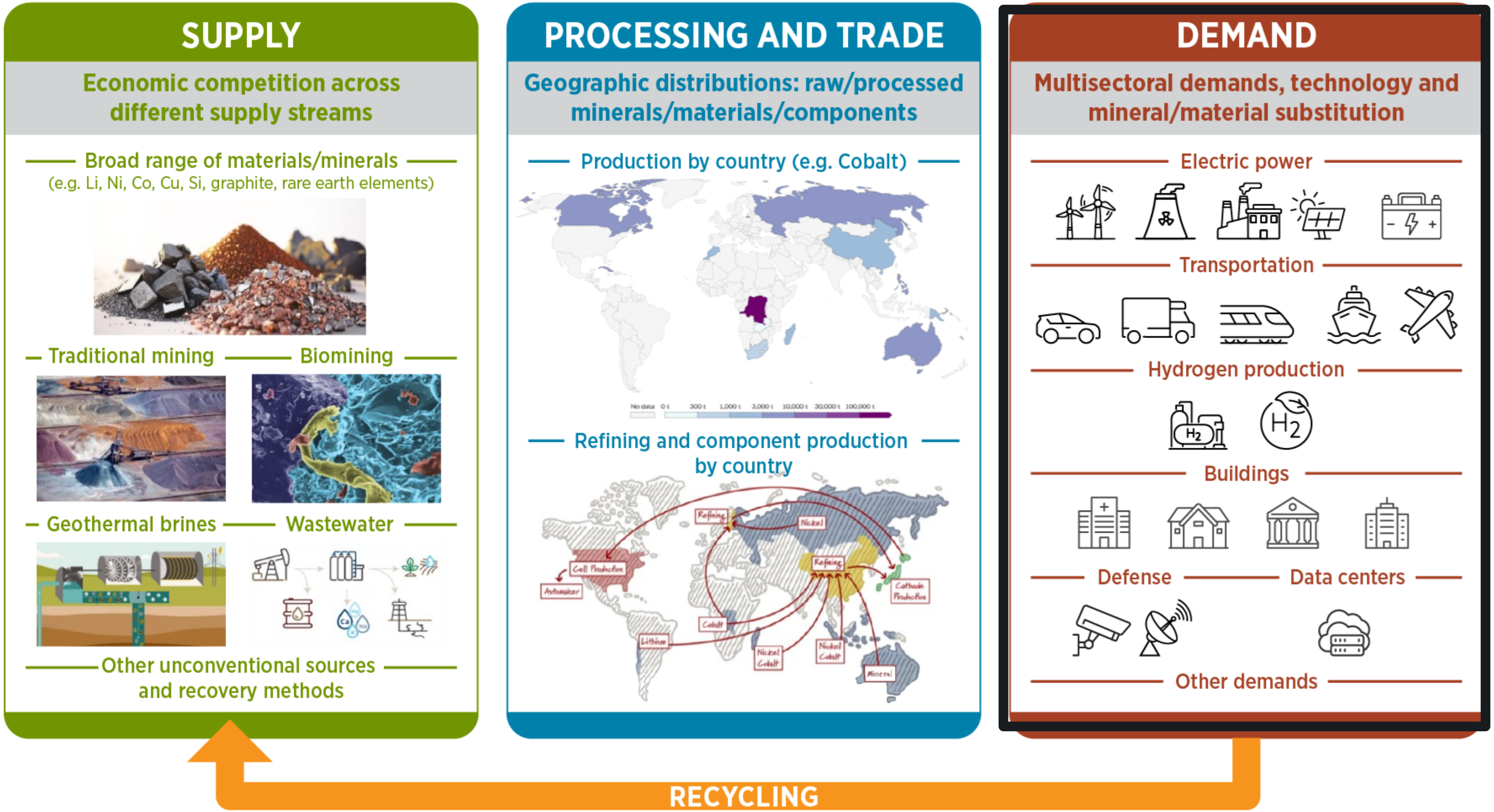
Critical minerals and materials modeling (CMM) in GCAM: Our vision



Critical minerals and materials modeling (CMM) in GCAM: Our vision



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The coverage of CMM by sectors - we maintain flexible capabilities to include additional CMMs and sectors

	Electricity (generation + T&D)	Transportation	H2 production	Buildings	Other
Steel	X	X	X	X	X
Aluminum	X	X	X	X	X
Copper	X	X	X	X	X
Silicon	X	X	X		X
Graphite	X	X			X
Lithium	X	X			X
Cobalt	X	X	X		X
Nickel	X	X	X		X
Manganese	X	X	X		X
Platinum		X	X		X
Neodymium	X	X	X		X
Tellurium	X	X			X
Vanadium	X	X			X

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	Electricity (generation + T&D)	Transportation	H2 production	Buildings	Other	Data Centers (US focused)
Steel	X	X	X	X	X	X
Aluminum	X	X	X	X	X	X
Copper	X	X	X	X	X	X
Silicon	X	X	X		X	X
Graphite	X	X			X	X
Lithium	X	X			X	X
Cobalt	X	X	X		X	X
Nickel	X	X	X		X	X
Manganese	X	X	X		X	X
Platinum		X	X		X	X
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Tellurium	X	X			X	X
Vanadium	X	X			X	X
Additional 30 CMMs	X	X				X

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Adding subtype technologies to represent CMM demand more accurately and allow for technology and material substitution

Solar PV
- c-Si PV
- CIGS thin film PV
- CdTe thin film PV
- a-Si PV

Wind turbine
- GB-DFIG
- GB-PMSG
- DD-PMSG
- DD-EESG

Building
- Apartment
- High-rise
- House
- Hotel
- Office
- Retail

Grid battery storage
- LFP
- NMC (532, 811)
- Vanadium flow battery

Electric vehicle
- LFP
- NCA
- NMC (111, 622, 811)
- Sodium-ion battery
- Solid-state batteries

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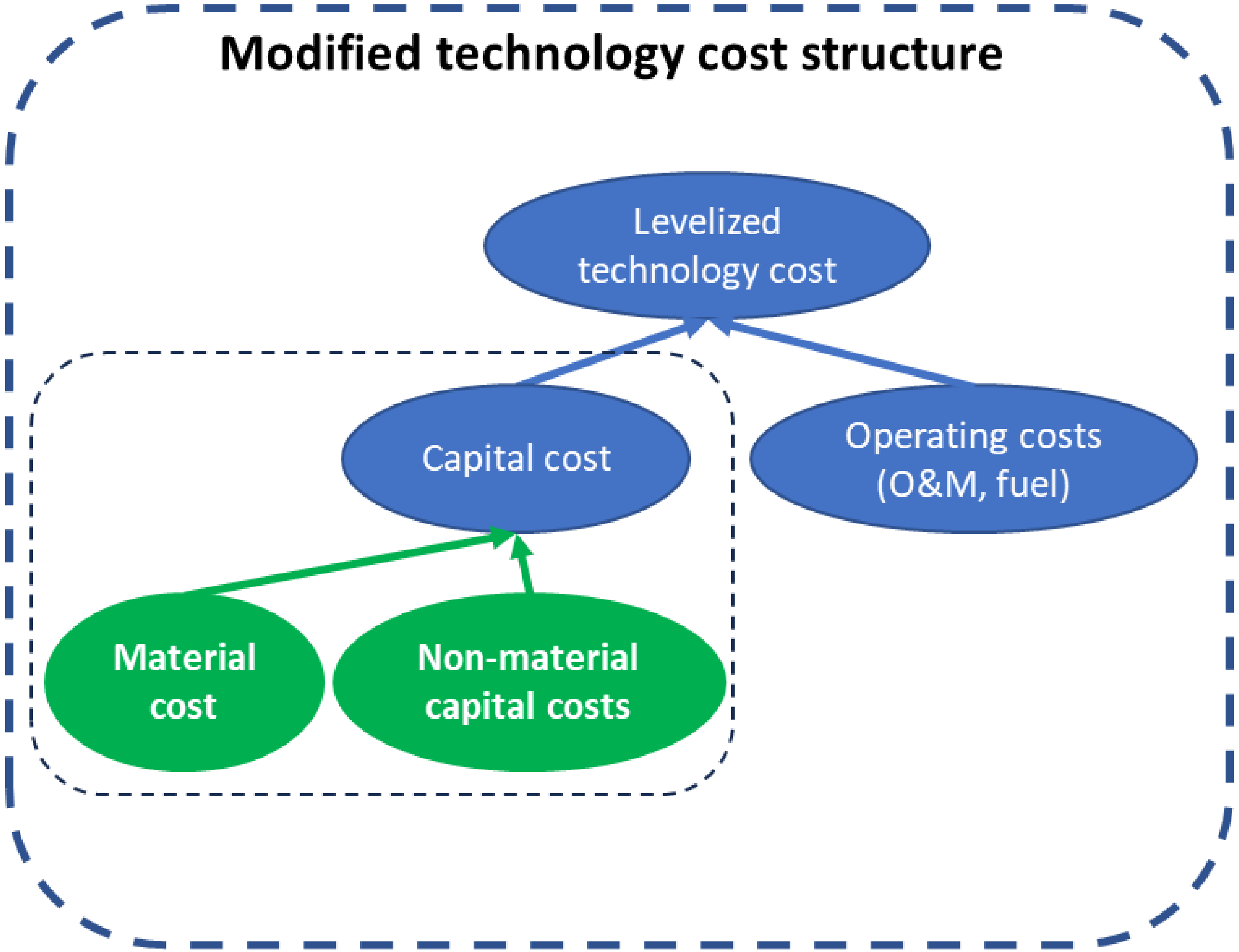
Structural change to explicitly track material and non-material cost components of technologies

- Splitting capital costs into: material costs and non-material capital costs.
- By modeling material cost separately, we can capture how material price changes could affect technology costs, and competition.



We model the evolution of mineral demands across multiple sectors

The multi-sectoral modeling capabilities of GCAM allow us the answer questions related to the energy-material nexus

Our recent study has explored the implication of CMM availability on energy system development. Here are the specific research questions:

1. How do material production constraints affect energy technology deployment?
2. What are the sectoral interactions (in energy system) under potential material production constraints?
3. What are the key factors that drive the sectoral competition for limited CMM?

(Qiu et al under review)

Scenario design to evaluate the implications of CMM production constraints on energy sectors

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We design a suite of exploratory scenarios shown in the table below.

Scenario names	Energy system development	Constraints on CMM production
Central	Reference	No constraint
Constrained scenarios *(A total of 13 x 3 = 39 scenarios)*	Reference	Exogenous constraints limit the annual production of 13 CMMs at 25%, 50%, 75% of the projected demand under the *Central (No constraint) scenario*.

In this study, production constraints are imposed exogenously as upper limits on CMM supply. When demand reaches these limits, GCAM endogenously increases material prices, raising the costs of technologies that rely on the constrained materials. Higher technology costs reduce technology deployment and material demand, so that demand does not exceed the limits.

Note, we have been also developing endogenous supply curves for CMMs in GCAM, which will be discussed in detail later.

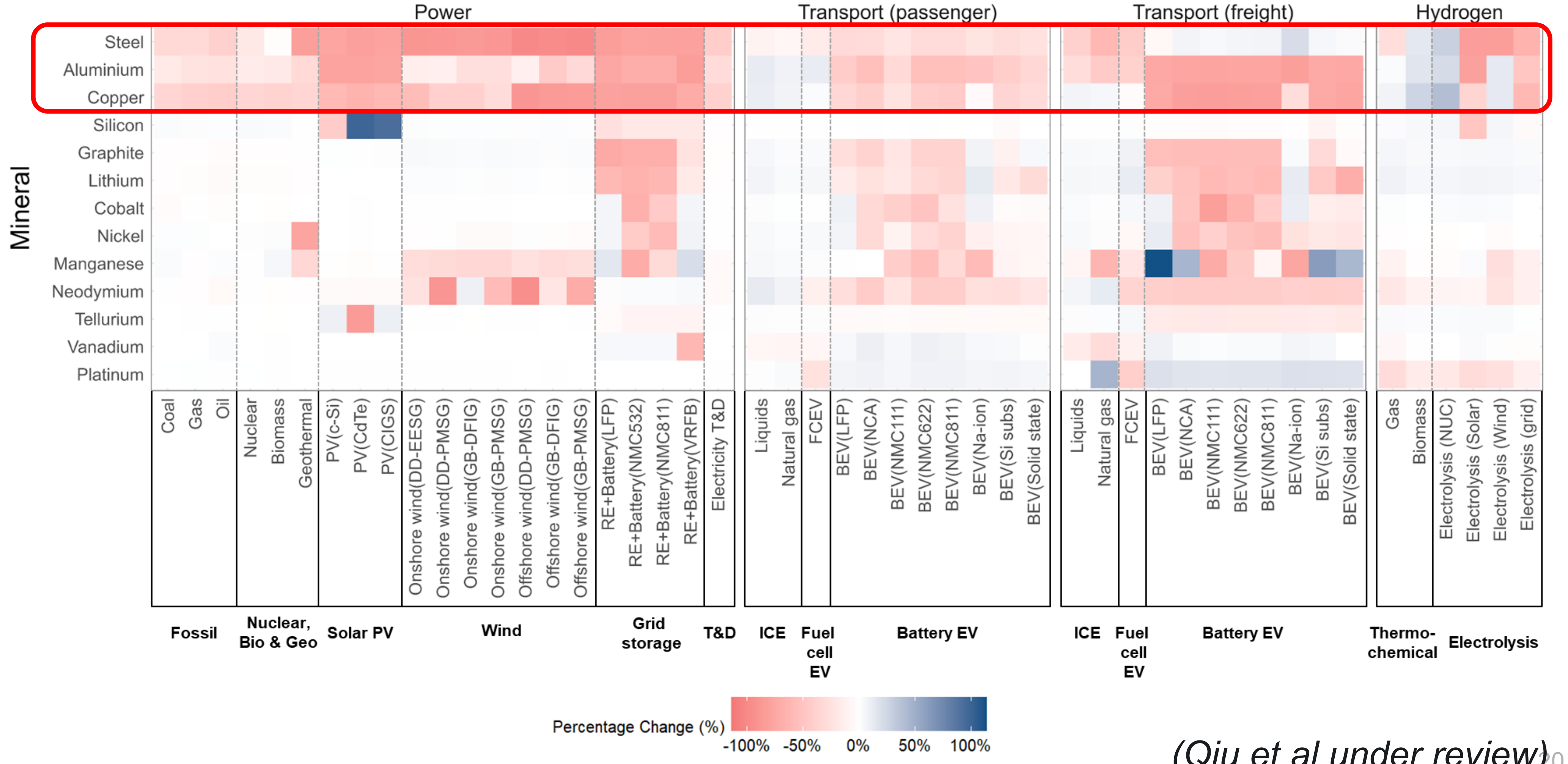
(Qiu et al under review)

The interdependence between material availability and technology deployment

Production constraints on different CMMs can affect technology deployment differently.

Bulk materials (Steel, Al, Cu) – reduce deployment across a broad range of energy technologies due to its wide applications.

Percentage change of technology deployment (cumulative from 2020 to 2050) under CMM production constraint (50% production level relative to *Central* case)



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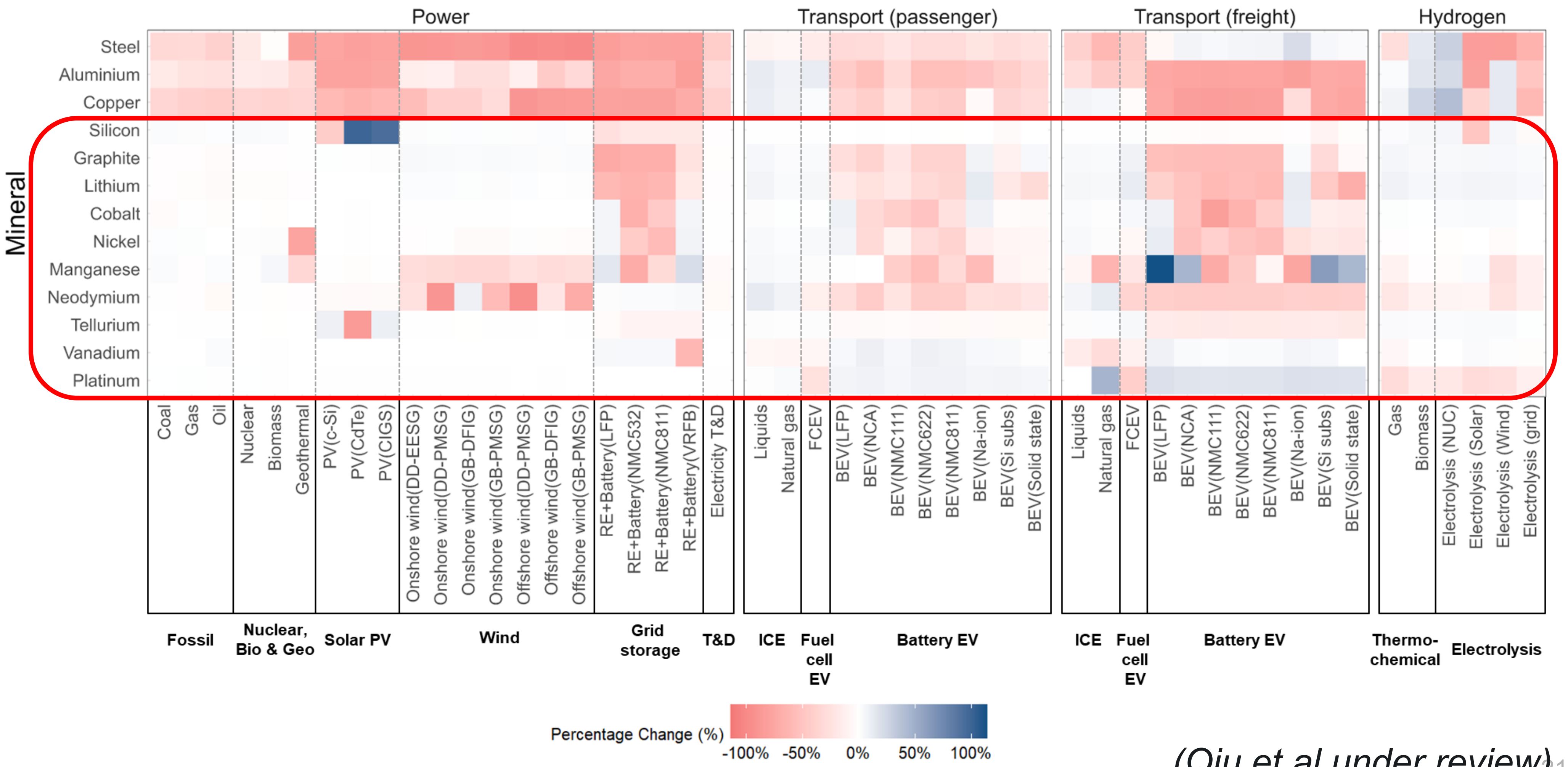

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Substitution effects:

- Silicon – reduces c-Si PV deployment but increase thin-film (CdTe, CIGS) PV deployment.
- Lithium – reduces BEV (Li-ion battery) deployment but increases BEV (Na-ion battery) deployment

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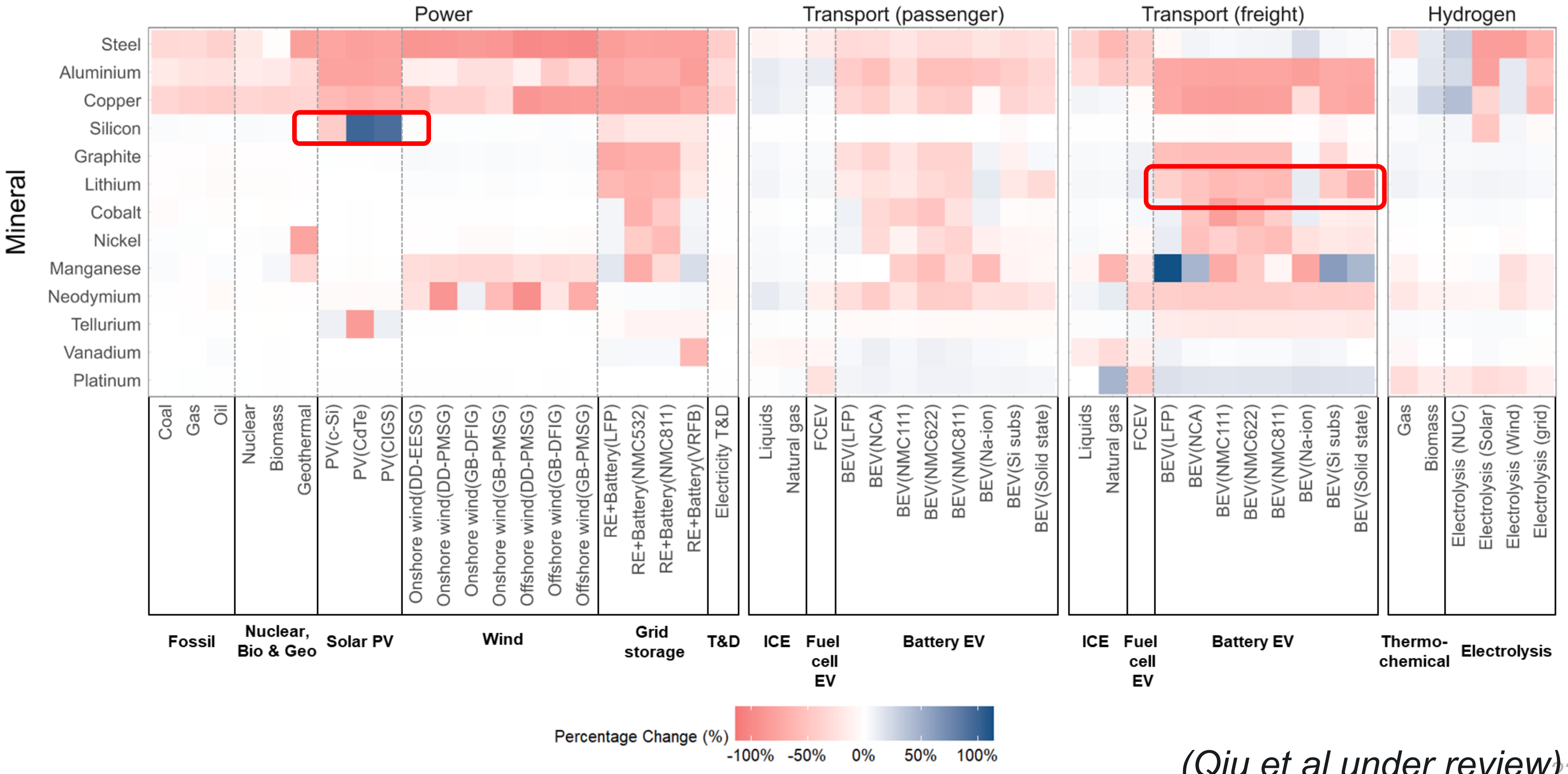


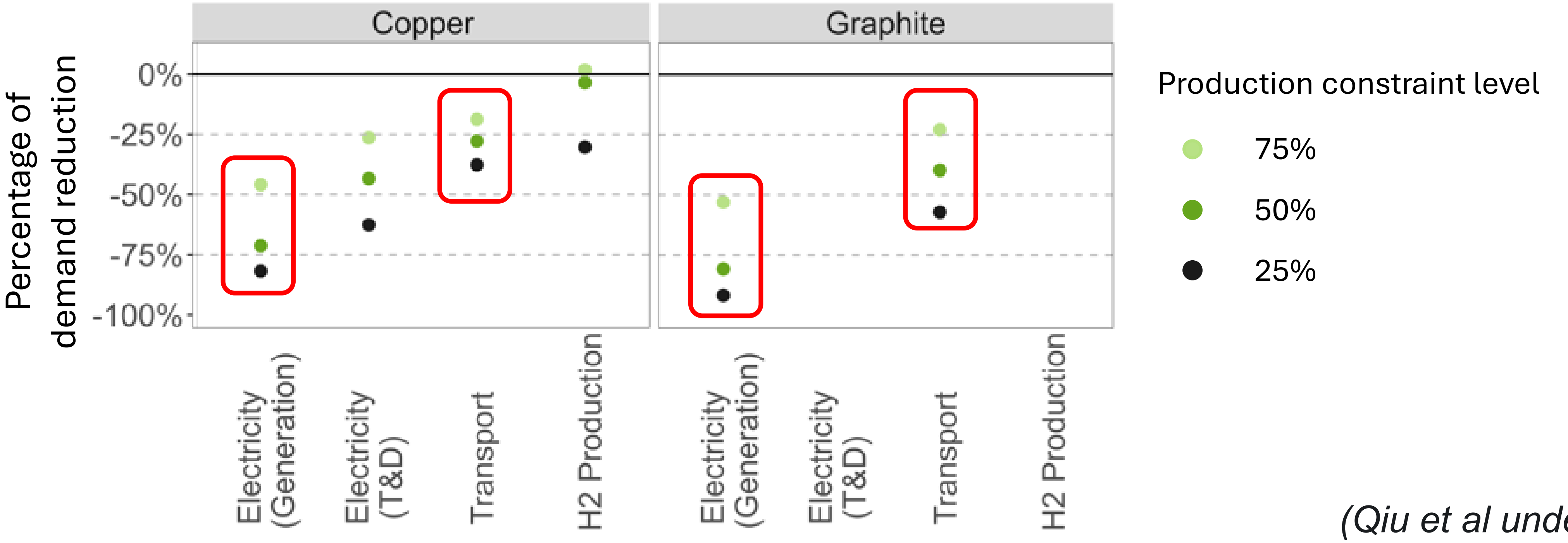
(Qiu et al under review)

The response of sectoral CMM demand to production constraint

Sectoral CMM demand shows different responses to production constraints depending on substitution flexibility and material intensity:

- **Cu constraint case:** Cu demand adjusts due to **sectoral substitution in service output**—energy generation shifts from electricity to less copper-intensive sectors (e.g., oil refining, gas processing), while mobility service has limited sectoral substitution, so transport sector Cu reduction is smaller.
- **Graphite constraint case:** Graphite demand adjusts driven by **technology material intensity**—grid battery storage is more sensitive to graphite price increase than BEV (due to higher Graphite intensity in grid battery storage), leading to greater demand decline in the power sector.

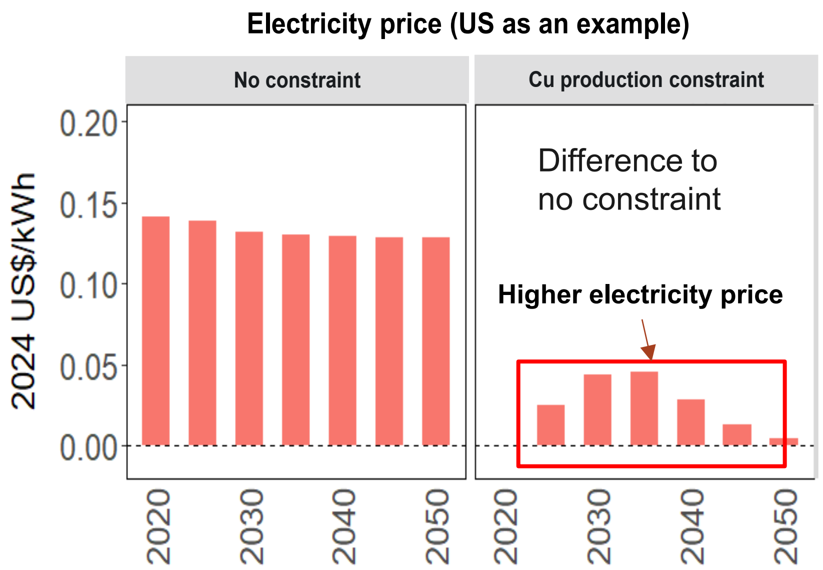
Changes of Cu and graphite demand by sectors under Cu and graphite constraint scenarios



(Qiu et al under review)

A more focused example: a constraint on annual copper (Cu) production has cascading and compounding multisectoral impacts

1. Higher Electricity prices



- Cu is demanded by electricity generation technologies + T&D networks
- Under a Cu constraint, higher Cu price leads to higher electricity prices.

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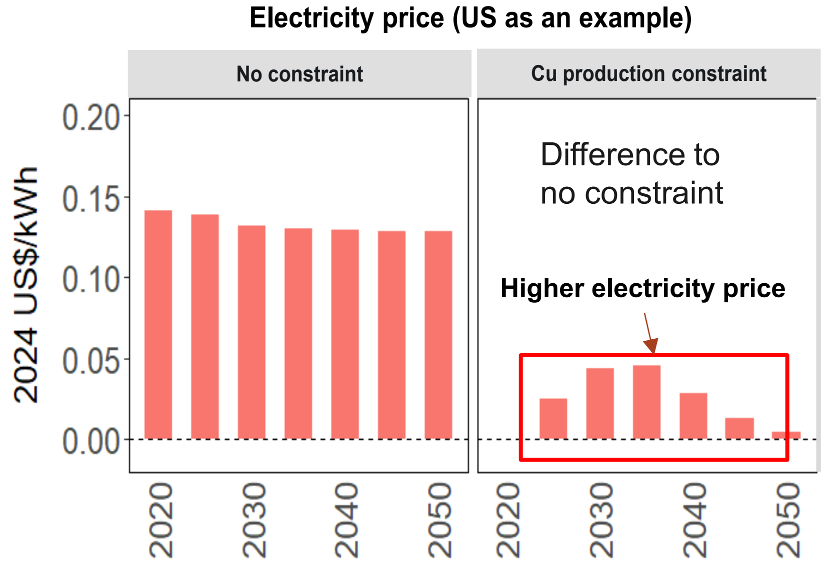

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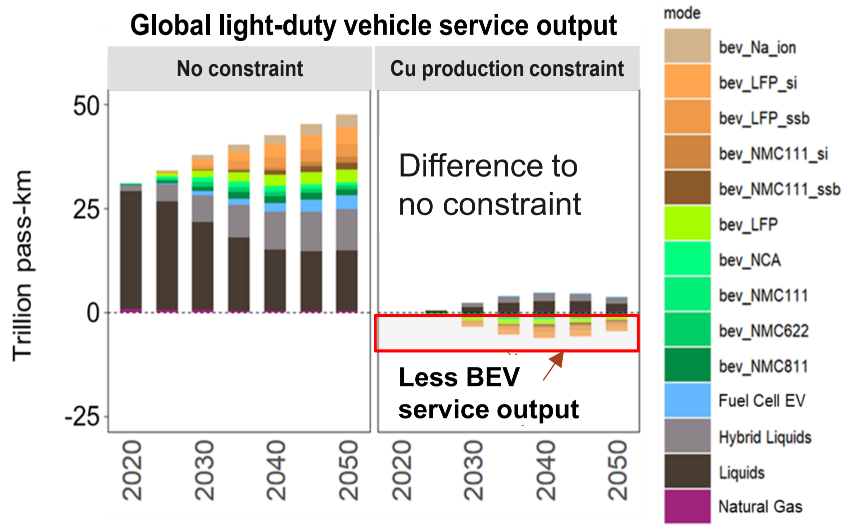
2. Lower deployment of battery electric vehicles (BEVs)



- Cu is demanded by both BEVs and gasoline cars, but BEVs have higher Cu intensity than gasoline cars;
- A Cu constraint results in higher increases in BEVs non-energy cost than gasoline cars..
- Higher electricity prices + higher BEV non-energy cost make BEV less competitive, leading to lower BEV deployment.

(Qiu et al under review)

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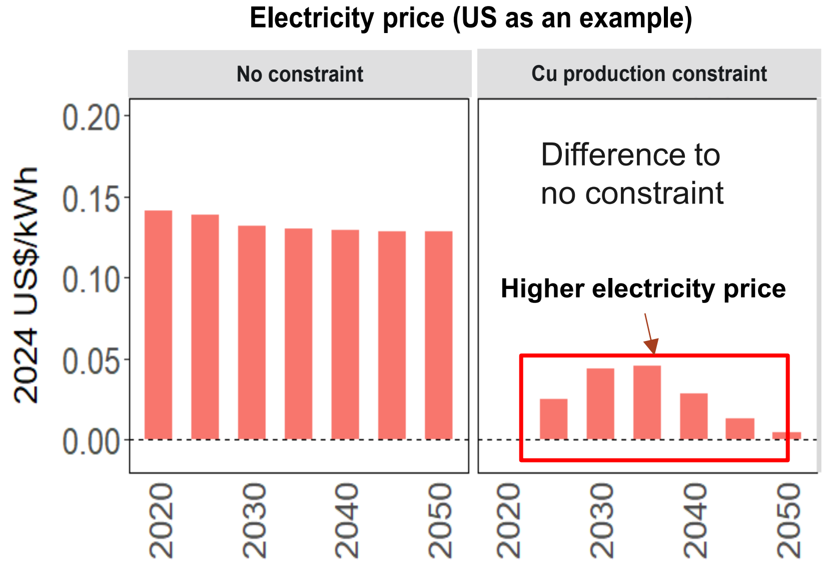

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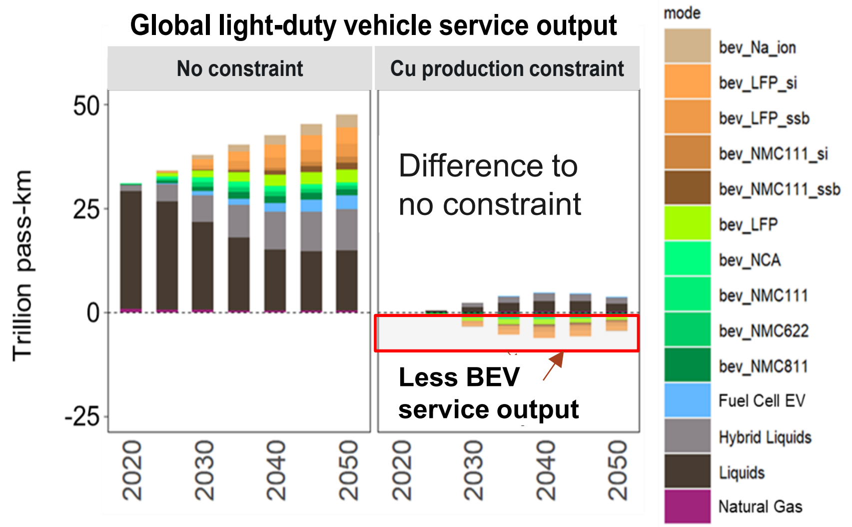

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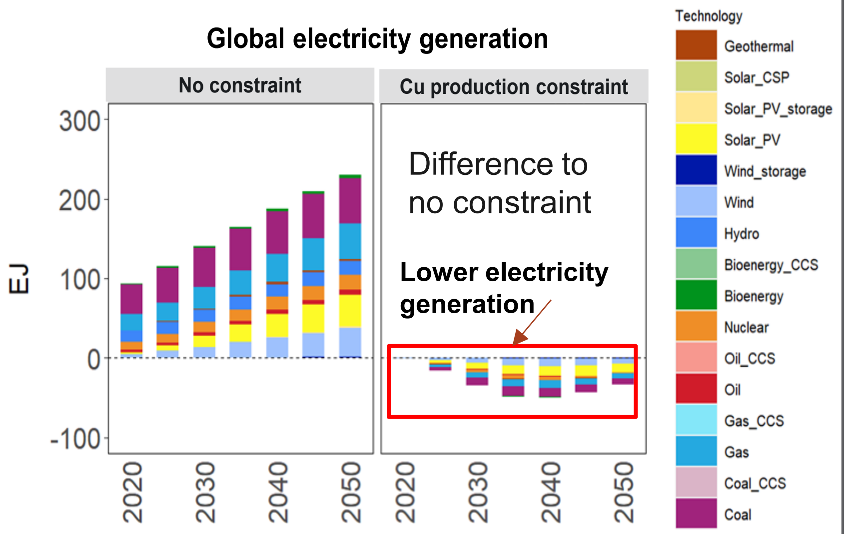
3. Lower electricity generation



- Higher electricity prices and lower electricity demands (through lower BEV deployment) result in lower electricity generation

(Qiu et al under review)

Key takeaway messages

- Production constraints on bulk materials (Steel, Al, and Cu) exert broader system impact due to their wide applications. Therefore, their supply security are essential for future energy system development.

- Production constraints on specialty CMMs mainly reduce deployment for specific technologies that uses the materials, and technology substitution represent a key strategy for reducing vulnerability to their supply risks.

- Sectoral CMM demand shows different responses to production constraints depending on substitution flexibility and material intensity.

- Due to the sectoral linkages of different energy sectors, CMM supply constraints could have cascading effect across multiple sectors, highlighting the importance of using integrated, multi-sector modeling approach to understand the implication of material supply availability on energy system development.

(Qiu et al under review)

Q&A

Estimating Future CMM Demands for Data Centers

Neal Graham Mengqi Zhao, Stephanie Morris, Gokul Iyer, Yang Qiu, Brinda Yarlagadda, Pralit Patel, Thomas Wild, Marshall Wise

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Research Objective

Quantify the demand for critical minerals and materials in future projections of uncertain technological development and data center service growth.

GCAM approach to analyzing the future of energy, water, CMM, and economic implications of DCs

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Distinguish data centers services and structural drivers of demands for those services

- Storage, streaming, telecom
- Cloud, HPC, AI

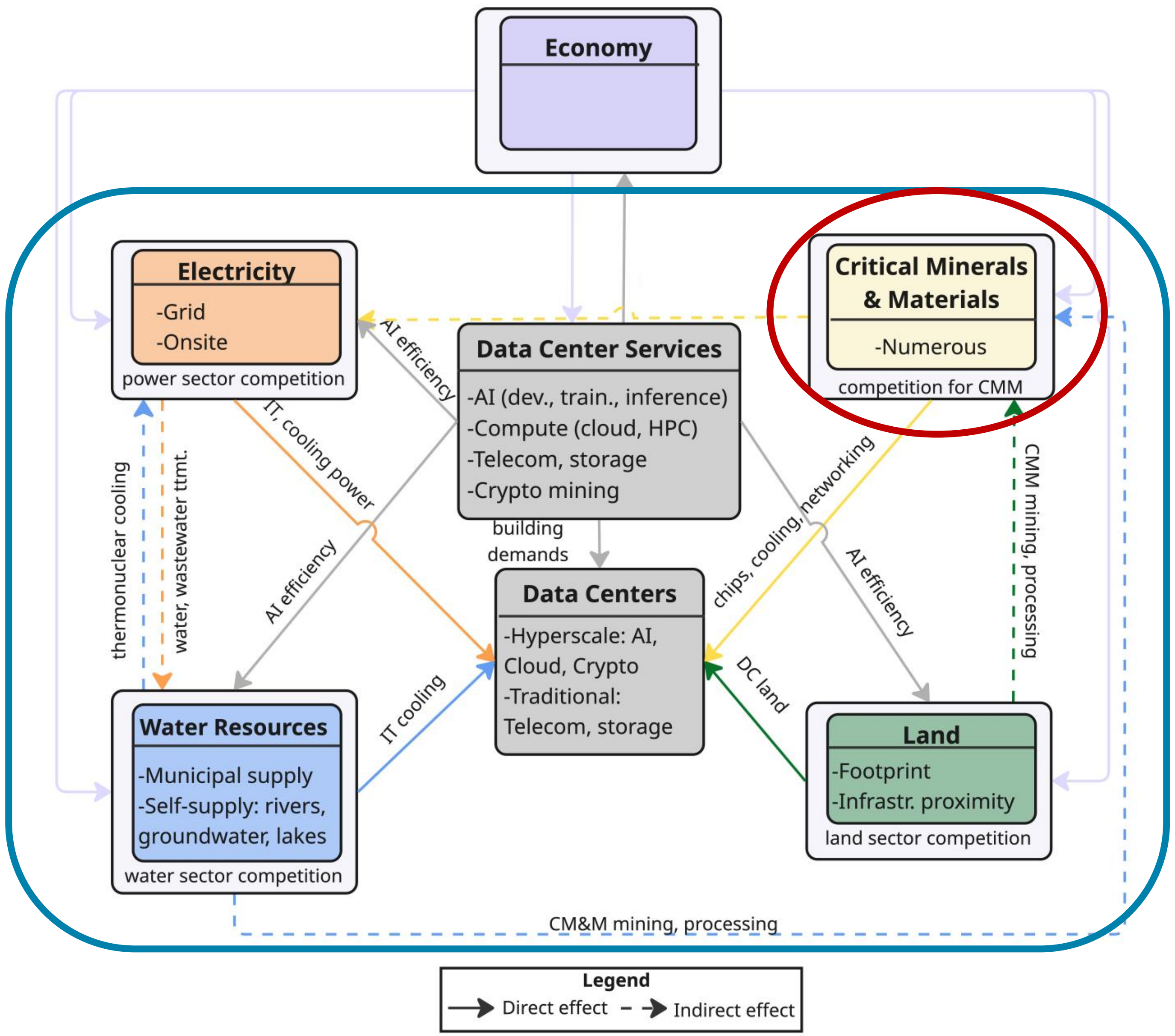
Categorize service demands for DC types

- Co-located/traditional
- Hyperscale

Quantify resource intensity of DCs and competition across demands for electricity, water, land, and ***critical minerals***

- Grid and onsite generation
- Water demands are both direct (onsite cooling) and indirect (electricity generation)

Modeling DC service feedbacks to the economy through improved energy efficiency, labor, energy, and capital productivity



Data Center components require a vast number of CMMs, many of which compete for use in other sectors such as electricity and transportation

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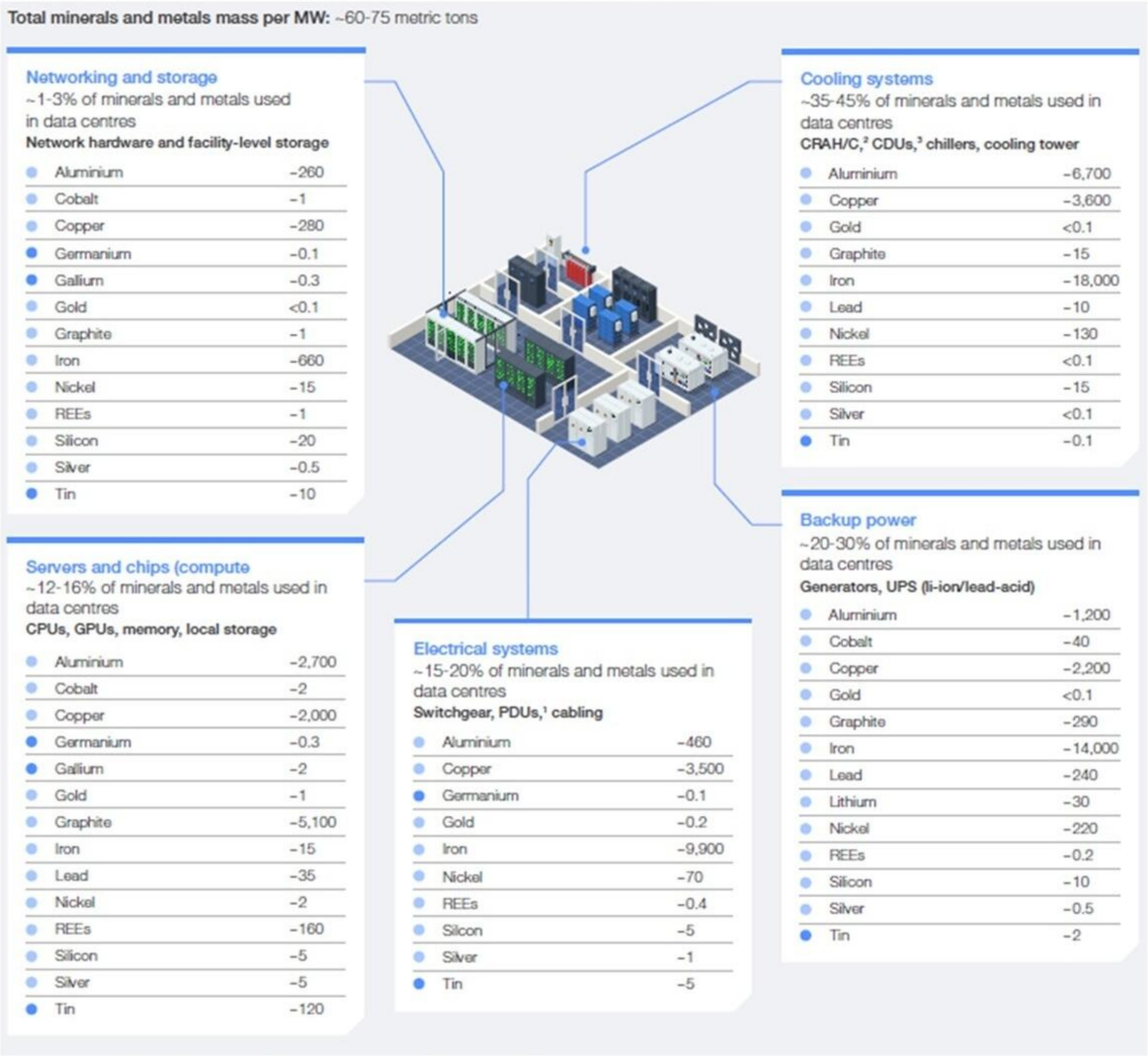
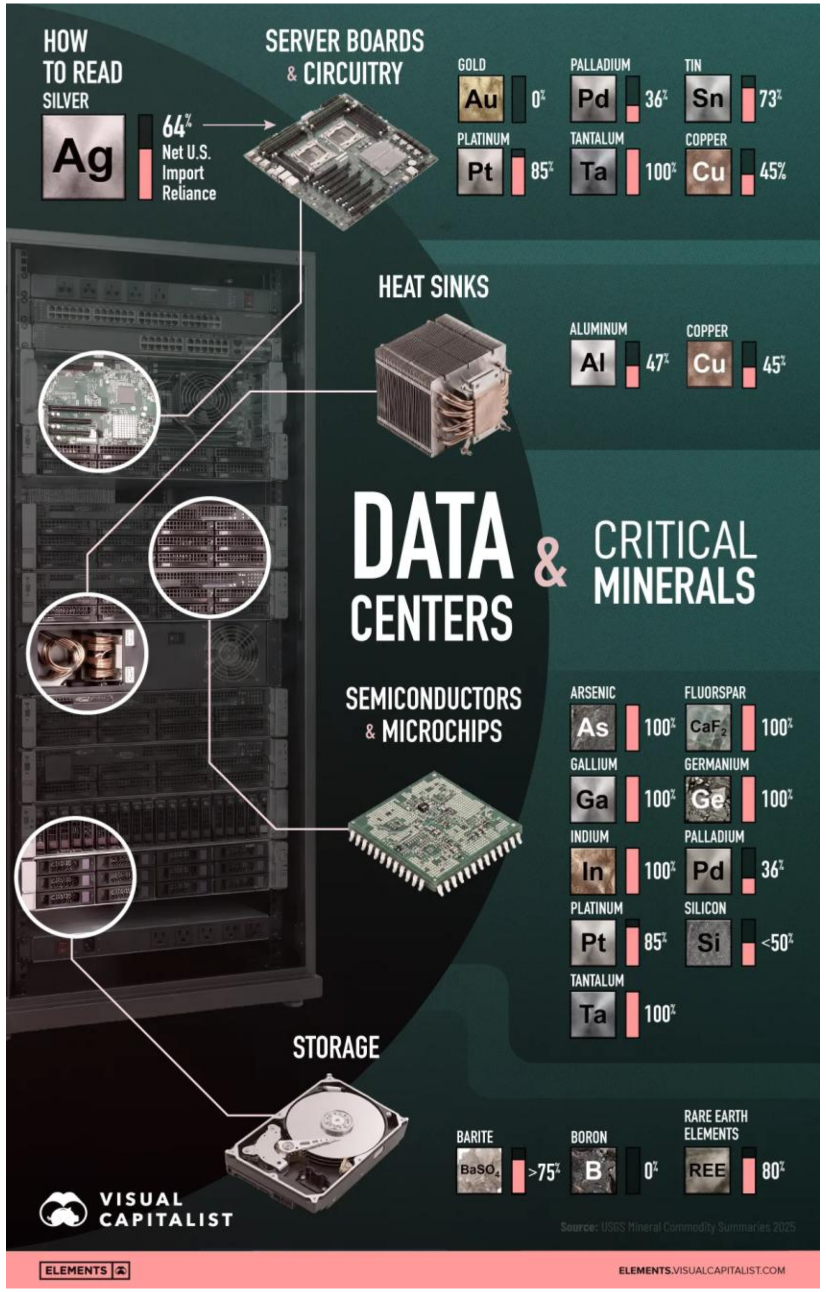


World Economic Forum, 2025



Adopted and edited from USGS

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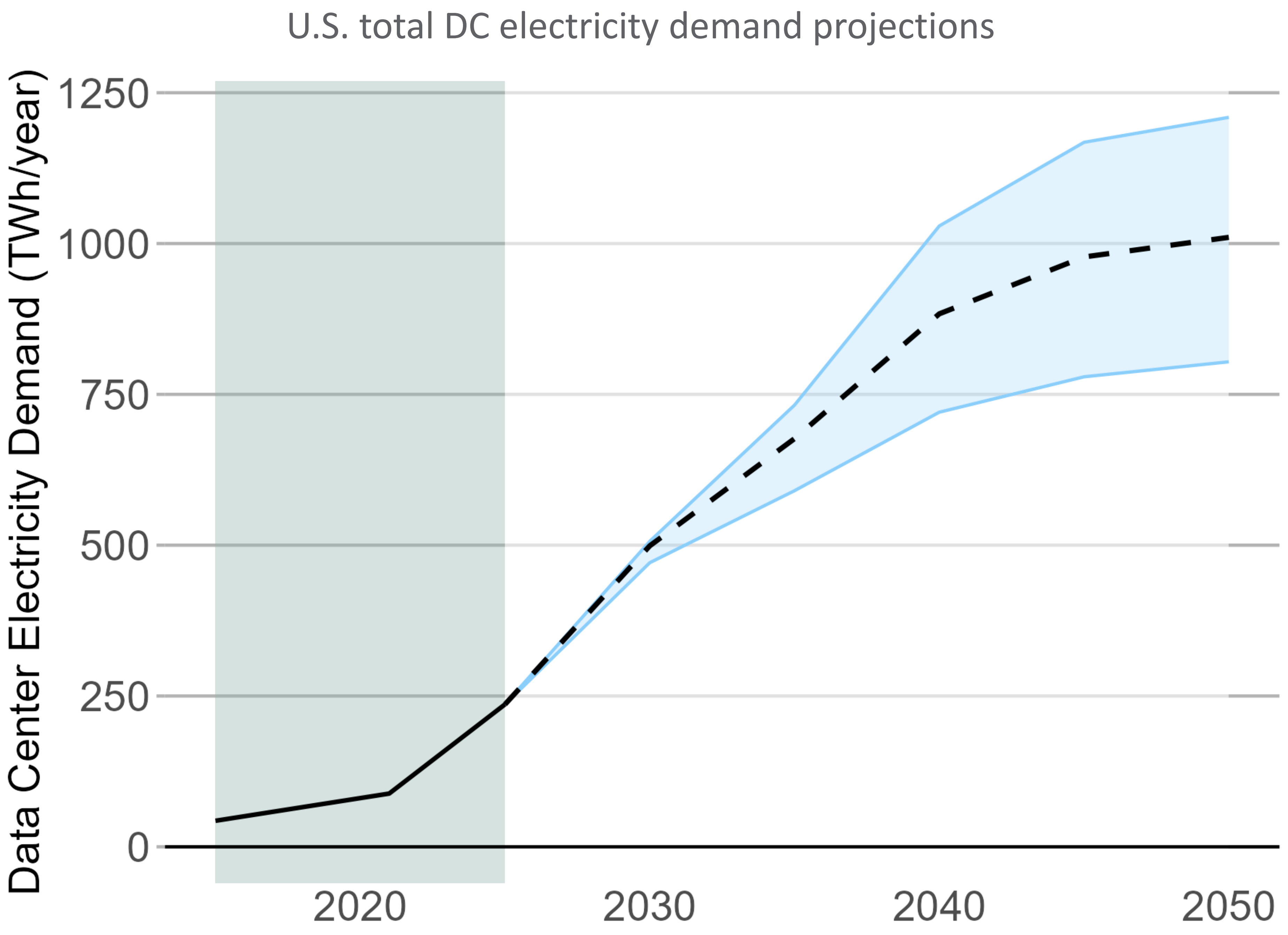
Range of U.S. DC electricity demand under alternative scenario component parameterizations



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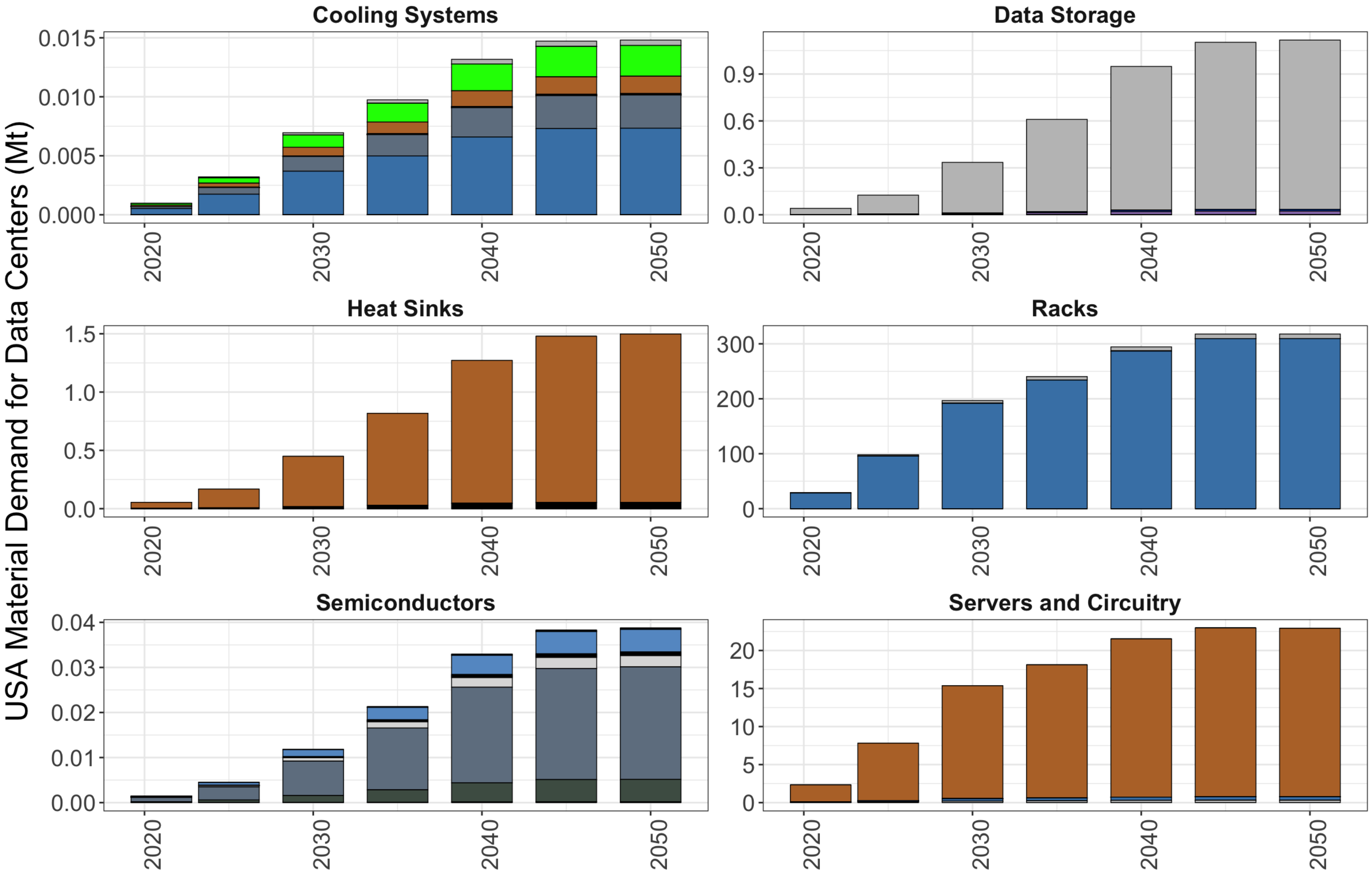
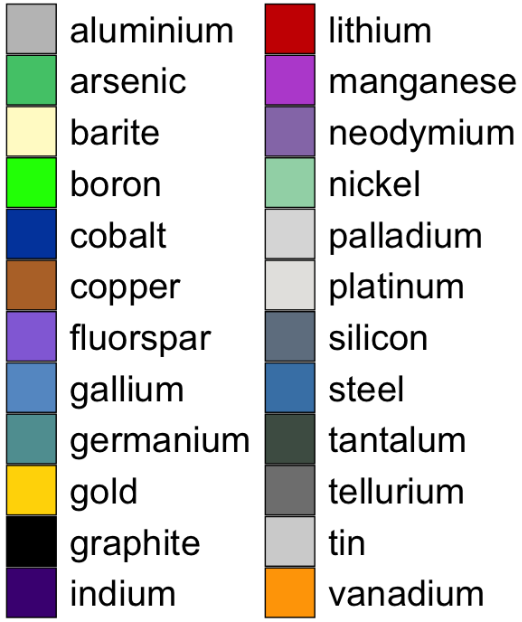
DCs place pressure on CMM systems which already have multisectoral pressures from transport and energy



Some (platinum, neodymium, tantalum) are in direct competition with energy and transport



Small but consequential quantities: even modest DC demand growth places pressure on REE's and supply chains

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Key Takeaways and Next Steps

- Future US data center growth results in a significant increase in REE’s via semiconductors, data storage, and cooling system components.
- Bulk materials such as copper, steel, and aluminum show large DC demands, but are outweighed by other sectors.
- Cross-sector demand competition for CMMs will drive uncertain responses in the technological growth.

- Evaluate future technological change brought upon by MSD competition and CMM supply chain constraints.
- Refine material intensity and technological improvement estimations for data center components to increase quantification robustness.

Q&A

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Modeling CMM Supplies in GCAM

Brinda Yarlagadda, Anastasiia Zagoruichyk, Yang Qiu, Karan Bhuwalka, Pralit Patel, Neal Graham, Marshall Wise, Maggie Liu, Siddarth Durga, Allen Fawcett and Gokul Iyer

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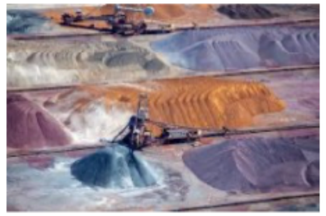
(e.g. Li, Ni, Co, Cu, Si, graphite, rare earth elements)

Traditional mining



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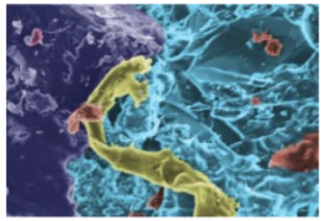

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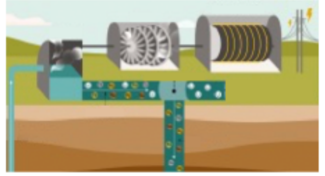


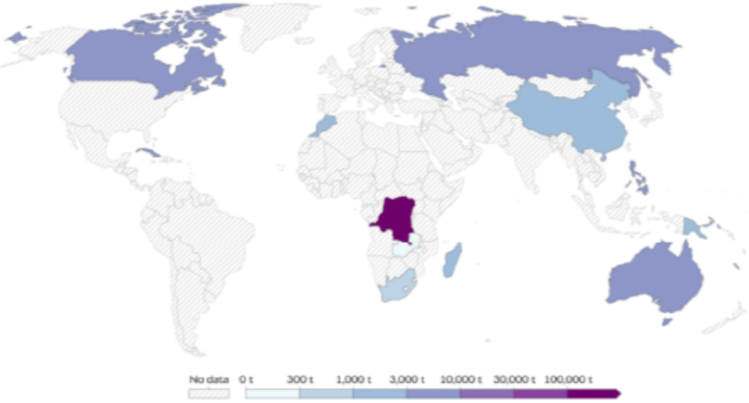
Wastewater

Other unconventional sources and recovery methods

PROCESSING AND TRADE

Geographic distributions: raw/processed minerals/materials/components

Production by country (e.g. Cobalt)



Refining and component production by country

DEMAND

Multisectoral demands, technology and mineral/material substitution

Electric power

Transportation

Hydrogen production

Buildings

Defense

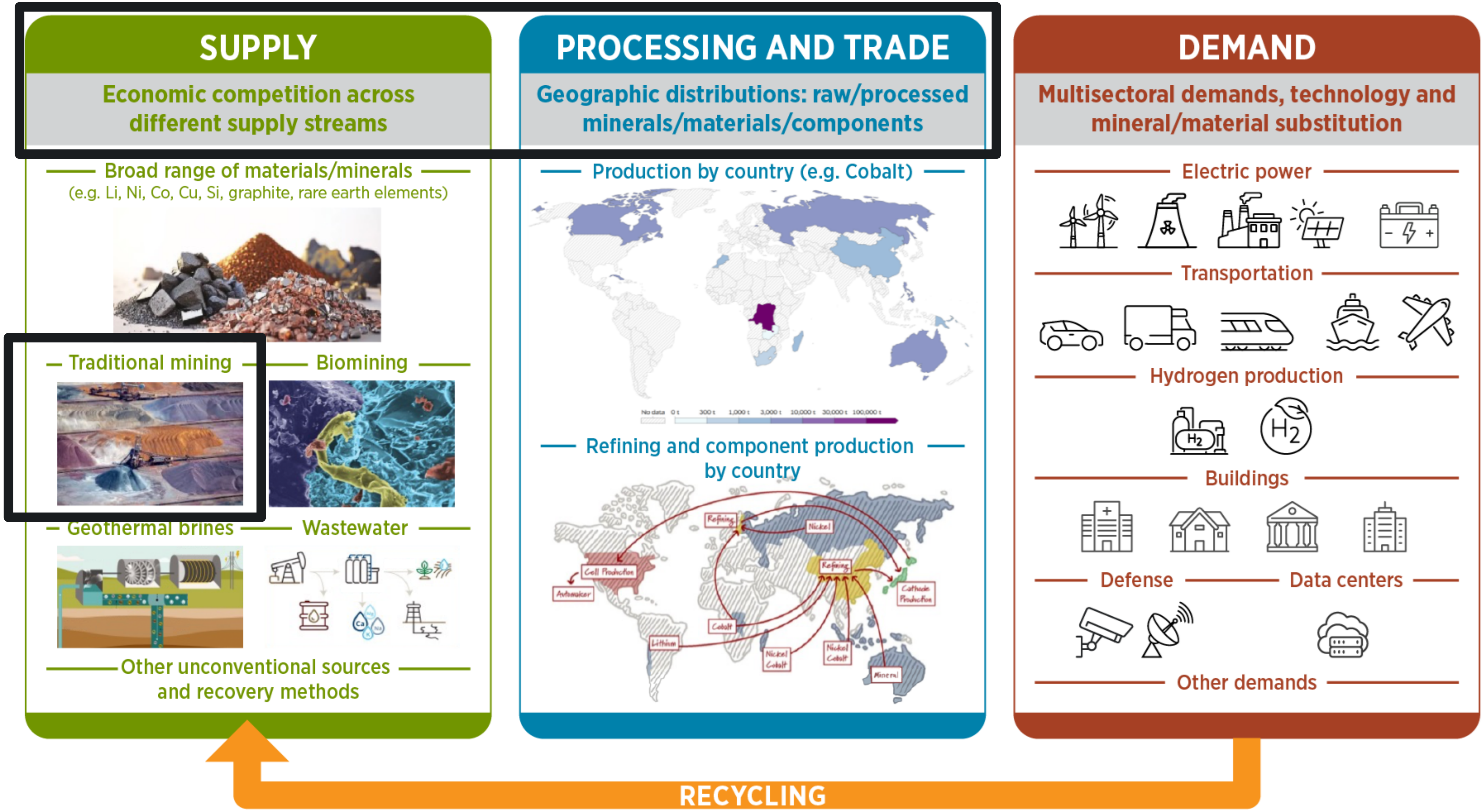
Data centers

Other demands

RECYCLING

GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Critical minerals and materials modeling (CMM) in GCAM: Our vision

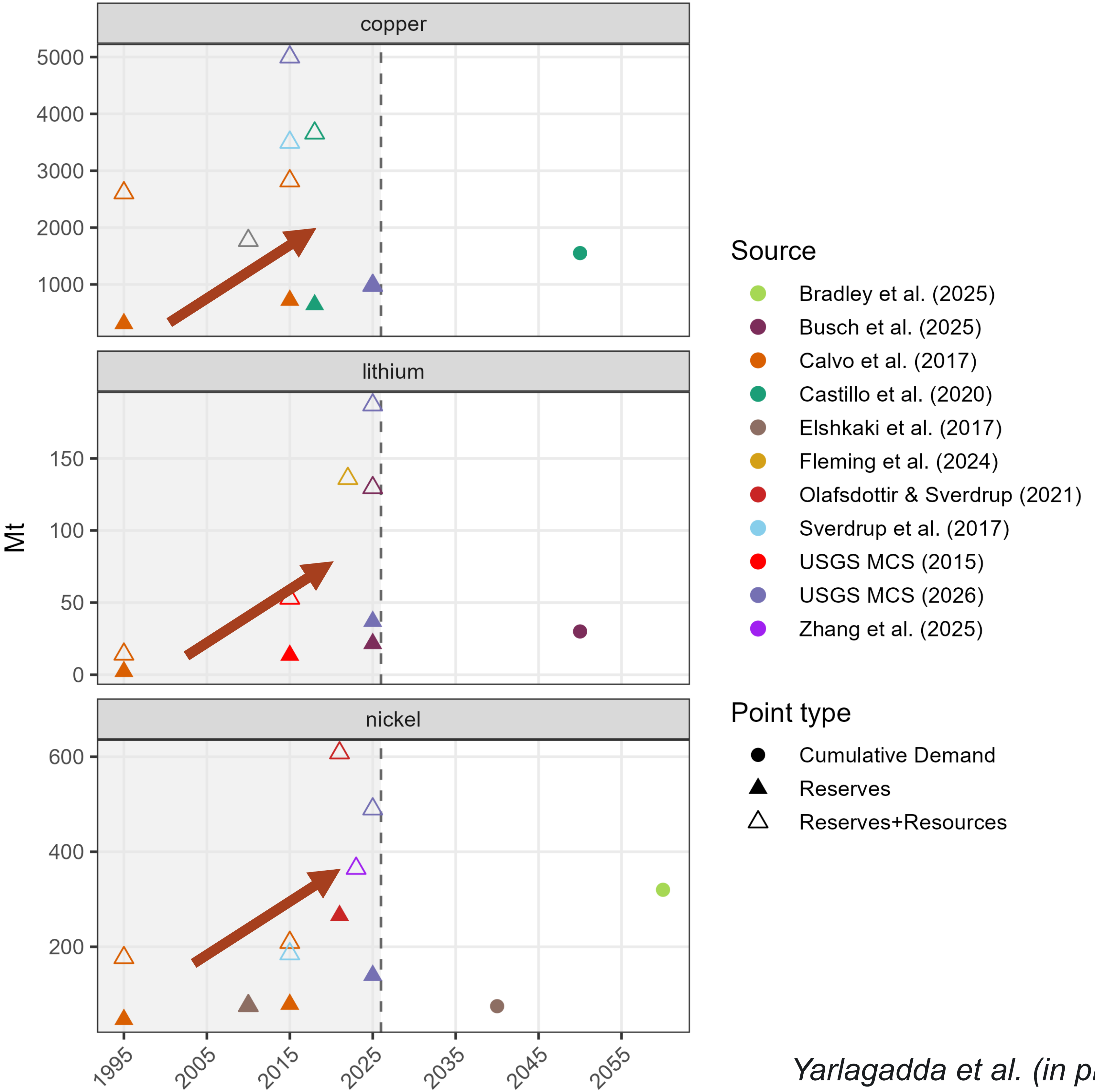


GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Future demand for CMMs could grow significantly in the coming decades.

Is there enough supply?

Estimates of resources and reserves have increased over time, indicating that enough physical resources likely exist…



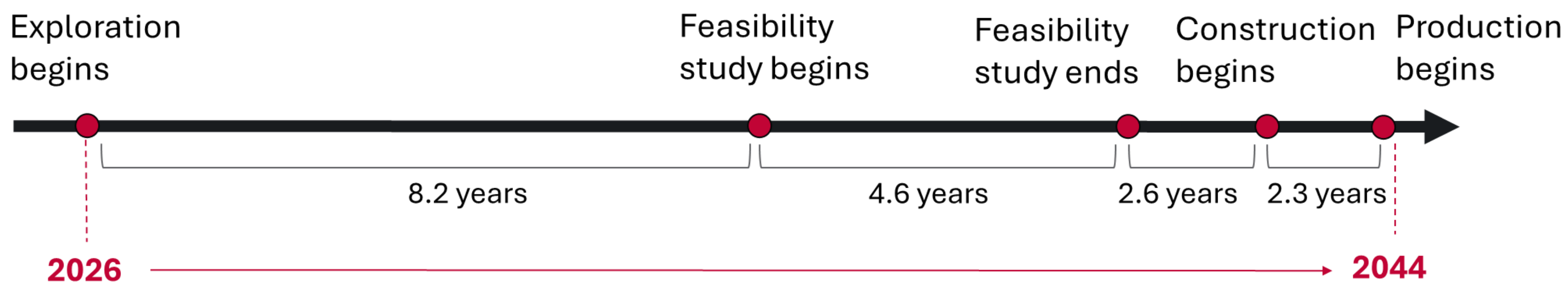
Yarlagadda et al. (in prep.)

GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Future demand for CMMs could grow significantly in the coming decades.

Is there enough supply?

…however, **recent declines in exploration** and **long lead times for mining projects to reach completion** are potential bottlenecks.

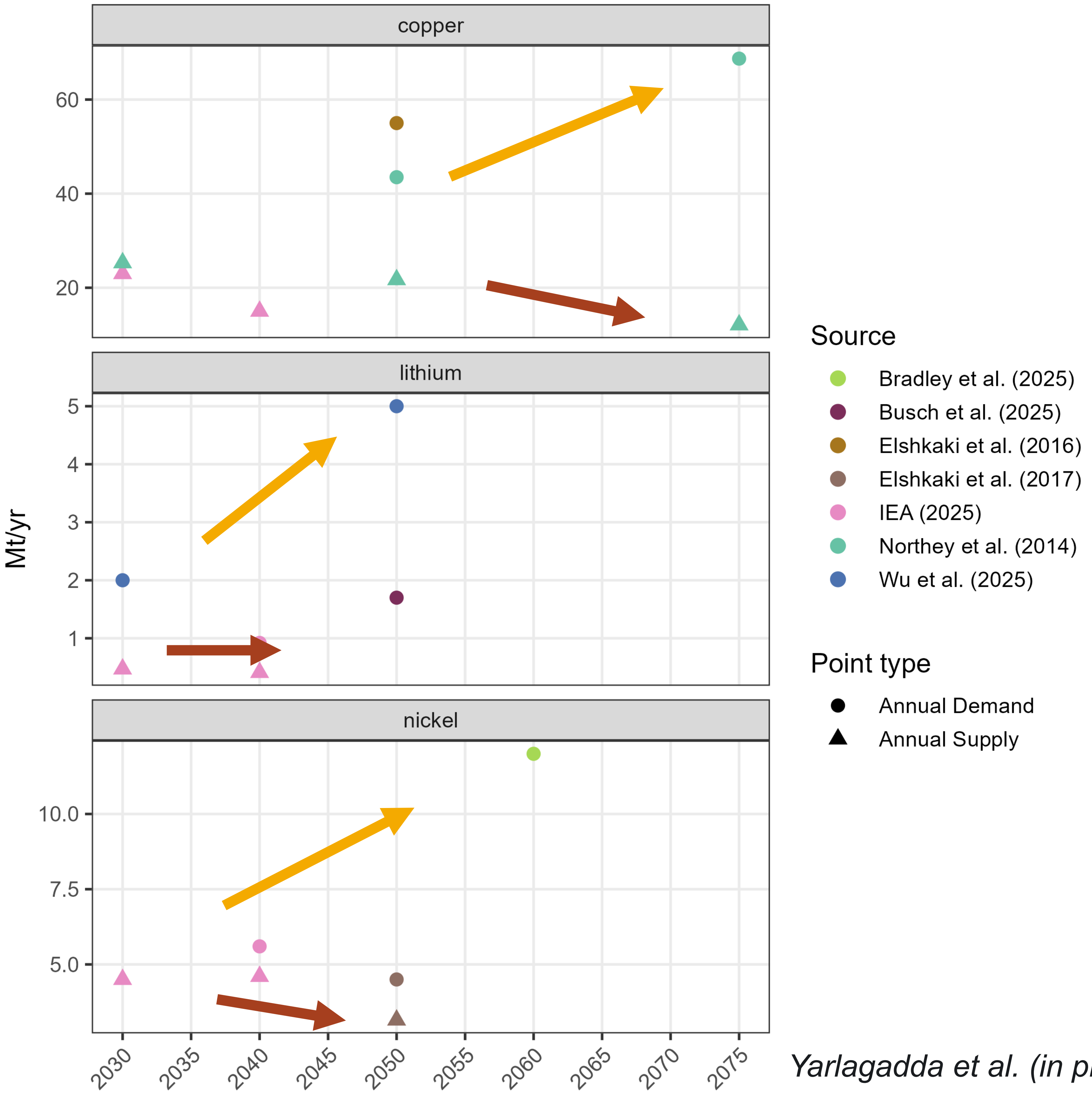


Yarlagadda et al. (in prep.)

GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

CMM supplies and demands must both be characterized in a dynamically-evolving manner

Many studies characterize **increasing CMM demands** over time, but take a **static view of supplies** (e.g. based only on mining projects that exist today).



Yarlagadda et al. (in prep.)

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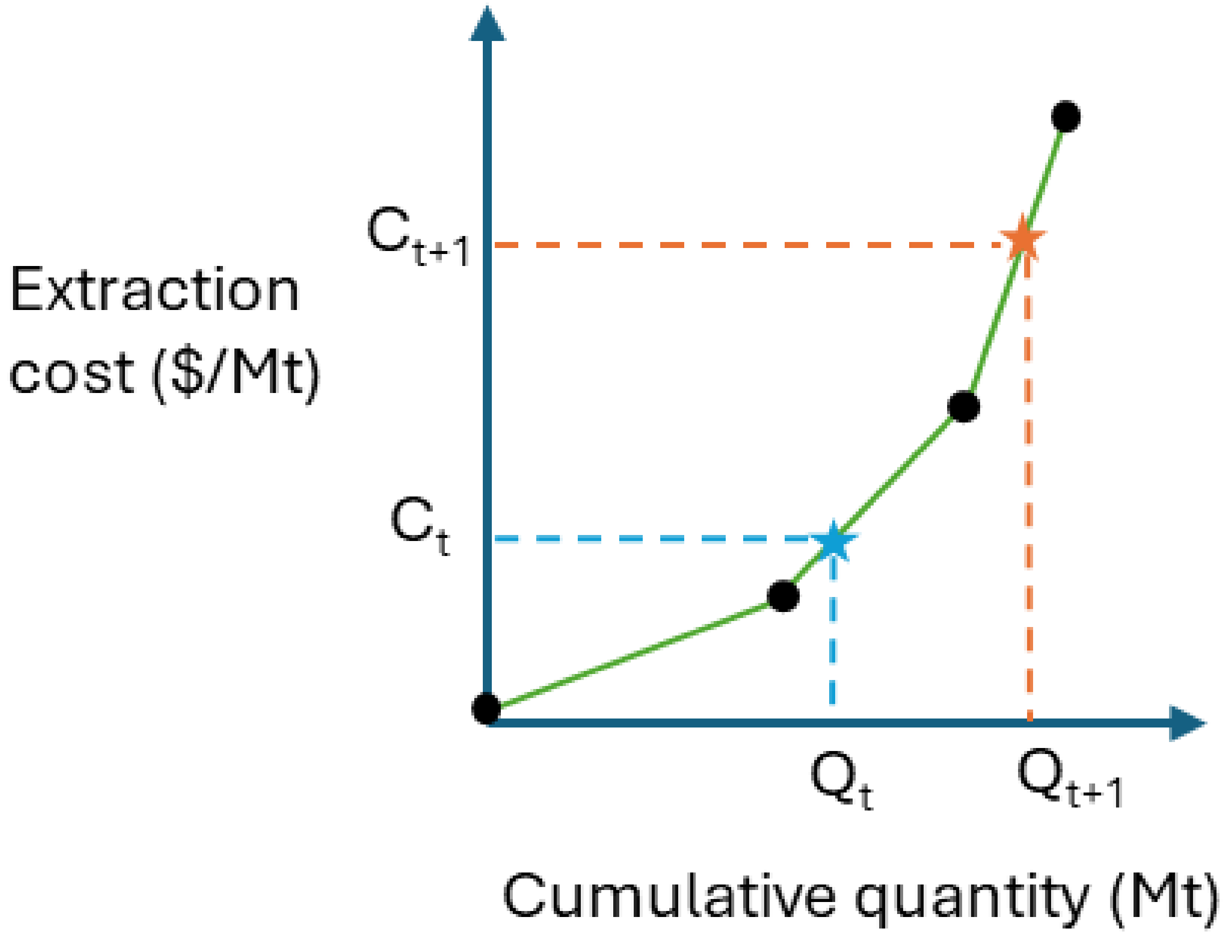
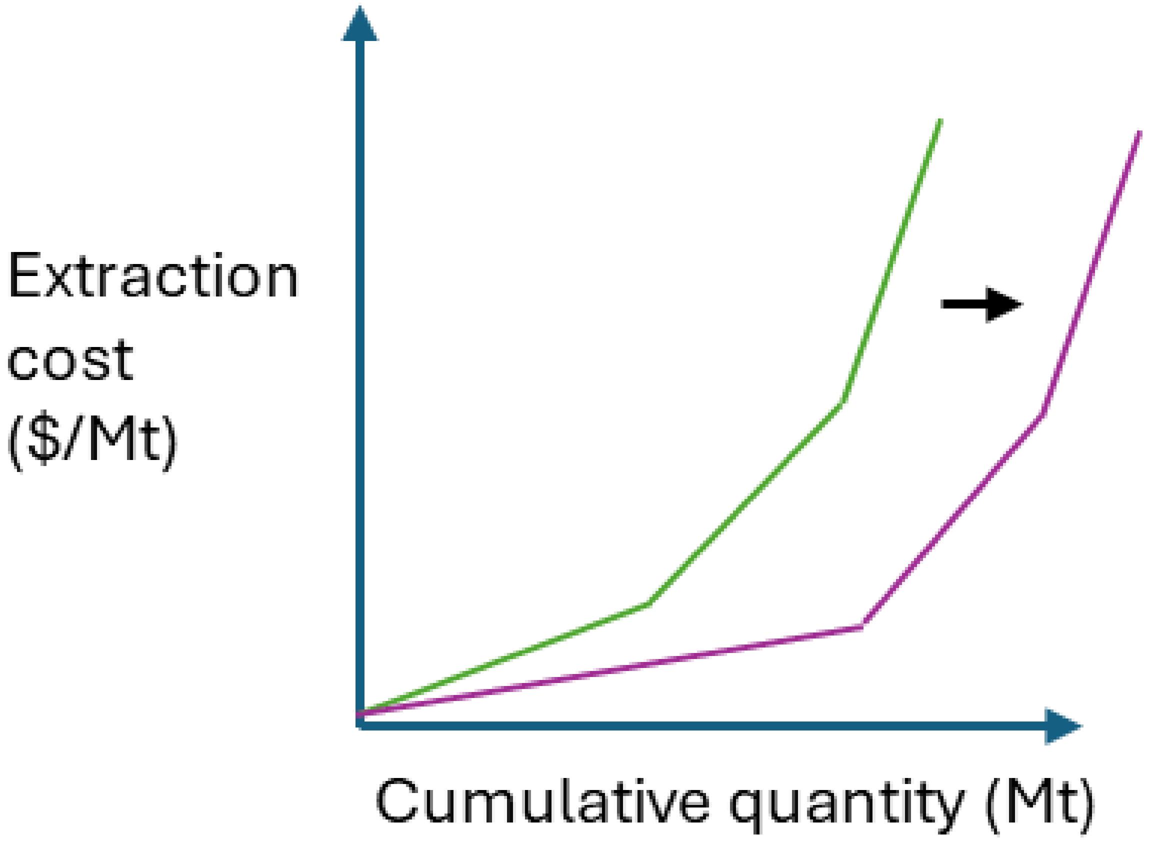
We created time-evolving regional CMM resource supply curves for GCAM

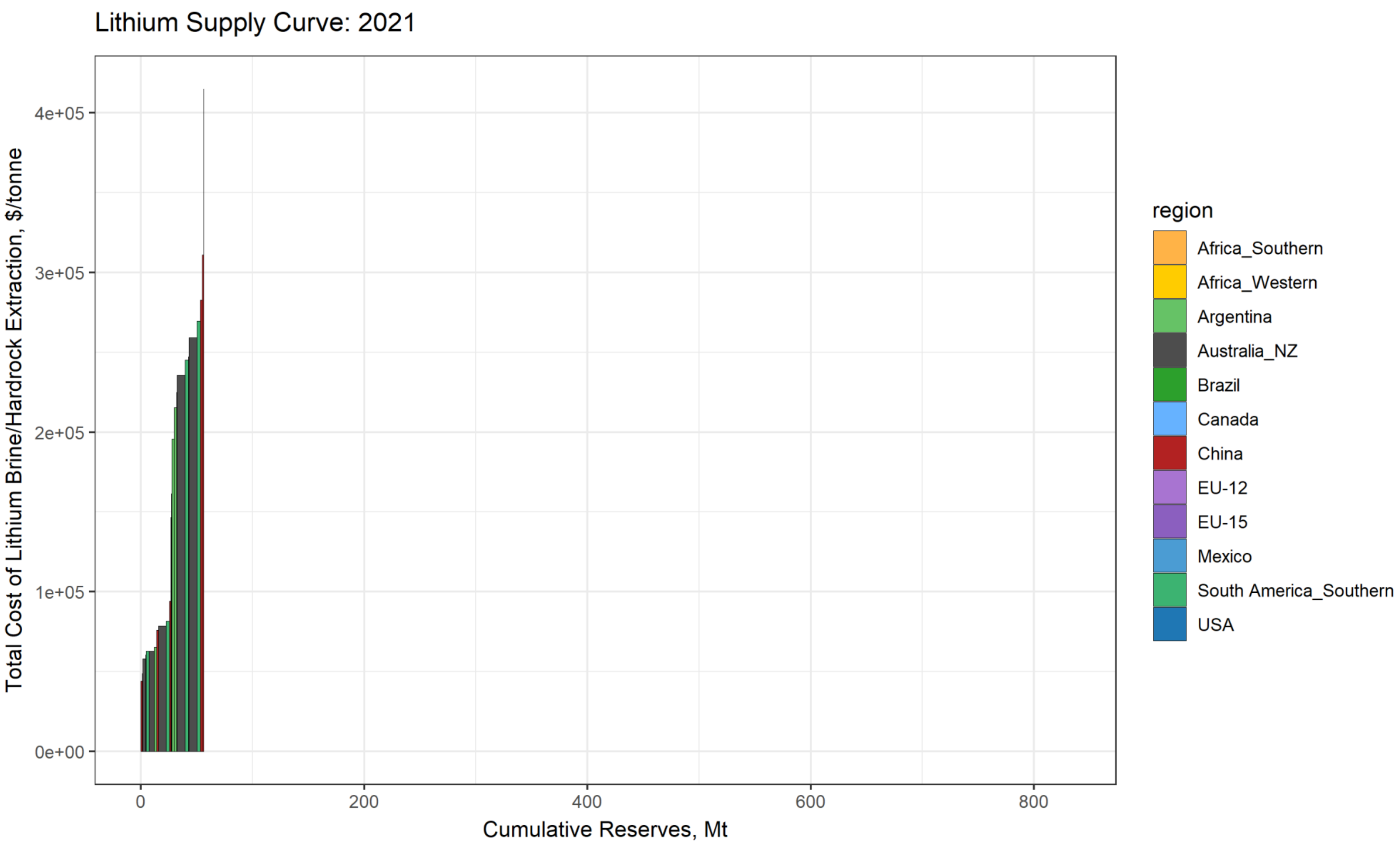




Time-evolving supply curve

Yarlagadda et al. (in prep.)

We created time-evolving CMM resource supply curves for GCAM

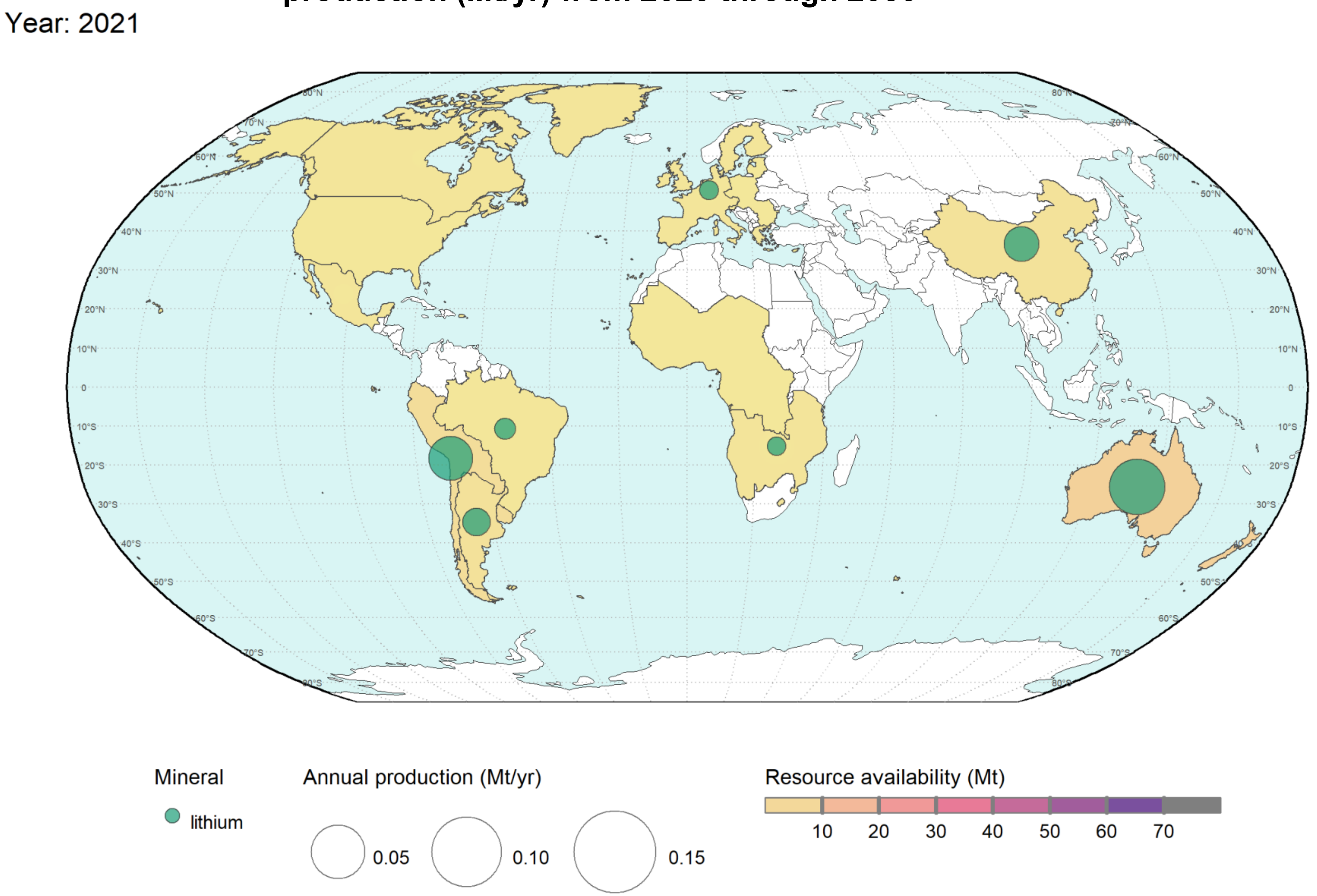


Note: here we show a single global curve, but each region has separate supply curves and produces CMMs based on logit competition and costs.

Yarlagadda et al. (in prep.)

We use GCAM to project dynamically-evolving CMM supplies and demands

Example: Lithium resource availability (Mt) and annual production (Mt/yr) from 2020 through 2050

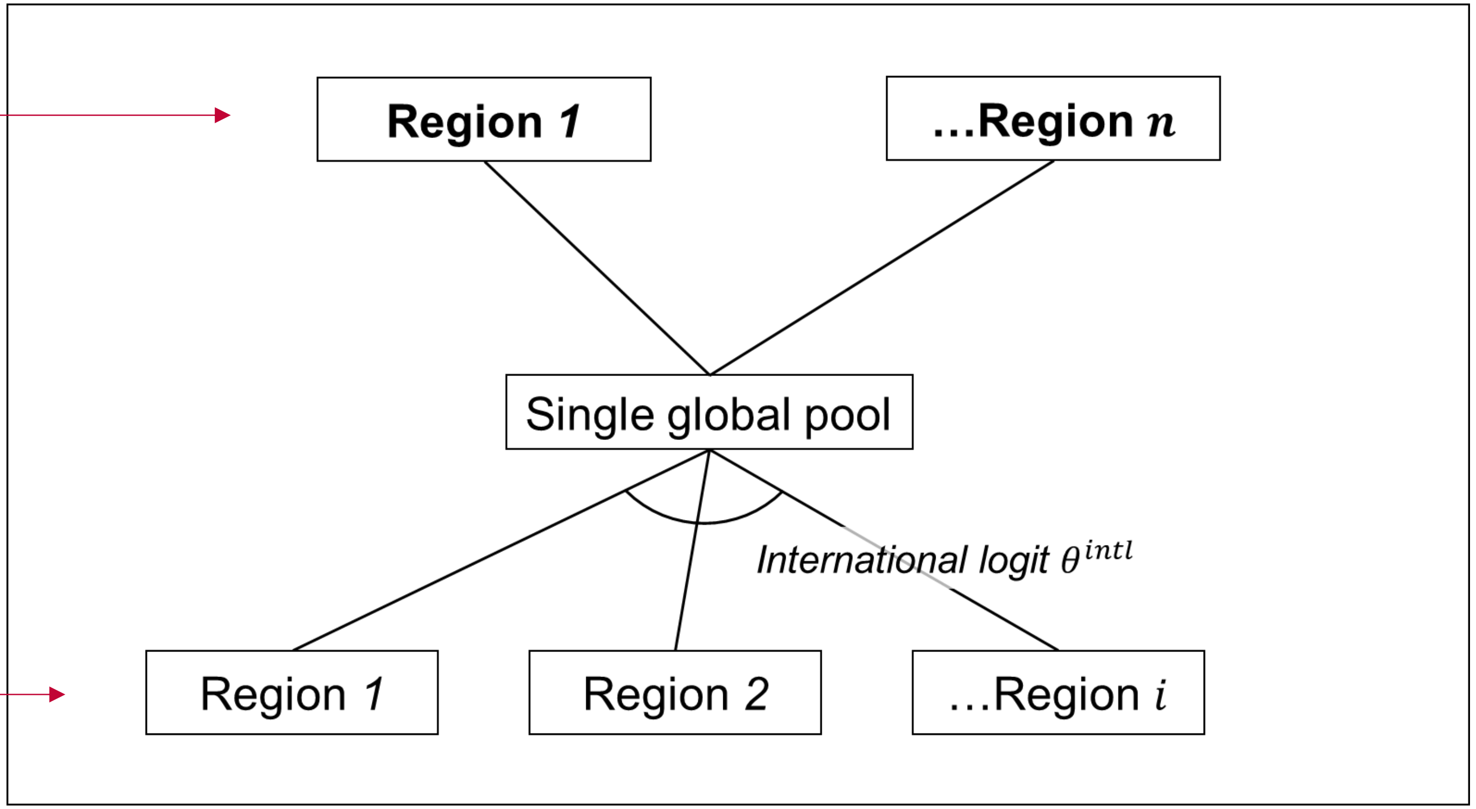


Yarlagadda et al. (in prep.)

We represent the bookends of the CMM supply chain— regional raw ore extraction and embedded end-use demands

Single **consumer price** across all regions, domestic vs. imported not tracked

Different **producer price** in each region



- Supplies and demands are connected by global CMM markets, abstracting representation of intermediate stages (e.g. refining and manufacturing) and bilateral trade flows.

Yarlagadda et al. (in prep.)

GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Scenario design

Unconstrained supply	Reference (Average lead times)	Short lead times
No supply curves; unlimited Cu, Li, Ni available at constant price	All regions adopt global average lead times for Cu, Li, Ni across all development stages, resulting in total project lead times of 17-19 years.	All regions adopt lead times for Cu, Li, Ni that are 30% shorter than in the Reference case, (corresponding to the lower bound of observed global lead times), resulting in total project lead times of 12-13 years.

Yarlagadda et al. (in prep.)

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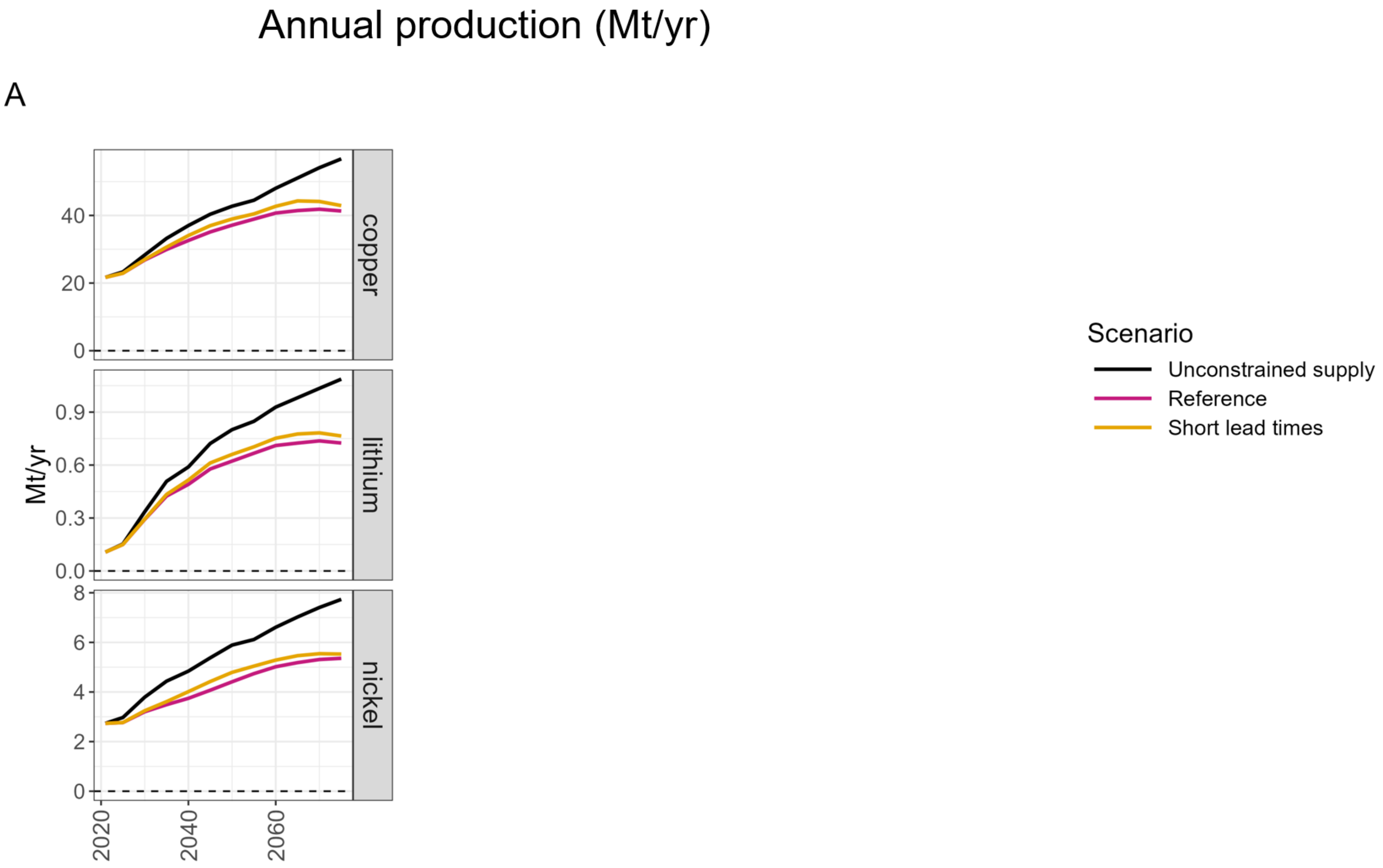
Regional CMM availability and lead times could constrain supplies. Shorter lead times help alleviate these constraints.



Yarlagadda et al. (in prep.)

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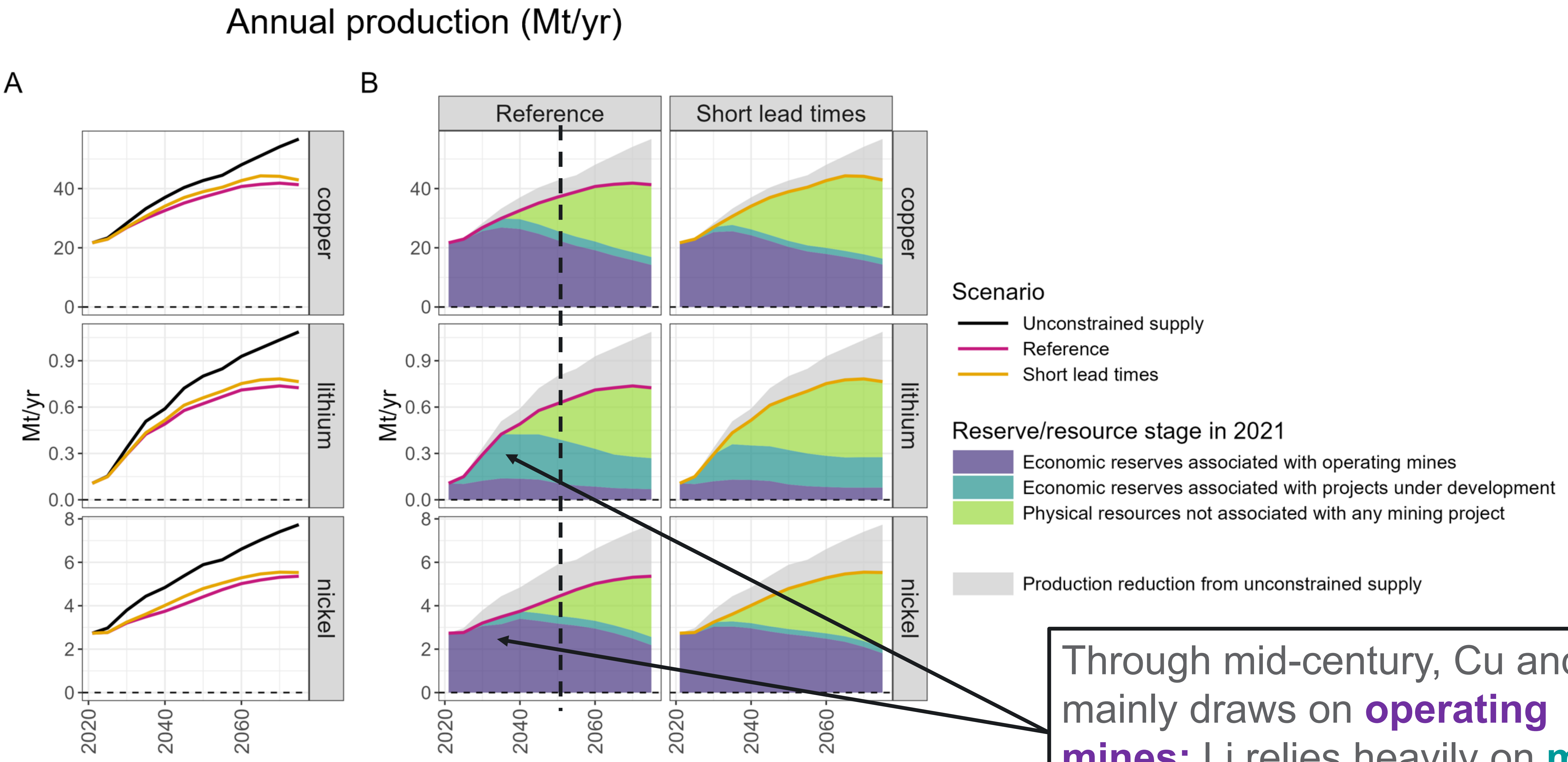
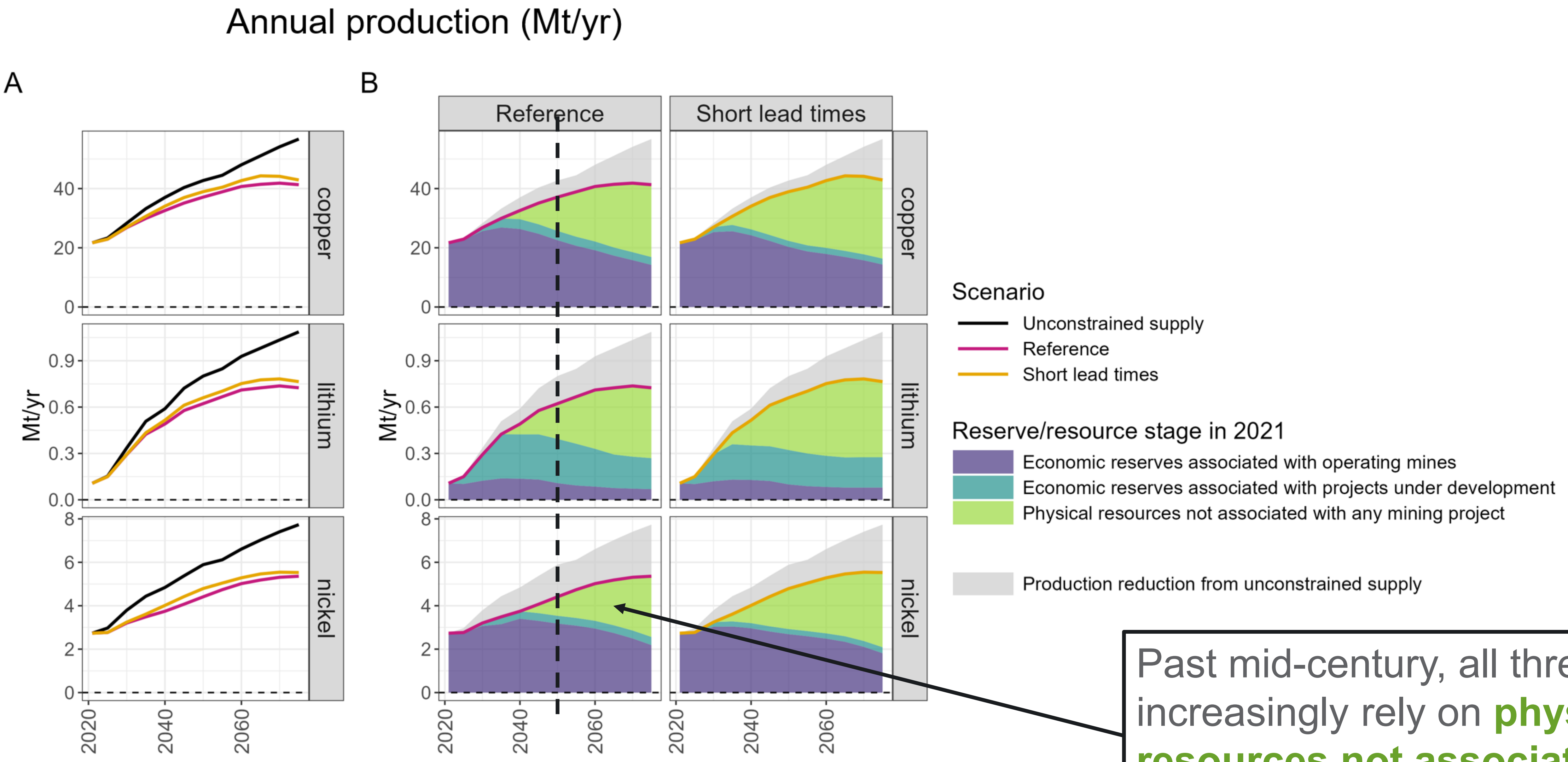


Through mid-century, Cu and Ni mainly draws on **operating mines;** Li relies heavily on **mines in development**

Yarlagadda et al. (in prep.)

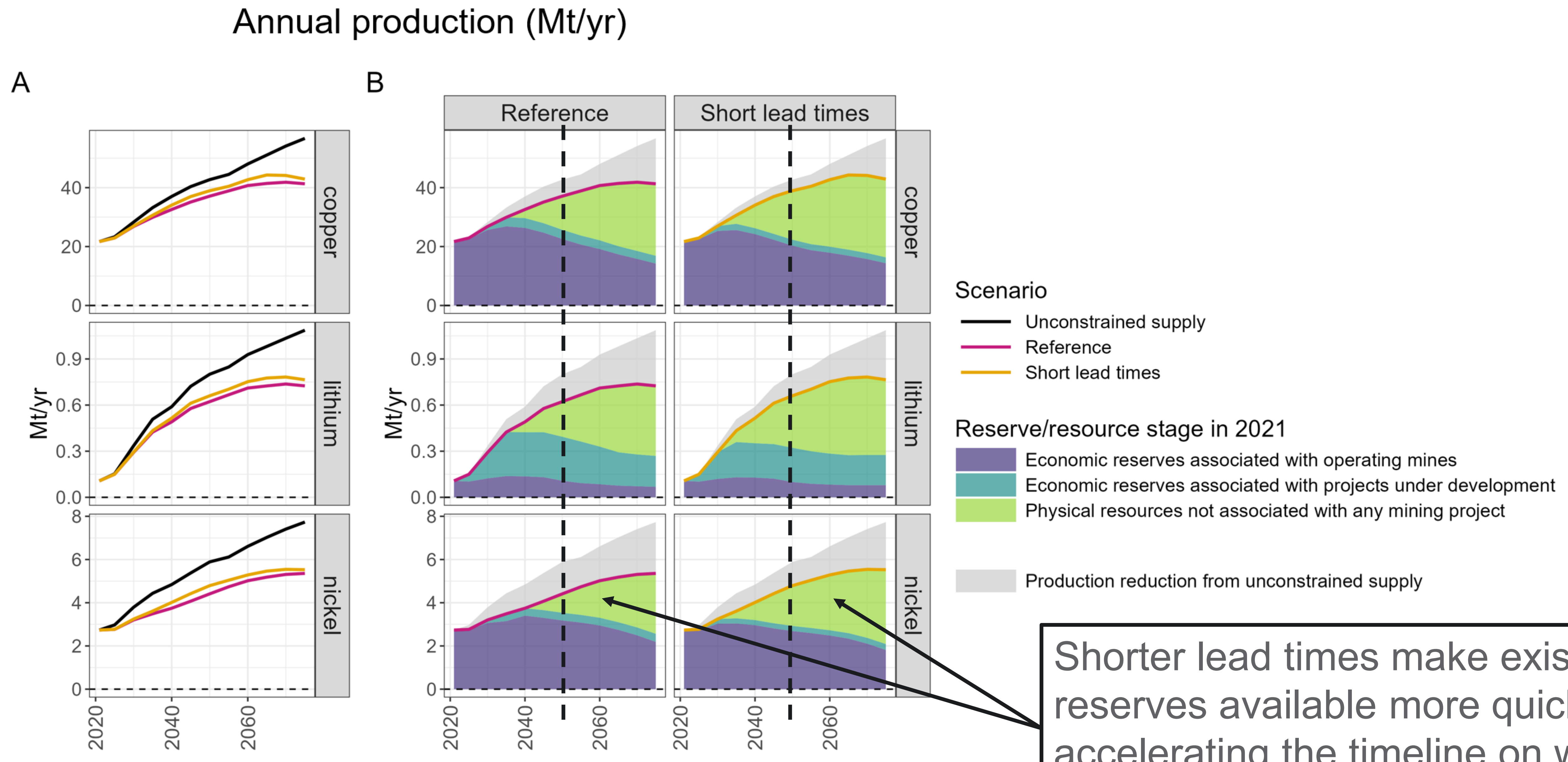
Regional CMM availability and lead times could constrain supplies. Shorter lead times help alleviate these constraints.



Past mid-century, all three CMMs increasingly rely on **physical resources not associated with any mine project**

Yarlagadda et al. (in prep.)

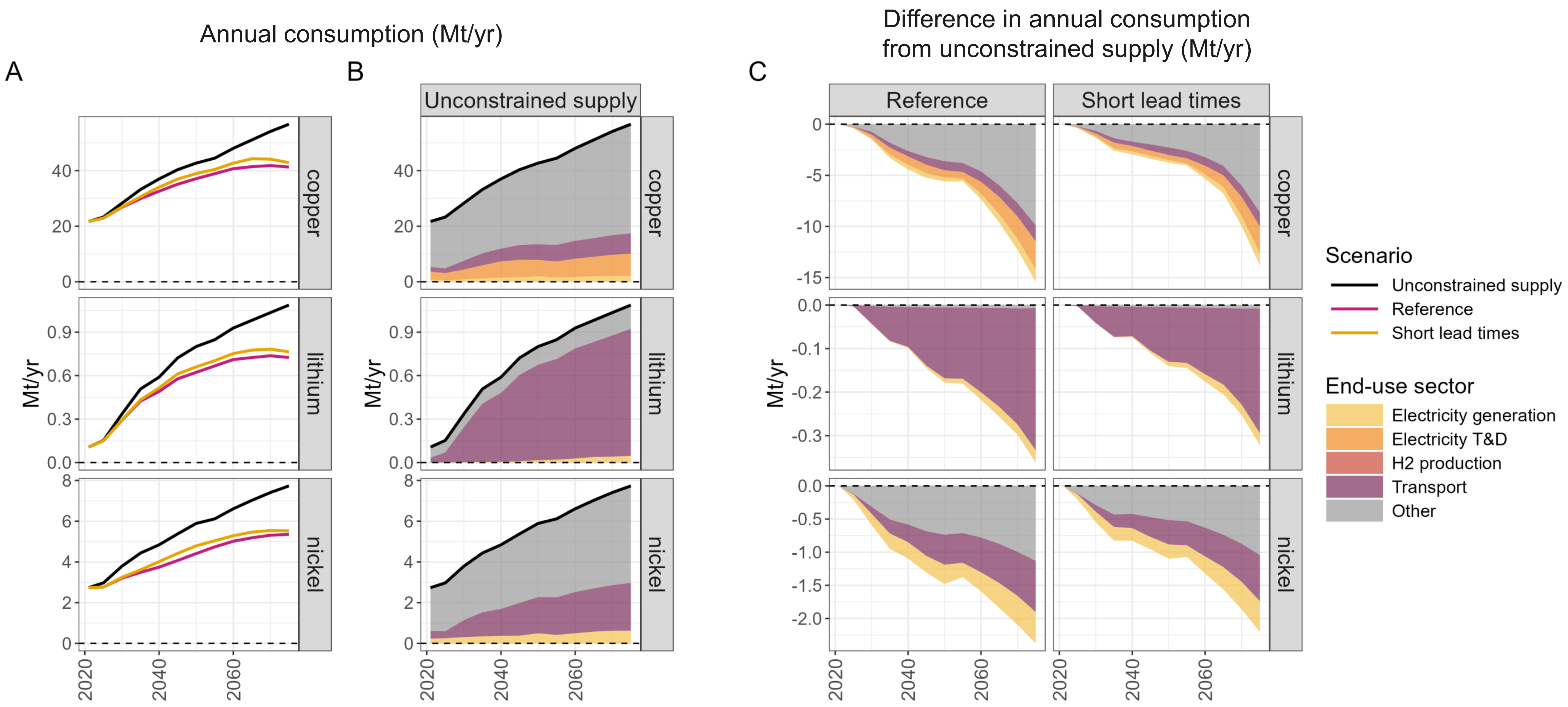
Regional CMM availability and lead times could constrain supplies. Shorter lead times help alleviate these constraints.



Shorter lead times make existing reserves available more quickly, accelerating the timeline on which unassociated resources are needed

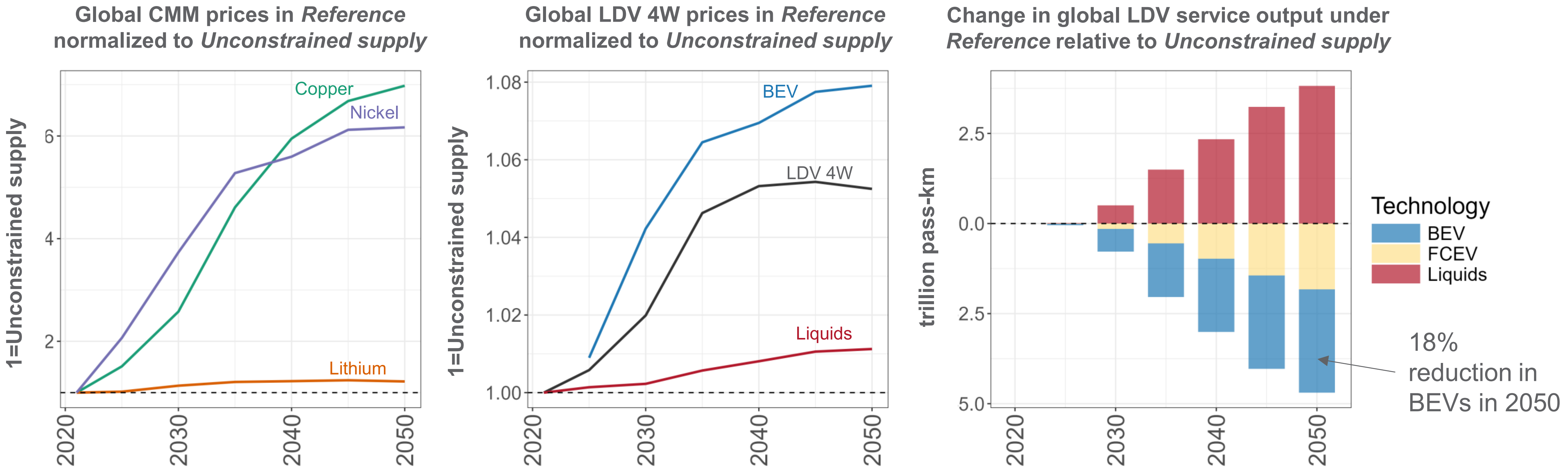
Yarlagadda et al. (in prep.)

We can characterize the multi-sectoral demand responsiveness to constrained supply availability



Yarlagadda et al. (in prep.)

Constrained supplies result in multi-fold mineral price increases and changes in energy technology deployment



Despite multi-fold increases in mineral commodity prices, there are relatively smaller increases in aggregate LDV 4W prices because demand-side substitutions (e.g. from BEV to Liquids) buffer these changes

Yarlagadda et al. (in prep.)

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Discussion

- CMM production will be influenced by several supply and demand pressures that are in effect in the near-term and change over the multi-decadal time horizon

- Supply-demand pressures on CMMs propagate to the energy system, but impacts might not be obvious unless considering the simultaneous impacts across multiple technologies or sectors.

- By considering both supply- and demand- side dynamics in a unified framework like GCAM, we can better understand how and on what timelines different factors can alleviate production constraints

Yarlagadda et al. (in prep.)

Q&A

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Recycling, unconventional sources, trade, and other topics

Gokul Iyer, Yang Qiu, Brinda Yarlagadda

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GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

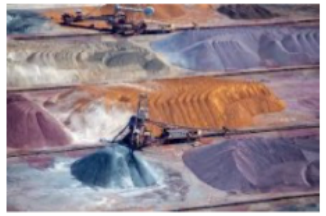
Critical minerals and materials modeling (CMM) in GCAM: Our vision

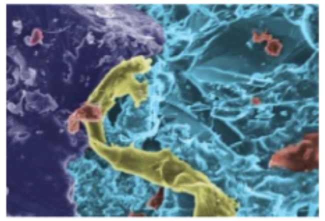
SUPPLY

Economic competition across different supply streams

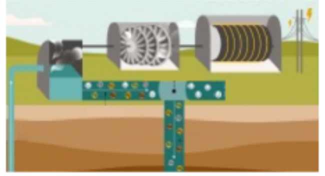
Broad range of materials/minerals
(e.g. Li, Ni, Co, Cu, Si, graphite, rare earth elements)

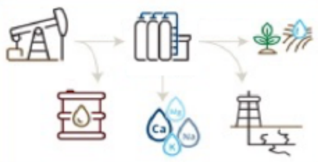
Traditional mining — Biomining





Geothermal brines — Wastewater





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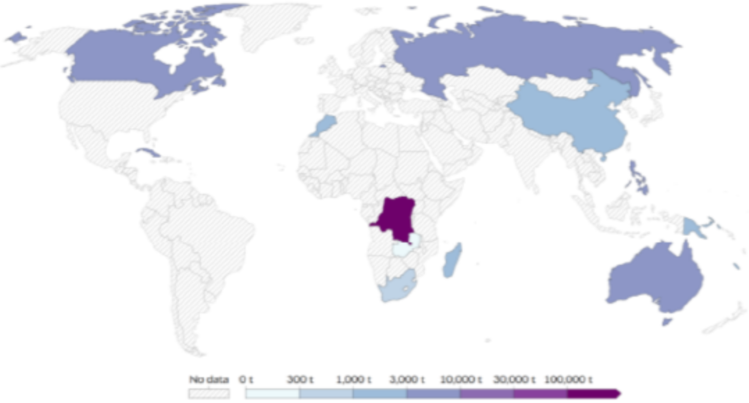

Refining and component production by country

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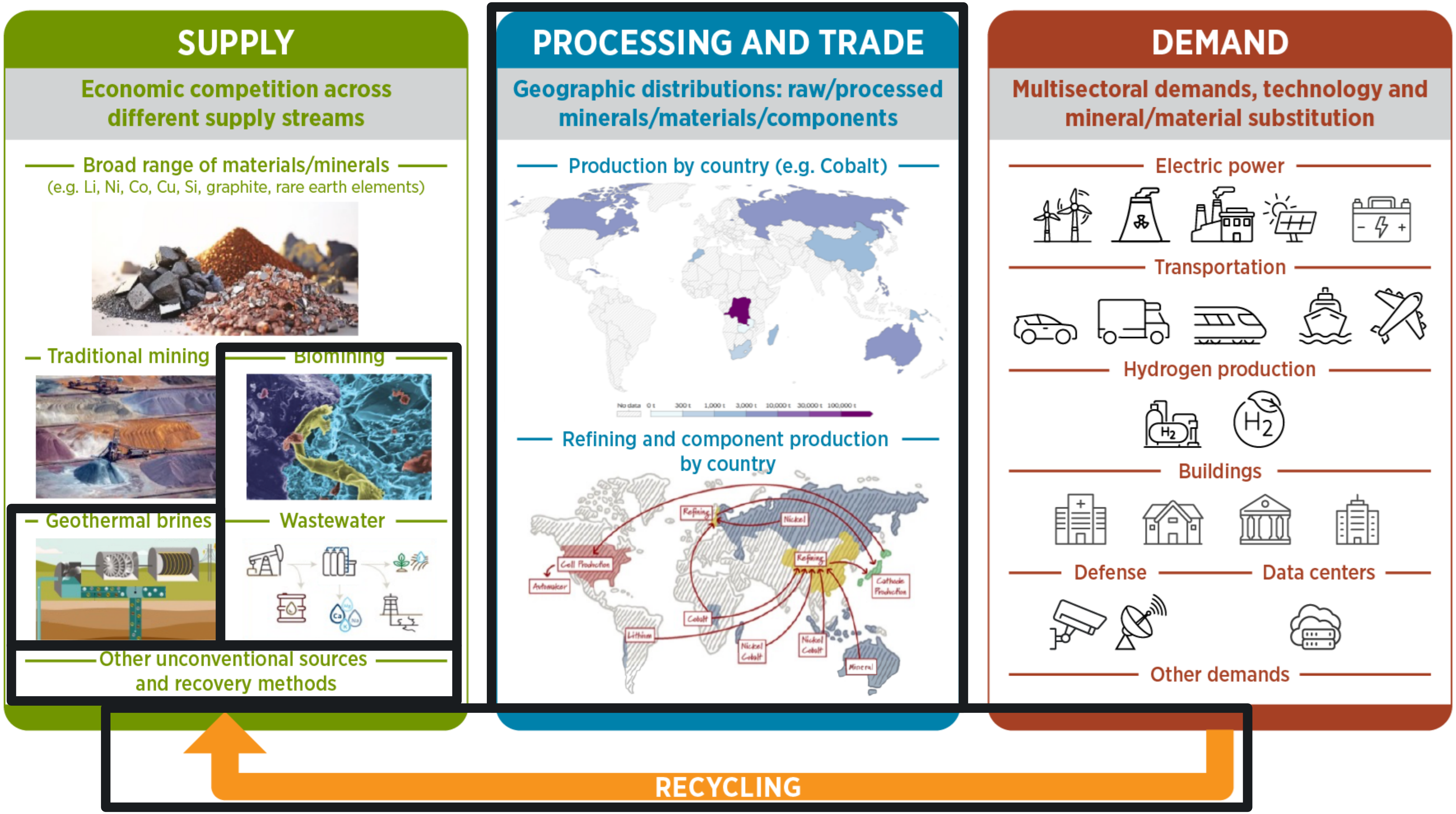
Critical minerals and materials modeling (CMM) in GCAM: Our vision



Material recycling is an important secondary source

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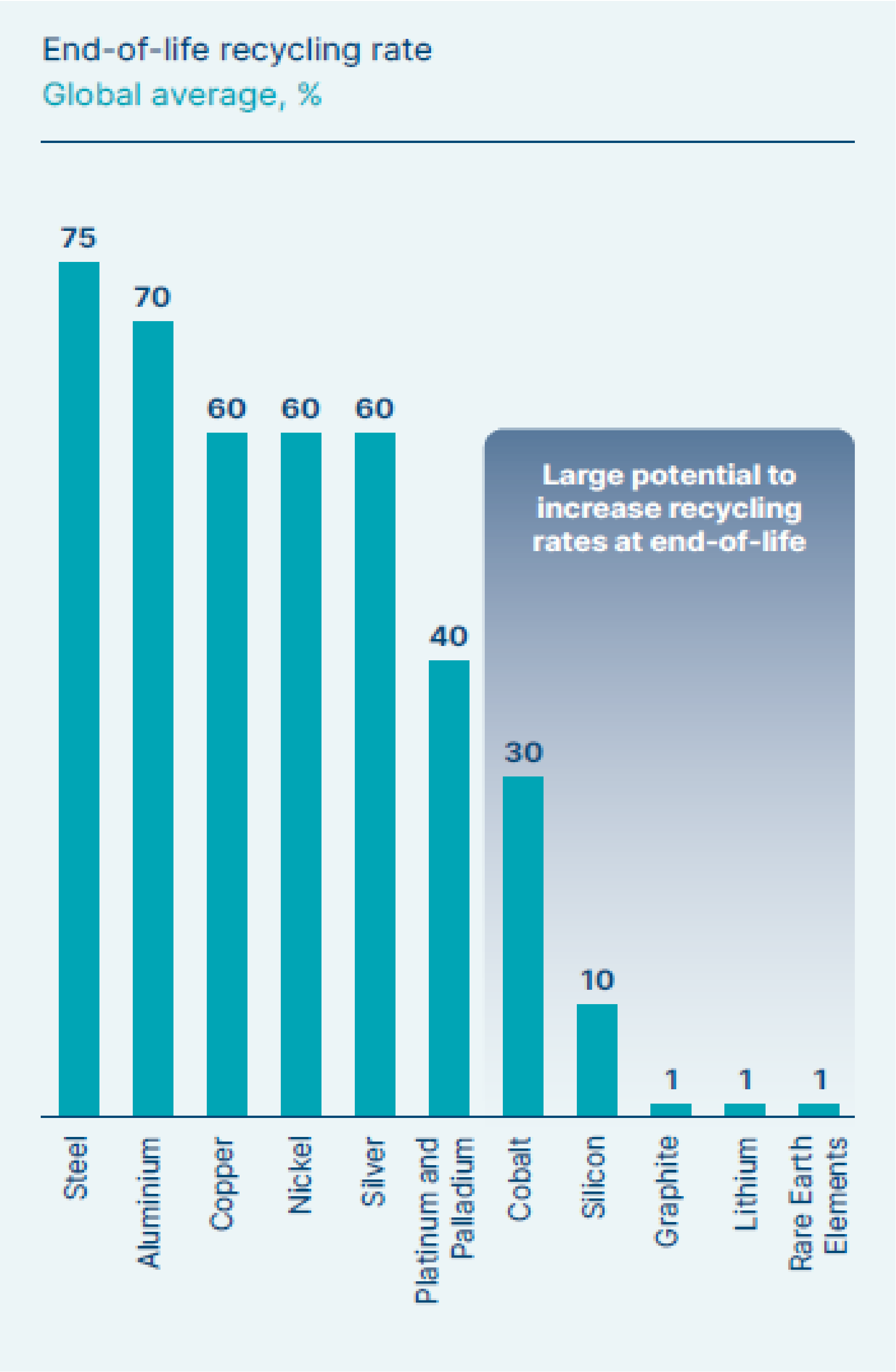
CMM recycling can be an important future supply source, which strengthens domestic supply chains and improves supply security.

Recycling rates vary widely across materials. Some specialty CMMs (e.g., lithium, rare earths, graphite) have low recycling rates due to limited end-of-life (EoL) material availability and less favorable recycling economics.

In GCAM, we are developing capabilities to:

1. Track material EoL flows endogenously to identify when, where recyclable materials become available.
2. Model the economics of CMM recycling to understand its future role in the overall CMM supply.



(Energy Transitions Commission, 2023)

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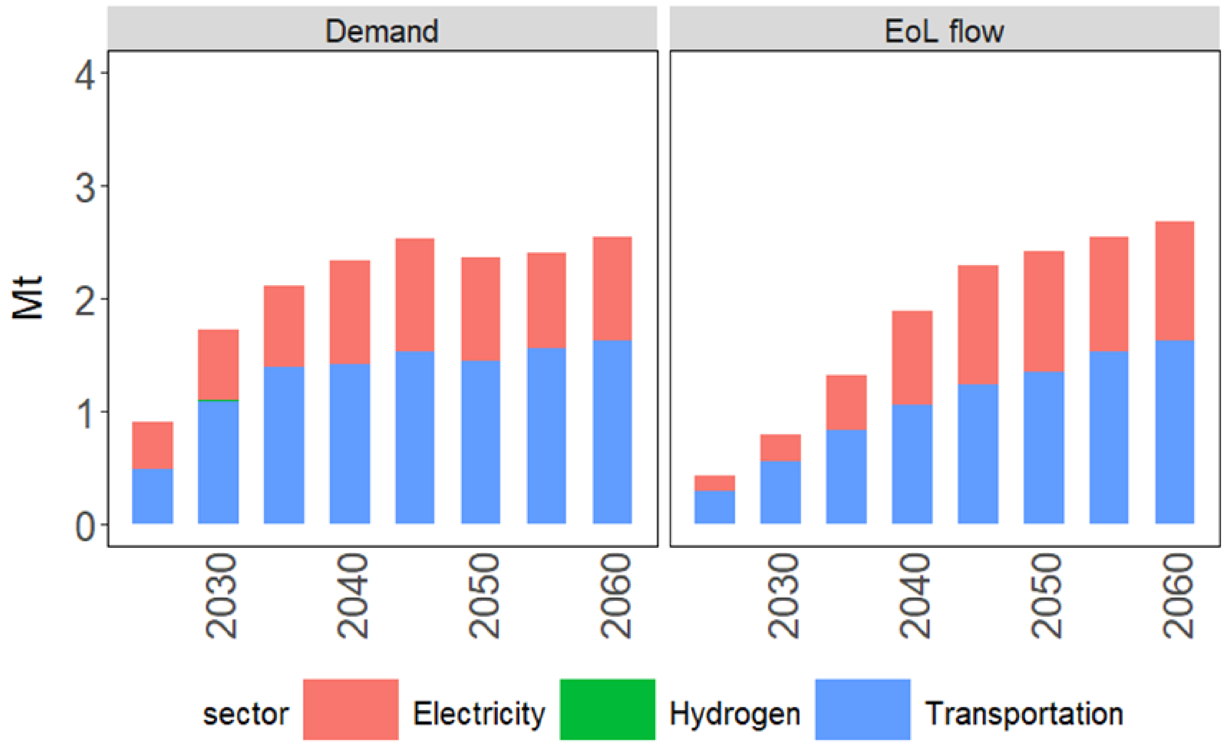
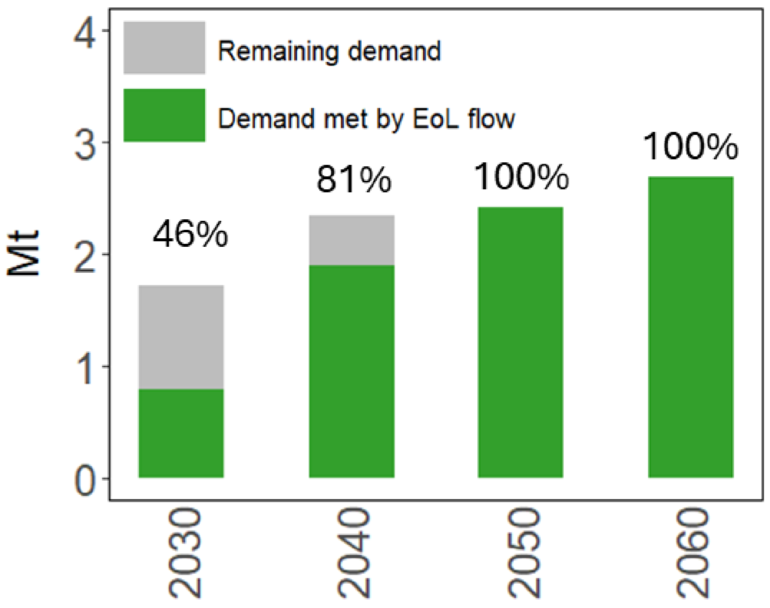
GCAM modeling can offer insights into role of recycling in meeting future CMM demands

- Our initial results show Cu demand and EoL Cu flows from the electricity, hydrogen, and transportation sectors in the US under the Reference scenario.
- EoL Cu flows increase over time and could potentially supply up to ~100% of Cu demand from these same sectors by 2050.

Cu Demand and EoL flow from electricity, hydrogen production and transport sectors in the US



Cu Demand met by Cu EoL flow



These results only represent the "potential contribution" of EoL Cu to meet future demand. The actual quantity of recycled Cu will depend on the economics of recycled Cu, which is currently under development.

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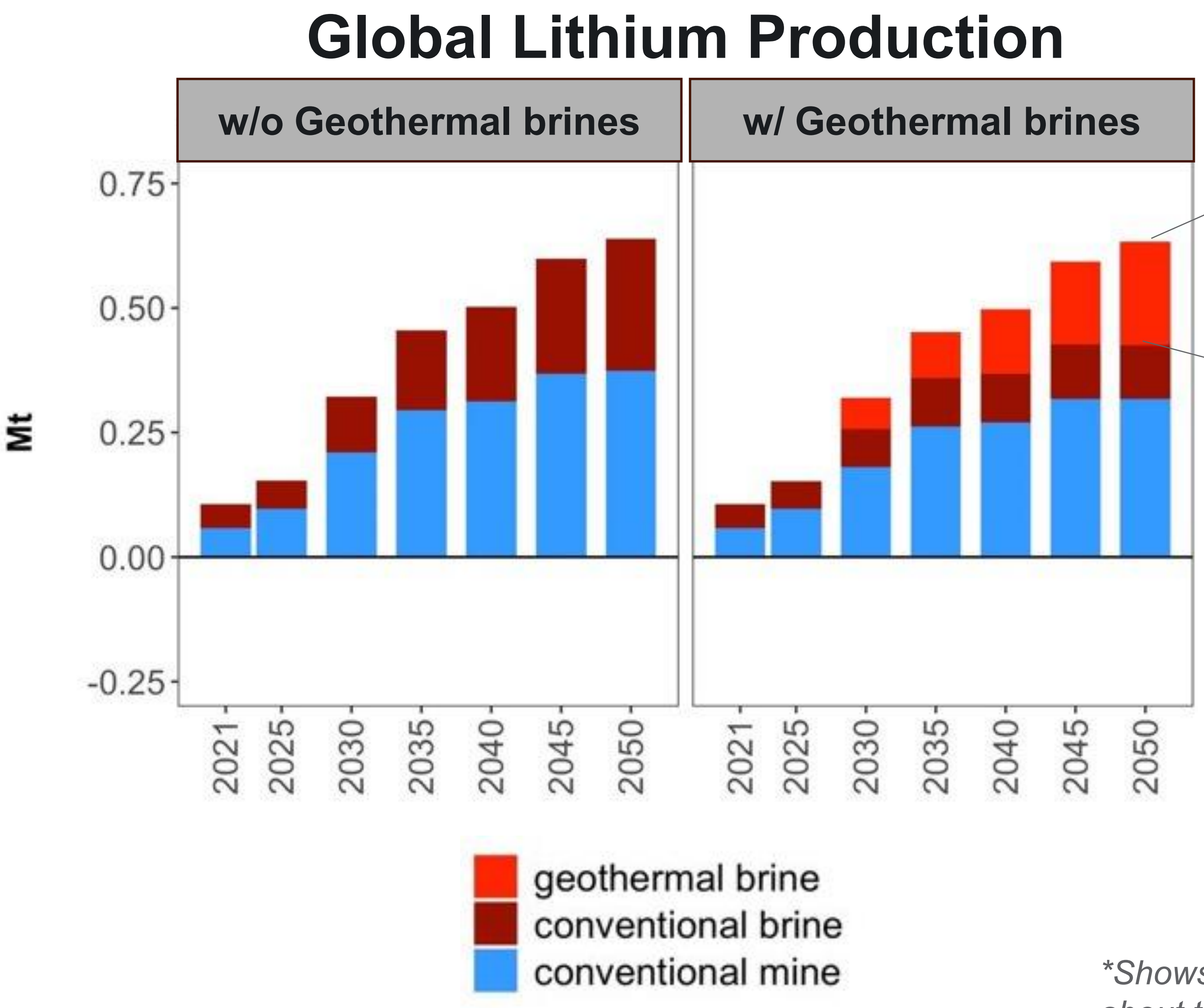
Modeling of unconventional supply streams

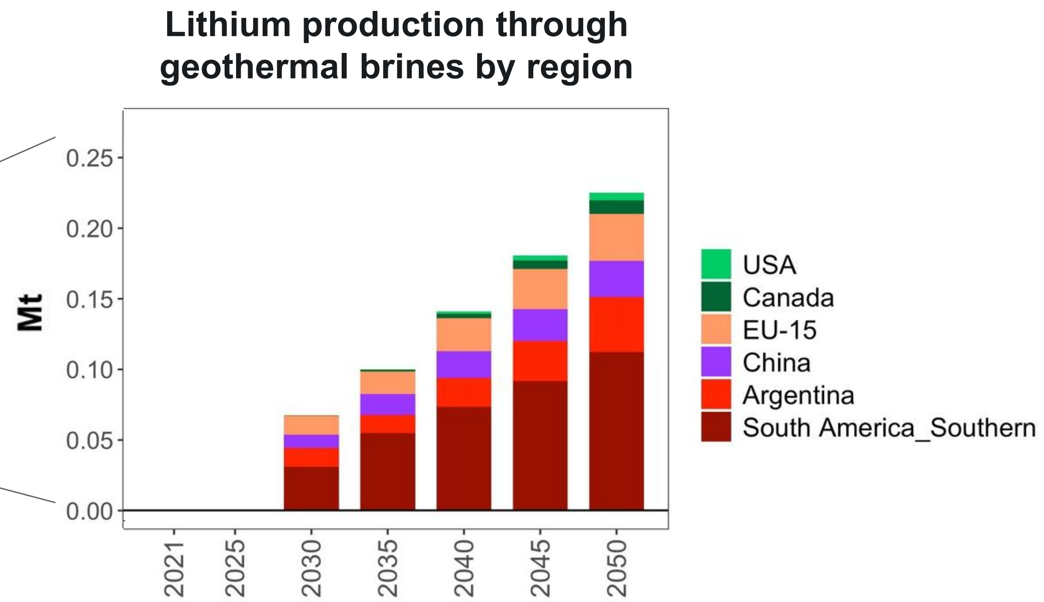
- Unconventional supply streams could be crucial for meeting future multi-sectoral demands
  - Often from industrial or waste streams, or by-product of other energy production processes
- We aim to represent the potential for unconventional supply streams to compete with conventional supply streams within GCAM
  - We have started with geothermal brines and oil/gas wastewater for lithium extraction

Geothermal power plant near California's Salton Sea

https://www.energy.gov/hgeo/geothermal/articles/can-geothermal-energy-solve-lithium-shortfall

Availability of geothermal brines reduces need for conventional lithium production

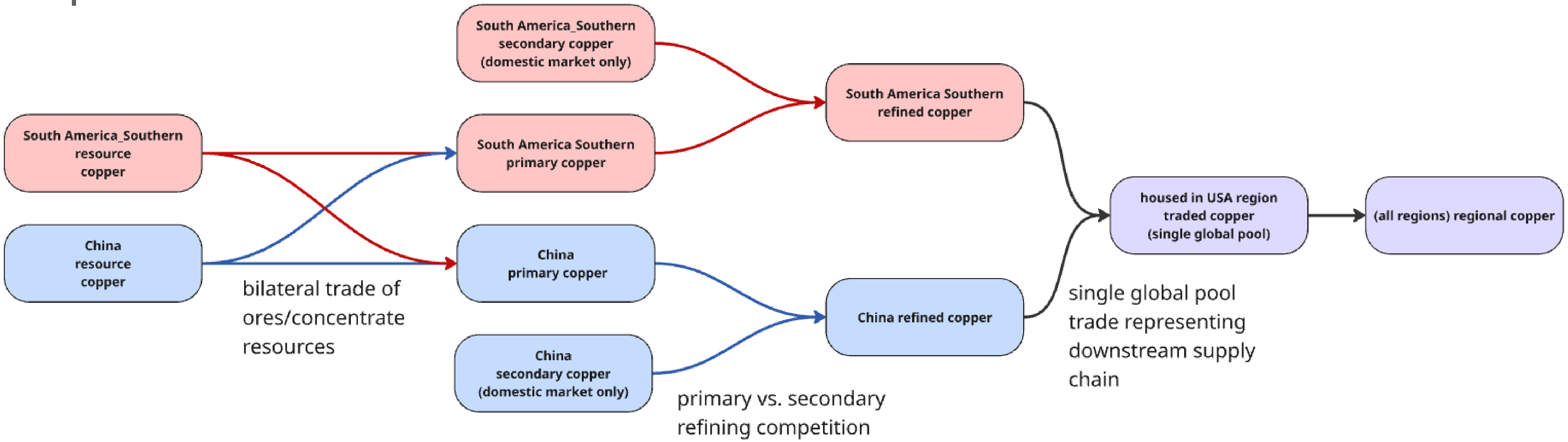




**Shows preliminary GCAM results for a "reference" scenario with central assumptions about technology, population growth, etc. and no policies. Supplies for copper, lithium, and nickel are constrained using regional supply curves.*

Modeling of trade in CMMs

- We've begun development on bilateral trade between the raw extraction and refining stages of CMM supply chains along with energy/water use implications



- We are exploring the use of AI/ML based emulators to model complete supply chains

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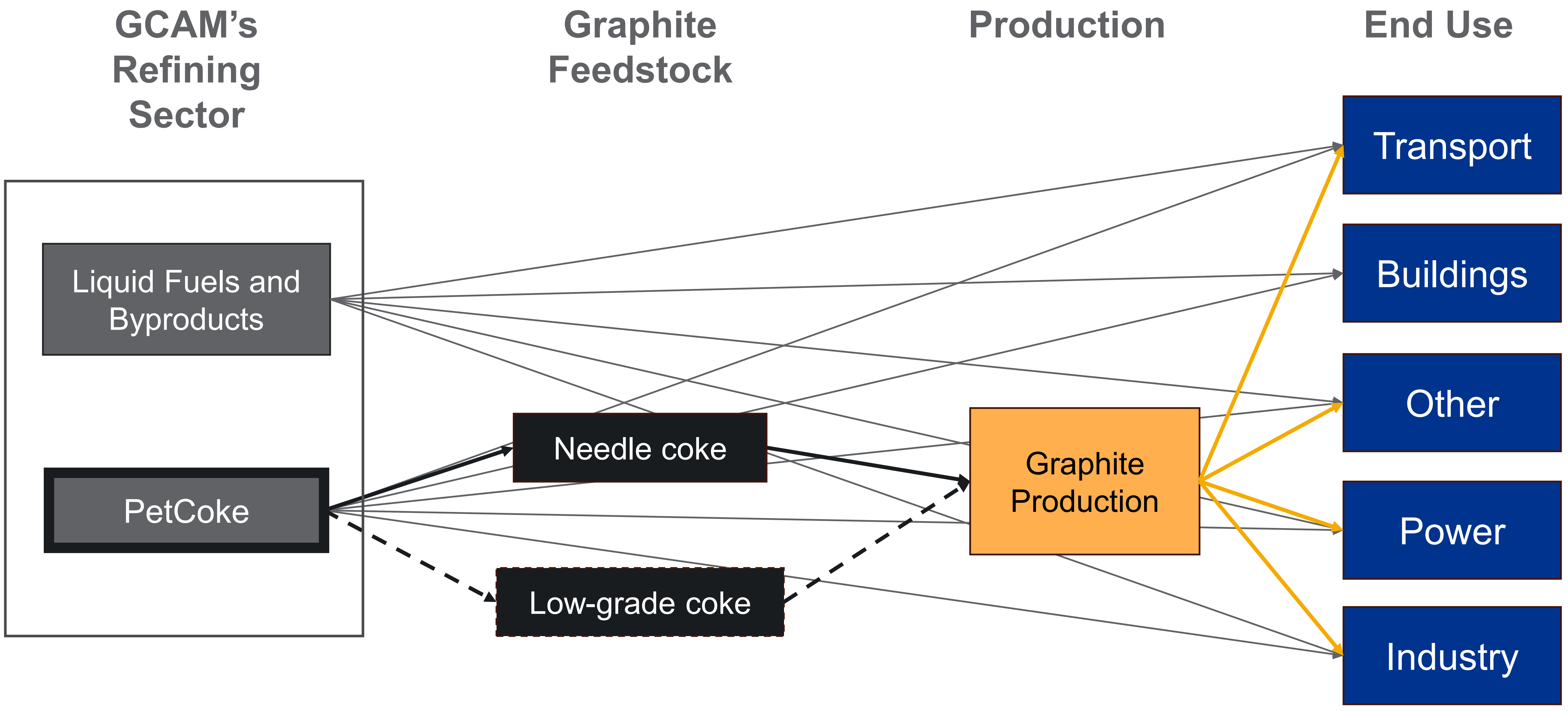
Detailed modeling of individual CMMs: Example of graphite

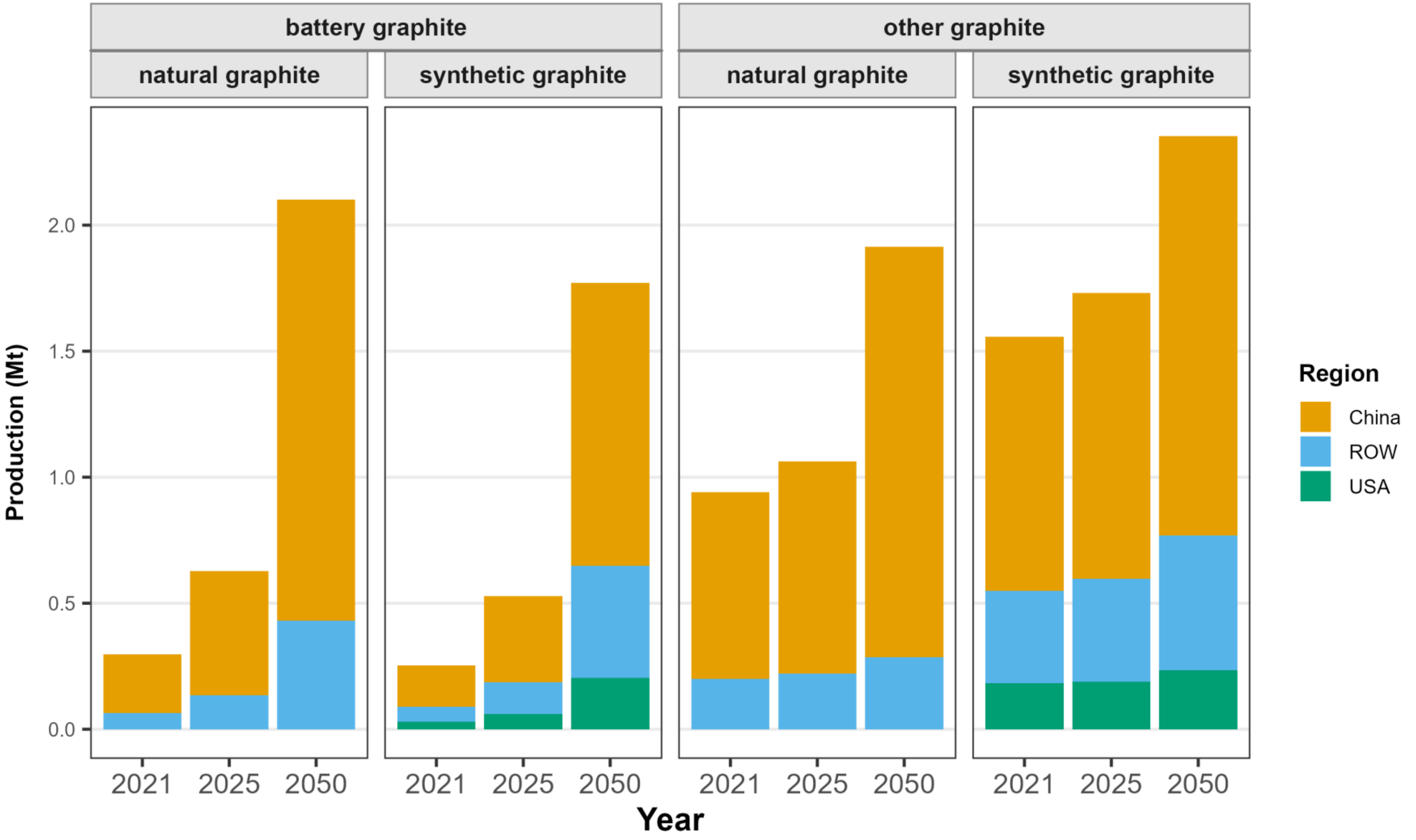


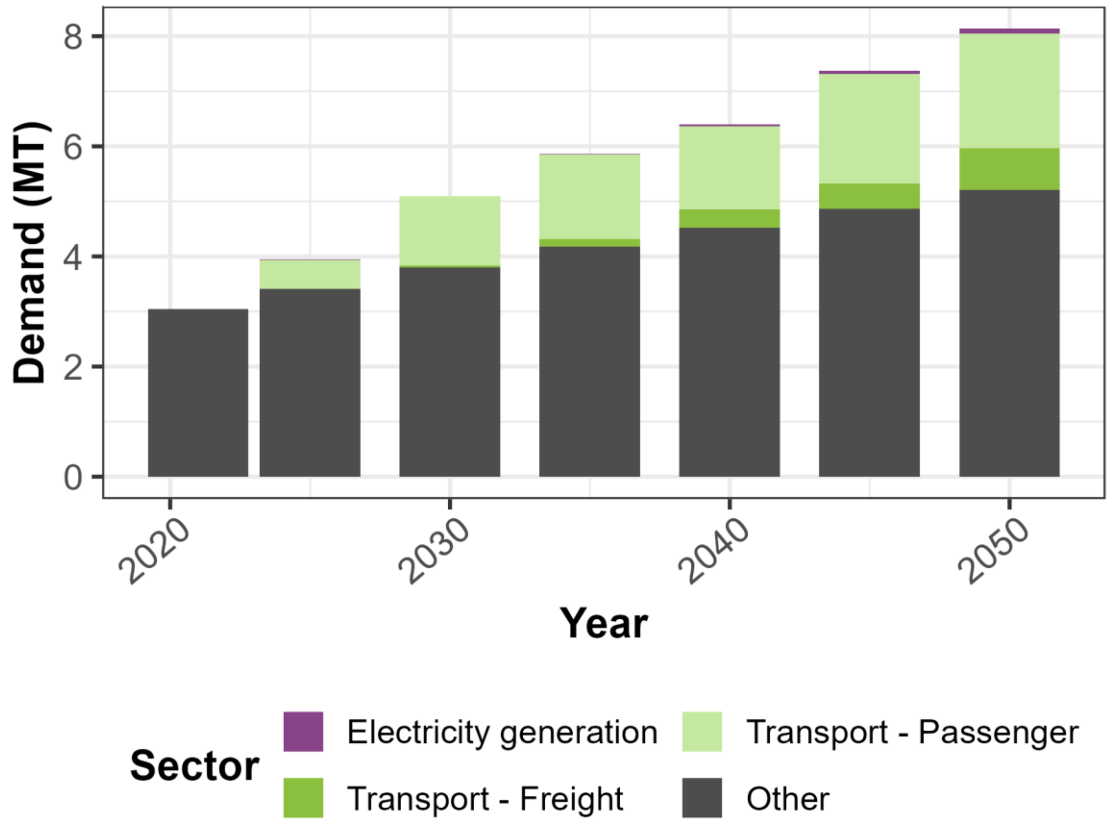
- GCAM refining only has a single liquid output
- With petroleum coke split out we can better model graphite supplies

GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Most of U.S. production of graphite is synthetic

Global graphite production*





**Shows preliminary GCAM results for a "reference" scenario with central assumptions about technology, population growth, etc. and no policies. Assumes no new graphite mines in regions without historical production. These are preliminary model outputs and should not be interpreted as USG policy goals or expectations.*

Q&A

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Thank you

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