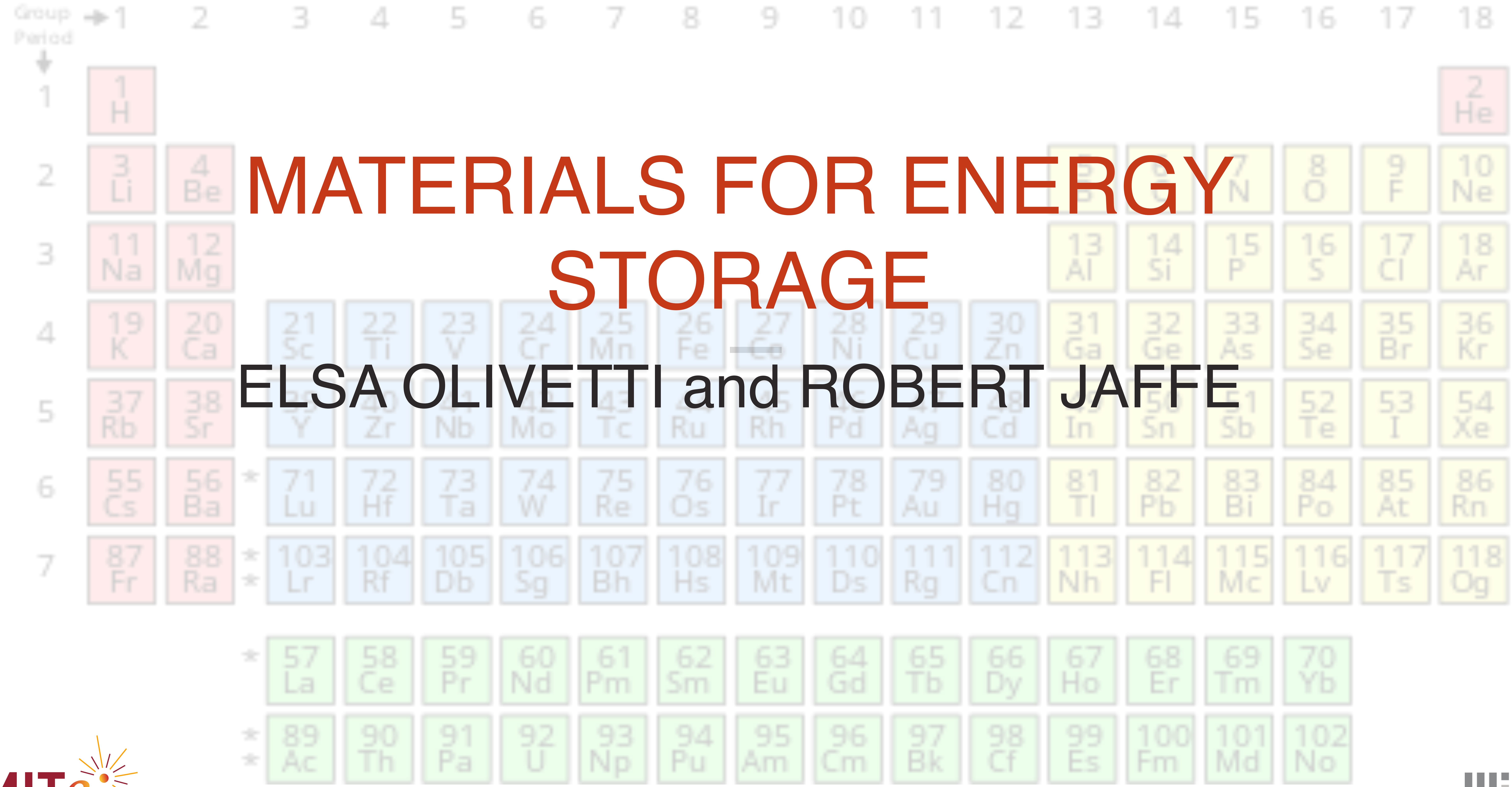


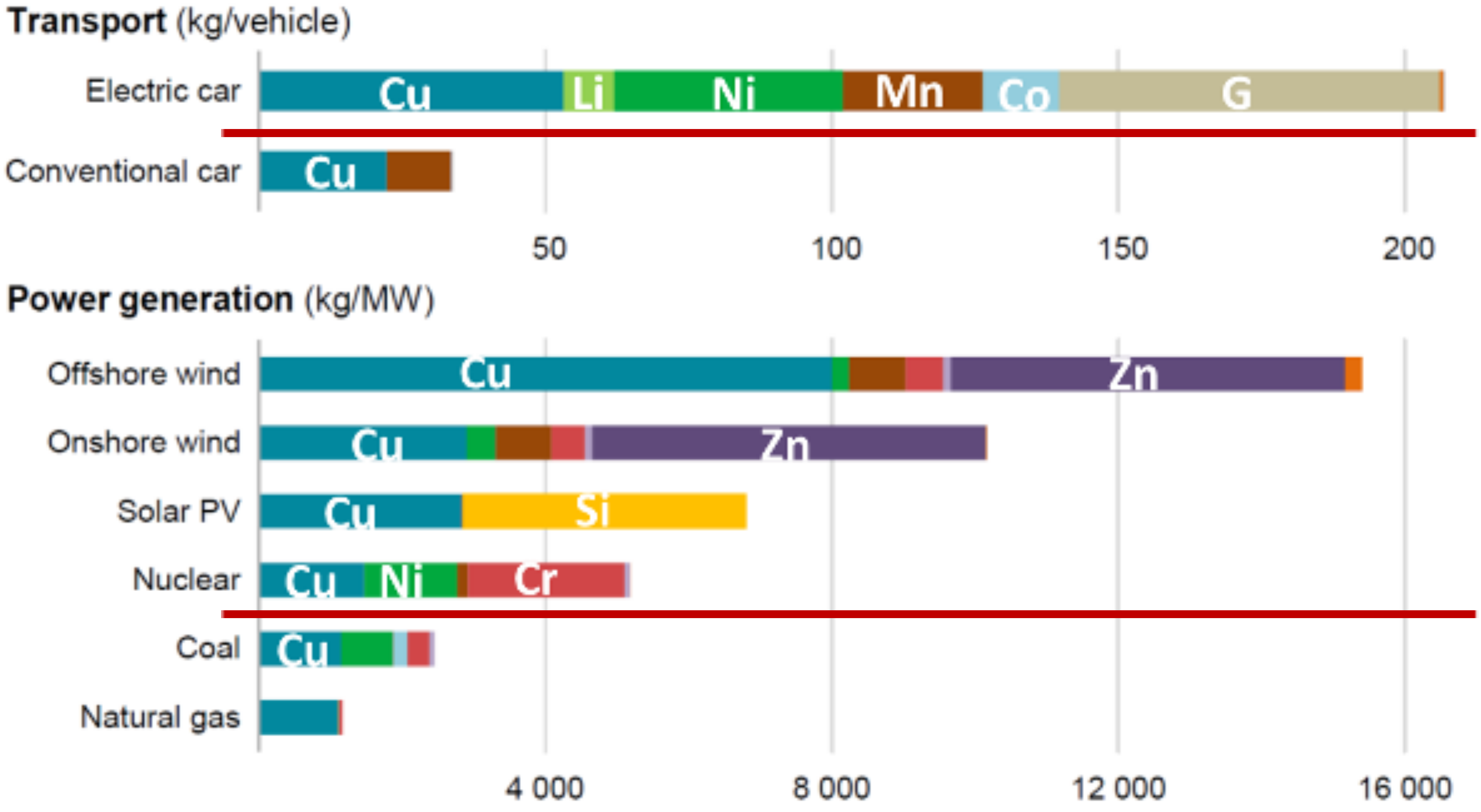
MATERIALS FOR ENERGY STORAGE

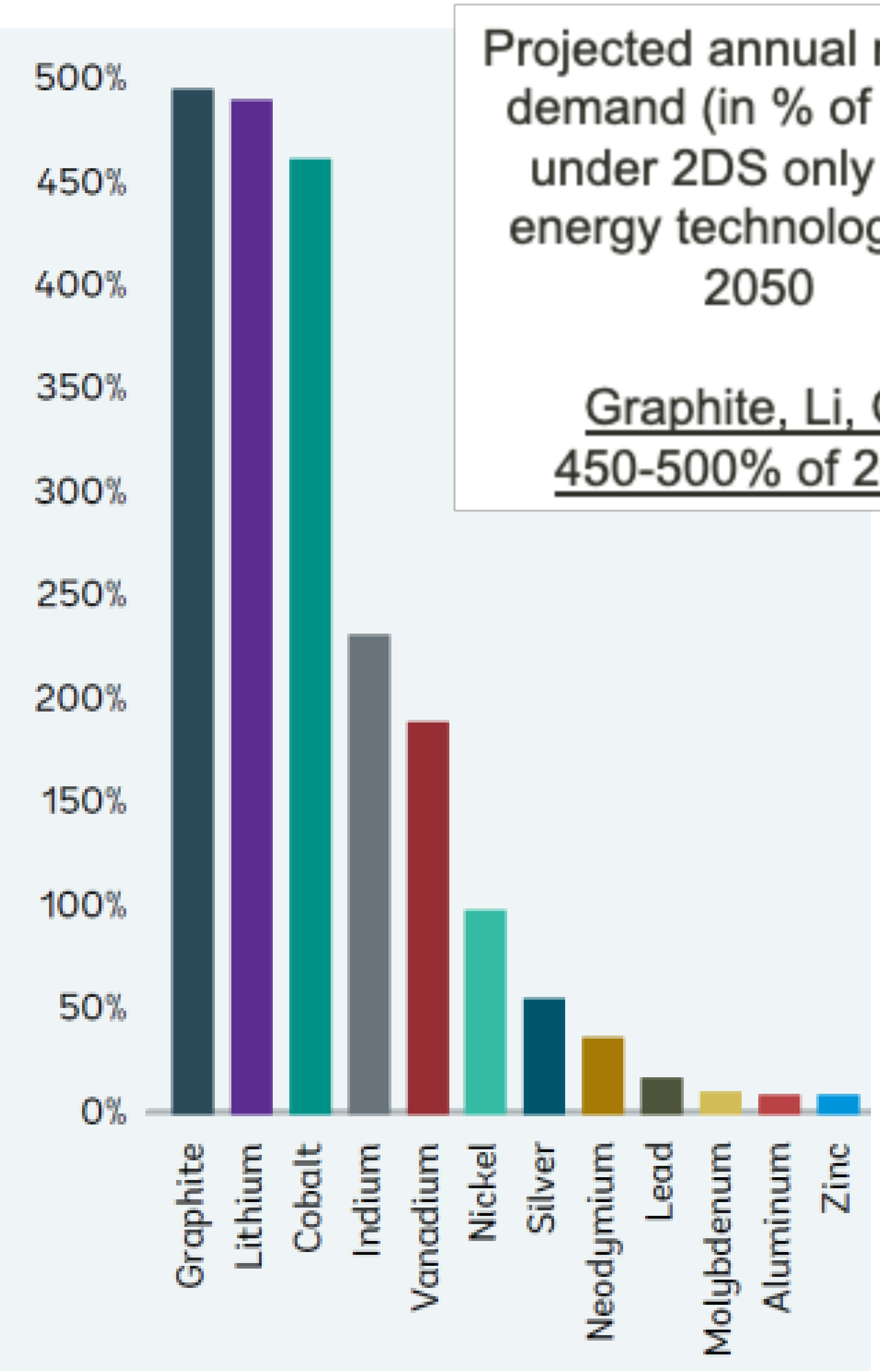
ELSA OLIVETTI and ROBERT JAFFE

Our low-carbon future is mineral intensive

Many of the technologies we consider necessary for the transition to low-carbon energy production rely on materials

Rapid deployment of energy transition technologies implies a significant increase in demand for minerals



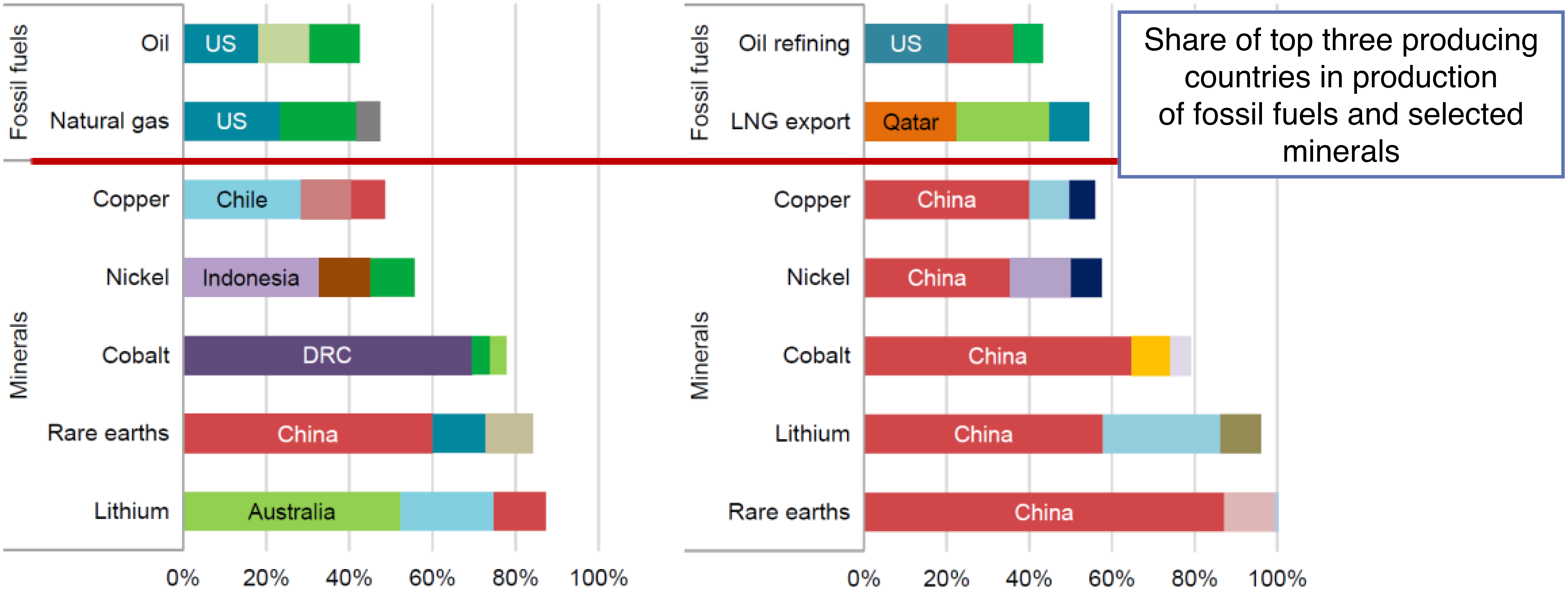


Projected annual mineral demand (in % of 2018) under 2DS only from energy technologies in 2050

Graphite, Li, Co
450-500% of 2018

IEA 2020

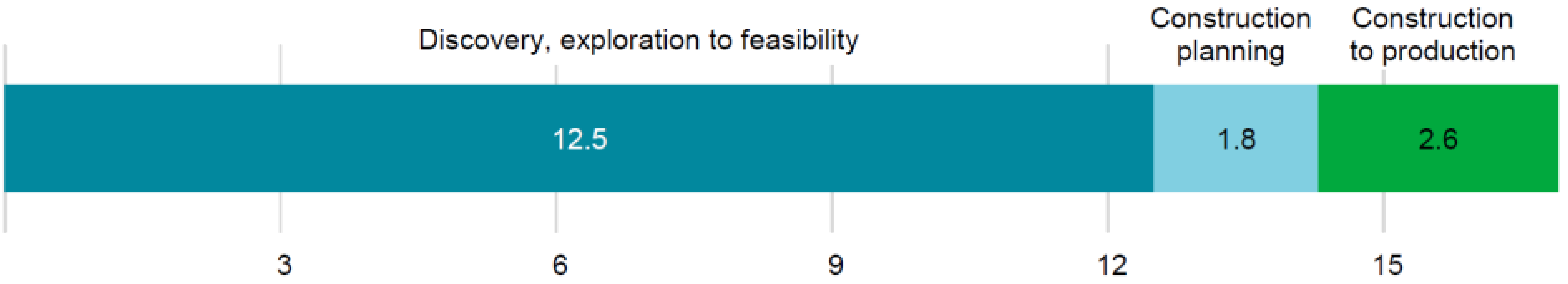
Production of energy transition minerals is more geographically concentrated



Share of top three producing countries in production of fossil fuels and selected minerals

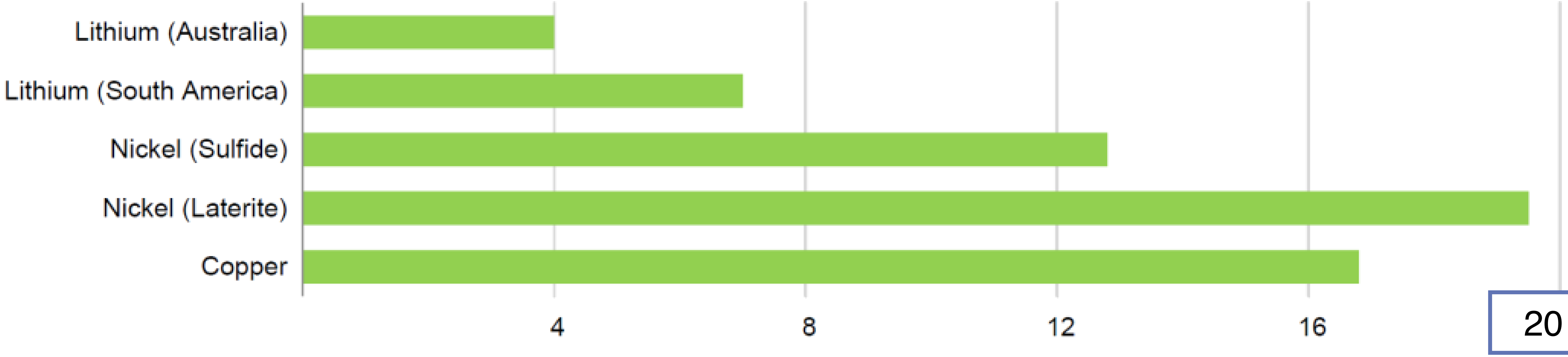
IEA 2020

Temporal challenges: Time to prospect, plan, fund, permit and deploy is 5-15+ years



18 years

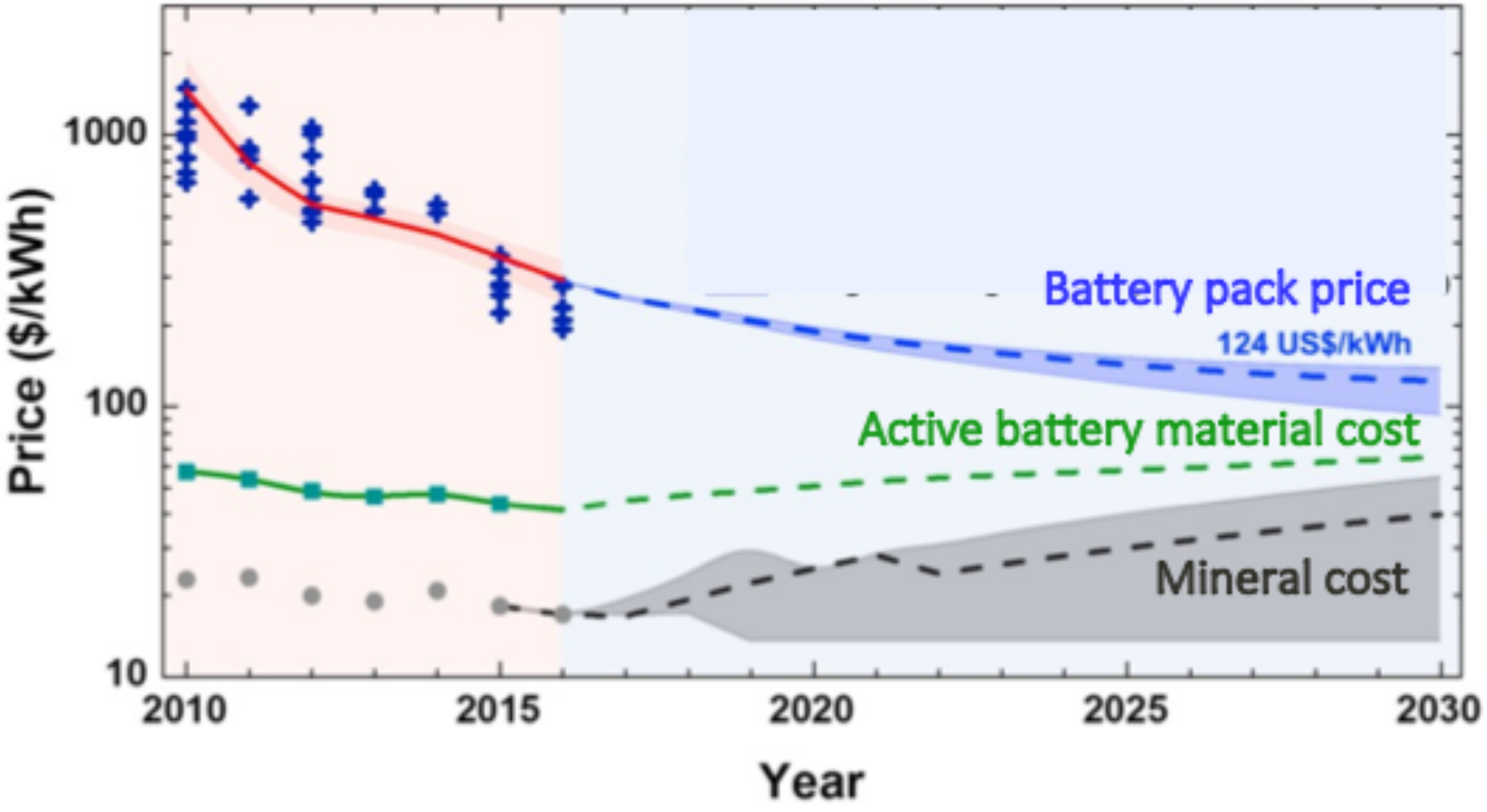
Average observed lead time for selected minerals (from discovery to production)



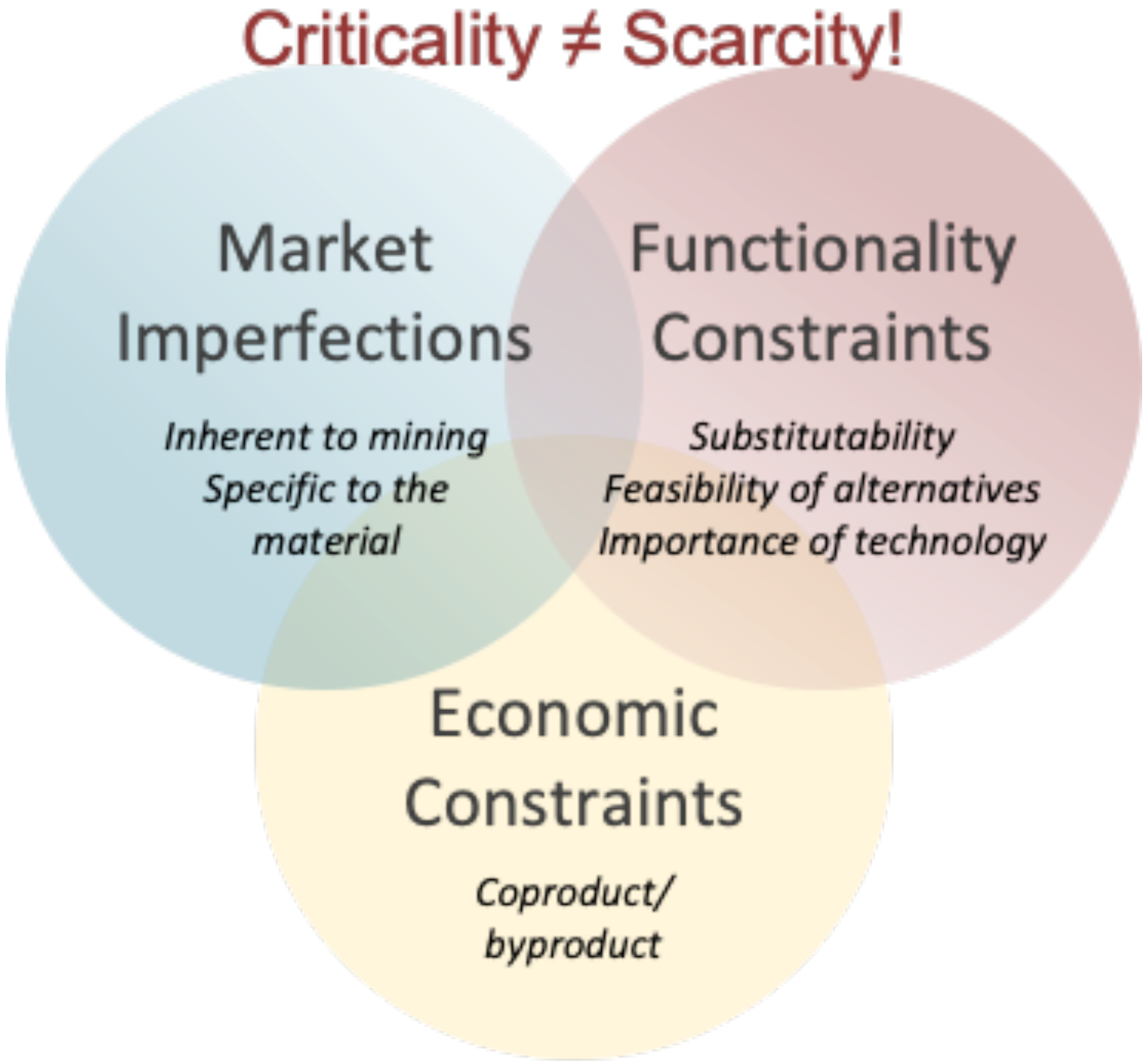
20 years

IEA 2020; Harrington 2022

Practical limits on energy technology scaling may be impacted by materials



Past and projected price trajectory of NMC Li-ion battery pack from 2-stage learning curve model.



Criticality
Risk deemed too high by a decision-maker

I-Y. Hsieh et al., Applied Energy 239, 28-224 (2019)

CRITICAL MATERIALS

FOR

(ELECTROCHEMICAL) ENERGY STORAGE

MATERIAL INTENSITY

MATERIAL DEMAND SCALES WITH ENERGY STORAGE CAPACITY

- Pumped hydro $\Longrightarrow$ water
- Thermal $\Longrightarrow$ oil, rocks, molten salt
- Electrochemical (batteries) $\Longrightarrow$ electrochemically active elements in cathode, anode, electrolyte,…

FOCUS ON BATTERIES

SCALE

“As discussed in Chapter 6, the total energy storage capacity that may need to be deployed to fully decarbonize the US electricity sector might approach 100 terawatt-hours (TWh) by 2050”

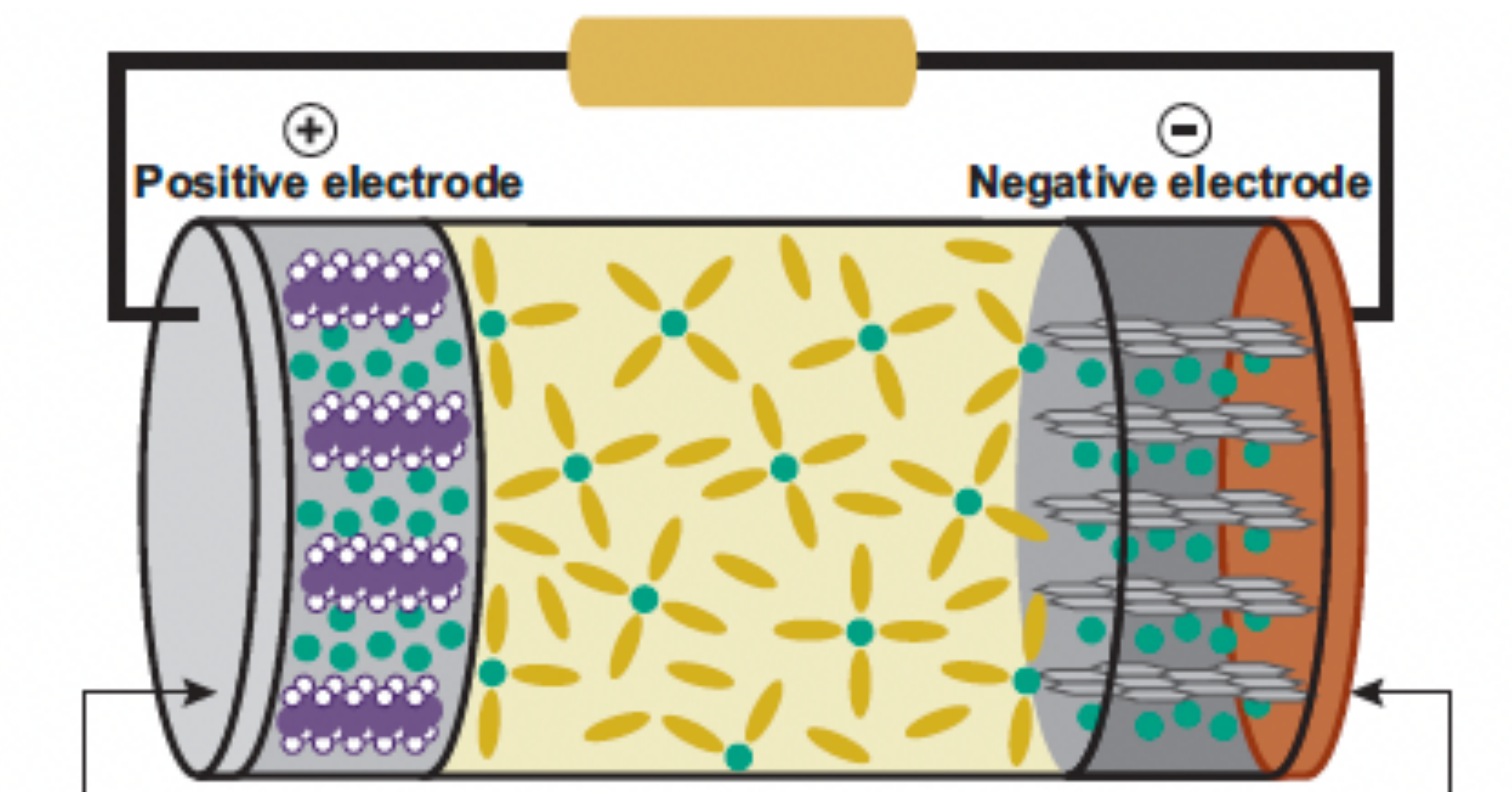
To achieve near-decarbonization of the US economy by 2050, battery deployment for both grid-scale storage and electric vehicle applications will have to scale rapidly to very high levels. Similar efforts overseas will further add to global demand.

MATERIAL AVAILABILITY IS SENSITIVE TO GLOBAL AND EV DEMAND

MUST CONSIDER 100’S TO 1000’S OF TWH DEMAND FOR ELECTRO-CHEMICAL STORAGE

PRESENTLY DOMINANT TECHNOLOGIES

Lithium-ion batteries

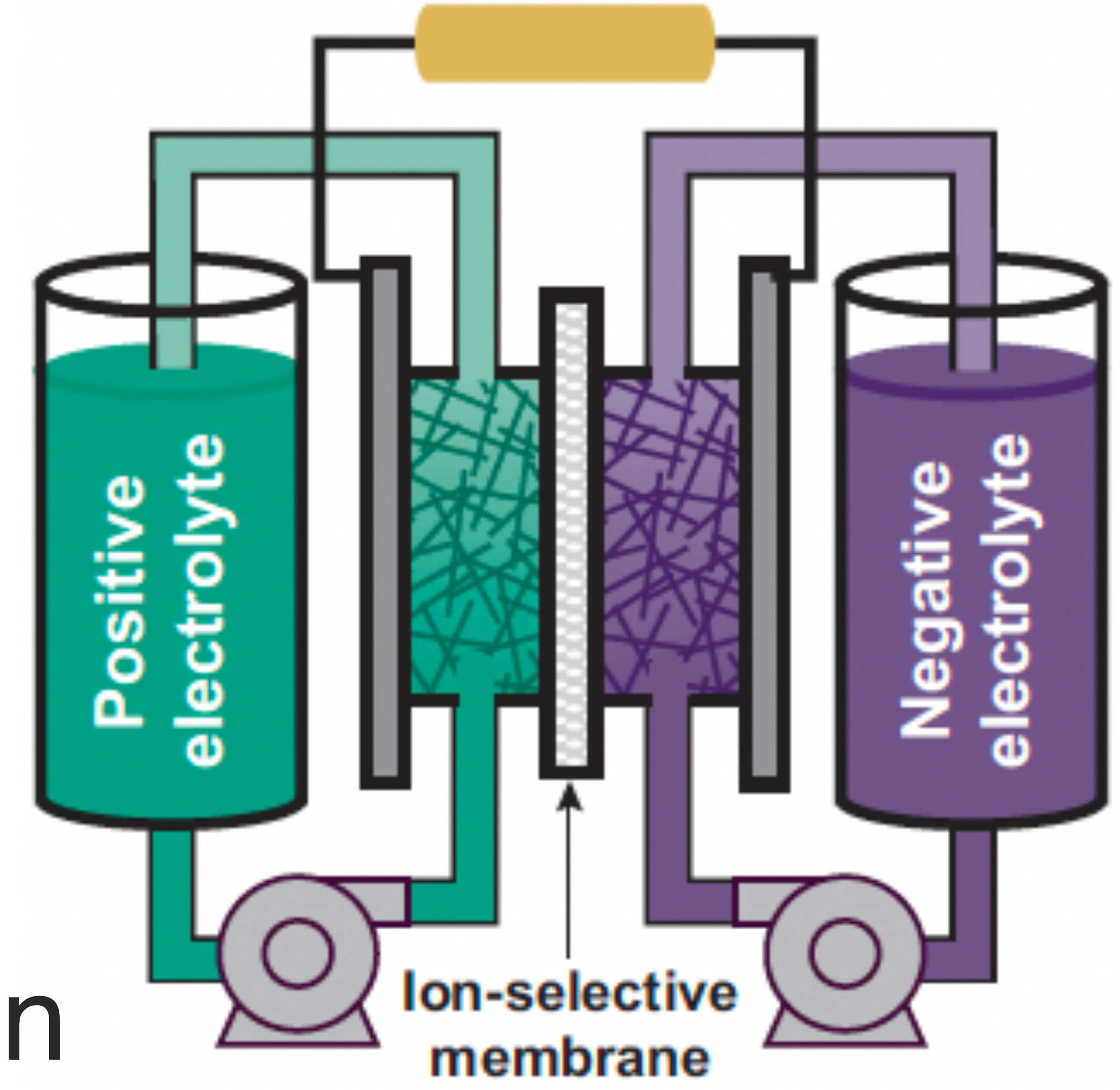


Materials of concern

Lithium Cobalt Nickel

[NMC] = Ni : Mn : Co

Redox flow batteries



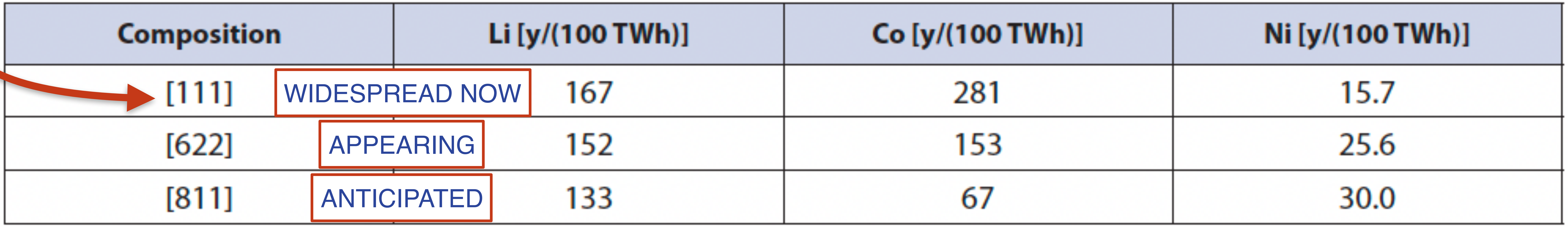
Material of concern

Vanadium

CRUDE FIRST LOOK

[Ni:Mn:Co]

- Years of current production for **100 TWh** of Li-ion batteries



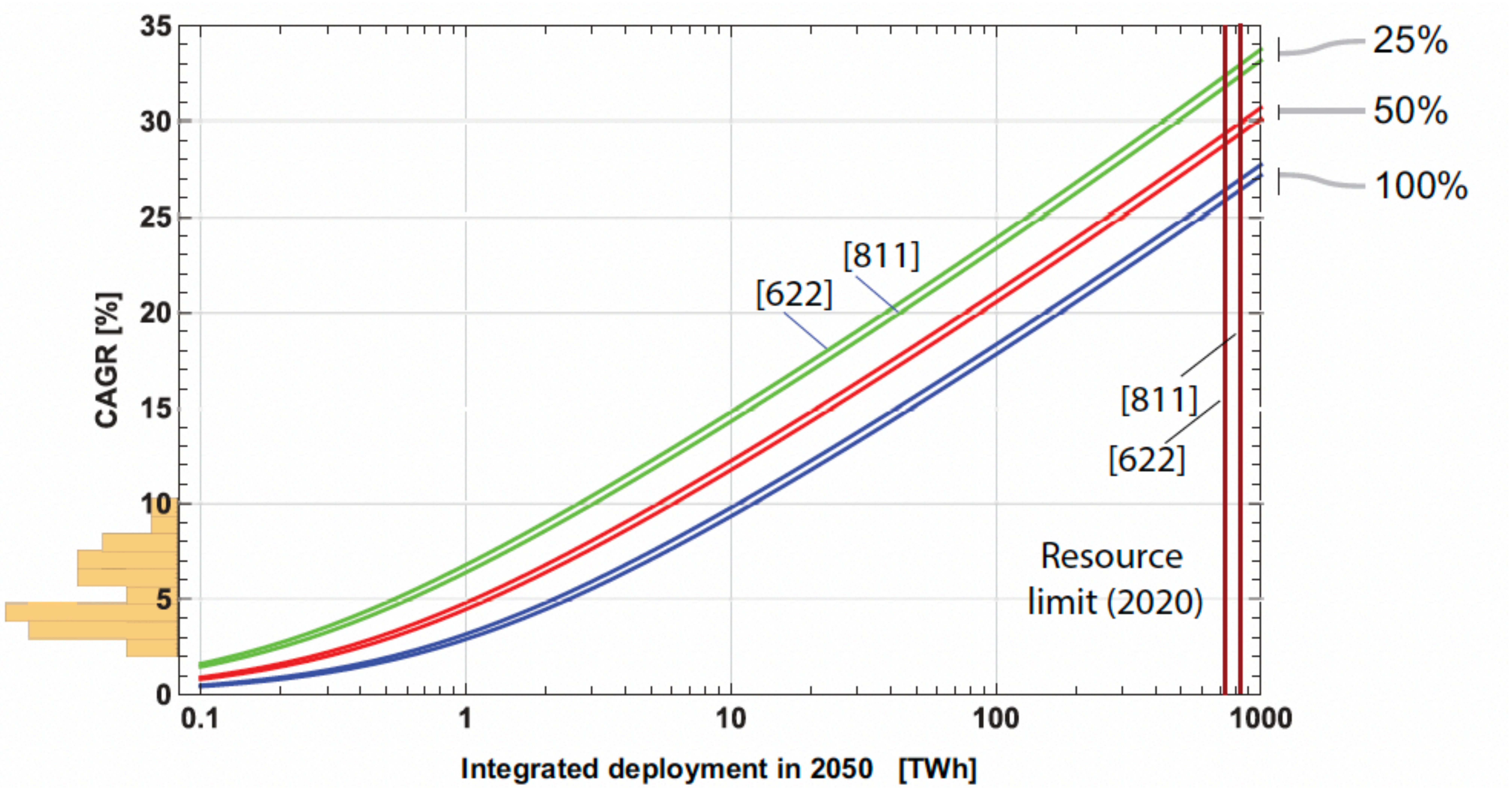
Composition	Li [y/(100 TWh)]	Co [y/(100 TWh)]	Ni [y/(100 TWh)]
[111] WIDESPREAD NOW	167	281	15.7
[622] APPEARING	152	153	25.6
[811] ANTICIPATED	133	67	30.0

- **395** Years of current production for **100 TWh** of vanadium RFB

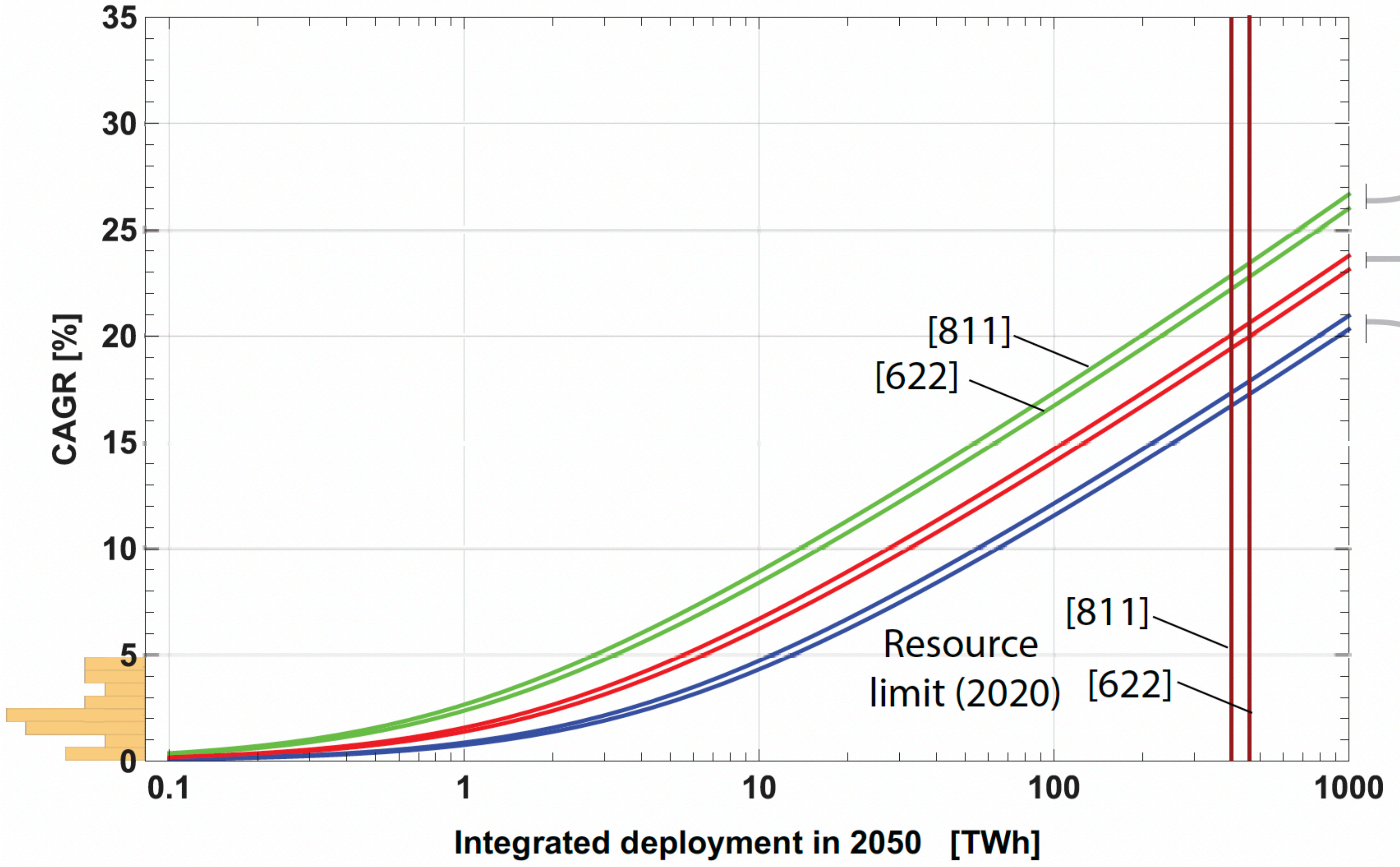
FINDINGS IN A NUTSHELL

“Rapid deployment of batteries in the United States and abroad, primarily in electric vehicles and secondarily for grid-scale energy storage, will require increased production of certain critical battery elements at rates that far exceed historical averages. Constraints on scaling the production of these critical elements already exist and will likely persist, which will have implications for technology development pathways.”

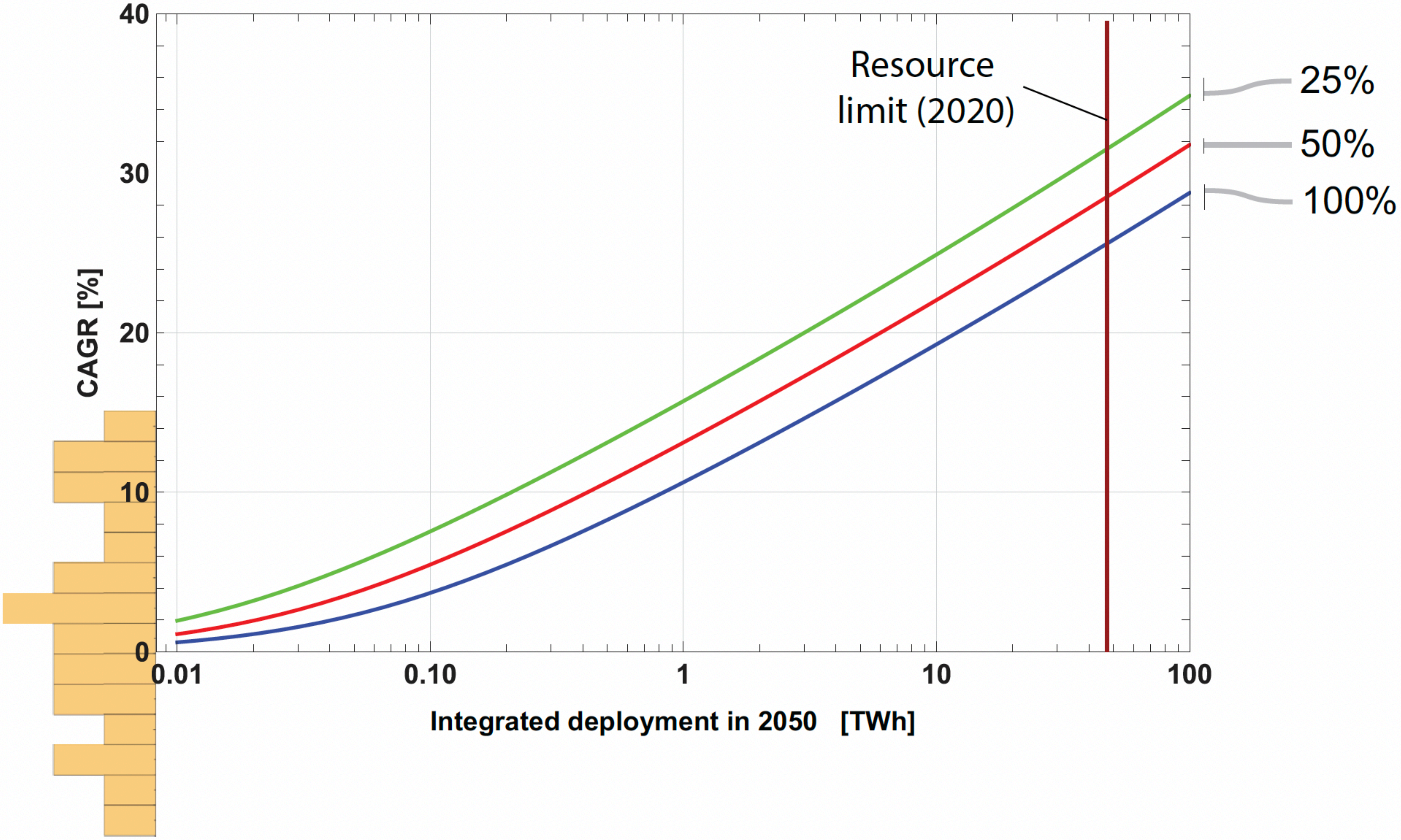
Lithium CAGR for Li-NMC deployment through 2050



Nickel CAGR for Li-NMC deployment through 2050



Vanadium CAGR for Li-NMC deployment through 2050



FINDINGS IN MORE DETAIL

At the higher ends of deployment rate considered in this report, the required rate of increase of production of critical elements such as Co, Ni, Li, and V equals or exceeds historical rates of growth. This implies the expansion of extraction, beneficiation, and refinement facilities beyond current infrastructure.

Producers should consider the use of appropriate technology for a given application. Since space and weight constraints are of greater importance in mobile applications, high energy density technologies, such as Li-NMC, may be more necessary for these applications to achieve rapid scaling required. This is in contrast to lower energy density chemistries, such as LFP, lead-acid, and metal-air batteries, which could play a greater role in stationary battery energy storage.

We recommend research and development on battery technologies that make use of earth abundant materials. Note that neither weight, nor round trip efficiency is as great a constraint on stationary storage as it is on mobile (EV) energy storage.

Given the significant scaling required, it is necessary to more effectively manage resource extraction for energy storage including the environmental and social implications of mining and beneficiation.

COMMENTS ON LITHIUM

Most optimistic among Li, Ni, Co, V

- \+ Already more than 70% directed toward batteries
- \+ Production had grown rapidly in recent years
- \+ Promising extraction directly from brine without evaporation
- \+ Brine, clay, pegmatite
- – But still required in some “earth abundant” battery technologies: e.g. $LiFePO_4$

COMMENTS ON COBALT

Illustrative of risks associate with critical elements

– Production highly concentrated (~70% in DRC)

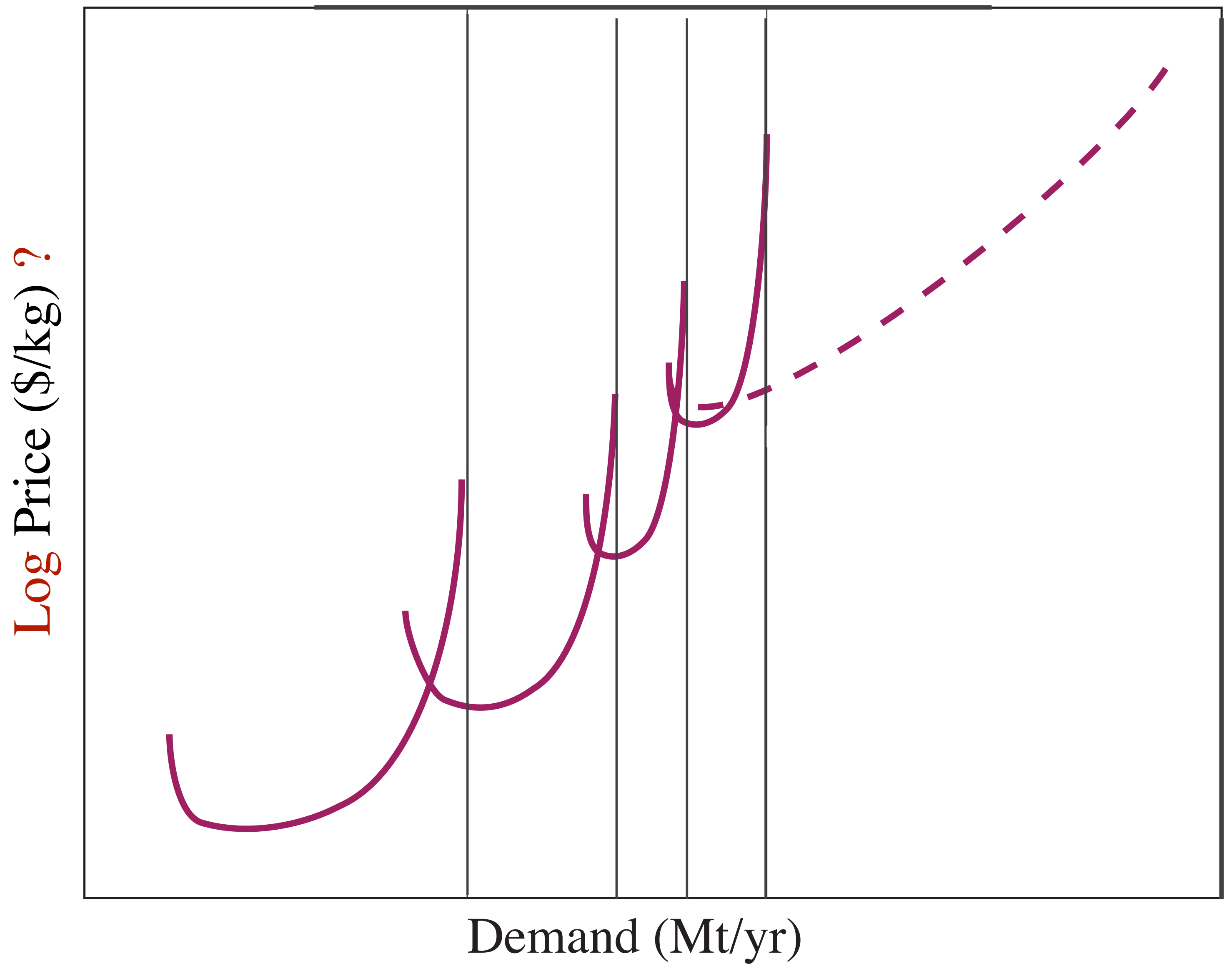
– Processing highly concentrated (~70% in China)

• Considerable artisanal mining

– Social and political consequences of extraction

– By/Co-product economics (Cu, Ni) $\Longrightarrow$ inelastic supply in response to demand

~ Anticipated shift from coproduction with Cu to Ni as well as secondary recovery require investment and may cause supply disruptions



COMMENTS ON NICKEL

Most mature technology & supply chains

– Challenging historical CAGR

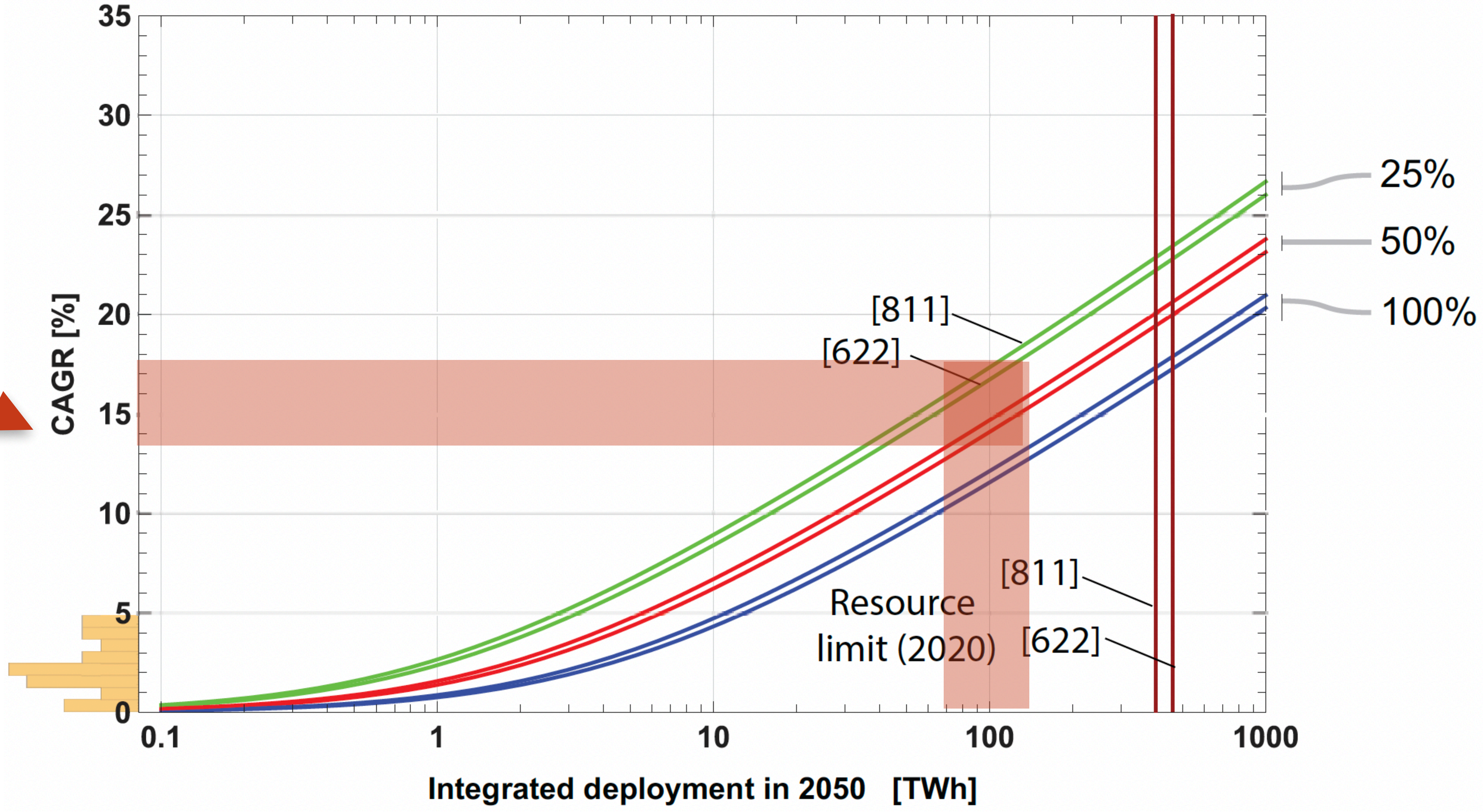
– Demand pressure from stainless steel

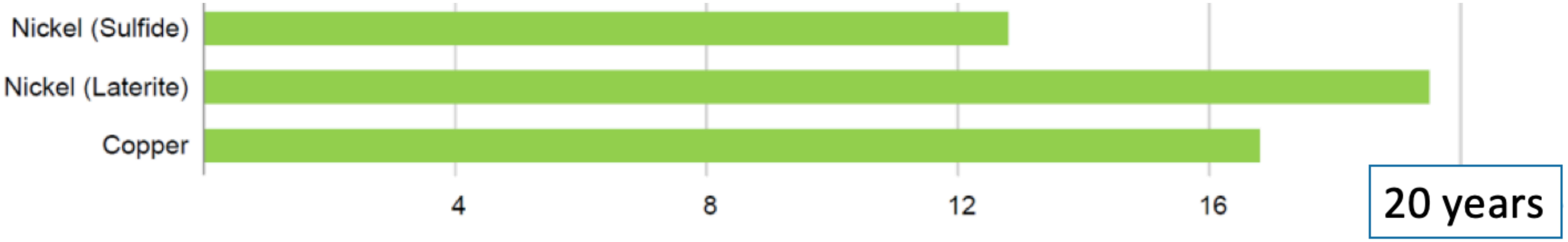
– Most produced via ferronickel, but only nickel sulfate is suitable for battery use

± Possible market disruption from discovery of ferronickel $\Longrightarrow$ battery grade

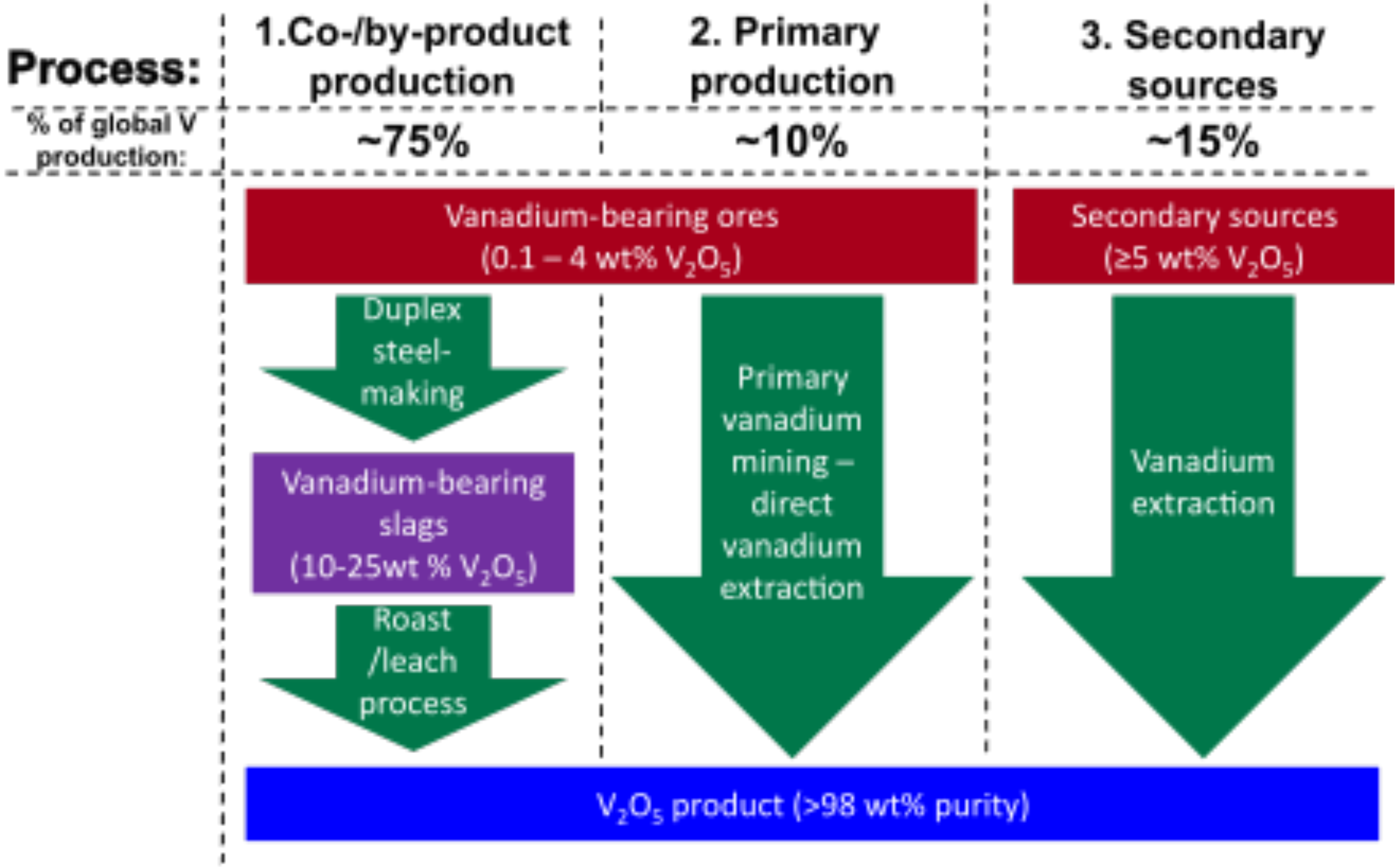
– Long lead time discovery-to-production

\+ Coproduction with cobalt may improve economics





COMMENTS ON VANADIUM



Process:

% of global V production:

1.Co-/by-product production — **~75%**

2. Primary production — **~10%**

3. Secondary sources — **~15%**

Vanadium-bearing ores (0.1 – 4 wt% V_2O_5)

Secondary sources (≥5 wt% V_2O_5)

Duplex steel-making

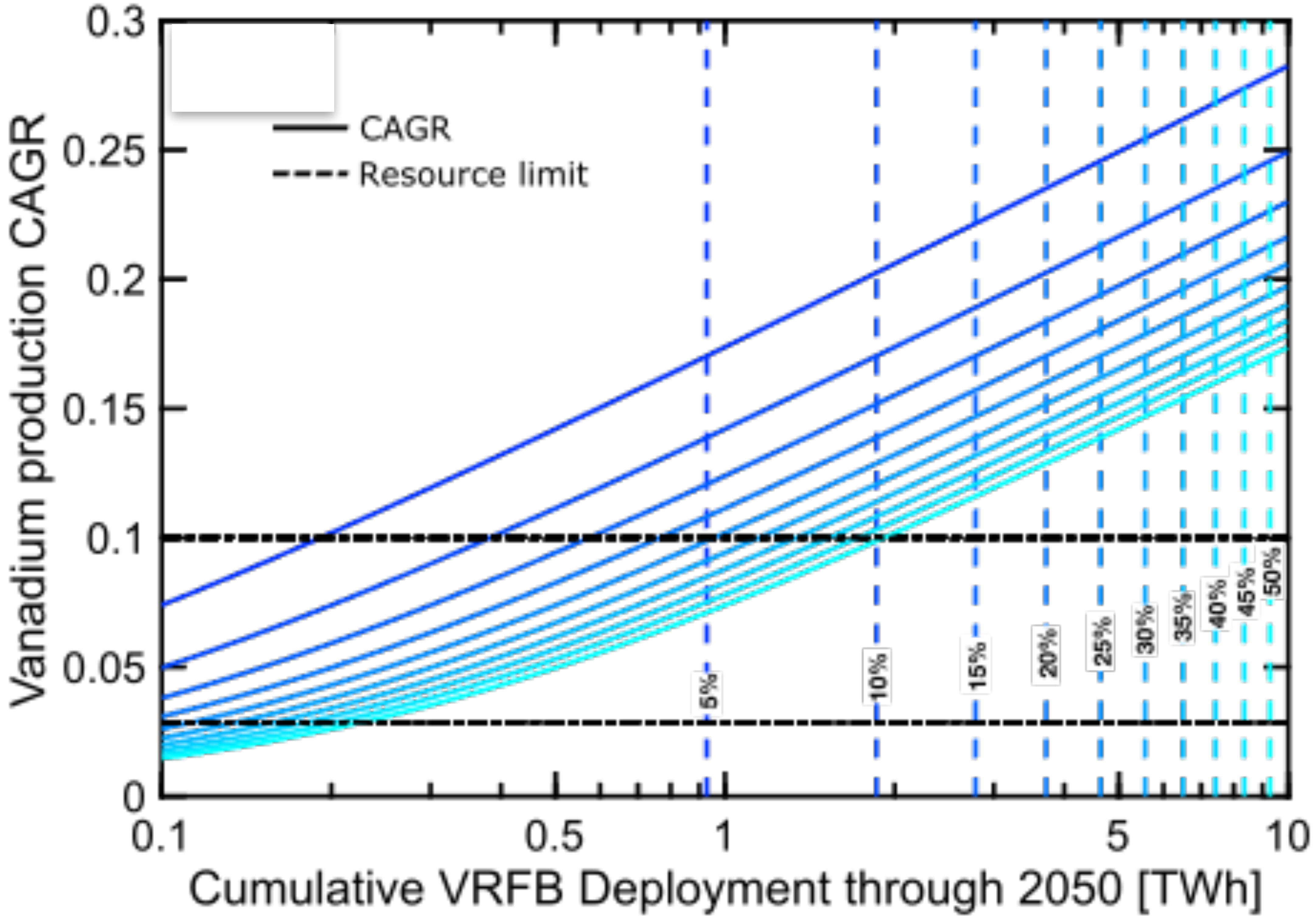
Vanadium-bearing slags (10-25wt % V_2O_5)

Roast /leach process

Primary vanadium mining – direct vanadium extraction

Vanadium extraction

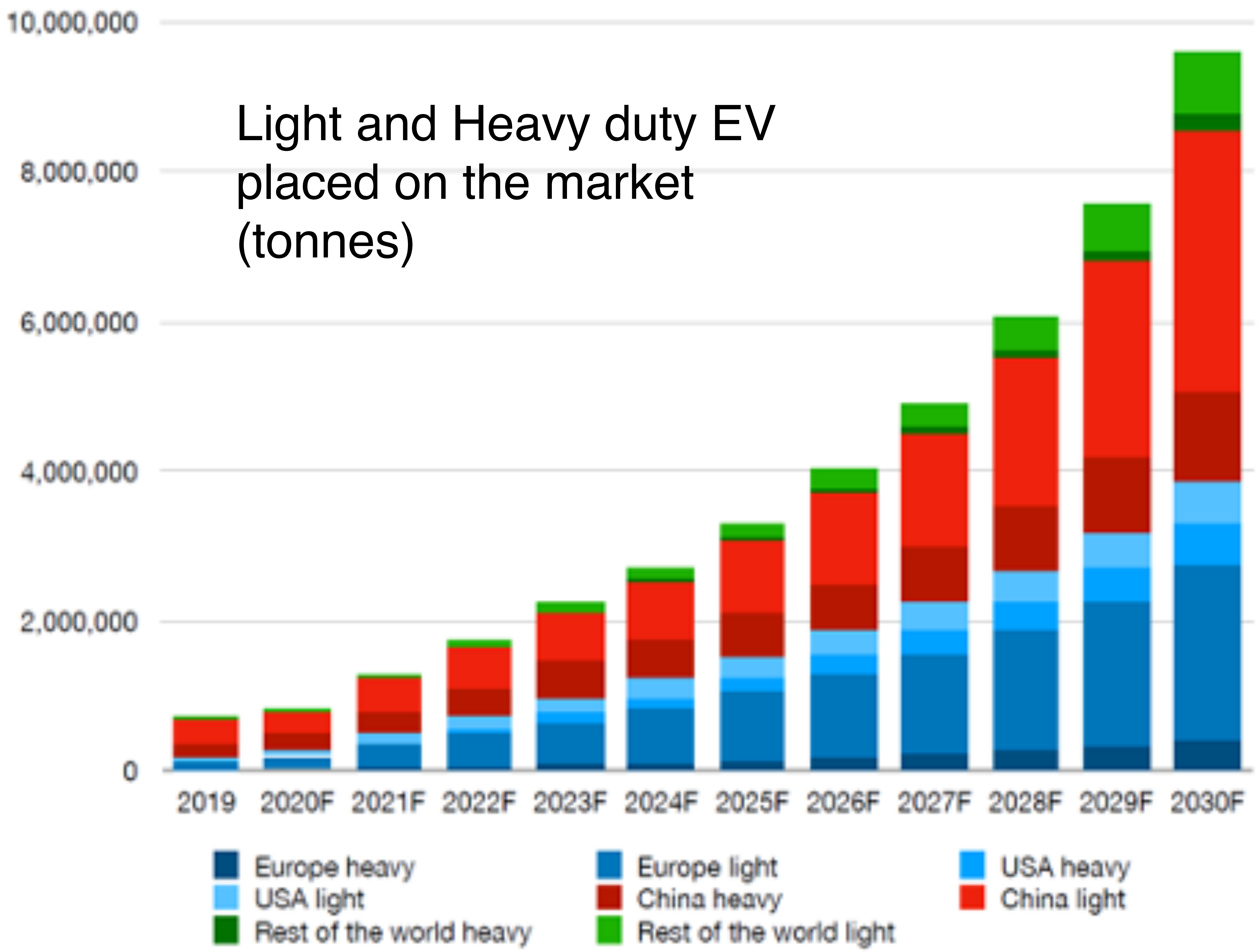
V_2O_5 product (>98 wt% purity)

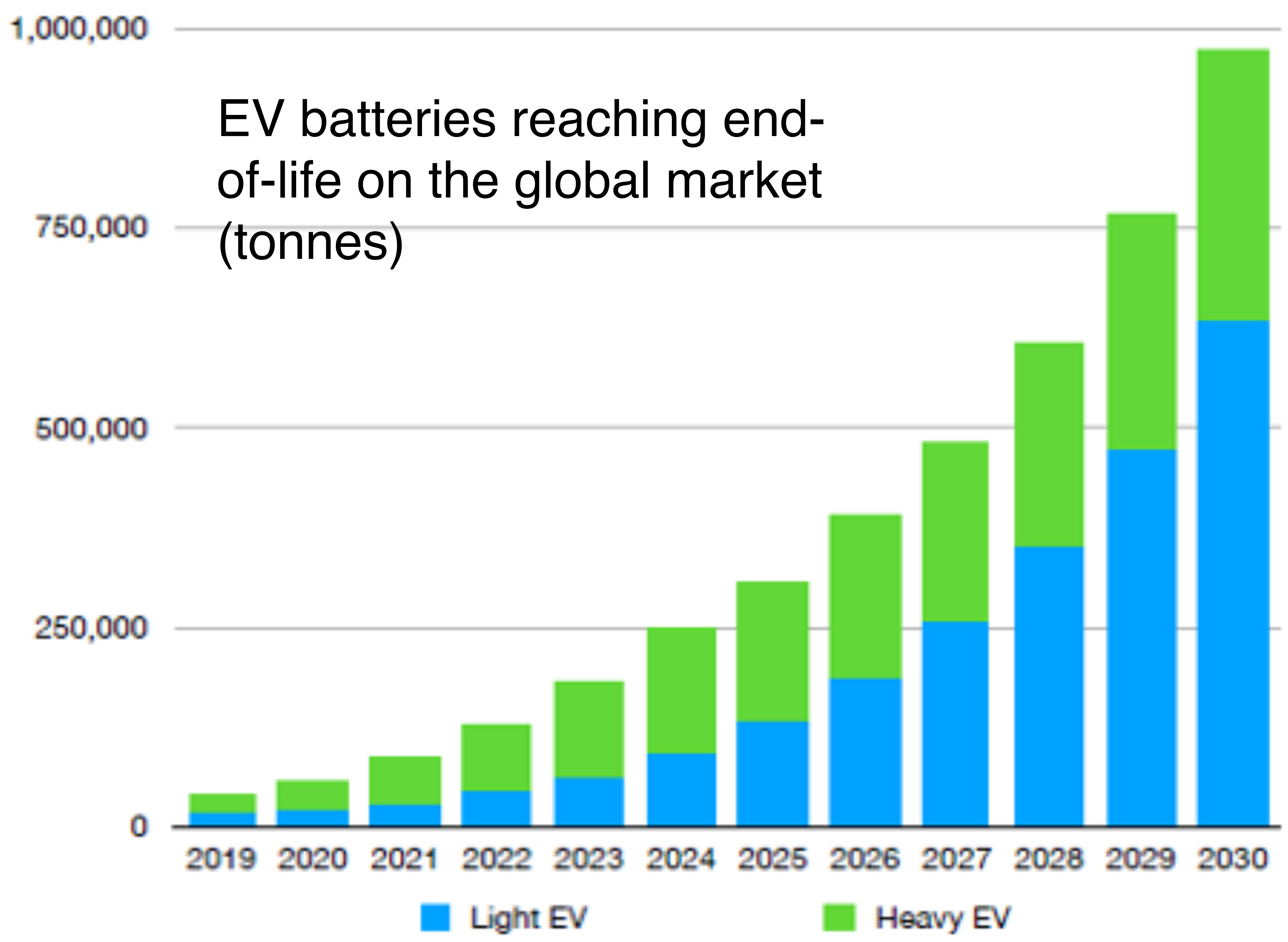


~85% of world’s vanadium from South Africa, China and Russia.

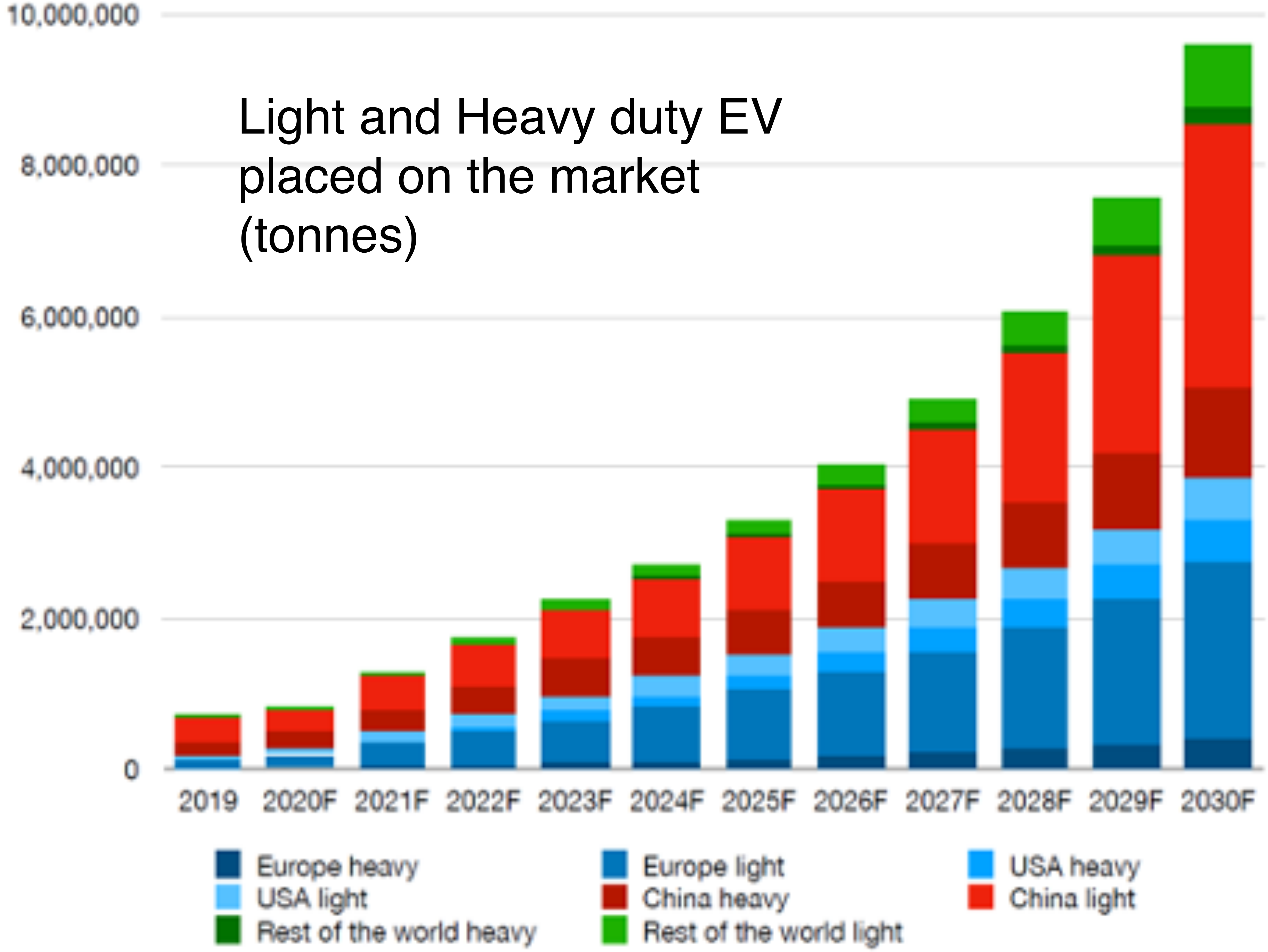
~85% of current demand is for ferrovanadium for alloying with steel.

Over the next decade, managing end-of-life batteries through recycling will become a requirement


Light and Heavy duty EV placed on the market (tonnes)

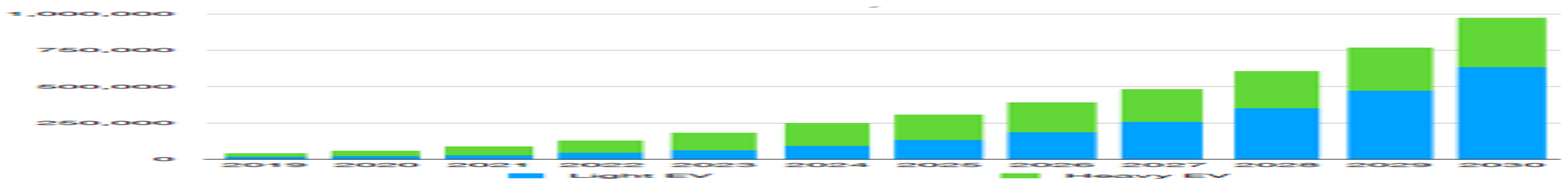

EV batteries reaching end-of-life on the global market (tonnes)

Over the next decade, managing end-of-life batteries through recycling will become a requirement

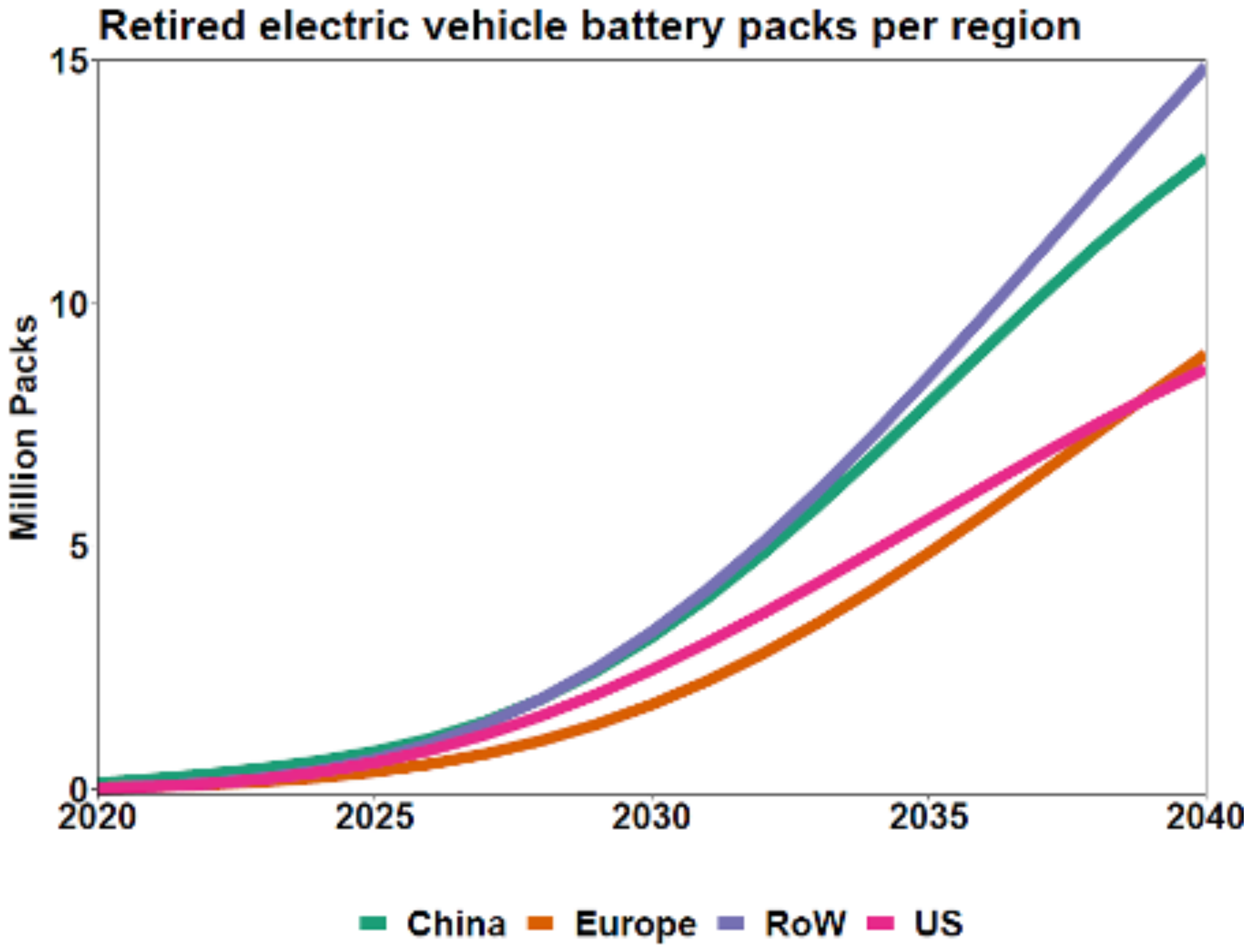


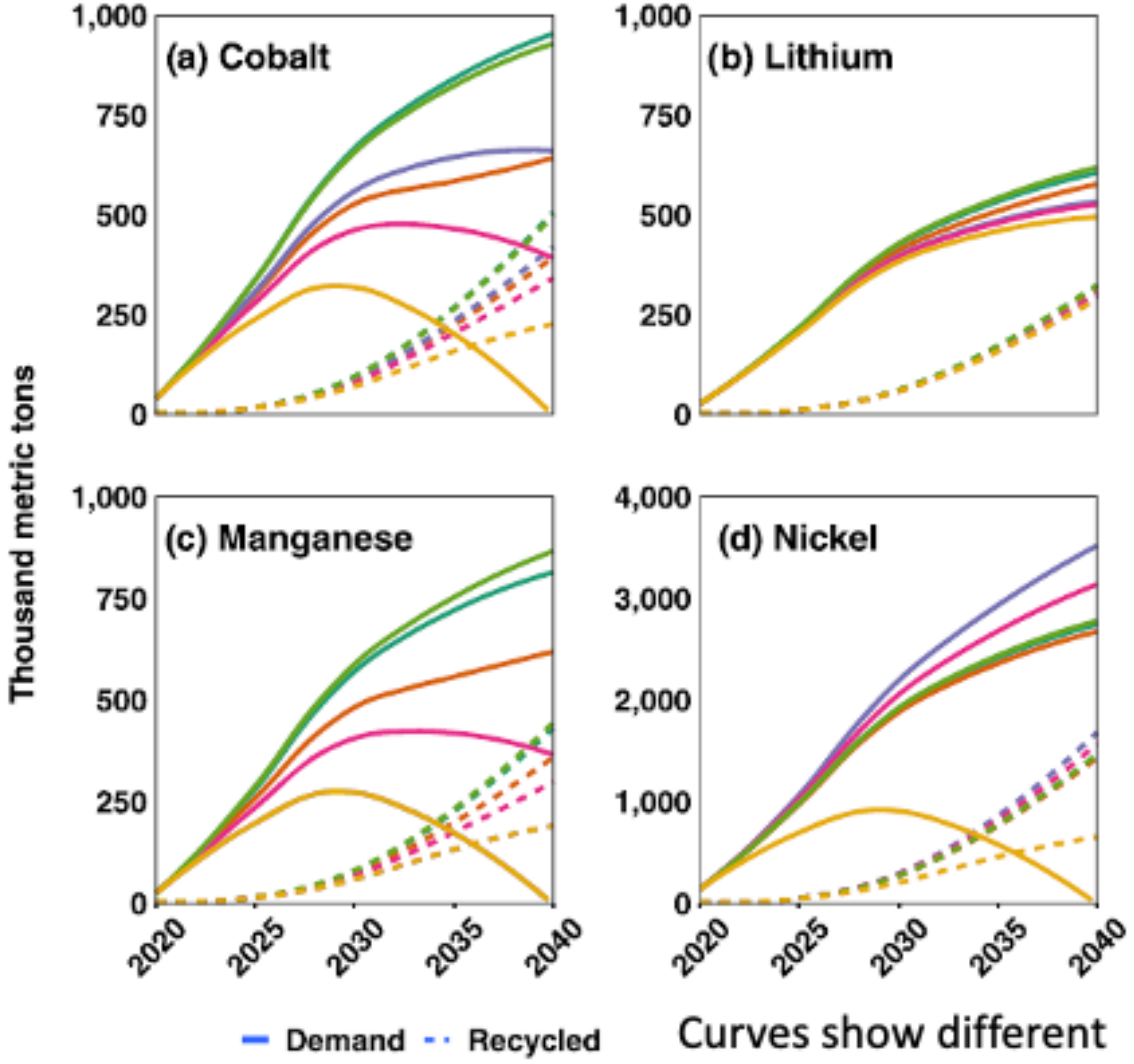
Light and Heavy duty EV placed on the market (tonnes)

EV batteries reaching end-of-life on the global market (tonnes)



Recycling will not contribute significantly to meeting material supply now for exponentially growing deployment trajectory

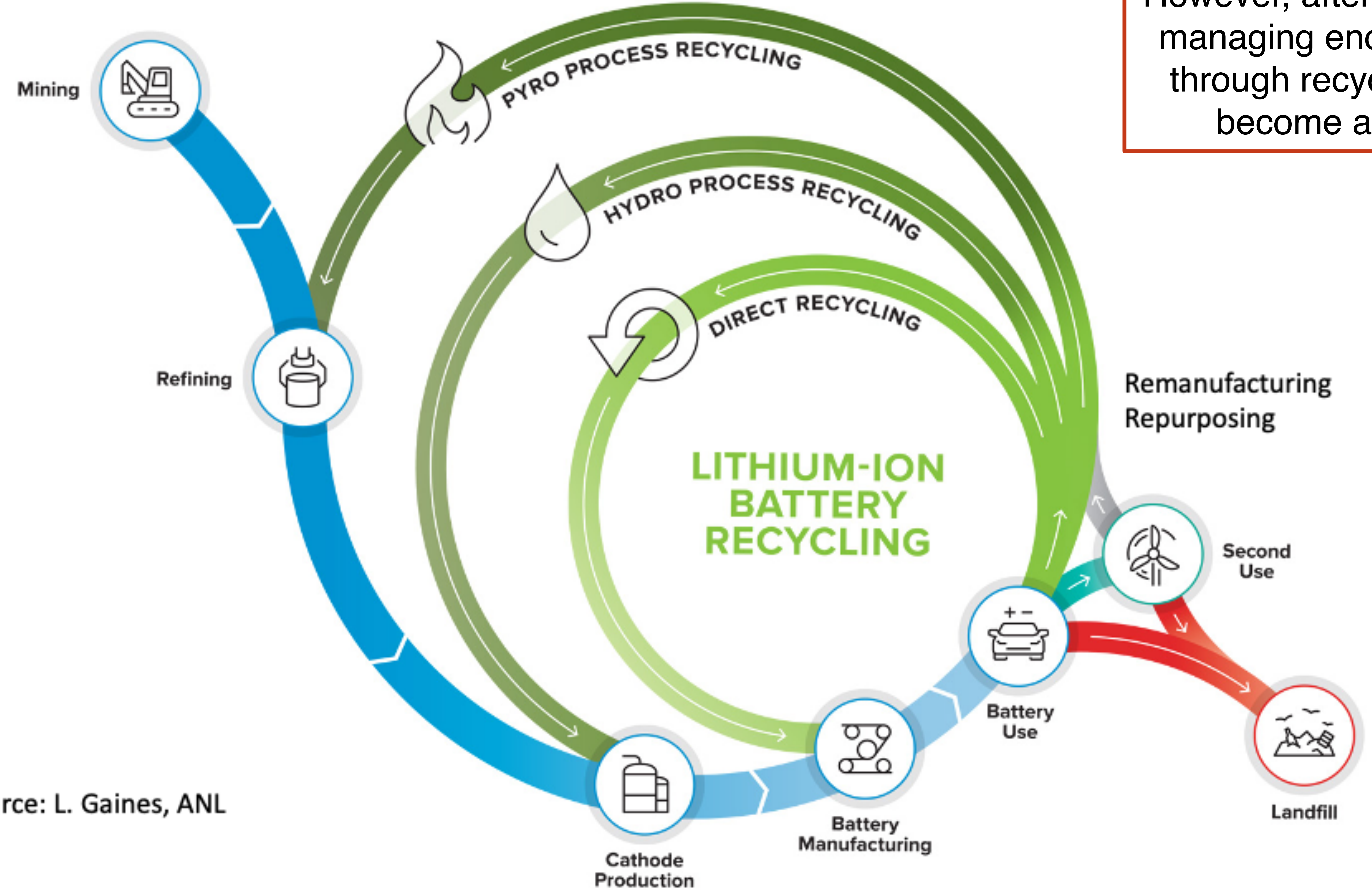




Curves show different demand scenarios

Source: Dunn, et al. ES&T https://doi.org/10.1021/acs.est.0c07030

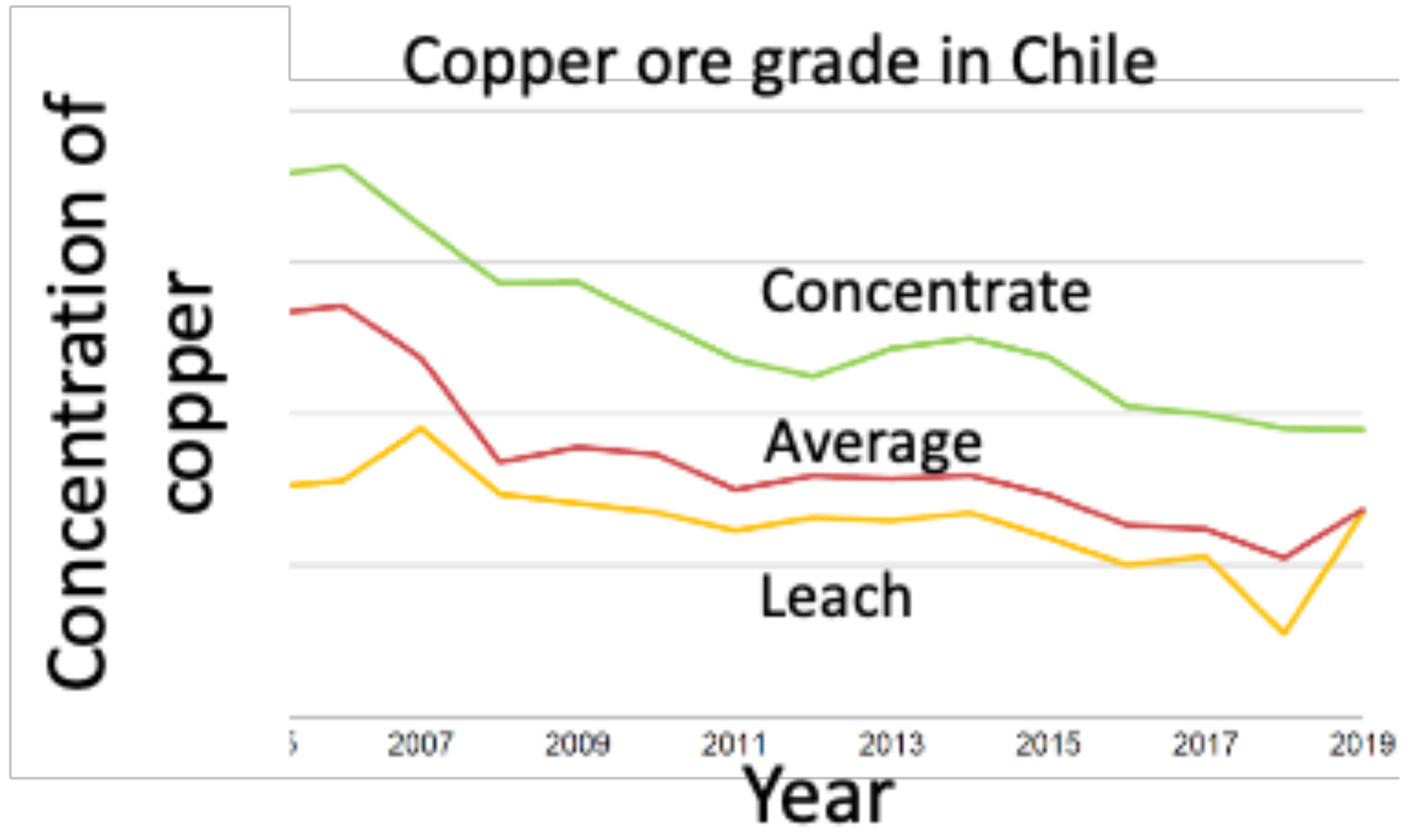
However, after the next decade, managing end-of-life batteries through recycling will quickly become a requirement

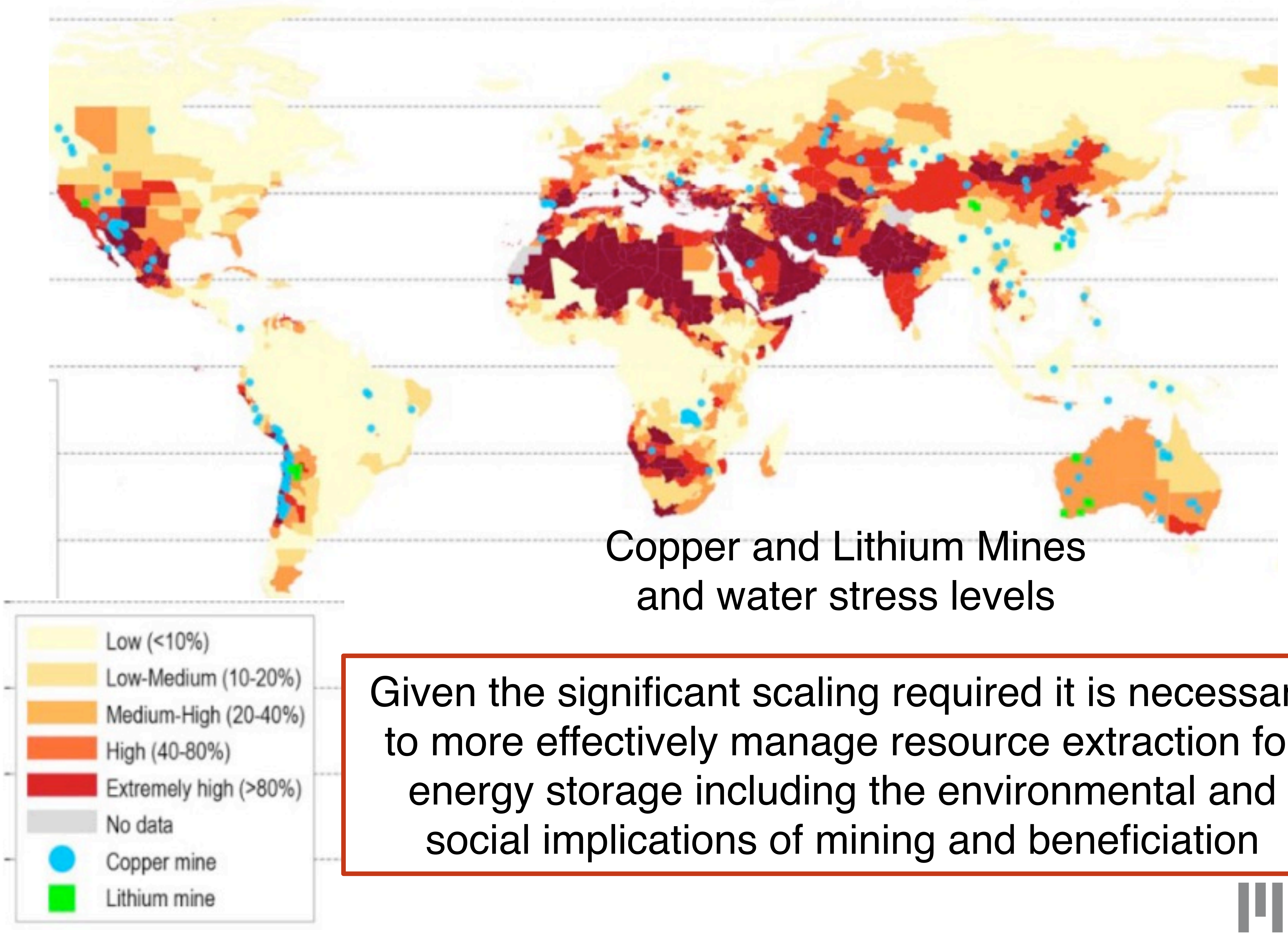


Source: L. Gaines, ANL

Energy transition minerals may involve higher environmental impacts and emissions intensities

Technology	$kgCO_2$-eq/ kg Ni
Today's technology for Ni extraction	5-10
Emerging tech 1	20-30
Emerging tech 2	50-60


Copper ore grade in Chile



Copper and Lithium Mines and water stress levels

Given the significant scaling required it is necessary to more effectively manage resource extraction for energy storage including the environmental and social implications of mining and beneficiation

IEA 2020

Summary thoughts

- Materials demand will grow to meet decarbonization needs
- The challenges across materials are not monolithic
- Physical scarcity will not be a major concern but rather...
- Temporal and contextual issues dominate
  - Technology evolution makes it difficult to plan
  - Mining operation time lags and limited expansion rates
  - Recycling only becomes viable supply as demand declines
- These materials have significant environmental impacts and social conflicts
  - Mineral trade and geopolitics are very unstable
  - By-production constraints pose a big risk
- Materials efficiency has a role, let’s be specific about what that role can be