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Assessment of Transitioning Australia to a Fully Electric Vehicle Transport Fleet

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Assessment of Transitioning Australia to a Fully Electric Vehicle Transport Fleet

Abstract

A study was conducted to assess what would be required to develop a 100 % Electric Vehicle (EV) transport fleet in Australia. The size of the existing Australian transport fleet and the distance travelled over a 12 month period was examined. It was assumed that the same number of vehicles would travel the same distance for the given target year of reported data.

Given that the entire transport fleet was to be electrified, the number of new EV's by vehicle class was estimated, resulting in the size of the projected Australian EV fleet (20 million EV's). The total capacity of EV batteries was calculated for each vehicle class. The size of the Australia battery market would be 1 TWh in scope. The number of new charging stations needed to service the EV fleet was estimated 17 million. The required extra electrical power needed to annually charge the EV fleet was estimated 86.8 TWh which resulted in a required 33% expansion of capacity.

Using an International Energy Agency (IEA) report, an estimation of what the market share of different battery chemistries could be in 2050. The capacity quantity of different battery chemistries was estimated for each Australian vehicle class. Thus, the quantity of metals needed to produce the EV's and their batteries, that Australia would have to source off the international market was estimated.

The quantity of comparatively exotic metals (like lithium, cobalt or germanium) required to produce a 100 % Australian EV transport fleet is quite large compared to global annual production, remembering Australia is a small economy. For this to work as planned, the global mining and refining industrial capacity would have to greatly expand, at a rate that is probably impractical, and in some cases impossible.

This report assumes the global demand for these metals (and minerals) is not increasing. But if Australia is pursuing a 100% EV fleet, it is safe to presume other parts of the world would be doing the same. Australia is a very small proportion of global population and global Gross Domestic Product (GDP). It may be that Australia will only be able source the quantity of metals in proportional amounts similar to the Australian market share of GDP.

The global markets for EV's and batteries may well become inelastic due to practical logistical supply bottlenecks. Australia will struggle to procure enough EV's or batteries in the global markets as all other nation states will be attempting to do the same. Data in this report suggests the supply chain for EV's and lithium-ion batteries could be highly volatile and unreliable. In fact, the current global mineral production rates, and the global experiences in time needed to increase mining outputs and battery production suggest that a complete replacement of Australia's ICE vehicle fleet into an EV fleet seems somewhat unrealistic.

Keywords
Electric Vehicle, battery, battery chemistry, charging, lithium

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Contents

1. INTRODUCTION

The need to phase out fossil fuels as an energy source is imminent, as the urgency of the task is increasingly acknowledged. However, the scale and scope of complexity of this task has been underestimated by strategic planners (Michaux 2021a). In the Net Zero Emissions pathway, by 2050, the entire (100 %) global transport fleet will be made up of electric vehicles (PHEV and BEV) and hydrogen fuel cell vehicles (FCEV) (IEA 2021). This is just 26 years away. A short description of the Green Transition (GT) is shown in Appendix A.

The House of Representatives Standing Committee on Climate Change, Energy, Environment and Water has commenced an inquiry into the transition to electric vehicles (EVs). Associate Professor Simon P. Michaux was invited to submit a paper on this matter to contribute to the discussion (in collaboration with other GTK staff).

An Internal Combustion Engine (ICE) powered vehicle is a transport technology that is powered with petroleum products derived from oil (Moran *et al*. 2014). An EV powered vehicle is a transport technology that is powered with electric propulsion in some form, where electrical power is stored in an onboard battery (IEA 2023). Figure 1 shows the different kinds of EV vehicles.

This study was conducted to examine what is going to be required to fully phase out fossil fuel powered Internal Combustion Engine (ICE) transport and replace the entire existing Australian transport fleet with EV's, by 2050. The required quantity of metals needed to manufacture the Australian EV fleet was also estimated.

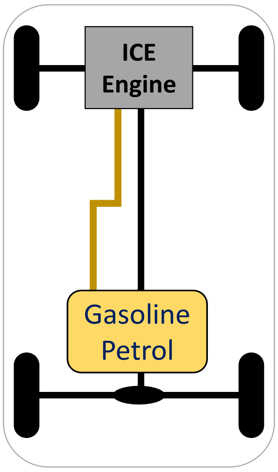
2. ASSUMPTIONS LISTED

The following assumptions were included in this study.

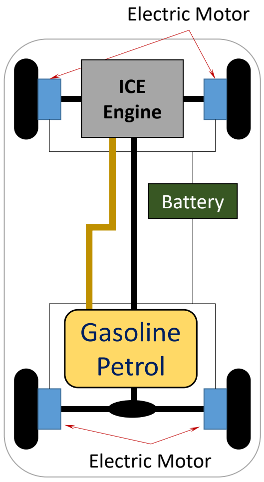
- All vehicles were Electric Vehicle (EV) systems. This was assumed to be achieved by the year 2050, as per decarbonization objectives proposed by the International Energy Agency (IEA 2021).
- Economic activity in the Australia was the same as 2018. This would mean the same physical work was to be done by the transport fleet.
- The Australian transport fleet was the size and vehicle class proportion, as the recorded vehicle registration in 2021.
- Each vehicle in each class travelled the same distance as the average estimate calculated for 2018.
- Australian electrical power was assumed to be generated by the same systems used in 2018. Data from 2018 was used as it was not affected by impacts of the Covid 19 pandemic supply chain disruptions.

Not included in this study

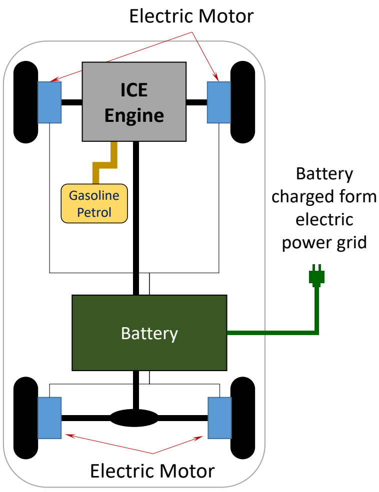
- The domestic maritime shipping and domestic aviation industries were not assessed or included in this study.
- This study suggests a replacement of the entire ICE vehicle fleet based on the numbers of vehicles in 2018, and on the currently most typically applied battery technology. It is thus a straight forward exercise to calculate the scale of needed material and energy to replace the current technology. This report did not build scenarios that consider a reduction in the transport fleet size (less cars).



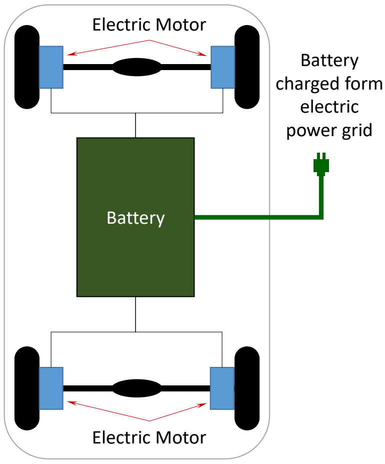
ICE Internal Combustion Vehicle
Powered by a gasoline or diesel internal combustion engine. Uses fuel derived from oil.



HEV Hybrid Electric Vehicle
Powered by both gasoline/diesel and an electric motor. The battery is recharged by the ICE engine when it is running. The vehicle alternates between ICE and electric motor to optimize efficiency and performance.



PHEV Plug-in Hybrid Electric Vehicle
Versatile hybrids in which the electric battery can be charged both by the electric grid and/or the ICE engine. Like HEV's, PHEV have greater range than BEV.



BEV Battery Electric Vehicle
Also known as 'plug in' electric vehicles. They are propelled by an electric motor that is powered from a battery, which is charged of the electric grid. BEV are a short range vehicle that requires infrastructure to be practical.

Figure 1. The different kinds of Combustion and Electric Vehicles
(Image: Simon Michaux)

3. THE AUSTRALIAN TRANSPORT SYSTEM

Data on size, form, and physical work done of the Australian transport fleet was collected from the Australian Bureau of Statistics. The purpose of this study was to examine what an entirely Australian EV transport fleet would look like. An effort was made to assemble the most up to date data that would give the most appropriate result to study.

In 2020, the Covid-19 pandemic was declared, global supply chains were disrupted, and economic consumption of all goods was significantly changed. Interstate border closures began on 19th March 2020 (Parliament of Australia, COVID-19: a chronology of state and territory government announcements). The Australian government declared the emergency response finished in September 2022 and removed all restrictions including the requirement to isolate if one was infected (ABC News 2022).

During the Covid-19 pandemic, the global supply chain disruption resulting from quarantine measures, and the several years following 2020 have resulted in data distortions in comparison to constant or linear socio-economic developments and patterns of the previous 40 years. The purpose of this study was to examine the scale of the physical task to phase out fossil fuels, at a time when society was operating relatively 'normally', hence 2018 and 2019 data was used.

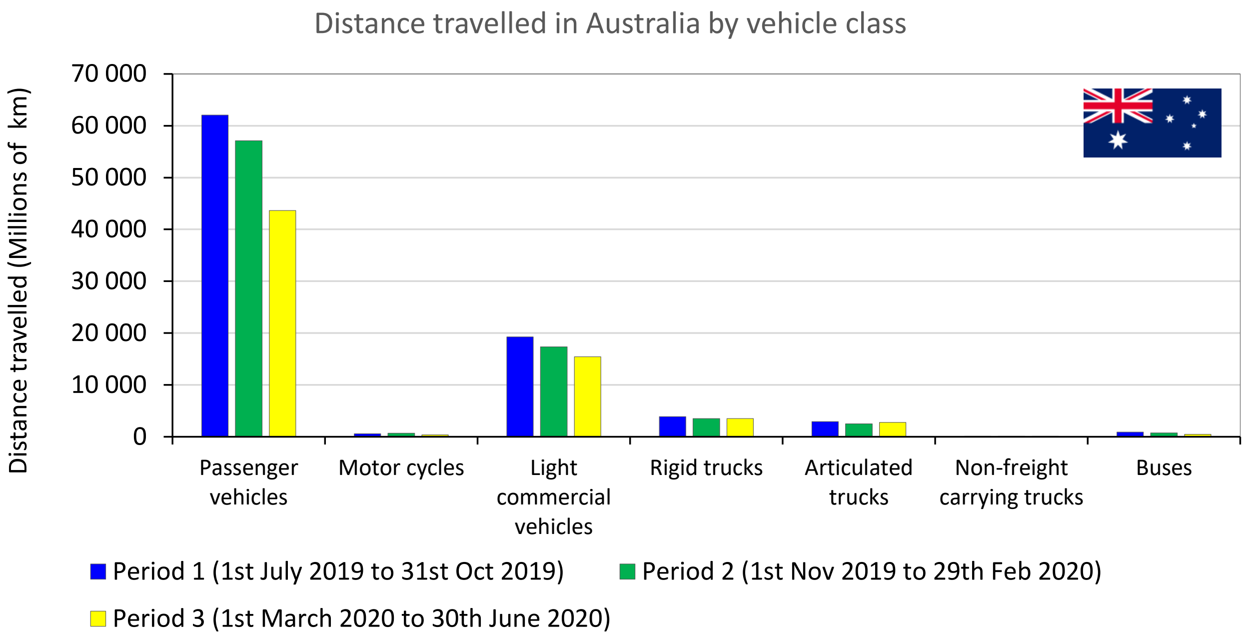


Figure 2. Distance travelled in Australia by vehicle class
(Source: ABN 2021, Australian Bureau of Statistics, Motor Vehicle Census, Australia 31 Jan 2021)

Figure 2 shows this disruption graphically. Figure 2 has data for three consecutive time periods. Period 1 (1st July 2019 to 31st Oct 2019) was before the pandemic lockdowns were in effect. Period 2 (1st Nov 2019 to 29th Feb 2020) and Period 3 (1st March 2020 to 30th June 2020) were during the pandemic quarantine lockdowns. Between Periods 1 and 3, there was 29.7% contraction in the distance travelled by passenger cars (which was by far the largest subgroup). The physical work done across 2020 was quite different in scope and form compared to other years. Since 2020, the transport sector's recovery after Covid-19 has been quicker than expected, and therefore figures representing the pre-pandemic year 2019 are safe to use for this exercise (OECD 2023).

The following choices were made regarding what data to use in this study, to provide the most up to date but appropriate analysis of the Australian transport fleet:

- Data used to assess the number of vehicles in the Australian transport fleet was from the year 2021 (ABN 2021, Appendix B).

- Data used to assess the distance travelled in the Australian transport fleet was from the year 2019 (ABN 2020). This was the most current year for normal economic physical work done.

Figure 3 shows the size of the Australian transport fleet across all states and territories for the years 2016, 2020 and 2021 (data in Appendix B). As can be seen the transport fleet has been steadily growing in size with each passing year, with the majority of the network being in New South Wales, Victoria and Queensland.

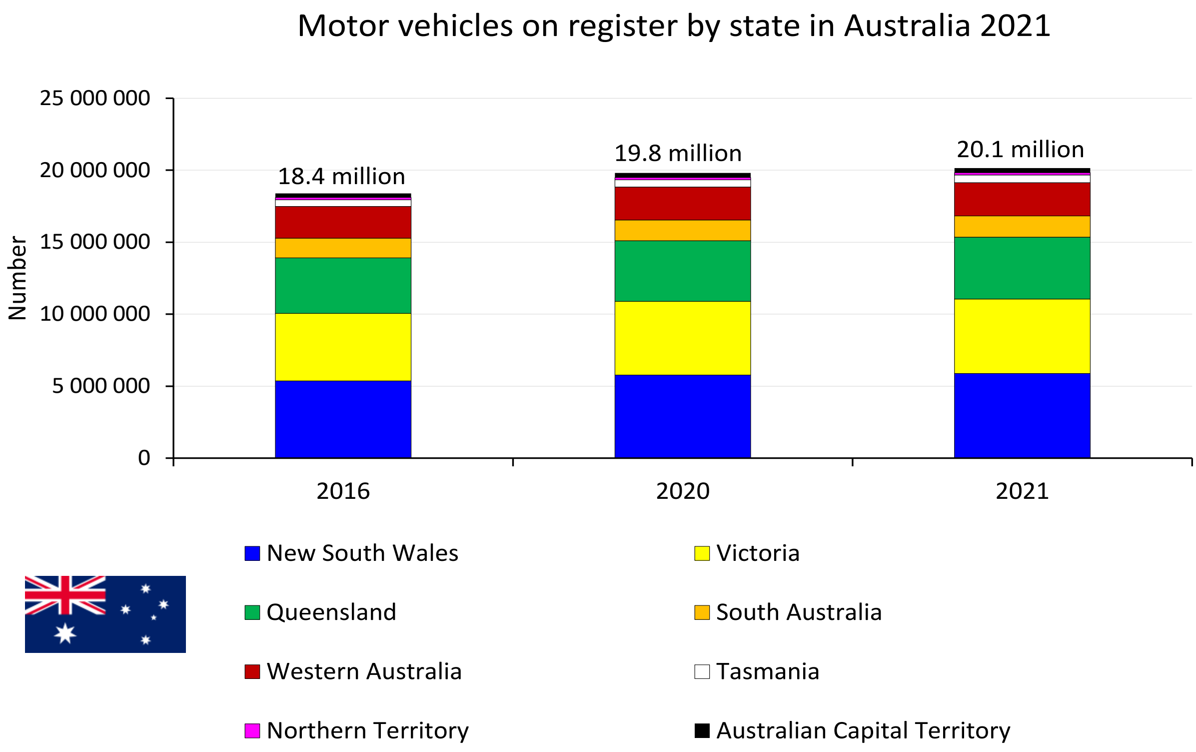


Figure 3. Size of the Australian transport fleet, by state
(Source: ABN 2021, Australian Bureau of Statistics, Motor Vehicle Census, Australia 31 Jan 2021)

Figure 4 shows the proportions of different vehicle classes for the transport fleet in 2021 (data in Appendix B). Passenger cars make up the majority of the transport fleet. The trucking fleet accounts for just 3.3% of the whole transport fleet yet moves the majority of the physical goods in freight.

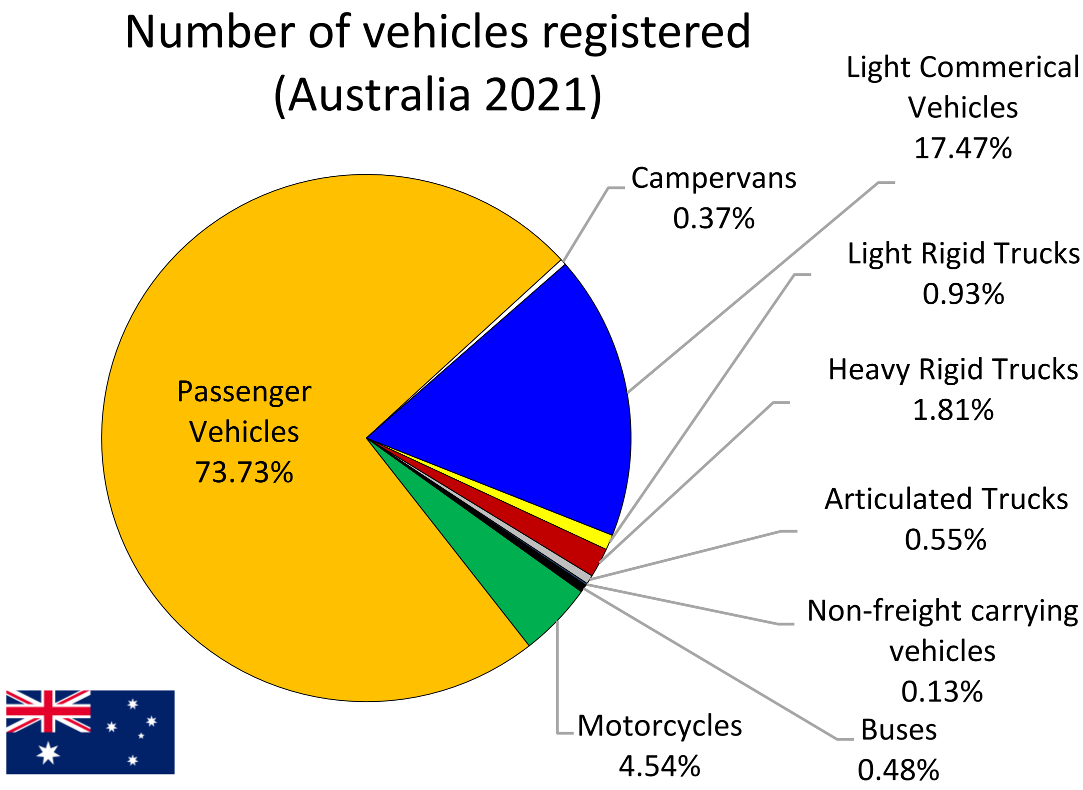


Figure 4. Number of vehicles registered in the 2021 Australian transport fleet
(Source: ABN 2021, Australian Bureau of Statistics, Motor Vehicle Census, Australia 31 Jan 2021)

The estimated distance an average vehicle travelled is shown in Table 1. As discussed above, the most appropriate data to use was Period 1 (1st July 2019 to 31st Oct 2019) from the Australian Bureau of Statistics (ABN 2020). This was a period of just 4 months. For the purpose of this study, an equivalent distance was calculated for 12 months, resulting in Table 1.

Table 1. Estimated distance travelled in Australia for an equivalent 12 month time period (Source: ABN 2020)

Class of Vehicle	Recorded distance travelled in Australia over 4 months (based on 1st July to 31st Oct 2019) (km travelled)	Estimated distance travelled in Australia for an equivalent 12 month time period (km travelled)
Passenger vehicles	4 200	12 600
Motor cycles	700	2 100
Light commercial vehicles	5 600	16 800
Rigid trucks	7 500	22 500
Articulated trucks	28 200	84 600
Non-freight carrying trucks	4 800	14 400
Buses	10 300	30 900
Total for all vehicle classes	61 300	183 900

Table 2 shows a summary of the pertinent data for this study; the number of vehicles, by class, the estimated distance an average vehicle of each class would have travelled over 12 months, and the total distance travelled by the entire vehicle class. The whole Australian transport fleet travelled approximately 273 billion kilometers in 12 months (based on a 4 month period in 2019).

Table 2. Number of vehicles in the Australian transport fleet and estimated distance travelled in a 12 month time period

Class of Vehicle	Number of vehicles registered in Australia 2021 ‡ (number)	Estimated distance travelled in 12 months per vehicle * (km travelled)	Total distance travelled in a 12 month time period for that entire vechicle class (km travelled)
Passenger Vehicles	14 850 675	12 600	1.87E+11
Campervans	74 324	-	-
Light Commerical Vehicles	3 519 457	16 800	5.91E+10
Light Rigid Trucks	187 329	22 500	4.21E+09
Heavy Rigid Trucks	364 989	22 500	8.21E+09
Articulated Trucks	109 927	84 600	9.30E+09
Non-freight carrying vehicles	25 378	14 400	3.65E+08
Buses	97 060	30 900	3.00E+09
Motorcycles	913 803	2 100	1.92E+09
Total in Australia	20 142 942		2.73E+11

‡ Source: ABN 2021
* based on a rate recorded from 1st July to 31st Oct 2019, (Source: ABN 2020)

273.3 billion km
Total in Australia

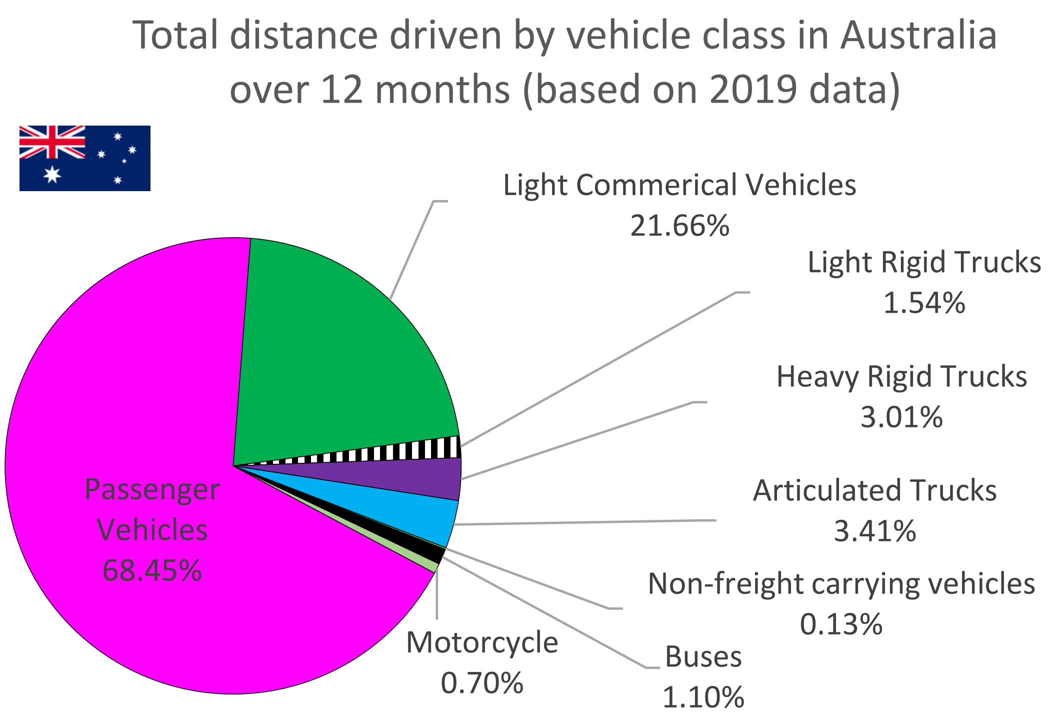


Figure 5. Total distance driven by vehicle class in Australia over 12 months (based on 2019 data, ABN 2020)

The transport network shown in Table 2 was supported by a network for refueling stations. In Australia, there are approximately 9 700 fuel stations (Source: FuelPrice Australia, https://fuelprice.io/brands/). The average fill-up time to fuel an average ICE passenger car takes approximately two minutes (Source: American Petroleum Institute).

The number of Electric Vehicles (EV) has been increasing each year. Table 3 shows the number of EV's in Australia for 2021. These EV vehicles were subtracted from the passenger cars and motorcycles in Table 2 to estimate the number of EV's to be constructed and procured by Australian society (shown in Table 5). The Australian market would have to compete with international market forces to function.

The mandate of this study was to examine what footprint a 100 % EV fleet would have, in context of a 100% phasing out of petroleum fueled ICE technology. It is possible to include hydrogen fuel cell vehicles and ammonia fueled ICE vehicles, but this would be beyond the scope of this report. To include hydrogen fueled vehicles, an assessment of market split across the different vehicle classes and extra electrical power demand for hydrogen production would be required. Ammonia fueled ICE vehicles are not commercially viable yet.

Table 3. Electric vehicle registrations in Australia from 2020 - 2021, by vehicle type
(Source: ABN 2021, Australian Bureau of Statistics, Motor Vehicle Census, Australia 31 Jan 2021)

Vehicle type	2020	2021
Passenger vehicles	12 651	20 095
Motorcycles	1 308	2 706
Other	294	327
Total	14 253	23 128

4. EV SUBSTITUTE FOR EACH CURRENT VEHICLE CLASS IN THE AUSTRALIAN TRANSPORT FLEET

For each class of vehicle in the Australian transport fleet (Figure 4), a representative EV substitute was selected. The performance metrics were collected, and it was assumed that all vehicles in that class performed to the same metrics. While this was a crude calculation, it did give a useful high level nation wide estimate of what an all EV transport fleet in Australia might look like. To replace the existing fossil fuel powered Internal Combustion Engine (ICE) vehicle fleet and construct a 100 % EV transport fleet in Australia, 20 million Electric Vehicles (EV) are required to be manufactured (Table 2) and purchased/paid for by consumers. Furthermore, the 20 million outgoing ICE vehicles would need to be disposed of in a sustainable manner.

Appendix C provides a list of current electric vehicles (EV), with battery size, efficiency, average range, and a range of ranges in the city, and out on the open freeway. The range is between driving in sub-zero temperatures with heating on and driving in warm weather conditions with no air conditioning. All of these vehicles listed can achieve longer ranges on road trips, if driven economically.

Table D2 in the Appendix D shows a range of EV units, which for an average passenger car (car) consumes 0.19 kWh/km, or for every kilometer traveled, the vehicle needs 0.19 kWh. Table D3 in the Appendix D shows the specifications of a series of electric commercial vans. These vehicles are in production and specifications are readily available. An average energy consumption of 0.23 kWh/km has been chosen for Light Truck/Van vehicles. Table D5 in the Appendix D shows the specifications of EV buses to transport lots of people. Only two examples are shown here (7900 Volvo and BYD K9), but these two models represent a large proportion of the current global EV bus fleet. An average energy consumption for a Transit Bus, Paratransit Shuttle, or School Bus EV vehicle to be used is 1.32 kWh/km. Table D6 in the Appendix D shows the specifications for a range of trucks, including HCV Class 8 trucks if they were EV systems with average energy consumption of 1.46 kWh/km. Specifications are from manufacturer's press releases. All of this is summarized in Table 4.

Table 4. Specifications of Electric Vehicles selected by vehicle class for this study

Vehicle Class EV	Specifications selected for vehicle class from Appendix D	KiloWatt-Hour power to distance consumption vehicles were EV (kWh/km)	Estimated individual vehicle battery capacity (kWh)
Passenger Vehicles	Table D1	0.19	46.79
Light Commerical Vehicles	Table D3	0.23	42.14
Light Rigid Trucks	Table D6	0.82	194.3
Heavy Rigid Trucks	Table D6	1.01	206
Articulated Trucks	Table D6	1.46	450
Non-freight carrying vehicles	Table D6	1.01	206
Buses	Table D5	1.32	227.5
Motorcycle	Table D2	0.056	12.73

4.1 The number of EV's and type of Batteries required when transport fleet is fully EV

The number of needed new EV units and their batteries for Australian society to develop a 100 % EV transport fleet in Australia is shown in Table 5. To put this in context, the global EV fleet in 2023 was estimated to be 26 million vehicles (mostly passenger cars) (IEA 2023).

Table 5. Estimated total battery capacity of a completely EV Australian transport fleet

Vehicle Class EV	Number of EV's to be constructed & procured (number)	Estimated individual vehicle battery capacity (kWh)	Total battery capacity for that vehicle class (GWh)
Passenger Vehicles	14 830 580	46.79	693.9
Light Commerical Vehicles	3 519 457	42.14	148.3
Light Rigid Trucks	187 329	194.3	36.4
Heavy Rigid Trucks	364 989	206	75.2
Articulated Trucks	109 927	450	49.5
Non-freight carrying vehicles	25 378	206	5.2
Buses	97 060	227.5	22.1
Motorcycle	913 803	12.73	11.6
Total	**20 048 523**		**1 042.2**
	20.0 million EV vehicles		1.04 TWh of battery capacity

4.2 Number of EV charging stations

The National Renewable Energy Laboratory (NREL) did a study (Wood *et al.* 2023), where it was calculated that 28 million charging ports would be required to service an electric vehicle fleet size of 33 million cars (this was the target of the study to be achieved by 2030). Assuming this same ratio between Electric Vehicles and charging ports, and that Australia would have an EV fleet of 20 million vehicles, then 17 million (17 010 868) charging stations would be needed across all states and territories of Australia. It is not clear how many of these could be residental home charging units and how many would have to be constructed in a public service point. As such metal content in EV charging points was not included in total metal quantity calculations.

There are several kinds of EV charging station technologies. EV's can be charged using electric vehicle service equipment (EVSE) operating at different charging speeds (U.S. Department of Transport).

- **EVSE Level 1**
  Level 1 equipment provides charging through a common residential 120-volt (120V) AC outlet. Level 1 chargers can take 40-50+ hours to charge a BEV to 80 percent from empty and 5-6 hours for a PHEV. This is not relevant for Australia as 240 V electrical power is standard. This Level 1 EVSE unit would dominate the international market though as the United States would need the 120 V service.

- **EVSE Level 2**
  Level 2 equipment offers higher-rate AC charging through 240V (in residential applications) or 208V (in commercial applications) electrical service, and is common for home, workplace, and public charging. Level 2 chargers can charge a BEV to 80 percent from empty in 4-10 hours and a PHEV in 1-2 hours.

- **DCFC**
  Direct current fast charging (DCFC) equipment offers rapid charging along heavy-traffic corridors at installed stations. DCFC equipment can charge a BEV to 80% in just 20 minutes to 1 hour. Most PHEVs currently on the market do not work with fast chargers.

Level 2 EVSE and DCFC equipment has been deployed at various public locations in the United States and Australia including, for example, at grocery stores, theaters, or coffee shops. It was recommended that when selecting a charger type, consider its voltages, resulting charging and vehicle dwell times, and estimated up-front and ongoing costs.

The infrastructure required to do this is much larger in scope, and requires more capital, and more extensive logistical support than current strategic thinking allows for.

Only approximately 558 high-power public charging locations in Australia in 2023 (Thompson 2023), some with multiple charging bays. While this is a significant improvement over 2022, to reach the full EV fleet support requirements, a lot more capital and logistical support would be required with associated strategic planning to deploy many millions of additional stations - with corresponding transmission capacity.

Consider the EV charge times at charging stations listed above and compare them to the average ICE passenger car fueling time of 2 minutes (Source: American Petroleum Institute). The implications are that society would have to undergo a major restructure in how the transport fleet would operate, particularly in planning and arranging recharging activities. This does not account for domestic charging, done overnight, so there may be no real issue for future planning, but the total energy available and transmission capacity needs to be thought through.

5. ANNUAL RATE OF DELIVERY IF FULL SYSTEM WAS OPERATIONAL IN 2050

This report has assembled data to examine what a 100 % EV transport fleet would look like in Australia as a final outcome. Strategic planners have been advocating for The Green Transition to be completed by 2050 (IEA 2021). Tables 6 to 8 show what an annual rate of procurement would be if the entire system would be established in 2050, which is 26 years from now.

Table 6. Annual construction and procurement of EV's in Australia to deliver 100% EV's in 26 years

Vehicle Class EV	Number of EV's for a 100% EV transport fleet in Australia (number)	Annual construction and procurement of EV's in Australia to deliver 100% EV's in 26 years (number)
Passenger Vehicles	14 830 580	570 407
Light Commerical Vehicles	3 519 457	135 364
Light Rigid Trucks	187 329	7 205
Heavy Rigid Trucks	364 989	14 038
Articulated Trucks	109 927	4 228
Non-freight carrying vehicles	25 378	976
Buses	97 060	3 733
Motorcycle	913 803	35 146
Total	**20 048 523**	**771 097**

Table 7. Annual construction and commissioning rate of EV charging stations to establish full network in 26 TWh years

Estimated number of EV charging stations required for a 100% EV transport fleet in Australia	Annual construction and commisoning rate of EV charging stations to establish full network in 26 years
17 010 868	654 264

Table 8. Annual battery production and procurement in Australia to deliver 100% in 26 years

Battery chemistry	Acronym	Required battery capacity for a 100% Australian EV transport fleet (GWh)	Annual battery production and procurement in Australia to deliver 100% in 26 years (GWh)
Lithium Nickel-Cobalt-Aluminum Oxide	NCA+	46.4	1.78
Lithium Nickel Manganese Cobalt Oxides	NMC 622	69.7	2.68
Lithium Nickel Manganese Cobalt Oxides	NMC 811	445.5	17.13
Lithium Iron Phosphate	LFP	225.8	8.69
Solid State ($LiTi_2(PO_4)_3$)	ASSB*	94.3	3.63
Solid State ($Li_{14}Zn(GeO_4)_4$)	ASSB*	94.3	3.63
Solid State ($Li_7La_3Zr_2O_{12}$)	ASSB*	94.3	3.63
	Total ⁂	**1 070.4**	**41.2**

* The 283.4 GWh of ASSB batteries from Table 12-2 are split evenly between three

⁂ Values of this sum total differ to the total in Table 4 due to rounding errors

6. EXTRA ANNUAL ELECTRICAL POWER CAPACITY REQUIRED TO CHARGE EV FLEET

The national electrical power grid will have to expand in capacity to cater for the electrification of Australian society. This is a very important consideration that must be thought through properly. The extra annual power generated to charge the batteries for each vehicle in a 100 % EV Australian transport fleet over a period of 12 months was estimated. This extra capacity needed has to be mapped out in full and planning for extra grid capacity needs to be examined in an engineering feasibility context. Not doing this could potentially overload the power grid with a supply shortfall to meet demand. There are several international historical examples of this happening.

For example there is an electrical power supply crisis happening in Germany. It could be argued this has happened because of a series of interrelated events. Supply risks not meeting demand and Germany has experienced multiple interruptions in electrical power supply in the last few years.

In 2023, Germany shut down the last remaining German nuclear reactors (Maguire 2023). With natural gas supplies still severely constrained following Russia's invasion of Ukraine last year, the reactor shutdowns mean that two key sources of baseload power have now been disrupted or cut off to Europe's largest economy.

Supply of electricity in Germany has struggled to meet national electricity demand (Bundes Rechnungshof 2024). Renewable energy (wind and solar power generation systems) was greatly expanded but are subject to daily, seasonal and weather-related fluctuations. It must hence be secured by backup power plants and/or a power storage buffer. Technology to store such a large quantity of power for long time frames does not yet exist in an economically viable form (Menton 2022, Michaux 2021).

The German government had planned to shut down all coal fired power stations to meet carbon emission reduction targets (Eckert & Sims 2022). Instead of shutting down 1.6 GW of lignite-fired power plants by the end of 2022 as planned, the German government has issued a waiver to allow production until March 2024.

In summary, coal and nuclear systems were taken offline at the same time that gas supply was shut down. This means that all of the base load power generation systems had become very unreliable. Renewable power systems were not able to deliver the needed power when it was needed. Demand exceeded supply in quantity and quality.

The same fundamental problem could face Australia, in a situation such as the rapid transformation of transport electrification, where demand increases both significantly and rapidly, but generation capacity does not. Power supply in Australia is under stress as coal fired power stations are being shut down, while alternative systems have yet to become operational. This lack of capacity could be exacerbated by legislated closure of coal-fired power utilities before their original end-of-life date, before establishing alternative power generation sources introduced and placed in proximity to existing power distribution infrastructure.

This is a all to action for Australia to consider and plan for the extra power needed to support non fossil fuel technology. Plan for this and support that plan with appropriate resources.

Table 9 shows (drawing on data from Tables 2, 3, 4 and Appendix C) the estimated extra electrical power required annually from the Australian electrical power grid to charge a completely electrified transport fleet. The data in Table 9 has taken into account the EV's registered in Australia in 2021 (Table 3), where the number of passenger cars and motorcycles was adjusted to estimate the needed number of new units. The electrical power grid would have to expand by an annual power generation capacity of 87.64 TWh. The Australian national electrical power grid would have to expand 33% in capacity to charge the projected EV transport fleet (Figure 6). Figure 6 shows graphically the extra 86.8 TWh of extra annual capacity (an expansion of 33%) in addition to existing annual electrical power generation (Appendix C). Such a large expansion would also require a significant investment in transmission infrastructure as well as electricity generation power stations. This would then lead to what kind of electricity generation systems would be feasible or needed. Australian leadership could consider renewable wind and solar power generation but is this even feasible considering what would be required in context of power buffer capacity. The easy option would be expansion of the gas and coal fired power station fleet, but is this appropriate for long term sustainable goals? The other option could be to consider is the establishment of an Australian nuclear power plant fleet.

Table 9. Estimated kilowatt hours needed to charge the projected Australian fully EV fleet

Vehicle Class EV	Number of EV's to be constructed & procured (number)	Annual distance traveled by average vehicle in Australia (km)	Total distance driven by vehicle class in Australia over 12 months (2019 data) (km)	KiloWatt-Hour power to distance consumption vehicles were EV (kWh/km)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Passenger Vehicles	14 830 580	12 600	1.87E+11	0.19	3.91E+10
Light Commerical Vehicles	3 519 457	16 800	5.91E+10	0.23	1.50E+10
Light Rigid Trucks	187 329	22 500	4.21E+09	0.82	3.80E+09
Heavy Rigid Trucks	364 989	22 500	8.21E+09	1.01	9.12E+09
Articulated Trucks	109 927	84 600	9.30E+09	1.46	1.49E+10
Non-freight carrying vehicles	25 378	14 400	3.65E+08	1.01	4.06E+08
Buses	97 060	30 900	3.00E+09	1.32	4.35E+09
Motorcycle	913 803	2 100	1.92E+09	0.06	1.18E+08
Total	**20 048 523**		**2.73.E+11**		**8.68.E+10**
	20.0 million vehicles		273.3 billion km travelled in 12 months		86.75 TWh

Note:
Number of vehicles 2021 data (ABN 2021), adjusted for the numver of EV's in 2021
Distance travelled 2019 data (ABN 2020)

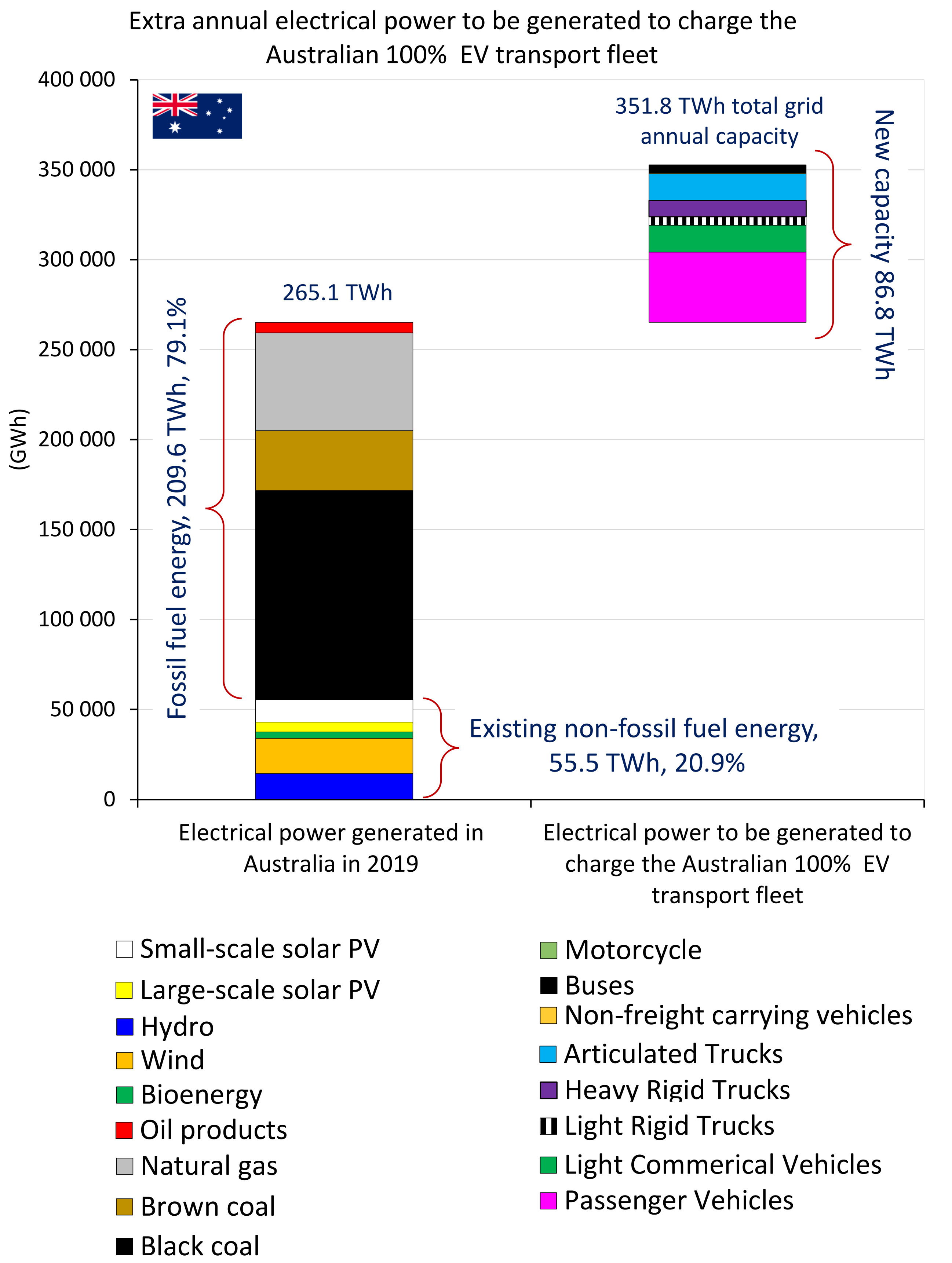


Figure 6. Extra annual electrical power to be generated to charge the Australian 100 % EV transport fleet

7. QUANTITY OF METAL REQUIRED TO PRODUCE EV'S (EXCLUDING BATTERIES)

The transition away from fossil fuels has been discussed in the literature extensively (Wang *et al.* 2023, Jacobsen *et al.* 2022, ReThinkX 2021). The general approach of most other studies has taken the approach of a top-down market price economic analysis and work with the paradigm that this set of challenges would be resolved with just the application of economic market forces. Most of the published studies don't consider the physical number of units needed, or what physical activity they would have to do, and what would be physically required to support the renewable technologies. They certainly don't consider the practicalities of a fully scaled up renewable technology industrial system.

However, strategic planning for delivering on the promised outcome has been seldom considered in detail, including where the range and quantities of raw materials required, where they might be sourced from and whether supply is assured, and where they might be refined into manufactured products. This study will now estimate the quantities of metals and other essential materials that need to be supplied from domestic and international markets.

Table 10. Metal and material content for select passenger car technologies
(Source: Dept of Energy 2015, IRENA 2022, units converted to metric)

Materials (kg per vehicle lifetime)	Passenger car (257 495 km lifetime)		
	ICE Vehicle (kg)	Electric Vehicle (kg)	Fuel Cell Vehicle (kg)
Steel	861.8	1 179.3	997.9
Cast Iron	140.6	33.6	24.9
Wrought Aluminium	28.6	17.7	77.1
Cast Aluminium	59.0	90.7	49.9
Copper [2]	24.0	53.39	72.6
Nickel	-	39.4	1.4
Manganese [2]		24.64	
Lithium		9.03	
Cobalt [2]		13.14	
Graphite [2]		66.53	
Magnesium	0.23	0.36	0.28
Platinium	0.007	-	0.092
Neodynium [3]		0.3	
Dysprosium [3]		0.1	
Praseodymium [3]		0.1	
Glass	37.2	59.0	45.4
Average Plastic	145.1	204.1	167.8
Rubber	136.1	140.6	136.1
Carbon fiber-reinforced plastic for general use	-	-	63.5
Carbon fiber-reinforced plastic for high pressure vessels	-	-	63.5
Perfluorosulfonic acid (PFSA) (Nafion 117 sheet)	-	-	5.4
Carbon paper	-	-	5.4
Polytetrafluoroethylene (PTFE)	-	-	1.4
Carbon and PFSA suspension (Nafion dry polymer)	-	-	0.5
Others	24.5	49.9	38.1
Vehicle Weight	1 315.4	1 678.3	1 587.6

[2] IEA 2021

[3] Metal-demand-of-Electric-Vehicles-ENG-1

Table 10 provides an estimate of metal and materials content in an average vehicle for ICE and EV (not all metals and materials used to construct these vehicles was included, only those considered essential).

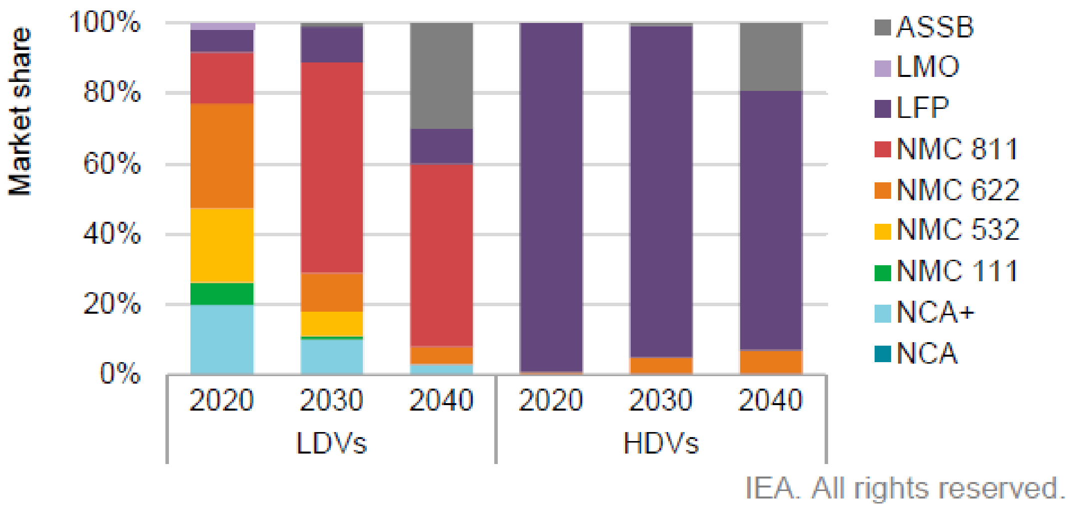
Table 11 shows the estimated mass of metals for just one generation of EV's that would make up the Australian transport fleet. This table assumes all EV classes, including buses and trucks have the same metal content as passenger cars. This assumption was made since it was not possible to obtain precise information for estimating the metal contents of EV buses and trucks. Batteries were excluded from this calculation. This does mean though that the numbers associated with estimations for larger vehicles like buses and trucks are too conservative.

Table 11. Estimated metal content in global EV fleet (excluding batteries) for a single generation of vehicles in an Australian 100 % EV transport fleet

Metal	Estimated mass in a single EV (kg)	Estimated mass in 20 048 523 EV's excluding batteries (tonnes)
Steel & Cast Iron	51.26	1 027 606
Aluminum (wrought & cast)	144.11	2 889 124
Copper	39.43	790 513
Magnesium	0.36	7 217
Neodynium	0.34	6 816
Dysprosium	0.11	2 205
Praseodymium	0.11	2 205

8. ESTIMATED EV BATTERY CHEMISTRY MARKET SHARE

There are many available battery chemistries that could be used to manufacture a battery for an Electric Vehicle (EV). A study was published in 2021 (IEA 2021) that developed a possible global EV battery market share for the year 2040 (Figure 7). The EV battery chemistry market share proportions assumed in this study were developed using the assumption for 2040 in Figure 7.



Notes: LDVs = light-duty vehicles (passenger cars and vans, light commercial vehicles, and 2- and 3-wheelers); HDVs = heavy-duty vehicles (trucks and buses).

Sources: IEA analysis complemented by Adamas Intelligence (2021a) and EV-Volumes (2021).

Figure 7. Electric Vehicle (EV) cathode chemistries estimated market share (Source: IEA 2021) (Copyright IEA) (Copyright IEA, permission to reproduce granted)

Table 12 shows the market proportion of EV battery type assumed for this study. This was developed by taking the 2040 market projections shown in Figure 7. Tables 13-1, 13-2 and 14 show these proportions projected into the vehicle class numbers from Table 2.

Table 12. Global market proportions of EV battery chemistries in 2040 (Source: IEA 2021)

Battery Chemistry	Acronym	Light Duty Vehicle (LDV) (%)	Heavy Duty Vehicle (HDV) (%)
Lithium Nickel Cobalt Aluminium Oxides	NCA+	3.5 %	
Nickel Manganese Cobalt	NMC 622	5.2 %	7.2 %
	NMC 811	52.2 %	
Lithium Iron Phosphate	LFP	10.1 %	73.9 %
All Solid State Batteries	ASSB	29.0 %	18.8 %
		100.0 %	100.0 %

Table 13-1. Battery chemistry proportion in Light Duty Vehicle (LDV) EV's used in this study

Light Duty Vehicle Class	Number of vehicles in a 100% Australian EV transport fleet (number)	Number of batteries projected proportion of EV battery chemistries		
		NCA+ (number)	NMC 622 (number)	NMC 811 (number)
Passenger Vehicles	14 830 580	515 846	773 769	7 737 694
Light Commerical Vehicles	3 519 457	122 416	183 624	1 836 238
Motorcycle	913 803	31 784	47 677	476 767
Total	**19 263 840**	**670 047**	**1 005 070**	**10 050 699**
	19.3 million EV vehicles			
Projected market used proportion in this study in (based on 2040 data in Figure 7)		3.5 %	5.2 %	52.2 %

Table 13-2. Battery chemistry proportion in Light Duty Vehicle (LDV) EV's used in this study

Light Duty Vehicle Class	Number of vehicles in a 100% Australian EV transport fleet (number)	Number of batteries projected proportion of EV battery chemistries	
		LFP (number)	ASSB (number)
Passenger Vehicles	14 830 580	1 504 552	4 298 719
Light Commerical Vehicles	3 519 457	357 046	1 020 132
Motorcycle	913 803	92 705	264 870
Total	**19 263 840**	**1 954 303**	**5 583 722**
	19.3 million EV vehicles		
Projected market used proportion in this study in (based on 2040 data in Figure 7)		10.1 %	29.0 %

Table 14. Battery chemistry proportion in Heavy Duty Vehicle (HDV) EV's used in this study

Heavy Duty Vehicle Class	Number of vehicles in a 100% Australian EV transport fleet (number)	Number of batteries projected proportion of EV battery chemistries		
		NMC 622 (number)	LFP (number)	ASSB (number)
Light Rigid Trucks	187 329	13 575	138 461	35 294
Heavy Rigid Trucks	364 989	26 448	269 774	68 766
Articulated Trucks	109 927	7 966	81 250	20 711
Non-freight carrying vehicles	25 378	1 839	18 758	4 781
Buses	97 060	7 033	71 740	18 287
Total	**784 683**	**56 861**	**579 983**	**147 839**
Projected market used proportion in this study in (based on 2040 data in Figure 7)		7.2 %	73.9 %	18.8 %

Table 15-1. Estimated EV battery capacity required by chemistry

Vehicle Class	Projected proportion of EV battery chemistries in EV's in 2040				
	Battery Capacity in EV (kWh)	NCA+ in EV's (number)	NCA+ sum total (GWh)	NMC 622 in EV's (number)	NMC 622 sum total (GWh)
Passenger Vehicles	46.8	515 846	24.1	773 769	36.2
Light Commerical Vehicles	42.1	122 416	5.2	183 624	7.7
Light Rigid Trucks	194.3			13 575	2.6
Heavy Rigid Trucks	206.1			26 448	5.5
Articulated Trucks	450.0			7 966	3.6
Non-freight carrying vehicles	206.1			1 839	0.4
Buses	227.5			7 033	1.6
Motorcycle	12.7	31 784	0.4	47 677	0.6
Total			**29.7**		**58.2**

As shown in Figure 14 and Table 12, solid state batteries (ASSB) are projected to account for between 1/5th and 1/3rd of the total EV battery market by 2040. Publicly available data for the metal content of solid-state batteries in the literature is sparse. This study accessed a series of material science papers and estimated the ASSB metal mass by examining published chemical formulas in context of atomic mass (Appendix E).

Tables 15-1 and 15-2 show the battery chemistry proportions in terms of battery capacity.

Table 15-2. Estimated EV battery capacity required by chemistry

Vehicle Class	Projected proportion of EV battery chemistries in EV's in 2040						
	Battery Capacity in EV (kWh)	NMC 811 in EV's (number)	NMC 811 sum total (GWh)	LFP in EV's (number)	LFP sum total (GWh)	ASSB in EV's (number)	ASSB sum total (GWh)
Passenger Vehicles	46.79	7 737 694	362.0	1 504 552	70.4	4 298 719	201.1
Light Commerical Vehicles	42.14	1 836 238	77.4	357 046	15.0	1 020 132	43.0
Light Rigid Trucks	206			138 461	28.5	35 294	7.3
Heavy Rigid Trucks	206			269 774	55.6	68 766	14.2
Articulated Trucks	450			81 250	36.6	20 711	9.3
Non-freight carrying vehicles	206			18 758	3.9	4 781	1.0
Buses	227.50			71 740	16.3	18 287	4.2
Motorcycle	12.73	476 767	6.1	92 705	1.2	264 870	3.4
Total			**445.5**		**227.5**		**283.4**

Table 16. Estimated EV battery capacity required by chemistry for a 100% EV Australian transport fleet

Battery chemistry	Acronym	Required battery capacity for a 100% Australian EV transport fleet (GWh)
Lithium Nickel-Cobalt-Aluminum Oxide	NCA+	29.7
Lithium Nickel Manganese Cobalt Oxides	NMC 622	58.2
Lithium Nickel Manganese Cobalt Oxides	NMC 811	445.5
Lithium Iron Phosphate	LFP	225.9
Solid State ($LiTi_2(PO_4)_3$)	ASSB*	94.3
Solid State ($Li_{14}Zn(GeO_4)_4$)	ASSB*	94.3
Solid State ($Li_7La_3Zr_2O_{12}$)	ASSB*	94.3

Total [2] **1 042.3**

* The 283.4 GWh of ASSB batteries from Table 12-2 are split evenly between three chemistries (94.3 GWh each)

2 Values of this sum total differ frm the total in Table 4 due to rounding errors

Table 16 show the Australian market size (1 Terawatt) for EV battery capacity for a predicted range of possible chemistries.

9. ESTIMATED EV BATTERY CHEMISTRY METAL CONTENT AND QUANTITY

The metal content for each battery chemistry used in this study needs to be presented in the form of metal content per MW. This is needed to estimate quantities of metals to service the needed battery capacity of the EV fleet. The specifications for some battery chemistries are shown in Appendix E. Table 17 shows the metal content in context of kg/MW for each battery chemistry.

Table 17. Metal content kg/MW by battery chemistry
(Source: Diouf & Pode 2015, Manthiram *et al.* 2017, Lourenssen *et al.* 2019)

Battery Chemistry	Units	NCA+	NMC 532	NMC 622	NMC 811	LFP	ASSB ($LiTi_2(PO_4)_3$)	ASSB ($Li_{14}Zn(GeO_4)_4$)	ASSB ($Li_7La_3Zr_2O_{12}$)	VRB
Specific Energy Density Range	(Wh/kg)	150-190	100-135	100-135	100-135	90-120	300-600	300-600	300-600	15-32
Specific energy used in this paper	(Wh/kg)	190	135	135	135	120	600	600	600	32
Mass of 1 MW battery	(kg)	5 263	7 407	7 407	7 407	8 333	1 667	1 667	1 667	31 250
Copper (Cu)	(% per kg)	13.9 %	14.4 %	14.1 %	14.1 %	29.6 %				
Copper (Cu)	(kg/MW)	729.3	1 064.6	1 046.6	1 045.8	2 470.5				
Lithium (Li)	(%)	4.4 %	5.5 %	5.1 %	4.9 %	5.7 %	1.8 %	13.7 %	6.9 %	
Lithium (Li)	(kg/MW)	232.1	409.5	378.6	364.8	473.8	29.8	228.4	114.2	
Manganese (Mn)	(%)		10.8 %	6.9 %	3.3 %					
Manganese (Mn)	(kg/MW)		798.5	512.2	243.2					
Cobalt (Co)	(%)	2.2 %	8.0 %	7.5 %	3.3 %					
Cobalt (Co)	(kg/MW)	116.0	593.7	556.7	243.2					
Germanium (Ge)	(%)							41.0 %		
Germanium (Ge)	(kg/MW)							682.9		
Zirconium (Zr)	(%)								25.7 %	
Zirconium (Zr)	(kg/MW)								428.8	
Lanthanum (La)	(%)								58.8 %	
Lanthanum (La)	(kg/MW)								979.5	
Vanadium (V)	(%)									31.3 %
Vanadium (V)	(kg/MW)									9 766
Nickel (Ni)	(%)	33.1 %	19.3 %	22.2 %	26.9 %					
Nickel (Ni)	(kg/MW)	1 740.5	1 433.2	1 647.9	1 994.4					
Graphite (C)	(% per kg)	39.1 %	34.5 %	36.7 %	40.1 %	57.3 %				
Graphite (C)	(kg/MW)	2 055.4	2 559.2	2 716.8	2 967.2	4 771.8				
Zinc (Zn)	(% per kg)							9.2 %		
Zinc (Zn)	(kg/MW)							153.7		

Table 18 calculates the metal content, by metal of the different battery chemistries (combining data from Tables 16 and 17). Table 19 shows the total metal content needed to produce enough EV's (Table 11) and their batteries (Table 18) to develop a 100 % EV transport fleet in Australia.

Table 18. Metal required for Electric Vehicles (EV) and their batteries to phase out fossil fuels

Metal	NCA+ (tonne)	NMC 622 (tonne)	NMC 811 (tonne)	LFP (tonne)	ASSB ($LiTi_2(PO_4)_3$) (tonne)	ASSB ($Li_{14}Zn(GeO_4)_4$) (tonne)	ASSB ($Li_7La_3Zr_2O_{12}$) (tonne)	Total (tonne)
Copper (Cu)	33 841	72 950	465 913	561 957				1 134 661
Lithium (Li)	10 768	26 386	162 528	107 773	2 820	21 576	10 788	342 637
Manganese (Mn)		35 699	108 352					144 051
Cobalt (Co)	5 384	38 803	108 352					152 539
Germanium (Ge)						64 514		64 514
Zirconium (Zr)							40 510	40 510
Lanthanum (La)							92 525	92 525
Nickel (Ni)	80 757	114 857	888 485					1 084 099
Graphite (C)	95 371	189 358	1 321 892	1 085 425				2 692 046
Zinc (Zn)						14 517		14 517

Table 19. Quantity of metal required to produce EV's and their batteries for an Australian 100 % EV transport fleet

Metal	Quantity of metal for 20 million EV's (tonnes)	Quantity of metal for batteries (tonnes)	Total (tonnes)
Steel & Cast Iron	1 027 606		1 027 606
Aluminum (wrought & cast)	2 889 124		2 889 124
Copper (Cu)	790 513	1 106 516	1 897 029
Lithium (Li)		333 605	333 605
Magnesium	7 217		7 217
Manganese (Mn)		138 161	138 161
Cobalt (Co)		144 200	144 200
Germanium (Ge)		64 422	64 422
Zirconium (Zr)		40 452	40 452
Lanthanum (La)		92 393	92 393
Nickel (Ni)		1 036 085	1 036 085
Graphite (C)		2 618 889	2 618 889
Zinc (Zn)		14 496	14 496
Neodynium	6 816		6 816
Dysprosium	2 205		2 205
Praseodymium	2 205		2 205

Table 19 shows the estimated quantity of metal required to construct and procure enough EV's (and their batteries) to develop a 100 % Electric Vehicle (EV) transport fleet in Australia. This metal would have to be sourced from the international market.

10. INSIGHTS INTO GLOBAL METAL MARKETS

The global situation concerning production in mining for the global Green Transition and Energy Transition can be described as follows (Appendix G, Figure G3): In 2022 the global mining (2.8 billion tons) can be split into iron ore mining (2.6 billion tons); industrial metals including aluminum (69 million tons), copper (22 million tons), manganese (20 million tons) and nickel (3.3 million tons); and technology and precious metals including REE (300 thousand tons) cobalt (190 thousand tons), lithium (130 thousand tons) and vanadium (100 thousand tons). Thus, global production of minerals and metals is not matching the requirements for a global Green Transition. As a result of this, it can be concluded that globally there is need for more mining and established mines.

Figure 8: Forecast of the number of mines to keep up with the exceptional demand

According to Benchmark Intelligence (2022) (Figure 8), the demand for lithium in 2035 is expected to increase to approximately 4 million tons. The expected demand for cobalt will be 489 thousand tons and the demand for nickel will be 6.2 million tons (Figure 8). For graphite (natural and synthetic) the demand will be approx. 7.2 million tons and 5.2 million tons (Figure 8).

The Green Transition can be classified into two groups of products that are needed to transform completely from fossil fuel energy systems. On the one hand there are wind turbines with the application of permanent magnets and on the other hand there are EV's and its batteries. In case of EV batteries there actually is a need of - in average - 52kg graphite, 35 kg aluminum, 29kg nickel, 20 kg copper, 20 kg steel, 10 kg manganese, 8 kg cobalt, 6 kg lithium and 5 kg iron for each EV that is manufactured (Figure G1).

In case of global production and processing of minerals and metals, China dominates most of the mineral value chains. In addition to above mentioned facts, China is dominating most of the production/ mining as well as the processing of the minerals (Co, Cu, Li, C, Ni and REE) that are critical to China's, EU's and US' national security as well as essential for the global Green Transition (Appendix H, Figure H4). E.g., in case of REE, China produces 60 % domestically and owns 100 % interest in mining REEs in Myanmar that accounts for 30 % of world production. Further, it refines approx. 85 % of REE and procures > 90 % of all REE metals for magnets. The importance of REE for the global Green Transition is based on the production of permanent magnets for wind turbines. An average permanent magnet (NdFeB) needs 500 kg Nd, 30 kg Pr, 50 kg Dy and approx. 7 kg Tb for its production. In case of Co, the DRC mines > 60 % of the world's cobalt but China controls > 85 % of the refined cobalt for EVs. China also produces 100 % of spherical graphite. In addition, China leads in mineral processing, controlling 100 % of the world's refined supply of natural graphite as well as approx. 70 % of synthetic graphite, over 90 % of manganese, 70 % of cobalt, nearly 60 % of lithium, and 40 % of copper refining (Venditti, 2023). According to Benchmark Intelligence (2022), China also is dominating the supply chain for Lithium ion battery (Benchmark Intelligence, 2022) in the downstream. China is responsible for 78 % of cathode production and 91 % anode production as well as 70 % of cell production (Benchmark Intelligence, 2022) (Appendix G, Figure G5) In case of Lithium trade which is an essential part of Lithium ion battery production, China owns the 100 % of global hard rock lithium conversion capacity in 2022. 95 % of spodumene global imports is done by China. It has a share in 80 % of global lithium hydroxide exports and 33 % share in lithium carbonate global imports. Appendix H shows the Chinese market share of the global mining production, and also describes the Chinese strategic minerals resource pan for the future.

11. COMPARISON OF AUSTRALIAN METAL DEMAND FOR A FULLY EV FLEET COMPARED TO GLOBAL MARKET DEMANDS

There is no longer the industrial capacity on Australian soil to manufacture Electric Vehicles or batteries. The capacity to smelt and refine metals from mineral concentrates in Australia has also declined, although there is still capacity in aluminum, zinc, and lead, each of which is listed in many countries as critical or strategic with respect to the electrification energy transition. This means that Australia is completely dependent on imports of finished goods in almost all sectors, including EV's and their batteries. Developments like Alcoa and Nyrstar, and lithium refining in WA progressing, are two examples of this trend reversing. Australia is a relatively small economy when compared to nations like China, Japan, or the United States. This means that Australia would have to compete with larger economies to procure products like EV's or batteries on the international open market.

Table 5 shows the number of EV's and batteries needed to produce a fully electrified Australian transport fleet. This would represent just one generation of technology units, each of which would have a working life of between 7 and 30 years (depending on unit and study referenced). At the end of its working life, each technology unit would need to be decommissioned, and recycled. Then a new unit would have to be manufactured. Recycling technology has been developed for some years and is now reasonably mature (Meskers *et al.* 2024). The challenges the recycling industry face are more logistical than technical though. Each recycling process plant is optimized for the recovery of one or two metals from a specific residue waste stream. End of life technology waste streams are notoriously variable in character (Reuter 2011). For a recycling plant to operate effectively, a sufficiently large quantity and consistent supply of the target residue need to be supplied over a sustained period of time. This is an issue of collection and getting the 'right' residue to the 'right' process plant. To date this has been very difficult, and as a result, the recycling of many of the more exotic metals has not been viable (Meskers *et al.* 2024). This will obviously change with future demand for metals being very high and the costs of mining increasing with each passing year.

In 2023, 1.85% of the global transport fleet was an Electric Vehicle, where the global fleet of EV's was 26 million (IEA 2023), and the total number of vehicles in the global transport fleet was 1.41 billion (Michaux 2021a). In 2023, renewable energy made up only 7.5% of global primary energy (IRENA 2023), and fossil fuels accounted for 82% of global primary energy. This means that the vast majority of the non-fossil fuel system has yet to be constructed. What has not yet been constructed cannot be recycled. The sourcing of this metal will therefore have to come from mining for at least the first generation of non-fossil fuel units. Appendix F shows data for the global mining of minerals and the production of refined metals. Appendix H shows a summary of a GTK study (currently in peer review) that examines what will be required to phase out fossil fuels globally. The quantity of metals needed globally for the Green Transition was examined.

The types of metals needed for the Green Transition have been mined and consumed in comparatively small quantities thus far (USGS Mineral Statistics). The Green Transition requires new, or different minerals that need to be mined, processed, and transported using production capacity that currently does not exist, as well as energy that is currently not available or can only be provided with conventional energy generation (Schernikau & Smith 2023).

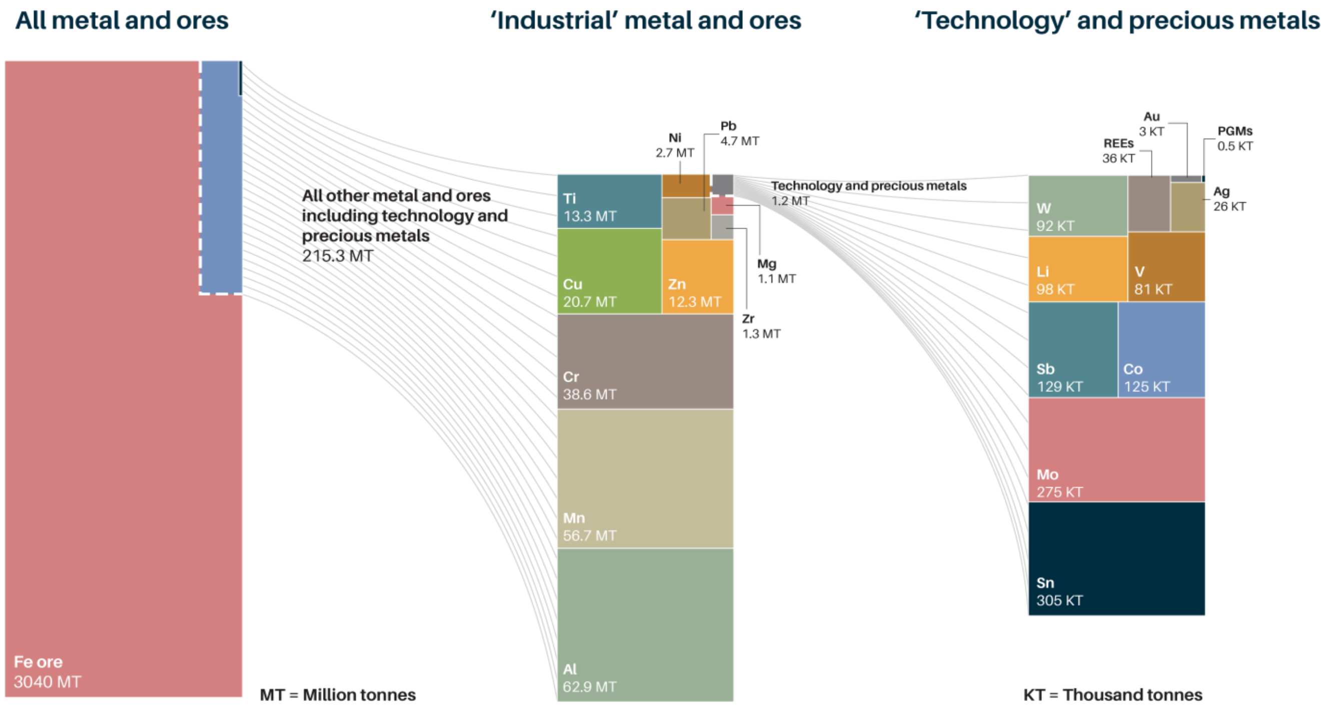


Figure 9. Global primary metal and ore production, MT = million metric tonne. (Source: British Geological Survey 2021) (copyright permission granted)

Figure 9 also shows that the needed metals for the green transition (needed in such large quantities), have not been mined in large quantities in the past. For example, even if all available metals were found and recycled, there is not enough copper, lithium or vanadium that has been mined in the historical past to supply future needs for just the manufacture of first-generation renewable technology units. To make the Green Transition happen, it will be necessary to mine previously exotic metals like lithium, at annual production rates normally associated with metals like copper (Figure 9). This is unlikely to go to plan (Figure 10).

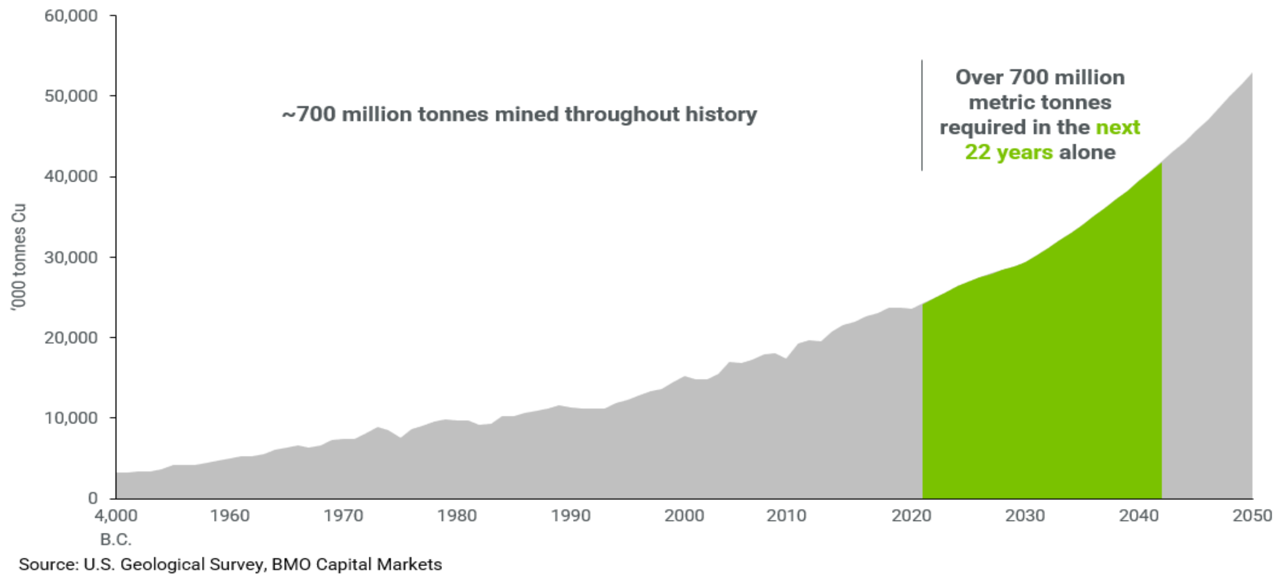


Figure 10. Historical quantities of copper mined, from 4 000 B.C. to 2020, and projection to 2050 (Source: USGS, BMO Capital Markets) (copyright USGS) (Copyright permission to reproduce granted)

Figure 10 shows a study that mapped the historical yearly production of copper between the year 2020 back to the year 4 000 B.C., for all of humanity around the world. The same figure also shows a prediction for the future yearly quantities of copper production if copper demand continues to grow according to market projections. The human species produced approximately 700 million tonnes of metal over the 4000 years prior to 2020. For global economic demand for copper to continue its current trajectory of growth, another 700 million tonnes would need to be produced in the next 22 years. Current stated copper reserves were 880 million tonnes (USGS Mineral Statistics), which would allow approximately 30 years of production at this growth rate. It is entirely possible that this is not practical, and a fundamentally new natural resource management paradigm is coming (Michaux 2021b). Table 20 shows the quantities of metals needed to produce a 100 % EV transport fleet in Australia, compared to global refined metal production in 2019 (Appendix F). It is important to appreciate that this does not include metals needed for infrastructure like EV charging stations.

Table 20. Quantity of metals needed for a 100 % EV Australian transport fleet, compared to refined metal production

Metal	Element	Global refined metal production 2019 (tonnes)	Quantity of metal needed to produce a 100% EV transport fleet in Australia (tonnes)
Aluminium	Al	63 136 000	2 889 124
Copper	Cu	24 200 000	1 897 029
Zinc	Zn	13 524 000	14 496
Magnesium Metal	Mg	1 120 000	7 217
Manganese	Mn	20 591 000	138 161
Nickel	Ni	2 350 142	1 036 085
Lithium*	Li	95 170	333 605
Cobalt*	Co	126 019	144 200
Graphite (natural flake + synthetic)	C	2 729 300	2 618 889
Zirconium ‡	Zr	1 338 463	40 452
Germanium **đđ**	Ge	130	64 422
Rare Earth Element			
Neodymium	Nd	23 900	6 816
Lanthanum	La	35 800	92 393
Praseodymium	Pr	7 500	2 205
Dysprosium	Dy	1 000	2 205

Note:

1 metric tons (mt) is equal to 1 tonne (t).

* 2018 production value

đđ Source: Mudd 2021

‡ Estimated from mining production. All other values are refining production values.

Several conclusions can be drawn Table 20, which are shown in Figures 11 to 13). As previously stated, Australia is a small economy and would have to compete for finished manufactured goods on the international open market with economies that are much larger and have more influence. The capacity of the existing mining industry will not be enough to supply enough metal quantities to fully develop the Green Transition (Appendices G, H, Michaux 2021a).

When comparing what Australia will need to develop a 100 % EV transport fleet against the current global mining production (data used was refined metal produced in 2019), certain signatures become clear. Projected quantities needed of base metals like aluminium, zinc, magnesium metal, manganese, and zirconium all are well within what the mining industry can supply.

Quantities of nickel were 46.1 %, and quantities of graphite was 98.4 % of 2019 global production (Figure 11). Considering that Australia is such a small market place, and the rest of the world will have similar demands, this suggests an inelastic market on a global scale.

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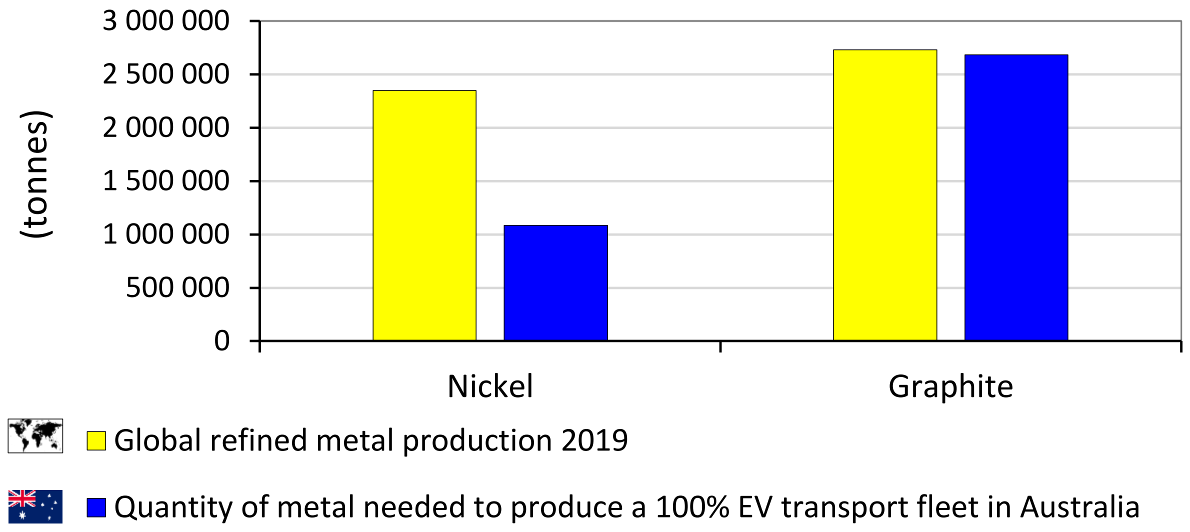

Figure 11. Quantity of metal needed for Australia EV's compared to global annual production, nickel and graphite (Image used from World Map Image by Clker-Free-Vector-Images from Pixabay)

Global production of lithium was just 27.8 % of what Australia would need to construct its EV fleet. Quantities needed for Cobalt was 82.6 %, Lanthanum was 38.7 % and Dysprosium was just 45.3 % of global production in 2019 (Figure 12).

In the same context, neodymium requirements for a fully EV Australian transport fleet would represent the equivalent of 28.5 % of global production, and the required quantity of praseodymium would amount to 29.4%.

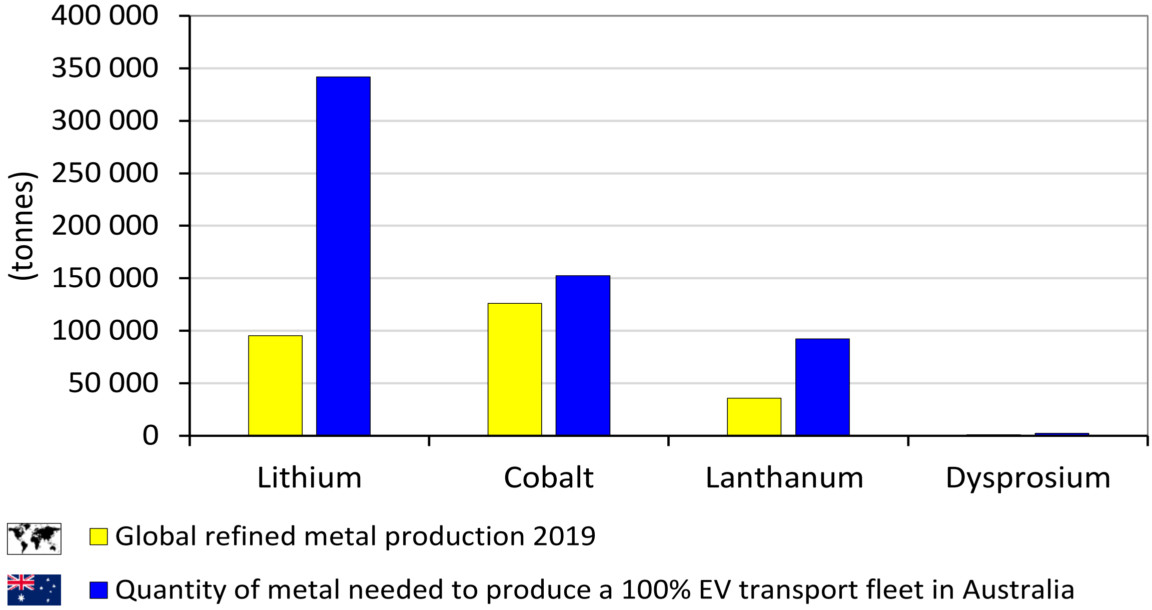

Figure 12. Quantity of metal needed for Australia EV's compared to global annual production, lithium, cobalt, lanthanum, and dysprosium
(Image used from World Map Image by Clker-Free-Vector-Images from Pixabay)

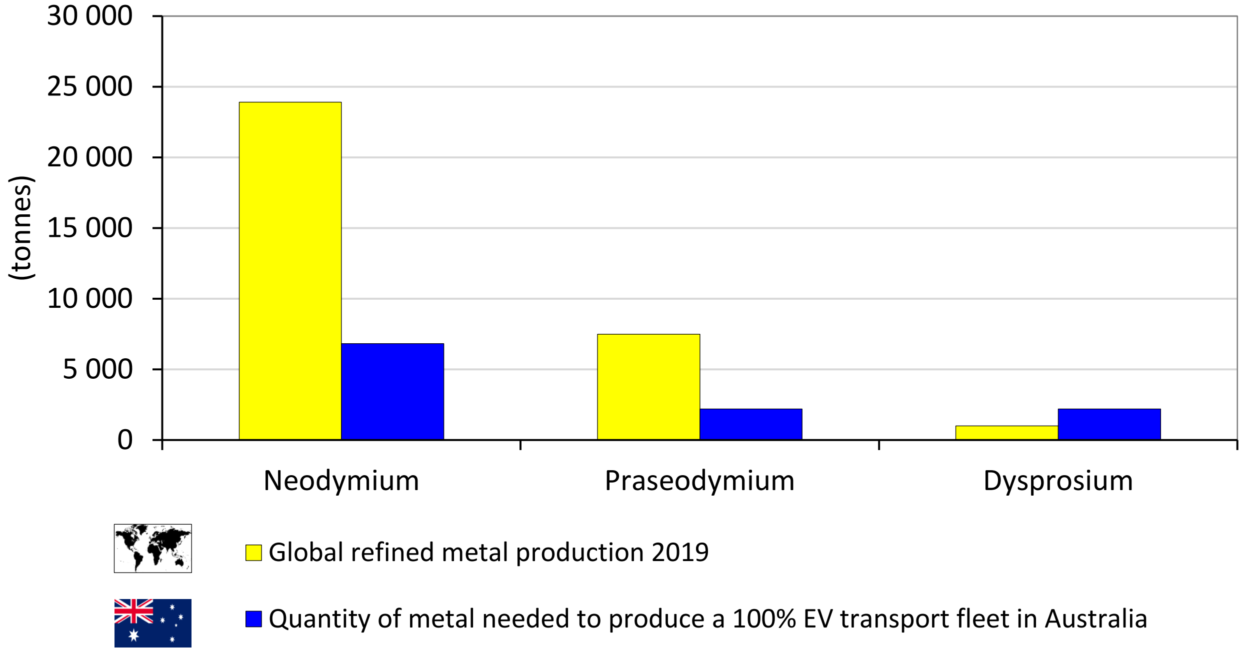

Figure 13. Quantity of metal needed for Australia EV's compared to global annual production, Neodymium, praseodymium and dysprosium
(Image used from World Map Image by Clker-Free-Vector-Images from Pixabay)

The standout metal was germanium. In 2019, just 130 tonnes of germanium were globally produced (Table 20). The projected quantity of germanium needed (64 420 tonnes) for a 100 % Australian EV fleet represents the equivalent of 0.202 % of global production, or alternatively 495 years of global production.

To develop a 100 % EV transport fleet (the construction of 20 million units) would take years. So, the comparison of the total metal needed against global annual production is a very illustrative and pragmatic way of demonstrating the scale of the task. That being stated, it is good to remember that all nation states around the world would attempt to achieve the same strategic tasks, all at the same time. All nations would require the same metals in proportion to the size of their own transport fleets. As such, these numbers are a precursor signature that suggest the pressure on the international mining markets will be immense. The simple corollary to this is that global mining capacity will have to greatly expand in annual production. The projected rate and capacity needed will be difficult at best, to not practical. It will clearly be challenging and difficult to comply with the projected rate and capacity required for implementing the transition. Furthermore, if fossil fuel sources are no longer available to power mining operations, the task will be even more formidable. What would be a sensible thing to consider, would be a different technology is developed that requires entirely different resources that are more abundant. This would have to have very quickly to be useful though. Once mining is done without the assistance of fossil fuels, capability will look very different.

Reserves are not static. With each passing year some reserves are mined, and exploration adds to the global reserve inventory. Figure 14 show the most sophisticated data set available at the time of writing this paper. Supply has been able to keep up with demand thus far. So in theory, the challenges shown in Table 20 could be addressed with more exploration. That being stated, how significant is the challenge for mining production to expand to meet the incoming demand, and how fast will it be needed?

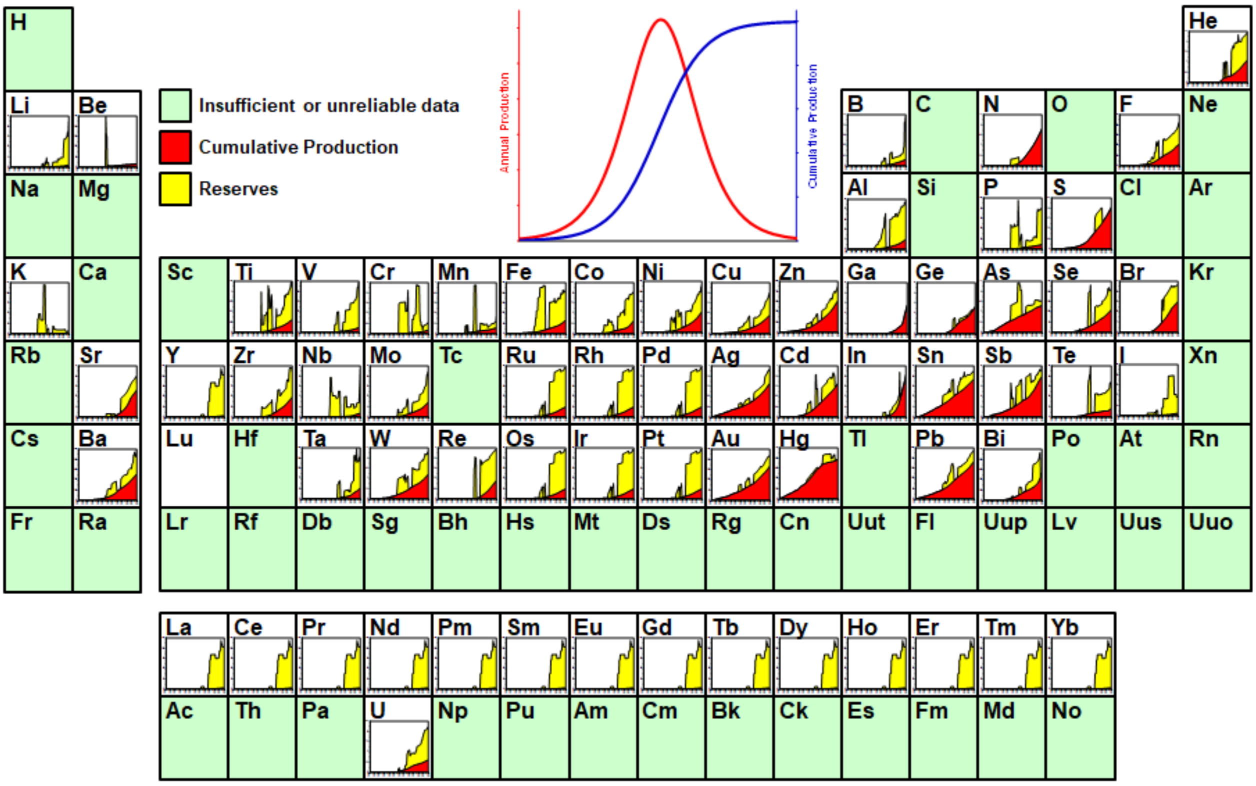

Figure 14. Hubbert-style curves of cumulative production (red shading) and reserves (yellow shading) for numerous elements inserted within the Periodic Table of the Elements (Source: Mudd 2021) (copyright permission granted)

Given that for every 1000 deposits discovered, only 1 or 2 become producing mines, and that it takes approximately 10-25 years to develop a discovered deposit to a producing mine (depending on the commodity), and that for every 10 producing mines, 2 or 3 mines will go out of business due to being not viable for market conditions, this task is larger than first understood (Cook 2019). It has taken an average of 16 years to progress and develop a major copper mine from discovery to production during the past 20 years (IEA 2021a). The task to explore for more of these metals far exceeds what is practical in the required time frame to be useful in fossil fuel transition. Comparing Figures 8, 9 and 10 against Table 20 (in context of Figure 14), it becomes apparent that this is an *unprecedented quantity step change demand problem, not a historically conventional supply problem*. The types of metals that are demanded by the Green Transition are in unprecedented quantities, that may not be feasible given the types of mineralogizes involved.

12. DISCUSSION OF ALTERNATIVE BATTERY CHEMISTRIES

These data-based conclusions suggest that while lithium-ion battery chemistry is the preferred option to develop EV transport technology, it is not feasible to scale up to be available for the whole global market. Even if it were possible to explore for more deposits to the quantity needed, there is not the time to develop them to be useful in phasing out fossil fuels. It is recommended to develop alternative battery chemistries that use mineral/metal feedstocks that are more abundant. Battery chemistries that are based on zinc, fluoride and sodium are all viable, and should be investigated in full (Corfe & Butcher 2022). There are other systems that show promise (Gschwind *et al.* 2016). (Gschwind *et al.* 2016) examined all of the theoretical combinations of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations, using atomic chemistry.

Figure 15 shows the grouping of battery chemistry energy footprint for several chemistries, after examining a series of combinations of gravimetric capacity for anode/cathode combinations and the volumetric energy density of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations.

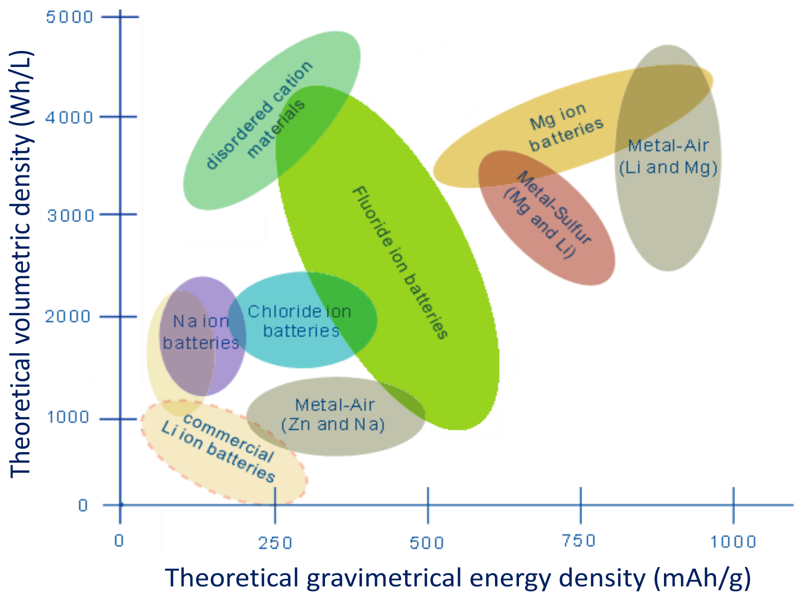

Figure 15. Possible battery chemistries (Witter 2021)

This implies that lithium-ion battery chemistry may not be the best option to pursue for high density applications. Many of the chemistries shown in Figure 15 require metals and minerals like fluoride, sodium, or zinc, which do not have the same resource scarcity issues that lithium and cobalt do. Moreover, they could be sourced from our industrial waste.

These ideas are not really part of the conventional problem solving paradigm at this time. So, aspects may be discussed but are not developed beyond conceptual state of readiness. At the time of writing this paper, lithium-ion chemistry was still the preferred option when it came to seek research funding. However, research into the development of sodium batteries has been accelerating globally, with commercial production of vehicles entering the market during 2024. Nevertheless, the extent to which sodium could replace lithium, rather than find applications in energy storage remains unclear.

All of the battery chemistry systems shown in Figure 15 would require many different metals. Most battery chemistries, once integrated into a battery, would need commensurate quantities of copper, nickel and graphite. So, if lithium-ion battery chemistries face raw material logistical bottlenecks, all other chemistries would need to be studied in the same context.

13. CONCLUSIONS

The following conclusions were drawn from the data assembled in this report.

- The task to fully electrify the Australian transport fleet with 100% registered vehicles being Electric Vehicle is much larger than conventional strategic planning allows for. The number of EV's required to do this 20 million (Table 5), which is comparable to the 2023 global EV fleet in size (26 million).

- Potentially approximately 17 million EV charging stations would need to be constructed and commissioned to service the operation of the EV fleet. The metal materials required to do this was not included in this report. This number may be significantly revised if EV charging was done at domestic residental homes. The logistics of this are unknown, however.

- The size of the projected Australian battery market to support an operational EV fleet is approximately one terawatt hour (1 TWh) in capacity. This is assuming all vehicles in Australia are EV and have a battery, which will probably not happen (the post fossil fuel fleet would have a combination of EV's, hydrogen fuel cell vehicles and ammonia ICE fueled vehicles). To put this context, the global transport EV fleet may have a battery capacity of 65 TWh (see Appendix I).

- The annual rate of procurement would be of the order of 770 000 EV's of various vehicle classes (Table 6), and 650 000 EV charging stations (Table 7), each year for the next 26 years, to achieve a 100 % EV transport fleet in Australia by 2050. The cost of this was beyond the scope of this report. In addition to the cost, global EV and battery production would have to expand greatly to meet international, as well as Australian demand.

- The Australian national electrical power grid would have to expand by 33%, from 265.1 TWh to a total capacity of 351.8 TWh (Figure 6) plus the needed electricity transmission infrastructure to handle the extra capacity, to charge the projected EV transport fleet. This would be an extra capacity of 86.8 TWh.

- The quantity of comparatively exotic metals required to produce a 100 % Australian EV transport fleet is quite large compared to global annual production, remembering Australia is a small economy. For this to work as planned, using current battery technology, the global mining and refining industrial capacity would have to greatly expand, at a rate that is probably impractical, and in some cases impossible.
- The global markets for EV's and batteries may well become inelastic due to practical logistical supply bottlenecks. Australia will struggle to procure enough EV's or batteries in the global markets as all other nation states will be attempting to do the same. Data in this report suggests the supply chain for EV's and lithium-ion batteries could be highly volatile and unreliable.
- In consequence, it is reasonable to state that a full replacement of the current (2019) Australian ICE vehicle fleet with EV vehicles seem improbable by 2050. Global production rates of minerals are not high enough, and there is little reason to presume that global production rates will increase as demanded. Further it remains open if the Australian charging facility infrastructure and the subsequently required power grid needed to charge all EV vehicles could be constructed in this timeframe.

14. CAVEATS TO THIS ANALYSIS

The projected requirements for metals and their Australian and global implications are based on a number of assumptions and have deliberately omitted the following from the analysis:

1. Metal and material requirements for charging station deployment has not been calculated.
2. Fundamental future changes in Australian population growth and demographic structure, which might impact on EV demand and metal projections are not considered.
3. It has been assumed that proportions of vehicle classes (and hence derived metal and energy consumption) will not substantially change. It has not been possible to analyze potential changes in consumer transport preferences, or the role of public transport and changing logistics.
4. The analysis has been made from the perspective of energy being primarily, if not exclusively supplied by grid-generated power. Scenarios in which independent and distributed renewable energy provides power for charging have not been evaluated, nor have the commensurate metal and material requirements for manufacturing such independent systems been calculated.

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16. APPENDIX A: THE GREEN TRANSITION

The Green Transition is the phasing out of the majority of fossil fuel systems by the year 2050 (IEA 2021). Figure A1 and Tables A1 to A3 show the 2050 targets for the Green Transition.

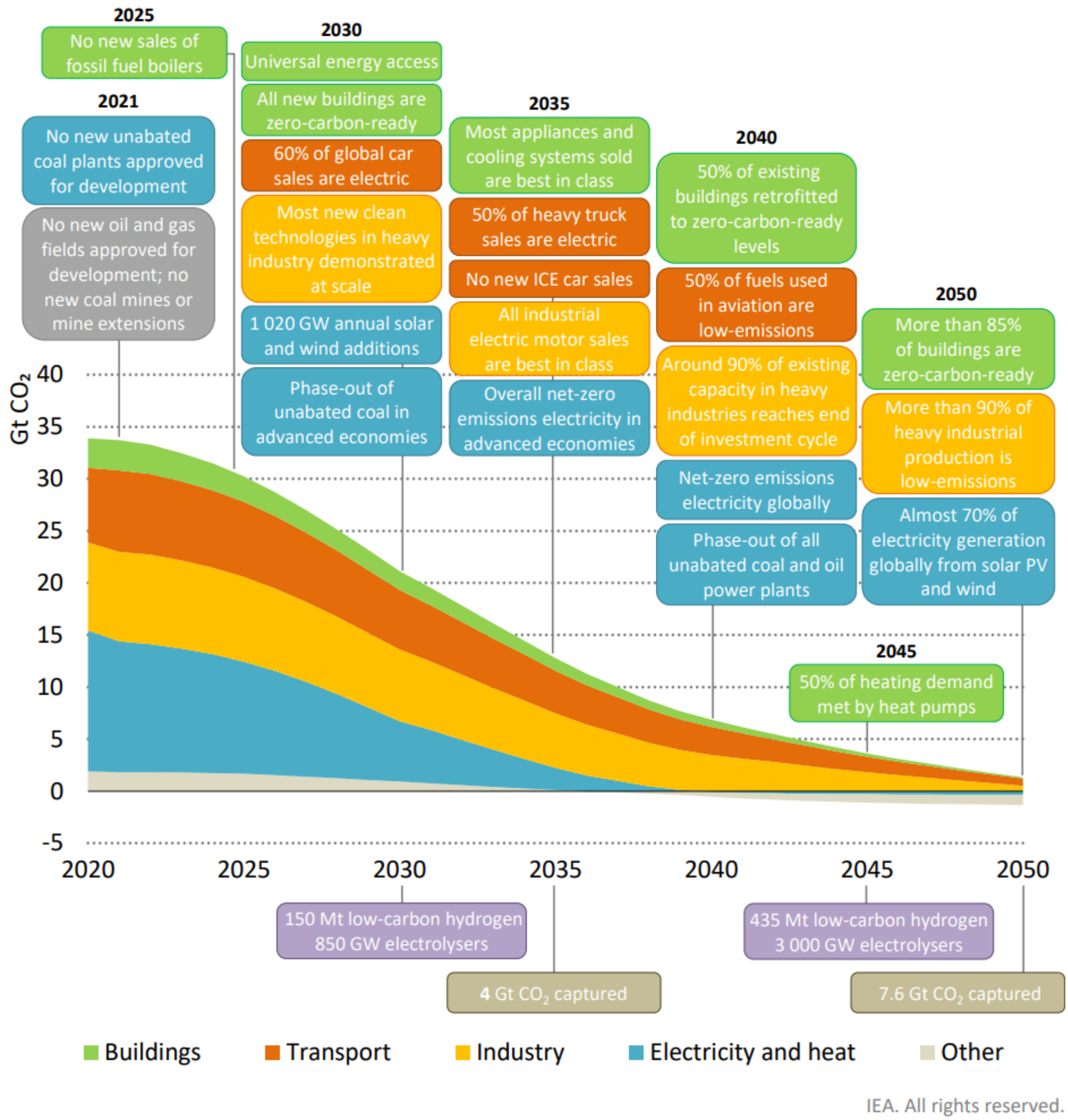

Figure A1. Selected global milestones for policies, infrastructure, and technology deployment in the Net Zero Emissions (NZE) (Source: IEA 2021)

Table A1. CO_2 emissions for the Net Zero Emissions pathway (Source: IEA 2021)

	CO_2 emissions (Mt CO_2)					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Total CO_2*	**35 926**	**33 903**	**21 147**	**6 316**	**0**	**-4.6**	**n.a.**
Combustion activities (+)	**33 499**	**31 582**	**19 254**	**6 030**	**940**	**-4.8**	**-11**
Coal	14 660	14 110	5 915	1 299	195	-8.3	-13
Oil	11 505	10 264	7 426	3 329	928	-3.2	-7.7
Natural gas	7 259	7 138	5 960	1 929	566	-1.8	-8.1
Bioenergy and waste	75	71	- 48	- 528	- 748	n.a.	n.a.
Industry removals (-)	**1**	**1**	**214**	**914**	**1 186**	**75**	**28**
Biofuels production	1	1	142	385	553	68	24
Direct air capture	-	-	71	528	633	n.a.	n.a.
Electricity and heat sectors	**13 821**	**13 504**	**5 816**	**- 81**	**- 369**	**-8.1**	**n.a.**
Coal	10 035	9 786	2 950	102	69	-11	-15
Oil	655	628	173	6	6	-12	-14
Natural gas	3 131	3 089	2 781	268	128	-1.0	-10
Bioenergy and waste	-	-	- 87	- 457	- 572	n.a.	n.a.
Other energy sector*	**1 457**	**1 472**	**679**	**- 85**	**- 368**	**-7.4**	**n.a.**
Final consumption*	**20 647**	**18 928**	**14 723**	**7 011**	**1 370**	**-2.5**	**-8.4**
Coal	4 486	4 171	2 935	1 186	117	-3.5	-11
Oil	10 272	9 077	6 973	3 242	880	-2.6	-7.5
Natural gas	3 451	3 332	2 668	1 453	303	-2.2	-7.7
Bioenergy and waste	75	71	40	- 70	- 176	-5.6	n.a.
Industry*	8 903	8 478	6 892	3 485	519	-2.0	-8.9
Iron and steel	2 507	2 349	1 778	859	220	-2.7	-7.6
Chemicals	1 344	1 296	1 199	654	66	-0.8	-9.5
Cement	2 461	2 334	1 899	906	133	-2.0	-9.1
Transport	8 290	7 153	5 719	2 686	689	-2.2	-7.5
Road	6 116	5 483	4 077	1 793	340	-2.9	-8.9
Passenger cars	3 121	2 746	1 626	547	85	-5.1	-11
Trucks	1 835	1 721	1 614	890	198	-0.6	-6.9
Aviation	1 019	621	783	469	210	2.4	-3.5
Shipping	883	800	705	348	122	-1.3	-6.1
Buildings	3 007	2 860	1 809	685	122	-4.5	-10
Residential	2 030	1 968	1 377	541	108	-3.5	-9.2
Services	977	892	432	144	14	-7.0	-13
Total CO_2 removals	**1**	**1**	**317**	**1 457**	**1 936**	**79**	**29**
Total CO_2 captured	**40**	**40**	**1 665**	**5 619**	**7 602**	**45**	**19**

**Includes industrial process emissions.*

Table A2. Key milestones in transforming global electrical generation (Source: IEA 2021, Table 3.2)

Category	
Decarbonisation of electricity sector	• Advanced economies in aggregate: 2035. • Emerging market and developing economies: 2040.
Hydrogen-based fuels	• Start retrofitting coal-fired power plants to co-fire with ammonia and gas turbines to co-fire with hydrogen by 2025.
Unabated fossil fuel	• Phase out all subcritical coal-fired power plants by 2030 (870 GW existing plants and 14 GW under construction). • Phase out all unabated coal-fired plants by 2040. • Phase out large oil-fired power plants in the 2030s. • Unabated natural gas-fired generation peaks by 2030 and is 90% lower by 2040.

Category	2020	2030	2050
Total electricity generation (TWh)	26 800	37 300	71 200
Renewables			
Installed capacity (GW)	2 990	10 300	26 600
Share in total generation	29%	61%	88%
Share of solar PV and wind in total generation	9%	40%	68%
Carbon capture, utilisation and storage (CCUS) generation (TWh)			
Coal and gas plants equipped with CCUS	4	460	1 330
Bioenergy plants with CCUS	0	130	840
Hydrogen and ammonia			
Average blending in global coal-fired generation (without CCUS)	0%	3%	100%
Average blending in global gas-fired generation (without CCUS)	0%	9%	85%
Unabated fossil fuels			
Share of unabated coal in total electricity generation	35%	8%	0.0%
Share of unabated natural gas in total electricity generation	23%	17%	0.4%
Nuclear power	*2016-20*	*2021-30*	*2031-50*
Average annual capacity additions (GW)	7	17	24
Infrastructure			
Electricity networks investment in USD billion (2019)	260	820	800
Substations capacity (GVA)	55 900	113 000	290 400
Battery storage (GW)	18	590	3 100
Public EV charging (GW)	46	1 780	12 400

Note: GW = gigawatts; GVA = gigavolt amperes.

In the Net Zero Emissions pathway, by 2050, the entire (100 %) global transport fleet will be made up of electric vehicles (PHEV and BEV) and hydrogen fuel cell vehicles (FCEV). Maritime shipping will be fueled by ammonia (46%), hydrogen (17%), and bioenergy (21%). Aviation will contract 38% in capacity, then be fueled with a combination of biofuels and synthetic hydrogen fuels. Rail transport will be a combination of electric and hydrogen fueled (Table A3).

Table A3. Key milestones in transforming the global transport sector (Source: IEA 2021, Table 3.4)

Category	
Road transport	• 2035: no new passenger internal combustion engine car sales globally
Aviation and shipping	• Implementation of strict carbon emissions intensity reduction targets as soon as possible.

Category		2020	2030	2050
Road transport				
Share of PHEV, BEV and FCEV in sales:	cars	5%	64%	100%
	two/three-wheelers	40%	85%	100%
	bus	3%	60%	100%
	vans	0%	72%	100%
	heavy trucks	0%	30%	99%
Biofuel blending in oil products		5%	13%	41%
Rail				
Share of electricity and hydrogen in total energy consumption		43%	65%	96%
Activity increase due to modal shift (index 2020=100)		100	100	130
Aviation				
Synthetic hydrogen-based fuels share in total aviation energy consumption		0%	2%	33%
Biofuels share in total aviation energy consumption		0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)		0	20	38
Shipping				
Share in total shipping energy consumption:	Ammonia	0%	8%	46%
	Hydrogen	0%	2%	17%
	Bioenergy	0%	7%	21%
Infrastructure				
EV public charging (million units)		1.3	40	200
Hydrogen refuelling units		540	18 000	90 000
Share of electrified rail lines		34%	47%	65%

Note: PHEV = plug-in hybrid electric vehicles; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.

17. APPENDIX B: STATISTICS ON THE AUSTRALIAN TRANSPORT FLEET

Table B1-1. Motor vehicles on register by vehicle class and by state in Australia (as of June 30th 2021)
(Source: ABN 2021, document 93090DO001_2021 Motor Vehicle Census, Australia, 2021)

Year	New South Wales (number)	Victoria (number)	Queensland (number)	South Australia (number)	Western Australia (number)
PASSENGER VEHICLES					
2016	4 134 786	3 666 505	2 715 055	1 061 776	1 583 939
2020	4 348 429	3 963 818	2 919 855	1 110 427	1 631 779
2021	4 404 673	3 970 844	2 975 229	1 131 199	1 653 342
CAMPERVANS					
2016	15 345	13 118	14 864	4 164	8 154
2020	19 601	15 268	18 131	5 050	8 336
2021	20 699	15 155	18 608	5 452	8 405
LIGHT COMMERCIAL VEHICLES					
2016	804 665	652 020	775 864	199 058	380 403
2020	941 140	753 341	887 239	226 726	406 009
2021	975 509	774 389	917 546	235 666	417 115
LIGHT RIGID TRUCKS					
2016	48 788	31 309	35 909	7 104	17 293
2020	58 530	41 478	43 220	7 947	19 071
2021	62 567	43 883	45 628	8 267	19 987
HEAVY RIGID TRUCKS					
2016	91 242	79 506	71 776	22 886	54 219
2020	101 814	88 175	76 083	22 713	54 112
2021	103 743	89 747	77 569	22 874	54 718
ARTICULATED TRUCKS					
2016	21 450	26 779	20 784	8 423	15 609
2020	23 475	30 010	23 106	8 837	16 206
2021	25 358	31 254	23 541	9 021	17 086
NON-FREIGHT CARRYING VEHICLES					
2016	2 908	6 550	5 556	1 874	5 214
2020	3 490	7 466	5 444	1 863	5 056
2021	3 591	7 734	5 476	1 888	5 100
BUSES					
2016	25 939	20 302	21 455	5 691	15 362
2020	27 838	21 853	21 989	6 077	14 945
2021	26 548	20 849	21 196	6 008	15 042
MOTORCYCLES					
2016	229 296	185 248	192 942	53 724	128 619
2020	254 722	198 151	210 033	55 320	123 245
2021	269 518	203 317	218 920	57 524	123 917
TOTAL MOTOR VEHICLES					
2016	5 374 419	4 681 337	3 854 205	1 364 700	2 208 812
2020	5 779 039	5 119 560	4 205 100	1 444 960	2 278 759
2021	5 892 206	5 157 172	4 303 713	1 477 899	2 314 712

Table B1-2. Motor vehicles on register by vehicle class and by state in Australia (as of June 30th 2021) (Source: ABN 2021, Document 93090DO001_2021 Motor Vehicle Census, Australia, 2021)

Year	Tasmania (number)	Northern Territory (number)	Australian Capital Territory (number)	Australia (number)
PASSENGER VEHICLES				
2016	316 904	95 196	240 946	13 815 107
2020	345 929	99 311	259 701	14 679 249
2021	349 959	100 676	264 753	14 850 675
CAMPERVANS				
2016	4 588	223	444	60 900
2020	5 157	189	488	72 220
2021	5 283	211	511	74 324
LIGHT COMMERCIAL VEHICLES				
2016	99 346	44 419	29 817	2 985 592
2020	114 299	44 762	33 500	3 407 016
2021	118 901	45 502	34 829	3 519 457
LIGHT RIGID TRUCKS				
2016	3 356	623	1 044	145 426
2020	4 281	769	1 384	176 680
2021	4 543	799	1 655	3 519 457
HEAVY RIGID TRUCKS				
2016	8 838	4 724	1 621	334 812
2020	9 761	4 593	1 583	358 834
2021	10 042	4 647	1 649	364 989
ARTICULATED TRUCKS				
2016	1 721	1 259	160	96 185
2020	2 140	1 171	192	105 137
2021	2 245	1 221	201	109 927
NON-FREIGHT CARRYING VEHICLES				
2016	965	368	132	23 567
2020	993	388	141	24 841
2021	1 064	379	146	25 378
BUSES				
2016	2 818	3 964	1 051	96 582
2020	3 112	3 532	1 127	100 473
2021	3 042	3 328	1 047	97 060
MOTORCYCLES				
2016	19 093	6 941	13 102	828 965
2020	20 719	5 759	12 932	880 881
2021	21 372	5 878	13 357	913 803
TOTAL MOTOR VEHICLES				
2016	457 629	157 717	288 317	18 387 136
2020	506 391	160 474	311 048	19 805 331
2021	516 451	162 641	318 148	20 142 942

18. APPENDIX C: ELECTRICAL POWER GENERATION IN AUSTRALIA

Table C1. Electrical power generated in Australia (Source: Australian Energy Statistics 2020)

Electrical Power Generation System	2015 (GWh)	2016 (GWh)	2017 (GWh)	2018 (GWh)	2019(e) (GWh)
Non-renewable fuels					
Black coal	111 628.3	115 331.6	120 864.6	120 583.1	116 359.0
Brown coal	50 547.9	46 990.9	38 276.7	35 961.4	33 136.8
Natural gas	50 883.1	48 533.1	55 329.1	51 373.8	54 357.5
Oil products	6 163.1	5 553.8	5 226.0	5 422.2	5 782.8
Total non-renewable	**219 222.4**	**216 409.4**	**219 696.3**	**213 340.6**	**209 636.1**
Renewable fuels					
Bioenergy	3 677.6	3 652.9	3 530.4	3 554.3	3 575.9
Wind	11 838.5	13 026.4	13 195.2	16 411.5	19 524.5
Hydro	14 206.3	17 927.8	13 750.2	17 491.9	14 429.9
Large-scale solar PV	283.5	593.9	825.4	2 338.7	5 495.4
Small-scale solar PV	5 923.0	6 880.9	8 132.0	9 940.5	12 455.3
Geothermal	0.4	0.4	0.3	0.0	0.0
Total renewable	**35 929.3**	**42 082.2**	**39 433.4**	**49 737.0**	**55 481.0**
Total	**255 151.7**	**258 491.6**	**259 129.7**	**263 077.6**	**265 117.1**

Totals may not add due to rounding.

a Includes multi-fuel fired power plants. This series was discontinued in 2013-14 and multi-fuel allocated to specific fuel types.

b The 2018-2019 and 2019 estimates may continue to grow as there can be a 12 month lag in the provision of small-scale solar data.

(e) estimate only, see method note

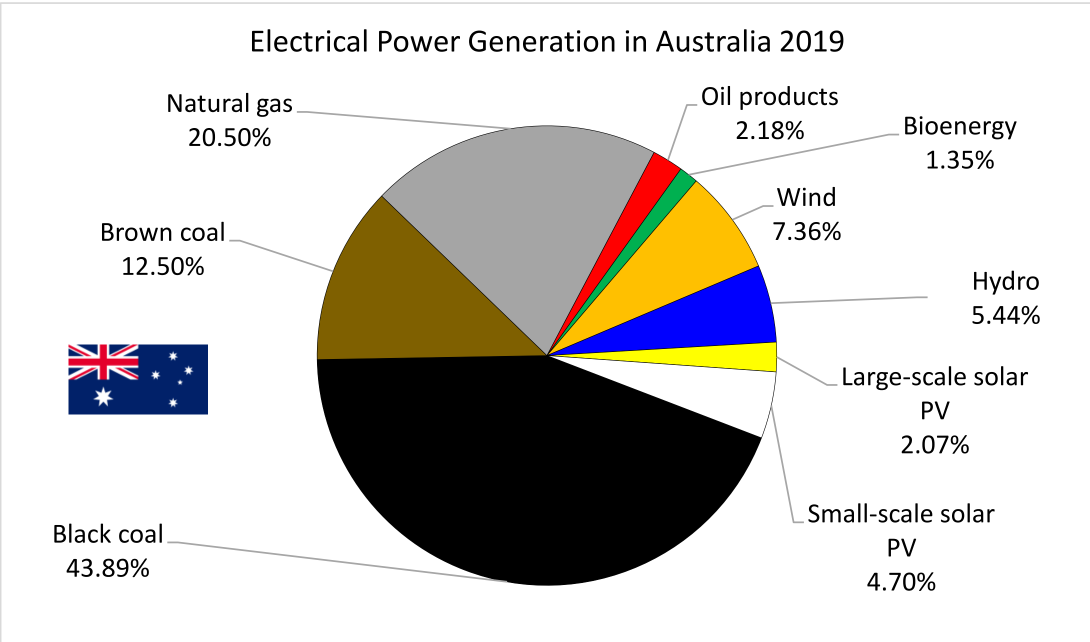

Figure C1. Electrical power generated in Australia by system in 2019 (Source: Australian Energy Statistics 2020)

19. APPENDIX D: ELECTRIC VEHICLE SPECIFICATIONS

Appendix D provides a list of current electric vehicles (EV), with battery size, efficiency, average range, and a range of ranges in the city, and out on the open freeway. The range is between driving in sub-zero temperatures with heating on and driving in the warm with no air conditioning. All of these vehicles listed can achieve longer ranges on road trips, if driven economically.

Table D1. Electric Vehicle Passenger car range and distance per kWh capacity
(Source: data taken from United States Environmental Protection Agency, Electric Vehicle Database https://ev-database.org/car/1125/Kia-e-Niro-64-kWh, and Cleantechnica https://cleantechnica.com updated October 17th, 2018)

Manufacturer	Model	Capacity (kWh)	per kWh (km/kWh)	Average (km)	Min Distance (km)	Max Distance (km)	Min Distance (km)	Max Distance (km)
Smart	EQ for-four	16.7	0.13	88.5	96.5	144.8	64.4	80.5
Mitsubishi	i-MiEV	15	0.12	88.5	88.5	136.8	56.3	88.5
Volkswagen	e-up!	18.7	0.13	104.6	104.6	160.9	72.4	88.5
BMW	i3	27.2	0.17	168.9	168.9	257.4	120.7	152.9
KIA	Soul EV	30	0.13	177.0	177.0	265.5	120.7	152.9
Hyundai	Ioniq	28	0.10	201.1	185.0	289.6	136.8	177.0
Volkswagen	e-Golf	32	0.14	201.1	193.1	297.7	136.8	185.0
Renault	Zoe	37	0.16	233.3	225.3	345.9	160.9	209.2
KIA	Niro EV Mid-Range	39.2	0.17	233.3	241.4	362.0	168.9	217.2
Nissan	Leaf 2018	38	0.17	241.4	233.3	362.0	168.9	217.2
Hyundai	Kona Electric	40	0.17	249.4	241.4	378.1	168.9	225.3
Tesla	Model 3 (Standard)	52	0.15	329.8	345.9	571.2	257.4	345.9
Tesla	Model X 75D	72.5	0.18	329.8	337.9	490.7	241.4	289.6
Mercedes	EQC (2019)	70	0.21	345.9	370.1	539.0	265.5	337.9
Chevrolet	Bolt *	60	0.47	378.1	-	410.3	-	345.9
Opel	Ampera*	60	0.47	378.1	-	410.3	-	345.9
Hyundai	Kona Electric (64 kWh)	64	0.19	386.2	386.2	595.3	281.6	362.0
Tesla	Model S 75D	72.5	0.22	386.2	378.1	555.1	281.6	362.0
Jaguar	i-Pace	85	0.25	402.3	402.3	579.2	281.6	362.0
Tesla	Model 3 (Long Range)	78	0.17	490.7	466.6	708.0	345.9	458.6
Average		46.79	0.19	270.71				

* Opel Ampera is the EU version of the Chevy Bolt, and figures are taken from the EPA site, where a range of ranges is not available, just city and highway ranges.
The Mitsubishi i-MiEV is not currently available, but is sold as Citroen C-Zero and Peugeot Ion.
All figures for range are rounded to 0 or 5.

Table D2. Electric motorcycles
(Source: The Best Electric Motorcycles Of 2023, https://luxe.digital/lifestyle/cars/best-electric-motorcycles/#Zero-FX)

Manufacturer	Model Electric Motorcycle	Range		Battery Size	Energy Consumption distance per kWh	Engine Torque	Engine Horsepower
		(km)	(miles)	(kWh)	(kWh/km)	(Nm)	(hp)
Energica	Experia	420	261	22.5	0.054	115	80
BMW	CE 04	128.7	80	8.5	0.066	62.0	20
Zero FX	ZF7.2	146.4	91	7.2	0.049	106	21
Average				12.73	0.056		

Table D3. Electric Vehicle commercial van (Light Truck/Van) range and distance per kWh capacity
(Source: https://evcompare.io/search/)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Citroen	Berlingo Electric	170	22.5			
Iveco	Daily Electric	280	91	0.33	300	107
Nissan	e-NV200	200	40	0.2	254	107
Peugeot	Partner electric	170	22.5			
Renault	Kangoo Z.E.	270	33	0.28	225	59
Renault	Master Z.E.	120	33	0.12	225	76
SAIC Maxus	EV-80	230	53	0.23	320	136
Average (Light Truck/Van)			42.14	0.23		

Table D4. Electric Vehicle Light-Duty Vehicle (Pick-up truck) range and distance per kWh capacity

Manufacturer	Model	Date of Release	Possible Battery Capacity (kWh)	Estimated Range (miles)	Estimated Range (km)	Power Horsepower (hp)	Estimated Distance per kWh (km/kWh)	Source (Manufacturer website)
Chevrolet Silverado / GMC Hummer Electrics	Hummer EV SUT	2021	200	400	643.6	1000	0.31	https://www.gmc.com/electric-truck/hummer-ev
Ford	Electric Ford F-150	2022		300	482.7			https://insideevs.com/reviews/377328/ford-f150-electric-truck-details/
Tesla	Cybertruck			500	804.5			https://www.tesla.com/en_gb/cybertruck
Rivian	R1T	2021	105	230	370.07		0.28	https://rivian.com/r1t
			135	300	482.7		0.28	
			180	400	643.6		0.28	
Lordstown	Endurance	2021				600	0.25	https://lordstownmotors.com/pages/endurance
Bollinger	B2	2020	142	200	321.8	614	0.44	https://bollingermotors.com/bollinger-b2/
Nikola	Badger	2022	160	300	482.7	455	0.33	https://nikolamotor.com/badger
Average (Light-Duty Vehicle - Pick up truck)			153.67	328.75			0.31	

Table D5. Electric Vehicle Bus (Transit Bus, Paratransit Shuttle, School Bus) range and distance per kWh capacity (Source: Volvo 7900 Electric specifications, www.volvobuses.co.uk and BYD 2020, www.byd.com)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Volvo	7900 Electric	200	150 200 250	1.25	400	160
BYD Auto	BYD K9	250	310	0.9-1.8	700 1100 3000	245 410 490

Average (Transit Bus, Paratransit Shuttle, School Bus)			227.5	1.32

Table D6. Electric Vehicle HCV Trucks (Refuse Truck, Medium Duty Delivery Truck, Large Duty Rigid Delivery Truck, Long Haul Semi-Trailer Class 8) range and distance per kWh capacity
(Source: Liimatainen *et al.* 2019)

Manufacturer	Commercial Name	Type	Maximum Weight (tonnes)	Battery Capacity (kWh)	Range (km)	Energy Consumption (kWh/km)
Mitsubishi	eCanter	medium duty	7.5	82.8	120	0.69
BYD	T7	medium duty	11	175	200	0.88
Freightliner	eM2 106	medium duty	12	325	370	0.88
Volvo	FL Electric	rigid	16	100-300	100-300	1.00
Renault	D Z.E.	rigid	16	200-300	300	1.00
eMoss	EMS18	rigid	18	100-250	100-250	1.00
Mercedes-Benz		rigid	26	212	200	1.06
Renault	D WIDE Z.E.	rigid	26	200	200	1.00
Tesla	Semi	semitrailer	36		480 - 800	1.25
BYD	T9	semitrailer	36	350	200	1.75
Freightliner	eCascadia	semitrailer	40	550	400	1.38

Average Medium Duty (Delivery Truck)	194.3	230.0	0.82
Average Rigid (Refuse Truck, Large Rigid Delivery Truck)	206.0	233.3	1.01
Average Semi Trailer (Class 8 Truck)	450.0	300.0	1.46

20. APPENDIX E: BATTERY CHEMISTRY SPECIFICATIONS

Table E1. Specifications by Battery Chemistry (Source: Diouf & Pode 2015)

Battery Specifications	Lead Acid	NiCd Nickel Cadmium	NiMH Nickel Metal Hydride	Li-ion Lithium Nickel Cobalt Aluminium Oxides (NCAs)	Li-ion Nickel Manganese Cobalt (NMC)	Li-ion Lithium Iron Phosphate (LFP)
Specific Energy Density (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal Resistance (mΩ)	<100 12V pack	100-200 6V pack	200-300 6V pack	150-300 7.2V	25-75 per cell	25-50 per cell
Life Cycle (80% discharge)	200-300	1000	300-500	500-1,000	500-1,000	1,000-2,000
Fast-Charge Time	8-16h	1h typical	2-4h	2-4h	1h or less	1h or less
Overcharge Tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-Discharge/month (room temp)	0.05	0.2	0.3	<10%		
Cell Voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge Cutoff Voltage (V/cell)	0.111111111 Float 2.25	Full charge detection by voltage signature		0.180555556		0.166666667
Discharge Cutoff Voltage (V/cell, 1C)	0.09375	0.041666667		2.50-3.00		0.138888889
Peak Load Current Best Result	5C 0.2C	20C 1C	5C 0.5C	>3C <1C	>30C <10C	>30C <10C
Charge Temperature	-20 to 50°C -4 to 122°F	0 to 45°C 32 to 113°F		0 to 45°C 32 to 113°F		
Discharge Temperature	-20 to 50°C -4 to 122°F	-20 to 65°C -4 to 149°F		-20 to 60°C -4 to 140°F		
Maintenance Requirment	3-6 Months (topping charge)	30-60 days (discharge)	60-90 days (discharge)	Not required		
Safety Requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
In Use Since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very High	Very High	Low	Low		

20.1 Solid state battery chemistry metal content

Solid state battery's (ASSB) are projected to account for a large proportion of future battery markets. For this study, the ASSB market was to be made up of three ASSB chemistries in equal proportions. These chemistries were selected from Manthiram *et al.* 2017, from a range of possible options, and are assumed to be the dominant products. The element proportion mass of each chemistry was estimated using atomic mass (Lide 1991). Assuming that the specific energy density of ASSB chemistries is 600 Wh/kg (Manthiram *et al.* 2017), the metal content was estimated in terms of kg/MW (Tables E2 to E4).

Table E2. Element proportions in lithium solid state battery solid-electrolyte chemistry $LiTi_2(PO_4)_3$
(Source: Manthiram *et al.* 2017)

Element	Symbol	Atomic Mass (amu)	Number of atoms in $LiTi_2(PO_4)_3$ (number)	Mass of atoms in molecule (amu)	Proportion of Element per unit mass (%)	Proportion of Element per kg (kg)	Metal content assuming energy density 600 Wh/kg (kg/MW)
Lithium	Li	6.941	1	6.941	1.8 %	0.0179	29.8
Titanium	Ti	47.867	2	95.734	24.7 %	0.2470	411.7
Phosphorus	P	30.974	3	92.921	24.0 %	0.2397	399.6
Oxygen	O	15.999	12	191.988	49.5 %	0.4953	825.6
Total				387.584	100.0 %	1.0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.6605402 x 10^{-27} kg

Table E3. Element proportions in lithium solid state battery solid-electrolyte chemistry $Li_{14}Zn(GeO_4)_4$
(Source: Manthiram *et al*. 2017)

Element	Symbol	Atomic Mass (amu)	Number of atoms in $Li_{14}Zn(GeO_4)_4$ (number)	Mass of atoms in molecule (amu)	Proportion of Element per unit mass (%)	Proportion of Element per kg (kg)	Metal content assuming energy density 600 Wh/kg (kg/MW)
Lithium	Li	6.941	14	97.174	13.7 %	0.1370	228.4
Zinc	Zn	65.38	1	65.38	9.2 %	0.0922	153.7
Germanium	Ge	72.640	4	290.560	41.0 %	0.4098	682.9
Oxygen	O	15.999	16	255.984	36.1 %	0.3610	601.7
Total				709.098	100.0 %	1.0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.6605402 x 10^{-27} kg

Table E4. Element proportions in lithium solid state battery solid-electrolyte chemistry $Li_7La_3Zr_2O_{12}$
(Source: Manthiram *et al.* 2017)

Element	Symbol	Atomic Mass (amu)	Number of atoms in $Li_7La_3Zr_2O_{12}$ (number)	Mass of atoms in molecule (amu)	Proportion of Element per unit mass (%)	Proportion of Element per kg (kg)	Metal content assuming energy density 600 Wh/kg (kg/MW)
Lithium	Li	6.941	7	48.587	5.8 %	0.0579	96.4
Lanthanum	La	138.905	3	416.71641	49.6 %	0.4962	827.1
Zirkonium	Zr	91.224	2	182.448	21.7 %	0.2173	362.1
Oxygen	O	15.999	12	191.988	22.9 %	0.2286	381.0
Total				839.739	100.0 %	1.0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.6605402 x 10^{-27} kg

20.2 Vanadium redox battery chemistry metal content

Vanadium Redox Battery (VRB) chemistry is projected to be part of the global battery market. It is being considered as a possible chemistry to manufacture stationary power storage in particular (IEA 2021). The VRB is a type of rechargeable flow battery, that employs vanadium ions as charge carriers (Sangwon 2019). The battery uses vanadium's ability to exist in solution in four different oxidation states to make a battery with a single electroactive element instead of two.

The specific energy of VRB is dependent on the electrolyte, which is in the range of 15–32 Wh/kg, and the energy density is in the range of 20–33 Wh/L (Lourenssen *et al.* 2019). VRB electrolyte can be manufactured from multiple compounds: vanadium trichloride (VCl_3), vanadium pentoxide (V_2O_5), and vanadyl sulphate ($VOSO_4$) were each considered with hydrochloric acid (HCl), sodium hydroxide (NaOH) and sulfuric acid (H_2SO_4) (Lourenssen *et al.* 2019, and Rychcik & Skyllas-Kazacos 1988).

For the purpose of this study, VRB electrolyte was assumed to be vanadyl sulphate ($VOSO_4$). Assuming that the specific energy density of VRB chemistries was 32 Wh/kg (Manthiram *et al.* 2017), the VRB metal content was estimated in terms of kg/MW (Table E5). This crude estimate does not account for metal content in electrodes or other parts of the VRB battery.

Table E5. Element proportions in VRB vanadium redox battery chemistry $VOSO_4$ (Source: Lourenssen *et al.* 2019)

Element	Symbol	Atomic Mass (amu)	Number of atoms in $VOSO_4$ (number)	Mass of atoms in molecule (amu)	Proportion of Element per unit mass (%)	Proportion of Element per kg (kg)	Metal content assuming energy density 32 Wh/kg (kg/MW)
Vanadium	V	50.942	1	50.942	31.3 %	0.3125	9766.3
Oxygen	O	15.999	5	79.995	49.1 %	0.4908	15336.3
Sulfur	S	32.065	1	32.065	19.7 %	0.1967	6147.4
Total				163.002	100.0 %	1.0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.6605402 x 10^{-27} kg

21. APPENDIX F: GLOBAL MINING PRODUCTION AND REFINING OF METALS

Table F1. Metal mining production in 2019 and 2023
(Source: Marscheider-Weidemann *et al.* 2021, USGS, Friedrichs 2022, Mudd 2021)

Metal	Element	Global Mine Production		Units
		2019	2023 e	
Aluminium	Al	354 244	400 000	1000 metric tons (bauxite)
Copper	Cu	20 664	22 000	1000 metric tons cont. metal
Zinc	Zn	12 873	12 431	1000 metric tons cont. metal
Magnesium Metal	Mg	♣	♣	
Manganese	Mn	16 628	20 000	1000 metric tons
Nickel	Ni	2 706 228	3 600 000	metric tons cont. metal
Lithium*	Li	95 170	170 800	metric tons cont. metal
Cobalt*	Co	151 060	230 000	metric tons cont. metal
Graphite (natural flake)*		1 700 000	1 300 000	metric tons
Graphite (synthetic)*	C			
Vanadium	V	96 021	100 000	metric tons cont. metal
Zirconium	Zr	1 338 463	1 575 000	metric tons
Germanium	Ge	♣	♣	
Rare Earth Element				
Neodymium	Nd	♣	♣	
Lanthanum	La	♣	♣	
Praseodymium	Pr	♣	♣	
Dysprosium	Dy	♣	♣	

* 2018 production value
♣ Data unavailable
e Data estimated by USGS
‡ Estimated from mining production. All other values are refining production values.

Table F2. Metal refining in 2019 and 2023
(Source: Marscheider-Weidemann *et al.* 2021, USGS, Friedrichs 2022, Mudd 2021)

Metal	Element	Global Refined Production		Units
		2019	2023	
Aluminium	Al	63 136	70 000	1000 metric tons cont. metal
Copper	Cu	24 200	27 000	1000 metric tons cont. metal (+ recycling)
Zinc	Zn	13 524	13 840	1000 metric tons cont. metal (+ recycling)
Magnesium Metal	Mg	1 120	940	1000 metric tons cont. metal
Manganese	Mn	20 591		1000 metric tons cont. metal
Nickel	Ni	2 350 142		metric tons cont. metal
Lithium*	Li	95 170		metric tons cont. metal
Cobalt*	Co	126 019		metric tons
Graphite (natural flake)*		1 156 300		metric tons
Graphite (synthetic)*	C	1 573 000		metric tons
Vanadium ‡	V	102 025		metric tons cont. metal
Zirconium ‡	Zr			
Germanium **đđ**	Ge	130		metric tons
Rare Earth Element				
Neodymium	Nd	23 900		metric tons
Lanthanum	La	35 800		metric tons
Praseodymium	Pr	7 500		metric tons
Dysprosium	Dy	1 000		metric tons

* 2018 production value

♣ Data unavailable

đđ Source: Mudd 2021

‡ Estimated from mining production. All other values are refining production values.

22. APPENDIX G: INSIGHT INTO POSSIBLE FUTURE DEMANDS FOR MINERALS & METALS MARKET

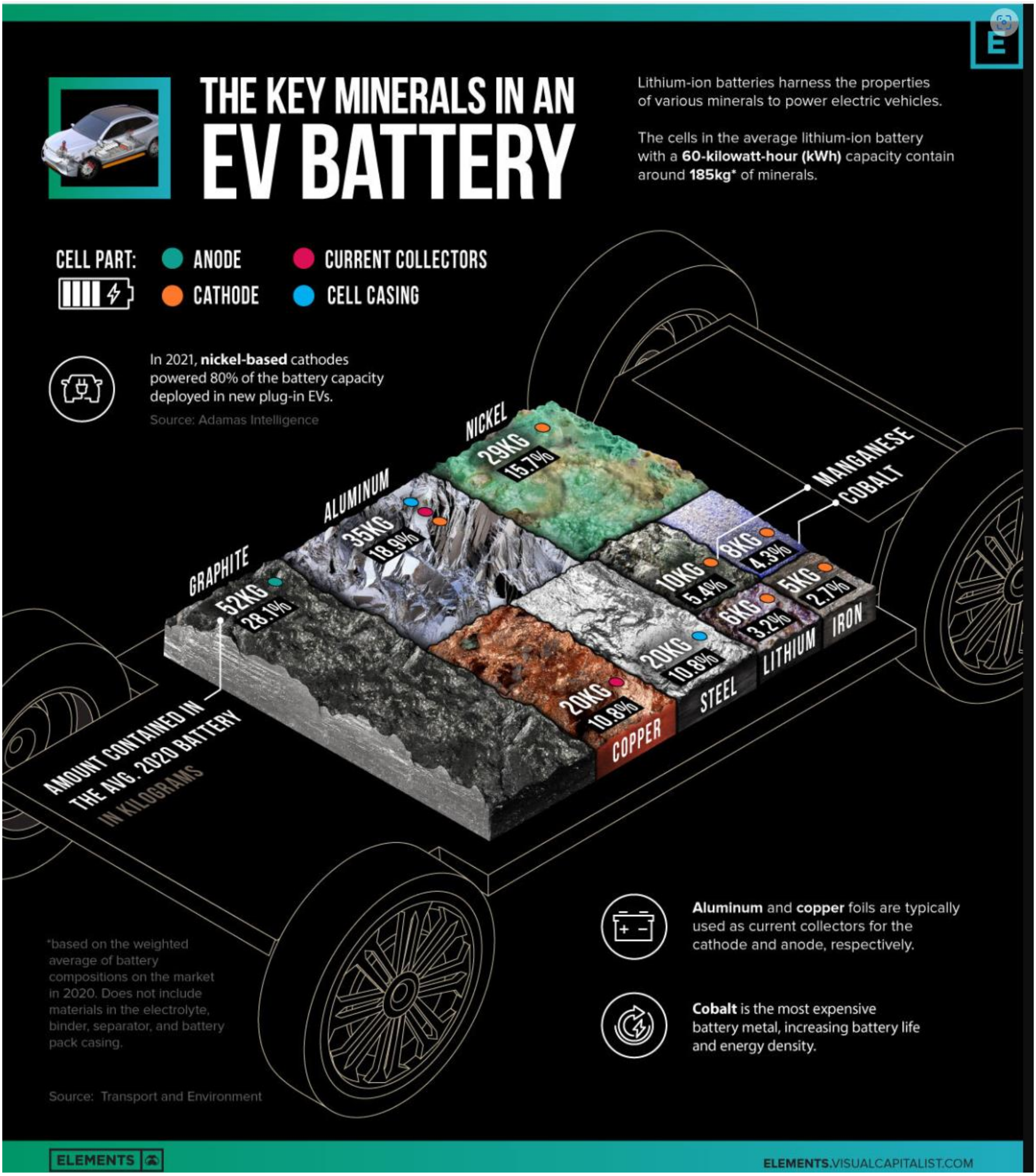

Figure G1: The key minerals in an EV battery

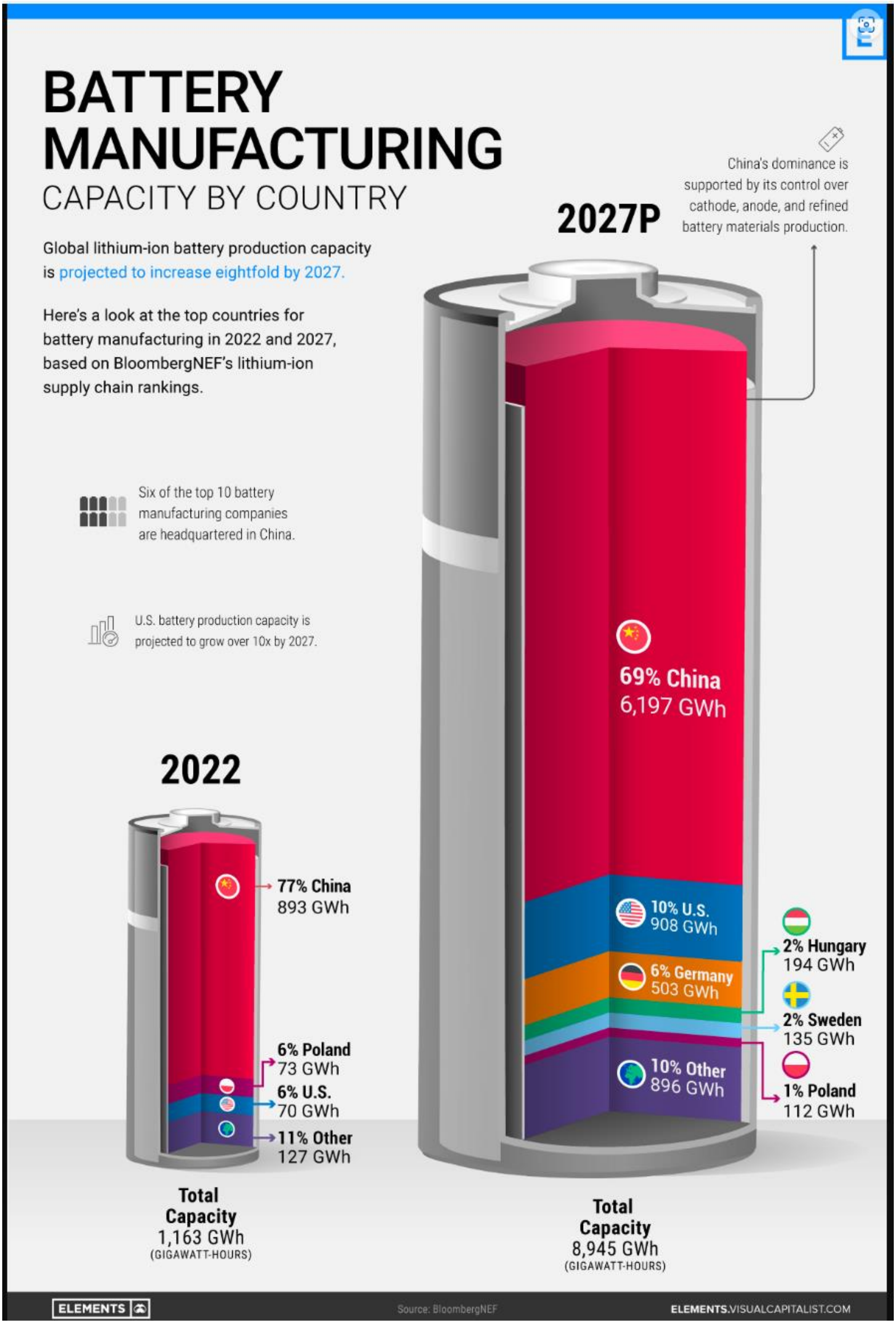

Figure G2: Battery manufacturing capacity by country

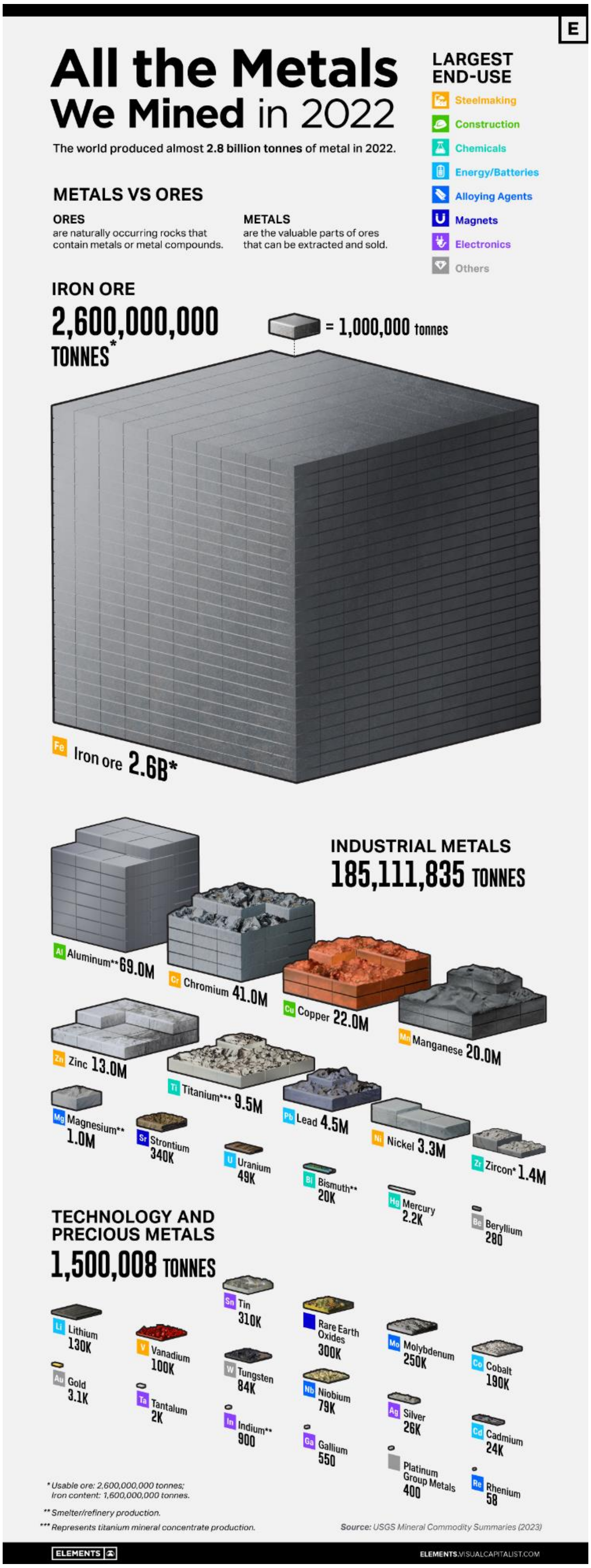

Figure G3: Mined metals in 2022 from iron ore to industrial and precious metals

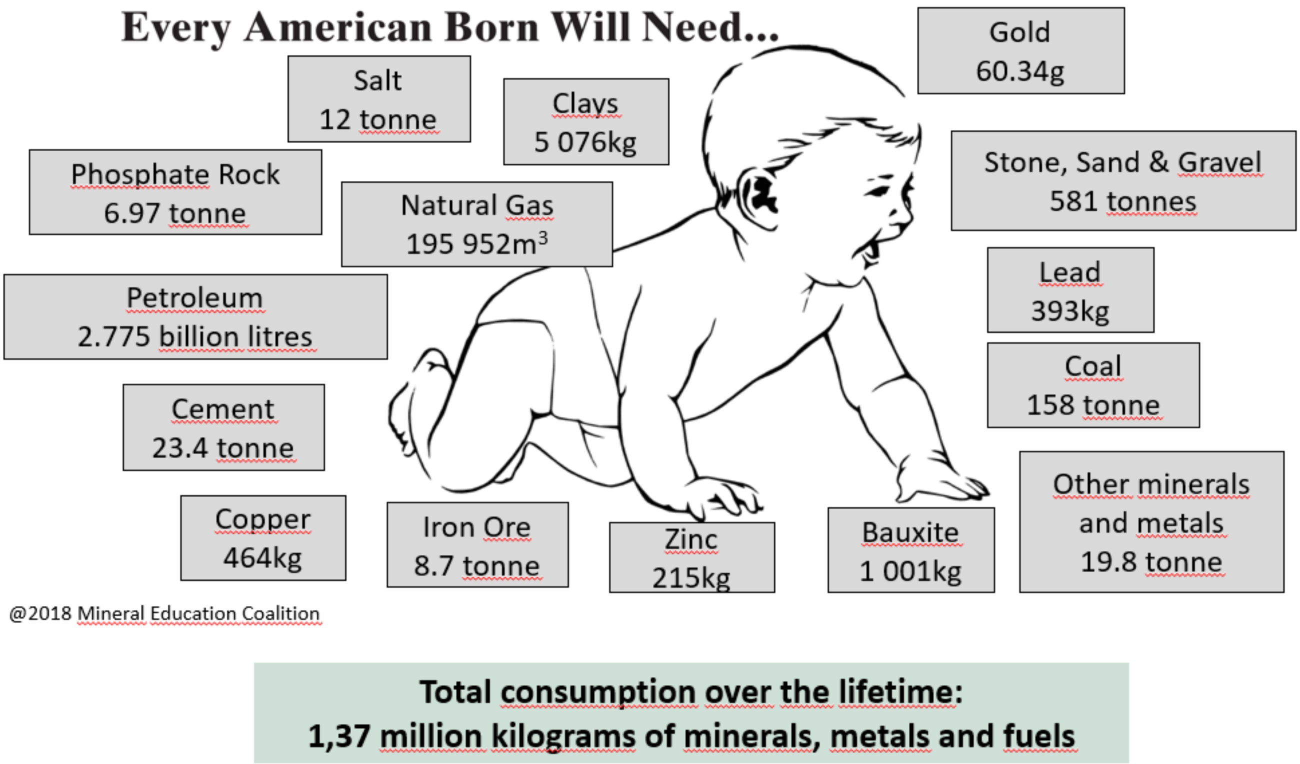

Figure G4. Average consumption of minerals for each American over their lifetime

23. APPENDIX H: CHINESE FUTURE RESOURCE PLAN & MARKET SHARE MINING PRODUCTION

This appendix is a compilation of data for the Chinese market share in the industrial ecosystem. Clearly it is not a comprehensive survey but only presents some of the parts of the industrial ecosystem. Some of the charts in this report were developed by Meng-Chun Lee in the FAME Project (Lee & Reimer 2018 and Lee 2019).

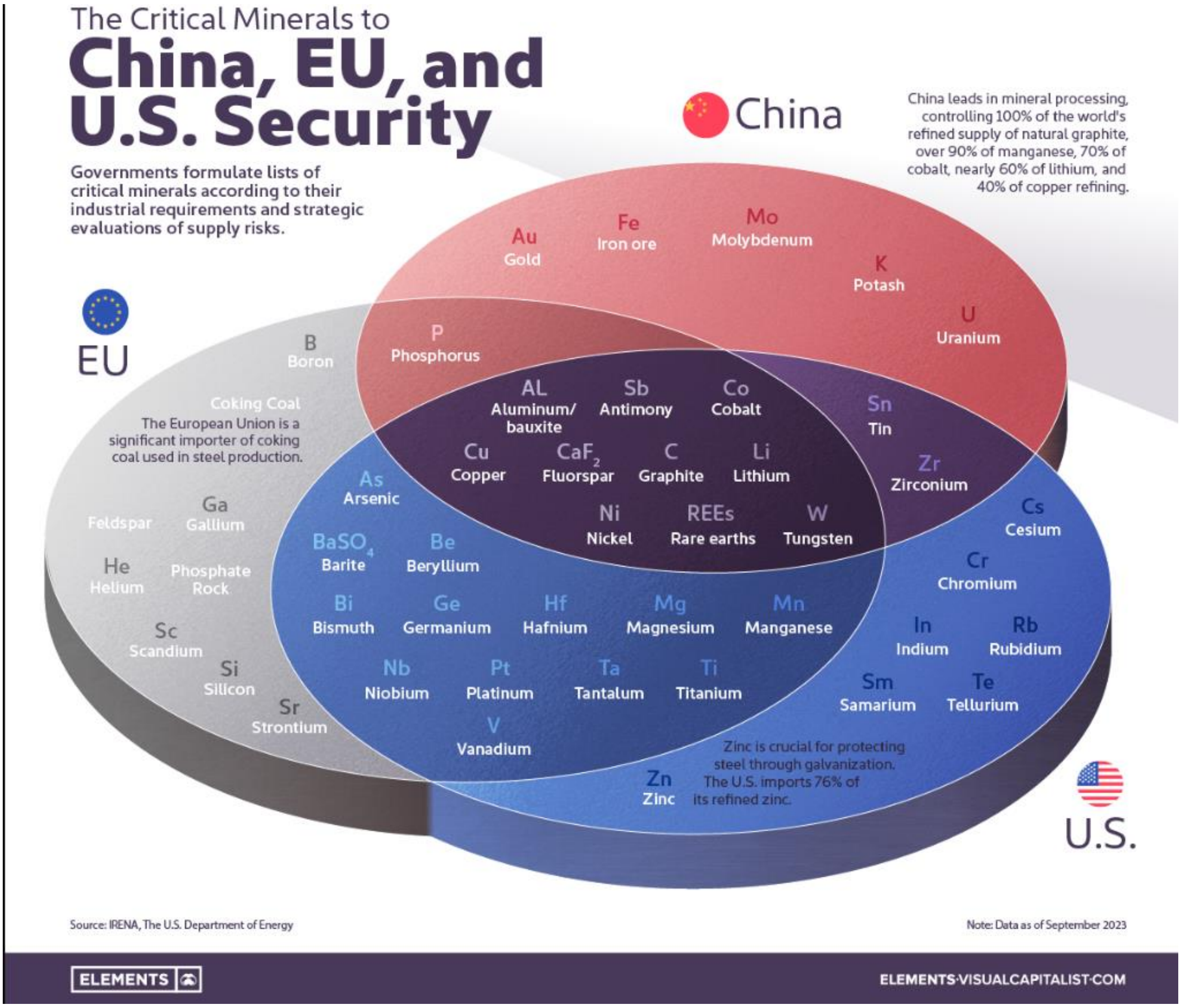

Figure H1: Critical minerals to China, EU and US, (Source: Benchmark Minerals 2022)

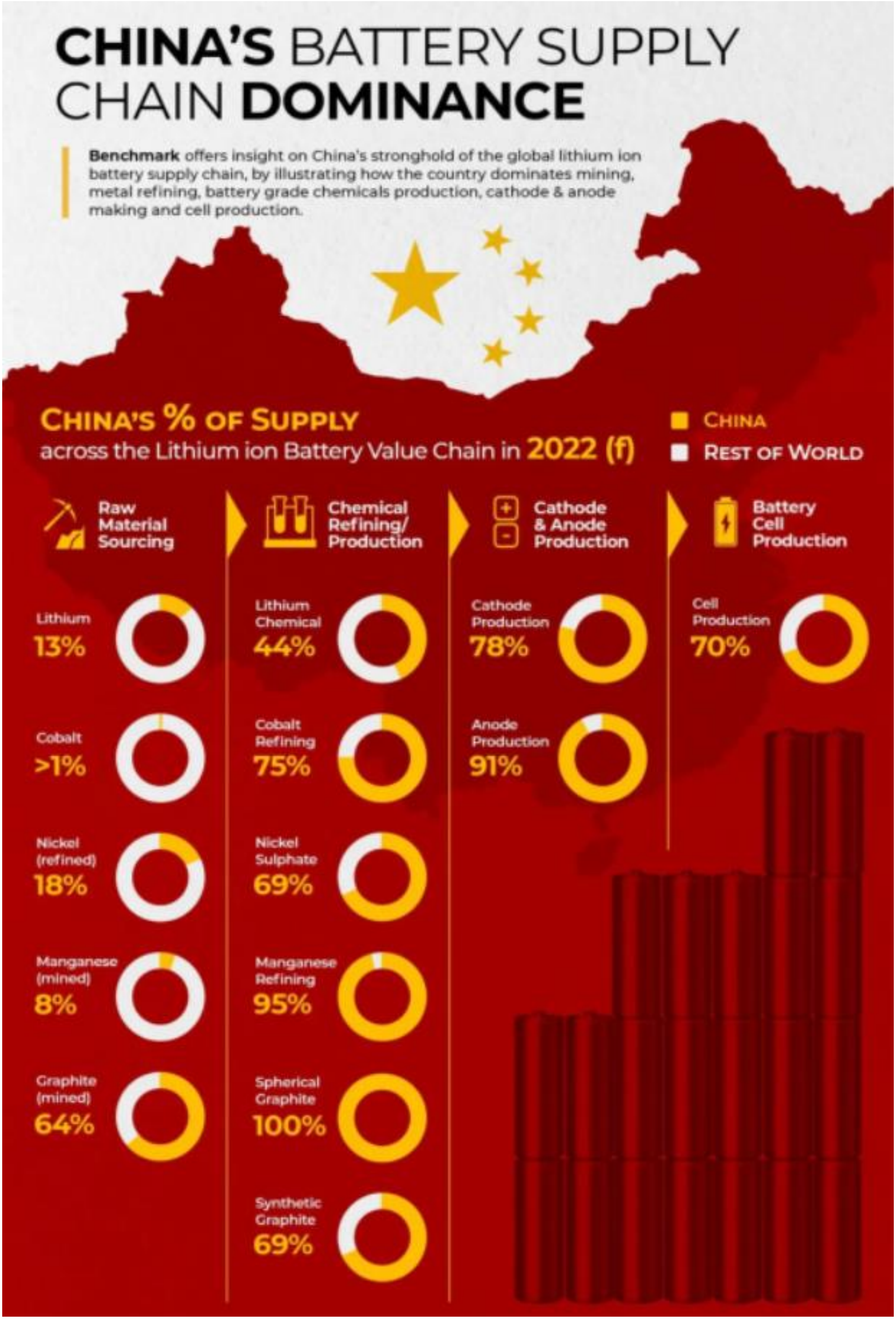

Figure H2: China dominates the Lithium-Ion battery supply chain, (Source: Benchmark Minerals 2022)

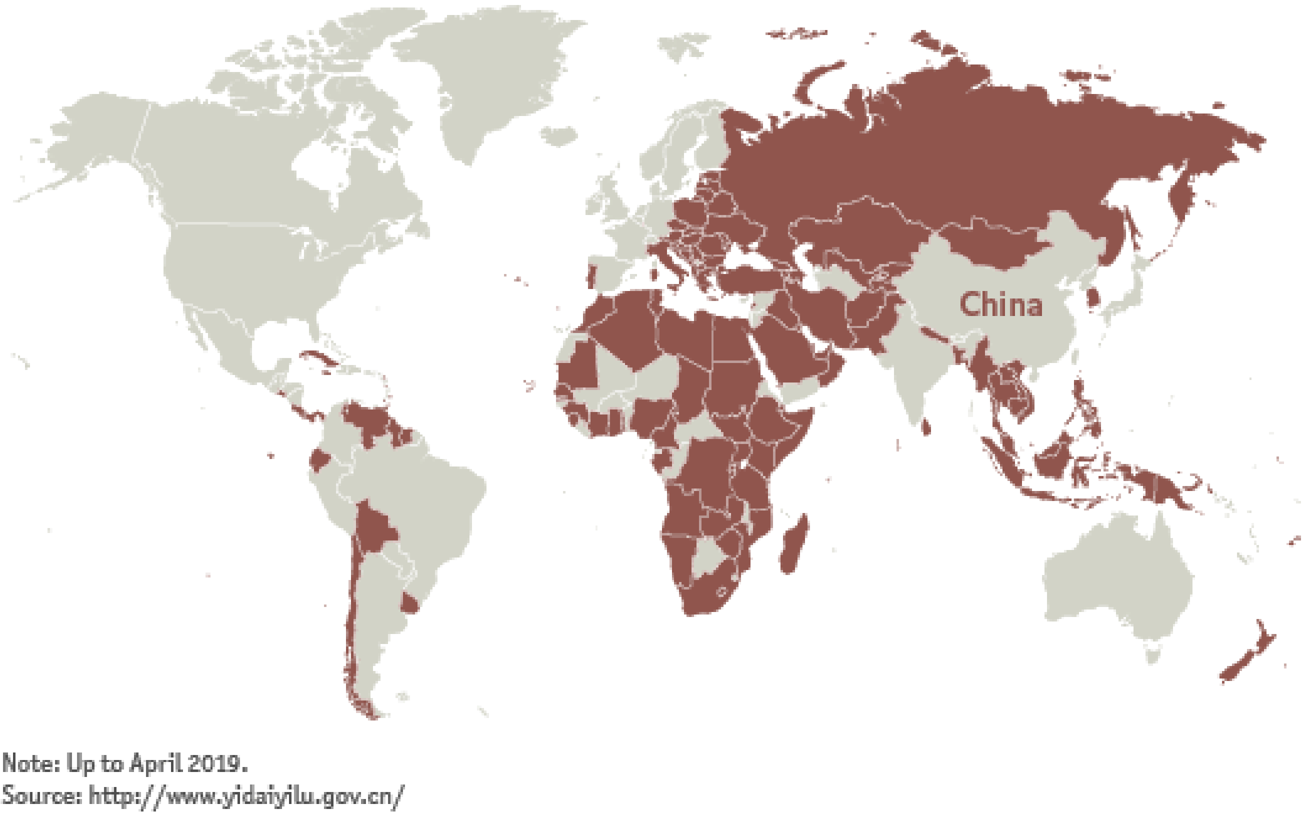

Figure H3. China Going Global 131 countries have signed China Belt and Road Initiative by 04/2019
(Source: Economist 2019, and CCP Belt and Road Portal, https://www.yidaiyilu.gov.cn/xwzx/bwdt/13764.htm)

Figure H4. Made in China 2025 is part of a larger plan: Made in China 2049 (Malkin 2018)

Made in China 2025 is part of a larger plan: Made in China 2049 (Global China 2049 Initiative) is the long term goal. It was first seen outside China in the China 1st National Mineral Resource Plan (Lee 2019, Lee and Reimer 2018, Figure H5), and current form is the China 3rd National Mineral Resource Plan (PRC 2016).

2020 年和 2025 年制造业主要指标

类别	指　标	2013 年	2015 年	2020 年	2025 年
创新能力	规模以上制造业研发经费内部支出占主营业务收入比重（%）	0.88	0.95	1.26	1.68
创新能力	规模以上制造业每亿元主营业务收入有效发明专利数 1（件）	0.36	0.44	0.70	1.10
质量效益	制造业质量竞争力指数 2	83.1	83.5	84.5	85.5
质量效益	制造业增加值率提高	-	-	比 2015 年提高 2 个百分点	比 2015 年提高 4 个百分点
质量效益	制造业全员劳动生产率增速（%）	-	-	7.5 左右（"十三五"期间年均增速）	6.5 左右（"十四五"期间年均增速）
两化融合	宽带普及率 3（%）	37	50	70	82
两化融合	数字化研发设计工具普及率 4（%）	52	58	72	84
两化融合	关键工序数控化率 5（%）	27	33	50	64
绿色发展	规模以上单位工业增加值能耗下降幅度	-	-	比 2015 年下降 18%	比 2015 年下降 34%
绿色发展	单位工业增加值二氧化碳排放量下降幅度	-	-	比 2015 年下降 22%	比 2015 年下降 40%

Figure H5. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H6. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H7. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H8. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H9. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H10. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H11. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H12. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H13. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H14. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H15. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H16. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H17. Made in China 2025 (Source: Lee and Reimer 2018)

Figure H18. China's Raw Materials Policies (Source: Lee 2019)

Figure H19. China's Raw Materials Policies (Source: Lee 2019)

Figure H20. China's Raw Materials Policies (Source: Lee 2019)

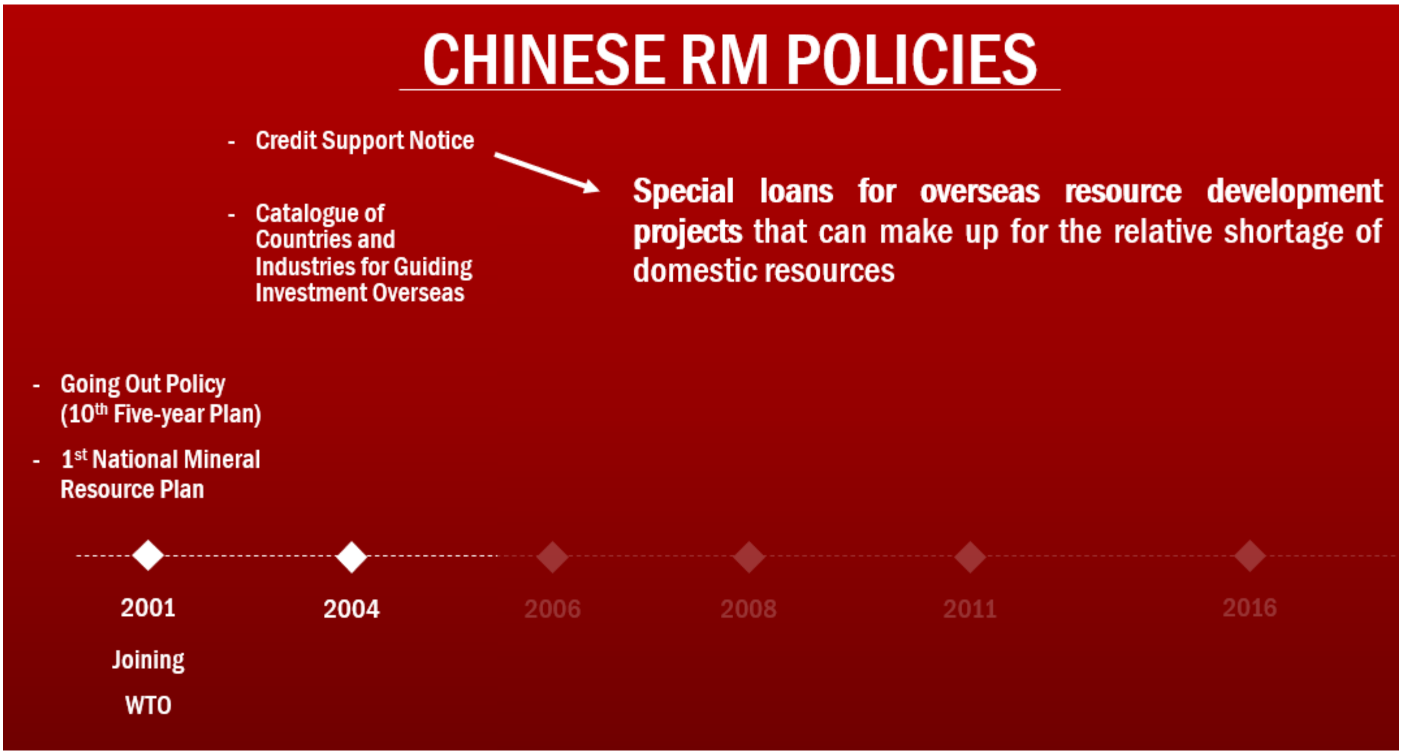

Figure H21. China's Raw Materials Policies (Source: Lee 2019)

Figure H22. China's Raw Materials Policies (Source: Lee 2019)

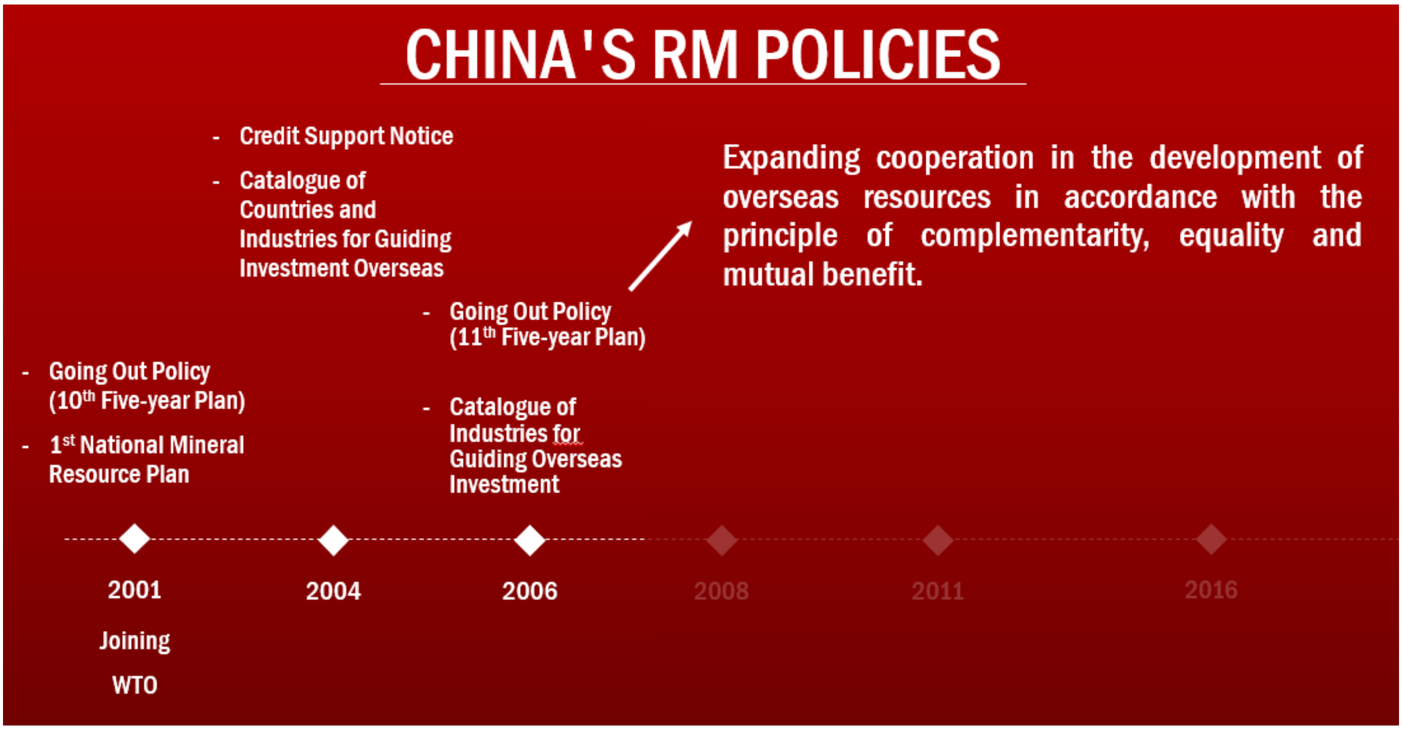

Figure H23. China's Raw Materials Policies (Source: Lee 2019)

Figure H24. China's Raw Materials Policies (Source: Lee 2019)

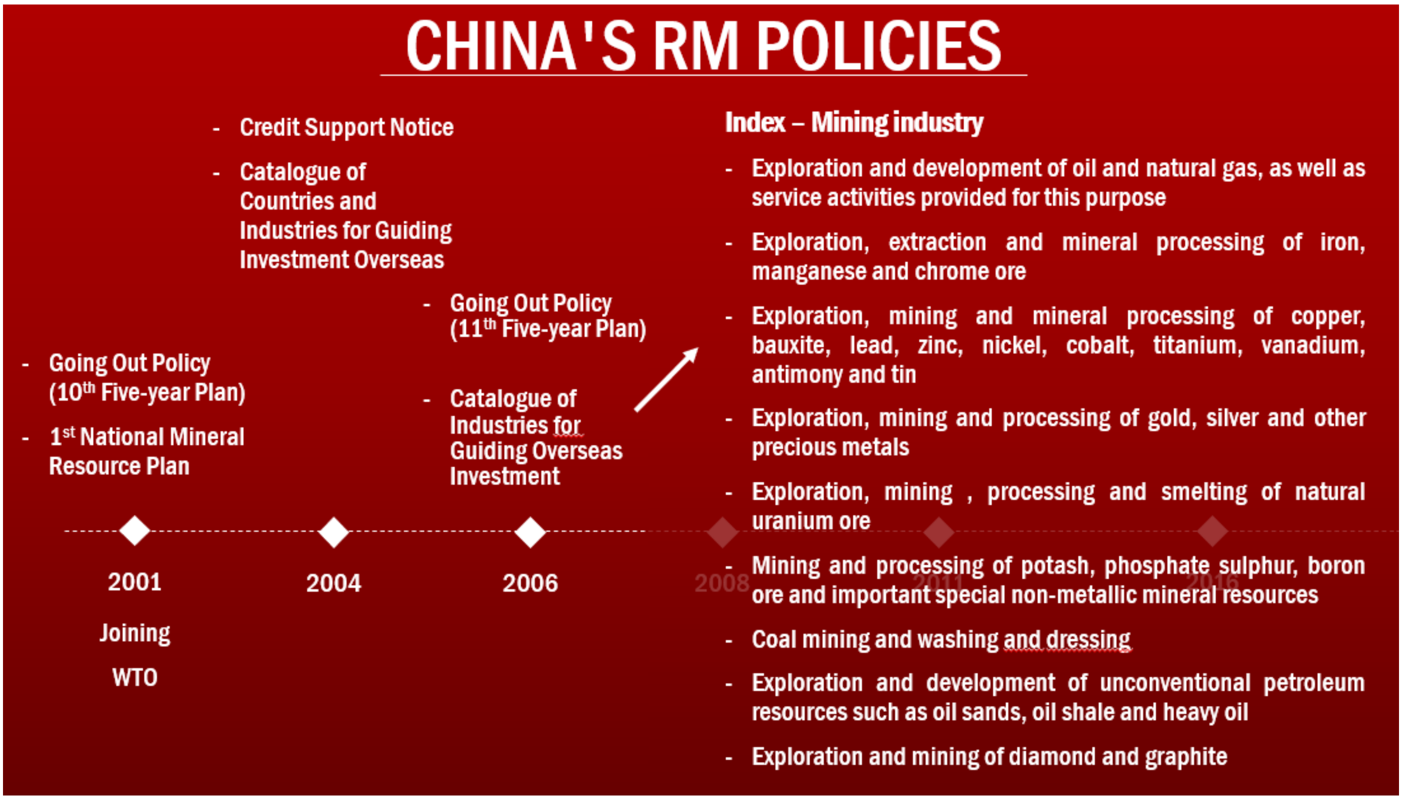

Figure H25. China's Raw Materials Policies (Source: Lee 2019)

Figure H26. China's Raw Materials Policies (Source: Lee 2019)

Figure H27. China's Raw Materials Policies (Source: Lee 2019)

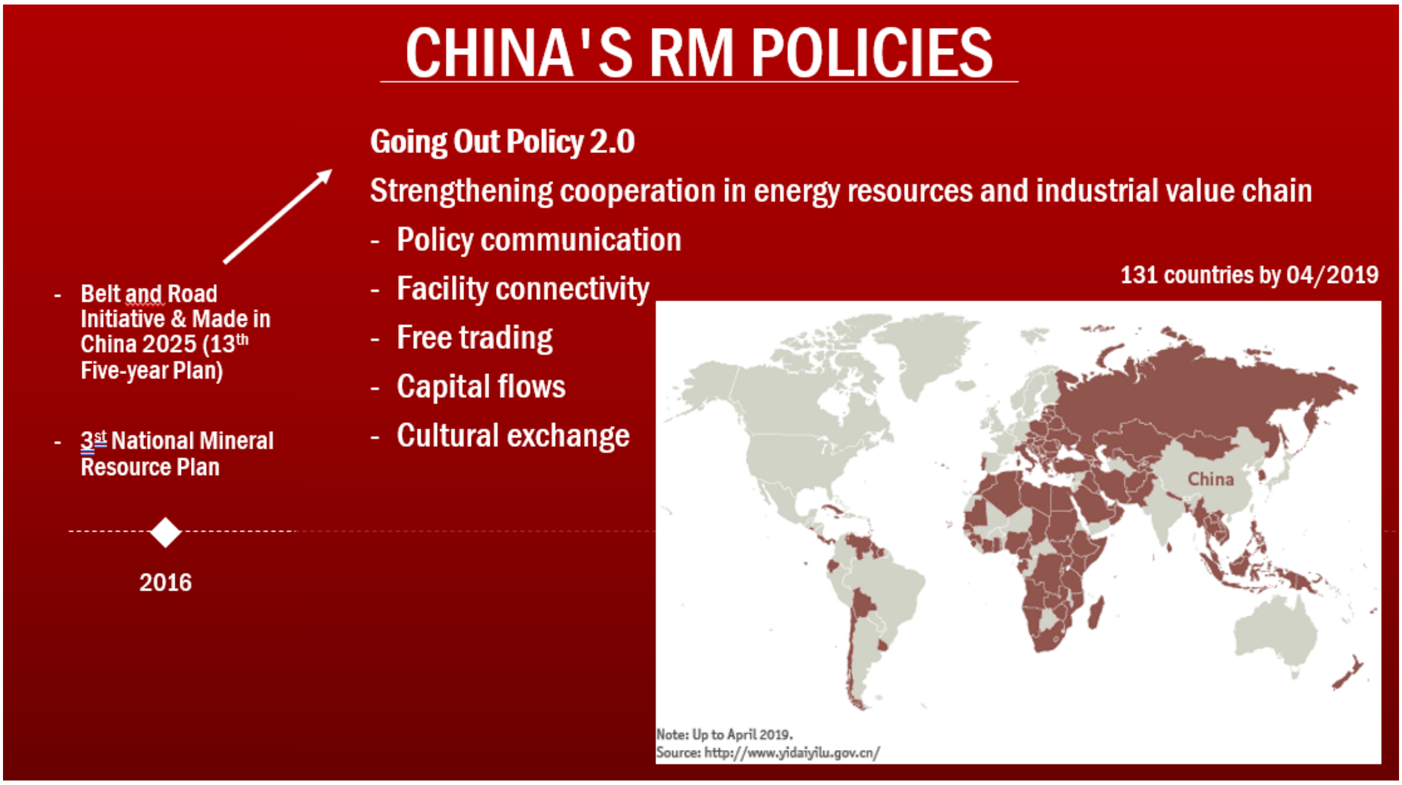

Figure H28. China's Raw Materials Policies (Source: Lee 2019)

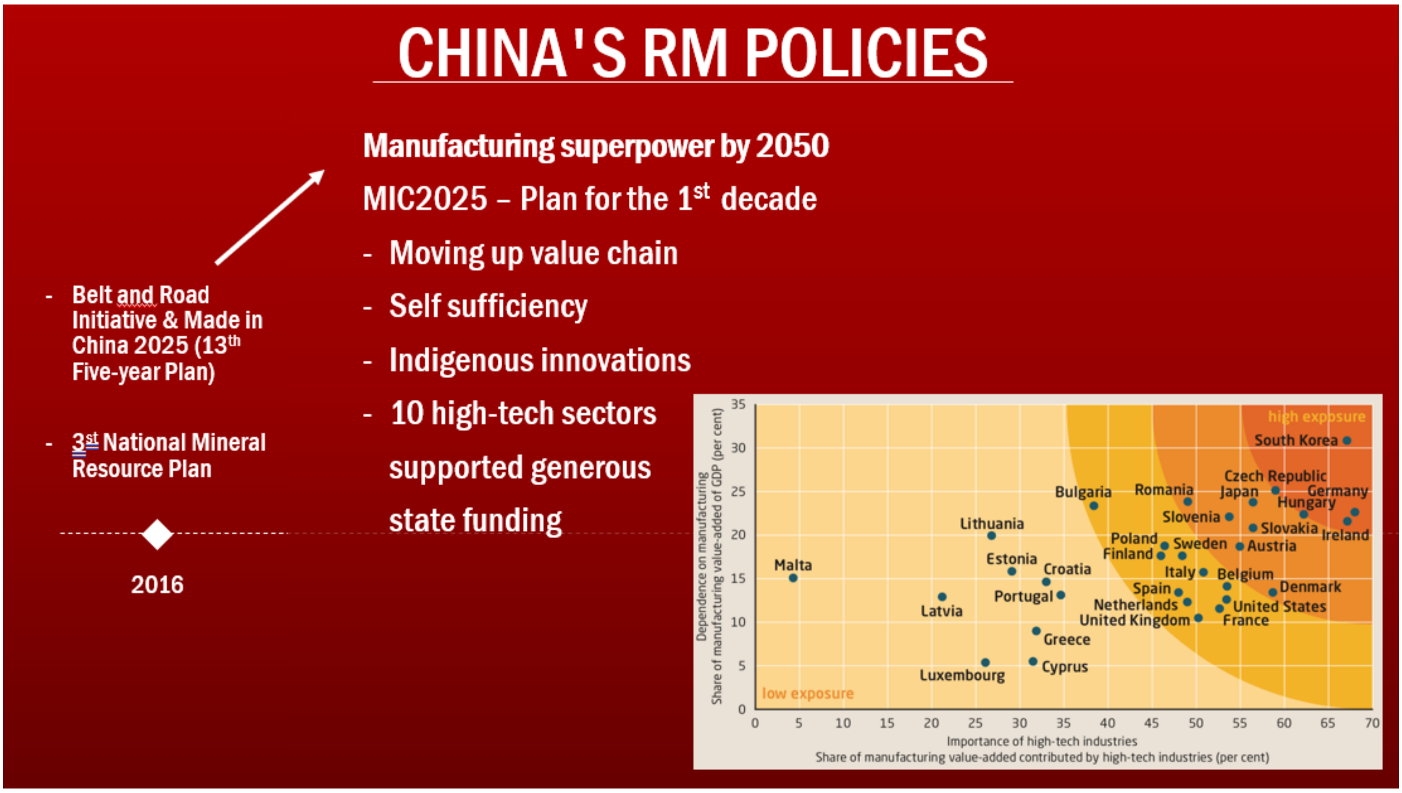

Figure H29. China's Raw Materials Policies (Source: Lee 2019)

Figure H30. China's Raw Materials Policies (Source: Lee 2019)

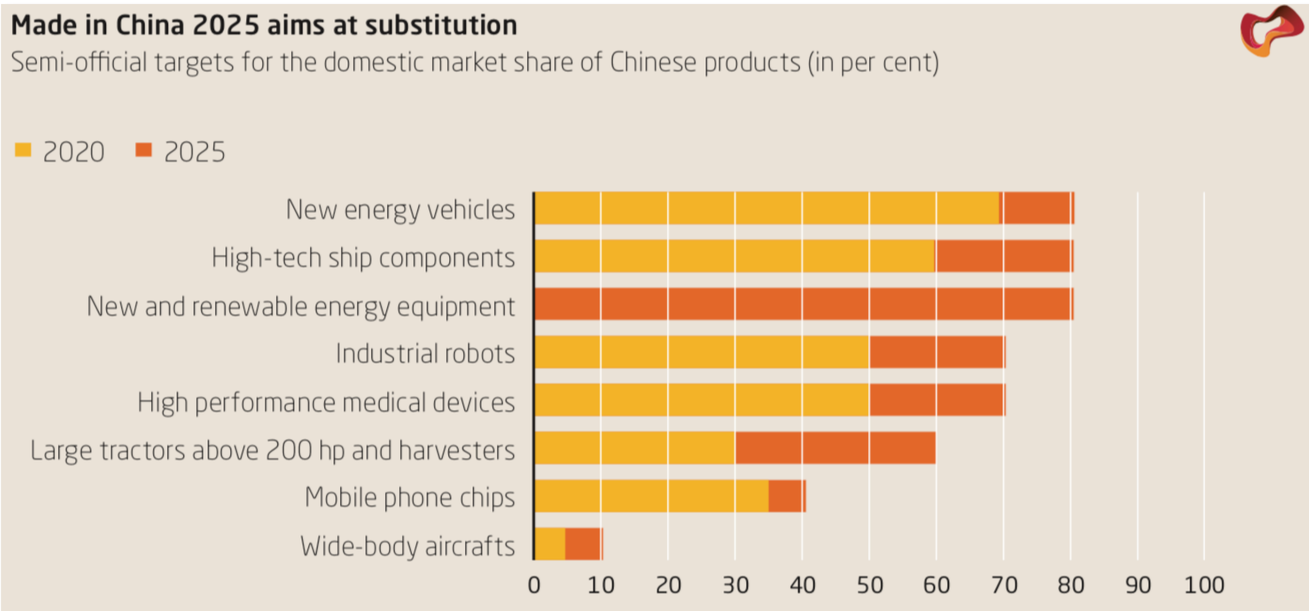

Figure H31. Semi-official targets for the domestic market share of Chinese products (Source: Malkin 2018, Wübbeke *et al.* 2016)

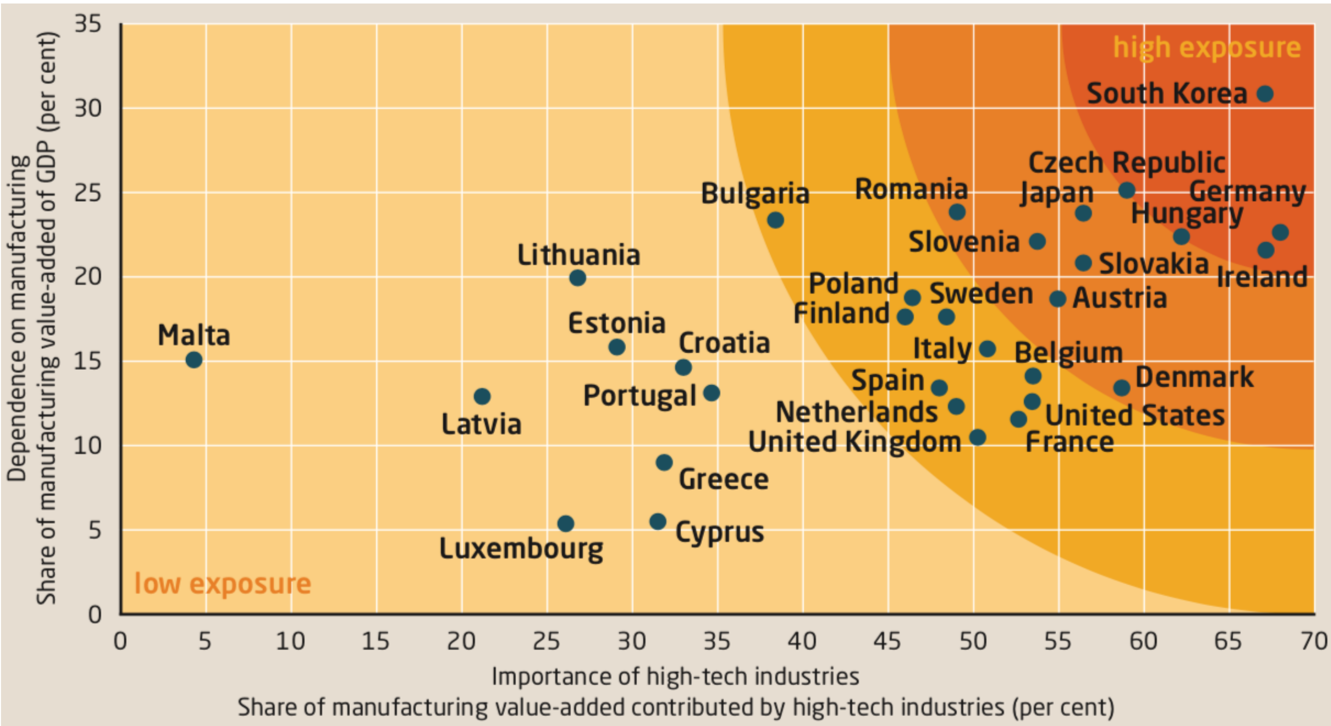

Figure H32. Level of risk exposure to Chinese corporate investment (Source: Malkin 2018)

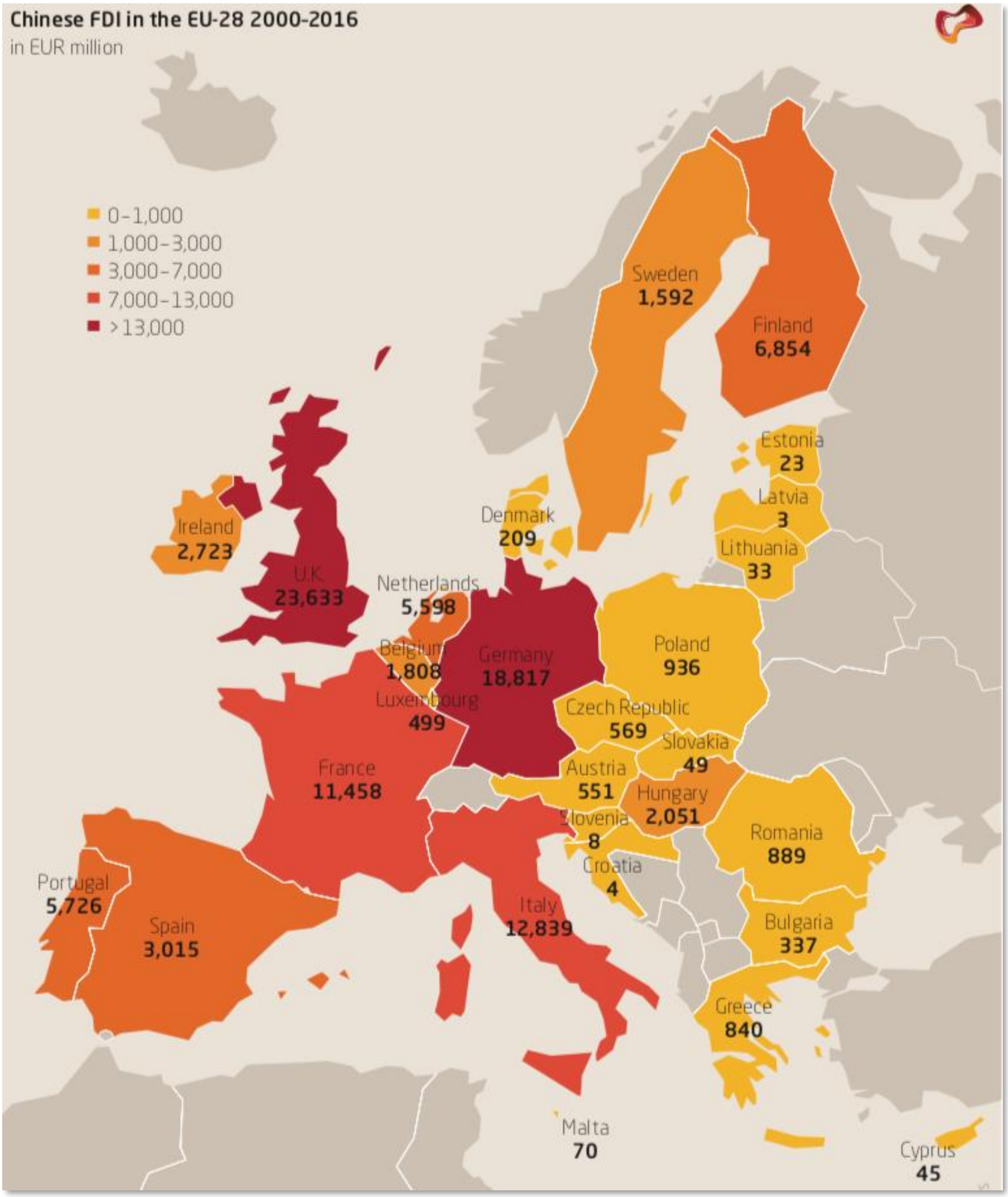

Figure H33. Chinese FDI in the EU-28 2000 to 2016 (Source: Wübbeke *et al.* 2016 & Rhodium Group 2017)

The European Union (EU) continues to be a favourite destination for Chinese investors, with more than EUR 35 billion of completed OFDI transactions in 2016, an increase of 77 per cent from 2015.

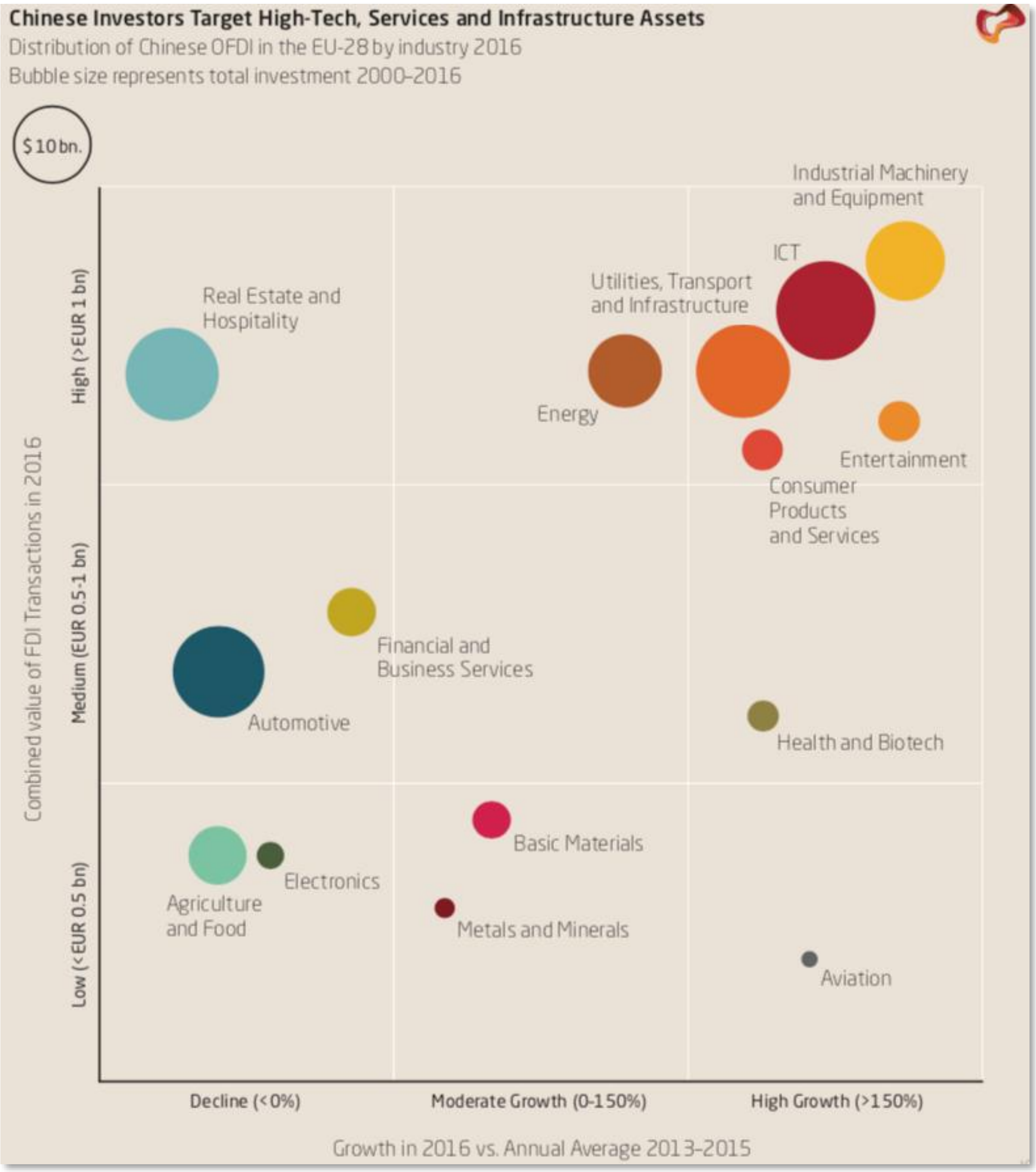

Figure H34. Chinese Investors Target high-technology, services and infrastructure assets
(Source: Wübbeke *et al.* 2016 & Rhodium Group 2017)

The growing imbalance in two-way FDI lows, persisting asymmetries in market access, and growing Chinese acquisitions of advanced technology and infrastructure assets have spurred heated debates in Germany and other nations about related risks.

In contrast to this sustained rise in Chinese investment in the EU, European companies have become more hesitant to invest in China. The value of EU FDI transactions in China continued to decrease for the fourth consecutive year to only EUR 8 billion in 2016, which is less than one third of the combined value of all Chinese investments in Europe.

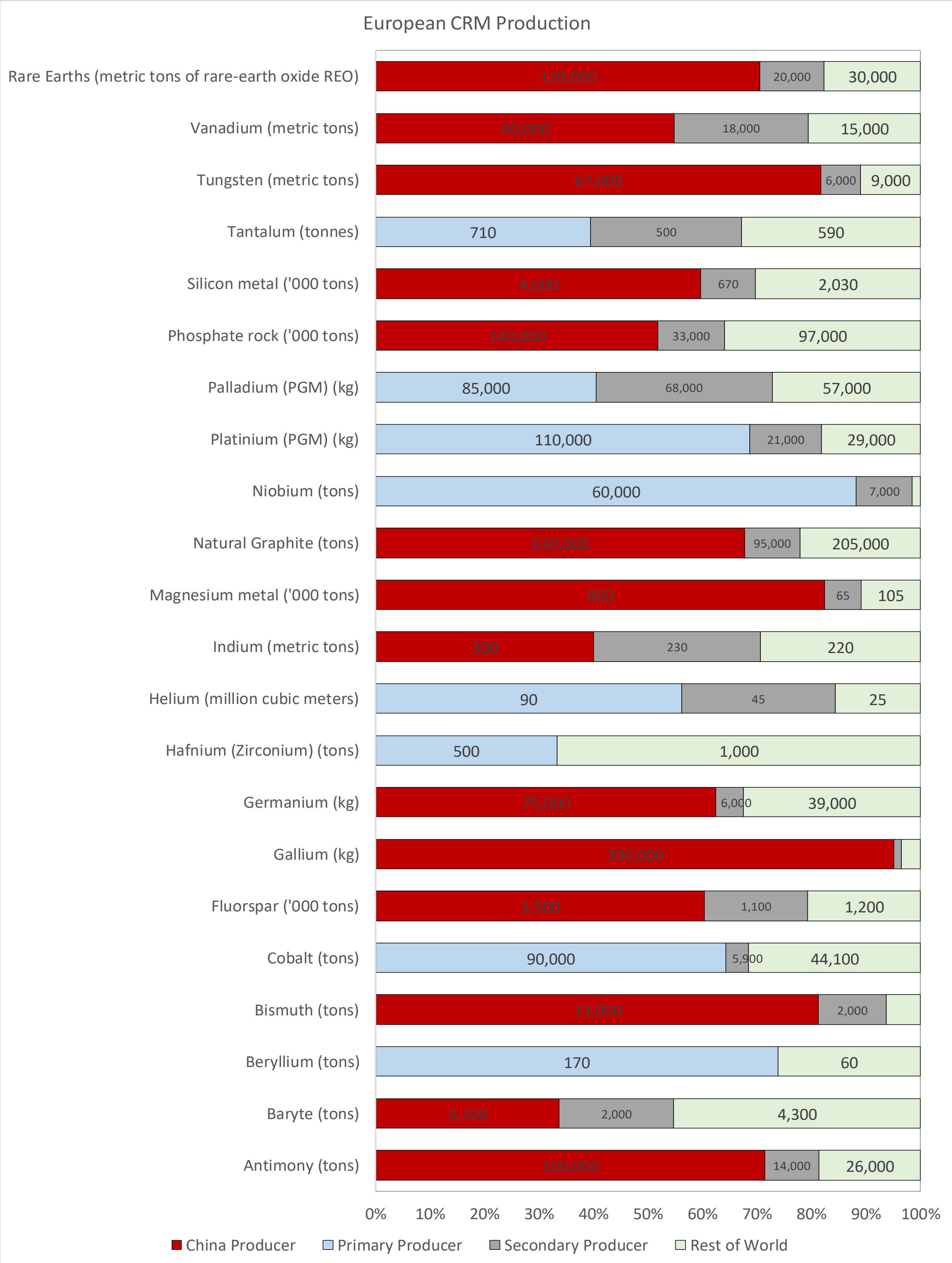

Figure H35. Chinese global market footprint of CRM raw material supply in 2018, (Source: USGS data)

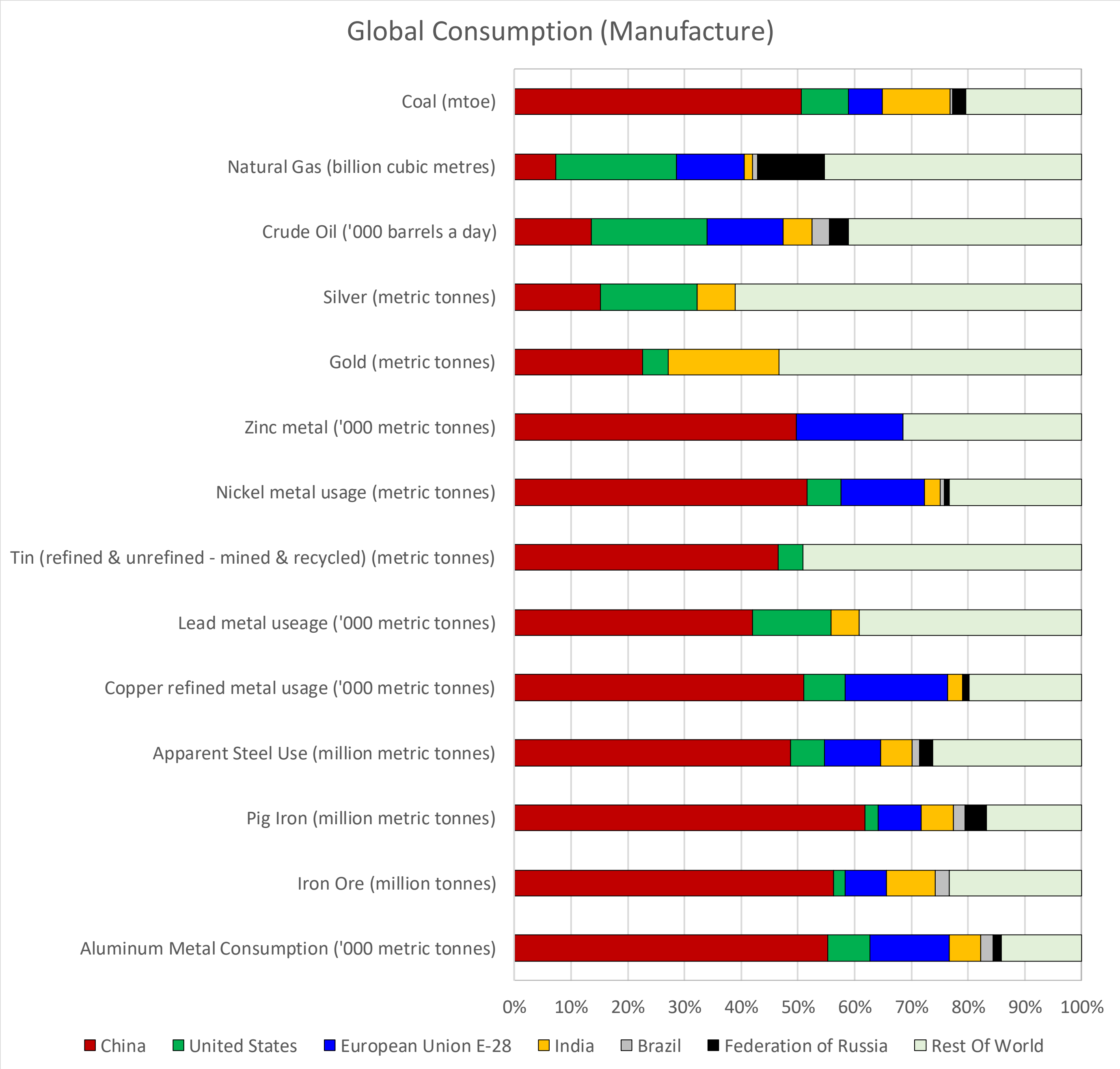

Figure H36. Chinese global market footprint of metal consumption in 2018
(Source: Data taken from World Coal association, World Gold Council, World Silver Council, BP Statistical Review of World Energy 2019, International Zinc Association, The Nickel Institute, International Tin Association, International Lead Association, International Wrought Copper Council, World Steel Association, Australian Aluminium Council, USGS)

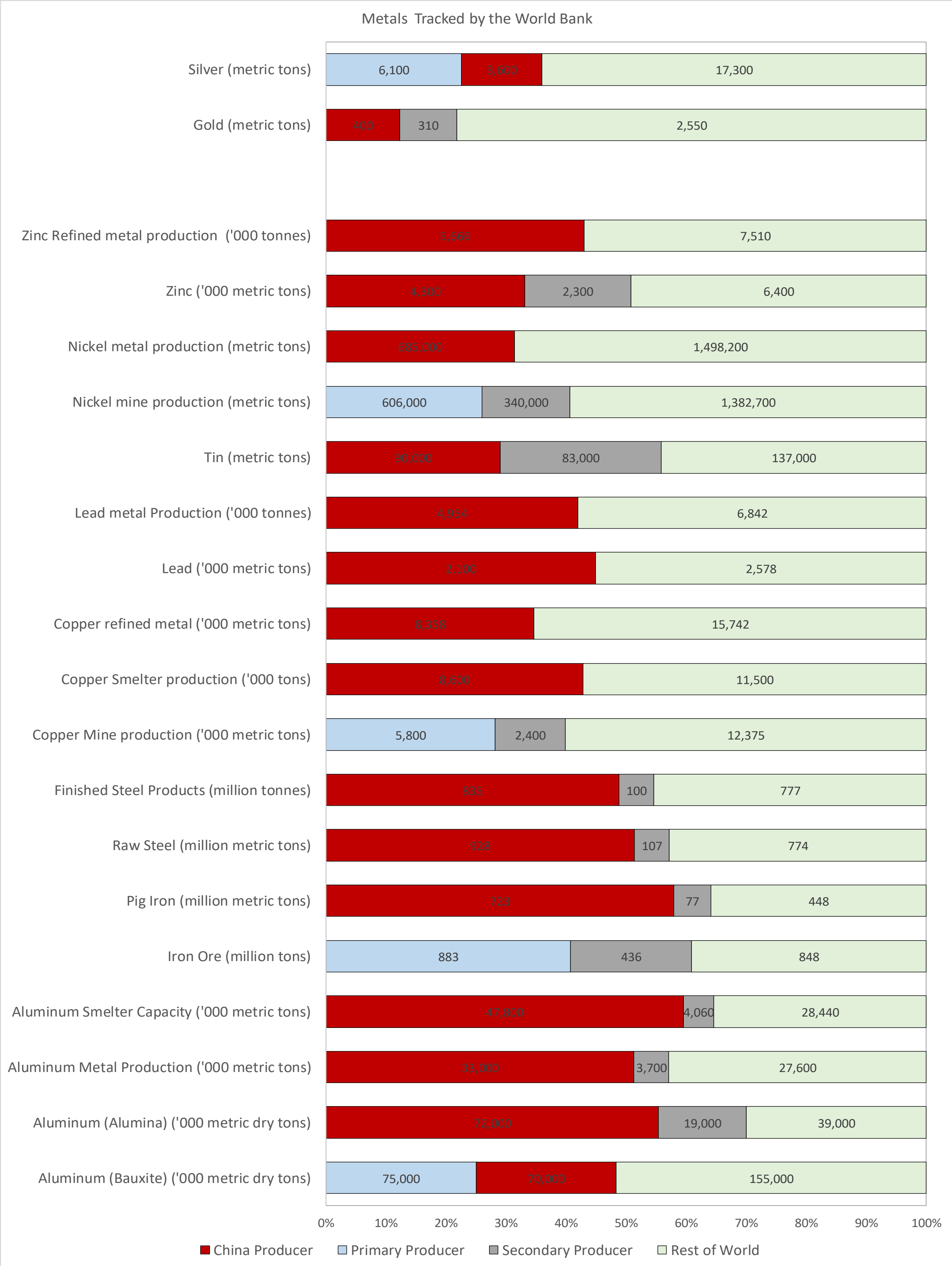

Figure H37. Global consumption of metals tracked by the World Bank in 2018
(Source: same data sources as Figure H36)

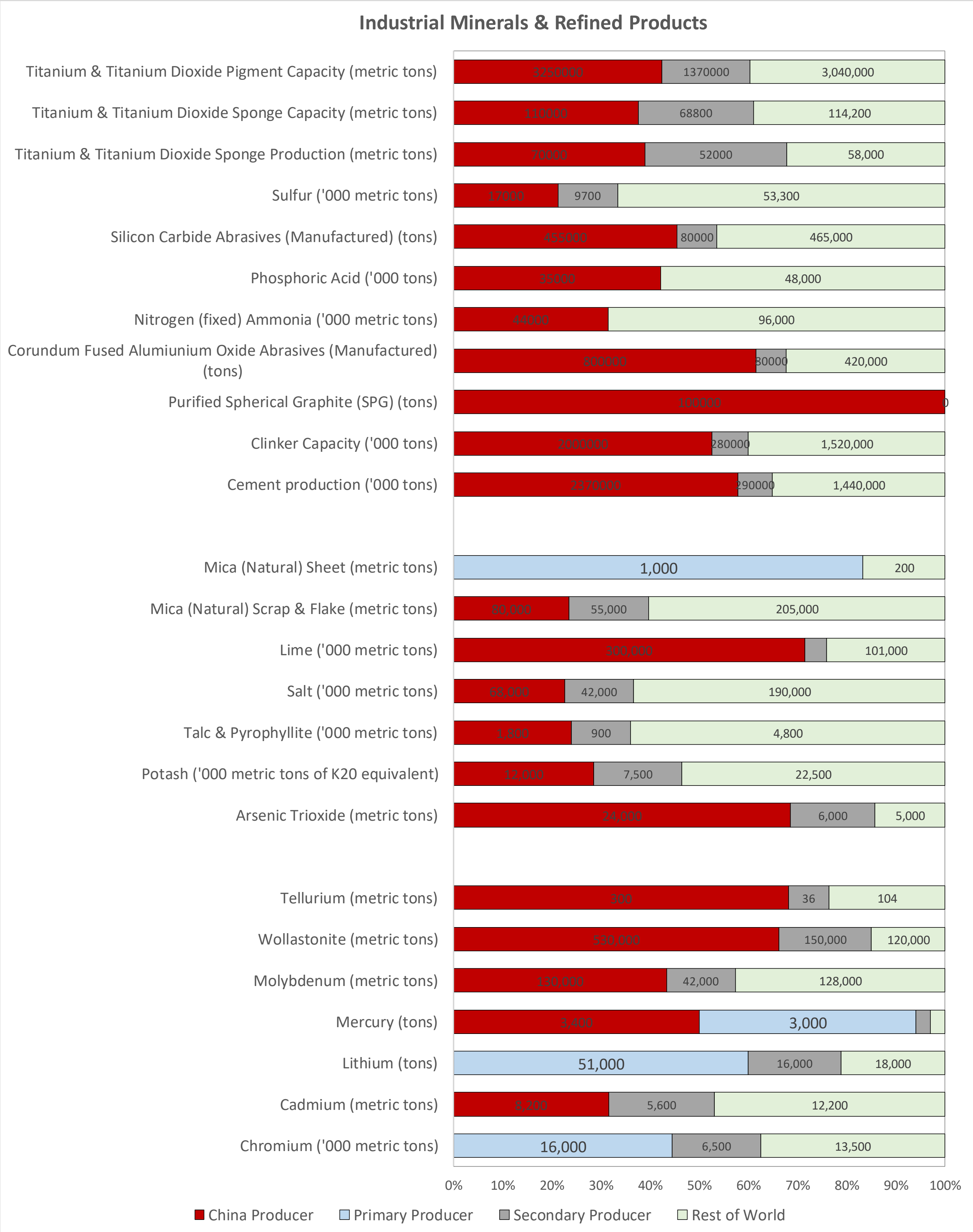

Figure H38. Chinese global footprint in industrial mineral supply in 2018 (Source: USGS data)

24. APPENDIX I: QUANTITY OF MINERALS NEEDED TO PHASE OUT FOSSIL FUELS GLOBALLY

This appendix shows summary outcomes of a 2 part GTK study that is currently in peer review.

24.1 Scope of the replacement system to globally phase out fossil fuels

Abstract

The task to phase out fossil fuels is now at hand. Most studies and publications to date focus on why fossil fuels should be phased out. This study presents the physical requirements in terms of required non-fossil fuel industrial capacity, to completely phase out fossil fuels, and maintain the existing industrial ecosystem. The existing industrial ecosystem dependency on fossil fuels was mapped by fuel (oil, gas, and coal) and by industrial application. Data were collected globally for fossil fuel consumption, physical activity, and industrial actions for the year 2018.

The number of vehicles in the global transport fleet was collected by class (passenger cars, buses, commercial vans, HCV Class 8 heavy trucks, delivery trucks, etc.). The rail transport network, the international maritime shipping fleet, and the aviation transport fleet was mapped, in terms of activity and vehicle class. For each type of vehicle class, the distance travelled was estimated. Non-fossil fuel technology units that are commercially available on the market were used as examples for how to substitute fossil fuel supported technology. For each vehicle class, a representative commercially available example was selected, for Electrical Vehicle and Hydrogen fuel cell systems. Biofuels and ammonia ICE was also considered. The requirements to substitute the ICE rail network and the maritime fleet with EV and hydrogen fuel cell systems were presented. It was assumed that the performance specifications of each selected example were representative for that vehicle class. The quantity of electrical energy required to charge the batteries of a complete EV system was estimated. The quantity of electrical energy to manufacture the required hydrogen for a complete H2 Cell system was also estimated. An examination and comparison between EV and H2 Cell systems was conducted. Other fossil fuel industrial tasks like electrical energy generation, building and construction, heating with gas, and steel manufacture with coal were mapped and requirements for non-fossil fuel substitution were estimated. The estimated sum total of extra annual capacity of non-fossil fuel power generation to phase out fossil fuels completely, and maintain the existing industrial ecosystem, at a global scale is 48 939.8 TWh. This builds upon an existing 9 528.7 TWh of non fossil fuel electrical energy generation annual capacity. If a non-fossil fuel energy mix was used (based on an IEA prediction for 2050, IRENA 2022) was assumed, then this would require an additional 796 210 new non-fossil fuel power plants to be commissioned and constructed. A discussion on the required size of the stationary power storage buffer to manage intermittent energy supply from wind and solar was conducted. Four calculations of the size of the power buffer were done (6 hours, 48 hours, 28 days and 12 weeks). Pumped hydro, hydrogen, biofuels, battery banks and ammonia were all examined as options in this paper.

Keywords: Energy, fossil fuel, oil, gas, coal, nuclear, solar photovoltaic, solar thermal, wind, hydroelectric, transport, vehicle fleet, kilometers driven, Electric Vehicle, battery, hydrogen fuel cell, power generation, ICE, rail, shipping, aviation, pumped hydro, ammonia

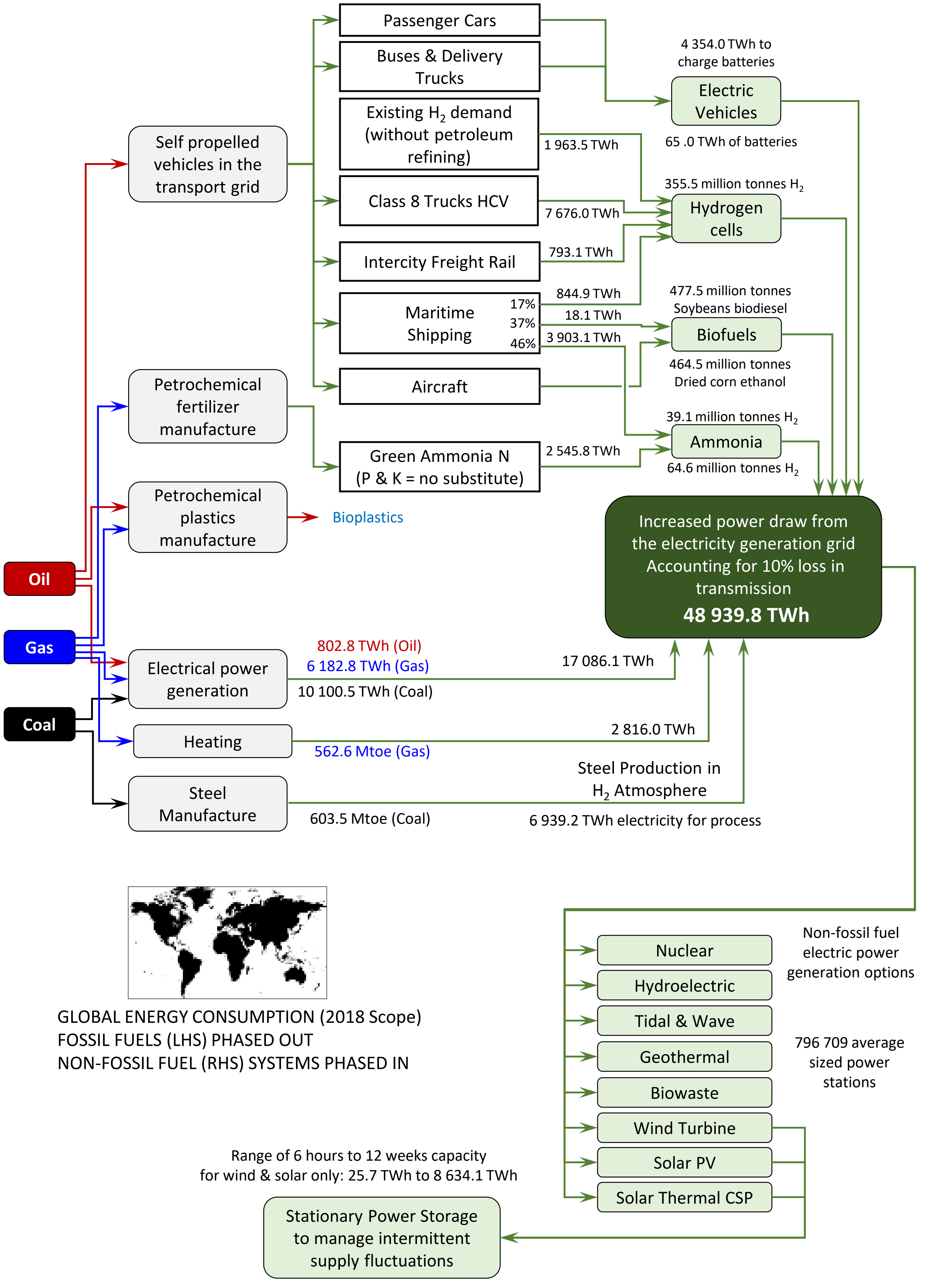

Figure I1. Fossil fuel energy consumption by application and proposed substitution systems

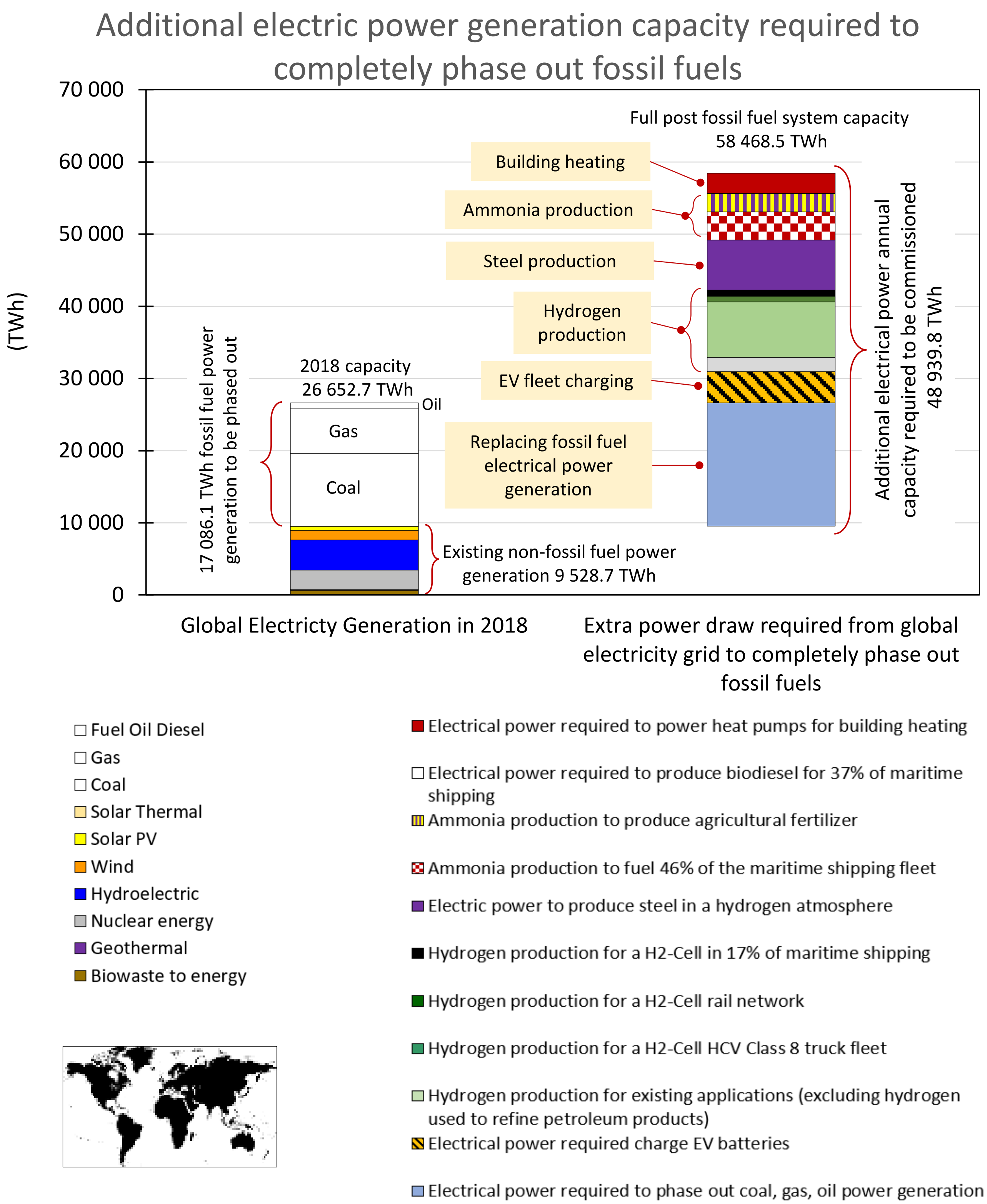

Figure I2. The estimated additional electrical power required globally to phase out fossil fuels

24.2 Quantity of metals required to manufacture one generation of renewable technology units to phase out fossil fuels

Abstract

An estimate is presented for the total quantity of raw materials required to manufacture a single generation of renewable technology units (solar panels, wind turbines, etc.) sufficient to replace energy technologies based on combustion of fossil fuels. This estimate was derived by assembling the number of units needed against the estimated metal content for individual battery chemistries, wind turbines, solar panels, and electric vehicles. It was shown that both 2019 global mine production, 2022 global reserve estimates, 2022 mineral resources, and estimates of undersea resources, were manifestly inadequate for meeting projected demand for copper, lithium, nickel, cobalt, graphite, and vanadium. Comprehensive analysis of these data suggests that lithium-ion battery chemistry (on its own) is not a viable option for upscaling to meet anticipated global market demand. Consequently, the development of alternative battery chemistries is recommended. The calculated shortfall in copper and nickel production was also of concern, as both metals are vital to the existing economy and there is no known viable substitute or alternative for either commodity.

Keywords

metals, renewables, production, reserves, resources, undersea resources, batteries, wind, solar

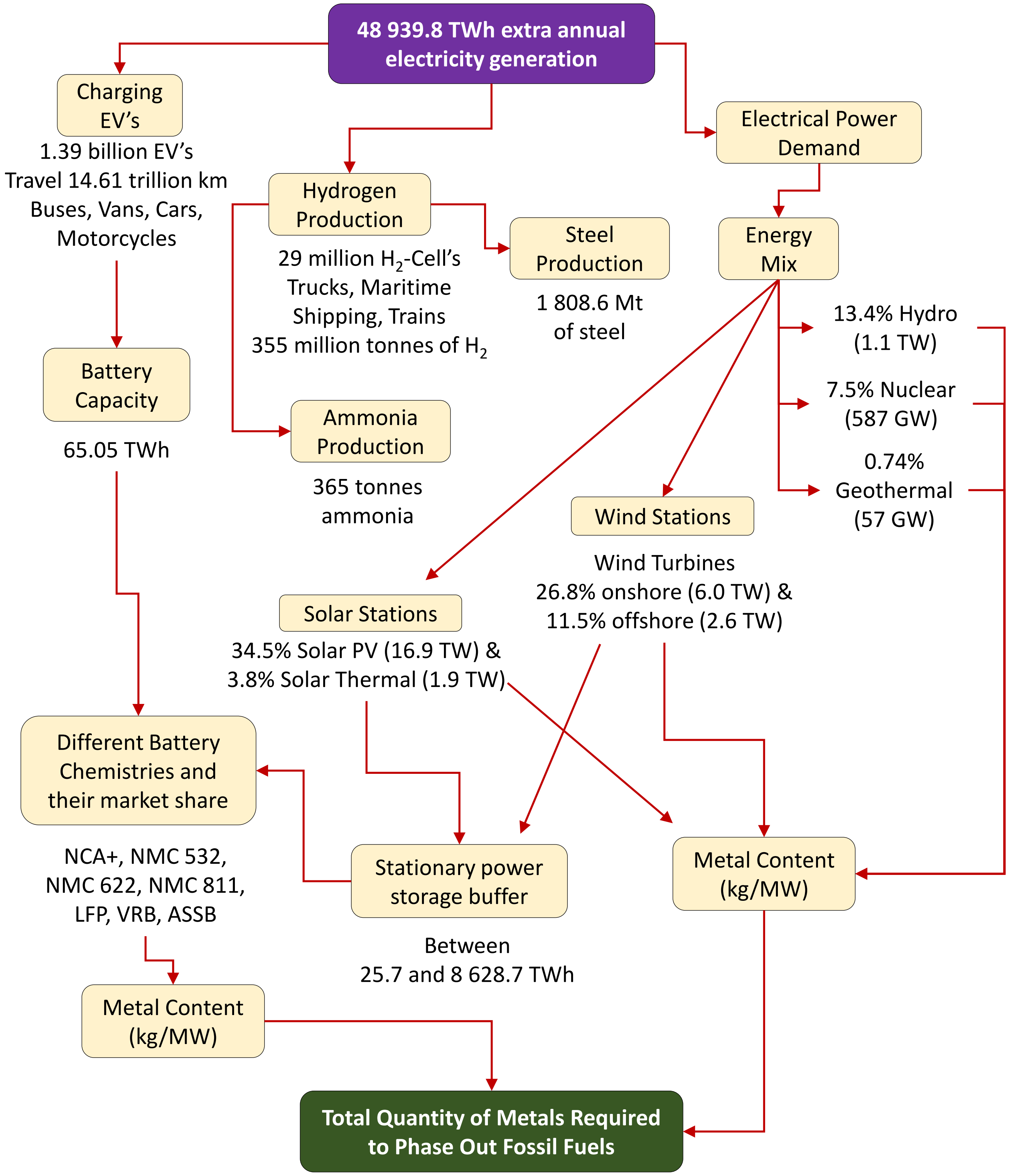

Figure I3. Quantity of metal required to phase out fossil fuels calculation flowchart for this study

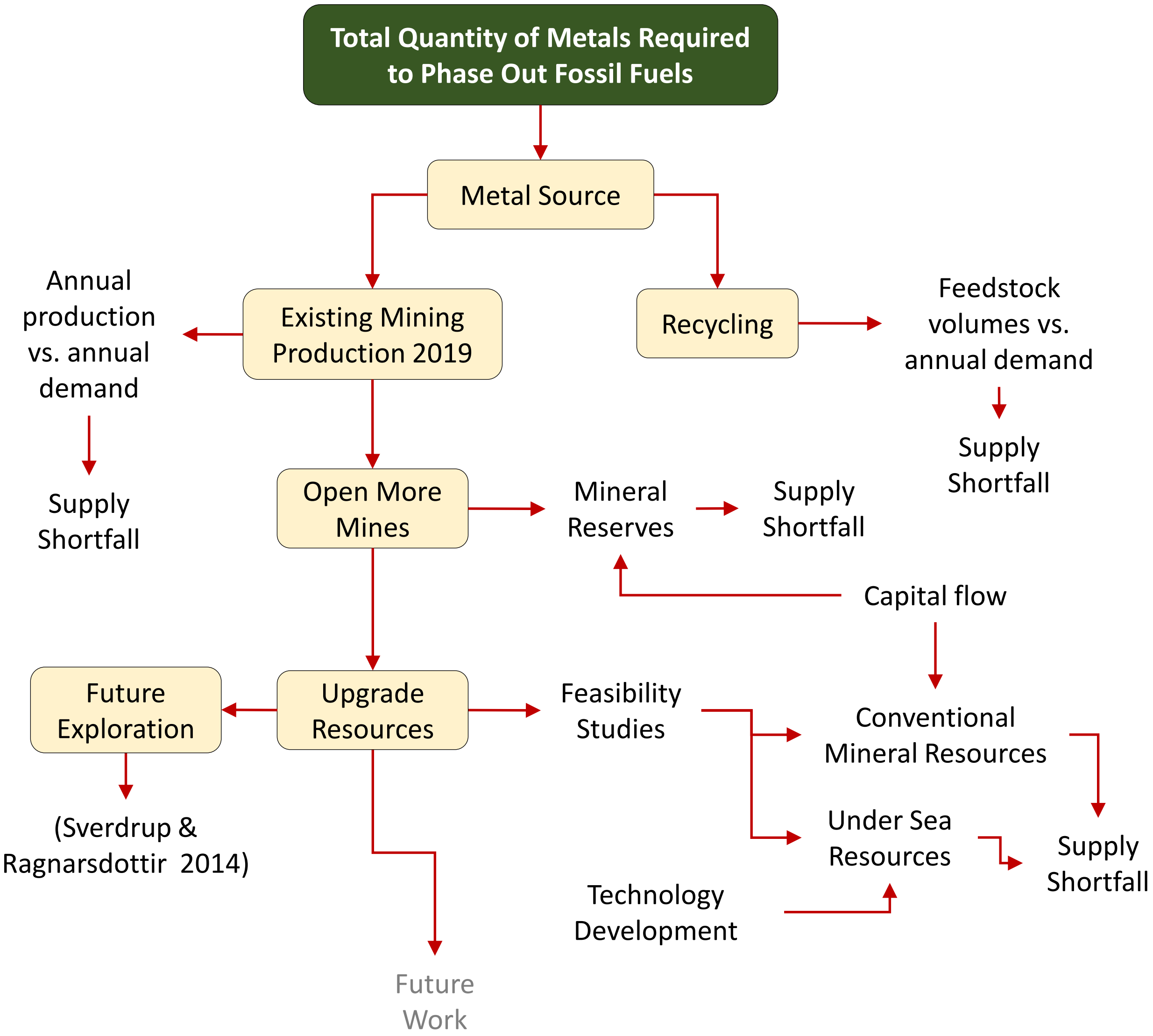

Figure I4. Metal supply from mineral reserves and resources calculation flowchart for this study

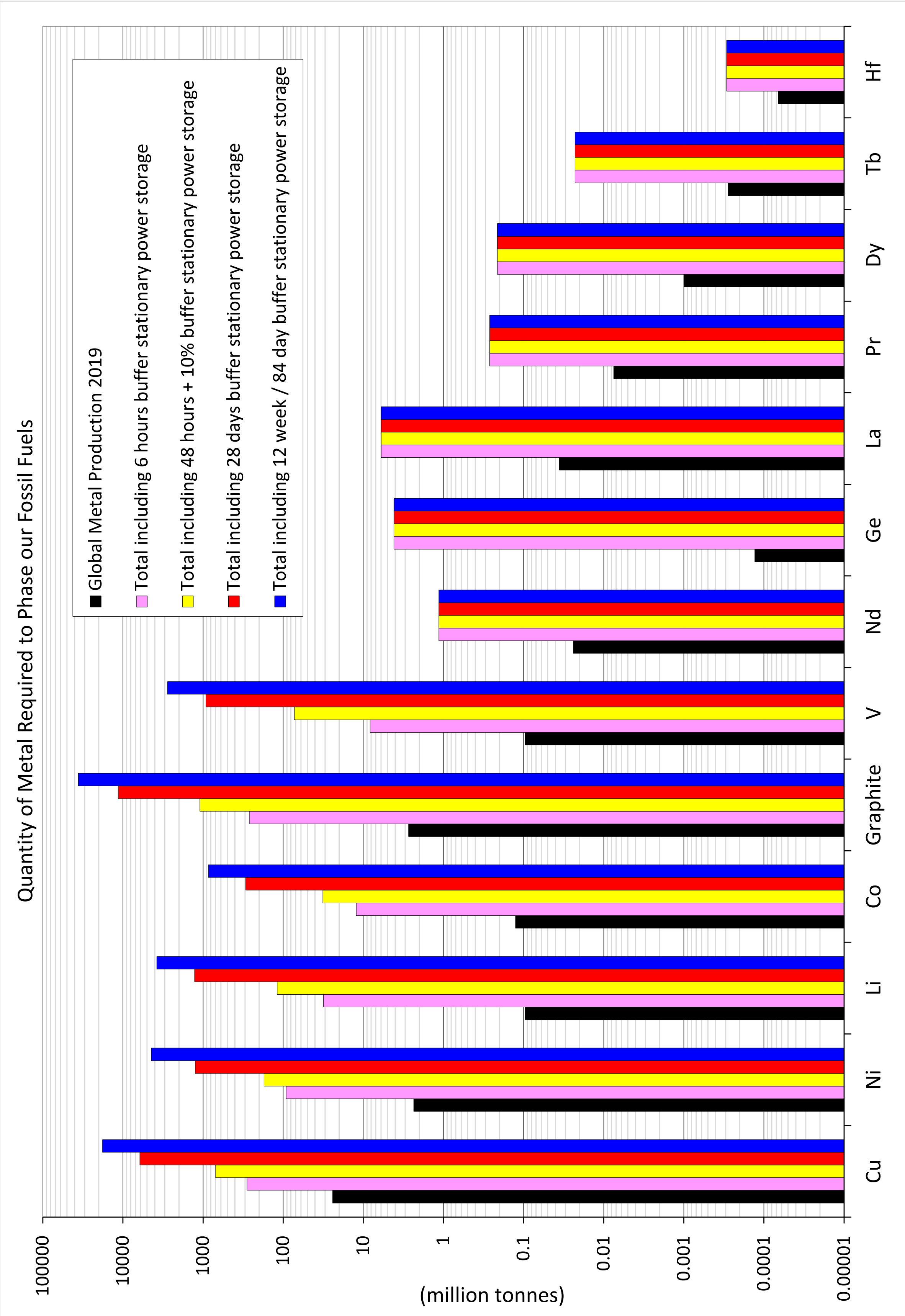

Figure I5. Metal required to phase out fossil fuels compared to global mining production in 2019, split into the four power storage buffer capacities (USGS Mineral Statistics)

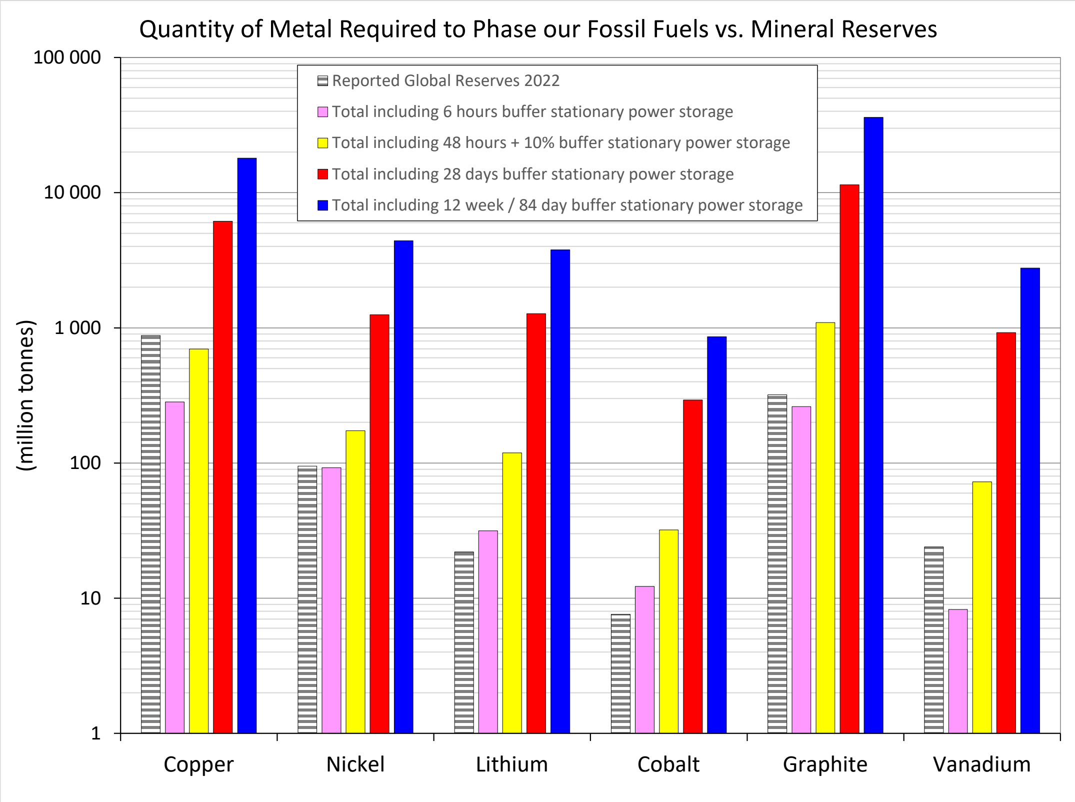

Figure I6. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves, using four different power buffer storage capacities (USGS Mineral Statistics)

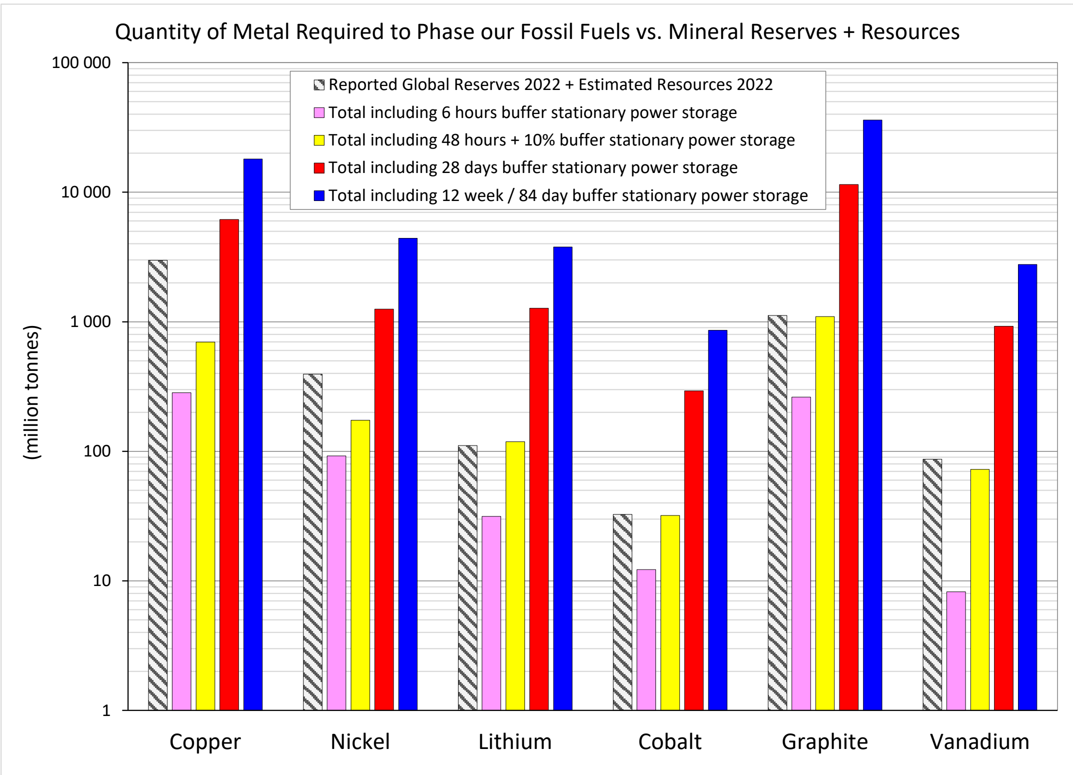

Figure I7. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves + estimated mineral resources, using four different power buffer storage capacities (USGS Mineral Statistics)

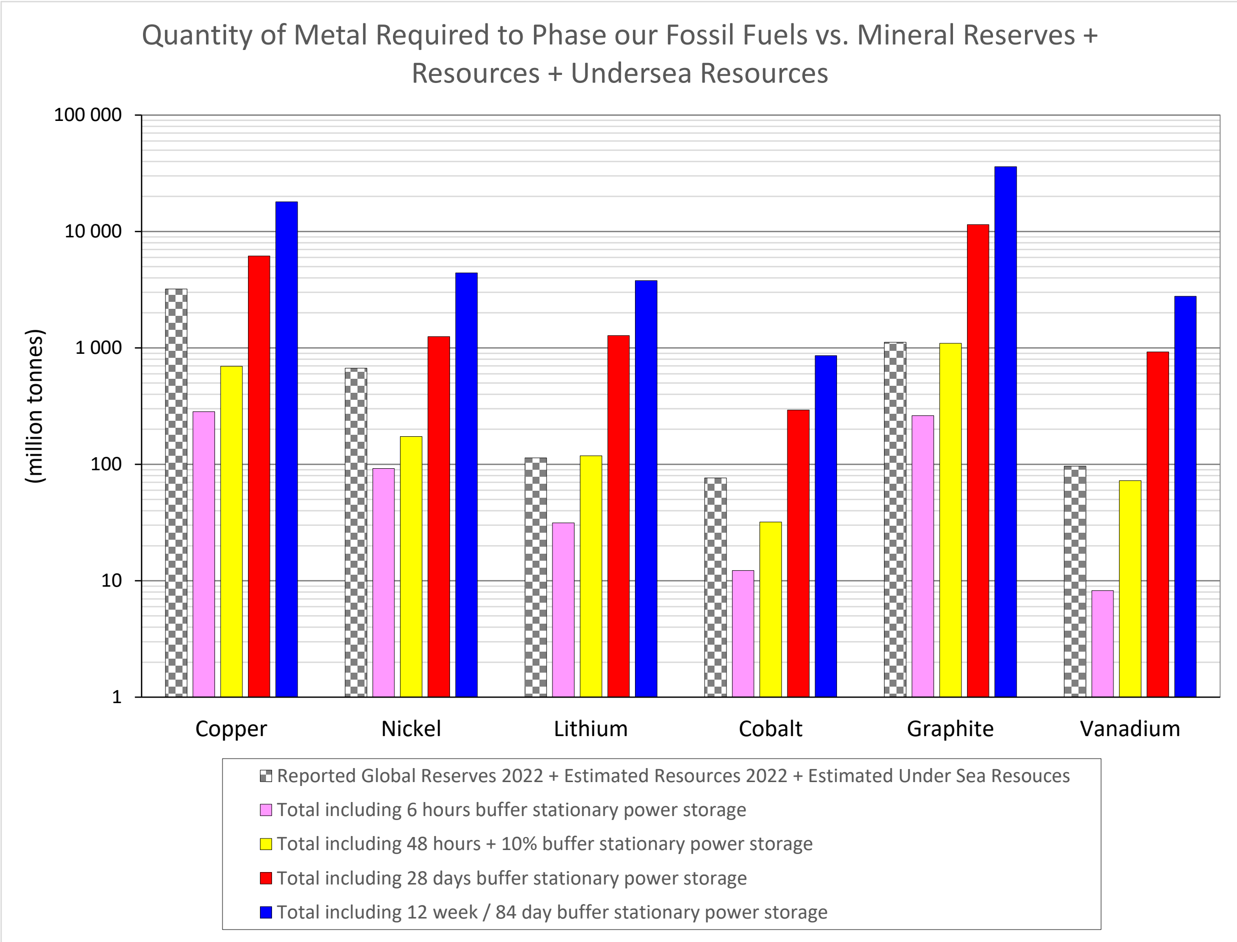

Figure I8. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves + estimated mineral resources + undersea mineral resources, using four different power buffer storage capacities (USGS Mineral Statistics, Hein *et al.* 2020)

This paper presents data presents data showing that the existing paradigm and strategic plan to phase out fossil fuels will not be practical for 8 billion people. It faces far too many macroscale challenges and logistical bottle necks in metal supply to be feasible. In conjunction with the eventuality of peak oil and/or the increasing deterioration in the effectiveness of crude oil as an energy source (Michaux 2019), could produce circumstances that will transform the global industrial system in an unplanned manner. The Green Transition will need to be reevaluated and requires the development of a new plan. This plan will have to deliver a new system of resource management that merges minerals, metals, and materials across the value chain with energy, and would honor industrial thermodynamic boundary conditions (Michaux 2021c). Figure I9 shows a possible path of development for future work to be considered.

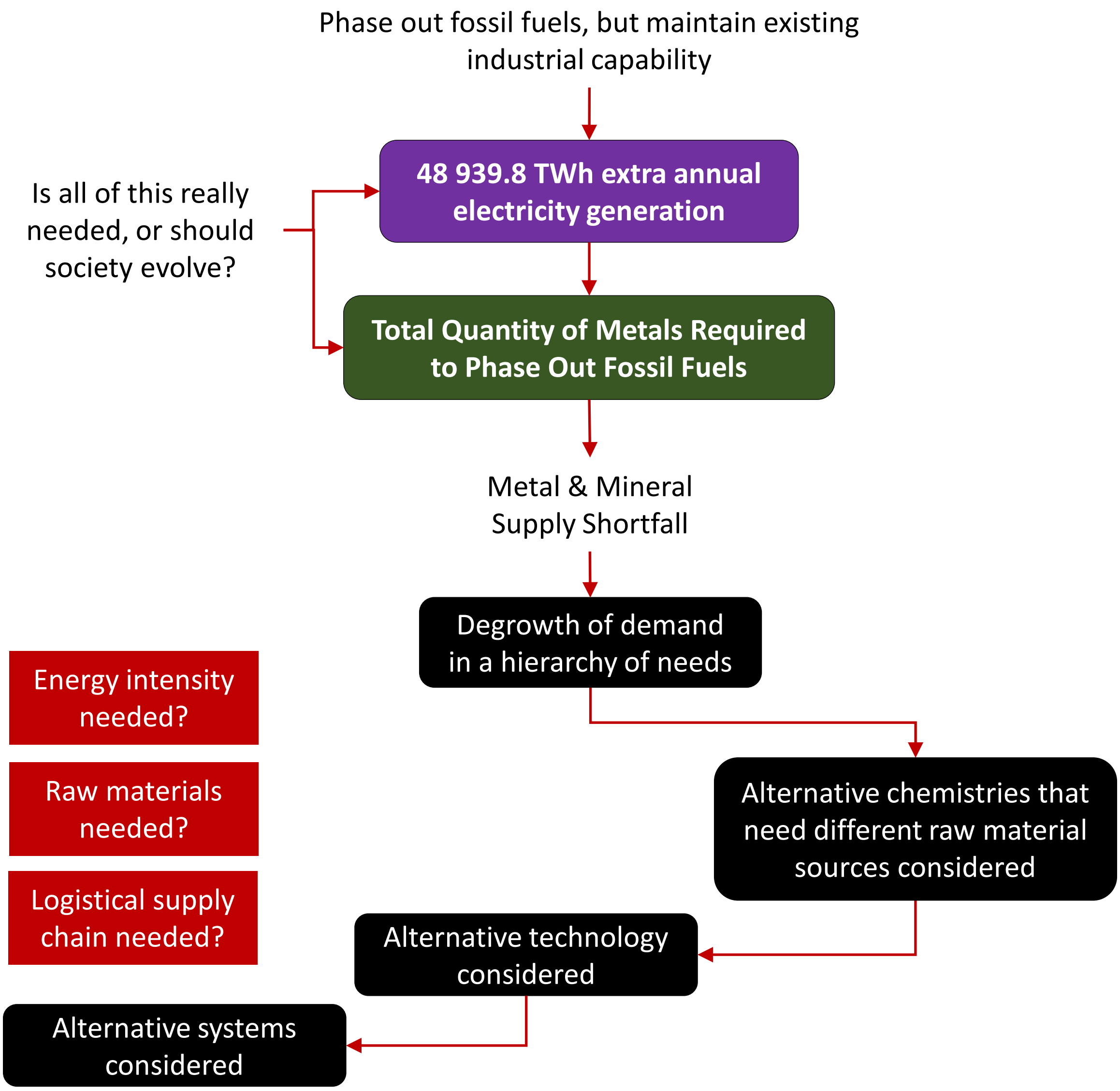

Figure I9. A possible path of development for future work in context of the outcomes of this study