Topic: What Would It Take to Completely Replace Fossil Fuels

Description: Discuss the tremendous challenge of replacing fossil fuels used for ICE and electrical power generation, primarily based on an assessment authored by Simon Michaux, Geological Survey of Finland

for

AAII Houston Retirement SIG

December 15, 2022

About me

Graduated from Texas A&M University in 1982 and started my career at Exxon Production Research Co.

Took early retirement from ExxonMobil 10 yrs ago

Spend a lot of time studying the global macro picture with a strong focus on energy and metals commodities

Very diversified investments – but heavy concentration in mining stocks (mostly small explorers and developers)

Mal’s Houston Rebels Investment Club leader for about 7 yrs

The largely unrecognized challenge of the energy transition has been a topic I've spoken about for over 10 years

Simon Michaux has taken on a huge undertaking to try to quantify the issue.

Reviewing his assessment, I discovered that the situation is much worse than I ever imagined

Simon began working on this issue about 14 years ago after sitting through various high-level presentations about making a rapid transition from fossil fuels that contained no actual details about how it could be done.

He started looking into it and discovered no one had done any work to actually quantify how much energy would be needed, much less how to make such a transition.

He has had no credible pushback to his findings.

Many implications for our future: investments, economy, lifestyle, and global stability

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Summary

We are highly dependent on fossil fuel for our economy and lives

Sufficient oil production will be a challenge based on recent and planned capital expenditures

What would it take to phase out fossil fuels

How much electrical power will be needed

How much metal do we need to make the transition

Can we do this with recycling

Mining of minerals

Energy is required for everything. Energy is the economy. Without sufficient energy, the economy cannot grow.

We have been fortunate/spoiled by cheap energy and taken it for granted in the developed economies of the world.

All out call for rapid energy transition to carbon zero by 2050 without any understanding of what it would actually take nor the consequences.

Visions full of platitudes but blissfully blind regarding the amount of energy and minerals required. Mining is a far more difficult venture than oil, at least an order of magnitude in the best case.

We need a lot more fossil fuels to make the energy transition happen. Yet there is no cohesive energy policy to support an energy transition. Instead many governments disincentivize fossil fuels through policies, regulations, taxes, and rhetoric. Groups supporting ESG mandates pressure financial institutions and pension funds to deny capital and investment in fossil fuel companies.   Environmental regulations greatly retard and in many cases prevent development of critical minerals.

Underinvestment in exploration for both oil and strategic metals has been ongoing for years even without considering the additional demands of the energy transition. That is going to result in an energy crisis for much of the world and push us even further from the goals of energy transition.

A billion people in the world have no electricity and another 2-3 billion have very little energy – typically burning dung, wood or other low quality fuels which are both toxic and highly polluting. Higher prices will only make this worse.

Advertised: ESG means **Environmental, Social** and **Governance**

Reality: ESG means **Energy Shortage Guaranteed!**

According to the numbers crunched by Mark Mills – the Co-Director of Northwestern University's Institute on Manufacturing Science and Innovation – In his report titled "Mines, Minerals and Green Energy: A Reality Check", Mills finds that a lithium electric vehicle battery weighs about 1000 pounds.

Such a battery typically contains about 25 pounds of lithium, 30 pounds of cobalt, 60 pounds of nickel, 110 pounds of graphite, 90 pounds of copper, about 400 pounds of steel, aluminum, and various plastic components.

From these figures and average ore grades, one can estimate the typical quantity of rock that must be extracted from the earth and processed to yield the pure minerals required to produce an electric vehicle battery.

Lithium brines typically contain less than 0.1 percent lithium, meaning some 25,000 pounds of brines to get the 25 pounds of pure lithium. Similarly, cobalt ore grades average about 0.1 percent, nearly 30,000 pounds of ore per battery. Nickel ore grades average about 1 percent, thus about 6000 pounds of ore per battery. Graphite ore is typically 10 percent, thus about 1,000 pounds per battery. Copper at about 0.6 percent in the ore, thus about 25,000 pounds of ore per battery.

In total then, acquiring just these five elements to produce the 1000-pound EV battery requires mining about 90,000 pounds (over 40 tonnes) of ore.

When accounting for all the earth moved (i.e. the materials first dug up to get to the ore), one battery requires digging and moving between **200,000 and 1,500,000 pounds (or between 90 and 680 tonnes) of earth per battery**.

Note these figures don't include the vast quantity of materials and chemicals used to process and refine all the various ores.

They don't count other materials used when compared with a conventional car, such as replacing steel with aluminum to offset the weight penalty of the battery.

Also excluded is the non-battery, electrical systems used in an electric vehicle. These add substantially to the environmental footprint as they use 300 percent more overall copper compared to a conventional vehicle.

ASSESSMENT OF THE EXTRA CAPACITY REQUIRED OF ALTERNATIVE ENERGY ELECTRICAL POWER SYSTEMS TO COMPLETELY REPLACE FOSSIL FUELS

Simon P. Michaux

19/08/2022

Associate Professor Mineral Processing & Geometallurgy

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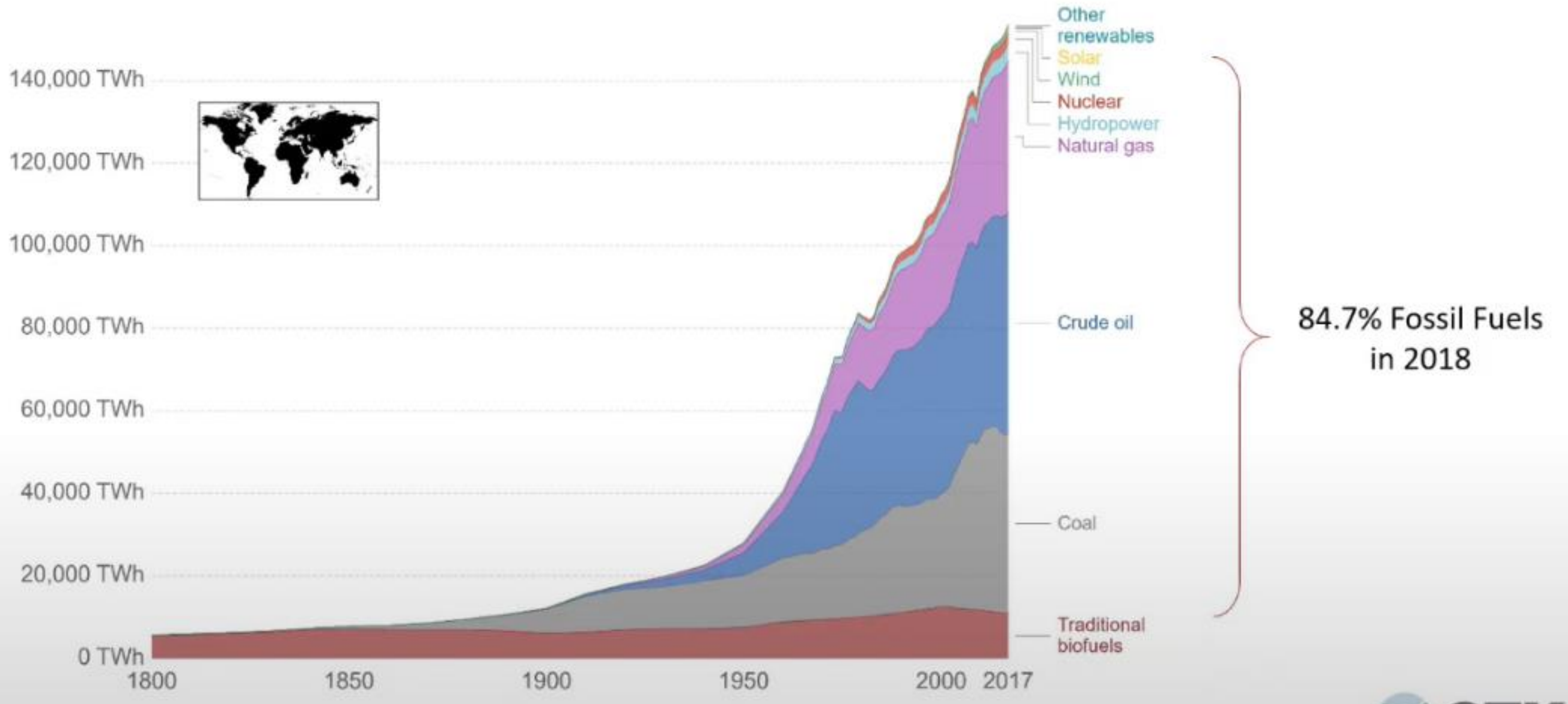
GLOBAL PRIMARY ENERGY CONSUMPTION. UNITS MEASURED IN TERAWATT-HOURS (TWH) PER YEAR



(Source: Our World in Data, BP Statistical review of World Energy 2019)

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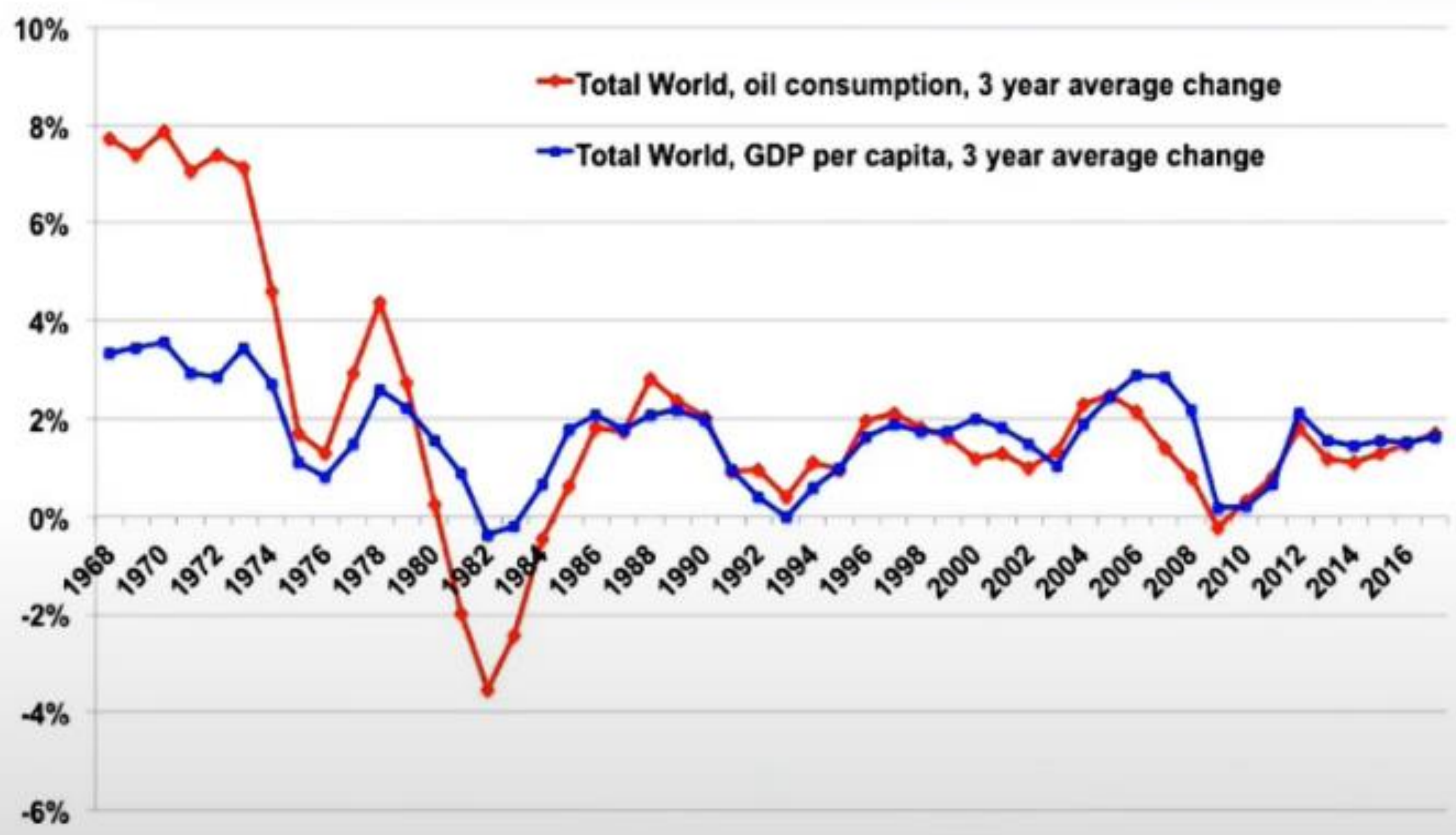
CORRELATION BETWEEN THE ANNUAL RELATIVE CHANGE IN WORLD OIL CONSUMPTION AND GDP PER CAPITA AVERAGED OVER THREE YEARS



(Source: Data from BP Statistical Review 2018, World Bank)

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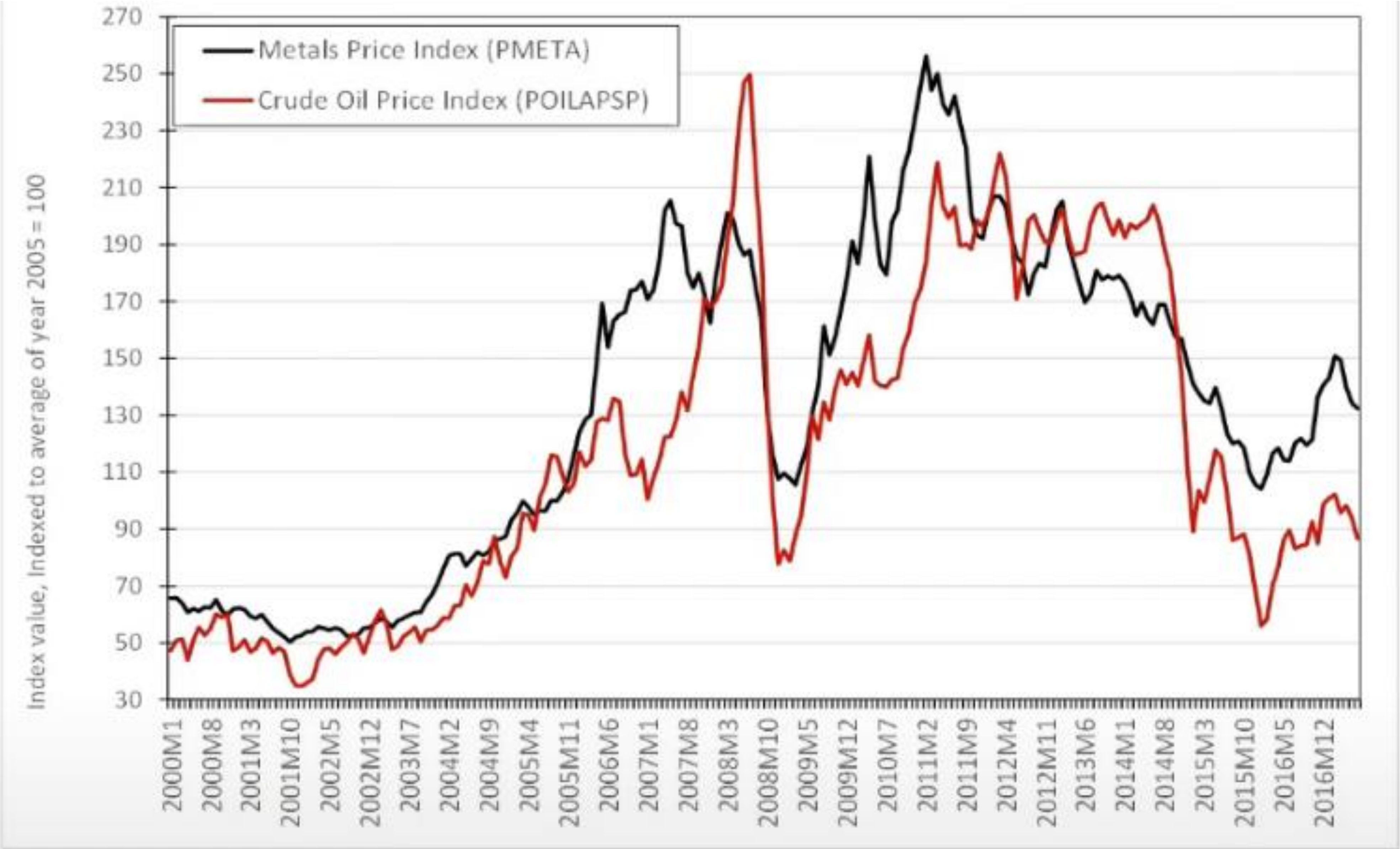
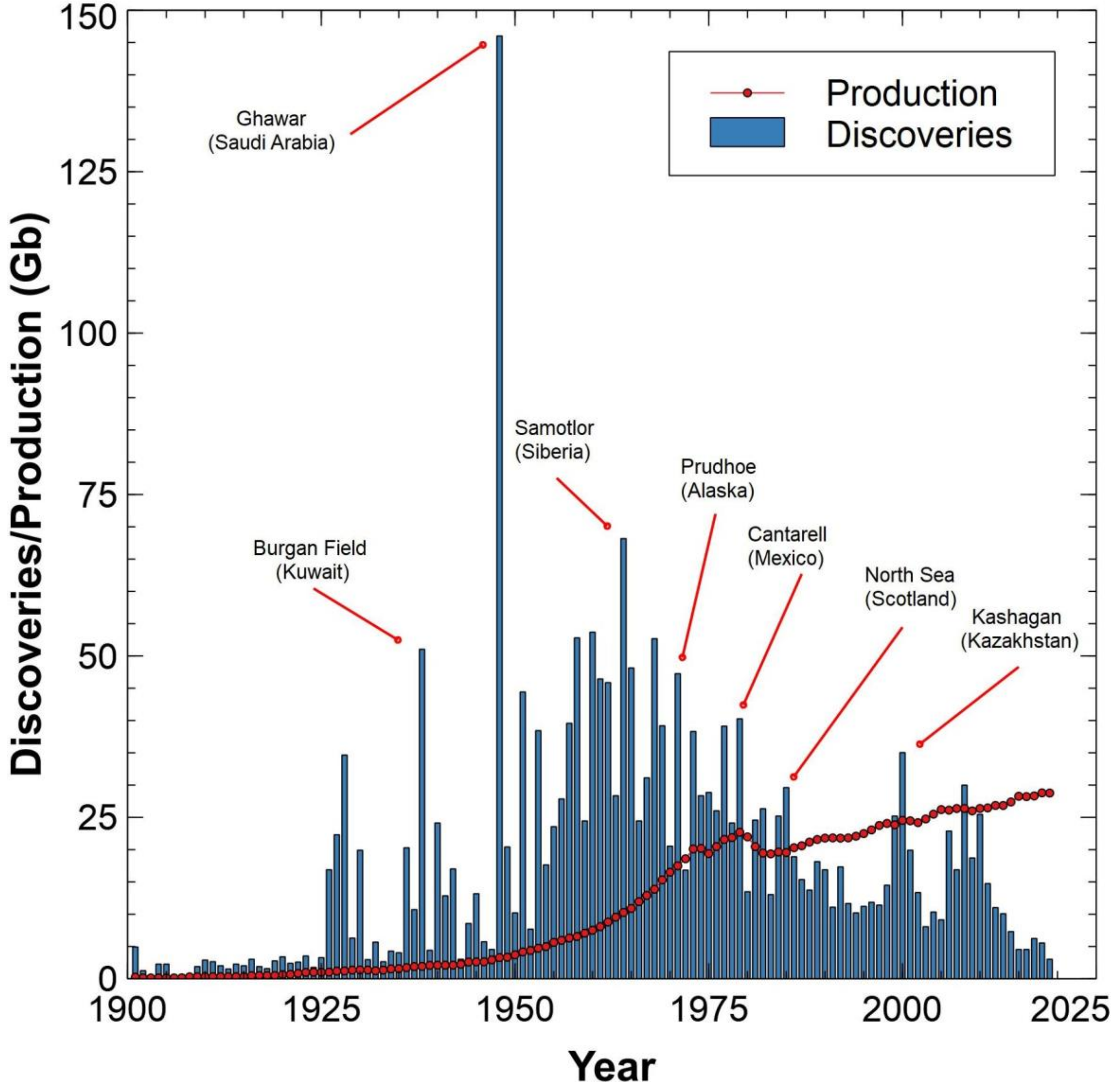
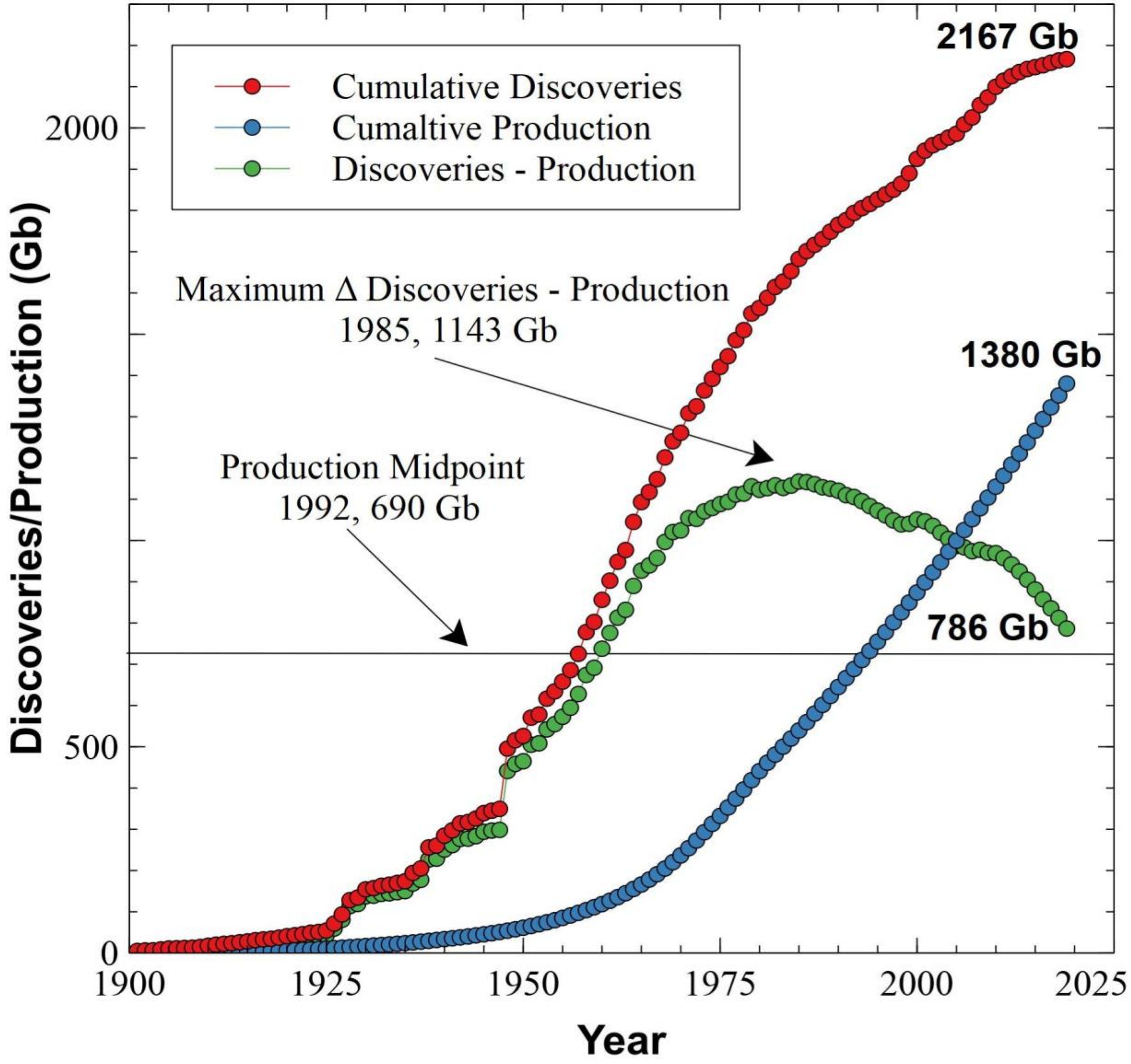


Figure 45. Correlation between global metal price and crude oil

(Source: IMF Primary Commodity Price System, http://www.imf.org/external/np/res/commod/External_Data.xls)

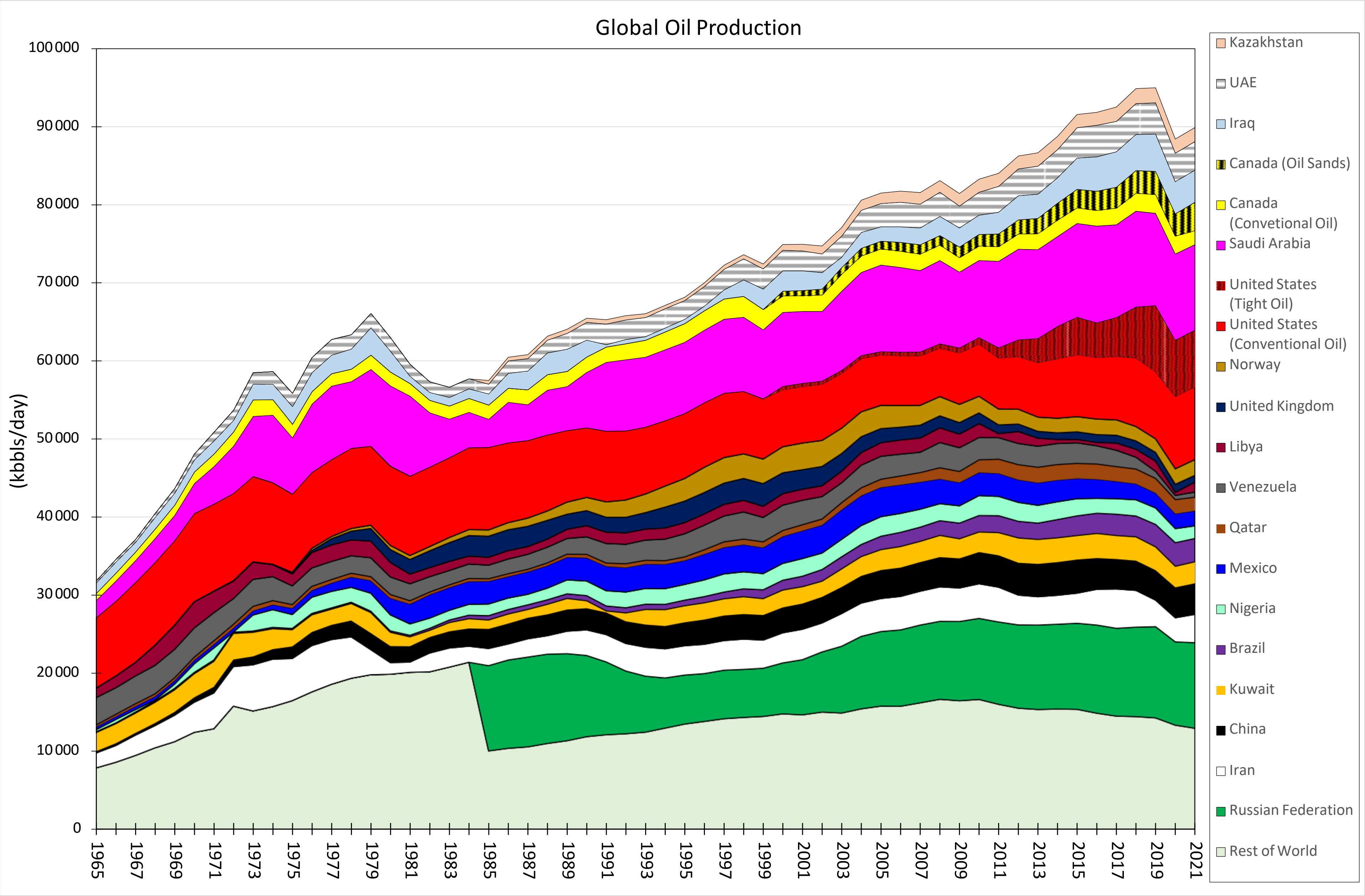




81% of existing producing fields are in decline at an average rate of 5-7% p.a. (HSBC 2016)

Of the largest 10 modern producing fields, the youngest was discovered in 1976 (Hirsch 2011)

(Source: John Peach, data from Laherrere et al 2022, Court & Fizaine 2017, BP Energy Statistics)



(Source: BP Statistical World Energy Review 2022, 2015, 2014, 2012, 2011, shaleoilprofile.com , Canadian Association of Petroleum Producers 2022)

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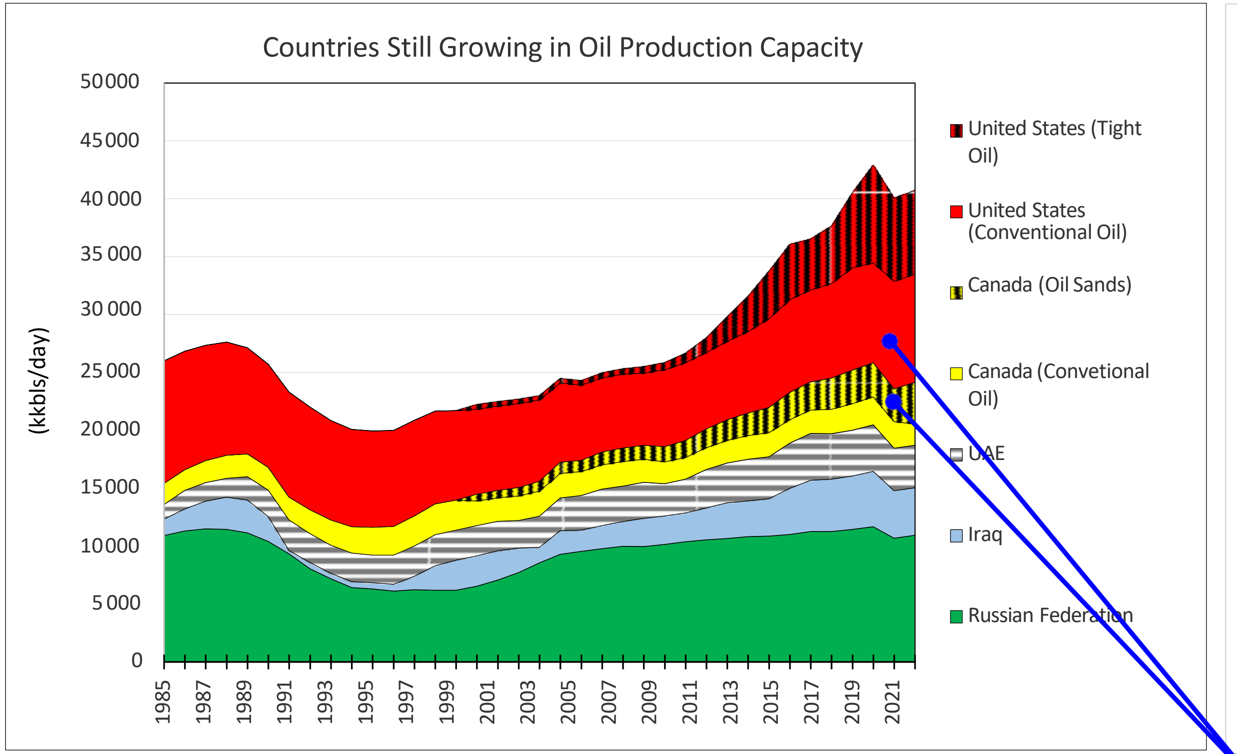
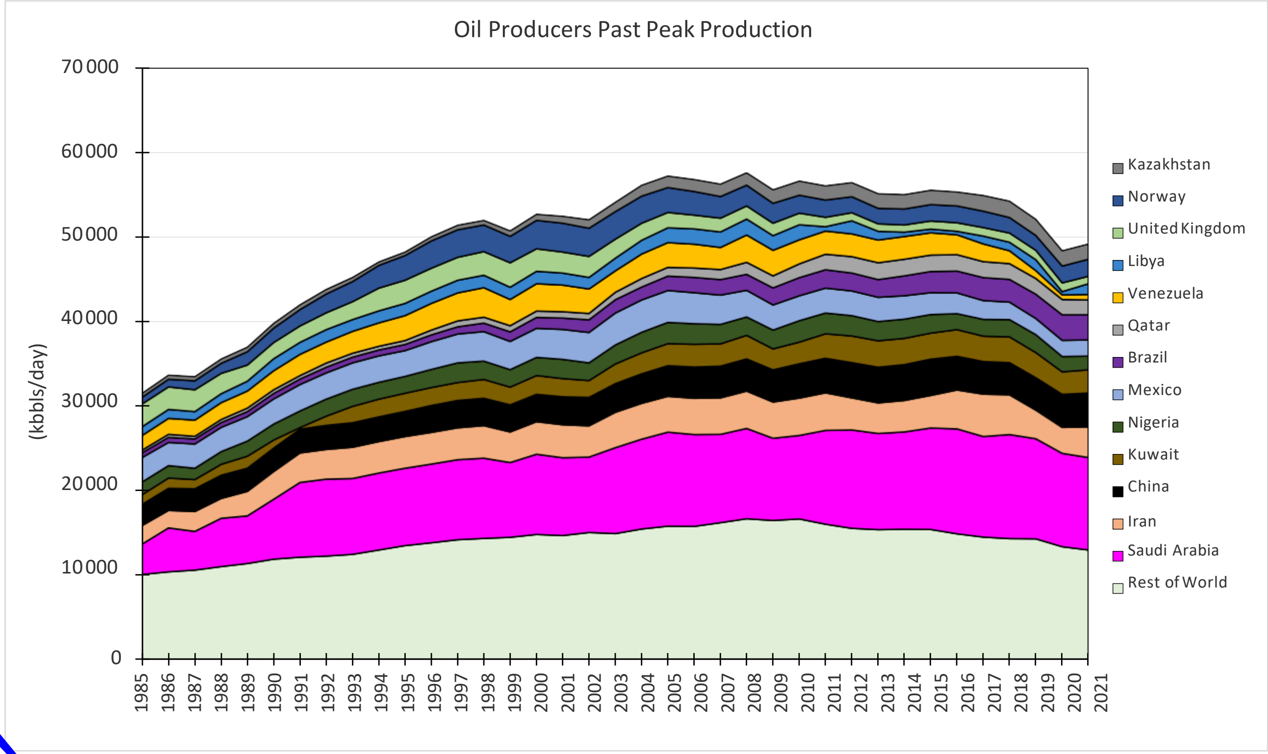
ONLY 5 COUNTRIES ARE STILL INCREASING OIL PRODUCTION

If United States and Iraq were excluded, global oil production peaked in 2016





Only United States conventional oil, and Canadian oil sands were expanding production in 2021. All other producers peaked in 2019. This could be a Covid 19 artefact

(Source: BP Statistical World Energy Review 2022)

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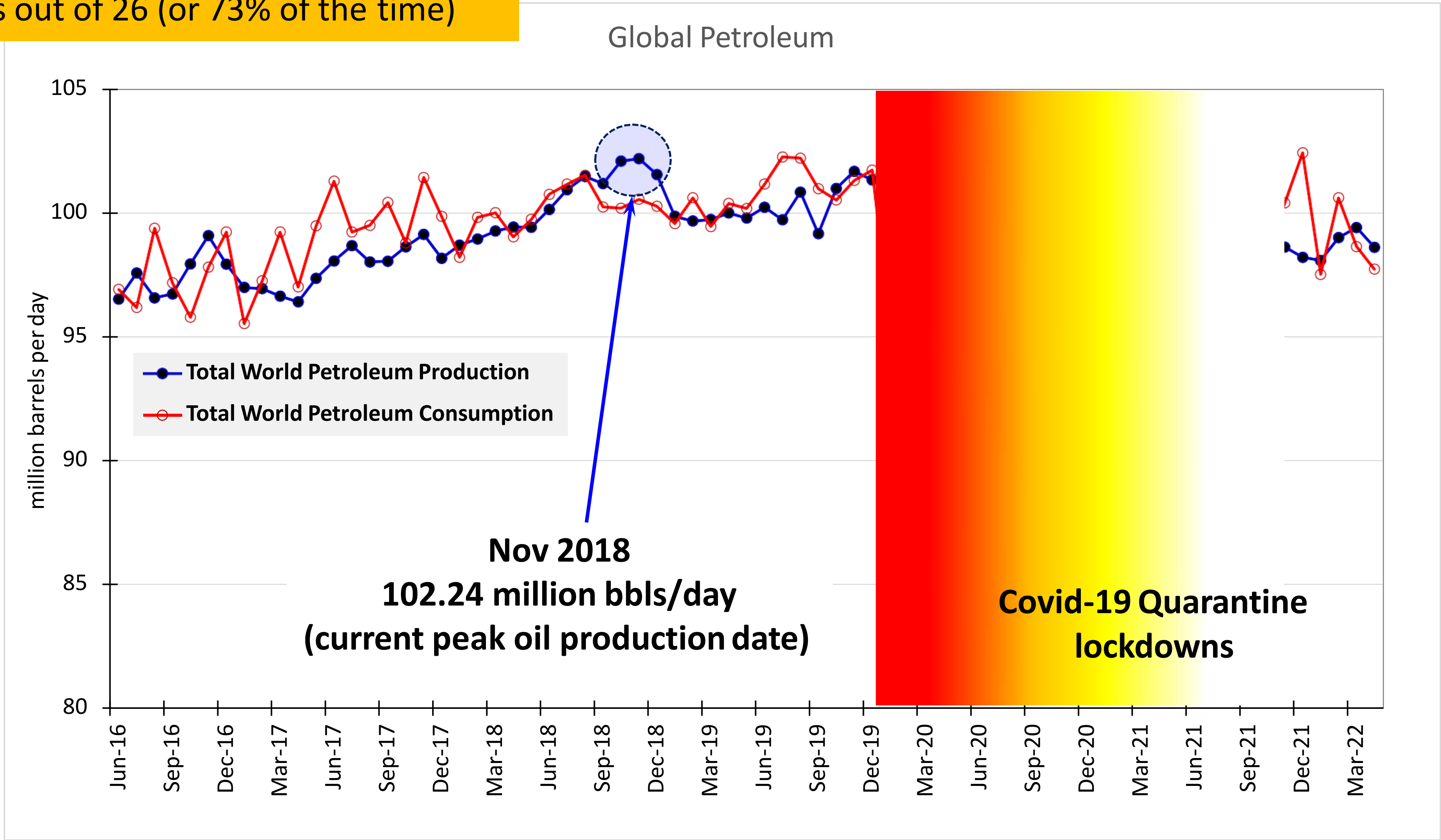
Since March 2020, demand exceeded supply 19 months out of 26 (or 73% of the time)



(Source: U.S. Energy Information Administration, Short-Term Energy Outlook, July 2022)

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SUMMARY

Physical Tasks done industrially by fossil fuels

↓

Determine the true scope of useful work done

↓

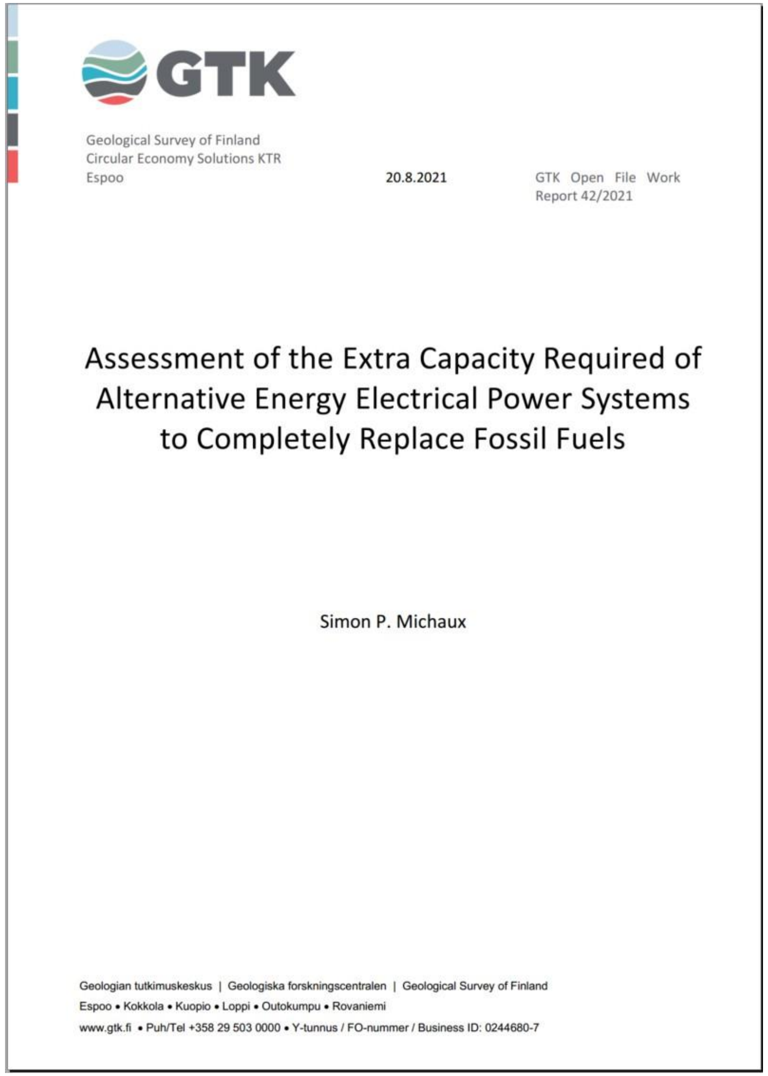
Assemble non-fossil fuel systems that could do the same useful work

↓

Calculate the quantity of electrical power needed

↓

Using same energy mix as 2018, determine how many new non-fossil fuel power stations are needed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20.8.2021

GTK Open File Work Report 42/2021

Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Simon P. Michaux

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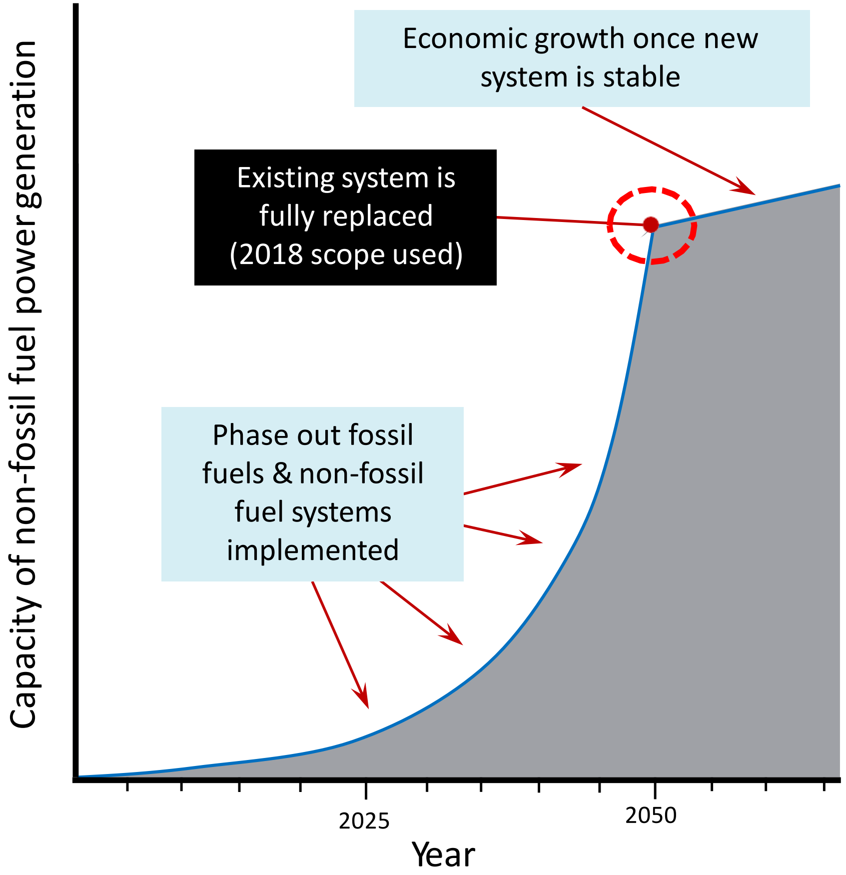
Link to full report below
https://tupa.gtk.fi/raportti/arkisto/42_2021.pdf

Link to 8 page summary
https://mcusercontent.com/72459de8ffe7657f347608c49/files/be87ecb0-46b0-9c31-886a-6202ba5a9b63/Assessment_to_phase_out_fossil_fuels_Summary.pdf

- Number of vehicles, by class
- Number and size of batteries
- An understanding of the EV to H_2-Cell split
- Estimates of EV & H_2-Cell rail transport
- Estimates of an EV & H_2-Cell maritime shipping fleet
- Estimates of phasing out of fossil fuel industrial applications
- Examination of the feasibility of expanding the nuclear NPP fleet
- Assessment of the feasibility of global scale biofuels
- Plastics & fertilizer industries

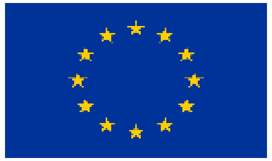
WHAT WOULD IT TAKE TO REPLACE THE EXISTING FOSSIL FUEL SYSTEM?



- What does fossil fuels do for us now?
- How much extra electrical power capacity is required to phase out fossil fuels completely?
- How many cars, trucks, ships, trains & aeroplanes are there?
- How many new power stations will be needed?
- How many batteries will be needed?
- How many solar panels will be needed?
- How many wind generator turbines will be needed?
- **What quantity of minerals will be needed to do this?**

CALCULATION ARC

- What is the true scope of tasks to fully phase out fossil fuels, and the complete replacement with non-fossil fuel powered systems?
- Existing ICE transport fleet size
  - *Cars & Trucks*
  - *Rail*
  - *Maritime shipping*
  - *Aviation*

- What is the number and size of required batteries/hydrogen cells/solar panels/wind turbines
  - *In what proportional mix?*
  - *In 2018, 84.5% of global primary energy consumption was fossil fuel based*
- Required power grid expansion to charge the needed number of batteries, and make hydrogen
  - *Number of new power stations*
  - *Required power storage to manage intermittent supply*

Current plans are not large enough in scope, the task before us is much larger than the current paradigm allows for

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BASELINE CALCULATION

- The global fleet of vehicles is estimated to be 1.416 billion, which travelled an estimated 15.87 trillion km in the year 2018
  - *0.7% is EV in 2020*

- For the same energy output:
  - *…an Electric Vehicle system requires **battery storage** mass **3.2 times** the fuel tank (@700bar) mass of a hydrogen H-Cell system*
  - *…meanwhile a hydrogen H-Cell system will require **2.5 times** more **electricity** compared to a Electric Vehicle system*

- All short-range transport could be done by Electric Vehicle systems
  - *All passenger cars, commercial vans, delivery trucks and buses (1.39 billion vehicles), would travel 14.25 trillion km in 365 days*
  - *This would require 65.19 TWh of batteries (282.6 million tonnes of Li-Ion batteries)*

- All long-range distance transport could be powered with a hydrogen fuel cells
  - *All Class 8 HCV trucks, the rail transport network (including freight), and the maritime ship fleet*
  - *In total, 200.1 million tonnes of hydrogen would be needed annually*

GLOBAL SYSTEM I

1.39 billion Electric Vehicles	Charging Batteries
695.2 million Passenger Cars 5.4 trillion km	1 128.5 TWh
29 million Buses & Delivery Trucks 803 billion km	1 166.1 TWh
601 million Vans, Light Trucks 7.9 trillion km	2 181.7 TWh
62 million Motorcycles 160 billion km	19.4 billion kWh

→ 4 495.7* TWh

*updates in EV energy efficiency reduced this number by 4% from (Michaux 2021)

Industry	
Electrical Power Generation	17 086.1 TWh
Building Heating	2 816.0 TWh
Steel Manufacture	56.5 TWh

→ 19 958.6 TWh

GLOBAL SYSTEM II

Hydrogen Economy

H_2-Cell Vehicles	Hydrogen		Manufacture of H_2
28.9 million Class 8 HCV Trucks Travelled 1.62 trillion km	129.9 million tonnes	200.1 million tonnes	7 503.7 TWh
Rail Transport 9 407 billion tkm freight 1 720 billion passenger-kilometers	18.5 million tonnes		1 066.5 TWh
Maritime Shipping cargo 72 146 billion tonne-km	51.7 million tonnes		2 983.4TWh

→ 11 553.6 TWh

Biomass Economy

Biomass Sustainably Sourced from the Planetary Environment

Aviation	Biofuel ??? liters
Plastics Manufacture	Biomass Feedstock ??? tonnes

Sustainability audit

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GLOBAL SYSTEM III

EV 4 495.7 TWh

Industry 19 958.6 TWh

H_2 11 553.6 TWh

Additional Annual Electrical Power Requires 36 007.9 TWh

=

586 032 NEW Non-Fossil Fuel Power Stations

Power plant fleet in 2018 was 46 423 stations

Hydro Power
4 809.6 TWh
3 628 stations

Nuclear Power
2 701.4 TWh
211 stations

Wind Power
13 800.4 TWh
169 867 stations

Solar Power
13 800.4 TWh
393 840 stations

Power storage buffer

Other Renewables
Geothermal & Tidal
266.7 TWh
442 stations

Biowaste to Energy
624.0 TWh
18 044 stations

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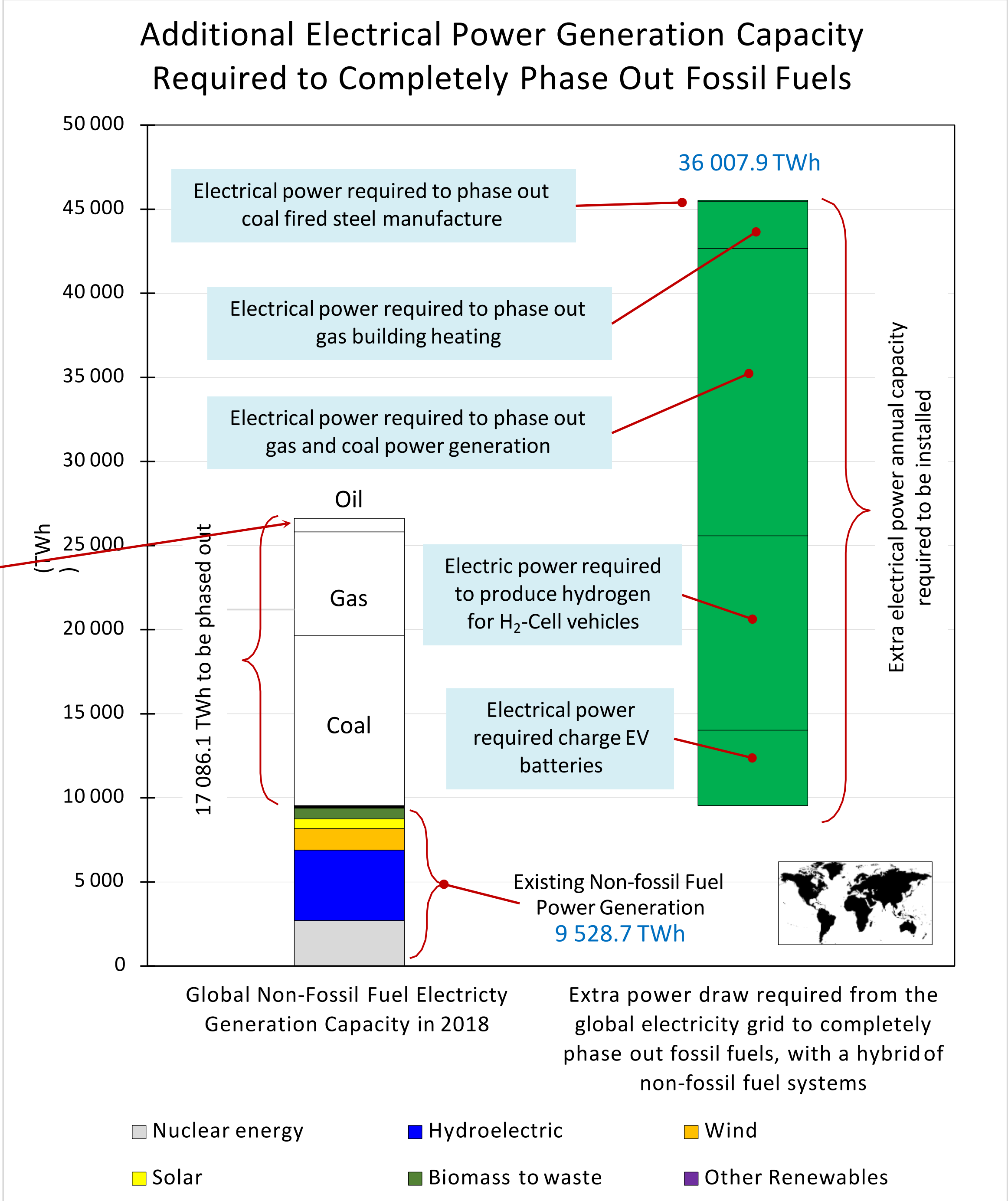
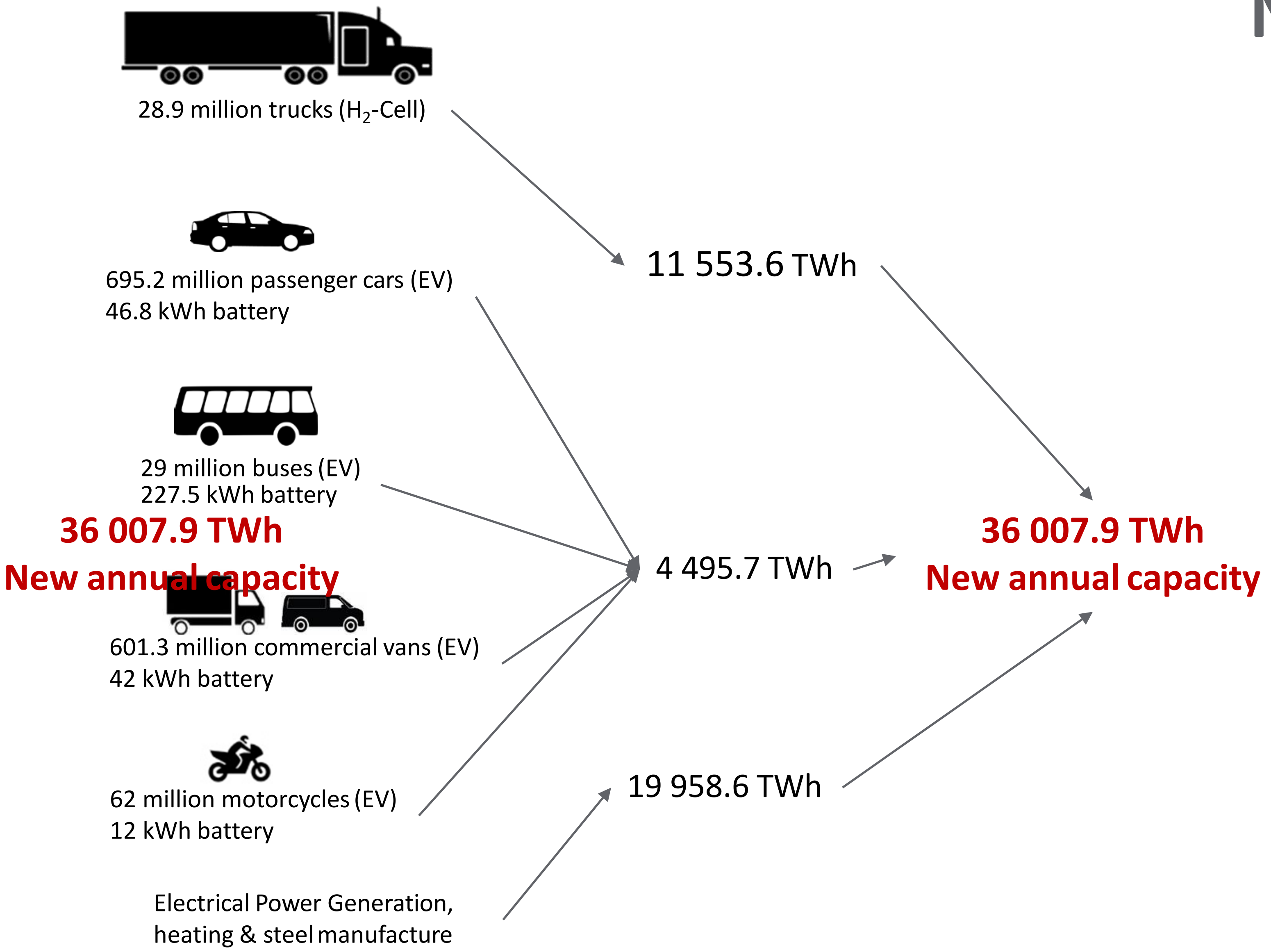
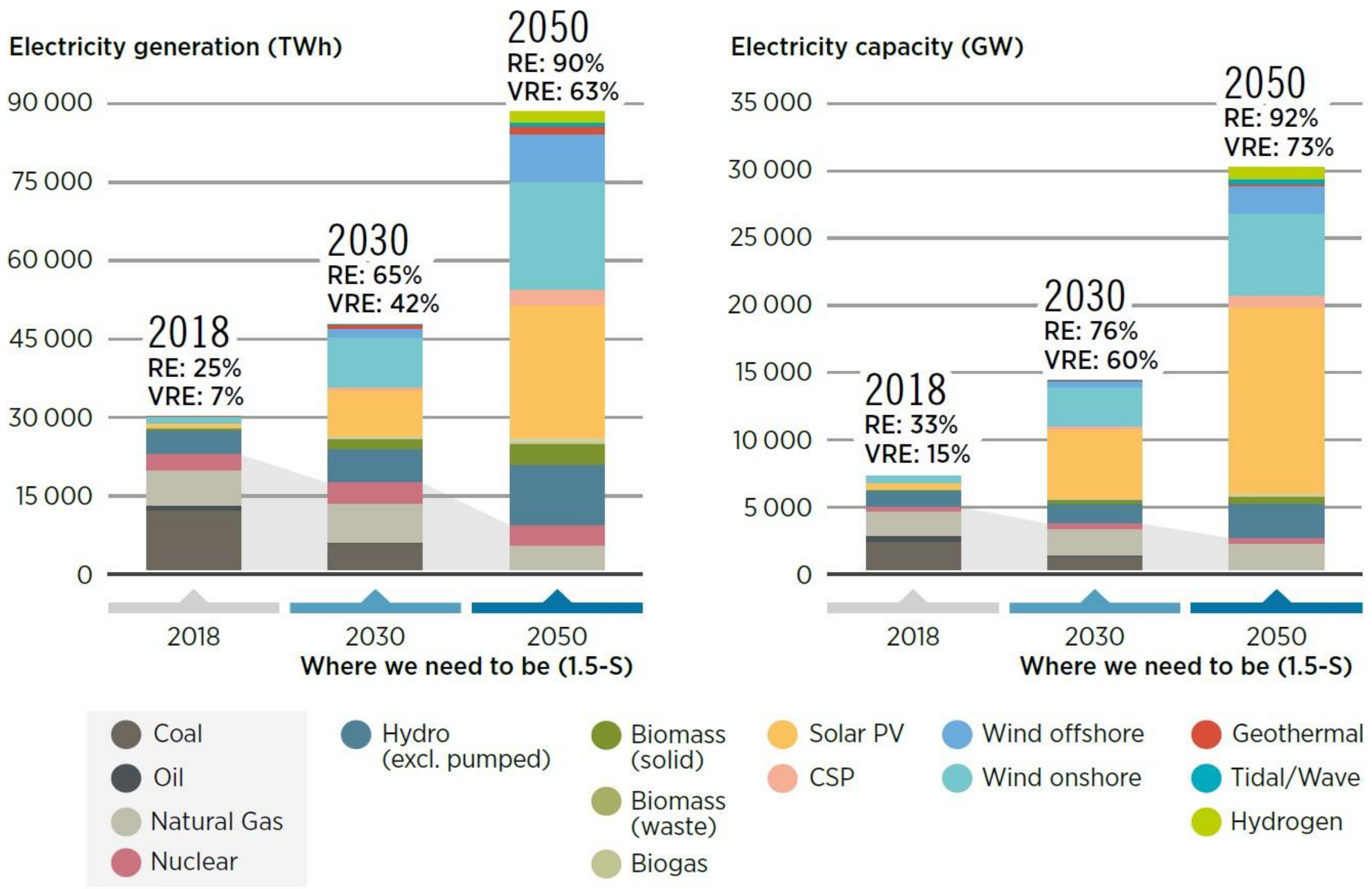
Total electrical power production in 2018 was 26 614 TWh



NEW ENERGY SPLIT





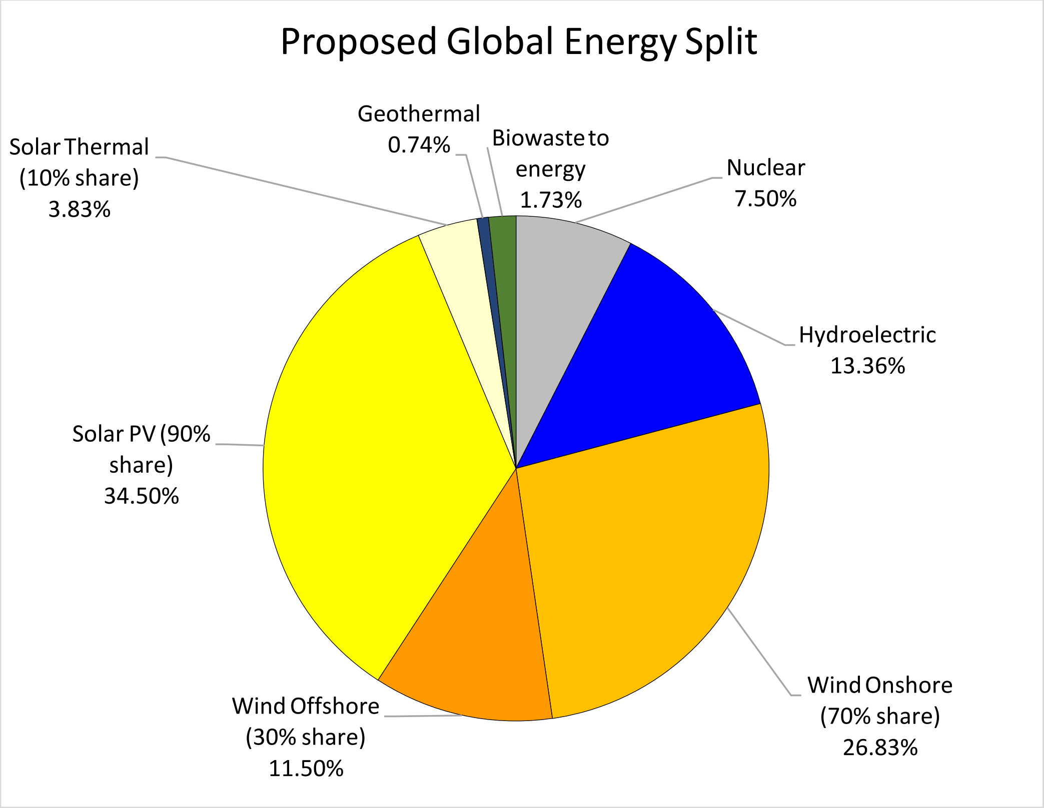
Note: 1.5-S = 1.5°C Scenario; CSP = concentrated solar power; GW = gigawatts; PV = photovoltaic; RE = renewable energy; TWh/yr = terawatt hours per year; VRE = variable renewable energy.

Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050 (Source: IRENA 2022)

THE FOLLOWING ASSUMPTIONS WERE MADE IN THE GLOBAL ELECTRICAL POWER GENERATION ENERGY SPLIT:

- All fossil fuels will be completely phased out
- Hydro will expand by adding 115 % capacity compared to 2018 production rates
- Nuclear will double in capacity from 2018 production rates
- Biowaste to energy cannot be expanded beyond what it is now, as planetary environmental sustainability limits may be exceeded (future work required). Any extra biomass harvest capacity should be tasked to generate biofuel for the aviation industry, feedstock for bioplastics and feedstock for the organic fertilizer industry
- Geothermal power generation will triple in producing capacity compared to 2018 production rates
- After the above calculations, all remaining new required capacity will be split equally between wind and solar
- New wind capacity will be a split between 70% onshore wind turbine site to 30% offshore wind turbine
- New solar power capacity will be split between 90% solar PV and 10% solar thermal

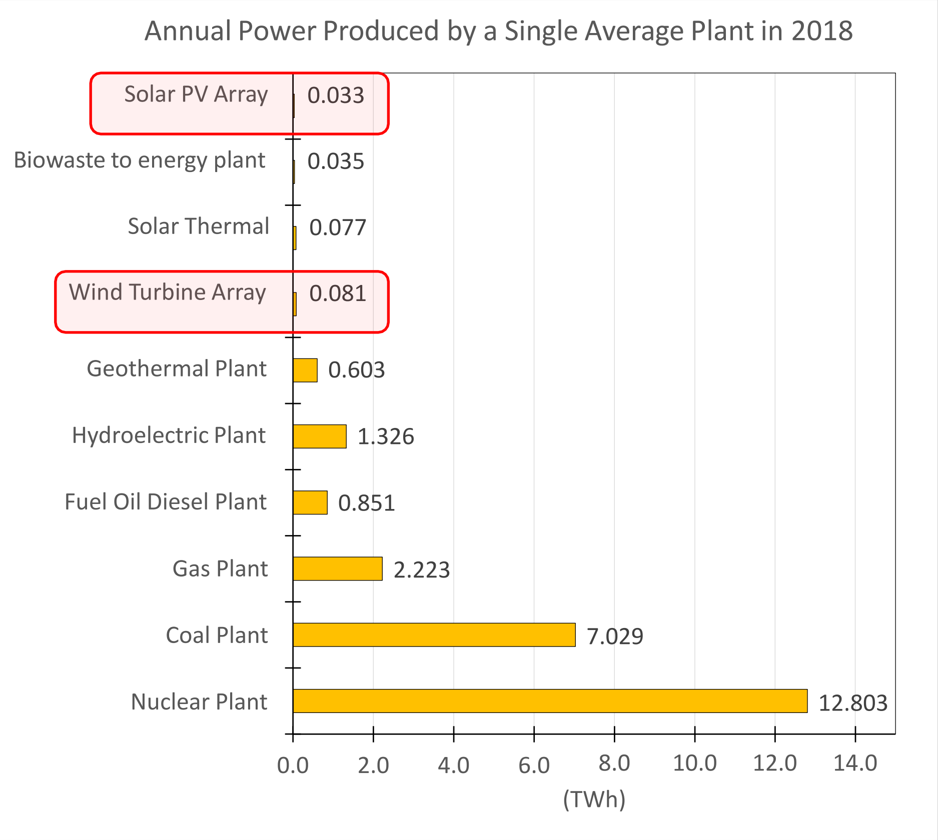
PROPOSED NEW GLOBAL ENERGY SPLIT

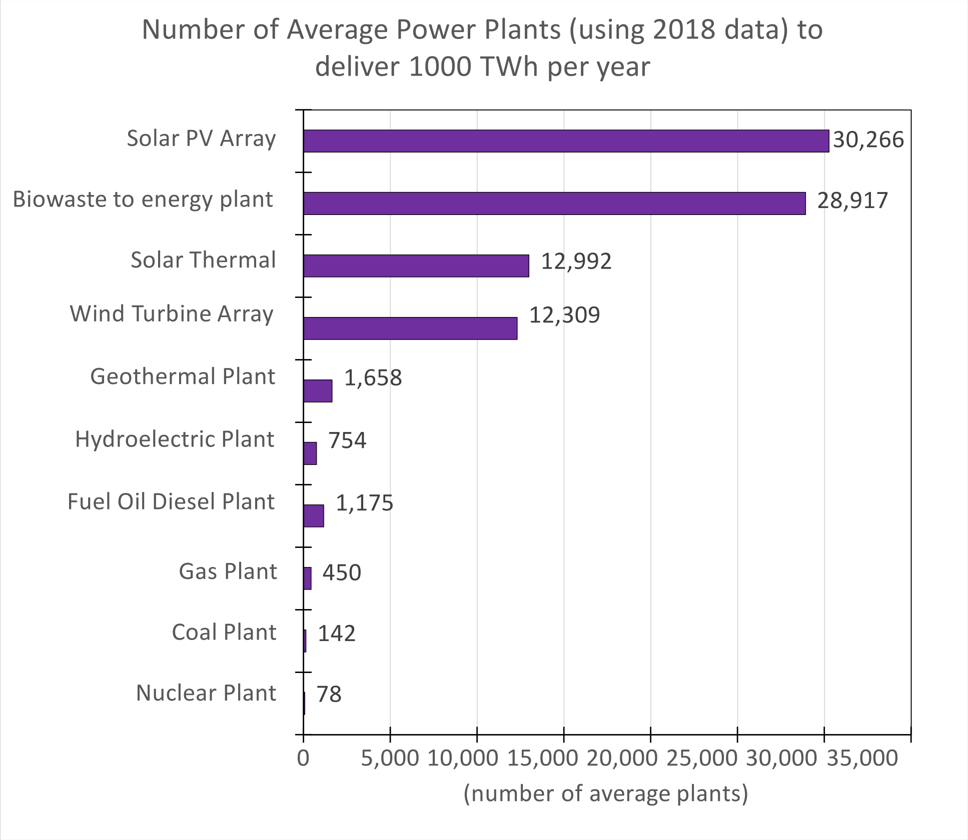


Power Generation System	Proposed Proportion of Energy Split on new annual capacity (%)	Extra required annual capacity to phase out fossil fuels (TWh)	Estimated number of required new power plants of average size to phase out fossil fuels (number)
Nuclear	7,50 %	2 701,4	211
Hydroelectric	13,36 %	4 809,6	3 628
Wind Onshore (70% share)	26,83 %	9 660,3	118 907
Wind Offshore (30% share)	11,50 %	4 140,1	50 960
Solar PV (90% share)	34,50 %	12 420,3	375 910
Solar Thermal (10% share)	3,83 %	1 380,0	17 930
Geothermal	0,74 %	266,7	442
Biowaste to energy	1,73 %	624,0	18 044
		36 007,9	586 032

Developed from a combination of an IRENA 2022 projection and some of my own assumptions

TO DELIVER 1000 TWH OF POWER TO THE GRID OVER 1 YEAR…





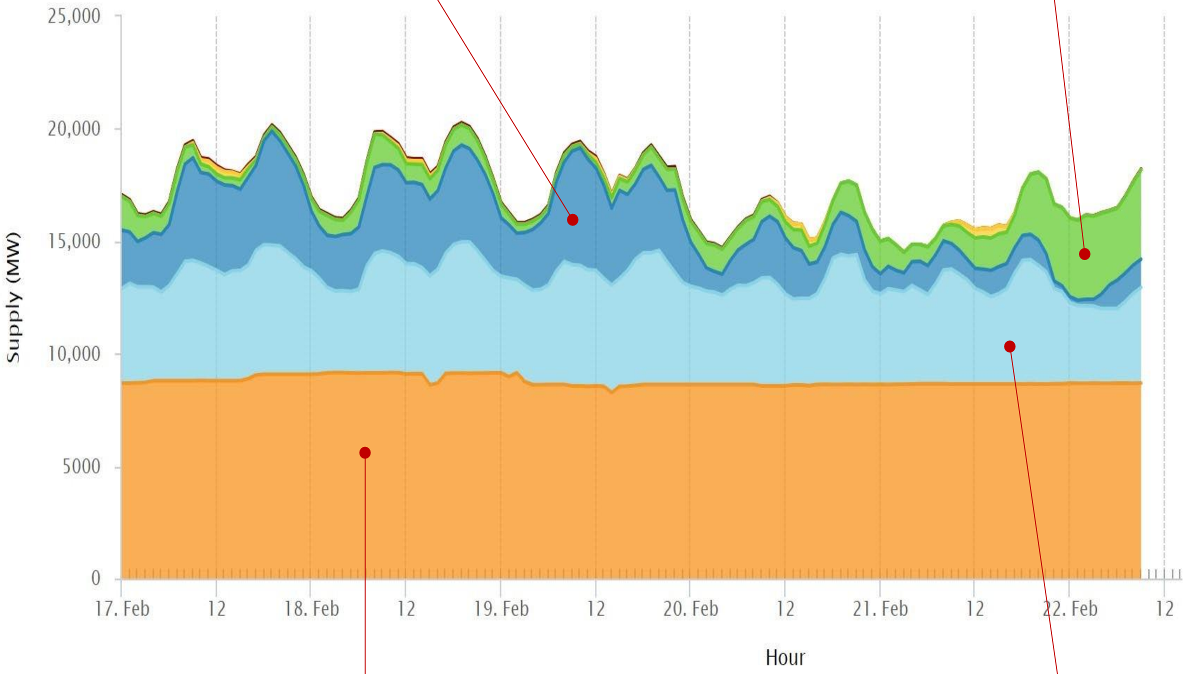
(Source Data: Global Energy Observatory, Agora Energiewende and Sandbag 2019)

Renewables have a much lower ERoEI ratio than fossil fuels and may not be strong enough to power the next industrial era

GAS AND HYDRO ARE THE EXISTING BUFFER

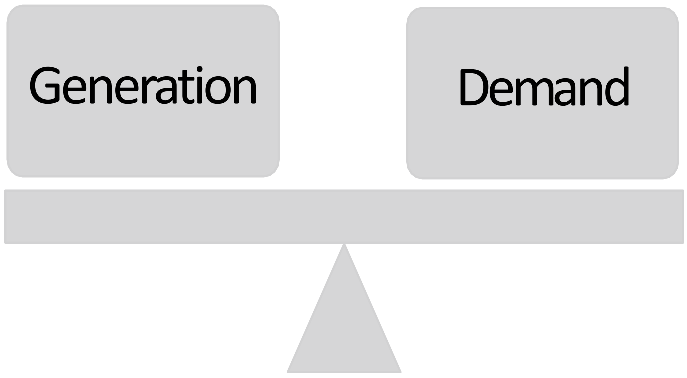
Important role of gas-fired units in making the balance

Maximum wind generation occurred in the demand valley



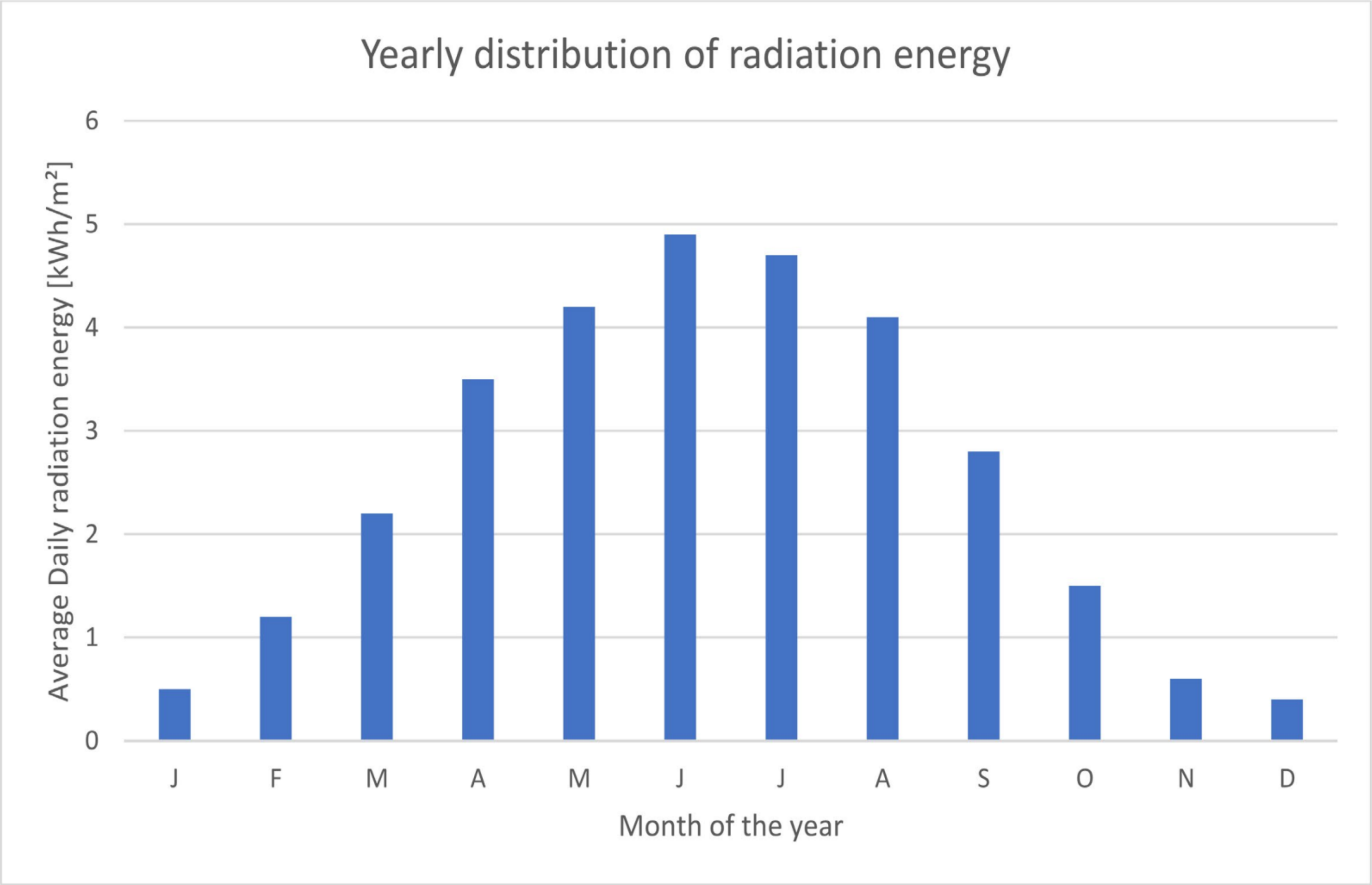
Monday, Feb 22, 04:00

Biofuel:	**17** MW
Solar:	**0** MW
Wind:	**3,595** MW
Gas:	**647** MW
Hydro:	**3,324** MW
Nuclear:	**8,686** MW



Electrical production by nuclear power plants is optimized to stay constant due to technical operational limitations

Average daily production of hydro units is dictated by their reservoir condition

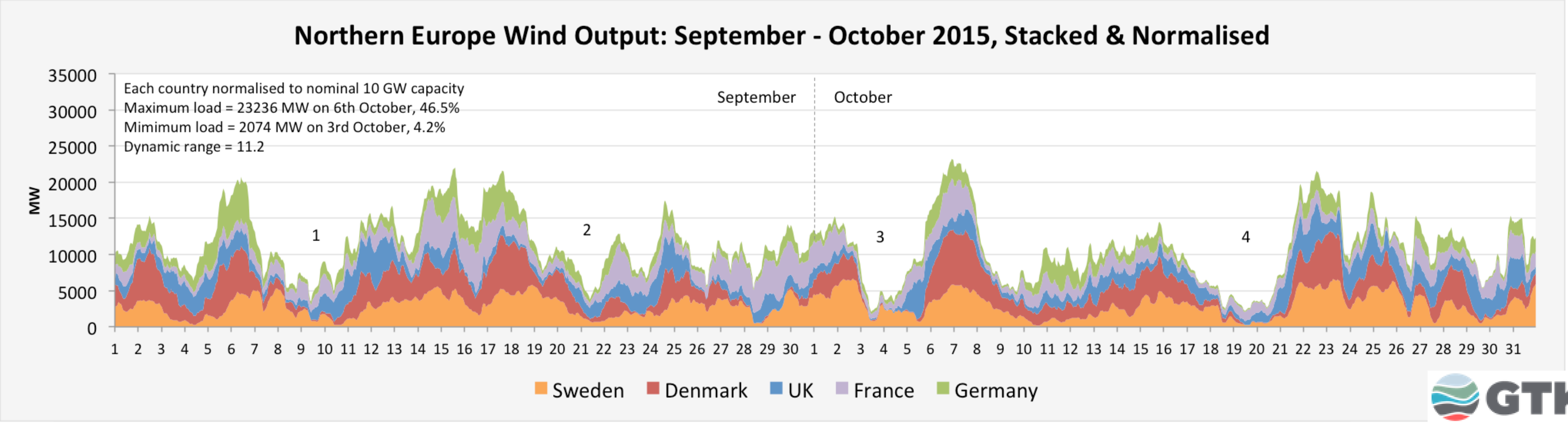


Distribution of the sun's radiation energy over the year in Germany (Wesselak & Voswinckel 2016)

WIND IS HIGHLY VARIABLE

- Reliable capacity as a % of max capacity for wind 7-25% (UK Parliament 2014)
  - *Power production was so erratic it could not be predicted*
- Variations in power produced can last weeks and, in some cases, months
- In practical terms, global power generation operating hours in 2018 (Global Energy Observatory)
  - *Solar PV units produced 11.4% of the calendar year*
  - *Wind units produced 24.9% of the calendar year*

Highly variable of when power was produced



POWER SUPPLY & DEMAND

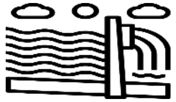
DEMAND

Transport demand could function on a 48-hour buffer

Must Balance

SUPPLY

Nuclear can’t vary at all and must be used as a base load



Hydro can vary within a small window

Wind & solar electrical power production could need a buffer of several months if they make up a large portion of the energy mix

Watch this presentation

Professor Jan Blomgren: Så här uppstod elkrisen i Sverige

https://www.youtube.com/watch?v=0Oh_w5KrEVc

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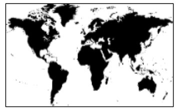
PROJECTED NEW ENERGY SPLIT FOR 2050

2nd generation of work done

Developed from a combination of an IRENA 2022 projection and some of my own assumptions

Power Generation System 	Proposed Proportion of Energy Split on new annual capacity (%)	Extra required annual capacity to phase out fossil fuels (TWh)	Estimated number of required new power plants of average size to phase out fossil fuels (number)
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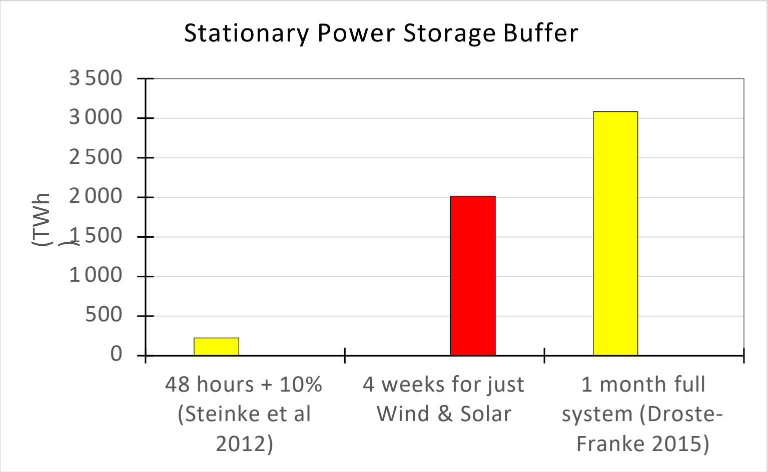

- Global Wind & Solar capacity only (72.8%) = 26 220.7 TWh
- 4 weeks Wind & Solar capacity only = **2 017.0 TWh**

This is the size of the needed power buffer

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STATIONARY POWER STORAGE BUFFER

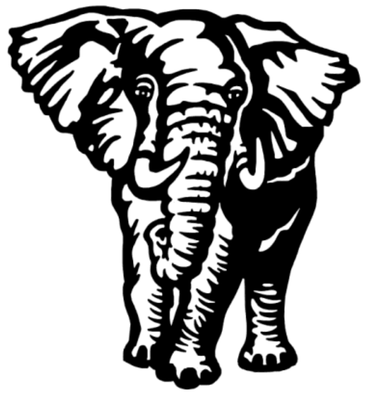
34.5% solar PV
12 420.3 TWh
375 910 average sized solar farms
(33.1 MW installed capacity)

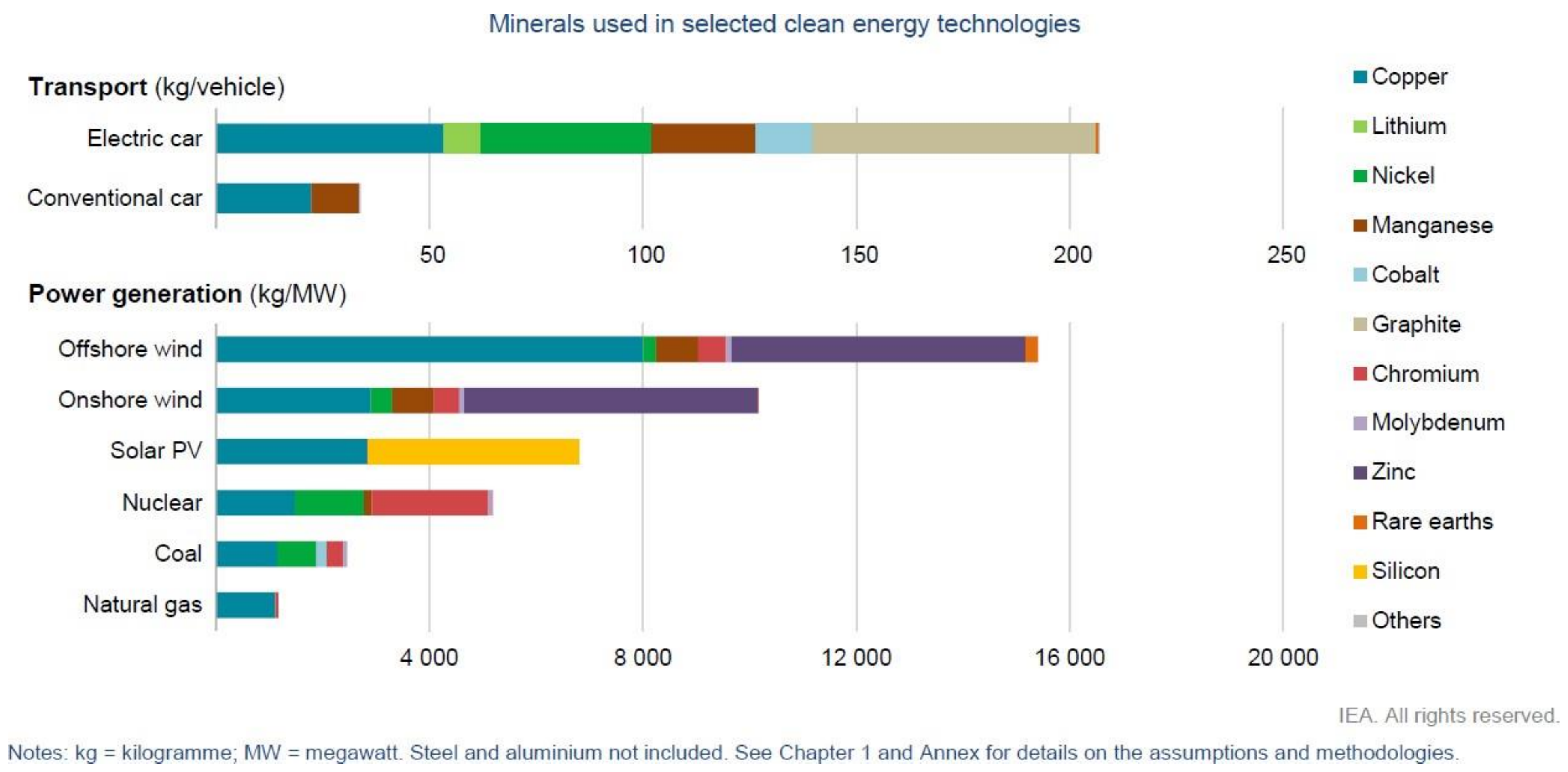
36 007.9 TWh
New annual capacity

38.3 % wind
13 800.4 TWh
2 106 361 wind turbines (3 MW) in 169 868
average sized arrays (37.2 MW installed capacity)
90% onshore, 10% offshore

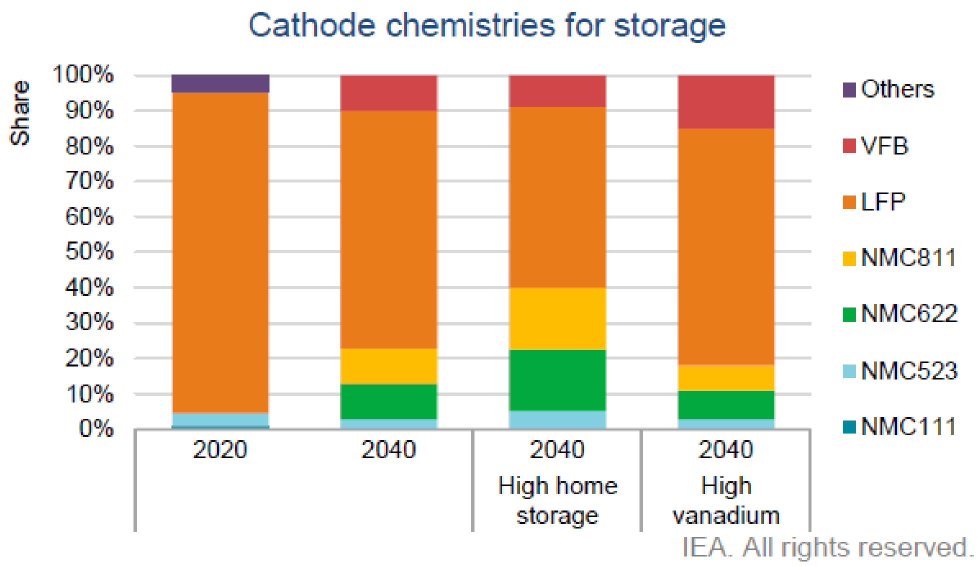
4 weeks buffer power
storage 2017.0 TWh

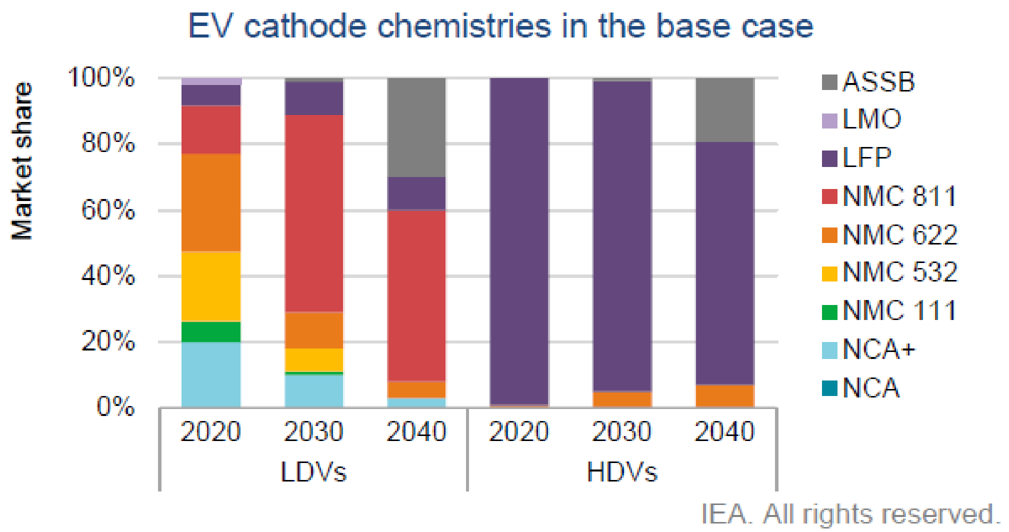
15 635 478
Hornsdale power stations
129MWh





(Source: The Role of Critical Minerals in Clean Energy Transitions IEA)





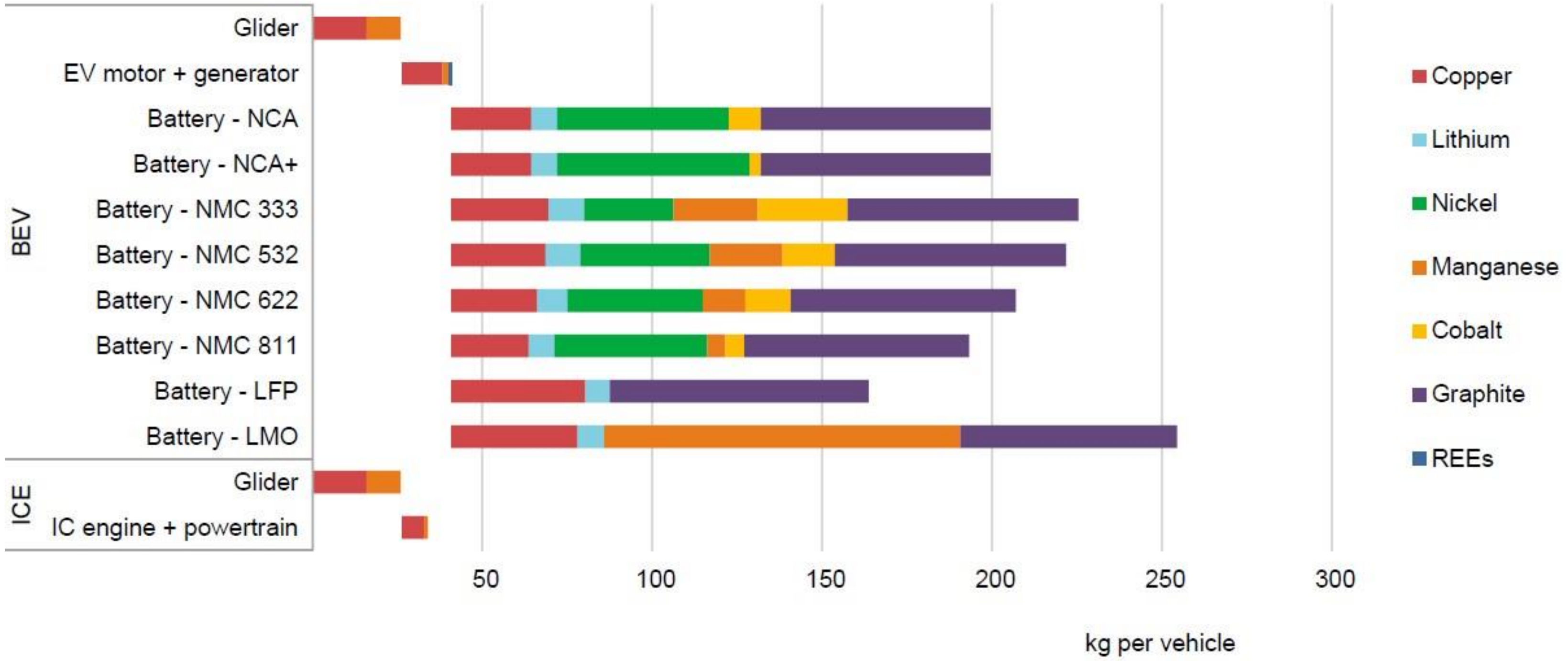
Notes: LDVs = light-duty vehicles (passenger cars and vans, light commercial vehicles, and 2- and 3-wheelers); HDVs = heavy-duty vehicles (trucks and buses).

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

(Source: The Role of Critical Minerals in Clean Energy Transitions IEA)

EVs use around six times more minerals than conventional vehicles

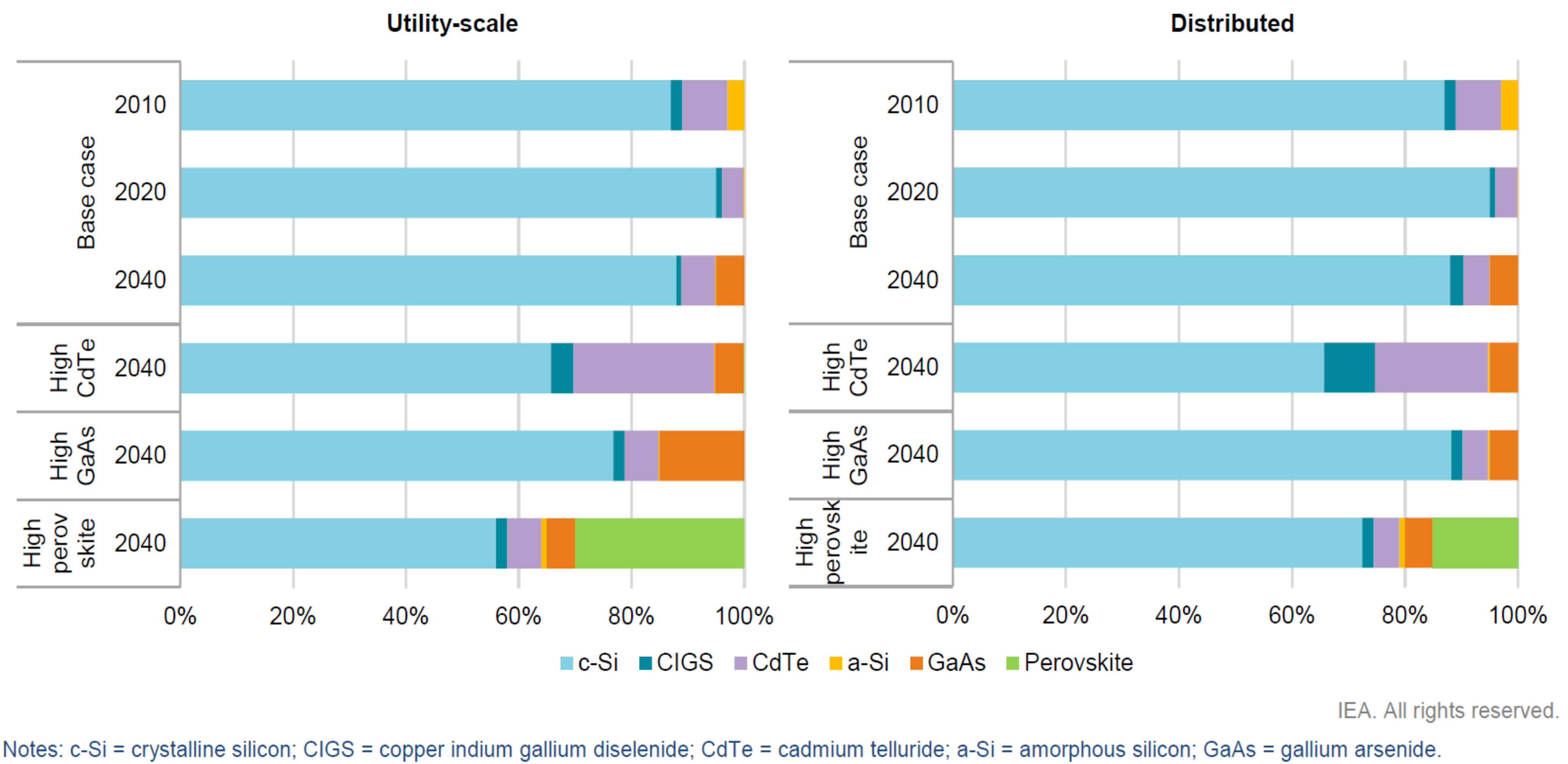
Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle



Notes: For this figure, the EV motor is a permanent-magnet synchronous motor (neodymium iron boron [NdFeB]); the battery is 75 kilowatt hours (kWh) with graphite anodes.

Sources: Argonne National Laboratory (2020b, 2020a); Ballinger et al. (2019); Fishman et al. (2018b); Nordelöf et al. (2019); Watari et al. (2019).

(Source: The Role of Critical Minerals in Clean Energy Transitions IEA)



Share of annual capacity additions by PV technology under different technology evolution scenarios

(Source: IEA 2021) (Copyright: IEA)

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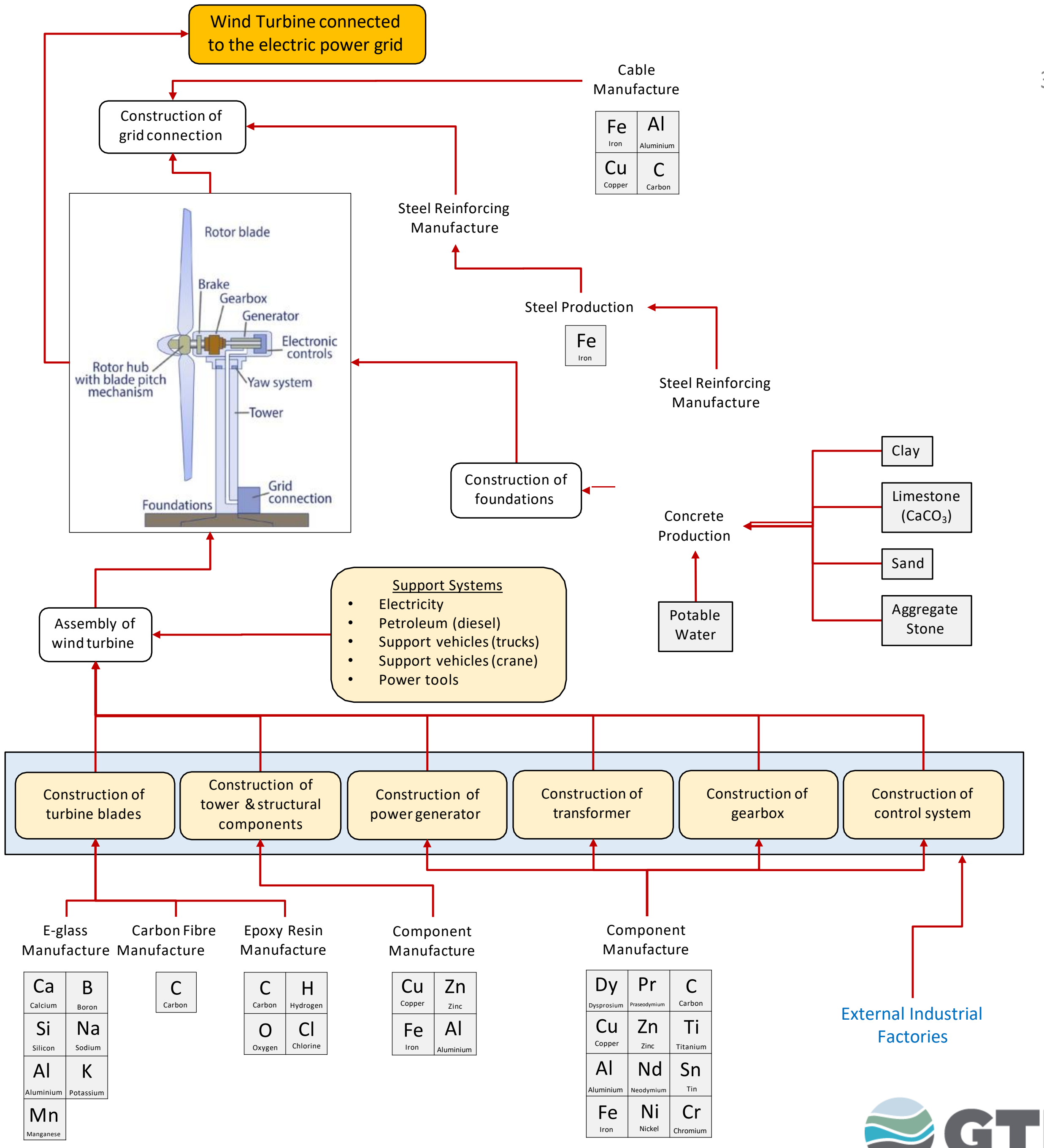
NUMBER OF TECHNOLOGY UNITS

Renewable Technology Unit or Service	Number (number)	Estimated total battery capacity (TW)	Estimated extra annual power output required (TWh)	Estimated extra total installed power generation capacity (MW)
Electric Vehicles				
Bus + Medium Delivery Truck	29 002 253	5,98		
Light Truck/Van + Light-Duty Vehicle	601 327 324	25,32		
Passenger Car	695 160 429	32,53		
Motorcycle	62 109 261	1,34		
Hydrogen Fuel Cells				
HCV Class 8 Truck	28 929 348		1 949,0	
Rail Freight Locomotive	104 894		277,0	
Maritime Small Vessel (100 GT to 499 GT)	53 854		7,7	
Maritime Medium Vessel (500 GT to 24 999 GT)	44 696		131,7	
Maritime Large Vessel (25 000 GT to 59 999 GT)	12 000		255,7	
Maritime Very Large Vessel (>60 000 GT)	6 307		379,7	
Nuclear Power (Annual Production)			2 701,4	431 800
Hydroelectricity (Annual Production)			4 809,6	817 720
Geothermal Power (Annual Production)			266,7	41 867
Wind Turbines				
3MW Onshore wind turbines (70% share)	1 474 452		9 660,3	4 423 357
3MW Offshore wind turbines (30% share)	631 908		4 140,1	1 895 725
Solar Panels				
450 MW solar panels	27 650 301 276		12 420,3	12 442 636
Stationary power storage buffer				
4 weeks capacity for wind & solar PV only		2 017,0		
	Total	**2 082,1**		

- Electric Vehicles (1.39 billion)
- EV Batteries
- Hydrogen fuel cells (29.1 million)
- Wind Turbines
- Solar Panels
- Power Storage Batteries (for 4 weeks of wind & solar capacity only)

WIND TURBINE METAL CONTENT

- Capacity required
- Market share of units
- Number of units by type
- Metal content in each unit type
- Sum total of global fleet by metal type



PROPOSED NEW GLOBAL ENERGY SPLIT

Power Generation System	Proposed Proportion of Energy Split on new annual capacity (%)	Extra required annual capacity to phase out fossil fuels (TWh)	Estimated number of required new power plants of average size to phase out fossil fuels (number)
Nuclear	7,50 %	2 701,4	211
Hydroelectric	13,36 %	4 809,6	3 628
Wind Onshore (70% share)	26,83 %	9 660,3	118 907
Wind Offshore (30% share)	11,50 %	4 140,1	50 960
Solar PV (90% share)	34,50 %	12 420,3	375 910
Solar Thermal (10% share)	3,83 %	1 380,0	17 930
Geothermal	0,74 %	266,7	442
Biowaste to energy	1,73 %	624,0	18 044
		36 007,9	586 032

Developed from a combination of an IRENA 2022 projection and some of my own assumptions

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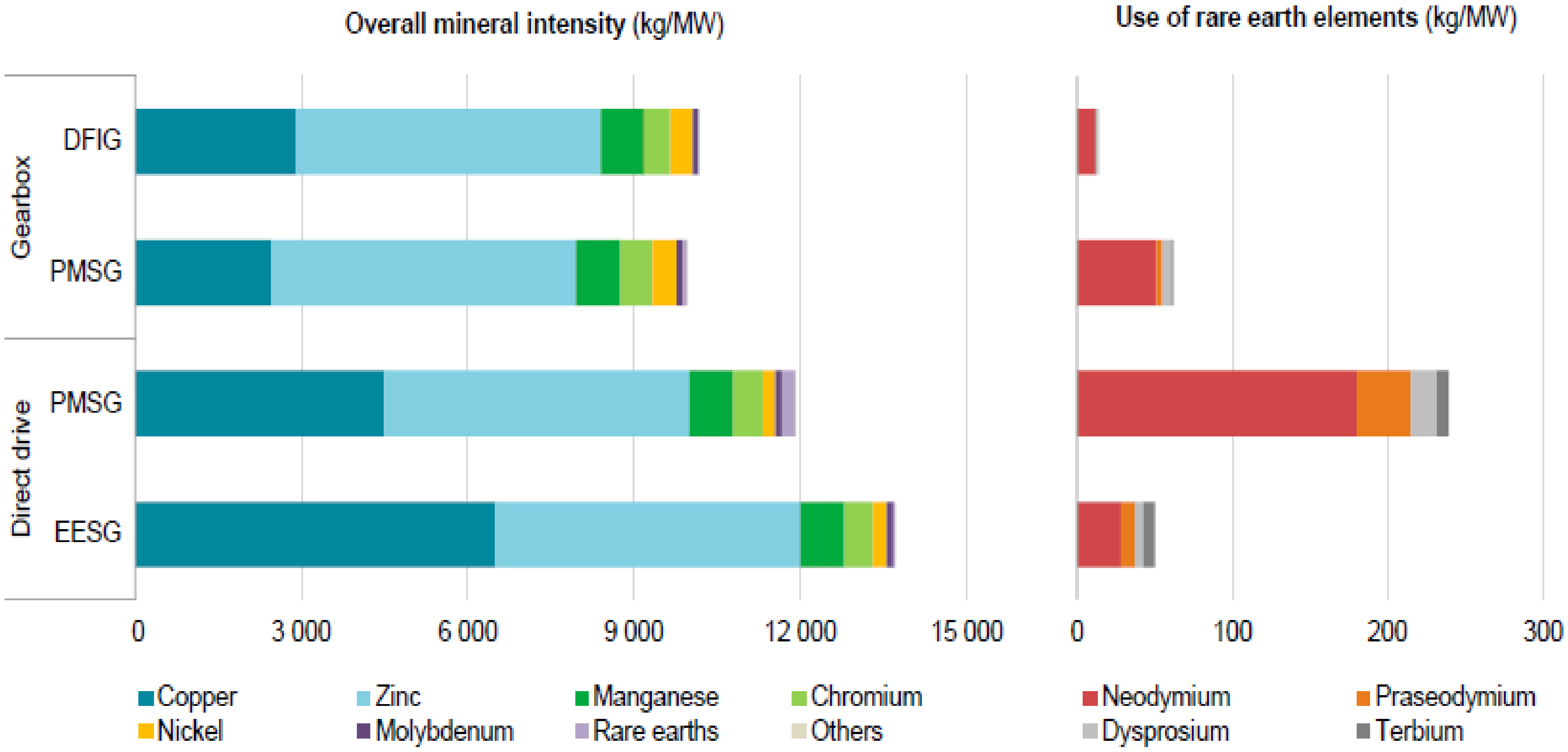
NUMBER AND TYPE OF WIND TURBINES

Table A3. Estimated number of new 3MW wind turbines and 450 MW solar panels to globally phase pout fossil fuels

Power Generation System	**Extra** required annual capacity to phase out fossil fuels (kWh)	Power produced by a **single** average plant in 2018 (kWh)	Estimated number of required new power plants of **average size** to phase out fossil fuels (number)	Average installed plant capacity in 2018 (Global Energy Observatory) (MW)	Total **new** annual installed capacity required (MW)	Number of 3MW wind turbines (number)	Number of 450 Watt Commercial grade solar panels (number)
Wind Onshore (70% share)	9.66E+12	8.12E+07	118 907	37.2	4 423 357	1 474 452	
Wind Offshore (30% share)	4.14E+12	8.12E+07	50 960	37.2	1 895 725	631 908	
Solar PV (90% share)	1.24E+13	3.30E+07	375 910	33.1	12 442 636		27 650 301 276



Metal content of different wind turbine units (Note: metal content intensity numbers are based on the onshore installation environment. More copper is needed in offshore applications due to much longer cabling requirements)

(Source: IEA) (Copyright IEA)

MARKET SHARE OF WIND TURBINES

Table A4. Projected market share of **onshore** wind turbine types used in this study

Onshore Wind Turbine Type	Acronym	Projected market share in 2040 (%)	Required new annual installed capacity required (4 423 357 MW) (MW)
Gearbox double-fed induction generator	GB-DFIG	69.0 %	3 051 148
Gearbox permanent magnet synchronous generator	GB-PMSG	11.7 %	516 596
Direct-drive permanent magnet synchronous generator	DD-PMSG	14.6 %	645 746
Direct-drive electrically excited synchronous generator	DD-EESG	4.7 %	209 867

Table A5. Projected market share of **offshore** wind turbine types used in this study

Offshore Wind Turbine Type	Acronym	Projected market share in 2040 (%)	Required new annual installed capacity required (1 895 725 MW) (MW)
Gearbox double-fed induction generator	GB-DFIG	-	
Gearbox permanent magnet synchronous generator	GB-PMSG	13.1 %	248 340
Direct-drive permanent magnet synchronous generator	DD-PMSG	86.9 %	1 647 385
Direct-drive electrically excited synchronous generator	DD-EESG	-	

METAL CONTENT IN A WIND TURBINE

Table A6. Estimated metal content in wind turbines by technology unit per MW

Metal Content in a Wind Turbine by Type	Gearbox double-fed induction generator GB-DFIG (kg/MW)	Gearbox permanent magnet synchronous generator GB-PMSG (kg/MW)	Direct-drive permanent magnet synchronous generator DD-PMSG (kg/MW)	Direct-drive electrically excited synchronous generator DD-EESG (kg/MW)
Copper (Onshore unit)	2895.8	2432.4	4459.5	6486.5
Copper (Offshore unit) *	7895.8	7432.4	9459.5	11486.5
Zinc	5501.9	5501.9	5501.9	5501.9
Manganese	752.9	781.9	747.1	752.9
Chromium	463.3	532.8	521.2	521.2
Nickel	463.3	463.3	231.7	231.7
Molybdenum	104.2	115.8	104.2	104.2
Rare Earth Metals				
Neodymium	12.4	49.7	180.0	22.8
Praseodymium		4.1	34.1	6.2
Dysprosium		6.2	16.6	4.1
Terbium		2.1	6.2	4.6

* An offshore wind turbine would require a much longer connecting cable to the power grid resulting in more copper required in manufacture. This is assumed to add 5 000 kg/MW (Source: estiamted from Bobba *et al.* 2020). So metla content for an onshore wind turbine is assumed to be the same as an offshore wind turbine, with the exception of copper.

METAL CONTENT IN ONSHORE WIND TURBINE GLOBAL FLEET

Table A7. Total metal content in onshore wind turbines to globally phase out fossil fuels

Combined Metal Content in an onshore wind turbine by Type	Gearbox double-fed induction generator GB-DFIG (tonnes)	Gearbox permanent magnet synchronous generator GB-PMSG (tonnes)	Direct-drive permanent magnet synchronous generator DD-PMSG (tonnes)	Direct-drive electrically excited synchronous generator DD-EESG (tonnes)	Metal quantity required for onshore wind turbines (tonnes)
Copper (Onshore unit)	8 835 370	1 256 586	2 879 676	1 361 302	14 332 934
Zinc	16 787 204	2 842 278	3 552 847	1 154 675	24 337 004
Manganese	2 297 196	403 903	482 439	158 008	3 341 546
Chromium	1 413 659	275 252	336 586	109 390	2 134 887
Nickel	1 413 659	239 350	149 594	48 618	1 851 220
Molybdenum	318 073	59 837	67 317	21 878	467 106
Rare Earth Metals					
Neodymium	37 876	25 652	116 234	4 776	184 539
Praseodymium		2 138	22 044	1 303	25 485
Dysprosium		3 206	10 688	868	14 763
Terbium		1 069	4 008	955	6 032

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METAL CONTENT IN OFFSHORE WIND TURBINE GLOBAL FLEET

Table A8. Total metal content in offshore wind turbines to globally phase out fossil fuels

Combined Metal Content in an offshore wind turbine by Type	Gearbox permanent magnet synchronous generator GB-PMSG (tonnes)	Direct-drive permanent magnet synchronous generator DD-PMSG (tonnes)	Metal quantity required for onshore wind turbines (tonnes)
Copper (Offshore unit)	1 845 770	15 583 368	17 429 138
Zinc	1 366 349	9 063 796	10 430 145
Manganese	194 165	1 230 768	1 424 933
Chromium	132 320	858 675	990 996
Nickel	115 061	381 634	496 694
Molybdenum	28 765	171 735	200 500
Rare Earth Metals			
Neodymium	12 331	296 529	308 861
Praseodymium	1 028	56 238	57 266
Dysprosium	1 541	27 267	28 808
Terbium	514	10 225	10 739

METAL NEEDED PART 1

Table A31-1. Total metal quantity required to manufacture one generation of technology units to phase out fossil fuels

Metal	Metal quantity required for onshore wind turbines (tonnes)	Metal quantity required for offshore wind turbines (tonnes)	Metal content in 12 442 636 MW of solar panels (tonnes)	Metal content in Nuclear power plant construction (tonnes)	Metal content in Hydro power plant construction (tonnes)
Steel					
Aluminium	*	*	149 311 627		
Copper	14 332 934	17 429 138	35 349 528	634 746	858 606
Zinc	24 337 004	10 430 145			
Magnesium Metal	*	*			
Manganese	3 341 546	1 424 933			163 544
Chromium	2 134 887	990 996		945 642	
Nickel	1 851 220	496 694		561 340	24 532
Lithium					
Cobalt					
Graphite					
Molybdenum	467 106	200 500			
Silicon (Metallurgical)			49 571 460		
Silver			145 579		
Platinum					
Vanadium					
Zirkonium					
Rare Earth Metals					
Neodymium	184 539	308 861	*		
Germanium	*	*	*		
Lanthanum	*	*	*		
Praseodymium	25 485	57 266	*		
Dysprosium	14 763	28 808	*		
Terbium	6 032	10 739	*		
Hafnium	*	*	*	216	
Yttrium	*	*	*	216	

* no data available

METAL NEEDED PART 2

Metal	Metal content in Geothermal power plant construction (tonnes)	Metal content in Electric Vehicle construction (tonnes)	Metal content in hydrogen fuel cell construction (tonnes)	Metal content in EV batteries (tonnes)	Metal content in stationary storage batteries (tonnes)
Steel		1 683 027473	(only Pt data		
Aluminium		150 427661	avilable)		
Copper		74 081275		63 251218	4 158 751 111
Zinc				936793	
Magnesium Metal		499536			
Manganese				9 317606	203 333 550
Chromium	2 701078				
Nickel	5 016288			70 999643	820 054 277
Lithium				20 291338	879 282 274
Cobalt				9 713443	198 614 462
Graphite				155 212285	8 392 933 607
Molybdenum	434102				
Silicon (Metallurgical)					
Silver					
Platinum			2 682		
Vanadium					647 928 875
Zirkonium				2 614126	
<u>Rare Earth Metals</u>					
Neodymium		471784	*	*	*
Germanium		*	*	4 163162	*
Lanthanum		*	*	5 970738	*
Praseodymium		152636	*	*	*
Dysprosium		152636	*	*	*
Terbium		*	*	*	*
Hafnium		*	*	*	*
Yttrium		*	*	*	*

* no data available

Table A31-2. Total metal quantity required to manufacture one generation of technology units to phase out fossil fuels

METAL PRODUCED IN 2019

Metal	Element	Total metal required produce one generation of technology units to phase out fossil fuels (tonnes)	Global Metal Production 2019 (tonnes)	Years to produce metal at 2019 rates of production (years)
Aluminium	Al	299 739 288	63 136 000	4.7
Copper	Cu	4 364 688 556	24 200 000	180.4
Zinc	Zn	35 703 942	13 524 000	2.6
Magnesium Metal	Mg	499 536	1 120 000	0.4
Manganese	Mn	217 581 179	20 591 000	10.6
Chromium	Cr	6 772 603	37 498 478	0.2
Nickel	Ni	899 003 994	2 350 142	382.5
Lithium	Li	899 573 612	95 170	9452.3
Cobalt	Co	208 327 906	126 019	1653.1
Graphite (natural flake)	C	8 548 145 892	1 156 300	6778.8
Graphite (synthetic)	C		1 573 000 ♦	
Molybdenum	Mo	1 101 708	277094 ‡	4.0
Silicon (Metallurgical)	Si	49 571 460	8 410 000	5.9
Silver	Ag	145 579	26282 ‡	5.5
Platinum	Pt	2 682	190 ‡	14.1
Vanadium	V	647 928 875	96021 ‡	6747.8
Zirkonium	Zr	2 614 126	1 338 463 ‡	2.0
Rare Earth Metals	-			
Neodymium	Nd	965 183	23 900	40.4
Germanium	Ge	4 163 162	143	29 113
Lanthanum	La	5 970 738	35 800	166.8
Praseodymium	Pr	235 387	7 500	31.4
Dysprosium	Dy	196 207	1 000	196.2
Terbium	Tb	16 771	280	59.9
Hafnium	Hf	216	66	3.3
Yttrium	Y	216	14 000	0.0154

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

♦ Natural flake graphite and synthetic graphite was combined to estimate total production

(Source: BGR 2021, USGS, Friedrichs 2022)

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METAL IN 2022 GLOBAL RESERVES

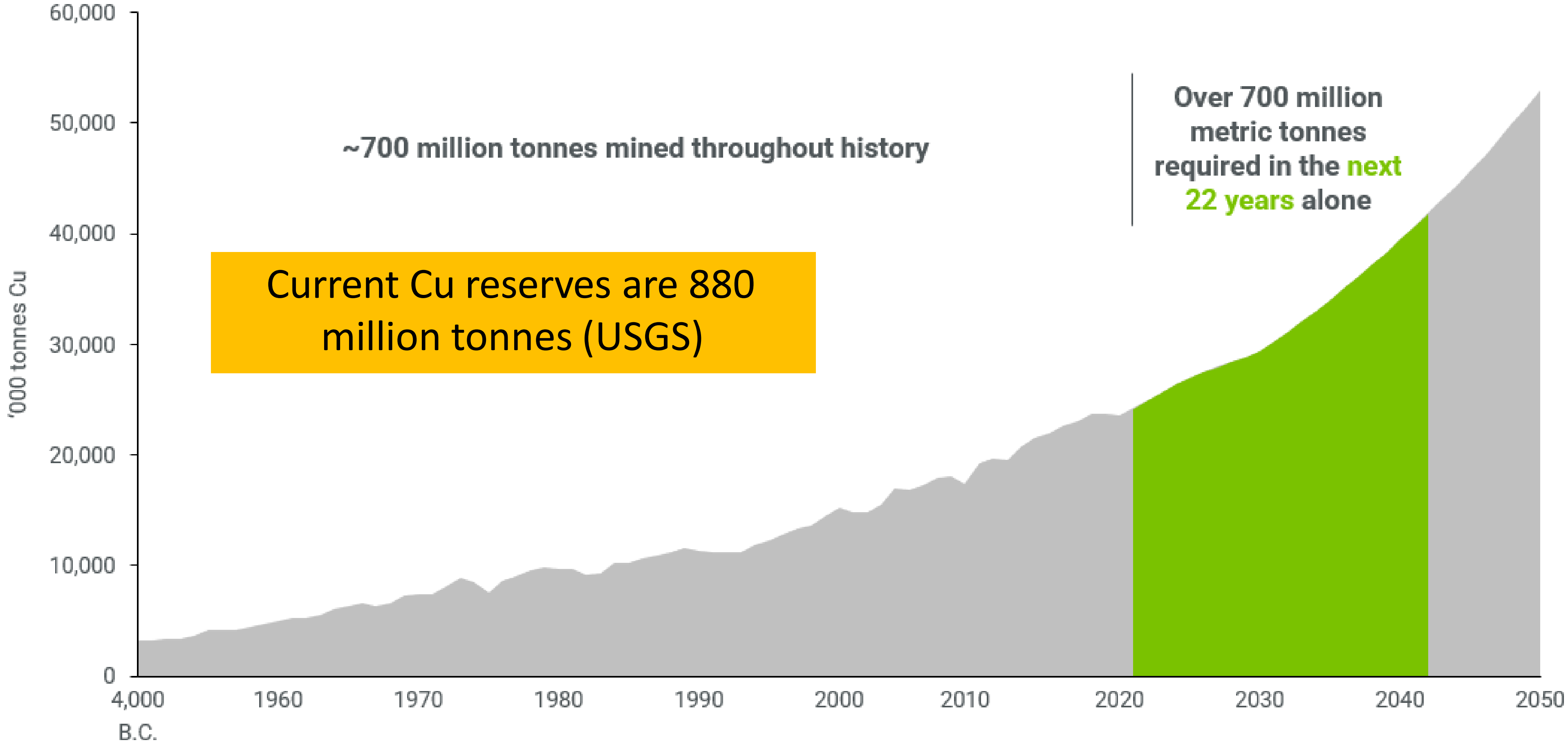
Metal Source: USGS	Total metal required produce one generation of technology units to phase out fossil fuels (tonnes)	Reported Global Reserves 2022 (tonnes)	Global Reseves as a proportion of metals required to phase out fossil fuels (%)
Copper	4 364 688 556	880 000 000	20.16 %
Nickel	899 003 994	95 000 000	10.57 %
Lithium	899 573 612	22 000 000	2.45 %
Cobalt	208 327 906	7 600 000	3.65 %
Graphite (natural flake)	8 548 145 892	320 000 000	3.74 %
Silver	145 579	530 000	
Vanadium	647 928 875	24 000 000	3.70 %

- For every 1000 deposits discovered, 1 or 2 become mines
- Time taken to develop a discovered deposit to a mine 20 years
- For every 10 producing mines, 2 or 3 will lose money and shut down

YOU CAN'T RECYCLE SOMETHING THAT IS NOT YET CONSTRUCTED OR MANUFACTURED

- 0.7% is EV in 2020
- 83.2% of global primary energy in 2020 was fossil fuel based
  - *Renewable 5.7%*
- 61.3% of global electricity generation in 2020 was fossil fuel based
  - *Renewable 11.7%*
- If it was all built tomorrow, most EOL units would be discarded between 2032 – 2042 (10 to 20 years)

ECONOMIC GROWTH AND RESOURCE SUPPLY



Current Cu reserves are 880 million tonnes (USGS)

Source: U.S. Geological Survey, BMO Capital Markets

We want 4.36 billion tonnes of Cu, just to manufacture one generation of renewable technology (6.2 x historical Cu mining)

COPPER DISCOVERY

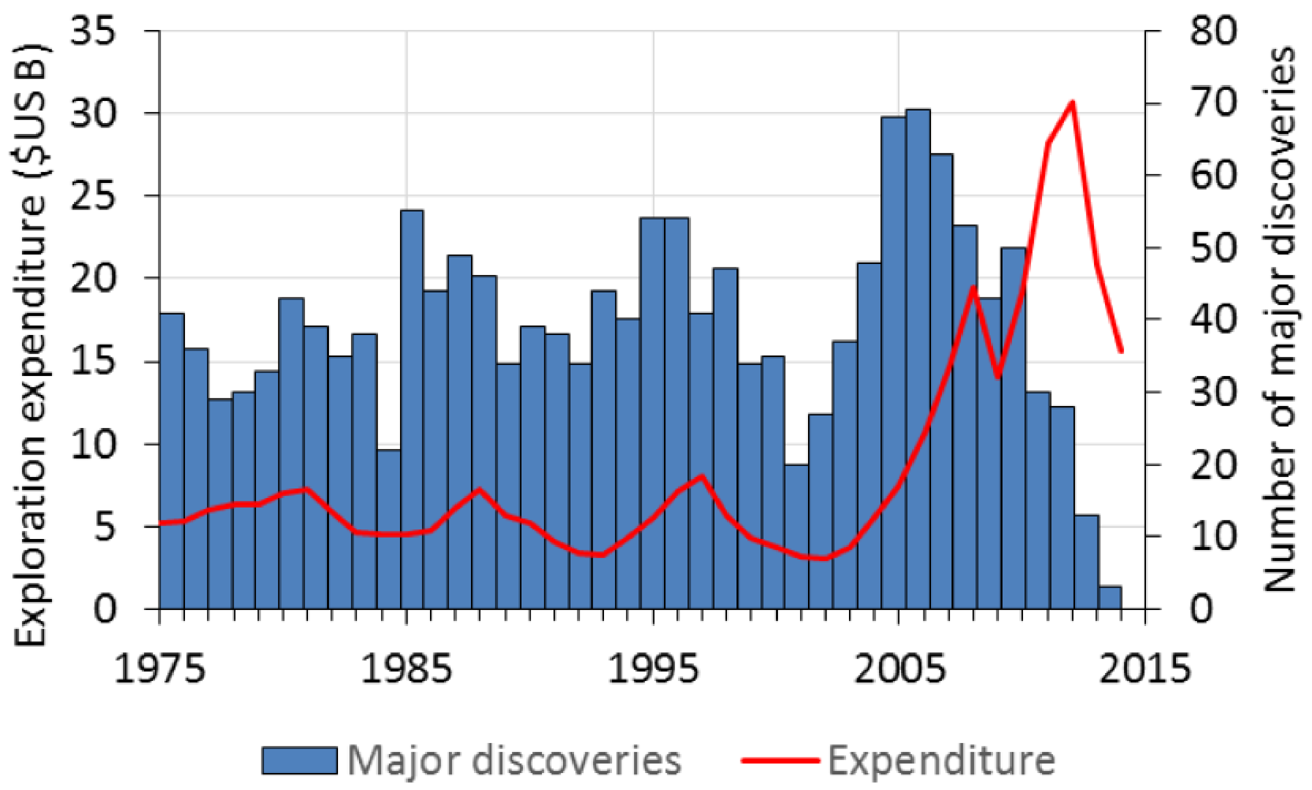
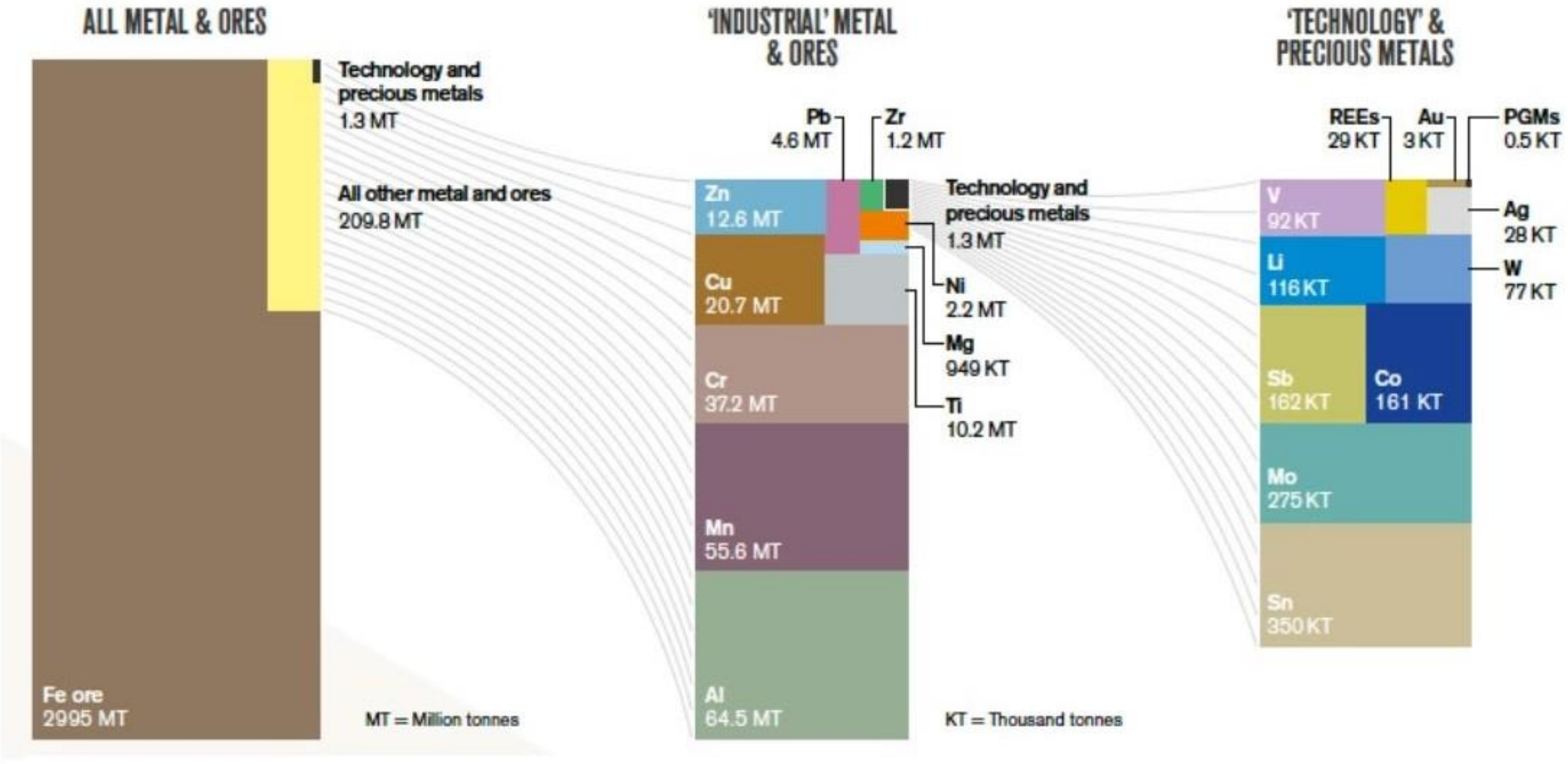


Figure 1: Exploration expenditures versus number of major discoveries, where major is defined as, for example, a gold deposit containing more than 1 Moz of gold or a copper deposit with more than 1 Mt of copper. (Data courtesy of MinEx Consulting)

(Source: Dunbar *et al.* 2016)

GLOBAL PRIMARY METAL AND ORE PRODUCTION



Global production of primary metals and ores. Source: British Geological Survey 2019.

*Excludes production of potash (~61mtpa) and phosphate rock (~157mtpa).

China leads world in production of minerals needed for clean energy

Share of top three countries for extraction and processing of key minerals and fossil fuels

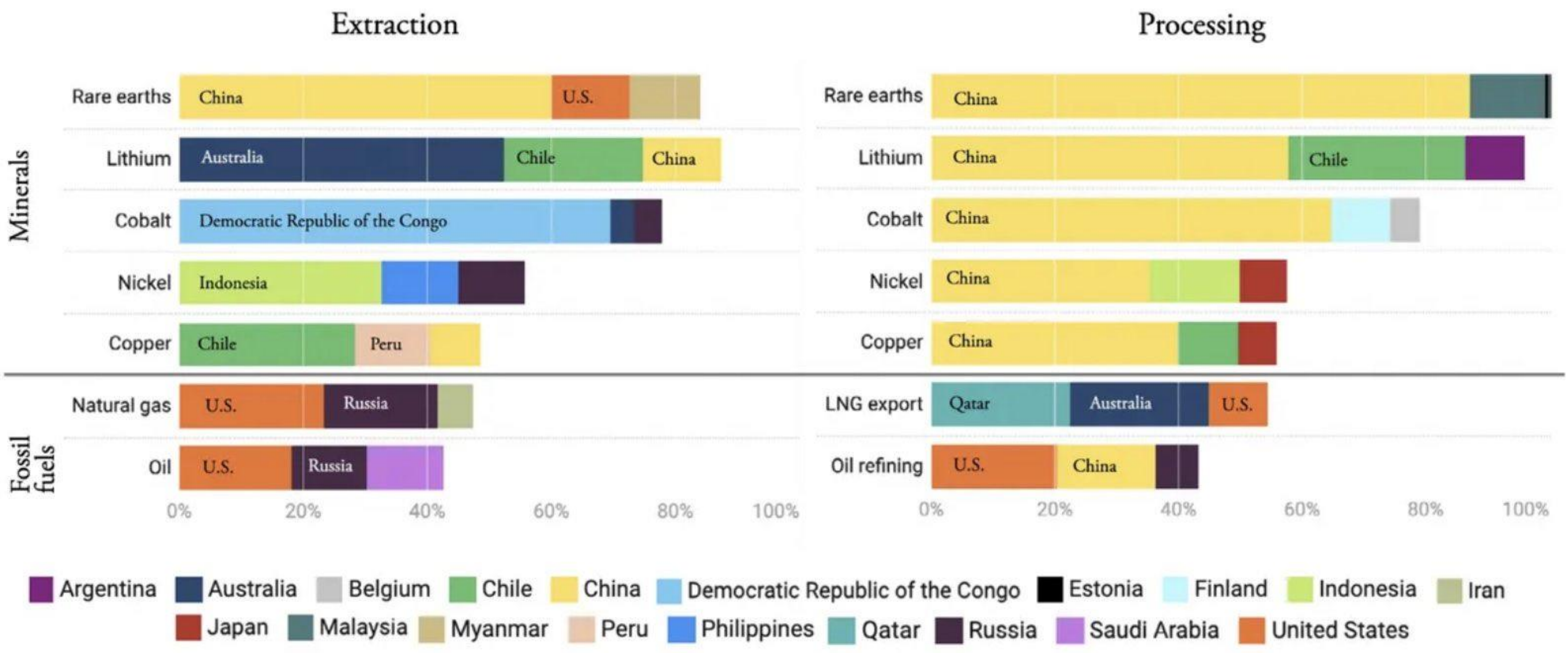
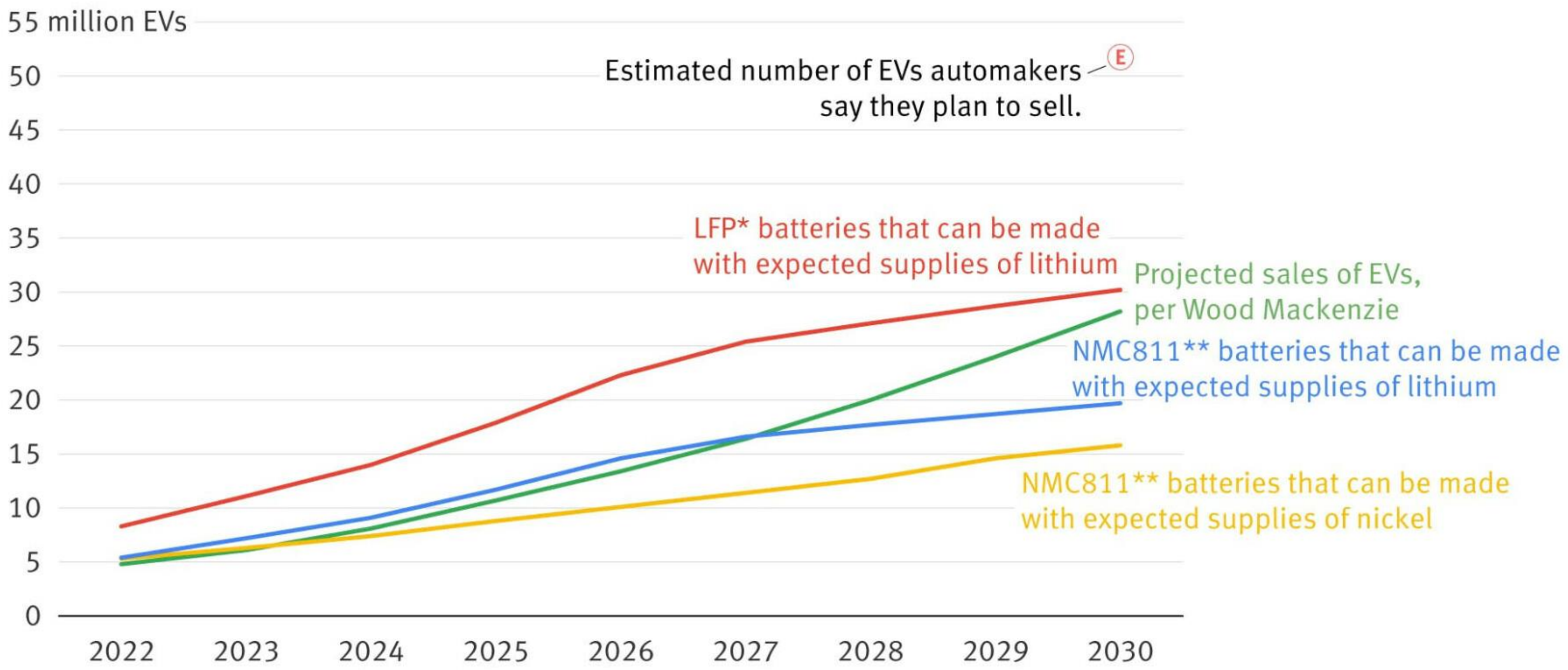


Chart: Canary Media • Source: IEA, The Role of Critical Minerals in Clean Energy Transitions

Out of Power?

A shortage of raw materials means there may not be batteries available for all the EVs automakers say they plan to sell.

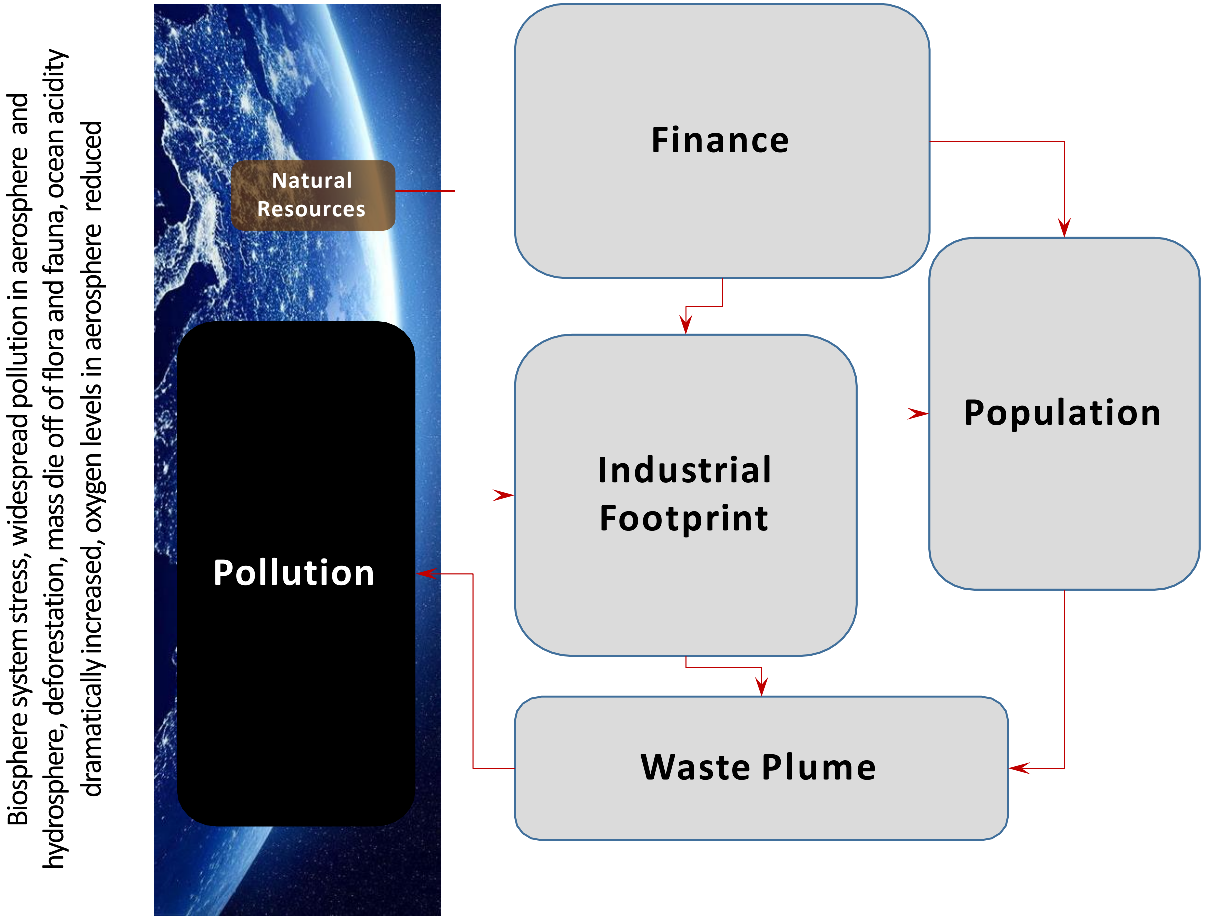


*60 kWh LFP batteries
**90 kWh NMC811 batteries
Sources: Wood Mackenzie, BloombergNEF, BATPaC

STEWARDSHIP OF PLANET EARTH

- An industrial ecosystem of unprecedented size and complexity, that took more than a century to build with the support of the highest calorifically dense source of cheap energy the world has ever known (oil) in abundant quantities, with easily available credit, and unlimited mineral resources

- We now seek to build an even more complex system with very expensive energy, a fragile finance system saturated in debt, not enough minerals, with an unprecedented number of human population, embedded in a deteriorating environment.



CONCLUSIONS - 1

- Additional non-fossil fuel electrical power annual capacity is 36 007.9 TWh
- The proposed non-fossil fuel energy mix translates into 586 032 new power plants
  - *To put this in context, the total power plant fleet in 2018 (all types including fossil fuel plants) was only 46 423 stations*
- Electrical power generated from solar and wind sources are highly intermittent, both across 24-hour cycle and in seasonal context.
  - *A power storage buffer is required if these power generation systems are to be used on a large scale.*
- A conservative estimate is a 4-week power capacity buffer for solar and wind
  - *The power storage buffer capacity for the global electrical power system would be 548.9 TWh*
  - *This is approximately 30 times what the EV fleet needs*
  - *The number of 100 MW stations would be 5.5 million*

CONCLUSIONS - 2

- The task to transition away from fossil fuels is much larger than first thought
- The ERoEI ratio for renewable energy systems is much lower than fossil fuel energy systems. Renewable energy technology may not be strong enough to replace fossil fuels.
- Mineral deposits are decreasing in grade, requiring more energy for extraction per unit of metal. This is happening at a time when energy is becoming more expensive and inelastic in supply
- Technology development in mining is comparatively slow, requiring enormous capital, and long time scales
- Hopes for future technology breakthroughs to ‘somehow’ deliver more commodity resources do not seem to consider the nature of what mineral resources that are left.
- The current ecosystem has no concept of its dependency on minerals and does not consider long term concepts like continuous growth in production against finite resources

Our industrial ecosystem is minerals blind

CONCLUSIONS - 3

- Current thinking has seriously underestimated the scale of the task ahead
- Nuclear is vital to keep industry going but can't be scaled up to be the only energy source
- Biofuels may be the only way to power aviation and plastics. It cannot be scaled up to replace petroleum.
- Battery chemistries other than lithium-ion should/will be developed, each with different mineral resources required
- Current mineral reserves are not adequate to resource the metal production to manufacture just one generation of renewable technology units
    - *2019 mining production is several orders of magnitude too small to be useful in transition away from fossil fuels*
    - *2022 mineral reserves are also not enough to manufacture just one generation of renewable energy technology units*
- Metals of all kinds are about to become much more valuable
    - *Evolution of the industrial ecosystem and its market is likely*
- There is a coming Renaissance for the exploration for and mining of minerals

The shift to "renewables" is a monumental undertaking

- energy density is much lower than fossil fuels and nuclear
- we have never switched from higher density to lower density fuel sources because it makes no economic sense
- new fuel sources such as oil and gas have not displaced coal, but took a larger share as the economy and energy demand grew
- it takes a lot of fossil fuel to mine, process and transport the minerals for this transition
- it also requires of lot of fossil fuels to manufacture solar panels and wind turbines as well as transport and install them, along with specialized large trucks and ships to install wind turbines
- the amount of minerals needed is unprecedented, in many cases much more than we have ever used to date
- acquisition of sufficient minerals poses many challenges including the fact we don't even know where they are
- geopolitical such as China being the largest provider for many critical minerals
- BANANA - Build Absolutely Nothing Anywhere Near Anything

Fossil fuel demand is not going away and oil demand in 2050 is not likely to be significantly less than it is today.
In fact, some projections suggest we need 700 million EVs to keep demand at the same level as today.

It does not appear that Simon's assessment includes all the energy to actually make the transition such as the mining and processing of the minerals, as well as manufacturing and installing the millions of power stations

There are many bottlenecks to increasing mineral supply, such as:

- often hosted in hostile territories
- often found in sensitive areas (sometimes legit, sometimes an excuse)
- other priorities – price and availability of electricity to refine
- water availability – 2000 liters/second for the largest open pit mine
- social license
- environmental regulations
- geopolitics – China, leftist governments, eco-terrorists

Often a challenge to build new power stations (e.g., solar, wind, nuclear) and transmission lines:
NIMBY - BANANA

THE END