Present to critics #14

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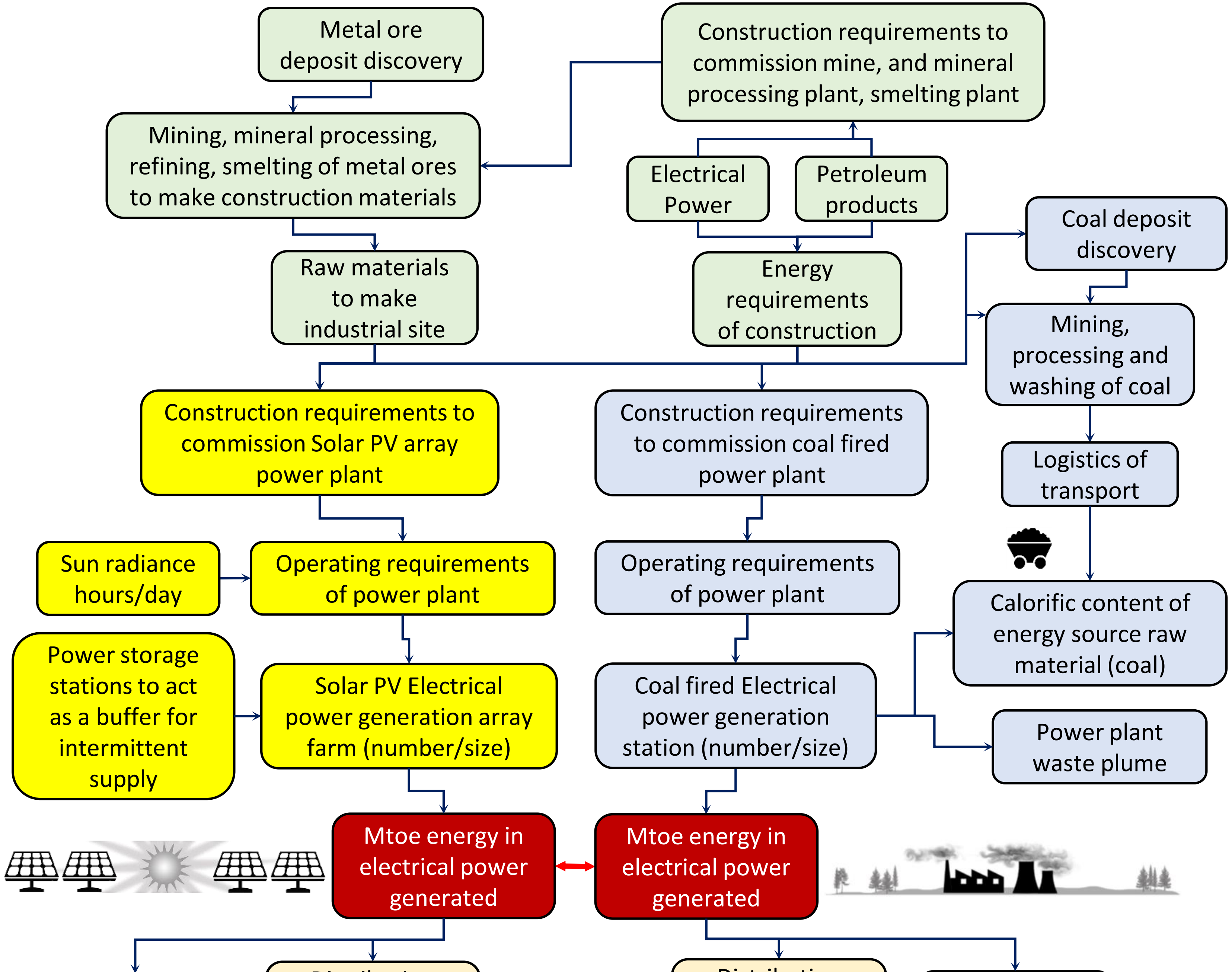
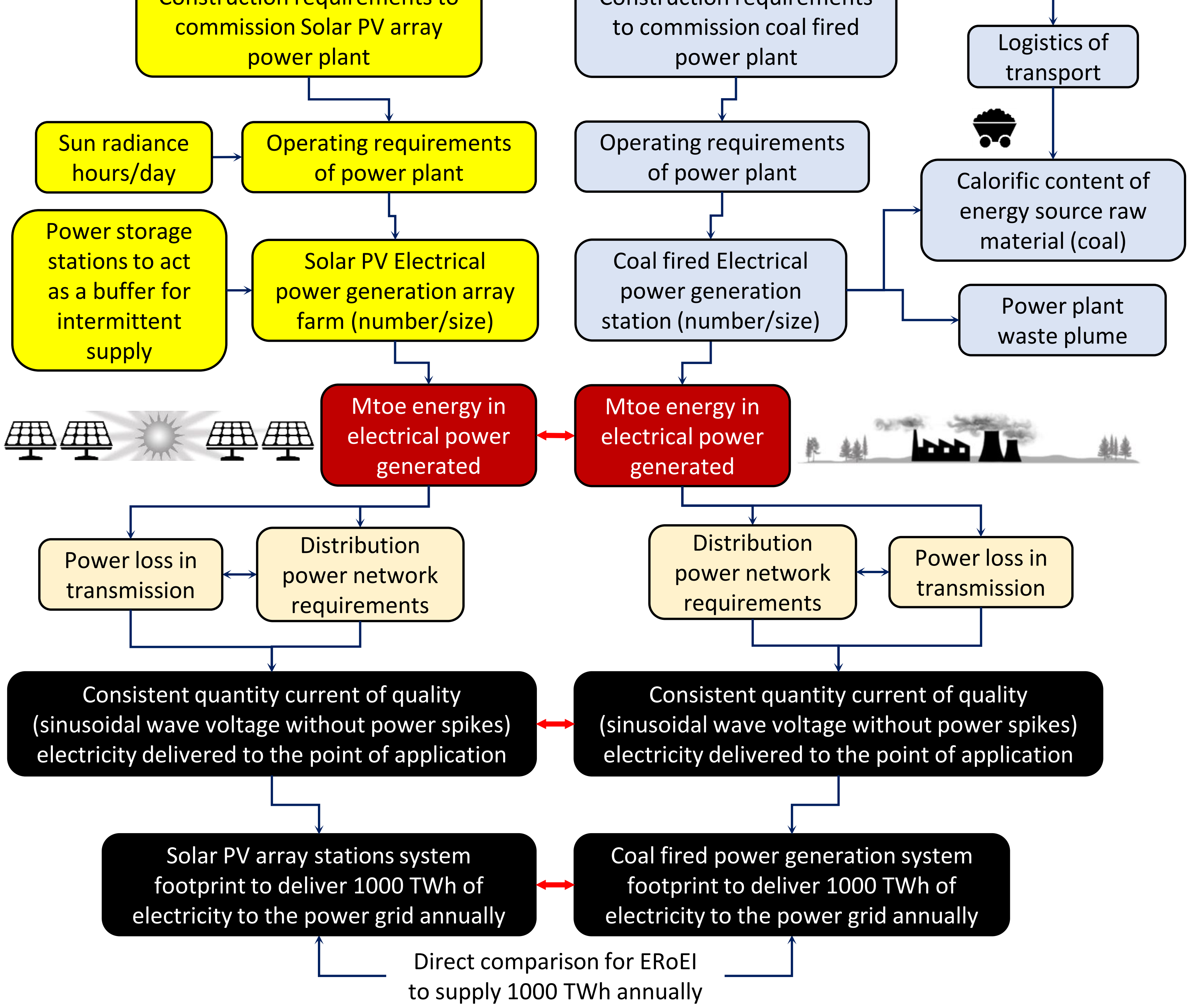
ERoEI is dodgy

(there is no good study)

(cost is usually tangled up with material needs)


Metal ore deposit discovery
Construction requirements to commission mine, and mineral processing plant, smelting plant
Mining, mineral processing, refining, smelting of metal ores to make construction materials
Electrical Power
Petroleum products
Coal deposit discovery
Raw materials to make industrial site
Energy requirements of construction
Mining, processing and washing of coal
Construction requirements to commission Solar PV array power plant
Construction requirements to commission coal fired power plant
Logistics of transport
Sun radiance hours/day
Operating requirements of power plant
Operating requirements of power plant
Calorific content of energy source raw material (coal)
Power storage stations to act as a buffer for intermittent supply
Solar PV Electrical power generation array farm (number/size)
Coal fired Electrical power generation station (number/size)
Power plant waste plume
Mtoe energy in electrical power generated
Mtoe energy in electrical power generated



commission Solar PV array power plant
to commission coal fired power plant
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Mtoe energy in electrical power generated
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Power loss in transmission
Distribution power network requirements
Distribution power network requirements
Power loss in transmission
Consistent quantity current of quality (sinusoidal wave voltage without power spikes) electricity delivered to the point of application
Consistent quantity current of quality (sinusoidal wave voltage without power spikes) electricity delivered to the point of application
Solar PV array stations system footprint to deliver 1000 TWh of electricity to the power grid annually
Coal fired power generation system footprint to deliver 1000 TWh of electricity to the power grid annually
Direct comparison for ERoEI to supply 1000 TWh annually

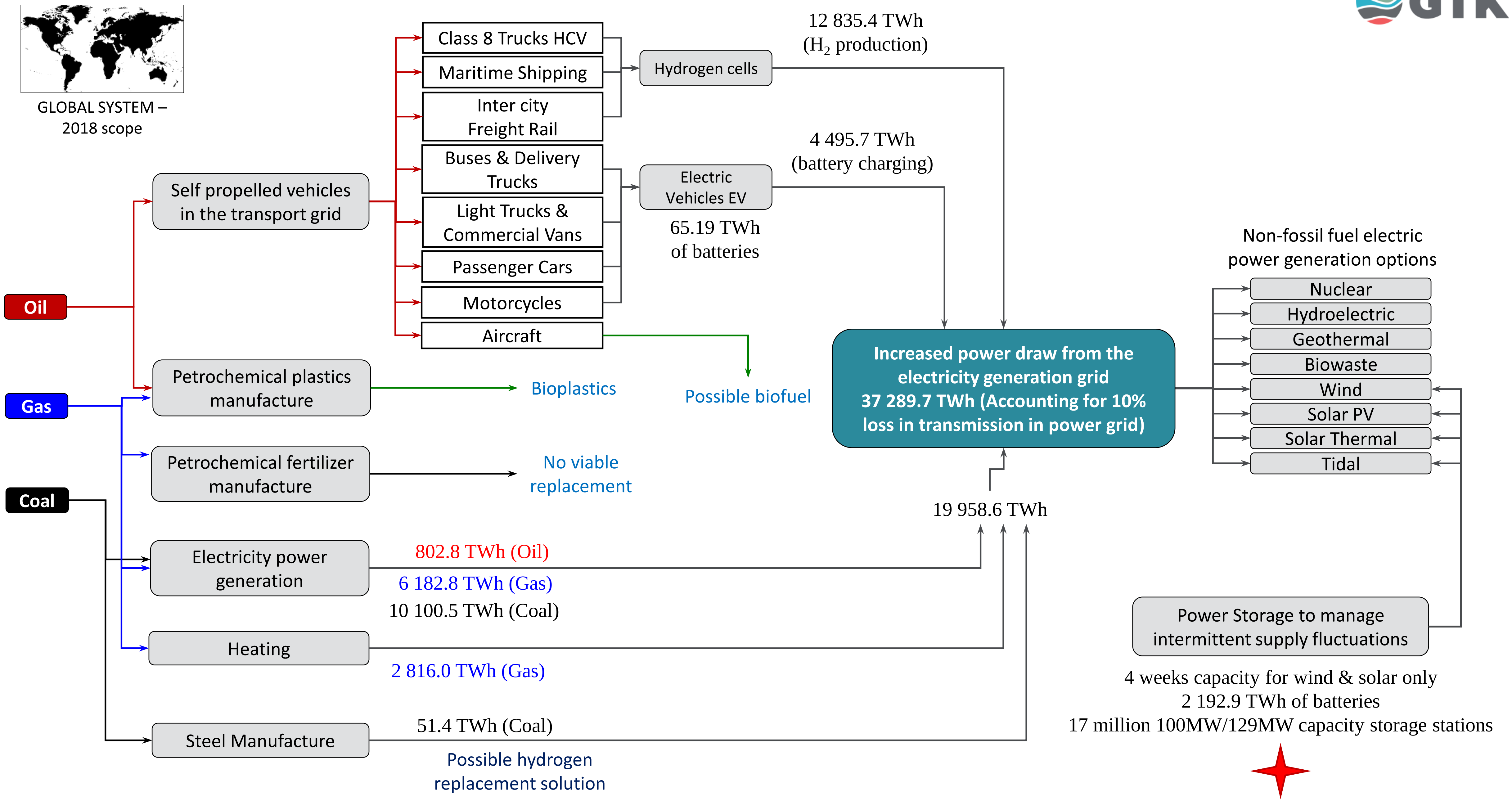
Scope of work done

Baseline calculation

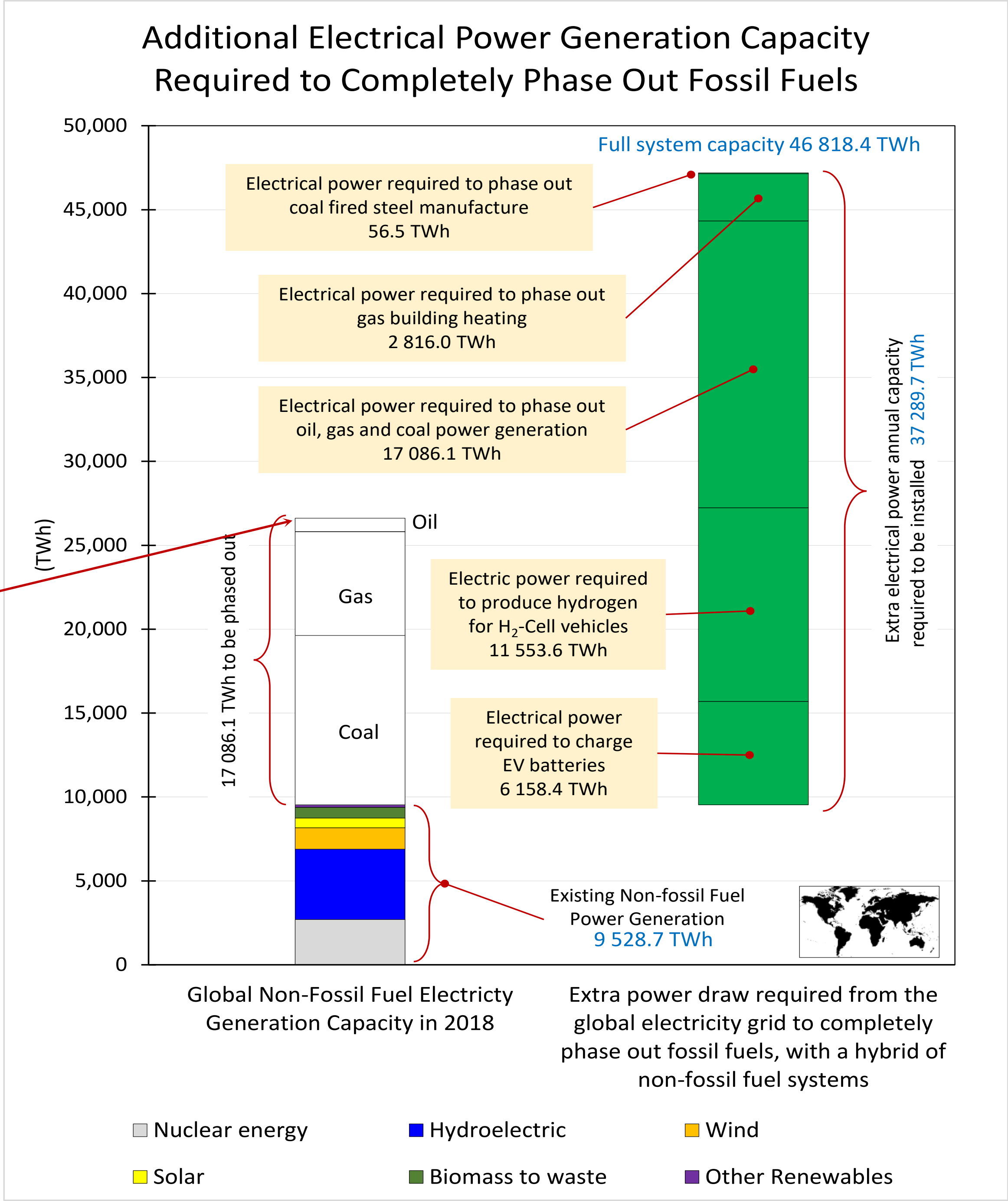
Vehicle Class 	Number of Self Propelled Vehicles in Global Fleet in 2018 (number)	Total km driven by class in Global Fleet in 2018 (trillion km)
Class 8 Truck	28 929 348	1.62
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29 002 253	0.80
Light Truck/Van + Light-Duty Vehicle	601 327 324	7.89
Passenger Car	695 160 429	5.40
Motorcycle	62 109 261	0.16
Total	1 416 528 615	15.87

1.416 billion vehicles   Travelled 15.87 trillion km in 2018

* A Class 8 Truck is a heavy duty truck or semi trailer. Weight 14 969–36 287 kg (and above).


GLOBAL SYSTEM – 2018 scope
Oil
Gas
Coal
Self propelled vehicles in the transport grid
Class 8 Trucks HCV
Maritime Shipping
Inter city Freight Rail
Buses & Delivery Trucks
Light Trucks & Commercial Vans
Passenger Cars
Motorcycles
Aircraft
Hydrogen cells
12 835.4 TWh (H_2 production)
Electric Vehicles EV
4 495.7 TWh (battery charging)
65.19 TWh of batteries
Possible biofuel
Petrochemical plastics manufacture
Bioplastics
Petrochemical fertilizer manufacture
No viable replacement
Electricity power generation
802.8 TWh (Oil)
6 182.8 TWh (Gas)
10 100.5 TWh (Coal)
Heating
2 816.0 TWh (Gas)
Steel Manufacture
51.4 TWh (Coal)
Possible hydrogen replacement solution
19 958.6 TWh
Increased power draw from the electricity generation grid 37 289.7 TWh (Accounting for 10% loss in transmission in power grid)
Non-fossil fuel electric power generation options
Nuclear
Hydroelectric
Geothermal
Biowaste
Wind
Solar PV
Solar Thermal
Tidal
Power Storage to manage intermittent supply fluctuations
4 weeks capacity for wind & solar only
2 192.9 TWh of batteries
17 million 100MW/129MW capacity storage stations

Total electrical power production in 2018 was **26 614 TWh**



We wish to construct an electrical system much larger than the existing power grid, using energy that is more expensive and not as effective as what we have now

This does not include coal and gas used directly by industry to generate heat for manufacture (more than half of coal)

Energy mix and number of power stations

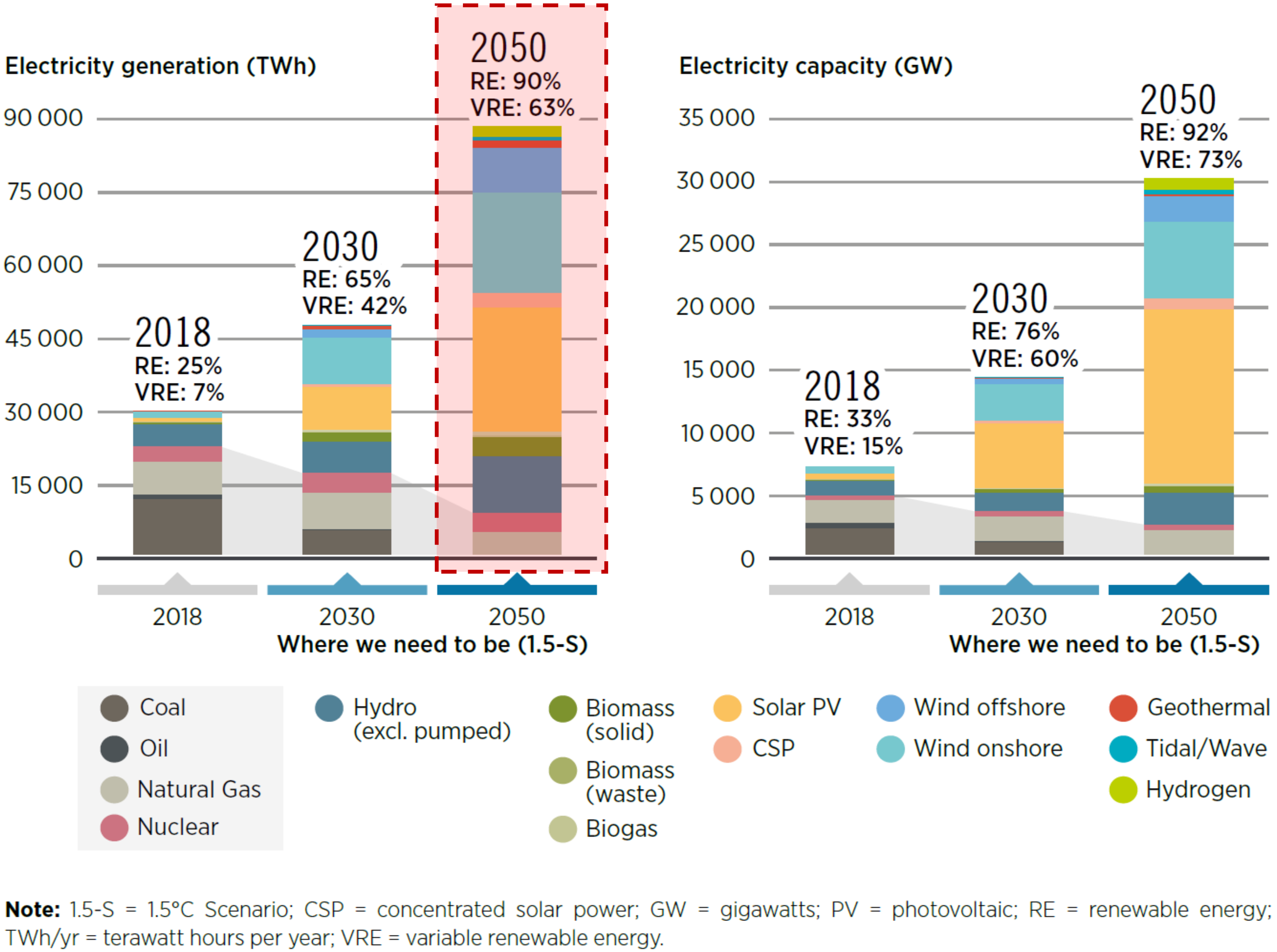


Figure 20. Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050 (Source: IRENA 2022, Figure 2.3, pg 61)

Energy split in this study

Power Generation System	Proposed Proportion of Energy Split on **new** annual capacity (%)
Nuclear	7,50 %
Hydroelectric	13,36 %
Wind Onshore (70% share)	26,83 %
Wind Offshore (30% share)	11,50 %
Solar PV (90% share)	34,50 %
Solar Thermal (10% share)	3,83 %
Geothermal	0,74 %
Biowaste to energy	1,73 %

IRENA (2022): World Energy Transitions Outlook 2022: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi, ISBN: 978-92-9260-429-5, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_World_Energy_Transitions_Outlook_2022.pdf

Power delivered to global grid in 2018

Table 19. Maximum and minimum capacity of electrical power stations by source in 2018

Power Generation System Source	Maximum Installed Plant Capacity Found in Data for 2018 (Global Energy Observatory & Agora Energiewende and Sandbag 2019) (MW)	Power Produced by a **Single** Average Plant in 2018 (kWh)	Minimum Installed Plant Capacity Found in Data in 2018 (Global Energy Observatory) (MW)	Standard Deviation of Installed Plant Capacities for 2018 (Global Energy Observatory) (MW)
Coal	6 600 MW	7,028,812,030	0.9 MW	926.6
Gas	5 040 MW	2,223,247,834	1 MW	560.2
Nuclear	8 212 MW	12,803,184,576	20 MW	1339.4
Hydroelectric	22 500 MW	1,325,746,584	0.005 MW	703.5
Wind	610 MW	81,241,809		
Solar PV	850 MW	33,040,663		
Solar Thermal	392 MW	76,970,000	0.25 MW	73.78
Geothermal	1273 MW	603,226,027	0.05 MW	163
Biowaste to energy		34,581,818		
Fuel Oil Diesel	5 523 MW	850,797,343	0.7 MW	520.5

Global Energy Observatory (2018): Data obtained from http://GlobalEnergyObservatory.org/

Power delivered to global grid in 2018

Table 20. Availability and power produced by average sized stations by source in 2018

Power Generation System Source	Operating hours in practice of existing installed capacity in 2018 (Global Energy Observatory) (h)	Availablity across the year (%)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a **Single** Average Plant in 2018 (kWh)	Power Produced by a **Single** Average Plant in 2018 (GWh)
Coal	8,161	93.2 %	861.3	7,028,812,030	7,028.8
Gas	5,120	58.5 %	434.2	2,223,247,834	2,223.2
Nuclear	6,256	71.4 %	2046.5	12,803,184,576	12,803.2
Hydroelectric	5,882	67.1 %	225.4	1,325,746,584	1,325.7
Wind	2,184	24.9 %	37.2	81,241,809	81.2
Solar PV	998	11.4 %	33.1	33,040,663	33.0
Solar Thermal	1,000	11.4 %	77.0	76,970,000	77.0
Geothermal	6,370	72.7 %	94.7	603,226,027	603.2
Biowaste to energy CHP	1,091	12.5 %	31.7	34,581,818	34.6
Fuel Oil Diesel	3,555	40.6 %	239.3	850,797,343	850.8

Global Energy Observatory (2018): Data obtained from http://GlobalEnergyObservatory.org/

Number of new power stations

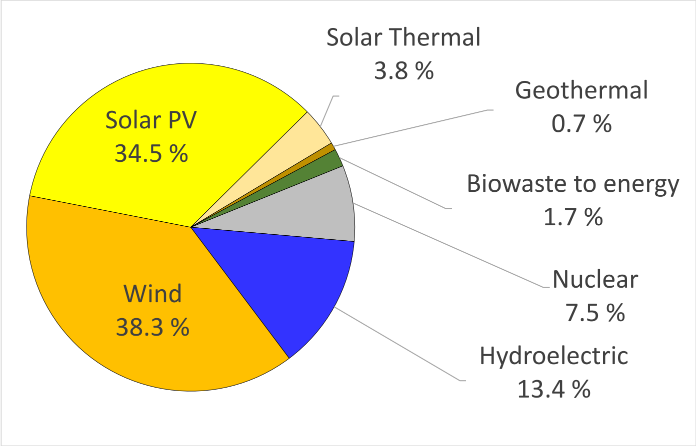
Table 22. Energy split used and number of new power stations in this study

Power Generation System 	Proposed Energy Split non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	7.50%	2.80E+12	1.28E+10	218
Hydroelectric	13.36%	4.98E+12	1.33E+09	3,758
Wind	38.33%	1.43E+13	8.12E+07	175,933
Solar PV	34.50%	1.29E+13	3.30E+07	389,367
Solar Thermal	3.83%	1.43E+12	7.70E+07	18,555
Geothermal	0.74%	2.76E+11	6.03E+08	457
Biowaste to energy	1.74%	6.49E+11	3.46E+07	18,762
Total (kWh)	100.00%	3.73E+13		607,052
Total (TWh)		37,289.7		

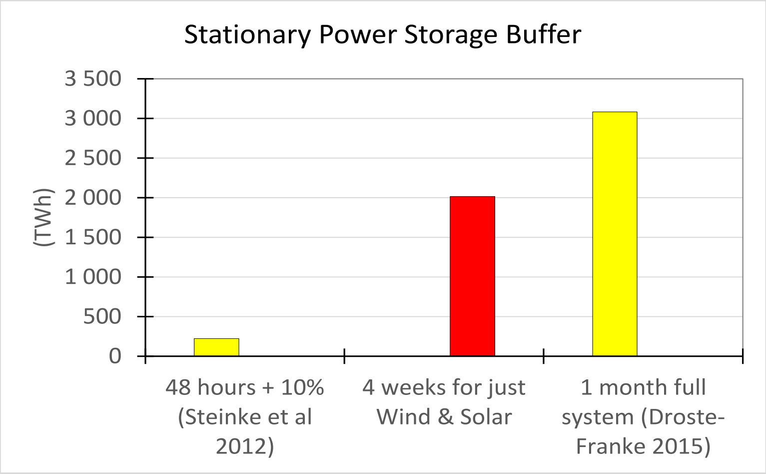
Stationary power storage buffer

(how big should it be?)

Projected New energy split for 2050



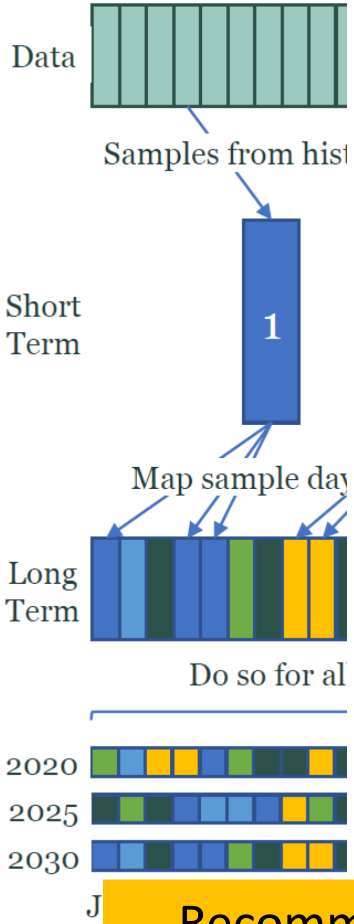
Power Generation System 	Proposed Energy Split non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)	Estimated Installed capacity (GW)
Nuclear	7.50 %	2.80E+12	1.28E+10	218	447
Hydroelectric	13.36 %	4.98E+12	1.33E+09	3 758	847
Wind	38.33 %	1.43E+13	8.12E+07	175 933	6 545
Solar PV	34.50 %	1.29E+13	3.30E+07	389 367	12 888
Solar Thermal	3.83 %	1.43E+12	7.70E+07	18 555	1 428
Geothermal	0.74 %	2.76E+11	6.03E+08	457	43
Biowaste to energy	1.74 %	6.49E+11	3.46E+07	18 762	595
	100.00 %	3.73E+13 37 289.7 Total (TWh)		607 052	22 793 Giga Watts



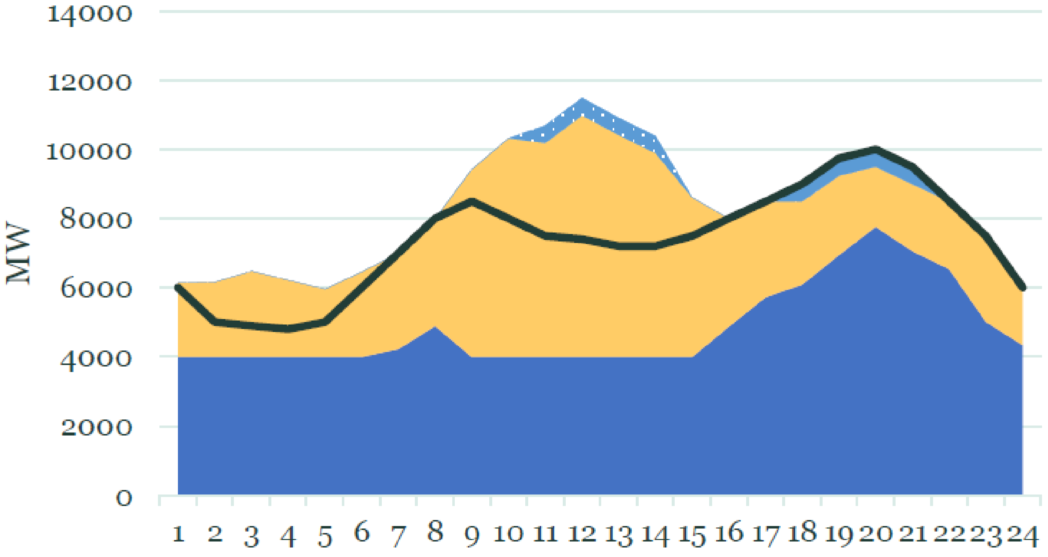
- Global Wind & Solar capacity only (76%) = 26 220.7 TWh
- 4 weeks Wind & Solar capacity only = **2192.9 TWh**
- 48+10% hours Wind & Solar capacity only = **172.3 TWh**

This is the size of the needed power buffer

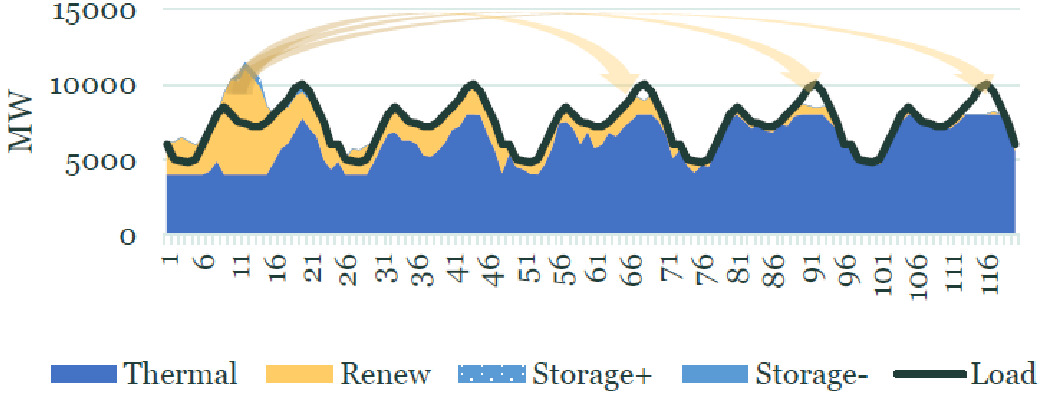
RIO power sector temporal modeling: Hourly operations for 41 … d…

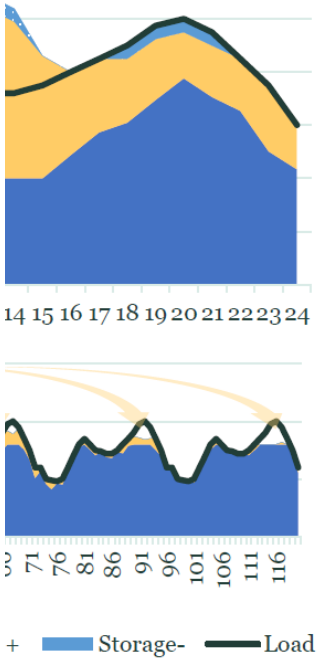


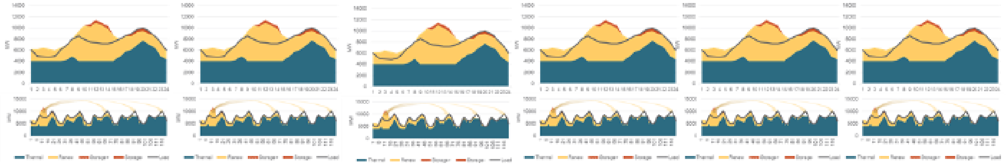
Detailed short term dispatch for every sample day. Dispatch decisions are the same across all days represented by the same sample day.

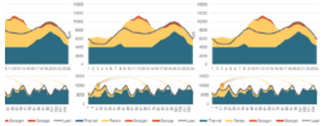


Time sequential long-term storage operations across sample day dispatches. Long-term dispatch decisions are different across days, based on long term needs.



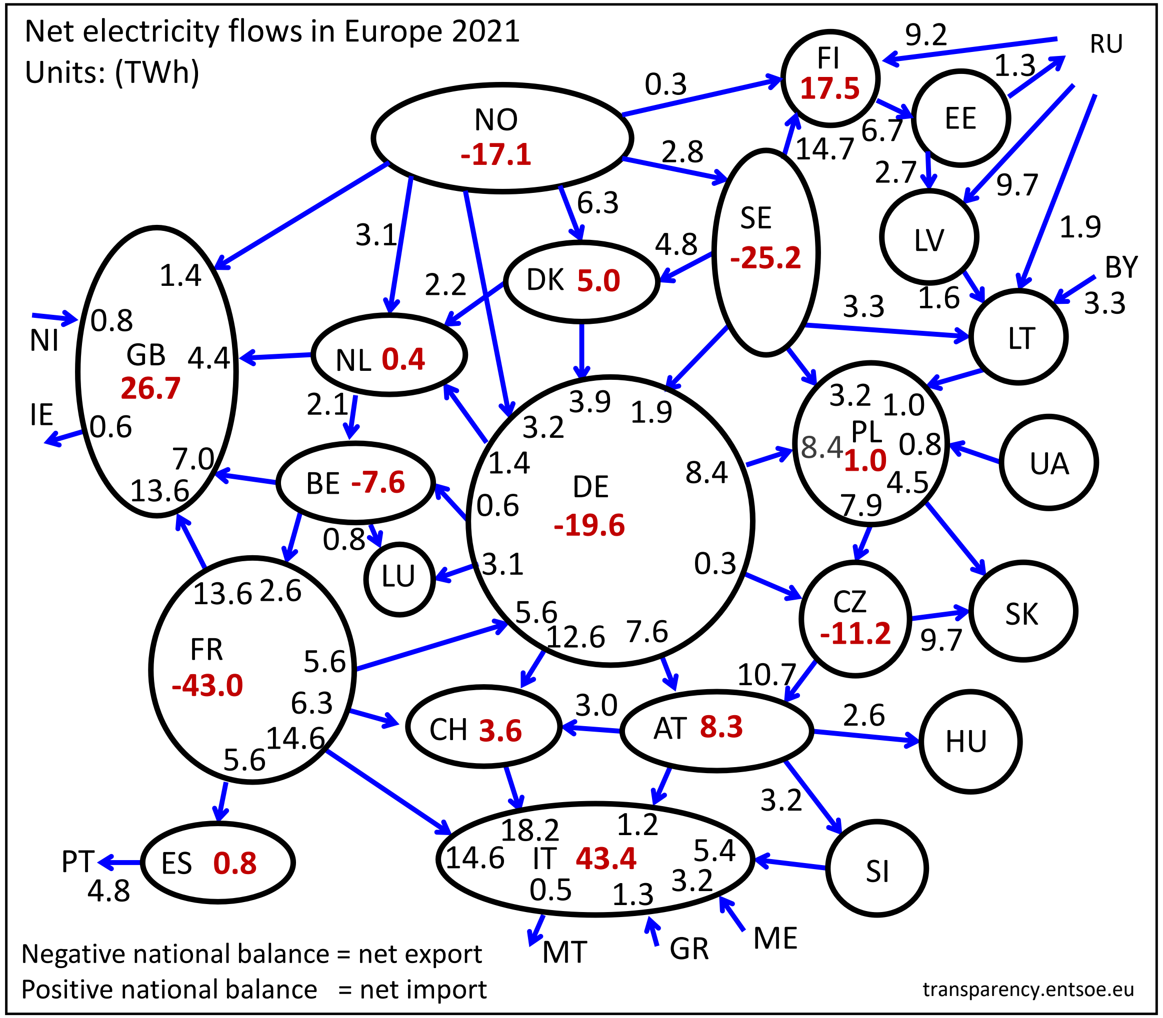






Recommend 5-7 hours power buffer storage

European net electricity exchanges in 2021



(Source: Entsoe)

All networks are balanced and buffered by other external networks

Almost always using fossil fuel sourced power generation (gas in particular)

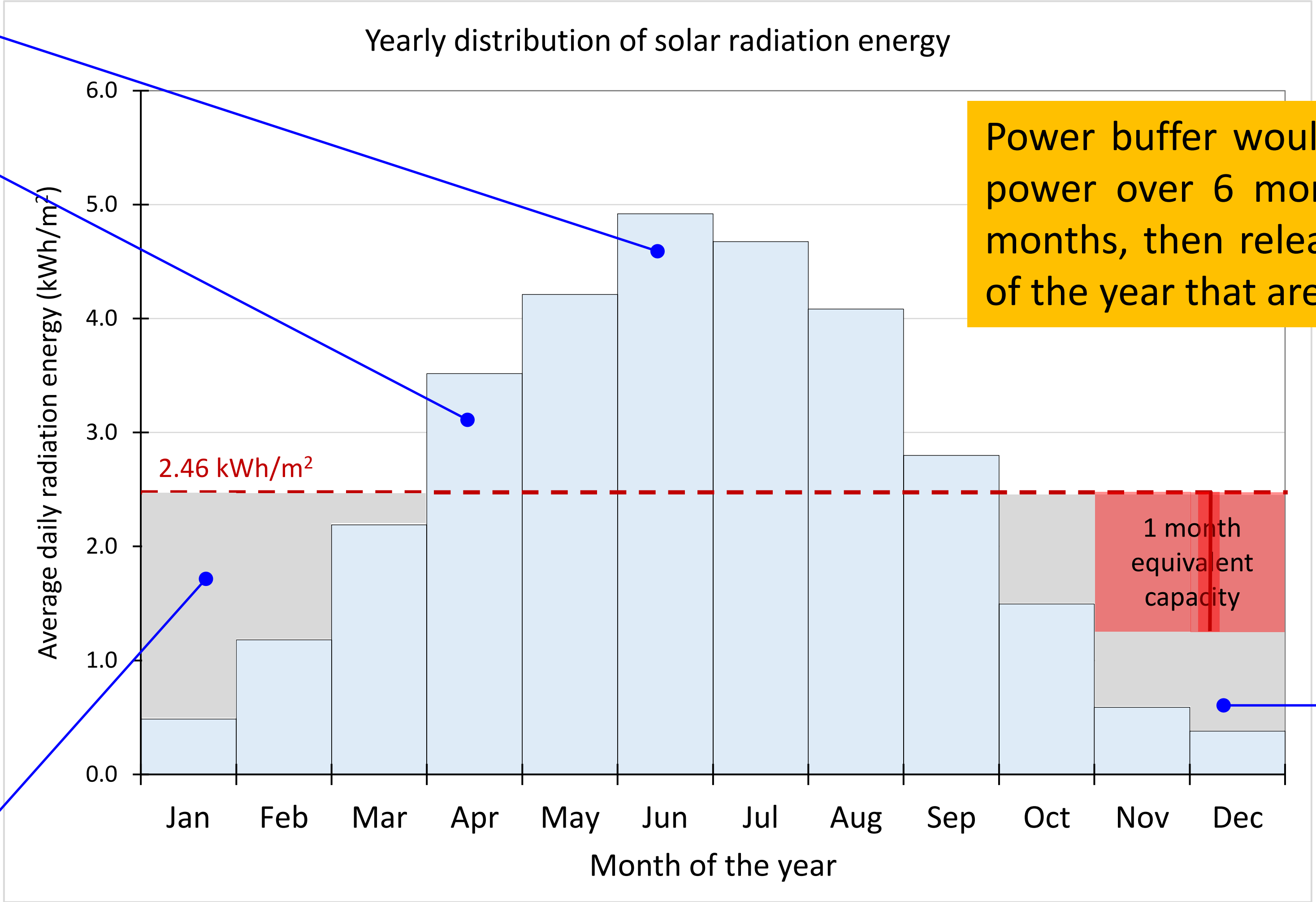
Most existing renewable power grids are balance with fossil fuels systems

We have never had to run a large renewable network in a self sufficient manner

The natural gas power industry is the existing power buffer

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

Excess needs to be stored



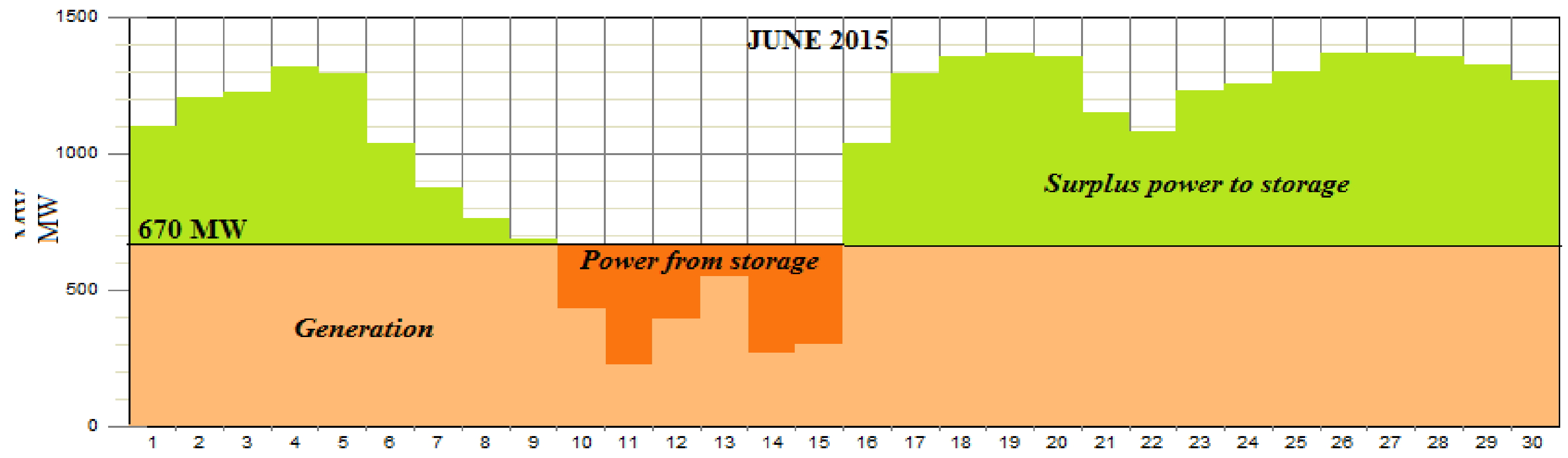
Power buffer would need to collect excess power over 6 months, store it for 6 to 7 months, then release it over the 6 months of the year that are below specification

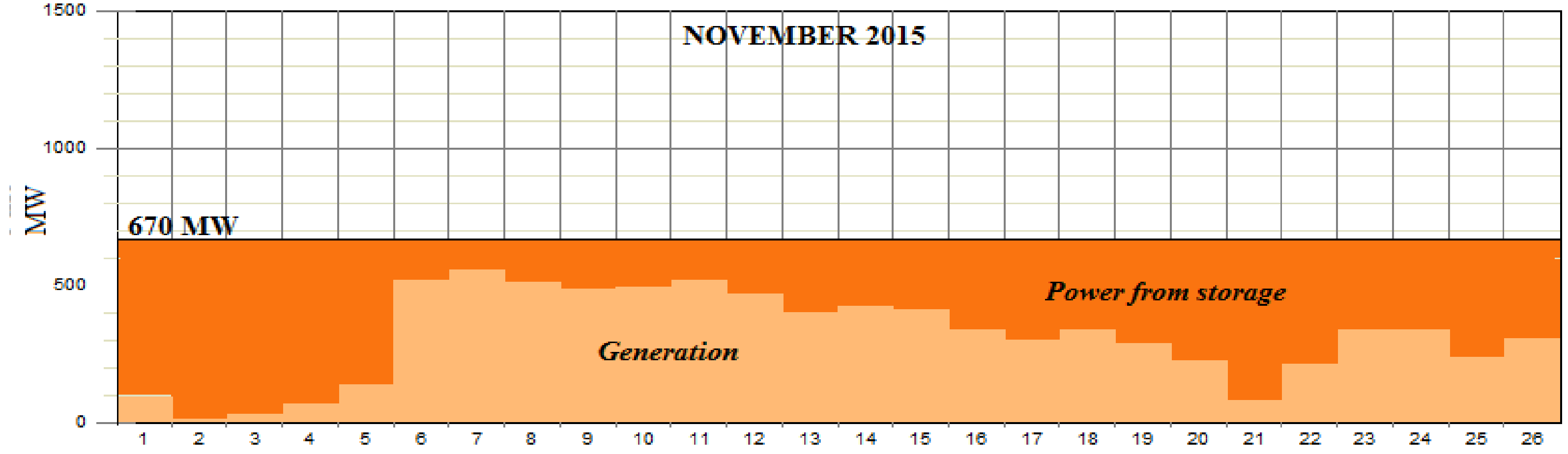
48 hours + 10% equivalent capacity

6 hours equivalent capacity

Excess needs to be released

Average daily CSP generation, June and November 2015





Spain

Power storage and release requirements that would have been needed to maintain a constant 670 MW of baseload generation during June and November (equivalent to 5.9 TWh per year)

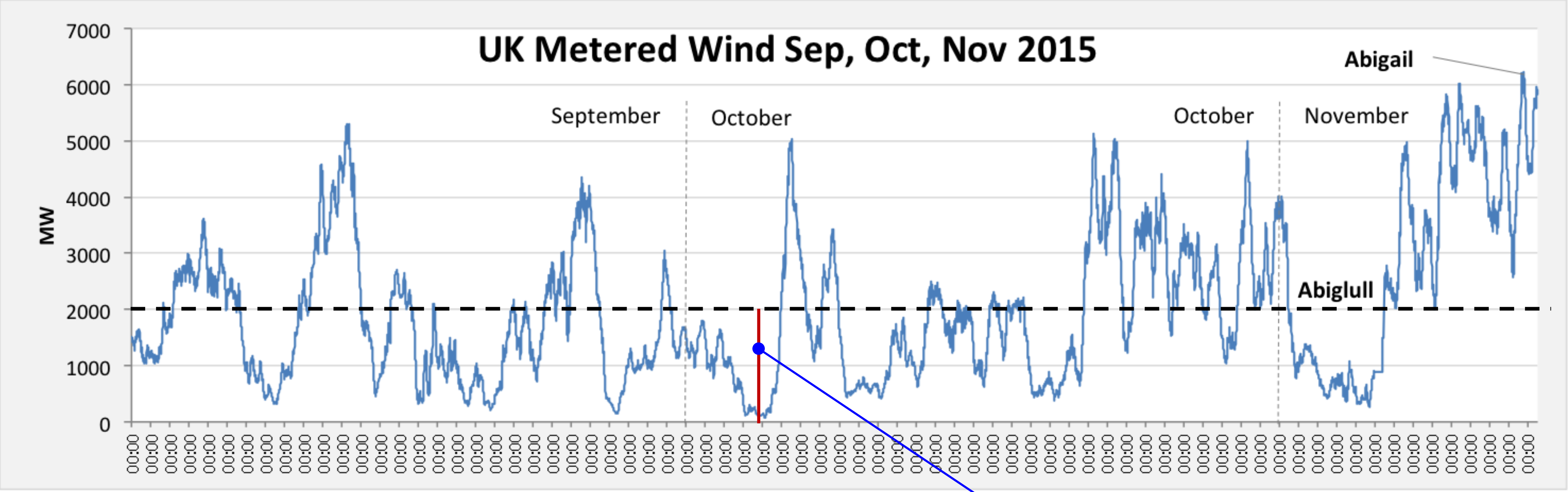
Approximately 260 GWh of storage would have been needed to cover the shortfalls in November alone. This is 16.2 days of buffer capacity, to be stored for approx. 4-6 months.

Mearns, E. (2015, Nov 17): A review of concentrated solar power (CSP) in Spain, Energy Matters blog, http://euanmearns.com/a-review-of-concentrated-solar-power-csp-in-spain/

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

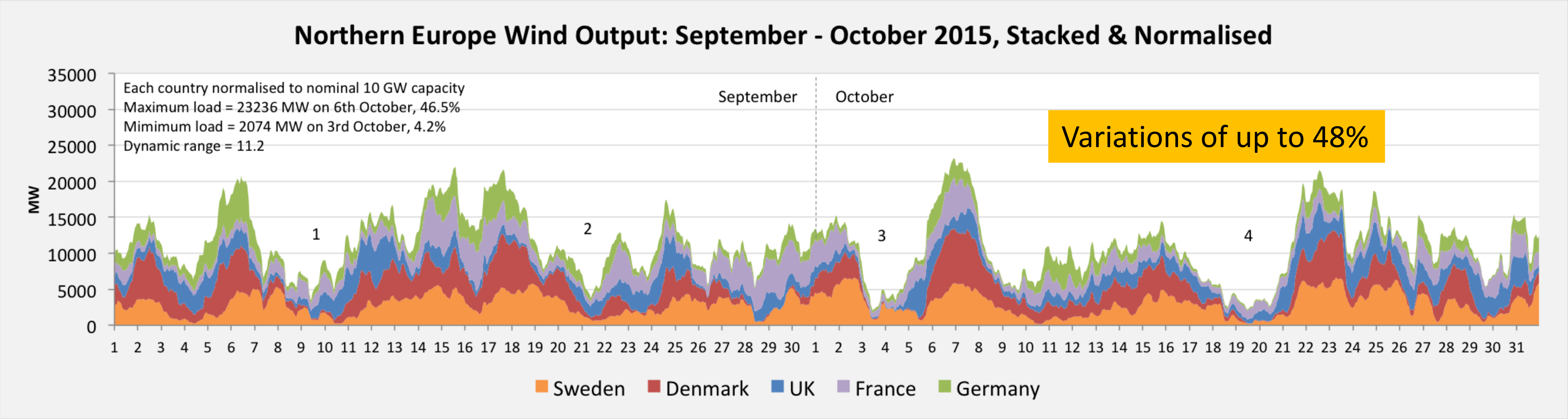
Highly variable of when power was produced



This would be 6 hours of buffer

Wind is highly variable

- When one region has a peak, often others do too. A peak or trough extends over a wide geographical area.
- We can't use say Germany to balance the UK as a wind farm in Germany would be having the same challenges as a wind farm in the UK



The full year of renewable generation capacity factors in the PJM RTO in the U.S.

GTK

the largest regional transmission organization, directly or indirectly affecting the electricity supply to nearly 100 million people

		PJM Monthly Wind and Solar Capacity Factors 2022/2023												
		January 1/31/22 thru 1/30/23	Feb-22	Mar-22	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Total
Solar 3,184 MW Capacity	MWh potential	2,837,616	2,563,008	2,837,616	2,746,080	2,837,616	2,746,080	2,837,616	2,837,616	2,746,080	2,837,616	2,746,080	2,837,616	**33,410,640**
	Actual MWh	336,822	432,939	586,966	718,934	745,154	865,656	771,788	765,286	677,478	524,646	420,135	311,577	**7,157,381**
	Capacity Factor	**11.9%**	**16.9%**	**20.7%**	**26.2%**	**26.3%**	**31.5%**	**27.2%**	**27.0%**	**24.7%**	**18.5%**	**15.3%**	**11.0%**	**21.4%**
Wind 9,991 MW Capacity	MWh potential	7,433,304	6,713,952	7,433,304	7,193,520	7,433,304	7,193,520	7,433,304	7,433,304	7,193,520	7,433,304	7,193,520	7,433,304	**87,521,160**
	Actual MWh	2,985,067	3,303,952	3,452,911	3,379,448	2,754,655	1,911,078	1,568,729	1,335,725	1,709,928	3,011,020	3,575,208	3,113,890	**32,101,611**
	Capacity Factor	**40.2%**	**49.2%**	**46.5%**	**47.0%**	**37.1%**	**26.6%**	**21.1%**	**18.0%**	**23.8%**	**40.5%**	**49.7%**	**41.9%**	**36.7%**
Blended Renewables Monthly and Annual Capacity Factors		**32.3%**	**40.3%**	**39.3%**	**41.2%**	**34.1%**	**27.9%**	**22.8%**	**20.5%**	**24.0%**	**34.4%**	**40.2%**	**33.4%**	**32.5%**

Not only are the capacity factors low, it turns out that both wind and solar capacity factors reach low points at precisely the seasonally worst possible times, wind at the peak of summer demand and solar at the peak of winter demand.

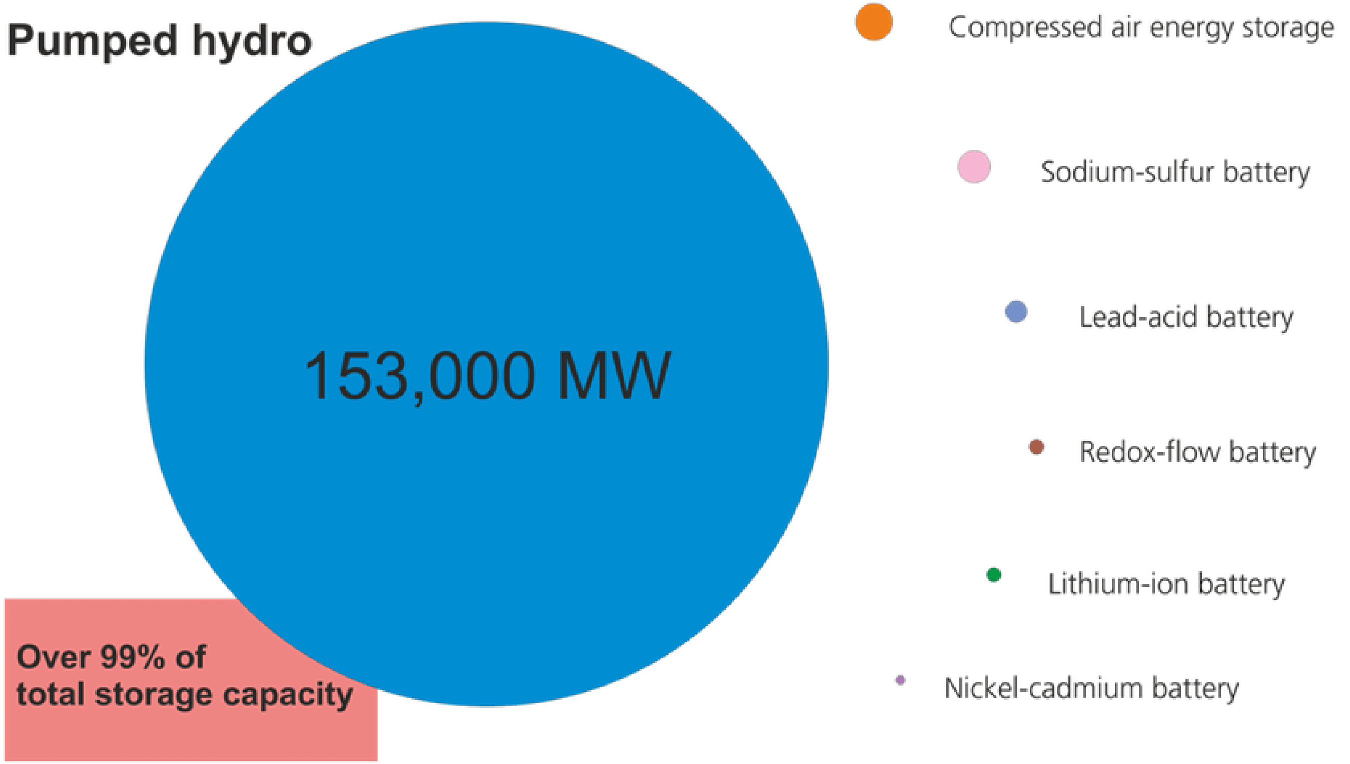
In practical terms, global power generation operating hours in 2018 (Global Energy Observatory)

- *Solar PV units produced 11.4% of the calendar year*
- *Wind units produced 24.9% of the calendar year*

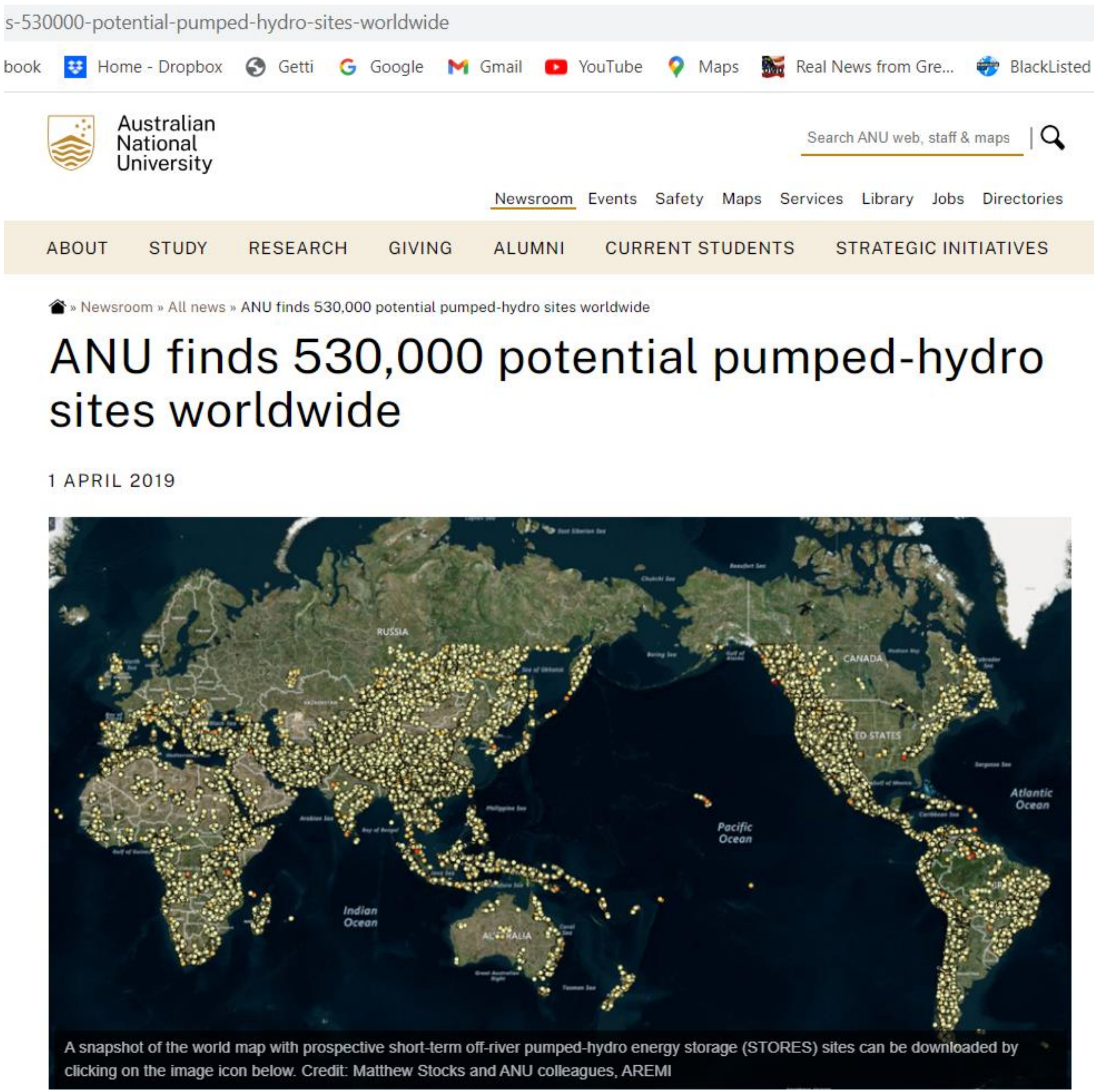
Pumped Hydro Power Storage

Storage Type	Form of energy stored	Technology
Mechanical	Potential	Compressed air energy storage (CAES)
		Pumped storage
	Kinetic	Flywheels
Electrical	Electrostatic	Capacitors
		Super capacitors
	Magnetic	Superconducting magnetic energy storage (SMES)
Chemical	Chemical	Batteries
	Electrochemical	Fuel cells
	Thermochemical	Fuels from solar power
Thermal	High temperature thermal	Sensible heat storage
		Latent heat storage

(Source: J.M.K.C. Donev et al 2018)



GTK


s-530000-potential-pumped-hydro-sites-worldwide

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» Newsroom » All news » ANU finds 530,000 potential pumped-hydro sites worldwide

ANU finds 530,000 potential pumped-hydro sites worldwide

1 APRIL 2019

A snapshot of the world map with prospective short-term off-river pumped-hydro energy storage (STORES) sites can be downloaded by clicking on the image icon below. Credit: Matthew Stocks and ANU colleagues, AREMI

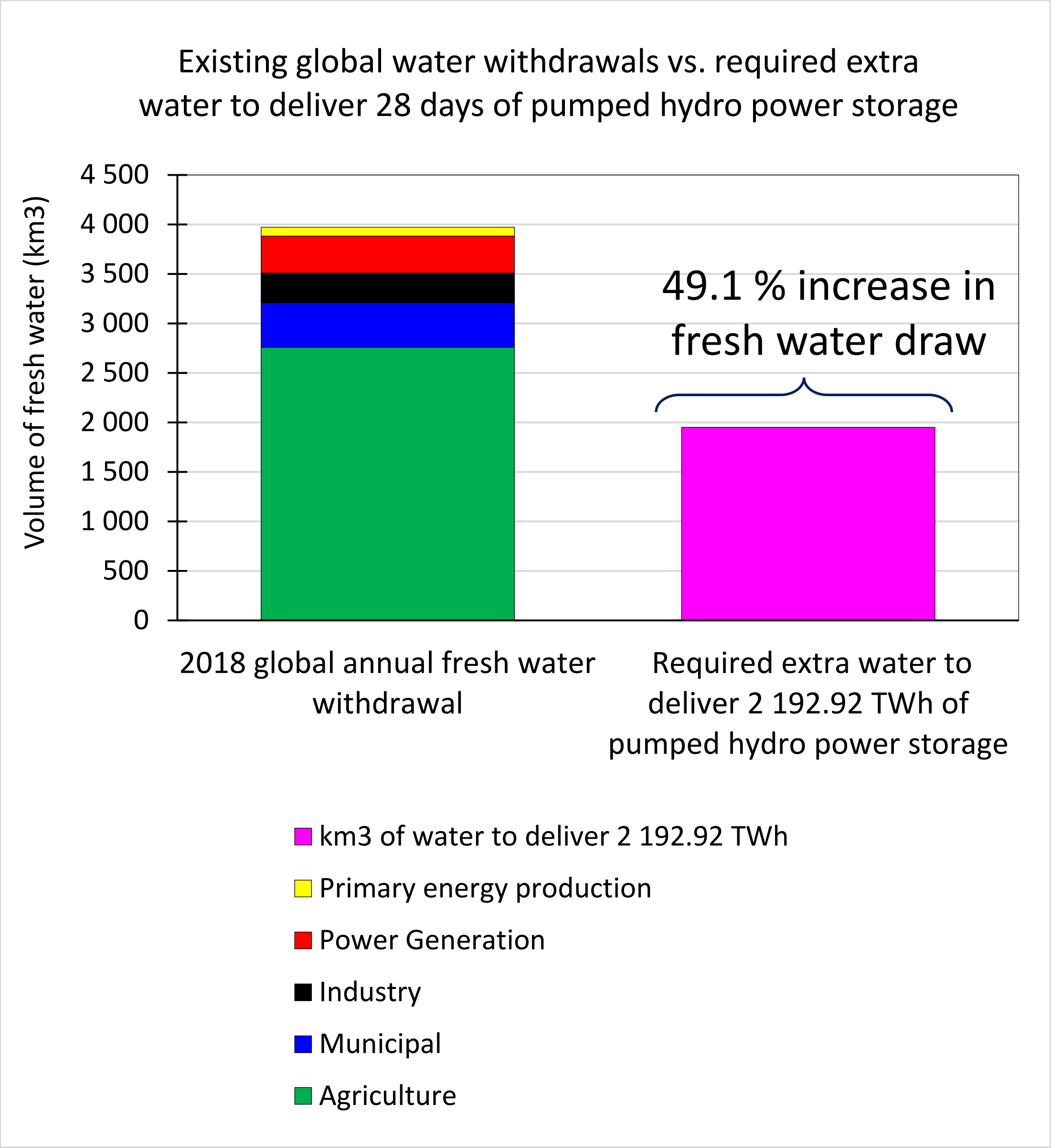
- 1360 GW of installed hydropower in 2021
  - (Hydropower Status Report 2022)
- 164 761 MW of installed PHS
  - (Hydropower Status Report 2022)
- 530 000 possible sites
- What is the net capacity storage for each of these sites?
- Pumped hydro is about 75-81% efficient in the storage of energy
  - (Andrew Blakers et al 2021, A review of pumped hydro energy storage Prog. Energy 3 022003)

https://www.anu.edu.au/news/all-news/anu-finds-530000-potential-pumped-hydro-sites-worldwide

How much fresh water?

- If we take the 28 day buffer, we will need 2 192.92 TWh
- A flow of 100 m^3 of water per second through a turbine/generator operating at 90% efficiency in a system with a head of 570 m will yield electrical power of 500 MW
  - *(Andrew Blakers et al 2021, A review of pumped hydro energy storage Prog. Energy 3 022003)*
- So, 500 MWh will need 360 000 m^3 of water
- Assume 81% efficiency, 500 MWh delivered to the grid will need 444 444 m^3 of water
- So, 2 192 920 000 MWh will require 1 949 262 222 222 m^3 of water

- **1 949.2 km^3**
  - *(1 cubic meter = 1.0×10^{-9} cubic kilometers)*
- Global annual fresh water withdrawals in 2018 was 4 trillion m^3 (3 990 km^3)



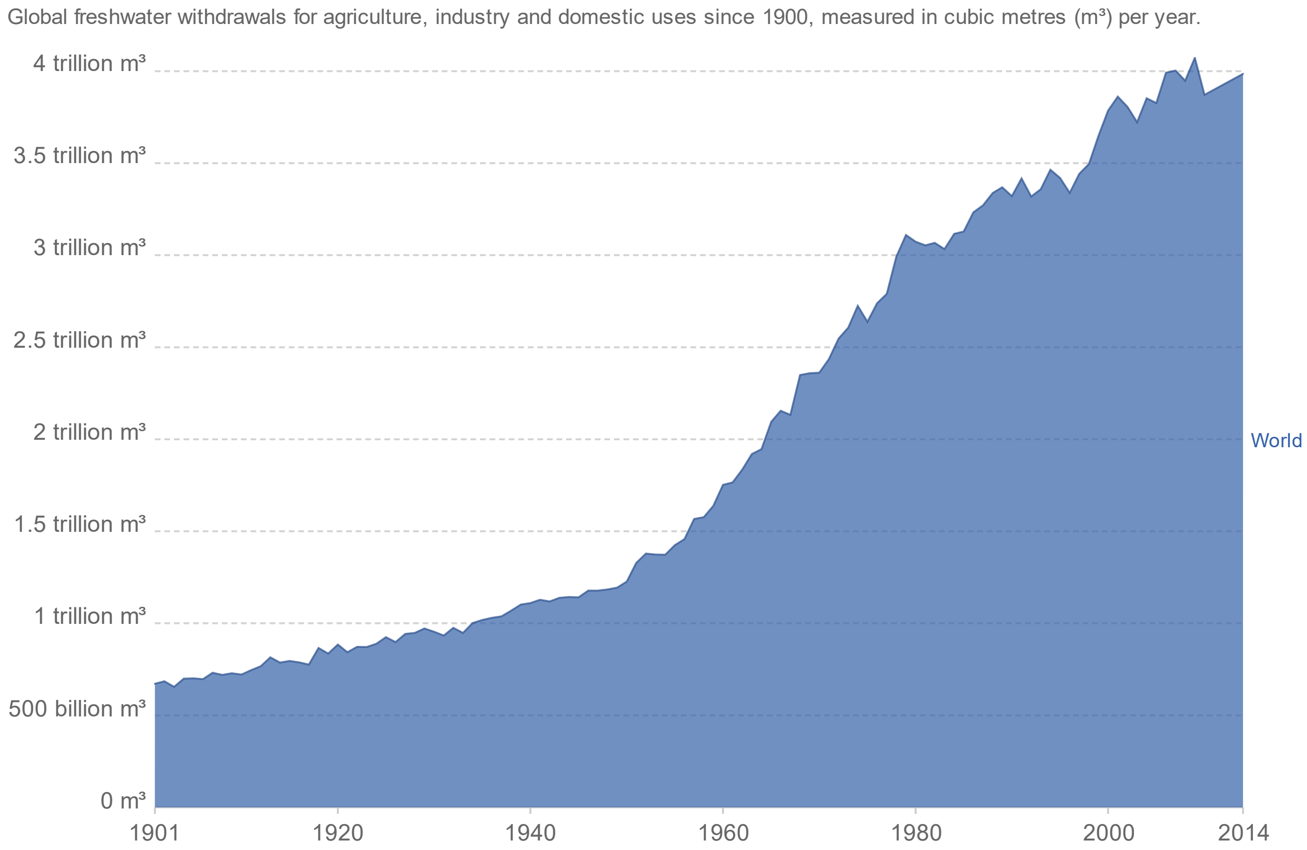


Figure 22.7. Global freshwater use between 1900 and 2014 (Source: Hannah Ritchie and Max Roser (2017) - "Water Use and Stress". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/water-use-stress' [Online Resource])

Batteries

What battery chemistry?

Table 15. Global market proportions of power storage chemistries in 2040 (Source: drawn from IEA 2021, Diouf & Pode 2015)

Battery Chemistry	Acronym	Specific Energy Density (Wh/kg)	Projected Market Proportion for Power Storage in 2040 (%)
Lithium Nickel Manganese Cobalt Oxides	NMC 523	100-135	3,3 %
	NMC 622	100-135	9,9 %
	NMC 811	100-135	9,9 %
Lithium Iron Phosphate	LFP	90-120	73,7 %
Vanadium Redox Battery	VRB	20 - 32	3,3 %
Total			100,0 %

Table 25. 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 %

IEA (2021): The role of critical minerals in clean energy transitions. Special Report of the World Energy Outlook (WEO) team of the IEA. IEA, Paris. 283 p. www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Number of technology units

Number of technology units

Renewable Technology Unit or Service	Number (number)	Estimated total battery capacity (TWh)	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		7.75	
Maritime Medium Vessel (500 GT to 24 999 GT) ♣	44 696		131.73	
Maritime Large Vessel (25 000 GT to 59 999 GT) ♣	12 000		255.72	
Maritime Very Large Vessel (>60 000 GT) ♣	6 307		379.70	
Nuclear Power (Annual Production)			2 796.7	447 037
Hydroelectricity (Annual Production)			4 981.9	847 010
Geothermal Power (Annual Production)			275.9	43 320
Wind Turbines				
3MW Onshore wind turbines (70% share)	1 527 101		10 005.2	4 581 304
3MW Offshore wind turbines (30% share)	654 472		4 287.9	1 963 416
Solar Panels				
450 Watt commerical grade solar panels	28 640 112 291		12 864.9	12 888 051
Stationary power storage buffer				
28 days capacity for wind & solar PV only		2 192.92		
	Total	**2 258.1**		

♣ Numbers drawn from Michaux 2023, and Michaux 2021

- Electric Vehicles
- EV Batteries
- Hydrogen fuel cells
- Wind Turbines
- Solar Panels
- Power Storage Batteries

Quantity of metals 28 days, 48 hours + 10%

Table 39. Total metal quantity required to manufacture one generation of technology units to phase out fossil fuels compared to 2019 global production

Metal	Element	Total metal required produce one generation of technology units to phase out fossil fuels (28 days buffer) (tonnes)	Total metal required produce one generation of technology units to phase out fossil fuels (48 hours + 10% buffer) (tonnes)	Global Metal Production 2019 (tonnes)	Years to produce metal at 2019 rates of production (assuming the 28 day buffer) (years)
Aluminium	Al	305 344 528	305 344 528	63 136 000	4.8
Copper	Cu	4 730 043 227	563 781 004	24 200 000	195.5
Zinc	Zn	36 945 387	36 945 387	13 524 000	2.7
Magnesium Metal	Mg	500 400	500 400	1 120 000	0.4
Manganese	Mn	235 494 311	31 793 521	20 591 000	11.4
Chromium	Cr	7 011 364	7 011 364	37 498 478	0.2
Nickel	Ni	970 817 173	149 281 798	2 350 142	413.1
Lithium	Li	976 274 657	95 404 313	95 170	10 258.2
Cobalt	Co	225 653 328	26 680 148	126 019	1 790.6
Graphite (natural flake)	C	9 280 273 442	872 181 376	1 156 300	6 778.8
Graphite (synthetic)	C			1 573 000 ♦	
Molybdenum	Mo	1 140 617	1 140 617	277094 ‡	4.0
Silicon (Metallurgical)	Si	51 345 993	51 345 993	8 410 000	6.1
Silver	Ag	150 790	150 790	26282 ‡	5.5
Platinum	Pt	2 682	2 682	190 ‡	14.1
Vanadium	V	704 448 633	55 349 535	96021 ‡	6 747.8
Zirconium	Zr	2 614 126	2 614 126	1 338 463 ‡	2.0
Germanium	Ge	4 163 162	4 163 162	143	29 113.0
Rare Earth Element	-				
Neodymium	Nd	983 617	983 617	23 900	41.2
Lanthanum	La	5 970 738	5 970 738	35 800	166.8
Praseodymium	Pr	238 605	238 605	7 500	31.8
Dysprosium	Dy	198 027	198 027	1 000	198.0
Terbium	Tb	17 370	17 370	280	62.0
Hafnium	Hf	224	224	66	3.4
Yttrium	Y	224	224	14 000	0.016

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

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

Metal produced in 2019

Metal in 2022 global reserves

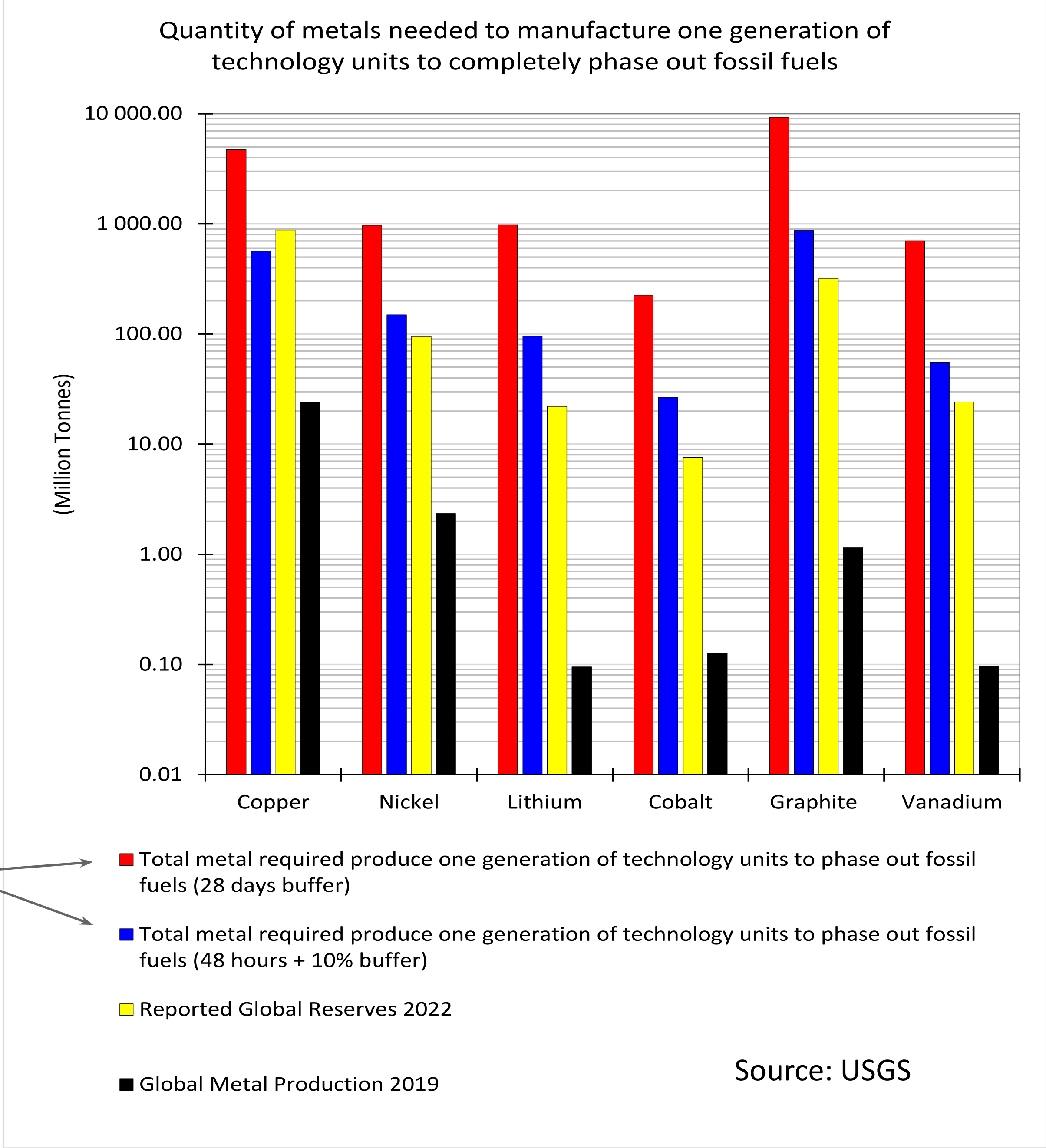
Metal Source: USGS	Total metal required produce one generation of technology units to phase out fossil fuels (tonnes)	Reported Global Reserves 2022 (tonnes)	Global Reseves as a proportion of metals required to phase out fossil fuels (%)
Copper	4 730 043 227	880 000 000	18.60 %
Nickel	970 817 173	95 000 000	9.79 %
Lithium	976 274 657	22 000 000	2.25 %
Cobalt	225 653 328	7 600 000	3.37 %
Graphite (natural flake)	9 280 273 442	320 000 000	3.45 %
Vanadium	704 448 633	24 000 000	3.41 %

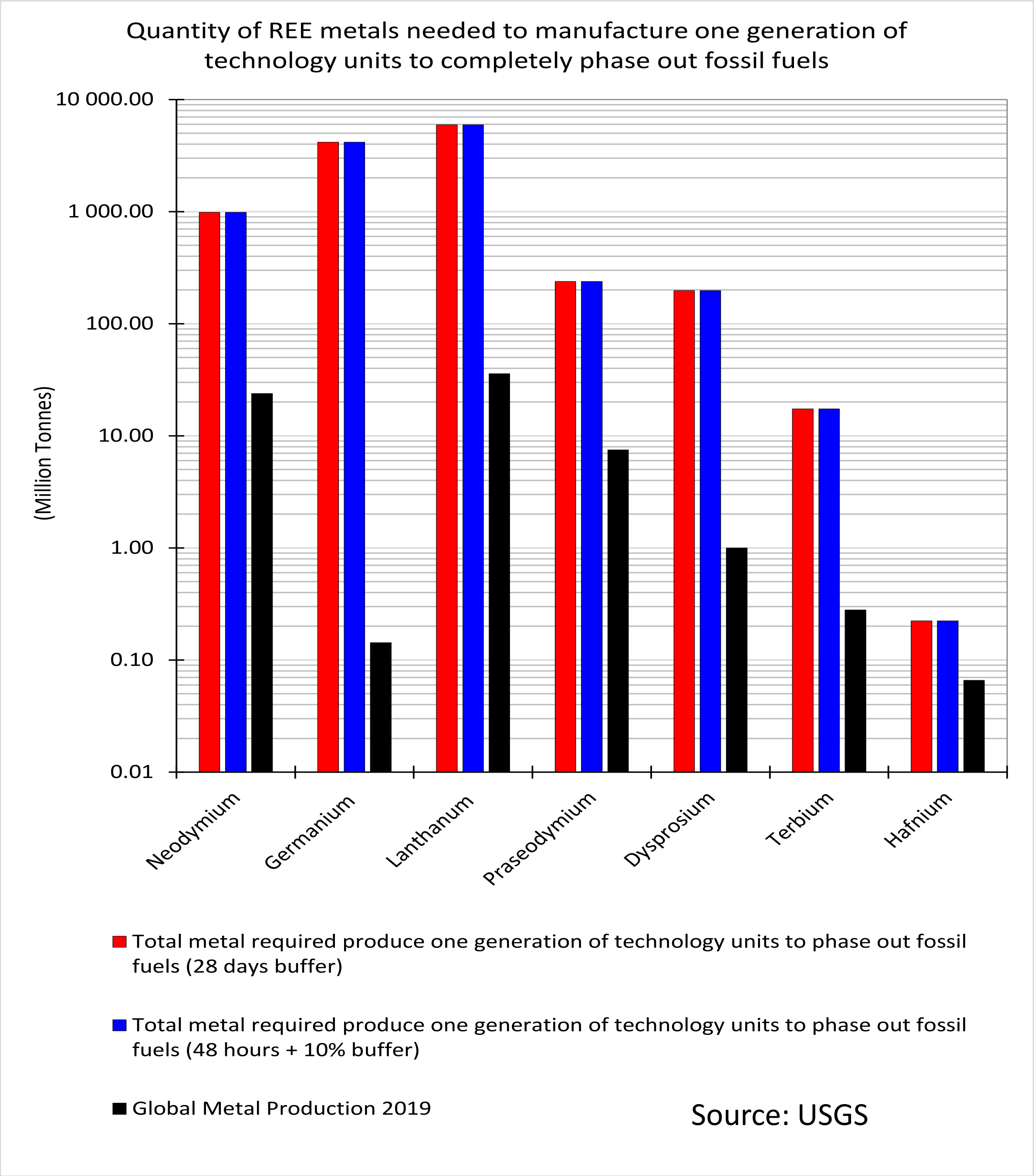
We can make batteries out of something else (Zinc, fluoride, sodium, etc.)

- 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

Remember,
this is for just the first generation of units.

They will wear out in **10 to 25 years**, after which they will need to be replaced



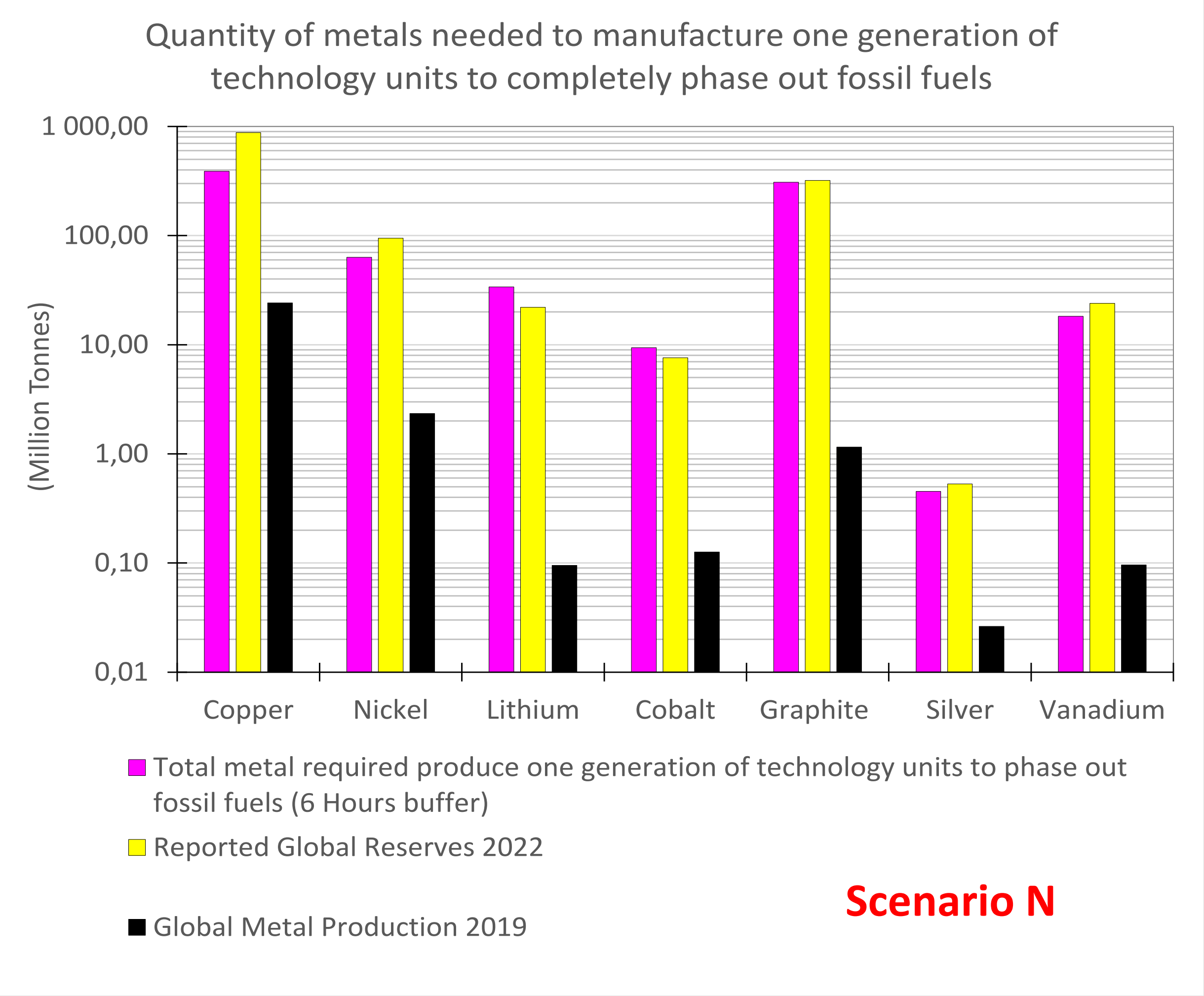


No data on reserves or resources

Scenario N

a 6 hour buffer + 90% reduction of passenger cars
+ 3x build out of wind & solar

The 6 hour buffer – Scenario N



- The passenger car fleet is cut back to 10% (automated AI shared fleet)
- The commercial van fleet is cut by 30% (so now 70% of the commercial van fleet are doing what the whole fleet does now)
- The distance travelled in a calendar year is the same (so now 1/10th of the cars are running flat out doing the same tasks for existing passenger car fleet)
- Heavy trucks, buses, rail and maritime shipping are unchanged
- The power storage buffer is cut back to 6 hours
- There is a 3X build out of wind and solar installed capacity
- Power needs outside the transport fleet are the same

Scenario N – Number of Tables

Table 4. Estimated number of new power stations and installed capacity to globally phase pout fossil fuels (Scenario N)

3 x build out of wind and solar

Power Generation System	**Extra** required annual capacity to phase out fossil fuels (GWh)	Proposed Proportion of Energy Split on **new** annual capacity (%)	Power produced by a **single** average plant in 2018 (GWh)	Estimated number of required **new** power plants of average size to phase out fossil fuels (number)
Nuclear	2 796 727,5	7,50 %	12 803,2	218
Hydroelectric	4 981 903,9	13,36 %	1 325,7	3 758
Wind Onshore (70% share)	30 015 598,2	26,83 %	81,2	369 460
Wind Offshore (30% share)	12 863 827,8	11,50 %		52 780
Solar PV (90% share)	38 594 839,5	34,50 %	33,0	1 168 101
Solar Thermal (10% share)	1 428 195,5	3,83 %	77,0	18 555
Geothermal	275 943,8	0,74 %	603,2	457
Biowaste to energy	648 840,8	1,73 %	34,6	18 762

Total (GWh)	91 605 877	1 632 093
Total (TWh)	91 605,9	

Power plant fleet in 2018 was 46 423 stations

35.2 times the sized of the existing fleet

The 6 hour buffer vs production – Scenario N

Metal	Element	Total metal required produce one generation of technology units to phase out fossil fuels (**6 Hours** buffer) (tonnes)	Global Metal Production 2019 (tonnes)	Number of years of production at 2019 rate (number)
Copper	Cu	389 139 158	24 200 000	16,1
Nickel	Ni	63 396 449	2 350 142	27,0
Lithium	Li	33 898 570	95 170	356,2
Cobalt	Co	9 404 502	126 019	74,6
Graphite	C	308 674 200	1 156 300	266,9
Silicon (Metallurgical)	Si	154 037 980	8 410 000	18,3
Silver	Ag	452 371	26 282	17,2
Vanadium	V	18 240 680	96 021	190,0
Neodymium	Nd	1 730 781	23 900	72,4
Germanium	Ge	4 163 162	143	29 113,0
Lanthanum	La	5 970 738	35 800	166,8
Praseodymium	Pr	321 087	7 500	42,8
Dysprosium	Dy	199 353	1 000	199,4
Terbium	Tb	52 110	280	186,1
Hafnium	Hf	224	66	3,4
Yttrium	Y	224	14 000	0,0

Scenario N

The 6 hour buffer vs Reserves – Scenario N

Metal	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	389 139 158	880 000 000	226,14 %
Nickel	63 396 449	95 000 000	149,85 %
Lithium	33 898 570	22 000 000	64,90 %
Cobalt	9 404 502	7 600 000	80,81 %
Graphite (natural flake)	308 674 200	320 000 000	103,67 %
Vanadium	18 240 680	24 000 000	131,57 %

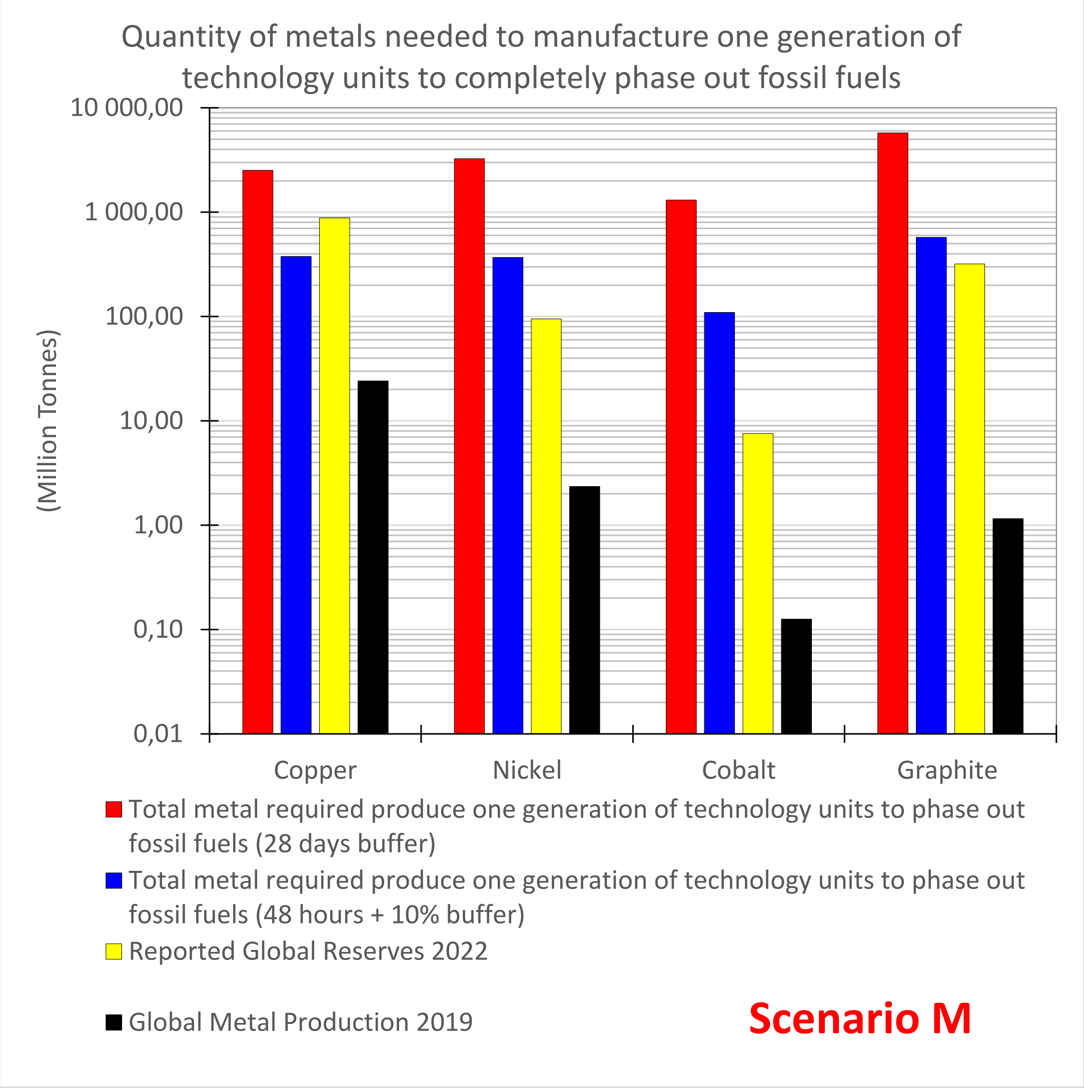
Scenario N

- These numbers calculate what is needed for just one generation of tech units
- In 10 – 50 years we do it all again, replacement units (recycling?)

Scenario M

All batteries are made without lithium using a variant of NMC 532 chemistry

All batteries are made without lithium – Scenario M



- All batteries are made without lithium. This is using a variant of the NMC 532 Battery chemistry
- Based on Elon Musks Master Plan 3 2023 Investor Day (https://www.youtube.com/watch?v=Hl1zEzVUV7w)
- So, the metals needed for all batteries will be based on NMC532, except lithium. In a tip of the hat to Musk and his team, it is assumed that the mass of the battery is smaller, thus the mass shortfall of removing lithium is not projected onto the remaining metals. This is to reflect an advance in materials engineering, with a lighter battery mass per kWh.

Scenario M - Reserves

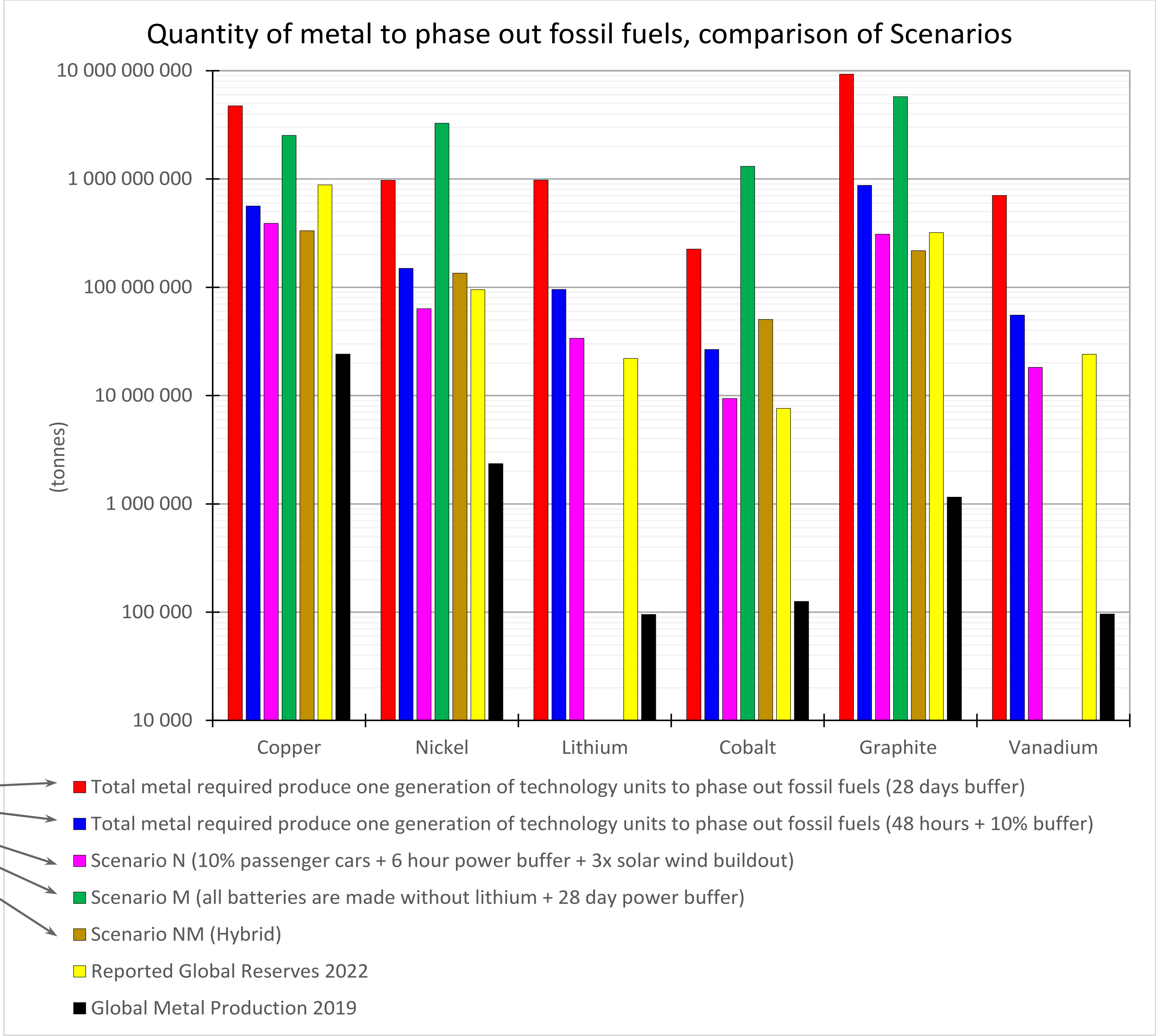
Metal	Total metal required produce one generation of technology units to phase out fossil fuels (tonnes)	Reported Global Reserves 2022 (tonnes)	Global Reseves as a proportion of metals required to phase out fossil fuels (%)
Copper	2 527 472 059	880 000 000	34,82 %
Nickel	3 264 498 462	95 000 000	2,91 %
Lithium	0	22 000 000	
Cobalt	1 309 586 408	7 600 000	0,58 %
Graphite (natural flake)	5 746 153 216	320 000 000	5,57 %

All batteries are made without lithium – Scenario M

Metal	Element	Total metal required produce one generation of technology units to phase out fossil fuels (28 days buffer) (tonnes)	Total metal required produce one generation of technology units to phase out fossil fuels (48 hours + 10% buffer) (tonnes)	Global Metal Production 2019 (tonnes)	Number of years of production at 2019 rate (number)
Copper	Cu	2 527 472 059	376 248 435	24 200 000	104
Nickel	Ni	3 264 498 462	368 620 506	2 350 142	1 389
Lithium	Li	0	0	95 170	
Cobalt	Co	1 309 586 408	109 865 541	126 019	10 392
Graphite	C	5 746 153 216	574 942 582	1 156 300	4 969
Neodymium	Nd	983 617	983 617	23 900	41
Germanium	Ge	4 163 162	4 163 162	143	29 113
Lanthanum	La	5 970 738	5 970 738	35 800	167
Praseodymium	Pr	238 605	238 605	7 500	32
Dysprosium	Dy	198 027	198 027	1 000	198
Terbium	Tb	17 370	17 370	280	62
Hafnium	Hf	224	224	66	3
Yttrium	Y	224	224	14 000	0

Scenario M

Comparison of Scenario’s



Remember,
this is for just the first generation of units.

They will wear out in **10 to 25 years**, after which they will need to be replaced

Substitution of aluminium into copper applications

The are some material science issues to overcome

- Greater thermal expansion is a problem (joints), and one can imagine that connects in solar panels might cause more early failures.
- However, Al is only about 60 % as conductive as Cu. Aluminium has a higher specific electrical resistivity than copper.
- Aluminium is far more prone to become brittle and corroding. It’s liable to crack and break, especially where there is movement and vibration involved. It’s less flexible and doesn’t take kindly to being bent round tight corners.
- Aluminium also prone to galvanic corrosion (copper isn’t) which can lead to a lot of problems.
- Aluminium wire requires a 56% larger cross-section than copper for same current carrying capability.
- Aluminum also has a higher voltage drop over time.
- To avoid galvanic corrosion — serious risk factor especially in damp conditions — aluminum requires a special compound at termination connector points (or an Al-Cu lug). More expense, higher risk.

Hydrogen for power storage

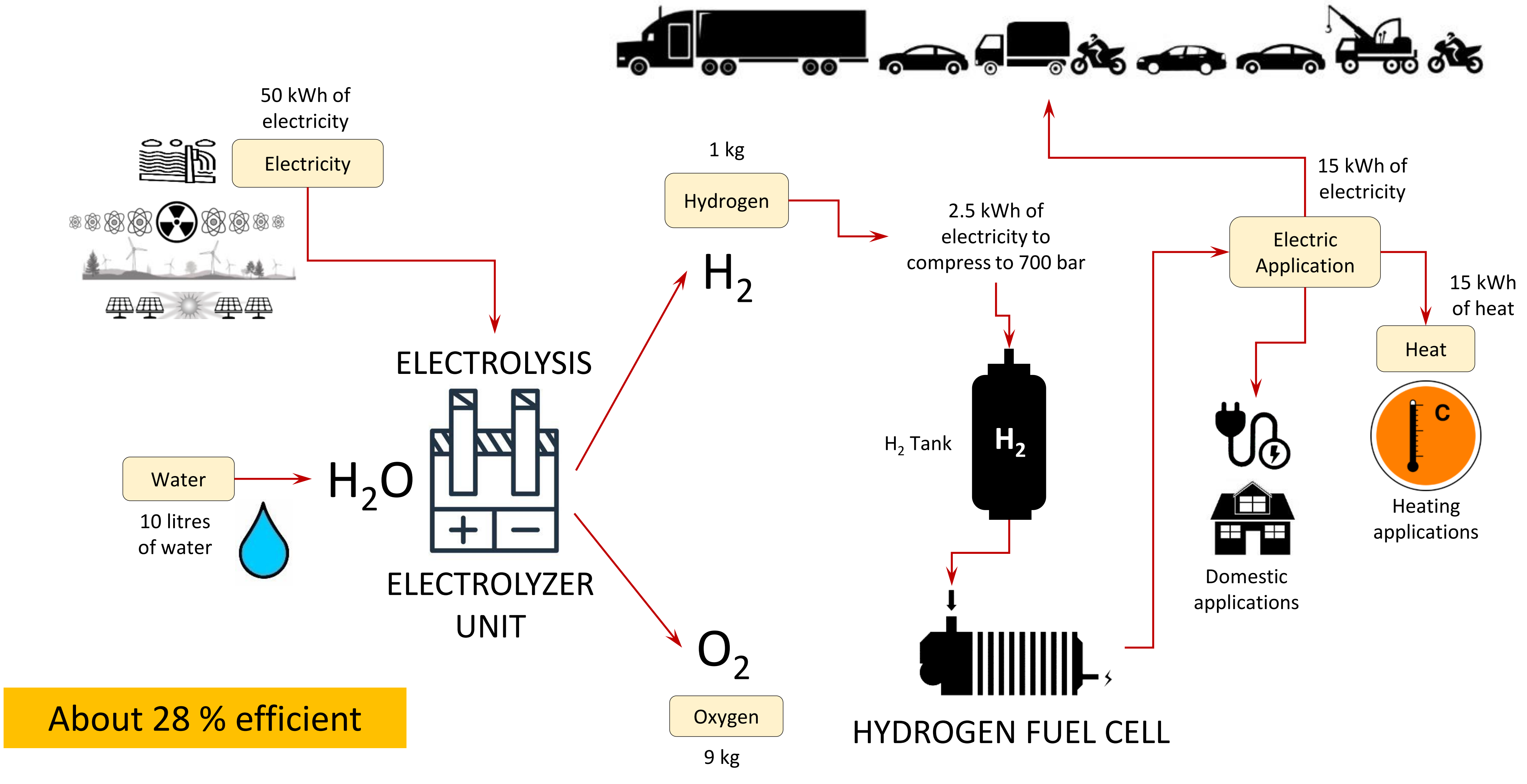


Figure 19.27. Production and use of 1kg of hydrogen in the proposed Hydrogen Economy (Image: Simon Michaux) (Data taken from EIA)

Production of hydrogen as a power storage

- If we take the 28 day buffer, we will need 2 192.92 TWh
- Each 1 kg of H_2 can produce 15 kWh of electricity
- So, 146.2 million tonnes of H_2 is needed annually to deliver the 2 192.92 TWh
- It requires 52.5 kWh to produce 1kg of hydrogen
- 7 675.2 TWh are needed to produce the hydrogen (29% of 2018 electrical power consumption)
  - *This is a 20.6% increase on the annual need for power for Green Transition simulation*

- 124 934 number of stations (using the same IEA 2050 energy mix split)
- Power storage for wind and solar will be needed for this as well

Number of new power stations to support storage

Table 4. Estimated number of new power stations and installed capacity to globally support stationary power storage with hydrogen production

Power Generation System	Global non-fossil fuel electricity production in 2018 (Agora Energiewende and Sandbag 2019) (GWh)	Extra required annual capacity to phase out fossil fuels (GWh)	Proposed Proportion of Energy Split on new annual capacity (%)	Power produced by a single average plant in 2018 (GWh)	Estimated number of required new power plants of average size to phase out fossil fuels (number)
Nuclear	2 701 400	575 901,1	7,50 %	12 803,2	45
Hydroelectric	4 193 100	1 025 345,5	13,36 %	1 325,7	773
Wind Onshore (70% share)	1 303 800	2 059 433,1	26,83 %	81,2	25 349
Wind Offshore (30% share)		882 614,2	11,50 %	81,2	10 864
Solar PV (90% share)	579 100	2 647 842,5	34,50 %	33,0	80 139
Solar Thermal (10% share)	5 500	294 204,7	3,83 %	77,0	3 822
Geothermal	93 000	56 853,6	0,74 %	603,2	94
Biowaste to energy	652 800	133 025,2	1,73 %	34,6	3 847
Total (GWh)	9 528 700	7 675 220,0	100,0 %		124 934
Total (TWh)	9 528,7	7 675,2			

An extra 451.4 TWh for a 28 day secondary buffer is needed (20.6 %)

30.1 million tonnes of H_2
1 579.8 TWh

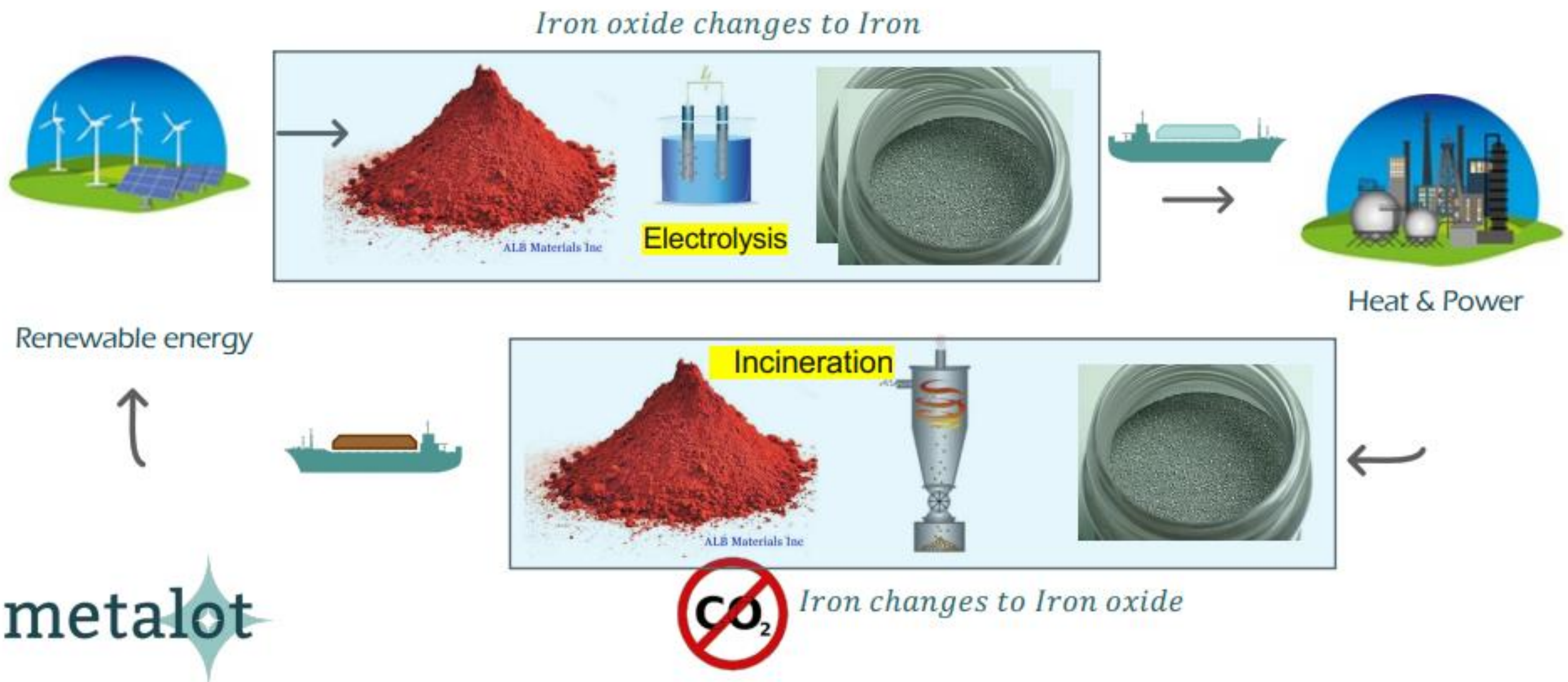
Burning iron powder as power storage

(what might work to replace batteries)

Iron Power – a circular and CO2 free & low NOx energy carrier

Solution: Green Iron Power; green energy storage, transport & import complementary to H2 & NH3

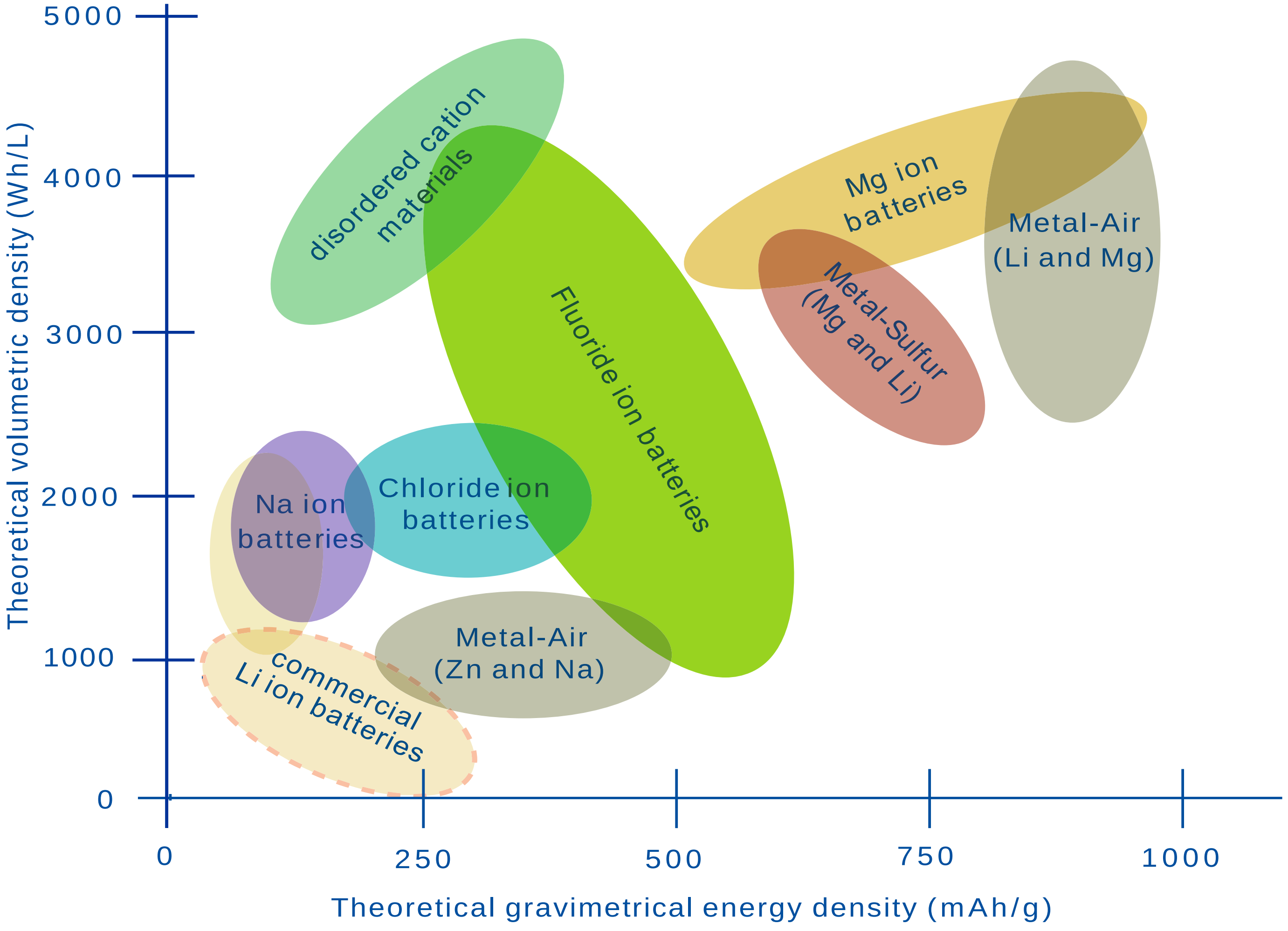
Circular, renewable, no CO2, low NOx, no water consumption



Iron power provides a high temperature heat (up to 1000 ^{0}C) for industrial and household applications

Make Batteries out of something else

Figure 28.2. Overview of the different anode/cathode combinations in terms of specific capacity and volumetric energy density (Source: Gschwind *et al* 2016)



Every battery chemistry I have seen requires Cu, Ni, Mn, Al & Graphite

What is the cathode made of?
What is the Anode made of?

Figure 28.1. Comparison of theoretical gravimetrical energy density to theoretical volumetric density for several battery chemistries (Source: Witter 2021)

To use these new battery chemistries

- My work mapped out the plan as it was in 2020, as perceived by the European policy makers
  - *The outcome mapped out the quantity and type of metals needed to replace the existing system*
  - *It was apparent that the mining industry was probably not going to be able to deliver the needed quantities for multiple basic metals*
- Any new plan should be required to past this fundamental milestone
  - *How much metal will be needed, what kind, where do we get it*
- What is the metal content of a sodium battery (cathode/anode/electrolyte) in units of kg/MW?
  - *So far a commercial secret*

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Kiitos & Thank you