DATA CENTRE TRANSFORMATION

The Energy Paradox Part 1

Why The Green Transition is Impossible

Presented by:

Simon Michaux

Associate Professor

Geological Survey of Finland

The task to phase out fossil fuels is upon us. This requires unprecedented industrial activity to restructure society to a new energy system. The Green Transition will not go as planned, it faces many logistical and practical bottlenecks in application for everyone globally.

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IET Birmingham

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The Energy Paradox Part 1 – Why The Green Transition is Impossible

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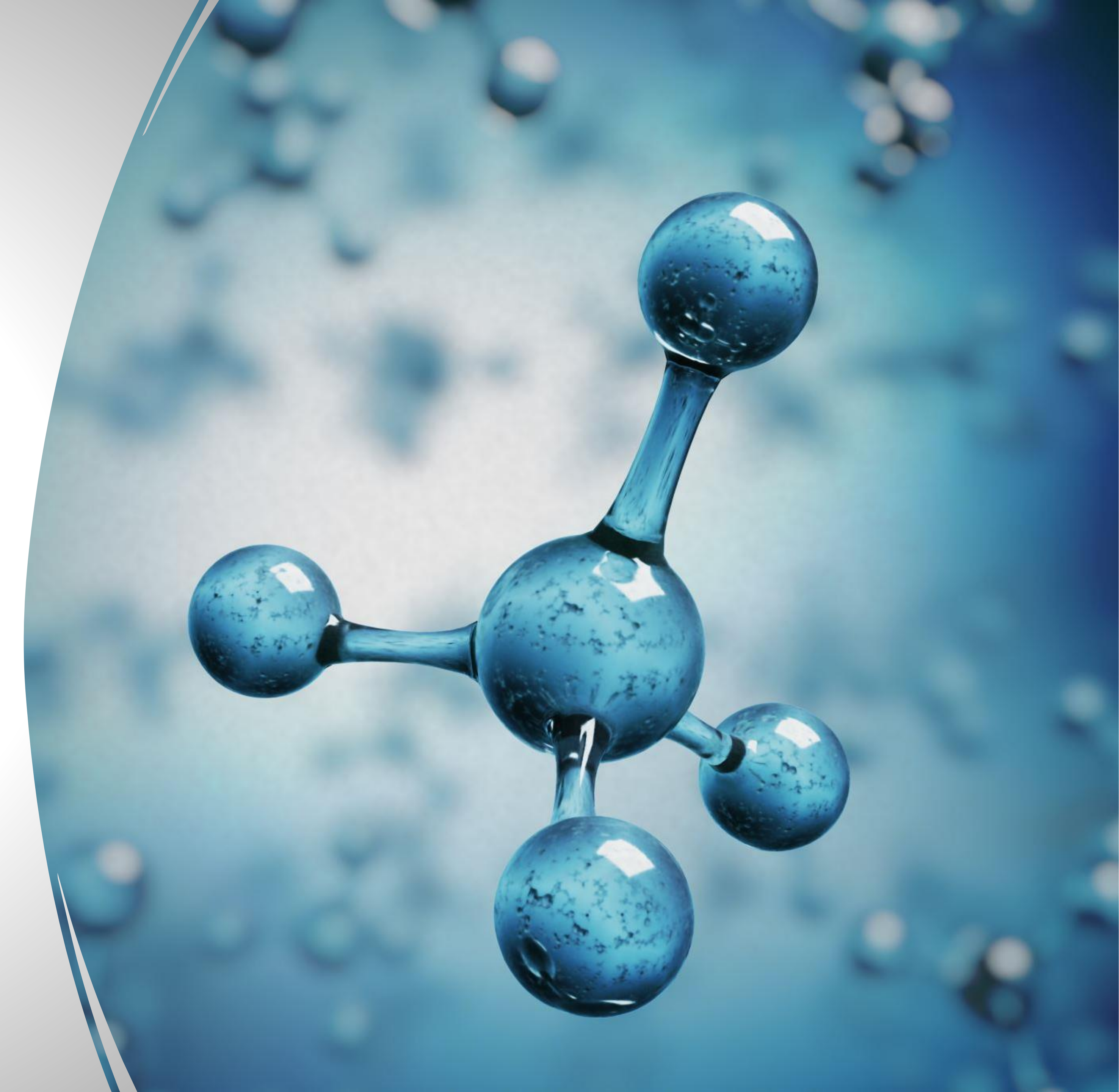
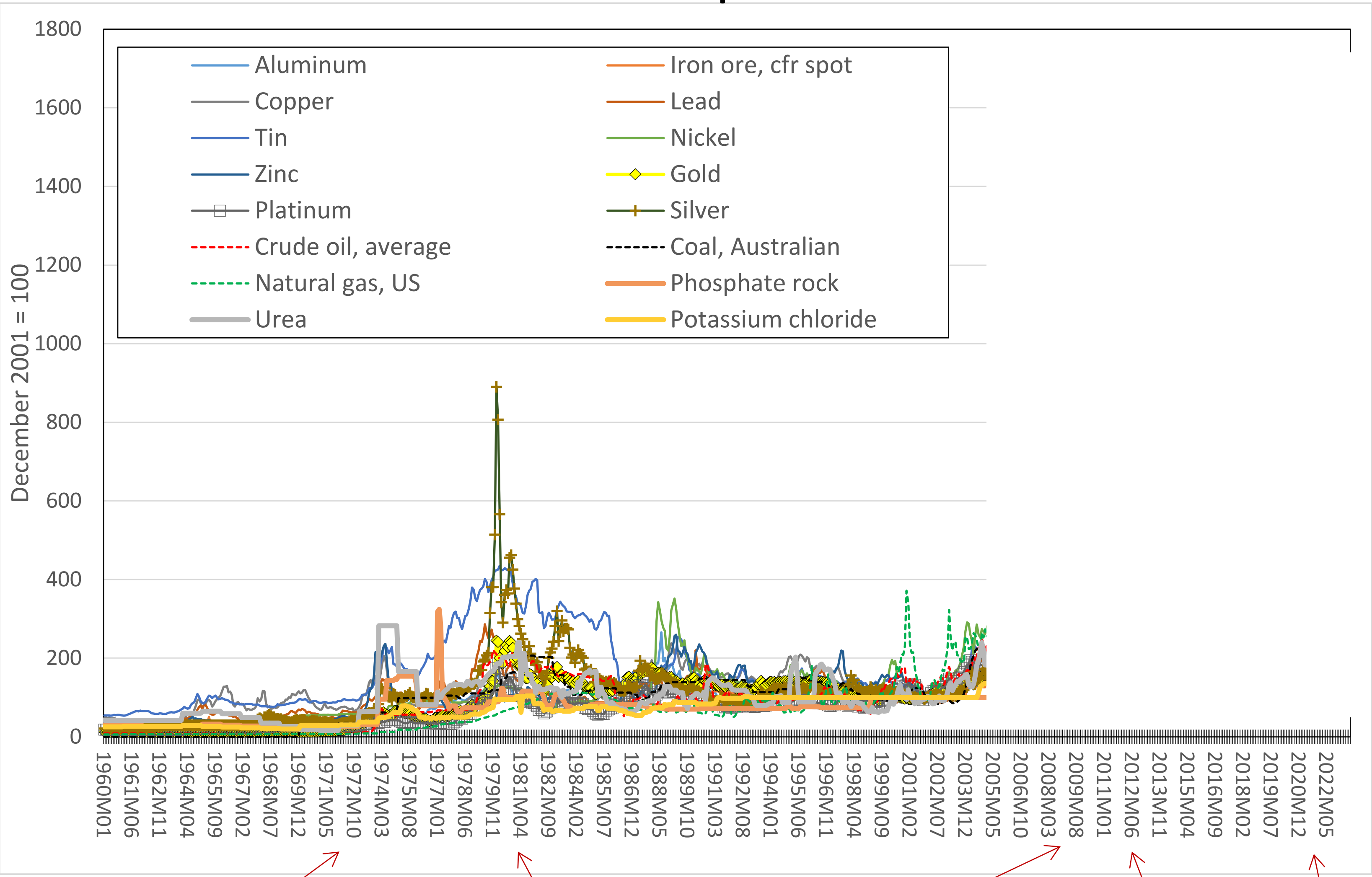
Summary

- Oils' ain't oils
  - Fossil fuels are being phased out
- Mapping the Green Transition
- How big should the buffer be to manage intermittency of solar and wind power supply?
  - 4 sizes calculated
  - PHS & hydrogen storage
- Quantity of metals needed
- Recycling
- Compared to global annual mining production 2019
- Compared to mineral reserves, resources and under sea resources
- The Green Transition not viable



The industrial system started to correct to a new equilibrium in 2005



$USD decouples from gold standard

1979 Iran oil embargo

Global Financial Crisis (GFC)

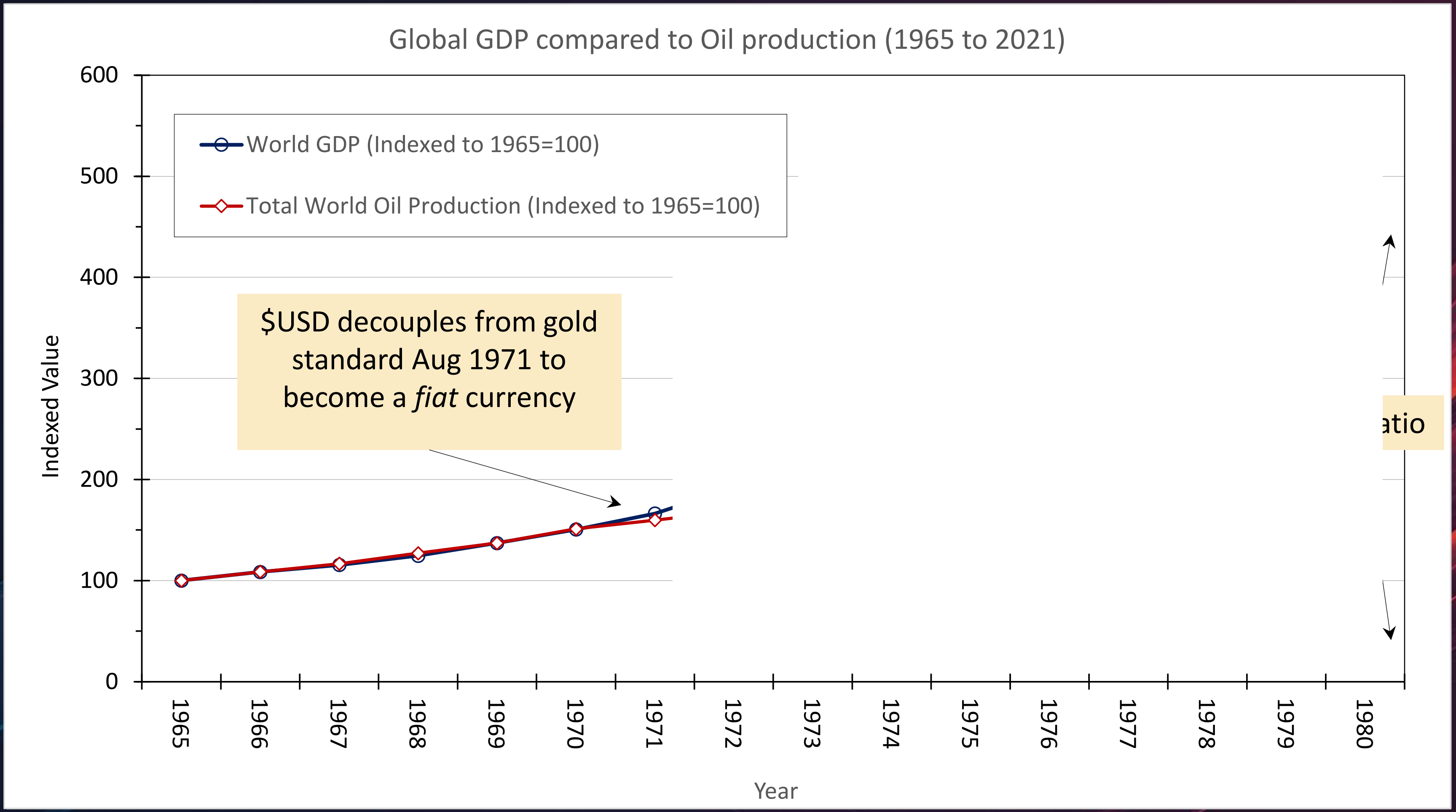
Q.E. era

Covid-19

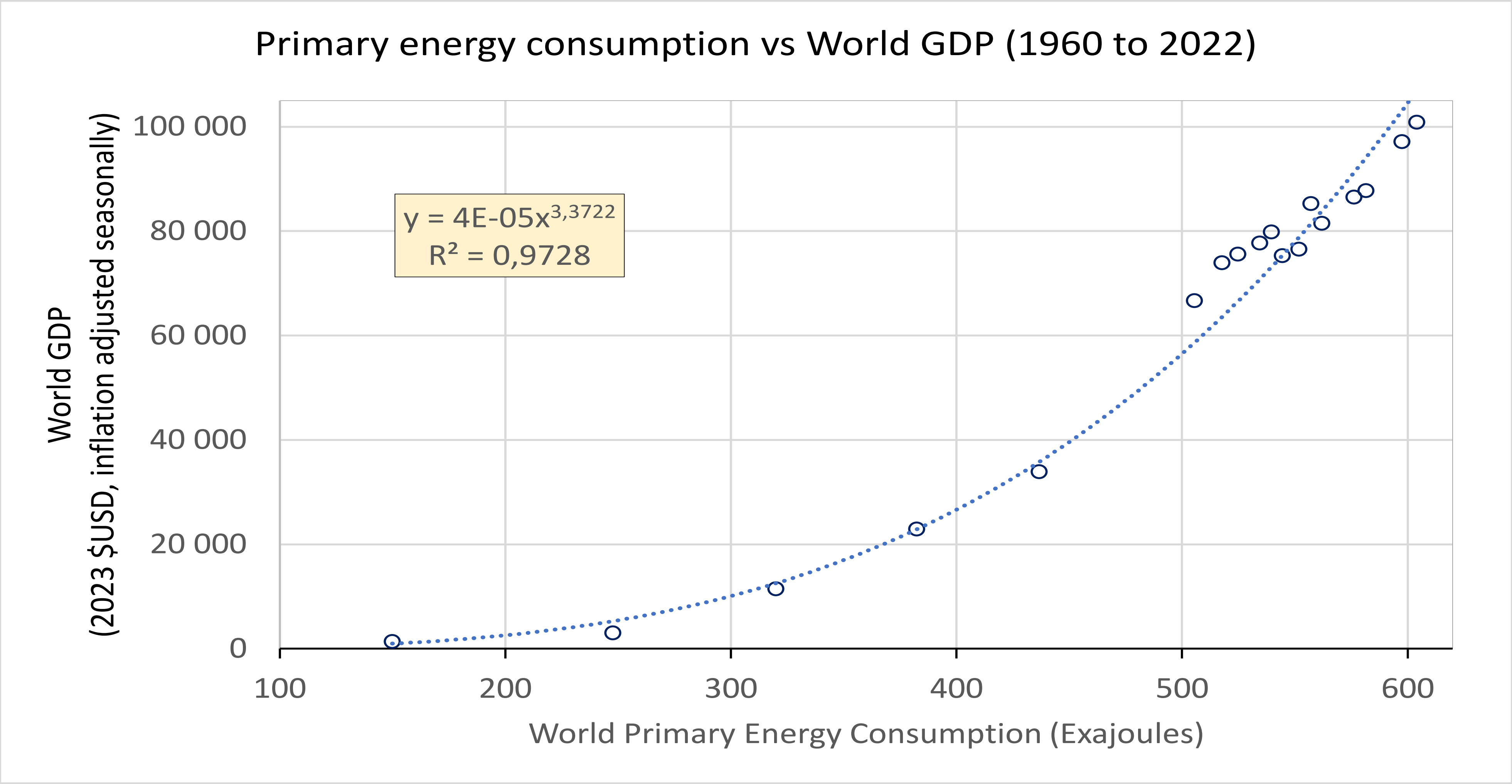
A case can be made that this blow out was a chain reaction started in the oil industry

A major economic correction (GFC 2008) did not resolve the problems

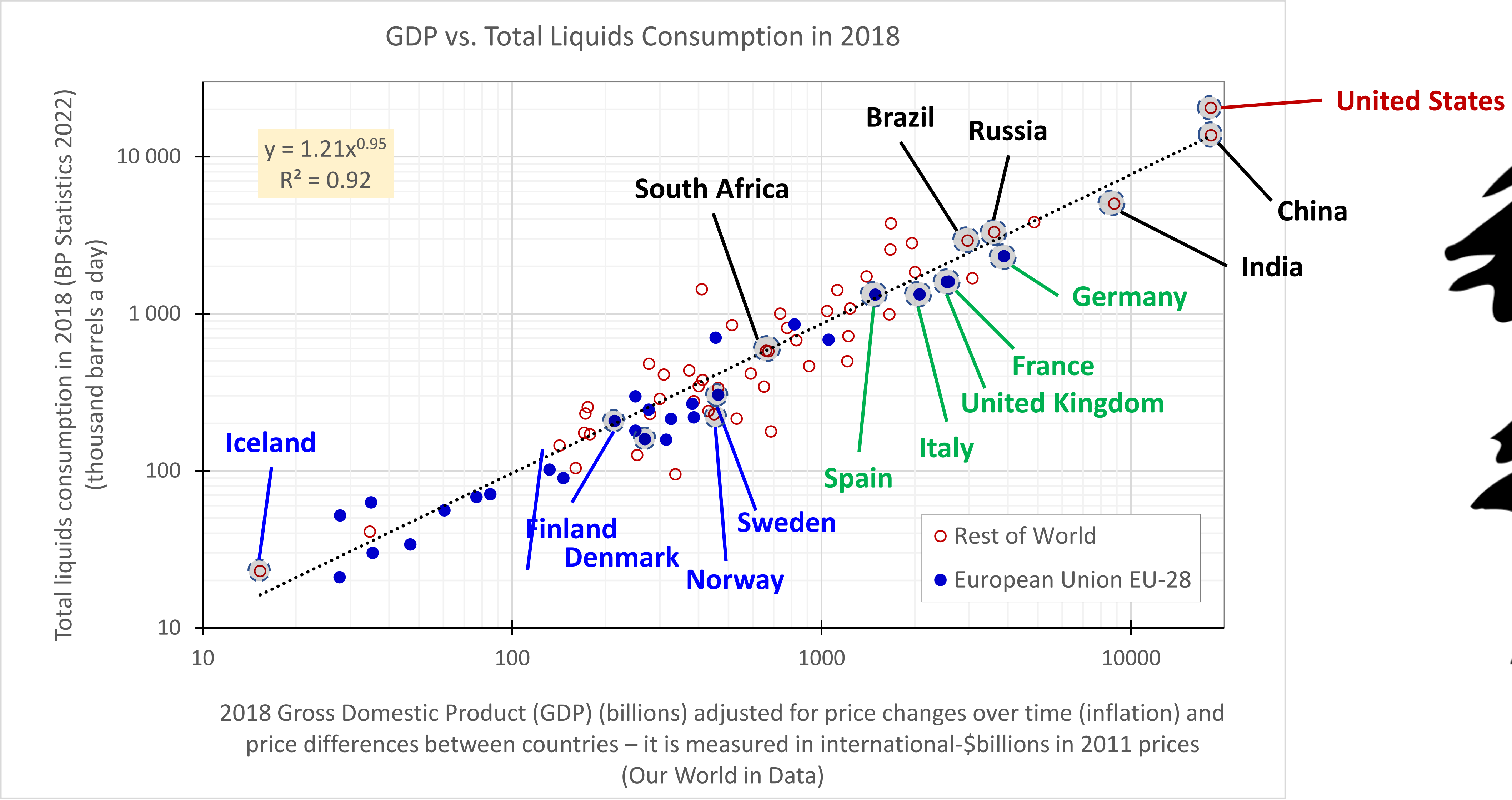
The change started something like 19 years in our past



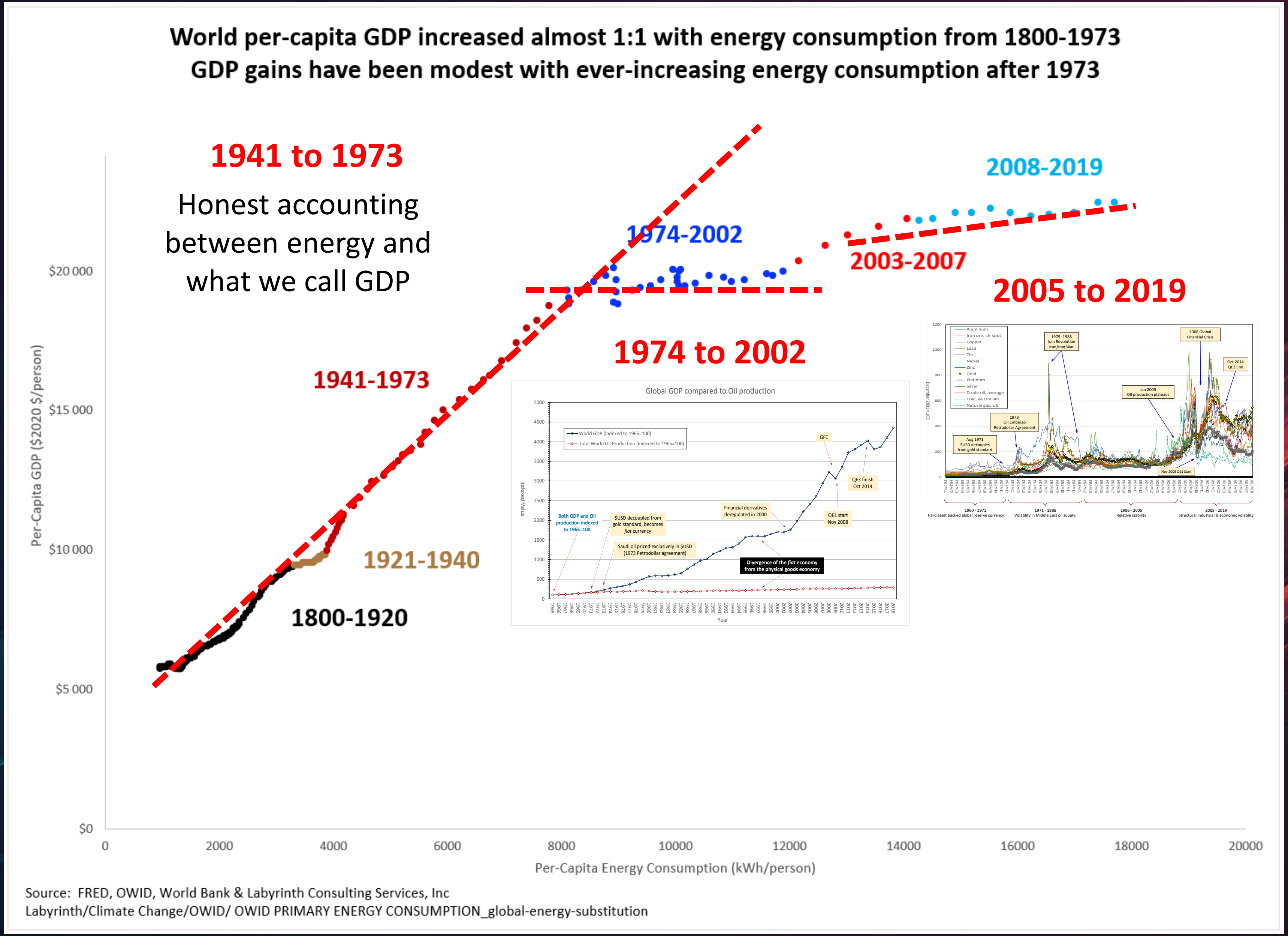
Global GDP compared to Oil production (1965 to 2021)
World GDP (Indexed to 1965=100)
Total World Oil Production (Indexed to 1965=100)
$USD decouples from gold standard Aug 1971 to become a fiat currency
atio
Indexed Value
0
100
200
300
400
500
600
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
Year



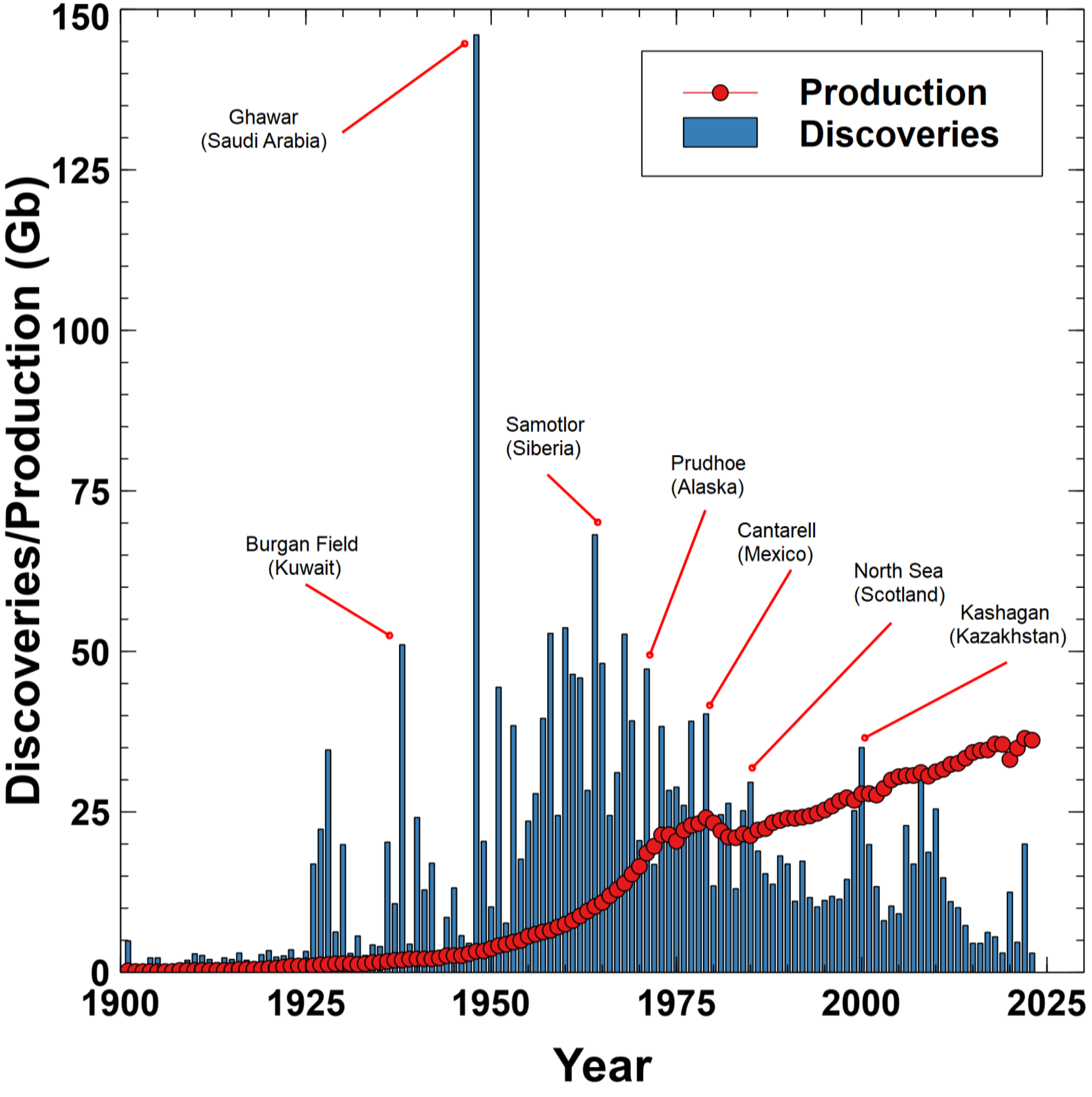
World GDP in 2023, seasonally adjusted US Dollars (vertical axis) (World Bank, OECD)
plotted against the world energy consumption from 1960 to 2022 (horizontal axis) (BP Statistics)

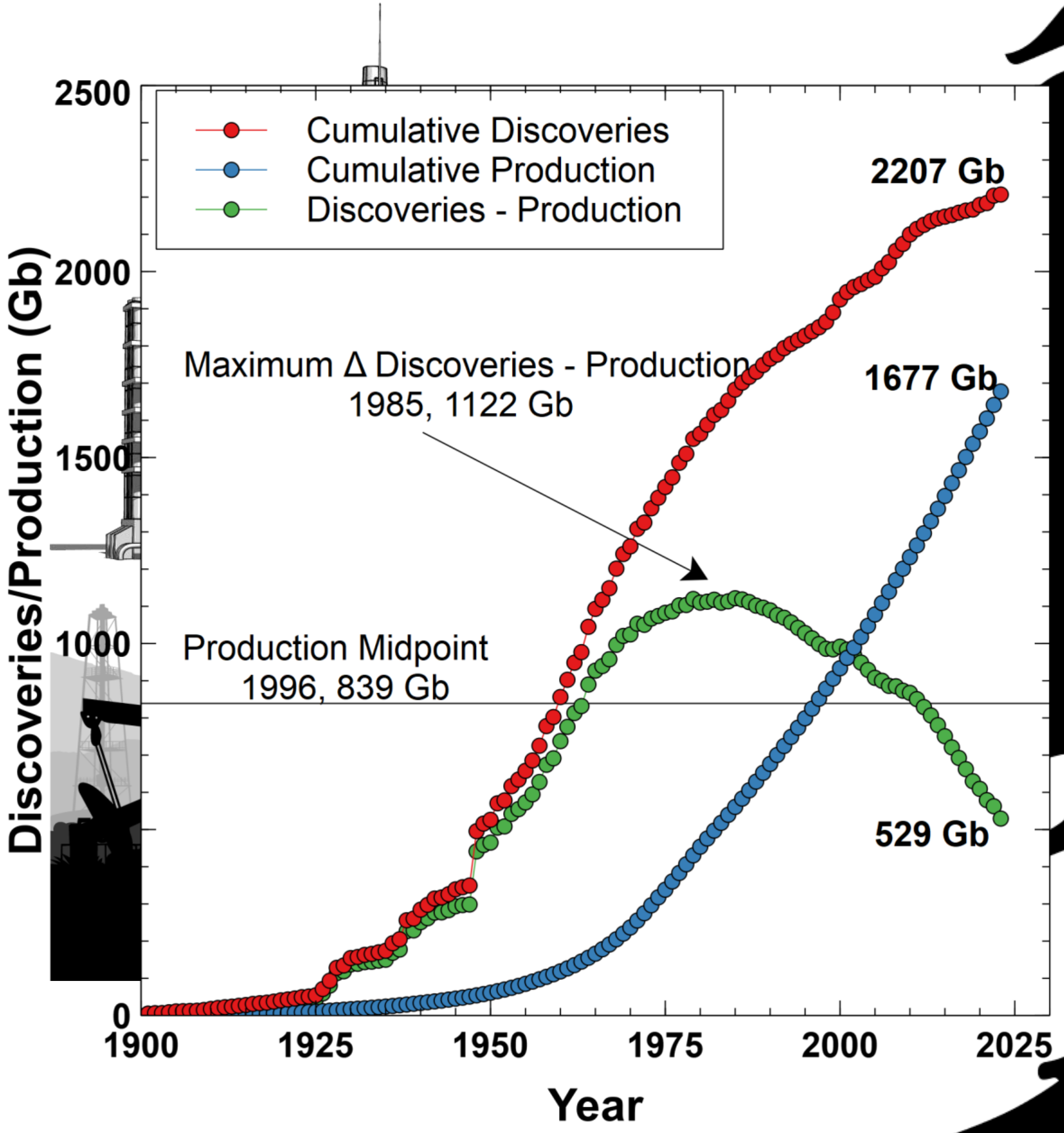


Developed from previous work, Labyrinth Consulting Services, Inc., Art Berman

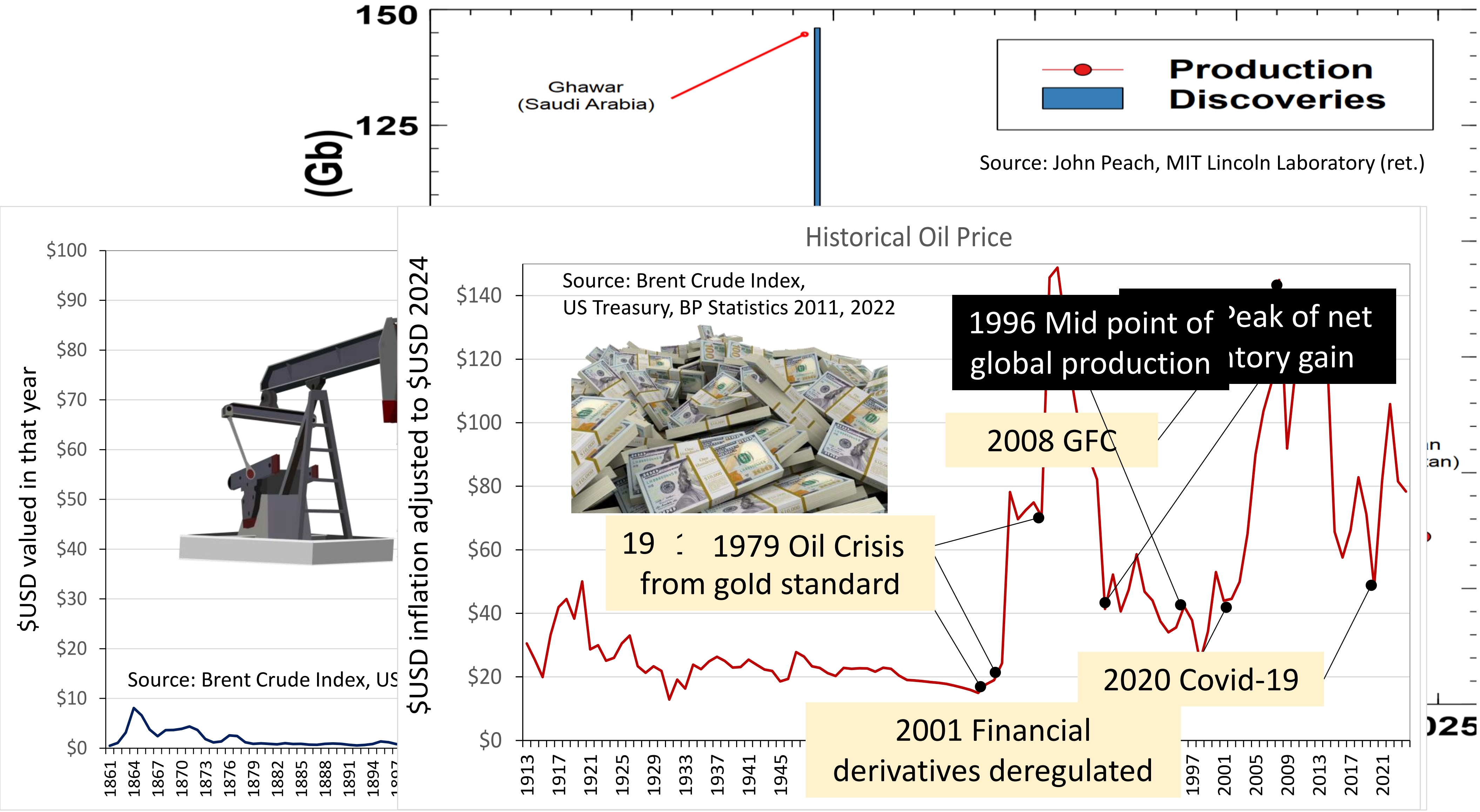


(Source: Labyrinth Consulting Services, Inc., Art Berman)



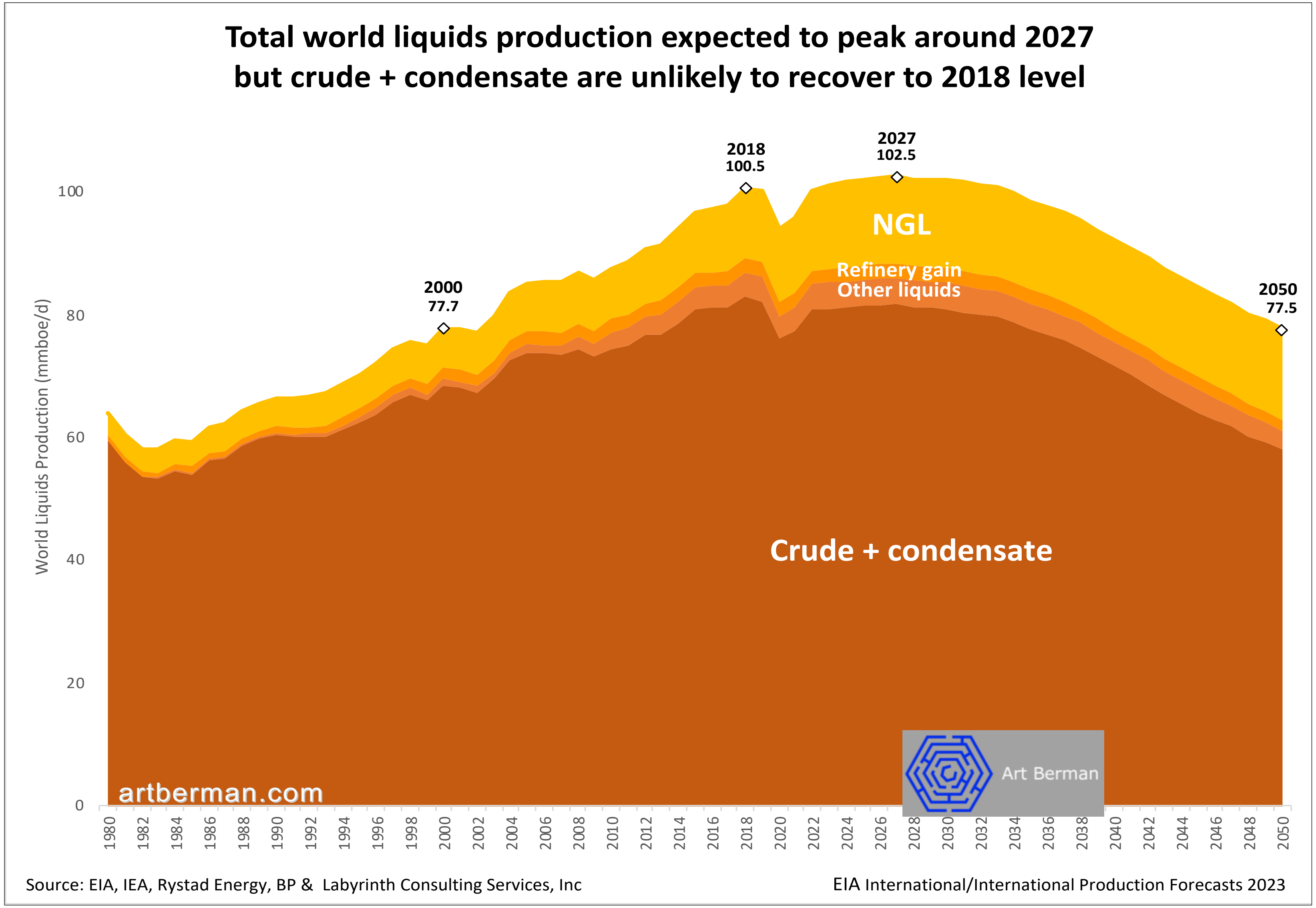


Source: John Peach, MIT Lincoln Laboratory (ret.)



150
125
(Gb)
Ghawar
(Saudi Arabia)
Production
Discoveries
Source: John Peach, MIT Lincoln Laboratory (ret.)
$100
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
$USD valued in that year
Source: Brent Crude Index, US
1861
1864
1867
1870
1873
1876
1879
1882
1885
1888
1891
1894
Historical Oil Price
$USD inflation adjusted to $USD 2024
$140
$120
$100
$80
$60
$40
$20
$0
Source: Brent Crude Index,
US Treasury, BP Statistics 2011, 2022
1996 Mid point of
global production
eak of net
tory gain
2008 GFC
1979 Oil Crisis
from gold standard
2020 Covid-19
2001 Financial
derivatives deregulated
1913
1917
1921
1925
1929
1933
1937
1941
1945
1997
2001
2005
2009
2013
2017
2021

Oils ain't oils....



Fossil fuels are being phased out

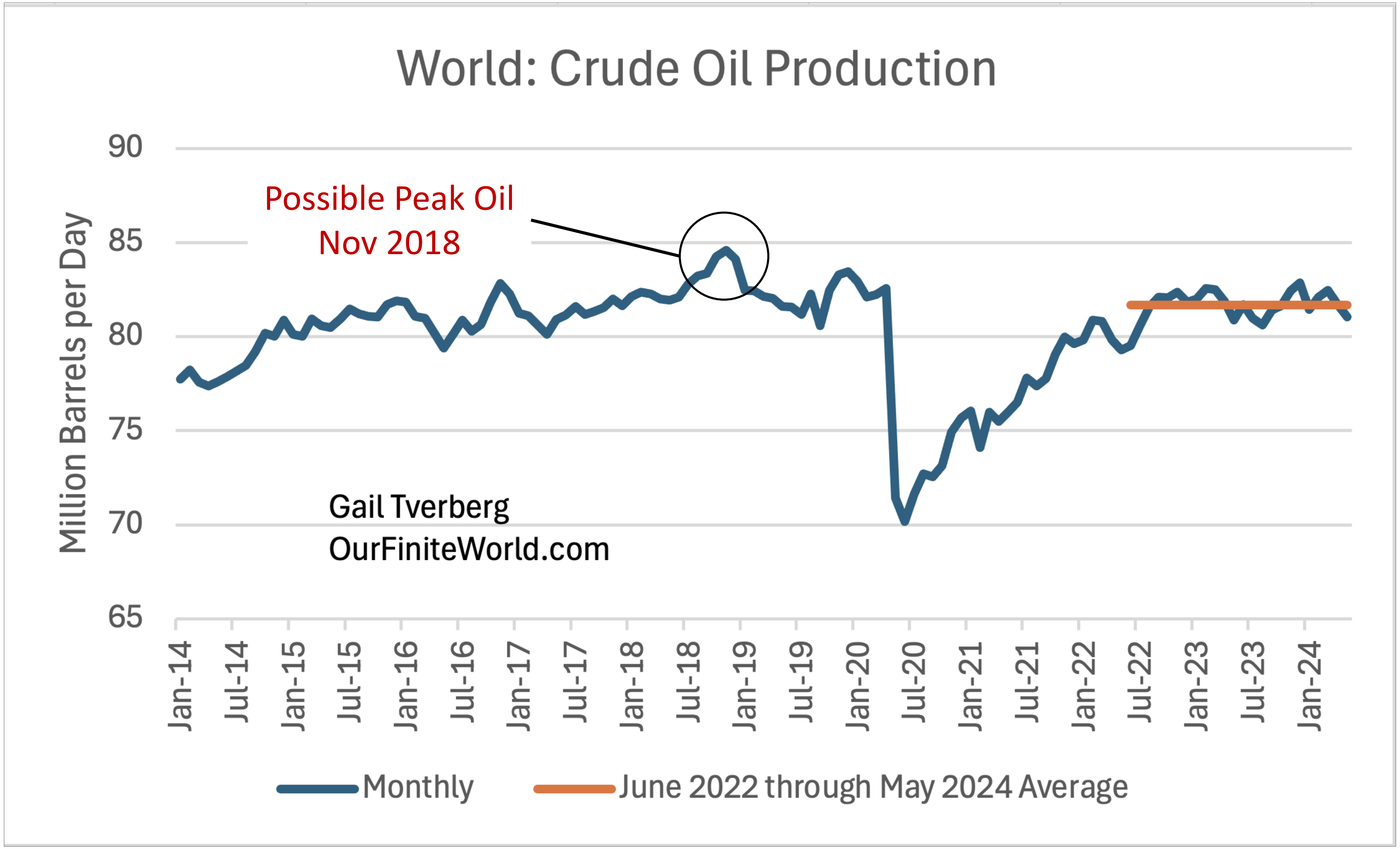
Sensitivity analysis: The economic effects of this kind of supply sho

The world would experience severe energy shortages and disruption to daily lives within a year of investment ceasing.

Given price responses to past oil supply shocks, the permanent loss of 15% of oil supply per year could raise oil prices by more than 400%. By comparison, prices rose 200% during the oil price shocks of the 1970s.

Within 10 years, unemployment rates would likely reach **30%**. That's higher than during the Great Depression of the 1930s.

https://corporate.exxonmobil.com/sustainability-and-reports/global-outlook



https://ourfiniteworld.com/2024/09/11/crude-oil-extraction-may-be-well-past-peak/

81% of existing oil reserves are being annually depleted at a rate ranging between 5 to 15%


Will this work for everyone the way we plan?

How
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Using ene
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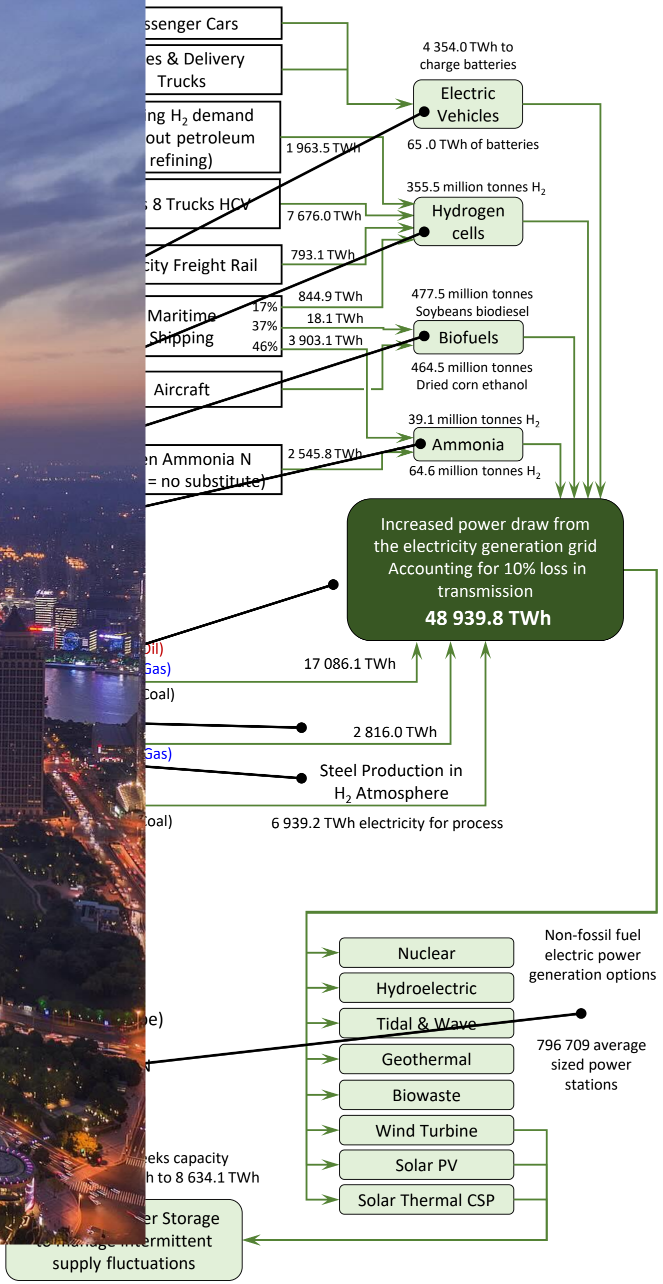
power stations are needed

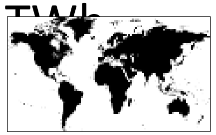


Baseline calculation

- The global fleet of vehicles (cars, trucks, buses, etc, not maritime shipping, rail or aviation) is estimated to be 1.416 billion, which travelled an estimated 15.87 trillion km in the year 2018
  - 1.1% of transport is EV in 2021 (EV Outlook 2022)
  - Renewable energy accounts for 6.69% of global primary energy in 2022 (BP Statistic World Energy Review 2023)
  - The non-fossil fuel system has yet to be constructed

- Electric power to charge the EV fleet (1.39 billion vehicles): 4 495.7 TWh
- Electrical power to produce hydrogen as a direct fuel: 11 105.2 TWh
- Electrical power to produce steel in a hydrogen atmosphere: 6 939.2 TWh
- Electrical power to produce ammonia (via hydrogen): 6 448.9 TWh
- Phasing out of fossil fuel electrical power generation: 17 086.1 TWh
- Electrical power for heat pumps to heat buildings: 2 816.0 TWh

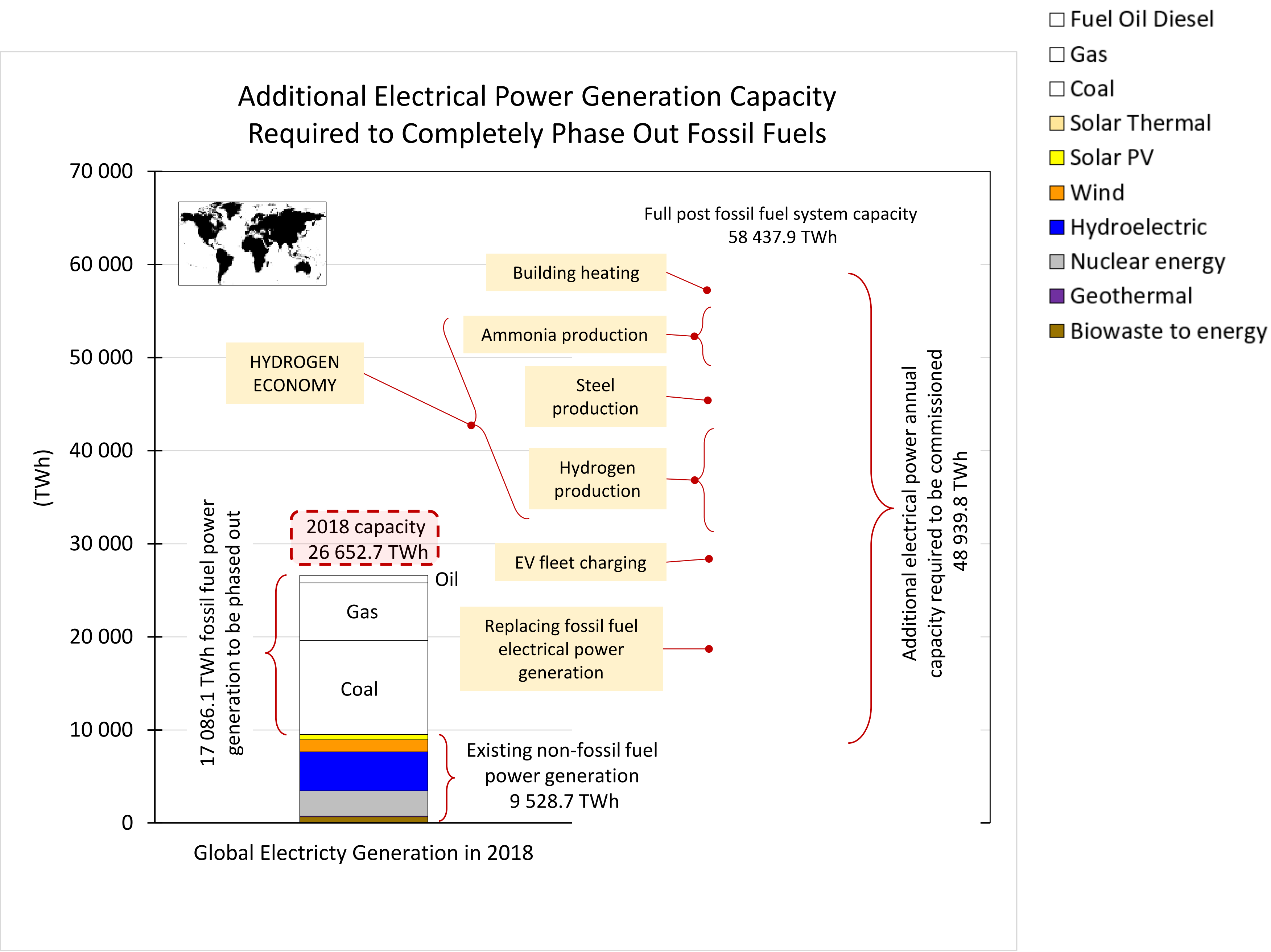
48 909.2 TWh



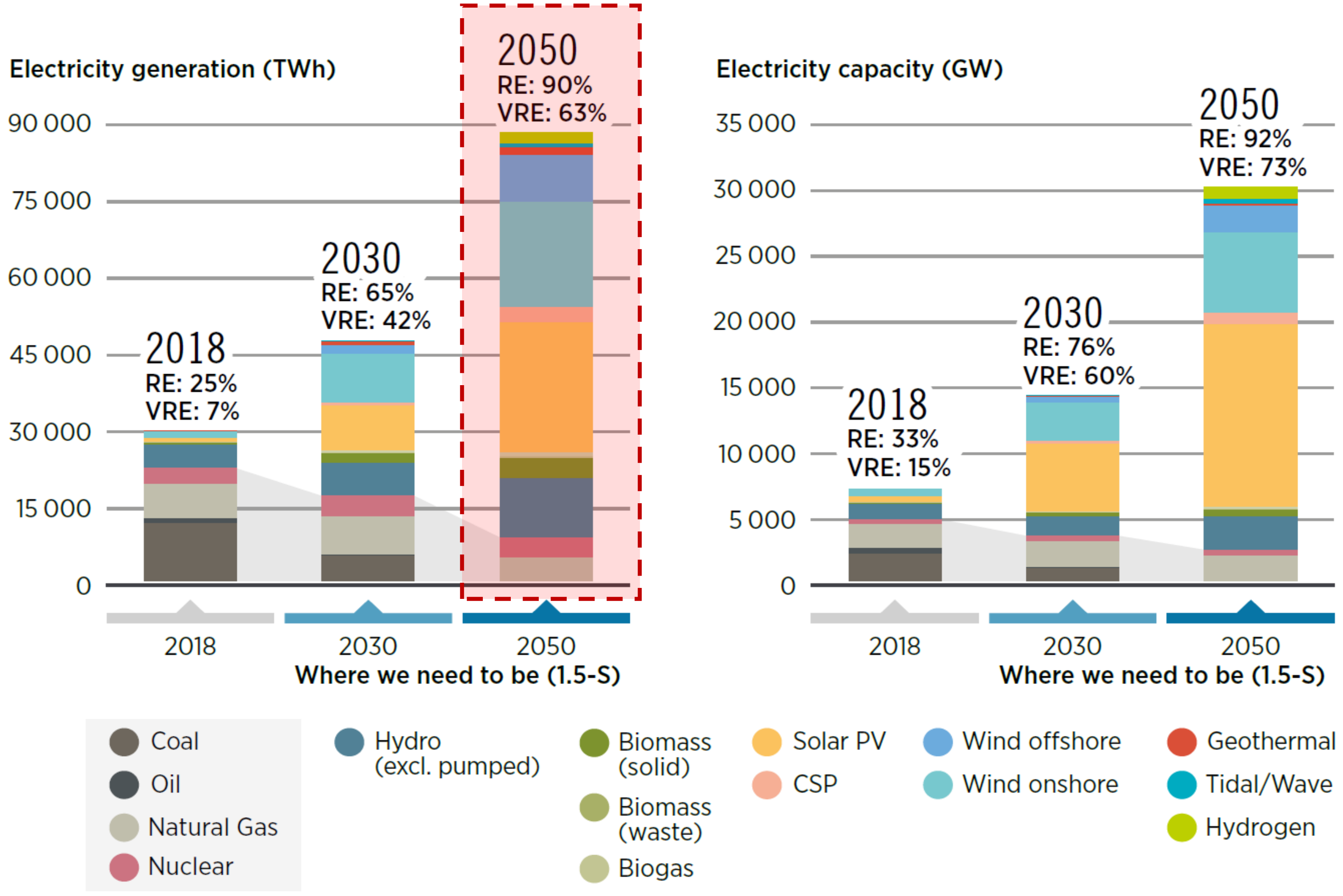
- Biomass feedstock to produce biofuels: 940.88 million tonnes

37% of maritime shipping & 62% of aviation

2018 wheat crop was 402 million tonnes



The IEA predicts that the 2050 electrical power grid will be 71 200 TWh



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.

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)	Estimated Installed capacity (GW)
Nuclear	7.50 %	3.67E+12	1.28E+10	287	586
Hydroelectric	13.36 %	6.53E+12	1.33E+09	4 929	1 111
Wind	38.33 %	1.87E+13	8.12E+07	230 754	8 584
Solar PV	34.50 %	1.69E+13	3.30E+07	510 694	16 904
Solar Thermal	3.83 %	1.87E+12	7.70E+07	24 337	1 873
Geothermal	0.74 %	3.62E+11	6.03E+08	600	57
Biowaste to energy	1.74 %	8.51E+11	3.46E+07	24 609	780
Total (kWh)	100.00 %	4.89E+13		796 210	29 895
Total (TWh)		48 909.2			Giga Watts

GLOBAL SYSTEM

Additional Annual Electrical Power Requires **48 939.8 TWh**

=

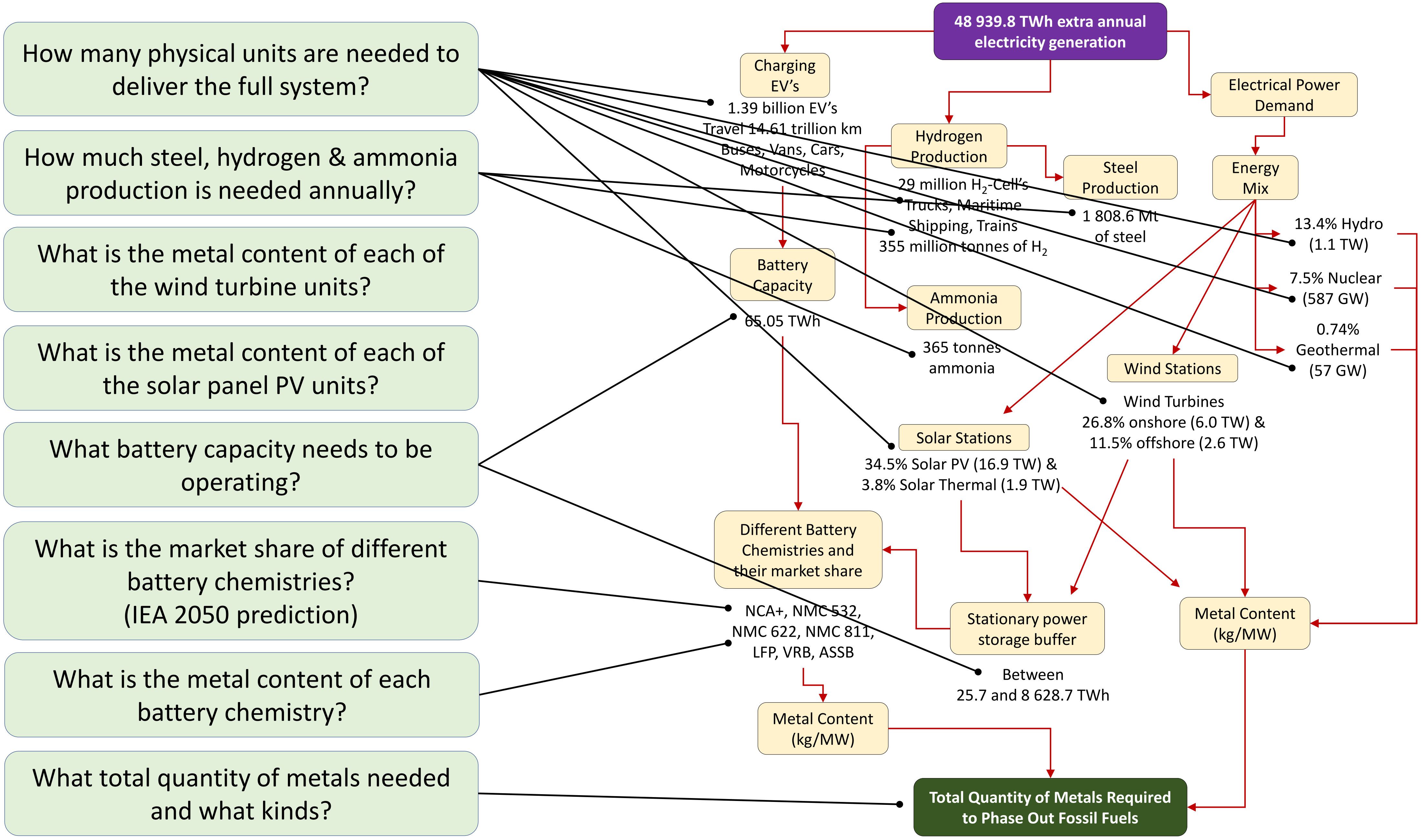
796 709 NEW Non-Fossil Fuel Power Stations

Electricity produced in 2018
26 652.7 TWh

Power plant fleet in 2018 was
46 423 stations

HYDRO POWER **6 538** TWh 4 932 stations	**NUCLEAR POWER** **3 670**TWh 287 stations	
WIND POWER 18 759 TWh 230 899 stations	**SOLAR POWER** 16 884 TWh 511 015 stations	**Power storage buffer**
OTHER RENEWABLES Geothermal & Tidal 361.9 TWh 600 stations	**BIOWASTE TO ENERGY** **852** TWh 24 624 stations	

The global fleet of vehicles (cars, trucks, buses, etc. not including maritime shipping, rail or aviation) is estimated to be 1.416 billion, which travelled an estimated 16.24 trillion km in the year 2018



How many physical units are needed to deliver the full system?
How much steel, hydrogen & ammonia production is needed annually?
What is the metal content of each of the wind turbine units?
What is the metal content of each of the solar panel PV units?
What battery capacity needs to be operating?
What is the market share of different battery chemistries? (IEA 2050 prediction)
What is the metal content of each battery chemistry?
What total quantity of metals needed and what kinds?
48 939.8 TWh extra annual electricity generation
Charging EV's
1.39 billion EV's
Travel 14.61 trillion km
Buses, Vans, Cars, Motorcycles
Hydrogen Production
29 million H2-Cell's
Trucks, Maritime Shipping, Trains
355 million tonnes of H2
Steel Production
1 808.6 Mt of steel
Electrical Power Demand
Energy Mix
13.4% Hydro (1.1 TW)
7.5% Nuclear (587 GW)
0.74% Geothermal (57 GW)
Battery Capacity
65.05 TWh
Ammonia Production
365 tonnes ammonia
Wind Stations
Wind Turbines
26.8% onshore (6.0 TW) &
11.5% offshore (2.6 TW)
Solar Stations
34.5% Solar PV (16.9 TW) &
3.8% Solar Thermal (1.9 TW)
Different Battery Chemistries and their market share
NCA+, NMC 532, NMC 622, NMC 811, LFP, VRB, ASSB
Stationary power storage buffer
Between 25.7 and 8 628.7 TWh
Metal Content (kg/MW)
Metal Content (kg/MW)
Total Quantity of Metals Required to Phase Out Fossil Fuels

RIO pow 41

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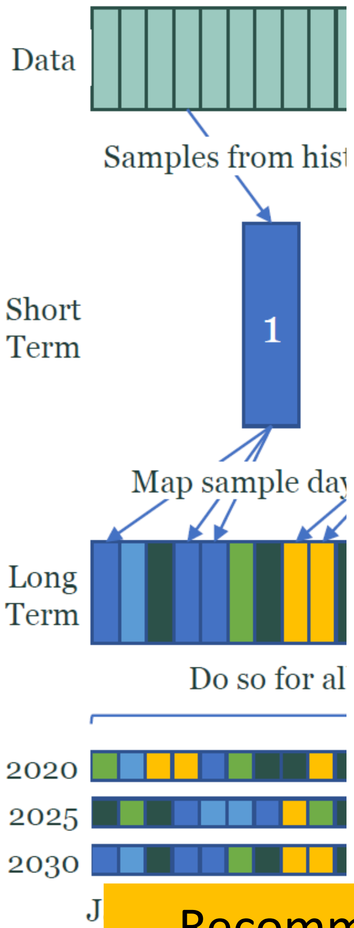
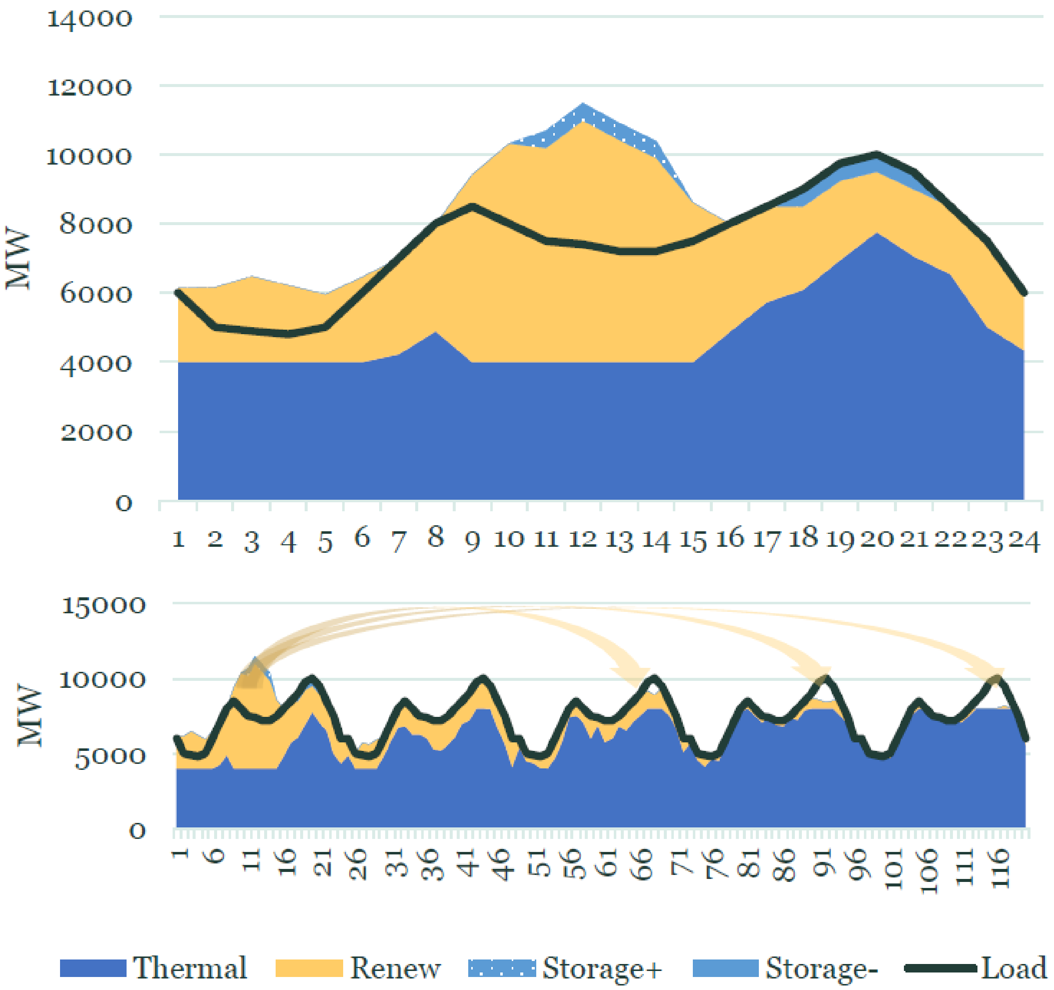
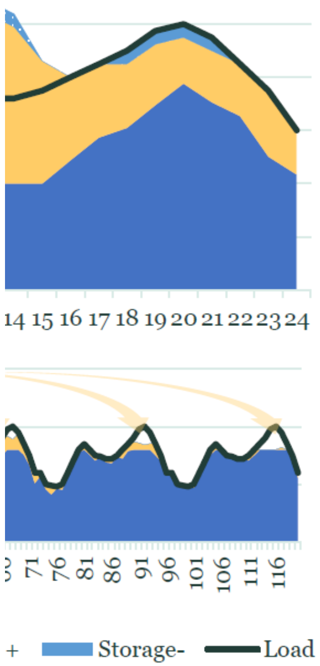
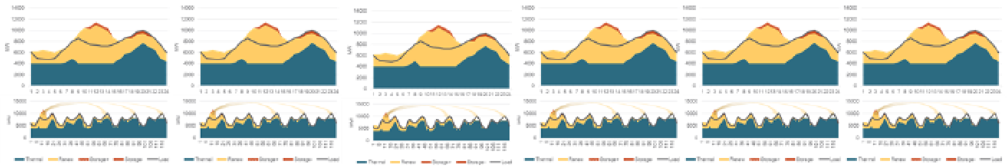


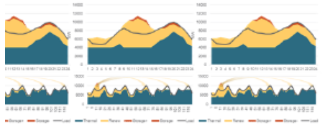
Detailed short term dispatch for every sample day. Dispatch decisions are the same across all days represented by the same sample day.

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





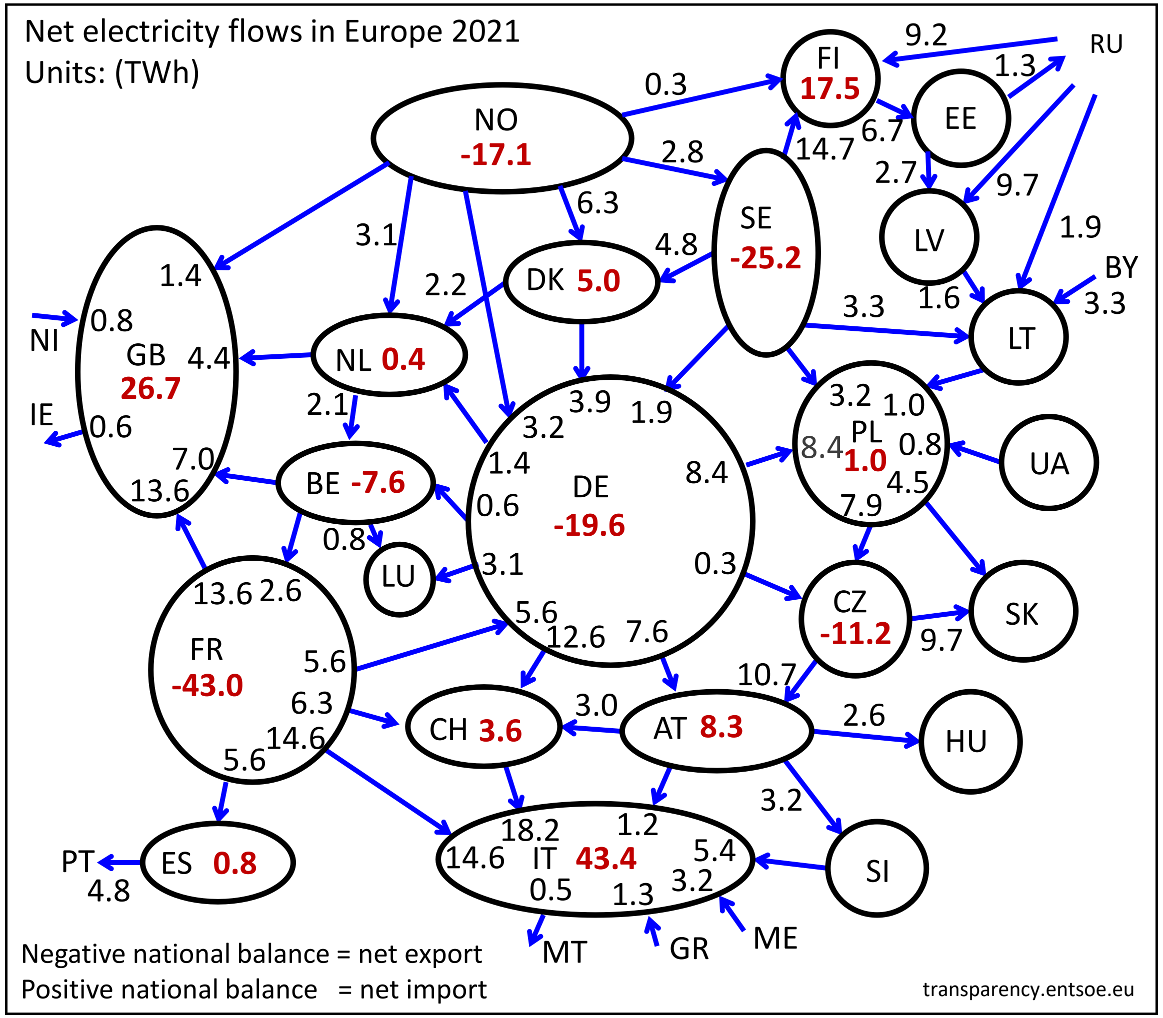




Recommend 5-7 hours power buffer storage

RETURN TO TABLE OF CONTENTS

European net electricity exchanges in 2021



(Source: Entsoe)

All networks are balanced and buffered by other external networks

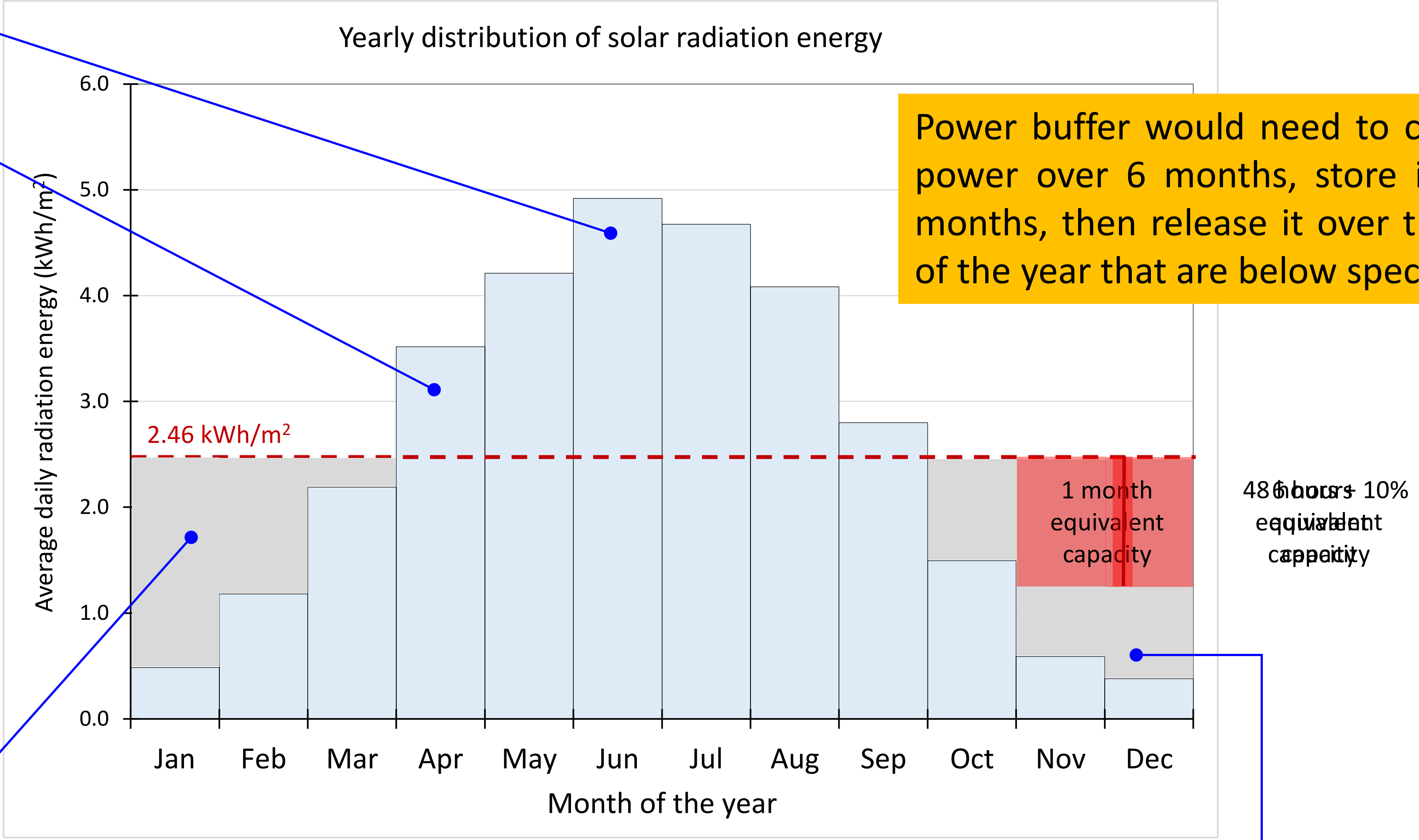
Almost always using fossil fuel sourced power generation (gas in particular)

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

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

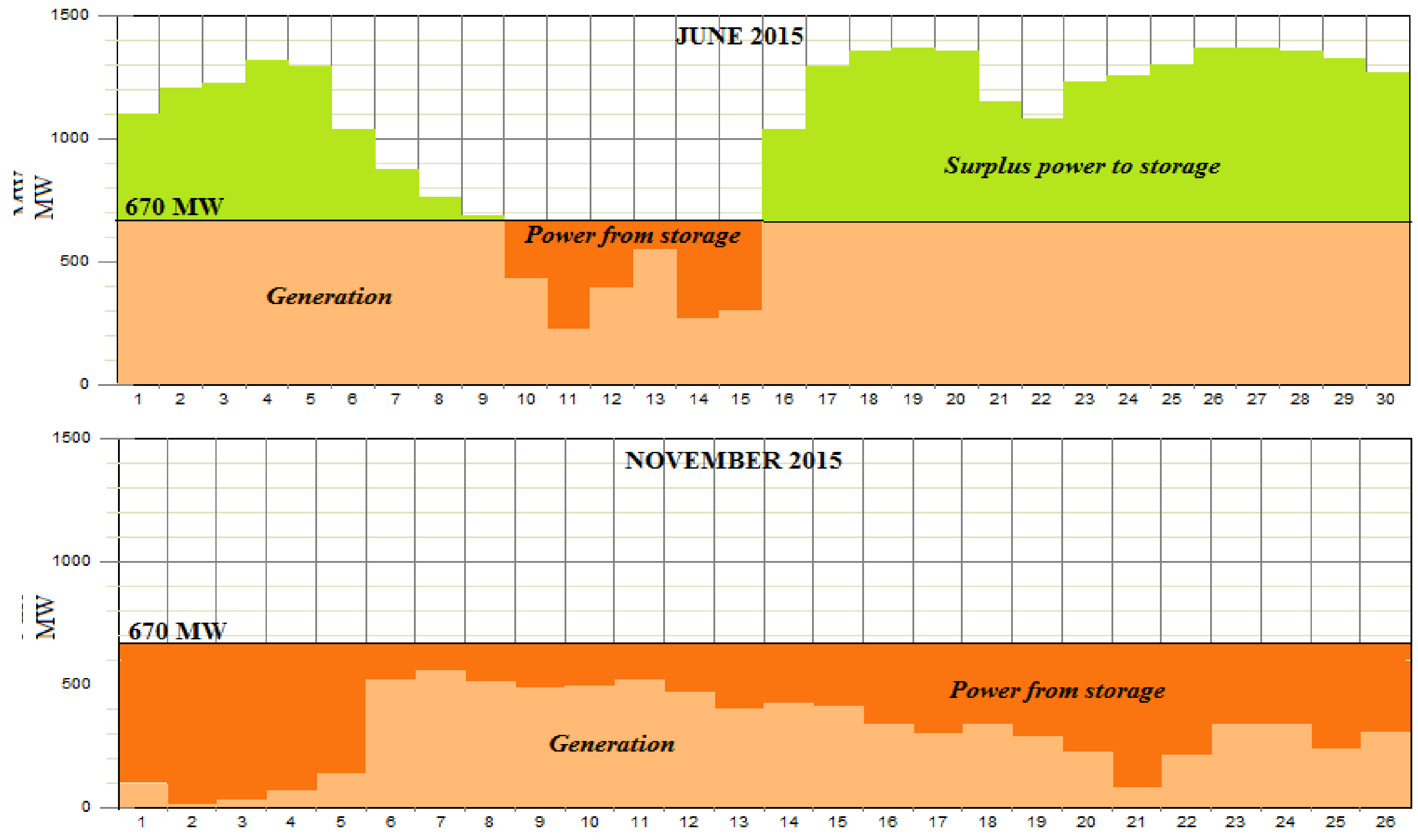
Excess needs to be stored



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

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)

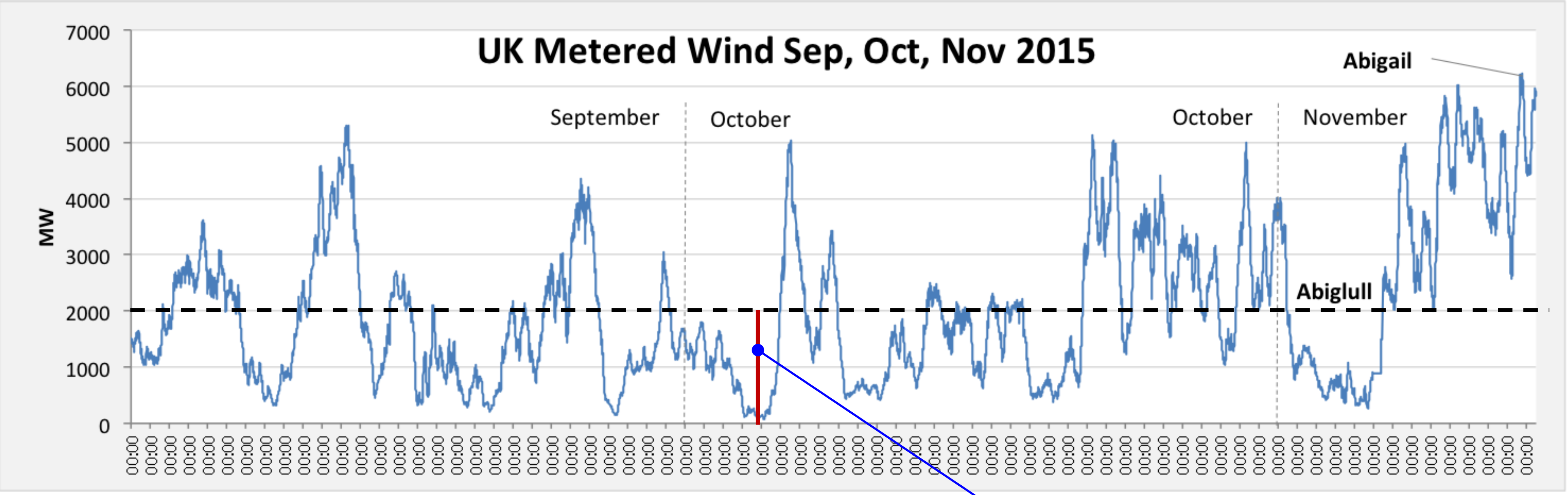
Approximately 260 GWh of storage would have been needed to cover the shortfalls in November alone. This is 16.2 days of buffer capacity, to be stored for approx. 4-6 months.

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

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

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

2023

PJM Monthly Wind and Solar Capacity Factors 2023

		Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23	Nov-23	Dec-23	Total
Solar	MWh potential	4,677,528	4,224,864	4,677,528	4,526,640	4,677,528	4,526,640	4,677,528	4,677,528	4,526,640	4,677,528	4,526,640	4,677,528	55,074,120
6,287 MW	Actual MWh	324,092	482,879	760,638	861,377	1,013,308	865,656	1,142,976	1,040,919	923,233	848,661	703,974	499,044	9,466,757
Capacity	Capacity Factor	6.9%	11.4%	16.3%	19.0%	21.7%	19.1%	24.4%	22.3%	20.4%	18.1%	15.6%	10.7%	17.2%
Wind	MWh potential	8,753,904	7,906,752	8,753,904	8,471,520	8,753,904	8,471,520	8,753,904	8,753,904	8,471,520	8,753,904	8,471,520	8,753,904	103,070,160
11,766 MW	Actual MWh	2,942,169	3,477,932	3,647,419	2,863,473	2,174,829	1,762,604	1,110,364	1,553,830	1,307,310	2,654,021	3,124,899	2,835,646	29,454,496
Capacity	Capacity Factor	33.6%	44.0%	41.7%	33.8%	24.8%	20.8%	12.7%	17.8%	15.4%	30.3%	36.9%	32.4%	28.6%
Blended Renewables Monthly and Annual Capacity Factors		24.3%	32.6%	32.8%	28.7%	23.7%	20.2%	16.8%	19.3%	17.2%	26.4%	29.5%	24.8%	24.6%

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.

Table 17. Estimated size of buffer needed if the PJM RTO Solar network was self sustaining at 22% capacity

	Solar PJM RTO	
	2022	2023
Power generated in months below specified 22% capacity	3 371 998	5 115 739
Power that would have been generated at 22% installed capacity	5 976 691	10 079 389
Shortfall	2 604 693	4 963 651
Days of solar poduction to be kept in storage	17	23
Number of days for the continuous time where solar production was below 22%	182	212

Table 18. Estimated size of buffer needed if the PJM RTO Wind Turbine network was self sustaining at 24% capacity

	Wind PJM RTO	
	2022	2023
Power generated in months below specified 24% capacity	6 202 253	5 452 379
Power that would have been generated at 24% installed capacity	7 726 969	7 776 364
Shortfall	1 524 715	2 323 985
Days of wind poduction to be kept in storage	6	8
Number of days for the continuous time where wind production was below 24%	122	122

Buffer size at least 23 days

Power storage methods compared

Table 2.1.1 Techno-Ec
Hydrowires Report [8] a

adapted from US

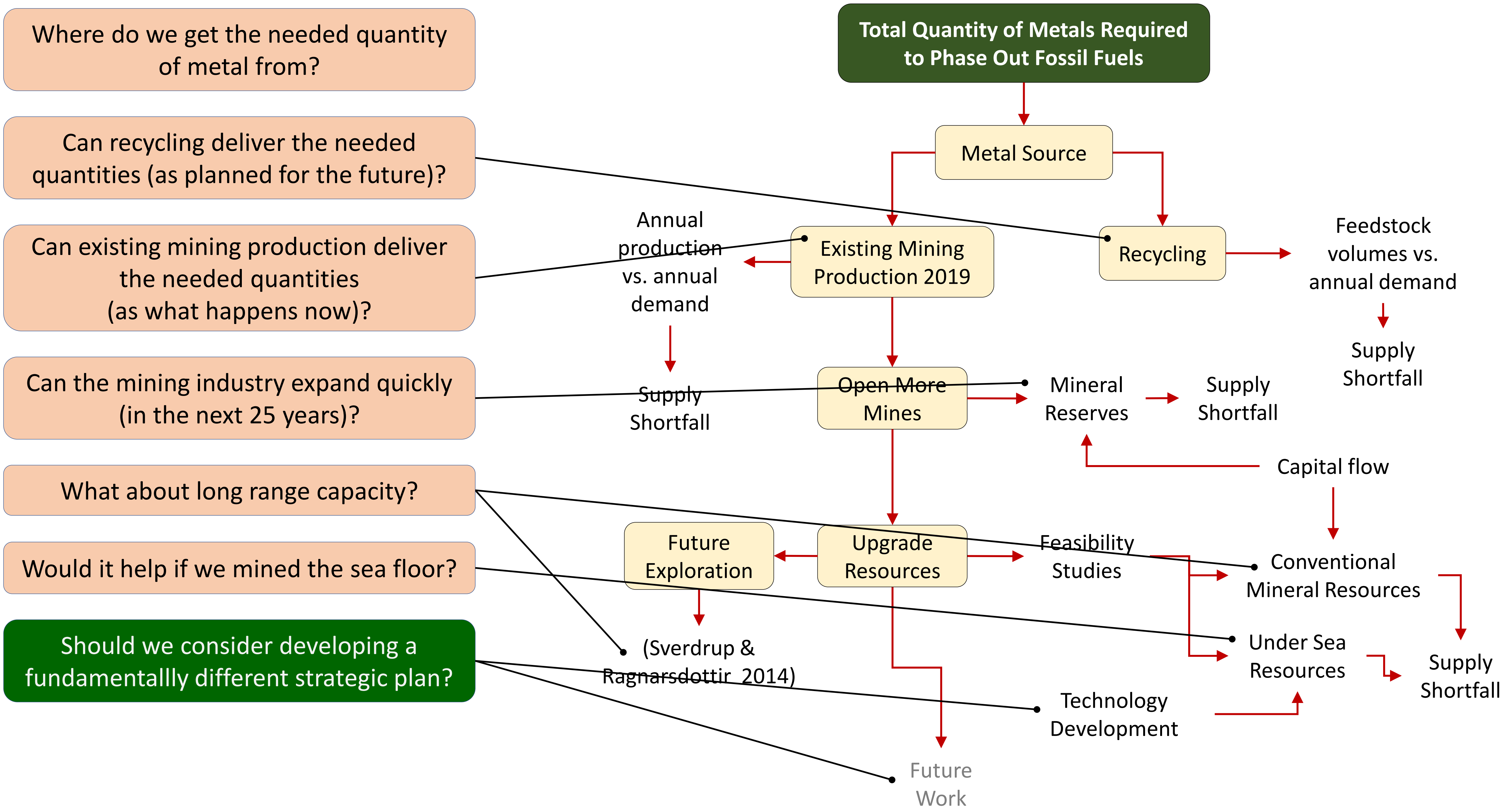
More favorable

Parameter	Flyw	ZEBRA (NaNiCl) [(c)]	Flow Battery[(c)]
Efficiency* (%) (DC+AC)	70	80-85	65-70
Response (seconds)	0.	0.1-1	1-10
Lifetime (cycles to 80% DOD)	10	3.5K	10K
Lifetime (years)	2	10-15	15
CAPEX (DC+AC) (USD/kW)	1080	2810-5094	2742-5226
CAPEX (DC+AC) (USD/kWh)	4320-	703-1274	686-1307
Energy Density (Wh/L)	20	170-190	20-70
Power Density (W/L)	50	250-260	0.5-2
Self-discharge per day (%)	1.3-	1-14	0.2
Typical charging rate* [10], [11],[12]	N	0.1-0.15 C	0.1-0.15 C

(a) E/P = 0.25 h, (b) E/P = 0.0125h, (c) E/P = 4 h

(Source: EMA (2020): Energy Storage Systems Technology Roadmap for Singapore, PUBLIC VERSION, Prepared for Energy Market Authority (EMA), Lead Authors: Dr. Sivanand SOMASUNDARAM, EPGC, ERI@N, NTU, https://www.ntu.edu.sg/docs/librariesprovider60/publications/ess-technology-roadmap-singapore.pdf?sfvrsn=c91c9ae8_2)

Super capacitors were limited by the required time of power storage


Where do we get the needed quantity of metal from?
Can recycling deliver the needed quantities (as planned for the future)?
Can existing mining production deliver the needed quantities (as what happens now)?
Can the mining industry expand quickly (in the next 25 years)?
What about long range capacity?
Would it help if we mined the sea floor?
Should we consider developing a fundamentallly different strategic plan?
Total Quantity of Metals Required to Phase Out Fossil Fuels
Metal Source
Existing Mining Production 2019
Recycling
Feedstock volumes vs. annual demand
Supply Shortfall
Annual production vs. annual demand
Supply Shortfall
Open More Mines
Mineral Reserves
Supply Shortfall
Capital flow
Future Exploration
Upgrade Resources
Feasibility Studies
Conventional Mineral Resources
Under Sea Resources
Supply Shortfall
(Sverdrup & Ragnarsdottir 2014)
Technology Development
Future Work

Total metal quantity required to phase out fossil fuels

Copper

Global Mining Metal Production 2019 (million tonnes)	Metal
24.2	Copper

- 1.39 billion EV's
- 65.05 TWh of EV batteries
- 29 million H_2-Cell vehicles
- 37.6 billion PV solar panels (450 watt)
- 1.3 million wind turbines (6.6 MW)
- Stationary power storage 25.7 – 8 628.7 TWh
- Nuclear power 587 GW
- Hydropower 1.1 TW
- Geothermal 57 GW
- Biowaste 780.6 GW

...ng ...er ...ge	Total including 48 hours + 10% buffer stationary power storage	Total including 28 days buffer stationary power storage	Total including 12 week / 84 day buffer stationary power storage
...es)	(million tonnes)	(million tonnes)	(million tonnes)
	697.3	6 165	18 033

11.7 years

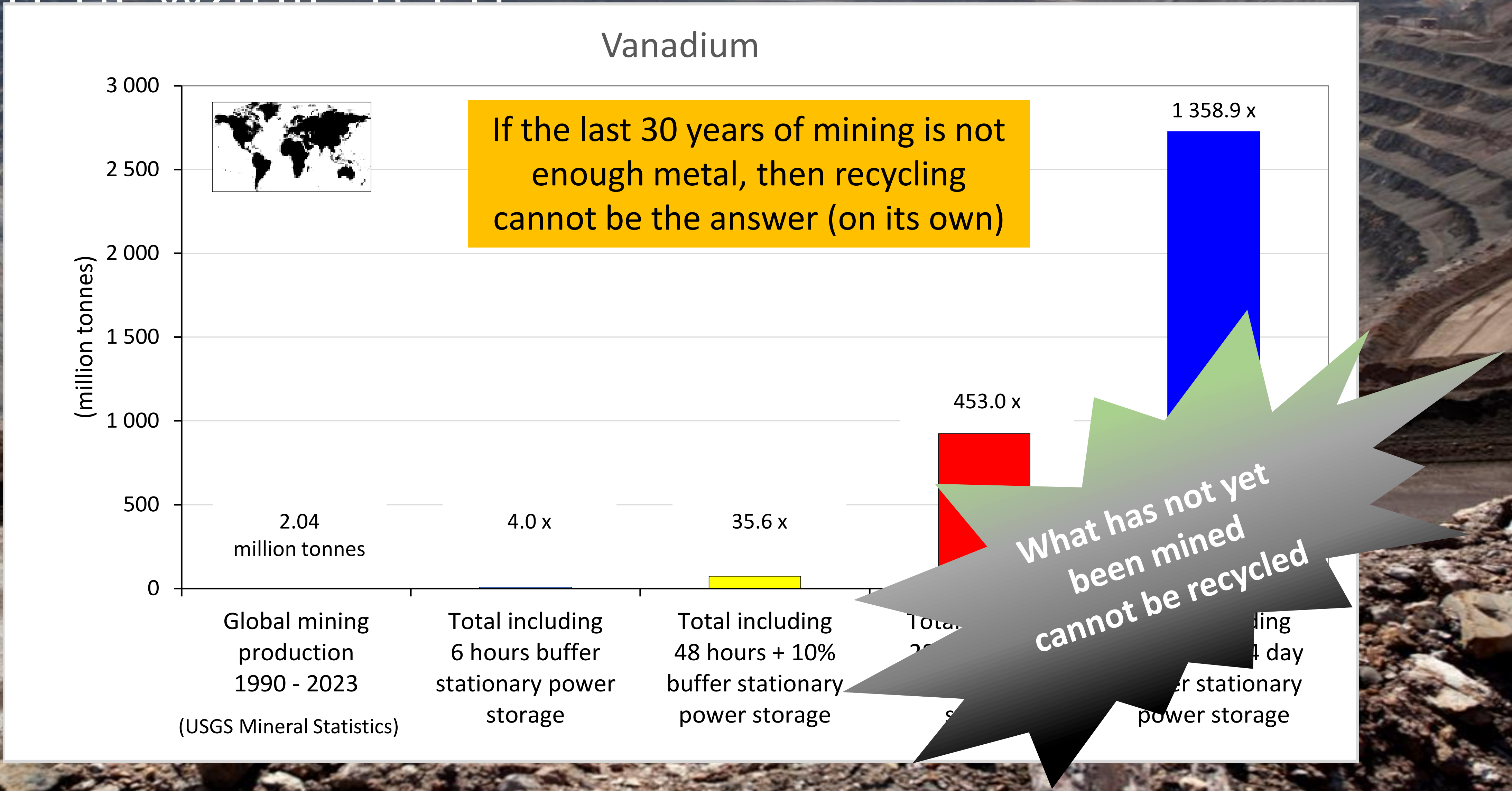
254.8 years

one in 25.5 years (2050)

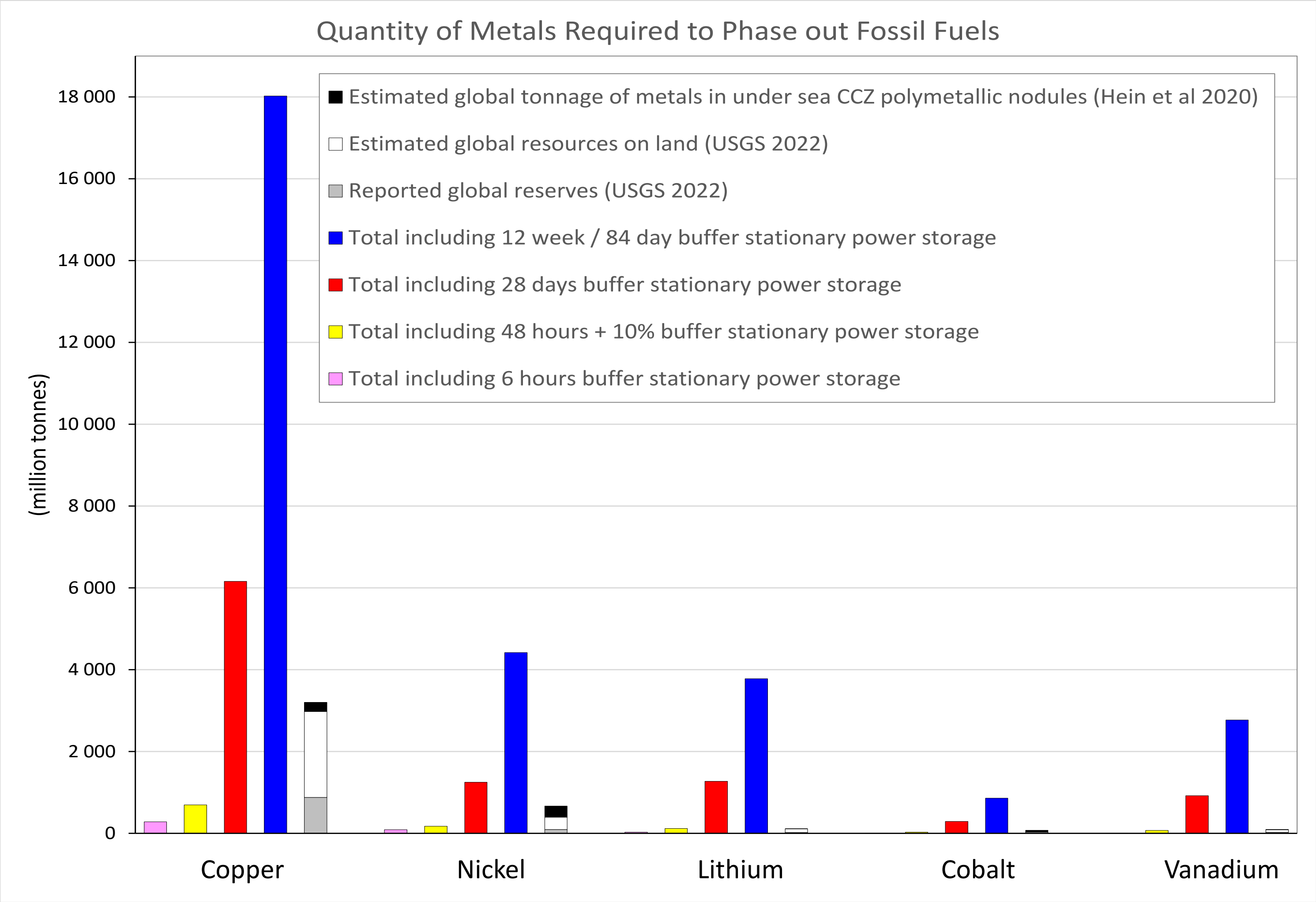
Metal	Total including 6 hours buffer stationary	Total including 48 hours + 10% buffer stationary	Total including 28 days buffer stationary power	Total including 12 week / 84 day buffer stationary
Nickel	91.65	173.14	1 251.34	4 421
Lithium	31.49	118.87	1 274.95	3 784
Cobalt	12.17	31.91	293.05	860
Graphite	262.5	1 096	11 474	36 083
Molybdenum	1.50	1.50	1.50	1.50
Silicon (Metallurgical)	67.39	67.39	67.39	67.39
Silver	0.198	0.198	0.198	0.198
Platinum	0.0027	0.0027	0.0027	0.0027
Vanadium	8.25	72.6	924.5	2 773.6
Zirconium	2.61	2.61	2.61	2.61
Germanium	4.16	4.16	4.16	4.16
Rare Earth Element				
Neodymium	1.14	[illegible]	[illegible]	.14
Lanthanum	5.97	[illegible]	[illegible]	.97
Praseodymium	0.27	[illegible]	[illegible]	.27
Dysprosium	0.21	0.21	0.21	0.21
Terbium	0.0228	0.0228	0.0228	0.0228
Hafnium	0.00029	0.00029	0.00029	0.00029
Yttrium	0.00029	0.00029	0.00029	0.00029

The practical answer is somewhere here

Quantity of metal mined in the last 34 years compared to metal needed for 1st generation of renewable tech



Reported Mineral Reserves + Estimated Resources + Undersea Resources



(USGS Mineral Statistics 2023, Hein *et al.* 2020)

Remember, this is just to produce the 1st generation of renewable technology units

20 years later, we do it all again

Recycling?

Mining production, existing mineral reserves, resources and recycling will not be enough to manufacture the first generation of renewable technology

Geological Survey of Finland

2024

Estimation of the quantity of metals to phase out fossil fuels in a full system replacement, compared to mineral resources

Simon P. Michaux

Bulletin 416 • Special Issue

GTK

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Kiitos, Danke
& Thank you

The Energy Paradox Part 1

Why The Green Transition is Impossible

Q&A ?

If you have any questions, please ask away or come and find me during the next session break.

Presented by
Simon Michaux
Associate Professor
Geological Survey of Finland

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