Black Swans, White Swans and the Purple Transition

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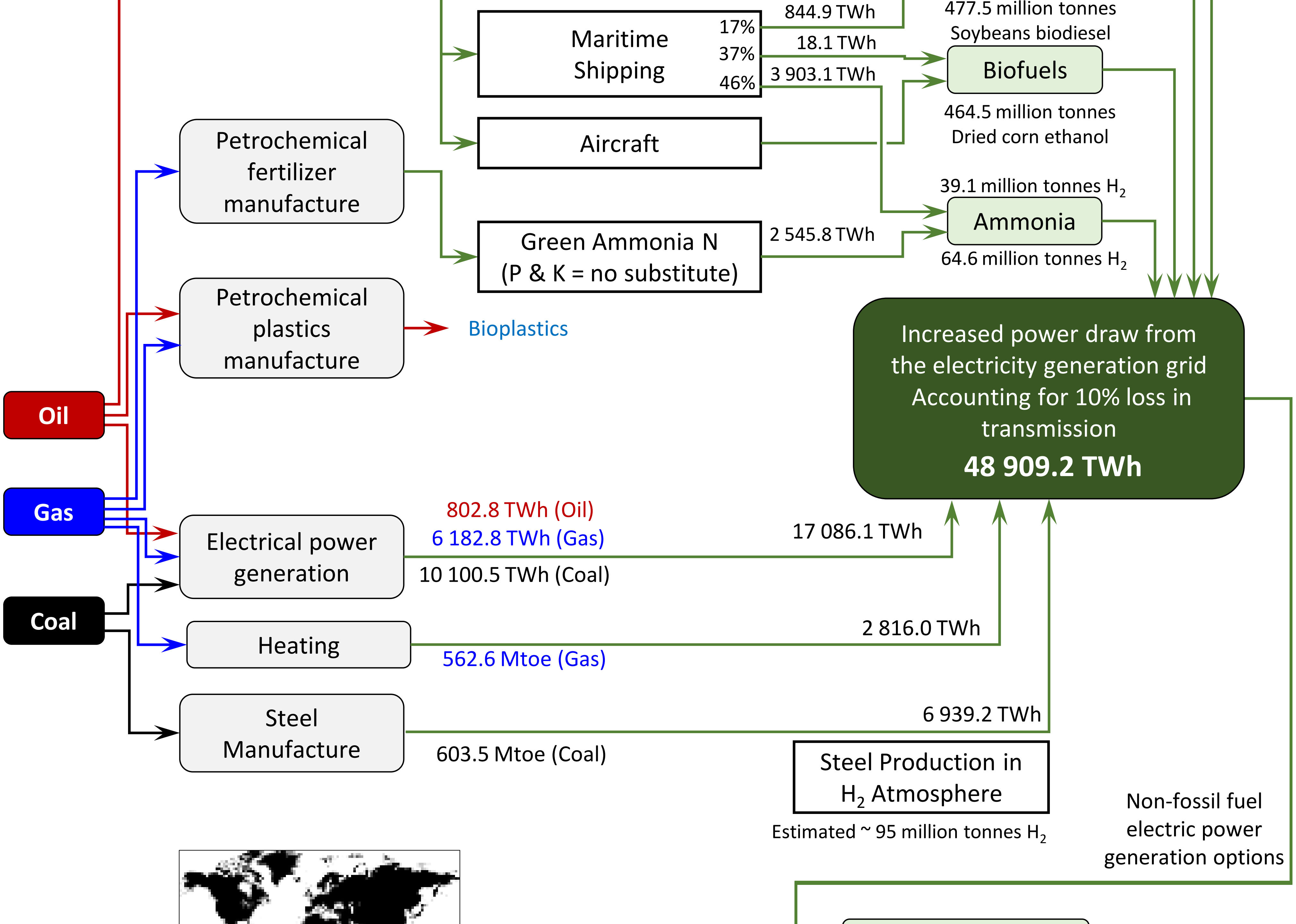
Associate Professor Mineral Processing & Geometallurgy

Summary

- Mapping the Green Transition
- 4 buffer sizes to manage intermittency of solar and wind power supply
- Quantity of metals needed
  - *Compared to global annual mining production 2019*
  - *Compared to mineral reserves, resources and under sea resources*
- Make batteries of something other than lithium-ion chemistry
- The commodities industry has been misunderstood
- Liquid fuel fission using thorium as the fuel
- Ammonia fueled ICE
- The Purple Transition


844.9 TWh
477.5 million tonnes
Soybeans biodiesel
Maritime Shipping
17%
37%
46%
18.1 TWh
3 903.1 TWh
Biofuels
464.5 million tonnes
Dried corn ethanol
Aircraft
Petrochemical fertilizer manufacture
39.1 million tonnes H_2
Ammonia
Green Ammonia N
(P & K = no substitute)
2 545.8 TWh
64.6 million tonnes H_2
Petrochemical plastics manufacture
Bioplastics
Increased power draw from the electricity generation grid
Accounting for 10% loss in transmission
48 909.2 TWh
Oil
Gas
Coal
802.8 TWh (Oil)
6 182.8 TWh (Gas)
10 100.5 TWh (Coal)
Electrical power generation
17 086.1 TWh
Heating
2 816.0 TWh
562.6 Mtoe (Gas)
Steel Manufacture
6 939.2 TWh
603.5 Mtoe (Coal)
Steel Production in H_2 Atmosphere
Estimated ~ 95 million tonnes H_2
Non-fossil fuel electric power generation options

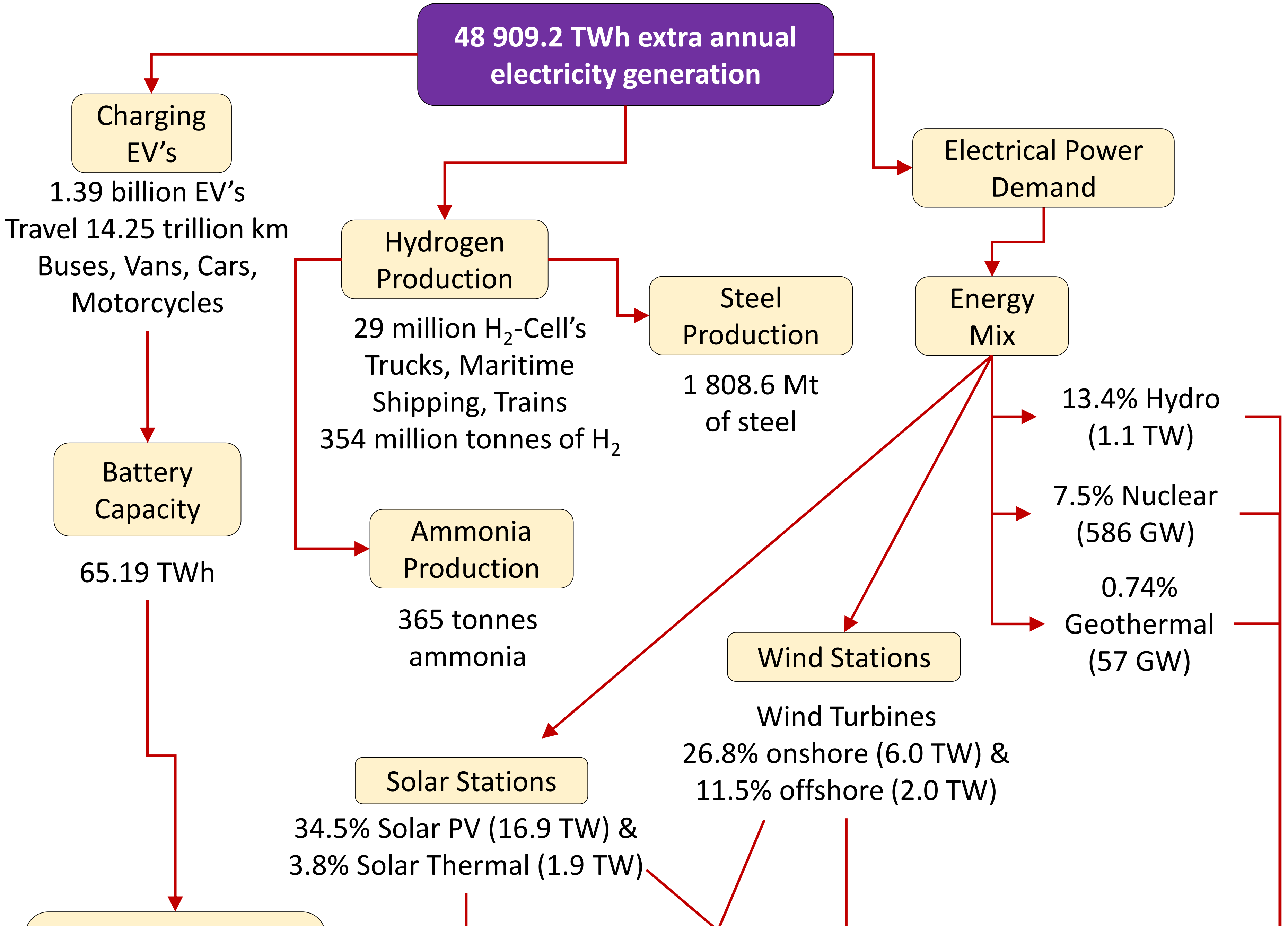

48 909.2 TWh extra annual electricity generation
Charging EV's
1.39 billion EV's
Travel 14.25 trillion km
Buses, Vans, Cars, Motorcycles
Battery Capacity
65.19 TWh
Hydrogen Production
29 million H_2-Cell's
Trucks, Maritime Shipping, Trains
354 million tonnes of H_2
Ammonia Production
365 tonnes ammonia
Steel Production
1 808.6 Mt of steel
Electrical Power Demand
Energy Mix
13.4% Hydro (1.1 TW)
7.5% Nuclear (586 GW)
0.74% Geothermal (57 GW)
Wind Stations
Wind Turbines
26.8% onshore (6.0 TW) &
11.5% offshore (2.0 TW)
Solar Stations
34.5% Solar PV (16.9 TW) &
3.8% Solar Thermal (1.9 TW)

Table 43. Total metal quantity required to phase out fossil fuels, by different buffer for stationary power storage capacity

Metal	Total including 6 hours buffer stationary power storage (million tonnes)	Total including 48 hours + 10% buffer stationary power storage (million tonnes)	Total including 28 days buffer stationary power storage (million tonnes)	Total including 12 week / 84 day buffer stationary power storage (million tonnes)
Steel	1 686	1 686	1 686	1 686
Aluminium	353.5	353.5	353.5	353.5
Copper	283.6	696.6	6 161	18 022
Zinc	48.17	48.17	48.17	48.17
Magnesium Metal	0.50	0.50	0.50	0.50
Manganese	18.60	38.80	305.97	885.88
Chromium	9.20	9.20	9.20	9.20
Nickel	92.23	173.67	1 251.20	4 418
Lithium	31.49	118.81	1 274.16	3 782
Cobalt	12.24	31.97	292.94	859
Graphite	262.1	1 096	11 466	36 061
Molybdenum	1.50	1.50	1.50	1.50
Silicon (Metallurgical)	67.35	67.35	67.35	67.35
Silver	0.198	0.198	0.198	0.198
Platinum	0.0027	0.0027	0.0027	0.0027
Vanadium	8.25	72.6	924.0	2 771.9
Zirconium	2.61	2.61	2.61	2.61
Germanium	4.16	4.16	4.16	4.16
Rare Earth Element				
Neodymium	1.14	1.14	1.14	1.14
Lanthanum	5.97	5.97	5.97	5.97
Praseodymium	0.27	0.27	0.27	0.27
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

- 6 hours (Larson et al 2021)

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J. Williams, R., Pacala, S., Socolow, R., Baik, E.J., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., and Swan, A., (2021): Net Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report Summary, Princeton University, Princeton, NJ, 29 October 2021, https://netzeroamerica.princeton.edu/?explorer=pathway&state=national&table=e-positive&limit=200

- 48 hours +10% (Steinke et al 2012)

Steinke F., Wolfrum Ph., and Hoffmann C. (2012): Grid vs. storage in a 100 % renewable Europe. Renewable Energy, 50 (2013), 826-832

- 28 days (Droste-Franke 2015)

Droste-Franke, B. (2015): Review of the need for storage capacity depending on the share of renewable energies (Chap. 6). In Electrochemical energy storage for renewable sources and grid balancing. Netherlands: Elsevier

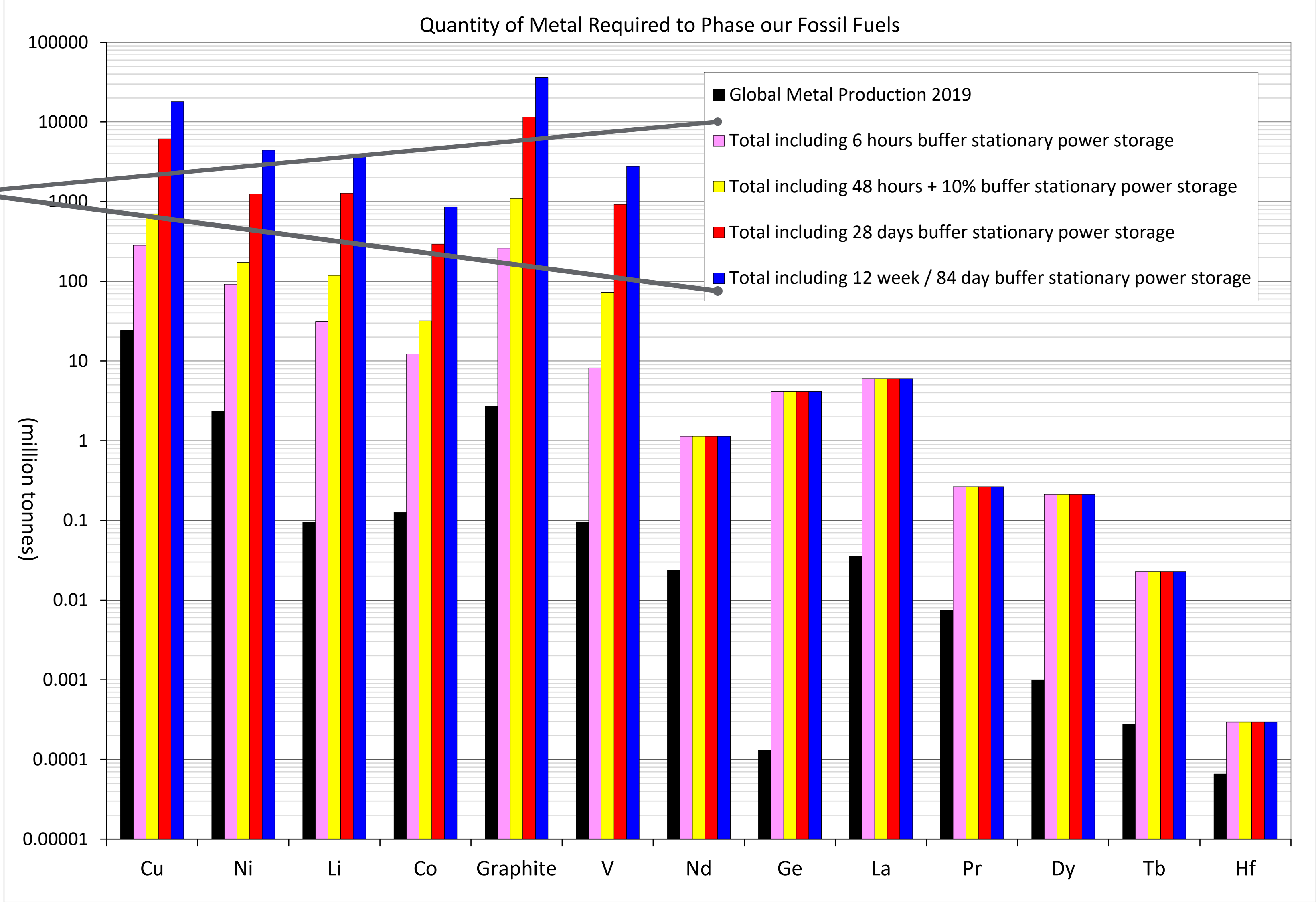
- 12 weeks (Ruhnau & Qvist 2021)

Ruhnau, O., and Qvist, S., (2021): Storage requirements in a 100% renewable electricity system: Extreme events and inter-annual variability, ZBW – Leibniz Information Centre for Economics, Kiel, Hamburg, https://www.econstor.eu/bitstream/10419/236723/1/Ruhnau-and-Qvist-2021-Storage-requirements-in-a-100-renewable-electricity-system-EconStor.pdf

Mining production in 2019 (the last year of sensible data)

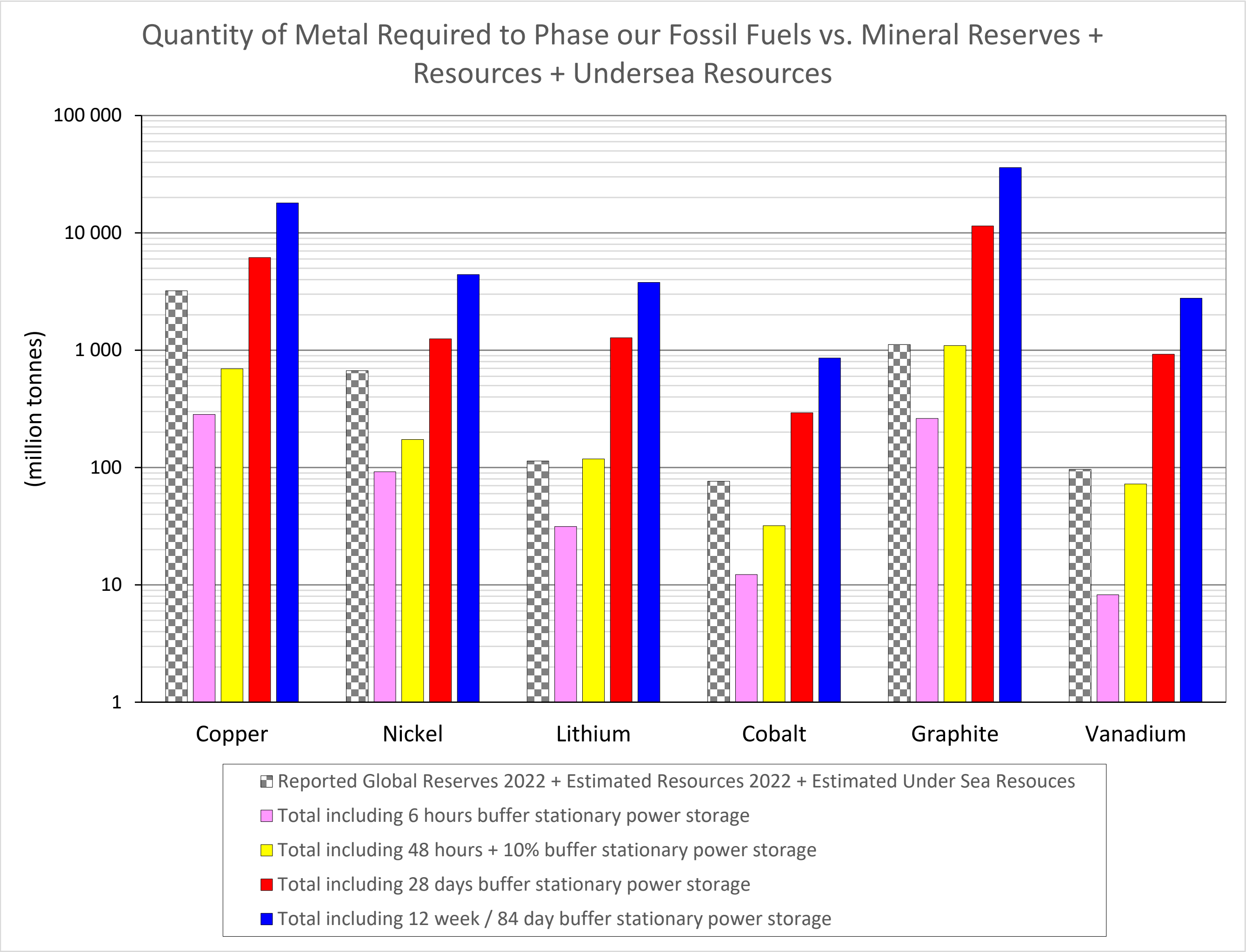
Remember,
this is for just the first generation of units.

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



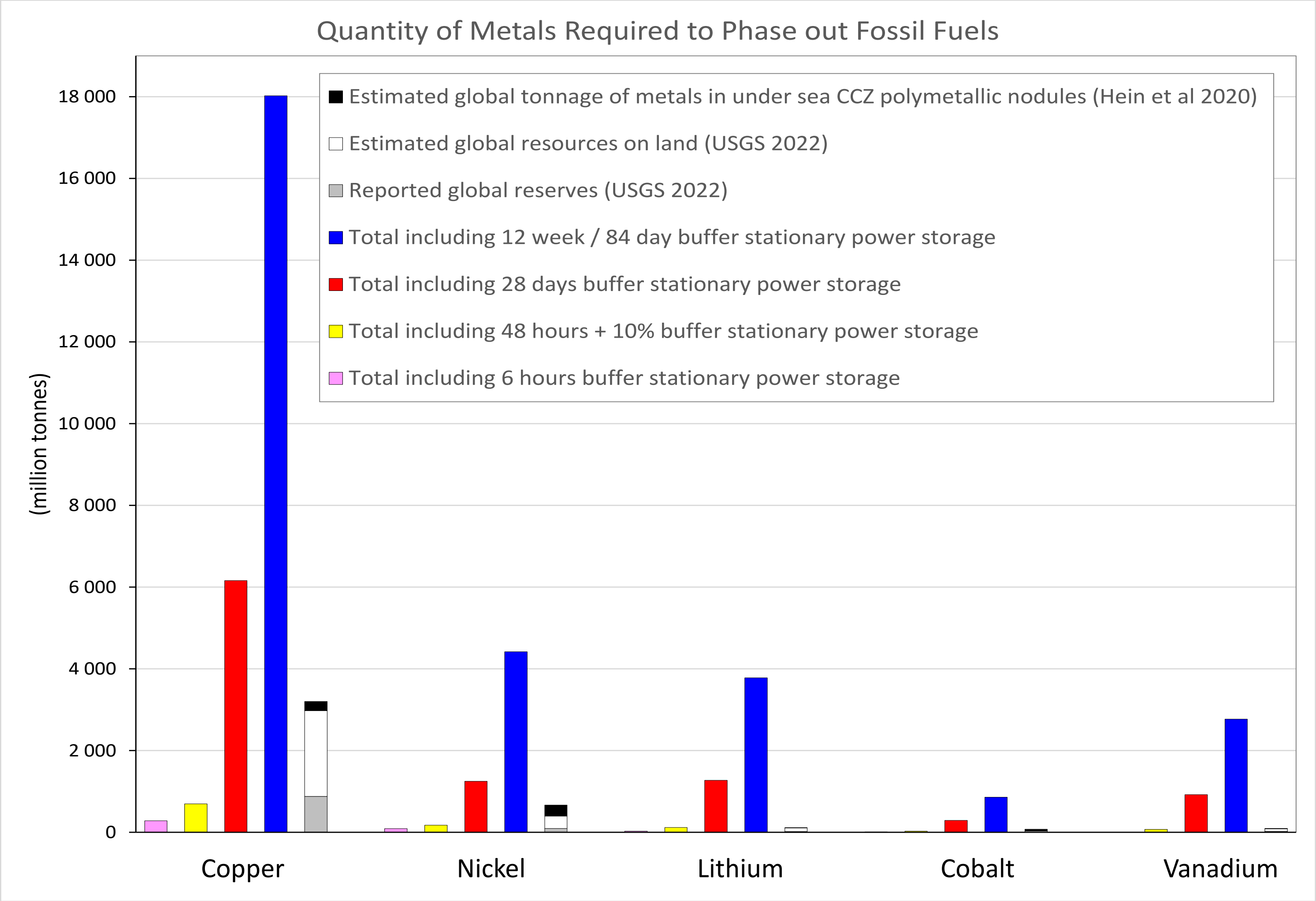
(USGS Mineral Statistics 2023)

Reported Mineral Reserves + Estimated Resources + Undersea Resources



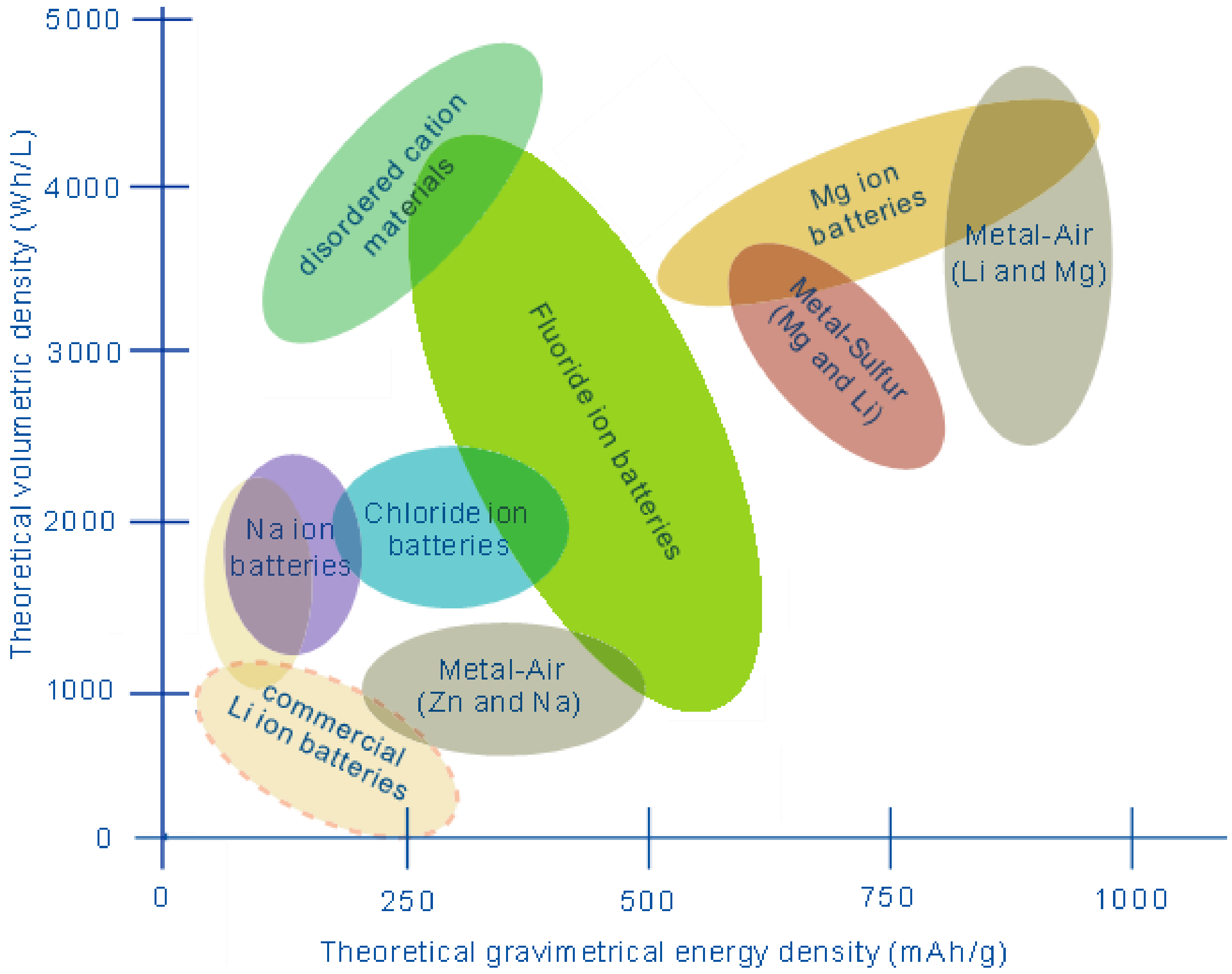
(USGS Mineral Statistics 2023, Hein *et al.* 2020)

Reported Mineral Reserves + Estimated Resources + Undersea Resources



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

Make batteries out of something else

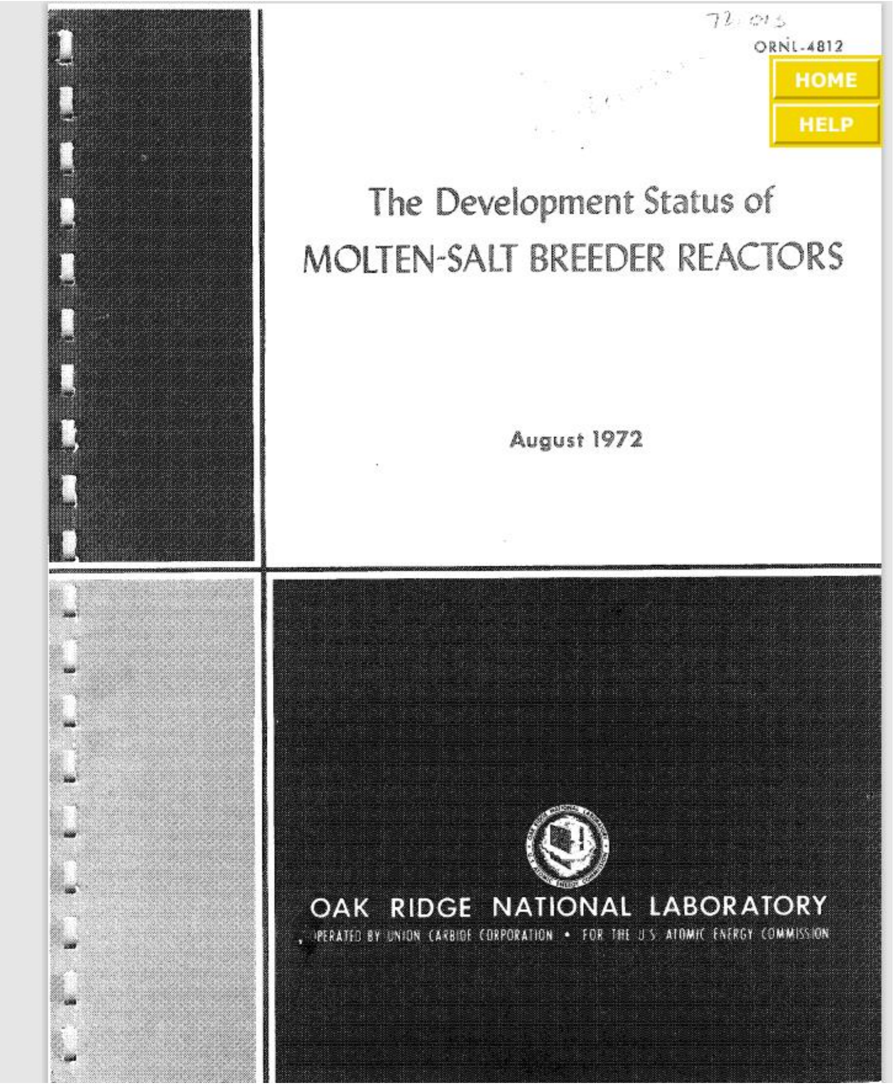


- Zinc
- Fluoride
- Sodium
- Magnesium

- Most of these things can be found in industrial waste

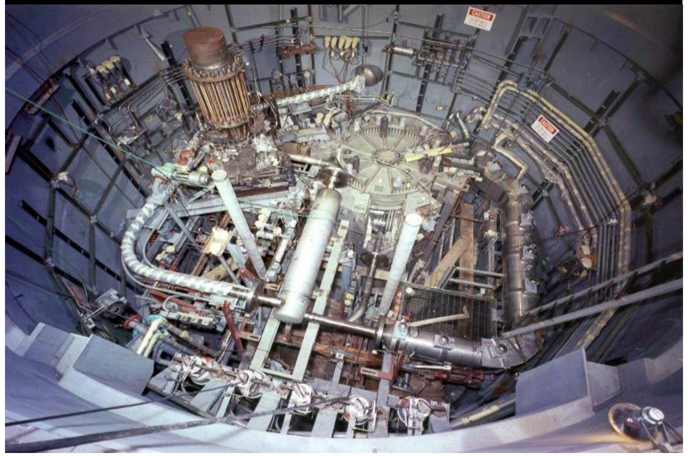
- The valuable part becomes processing and refining into something useful

A Circular Economy action


ORNL-4812
HOME
HELP
The Development Status of
MOLTEN-SALT BREEDER REACTORS
August 1972
OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

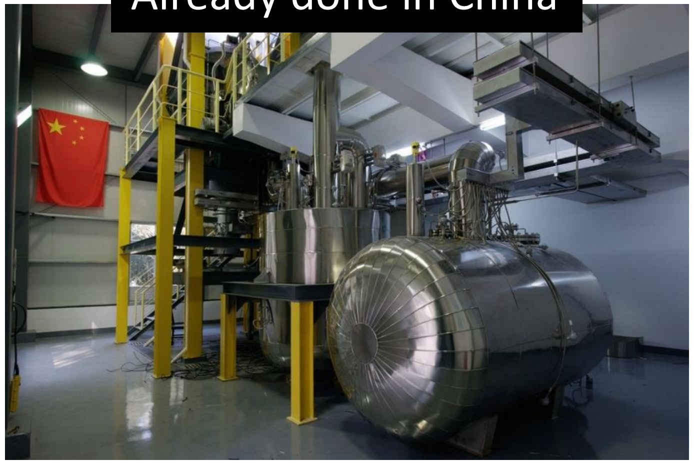
ORNL (1972): The Development Status of Molten Salt Breeder Reactors, Report ORNL - 4812, Oakland Ridge Nuclear Laboratory, United States Atomic Energy Commission (AEC)

6000 hours power generation



The MSR used in the Oak Ridge Molten salt reactor (7.4 MW) commercial pilot 1969

Already done in China



The LFTR (2 MW) used in Circa Whuhai, China in 2022 – now commercially selling power

Preußische Allgemeine

Zeitung für Deutschland · Das Ostpreußenblatt · Pommersche Zeitung

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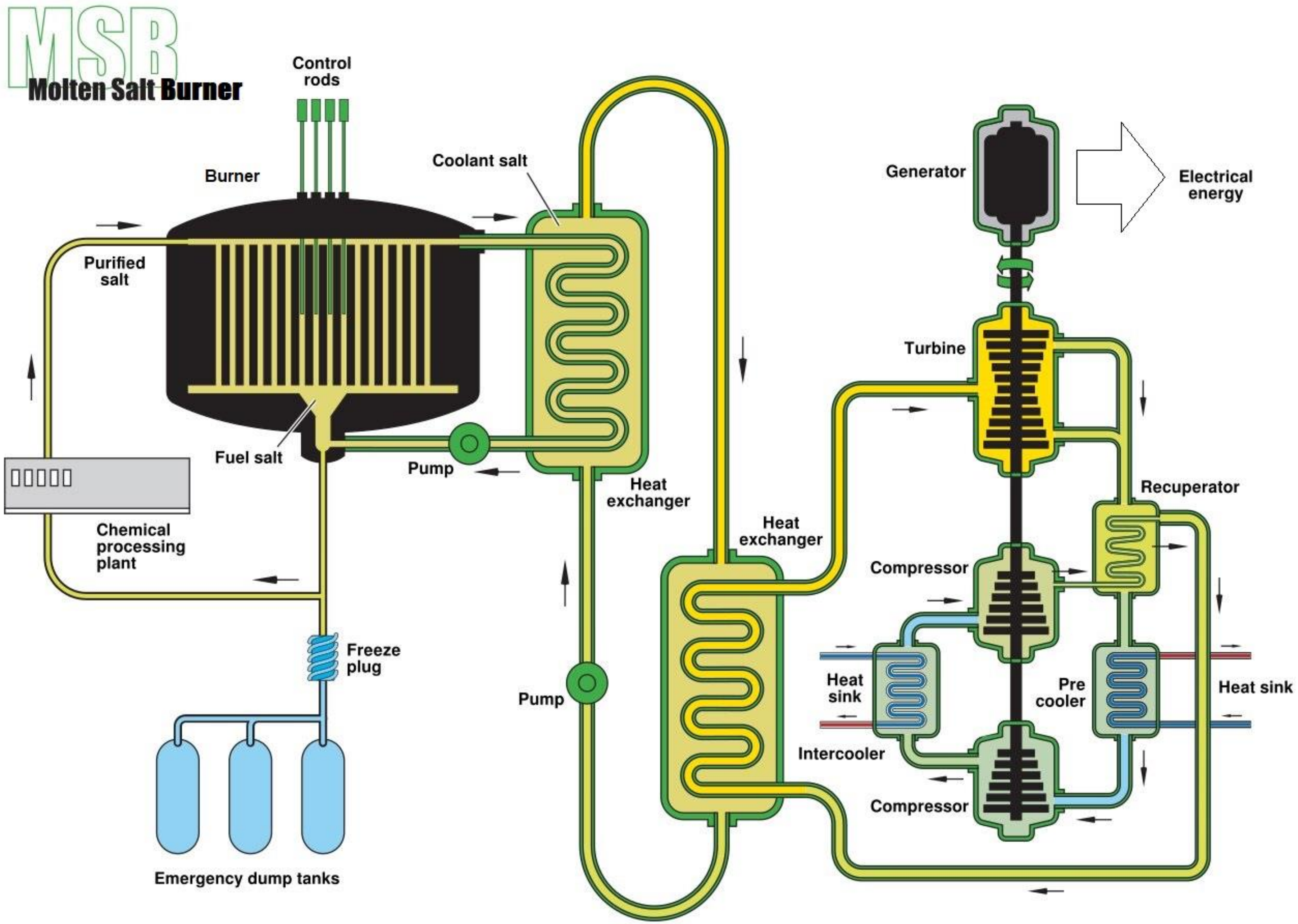
ドイツのための新聞·オストプレウセンブラット·ポメラニアン新聞	Newspaper for Germany · The Ostpreußenblatt · Pomeranian Newspaper
トリウムベースの溶融塩原子炉·液体燃料No.1 の責任:上海応用物理学研究所	Responsible for the Thorium-based Molten Salt Reactor-Liquid Fuel No. 1: The Shanghai Institute of Applied Physics

中国の溶融塩ループ実験 / China's molten salt loop experiment

https://thethoriumnetwork.com/2022/05/03/%e3%83%91%e3%83%bc%e3%83%95%e3%82%a7%e3%82%af%e3%83%88%e3%83%86%e3%82%af%e3%83%8e%e3%83%ad%e3%82%b8%e3%83%bc-%e3%83%90%e3%82%a4%e3%83%aa%e3%83%b3%e3%82%ac%e3%83%ab%e8%a8%98%e4%ba%8b-%e6%97%a5%e6%9c%ac/


MSB
Molten Salt Burner
Control rods
Burner
Coolant salt
Purified salt
Chemical processing plant
Fuel salt
Pump
Heat exchanger
Freeze plug
Emergency dump tanks
Pump
Heat exchanger
Generator
Electrical energy
Turbine
Recuperator
Compressor
Heat sink
Intercooler
Pre cooler
Heat sink
Compressor

Liquid Fuel Thorium Molten Salt Reactor

Can also run with a U salt mix, and with some SNF

1.45 tonne of natural ThO_2 mined from approx. 280 tonne of monazite mineral sands (@0.5% grade Th)

1.34 tonne of ^{232}Th in Thorium fluoride salt

10 000 GWh of electrical power is generated (365 days)

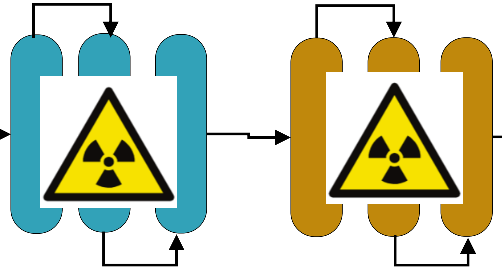
1-5% radioactive isotopes

53.84 kg of contaminated fuel (LLW). Mostly medical isotopes (Xe, Ce, Sr, Zr, I, etc.) Stored for 300 years if not recycled

Uranium Light Water Reactor

https://www.wise-uranium.org/nfcm.html

278.8 tonne of natural U_3O_8 mined from approx. 123 Mt of ore (@0.5% grade)



Conversion of U_3O_8 to UF_6 (347.9 tonne)

Enrichment of UF_6 ^{235}U @ 4.09% (43.3 tonne)

Nuclear fuel UO_2 assembly fabrication (32.9 tonne) with 4.9% ^{235}U

10 000 GWh of electrical power is generated (365 days)

96% Waste fuel SNF

SNF (kg)	Waste Class	Storage
9 222.5	VLLW	Permenant
21 824.5	LLW	300 yrs
347.4	ILW	~3000 yrs
19.0	HLW	100 000 yrs
31 584.0		

THE THORIUM NETWORK

Technical Memorandum TTN-TM-001
Status Review of Molten Salt Technology May 2019

Needs to be updated with data from page 73 of GIF Annual Report 2017:
https://tinyurl.com/GIF-Annual-Report-2017 & https://www.gen-4.org/gif/jcms/c_44720/annual-reports

#	Company Name	Contact Details (name, number, email, linkedin)	Reactor	Fuel	Moderator	Fuel Salt	Working Fluid	Size
1	Terrestrial Energy		IMSR	LEU	Graphite	FliBe	N/S	600 MWth
2	Moltex Energy		Stable Salt Reactor	TRU	ZrF4/KF/NaF (coolant)	NaCl-MgCl2/-CaCl (Tube)	Steam (SuperCritical	300 MWe
3	---		SSR (Thermal)	(U &/ Th)	Graphite Coolant (ThF4/NaF)	NaCl-MgCl2/-CaCl (Tube)	Steam (SuperCritical	300 MWe
4	ThorCon Power		IMSR	LEU/Th	Graphite	BeF2-NaF	Steam (Super Critical) 500 MWe	
5	TerraPower		MCFR	Pu	None (fast reactor)	N/A	N/S	
6	Flibe Energy		LFTR	Th-U-233	Graphite	LiF_2-BeF_2	CO2 (?)	250 MWe
7	Transatomic Power Corp.		TAP concept	LiF	Zirconium Hydride		N/S	1000 MWe
8	UC Berkeley		MK1 PB-FHR	TRISO (pebble bed)	Graphite	Coolant (Li2BeF4)	Air	100 Mwe
9	Elysium Industries		MCSFR	X-U-Pu	None	NaCl-UCl3/4-PuCl3-FPCly	N/S	50-1200 MWe
10	Copenhagen Atomic		MSR	Pu-MA additive (U233)	N/S	LiF_2-BeF_2	N/S	50 MWe

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11	Seaborg		CMSR	TRU in Tubes	Liquid	LiF_2-BeF_2	N/S	250/100 MWe
12	Fuji MSR		FUJI-U3	Th/U & Pu+MA	Graphite	LiF_2-BeF_2	Steam (SuperCritical)	200 MWe
13	---		MSR-FUJI	Th/U	Graphite	LiF_2-BeF_3	Steam (SuperCritical	1000 MWe
14	SINAP		TMSR-SF	TRU (Solid Balls)	None	LiF2-BeF2 (Coolant)	TBD	
15	---		TMSR-LF	Th-U(19.75%U235)	Graphite	LiF2-BeF2	C02	168 Mwe
16	Kurchatov Institute		MOSART	TRU		LiF-BeF2-TRUF3	N/S	2400 MWth
17	SAMOFAR /SAMOSAFER (Consortium : CNRS, JRC, TU Delft, PSI, CIRTEN)		MSFR	Th/U233 + M.A	None (fast reactor)	LiF–ThF –233UF and LiF–ThF – (enrUF –PuF). 18m3	Steam (TBC)	3 GWth
18	Kairos		KP-FHR	TRISO fuel in pebble form combined with a low-pressure fluoride salt coolant.			Fl Nitrate “Solar” salt	140 MWe
19	Oklo		SMR - LWR	HALEU			sCO2	1.5 MWe
20	Nuscale Power		SMR - LWR	U		N/A	Steam	720 MW
21	GE-Hitachi		SMR - LWR	U				

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22	USNC		MMR - LWR	FCM				15 MWt
23	Rolls Royce		SMR - LWR	U				

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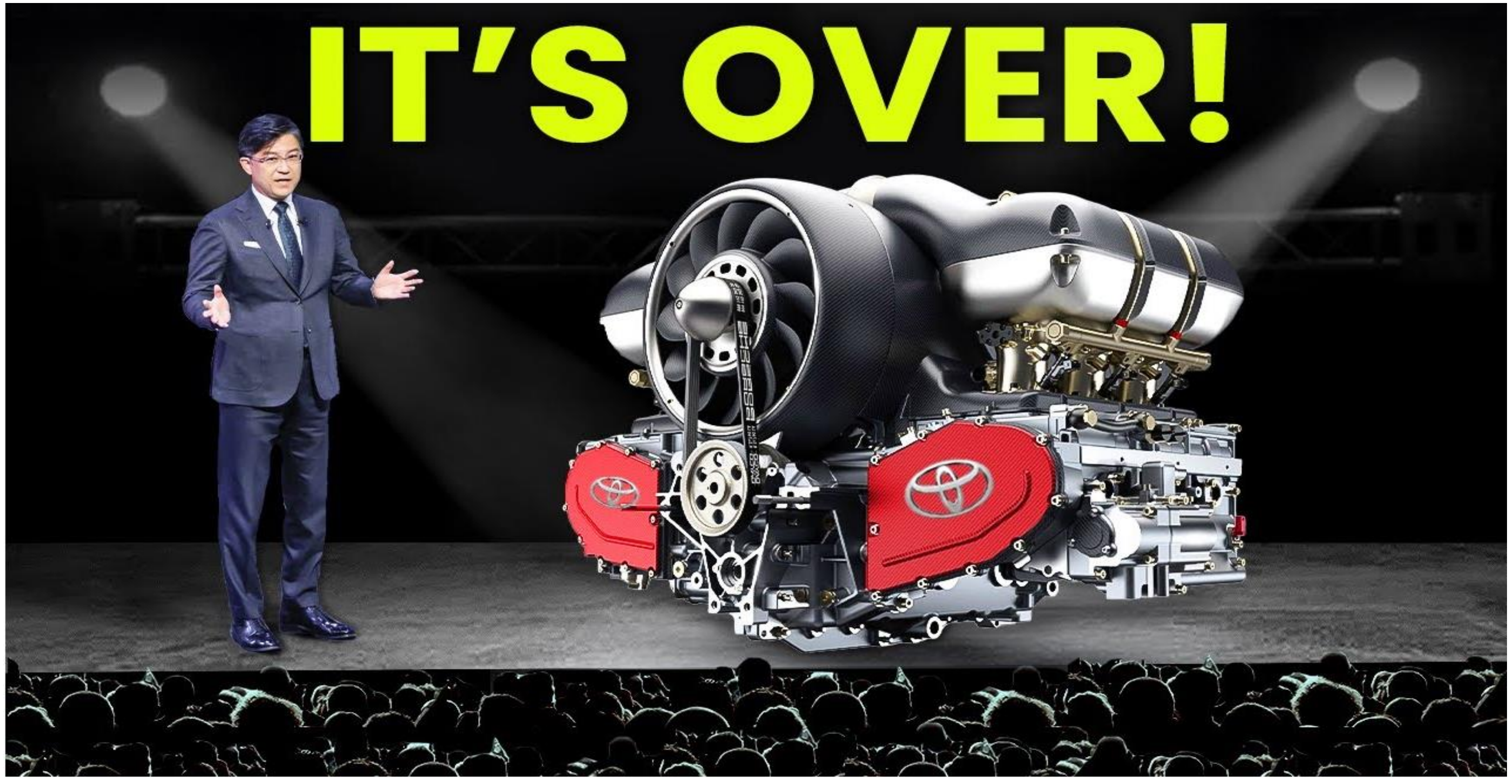
Copenhagen Atomics

- Each commercial rector is planned to be able to produce 100 MW of thermal heat, or 40 MW of electricity
- Each reactor is the size of a 40 foot shipping container
- Electricity will be sold at a projected 2 cents/kWh
- 1g of thorium or uranium produces 24 MWh of thermal energy.
  - *A plant producing 1 GW electricity needs 800kg of Th_{232} metal in salt form each year.*
- First test of complete system to generate electricity in late 2025 to 2026
- Commercial reactors will be available for sale in 2028 (at this stage)

Test rig with a full sized reactor to pilot test the water circuit

https://www.copenhagenatomics.com/

Ammonia Fueled ICE – passenger vehicles to ships



AUTOMOTIVE HOT NEWS

Toyota CEO: "Our Ammonia Engine will be the end of EV's"

Posted by AR1 staff • October 16, 2023

Toyota has been clear about the fact that it does not believe in all-electric cars and is exploring other forms of fuel such as Ammonia.

https://www.autoracing1.com/pl/413299/toyota-ceo-our-ammonia-engine-will-be-the-end-of-evs/

The EV Black Swan is here

The sourcing of raw materials for manufacture drove this decision

The battery market will now crash (opinion)

Metal fuels are metal powders that are used as energy carrier by means of a circular process – Iron powder is metal fuel with most potential

Metal fuels introduction

Metal fuels description

- **Metal fuels** are metal powders that are oxidized to release their chemical energy
- After oxidation, metal fuels can regain their energy by means of reduction, leading to a **circular process** which allows metal fuels to act as energy carrier
- **A range of metals** is applicable as metal fuel, amongst others iron, silicon, magnesium and aluminium
- **Iron powder** shows most potential for applicability as metal fuel due to its abundant occurrence and reduction potential using sustainable energy
- Metal fuels have already been used in different industries, with **applications** ranging from machine building to magnetic products

Key advantages of metal fuels

High performance

- High **output temperature** (up to >1500°C)
- High volumetric **energy density**
- **Low flow rate** required to generate **stable flame**

Competitive transport and storage

- High direct **oxidation efficiency** leading to less material needed
- Possibility of **reusing** and **retrofitting** existing transport and storage infrastructures

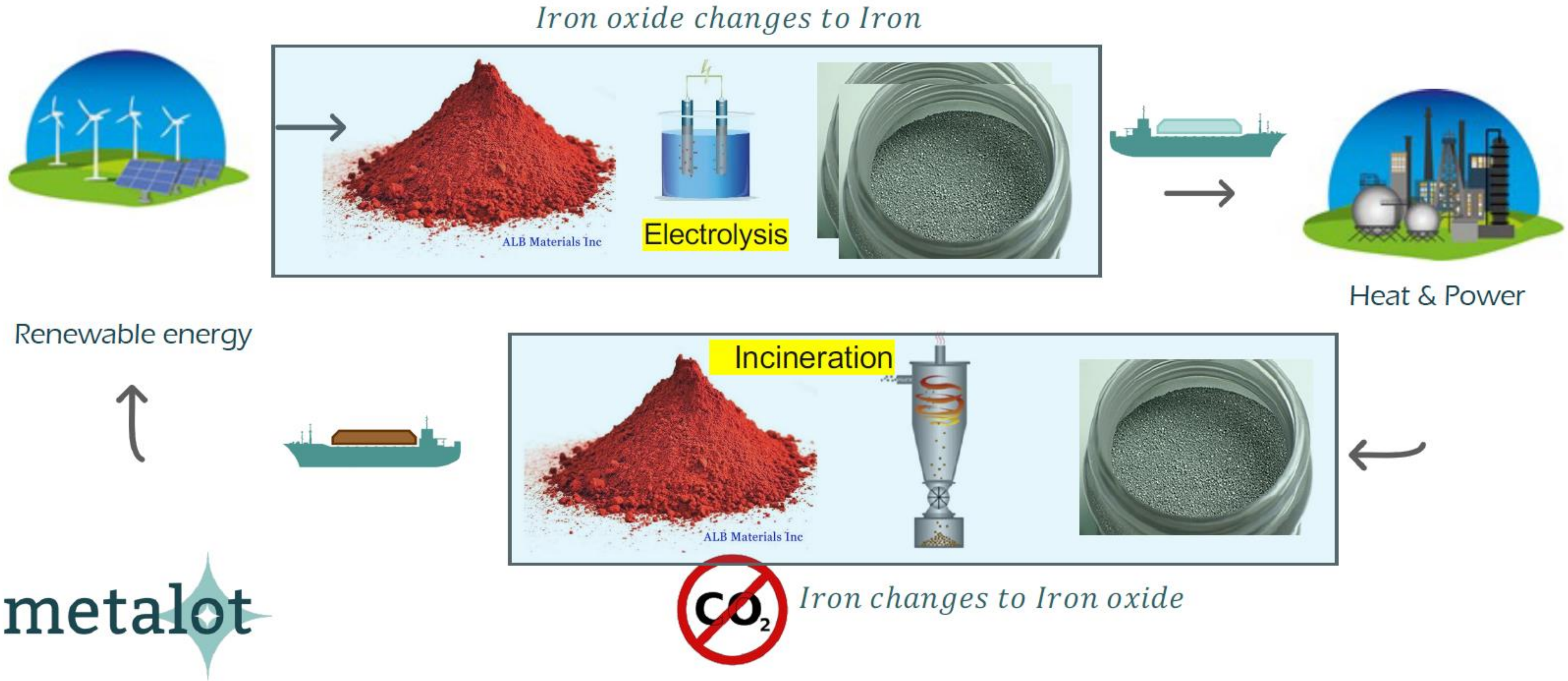
Sustainable and safe

- **No** direct $\mathbf{CO_2}$ emissions and **low/no** direct emissions of NO_x and SO_x
- Full **recyclability** and **circularity**
- **No health or environmental** hazard and **no toxicity**

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

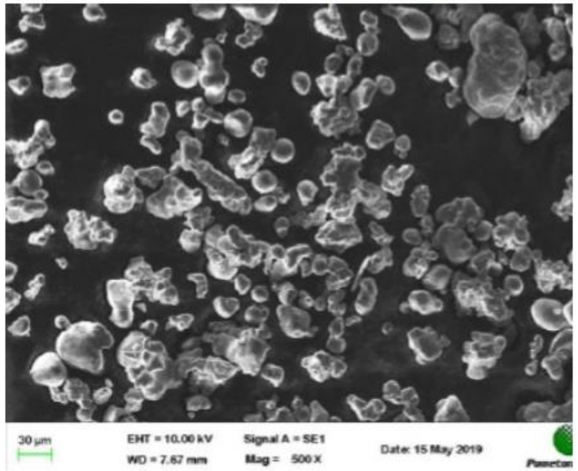
Solution: Green Iron Power; green energy storage, transport & import complementary to H2 & NH3

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



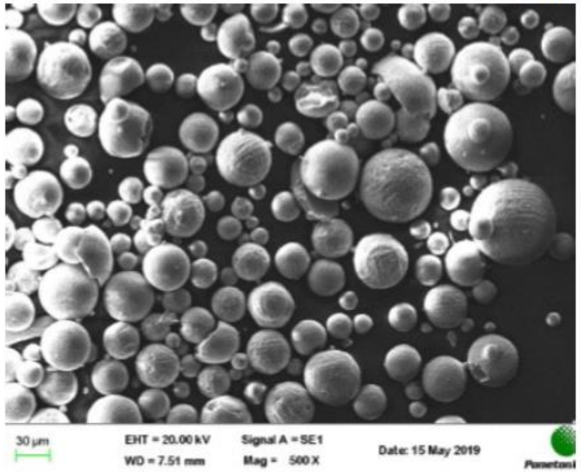
Proof of Concept:
Regeneration systems & Powder specifications

Iron Powder (initial)



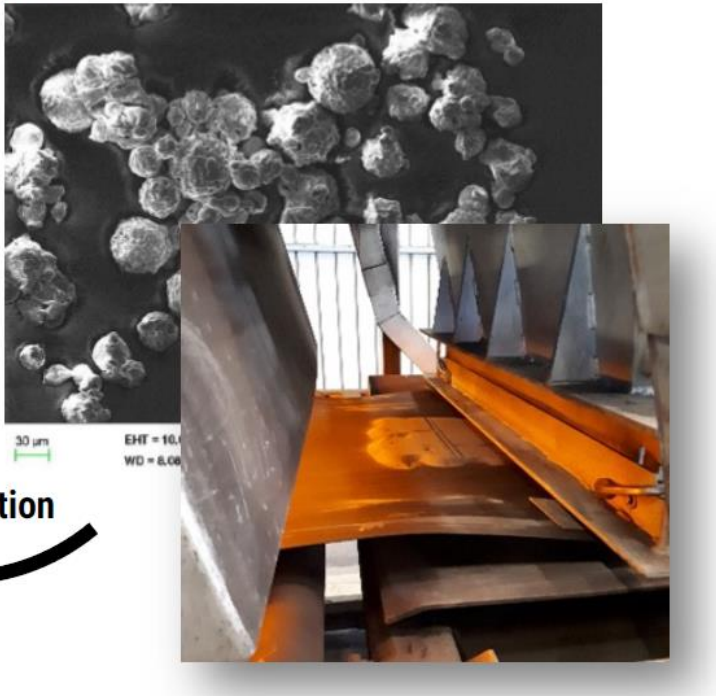
1st burn

Iron Oxide Powder



Regeneration

Iron Powder



Combustion

metalot

Iron powder is well-performing as transport carrier due to its safety, high volumetric energy density, high cycle efficiency, high infra simplicity and overall low costs

Back-up: Qualitative assessment of sustainable energy carriers for long-haul vessel transport

Carrier	Safety: No environ. & health issues	Safety: Non-toxic	Safety: Non-flammable	Safety: Non-explosive	Volumetric energy density	Cycle efficiency[3] [%]	Infrastructure simplicity	Overall cost assessment
Iron powder	✓	✓		✓	8-12 kWh/L	80-90	◕	€
Liquid H_2	✓	✓			0-4 kWh/L	60-70	◔	€ € €
LOHC – H_2[1]			✓	✓	4-8 kWh/L	70-80	◕	€ €
Ammonia - H_2[1]				✓	0-4 kWh/L	60-70	◑	€ €
Methanol – H_2[1]		✓			4-8 kWh/L	70-80	◕	€ €
Methanol		✓			4-8 kWh/L	70-80	◕	€ €
Gaseous H_2 (no pipeline)[2]	✓	✓			0-4 kWh/L	c. 100	◔	€ €
Ammonia				✓	0-4 kWh/L	80-90	◑	€

✓ No issues; 0-4 kWh/L; 4-8 kWh/L; 8-12 kWh/L; High simplicity; Low simplicity; € Low costs; € € Medium costs; € € € High costs

1) Carriers reconverted to hydrogen; 2) Assessment of decentral gaseous hydrogen use - silos instead of pipeline - as defined use case is not connected to hydrogen backbone; 3) Excluding external energy needs

Source: IRENA, desk research, Roland Berger

GTK

Iron powder is expected to have market potential in specific use cases: process heat, district heating, electricity generation and direct production of iron

Back-up: Market potential of iron powder per direct use case (without reconversion)

	Use case	Electricity	Hydrogen	NH_3	MeOH	Iron powder	Market potential for iron powder
Direct industry	Synthetic fuels[1]	✗	✓	✓	✓	✗	
	Iron & Steel[1]	✓	✓	✗	✗	✓	(Medium) Opportunity to produce or import **DRI**, potential to decarbonize steel industry
	Ammonia end-products[1]	✗	✓	✓	✗	✗	
	Methanol end-products[1]	✗	✓	✗	✓	✗	
	Process heat[2]	✗	✓	✓	✗	✓	(High) **Efficient direct oxidation** of iron powder and high resulting heat
Centralized energy	Rankine cycle	n.a.	✓	✓	✗	✓	(Medium) Opportunity to fuel **steam engine** for electricity generation
	Combined cycle	n.a.	✓	✓	✗	✓	(Medium) Opportunity to fuel **steam engine** as part of combined cycle turbine
Mobility	Light duty	✓	✓	~	✓	✗	
	Heavy duty	✓	✓	~	✓	✗	
	Rail	✓	✓	~	✓	✗	
	Inland shipping	~	✓	✓	~	~	
	Marine	~	✓	✓	~	~	
	Aviation	✓	✓	✗	✓	✗	
Built environm.	District heating	✓	✓	~	~	✓	(High) Use of iron powder **heat**, especially for peak-load applications
	Local boiler/heat pump	✓	~	✗	✗	~	
	Other[3]	✓	✗	✗	✗	✗	

✓ Expected viable use case ~ Potentially viable use case ✗ No viable use case

High market potential / Medium market potential / No market potential

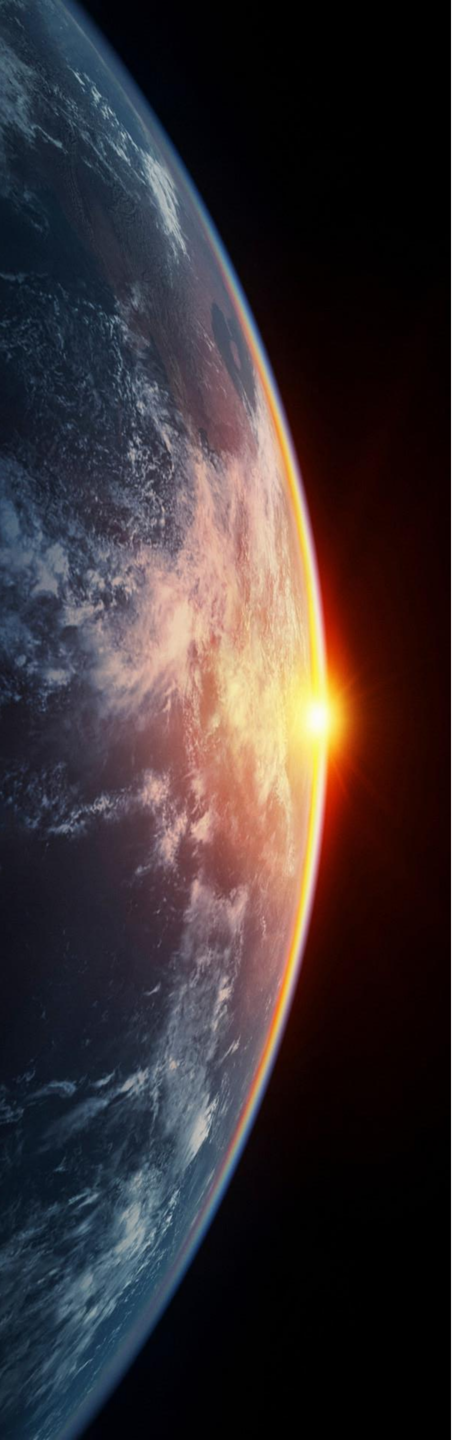
Key advantages of iron powder in relation to direct use applications

- High output temperature
- Stable flame
- High oxidation efficiency
- Full circularity
- Full recyclability
- No direct CO_2, NO_x and SO_x emissions
- No toxicity or environmental and health hazards

metalot

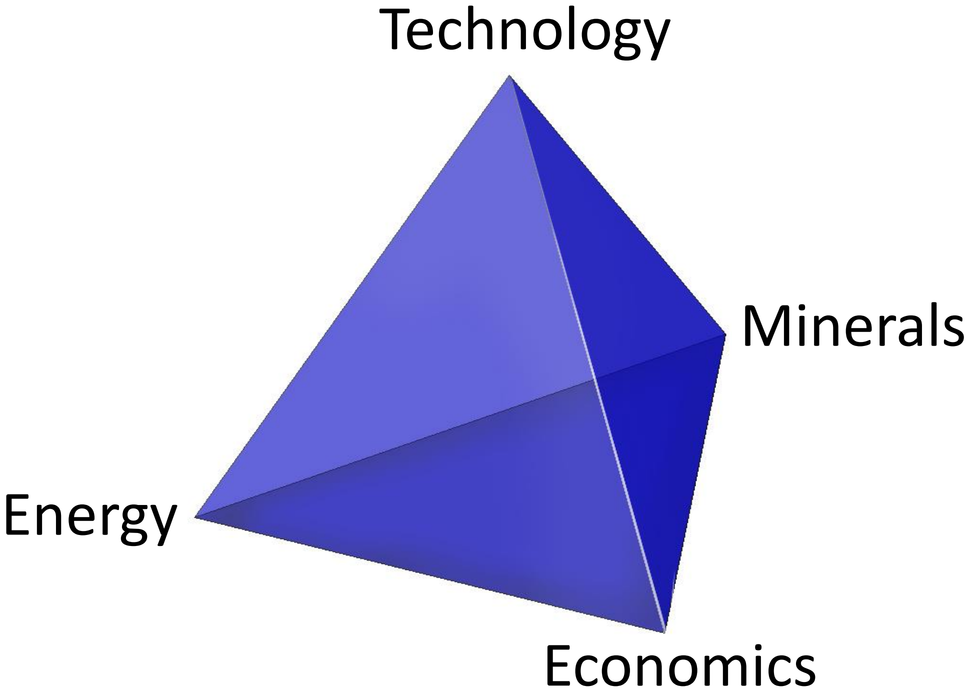
1) As feedstock; 2) Only mid- and high-grade heat; 3) Other = Wood / solar thermal + electric + oil

Source: Roland Berger; European Hydrogen Backbone June 2021



The commodities sector has been misunderstood

Our relationship between all 4 aspects & the planetary environment is changing



This is how our system is really structured

Any new system will have to have a similar structure

All of these aspects and human society functions by harvesting feedstock from the planetary environment

Generation

Application

Buffer to manage intermittency → ~~Solar~~, ~~Wind~~

Natural limitations to expansion → ~~Hydro~~, ~~Geothermal~~, ~~Biowaste~~, ~~Wave~~

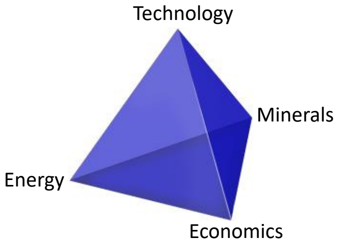
Can't expand fast enough → ~~Nuclear U (LWR)~~

Oil

Gas

Coal

Liquid Fuel Fission Th MSR



Heat

Transport

Electricity

Manufacture

~~ICE Petroleum~~ ← To be phased out

~~Electric Vehicles~~ ← Batteries

~~Biofuels~~ ← Limited supply of biomass

~~Hydrogen Fuel Cell~~ ← Limitations in storage and transport of H_2

ICE Ammonia ← Exhaust gas?

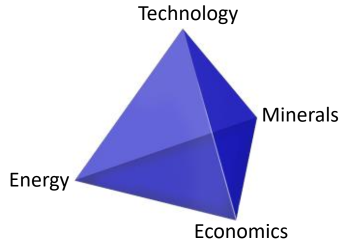
← Can we produce the ammonia from seawater?

The Purple Transition

Generation

Application

Liquid Fuel Fission
Th MSR (560^{0}C)



Transport

Electricity

Manufacture

ICE
Ammonia

Heat

Combustion of iron oxide powder to produce high temperatures (1800^{0}C)

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GTK

Kiitos & Thank you