New Nuclear is Hot!

Session 2

Economics, EROI, Wind, Solar, Batteries, Nuclear, New Nuclear, ThorCon

Literally red hot!
Cheaper than coal.
Lets developing nations prosper.
Cuts rapacious minerals mining.
Zeros electric power CO2.

Public support

Five supporters per opponent.
Relieves energy security concerns.

Seafuel

Net-zero gasoline for your car.
Climate-neutral diesel for industry.
Guilt-free jet flights.
Uses existing combustion engines.
Zeros transportation CO2.

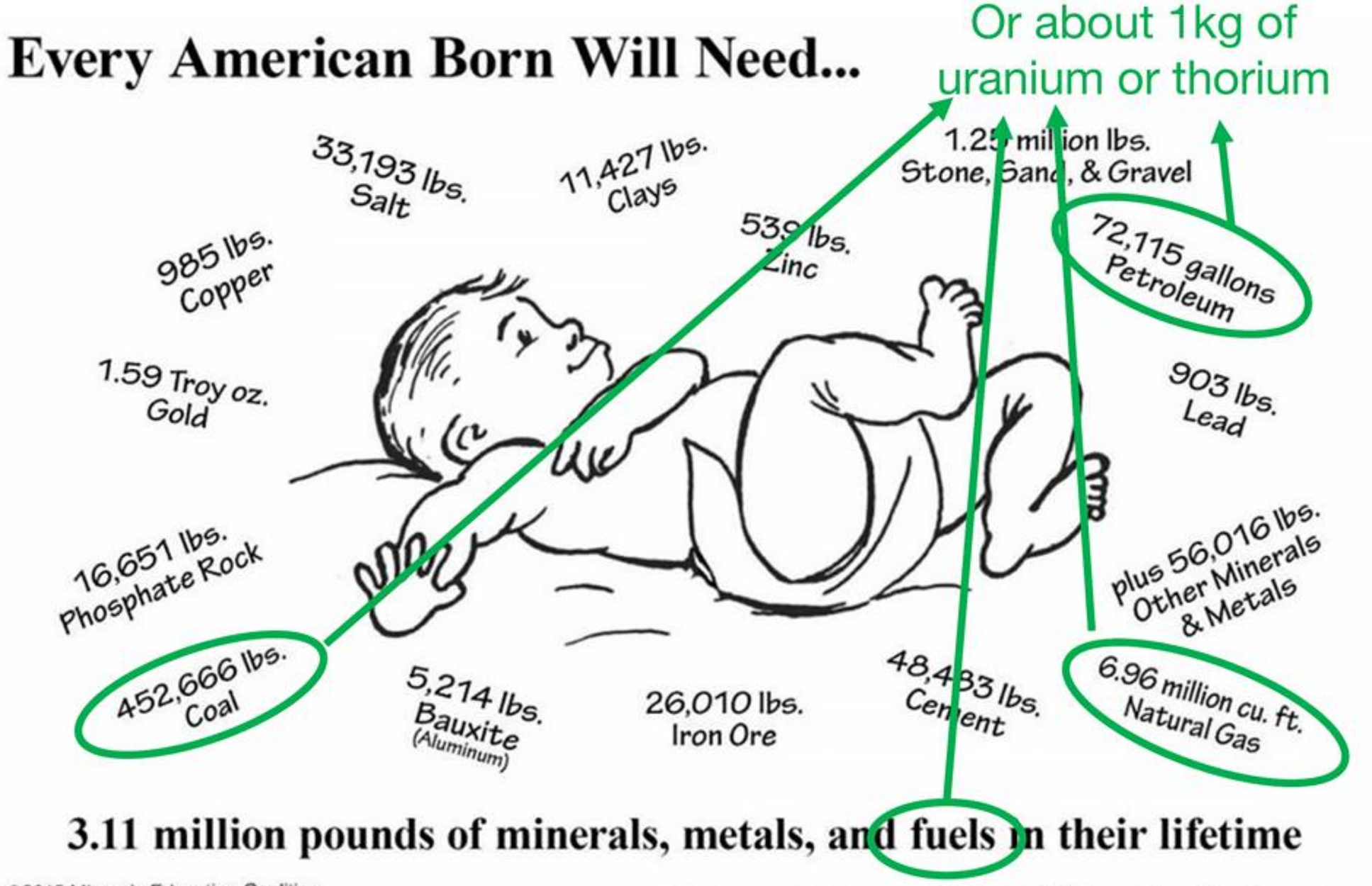
Energy IS the Economy!

Energy drives the economy. There is no substitute for energy.

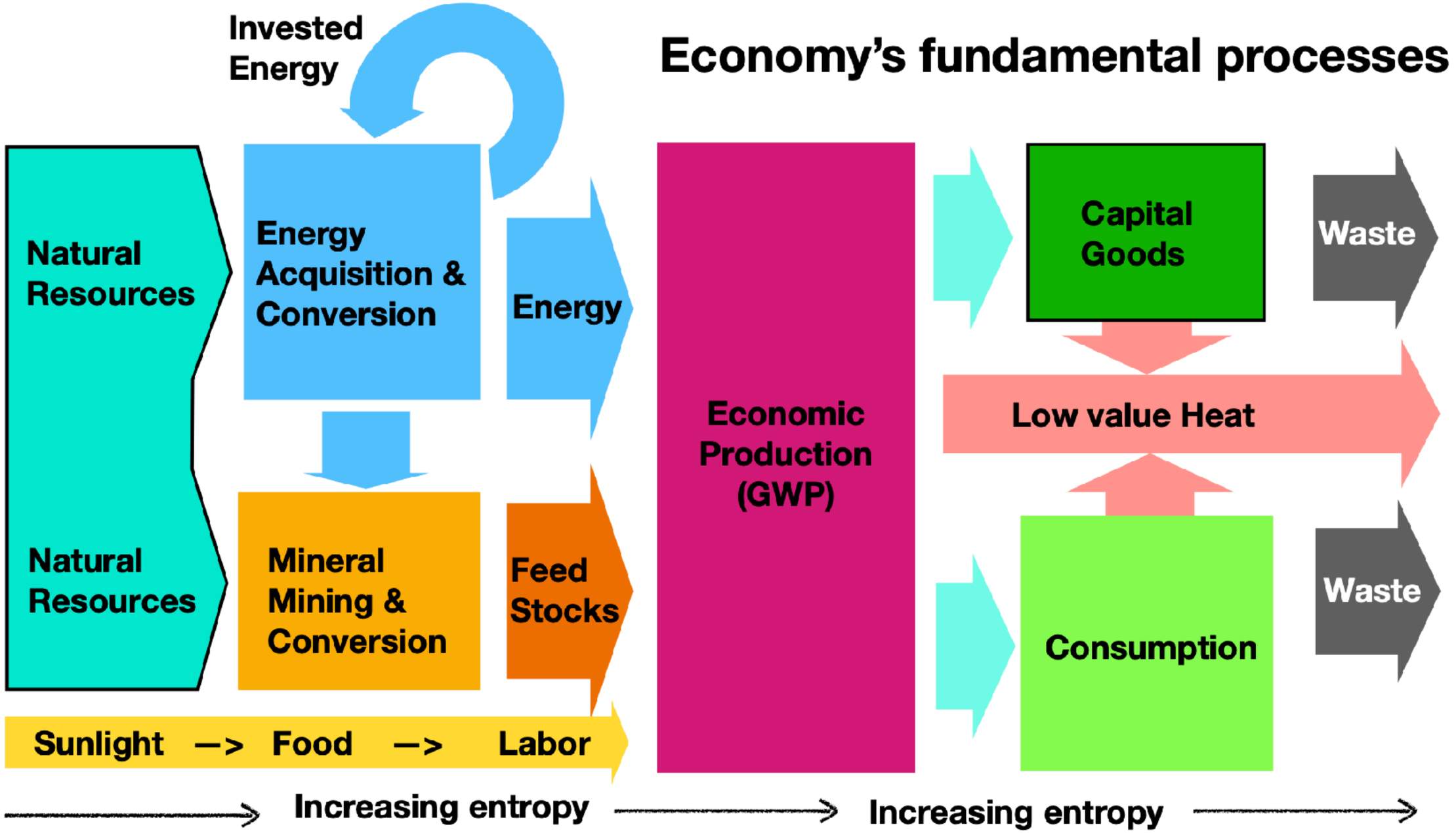
On average in 2022 each $1 of economic production, gross world product (GWP),

- demands 1 kWh of heat energy,
- uses 0.27 kWh(e) of electric energy,
- emits 0.21 kg of CO2, and
- requires 0.96 kg of mined minerals.

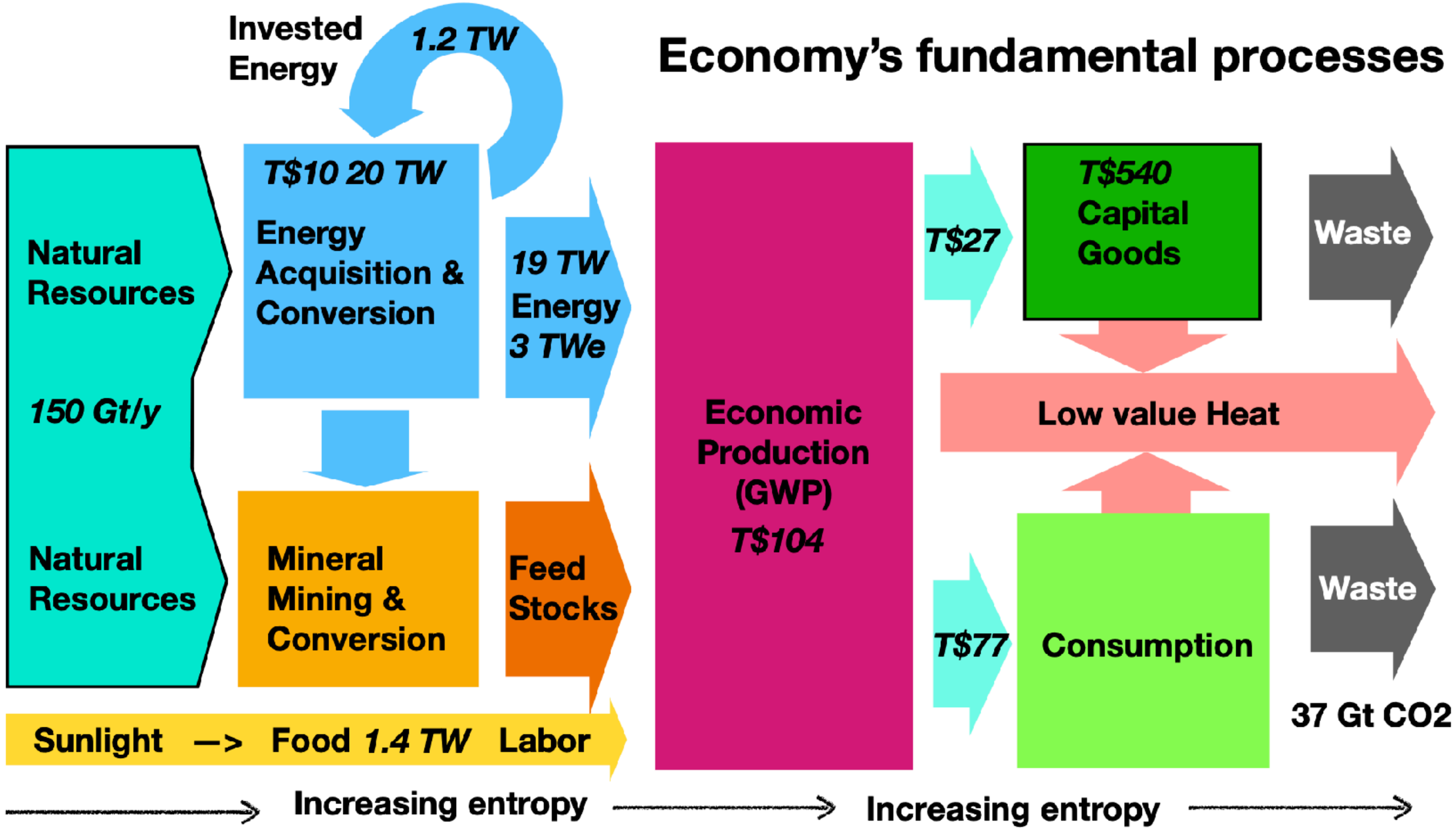
People compete for finite, mined world resources.



World natural resources, energy, and entropy

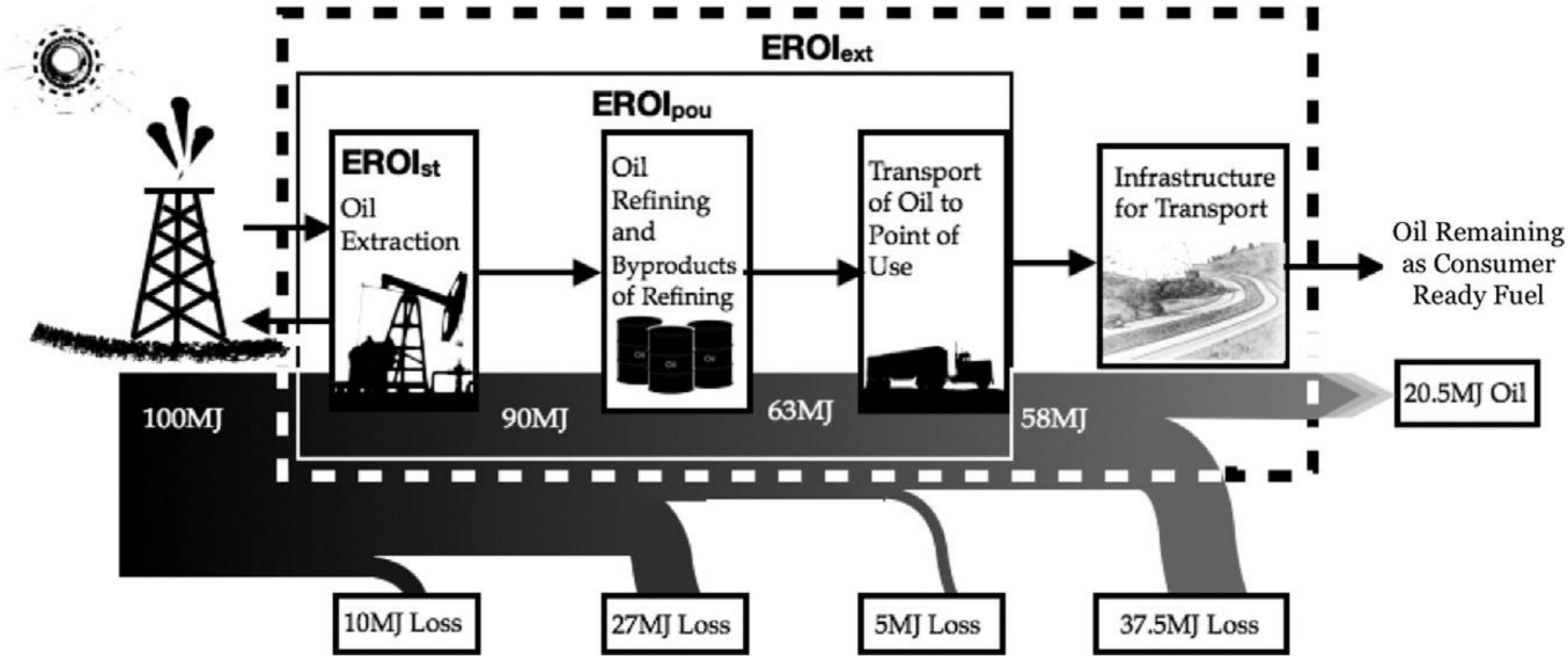


Enumerated natural resources and energy



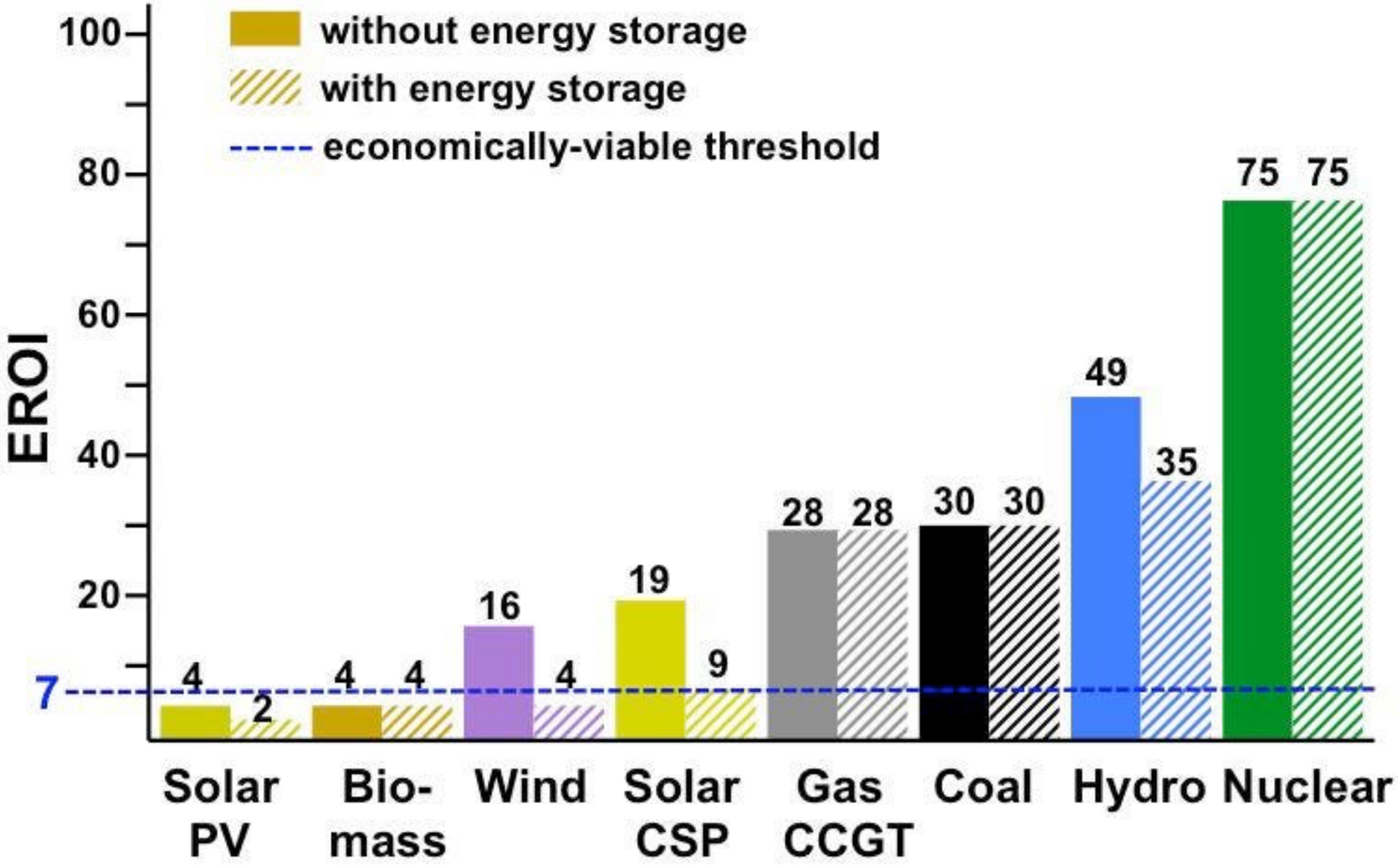
Energy Return on Invested Energy (EROIE or EROI)

fictitious example: Invest 79.5 MJ to get 20.5 MJ to consumer use



Oil's 100 MJ is "free", created from sunlight 100 million years ago.

Energy return on investment in electricity generation.

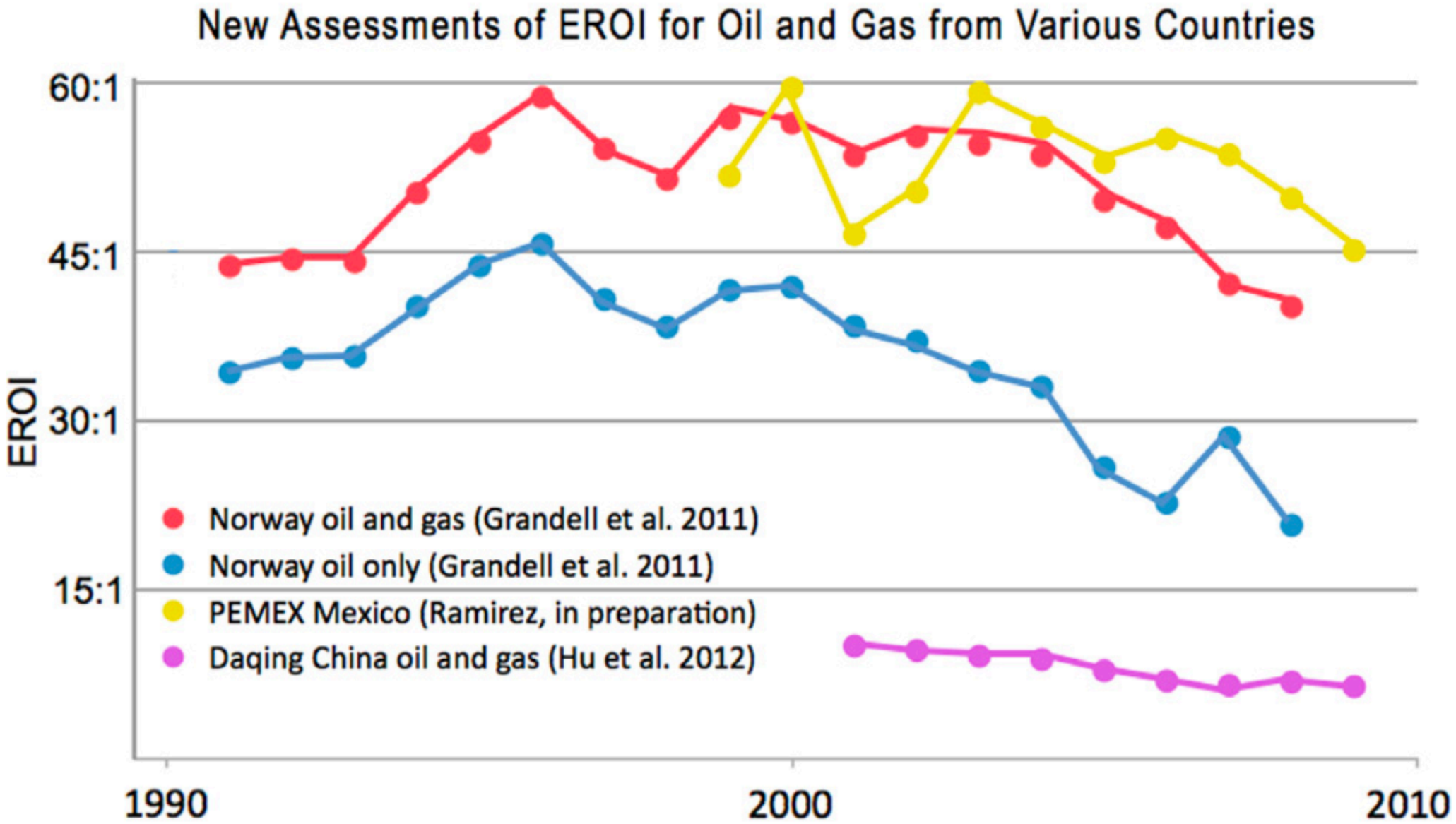


Hall: EROI from oil sources is declining.

Discovering oil	**1000:1** 1919	**5:1** 2010
Producing oil	**25:1** 1970s	**10:1** 2007
Shale oil		**7:1** 2012
Tar sands		**4:1** 2012

https://www.sciencedirect.com/science/article/pii/S0301421513003856

EROI declines in Norway, Mexico, and China



https://www.sciencedirect.com/science/article/pii/S0301421513003856#bib35

Goehring & Rozencwajg: EROI explains world prosperity.

				Energy uses			
Year	Energy sources	GJ/yr/ capita	EROI	Energy	Food	Shelter, work	Surplus
ancient	Food, feed, wood	5	5:1				
1	Food, feed, wood	17	5:1	3	4	10	<< 1
1650	No forest wood Coal discovery	20	10:1	2	4	10	4

5 GJ/yr = ~160 watts

https://f.hubspotusercontent40.net/hubfs/4043042/Content%20Offers/2021.Q4%20Commentary/2021.Q4%20GR%20Market%20Commentary.pdf

Goehring & Rozencwajg: EROI explains world prosperity.

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1900	Oil, gas, coal	25	30:1	1	4	10	10
2019	OIl, gas, coal	75	30:1	1	4	10	56

https://f.hubspotusercontent40.net/hubfs/4043042/Content%20Offers/2021.Q4%20Commentary/2021.Q4%20GR%20Market%20Commentary.pdf

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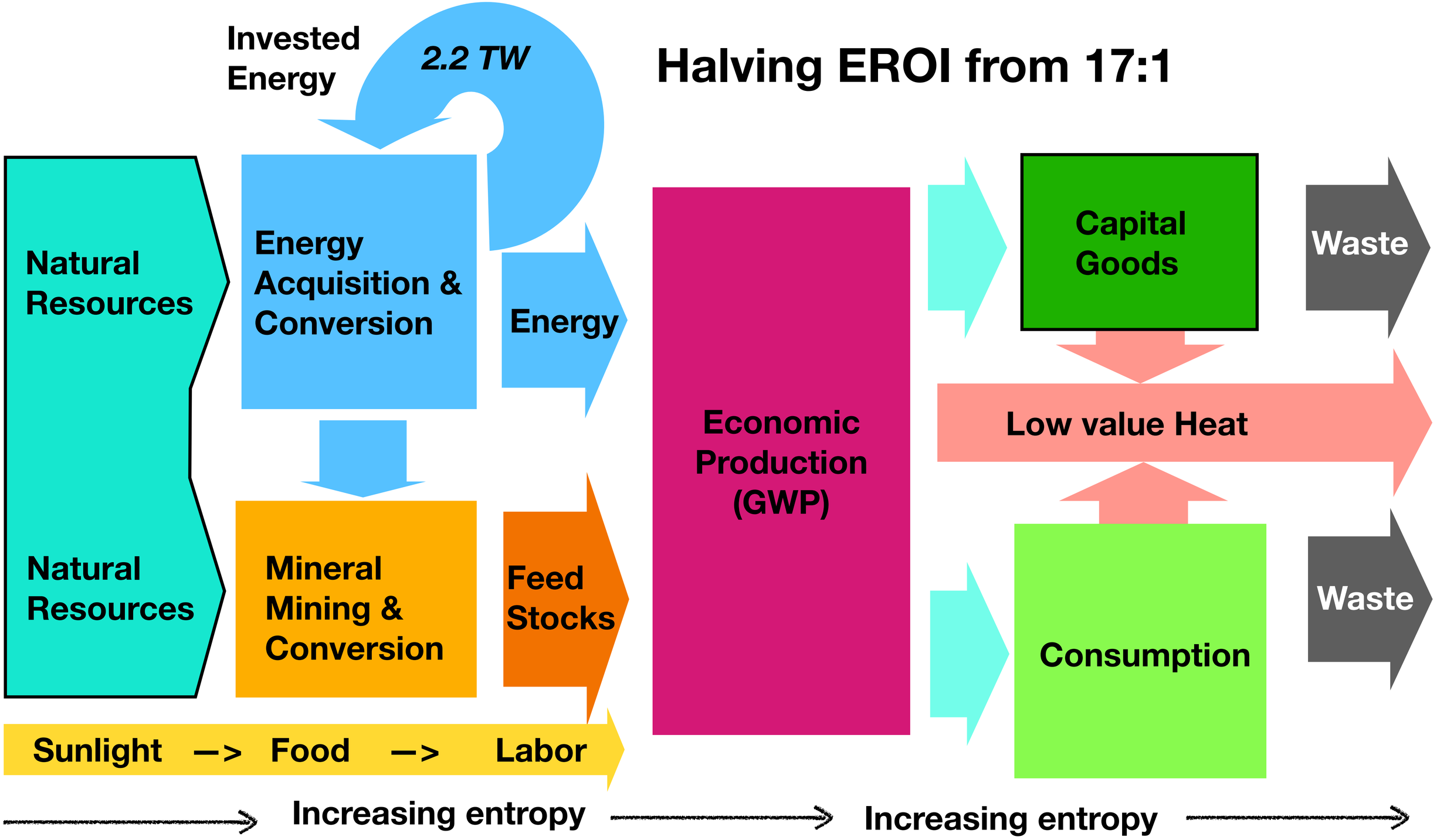
2019	OIl, gas, coal	75	30:1	1	4	10	56
2030 ?	Wind, solar	**75?**	3.5:1	**25?**	4	10	**-39?**

https://f.hubspotusercontent40.net/hubfs/4043042/Content%20Offers/2021.Q4%20Commentary/2021.Q4%20GR%20Market%20Commentary.pdf


Halving EROI from 17:1
Invested Energy
2.2 TW
Natural Resources
Energy Acquisition & Conversion
Energy
Natural Resources
Mineral Mining & Conversion
Feed Stocks
Economic Production (GWP)
Capital Goods
Waste
Low value Heat
Consumption
Waste
Sunlight —> Food —> Labor
Increasing entropy
Increasing entropy

Princeton University Net-Zero America

345 page PowerPoint presentation; $2.5 trillion by 2050.

Table of Contents

PRINCETON UNIVERSITY

andlinger center for energy+the environment

High Meadows Environmental Institute

Carbon Mitigation Initiative

3

<u>USA only</u>

wind, solar

batteries

transmission

bioenergy

CCS

H2 for synfuel

https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Princeton University Net-Zero America

Practical? Technology? Cost? Mining? Land area? Just US?

Executive Summary (4/9)

Six pillars expand rapidly for 3 decades. By 2050:

1. Efficiency & Electrification

Consumer energy investment and use behaviors change

- 300 million personal EVs
- 130 million residences with heat pump heating

Industrial efficiency gains

- Rapid productivity gain
- EAF/DRI steel making

2. Clean Electricity

Wind and solar

- Rapidly site 10s-100s of GW per year, sustain for decades
- 3x to 5x today's transmission

Nuclear

- In RE- scenario site up to 250 new 1-GW reactors (or 3,800 SMRs).
- Spent fuel disposal.

NGCC-CCS

- In RE-, 300+ plants (@750 MW)

Flexible resources

- Combustion turbines w/high H_2
- Large flexible loads: electrolysis, electric boilers, direct air capture
- 50 - 180 GW of 6-hour batteries

3. Zero-Carbon Fuels

Major bioenergy industry

- 100s of new conversion facilities
- 620 million t/y biomass feedstock production (1.2 Bt/y in E- B+)

H_2 and synfuels industries

- 8-19 EJ H_2 from biomass with CCS (BECCS), electrolysis, and/or methane reforming
- Largest H_2 use is for fuels synthesis in most scenarios

4. CO_2 capture & storage

Geologic storage of 0.9 – 1.7 $GtCO_2/y$

- Capture at ~1,000+ facilities
- 21,000 to 25,000 km interstate CO_2 trunk pipeline network
- 85,000 km of spur pipelines delivering CO_2 to trunk lines
- Thousands of injection wells

5. Non-CO_2 Emissions

Methane, N_2O, Fluorocarbons

- 20% below 2020 emissions (CO_{2e}) by 2050 (30% below 2050 REF).

6. Enhanced land sinks

Forest management

- Potential sink of 0.5 to 1 $GtCO_{2e}/y$, impacting ½ or more of all US forest area (≥ 130 Mha).

Agricultural practices

- Potential sink ~0.20 $GtCO_{2e}/y$ if conservation measures adopted across 1 – 2 million farms.

https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Copper Mountain solar facility, Nevada, 802 MW
largest in US

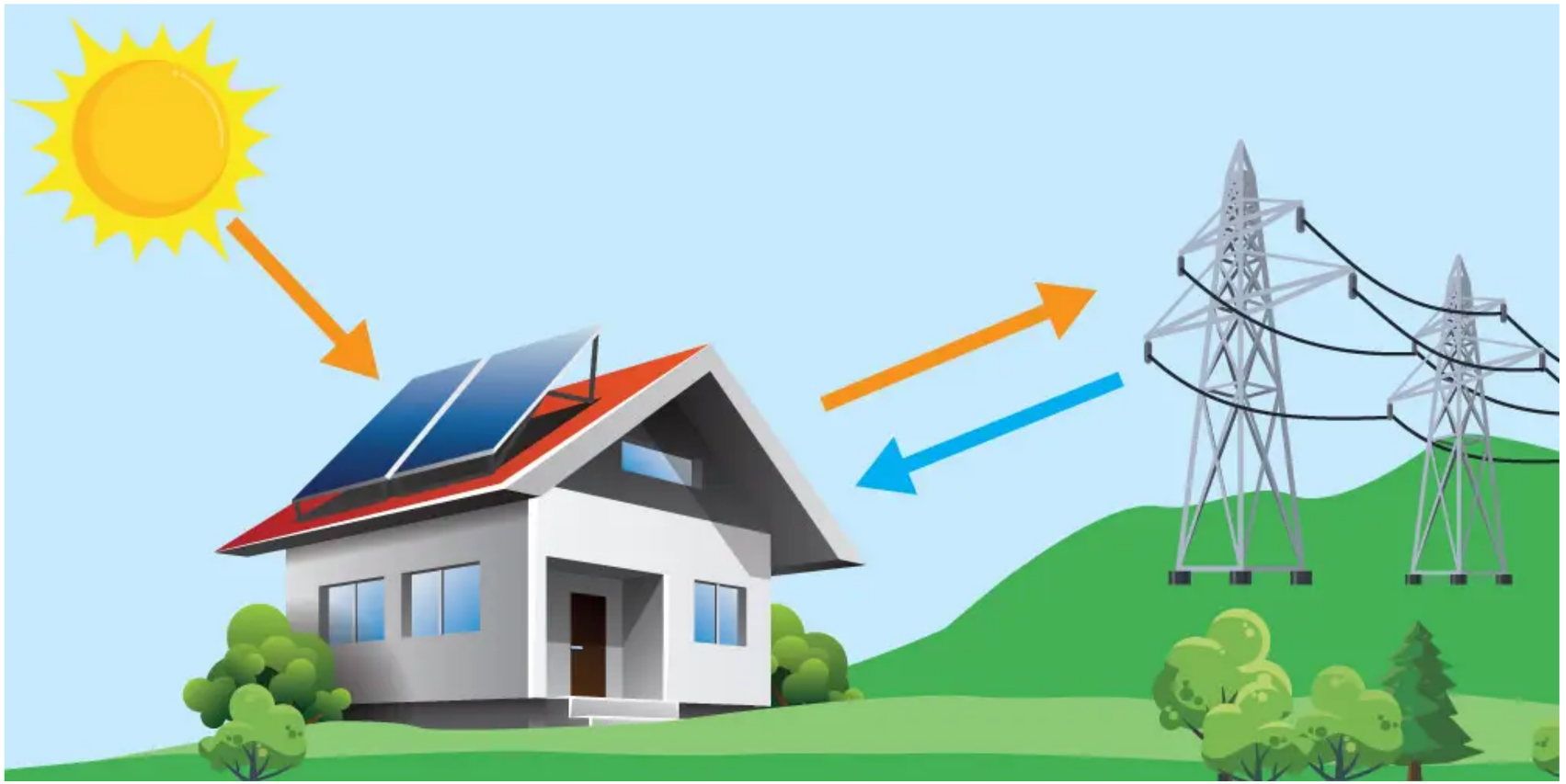
https://www.ysgsolar.com/blog/15-largest-solar-farms-world-2021-ysg-solar

Solar power needs 450X the land of fission plants.

https://environmentalprogress.org/the-complete-case-for-nuclear

Net metering: Utilities must buy electricity from rooftop solar panels at retail (~20 ¢/kWh) not grid market (~5 ¢/kWh).

Power can’t be controlled by utility.
Exacerbates duck curve.



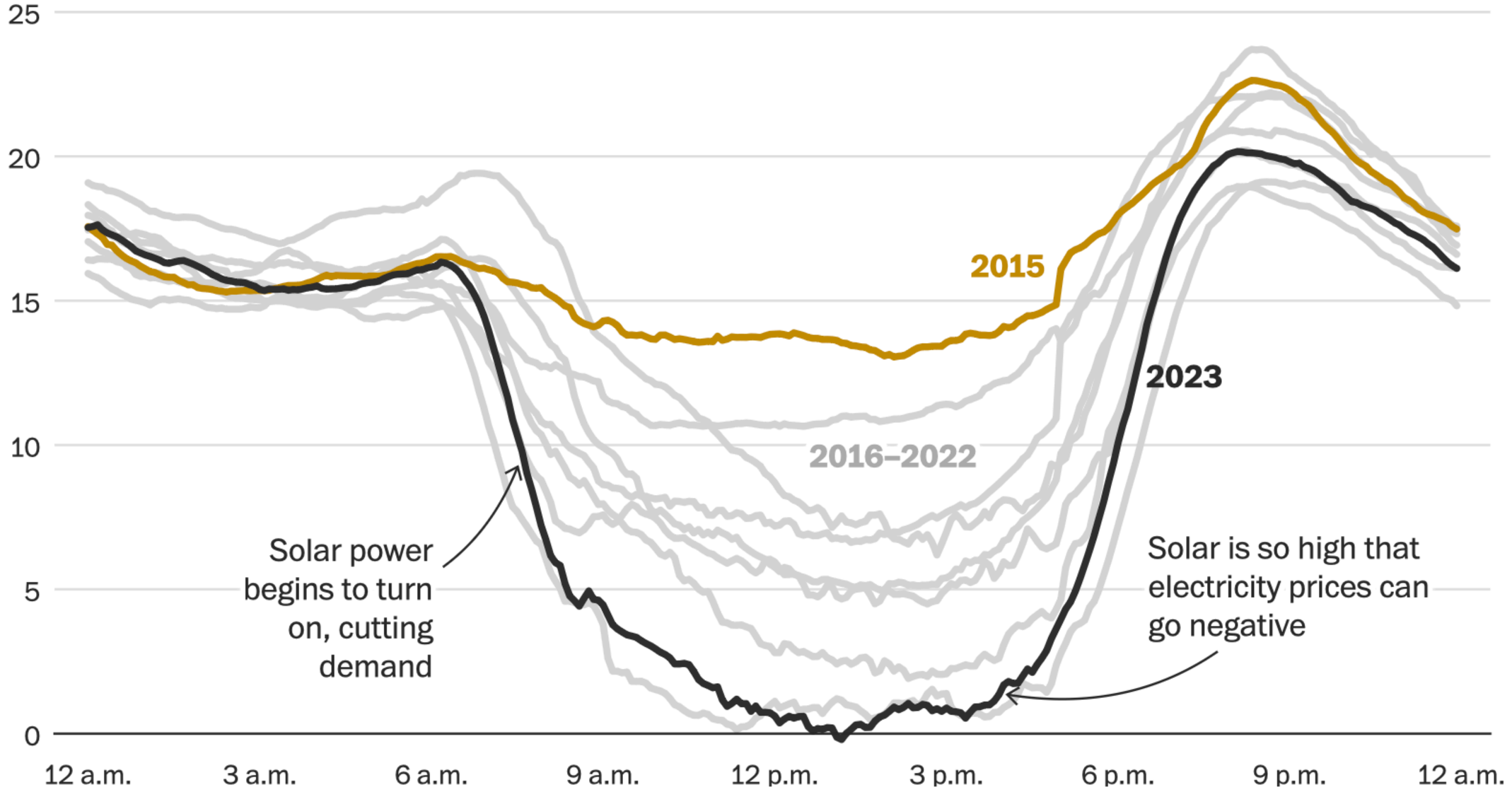
Increases total power costs; paid by other customers.

The most expensive “renewable” energy.

Community solar brings benefits to homes in shade.

https://www.solarreviews.com/blog/california-net-metering-nem-2

California's “duck curve” causes mid-day shutdown of power plants.



https://www.washingtonpost.com/climate-environment/2024/04/22/california-solar-duck-curve-rooftop

Wind power needs 400X the land of fission plants.

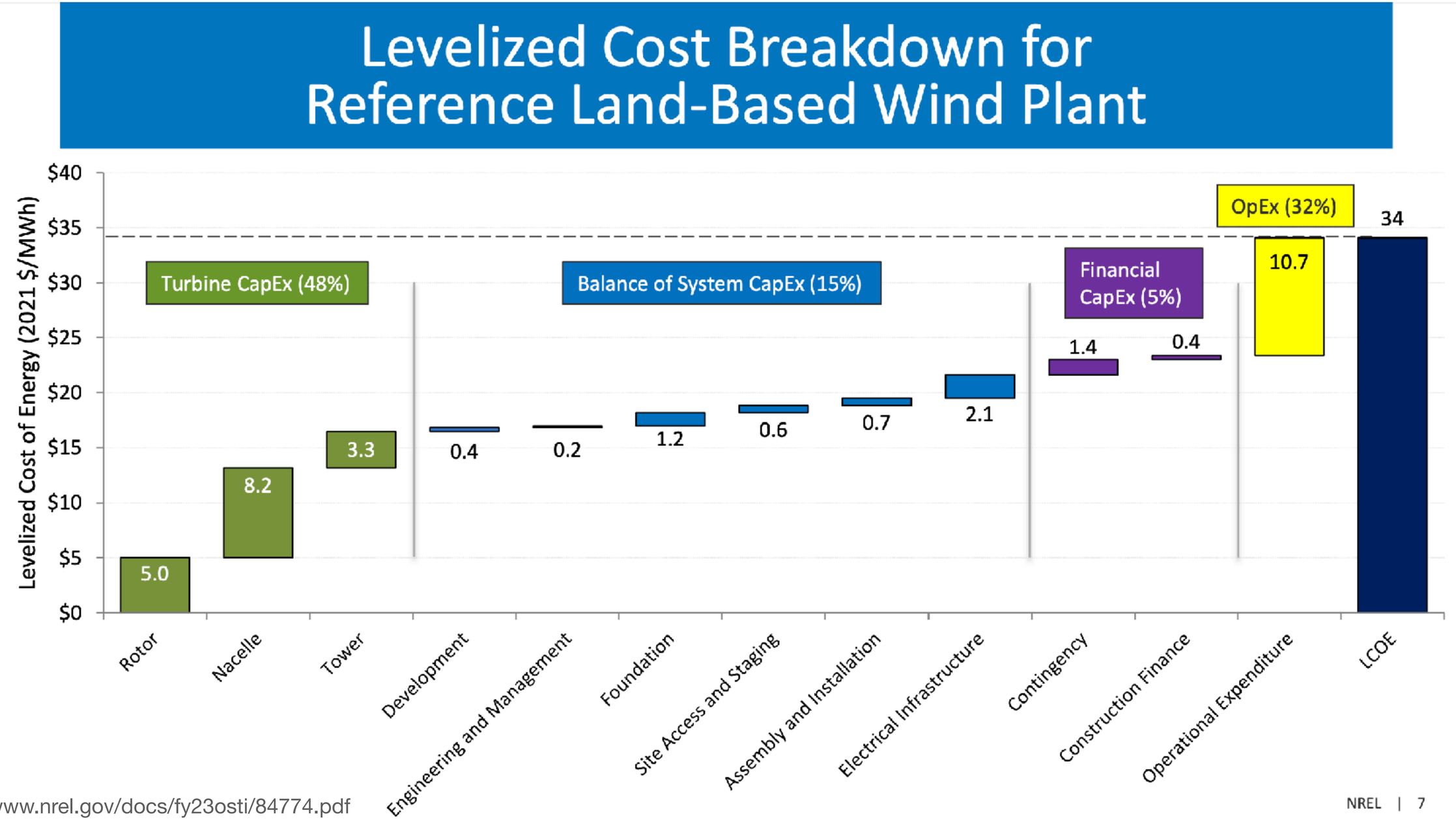
ENVIRONMENTAL PROGRESS

Source: Comparison between Diablo Canyon Nuclear Plant and Alta Wind Energy Center. In 2017, Diablo Canyon produced 17.90 TWh of electricity on an approximate land area of .84 square kilometers. In 2017, Alta produced 3.18 TWh of electricity on an approximate land area of 60.4 square kilometers. Generation data from Energy Information Agency.

Ergo the emphasis on expensive off-shore wind.

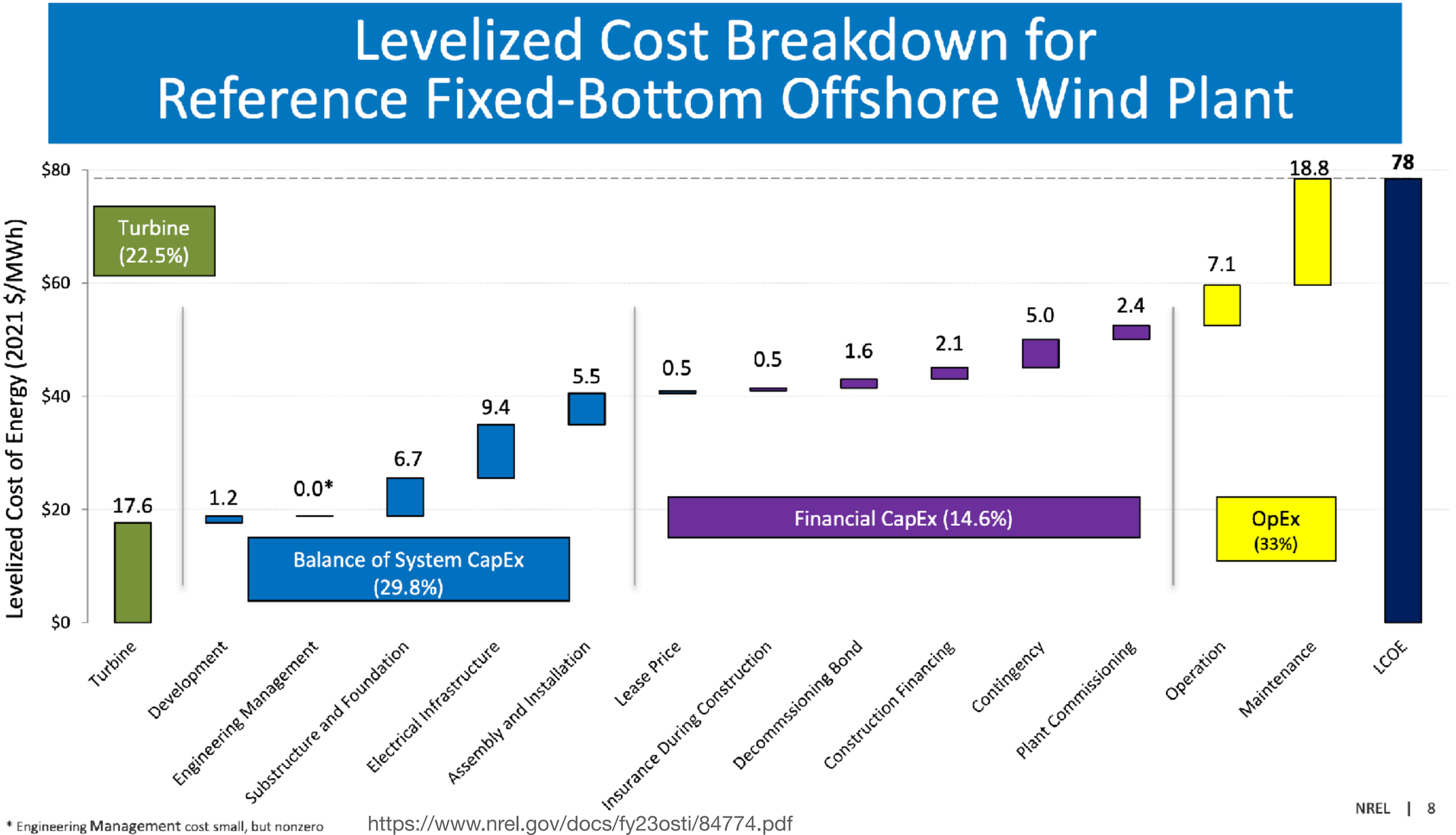
https://environmentalprogress.org/the-complete-case-for-nuclear

US NREL 2022: Wind energy costs ~ $34/MWh.



https://www.nrel.gov/docs/fy23osti/84774.pdf

US NREL 2022: Offshore wind costs $78/MWh



* Engineering Management cost small, but nonzero

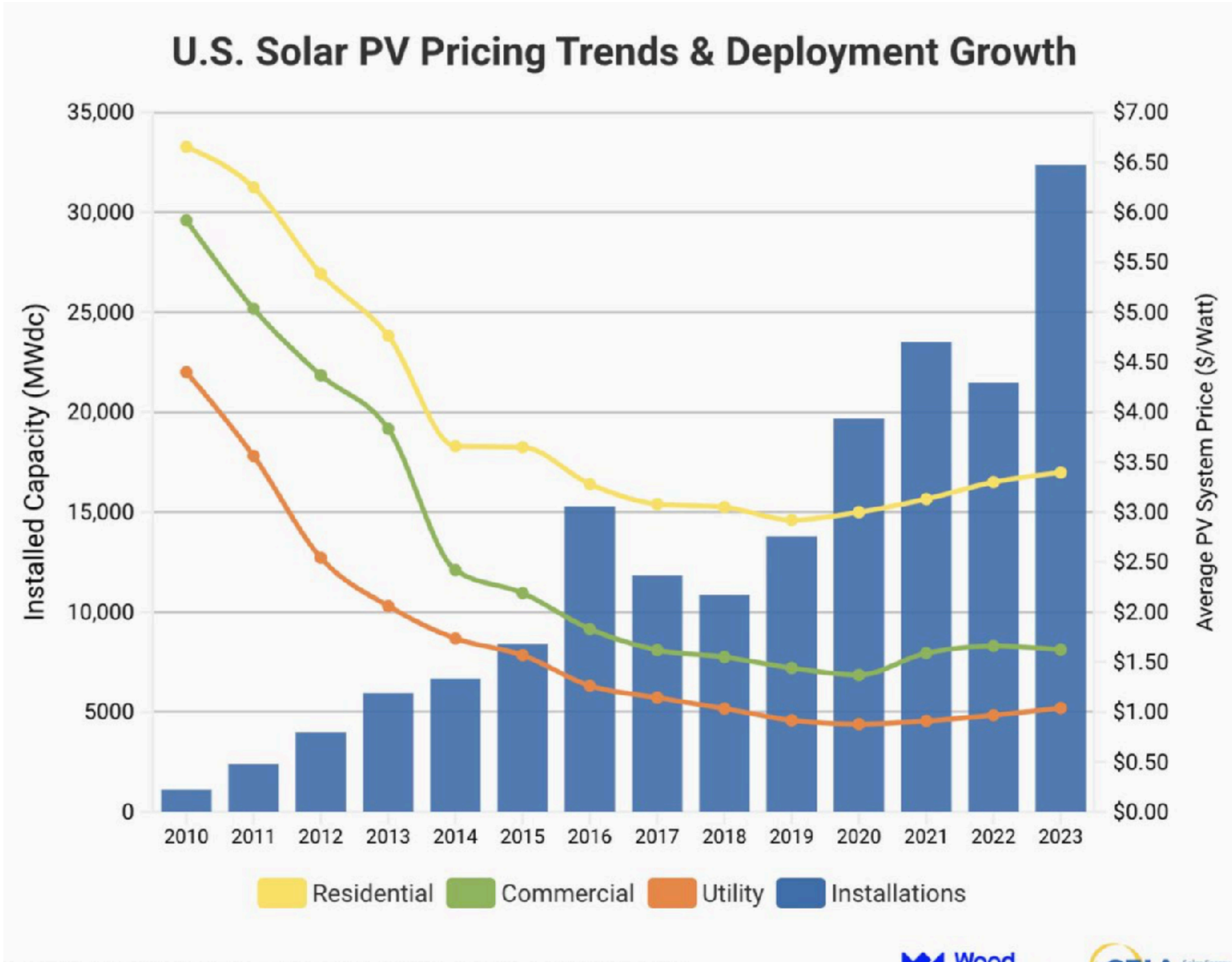
https://www.nrel.gov/docs/fy23osti/84774.pdf

Wood Mackensie

Solar PV cost

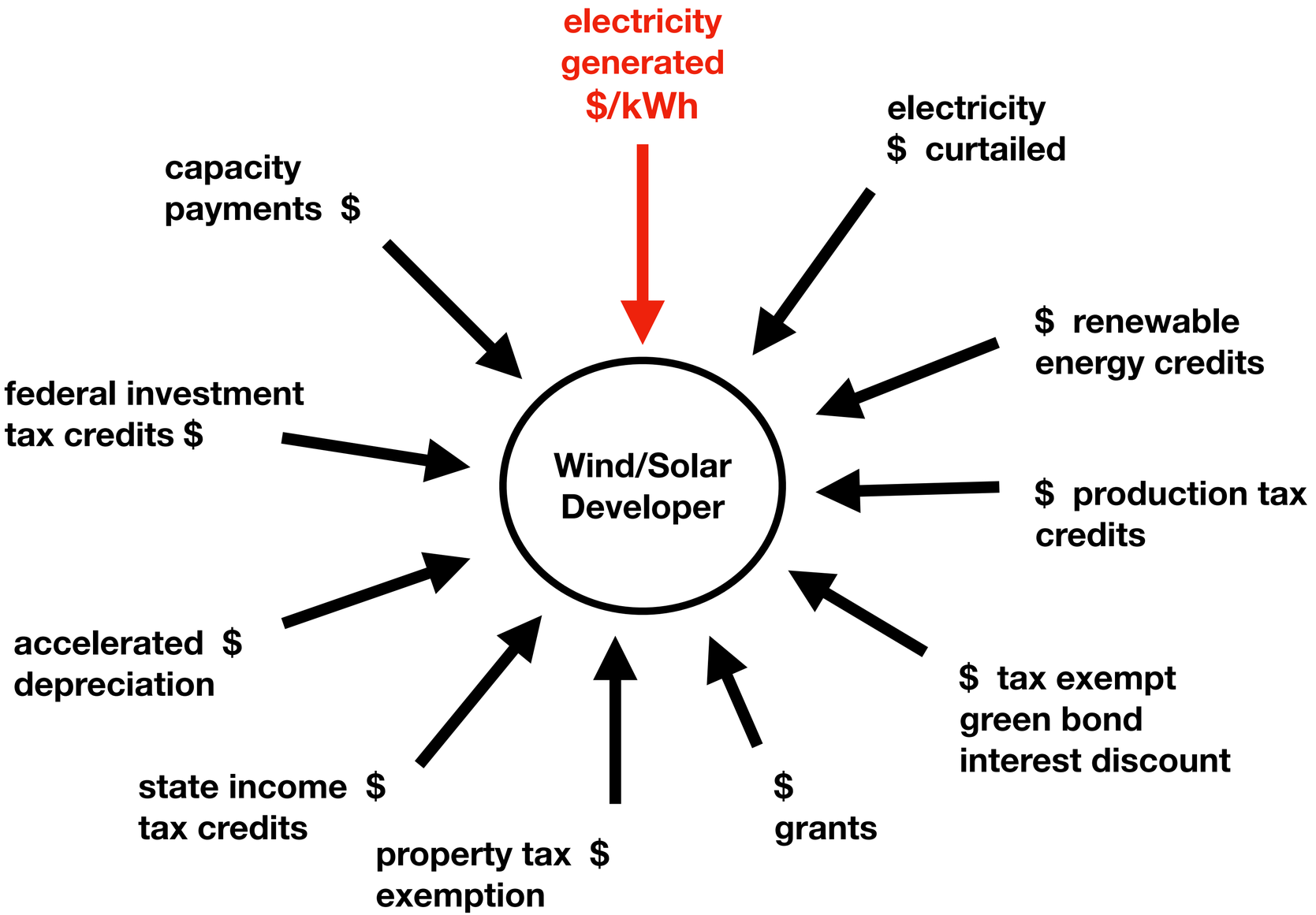
$1.00/W utility

$3.50/W home



Source: SEIA/Wood Mackenzie Power & Renewables U.S. Solar Market Insight 2023 Year in Review

Often wind/solar $/kWh is < 50% of revenue.



Wind/Solar preferences

Feed-in tariffs

Renewable portfolio standards

Bird kill examptions

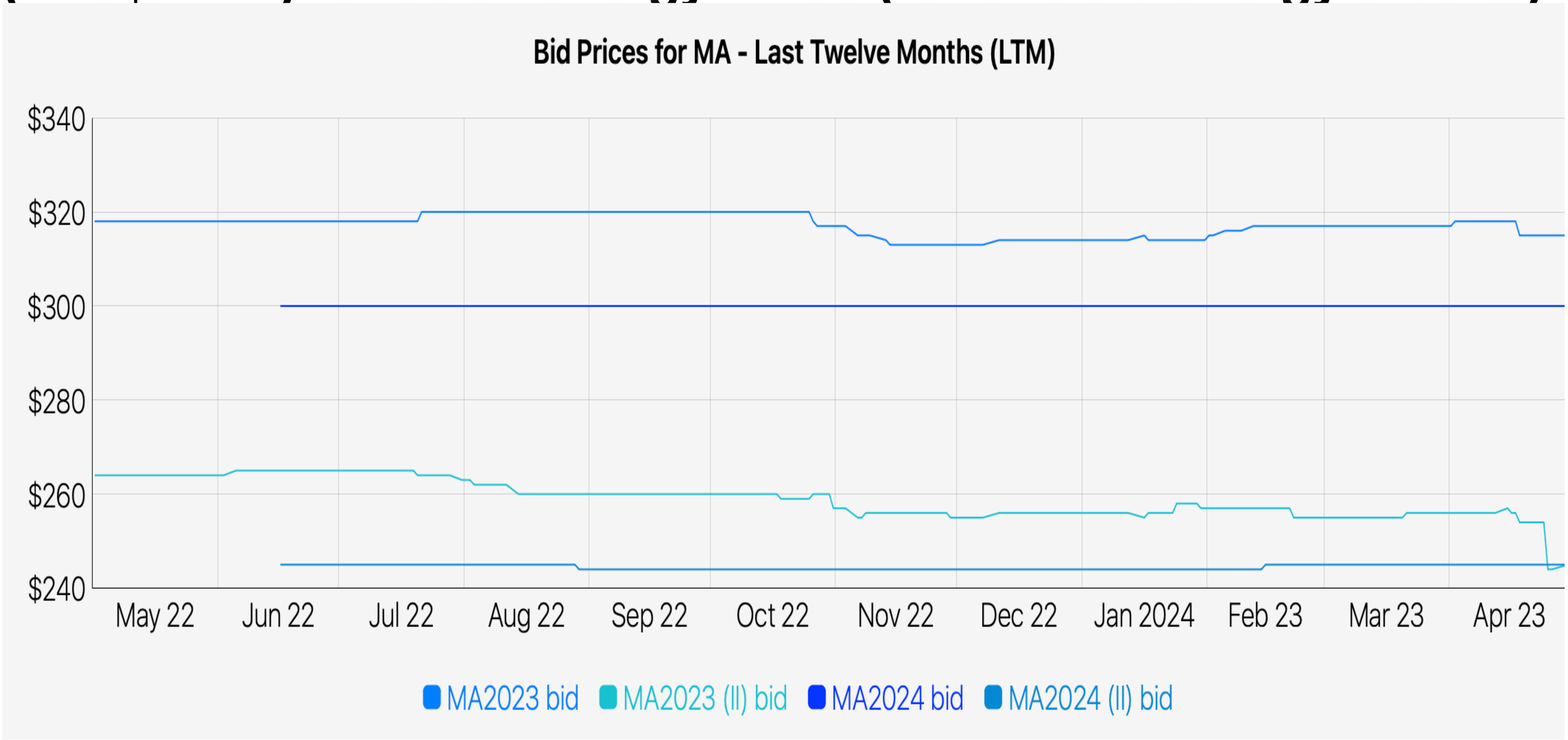
Local zoning overrides

15-50% credit in auctions for firm power capacity

No toxic recycling penalty

Angwin: Shorting the Grid

Massachusetts utilities pay solar panel generators $245/MWh (24.5¢/kWh) for solar energy RECs (renewable energy credits).



https://www.srectrade.com/markets/rps/srec/massachusetts

Wind/solar power costs kept secret from public.

SECTION 83C

Request for Proposal Application Form

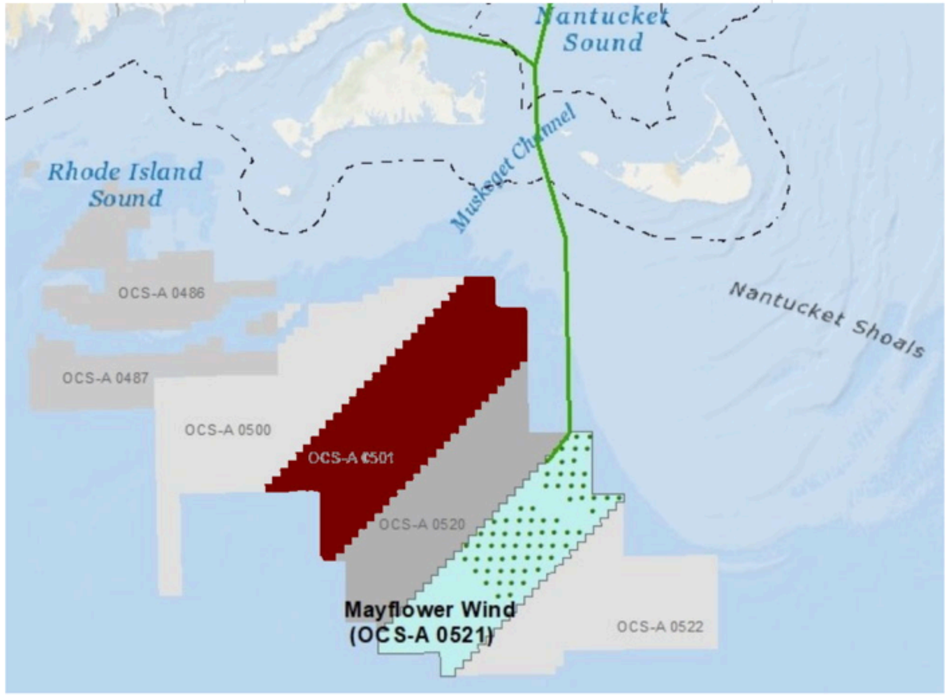
Proposal Mayflower Wind Project 2 (804 MW Low Cost Energy)

- Proposal 1: the required 408 MW Project
- Proposal 2: **Low Cost Energy** – 804 MW Project delivering the lowest cost offshore wind energy ever in the U.S.
- Proposal 3: **Infrastructure and Innovation** – 804 MW Project with over [redacted] of strategic investments in port infrastructure, technology, and innovation to position Massachusetts as a global leader in offshore wind
- Proposal 4: **Massachusetts Manufacturing** – 804 MW Project with all the benefits included in Infrastructure and Innovation as well as investment of [redacted] in a new manufacturing facility at [redacted], creating [redacted] manufacturing jobs annually, bringing the offshore supply chain to the Commonwealth with export opportunities within the U.S. and farther afield

The three main (804 MW) proposals provide Massachusetts with the ability to select the project scope that best meets your needs. Each of these proposals meet the requirements of the RFP by providing significant ratepayer benefits and providing for strong economic development in the Commonwealth with each targeted at different elements in that required formulation. The **Low Cost Energy** proposal is focused on generating the maximum benefits to ratepayers while providing [redacted] over the life of the project for initiatives to support the industry and local economy. The **Infrastructure and Innovation** Proposal builds on the initial proposal by [redacted] of immediate investment in port infrastructure and an [redacted] in near term funding to spur innovation in technology and the blue economy. Finally, the **Massachusetts Manufacturing** Proposal adds over [redacted] in investment during 2020-2023 and an [redacted] of lease payments over the next 12 years to support tower manufacturing. This manufacturing base, with tower production beginning in 2021, would represent a key step in Massachusetts becoming a true hub for the offshore wind industry in the U.S. and set the stage for the industry and local companies to compete globally.

Mayflower Wind Picked For 800-Megawatt Project Off Of Nantucket, Martha's Vineyard

Updated October 30, 2019 | By Colin A. Young, State House News Service



https://static1.squarespace.com/static/5cffcb6d97cc59000115fa39/t/5d683e54c6a21e0001f18cc2/1567112815707/Mayflower+Wind+Project+2+%28804MW+Low+Cost+Energy%29_Public+Version.pdf

INTERMITTENT wind and solar power generate power only ~ 1/3 of the time.

Ad

Each 1 GW of wind or solar needs 1 GW of natural gas (or hydro?) generation ~ 2/3 of the time.

https://www.ingaa.org/File.aspx?id=30374&v=b0798882

Do offshore wind turbines *increase* CO_2 emissions 10%?

Choice: Build full-time CCGT? or on/off NGCT and off/on wind?

Turbine type	Efficiency	Start time	Cost
NGCT natural gas combustion turbine	29%	10 min	$700/kW
CCGT combined cycle gas turbine	64%	30 min	$1100/kW

1,000 MW(e) power plant alternatives				
Power source	**Use**	**Efficiency**	**Gas burned**	
Wind turbine with	50%	-	-	
NGCT	50%	29%	1720 MW(t)	**0.50 x 1000 / 0.29**
CCGT only	100%	64%	1565 MW(t)	**1.00 s 1000 / 0.64**

US plans (planned?) 30 GW offshore wind turbines by 2030.

Only one, 30 **MW**, project operating in 2022.

Block Island 5 x 6 MW costing $400 million.

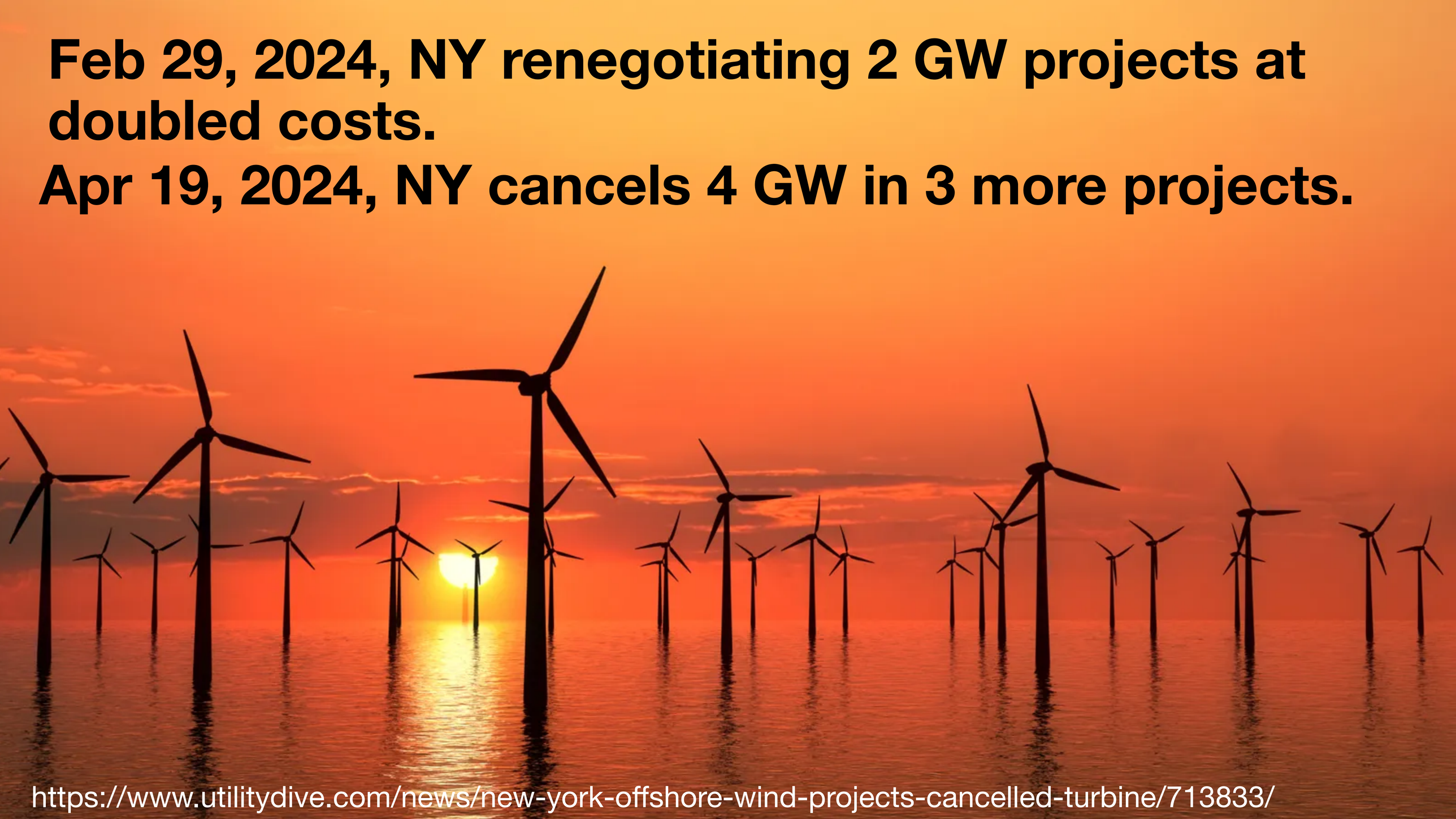
$13 million per MW of wind-dependent capacity.

Developers withdrawing though got 30% ITC!

https://www.manhattan-institute.org/lesser-biden-administrations-offshore-wind-fantasy

Feb 29, 2024, NY renegotiating 2 GW projects at doubled costs.

Apr 19, 2024, NY cancels 4 GW in 3 more projects.



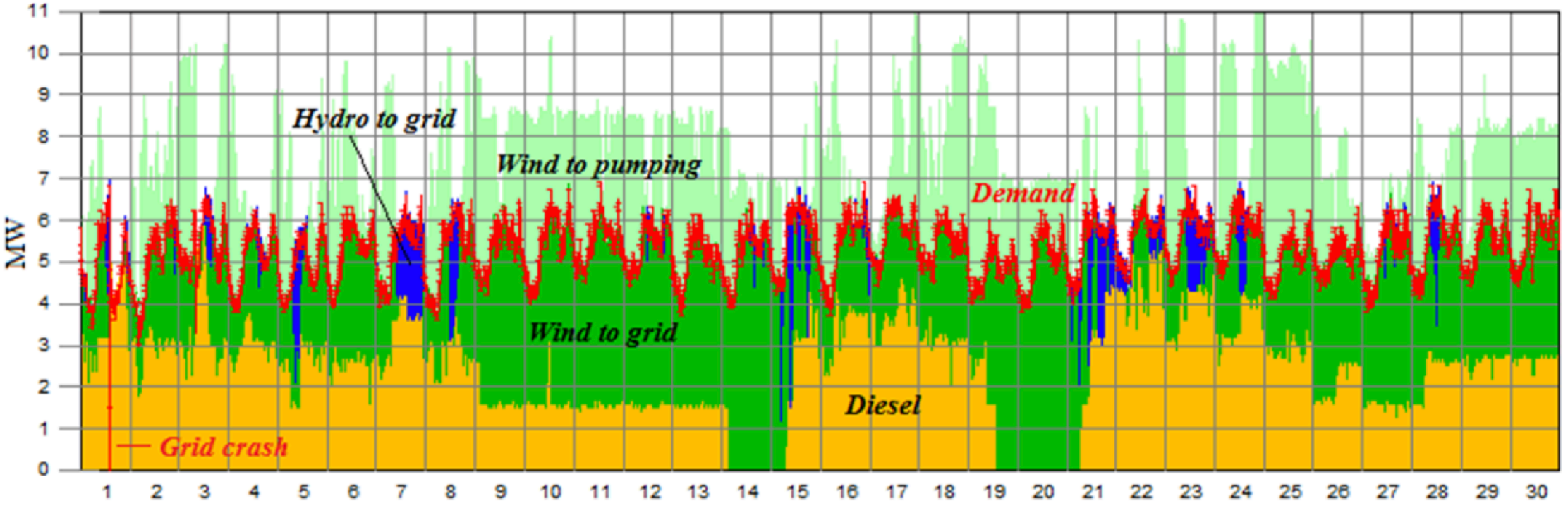
https://www.utilitydive.com/news/new-york-offshore-wind-projects-cancelled-turbine/713833/

"El Hierro is the first fully sustainable island in the world…”

https://www.enel.com/company/stories/articles/2016/09/el-hierro-island-renewables-treasure

Spain's El Hierro island attempted 100% renewable power.

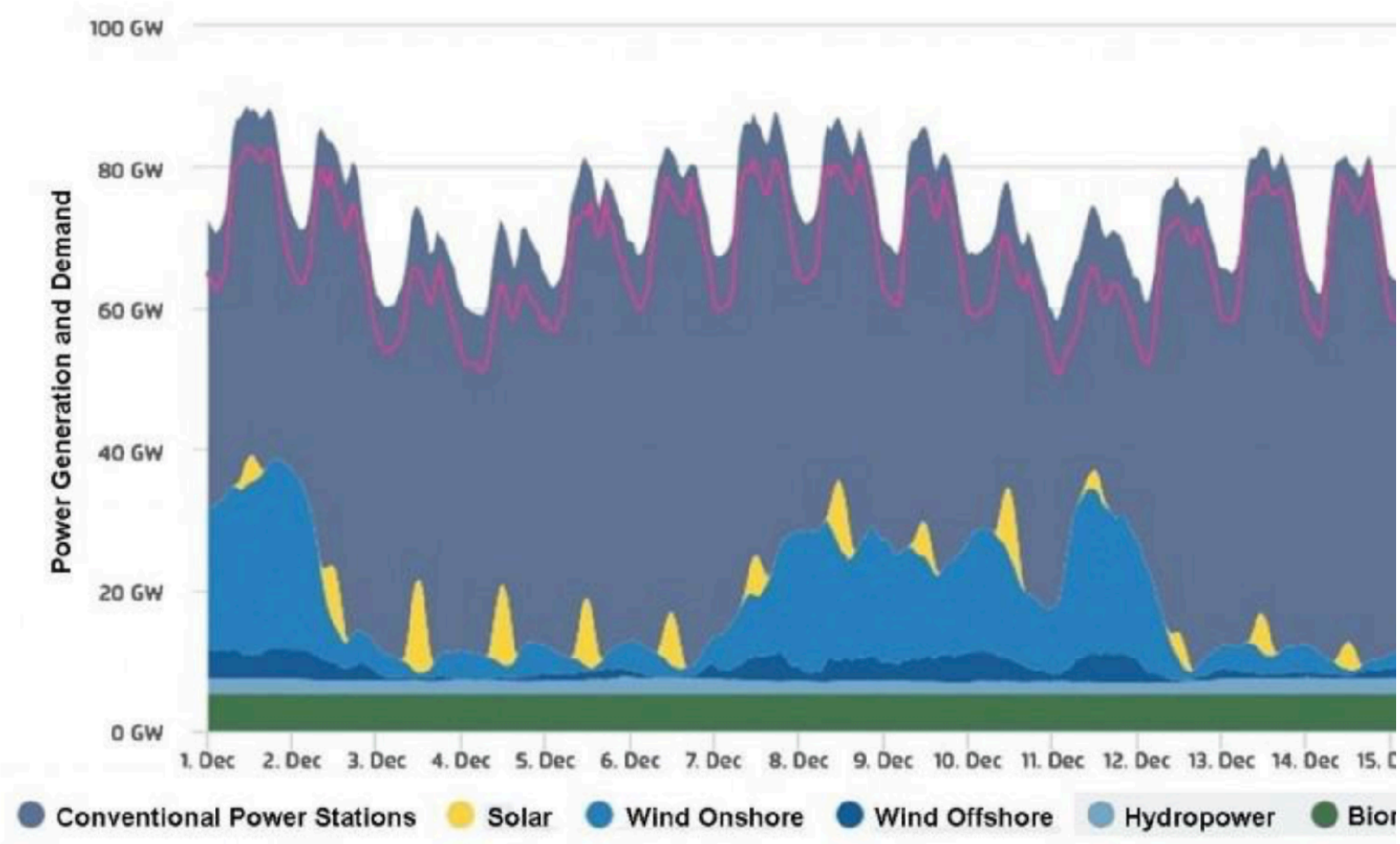
Three wind turbines with pumped hydro energy storage.



During 2018 it supplied 57% of El Hierro's electricity, 10 MWe, though only 28% during 4Q 2018.

https://euanmearns.com/tag/el-hierro/

Adding more solar and wind generation does not fix lulls. Germany experienced a 100 hour lull, 3-6 Dec 2016.



Wind and solar supplied just 2% of nameplate capacity.

Power sources	GW nameplate	GW delivered
Solar	41.0	0.7
Wind	47.8	1.4
Reliables		68.0
Total		70.0

https://energycentral.com/c/ec/wind-and-solar-energy-lulls-energy-storage-germany

100% Delusion! | **Sun sets.** | **Wind lulls.**

Batteries? to give 1 day of energy use...

- 36 billion Tesla Powerwalls
- Build 1000 per second for 10 years
- **$250 trillion**

Least expensive Megapack cost $666/kWh in 2023.

TESLA

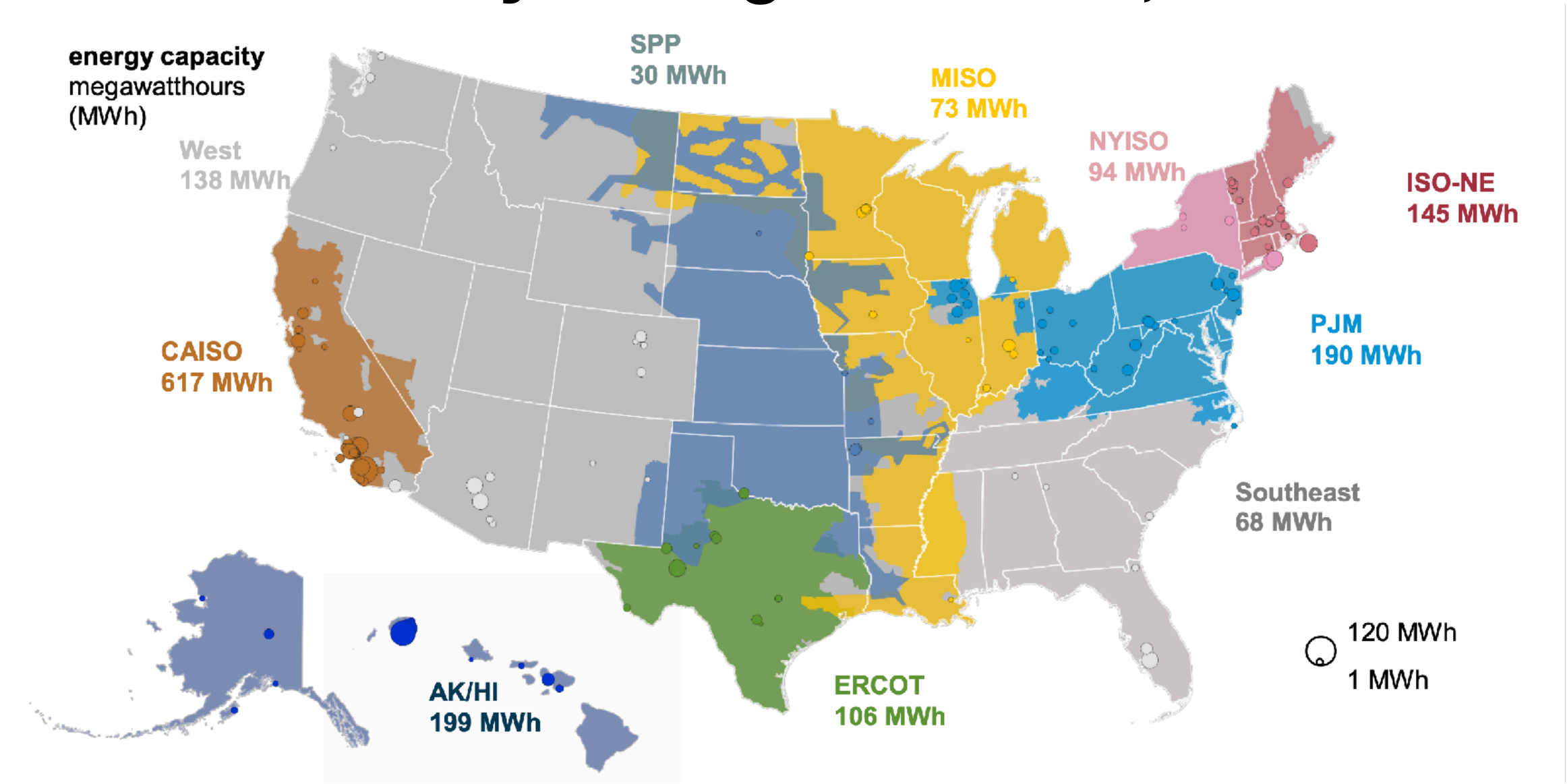
US

1.9 MW	3.9 MWh
Power	Energy

Megapack Quantity	1
Megapack Duration	2 hr / 4 hr
Include Installation Learn More	Yes / No
Site Location	California
Desired Delivery Date	Q4 2024
Estimated Price Subject to change, taxes not included	$2,596,910
Est. Annual Maintenance Price escalates at 2% per year	$8,290
Due Today Non-refundable Reservation Deposit	$1,000

https://electrek.co/2021/07/26/tesla-reveals-megapack-prices/ https://www.tesla.com/megapack/design

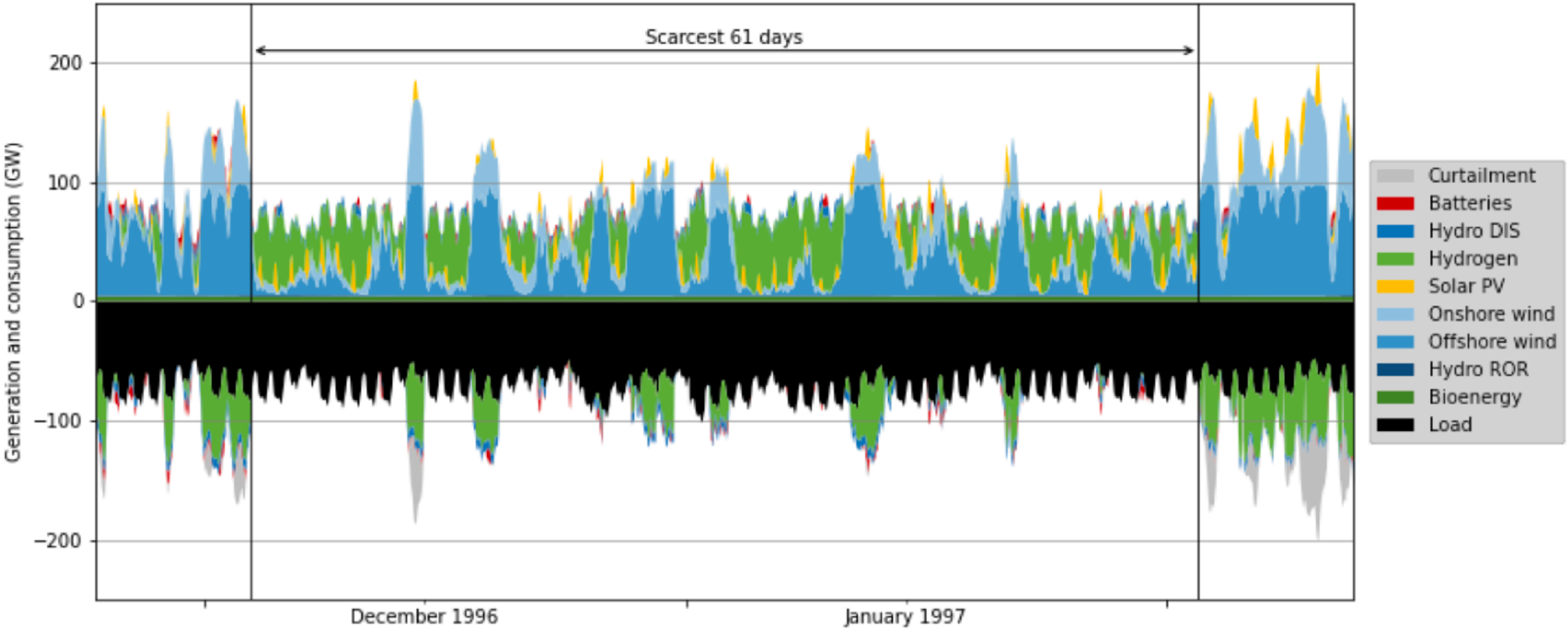
US 2021 battery storage < 2 GWh; @ $589/kWh



https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage_2021.pdf

Observed *Dunkleflaute* needs 24 days of power storage.

Cost-optimized storage, solar, wind. Studied 35 years of hourly German power. Need time between Dunkleflauten to recharge.



https://www.econstor.eu/handle/10419/236723 Ruhnau, Qvist

IEEE, Vaclav Smil: To Get Wind Power You Need Oil

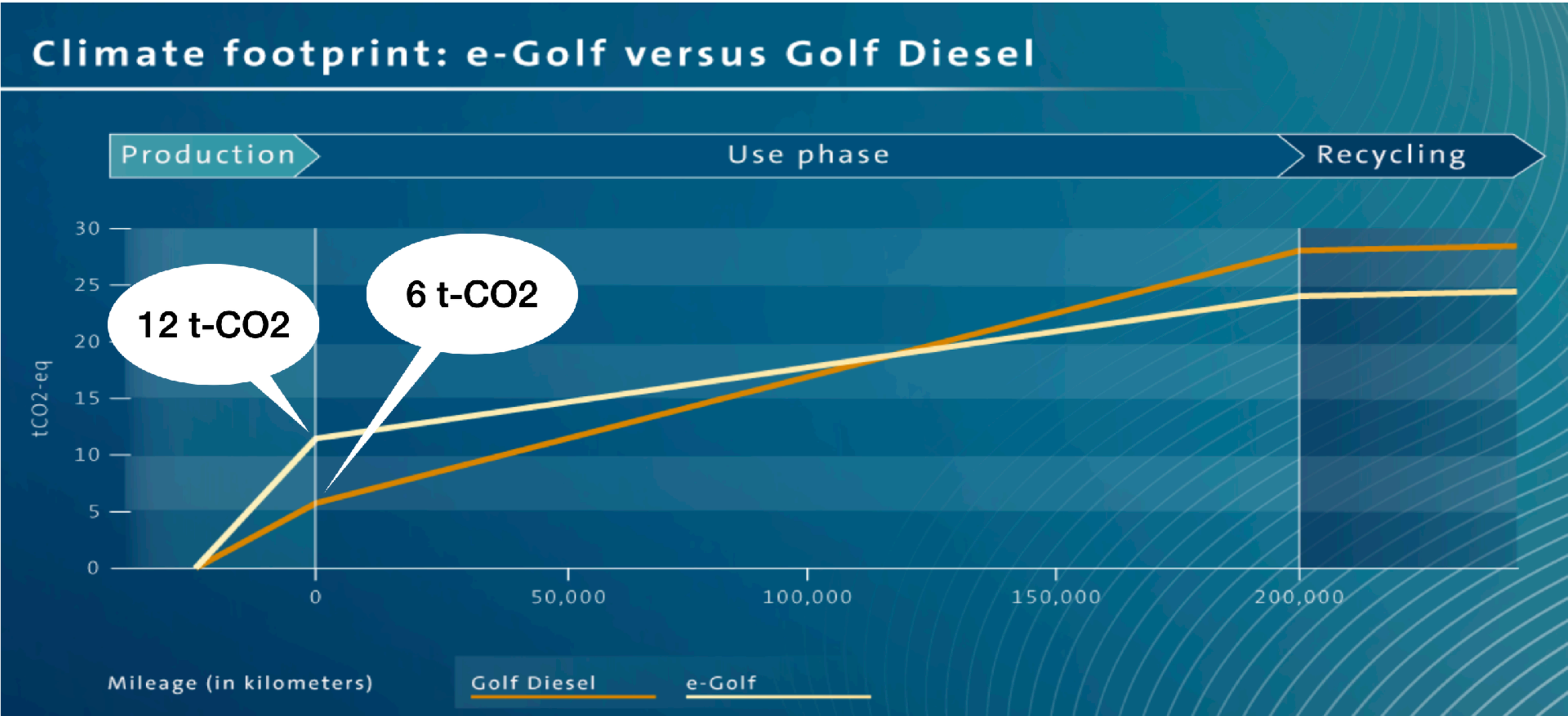
Each wind turbine embodies a whole lot of petrochemicals and fossil-fuel energy

Large trucks bring steel and other raw materials to the site, earth-moving equipment beats a path to otherwise inaccessible high ground, large cranes erect the structures, and **all these machines burn diesel fuel.** So do the freight trains and cargo ships that convey the materials needed for the production of cement, steel, and plastics.

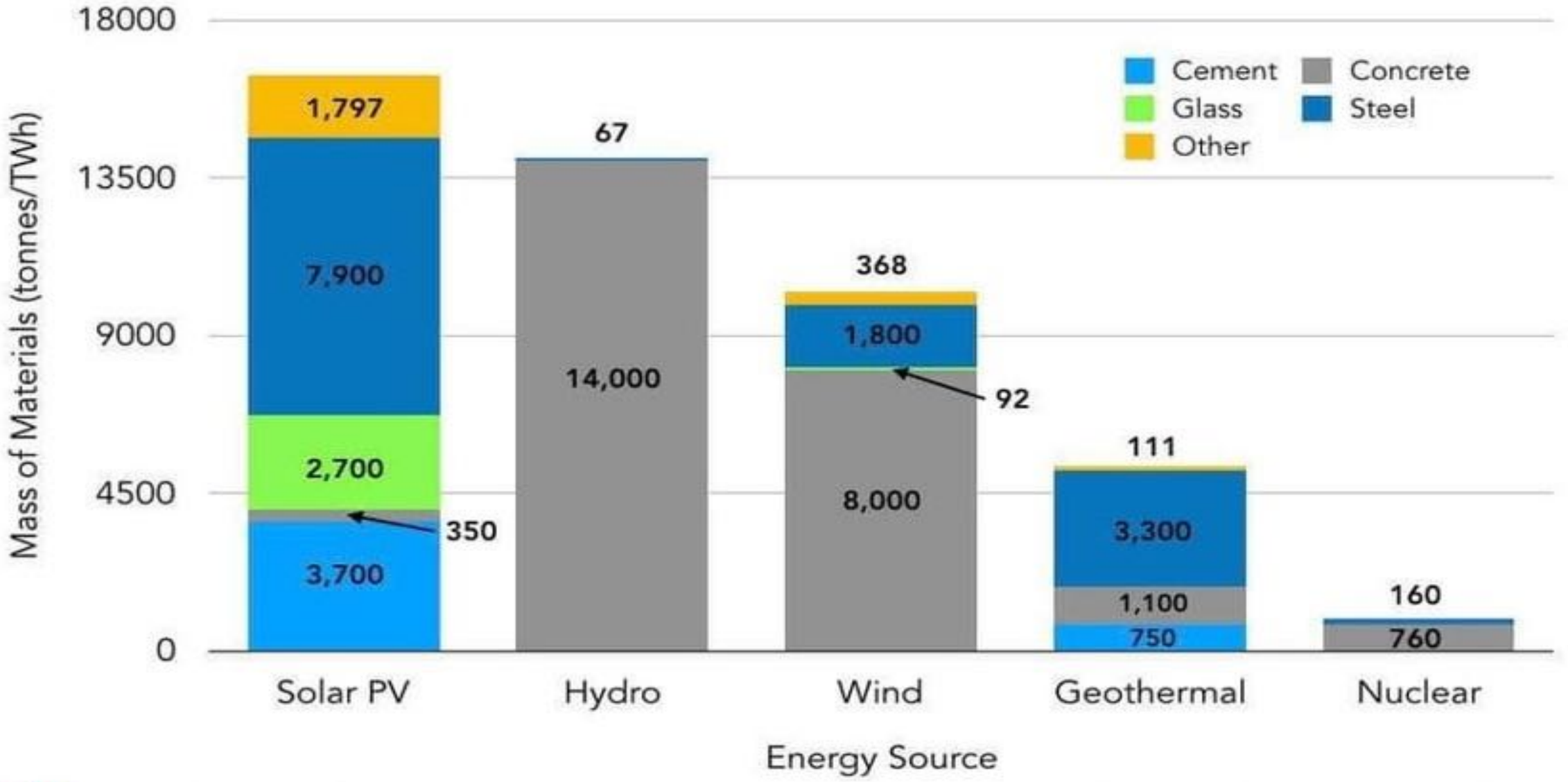
For a **5-megawatt turbine**, **the steel alone averages 150 metric tons for the reinforced concrete foundations**, **250 metric tons for the rotor hubs and nacelles (which house the gearbox and generator), and 500 metric tons for the towers.**

https://spectrum.ieee.org/to-get-wind-power-you-need-oil

Capital goods have embedded energy and CO2. costing ~ 0.21 kg-CO2/$ of capital good value.



Materials used per TWh generated, by energy source (2015)

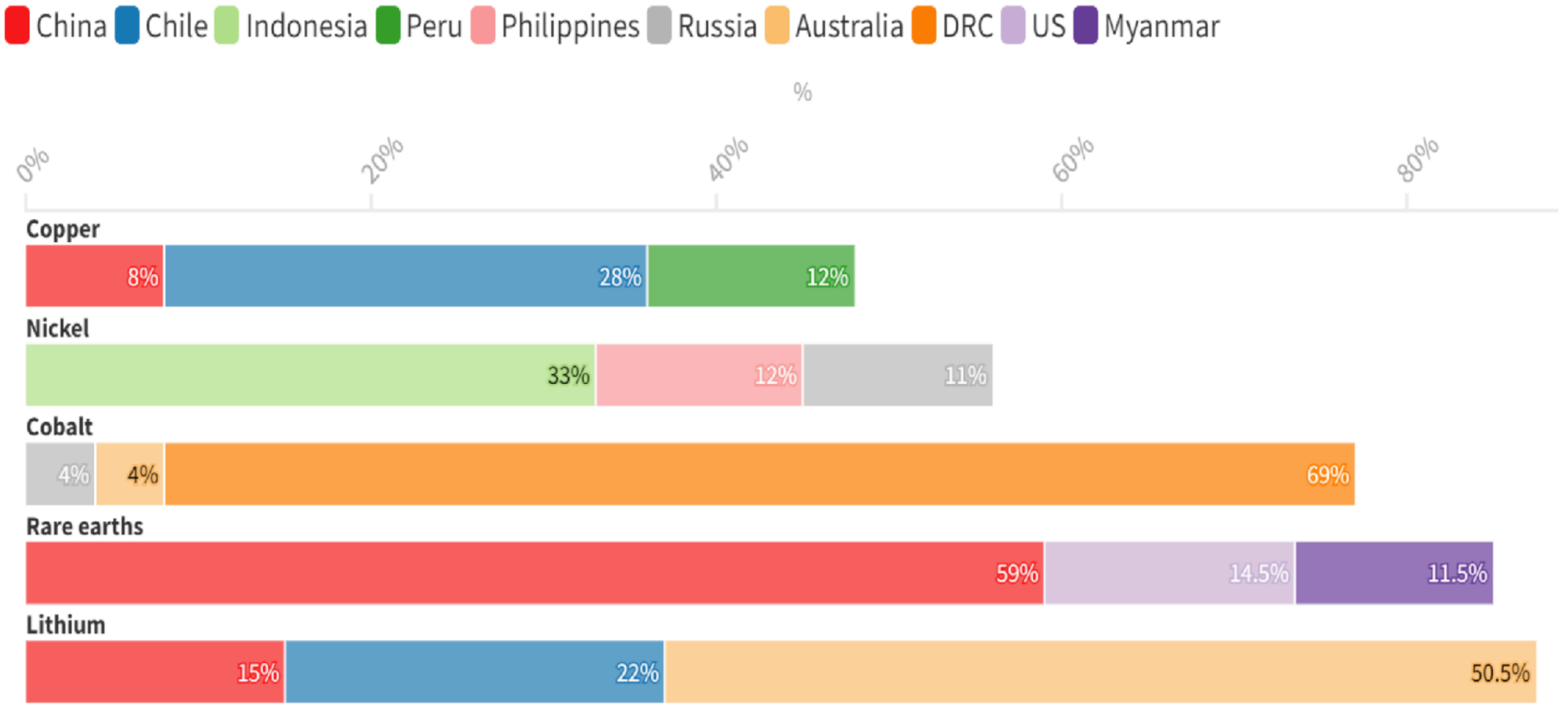


"Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities." Table 10. September 2015. United States Department of Energy. Nuclear and hydro require 10 tonnes/TWh and 1 tonne/TWh of other materials, respectively, but are unable to be labeled on the graph.

China monopolized magnet component rare earths, which US dominated in 1990s.

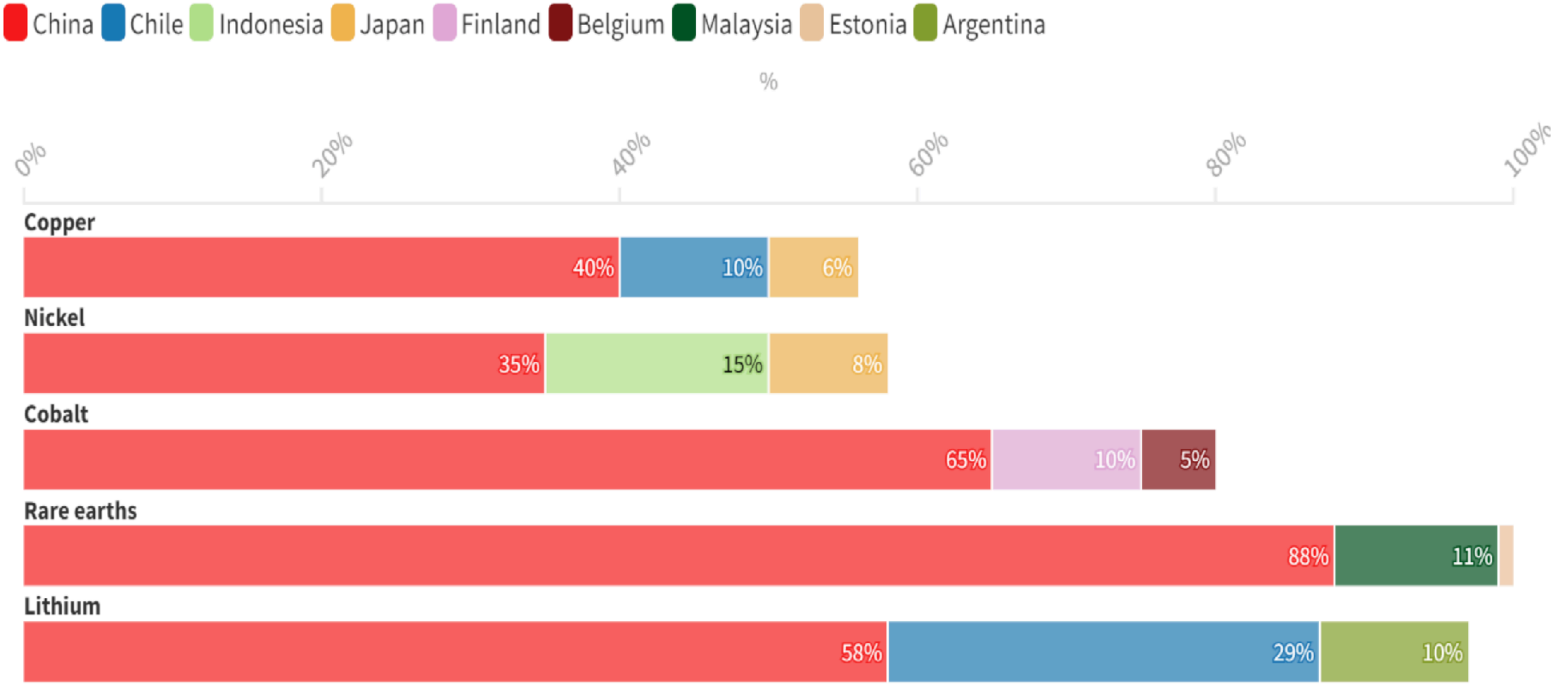
ttps://doomberg.substack.com/p/not-a-rare-to-spare

Where critical minerals are mined



https://energypost.eu/critical-minerals-and-materials-supply-bottlenecks-and-risks-need-international-cooperation/

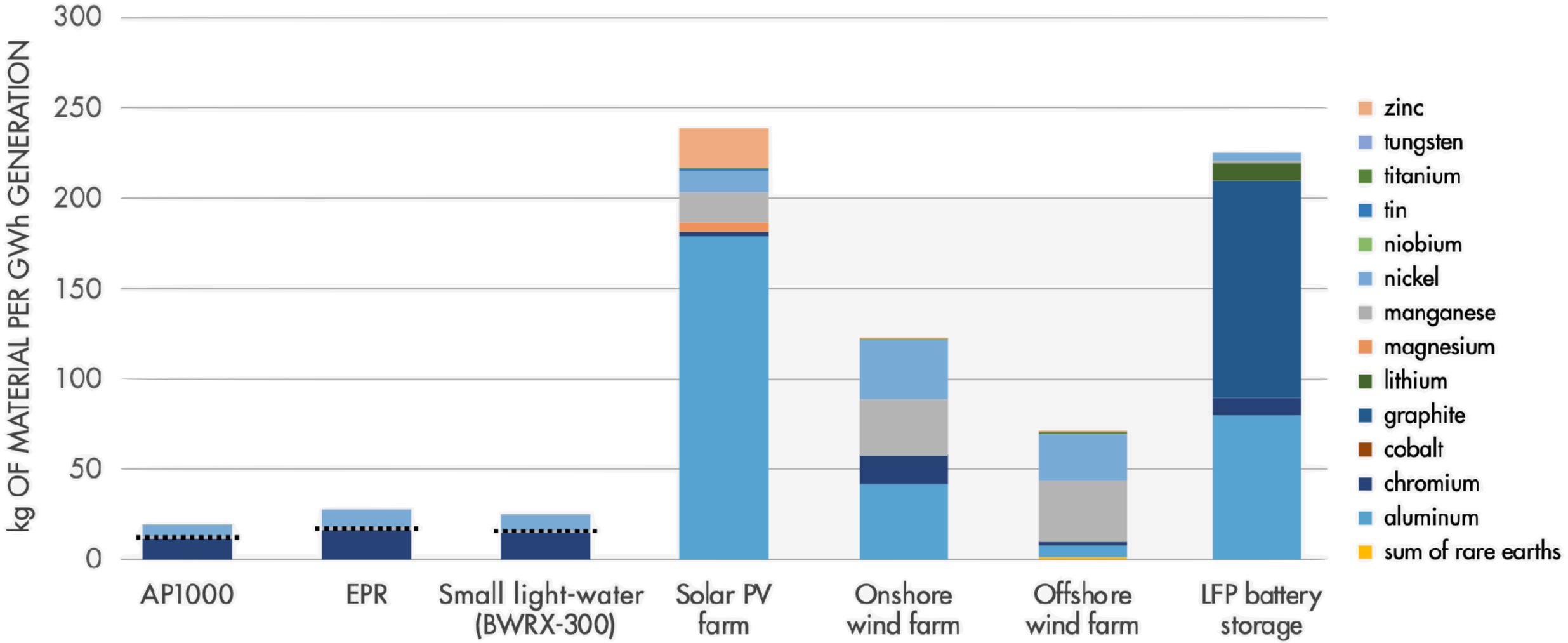
Where critical minerals are processed



Source: IRENA, IEA

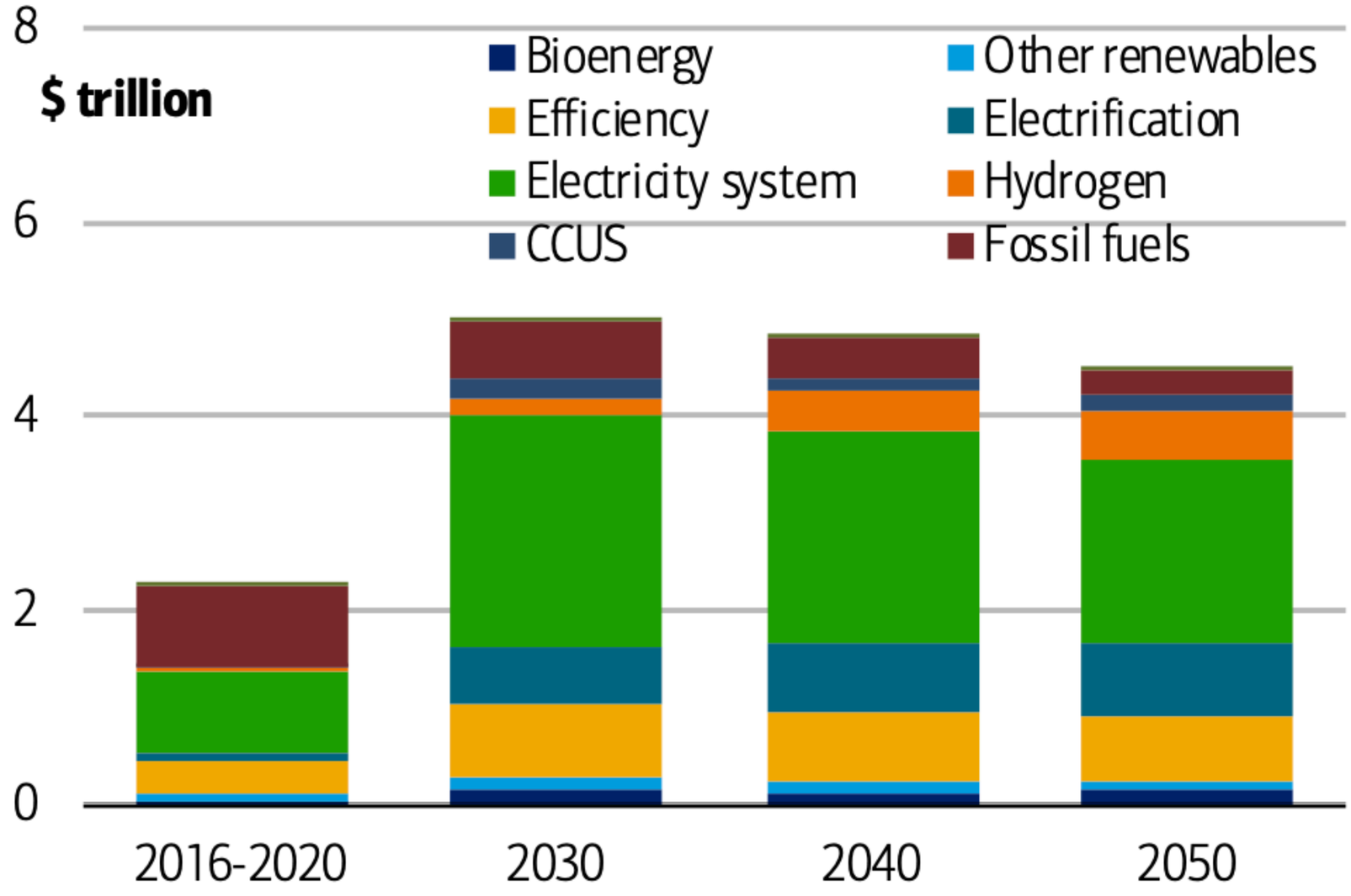
https://energypost.eu/critical-minerals-and-materials-supply-bottlenecks-and-risks-need-international-cooperation/

Critical minerals intensity of clean energy generation



https://thebreakthrough.org/issues/energy/updated-mining-footprints-and-raw-material-needs-for-clean-energy

BofA: Green energy transition costs $5 trillion/yr x 30 yrs.



Source: International Energy Agency (2021), Net Zero by 2050, IEA, Paris

"Even in global terms and over a 30-year span, $150 trillion is a gargantuan amount.

The latter number is almost twice the total global GDP in 2019…"

https://news.yahoo.com/fighting-climate-change-a-150-trillion-battle-bank-of-america-report-163422676.html

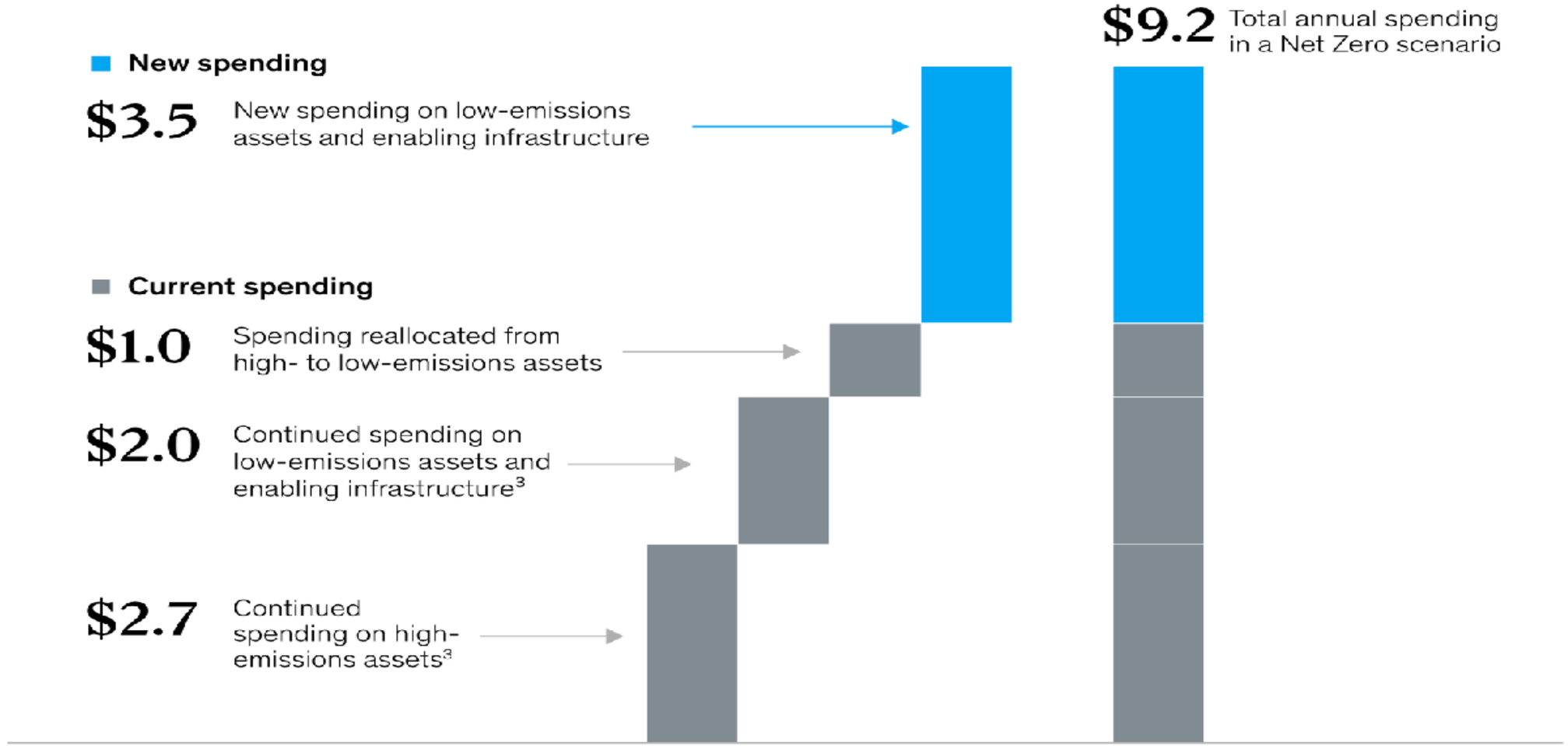
Note: no fission power.

https://business.bofa.com/content/dam/boamlimages/documents/articles/ID21_1543/Net_Zero_Redacted_Note_Updated_Final.pdf

McKinsey: $9.2 trillion/yr including ongoing capital spending.

Spending on physical assets for energy and land-use systems in the NGFS Net Zero 2050 scenario would rise by about $3.5 trillion annually more than today.

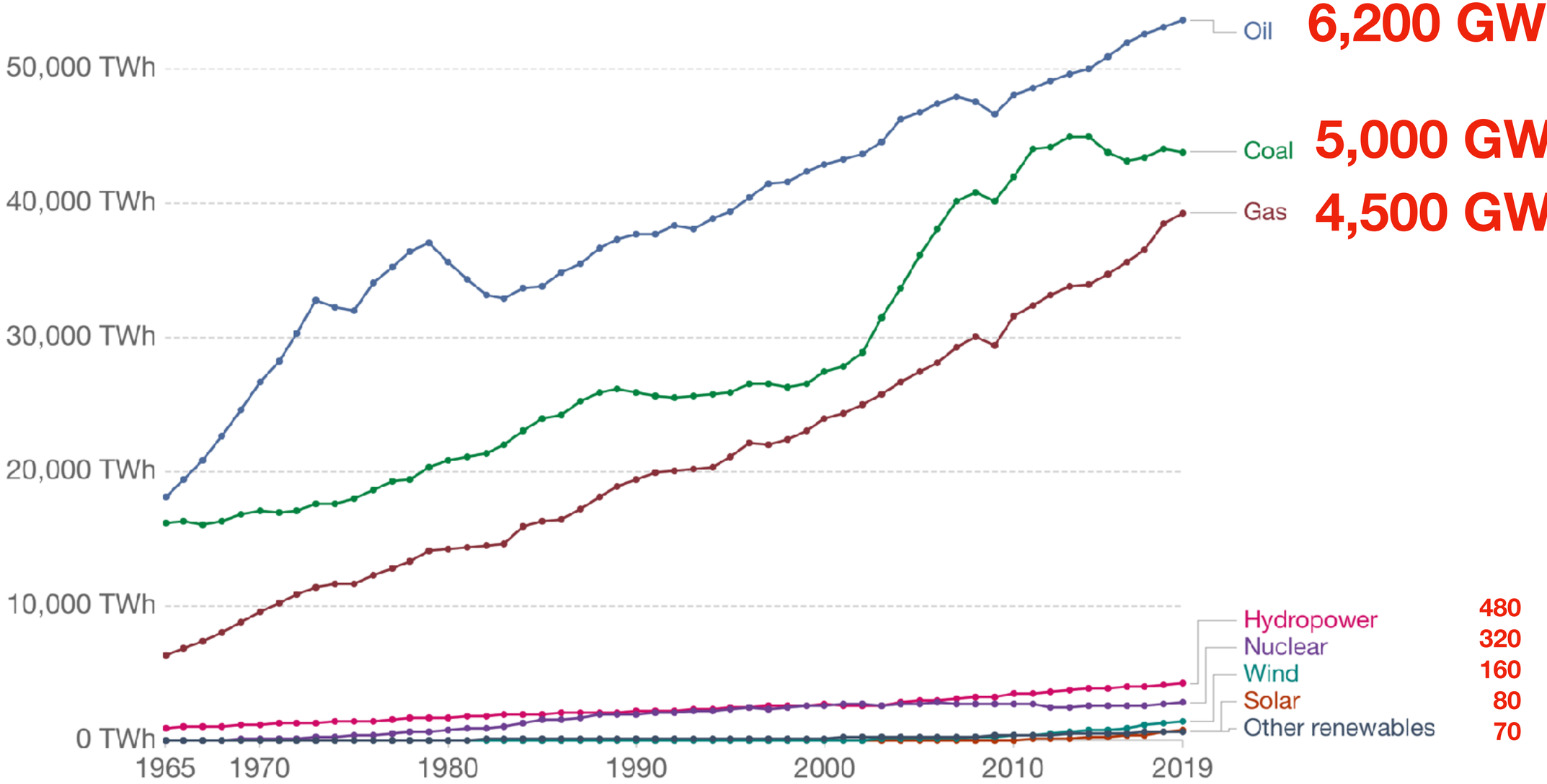
Annual spending on physical assets for energy and land-use systems[1] in a Net Zero 2050 scenario,[2] average 2021–50, $ trillion



https://www.mckinsey.com/business-functions/sustainability/our-insights/the-economic-transformation-what-would-change-in-the-net-zero-transition

Global power sources

Energy consumption is shown as direct primary energy. This means this does not correct for fossil fuel inefficiencies in conversion to useful energy estimates.



Oil 53,620 TWh/year

6,200 GW(t)

5,000 GW(t)

4,500 GW(t)

	GW(e)
Hydropower	480
Nuclear	320
Wind	160
Solar	80
Other renewables	70

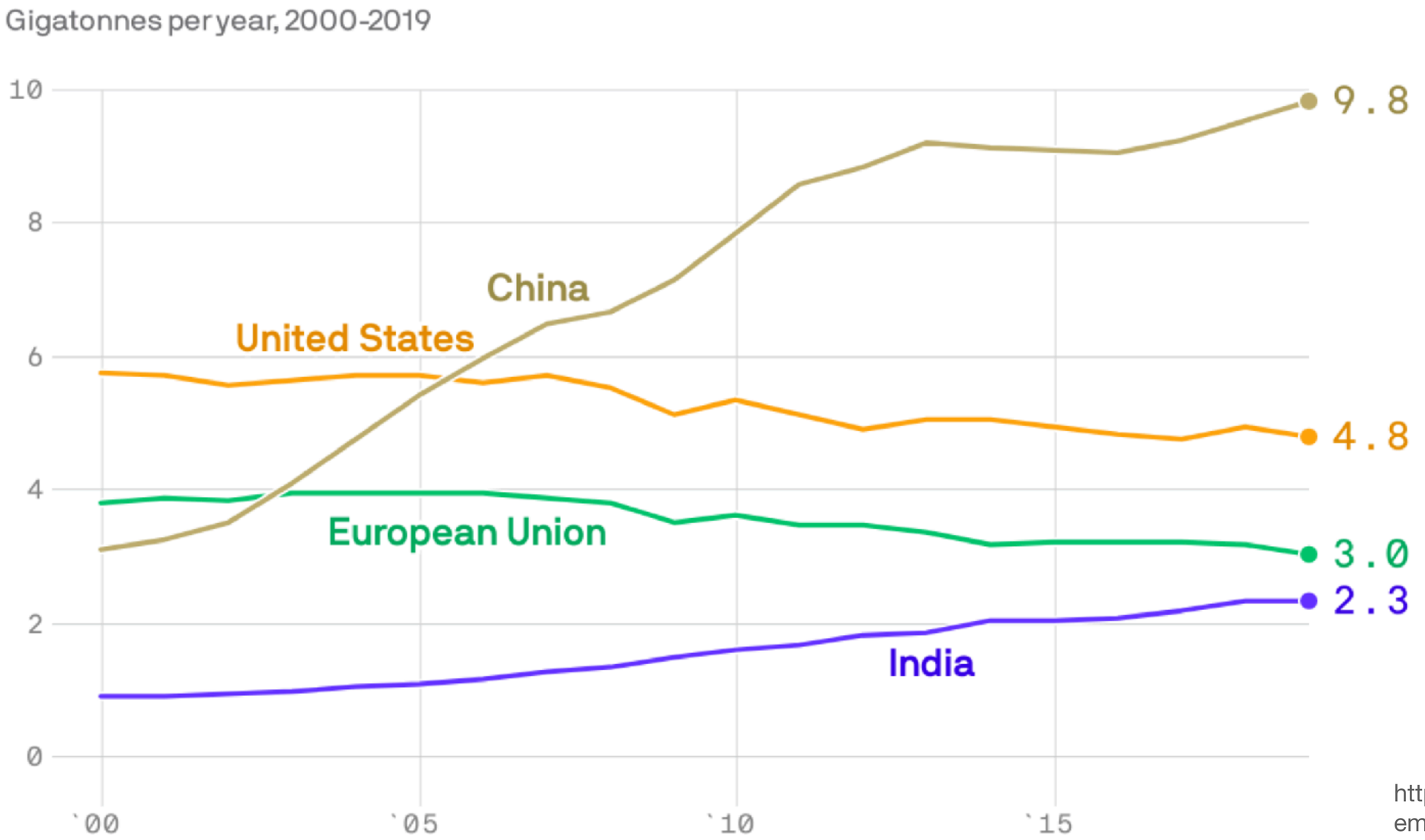
Source: BP Statistical Review of Global Energy

OurWorldInData.org/energy • CC BY

Note: Includes only commercially-traded fuels (coal, oil, gas), nuclear and modern renewables. As such, it does not include traditional biomass sources.

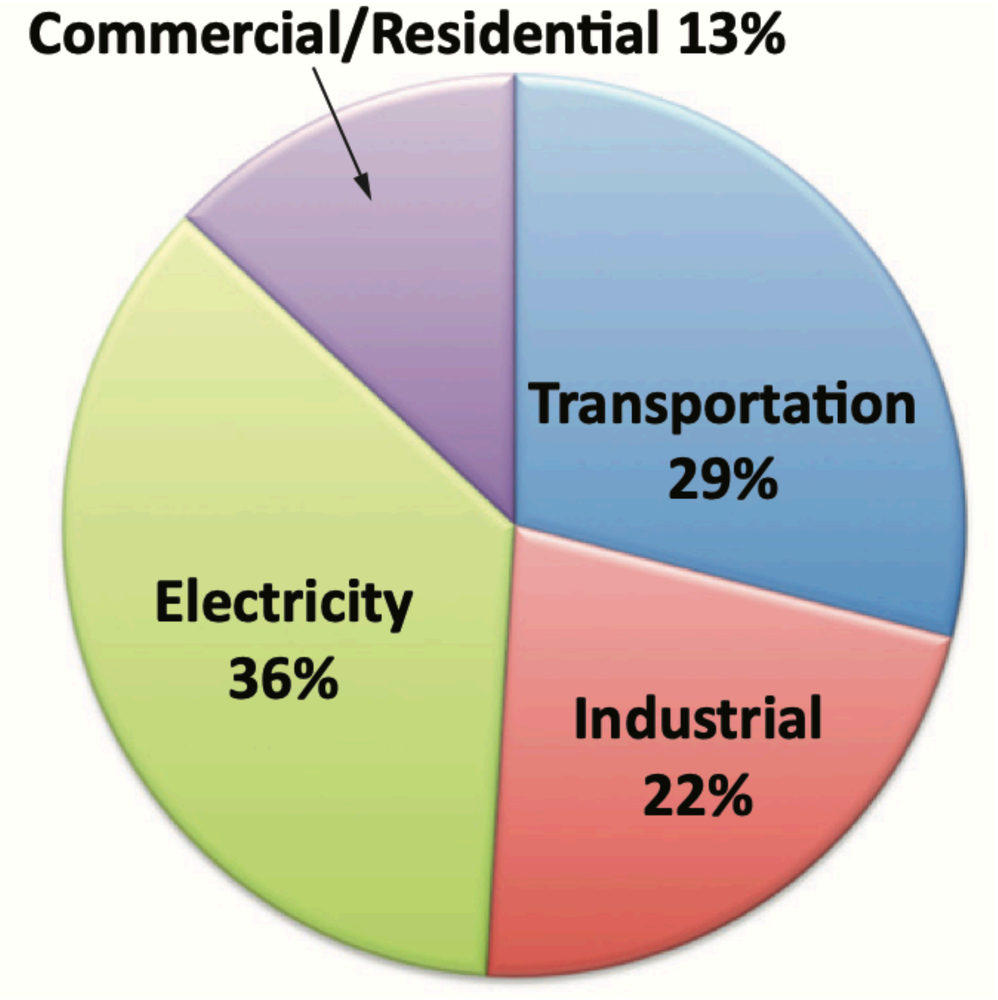
https://ourworldindata.org/grapher/primary-energy-consumption-by-source?year=latest&time=1965..2019

IEA: China, US, EU, and India emit most of the 32 Gt-CO2/year from fuel consumption.



https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview

US DOE EIA energy by use sector



Keep in mind
<u>Four sectors</u>

Electricity
Transportation
Buildings
Industry

HOT! plan

1 New Nuclear power, $ < coal

2 Seafuel

3 District heating

4 Work to lower industry CO2

Wade Allison: Energy options facing society today

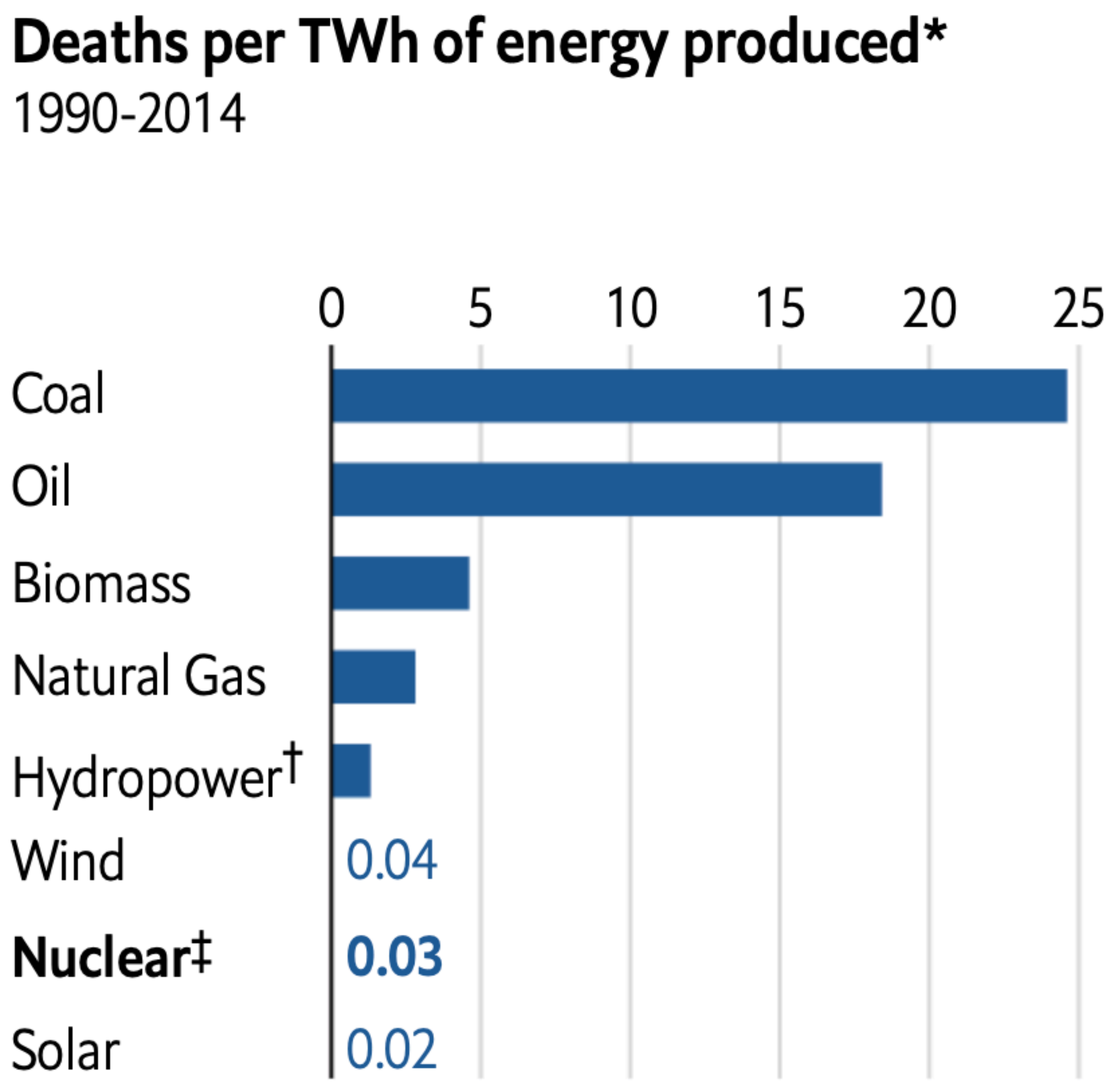
Adam Smith: “Science is the great antidote to the poison of enthusiasm and superstition.”

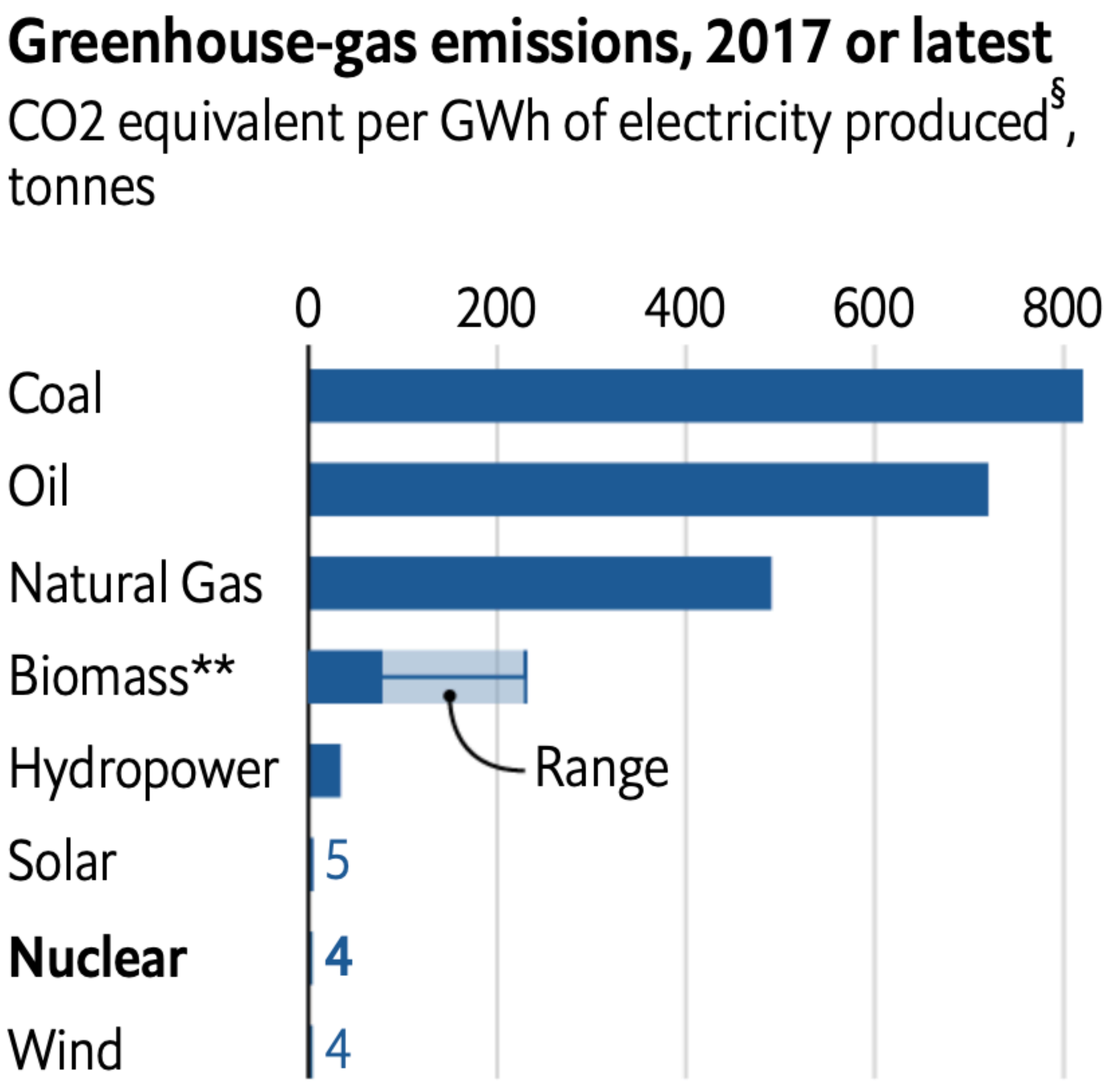
	“Renewables”	Chemical (electronic)	Nuclear
Fuels	Water, wind, sun	Fossil fuels, food, biofuels	Uranium, Thorium
Primed or renewed	Daily and seasonal sunshine	Sunshine in geological epochs	Pre-solar stellar collapse (supernova)
Energy density kWh/kg	0.0003	1 to 7	20 million
Fuel for a whole life	10 million tonnes	1000 tonnes	0.001 tonnes (1 kg)
Pro	Familiar, accepted	Reliable, available 24/7	Reliable, safe, compact, resilient, available 24/7
Con	Unreliable, weak, damaging to nature	Emissions, safety	Public apprehension, failed education

https://www.researchgate.net/publication/339629356_Nature_Energy_and_Society_A_scientific_study_of_the_options_facing_civilisation_today

Nuclear power is safe.

The Economist, July 19, 2022





https://www.economist.com/graphic-detail/2022/07/19/how-safe-is-nuclear-energy

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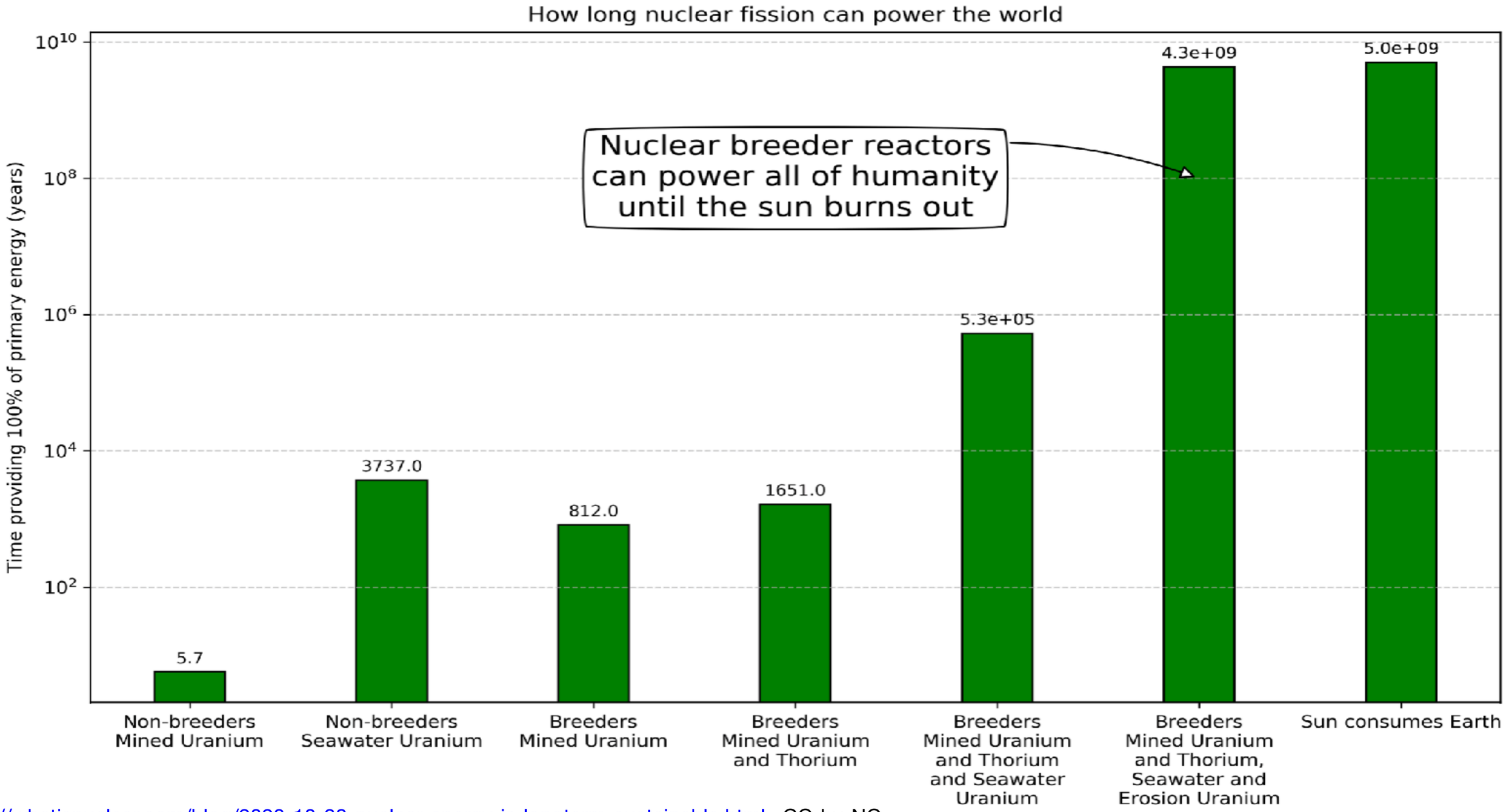
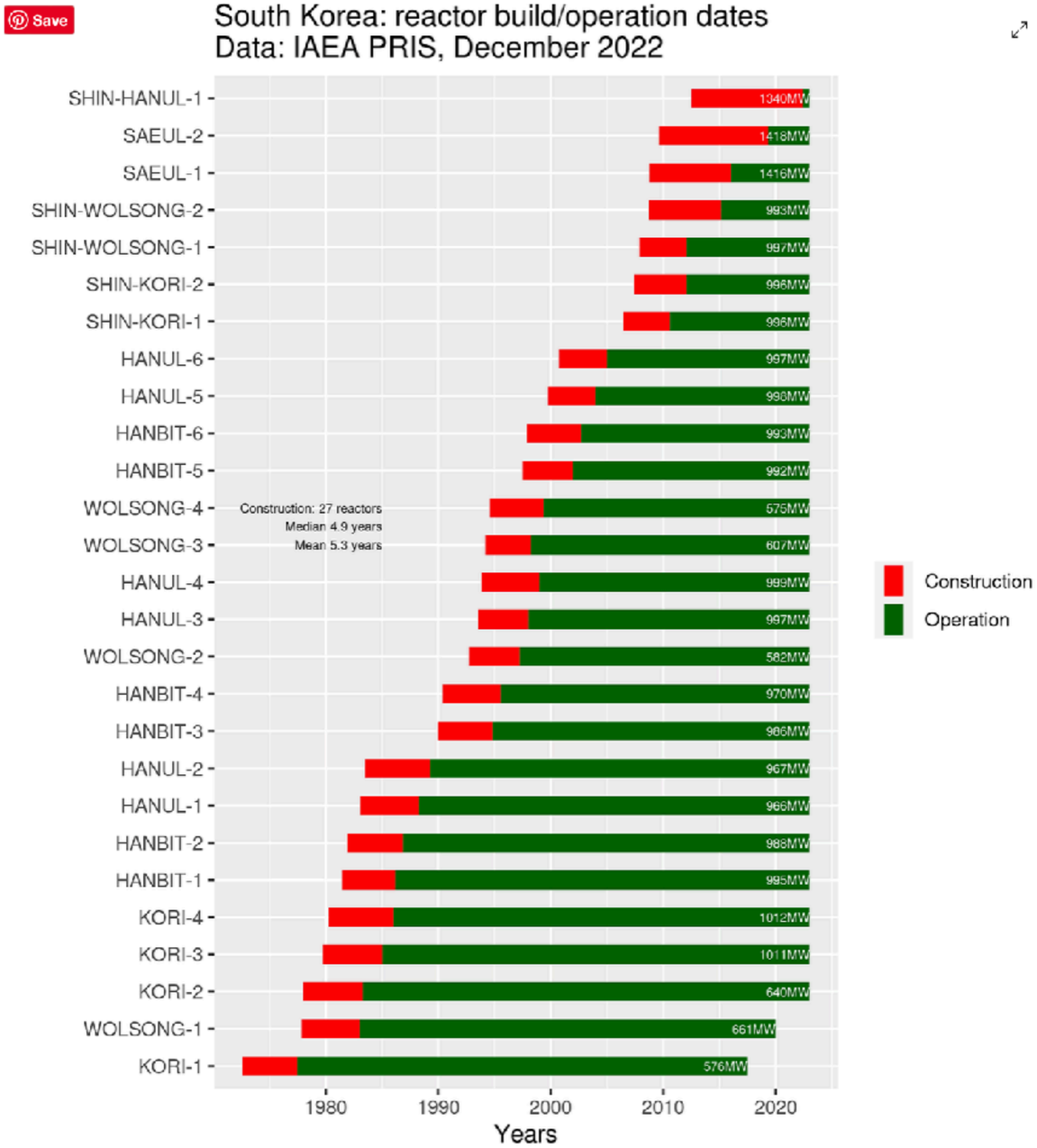
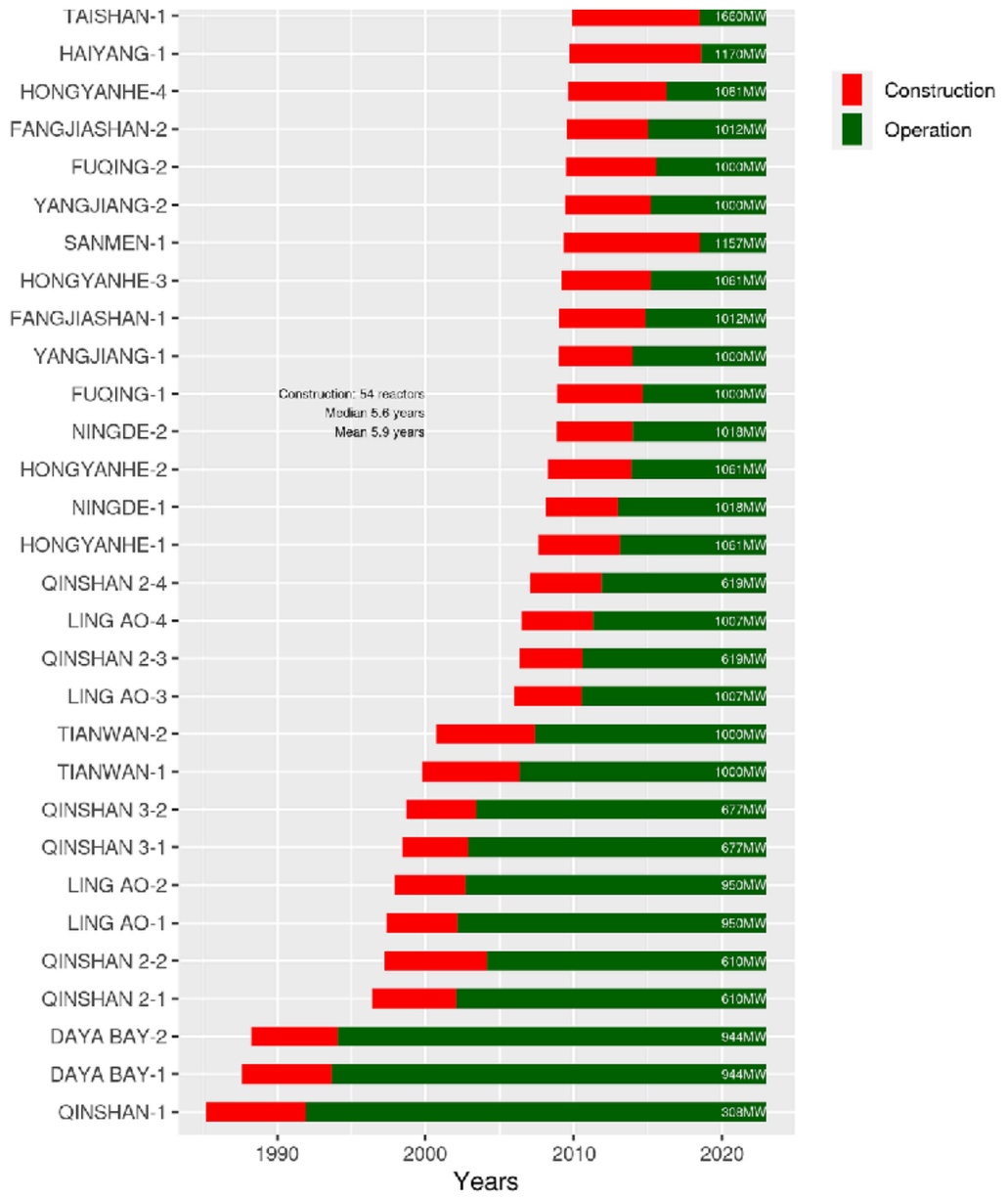
Nuclear fuel will last us for 4 billion years, writes Nick Touran.



https://whatisnuclear.com/blog/2020-10-28-nuclear-energy-is-longterm-sustainable.html. CC-by-NC

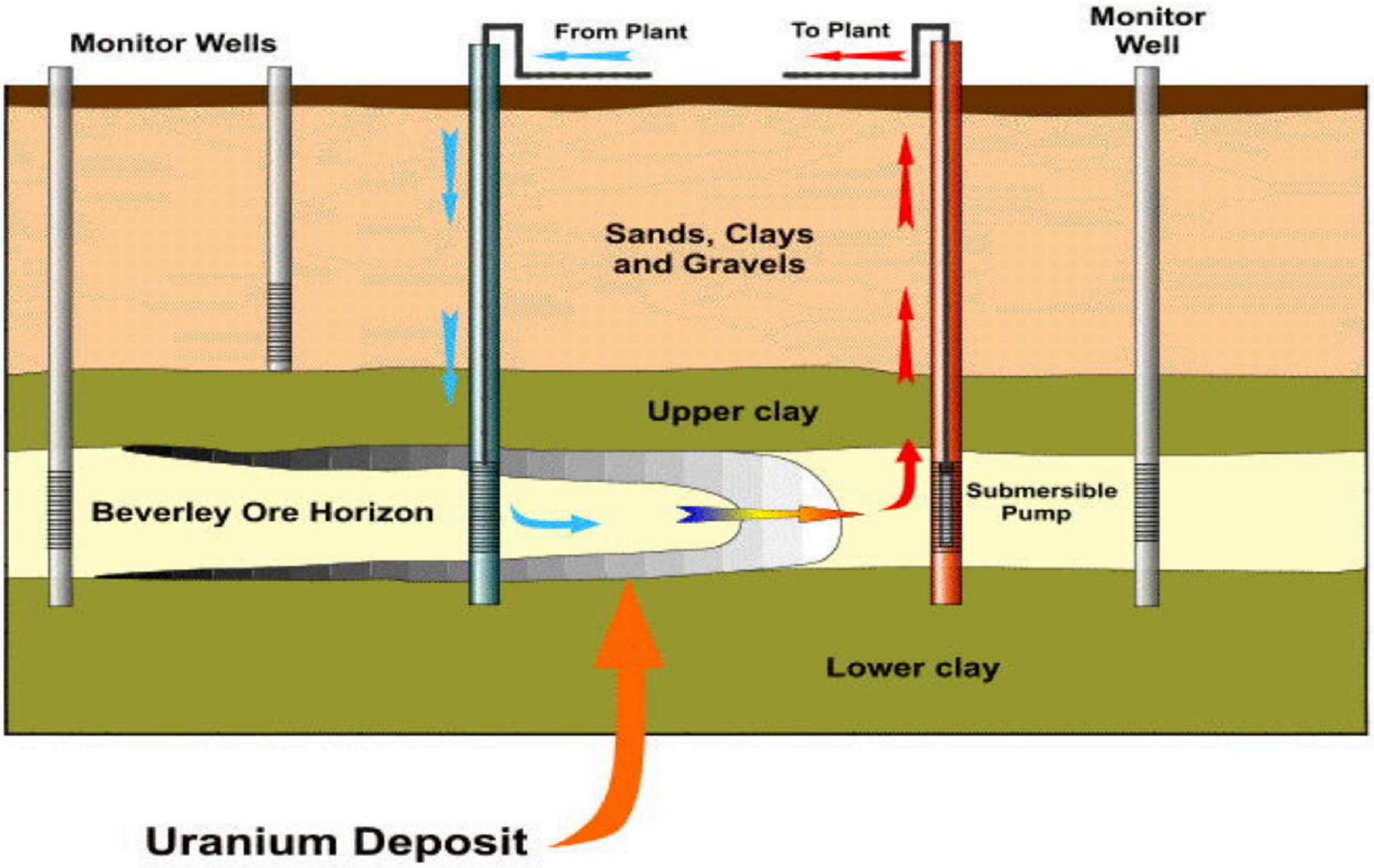
S Korea median build time 5.9 years, China 5.6 years, Japan < 4 years





https://www.blog.geoffrussell.com.au/post/merchants-of-doubt-and-merchants-of-fear?postId=c759af77-3886-4cec-ae43-f6882b1f83e7&utm_campaign=ff2cd9b2-5f35-4144-854e-70162fca7a1a&utm_source=so&utm_medium=mail&utm_content=de423800-66a5-4da5-b2f3-6bbbc32d8b00&cid=4830d732-e3fc-4996-83e9-7e5a357e2f79

In situ leach mining of uranium



https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx

Many laboratories are developing seawater uranium extraction.

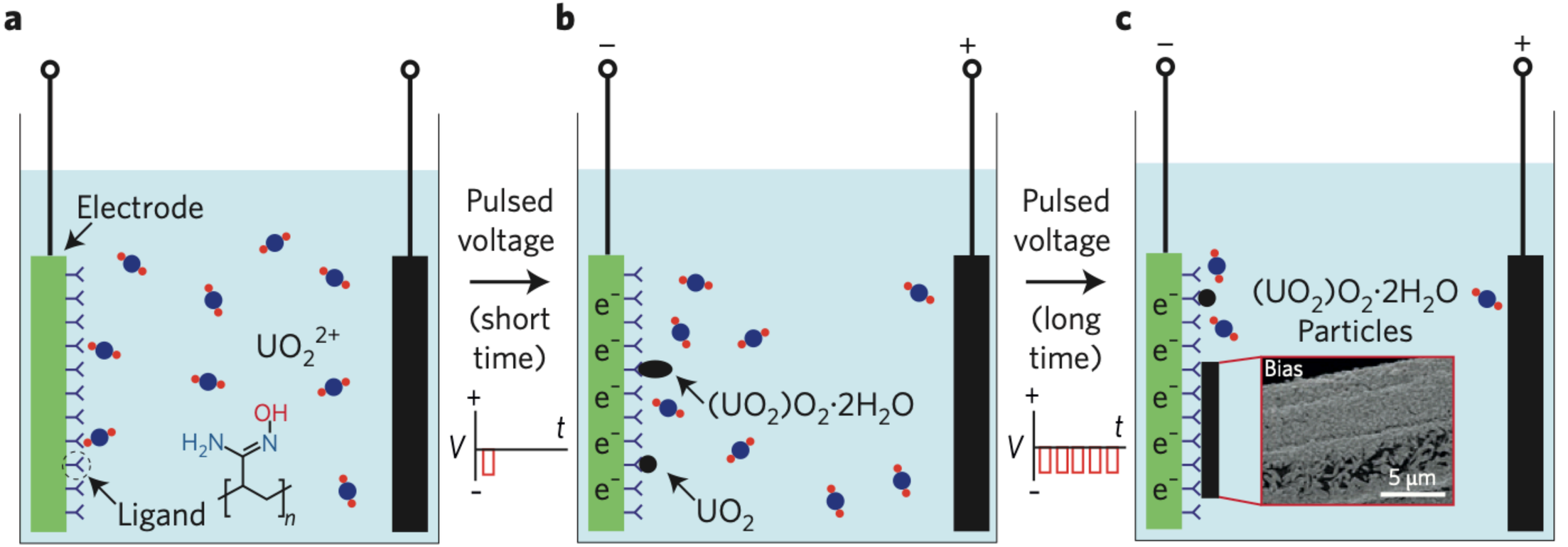


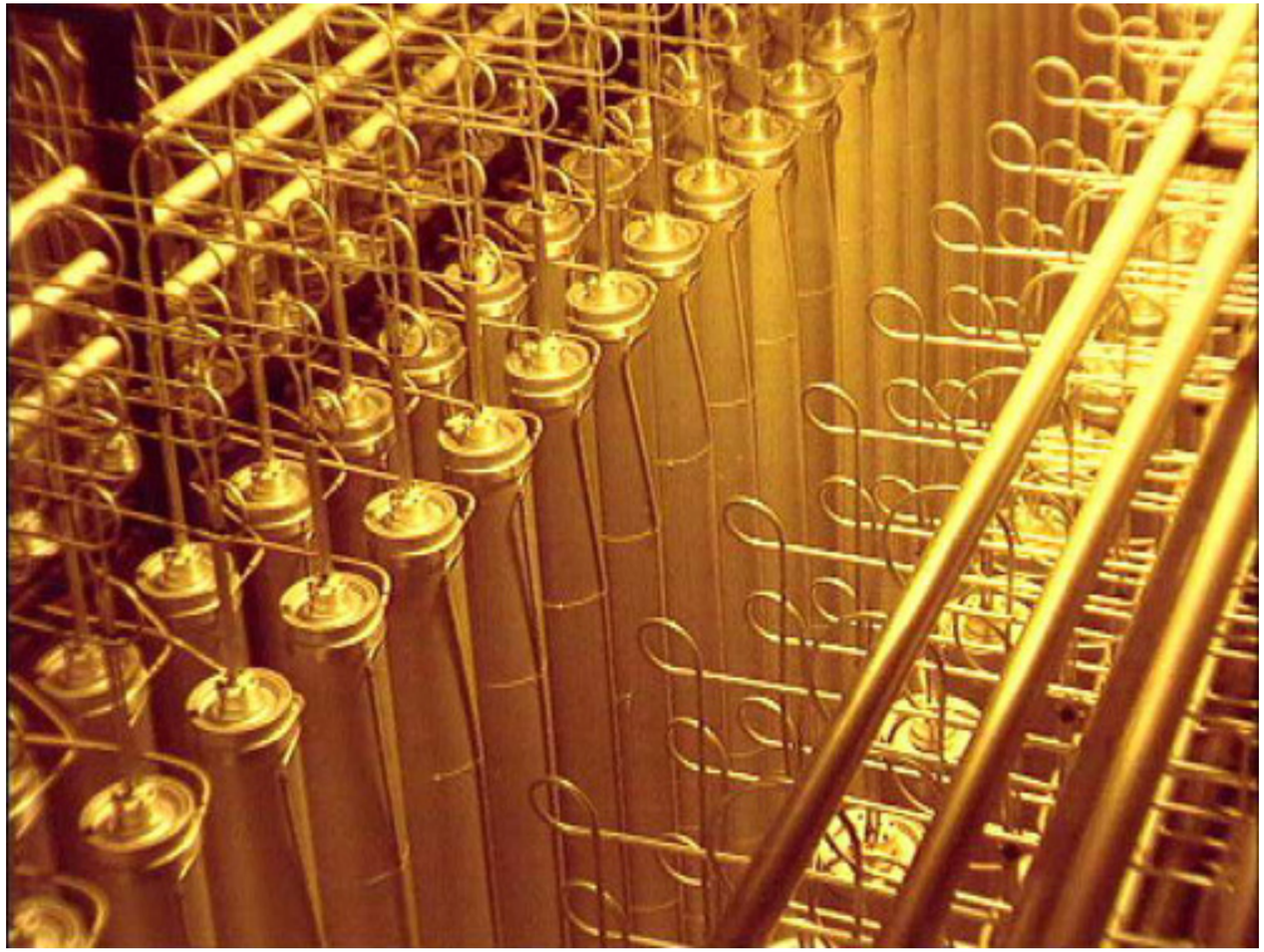
Figure 1 | Alternating-current method for electrochemical extraction of uranium. **a**, The amidoxime-functionalized electrode is submersed in uranium-spiked seawater. **b**, On application of a pulsed voltage, uranyl ions migrate towards the electrode leading to precipitation of uranium-rich particles. **c**, Continued pulsed voltage causes growth of the particles. The inset shows an SEM image of the amidoxime electrode covered by particles after 24 h of extraction with an initial uranium concentration of 1,000 ppm. Figure adapted from ref. 7, Macmillan Publishers Ltd.

https://www.nature.com/articles/nenergy201722.pdf.

Uranium fuel is typically enriched from 0.7% U-235 to 3-5%.

Centrifuge enrichment capacity.

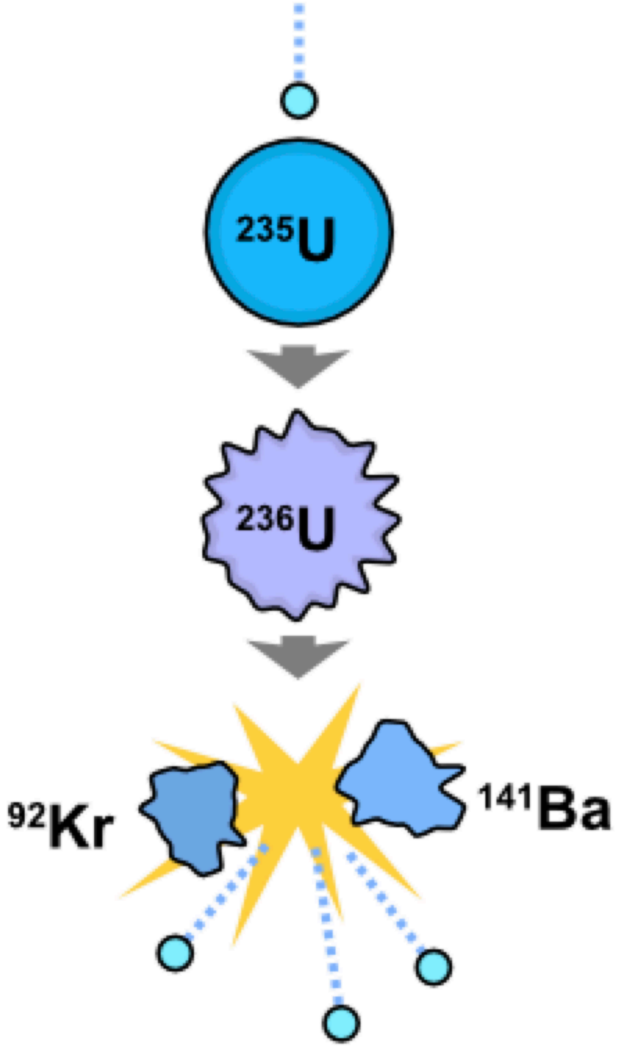
Operator	Capacity (thousand SWU/yr)		
	2020	2025	2030
CNNC	6300	11,000	17,000
Orano	7500	7500	7500
Rosatom	27,700	26,200	24,800
Urenco	18,600	17,300	16,300
Other	66	375	525
Total	60,166	62,375	66,125



Series of centrifuges concentrating U235 in UF6

https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx

Example of Uranium-235 fission to krypton and barium



The total mass of the resulting

barium-141
krypton-92
neutrons (3)

is a bit less than the mass of the U-235 + neutron,

and by $e = mc^2$
immediately releases 166 MeV of energy, totaling 200 MeV after Kr and Ba decay.

1 tonne-U235 fissioned -> 79,000 TJ
= 2.6 GW-years(t)

2 billion years ago
Oklo, Gabon

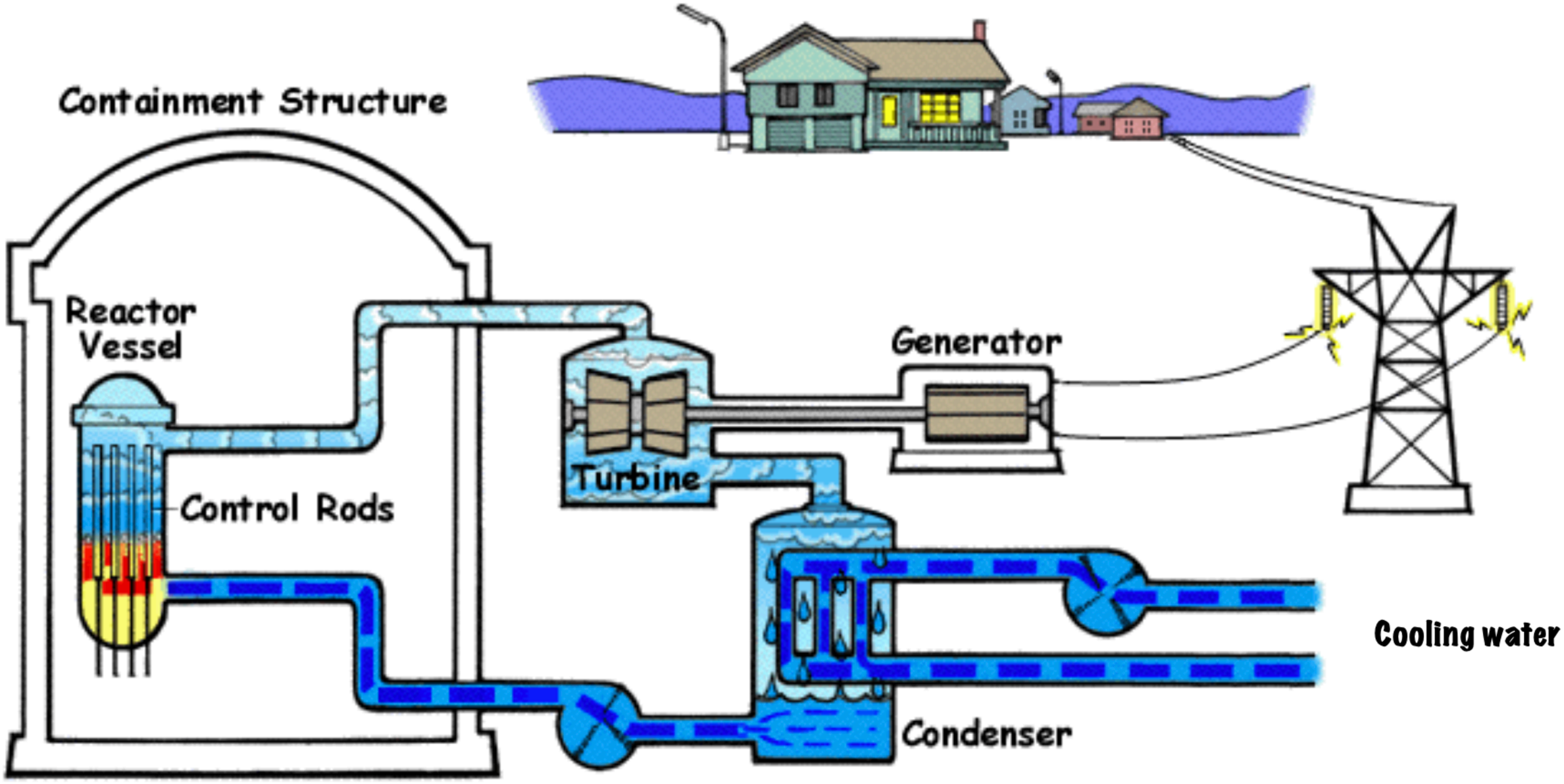
Fissile U-235 was
~ 3% of uranium.

Groundwater **H**2O
slowed neutrons to
fissioning speeds.

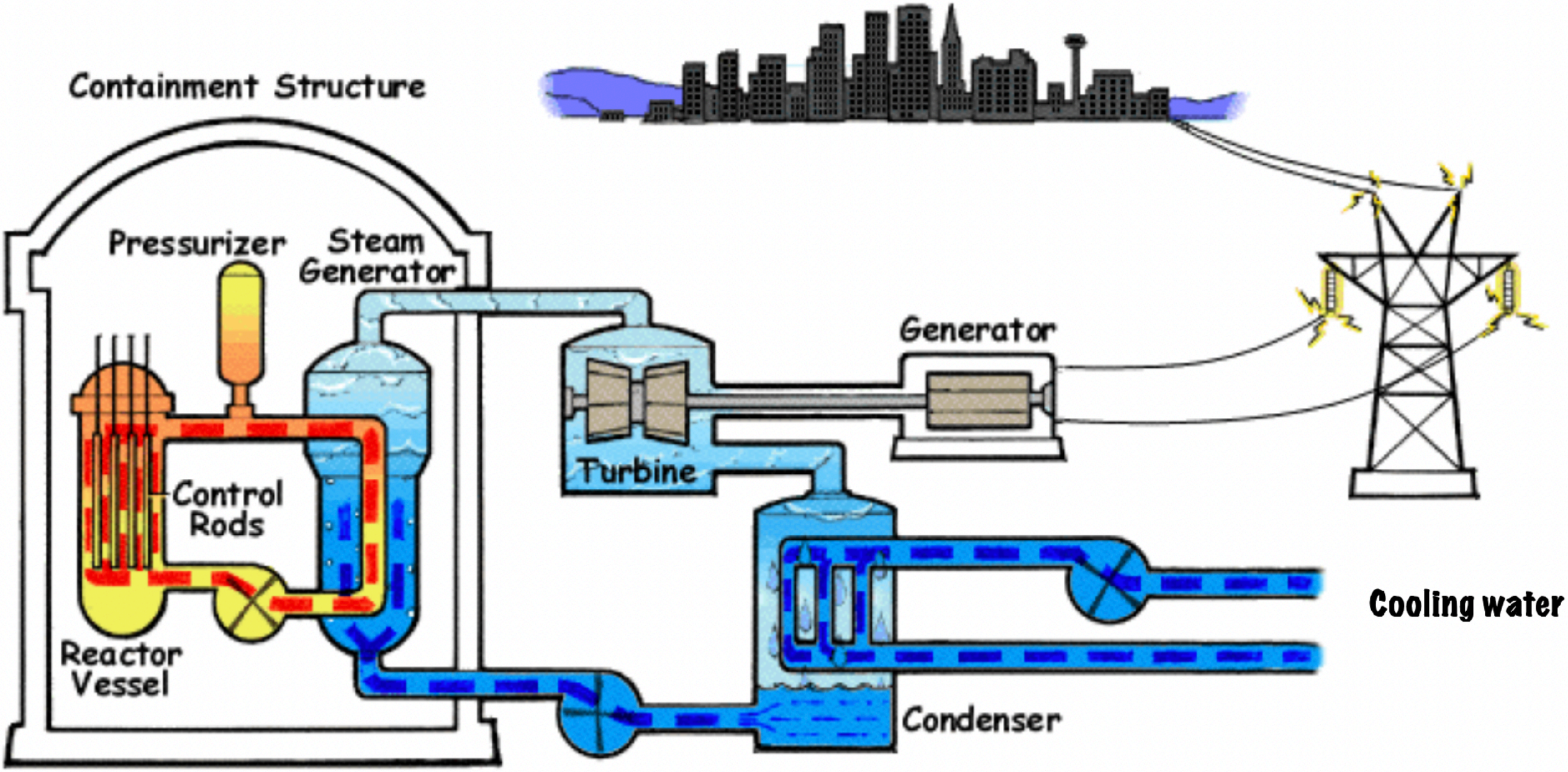
Fission heat
evaporated water.

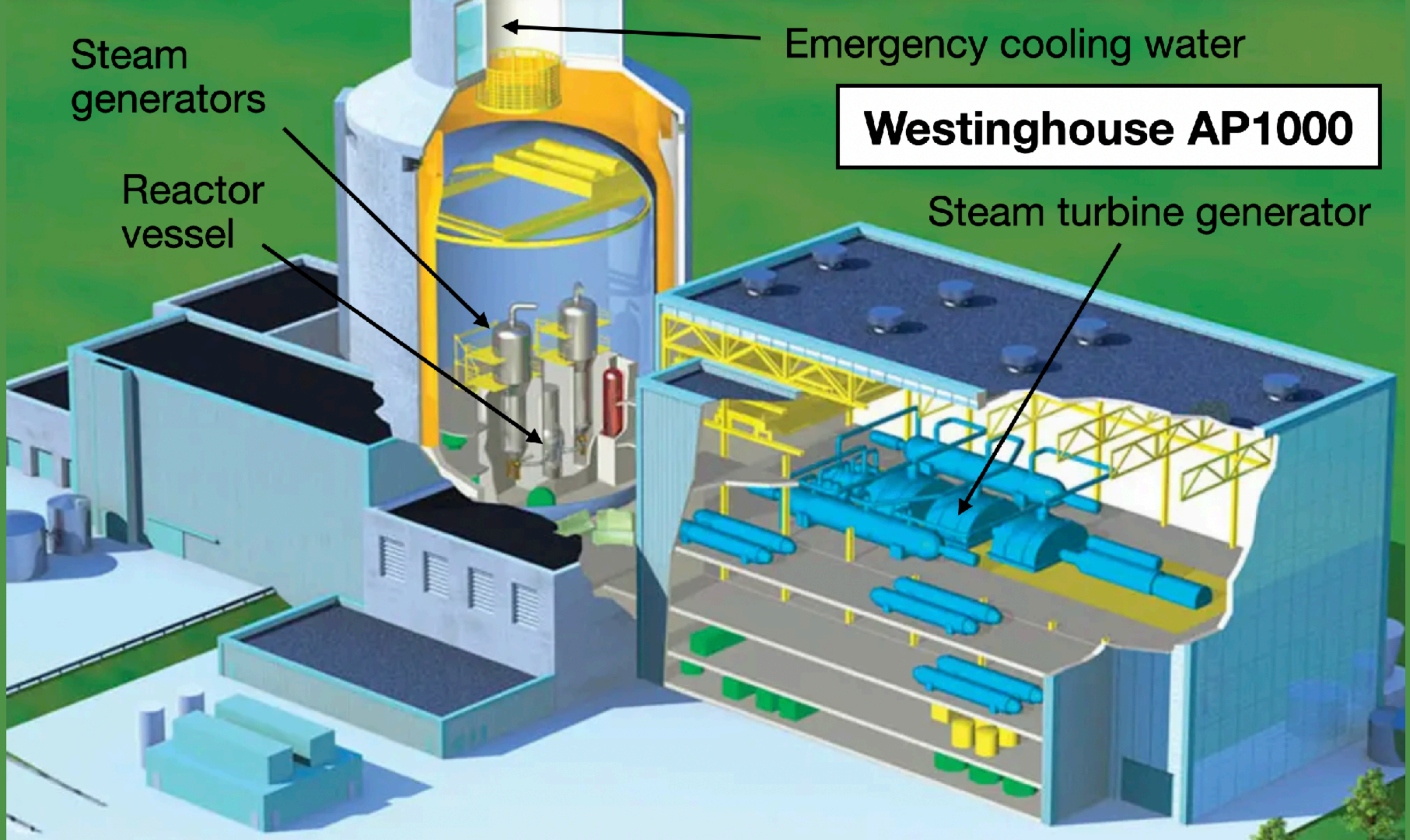
Reactor cycled
off/on, naturally.

Boiling water reactor 75 bar 285°C steam turns turbine-generator.

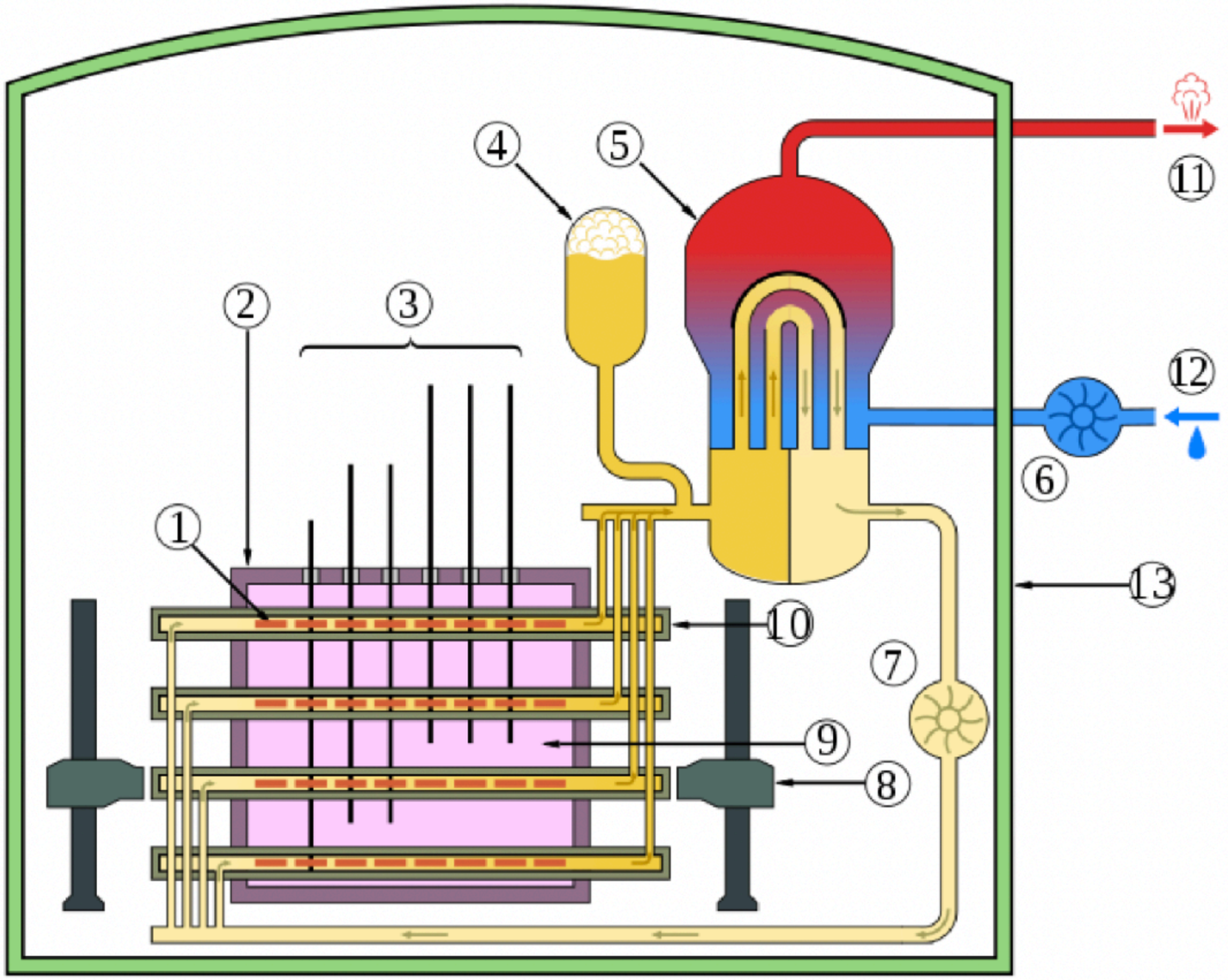


Pressurized water reactor uses155 bar, hotter 315°C water.




Steam generators
Reactor vessel
Emergency cooling water
Westinghouse AP1000
Steam turbine generator

CANDU reactor moderator is D2O, with no large pressure vessel.

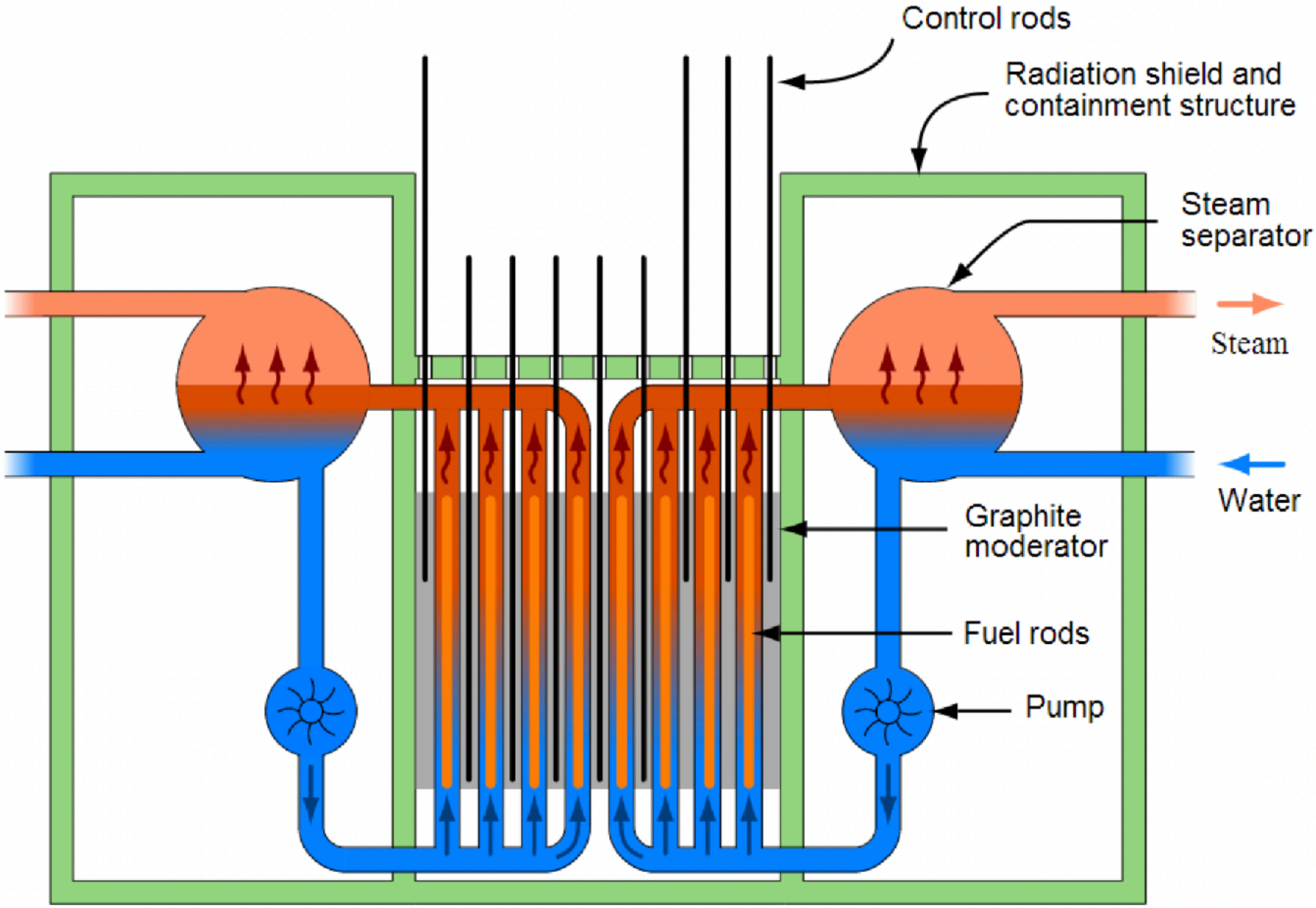


D2O is heavy water, H2O where each H has 1 proton and 1 neutron, so does not absorb fission neutrons.

CANDU can use natural, unenriched uranium.

- Hot and cold sides of the primary heavy-water loop
- hot and cold sides of secondary light-water loop
- cool heavy water moderator in the calandria,

Russia's RBMK graphite moderated, water cooled power plant



Chernobyl, 1986

Positive void coefficient

Safety systems improved

8 RBMK plants still operating in Russia.

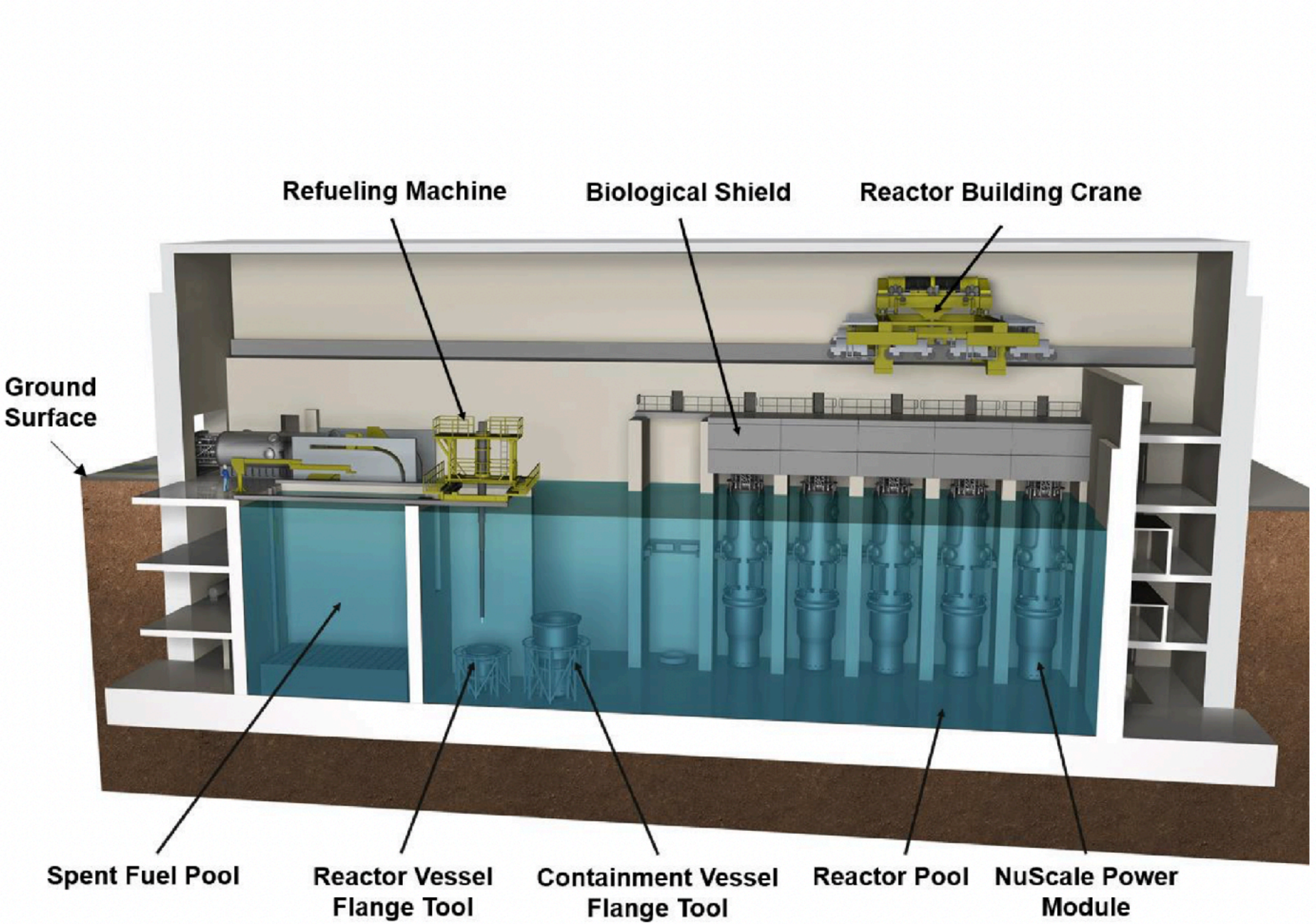
VVER (PWRs) are exported.

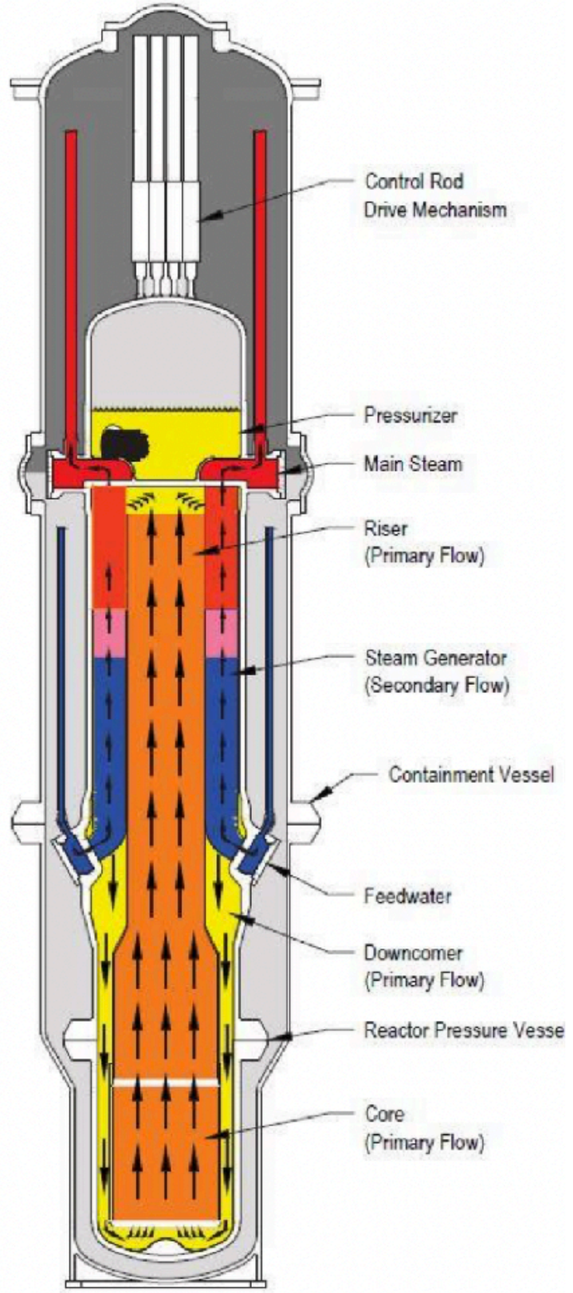
BN-800 sodium cooled fast reactor in operation

Russia’s Academik Lomonosov 70 MWe floating power unit

https://www.world-nuclear-news.org/Articles/Floating-nuclear-power-plant-set-for-first-refuell

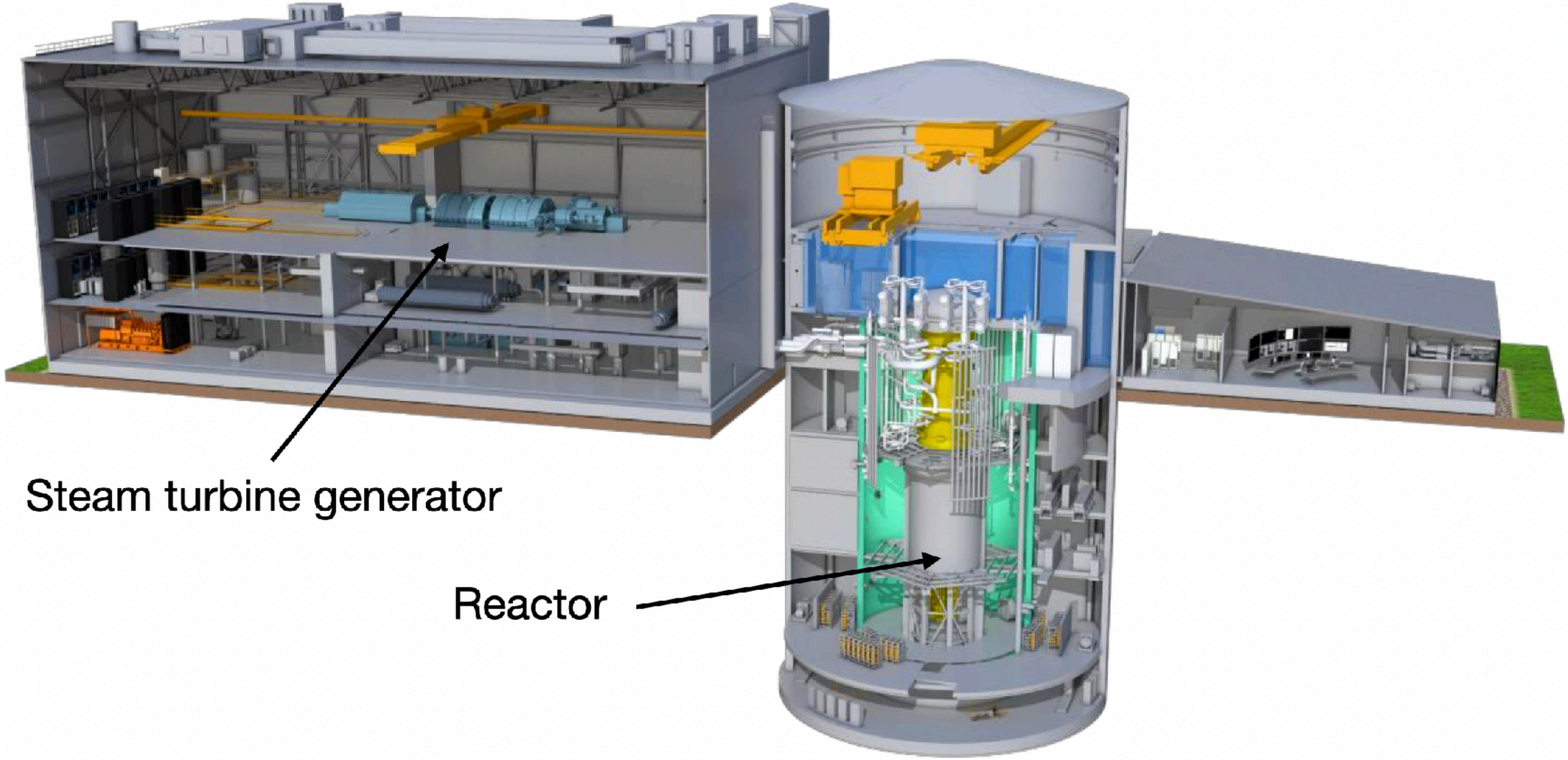
NuScale 200 MW(t) PWR modules are under water.





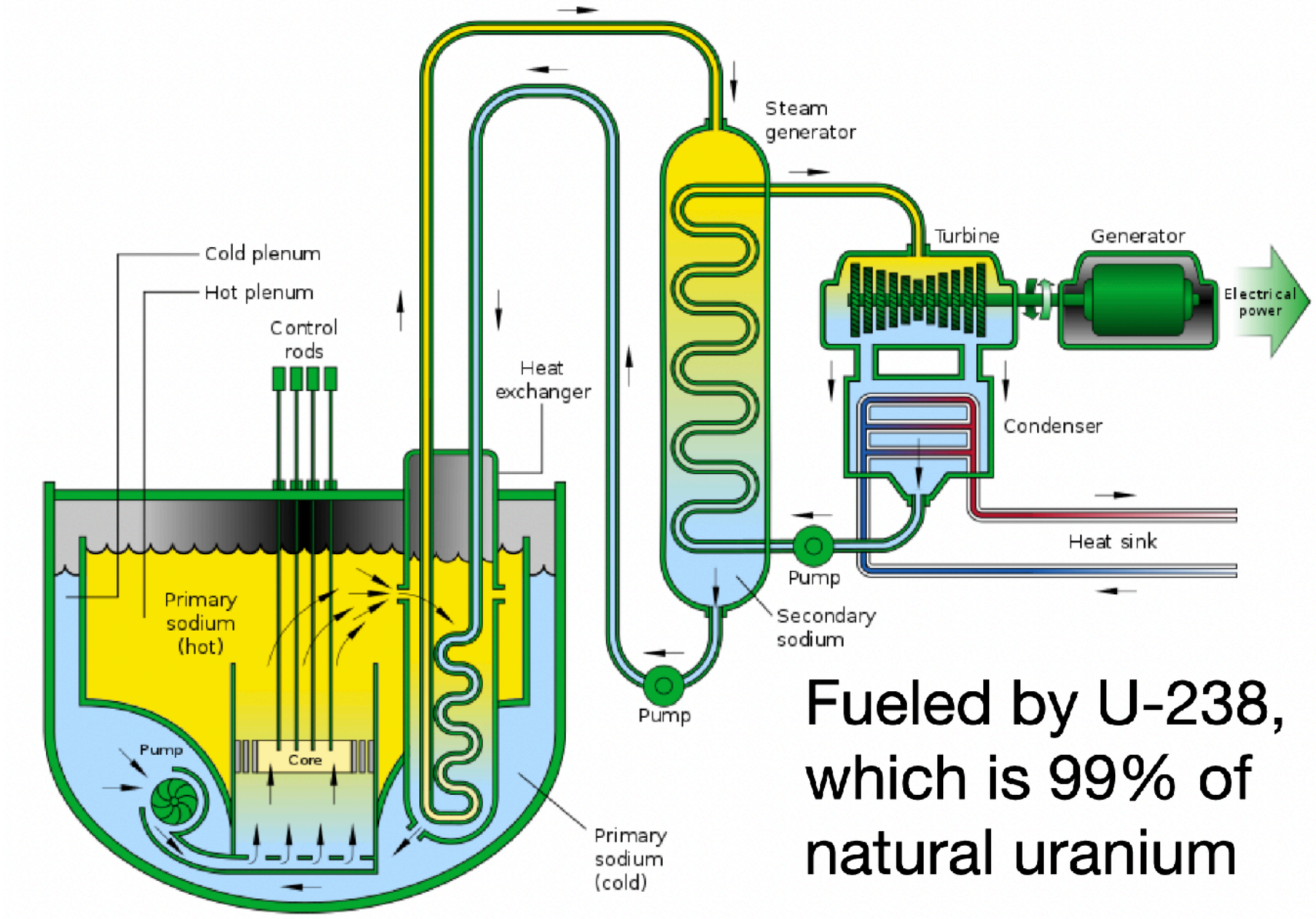
GE Hitachi BWRX-300.

300 MW @ $3/watt cost?



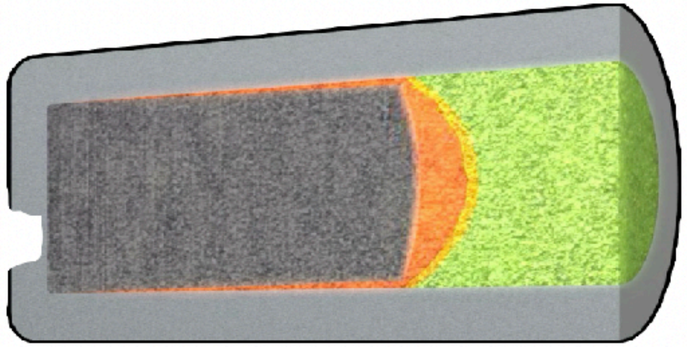
Holtec dual SMR-300

Fast reactors fission U-238 products with unmoderated neutrons.

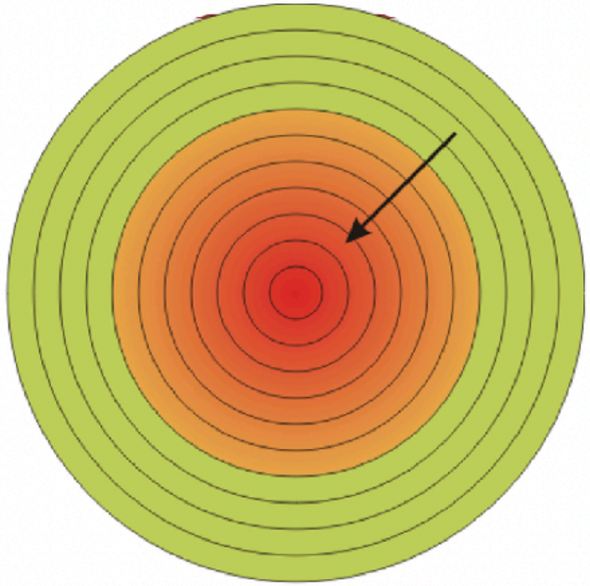


Fueled by U-238, which is 99% of natural uranium

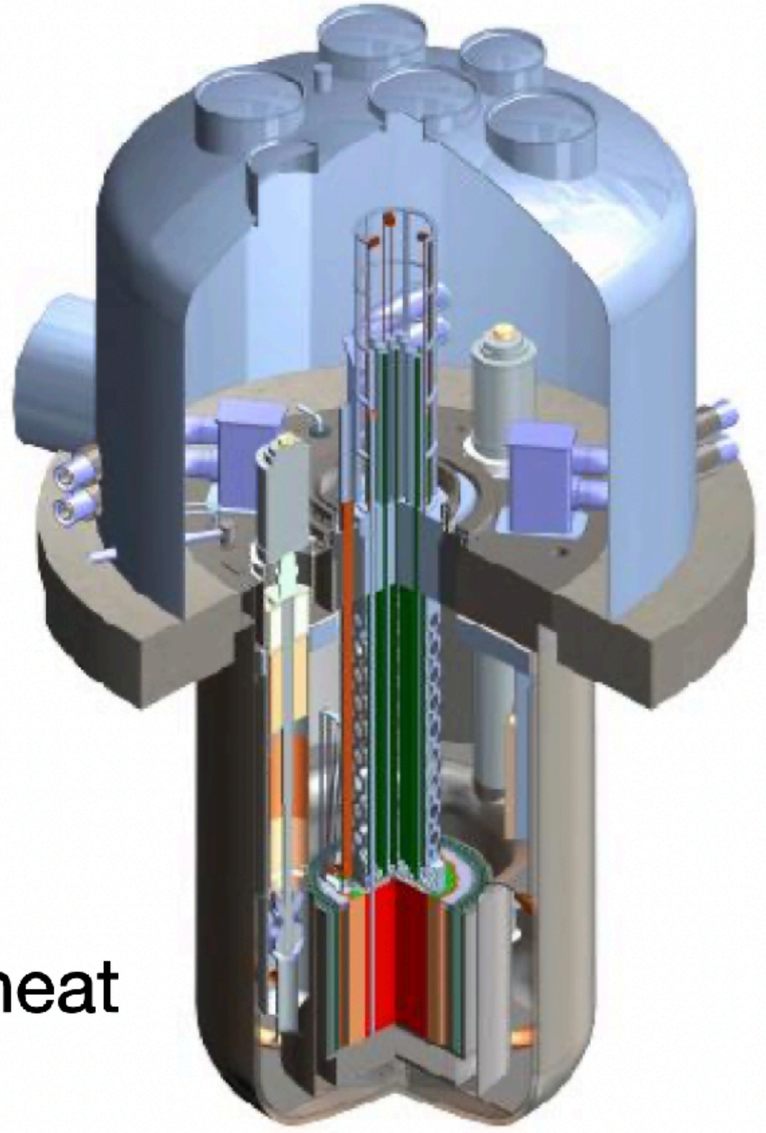
TerraPower Traveling Wave Reactor design evolved to Natruim.



Traveling
fission
wave



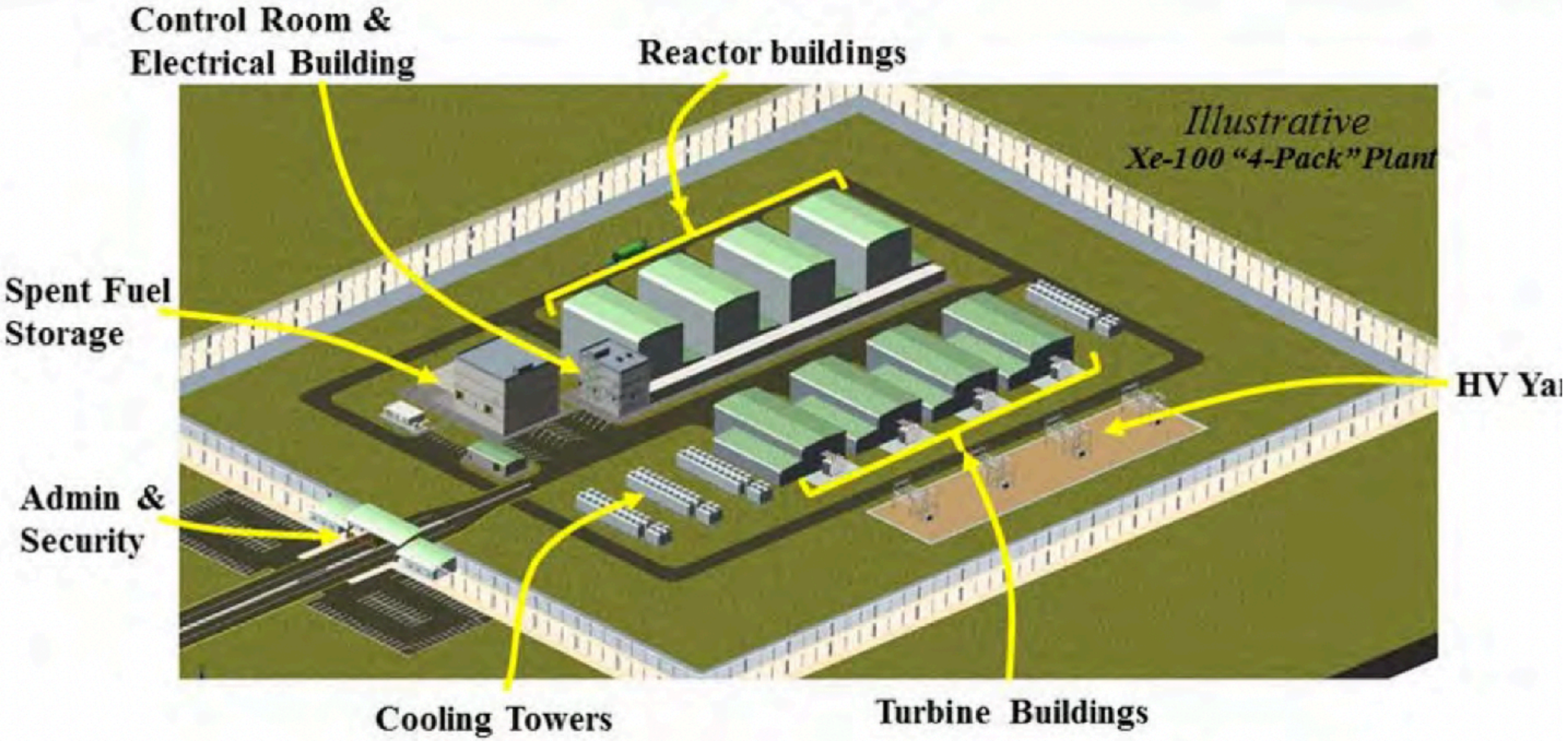
Distant U-238 fuel
rods breed Pu-239
then are moved to
fissioning center.



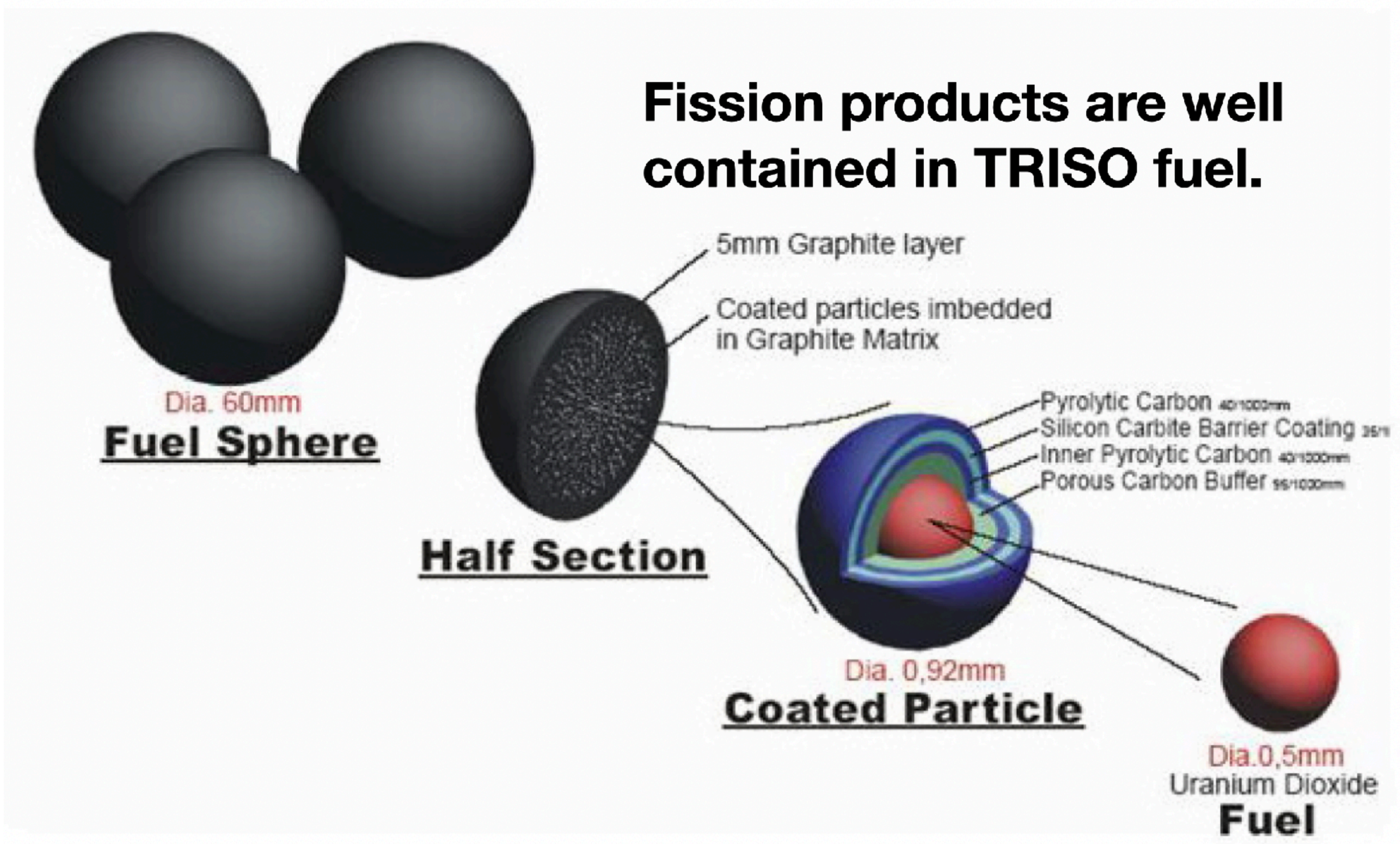
1475 MW heat
500°C
600 MW(e)

X-energy Xe-100 pebble bed reactor

Each Xe-100 reactor provides 200 MW of heat via 750°C helium gas.

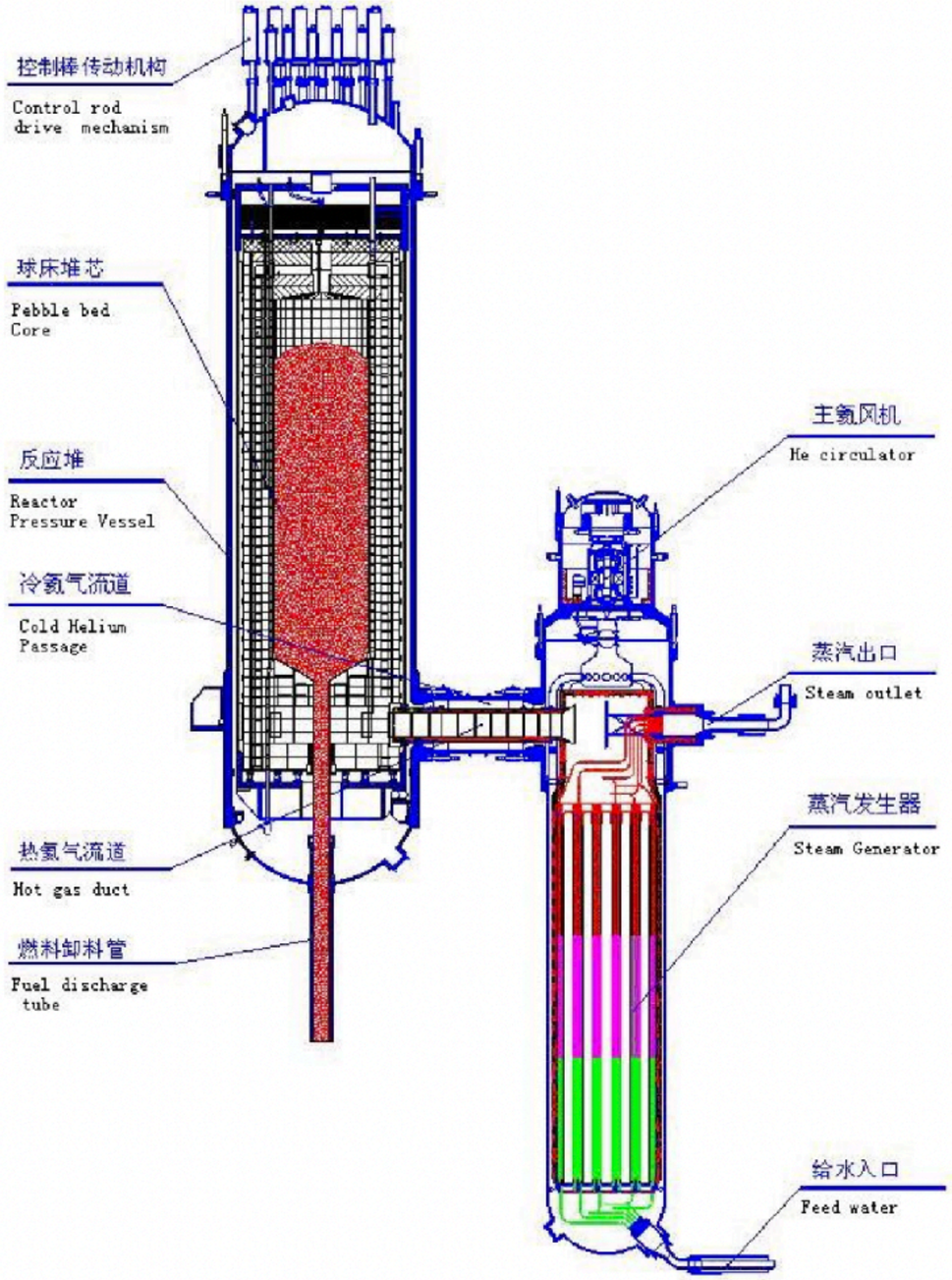


TRi-structural ISOtropic particle fuel (TRISO fuel)



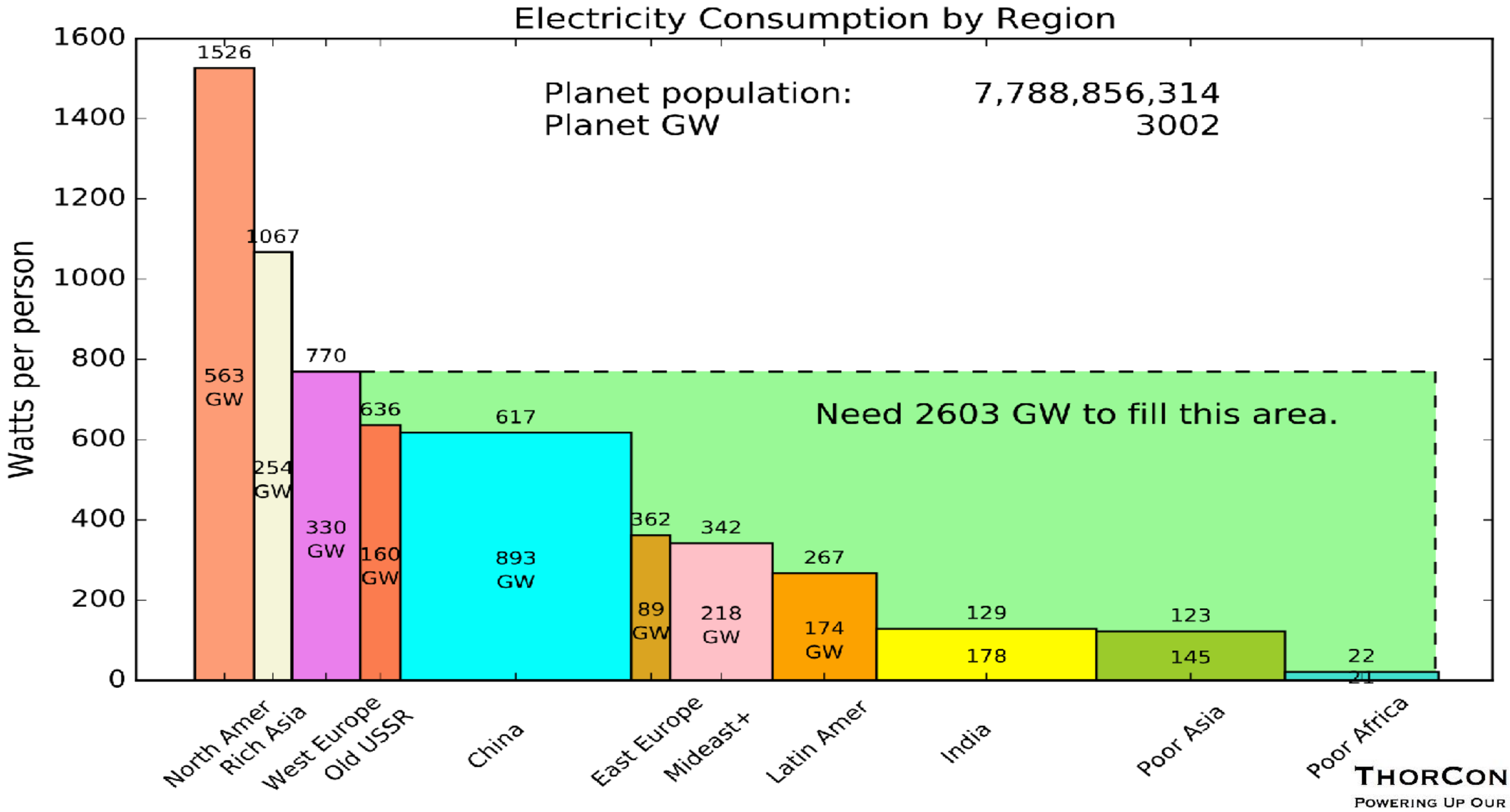
TRISO fuel new nuclear technology online in China.

HTR-PM high temperature, gas cooled, modular pebble bed reactor.




Developing nations now build coal-fired power plants.
Reliable, 24x7, affordable
574 GW in development
ThorCon
Powering Up Our World

3,000 GW global electricity use may grow by 2,600 GW.



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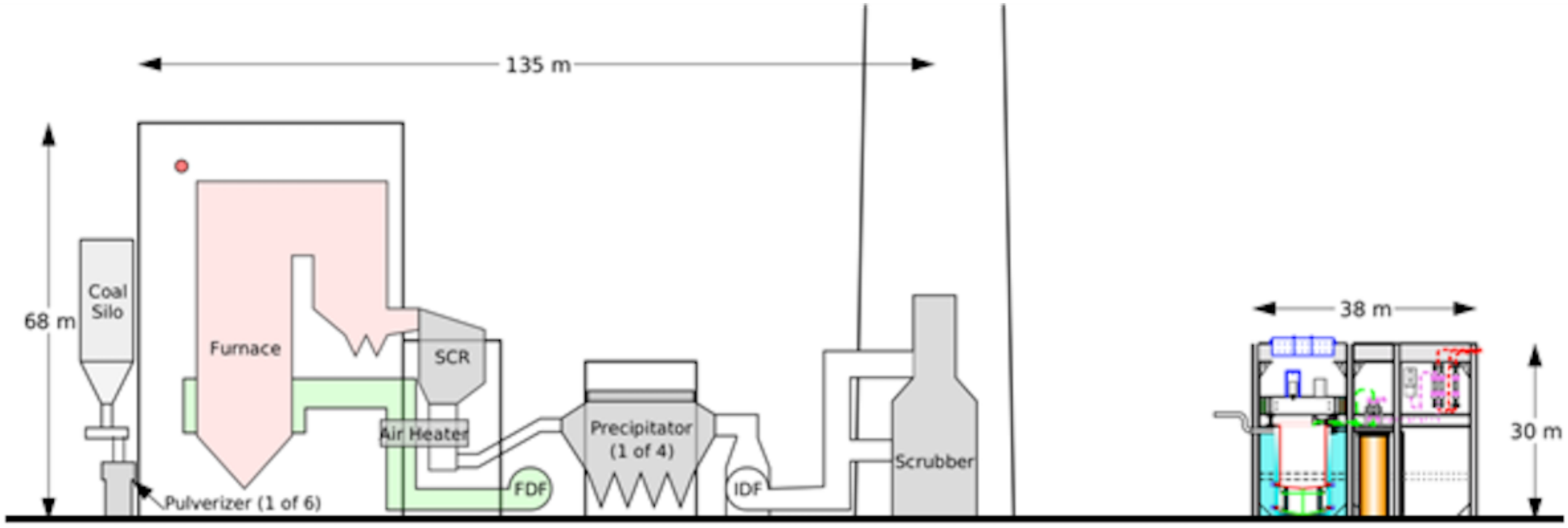
ThorCon fission power strategy

- to mass-produce fission power plants
- to generate CO2-free, 24x7 electricity
- cheaper than from coal or LNG
- at shipyard scale — 10 GW per year
- helping people achieve prosperity.

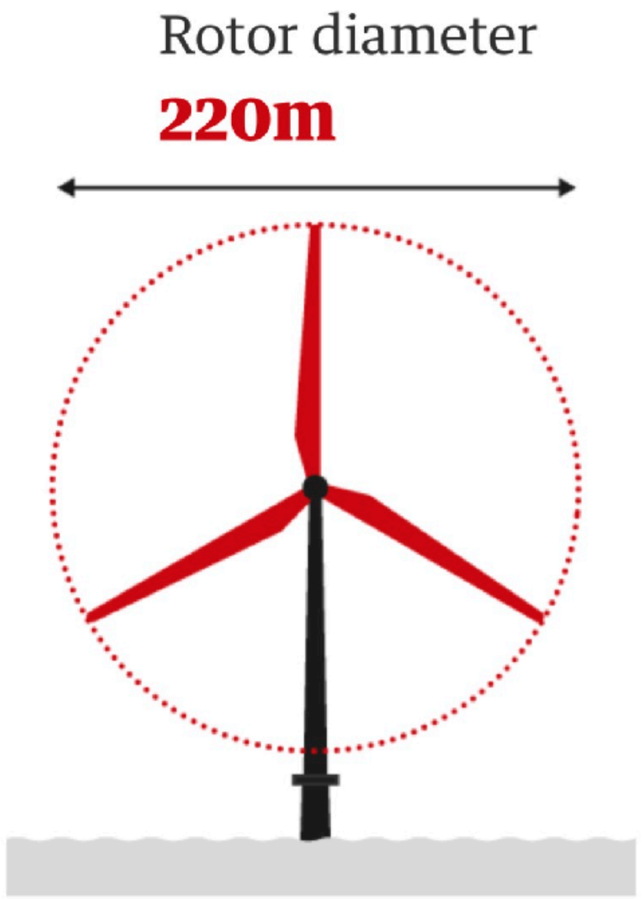
- Nations **will choose** 24x7 fission, if it's **cheaper.**

Economics	**Fission**	**Coal**
Capital cost, $/Watt	1.0	2.0
Fuel cost, cents/kWh	0.53	2.27
Electricity, cents/kWh	**3**	**5**

- **ThorCon 500 uses the same, commercially available turbine-generators as a coal plant.**
- **A coal plant of comparable electric output consumes 5,000-10,000 tons of fuel every day.**
- **ThorCon 500 needs only about 15 kilograms of uranium fuel.**

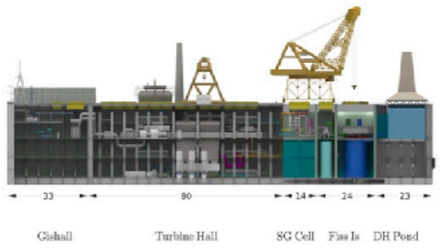


GE Haliade X
12 MW intermittent



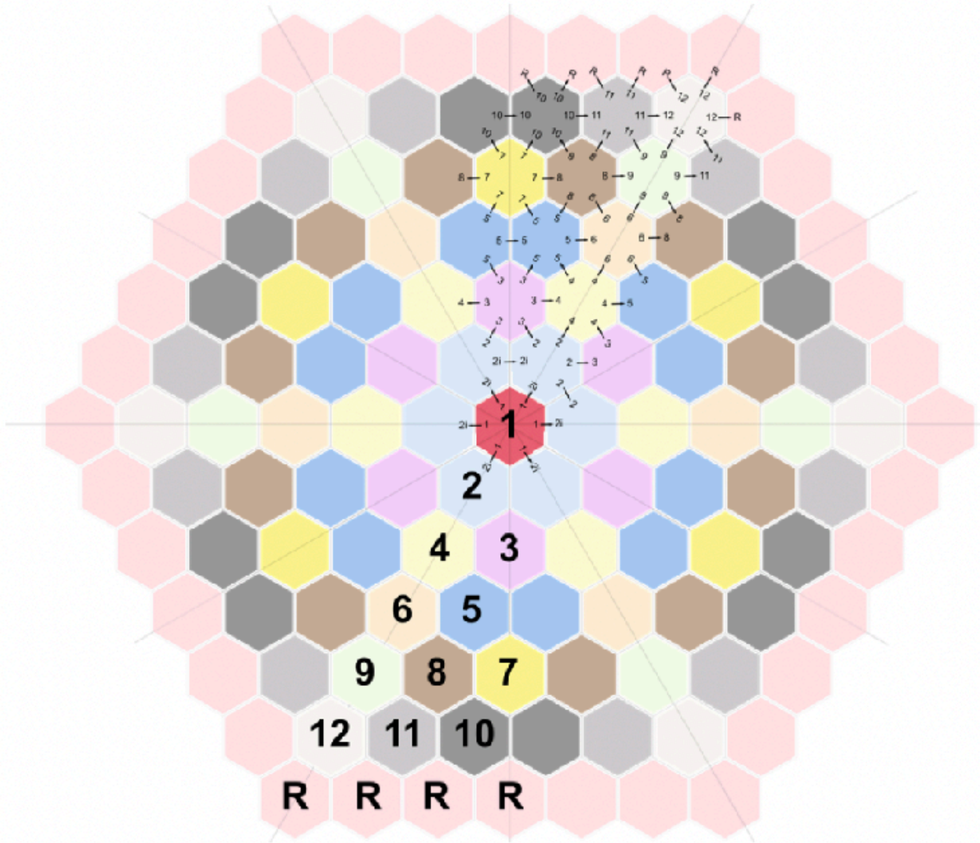
ThorCon liquid fission
500 MW full time
length 165 m

to scale



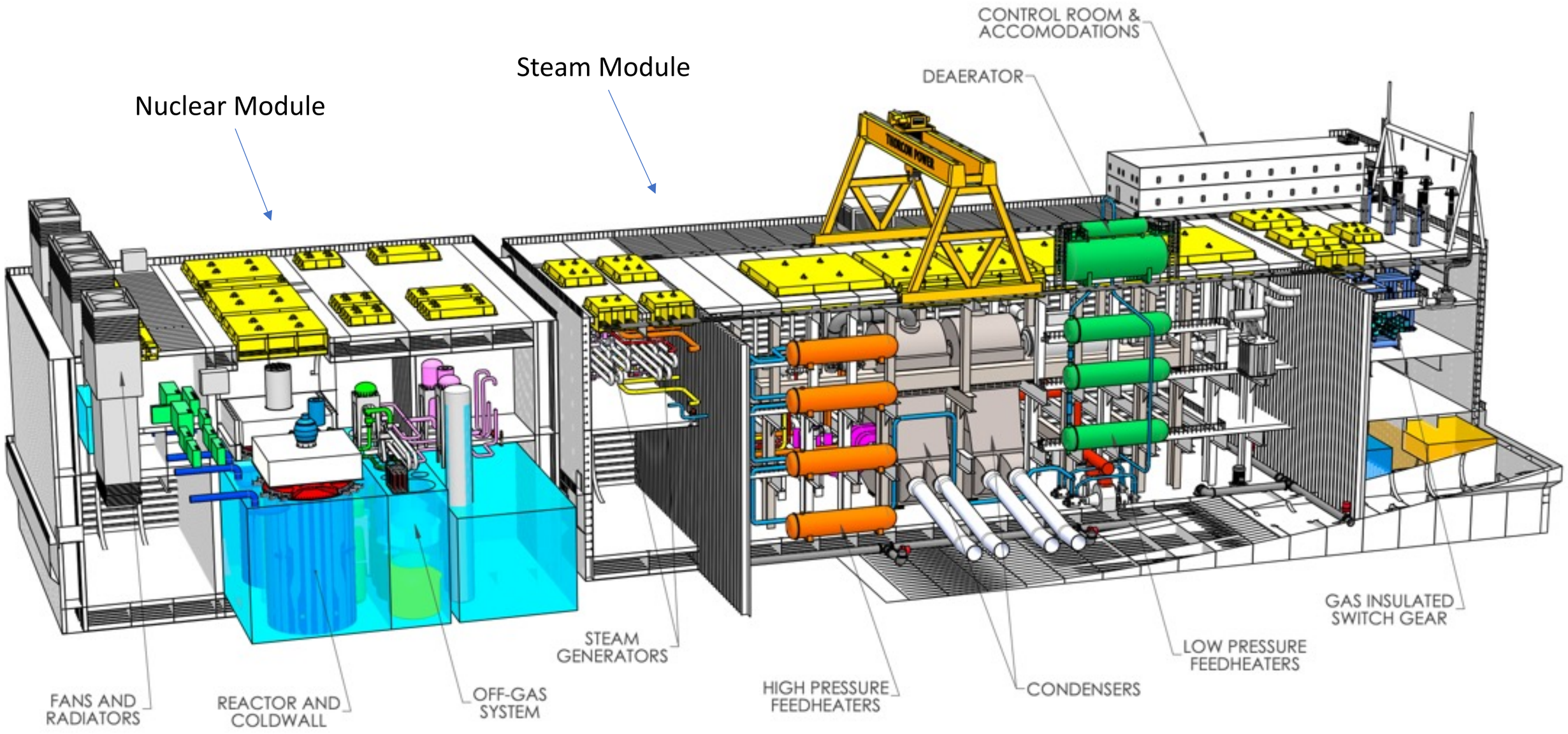
12 MW x 40% **vs** **500 MW x 90%**

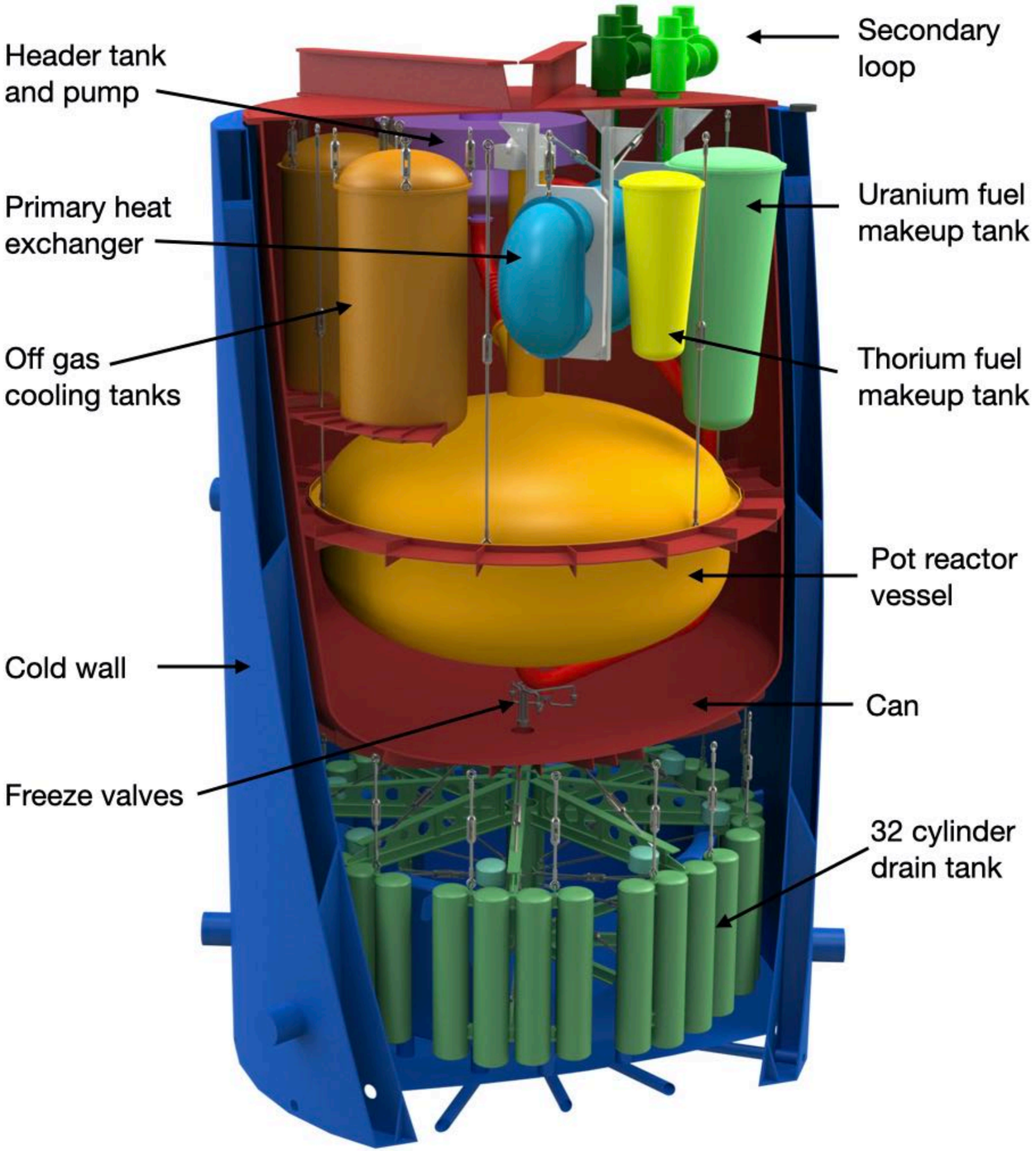
Oak Ridge National Labs developed a molten salt reactor.



- Uranium in salt fissions while flowing up in channels in a graphite moderator.
- Physics stops fission if temperature rises much over 700°C.

ThorCon 500 is designed for shipyard construction.

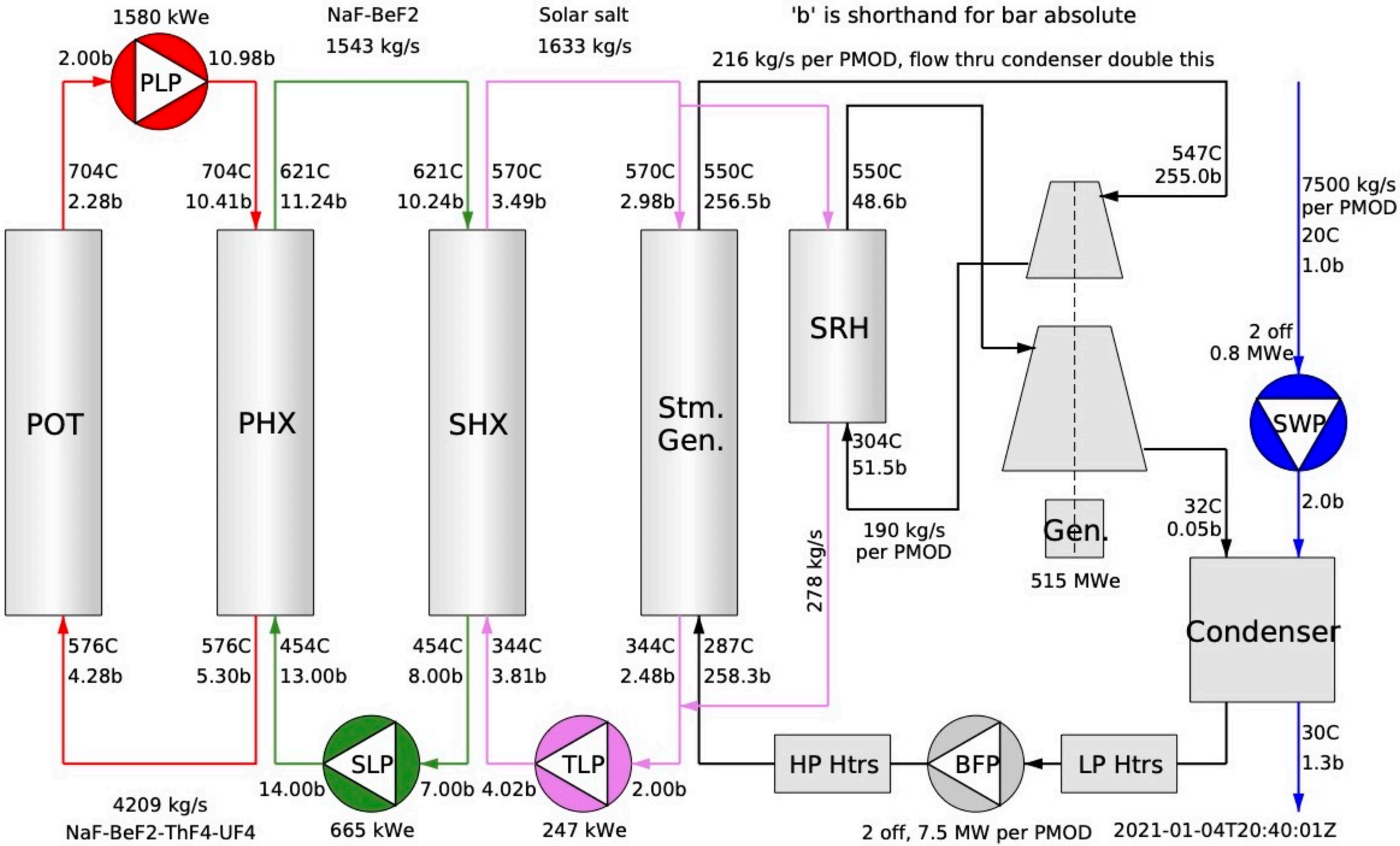




Replaceable Can, in Silo Cold Wall

- The reactor Pot contains the graphite moderator with channels for molten salt flow.
- Overheat drains salt to drain tank.
- Cold wall absorbs heat radiated from drain tank.
- Cold wall is cooled by natural water circulation.

Convert 2 x 557 MW thermal —> 515 MW electrial



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Devanney Ultra Large Crude Carrier cost $89 million, built in 10 months

ThorCon designers are experienced in shipyard construction technology.

- Built eight of the world's largest supertankers
- $600 million program
- responsible for all specifications, financing, yard negotiations and supervision
- Built on firm, fixed price, fixed schedule project.

THORCON
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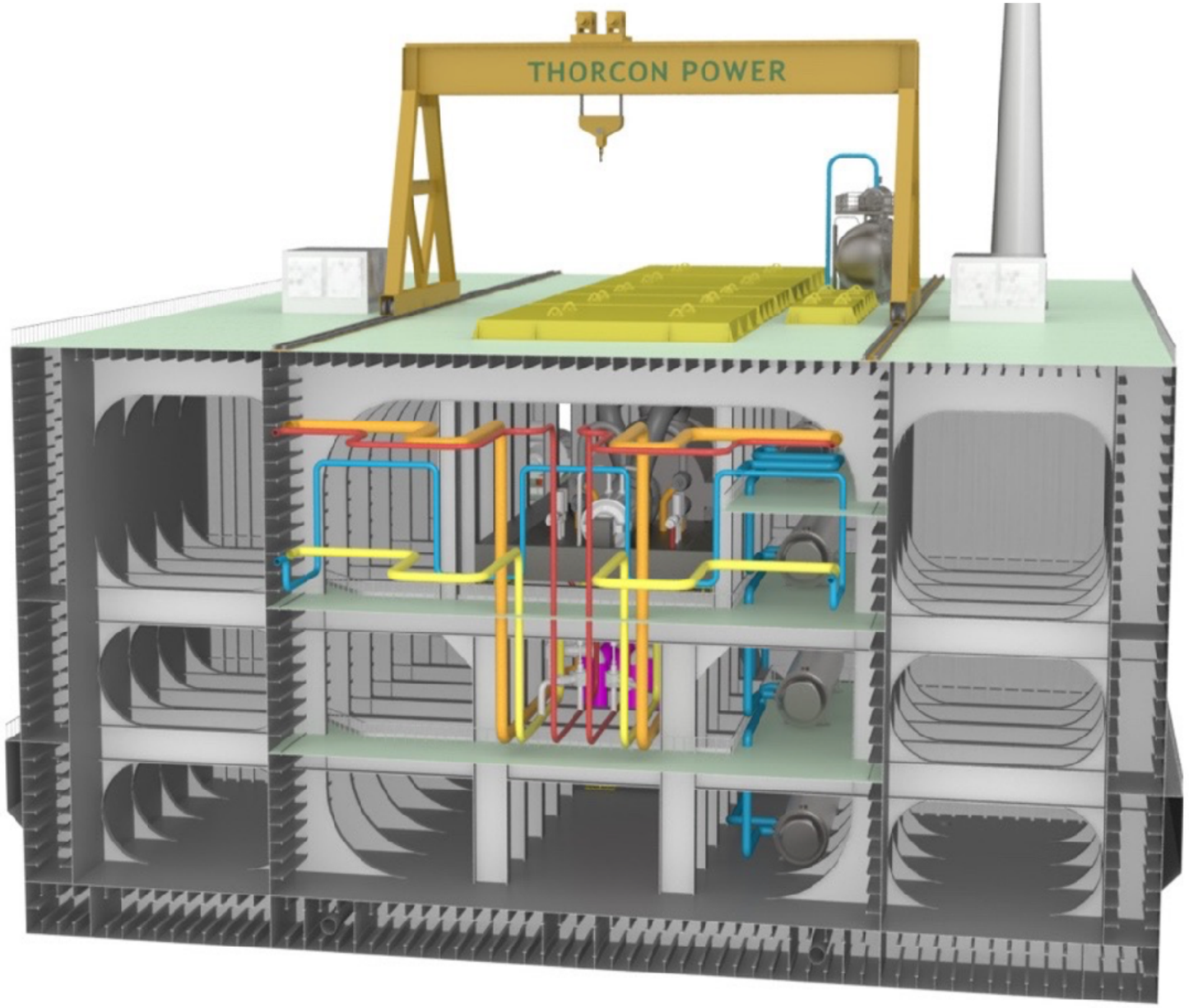
Same structural design as double-hull oil tanker.



- Important for structural design to match shipyard practice.
- Reduces costs.
- Enables 1-year shipyard fabrication, and
- Mass production of 20 plants per year.

ThorCon
Powering Up Our World

Shipyards fabricate vessels at 5 labor-hours per ton of steel.

THORCON
POWERING UP OUR WORLD

South Korea Hanwha Ocean will be ThorCon EPC.

Courtesy of DSME

ThorCon
Powering Up Our World

Prototype will be towed to Indonesia.

ThorCon
Powering Up Our World

Bangka-Belitung governor approved island site.

- Power company's PLN-Engineering carried out site feasibility study.
- Bapeten, the nuclear regulator, has promised efficient regulation.
- A MOU has been signed with PLN to write a 30-year PPA for the demo plant.
- Regulator received documents needed for preliminary review of ThorCon design.
- Recent poll: 74% of the public in Bangka are in favor of nuclear power.

ThorCon
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Compare to water reactor technology

ThorCon	Conventional nuclear
Low pressure	High pressure
Liquid fuel	Solid fuel
High temperature	Low temperature
46.5% efficiency	32% efficiency
Inherent safety	Engineered safety systems
2 years to build	Many years to build
$ 1 per watt	$ 3.5 to 7 per watt
3 cents/kWh	6-10 cents/kWh
Shipyard mass production	On-site construction

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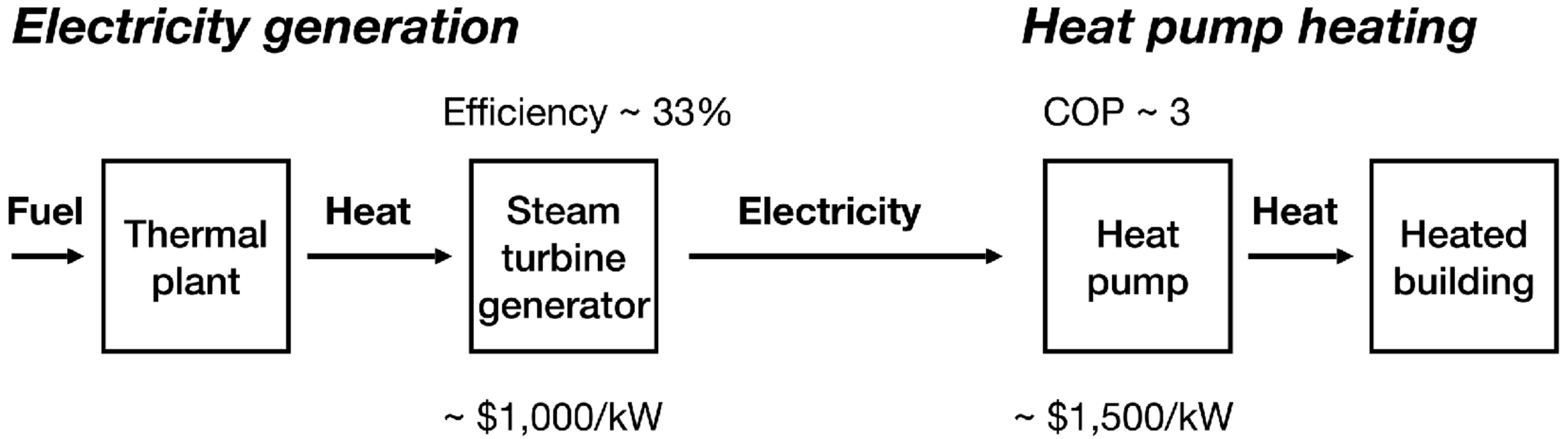
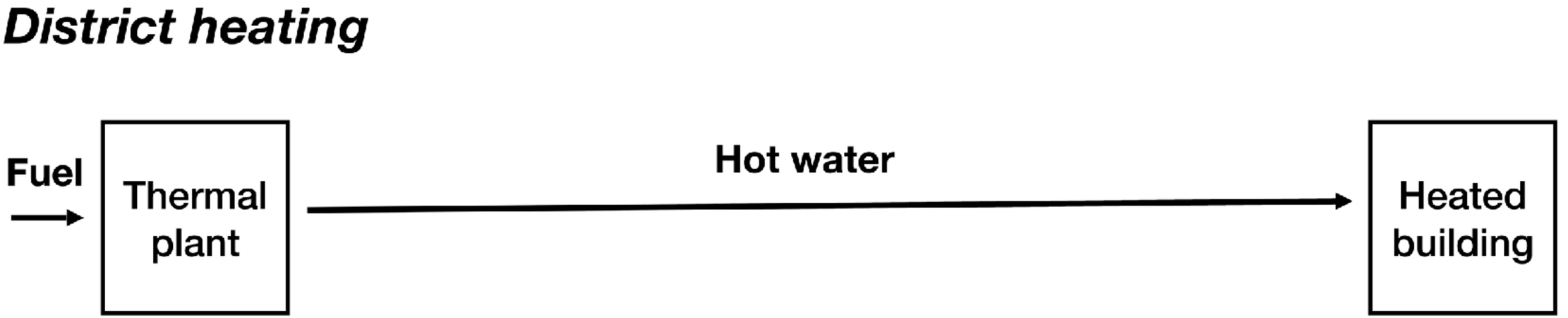
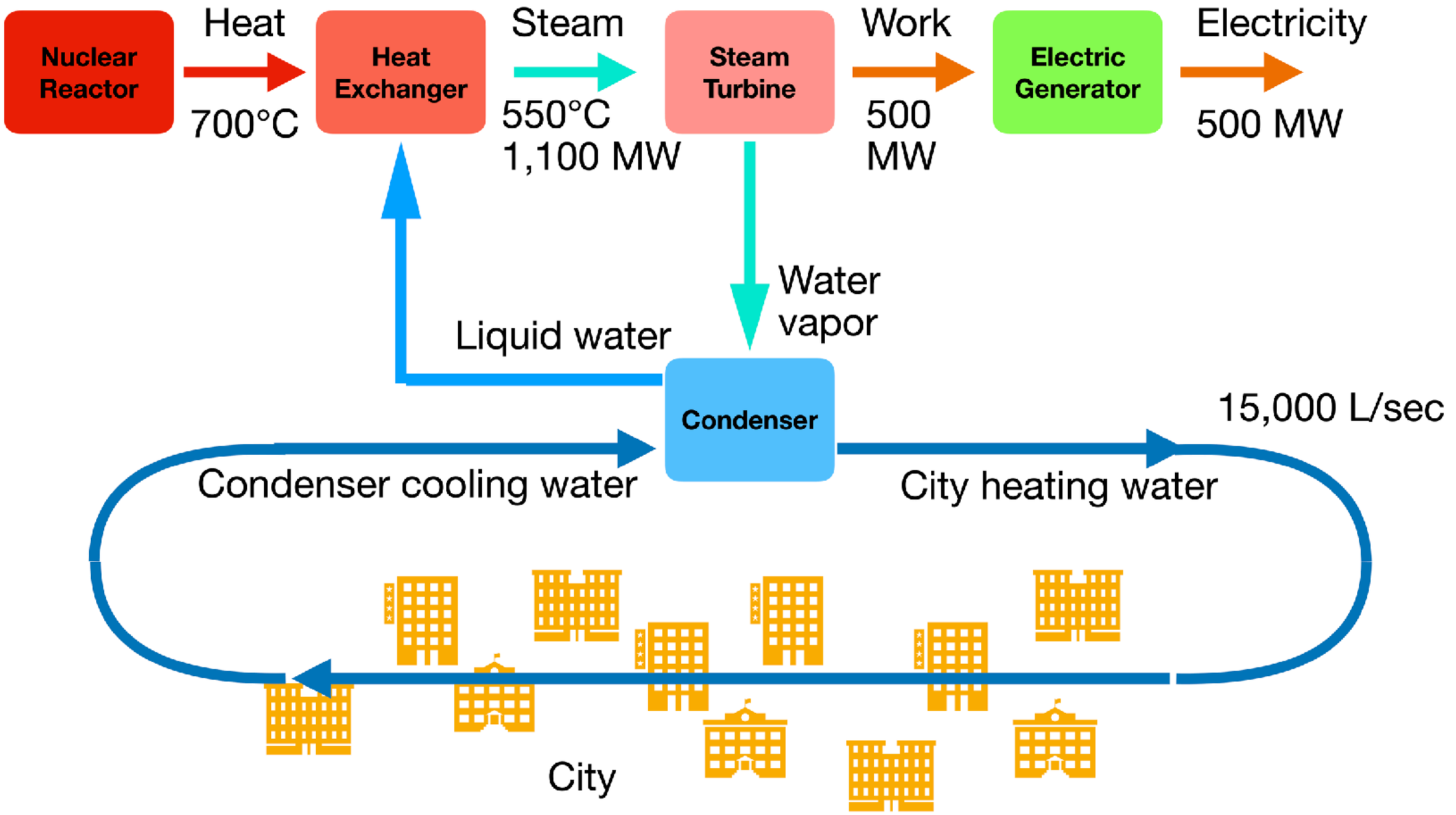
Powering Up Our World

Building heating with electric power or thermal power.

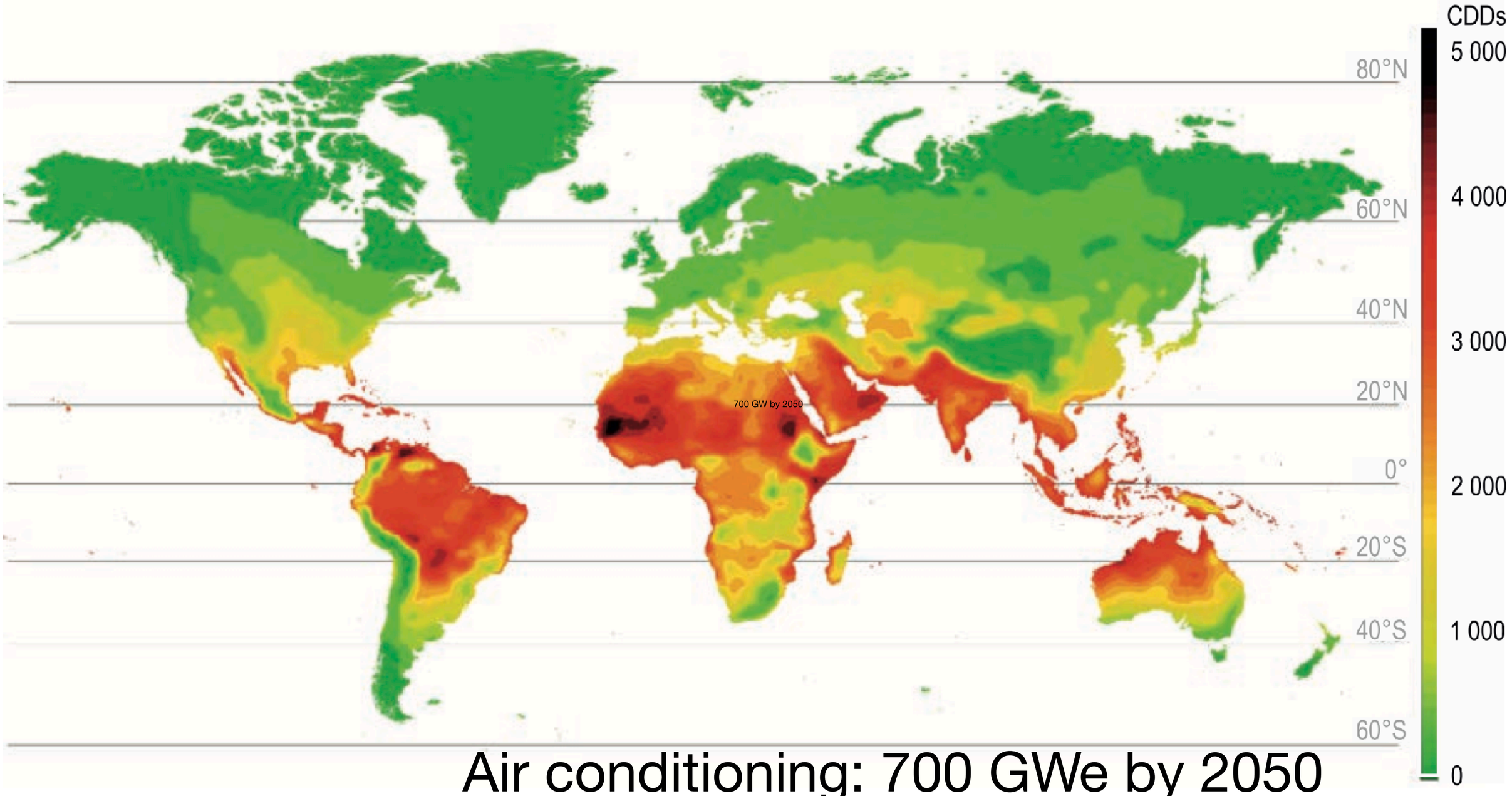




District heating from rejected heat of steam condenser.



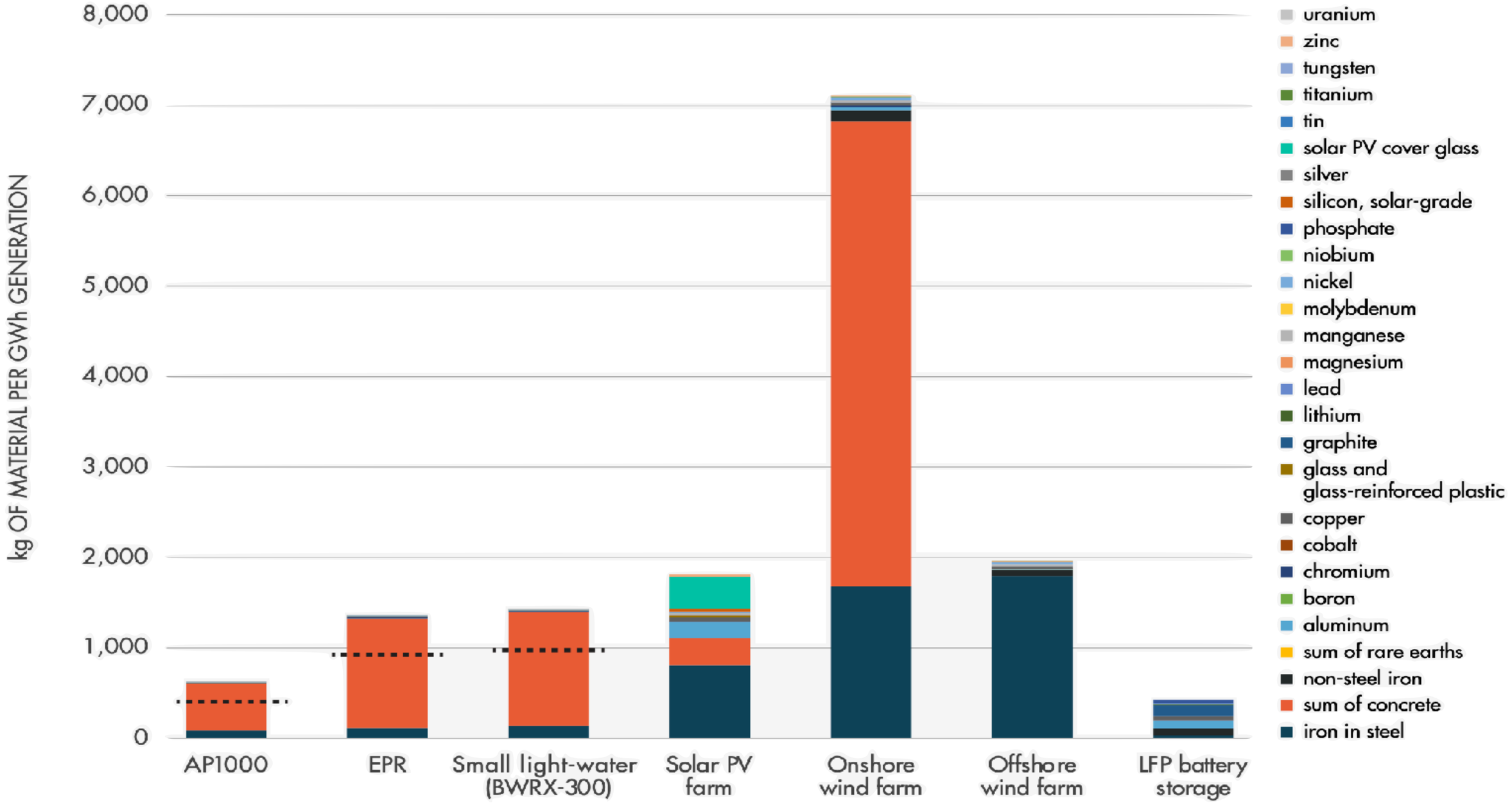
Developing nations have more cooling degree-days



Air conditioning: 700 GWe by 2050

The End Session 2

Materials used per GWh generated, by energy source (2024)



https://thebreakthrough.org/issues/energy/updated-mining-footprints-and-raw-material-needs-for-clean-energy