Our Burning Economy, Siren Song, and Fission Promise

Wind, Solar, Storage, Money, Scope

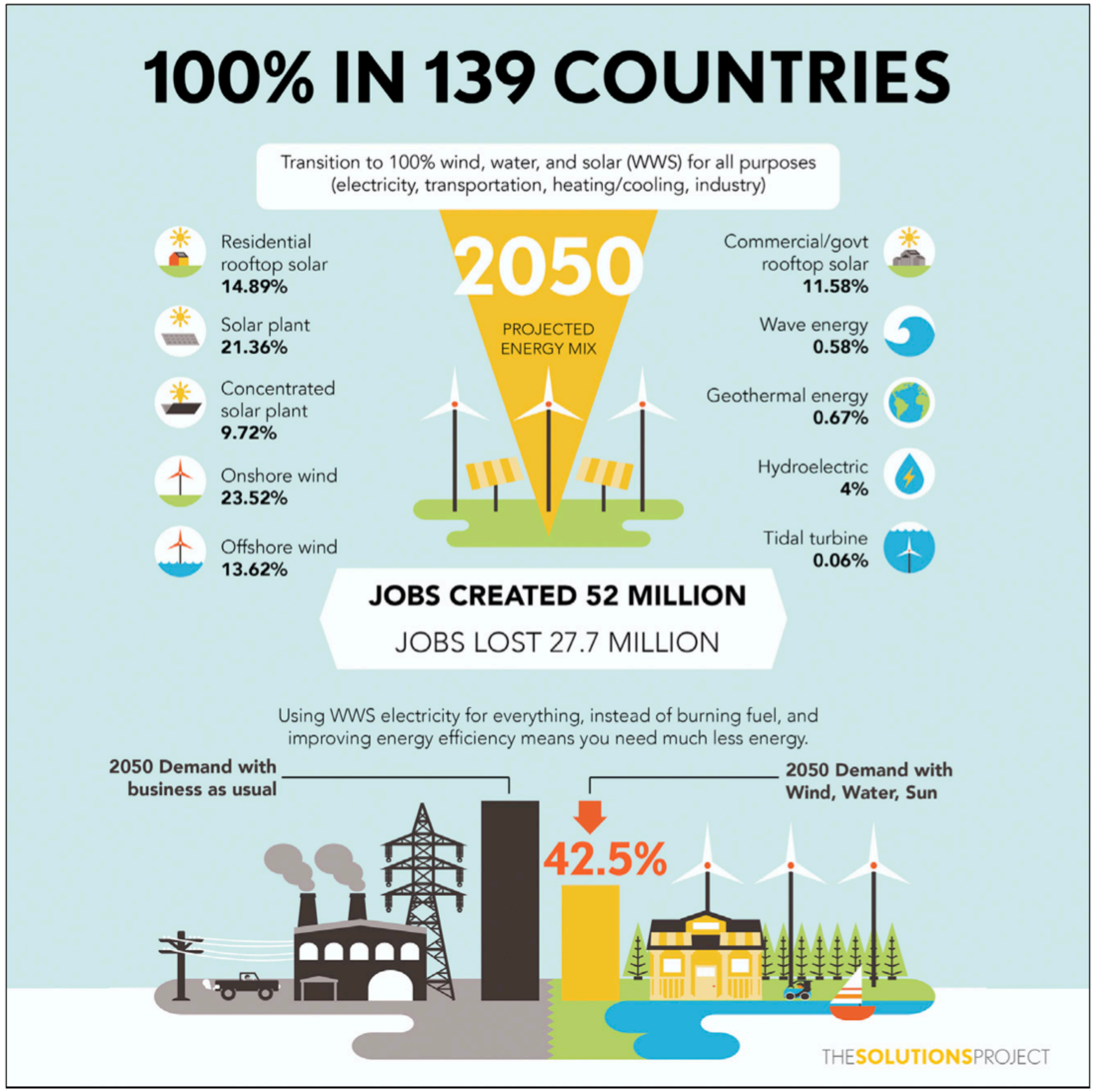
Osher @ Dartmouth

Robert Hargraves

Jan 11, 2023

Each new 1-GW coal plant emits 8 Mt CO2/year.
574 GW of new coal plants' emissions = 5 Gt/year.

Mark Z. Jacobson 2012 WWS (water/wind/solar) article



- **16,519 GW(t)** combustion power replaced by WWS sources.
- Everything is electrified, including transportation, industry.
- 2050 electricity demand grows to **11,800 GW(e)**.

https://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf

Mark Z Jacobson strategy is a 100% water/wind/solar zero-CO_2 solution.

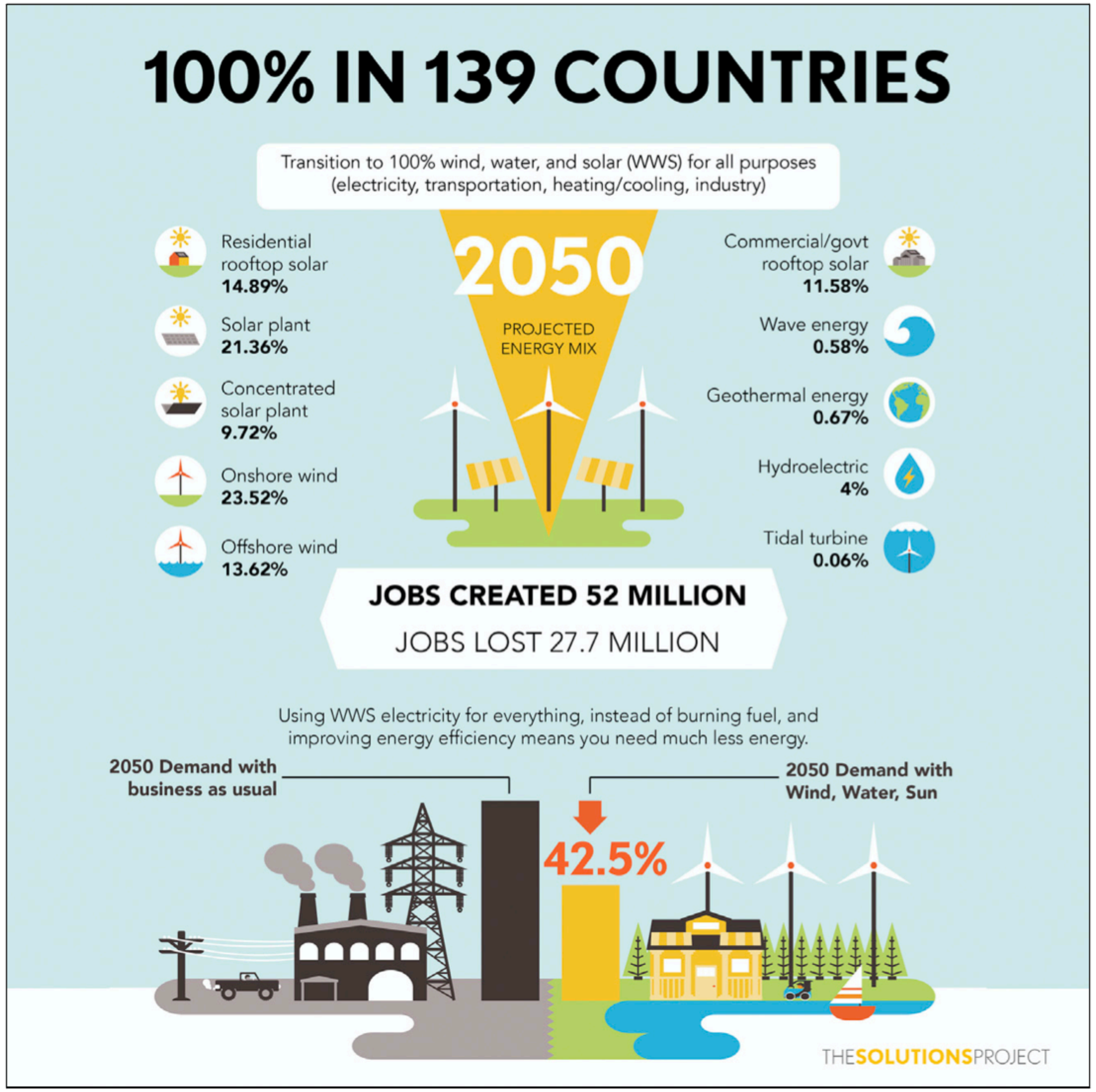
Inspired Green New Deal.

Refuted, discredited.

Jacobson sued refuting authors.

https://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf

100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World



Mark Z. Jacobson, Mark A. Delucchi, Zack A.F. Bauer, ..., Jingfan Wang, Eric Weiner, Alexander S. Yachanin

jacobson@stanford.edu

HIGHLIGHTS

Roadmaps for 139 countries to use 100% wind-water-solar in all energy sectors

Roadmaps avoid 1.5°C global warming and millions of annual air-pollution deaths

Roadmaps reduce social cost of energy and create 24.3 million net long-term jobs

Roadmaps reduce power disruption and increase worldwide access to energy

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

<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

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

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

5. Non-CO_2 Emissions

Methane, N_2O, Fluorocarbons

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

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

6. Enhanced land sinks

Forest management

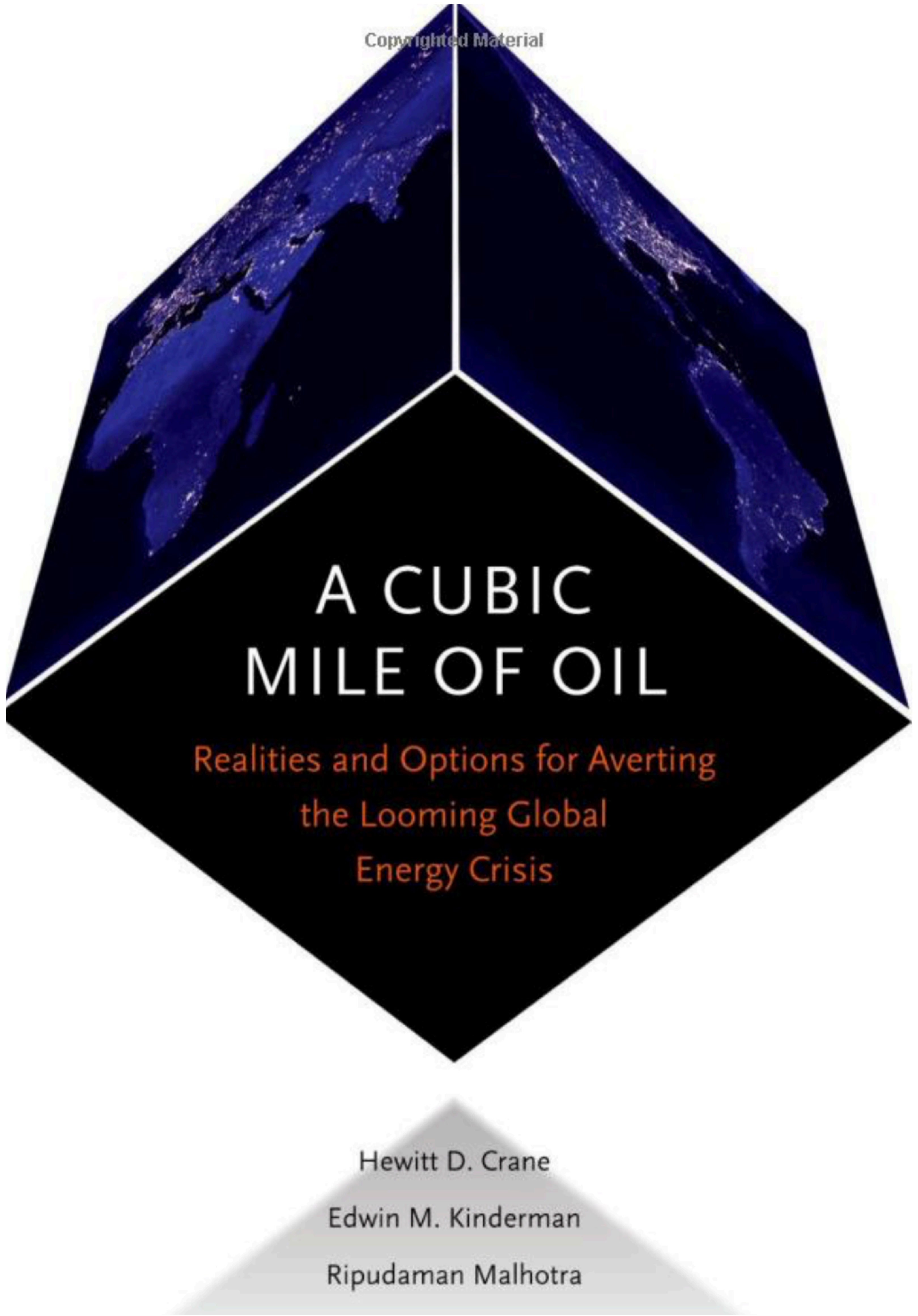
- Potential sink of 0.5 to 1 $GtCO_{2e}/y$, impacting ½ or more of all US forest area (≥ 130 Mha).

Agricultural practices

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

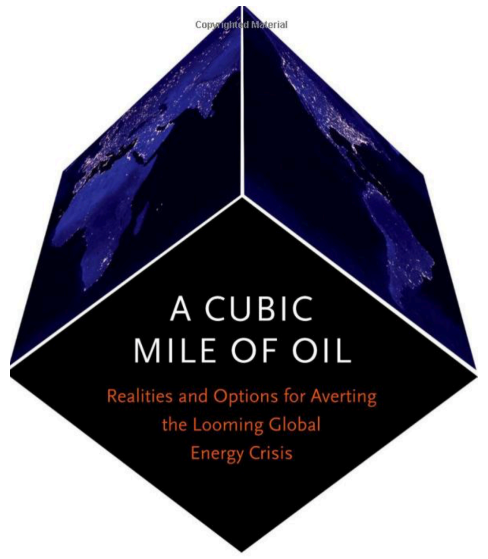
https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Global energy equivalent: 4 cubic miles of oil

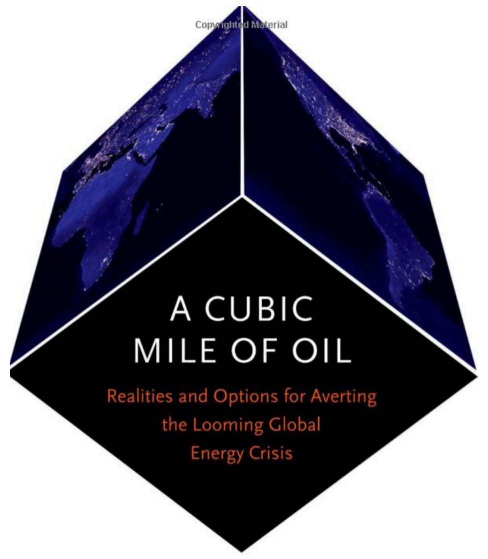


Ripu Malhotra et al, SRI

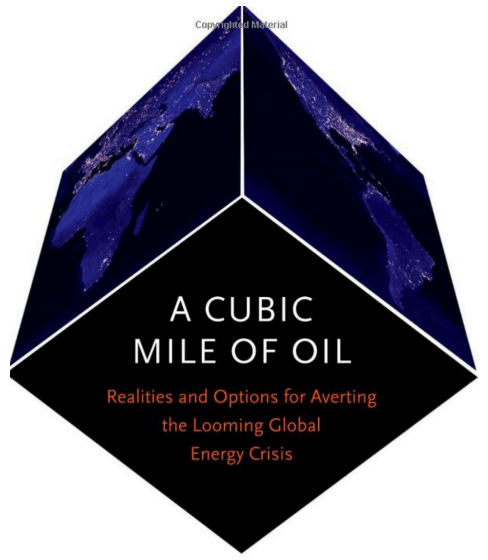
We might supply all the world's energy with ALL of these.



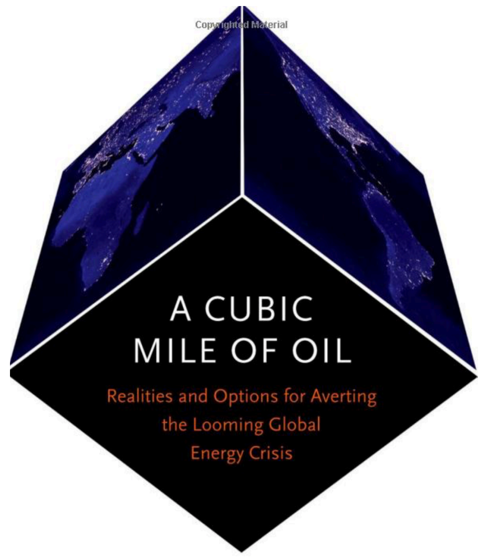
- **Solar Roofs (PV): 4.2 billion**
  - 250,000 roofs per day for 50 years
  - 2.1 kW with 20% availability



- **Solar CSP: 7,700 solar parks**
  - 3 per week for 50 years
  - 900 MW with 25% availability

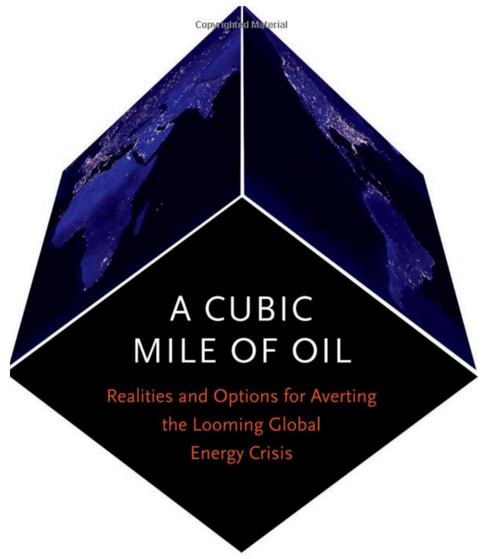


- **Hydro: 200 dams**
  - 1 every quarter for 50 years
  - 18 GW with 50% availability



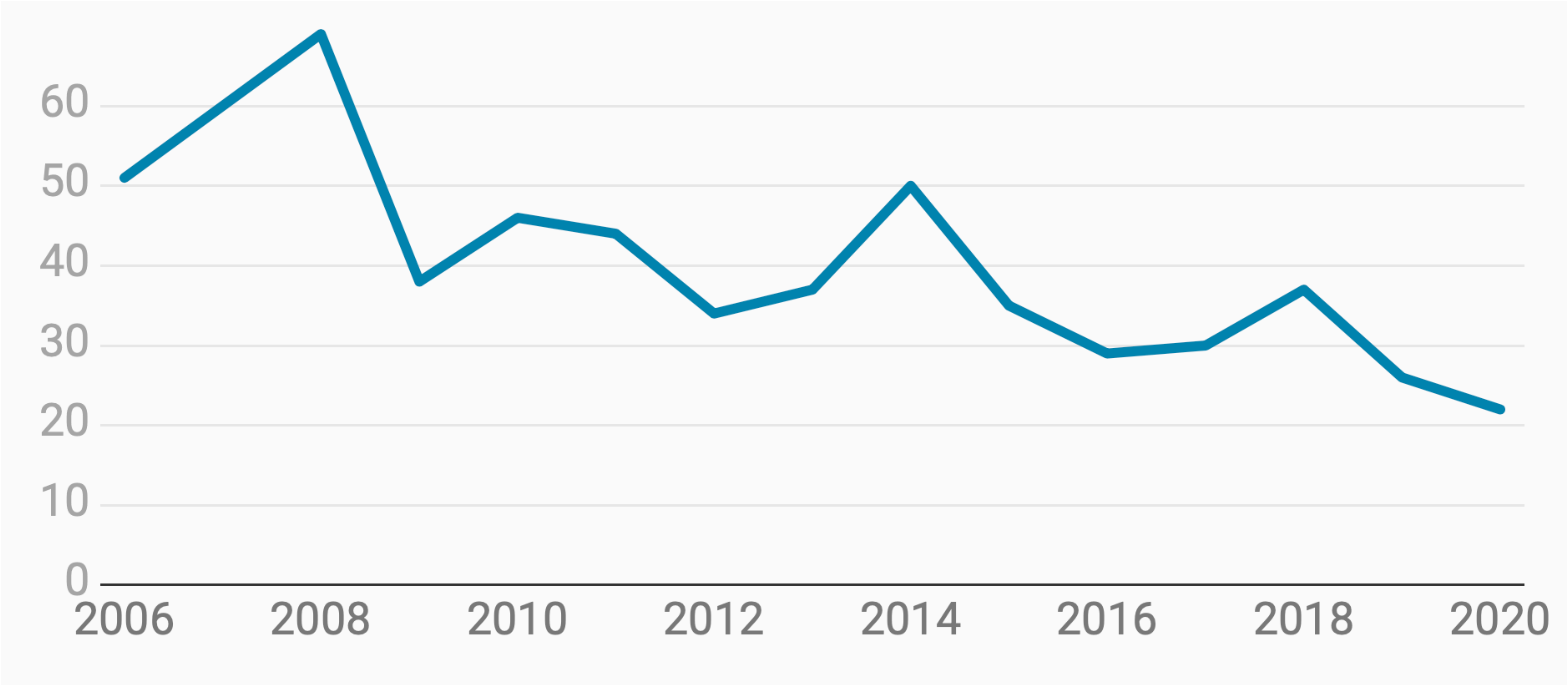
- **Windmills: 3 million**
  - 1200 per week for 50 years
  - 1.65 MW with 35% availability

Energy equivalent of 1 cubic mile of oil



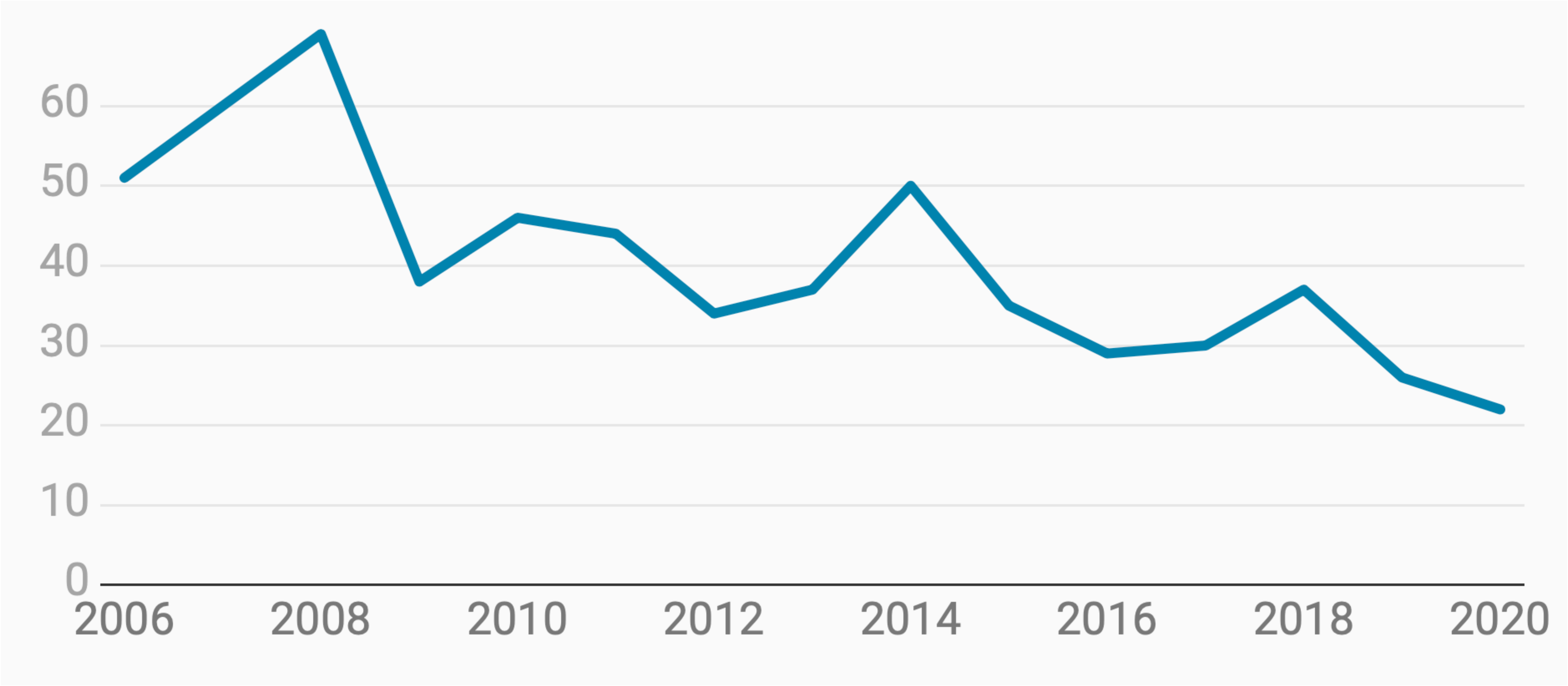
- Nuclear: **2,500 plants**[2]
  - 1 per week for 50 years
  - 900 MW with 90% availability

Low natural gas costs dropped electricity prices to ~ 2.5 cents/kWh in some US regions.



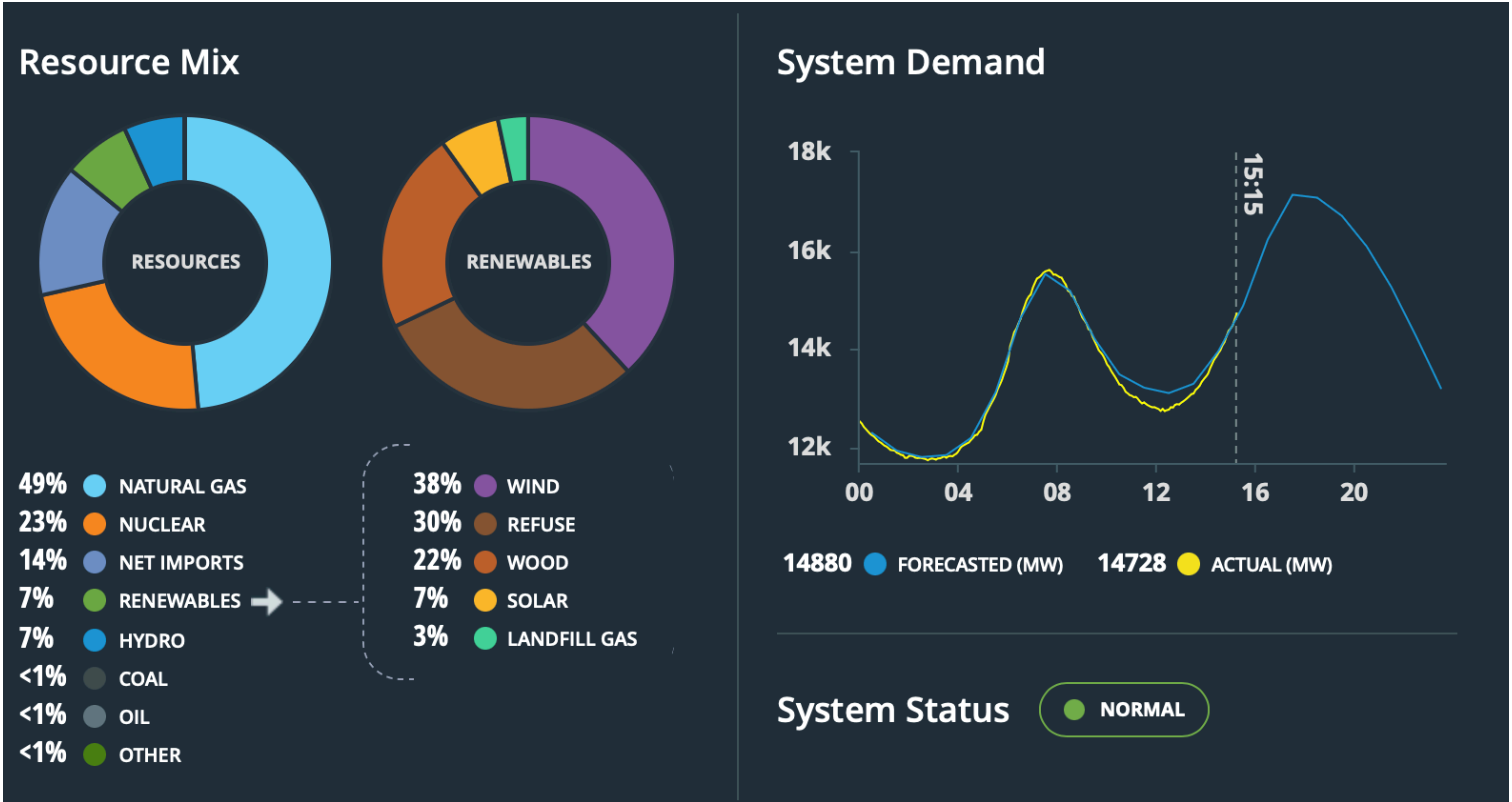
https://www.forbes.com/sites/scottcarpenter/2020/09/30/when-nuclear-plants-ask-for-money-states-find-they-cant-afford-to-say-no/#4d15dc4c4b9b

Low electricity prices made coal, nuclear less competitive.



https://www.forbes.com/sites/scottcarpenter/2020/09/30/when-nuclear-plants-ask-for-money-states-find-they-cant-afford-to-say-no/#4d15dc4c4b9b

New England electricity, 17 GW, 12/20/22 iso-ne.com



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

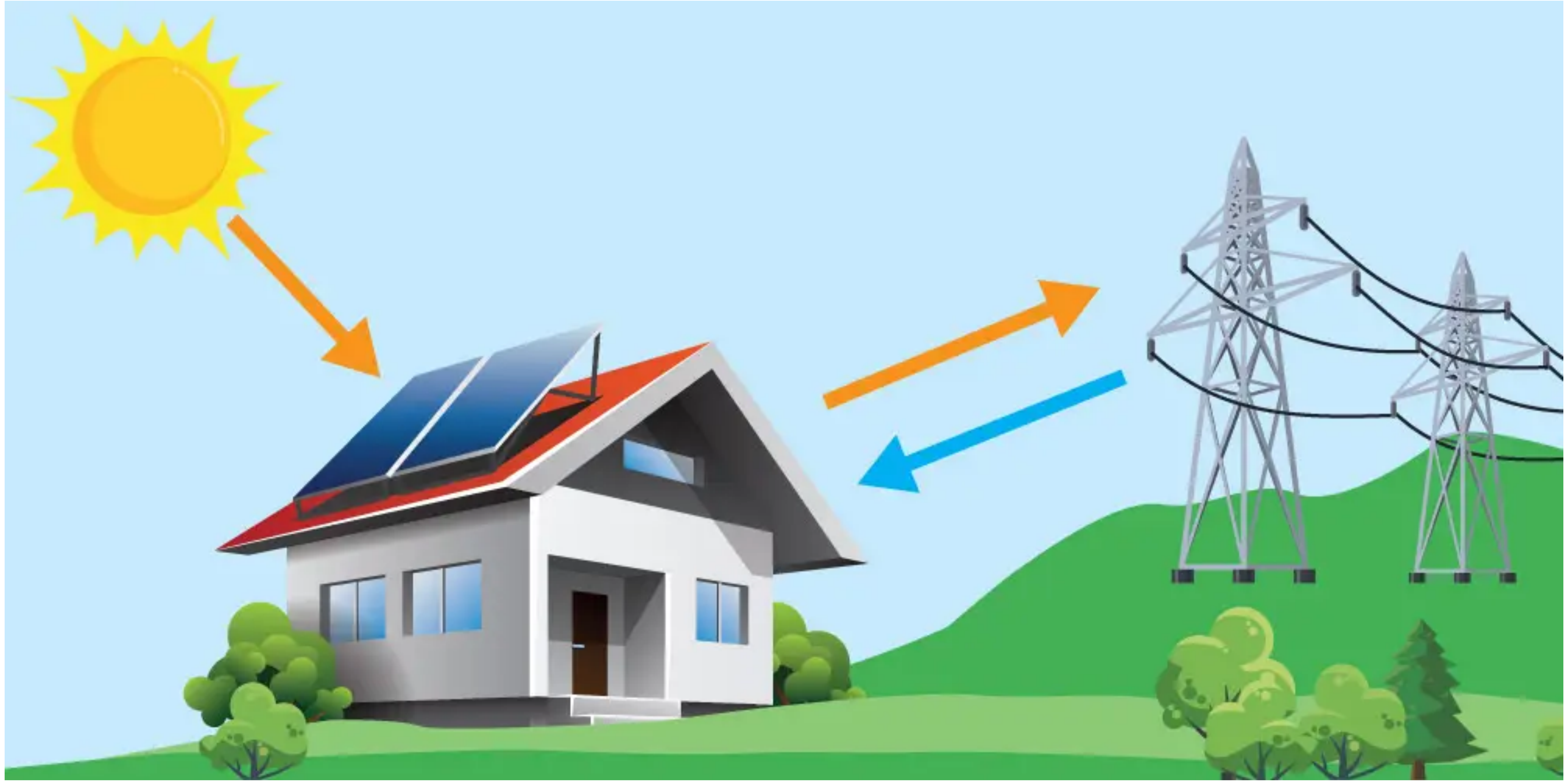
https://www.ysgsolar.com/blog/15-largest-solar-farms-world-2021-ysg-solar

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.



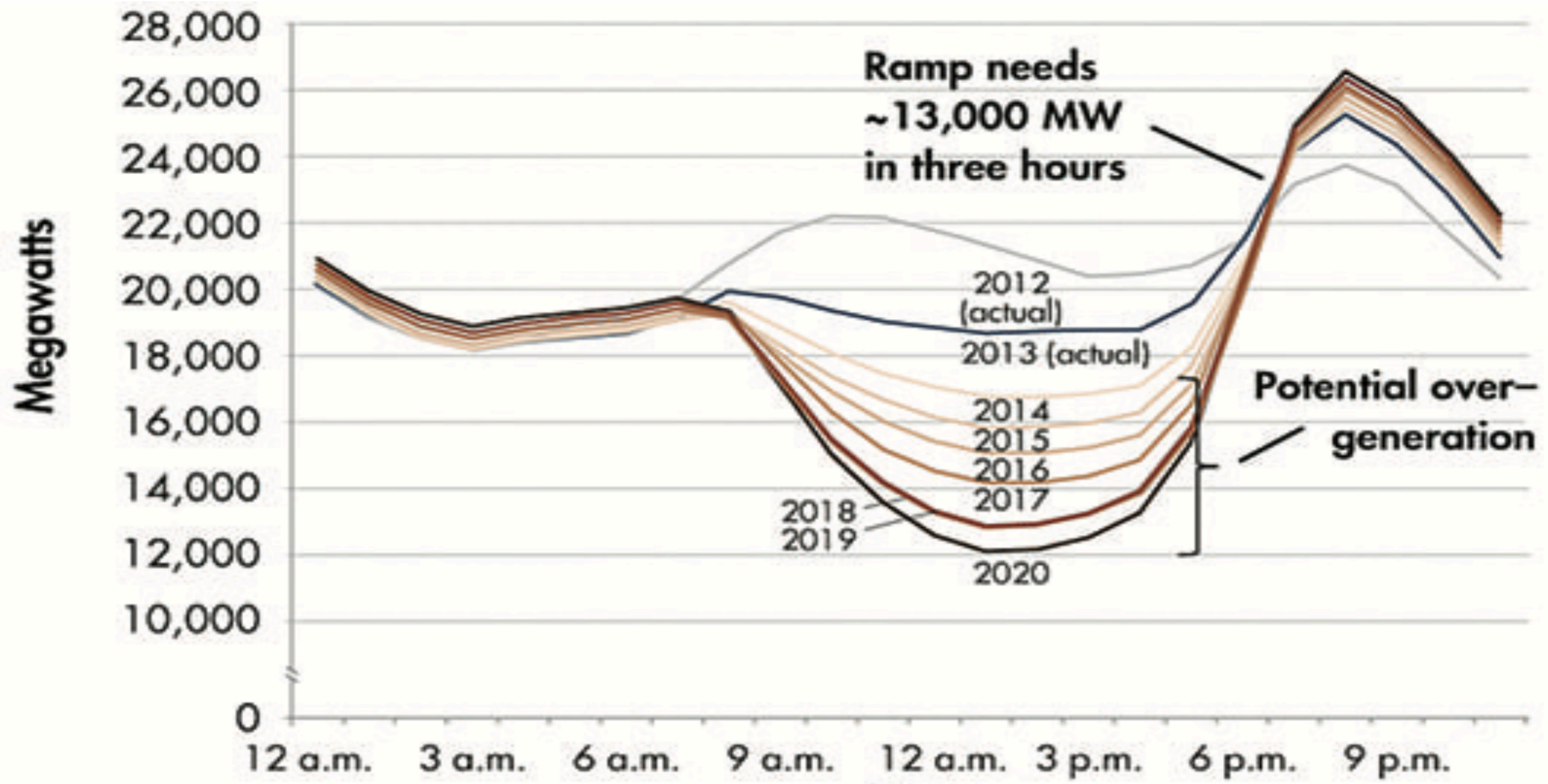
https://www.solarreviews.com/blog/california-net-metering-nem-2

Increases total power costs; paid by other customers.

The most expensive "renewable" energy.

Community solar brings benefits to homes in shade.

California's “duck curve”, created by by unmanaged, subsidized solar, causes mid-day shutdown of power plants.



https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

Wind power needs 400X the land of fission plants.

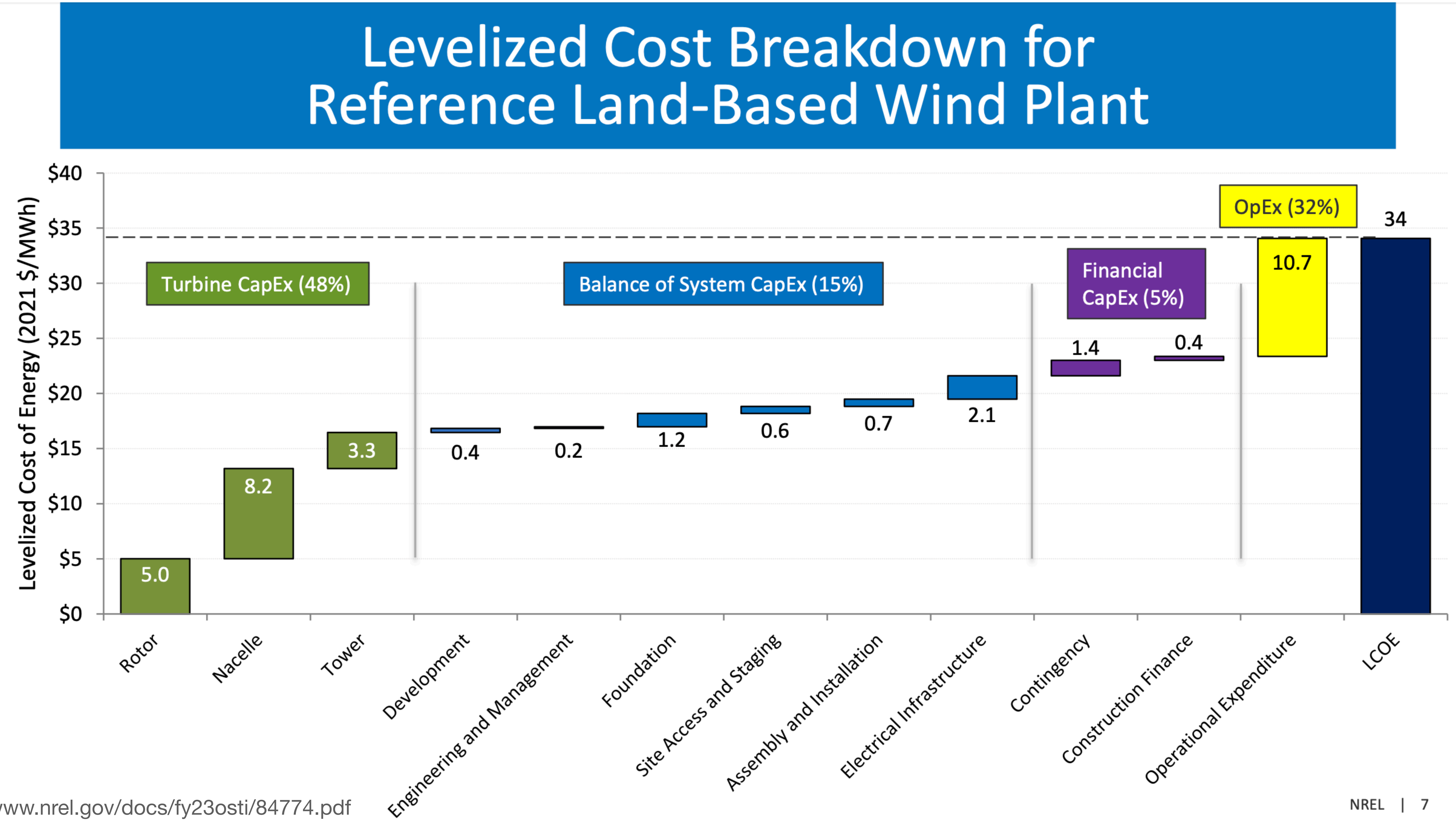
ENVIRONMENTAL PROGRESS

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.

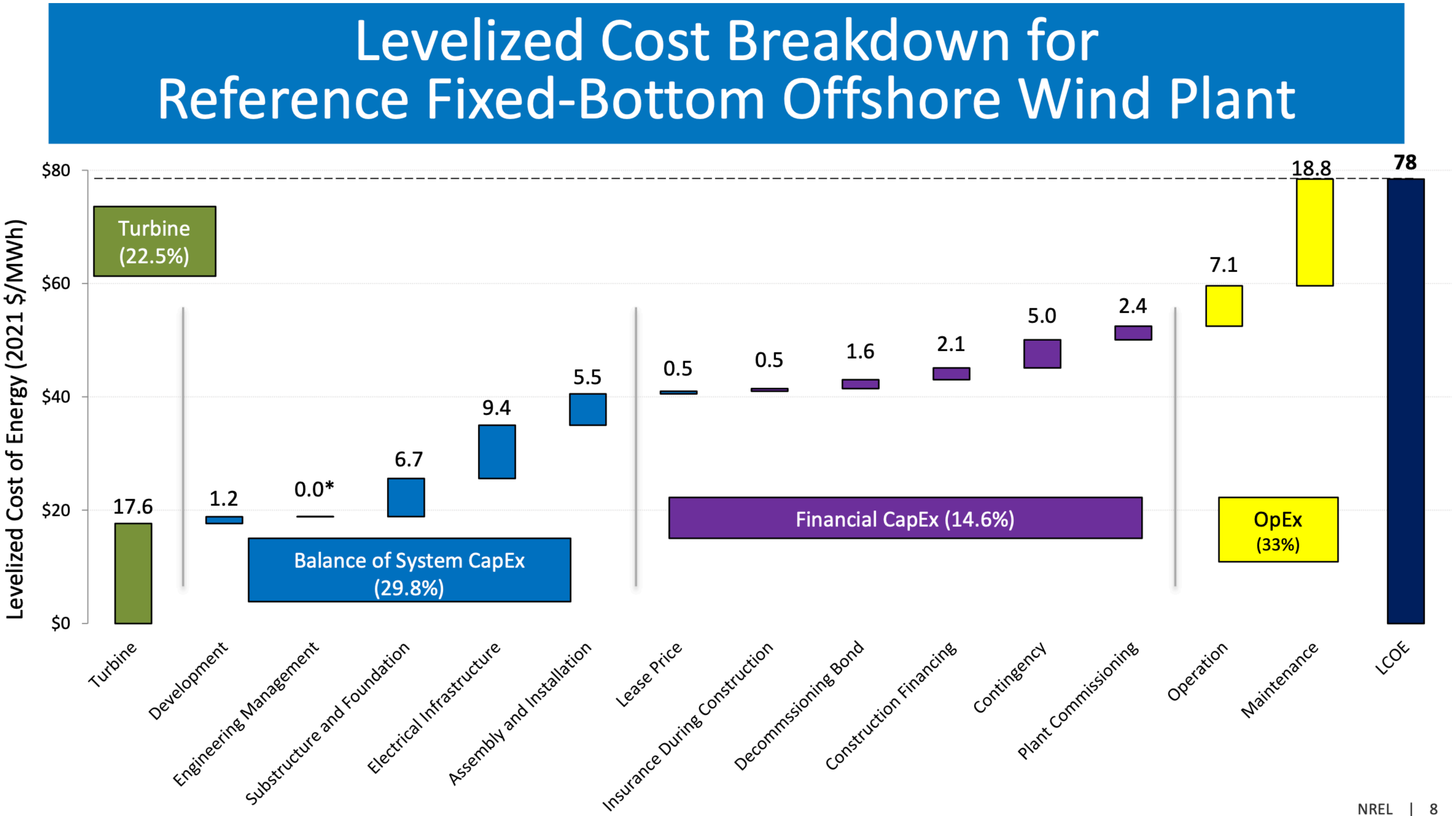
https://environmentalprogress.org/the-complete-case-for-nuclear

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



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

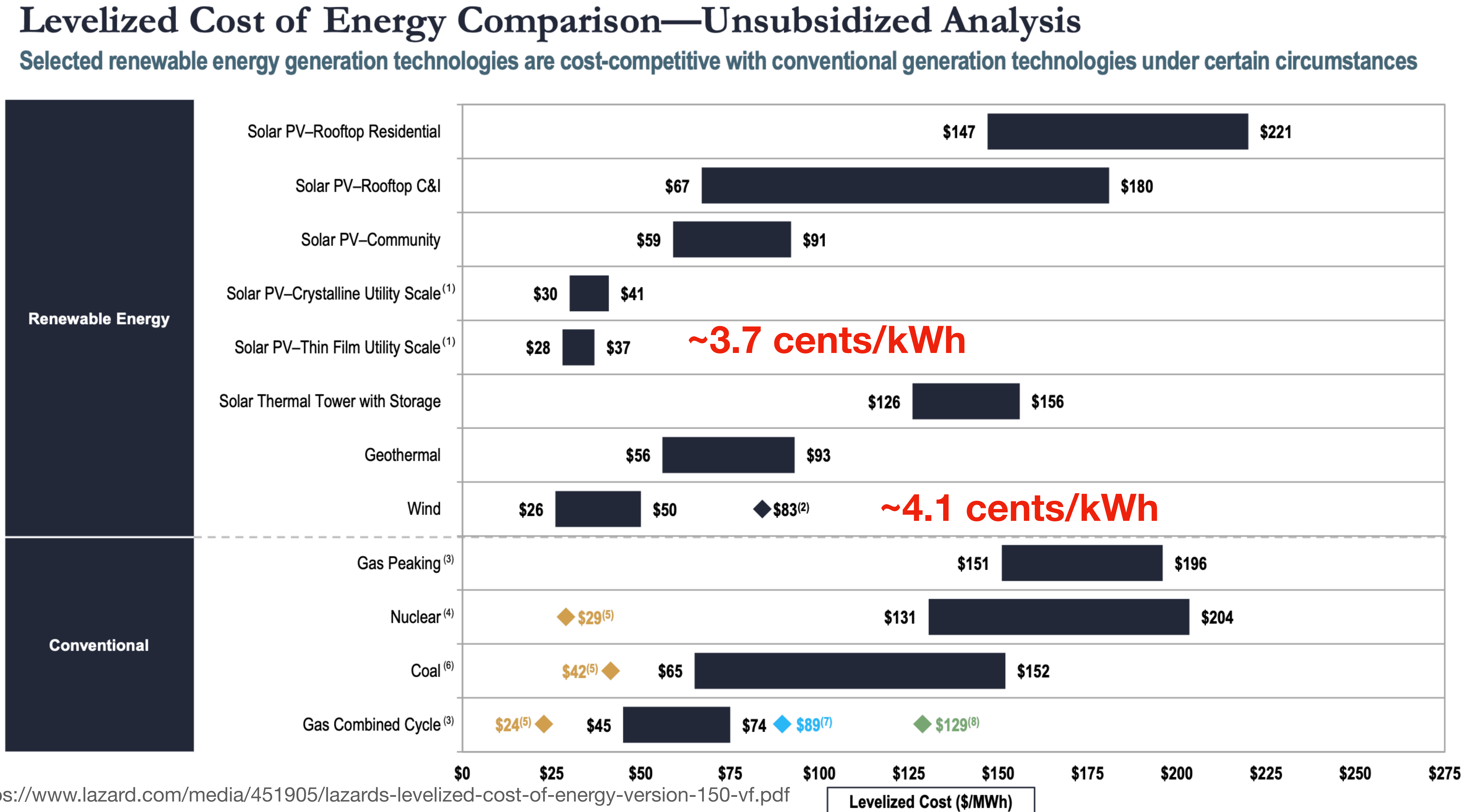
US NREL 2022: Offshore wind costs $78/MWh



* Engineering Management cost small, but nonzero

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

Lazard 2021: levelized cost of electric energy



https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf

LCOE conceptual problem

Electric **ENERGY** is not a **PRODUCT** you can easily buy and store, like gasoline at $3.69/gallon.

Electric **POWER** is a **SERVICE**, delivered and consumed on demand.

Wind/solar power service is not **AVAILABLE** during lulls/darkness.

Wind/solar power is generally not **DISPATCHABLE**, varying generation to meet changing load demand.

LFSCOE: Levelized full system cost of energy

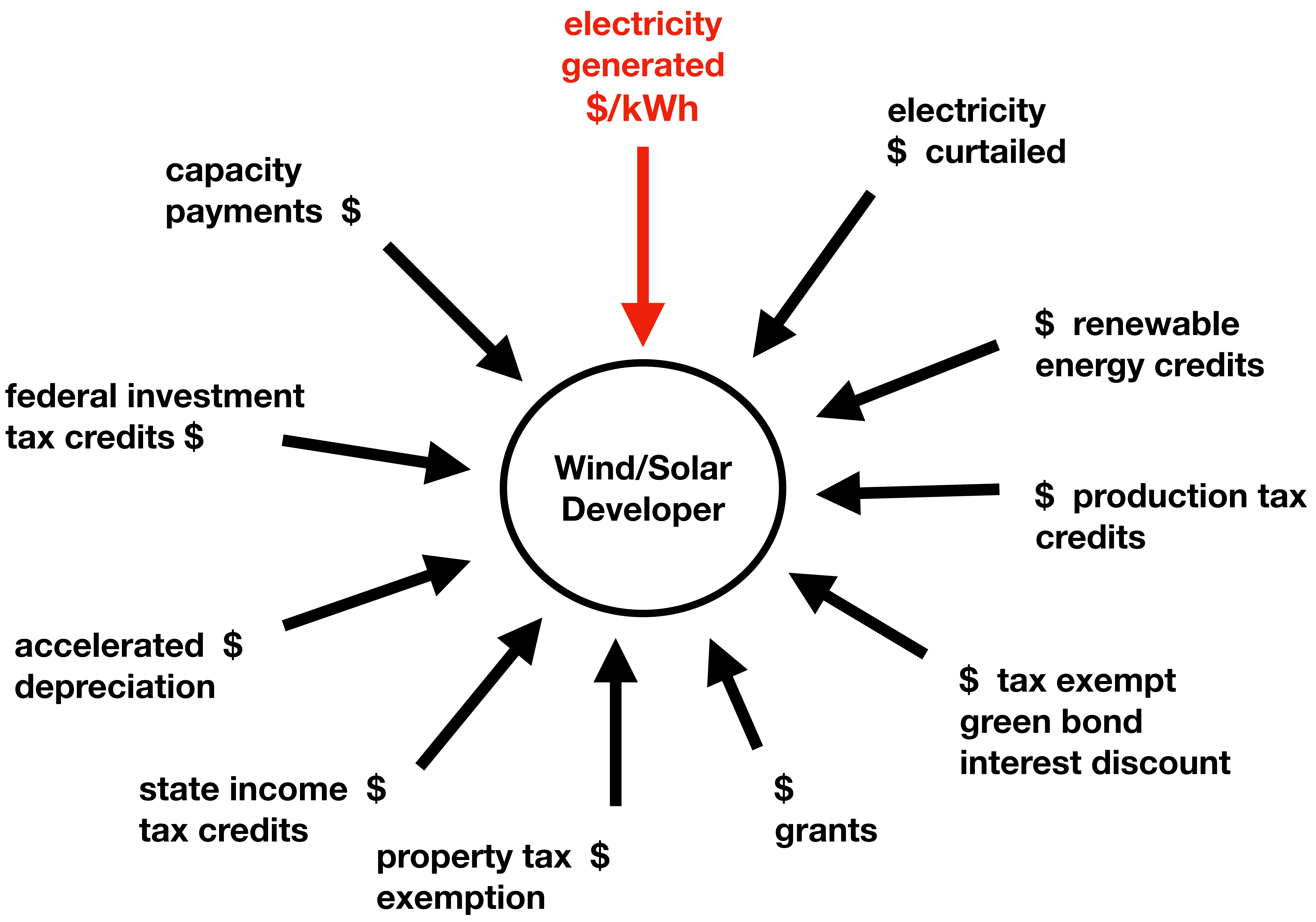
can be orders of magnitude higher than Lazard estimates.

Comparison of LCOE and LFSCOE.

Technology	LCOE	LFSCOE	
		Germany	Texas
	[USD/MWh]	[USD/MWh]	[USD/MWh]
Biomass	95	103	117
Coal (USC)	76	78	90
Natural Gas CC	38	35	40
Natural Gas CT	67	39	42
Nuclear	82	105	122
Solar PV	36	1380	413
Wind	40	483	291

https://reader.elsevier.com/reader/sd/pii/S0360544222018035?token=928A93FC41166DEFB274B0FF8D7F756436105CFF3E1D8A9F8B37F5A8A990A8C795FC8139154682383C881587C2531BA5&originRegion=us-east-1&originCreation=20230107194247

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



<u>Wind/Solar preferences</u>

Feed-in tariffs

Renewable portfolio standards

Bird kill examptions

Local zoning overrides

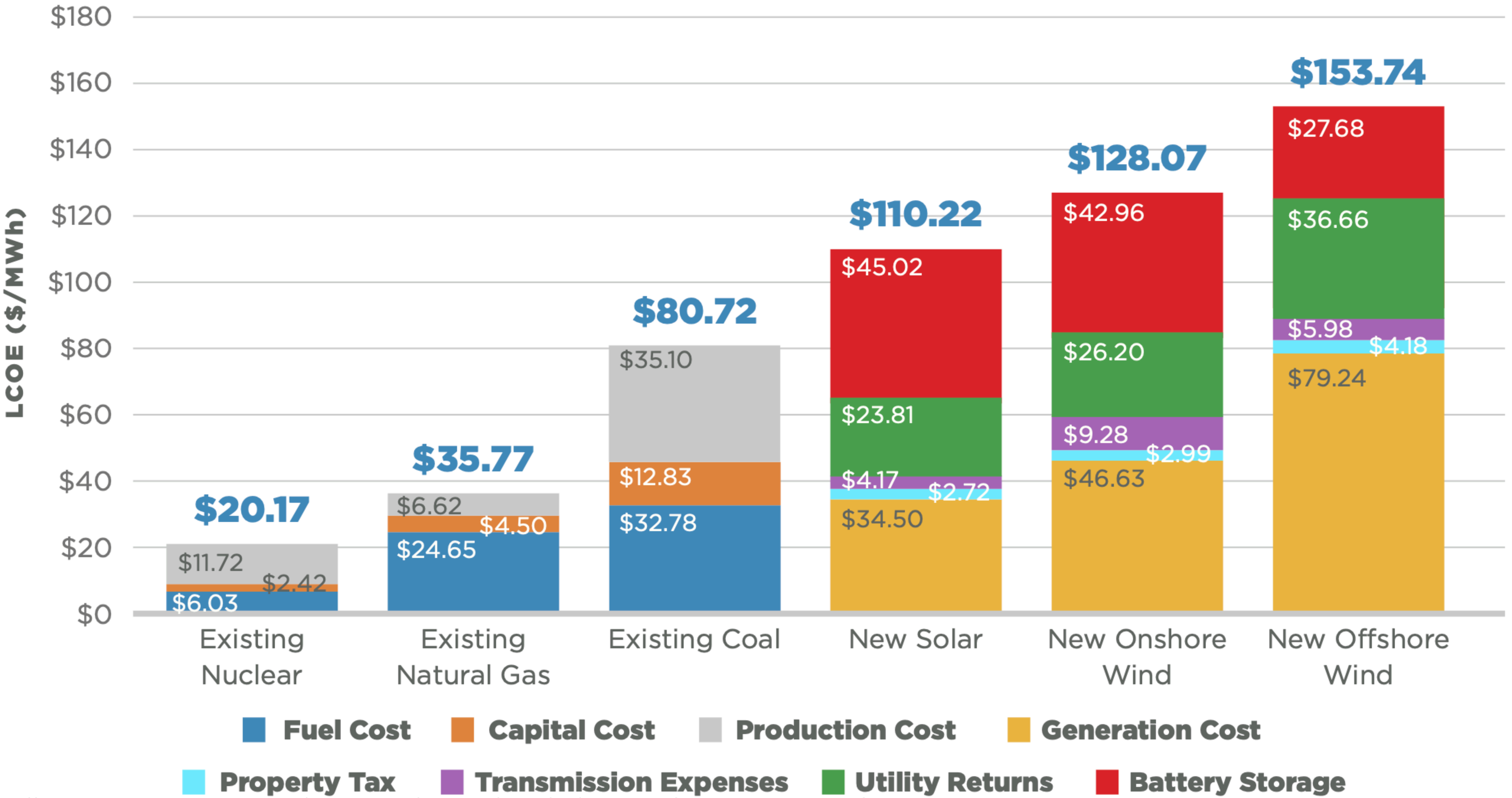
15-50% credit in auctions for firm power capacity

No toxic recycling penalty

Massachusetts utilities pay solar panel generators $345/MWh (34.5¢/kWh) for solar energy RECs (renewable energy credits).

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

American Experiment analysis of Virginia electricity costs



https://files.americanexperiment.org/wp-content/uploads/2022/02/The-Hgh-Cost-of-the-Virginia-Clean-Economy-Act.pdf

Wind/solar power costs kept secret from public.

SECTION 83C

Request for Proposal Application Form

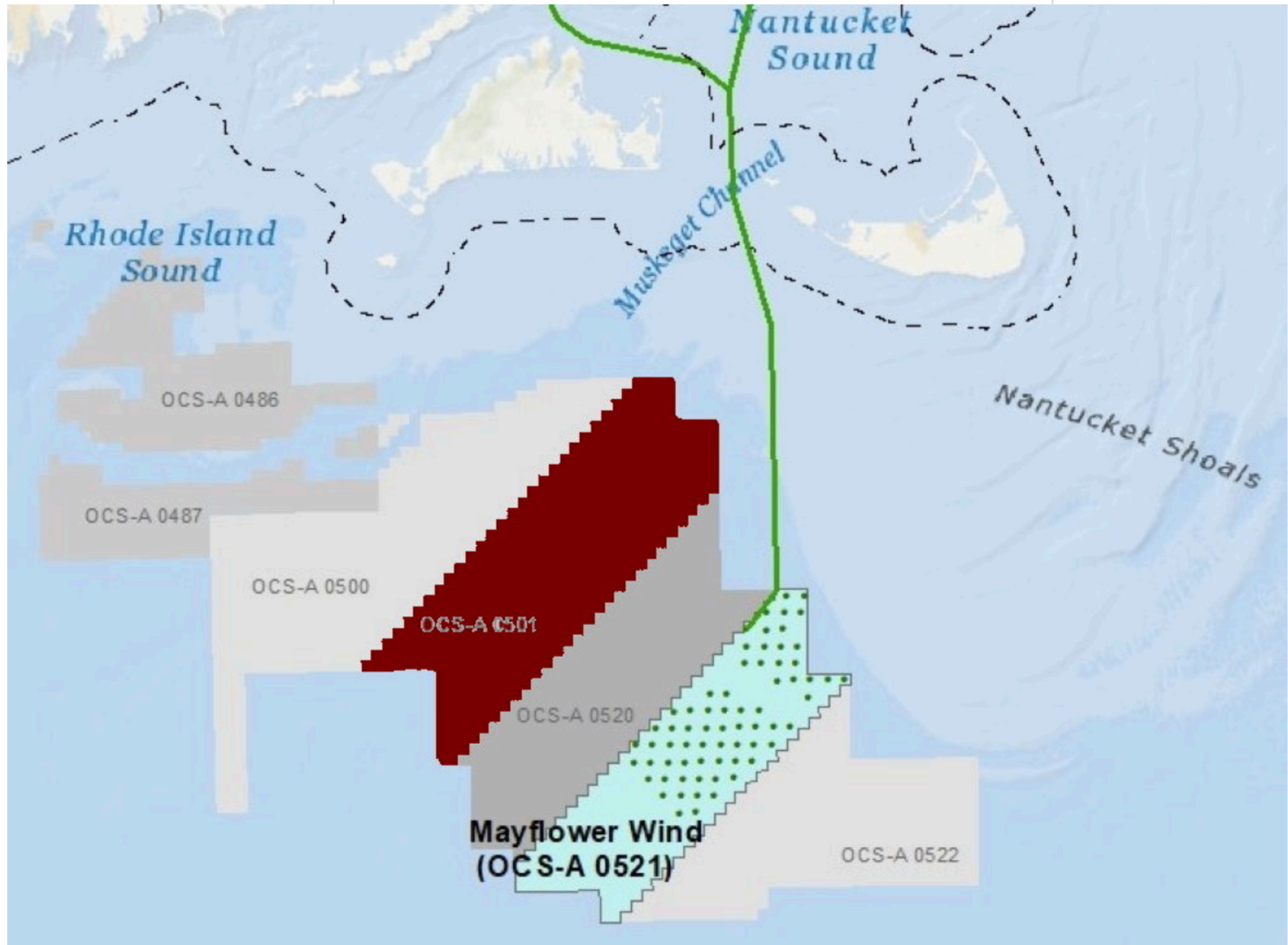
Proposal Mayflower Wind Project 2 (804 MW Low Cost Energy)

- 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] [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

High capital costs cause high electricity costs.

Rhode Island and Massachusetts state officials picked Deepwater Wind to build a $1.5-billion, 385-megawatt wind farm in federal waters off Block Island.

$1500/385W = **$3.90 per watt** (of capital cost)

Deepwater signed an agreement with National Grid to sell the power from a $200-million, 30-MW wind farm off Block Island, at an initial price of **24.4 ¢/kWh**

$200/30 = **$6.67 per watt.**

Completion update: **$13/watt**

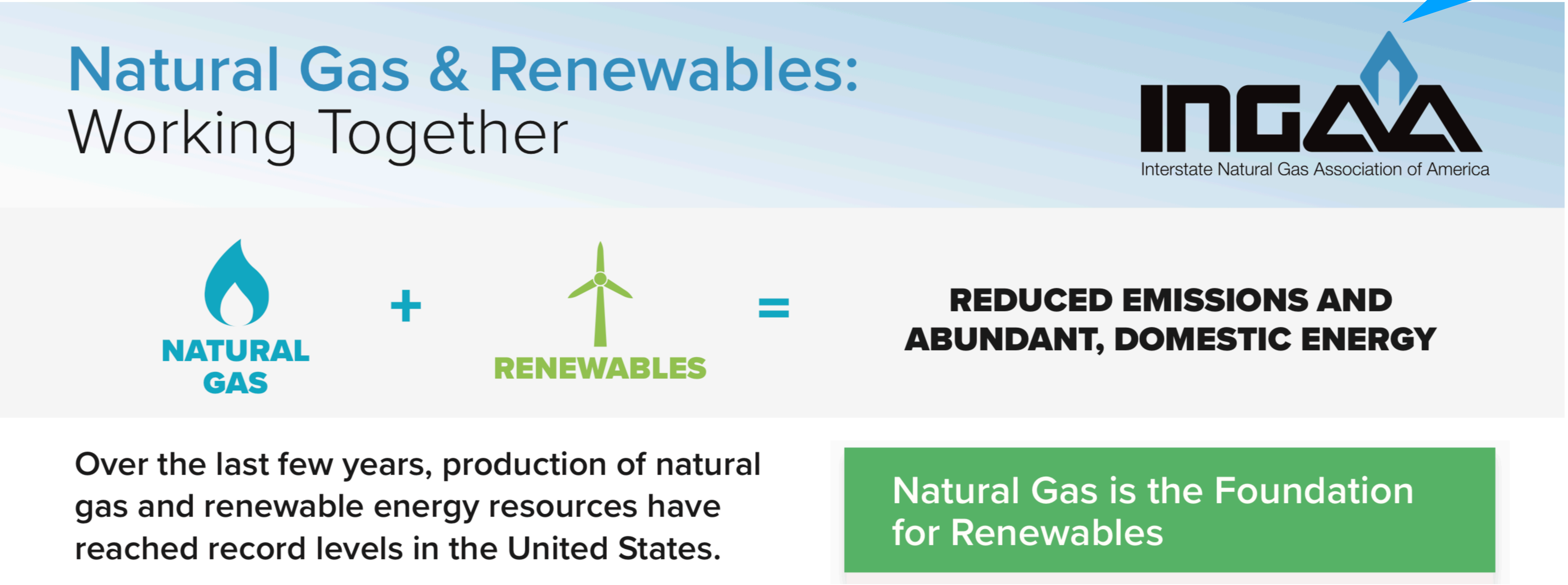
https://en.wikipedia.org/wiki/Wind_power_in_the_United_States

US wind turbine average capacity factor ~ 1/3.

https://www.nature.com/articles/s41598-020-59936-x

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

Ad



Each 1 GW of wind or solar is matched by 1 GW of natural gas generation ~ 2/3 of the time.

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

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 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.

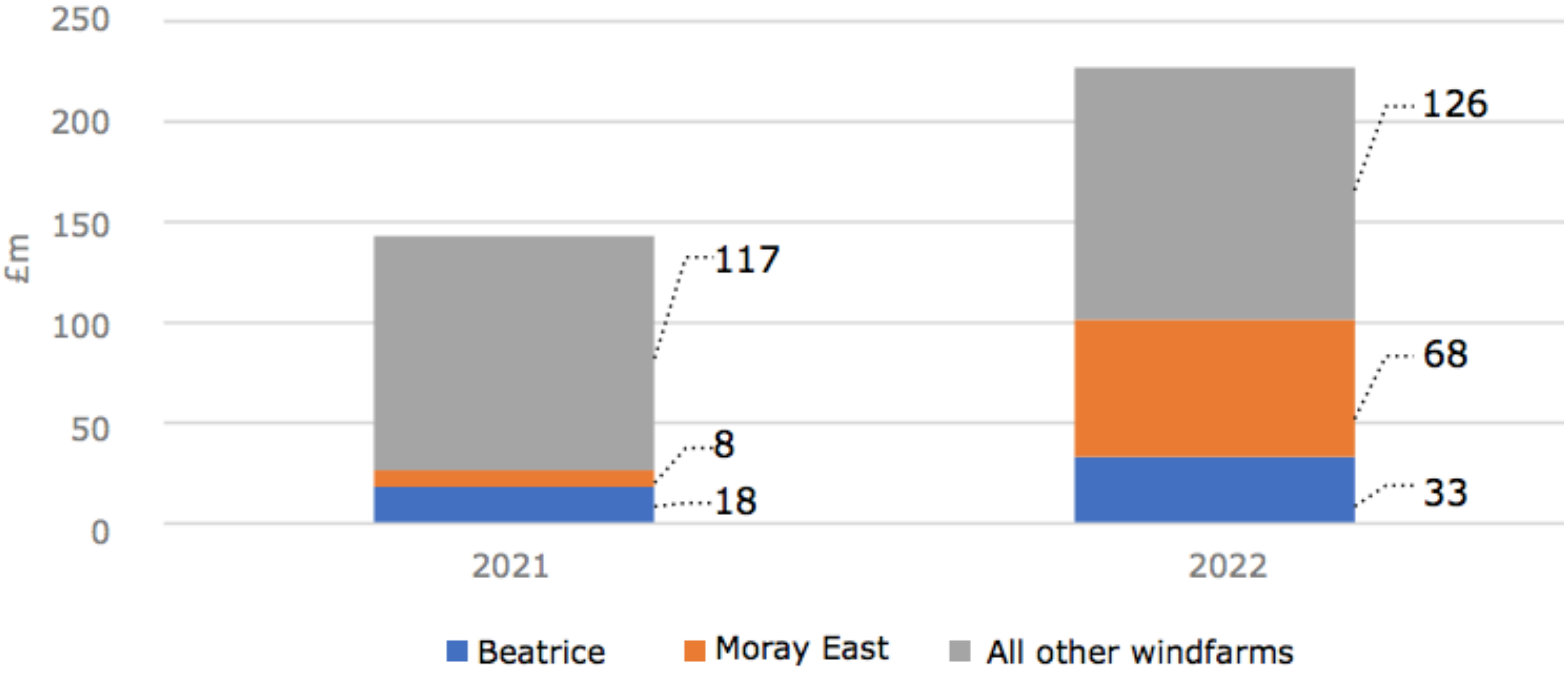
Developers withdrawing? got 30% ITC!

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

Levelized Costs for Offshore Wind PPAs Selling ORECs
Levelized 2019$/OREC
Power Purchase Agreements
Offshore Renewable Energy Credits
$200
$180
$160
$140
$120
$100
$80
$60
$40
$20
$0
$76.07
$55.52
$83.01
$71.96
$155.24
$179.27
$98.36
$76.54
$85.54
$138.68
$75.25
Revolution Wind - CT
Mayflower Wind
Vineyard Wind 1
Vineyard Wind 2
Skipjack Wind
US Wind
Ocean Wind
Sunrise Wind
Empire Wind
South Fork Wind
Revolution Wind - RI
Source: Author's calculations
https://www.manhattan-institute.org/dismal-economics-offshore-wind-energy

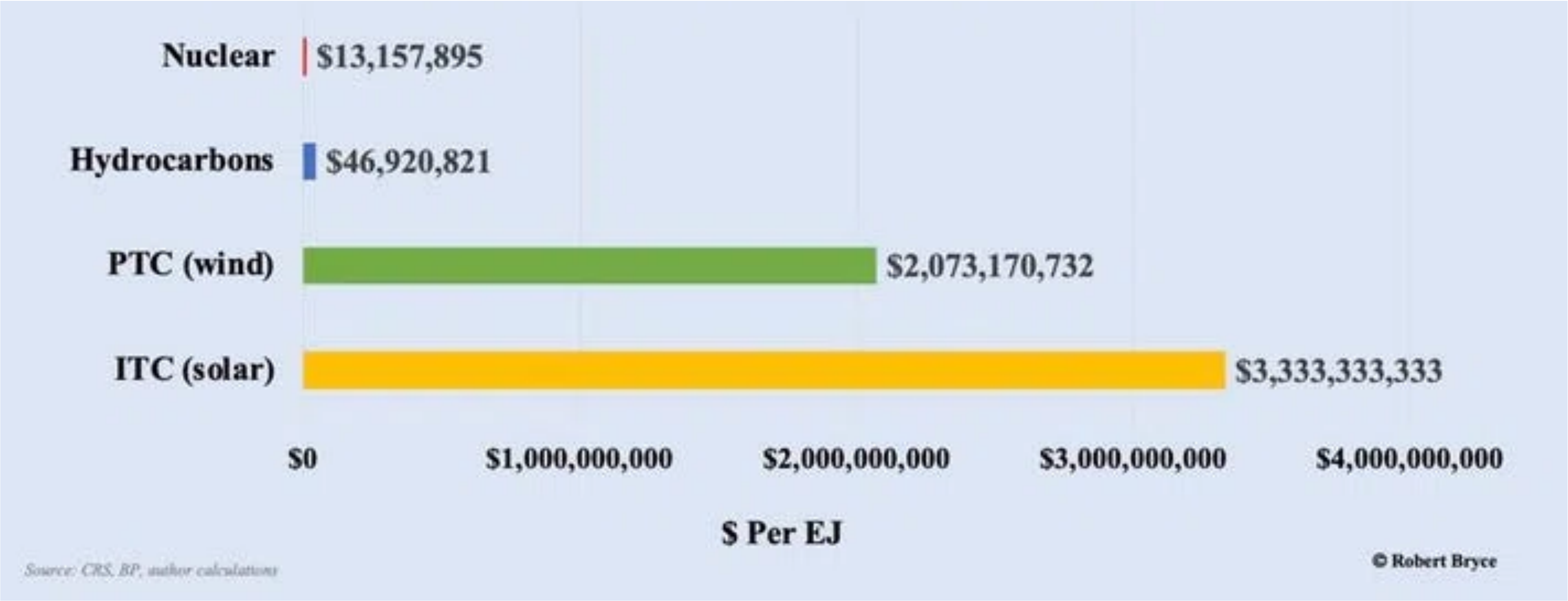
Offshore wind curtailment cost UK £227 million in 2022

because grid could not accept the power.



https://mailchi.mp/86e68627c77f/payments-for-windfarms-to-switch-off-soar-to-quarter-billion-pounds-193411?e=0c0eac7096

Robert Bryce: 2018 tax incentives per unit energy produced.



PTC = production tax credit, 2.5¢/kWh; ITC = investment tax credit

1 EJ = 1 exajoule ~ 32 GW-years

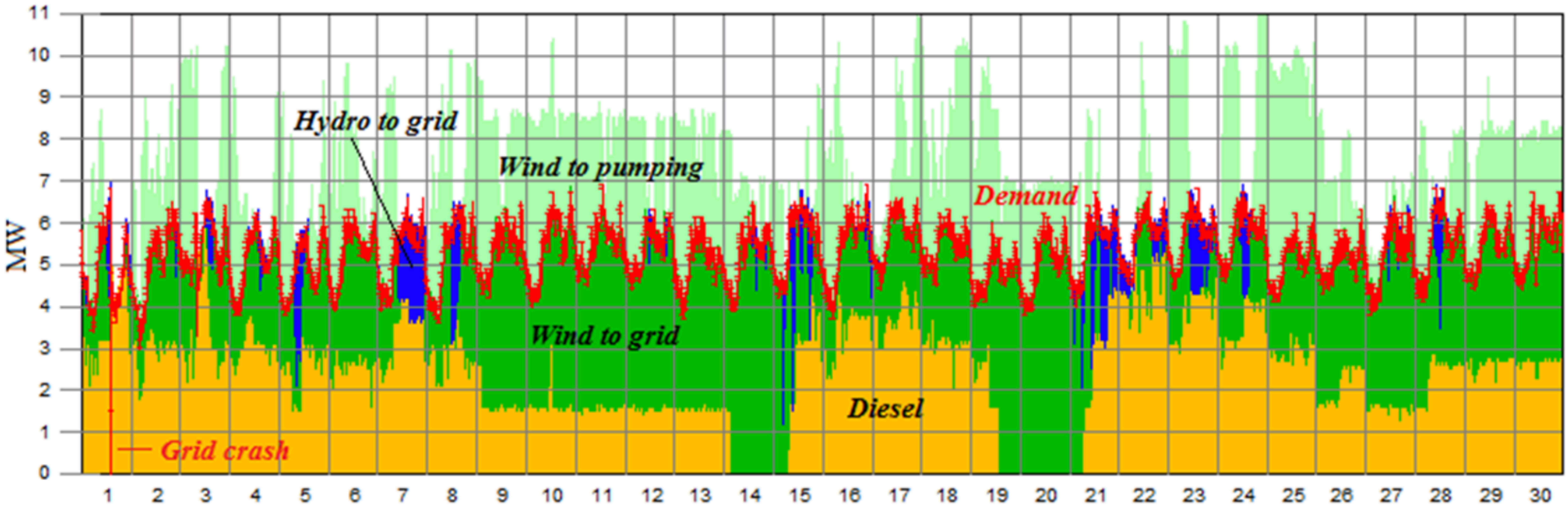
https://www.forbes.com/sites/robertbryce/2021/12/27/why-is-solar-energy-getting-250-times-more-in-federal-tax-credits-than-nuclear/?sh=42d0bc6721cf

https://www.energy.senate.gov/services/files/444FFC94-54BC-49BC-85B2-C694194F9232

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

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/

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**

100 Tesla 3100 kWh Megapack batteries cost $358/kWh.

Order Megapack

Megapack enables low-cost, high-density commercial and utility projects at large scale. It ships ready to install with fully integrated battery modules, inverters, and thermal systems. View product details

77 MW	308 MWh
Power	Energy

Megapack Quantity 100
Installation included

Site Location California
Earliest deliveries in late 2022

Price $110,346,840
Taxes not included

Annual Maintenance $375,180
Price escalates at 2% per year

Due Today $5,000
Non-refundable Order Deposit

By placing a deposit, I agree to the Megapack Order Agreement, Megapack Maintenance Agreement, and Privacy Notice

Site Contact Information

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

Least expensive Megapack costs $666/kWh in 2023

US

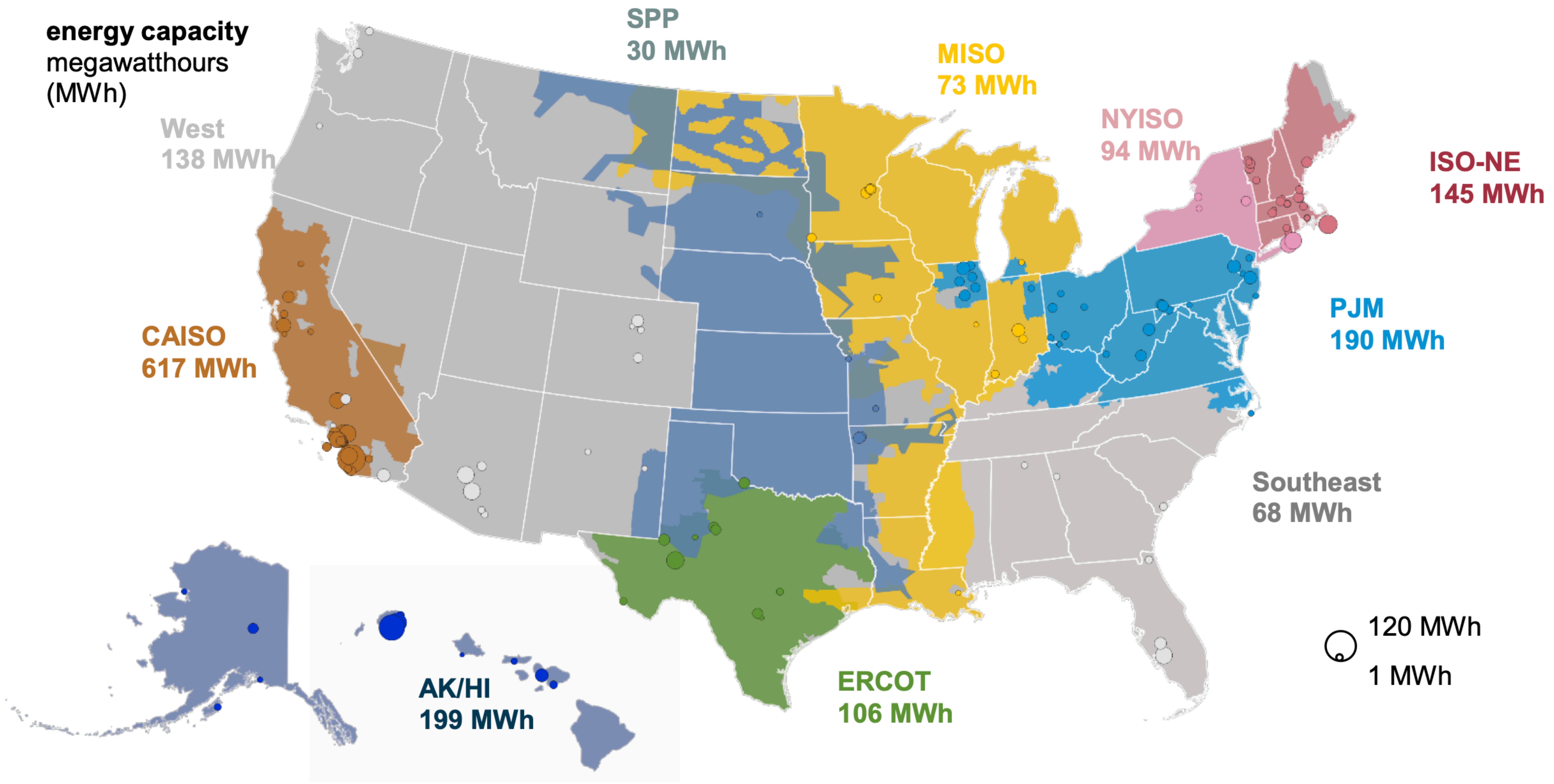
1.9 MW
Power

3.9 MWh
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

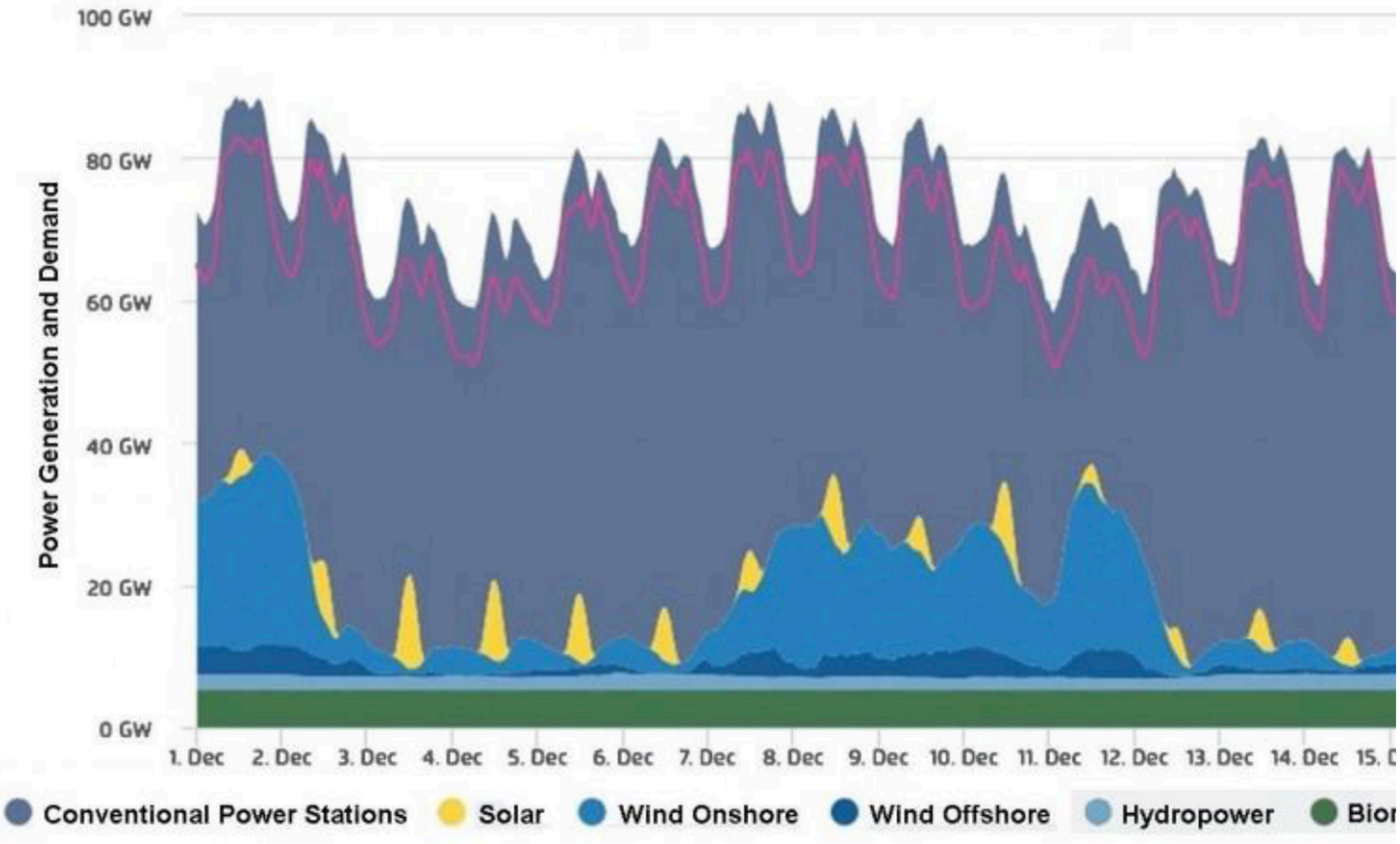
https://electrek.co/2021/07/26/tesla-reveals-megapack-prices/ https://www.tesla.com/megapack/design

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



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

Tripling 33%-capacity-factor wind, solar does not fix lulls. Germany experienced a 100 hour lull, 3-6 Dec 2016.



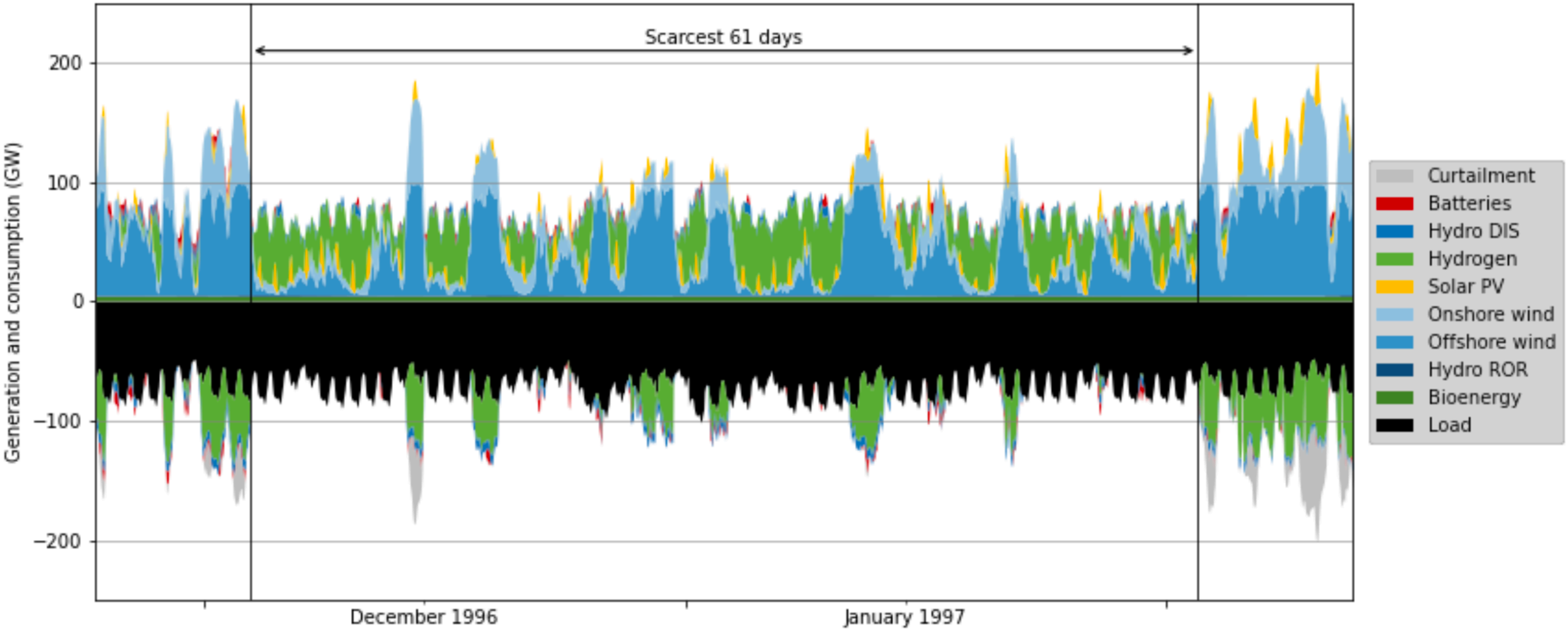
Wind and solar supplied just 2% of nameplate capacity.

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

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

Powering New England with just wind and solar requires 13,000 GW-hours of battery storage, costing $4.7 trillion.

- Actual 2018 hourly electricity demand, sun, and wind possible energy
- Tesla Megapack batteries @ $358/kWh
- 13,000 GWh x $358/kWh ~ $4.7 trillion

https://www.nae.edu/File.aspx?id=239123

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

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

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

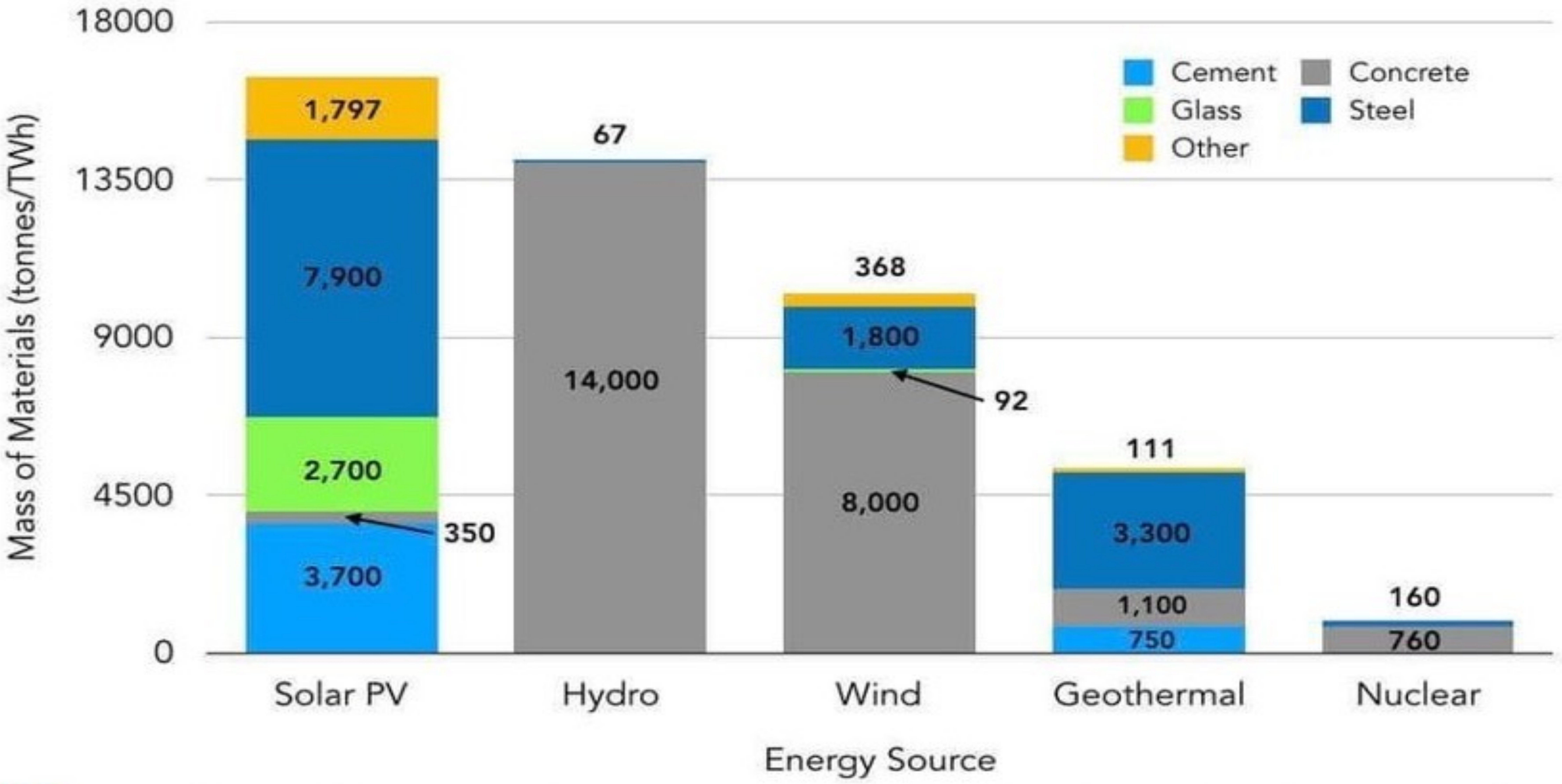
Each wind turbine embodies a whole lot of petrochemicals and fossil-fuel energy

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

Materials used per TWh generated, by energy source

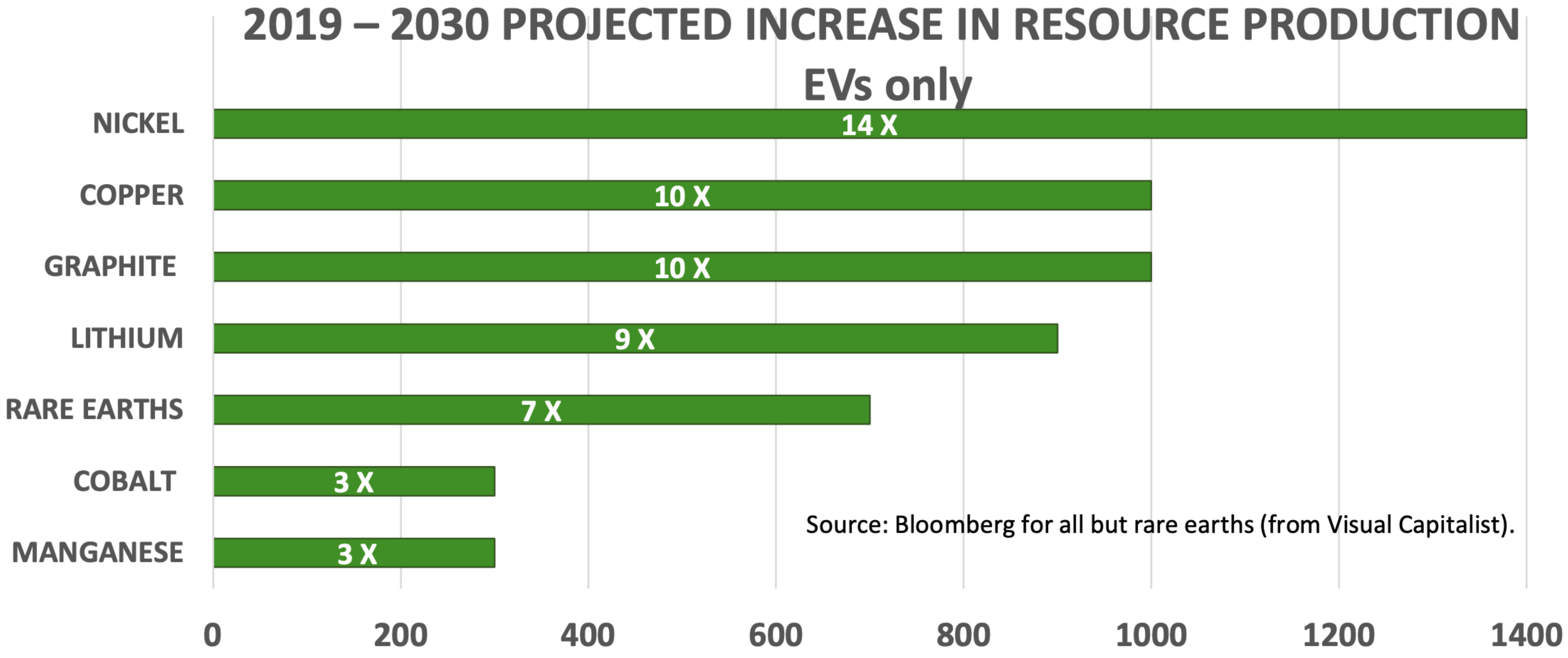


ENVIRONMENTAL PROGRESS

"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.

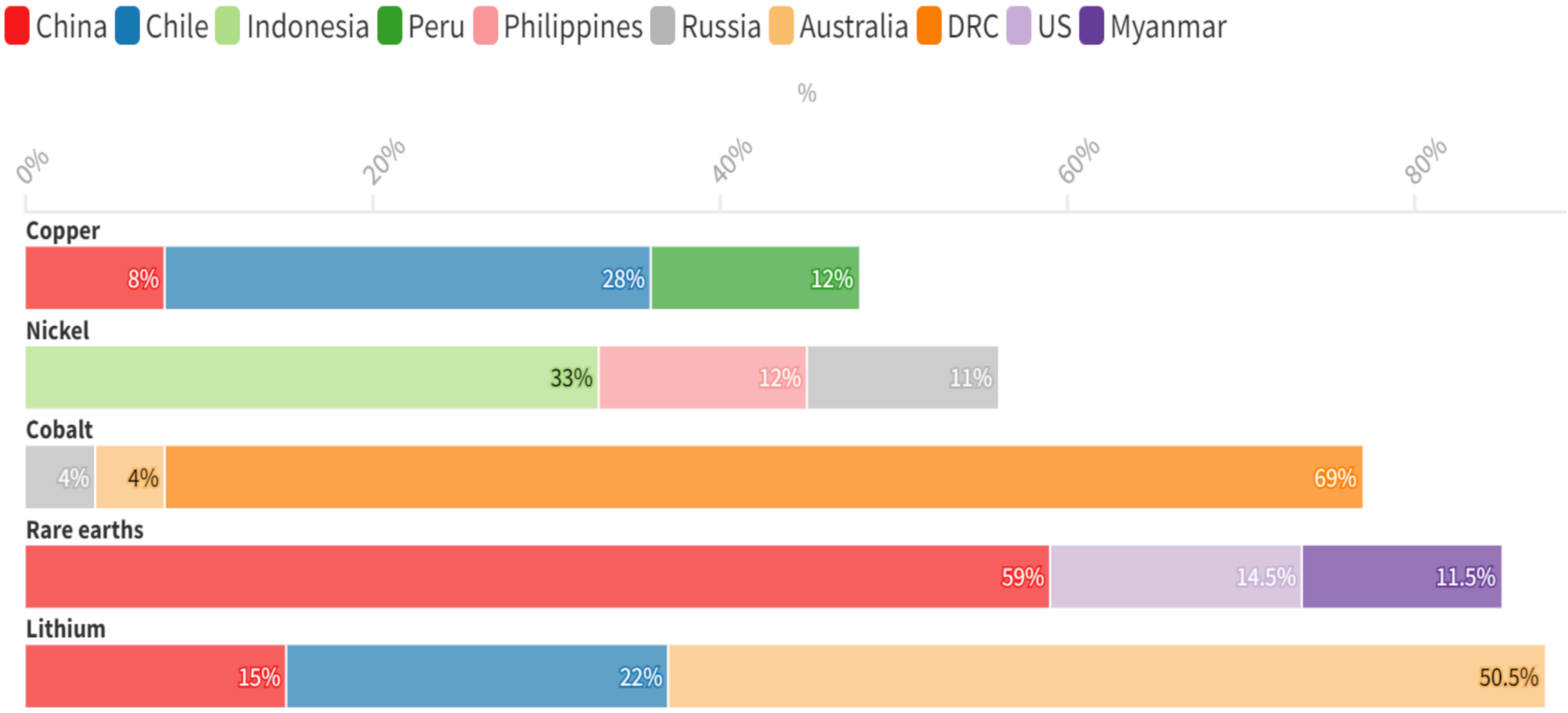
Jim Kennedy projects massive mining increases for EVs.

How much more mining is required for projected EV production ?



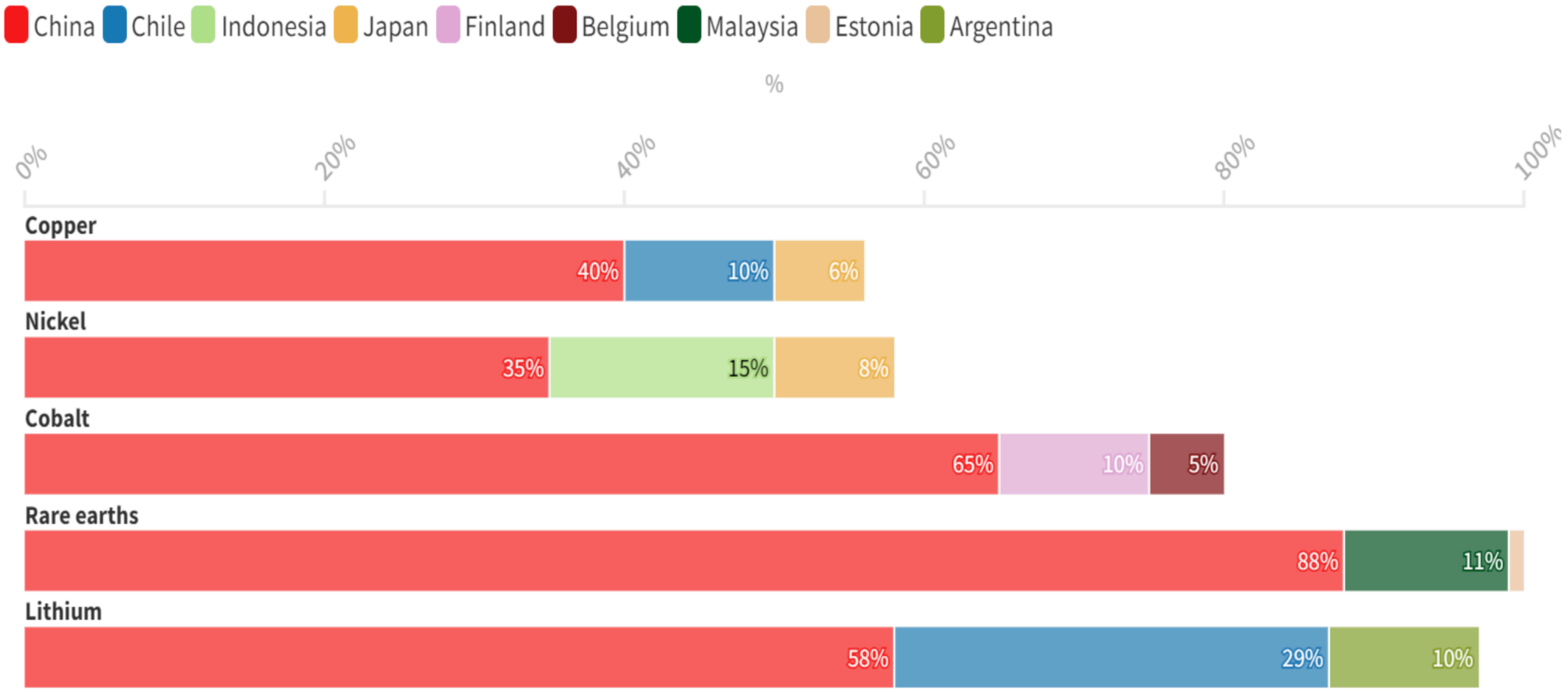
Presentation by James Kennedy, President of ThREE Consulting 2.25.22

Where critical minerals are mined



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

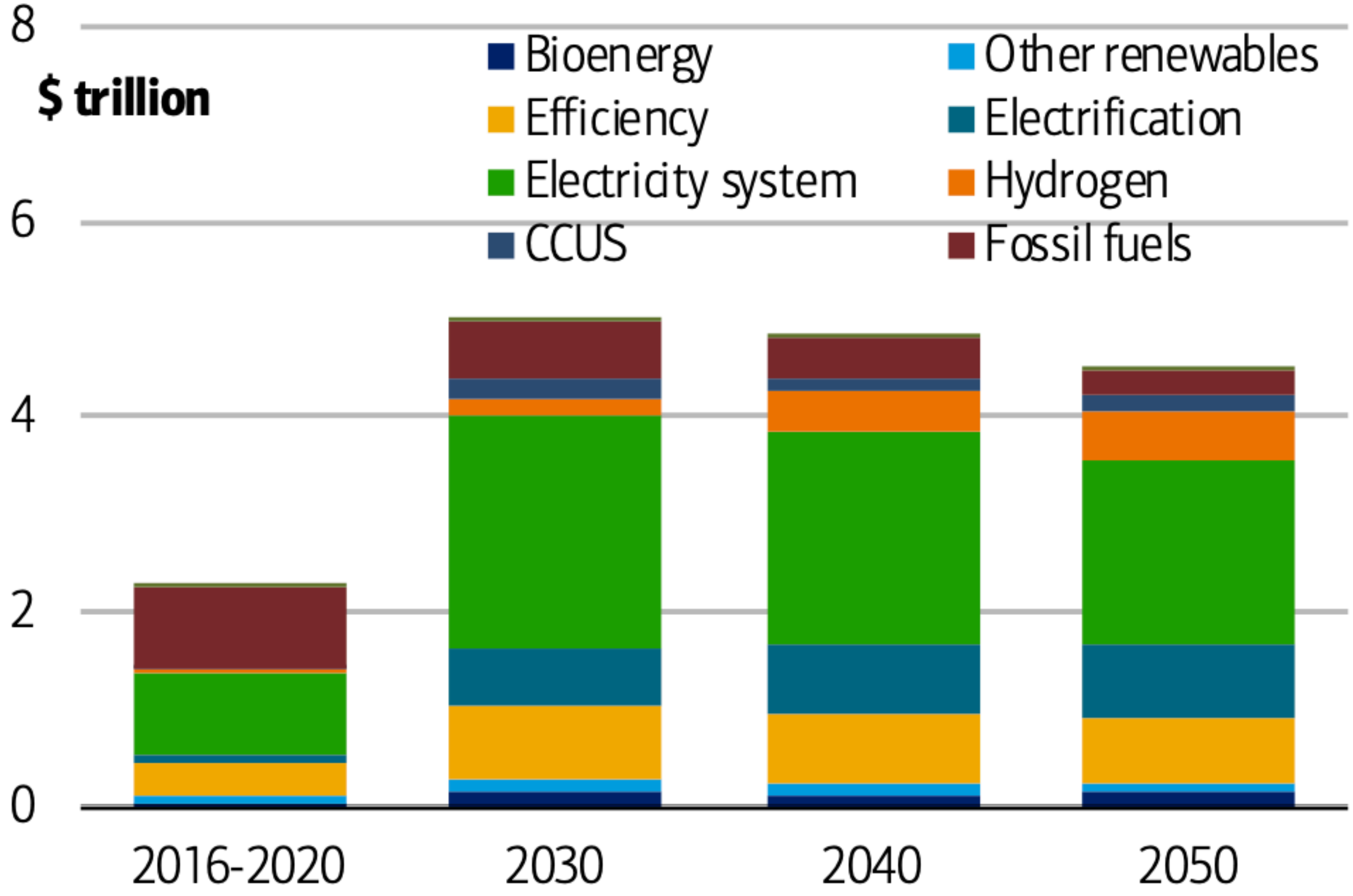
Where critical minerals are processed



Source: IRENA, IEA

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

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.

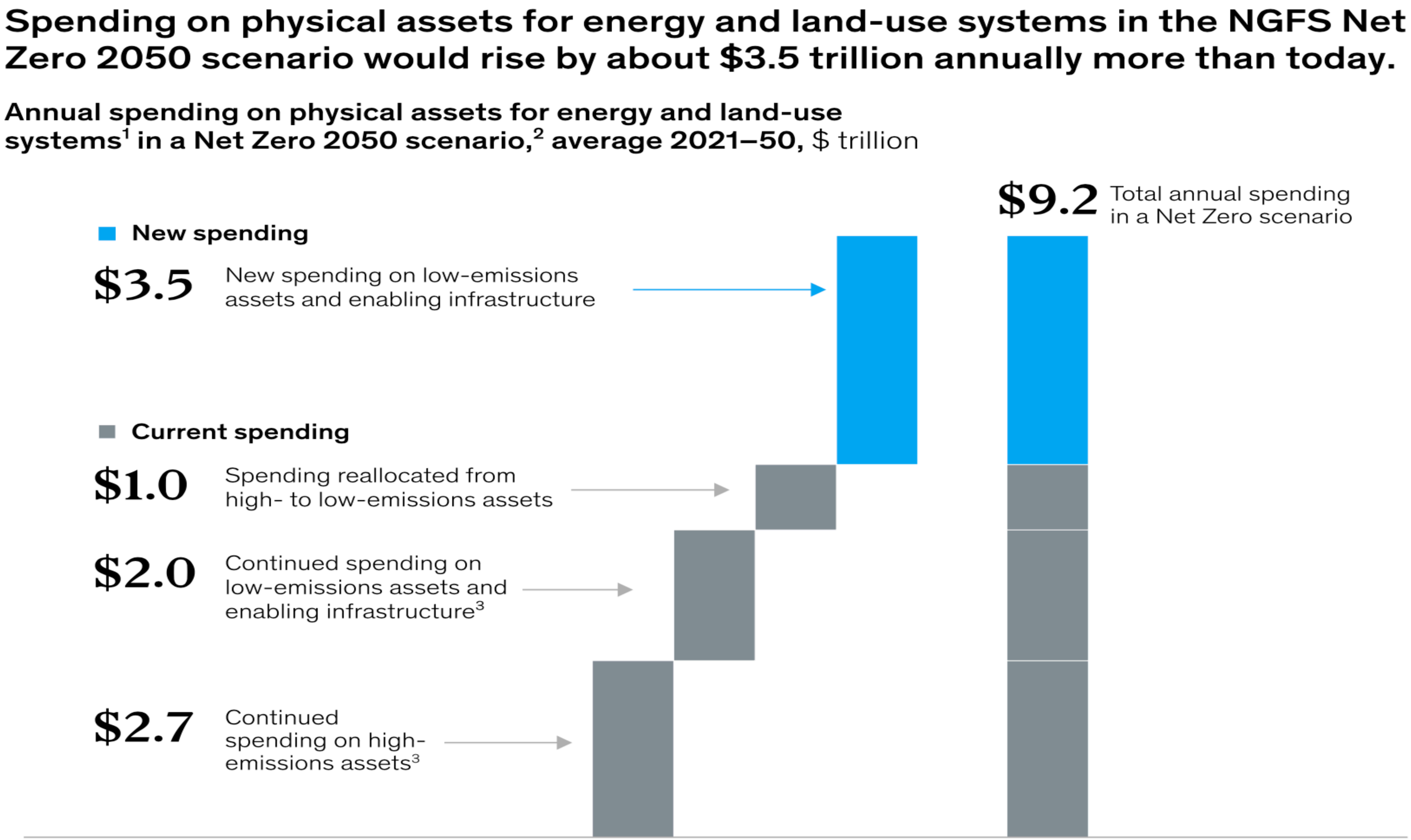
The latter number is almost twice the total global GDP in 2019…"

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

Note: no fission power.

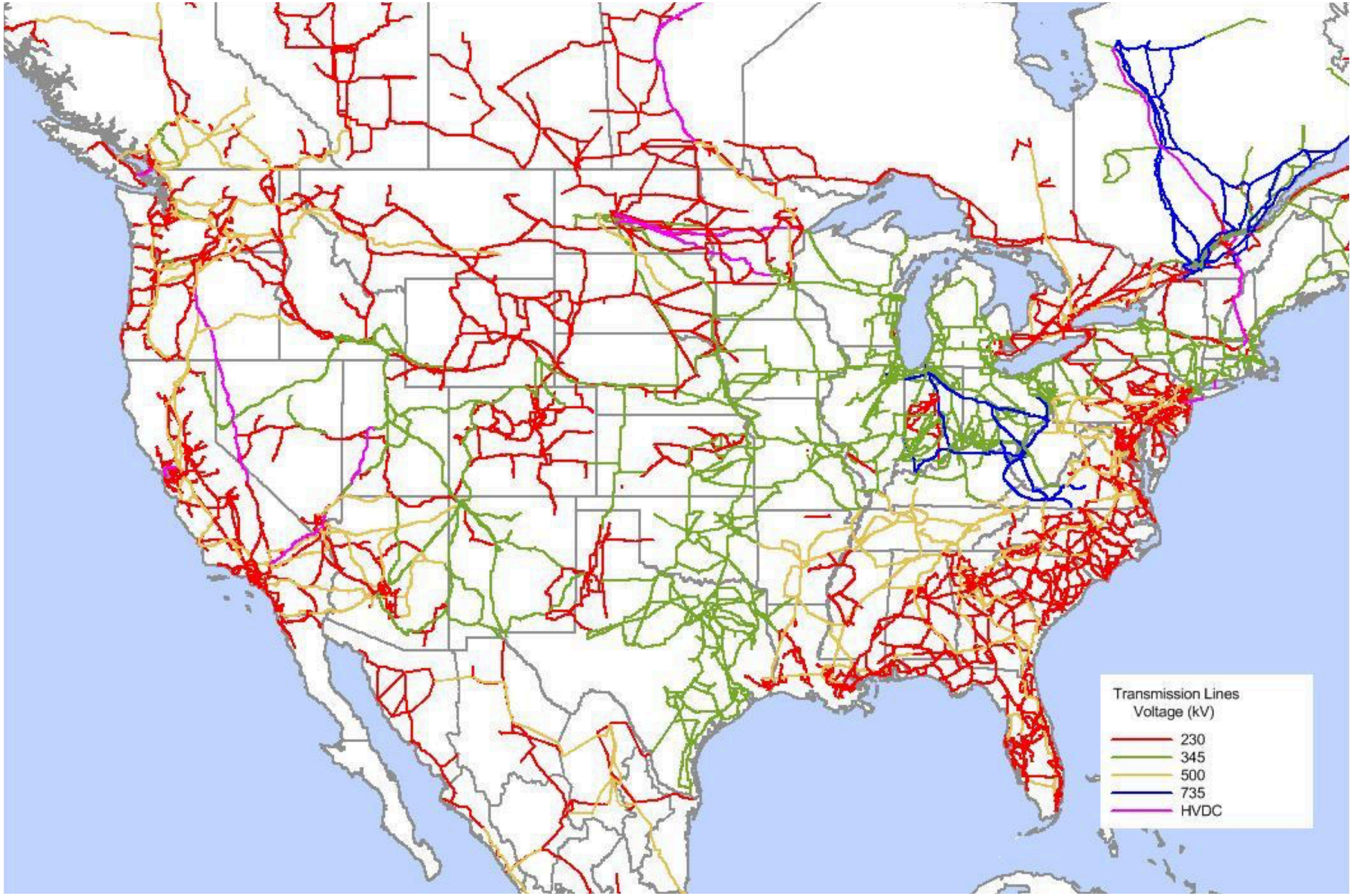
https://business.bofa.com/content/dam/boamlimages/documents/articles/ID21_1543/Net_Zero_Redacted_Note_Updated_Final.pdf

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



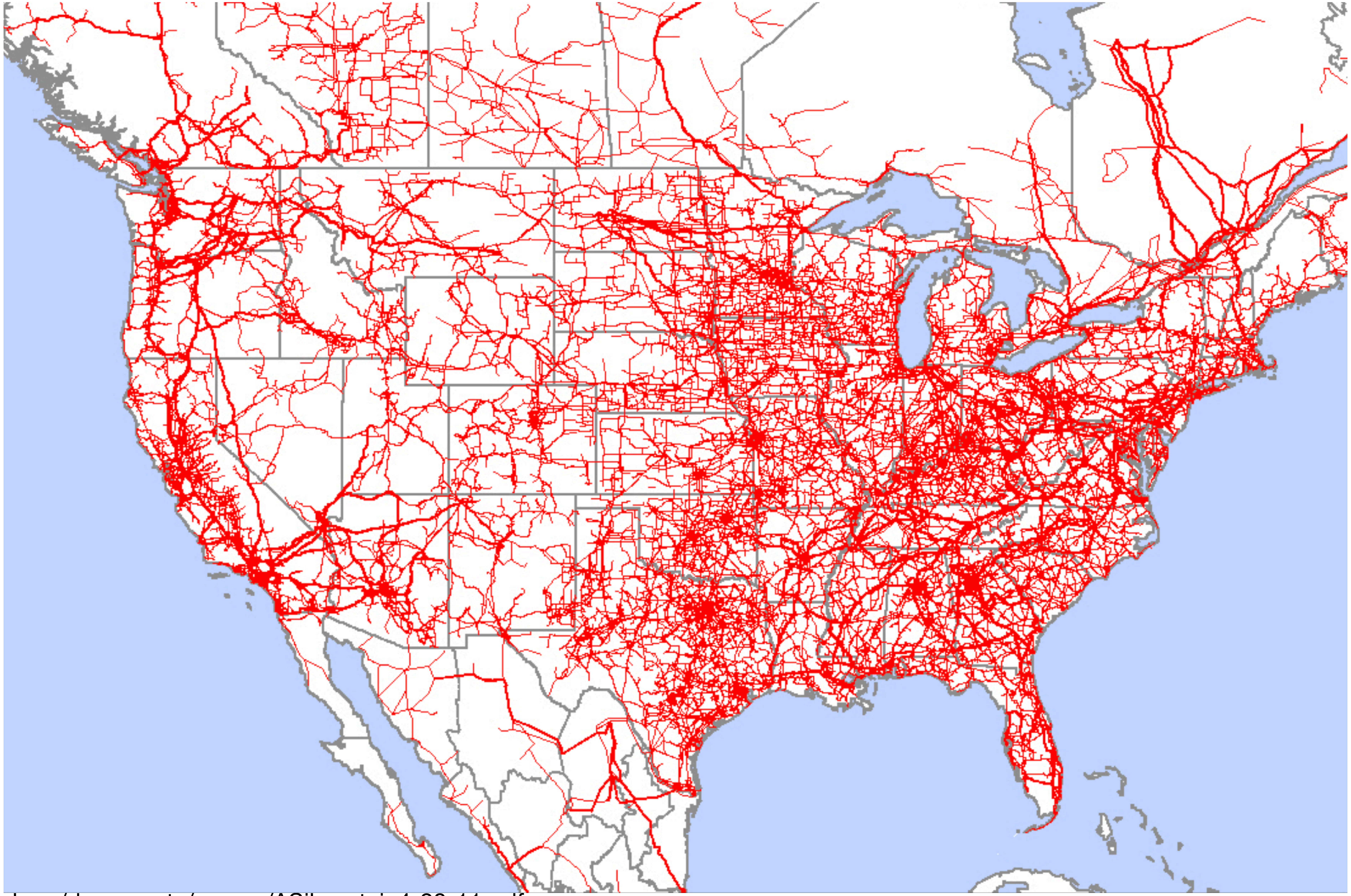
https://www.mckinsey.com/business-functions/sustainability/our-insights/the-economic-transformation-what-would-change-in-the-net-zero-transition

Upgrade US transmission, 230 kV and above?



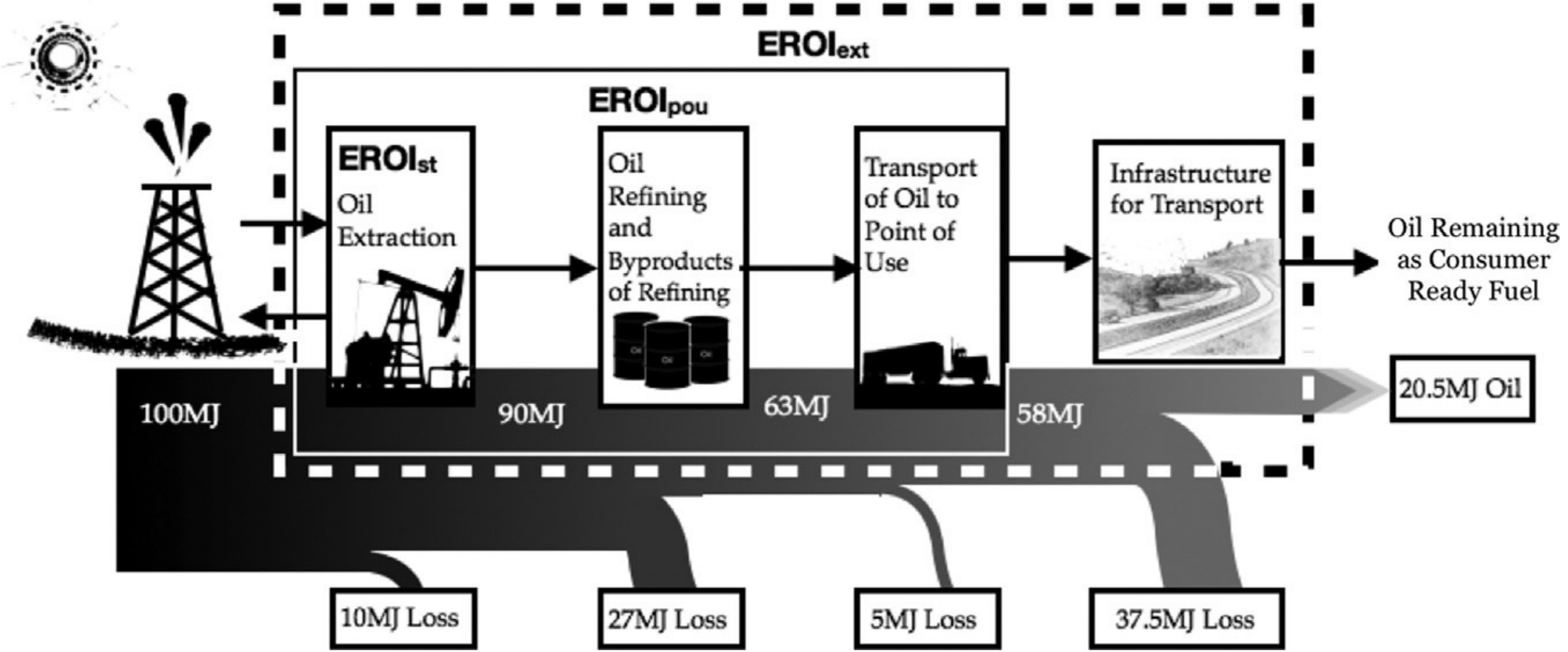
https://www.ncsl.org/documents/energy/ASilverstein4-20-11.pdf

Upgrade US transmission, 69 kV and above?



https://www.ncsl.org/documents/energy/ASilverstein4-20-11.pdf

EROI example: Invest 79.5 MJ to get 20.5 MJ to consumer use.

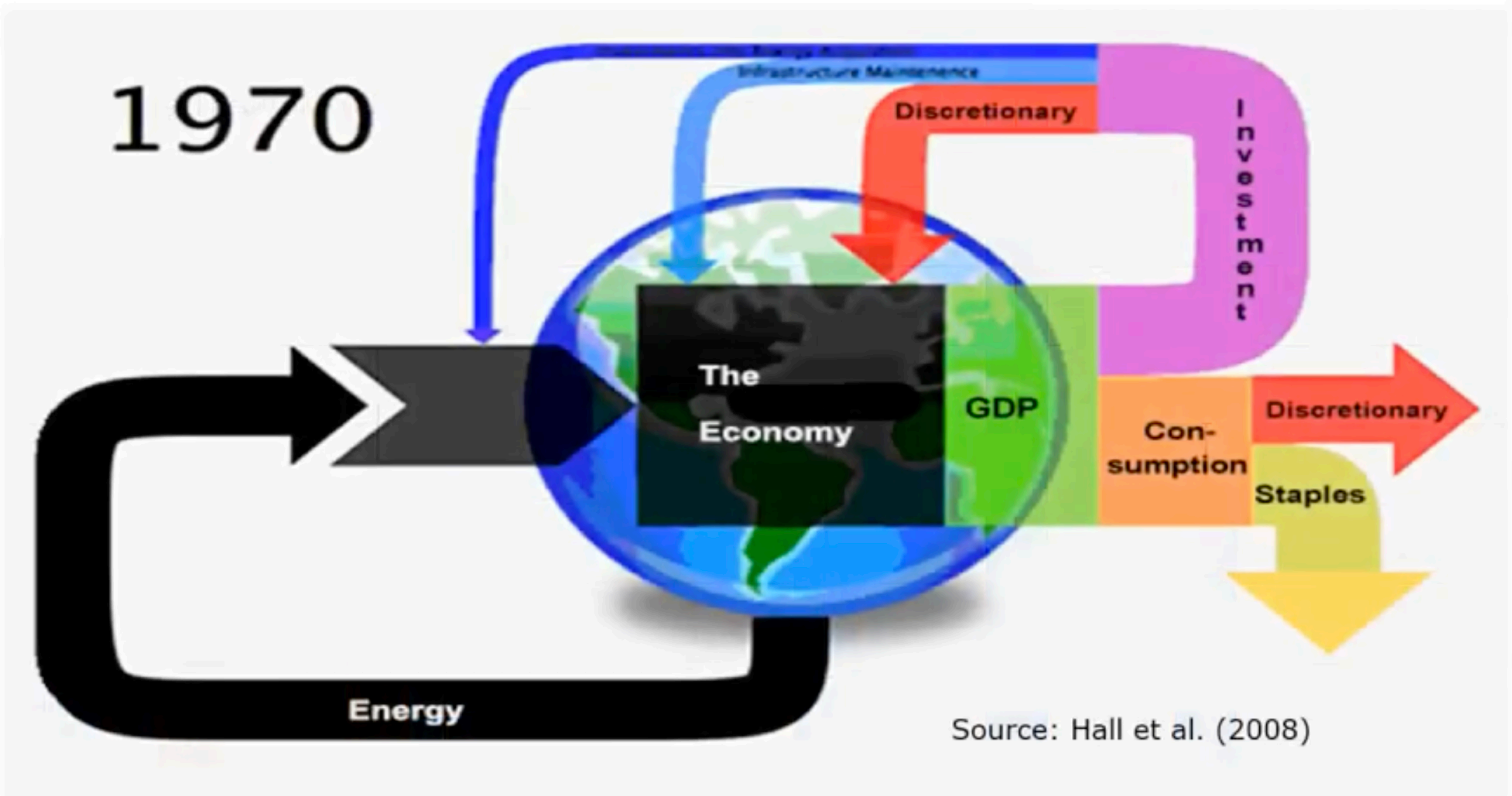


Oil's 100 MJ is “free”, created from sunlight 100 million years ago.

References

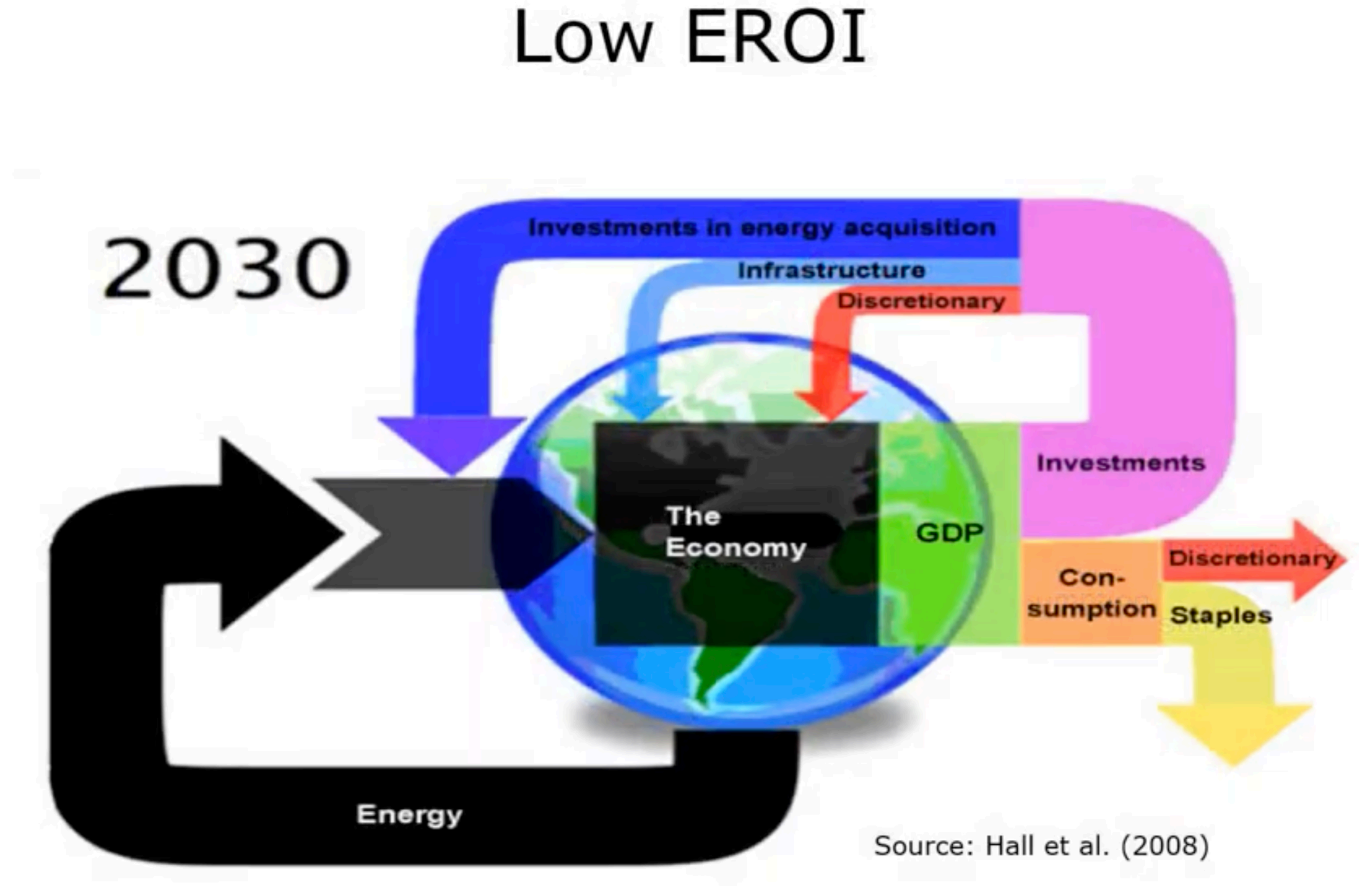
Society’s discretionary investment and consumption high.

High EROI



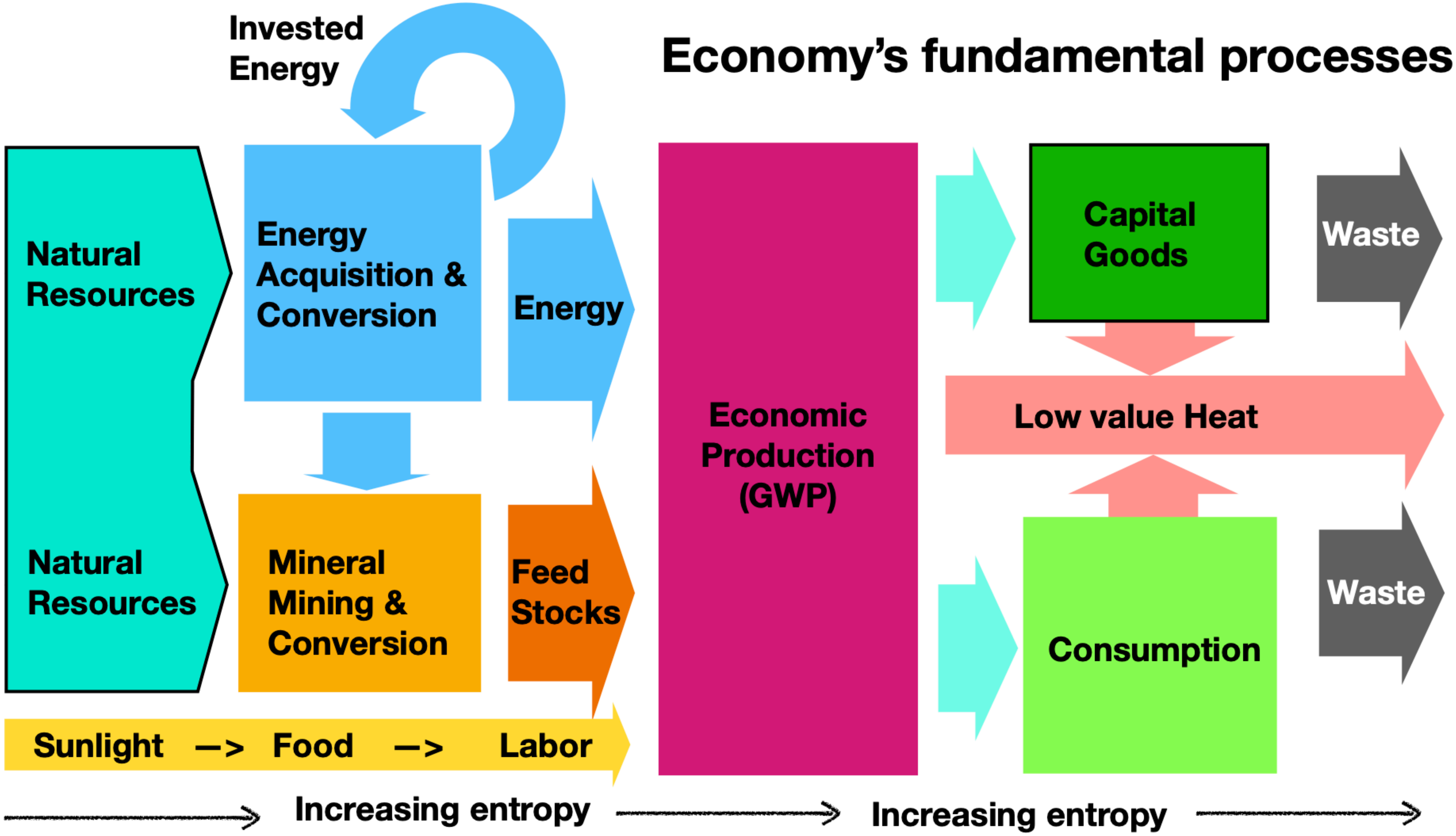
References

Society's discretionary investment and consumption low.

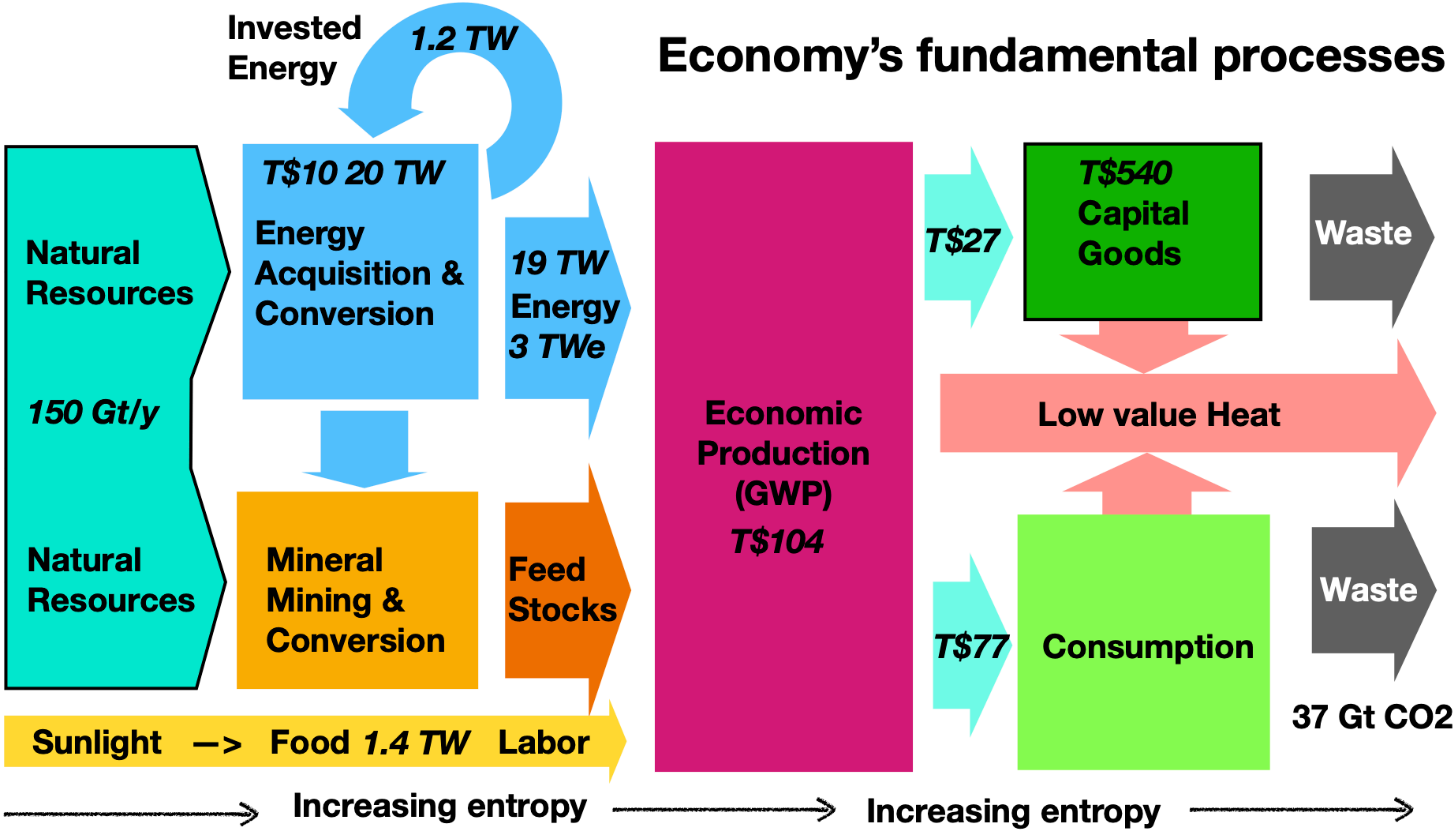


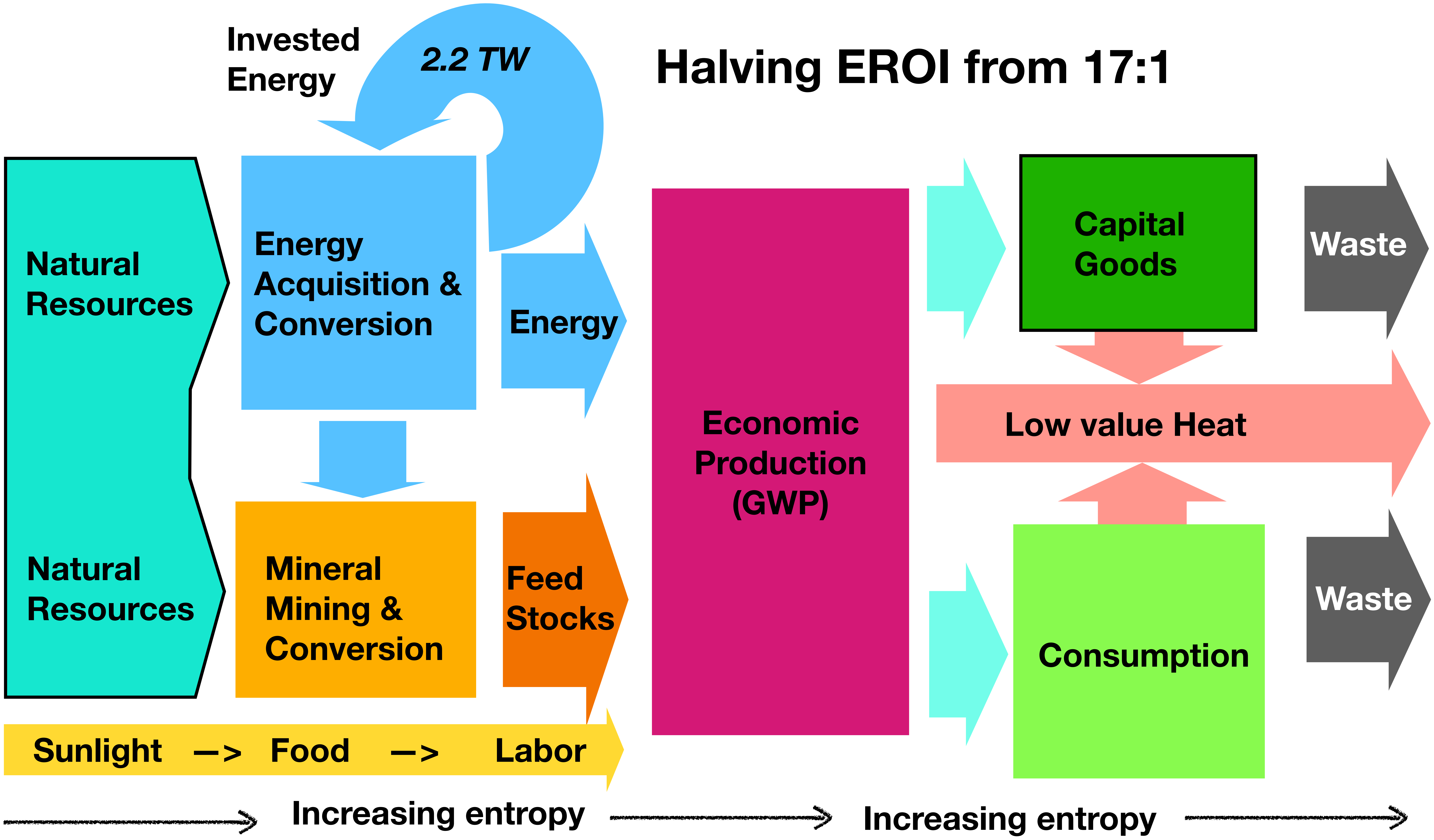
References

World natural resources, energy, and entropy



Enumerated natural resources and energy



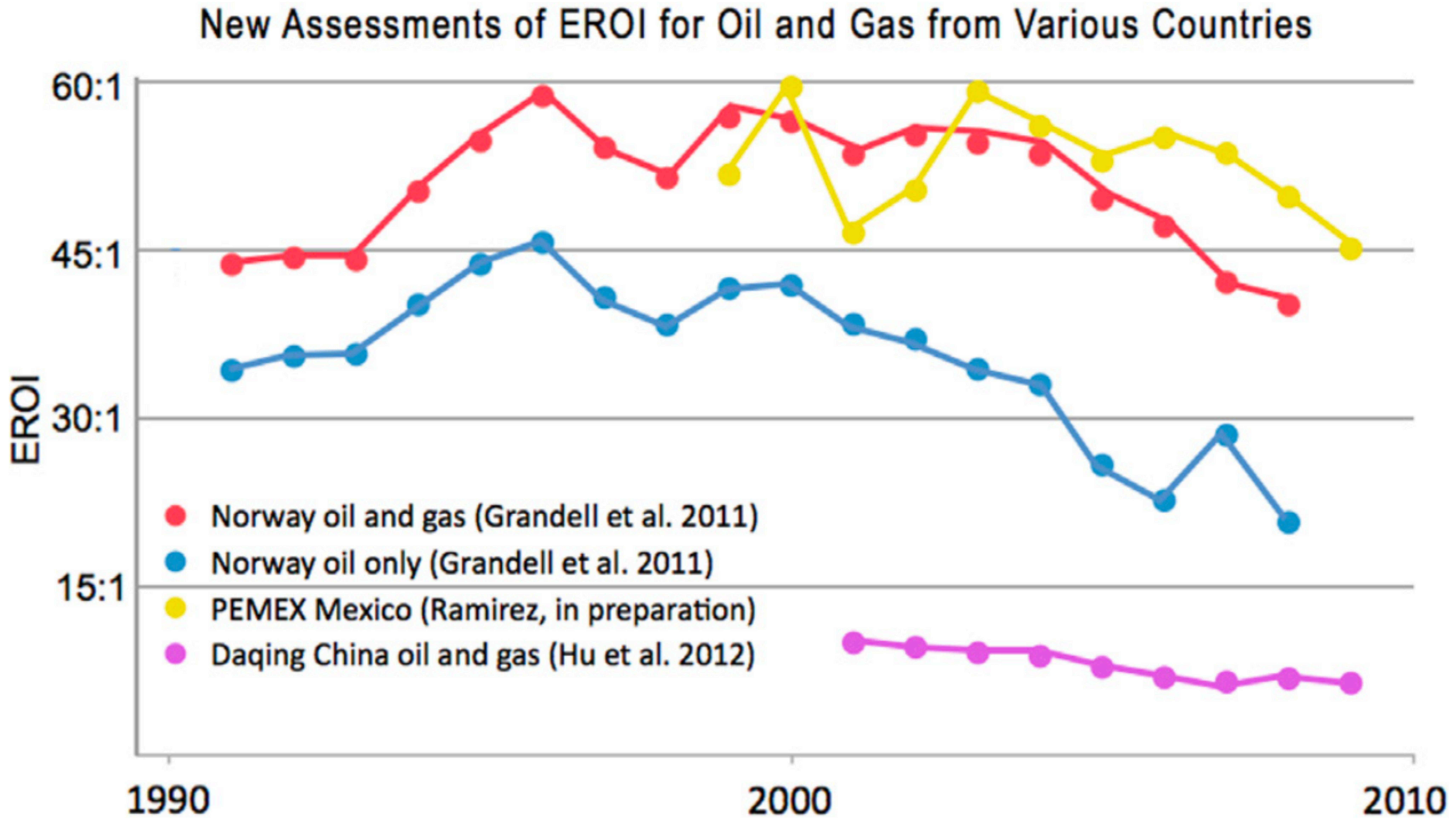

Invested
Energy
2.2 TW
Halving EROI from 17:1
Natural
Resources
Energy
Acquisition &
Conversion
Energy
Economic
Production
(GWP)
Capital
Goods
Waste
Low value Heat
Natural
Resources
Mineral
Mining &
Conversion
Feed
Stocks
Consumption
Waste
Sunlight —> Food —> Labor
Increasing entropy
Increasing entropy

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

Goehring & Rozencwajg: EROI explains world prosperity.

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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

Wade Allison: Energy options facing society today

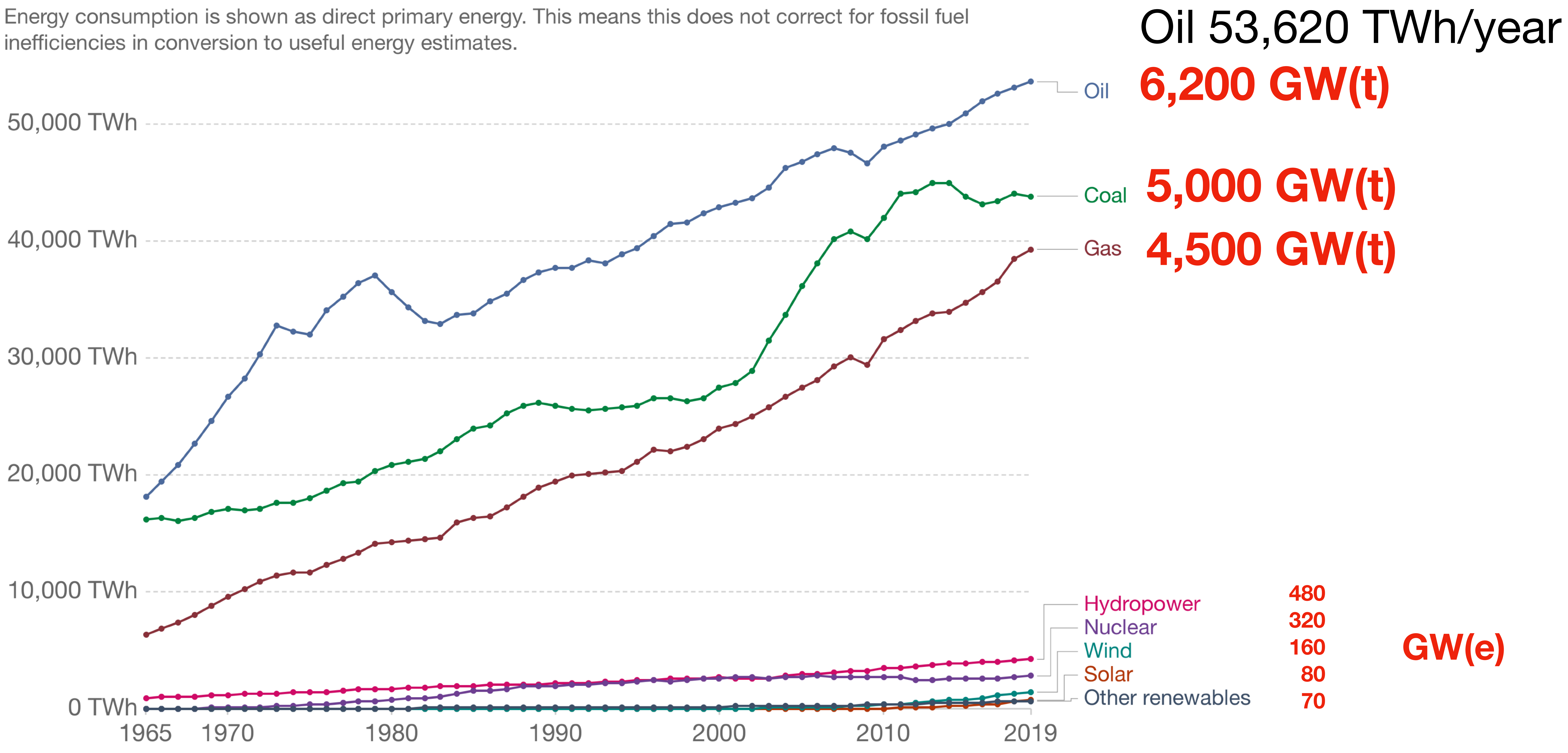
Adam Smith: “Science is the great antidote to the poison of enthusiasm and superstition.”

	“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

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.



Source: BP Statistical Review of Global Energy

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

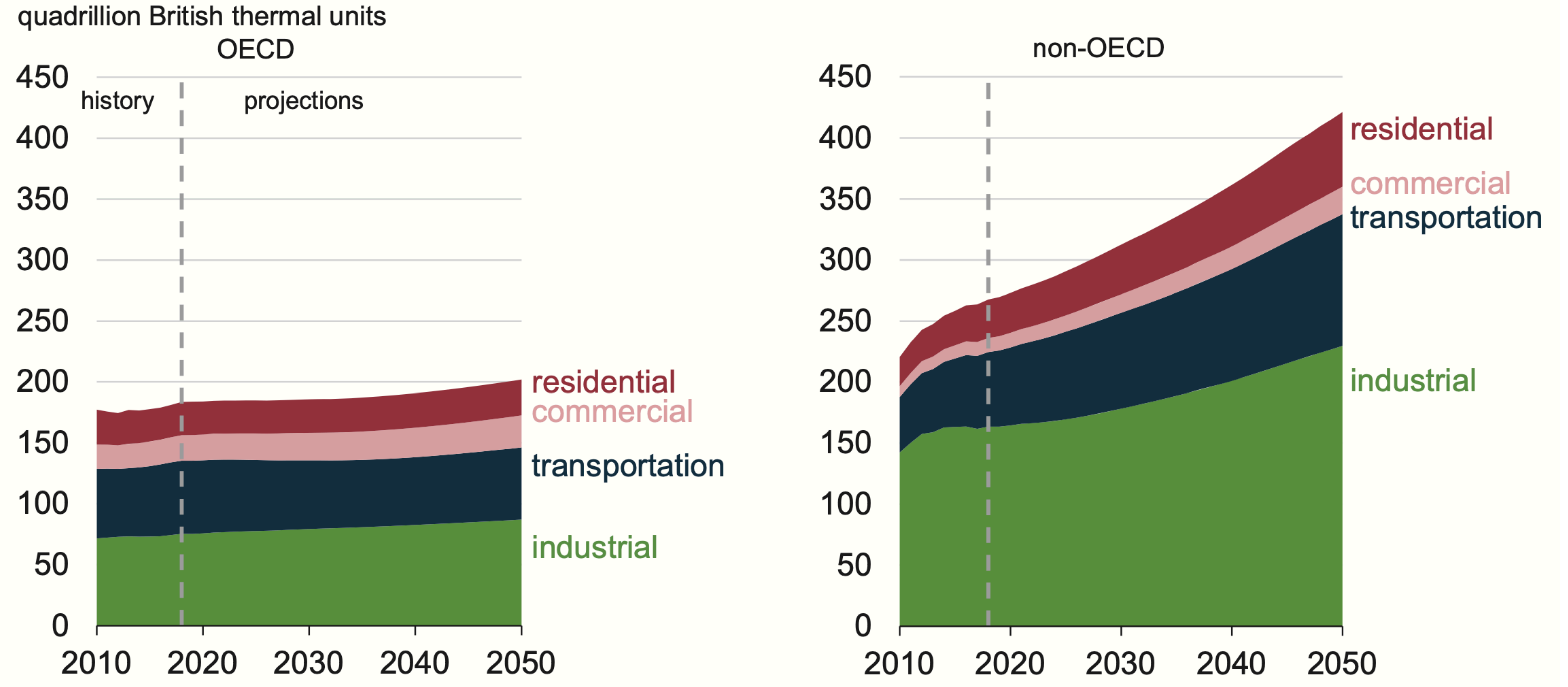
Handy math trick from Google:

OECD energy

180 quadrillion BTU/year ~ 6,000 GW(t)

non-OECD energy

270 quadrillion BTU/year ~ 9,000 GW (t)



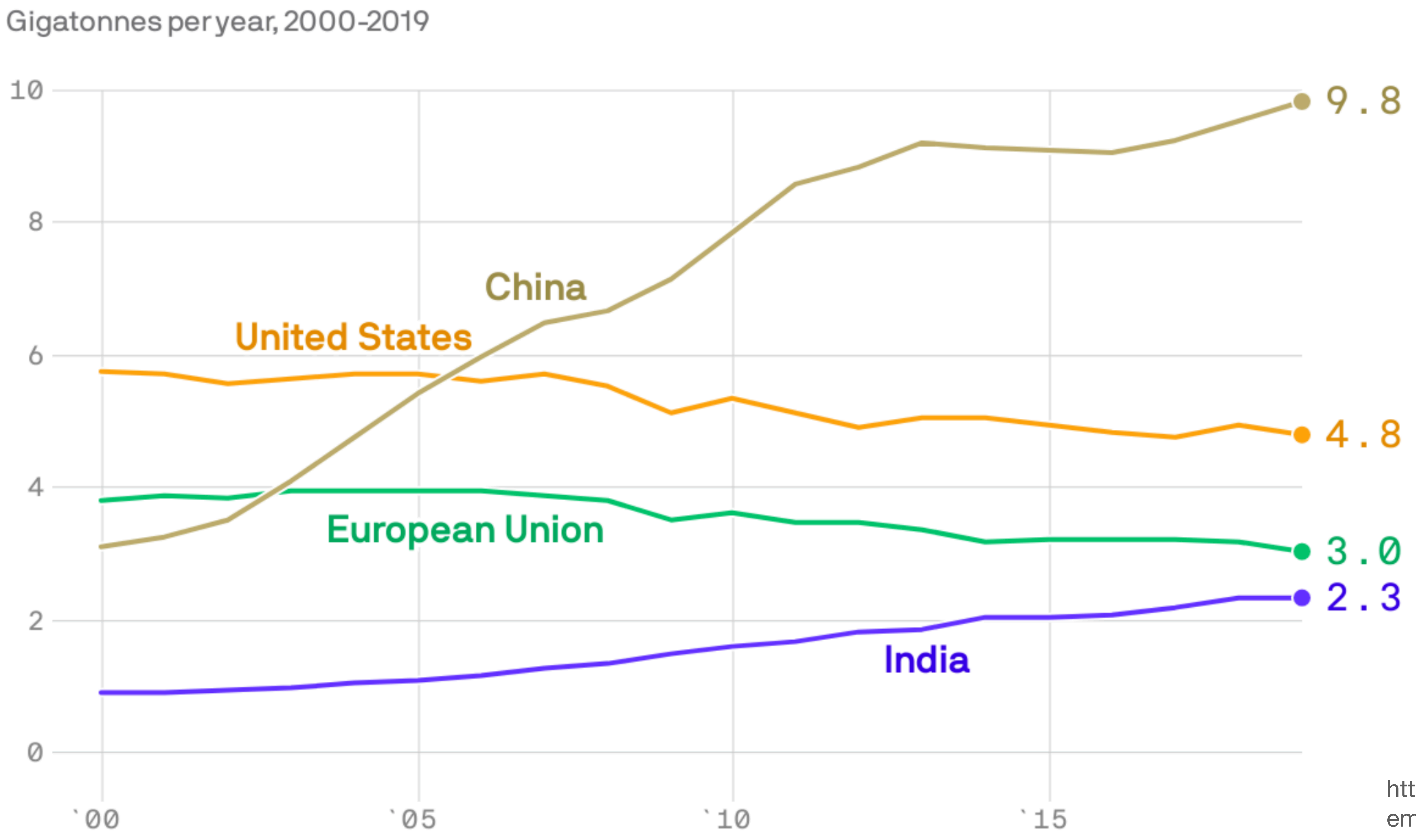
https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

IEA World thermal power (Mtoe/year) Gigawatts

		2000	2019	(Gigawatts)	Sustainable Development Scenario 2040	Sustainable Development Scenario 2070	(Gigawatts)	Stated Policies Scenario 2070	(Gigawatts)
uses	Industry	2 054	3 278	4,400	3 162	3 077		4 513	
uses	Transport	1 961	2 865	3,800	2 537	2 461		3 923	
uses	Buildings	2 345	3 087	4,100	2 648	2 868		4 193	
uses	Other	950	1 153		1 310	1 081		1 639	
	Total	**7 310**	**10 384**	13,800	**9 657**	**9 486**	12,600	**14 269**	19,000
sources	Coal	732	1 327		824	398		1 326	
sources	Oil	3 292	4 048		2 823	1 099		4 561	
sources	Natural gas	1 104	1 659		1 357	426		2 362	
sources	Electricity	1 076	1 943	2,600	2 909	4 507	6,000	4 004	
sources	Heat	240	312		272	187		356	
sources	Hydrogen	0	0		98	539		91	
sources	Ammonia	0	0		18	133		9	
sources	Bioenergy	859	1 035	1,400	1 035	1 315	1,700	1 285	
sources	Synfuels	0	0		32	254		0	
sources	Other renewables	7	60		290	629		275	
	Total	**7 310**	**10 384**		**9 657**	**9 486**		**14 269**	

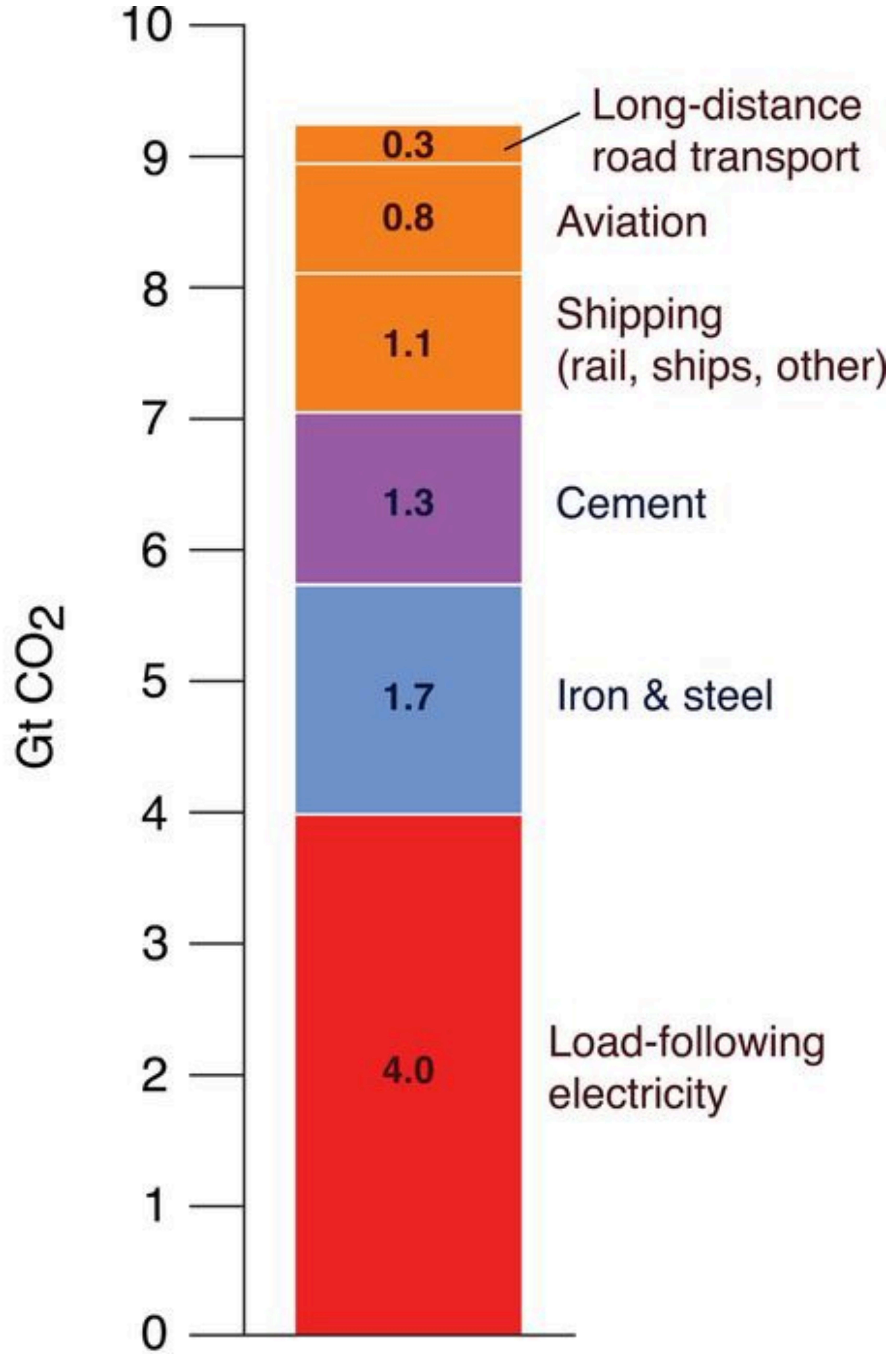
https://webstore.iea.org/download/direct/4165

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



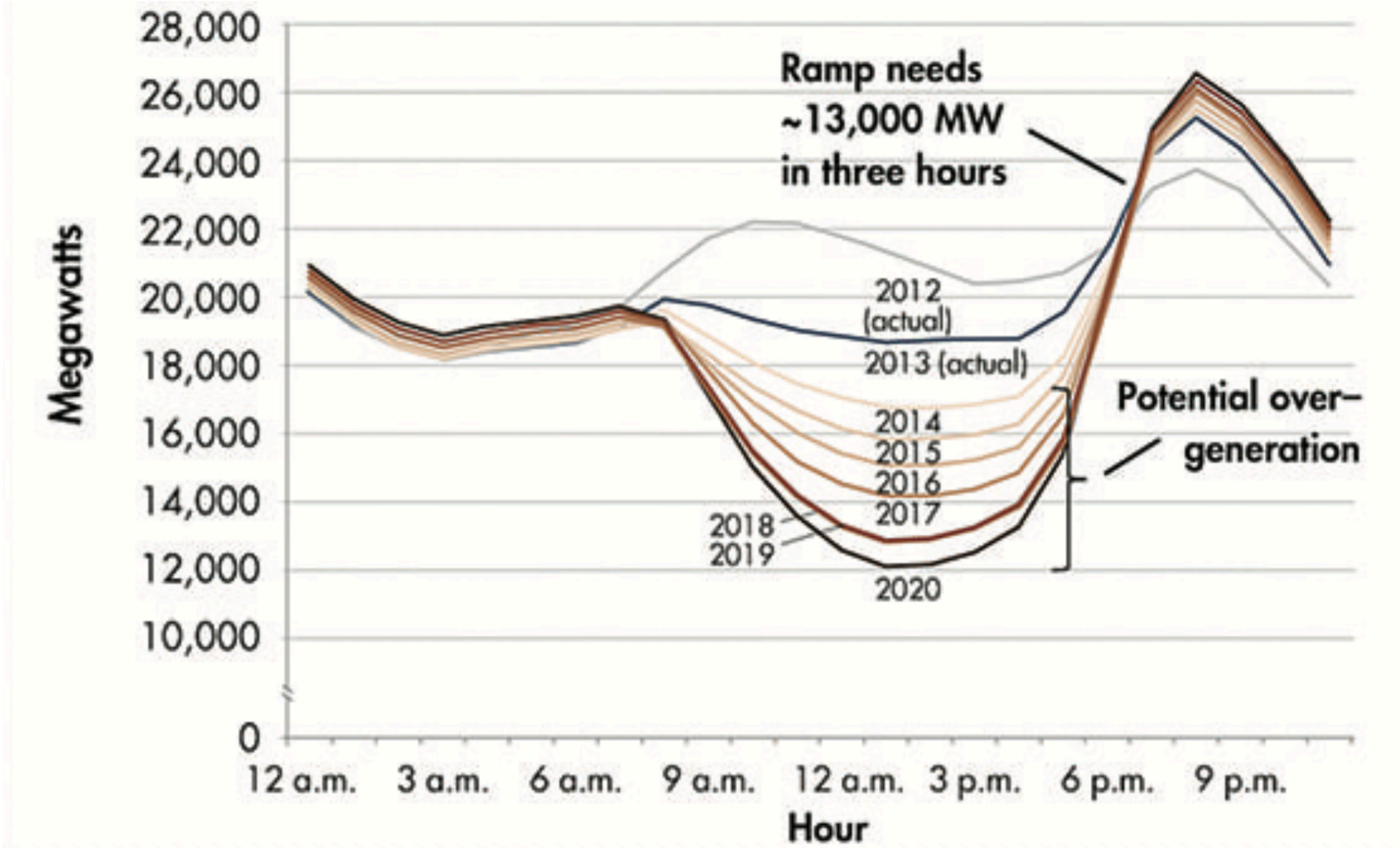
https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview

Difficult to eliminate emissions
9 Gt CO2 (2014)



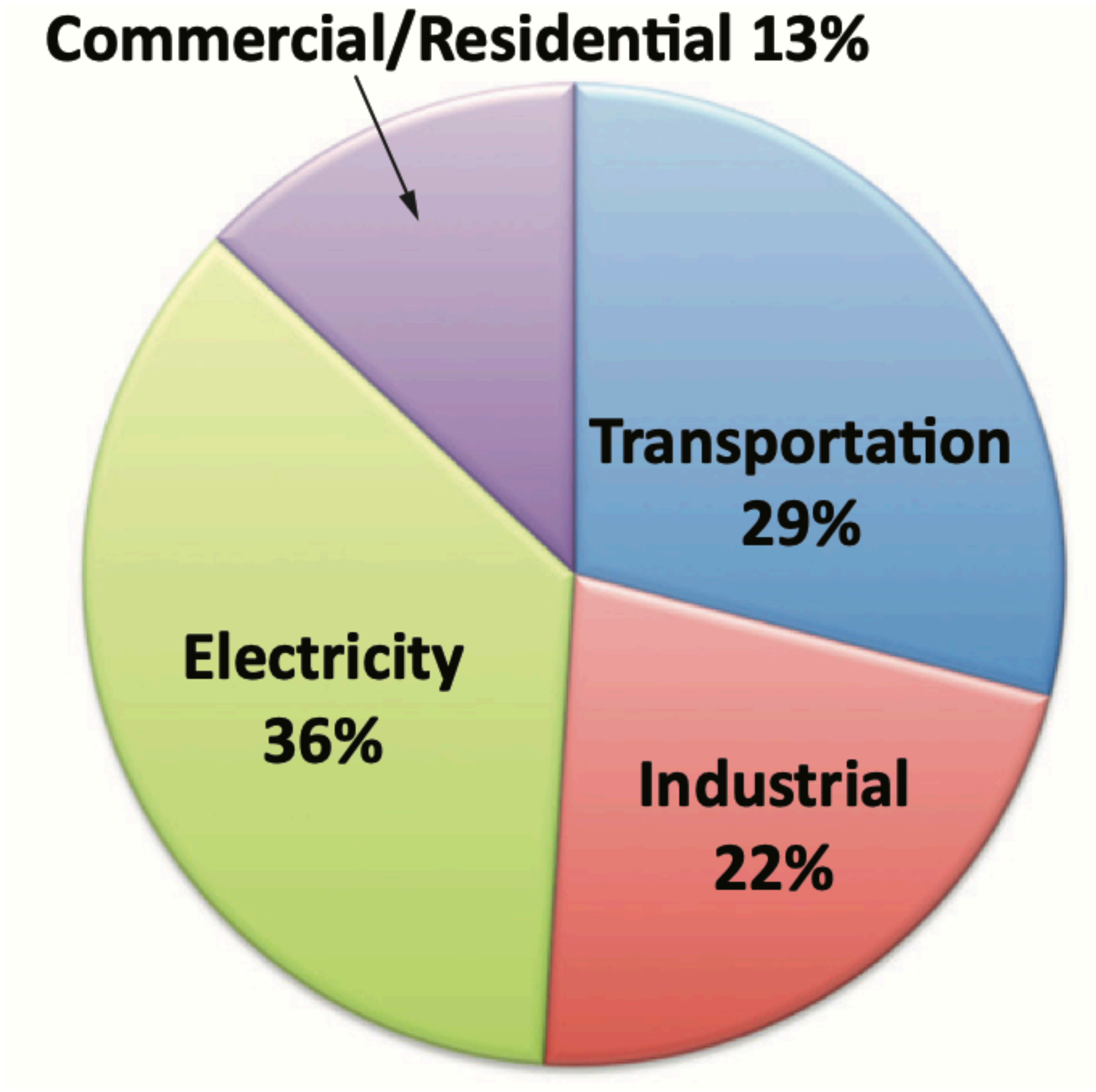
https://science.sciencemag.org/content/360/6396/eaas9793

Subsidized solar helped create the “difficult” load-following demand.



https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

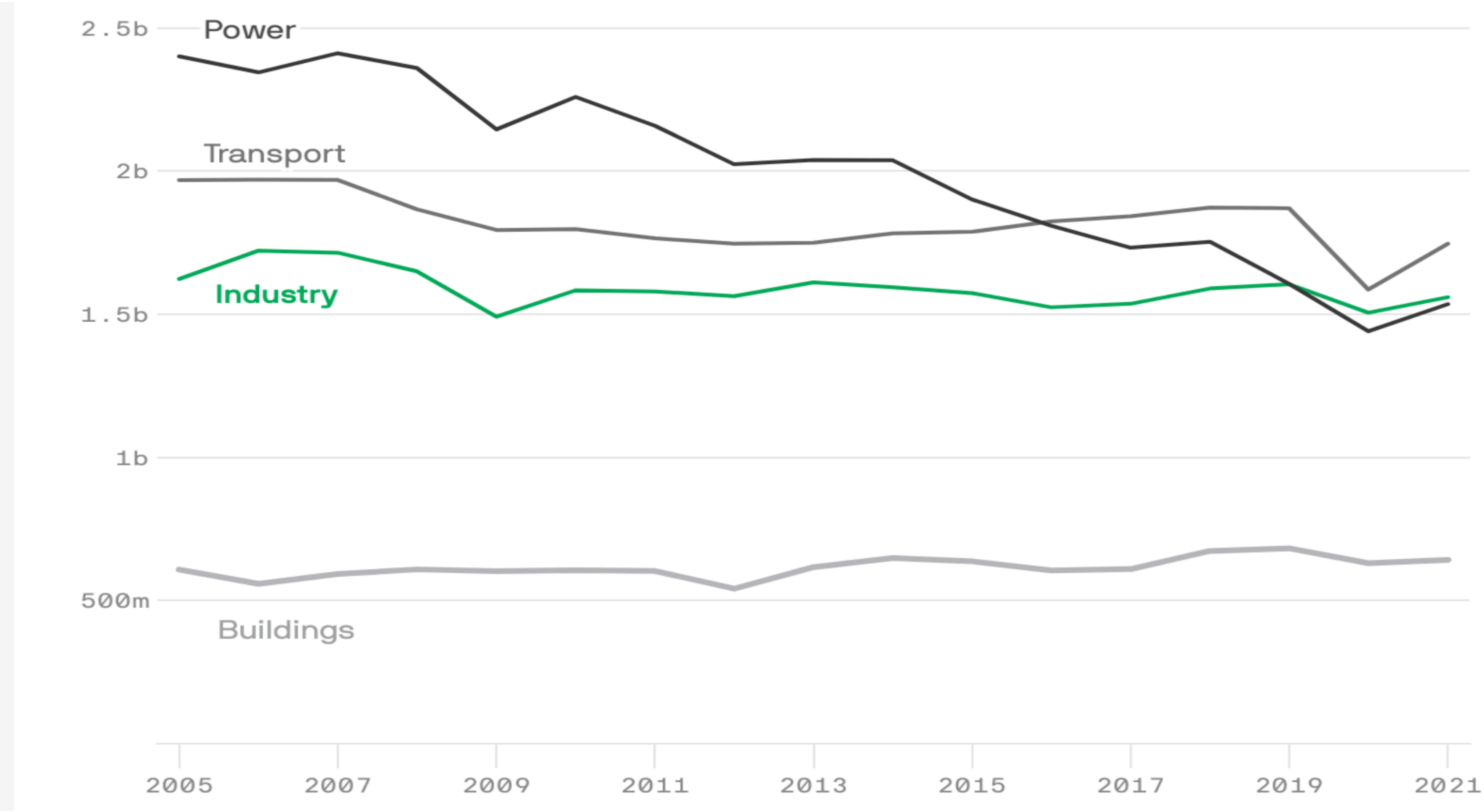
US DOE EIA energy by use sector



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

Electricity
Transportation
Buildings
Industry

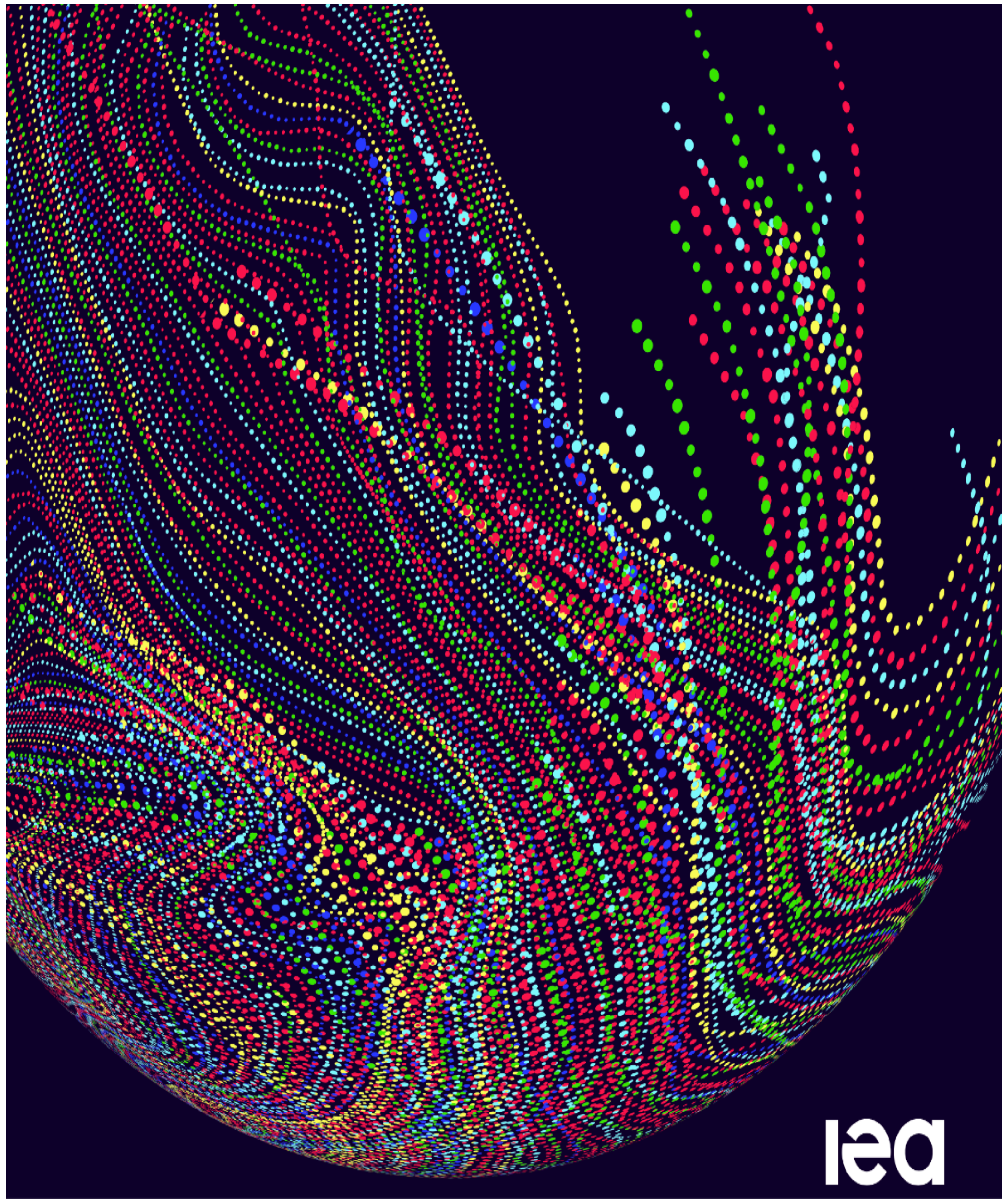
US annual CO2-eq emissions, tons. Axios/Rhodium



https://www.axios.com/newsletters/axios-generate-d6e39fe0-39f4-4082-a19c-3e59f68b459c.html

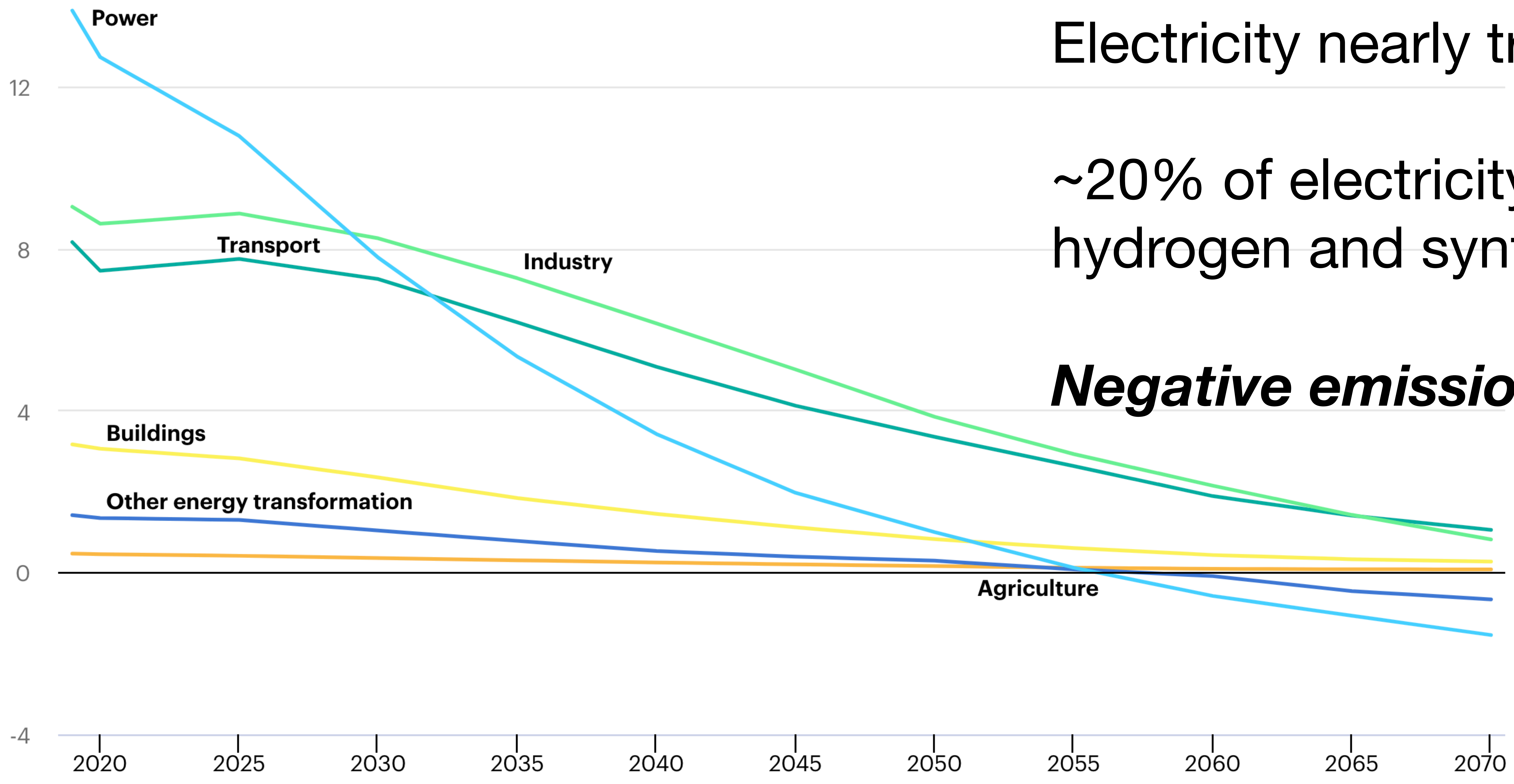
IEA strategy (Sept 2020)

1. Transforming the **power sector** alone would only get the world **one-third** of the way to net-zero emissions.
2. **Spreading the use of electricity** into more parts of the economy is the single largest contributor to reaching net-zero emissions.
3. **Hydrogen** extends electricity's reach.
4. Carbon capture and bioenergy play multifaceted roles. **X X X**
5. **Long-distance transport and heavy industry** are the hardest emissions to reduce.



https://www.iea.org/reports/energy-technology-perspectives-2020

IEA strategy: annual CO2 emissions over 50 years.



Electricity nearly triples.

~20% of electricity for hydrogen and synfuels

Negative emissions?!

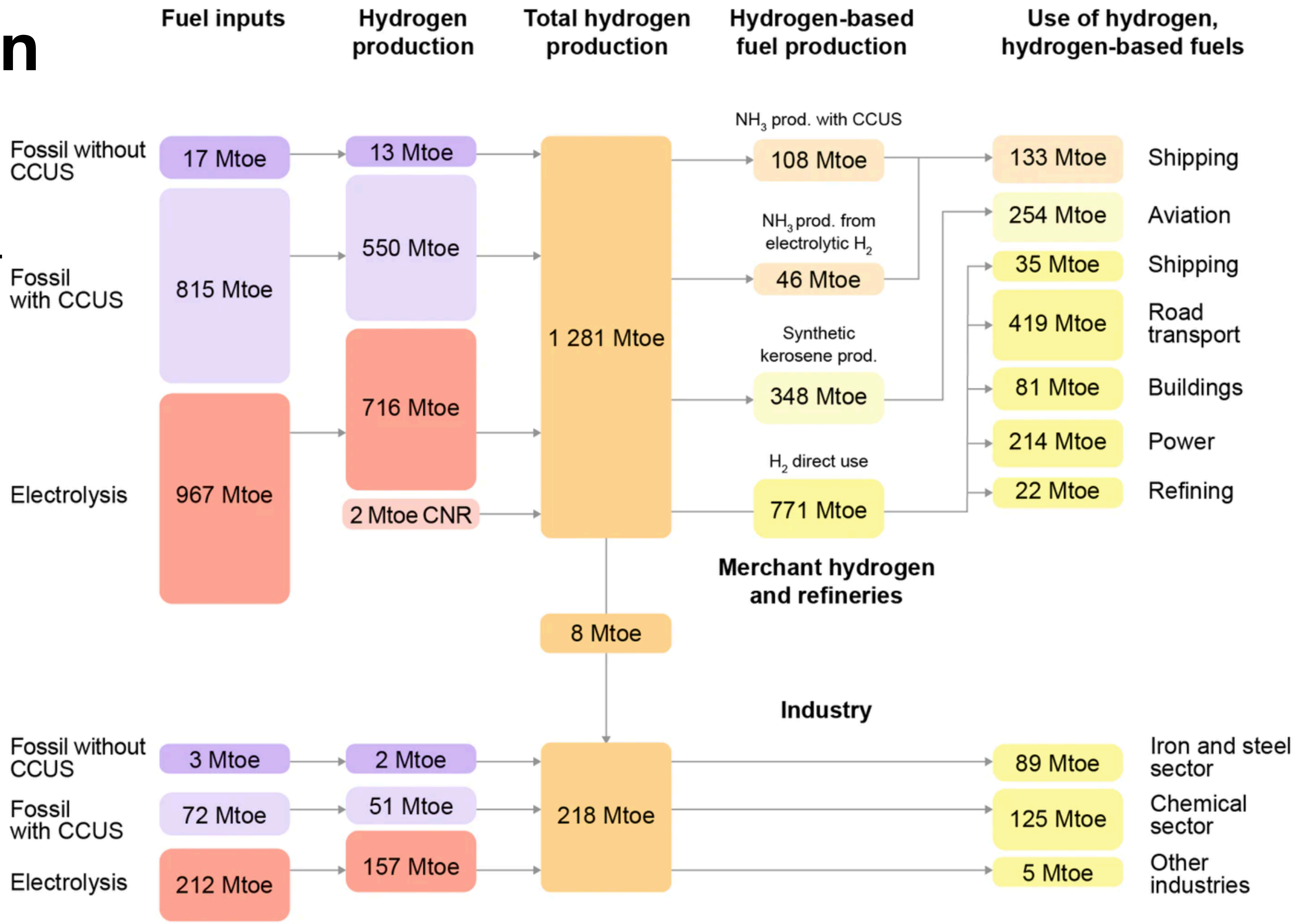
https://www.iea.org/reports/energy-technology-perspectives-2020

IEA Hydrogen strategy

Electrolyze 300 Mt-hydrogen per year (half H2 demand)

Total H2 prod = 1,281+218 = 1500 Mtoe/year = **2,000 GW**(t) of H2

CCUS = carbon capture underground storage



https://www.iea.org/reports/energy-technology-perspectives-2020

IEA synfuel strategy

154 Mtoe/year of **ammonia** = **204 GW** NH3 for shipping

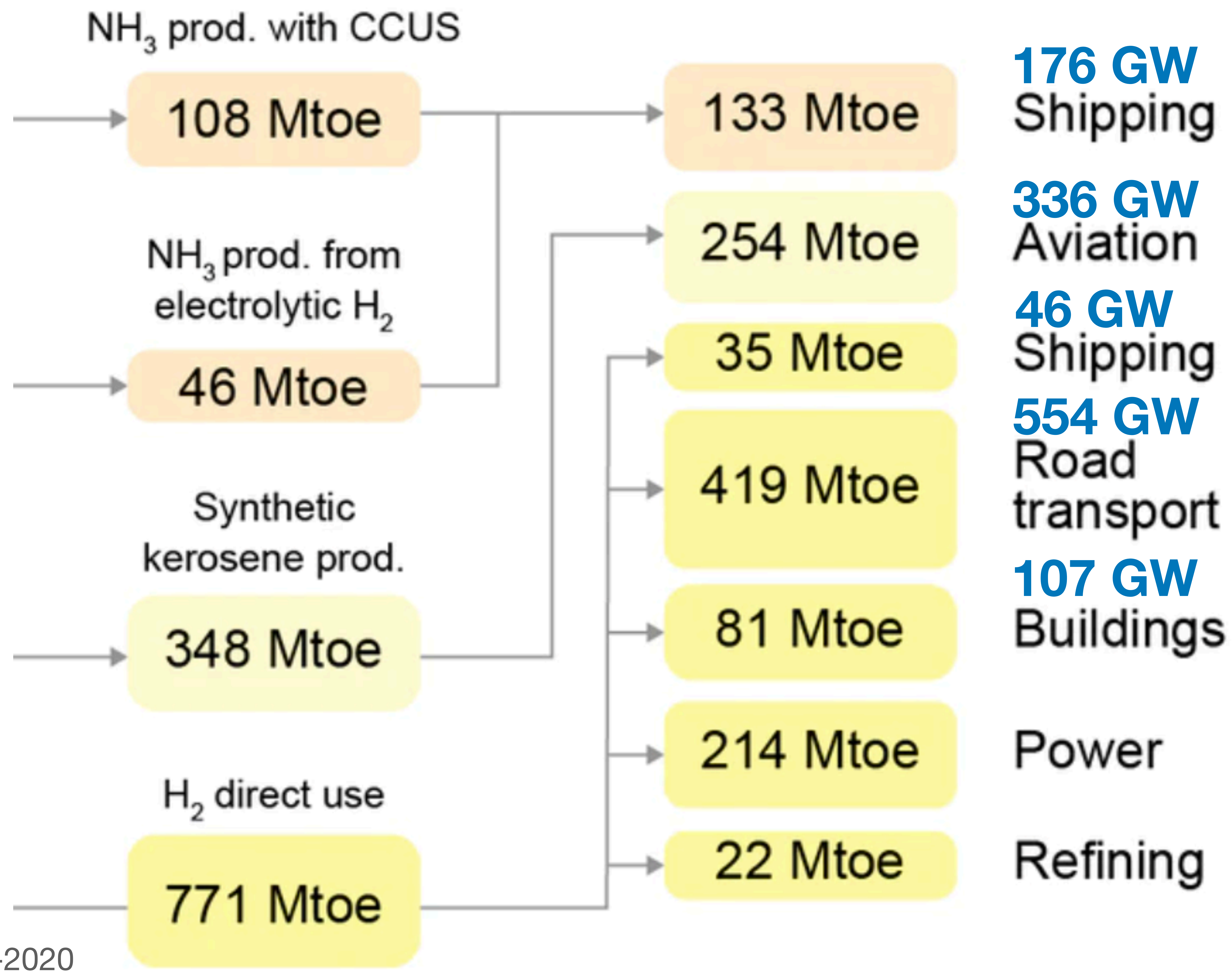
348 Mtoe/year **kerosene** = **462 GW** aviation fuel

771 Mtoe/year **hydrogen** = **1000 GW** H2 fuel

Note expectation of CCUS, carbon capture underground storage

Hydrogen-based fuel production

Use of hydrogen, hydrogen-based fuels



https://www.iea.org/reports/energy-technology-perspectives-2020

Lucid Catalyst fossil fuel replacement strategy.

1. **Clean hydrogen**, as fuel or feedstock.
2. **High temperature electrolysis**, to make hydrogen at 95% efficiency.
3. **Cheap electricity**, source of hydrogen energy.
4. **Full-time operation**, to minimize capital costs.
5. **Clean heat**, for industrial processes.
6. **Synfuels**, such as ammonia, for shipping.
7. **Shipyard mass production**, of power plants, electrolyzers, and factories.

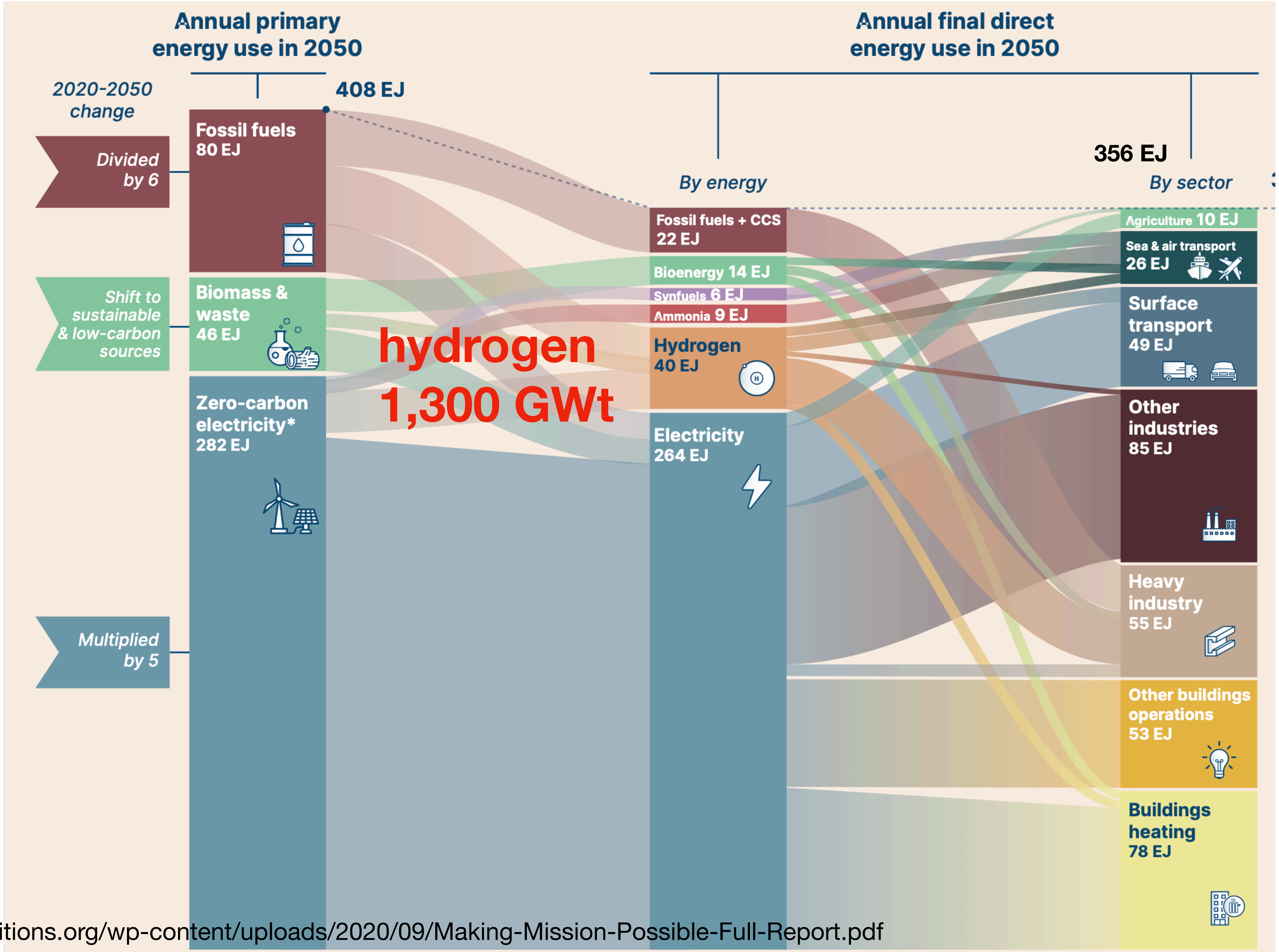
https://85583087-f90f-41ea-bc21-bf855ee12b35.filesusr.com/ugd/2fed7a_0d2e1cc06bff412cb3031fd4bdf93cb0.pdf

Energy Transitions Commission 2050 strategy (RMI, BNEF, ...)

fossil fuels
2,500 GWt

biomass
1,500 GWt

electricity
9,000 GWe



hydrogen
1,300 GWt

total
11,000 GWe

transport
2,400 GWe

lite industry
2,700 GWe

hvy industry
1,800 GWe

bldg ops
1,700 GWe

heating
2,500 GWe

https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Full-Report.pdf

Fission energy grand strategy

Electricity
- Ample, cheap, 24x7 electric power

Transportation
- electrify rail, light vehicles
- synfuels for air, sea, heavy land transport

Buildings
- building codes, heat pumps
- district heating

Industry
- high heat: electric arcs, plasma torches
- new processes, H2 reduction

Key technologies

Liquid fission
- high temp, low press
- liquid fuel

Hydrogen
- water electrolysis

Ammonia
- fuel, fertilizer

Shipyard manufacturing
- fast, efficient
- power plants
- factories

Electrified world power flow