5 Wind and solar power

Fission is in Fashion

CO2 quantities

Cubic mile of oil

Wind and solar costs

Capacity factor

Natural gas dependency

Intermittency

Materials mining

$ trillions per year?

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

Economic suicide?

Don’t end reliable, cheap power before getting a substitute!

Vaclav Smil:

Energy from burning carbon is the basis of civilization.

We need to put in place a different source of reliable, economic energy before removing the old.

https://www.wyodaily.com/photos/big/11242/12

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

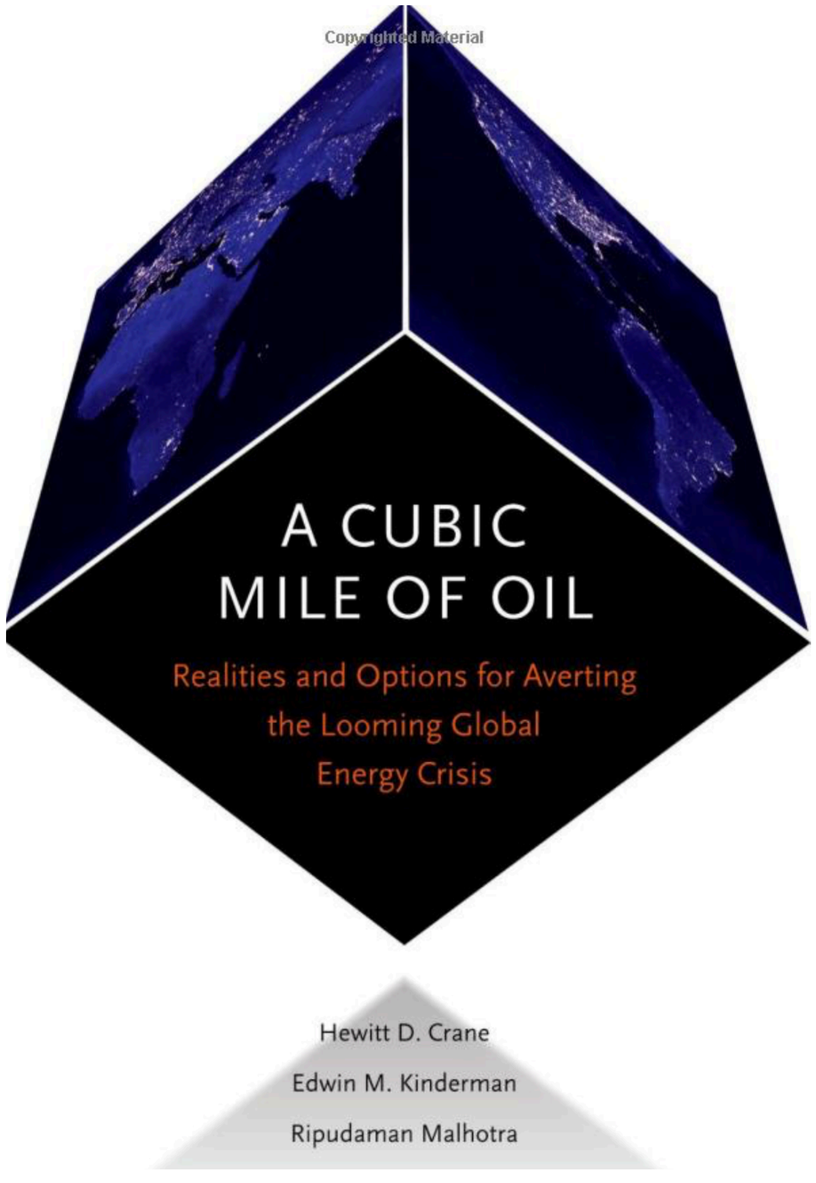
- Potential sink of 0.5 to 1 $GtCO_{2e}/y$, impacting ½ or more of all US forest area (≥ 130 Mha).

Agricultural practices

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

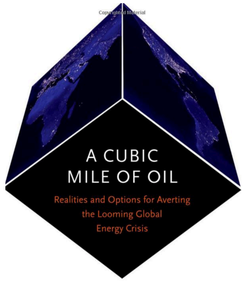
https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Global energy equivalent: 3 cubic miles of oil

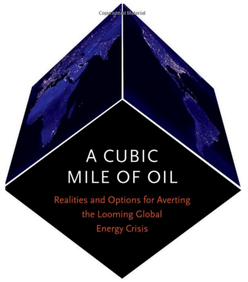


Ripu Malhotra et al, SRI

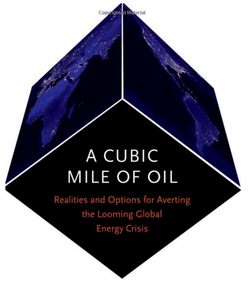
We might supply all the world's energy with ALL of these.



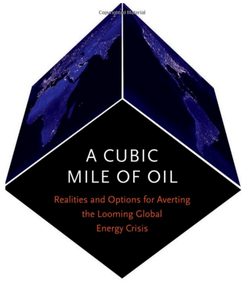
- **Solar Roofs (PV): 4.2 billion**
  - 250,000 roofs per day for 50 years
  - 2.1 kW with 20% availability



- **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

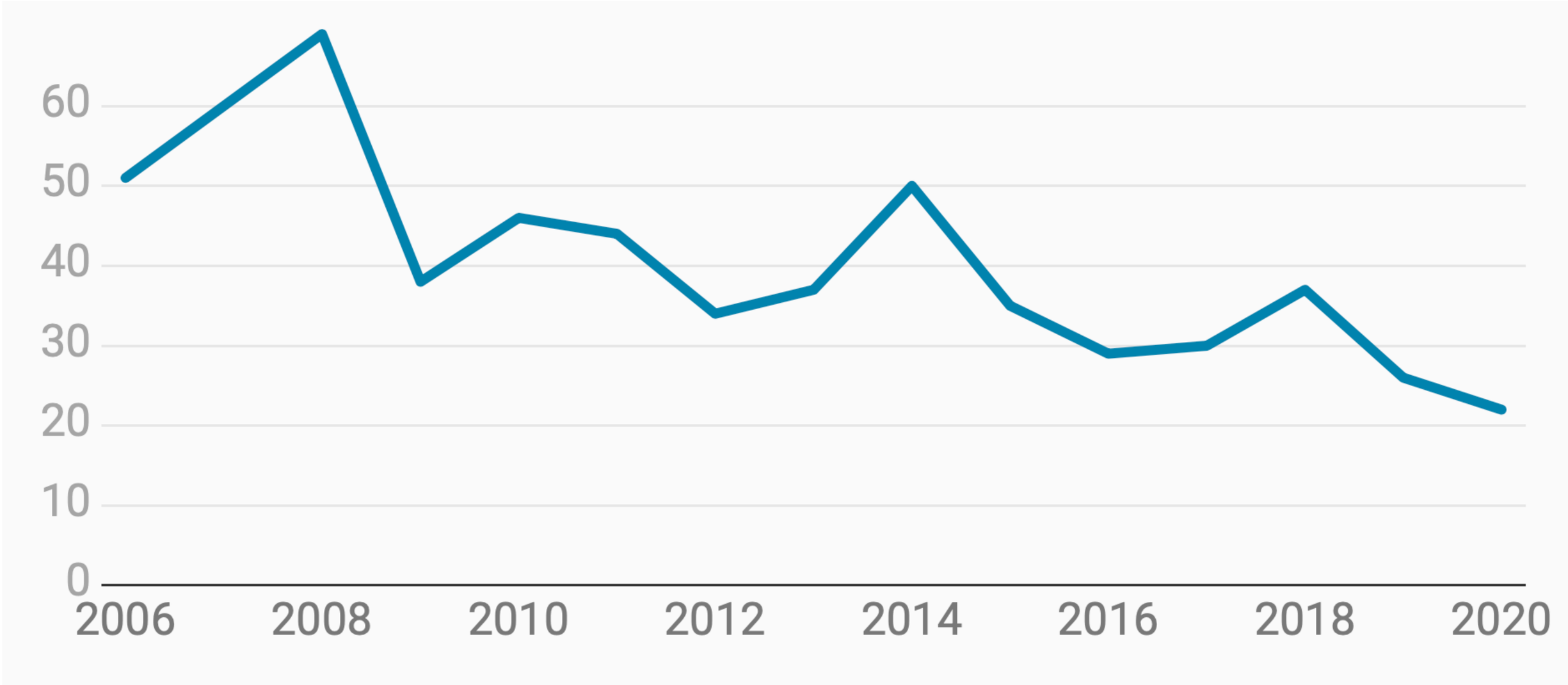


- **Windmills: 3 million**
  - 1200 per week for 50 years
  - 1.65 MW with 35% availability

Energy equivalent of 1 cubic mile of oil

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

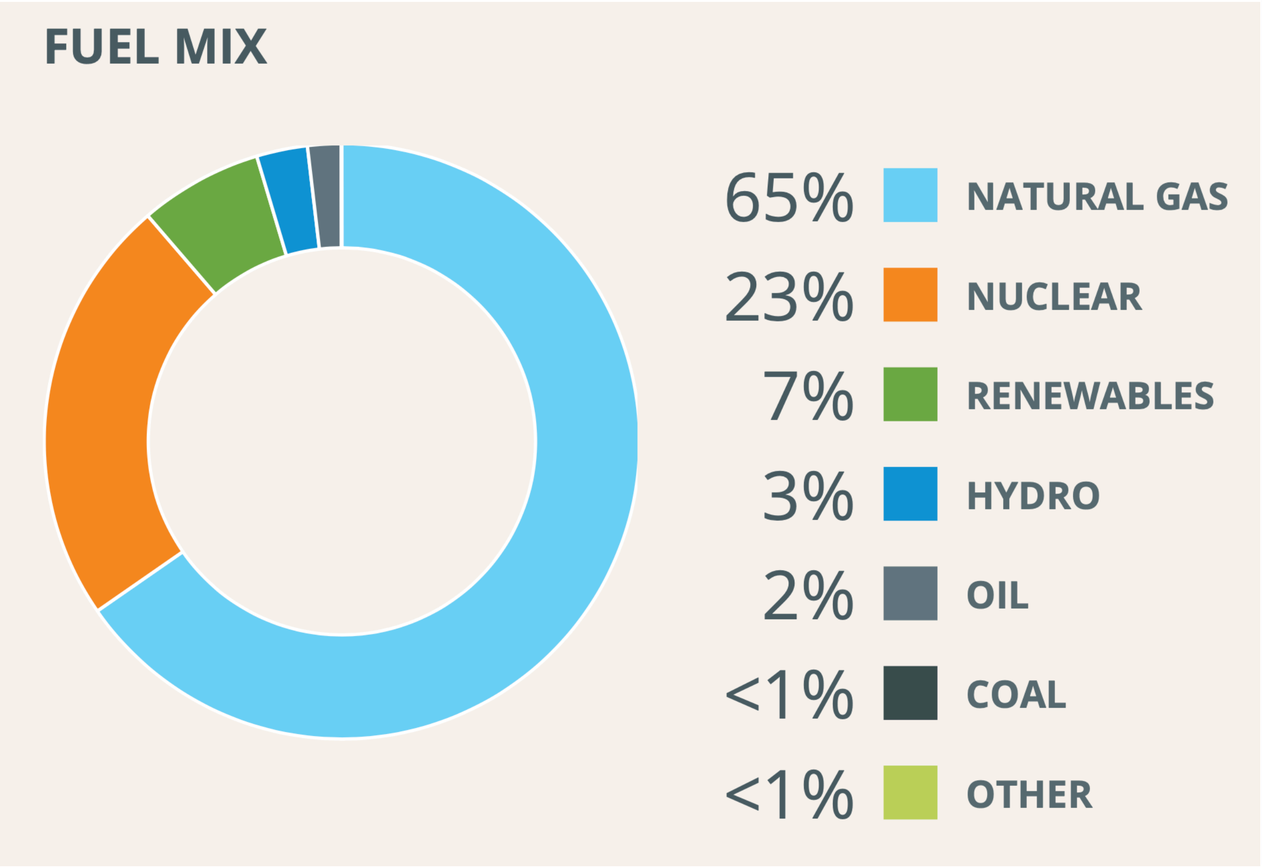
Low natural gas costs dropped electricity prices to ~ 2.5 cents/kWh in US mid-West and mid-Atlantic regions.



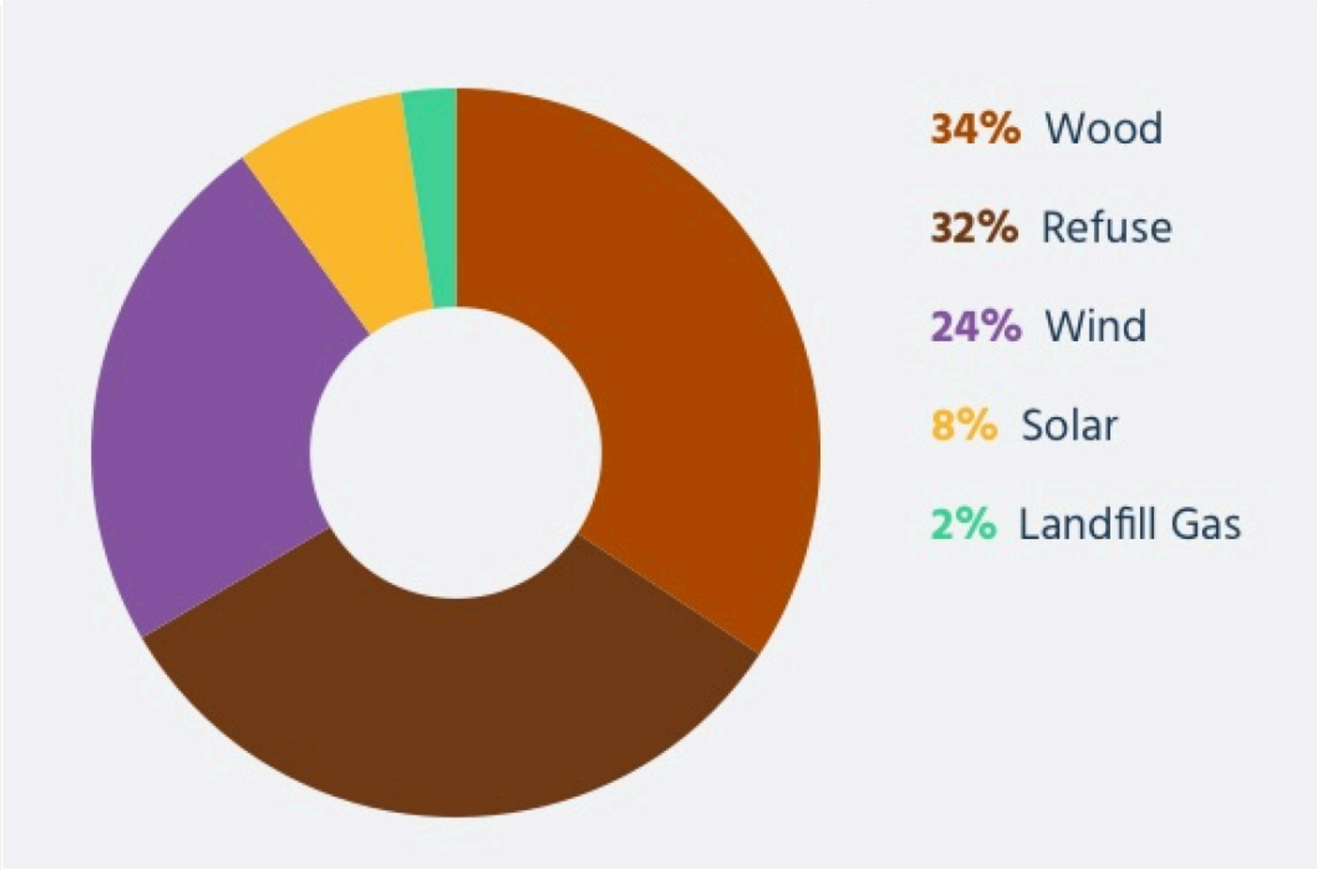
https://www.forbes.com/sites/scottcarpenter/2020/09/30/when-nuclear-plants-ask-for-money-states-find-they-cant-afford-to-say-no/#4d15dc4c4b9b

New England electricity generation 7/8/20

All sources



Renewables, % of 7%



Source: ISO-NE.com

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

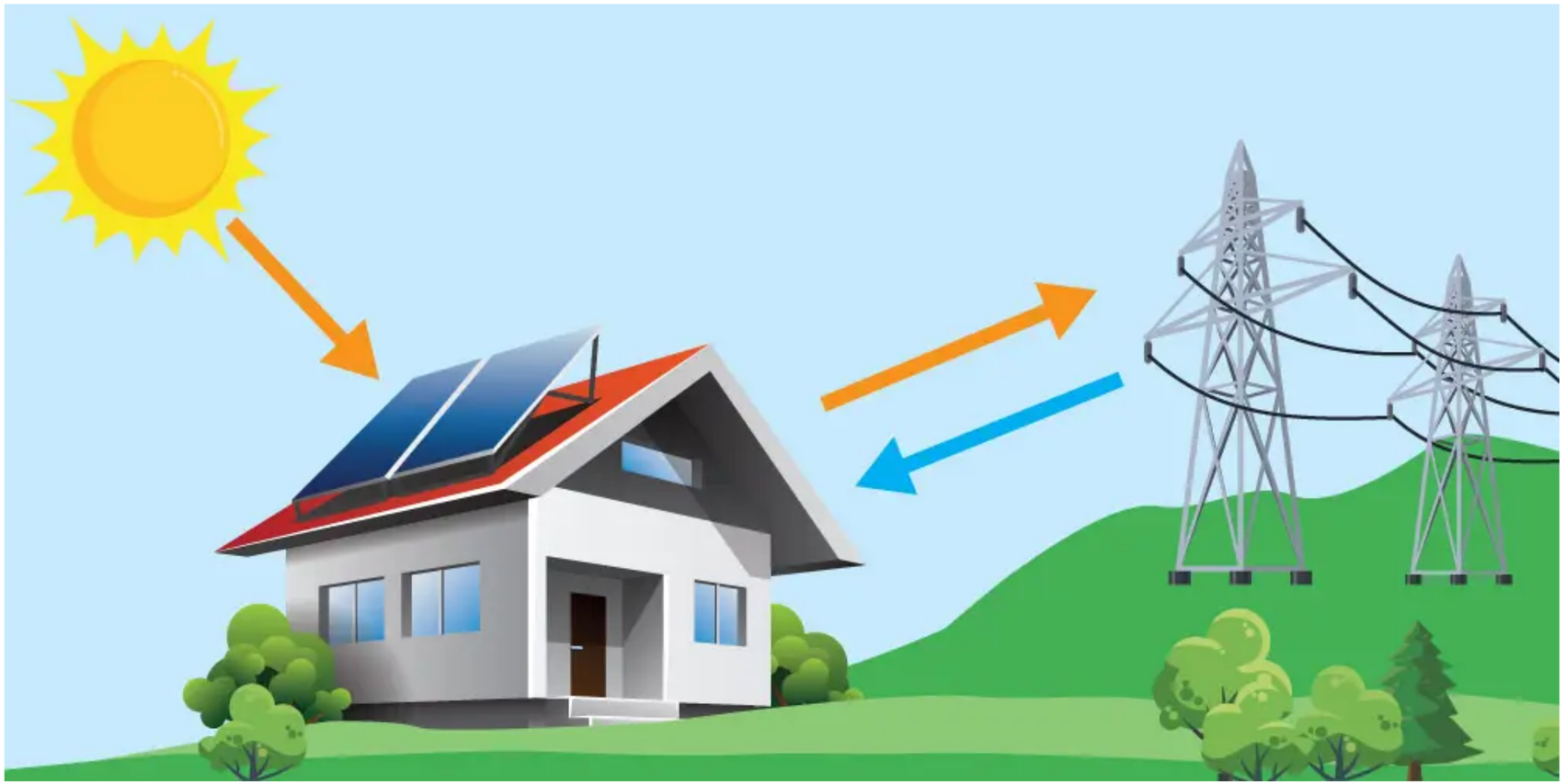
https://www.ysgsolar.com/blog/15-largest-solar-farms-world-2021-ysg-solar

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.



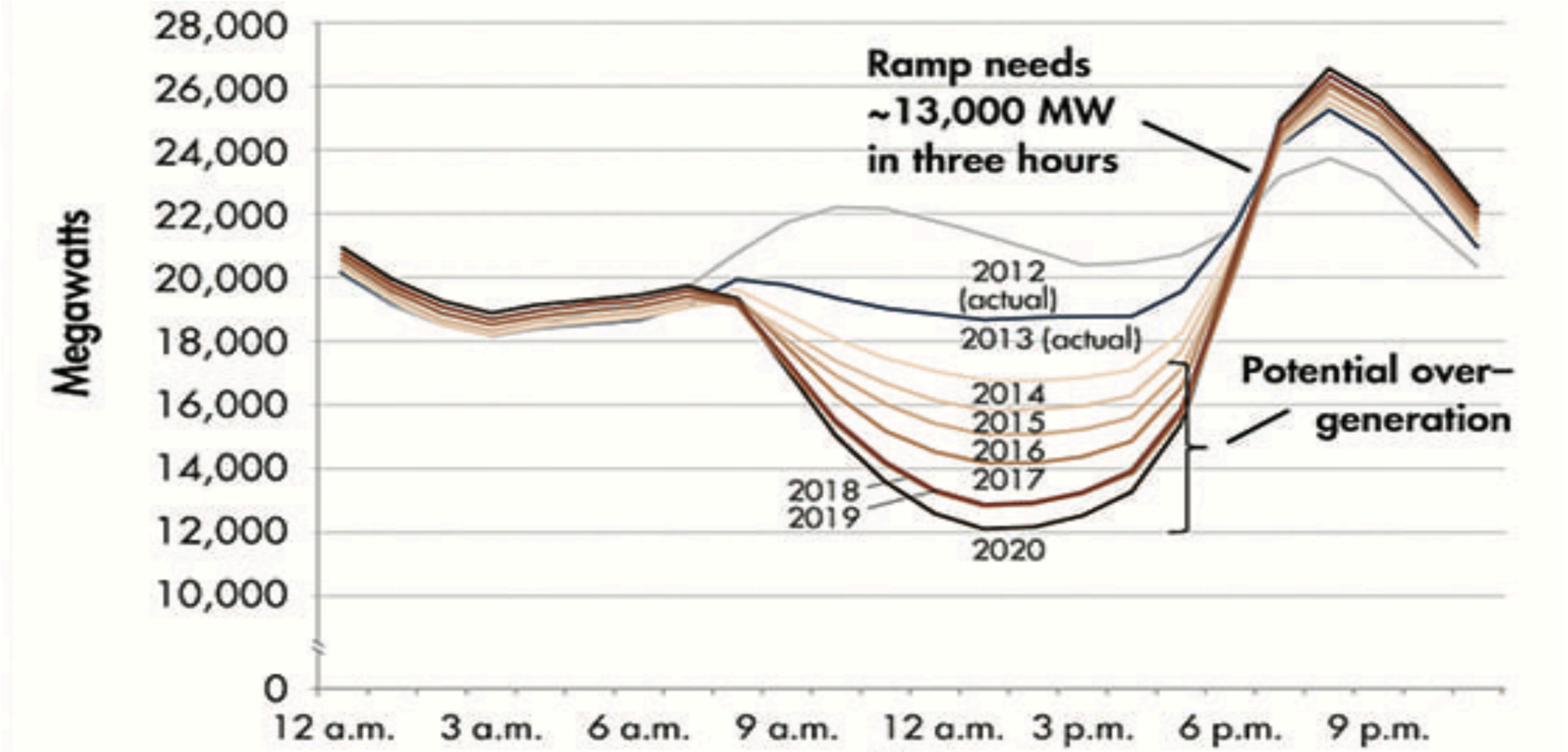
Increases total power costs; paid by other customers.

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”, 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

Duke Energy application points finger at solar for increased pollution

August 14, 2019 | Dan E. Way | For the North State Journal | Features, News

Pictured is the H.F. Lee power plant in Goldsboro, N.C. According to records obtained by NSJ, Duke Energy requested modifications to the air quality permit at the station due to the increasing amounts of solar energy cycling on the grid. (Photo: Duke Energy)

NOx emissions increase as gas turbines start/stop as solar panels stop/start.

Full time	264#/day
Off if sunny	624#/day
Idle if sunny	381#/day

https://nsjonline.com/article/2019/08/duke-energy-application-points-finger-at-solar-for-increased-pollution/

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

Wind energy costs ~ $42/MWh.

US National Renewable Energy Labs, on land @ 42% capacity factor)

https://www.nrel.gov/docs/fy20osti/74598.pdf	2.4-MW Land-Based Turbine ($/kilowatt [kW])	2.4-MW Land-Based Turbine ($/megawatt-hour [MWh])
Turbine capital cost	1,011	20.8
Balance of system	332	6.8
Financial costs	127	2.6
CapEx	**1,470**	**30.3**
Operational expenditures (OpEx) ($/kW/year [yr])	**44**	**12.1**
Fixed charge rate (real) [%]	7.5%	
Net annual energy production (MWh/MW/yr)	3,648	
Net capacity factor (%)	41.5%	
TOTAL LCOE ($/MWh)	**42**	

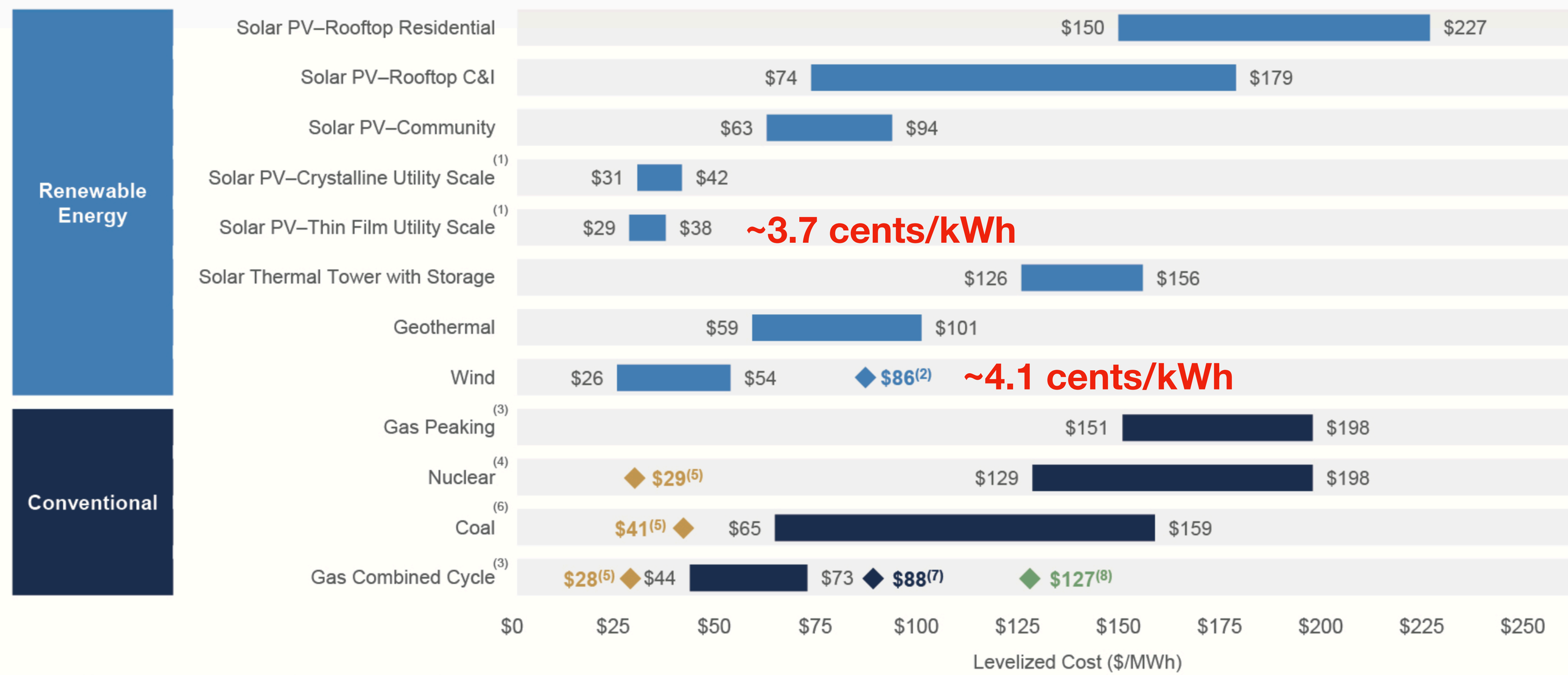
Offshore wind costs ~$89/MWh

(off shore @ 49% capacity factor)

https://www.nrel.gov/docs/fy20osti/74598.pdf	5.5-MW Fixed-Bottom Turbine	5.5-MW Fixed-Bottom Turbine
	($/kW)	($/MWh)
Turbine capital cost	1,301	17.2
Balance of system	2,498	33.0
Financial costs	645	8.5
CapEx	**4,444**	**58.8**
OpEx ($/kW/yr)	**129**	**30.3**
Fixed charge rate (real) [%]	5.6%	
Net annual energy production (MWh/MW/yr)	4,257	
Net capacity factor (%)	48.6%	
Total LCOE ($/MWh)	**89**	

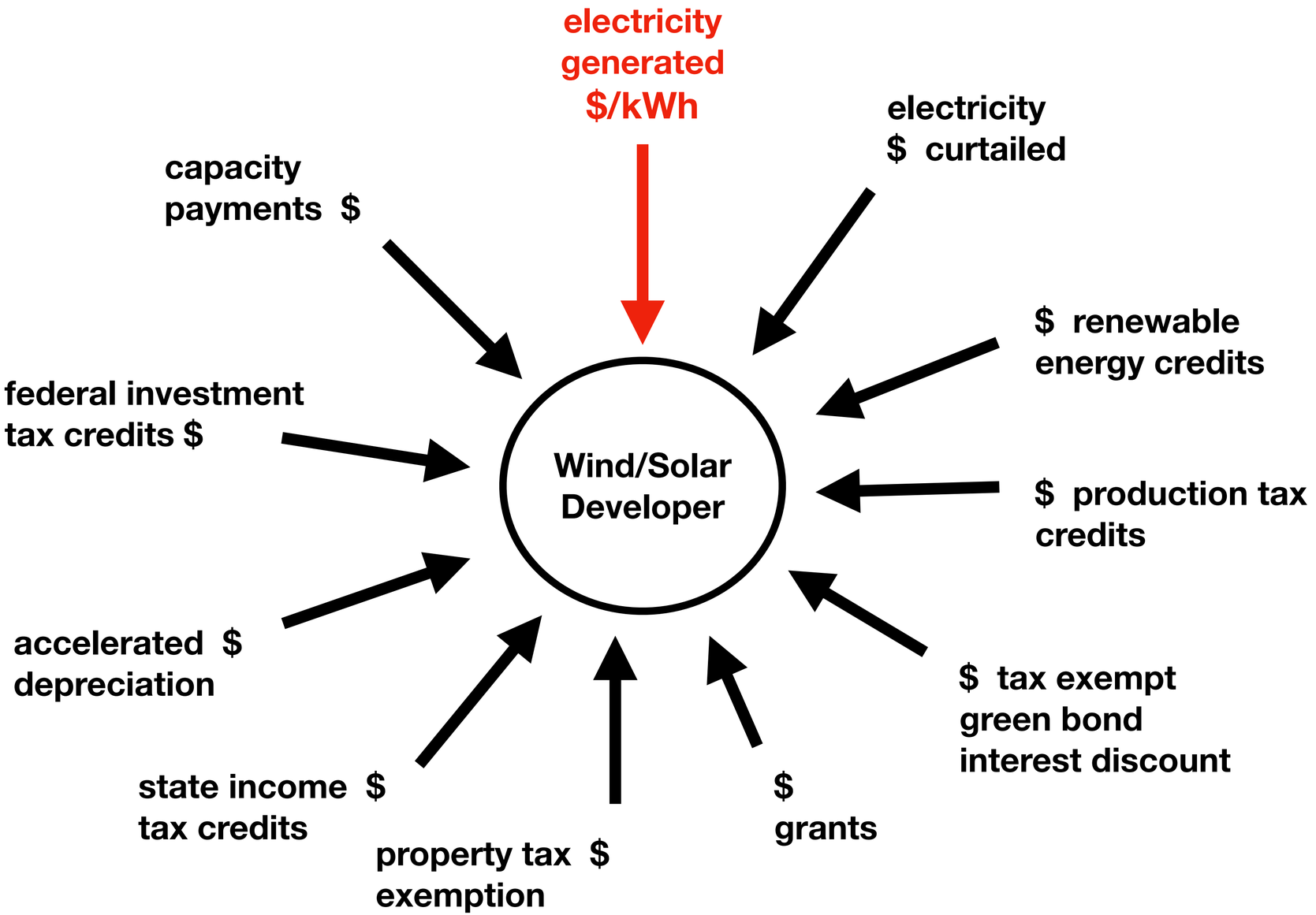
Lazard: levelized cost of electric energy

($100/MWh = 10 cents/kWh)



https://www.lazard.com/perspective/lcoe2020

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



Wind/Solar preferences

Feed-in tariffs

Renewable portfolio standards

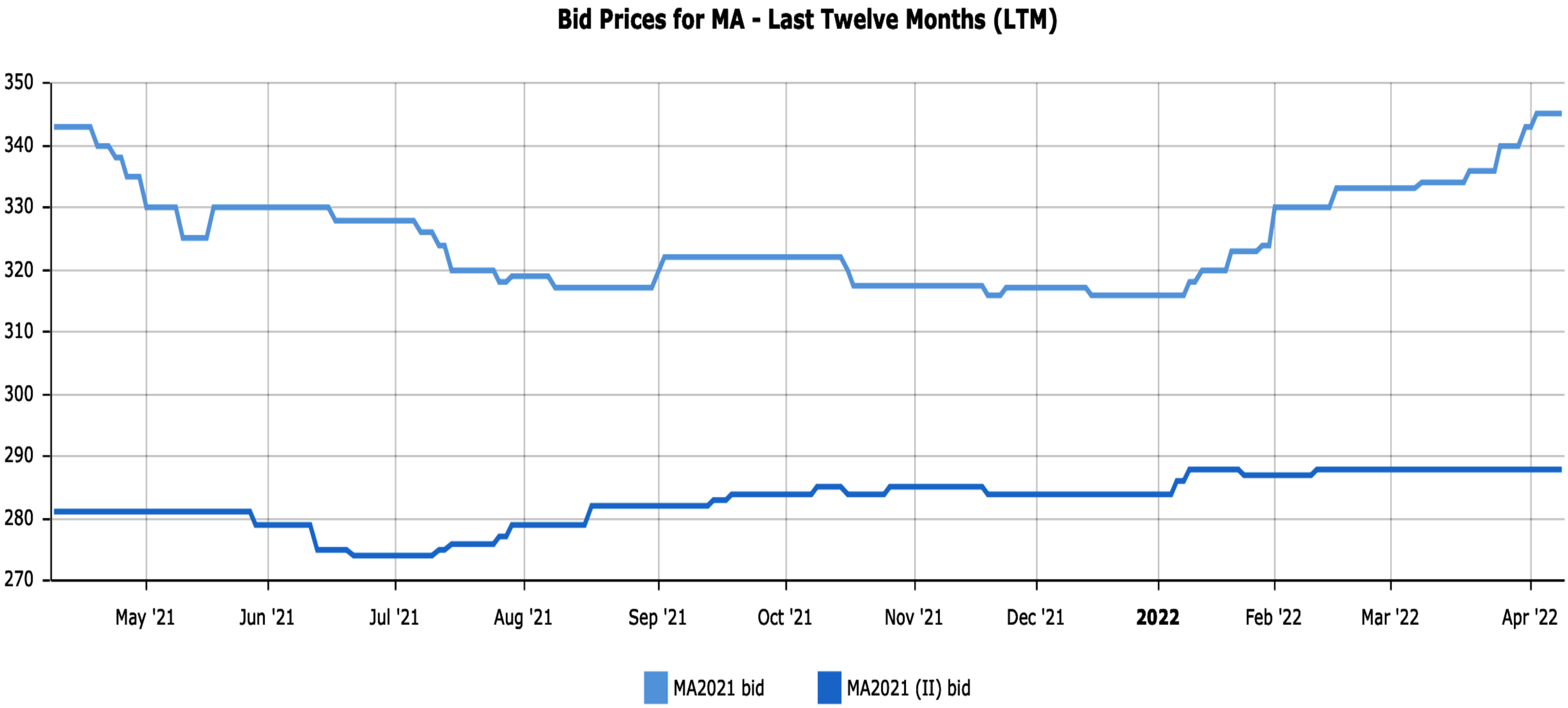
Bird kill examptions

Local zoning overrides

15-50% credit in auctions for firm power capacity

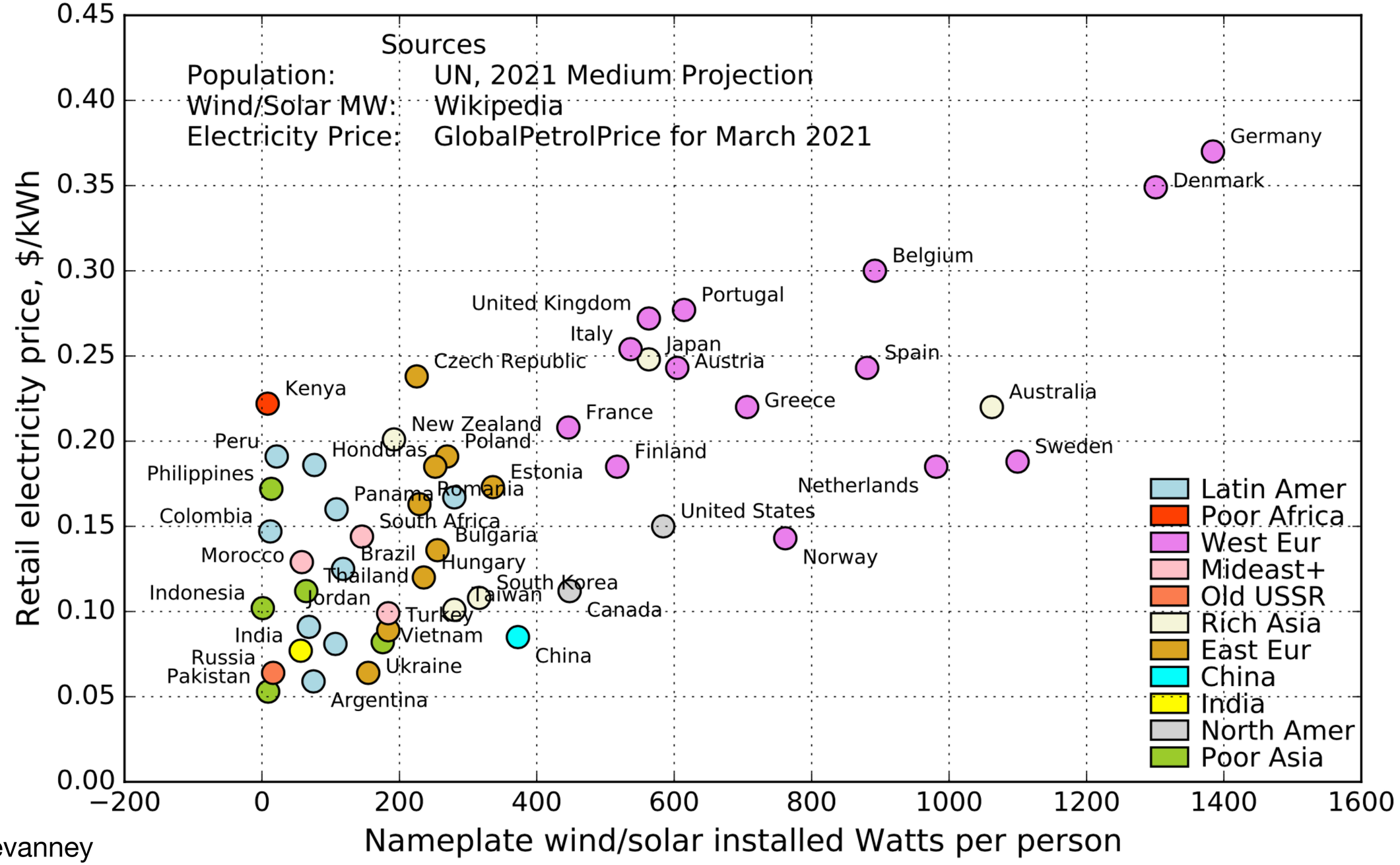
Angwin: Shorting the Grid

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



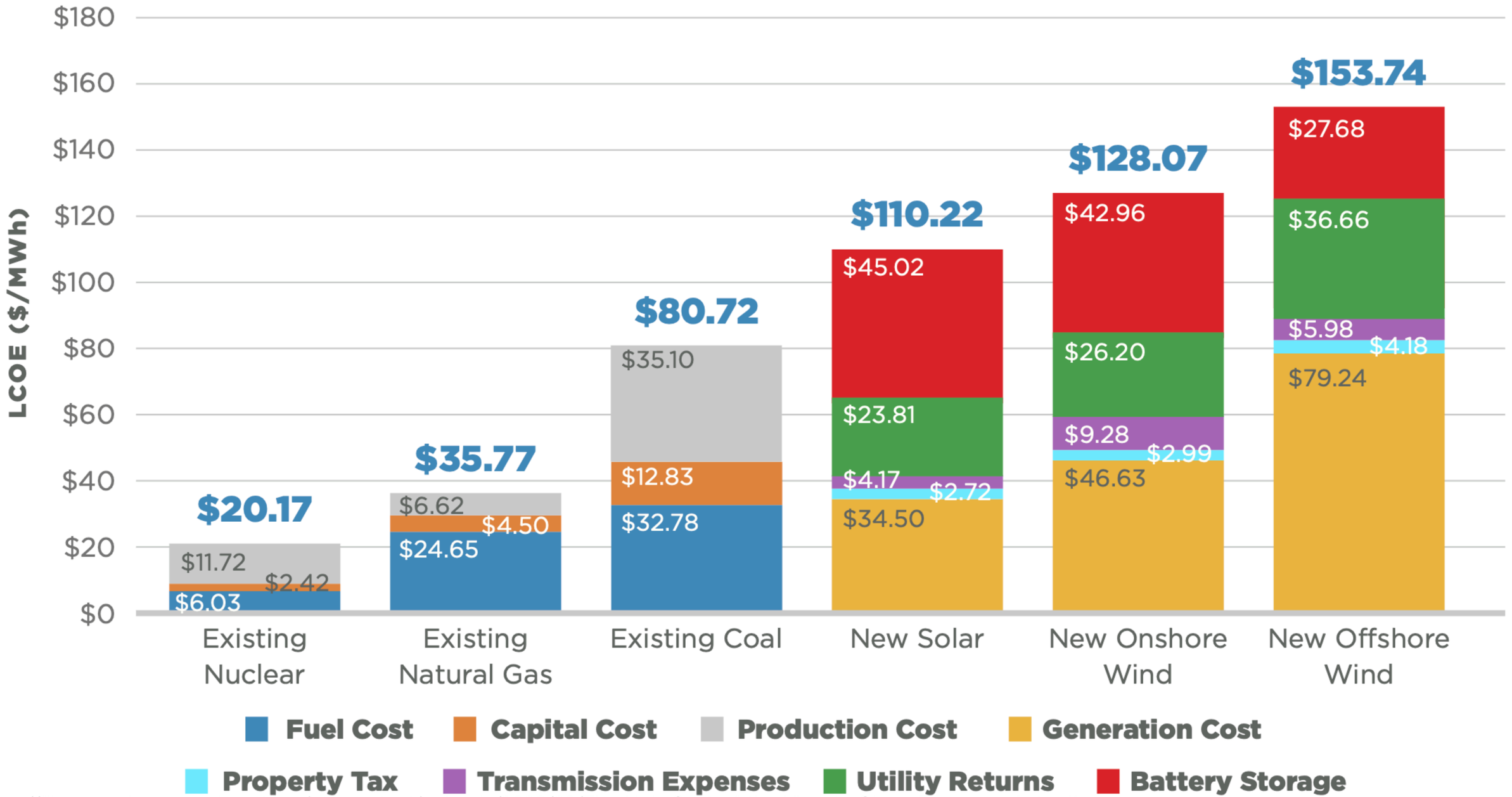
https://www.srectrade.com/markets/rps/srec/massachusetts

Nations supporting wind/solar doubled electricity prices.



Jack Devanney

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

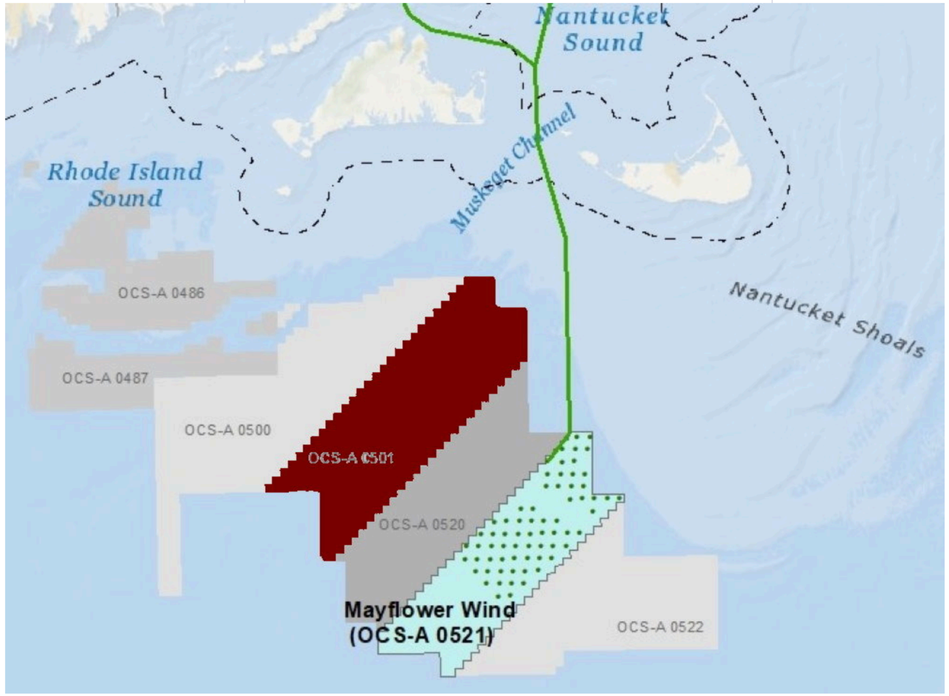
Proposal Mayflower Wind Project 2 (804 MW Low Cost Energy)

- 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] 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)

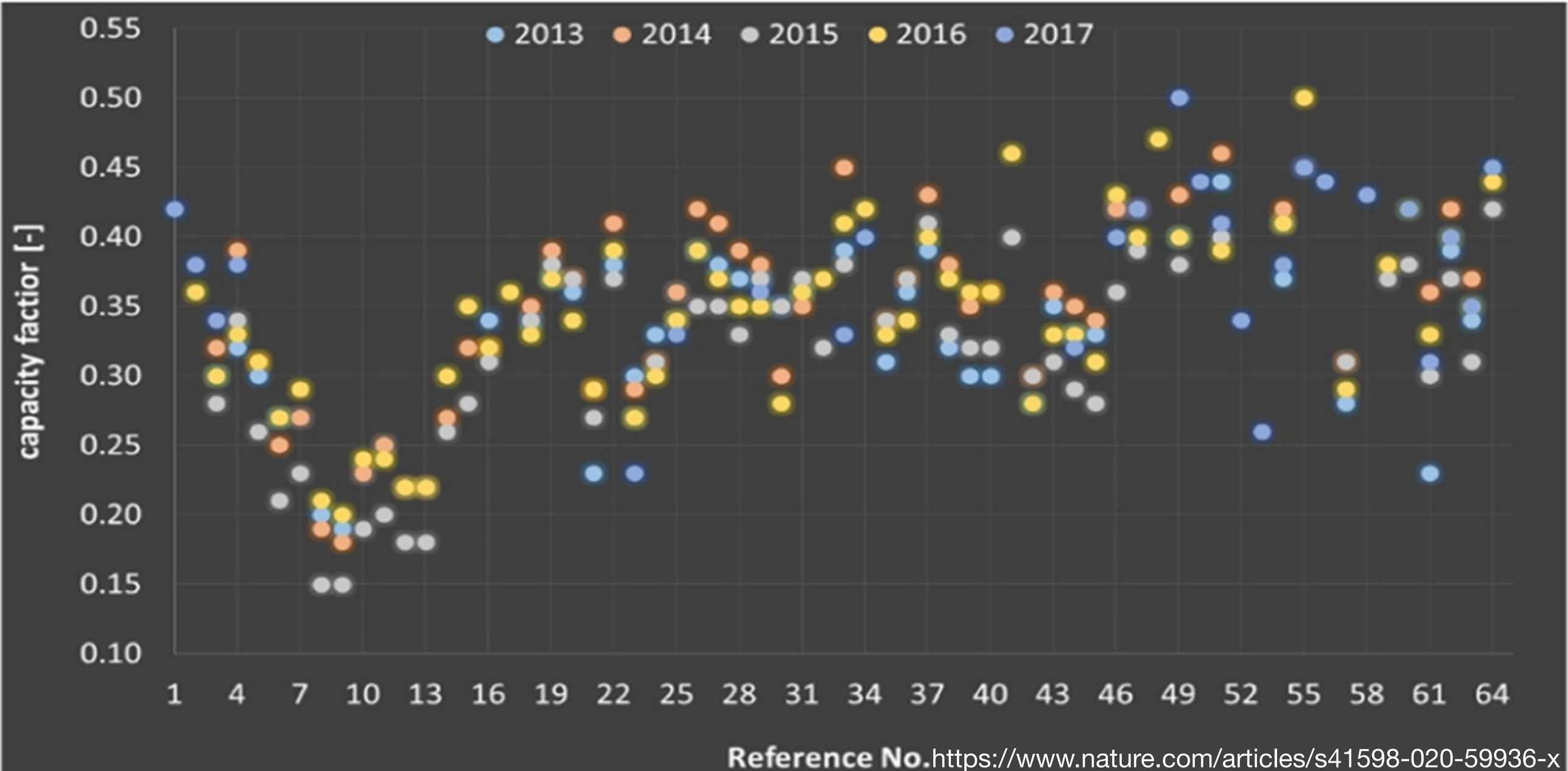
Deepwater signed an agreement with National Grid to sell the power from a $200-million, 30-MW wind farm off Block Island, at an initial price of **24.4 ¢/kWh**

$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.



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

Wind turbines *increase* CO_2 emissions 44%. (2014)

Scenario: Build full-time CCGT? or on/off NGCT for off/on wind?

Turbine type	**Efficiency**	**Start time**	**Cost**
NGCT natural gas combustion turbine	29%	10 min	$700/kW
CCGT combined cycle gas turbine	60%	30 min	$1100/kW

1,000 MW(e) power plant alternatives			
Power source	**Use**	**Efficiency**	**Gas burned**
Wind turbine with	30%	-	-
NGCT	70%	29%	2410 MW(t)
CCGT only	100%	60%	1670 MW(t)

Offshore wind turbines *increase* CO_2 emissions 10%.

Same scenario, 50% wind capacity factor, new 64% CCGT efficiency.

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)
CCGT only	100%	64%	1565 MW(t)

US plans 30 GW offshore wind turbines by 2030.

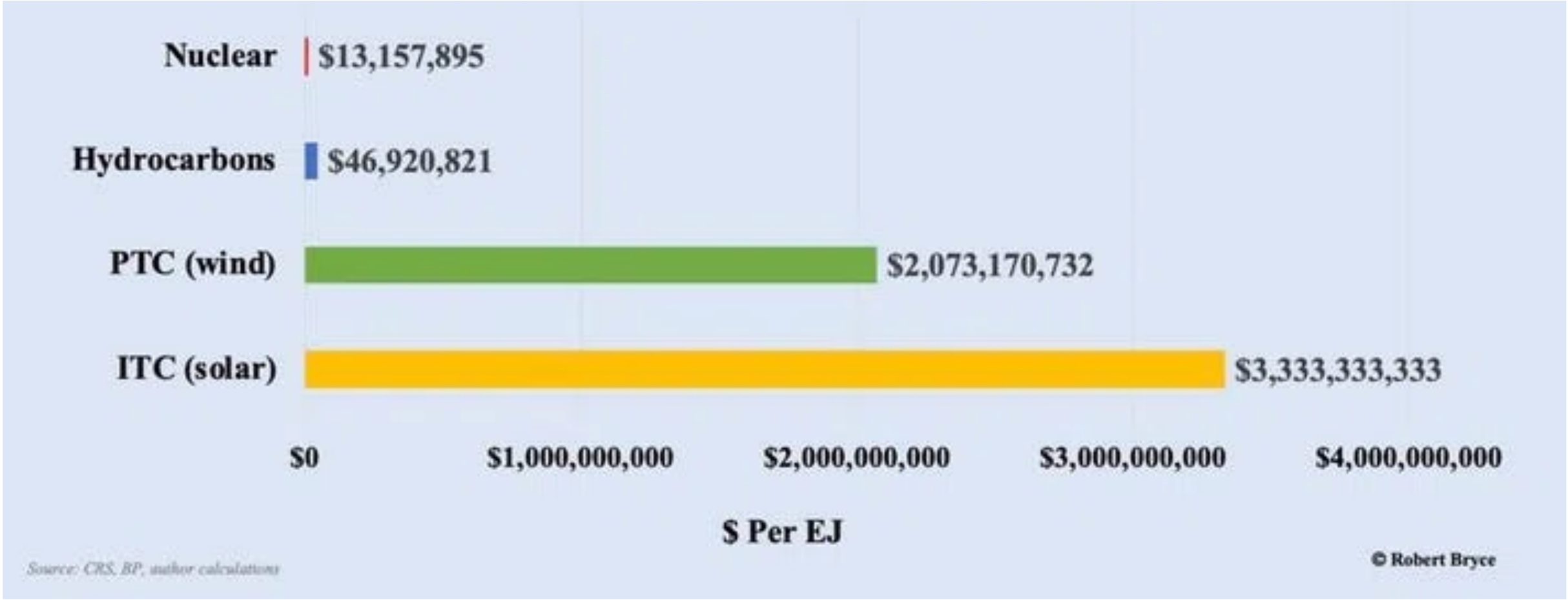
Only one, 30 **MW**, project operating in 2022.

Block Island 5 x 6 MW costing $400 million.

$13 million per MW of wind-dependent capacity.

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

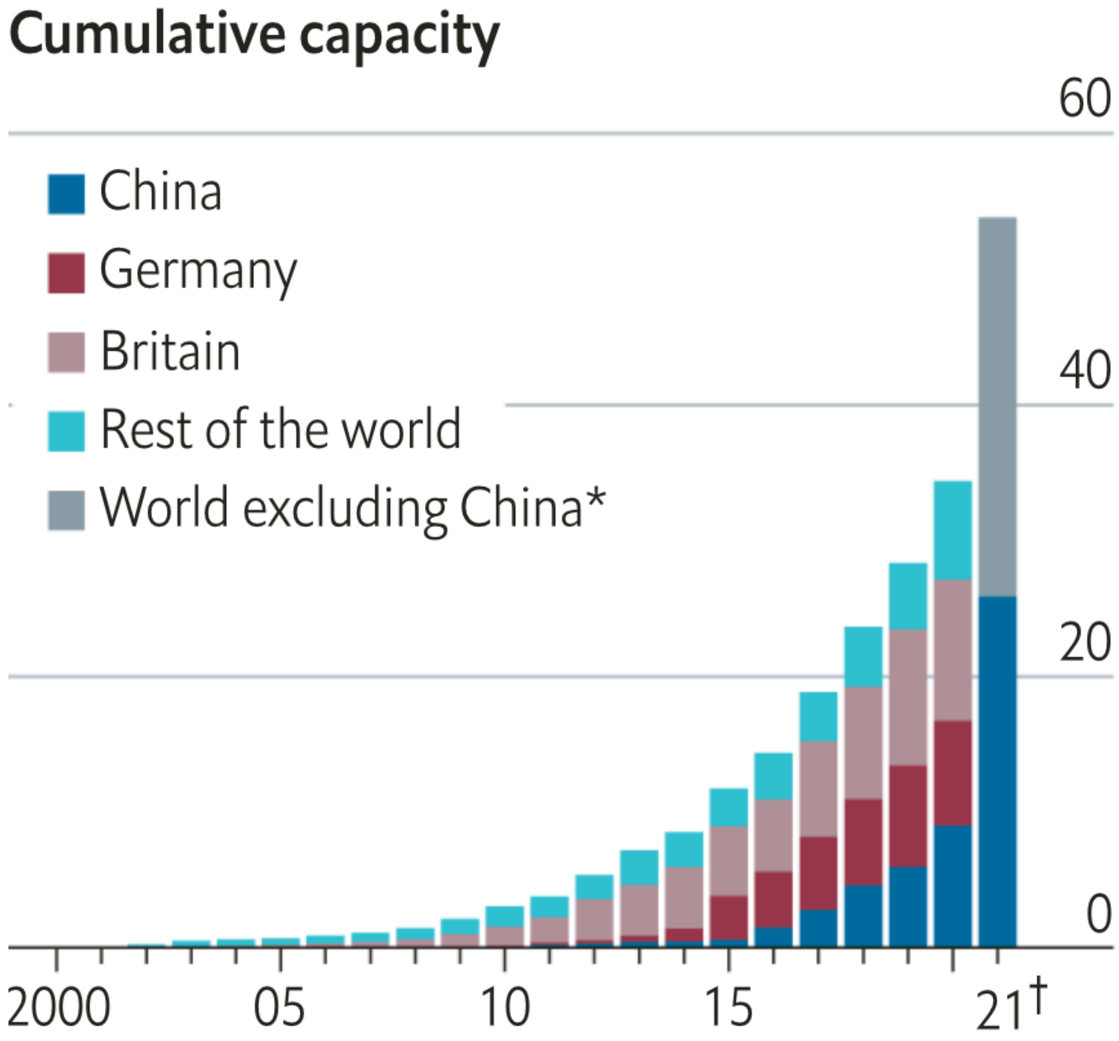
Robert Bryce: 2018 tax incentives per unit energy produced.

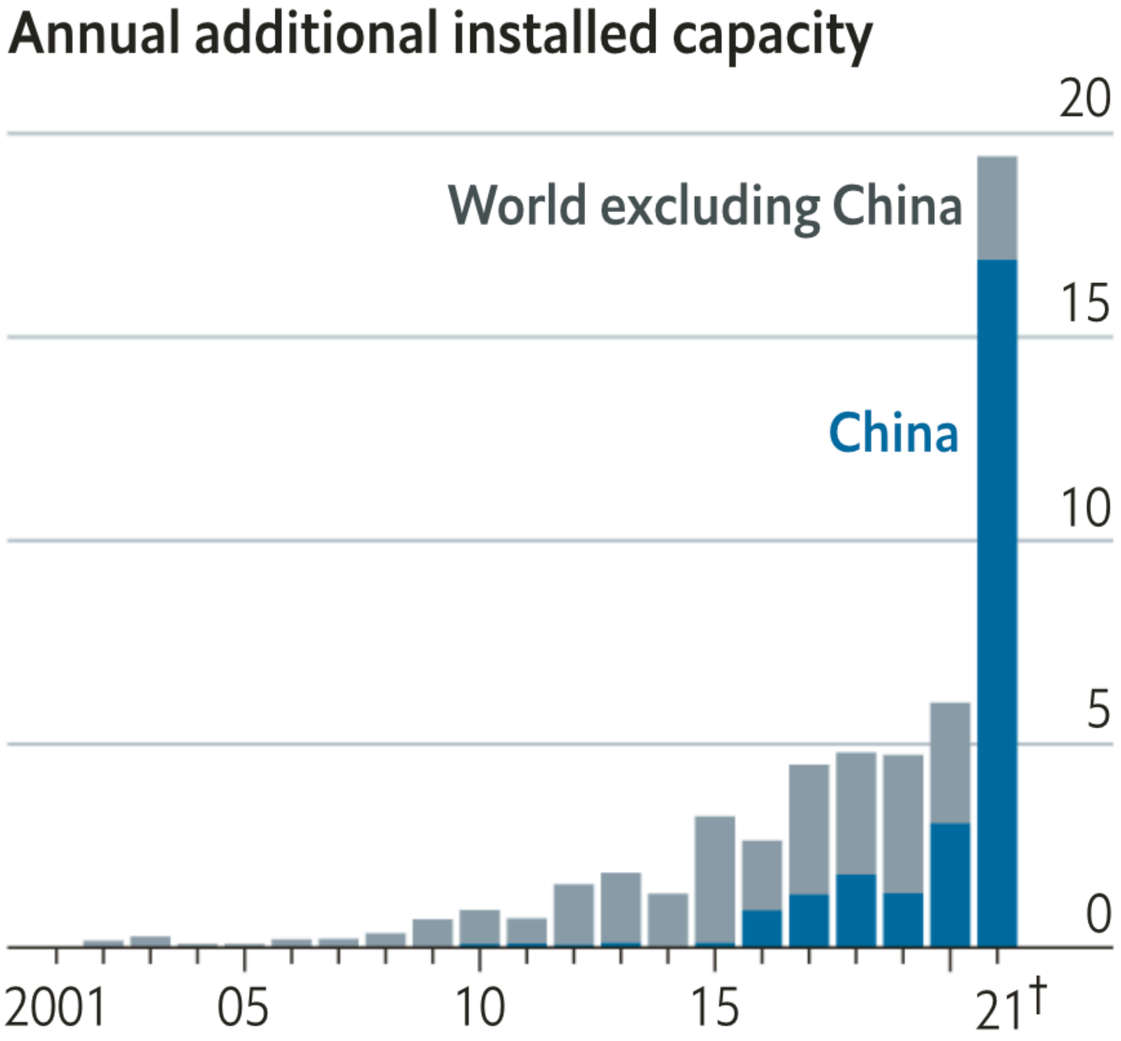


PTC = production tax credit, 2.5¢/kWh; ITC = investment tax credit
1 EJ = 1 exajoule ~ 32 GW-years

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

China added 17 GWe of offshore wind capacity in 2021.

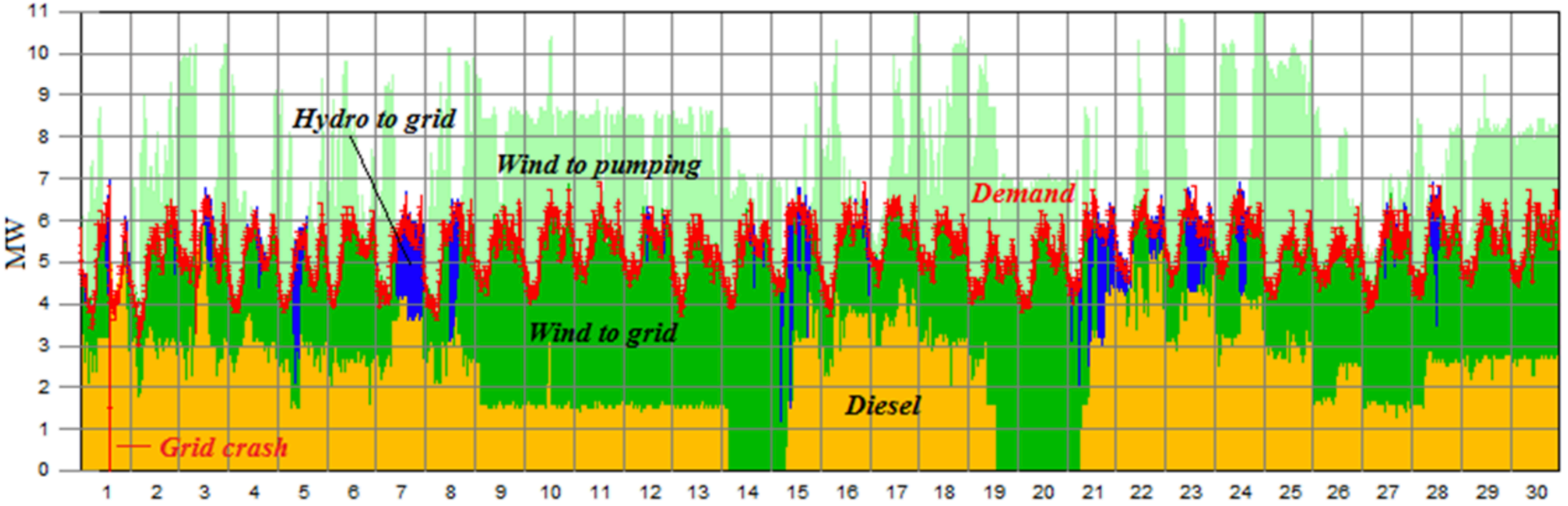




References

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

Three wind turbines with pumped hydro energy storage.



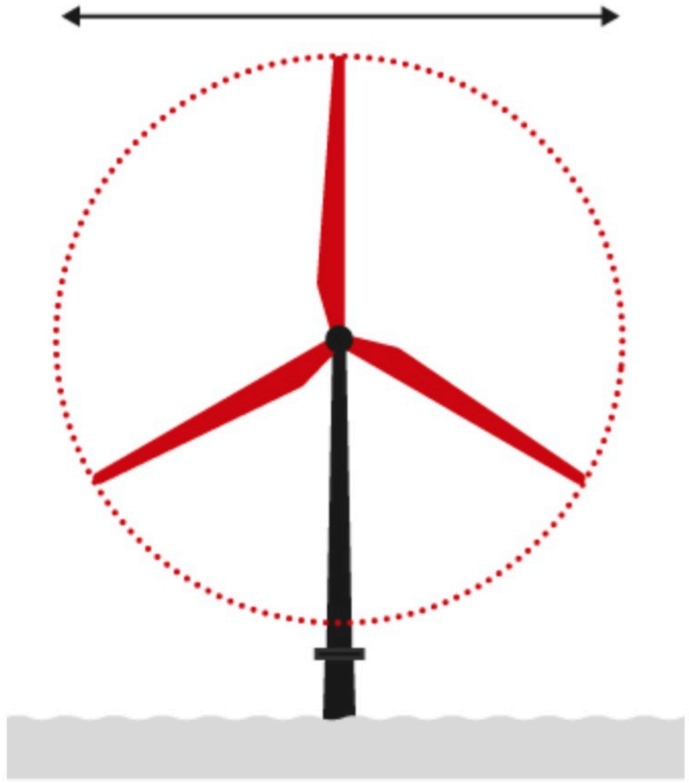
During 2018 it supplied 57% of El Hierro's electricity, though only 28% during 4Q 2018.

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

GE Haliade X
12 MW intermittent

Rotor diameter

220m

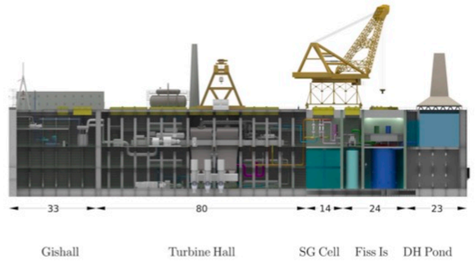


12MW turbine

260m high

ThorCon liquid fission
500 MW full time
length 165 m

to scale



Use batteries to store on/off wind/ solar power?

1 DAY of global energy use requires
1 cubic mile of batteries

- **36 billion Tesla Powerwalls @ 13.5 kWh**
- **Build 1000 per second for 10 years**
- **$250 trillion @ $7,000**
- **$518/kWh of storage**

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
Installation included — 100

Site Location
Earliest deliveries in late 2022 — California

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

“World’s biggest lithium battery storage facility now completely offline after weekend incident.”

100MW/400MWh expansion phase

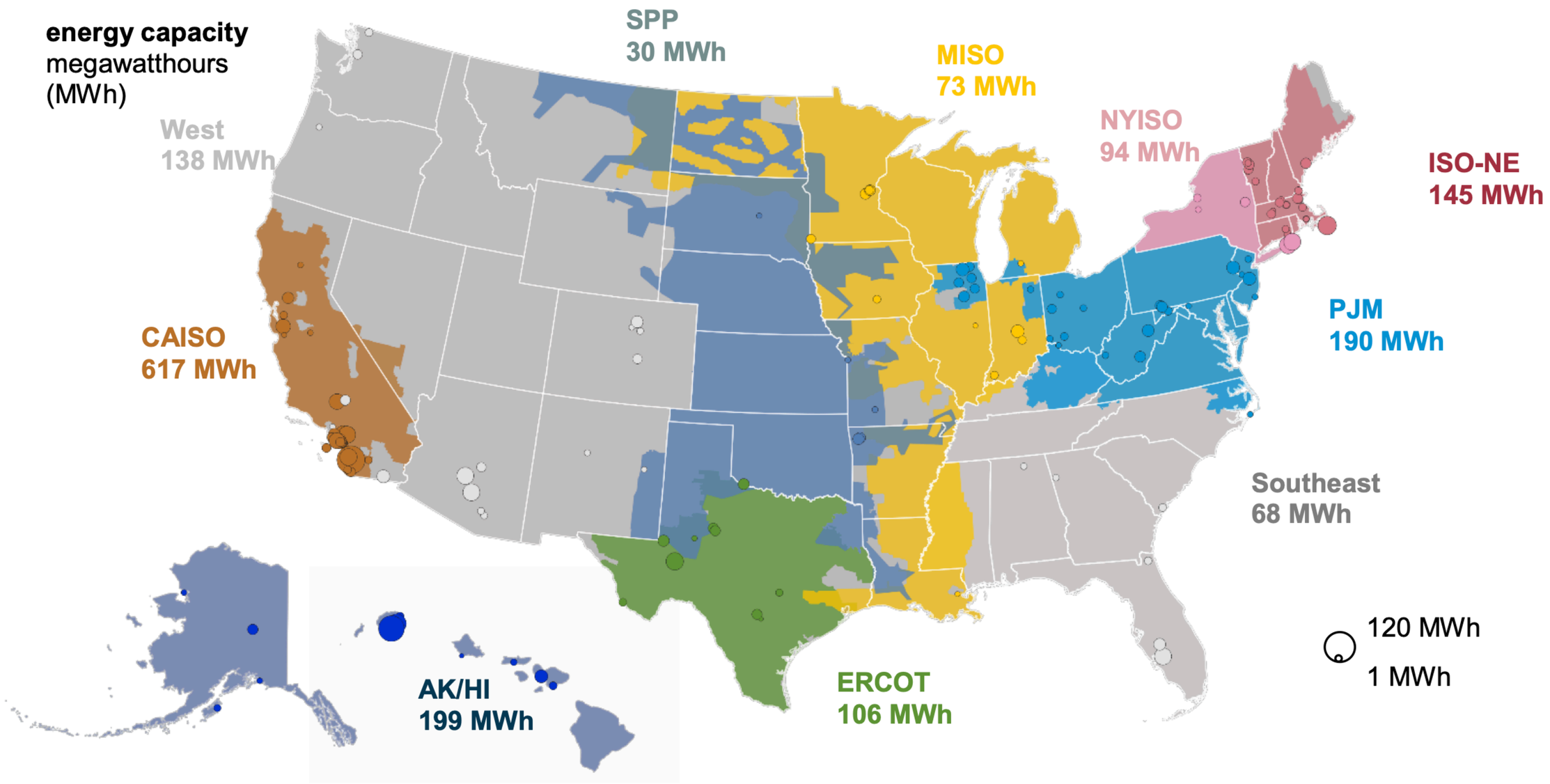
now joins

300MW/1,200MWh Phase I

in being out of action

https://www.energy-storage.news/worlds-biggest-lithium-battery-storage-facility-now-completely-offline-after-weekend-incident/

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



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

Leonardo DiCaprio? *Energy Vault* investment smart?

Do the math: F = m x g, E = F x D

Energy Valult raised $230 million.

Lifts 35 tonne blocks to store energy, lowers them to generate elecricity.

Force (neutons) = 9.8 x mass (kg)
Joules = Force x 100 meters (lift)
kWh = 1000 x 60 x 60 x joules

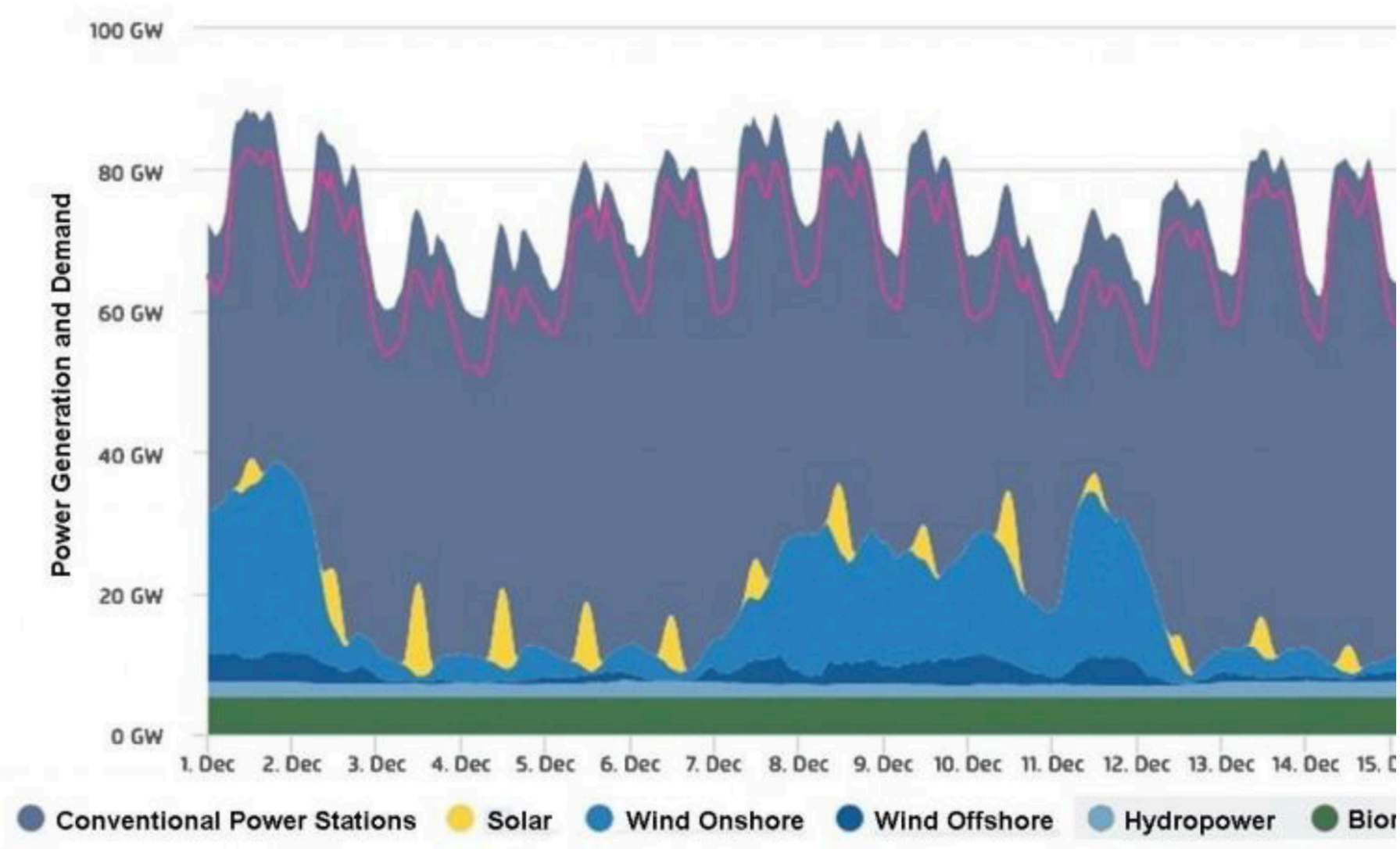
One lift stores 9.5kWh(e). [50¢ worth]

< $3400 for Tesla@$358/kWh?

4 GWh storage worth $1.4 billion?

https://spectrum.ieee.org/gravity-energy-storage-will-show-its-potential-in-2021

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

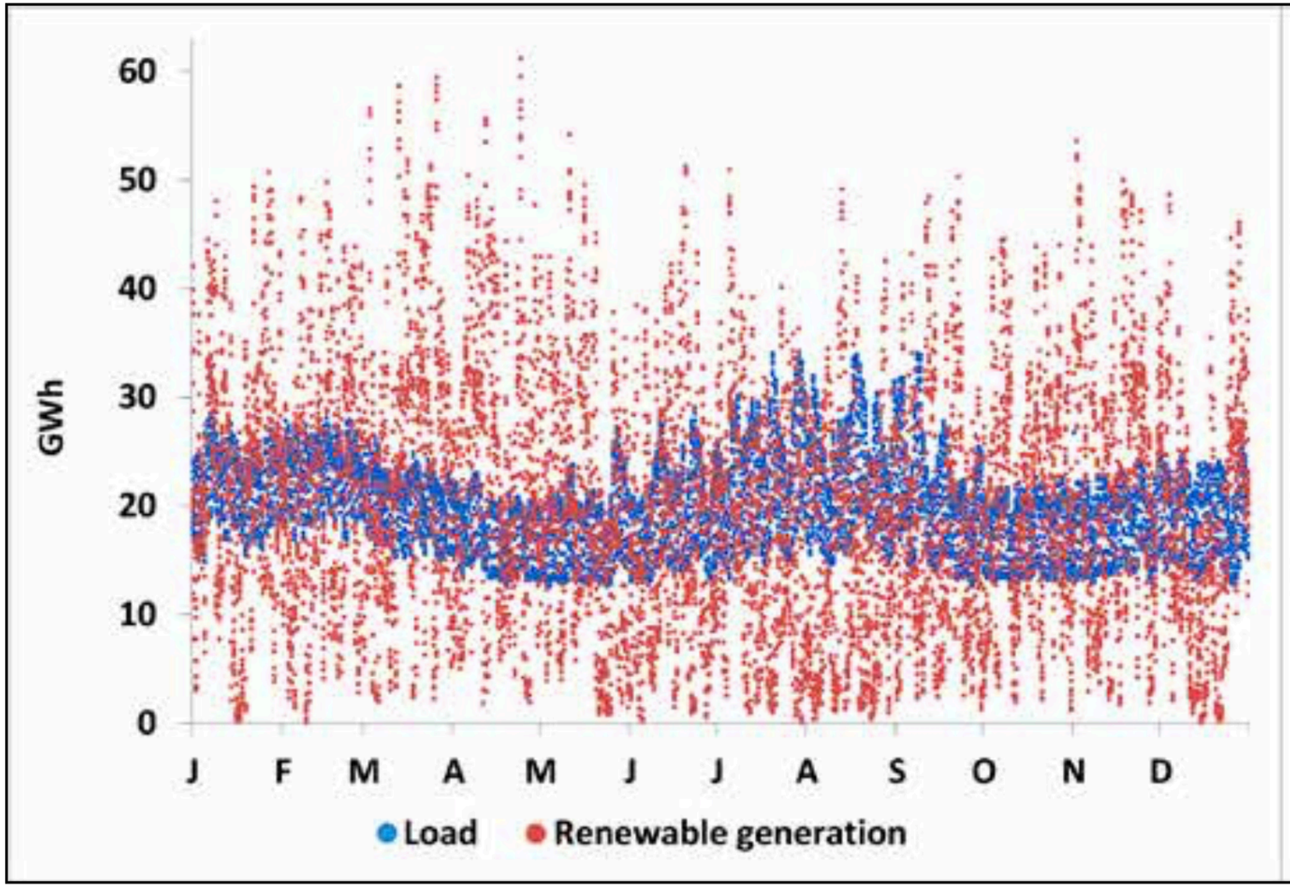


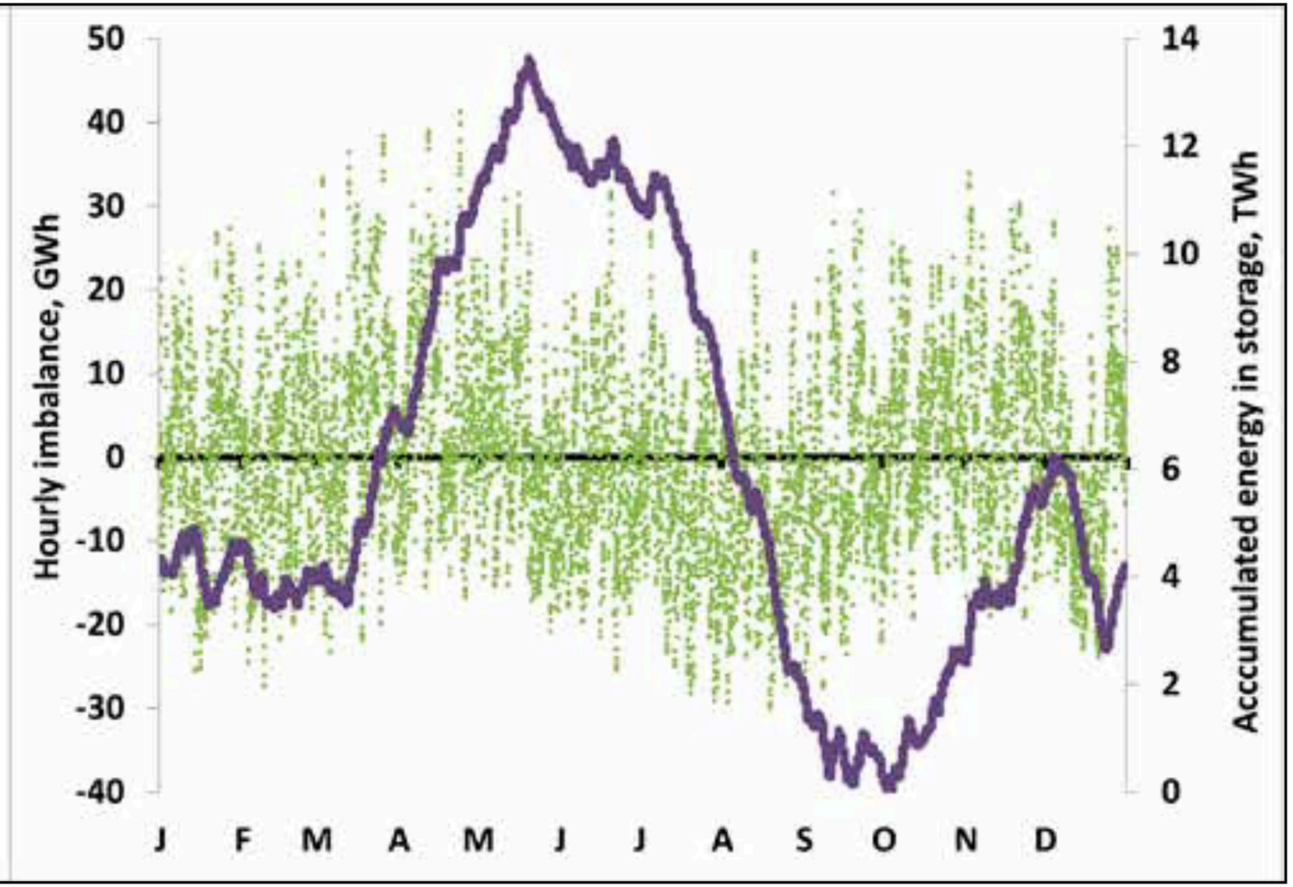
Wind and solar supplied just 2% of nameplate capacity.

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

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



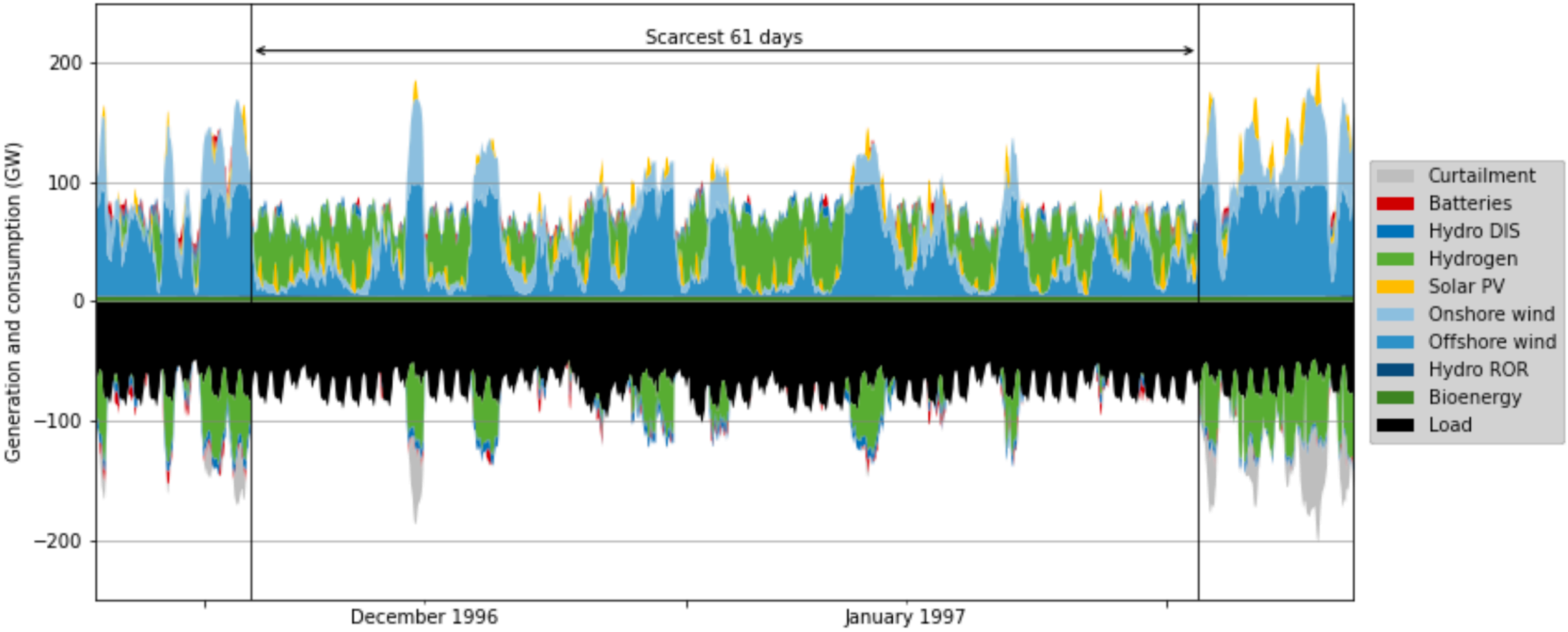


- Actual 2018 hourly electricity demand, sun, and wind possible energy
- Tesla Megapack batteries @ $358/kWh
- 13,000 GWh x $358/kWh ~ $4.7 trillion

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

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

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

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

China produces 41% of cathodes and 71% percent of anodes used in EV batteries; the US essentially none of such key components.

The West's Delusion of Energy Independence

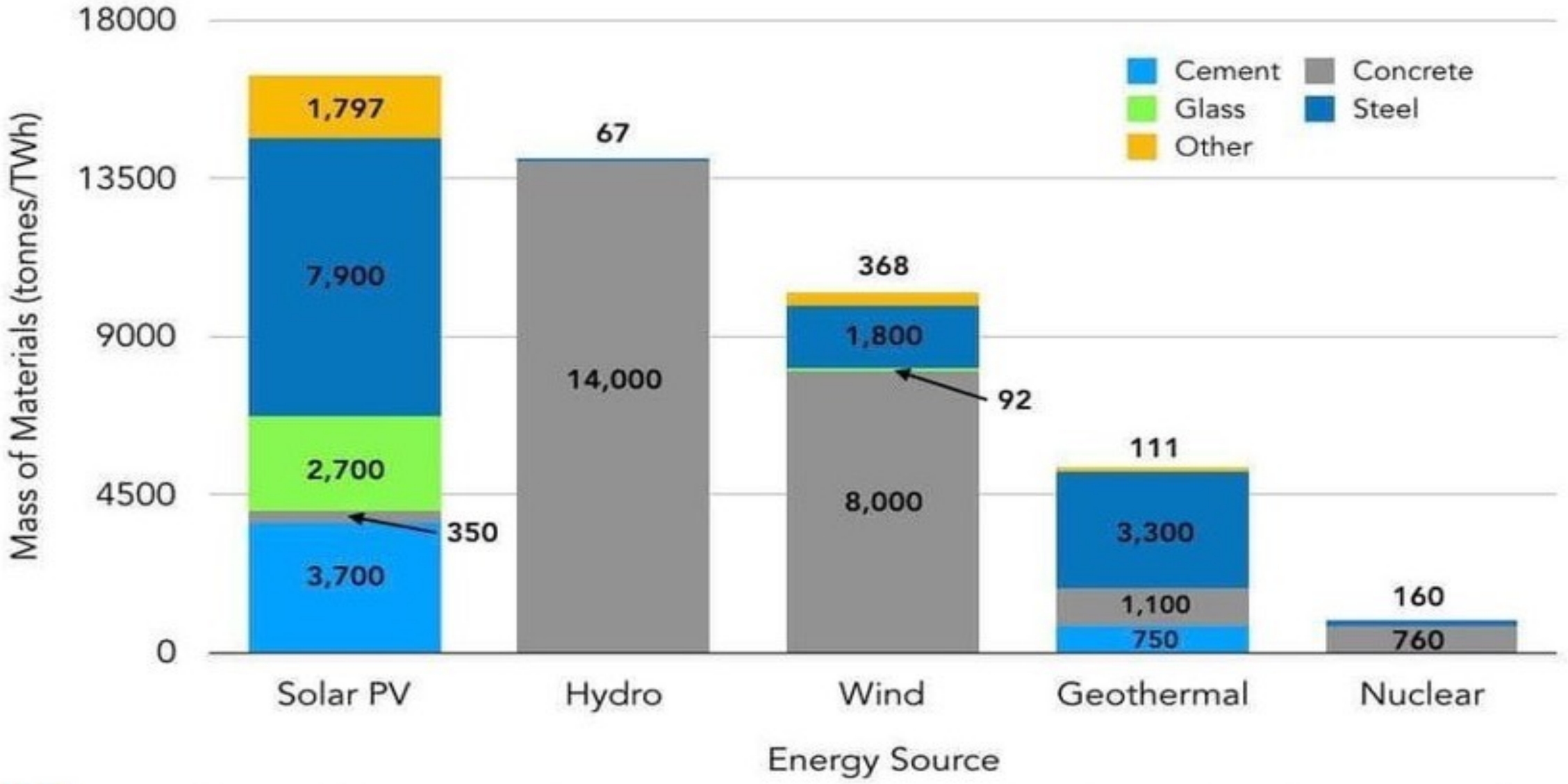
Feb. 22, 2022, 5:00 a.m. ET

The receiving station for the Russian-owned Nord Stream 2 natural gas pipeline near Lubmin, Germany. Sean Gallup/Getty Images

Electric vehicle batteries at a workshop in Nanjing, in the Jiangsu Province of China. Xu Congjun/VCG, via Getty Images

https://www.nytimes.com/2022/02/22/opinion/russia-ukraine-energy-conflict.html

Materials used per TWh generated, by energy source



"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.

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

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

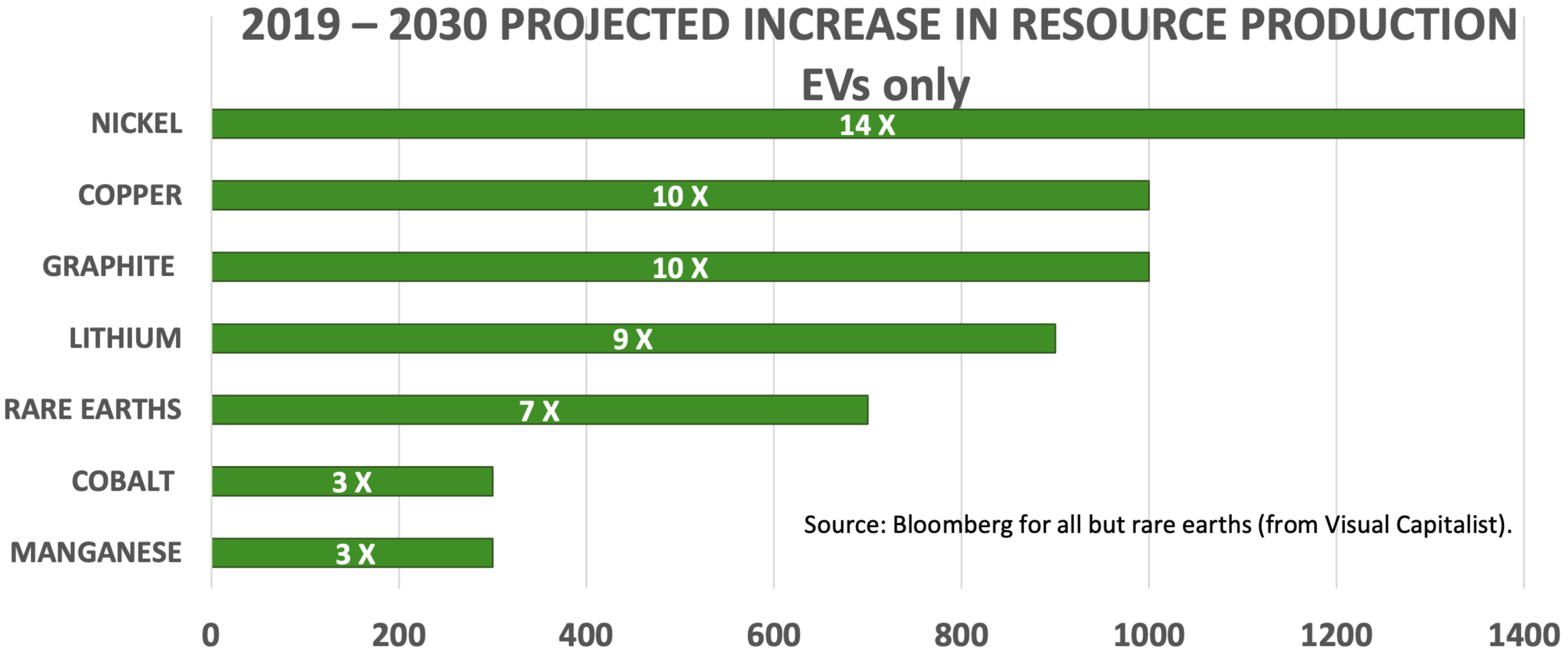
Large trucks bring steel and other raw materials to the site, earth-moving equipment beats a path to otherwise inaccessible high ground, large cranes erect the structures, and **all these machines burn diesel fuel.** So do the freight trains and cargo ships that convey the materials needed for the production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

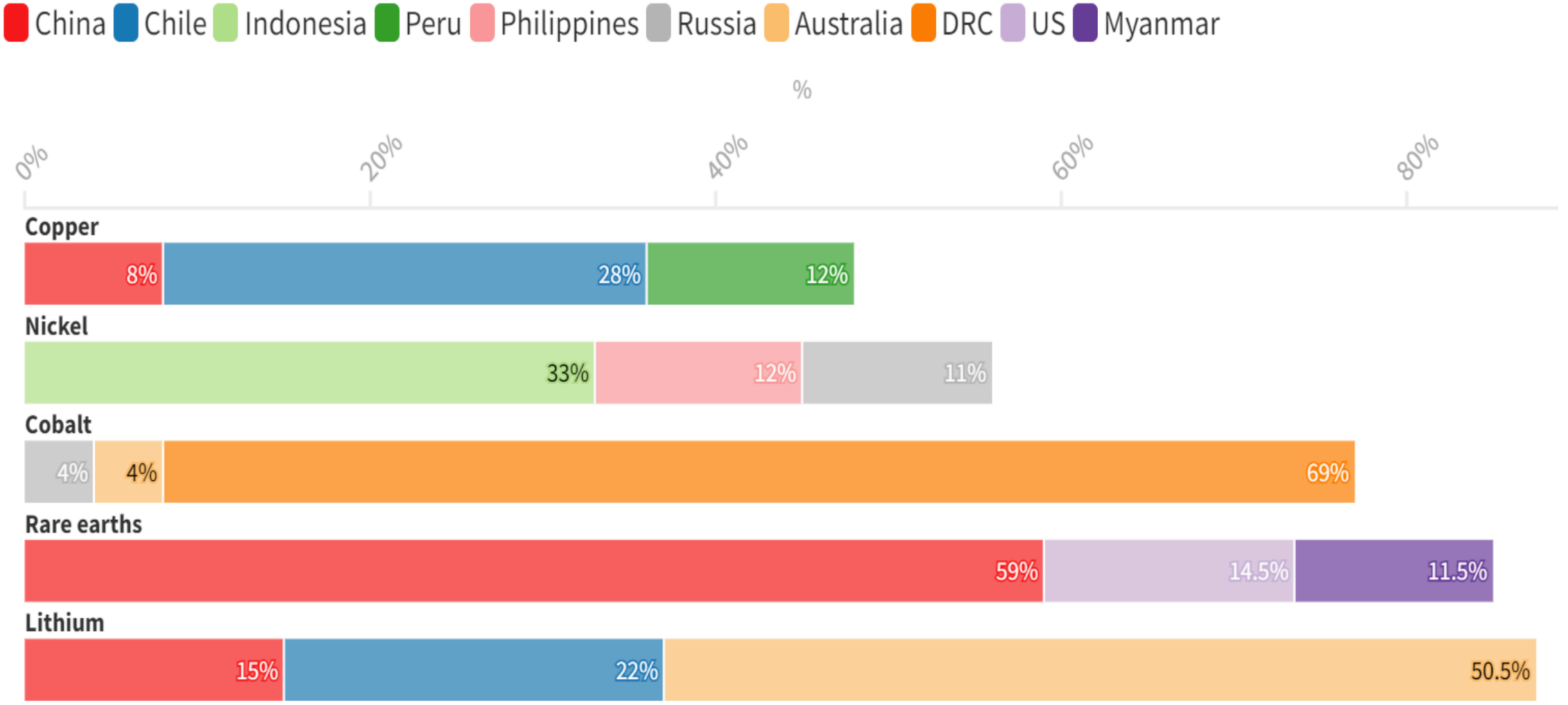
https://spectrum.ieee.org/to-get-wind-power-you-need-oil

Jim Kennedy projects massive mining increases for EVs.

How much more mining is required for projected EV production ?

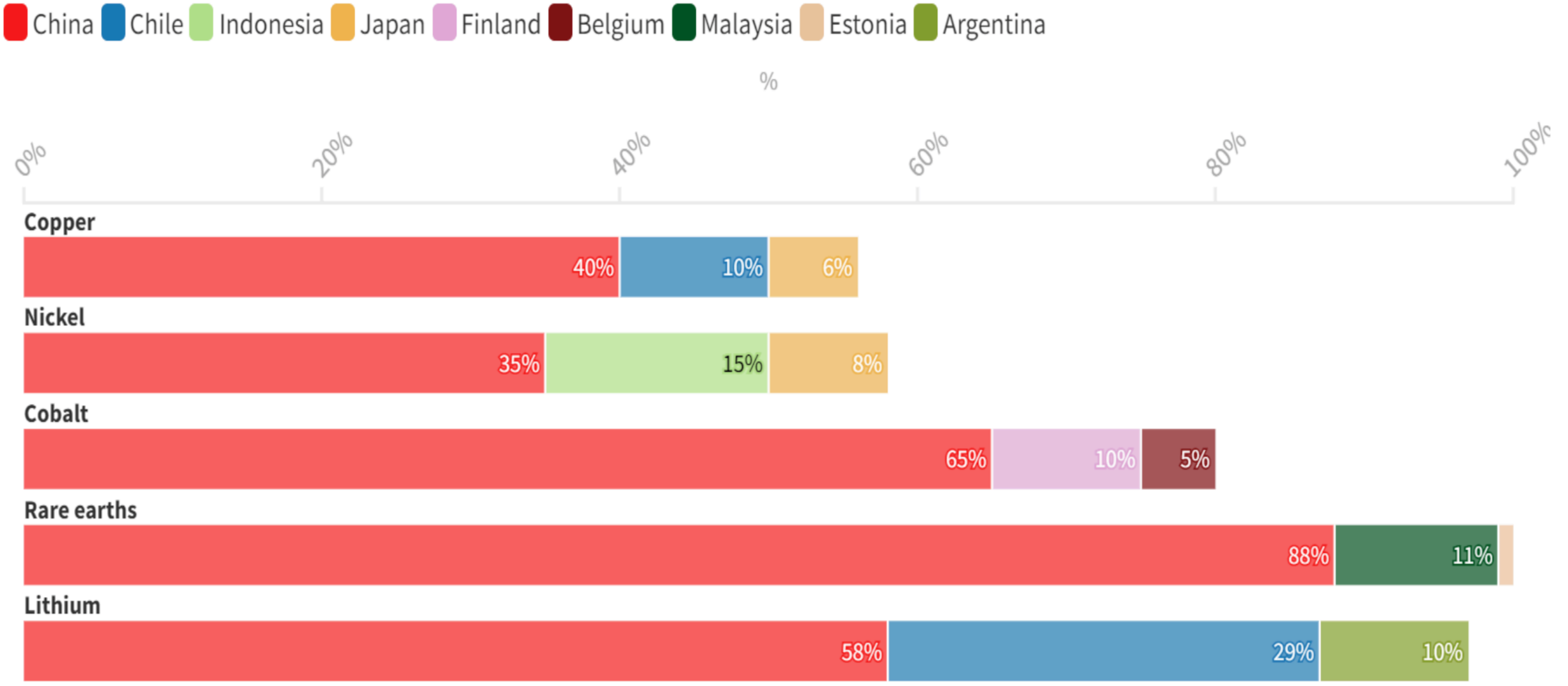


Where critical minerals are mined



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

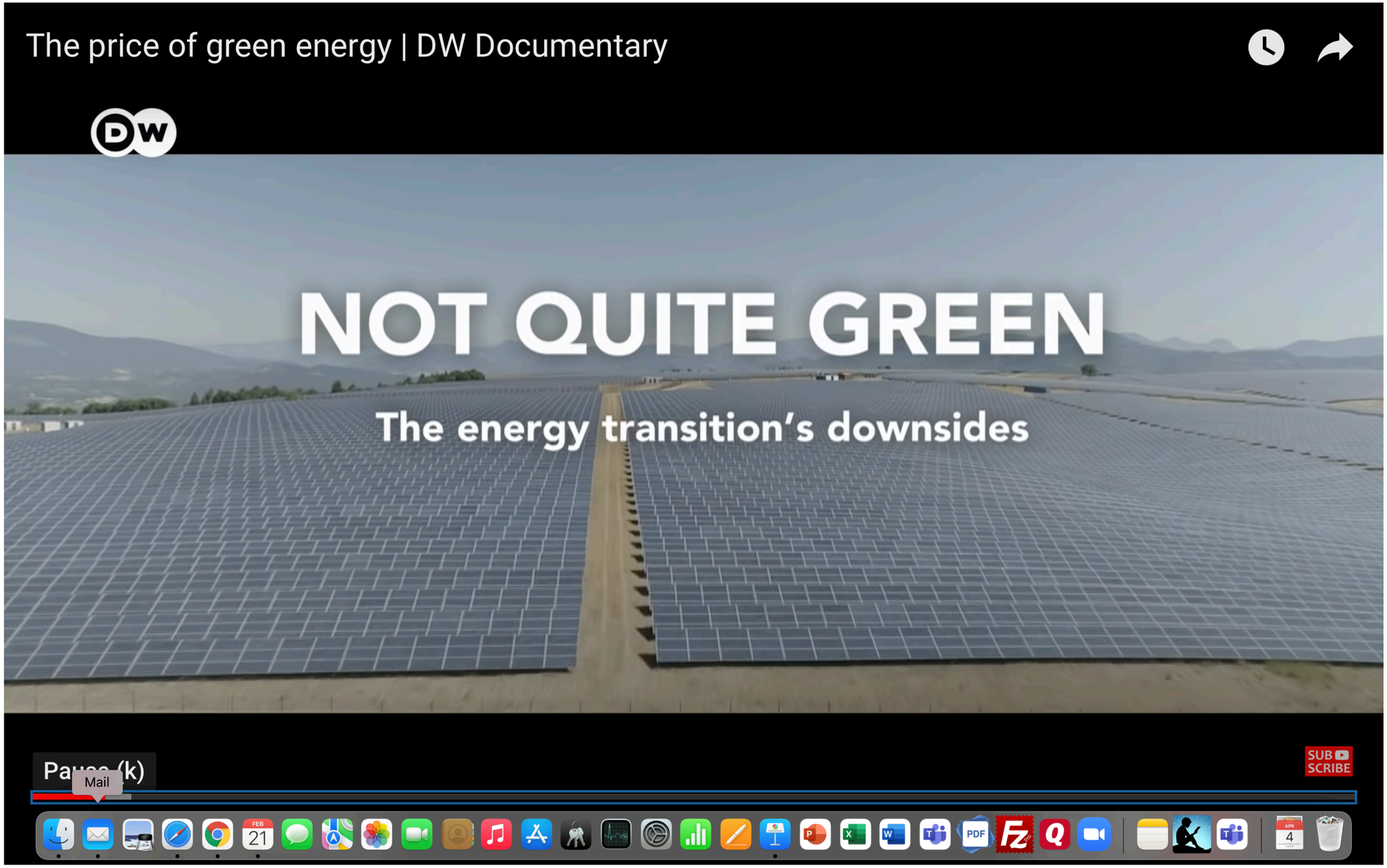
Where critical minerals are processed



Source: IRENA, IEA

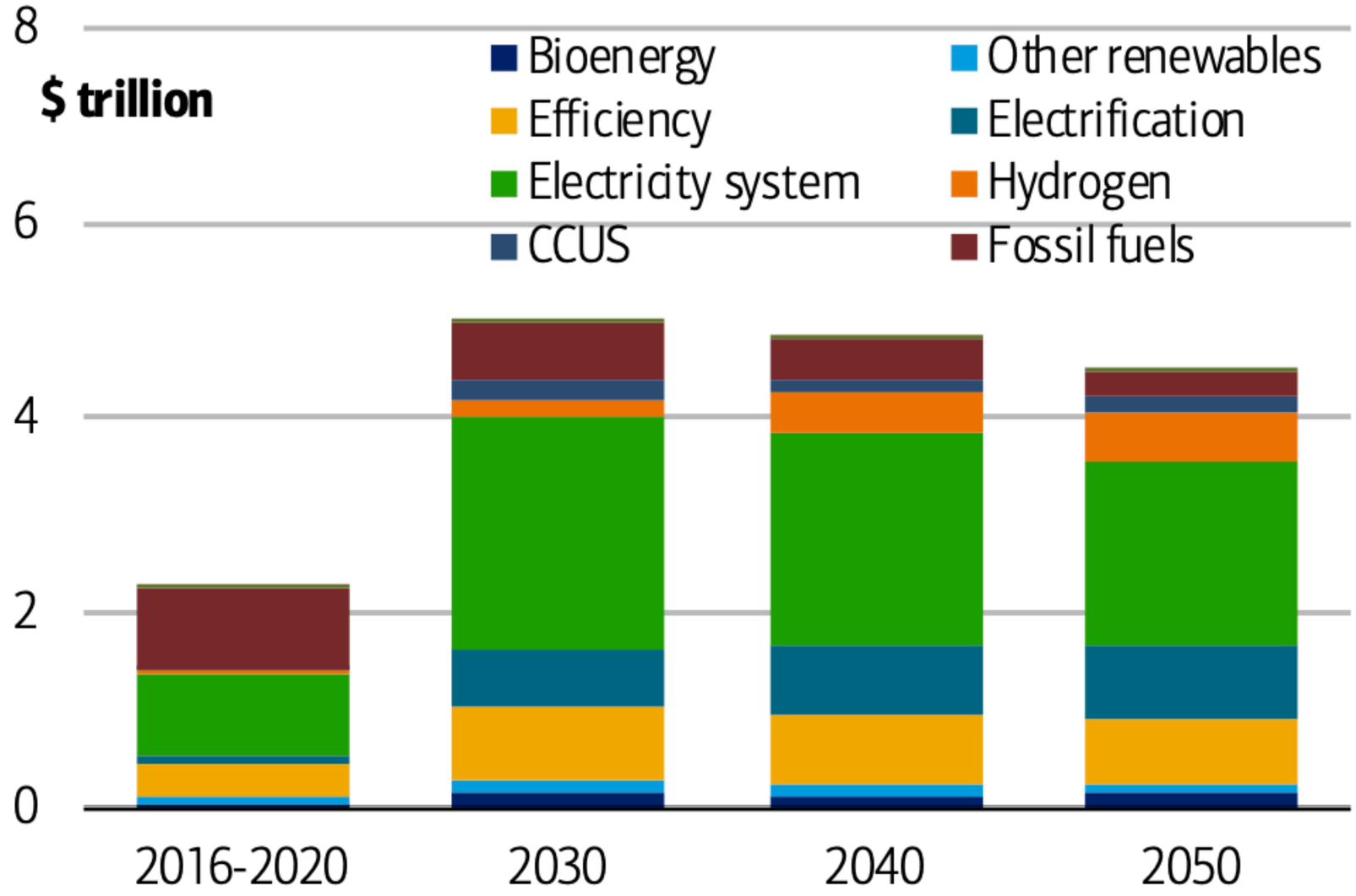
https://energypost.eu/critical-minerals-and-materials-supply-bottlenecks-and-risks-need-international-cooperation/

German documentary on mining impact



https://www.youtube.com/watch?v=CqSqNIsC04g

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

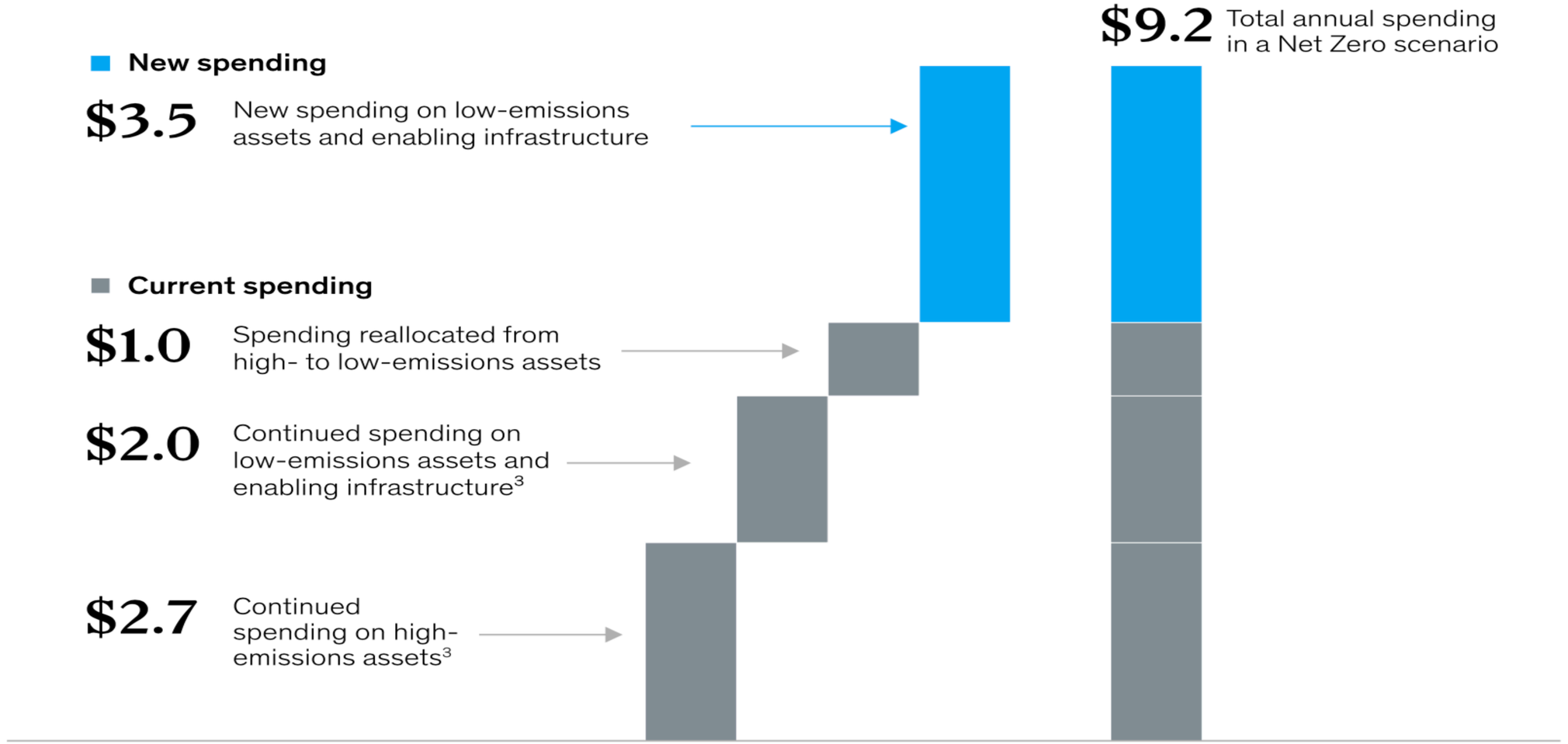
Note: no fission power.

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.

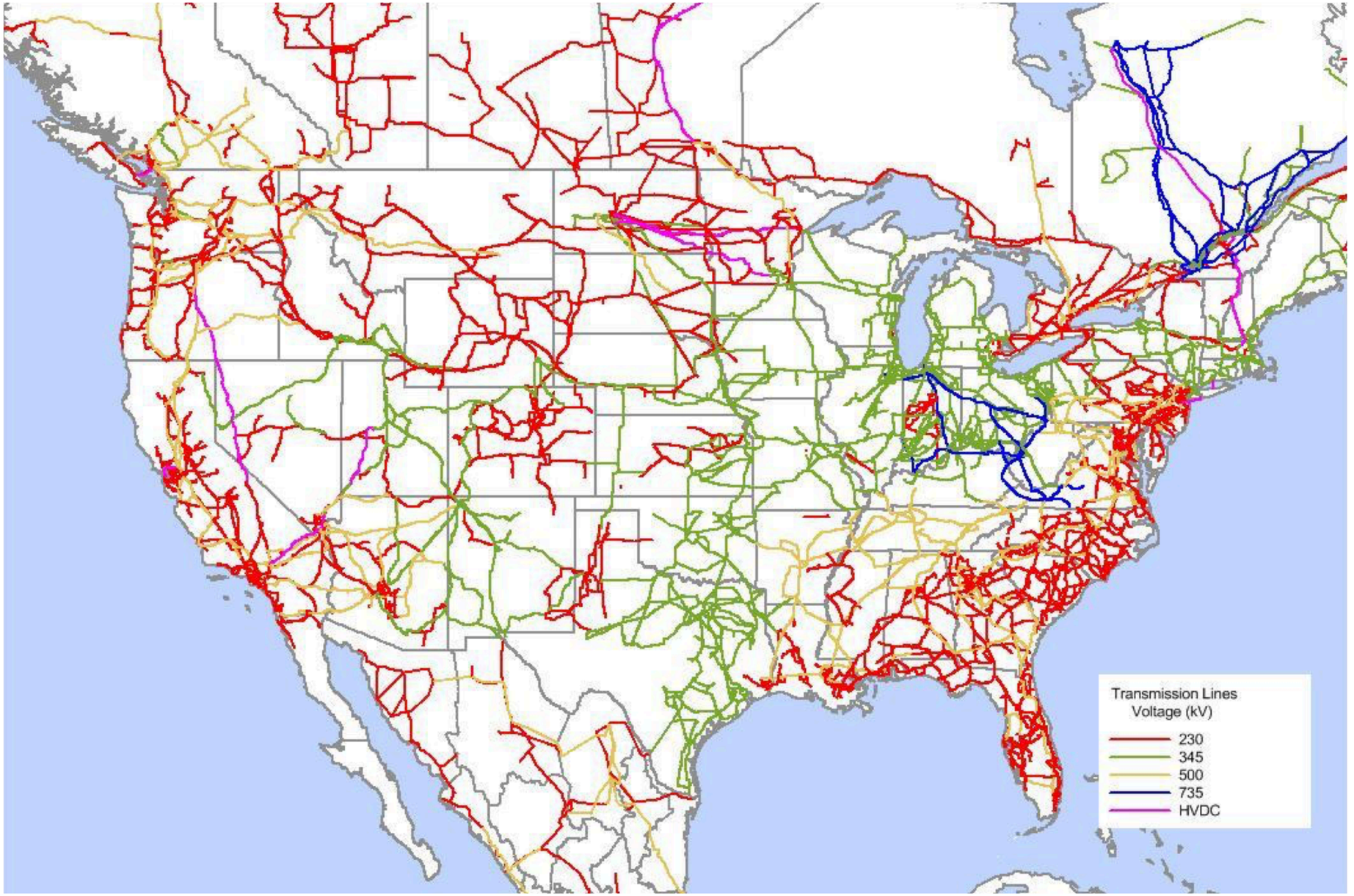
Spending on physical assets for energy and land-use systems in the NGFS Net Zero 2050 scenario would rise by about $3.5 trillion annually more than today.

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



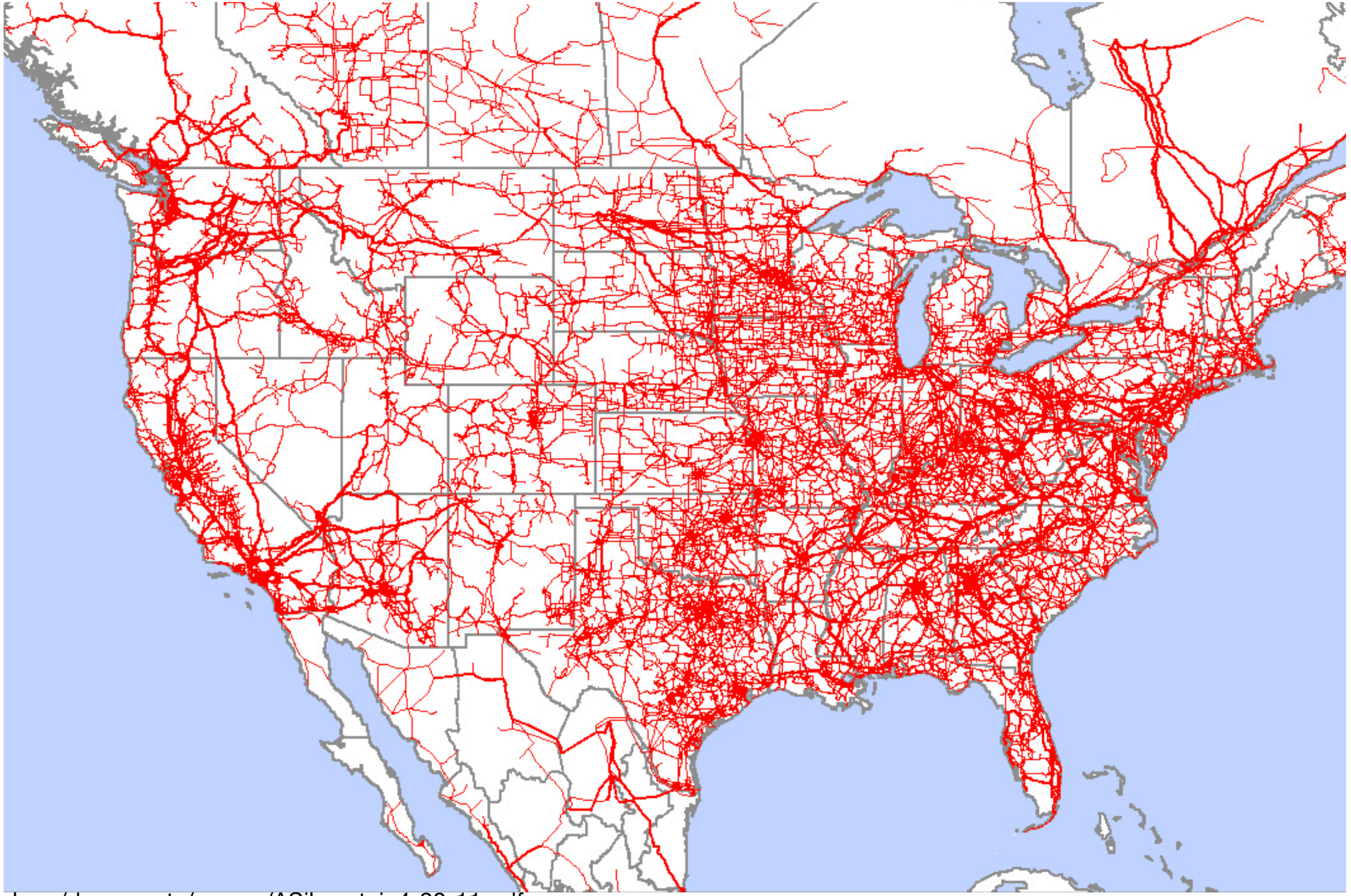
https://www.mckinsey.com/business-functions/sustainability/our-insights/the-economic-transformation-what-would-change-in-the-net-zero-transition

US transmission, 230 kV and above



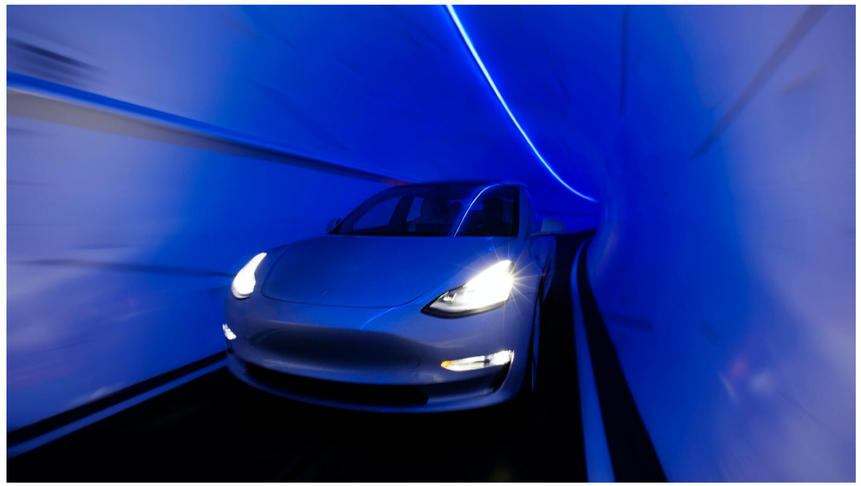
https://www.ncsl.org/documents/energy/ASilverstein4-20-11.pdf

US transmission, 69 kV and above



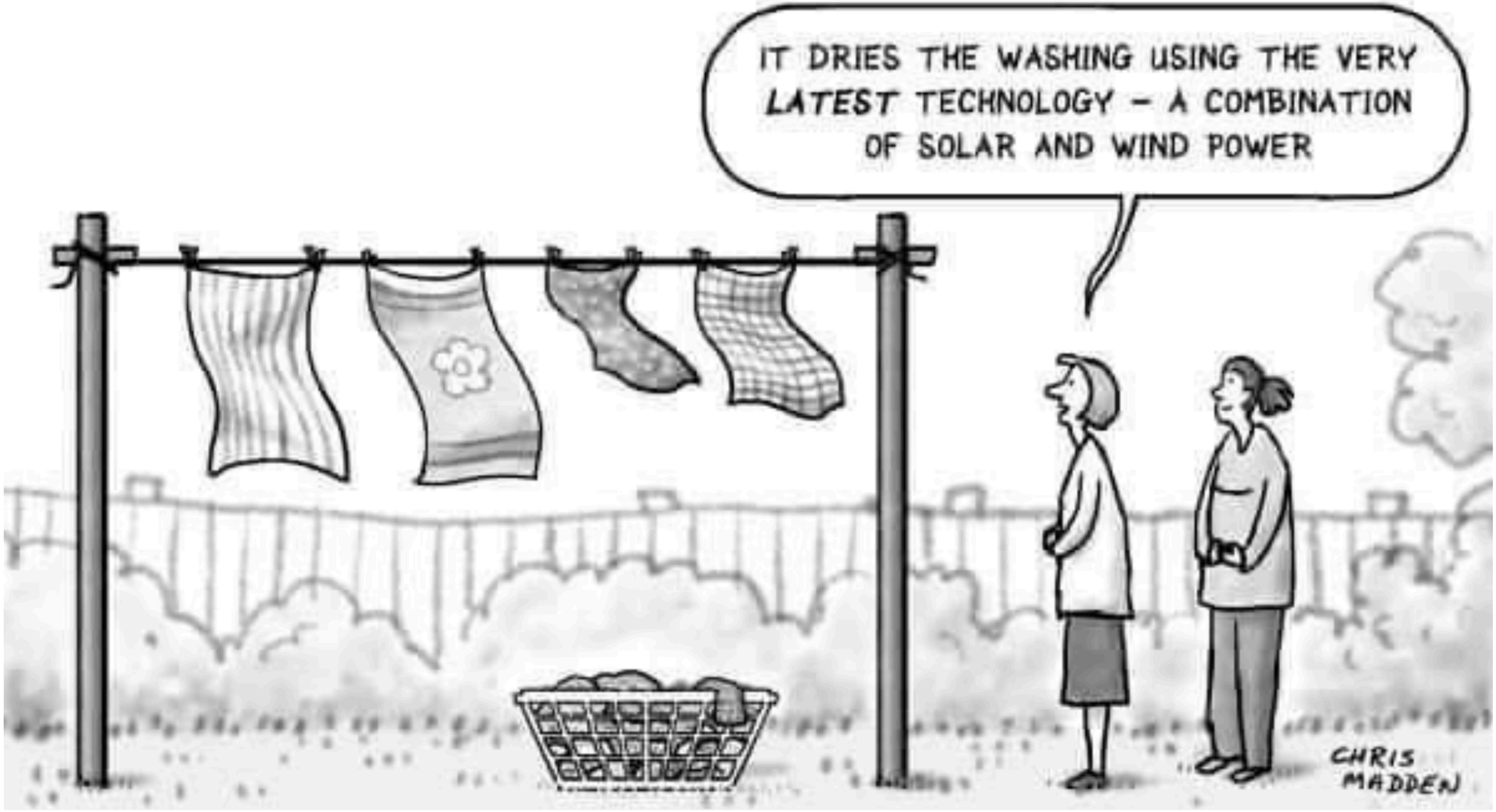
https://www.ncsl.org/documents/energy/ASilverstein4-20-11.pdf

Elon Musk's Boring Company might overcome right-of-way barriers to transportation and power.



- $10 million per mile
- build 1 mile/week
- goal: 7 miles/day

https://www.boringcompany.com



https://www.facebook.com/HeinleinSociety/photos/a.881625528546480/699756789695218 2/?type=3

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

5 Wind and solar

CO2 quantities

Cubic mile of oil

Wind and solar costs

Capacity factor

Natural gas dependency

Intermittency

Materials mining

Fission is in Fashion