The Role of Nuclear Power in US Electricity Markets

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Agenda

Key Takeaways

Background

Industry Trends

Value of Renewables vs. Nuclear

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Key Takeaways (1) – the Clean Energy Needs

Huge amounts of clean power will be needed to decarbonize the economy:

- Likely tripling the amount of capacity in the entire system by 2050, and doubling the annual total electric energy needed – because end-use electrification with clean upstream power often has been assessed to be more economical than other alternatives like hydrogen (though that is likely to be needed as well).
- So the ongoing need for nuclear is very strong.
  - The US nuclear fleet today provides more clean energy than all the wind and solar generation in the US combined.
  - Essentially all "pathway" models of 2050 decarbonization assume existing nukes will have lives extended to then

Using all renewables + storage is an unattractive way of fully decarbonizing: Their weather-dependent output does not match loads and it tends to overlap, so they eventually crowd each other out; their intermittency makes them less reliable, especially for occasional "renewable droughts".

The last 20% of **decarbonization is often estimated to cost about as much as the first 80% unless "clean dispatchable power" or very long duration storage becomes available.**

- Nuclear mitigates this problem considerably, and SMRs may be even more valuable
- But other technologies are emerging as candidates: iron-air storage, hydrogen under the IRA tax incentives, …

Nuclear-generated hydrogen may be an additional application for nuclear plants, as the electric load to produce H_2 by electrolysis is huge and nuclear provides a year-round, clean steady supply

Key Takeaways (2) – the Difficulties

Power systems have extremely sophisticated and complex pricing and scheduling.

- Which plants are utilized and how much they earn varies dramatically across the day and time of year.
- As a result, *nuclear plant profitability has been stressed* recently with about 1/10th of the fleet retiring prematurely in the last decade.

The short run variable costs of nuclear plants are extremely low, so they are run essentially all the time when available ("baseload")

- But their all-in costs (to-go, or to build new) are high relative to renewables, which are the dominant source of new power. (Renewables are very economical when displacing fossil, but less so when displacing each other.)
- Worse than high costs, the very long development time (10 or more years) for nukes is fatal to their expanded use – too much uncertainty over market conditions that will prevail once built
- Another drawback: current nuclear plants are not flexible to operate at different levels of output, so they cannot provide many grid-support services (missing a source of revenues that, e.g., natural gas plants get)

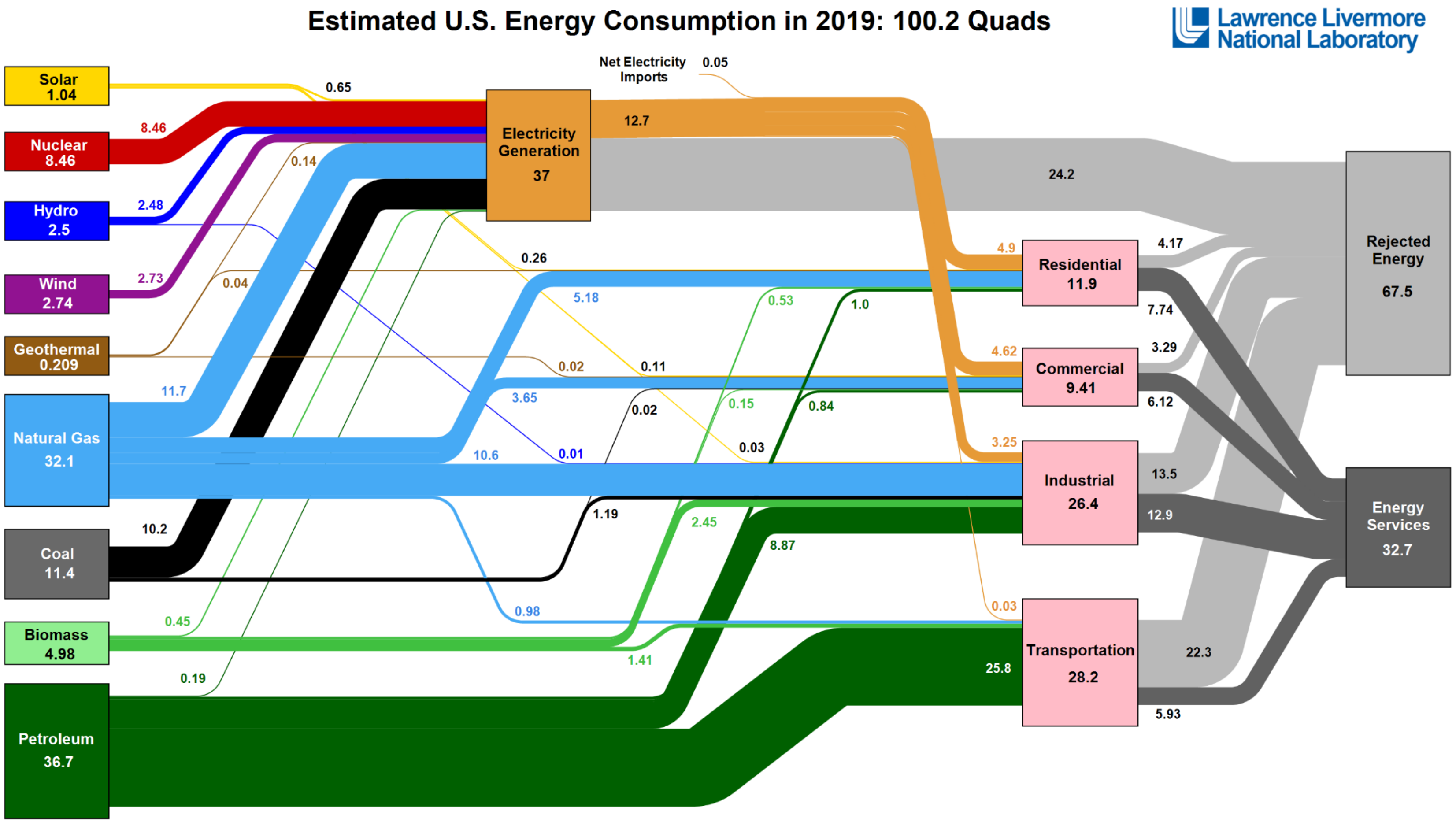
However, these limitations may be remedied if SMRs can be designed that are smaller, flexible to operate, and can be built quickly.

Background

U.S. Energy Flow Chart (2019)

Nuclear power provides about 8% of US total energy requirements but about 20% of its electricity generation.

Looking forward, renewables are by far the dominant source of new generation, due to favorable economics and climate concerns.



Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Types of Generating Sources

Generators produce electricity from a wide range of technologies and fuel types that offer unique advantages for meeting reliability, economic, flexible performance, and environmental needs.

- **Reliability**: Ability to count on the plant on system peak load; low outage or non-performance risk
- **Economic**: Operating cost advantages that encourage large volume of use; low fuel costs
- **Flexibility**: Ability to be turned on and off at short notice, to follow rapid variation in system needs with fast response output
- **Environmental**: Low emissions (or leakage) of air pollutants and GHGs

Overview of Resource Characteristics

Resource Type	Resource	Capital Costs ($/kW)	Variable Costs ($/MWh)	Dispatchable	Flexibility
Fossil	**Coal**	High	Varies	Y	Moderate
	Oil	Low	High	Y	High
	Natural Gas	Mid/Low	Highly volatile	Y	High
Renewable	**Wind**	Low	Zero	N	Low
	Solar	Low	Zero	N	Low
	Storage	High	Net in vs out	Y	High
Zero Carbon Non-intermittent	**Nuclear**	Very high	Low	N	Low
	Hydro	High	Zero	Y	Varies
	Hydrogen	TBD	TBD	Y	High

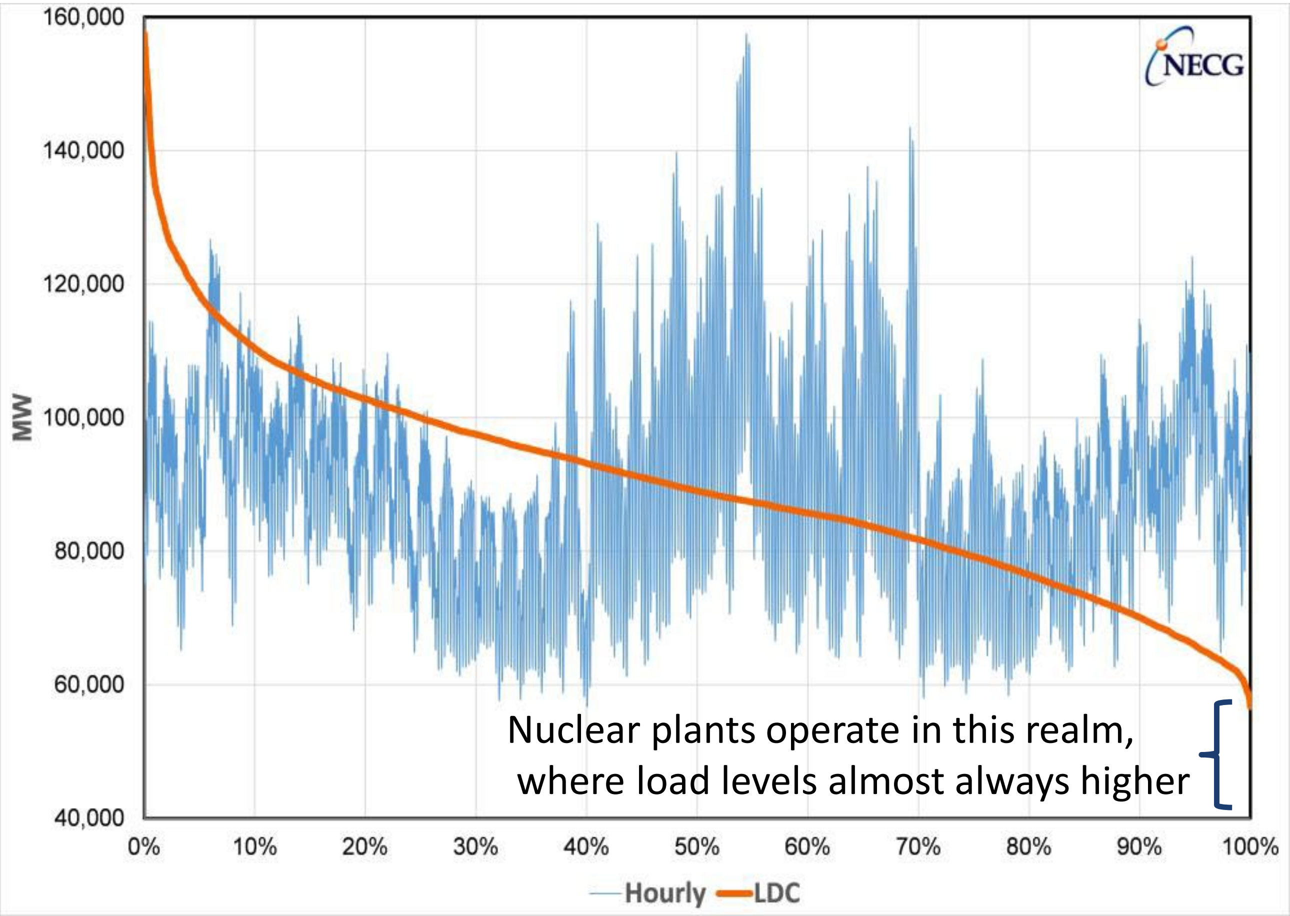
Load Variability/Load Duration Curve

Power demand is extremely variable diurnally and seasonally. It *must be exactly met in very short time intervals*, else the power system can destabilize and fail.

For this reason, power markets carry a "reserve margin" of plants that need to be available but may not be used. They are paid a capacity price based on their demonstrated reliability to be available on call.

A "load duration curve" summarizes annual demand from highest to lowest, and displays the frequency of load exceeding a given level.

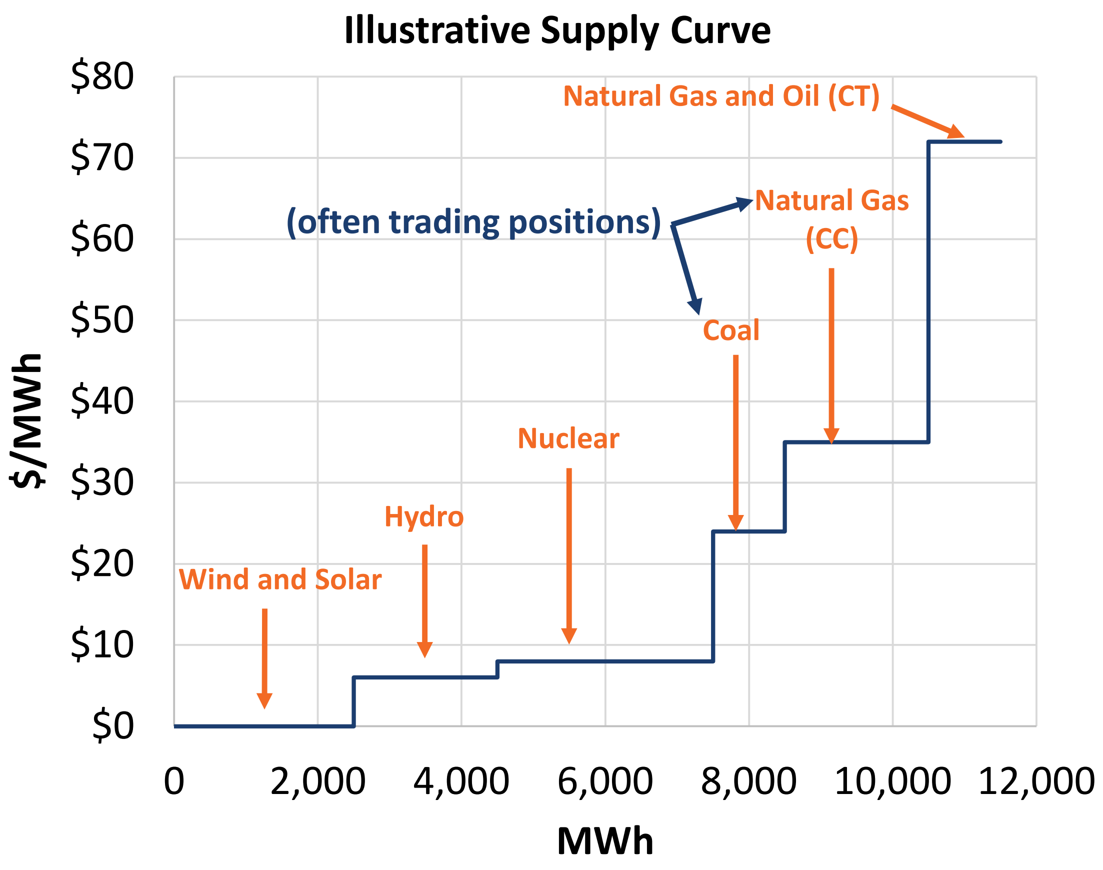
PJM Annual Hourly Demand (2013)



Source: NECG.

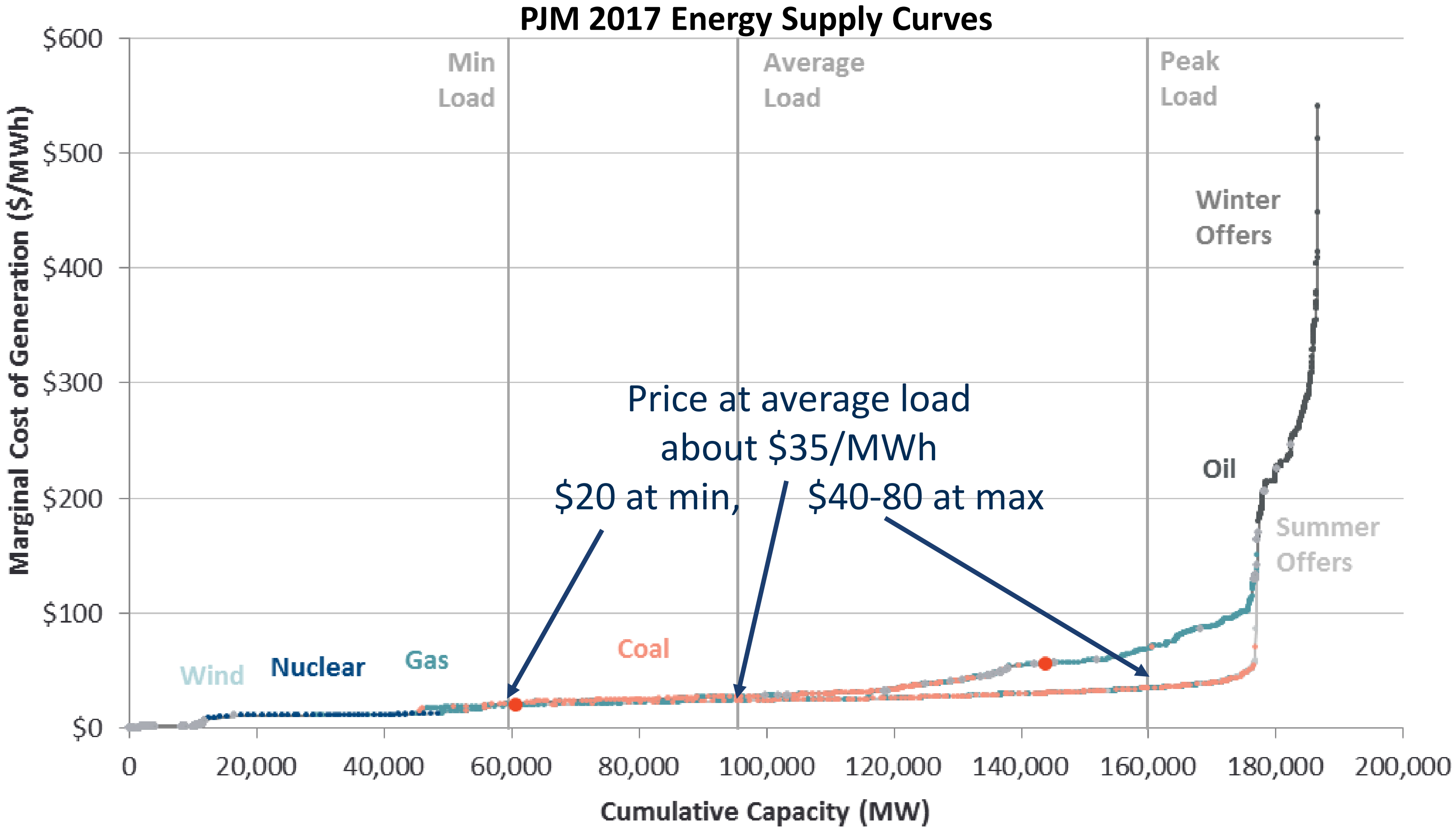
Illustrative Electricity Supply Curve

Lowest variable cost and must-run or inflexible baseload assets usually make up the bulk of generation in a supply curve, followed by more expensive assets such at CT gas or oil plants that are mostly brought online during peak demand.



- In competitive power markets, plant owners bid in daily offers to sell at whatever they are willing to take for each plant's output. The system operator rank-orders these and **dispatches** the plants up to the level of demand (load) in short time intervals (5 minutes or less)
- **Wholesale prices** are set based on where the offered supply curve intersect the contemporaneous demand curve, plus an adjustment for transmission difficulty
  - Markets tend to clear at the marginal cost of the last plant scheduled in each hour – often natural gas-fired
  - Plants with low operating costs earn profits on the energy they sell
- Plant owners also receive a "**capacity payment**" for being reliably available on peak, whether used or not
- Plants <u>not</u> in competitive markets schedule similarly but are compensated on an average cost basis (with less risk to nuclear plants)

Actual Energy Market Supply Curves – PJM 2017



System marginal costs and energy prices vary significantly during the day, and with it which plants are operating and profitable.

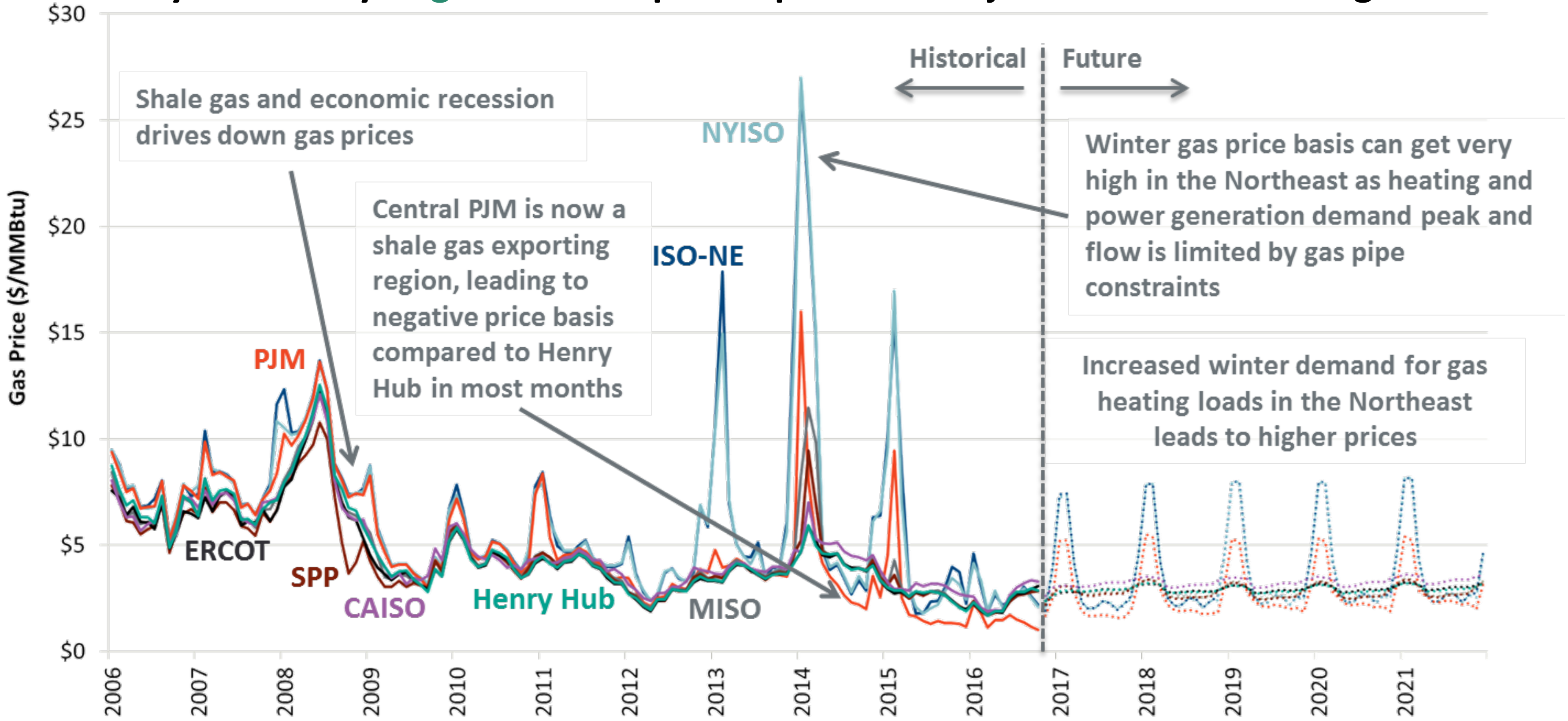
Each region of the US has a similar curve but with different costs and quantities of types of generation.

Sources and Notes: Average Coal Price is $2.78/MMBtu. Average Oil Price is $20.83/MMBtu. Marginal cost is the sum of Fuel, Variable O&M, and Emissions cost for each unit (pulled from Velocity Suite, ABB Inc., Generating Unit Capacity dataset). Summer cumulative capacity is represented for both seasons. For gas plants, fuel price is the average summer and January forwards respectively for 2017. Minimum, Average, and Peak Load shown for 2017. In Summer and Winter curves the RGGI CO_2 price from March 2015 auction has been considered. Wind and solar installed capacity derated by capacity credit levels. Retirements and new builds that are currently under construction are accounted for. Oil price is inflated from current prices to 2017 prices.

Natural Gas Often Sets Power Prices

Natural gas is often the marginal fuel so its cost determines much of the variation in electricity prices across the U.S.; higher gas prices increase nuclear value.

15-year history of gas costs vs. power prices at major electric market regions



As a consequence the profitability of baseload plants (e.g. nuclear) varies considerably from year to year.

Renewables have also been increasingly suppressing prices.

Sources: Velocity Suite, ABB Inc. and S&P Global Market Intelligence. Used Algonquin Citygates for ISO-NE, Tennessee Gas Zone 6 200L for NYISO, TETCO M3 for PJM, Chicago for MISO, NNG Demarc for SPP, Houston Ship Channel for ERCOT, and PG&E Citygates for CAISO.

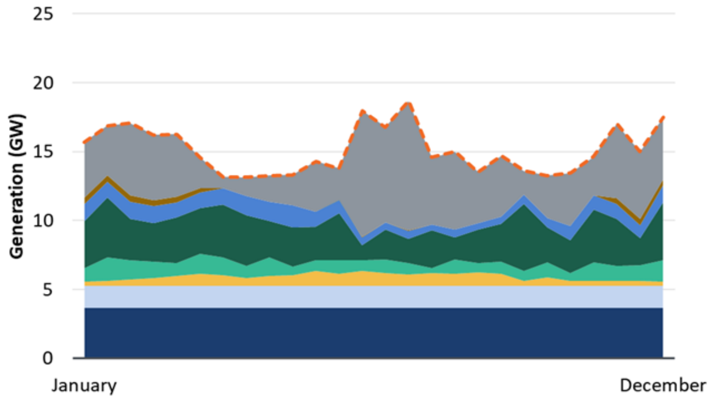
Dynamic Supply and Demand Conditions

In any given hour, day or season the supply curve changes for a variety of reasons:

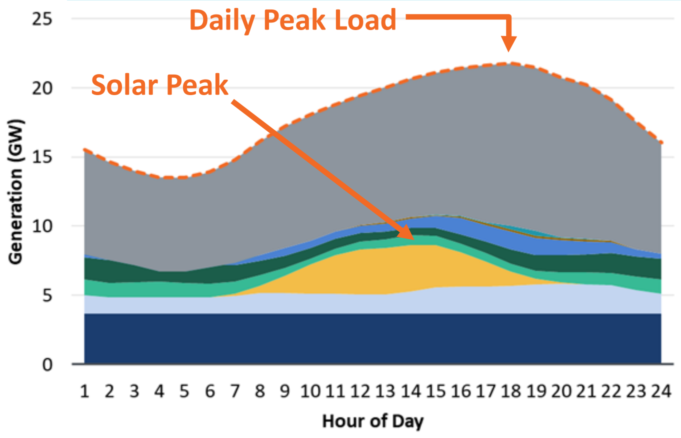
- Seasonal differences in how much required and time of day (winter vs. summer peak)
- Variation in renewable resources (seasonal, or hourly -- the wind stops blowing, cloud cover, etc.)
- Natural gas or other fuel prices moving up or down
- Major plant outages (planned for maintenance or unforeseen)
- Environmental emission limits reached

Nuclear plants operate quite steadily regardless of market conditions but profits or value vary because of what is happening on top (what is avoidable).

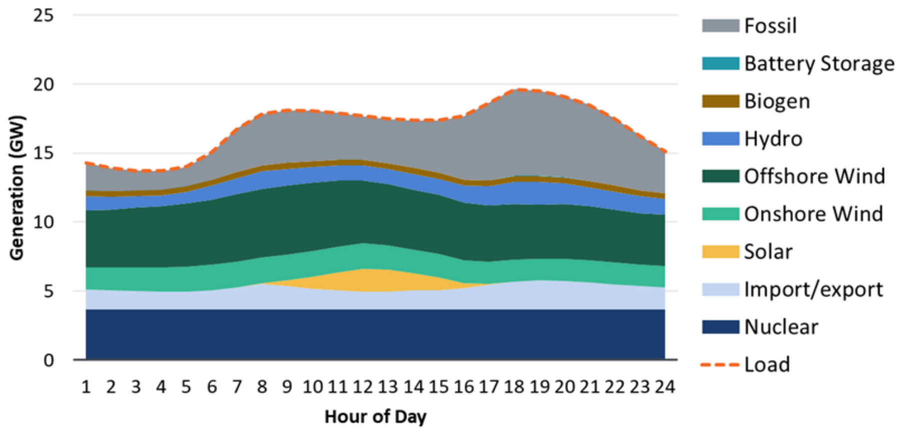
2024 Monthly Average



2024 Summer Day (hourly)



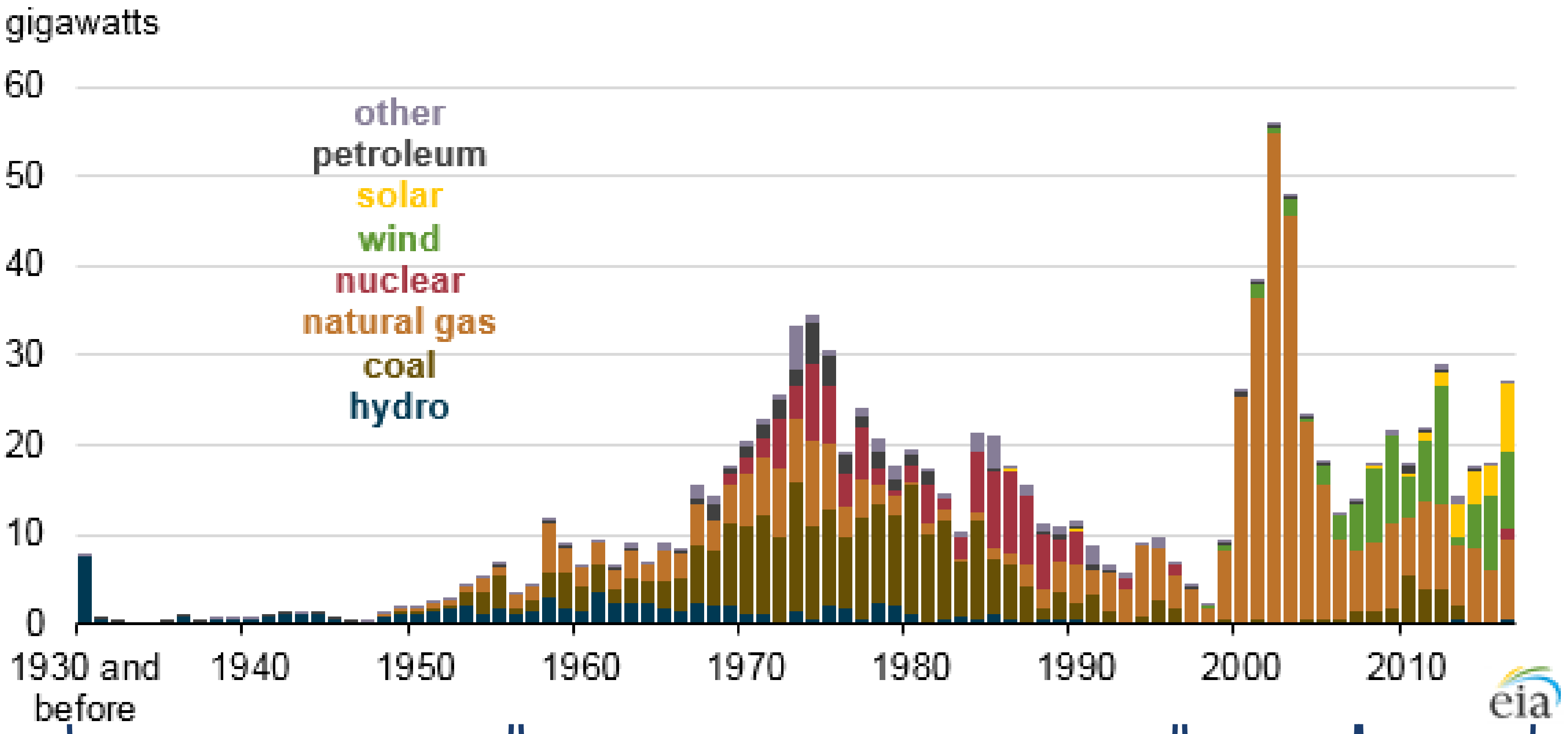
2024 Winter Day



Industry Trends

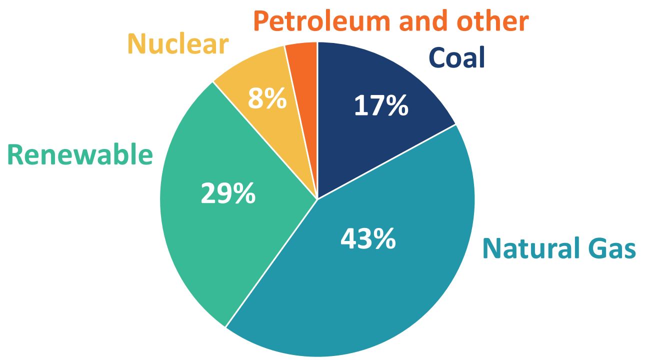
Historical Generation Infrastructure

Historically, generation capacity in the U.S. was primarily made up coal and oil with some gas and nuclear, however the 2000s have seen dominant growth in supply from gas then renewables.

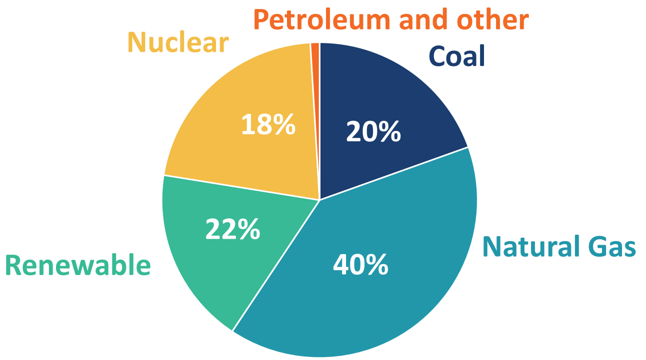


Petroleum and Coal | Coal, gas, and nuclear | Gas | Gas and Renewables

2022 Capacity by Source (1.2 TW)



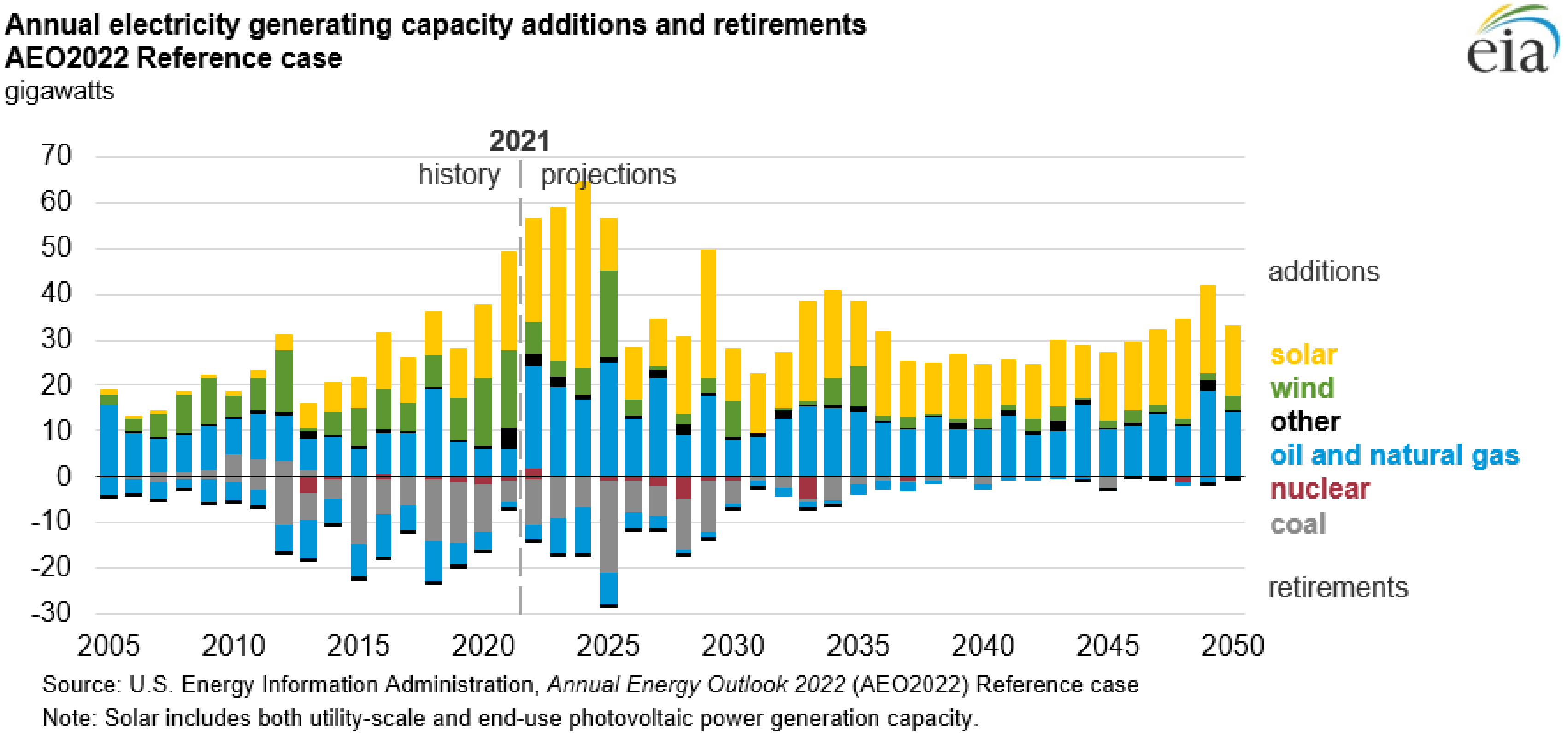
2022 Generation by Source (4,200 TWh)



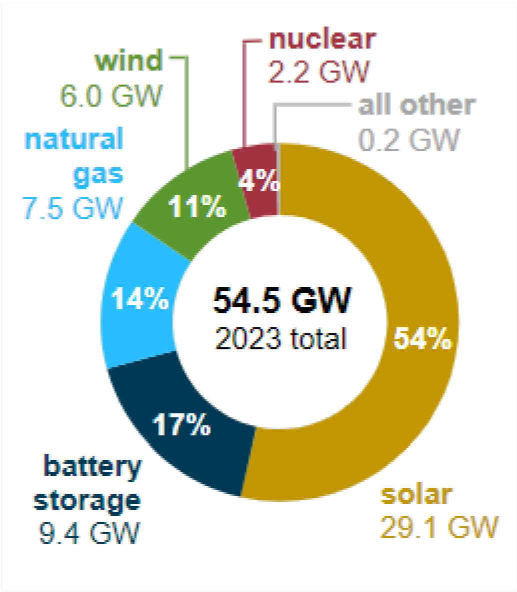
Source: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php; https://www.eia.gov/todayinenergy/detail.php?id=30112

Projected Generation Capacity

Since the shale gas boom around 2010, there has been a wave of nuclear, coal, and older oil and gas (CT) plant retirements due to the availability of low cost natural gas; replacing those resources, in the near and long-term, are an increasing share of lower cost renewables and more efficient CC gas plants



Planned 2023 Additions



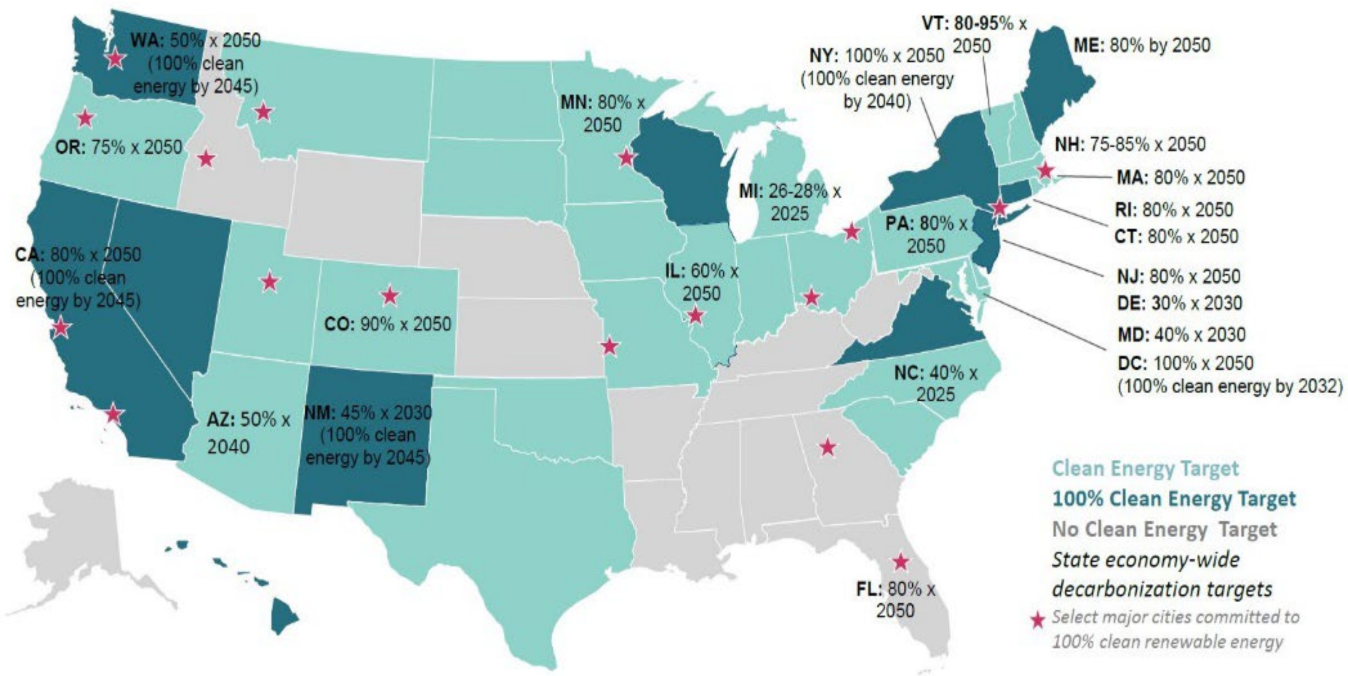
Source: https://www.eia.gov/outlooks/aeo/narrative/electricity/sub-topic-04.php; https://www.eia.gov/todayinenergy/detail.php?id=55419#:~:text=Developers%20plan%20to%20add%2054.5,by%20battery%20storage%20(17%25).

Renewable Energy and Clean Energy Mandates

In addition to falling costs of renewables, governmental decarbonization goals are driving renewable generation capacity as well as interest in maintaining existing nuclear.

- **Private Industry**
  - Many utilities have also established their own clean energy targets
  - Some of the largest companies in the US (e.g. Meta, Google, Microsoft, Walmart, and Amazon) are buyers or developers of renewable capacity for private use
- **Government**
  - The Inflation Reduction Act of 2022 (IRA) directs almost $400 billion in tax incentives, grants, and loan guarantees to lower carbon emissions by the end of the decade

States with Clean Energy Targets



Sources: Center for Climate and Energy Solutions (C2ES), Sierra Club, National Conference for State Legislatures. Includes states with executive orders for clean energy commitments; various sources.

State targets based on information from the National Council of State Legislatures.

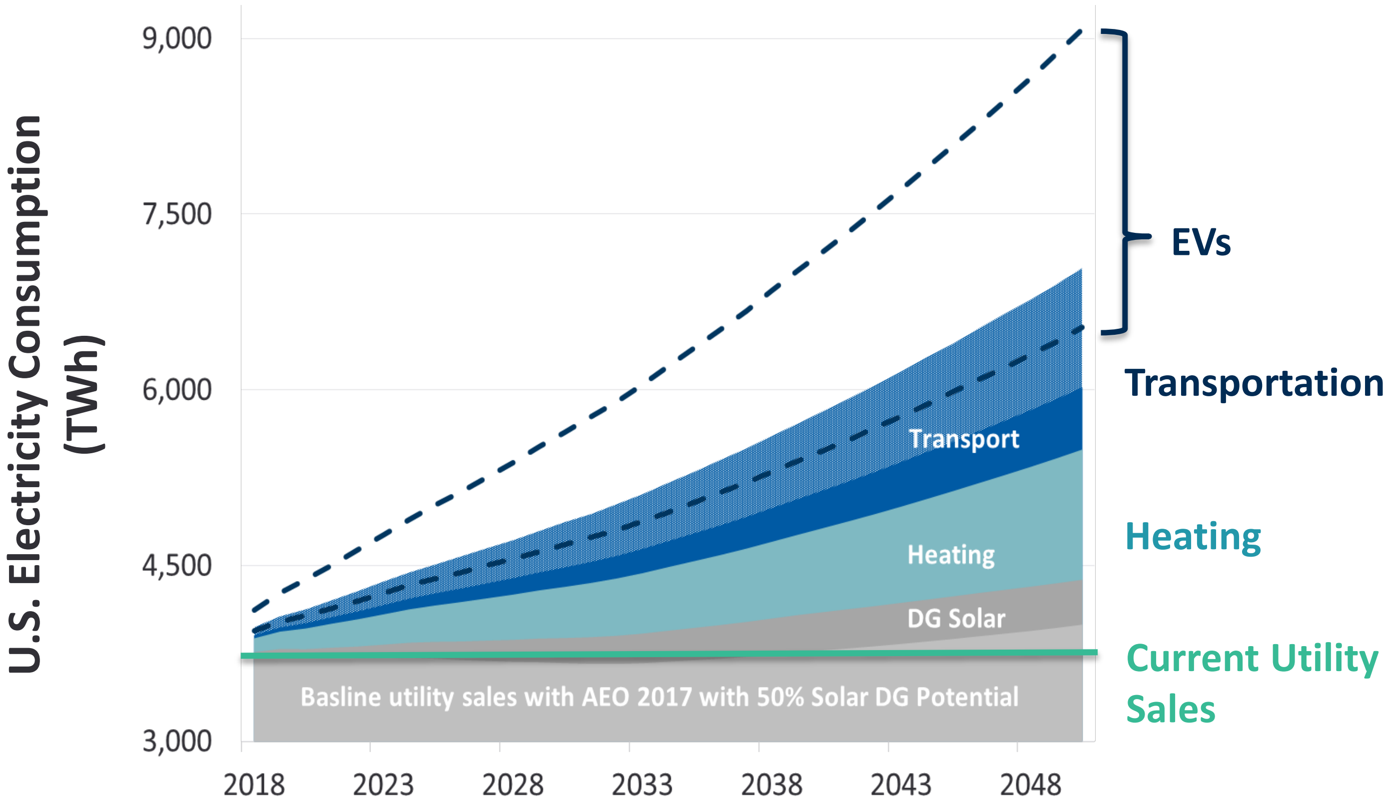
37 states in the U.S. have clean energy targets (with varying stringency)

Electrification

Most "pathway" studies of achieving deepdecarbonization find that electrification of end uses (HVAC, cooking, cleaning, commercial apps, light duty transportation) with all-clean electricity is likely to be most economical (though very difficult).

- Could cause electric energy demand to double by 2050 and electric peak to triple, requiring $trillions of new infrastructure.
- Electric vehicles and heat pumps for HVAC are the primary drivers, each representing about +1/3 or more of what a typical home now uses
- All existing fossil gen must be replaced and all new growth met with clean power.
  - Could require up to 100s of GW/year of new clean power (vs. 2022 renewable gen additions of 18 GW)
  - Also will require huge transmission build out to reach best locations for renewables
  - And additional new clean gen to create hydrogen for hard to electrify industrial loads.

Thus, retaining existing nuclear will be extremely important, and more are needed



Sources: The Brattle Group, BC Hydro, Global News.
http://files.brattle.com/files/7376_electrification_whitepaper_final_single_pages.pdf

Tax Credits and Incentives Under the IRA

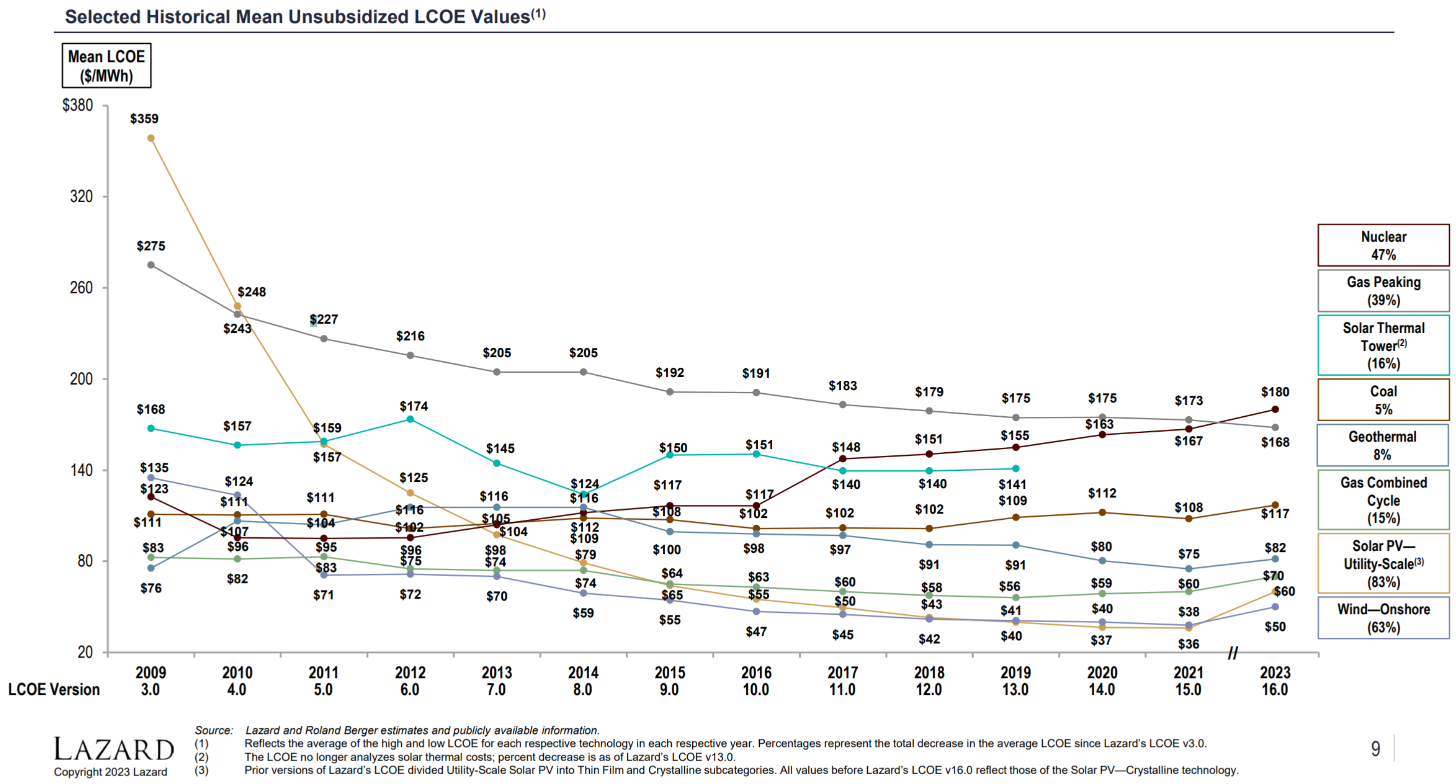
The recently enacted Inflation Reduction Act provides substantial tax credits and other incentives to support long-run decarbonization for renewables, nuclear, clean hydrogen production, and carbon capture and utilization storage (CCUS)

Resource	Provision	Credit	Notes
Nuclear	Production Tax Credit (PTC)	\$15/MWh PTC for 2024-2032	Zero emission nuclear credit (Section 45U)
	Loans	\$250 billion in DOE loans	
	Funding	\$700 million for HALEU funding	
Hydrogen	PTC	Maximum of \$3/kg H_2 (100% PTC)	
CCUS	PTC	Utilized: \$12/CO_2 ton Stored: \$17/CO_2 ton	The IRA extended the construction deadline 7 years from 2026 to 2033 The IRA extended the construction deadline 7 years from 2026 to 2033
	Investment Tax Credit (ITC)	Utilized: \$26/CO_2 ton Stored: \$36/CO_2 ton	

Value of Renewables vs. Nuclear

Relative Costs of Generation

Levelized Cost of Entry (LCoE, or breakeven unit price on a new plant) has declined rapidly and steadily for solar and wind (also storage) but not for coal and nuclear, making new nuclear very difficult to justify at present.



Source: "2023 Levelized Cost Of Energy+," Lazard, April 12, 2023, https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

Short run marginal costs of nuclear plants are **about $8-10/MWh** – very low, so always dispatched (high utilization, "baseload")

But **annual "to-go costs"** for nuclear are about **$40-50/MWh**, right at the edge or a bit above most wholesale power market prices (except when natural gas prices spike) – so viability can be tenuous absent Zero Emission Credits (ZECs)

New nuclear capital costs of $7000/kW or more and very long construction periods are prohibitive, but SMRs may prove more economical.

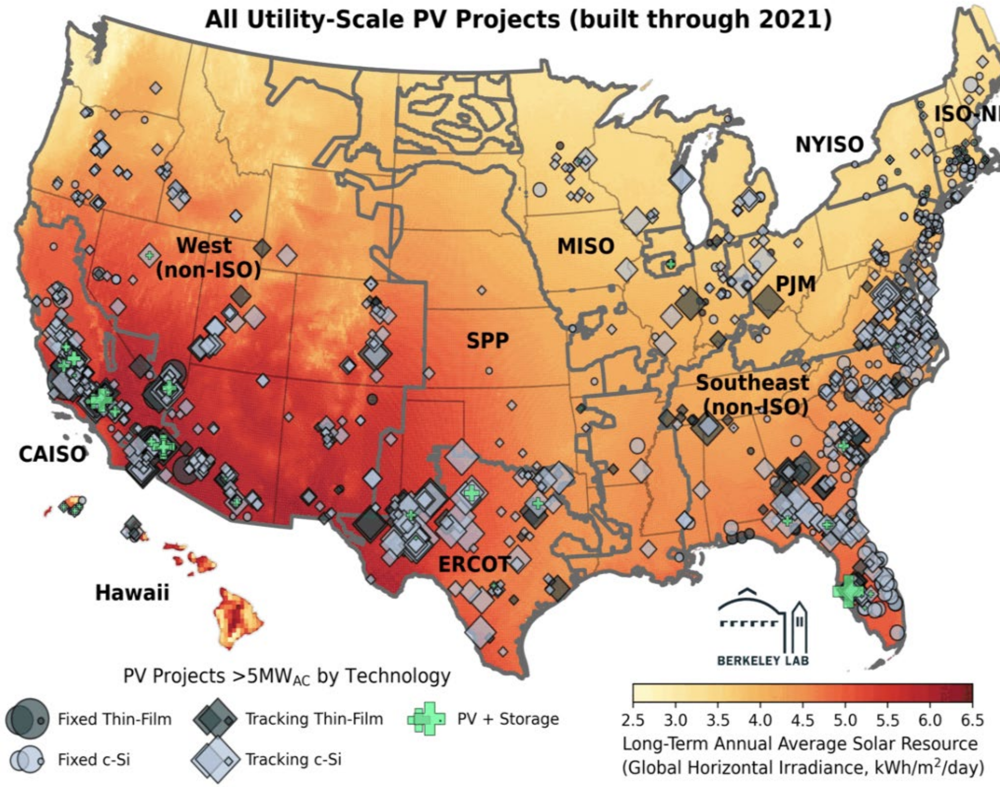
Projected Generation Capacity

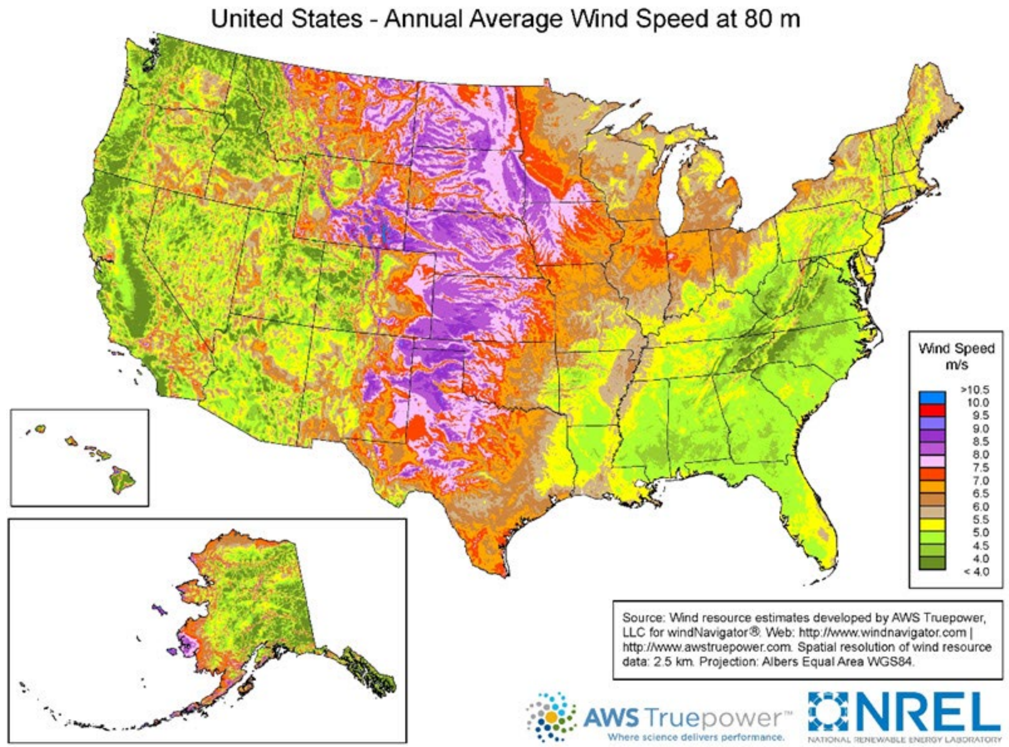
Renewable capacity is rapidly growing due declining costs relative to fossil and nuclear assets, but *it is very difficult to nearly impossible to have a 100% renewable grid* due to:

- **Regional Resource Availability:** The availability and intensity of wind and solar varies across the country.
- **Seasonality:** Normal variability of weather and solar or wind availability based on the season.
- **Intermittency:** output entirely dependent on uncontrollable weather, so unable to consistently produce energy throughout the day.
- **The "Duck Curve":** Large and rapid increase in the need for replacement energy and capacity towards the end of the day as the sun goes down.
- **Reliability:** Declining ability of renewables to serve peak load as more are used, due to high correlation in output.
- **Resiliency:** Risk of occasional "renewable droughts" that could last for multiple days.

Renewable Resource Availability Across Regions

Renewables are not equally available or productive across the whole U.S. Best wind locations are in the Midwest and offshore Atlantic, while solar is best in the southwest. Resulting cost differences per MWh are substantial. Expanded transmission will be necessary to bring clean power to market centers.





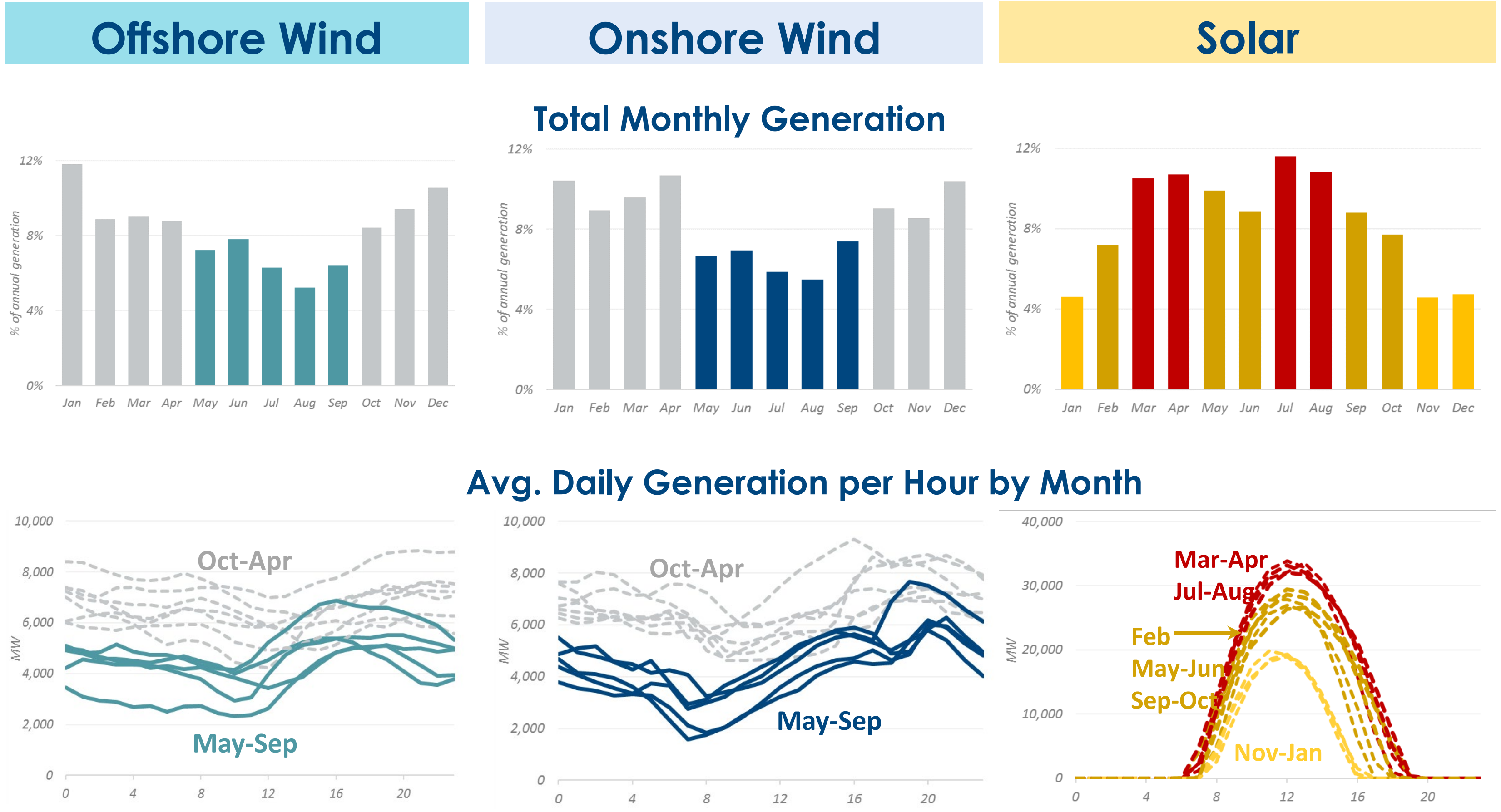
Source: https://www.eia.gov/energyexplained/wind/where-wind-power-is-harnessed.php

Seasonality

Wind assets generally perform best during the fall, winter, and spring seasons (sometimes best at night), whereas (in New England) solar resources perform the best during the spring and summer seasons.

Even with a wind-solar combination, there are risks of low renewable power that must be solved with other technologies.

Characteristic Monthly and Hourly Renewable Output in New England



Source: NREL's WIND Toolkit and NREL SAM PV dataset based on 2012 weather data for ISO-NE.

Intermittency vs. Steady Dispatchability

$$\text{Capacity factor} = \frac{Energy\ output\ during\ period\ A}{Max\ capacity\ \times Duration\ of\ period\ A}$$

Low capacity factors:

- Renewables have zero marginal cost but low capacity factors because of intermittent resource availability
- High variable cost technologies ("peakers", i.e. gas CTs) run occasionally but *as needed*, capturing high prices in scarce hours

High capacity factors: Techs with low variable but high fixed costs (nuclear, coal, some gas) that are economical when run almost non-stop (baseload)

Technology	Typical Capacity Factors, 2021 US average
Advanced Nuclear	65-95%, 92.7
Natural Gas (CC)	50-85%, 54.4
Coal (varies by age)	30-85%, 49.3
Biomass	60-85%, 63.5
Run of River Hydro	30-60%, 37.1
Wind (varies by location)	30-45%, 34.5
Solar (varies by location)	15-32%, 24.5
Natural Gas (CT)	2-15%, 12.1
Battery Storage	1-5%, 4.6

Source and Notes: "Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022," US EIA, March 2022.
2021 capacity factors from Statista Research Department, July 11, 2023.

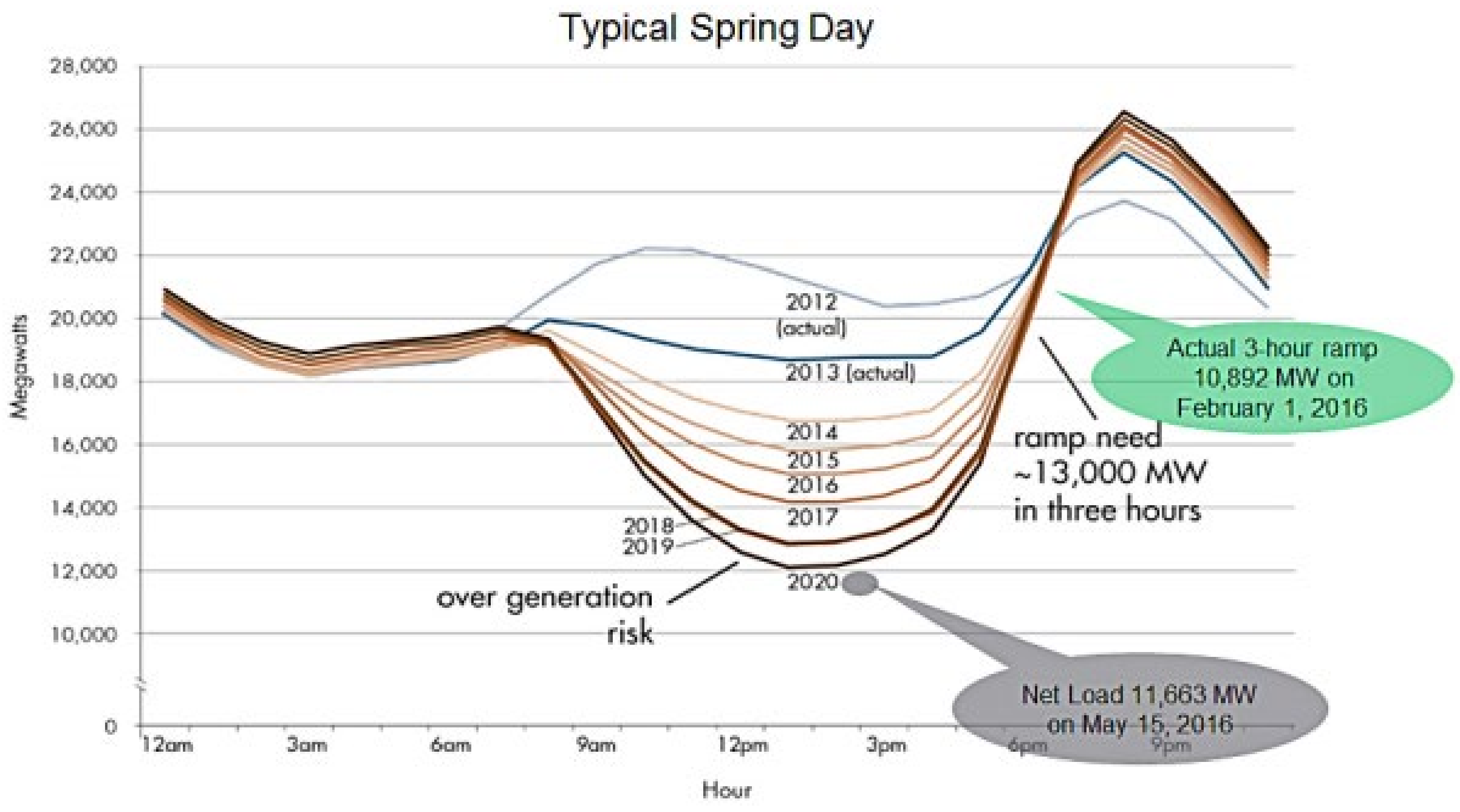
The Duck Curve

California has coined this term based on its net load shapes becoming more hollowed out during the day, as more solar power is used on the grid.

- Creates a *later evening peak out of reach of renewables*
- And *steep ramping* as the sun goes down

Current nuclear not suited for ramping (not flexible enough).

Evolving CA Hourly Load Net of Renewable Power



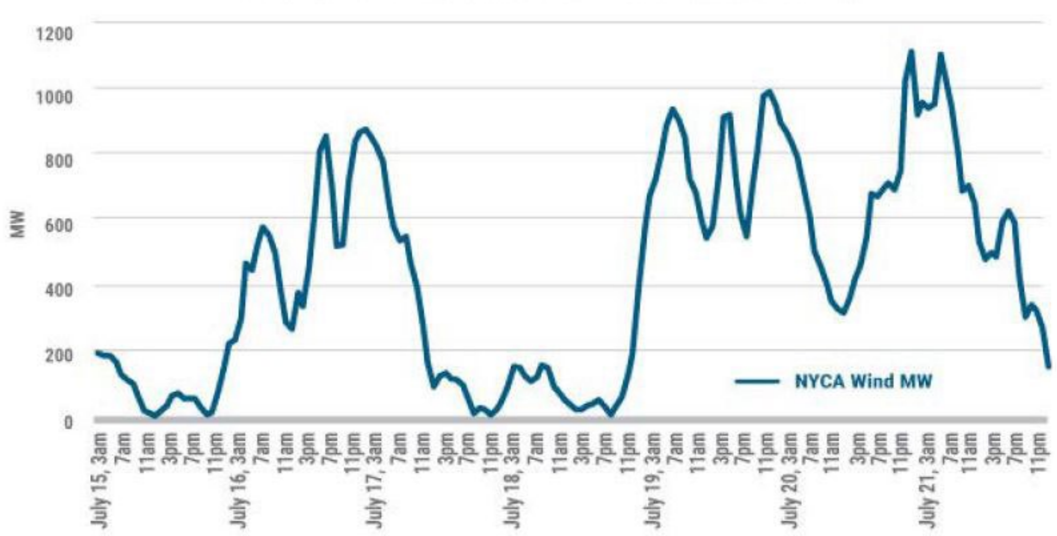
Source: https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Renewables and Reliability

Renewables are inexpensive per MWh *when they are working*, but their variability and tendency to coincide with each other makes them not very valuable on peak for reliability, the more so the deeper the system dependence on them.

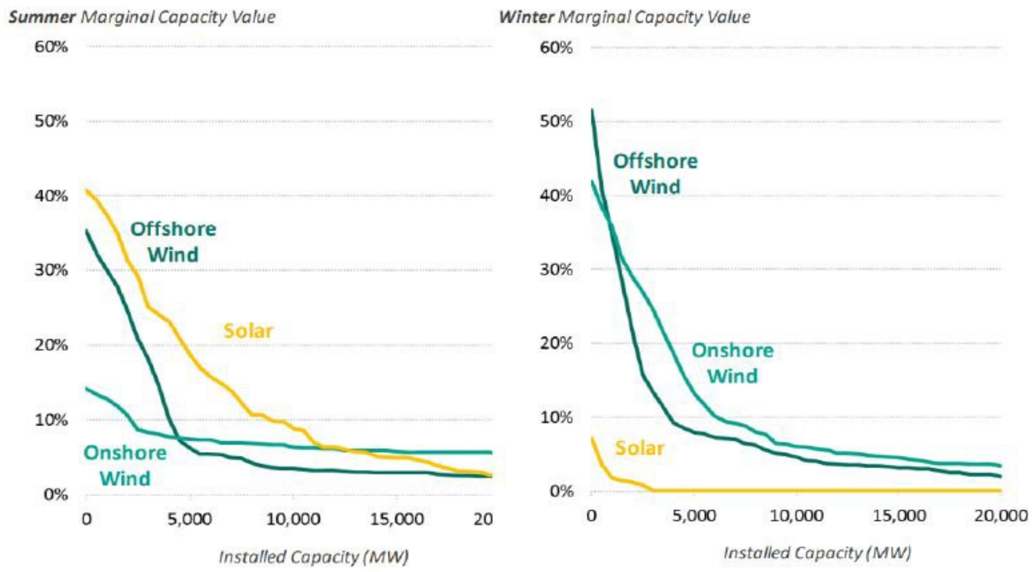
Storage also suffers steep declines in reliability value as it becomes large. For this reason, virtually all studies of deeply decarbonized systems find a need for clean dispatchable generation, i.e. gas with CCS, hydrogen gen, or nuclear.

Wind Performance During 2019 Peak Demand Week in NY



Source: NYISO, August 2019.(out of about 1700 MW of installed wind capacity)

NY Renewables' Effective Load Carrying Capability (ELCC) vs. Market Penetration

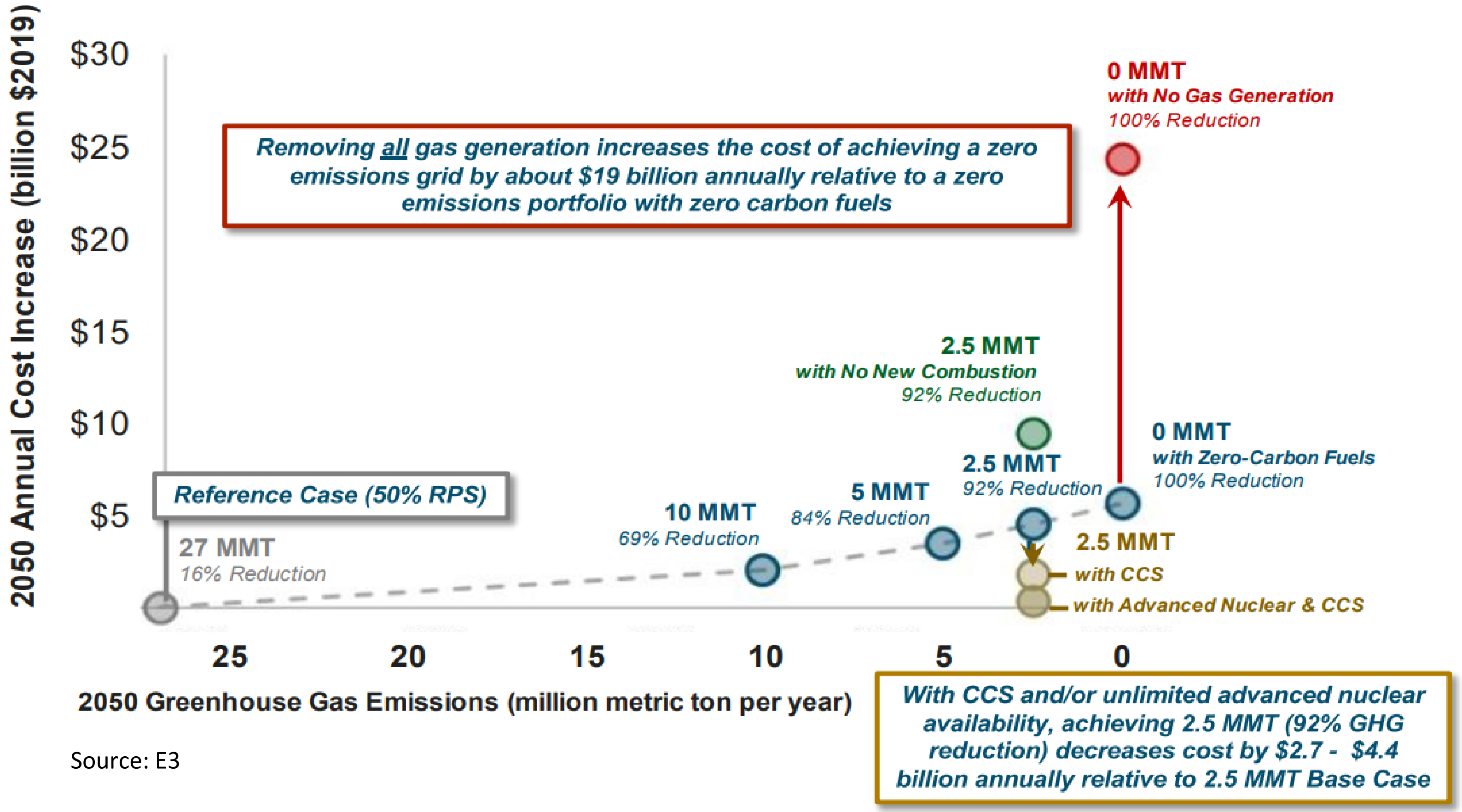


Source: NYISO Grid in Transition, The Brattle Group, March 2020.

Marginal Costs of the Last Few % Decarbonization

Many studies find that the cost of decarbonizing the last 10-20% of our economies is about the same as the cost of decarbonizing the first 80-90%, if no clean dispatchable generation is available.

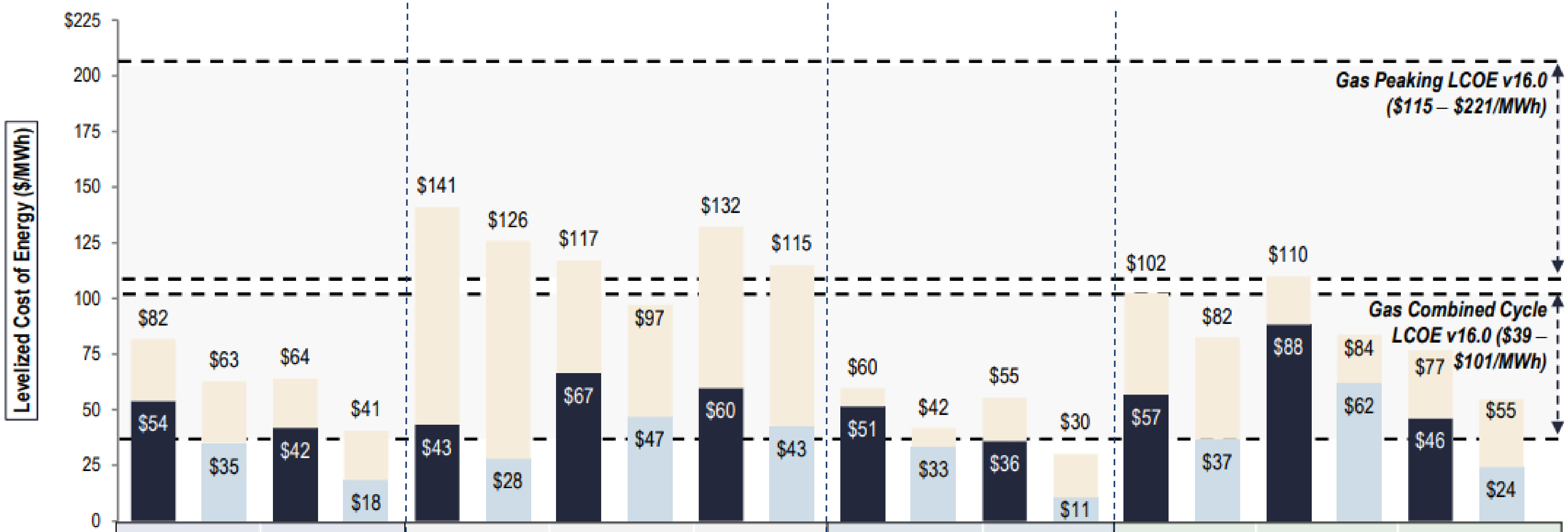
- New England results typical: renewables + storage requires huge overbuild to drive out the last portions of carbon.
- Clean dispatchable power becomes essential even if much more costly per MWh than renewable power.
- Nuclear essential even if not flexible, as reduces renewable reliance; even better if flexible like SMRs.
- Note: *This does not address the resiliency problem*



Source: E3

“LCoE+” (with reliability adders for renewables)

Because of intermittency and declining ELCCs with increased use, renewables need to be paired with, or backed up by, controllable peakers to provide reliability equal to their nameplate capacity.



	Solar	Wind	Solar	PV + Storage	Wind	Solar	Wind	Solar	PV + Storage	Wind
ELCC	50%	16%	7%	51%[4]	15%	85%	17%	38%	70%[4]	15%
Capacity Factor	20%	43%	25%	25%	30%	21%	50%	19%	19%	39%
Resource Penetration	3%	25%	32%	32%	19%	1%	56%	5%	5%	7%
	MISO		CAISO			SPP		PJM		

Lazard's Unsubsidized LCOE[3] Lazard's Subsidized LCOE[3] Firming Cost[1]

Source: “2023 Levelized Cost Of Energy+,” Lazard, April 12, 2023, https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

Resiliency Risks

A poorly understood but important problem is the likelihood and consequences of a protracted “renewable drought” for a power system mostly reliant on renewables.

In principle, if a system were nearly all solar and wind, a few days in a row without either resource could cause nearly catastrophic, prolonged blackouts, esp., if most end-uses were electrified.

- A “black swan” event – but how black and how rare? Need very long periods of meteorological data to assess likelihood, but such data often not available.
  - A recent study of Germany using 35 years of historical data found that the worst past sustained drought had been 2 weeks long with adjacent days also below average. Optimized 2030, all-clean power system for this required 81 GW of storage (mostly from H_2 in CCs, against a peak load of 105 GW), enough to cover the total average German load for 24 days! (*Envir. Res. Lett. 17*, March 15 2022)
  - A 2020 study of NYISO found that in 2007-2012 there had been 19 periods in the summers and 3 periods in the winters of four or more days with average wind capacity factors about 1/2 or less of normal. In a projected 2040 clean system, the winter wind lulls required up to 30,000MW of new, dispatchable clean energy resources (assumed to be mostly 8-hour storage) to prevent blackouts – in a system with about an 80GW winter peak. (Climate Change Impact and Resiliency Study – Phase 2, Analysis Group, September 2020)
- These results are shocking but not surprising, partly because they are deterministic, i.e. assuming a given drought will definitely happen. In fact, estimates of when, with what probability, and what size a shortfall should be anticipated are very poorly known. Further, the system needs to be modeled in a very complex, stochastic manner to find the optimal adjustment.
- *The most obvious cure, rather than holding a huge standby system that is used very rarely, is to use fewer weather-dependent clean resources in the first place, e.g. nuclear, natural gas with CCS, etc.*

Conclusions

and Additional Sources

What Role(s) for Nuclear fit in?

A reliable and economical transition to a decarbonized grid and electrified end-uses requires consideration of clean dispatchable resources in addition to solar, wind and currently available storage.

- **Nuclear power is still essential:** In the US, the nuclear fleet provides more clean energy per year than all other renewable resources -- about 50% of all US carbon-free energy
  - Annual energy from a single 1000MW nuclear power plant avoids power emissions equivalent to CO_2 from about 1 - 1.5 million gasoline-fired cars (roughly as much as avoided by all the BEVs in the US in 2023, about 2mm)
- **Decarb Planning Models:** nearly all assume or choose nuclear life extensions through 2050; they also show a consistent need (and savings from) clean dispatchable generation in late decarbonization stages
  - A problem for 2030 and beyond, but made worse if the solution is put off until then
- **The Achilles heel of conventional LWRs:** extreme capital costs, long construction times, slow regulatory approvals
  - These make investors reluctant to place such large and long-horizon bets, despite high social value
  - It is hoped that SMRs and microreactors can avoid these persistent industry problems
- **Resiliency problem:** unsolved, but seems to involve huge amounts of standby resources, which might be avoided if less weather-dependent clean resources were used in the first place.
- **Opportunities for an expanded role for nuclear:** “Pink” hydrogen production
  - At about $4-5/kg, pink hydrogen is about twice the cost of blue hydrogen at about $2/kg, however, the IRA can reduce the cost of pink hydrogen to ($2/kg) where it is near parity with subsidized blue hydrogen ($1.20/kg)

Select List of Decarbonization Pathway Studies

- "Pathways to Net-Zero for the US Energy Transition," J. Ewing et. al., Duke University, November 2022
- "Pathways Study: Evaluation of Pathways to a Future Grid," Analysis Group, Inc. on for ISO-NE, April 2022
- "NREL Examining Supply-Side options to achieve 100% clean electricity by 2035," National Energy Renewable Laboratory, 2022
- "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," E. Larson et. al., Princeton University, October 29, 2021
- "Decarbonizing Virginia's Economy: Pathways to 2050," W. Shobe and B. Haley, et. al., University of Virginia and Evolved Energy Research, January 2021
- "Energy Pathways to Deep Decarbonization: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study," Evolved Energy Research for the Commonwealth of Massachusetts, December 2020
- "Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future," E3 and Energy Futures Initiative, November 2020
- "Pathways to Deep Decarbonization in New York State," E3, June 24, 2020

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