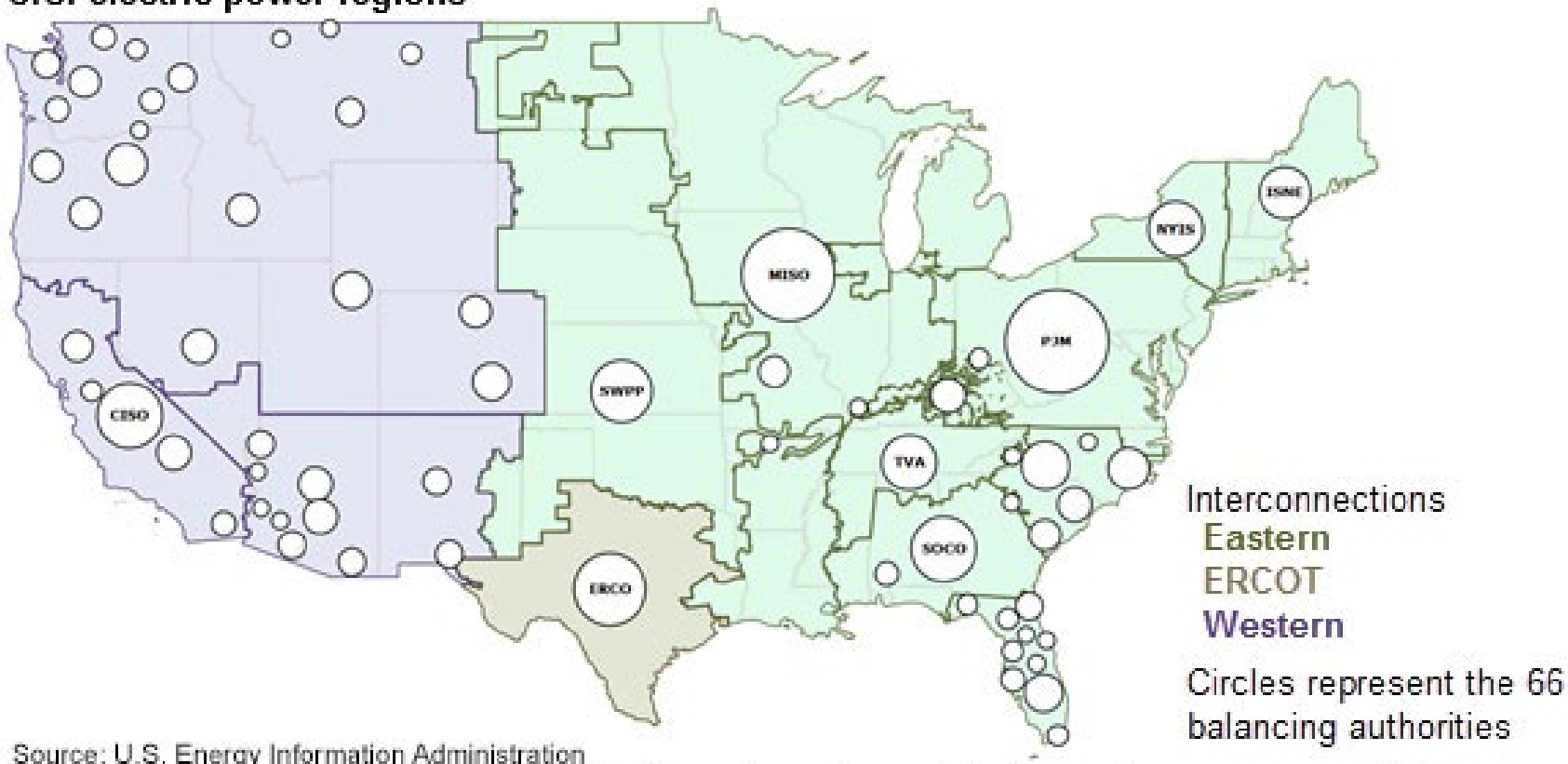
The Role of the Electricity Grid

- To understand the potential of renewable energy for electricity generation, it is important to understand how the electric grid works
  - Electricity cannot be stored. What goes on the grid must match what comes off
  - Because of this, wholesale prices can vary by a factor of 10 or more within a given day
  - Balancing authorities ensure electricity demand and supply are balanced (e.g. New York Independent System Operator (NYISO))
    - Calculate who can provide the power needed at lower cost
    - Have plants adjust every five minutes to keep the system balanced
    - Use weather forecasts to try to project production from wind and solar

U.S. electric power regions



Source: U.S. Energy Information Administration

Note: The locations of the electric systems are illustrative and are not geographically accurate. The sizes of the circles roughly indicate the size of the electric system.

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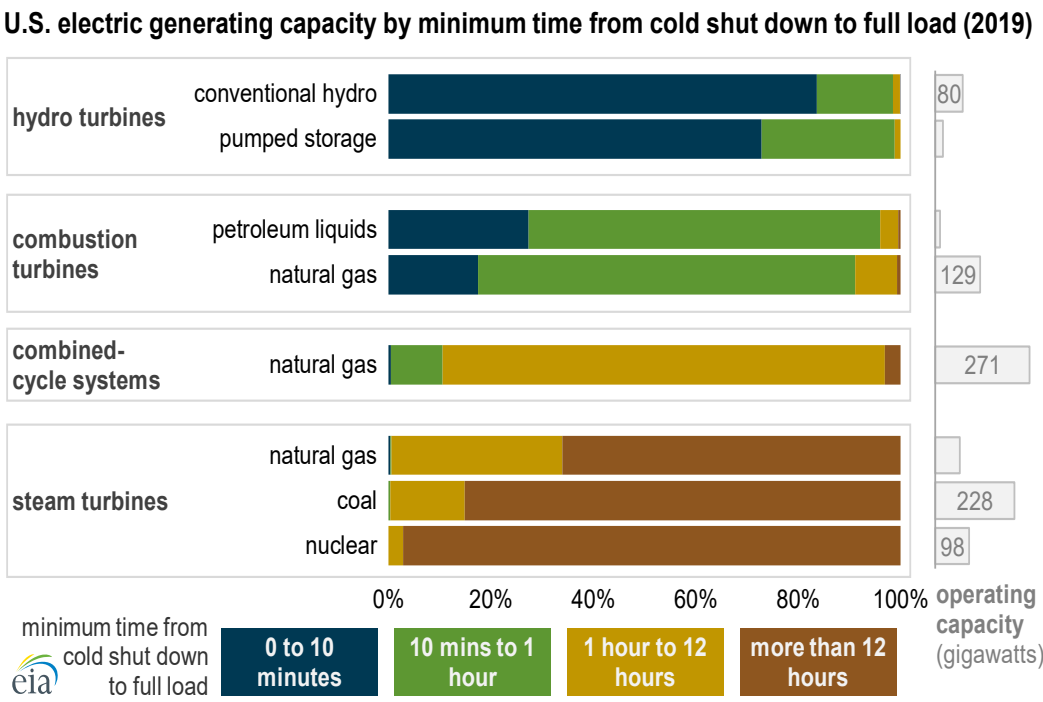
The Role of the Electricity Grid

- Two types of generation sources:
  - Dispatchable: operator has temporal control over. Can decide when to shut off or turn on.
  - Intermittent: Production varies due to exogenous factors, such as amount of wind blowing.
    - Generation is out of control of the operator
    - However, these plants can be shut down easily, so there is an upper limit on generation

The Role of the Electricity Grid

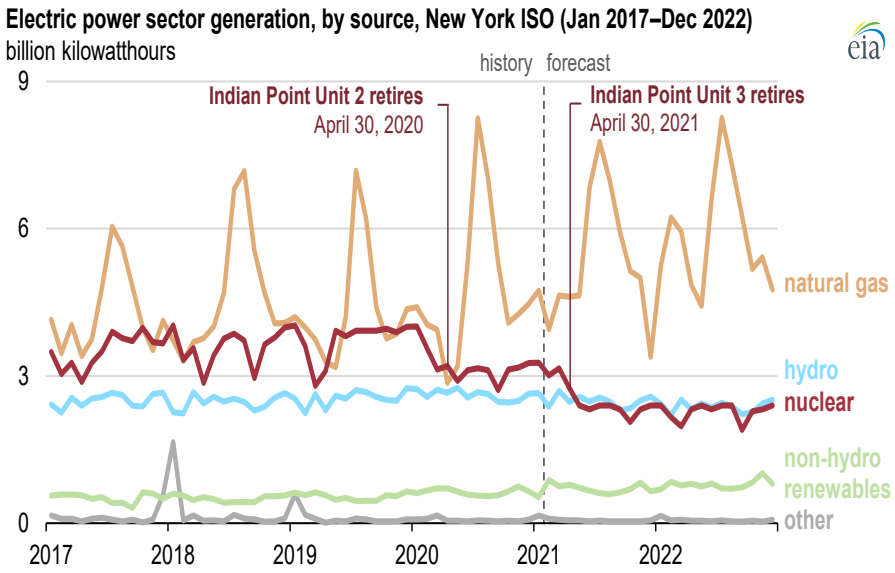
- Even when the owner has control, some plants can be switched on and off more quickly than others
  - Ramping rates: how quickly plants can change the level of output
  - Flexible sources with rapid ramping ability include:
    - Gas-fired peaker plants
      - Low fuel efficiency, but are flexible
      - Also have low start-up costs
    - Hydroelectric



Source: EIA Today in Energy, November 19, 2020

The Role of the Electricity Grid

- Even when the owner has control, some plants can be switched on and off more quickly than others
  - Ramping rates: how quickly plants can change the level of output
  - Flexible sources react to demand
  - Other sources (e.g. nuclear) serve as baseload power



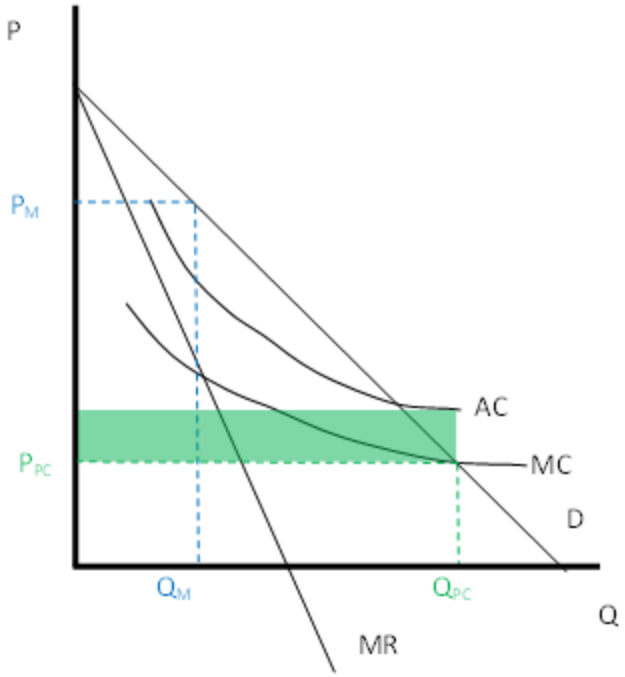
Source: EIA Today in Energy, April 30, 2021

The Role of the Electricity Grid

- Even when the owner has control, some plants can be switched on and off more quickly than others.
  - Ramping rates: how quickly plants can change the level of output.
  - There are also differences in often the plant must shut down for required maintenance.
  - System is designed to meet demand extremes. Some peaker plants may only run a few days a years.

The Role of the Electricity Grid

- Generation costs
  - Electricity generation has large fixed costs
  - Variable costs such as fuel costs and maintenance are typically low relative to fixed costs.
  - Thus, electricity generation has characteristics of a natural monopoly. Simple marginal cost pricing does not allow investors to recoup fixed costs:



The Role of the Electricity Grid

- Generation costs
  - To account for fixed costs, generation costs are typically measured using levelized cost of electricity
    - Levelized cost is the constant price for power that would equate the net present value of revenue from the plant's output with the net present value of the cost of production.
      - It is the price a generator would need to recoup both their fixed and marginal costs

The Role of the Electricity Grid

- Generation costs
  - Key assumptions can lead to different estimates of levelized costs:
    - Inflation rates
    - Real interest rates
    - How much the generator will be used
    - Productivity of the generator
      - » E.g. how much will it be used and how much electricity will it produce
      - » Future generation particularly relevant for renewables, as may depend on quality of the site
    - Future input costs (particularly fuel)
    - Future market prices

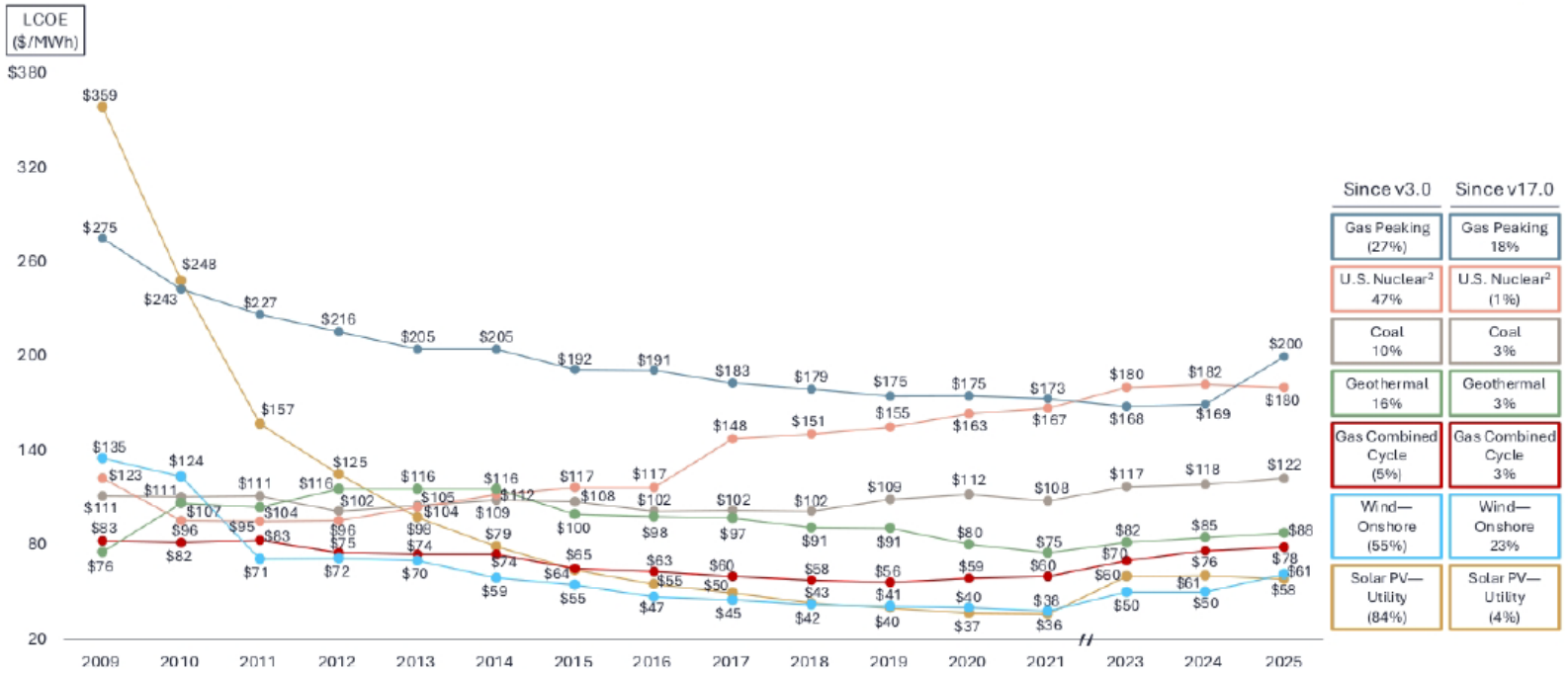


Figure 6: Levelized Cost of Electricity by Technology, 2009–2024

Note: Reproduced from Lazard (2025, pp. 14). The figure reports historical average levelized cost of electricity (LCOE) values, calculated as the midpoint between high and low estimates for each technology. It highlights the dramatic decline in renewable costs: utility-scale solar PV fell by more than 90% between 2009 and 2024, and onshore wind by around 70%. These reductions, driven by learning curves, economies of scale, and technological improvements, have made renewables broadly cost-competitive with fossil fuels. Lazard's analysis notes that these declines have begun to plateau and, in some cases, slightly reverse in recent years. For nuclear, LCOE estimates reflect Lazard's LCOE v14.0, adjusted for inflation, based on then-estimated costs of the Vogtle Plant.

Source: Dugoua & Noailly (WIPO Econ Research Working Paper 95/2026, 2026)

Electricity Prices

- In the United States, how electricity is bought and sold varies by region

- Most customers are served by investor-owned utilities.

- These operate in either traditional regulated markets or deregulated competitive markets.

Electricity Prices

- Regulated markets
  - Historically, most utilities were vertically integrated monopolies, meaning they owned the generators, transmission lines, and distribution lines
    - Today, about one-third of US electricity demand is serviced by this traditional model.

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  - Because they operate as monopolies, state regulators oversee how these utilities set prices to protect consumers.
    - Under this structure, customers bear the investment risk
  - Utilities may trade with one another in wholesale bilateral markets (e.g., buying excess hydro power when cheaper than generating their own)
    - These transactions are regulated by the Federal Energy Regulatory Commission (FERC)

Electricity Prices

- De-regulated markets
  - Beginning in the 1990s, many states transitioned to deregulation to create competition and lower costs
  - Utilities sold power plants to independent energy suppliers
  - They kept the transmission and distribution lines, which remain regulated as natural monopolies

Electricity Prices

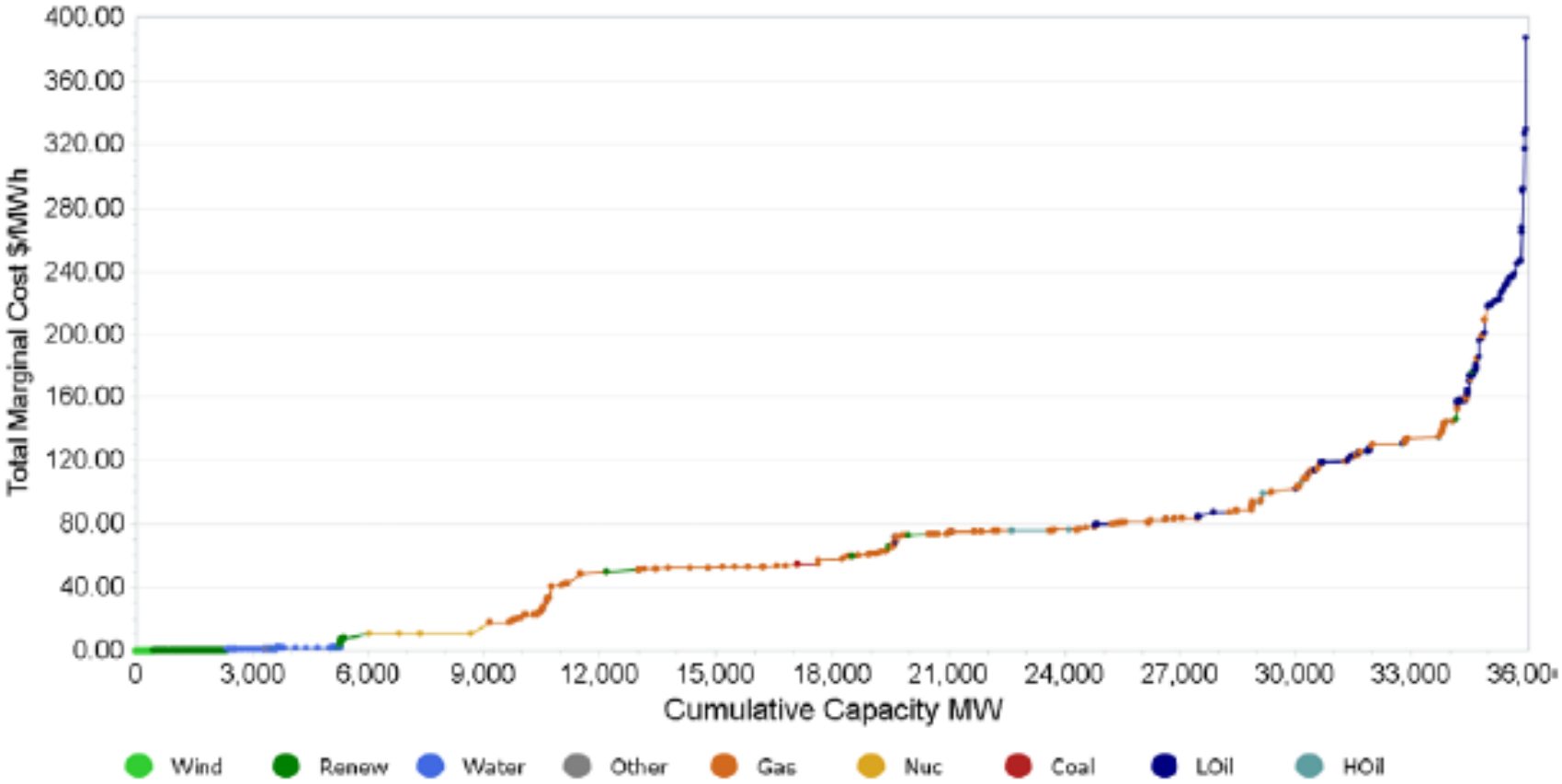
- Retail deregulation
  - Customers can choose their independent electric supplier rather than being forced to buy from the local utility
  - Retailers compete on price or specific preferences (e.g., clean energy)

Electricity Prices

- Wholesale deregulation
  - Regional Transmission Organizations (RTOs) replaced utilities as grid operators and managers of centralized wholesale markets
  - Investment risk shifts from the customer to the independent power suppliers
  - RTOs run two main types of markets:
    - Day-ahead market
      - Day-to-day auctions for producing electricity
      - Accounts for 95% of transactions
      - Based on forecasted load for the next day
    - Real-time markets
      - Typically run once every hour and once every five minutes
      - Accounts for real-time load changes to balance supply at all times

Electricity Prices

- Wholesale deregulation
  - How markets work
    - Suppliers bid a price to sell.
    - RTOs use these bids to decide which units to dispatch (e.g. to run to produce power) and in what order
      - Prices are determined by the marginal cost of the last power plant needed to meet demand
      - For plants with lower marginal costs, additional revenue helps cover fixed costs



Source: FERC 2024 Energy Primer

Electricity Prices

- Challenges for producers
  - Value of electricity varies depending on how much and when generated
    - Consider fixed costs versus variable costs
      - Nuclear (baseload) vs. natural gas (peak demand)

Electricity Prices

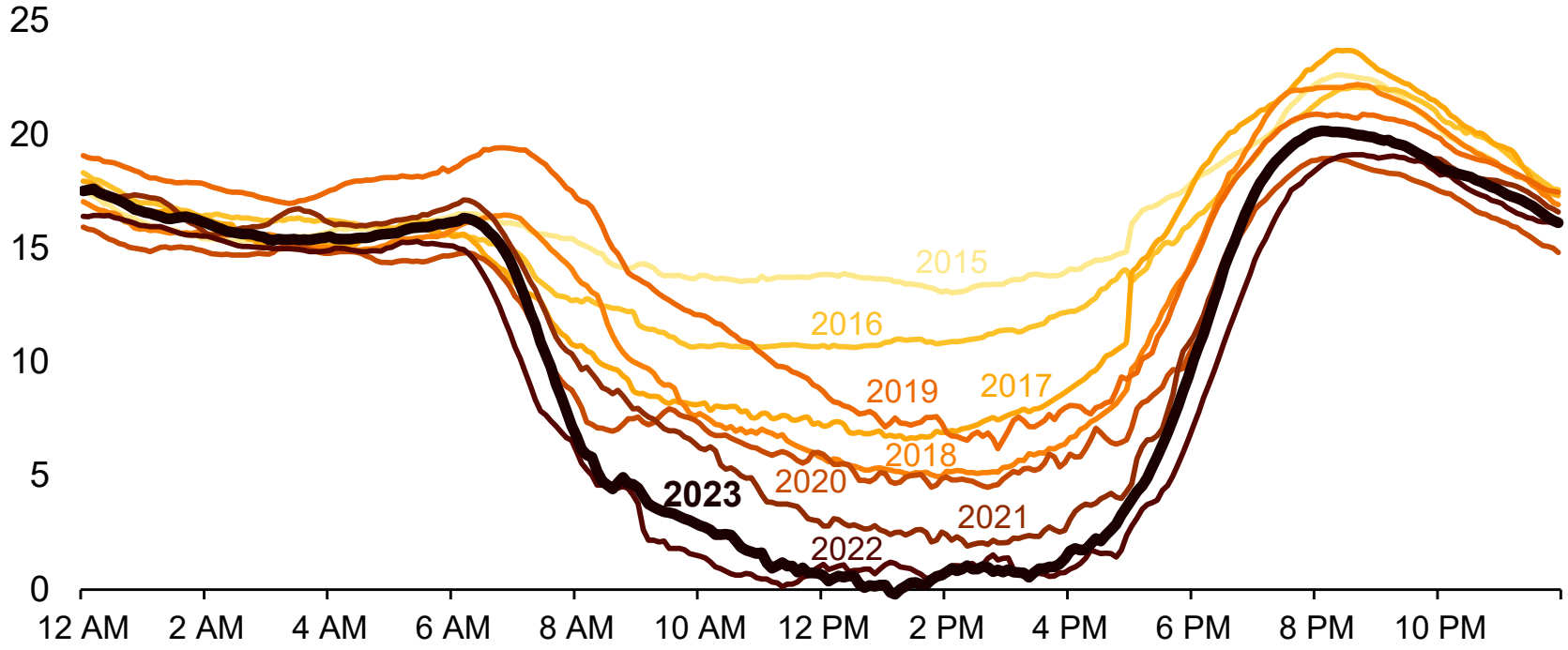
- Challenges for producers
  - Value of electricity varies depending on how much and when generated
    - Consider fixed costs versus variable costs
      - Nuclear (baseload) vs. natural gas (peak demand)
    - Renewable energy changes this
      - Because marginal cost of renewables is 0, it is offered to wholesale markets at very low costs

Electricity Prices

- Challenges for producers
  - Grid operators typically absorb all renewable power provided to the grid.
  - The remaining demand is the “net load”, to be met by other power plants

California's duck curve is getting deeper

CAISO lowest net load day each spring (March–May, 2015–2023), gigawatts



Source: EIA Today in Energy, June 21, 2023

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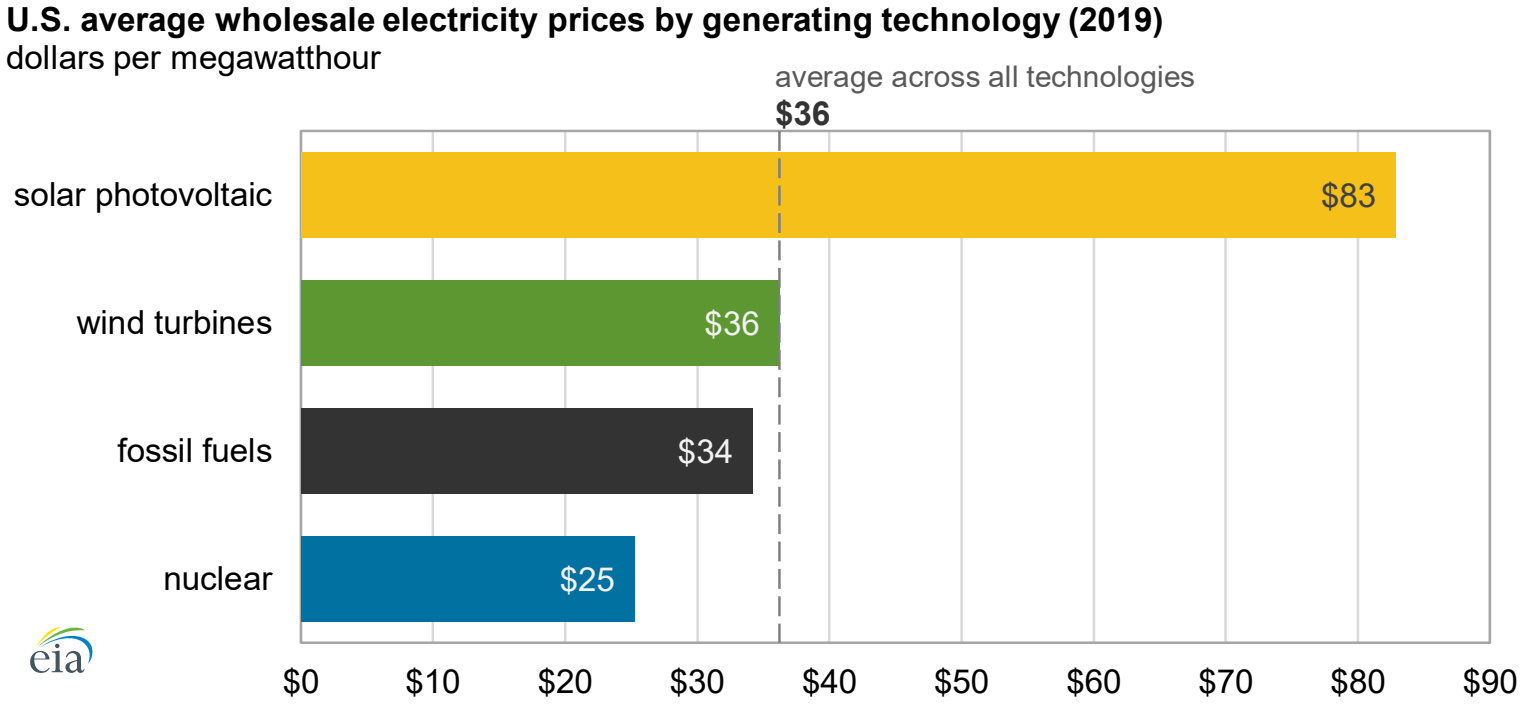
Electricity Prices

- Challenges for producers
  - Value depends on when electricity is produced
    - If used during periods of peak demand, wholesale prices of electricity will be higher



Source: EIA Today in Energy, October 9, 2020

Electricity Prices

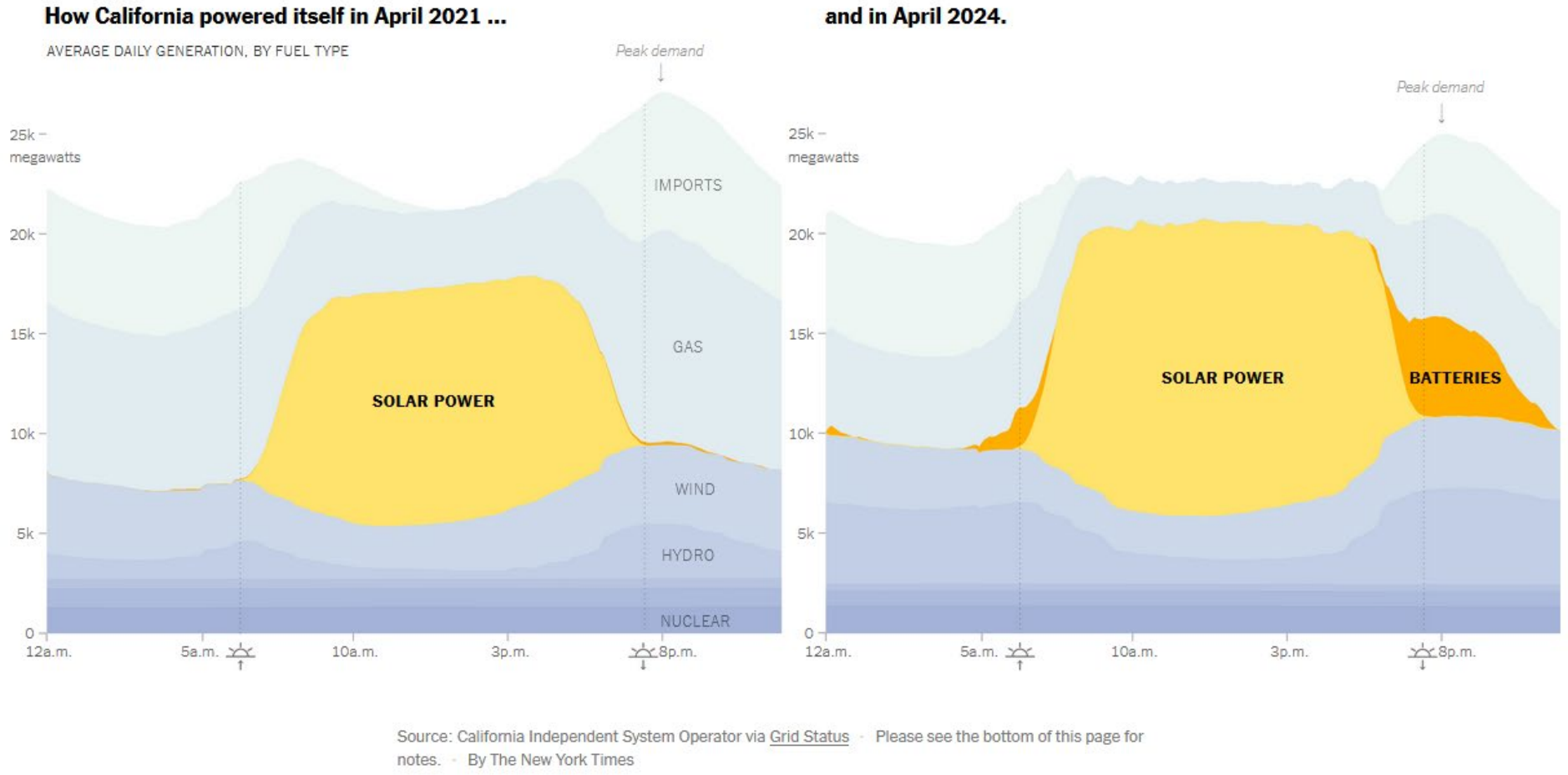
- Generation costs
  - Negative wholesale electricity prices
    - In some cases, producers find it cheaper to pay the grid to take their electricity than to shutdown
      - To receive subsidy from production tax credit for wind
      - To avoid costs of ramping down and ramping up later (e.g. nuclear)
    - Negative prices occurred 6% of the time in 2022

Electricity Prices

- Generation costs
  - Negative wholesale electricity prices
  - Competition from other sources has hurt nuclear power
    - Nuclear can place low bids, because most costs are fixed costs
      - However, because of these fixed costs, note that nuclear's levelized costs are larger
      - Competition from natural gas and wind is forcing nuclear plants to retire early
        - » Nuclear supporters argue that other carbon-free sources, such as wind and solar, benefit from subsidies

Electricity Prices

- Generation costs
  - Negative wholesale electricity prices
  - Competition from other sources has hurt nuclear power
  - Use of batteries to reduce fluctuations is growing
    - California subsidies batteries to accommodate renewables



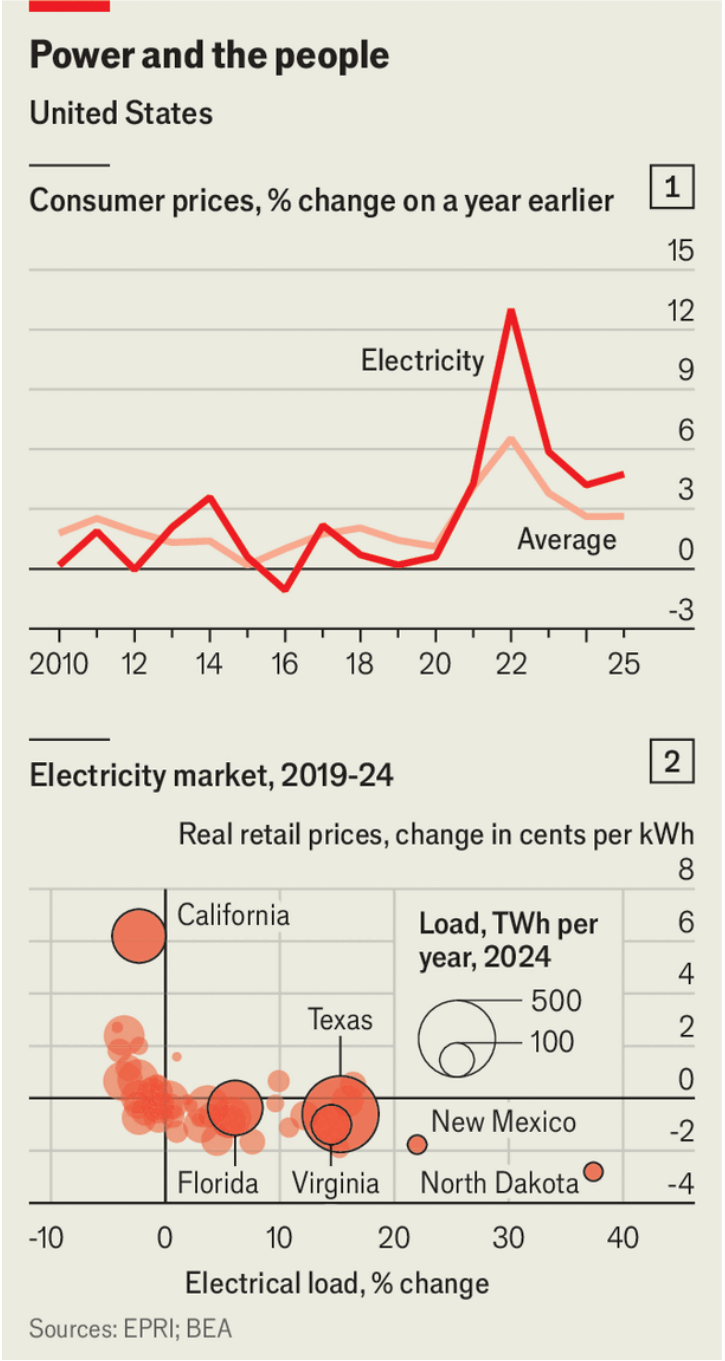
Source: "Giant Batteries are Transforming the Way the U.S. Uses Electricity," *The New York Times*, May 7, 2024

Electricity Prices

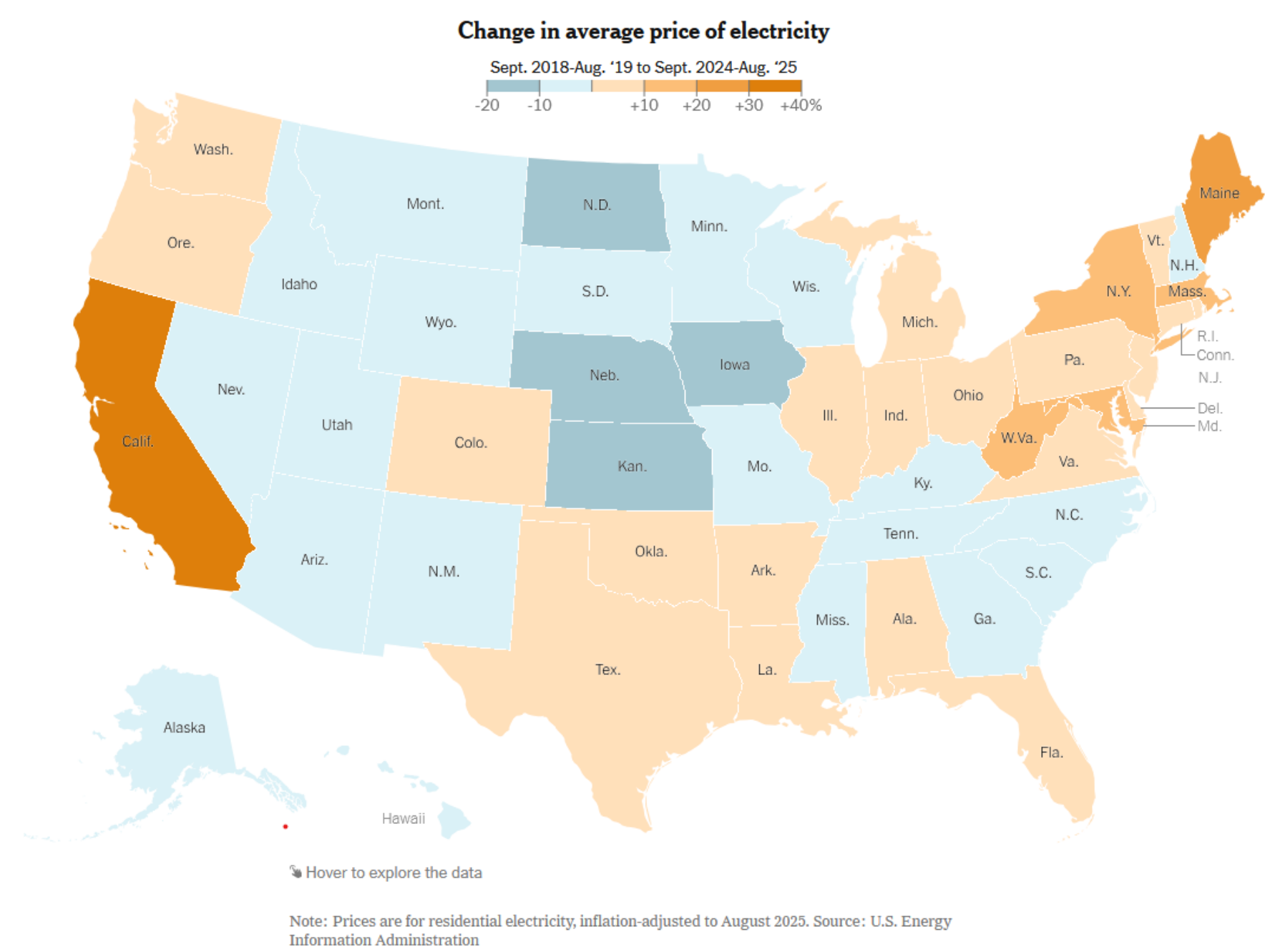
- Generation costs
  - Negative wholesale electricity prices
  - Competition from other sources has hurt nuclear power
  - Use of batteries to reduce fluctuations is growing
    - California subsidies batteries to accommodate renewables
    - In Texas, batteries used to smooth short-term market fluctuations
    - But battery storage is limited to just a few hours

Electricity Prices

- Rising electricity prices have become a concern for consumers and politicians



Source: “A load of nonsense,” *The Economist*, March 7, 2026, 73.

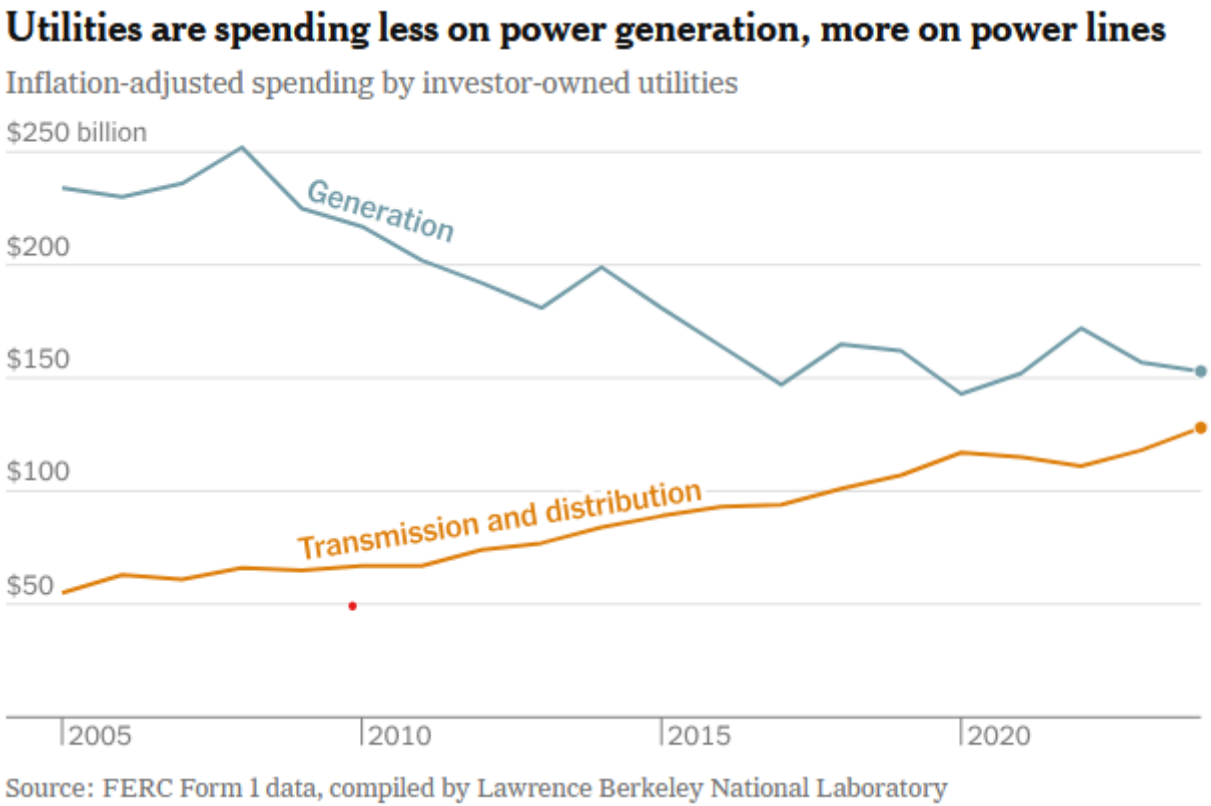


Source: "Why the Price of Electricity is Spiking Around the Country," *The New York Times*, October 30, 2025, https://www.nytimes.com/2025/10/30/climate/electricity-prices.html.

Electricity Prices

- Rising electricity prices have become a concern for consumers and politicians

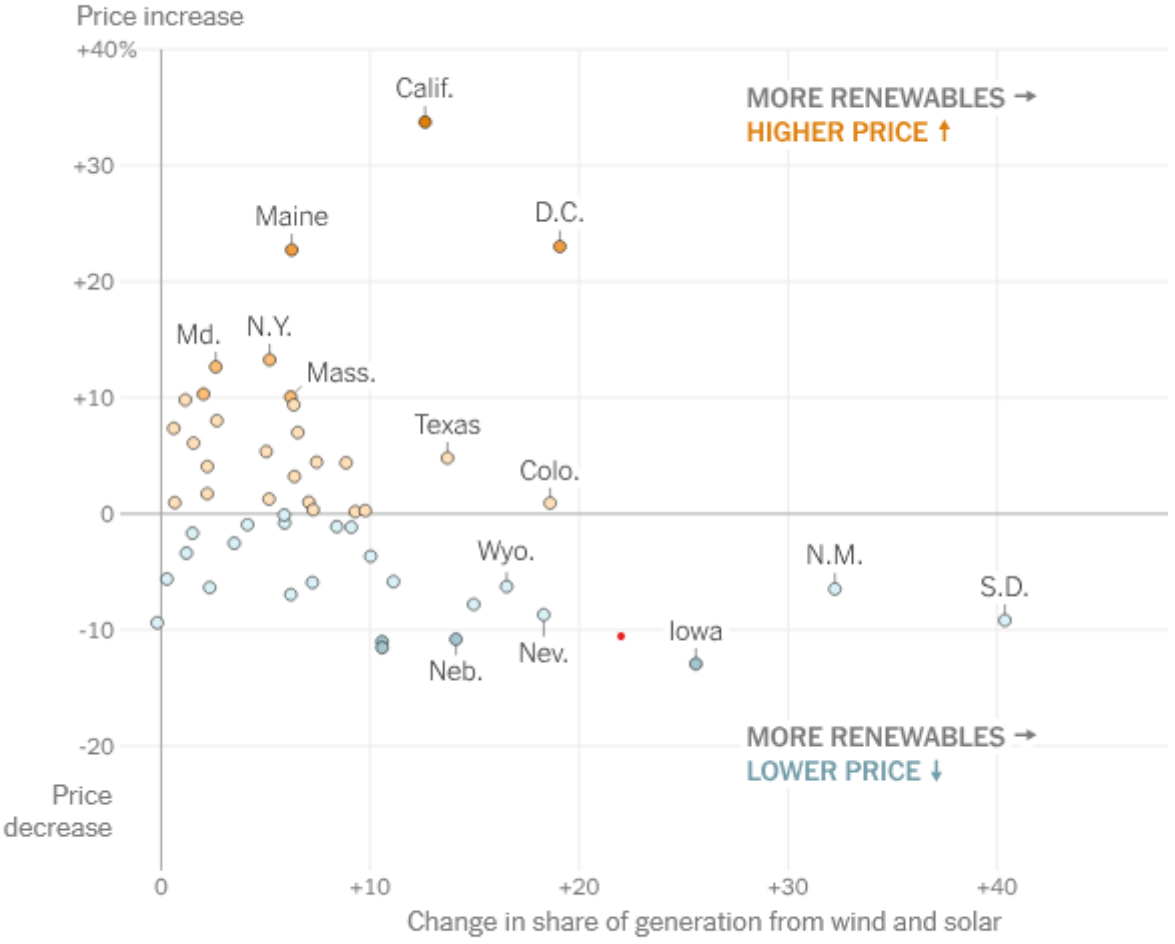
- *Question:* How might data centers and AI affect electricity bills?
- *Question:* What are other reasons that electricity prices have been rising?



Source: "Why the Price of Electricity is Spiking Around the Country," *The New York Times*, October 30, 2025, https://www.nytimes.com/2025/10/30/climate/electricity-prices.html.

Many states have added renewables and seen prices drop

Change from Sept. 2018-Aug. '19 to Sept. 2024-Aug. '25



Hover to explore the data

Note: Prices are for residential electricity, inflation-adjusted to August 2025. Source: U.S. Energy Information Administration

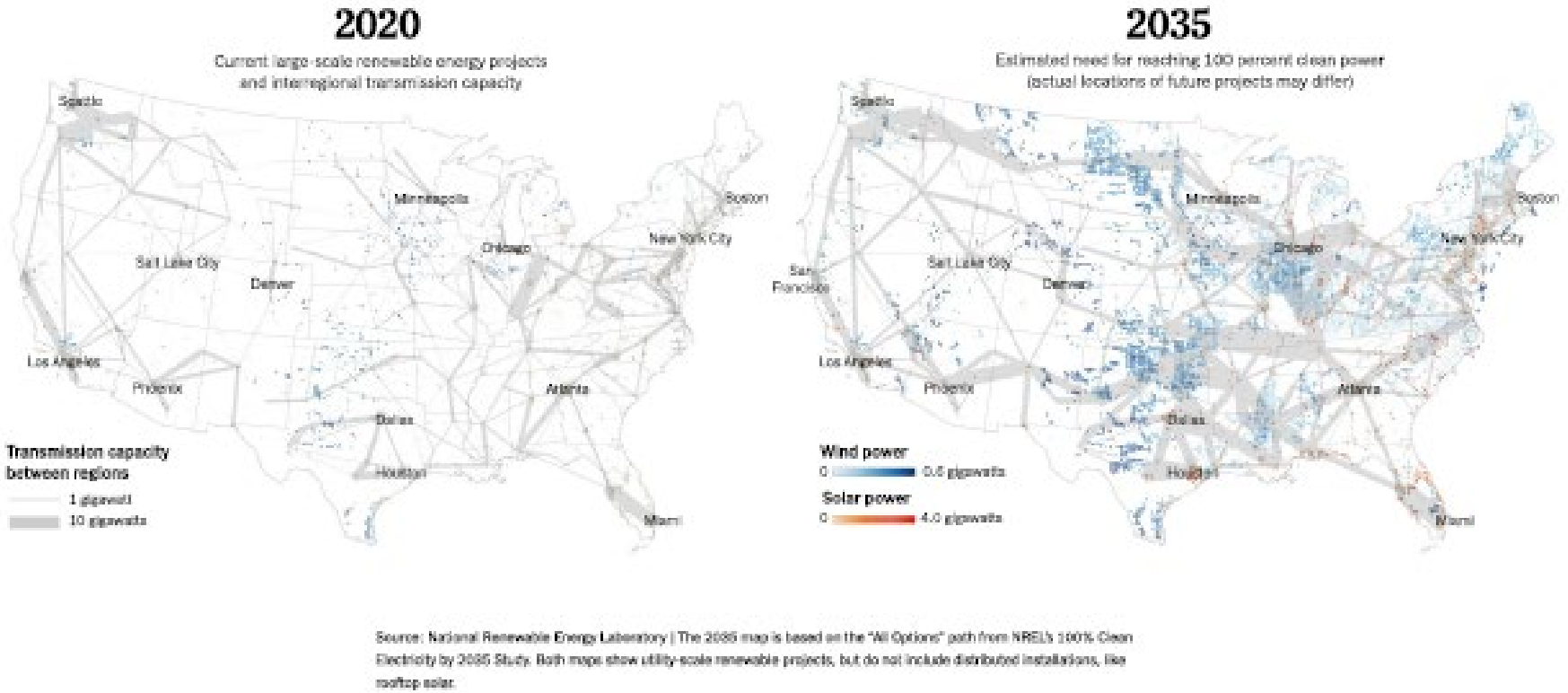
Source: "Why the Price of Electricity is Spiking Around the Country," *The New York Times*, October 30, 2025, https://www.nytimes.com/2025/10/30/climate/electricity-prices.html.

Transmission Lines

- Inadequate transmission infrastructure is a challenge for expanding renewable energy
  - Wind and solar must be located where resources are available
  - Electrification of other sectors will increase electricity demand, also requiring new transmission capacity

Transmission Lines

- Inadequate transmission infrastructure is a challenge for expanding renewable energy

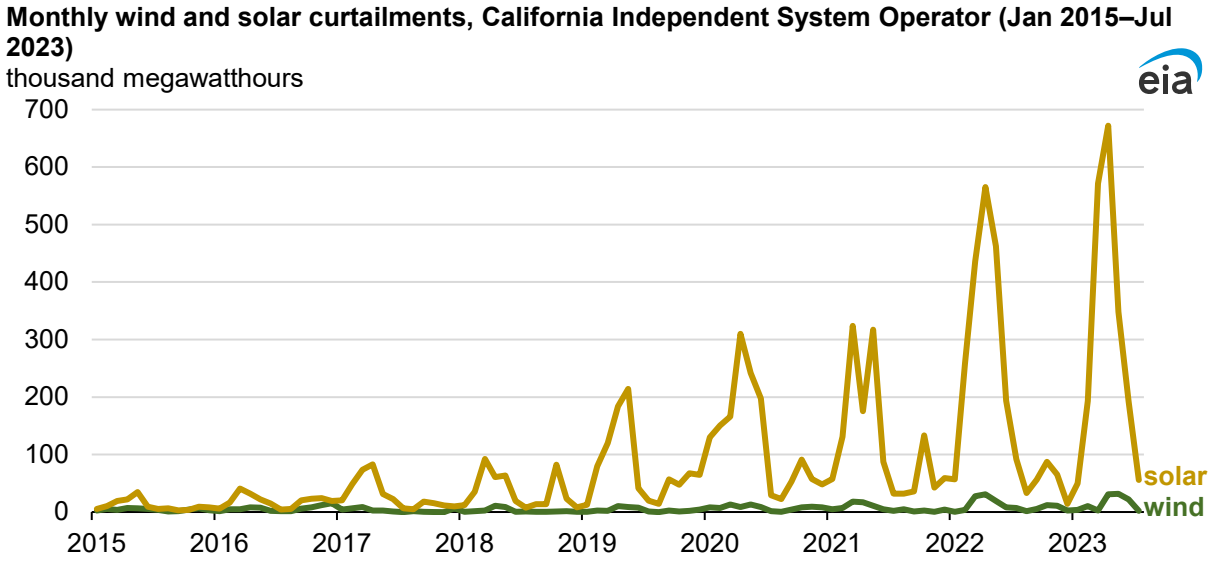


Source: National Renewable Energy Laboratory | The 2035 map is based on the "All Options" path from NREL's 100% Clean Electricity by 2035 Study. Both maps show utility-scale renewable projects, but do not include distributed installations, like rooftop solar.

Source: "Why America is not Ready for the Energy Transition," *The New York Times*, June 16, 2023, A12.

Transmission Lines

- Problems caused by inadequate transmission
  - Curtailment: quantity of electricity provided to the grid is reduced to keep in balance has been increasing



Source: EIA Today in Energy, October 30, 2023

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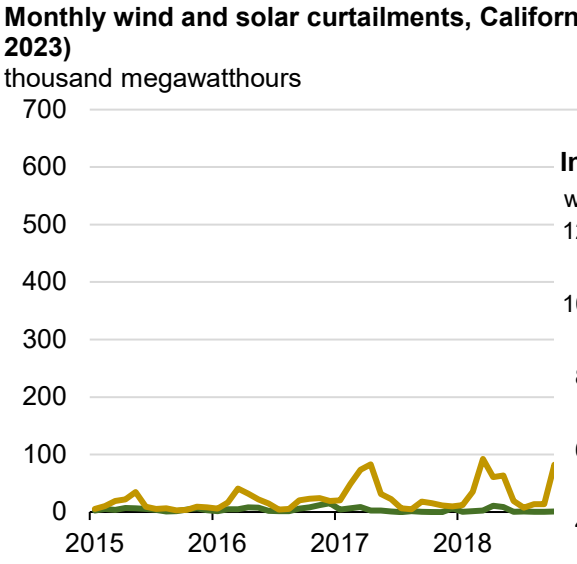
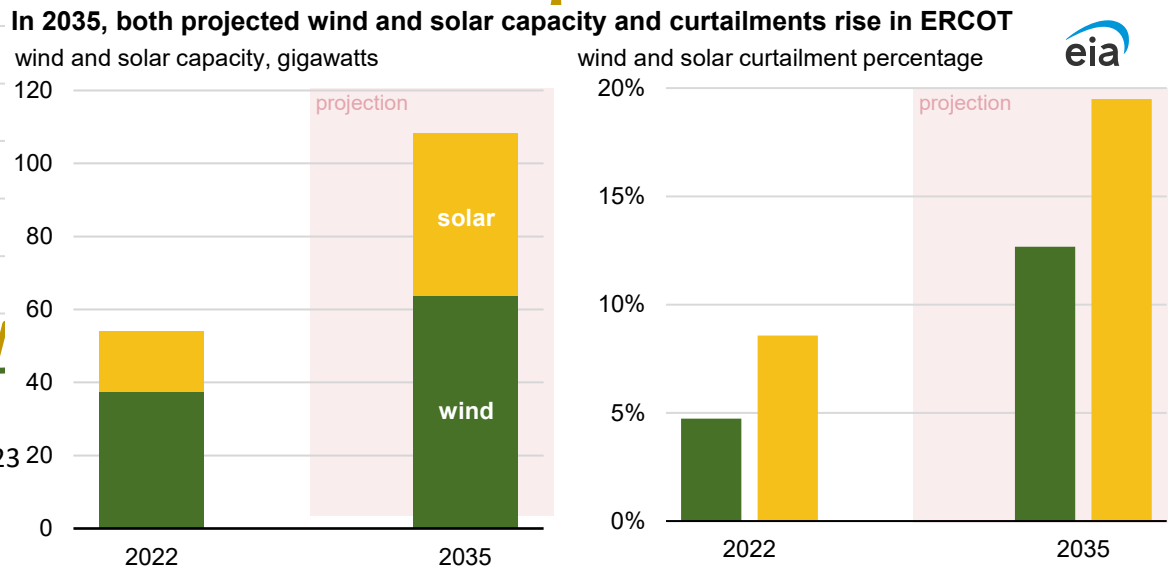


Source: EIA Today in Energy, October 30, 2023



Source: EIA Today in Energy, July 13, 2023

Transmission Lines

- Problems caused by inadequate transmission
  - Curtailment: quantity of electricity provided to the grid is reduced to keep in balance has been increasing
  - Negative wholesale electricity prices
    - Negative prices occur when other locations have positive prices
    - Thus, someone is willing to pay for the power generated, but we cannot get it to them

Transmission Lines

- *Question*: Why is expanding transmission difficult?

Transmission Lines

- *Question*: Why is expanding transmission difficult?
  - Approval takes time: there is a large backlog
  - The US electricity grid is decentralized
  - Who pays isn't clear: new transmission as a public good

Policy Questions

- *Policy question*: should households be rewarded for distributed generation?
  - Distributed generation is producing electricity at the consumer site, such as with solar PV panels
  - Electricity generated reduces the consumer's bill, since they take less power off the grid
  - Should they also be paid for any surplus power that they contribute to the grid?