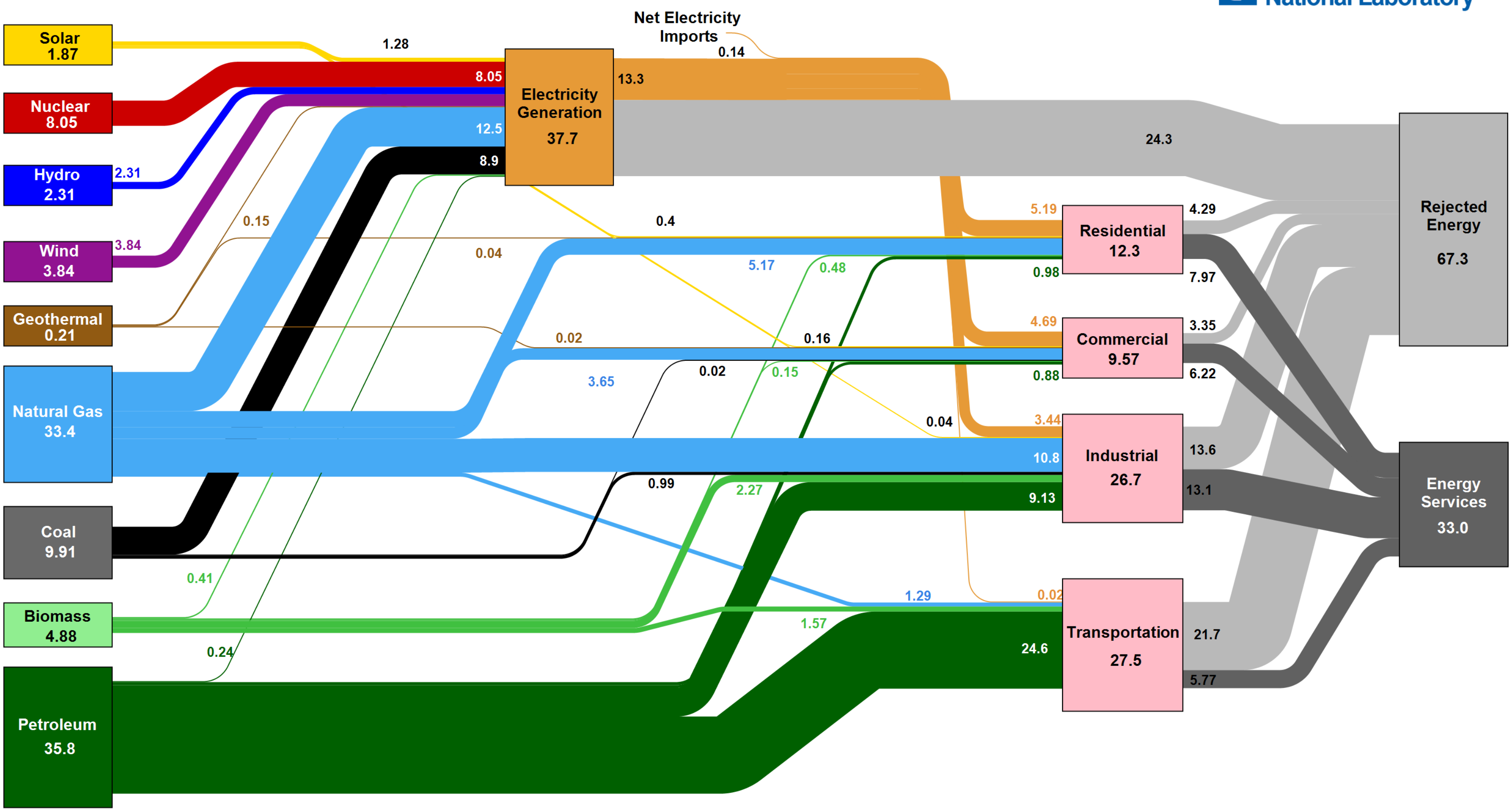
Estimated U.S. Energy Consumption in 2022: 100.3 Quads

Lawrence Livermore National Laboratory



Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). 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 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

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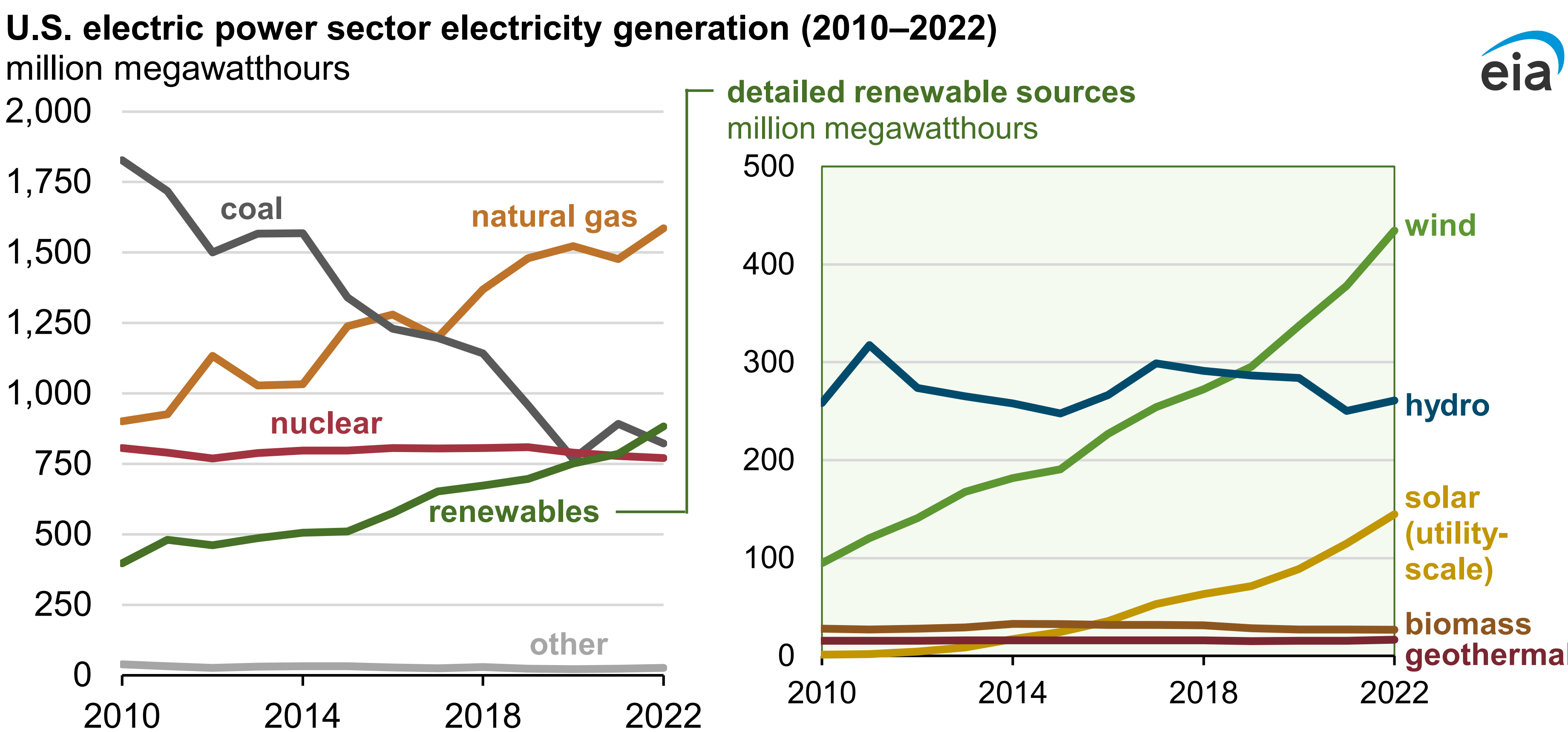

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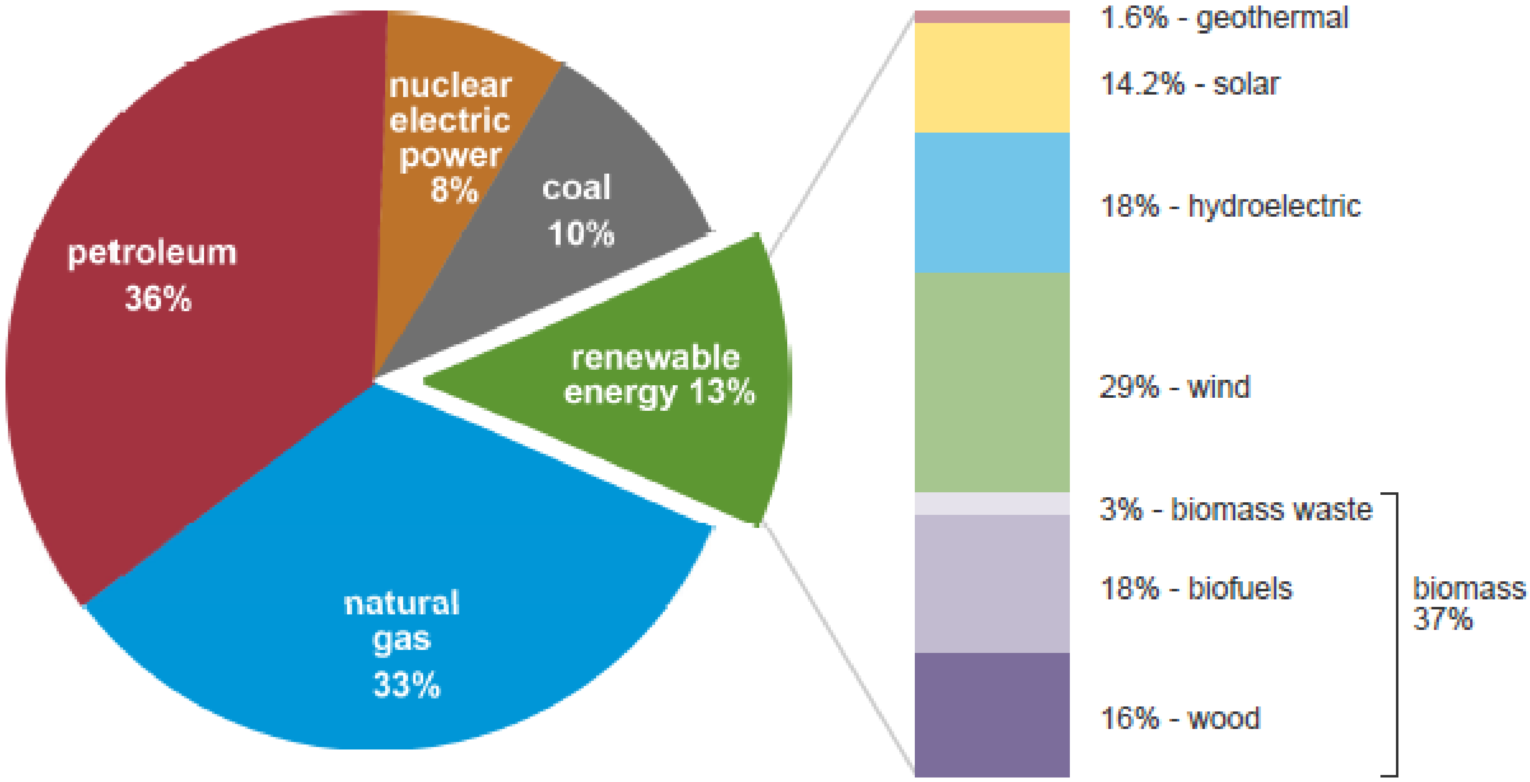
U.S. primary energy consumption by energy source, 2022

total = 100.41 quadrillion British thermal units (Btu)

total = 13.18 quadrillion Btu

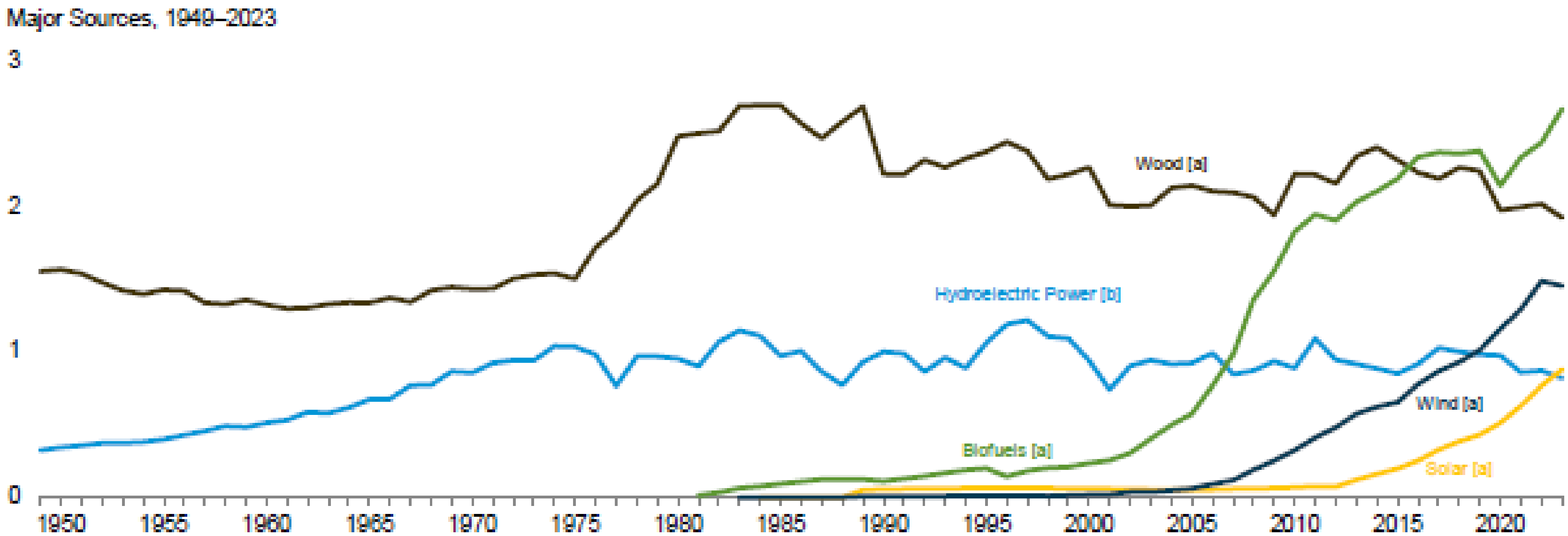


Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2023, preliminary data

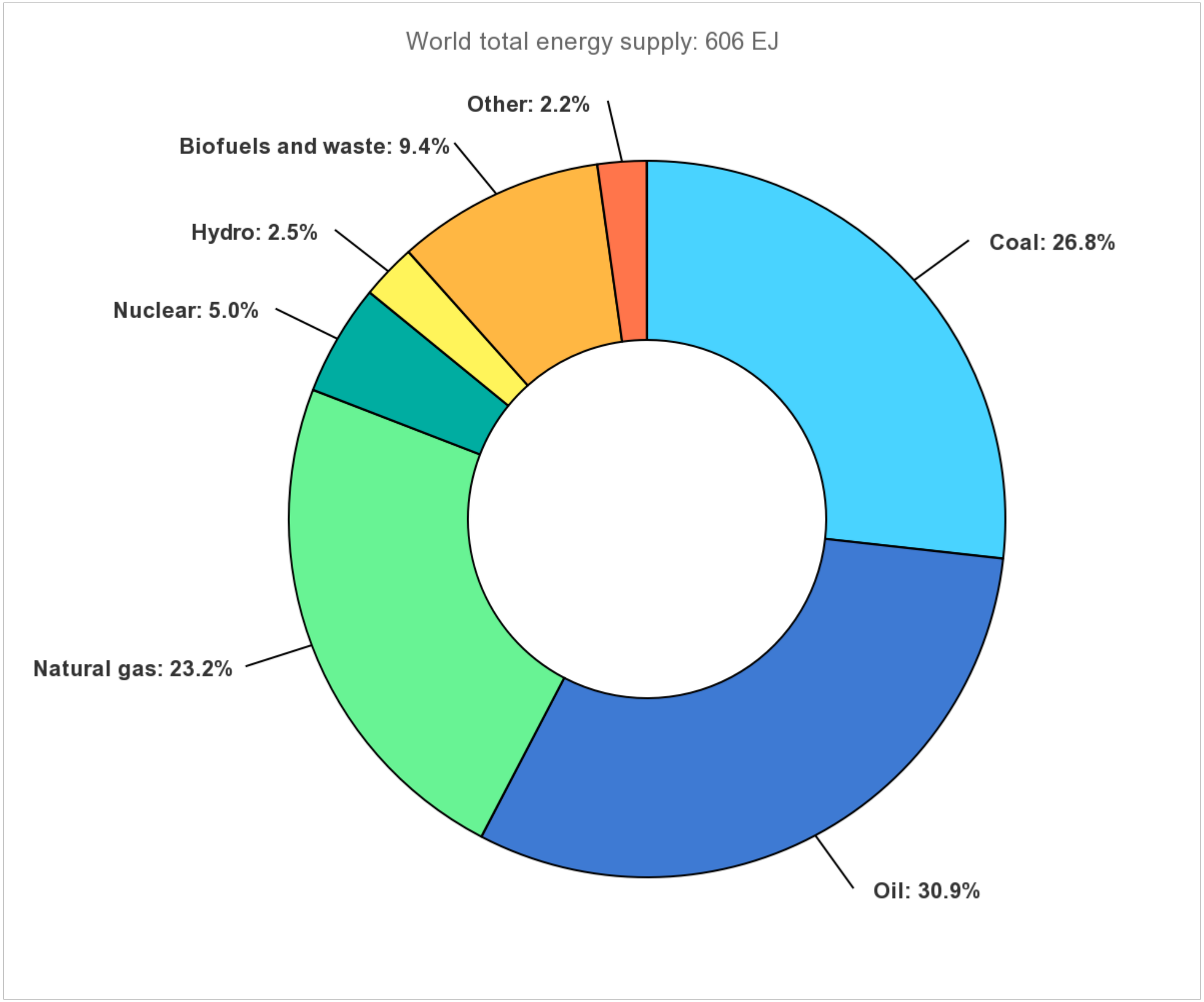
Note: Sum of components may not equal 100% because of independent rounding.

Figure 10.1 Renewable Energy Consumption

(Quadrillion Btu)



Source: U.S. Energy Information Administration/Monthly Energy Review, March 2024



Source: IEA Key World Energy Statistics 2021

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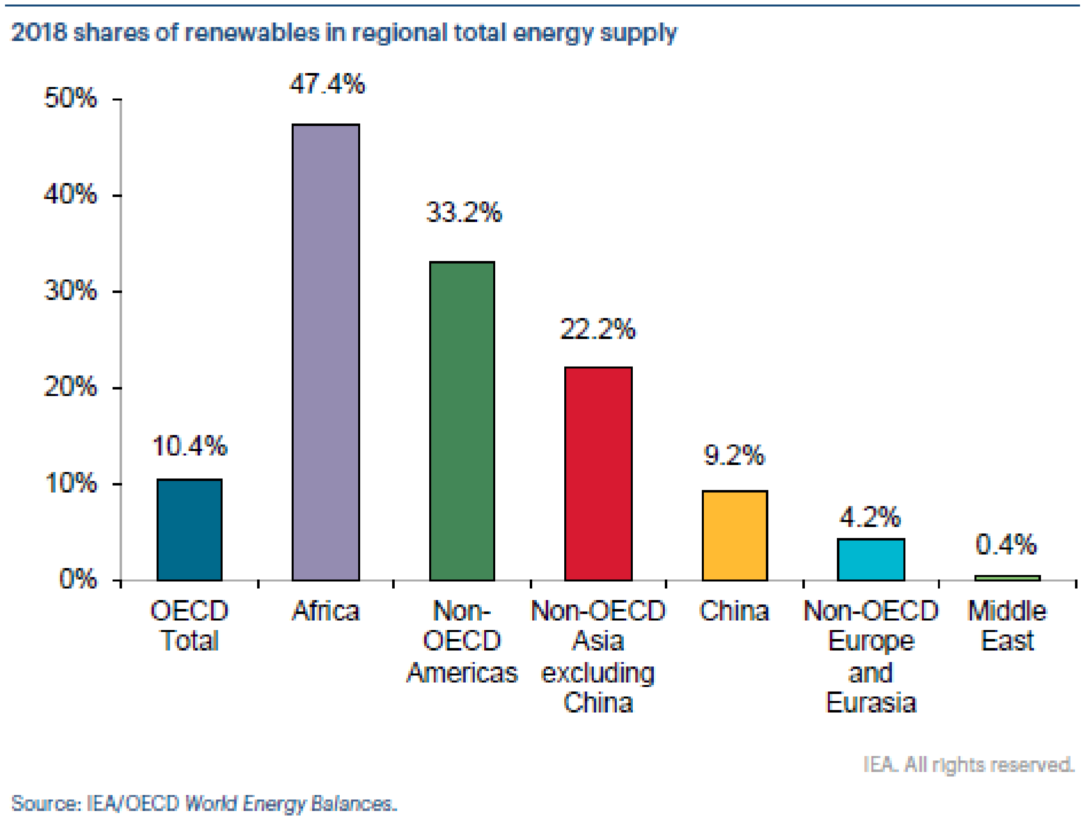


Source: IEA Renewables Information: Overview (2020 Edition)

The Climate Change Problem

- Electricity generation is the main source of carbon emissions (25% of carbon emissions globally), followed by deforestation & land use (24%), industry (21%) and transportation (14%)

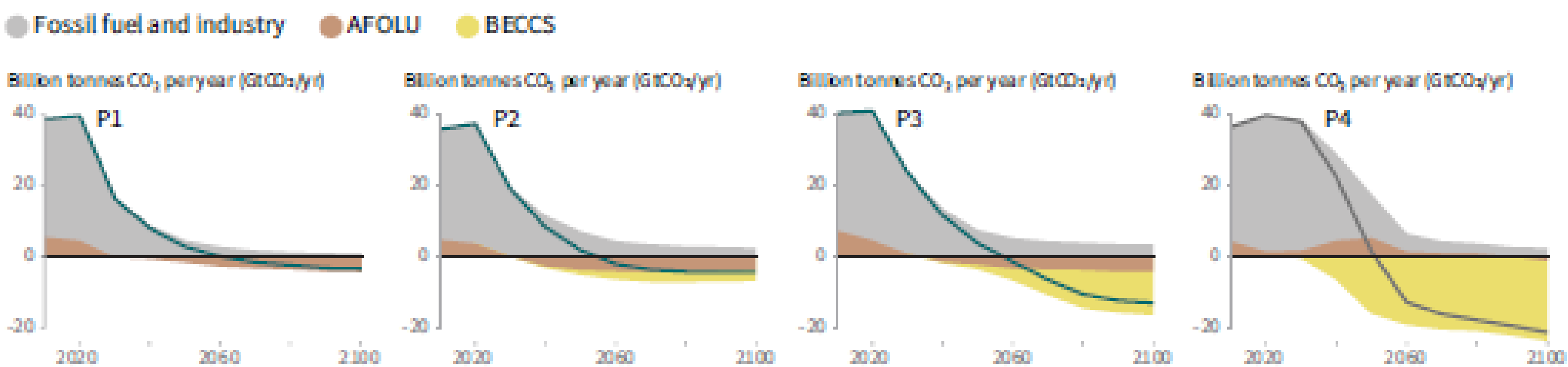
- IPCC estimates concentrations of 450 ppm or less are needed to keep temperature increase below 2^{o}C

- Meeting currently proposed carbon targets requires large emission reductions

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Source: IPCC (2018)

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Energy Transitions

- Energy transitions have occurred throughout history
  - Traditional biomass (wood, peat, and dung) was the main source of energy in the pre-industrial age
    - Wood became scarce in England during the 1500s and 1600s as the country grew

David Popp

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    - Coal has three times the energy density of dry wood

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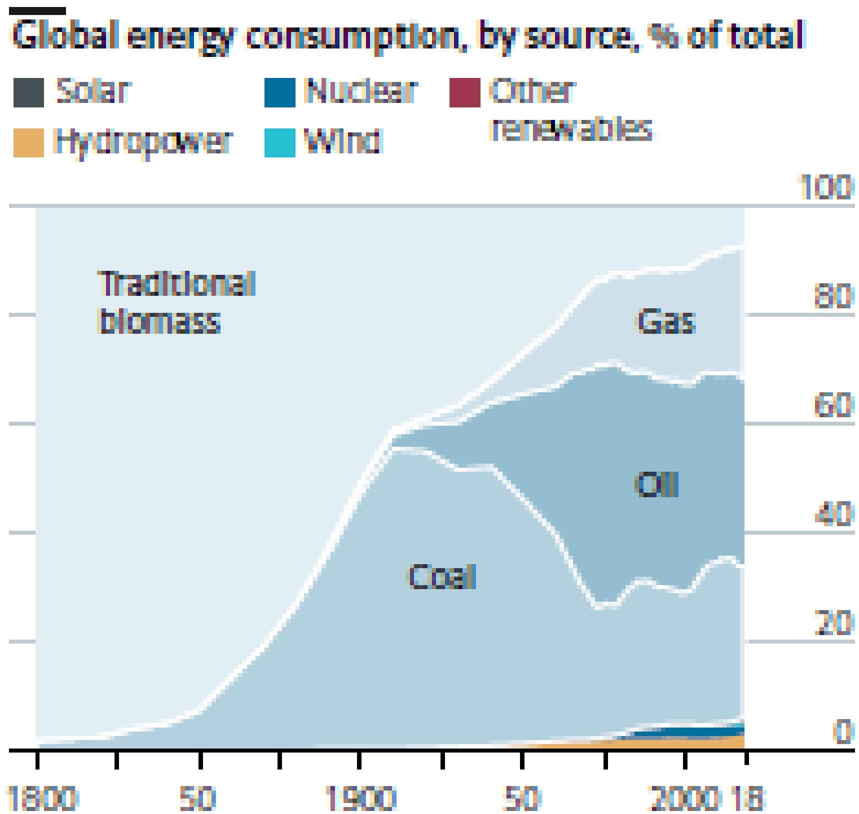
  - Oil emerges next
    - Liquid fuel useful for transportation. It is very energy dense.



Source: “Not-so-slow burn,” *The Economist*, May 23, 2020, 49-50.

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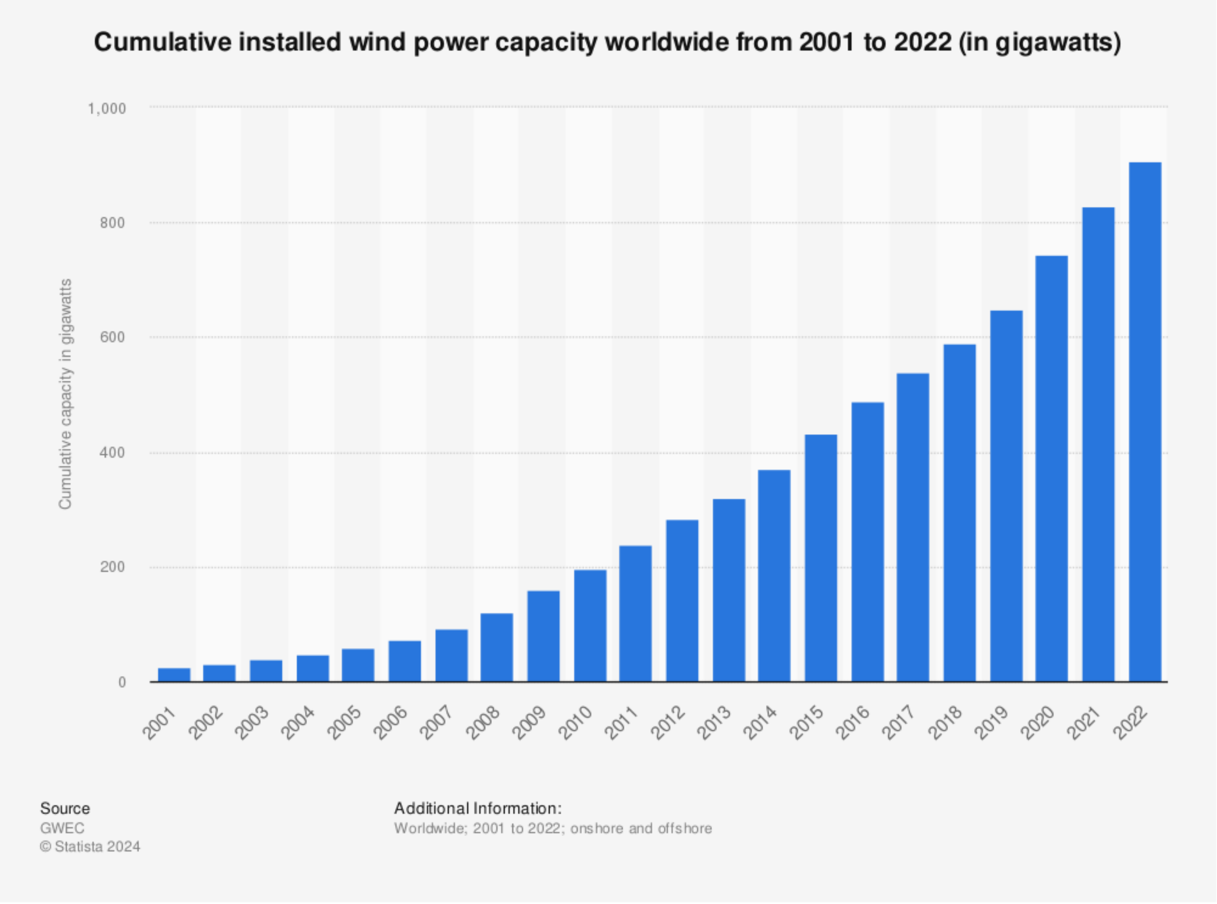
  - Natural gas is cleaner, but requires special infrastructure
  - Electrification
    - Also emerged during the 20th century
    - Not a fuel, but a new way of delivering energy

Energy Transitions

- Previous energy transitions move towards fuels that are more energy dense and convenient to use. Moving to renewables adds new challenges.
  - Solar energy is diffuse. It needs to be concentrated to provide energy.
    - This is where technology comes in
    - Wind and solar energy sources concentrate power
  - Renewable energy must be delivered to where it is needed
    - Increased electrification is key to the renewable energy transition

Potential Energy Sources

- Wind
  - Wind is now competitive in favorable locations
  - Capacity has grown quickly



Potential Energy Sources

- Wind
  - Onshore wind is now competitive in favorable locations
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  - Issues for expansion
    - Are there enough acceptable sites?
      - Good sites have sufficient wind or solar resources, are near where energy demanded (to avoid transmission losses) and are not ruled out politically.
    - New transmission lines may be needed in some areas, because most productive sites aren't near population centers

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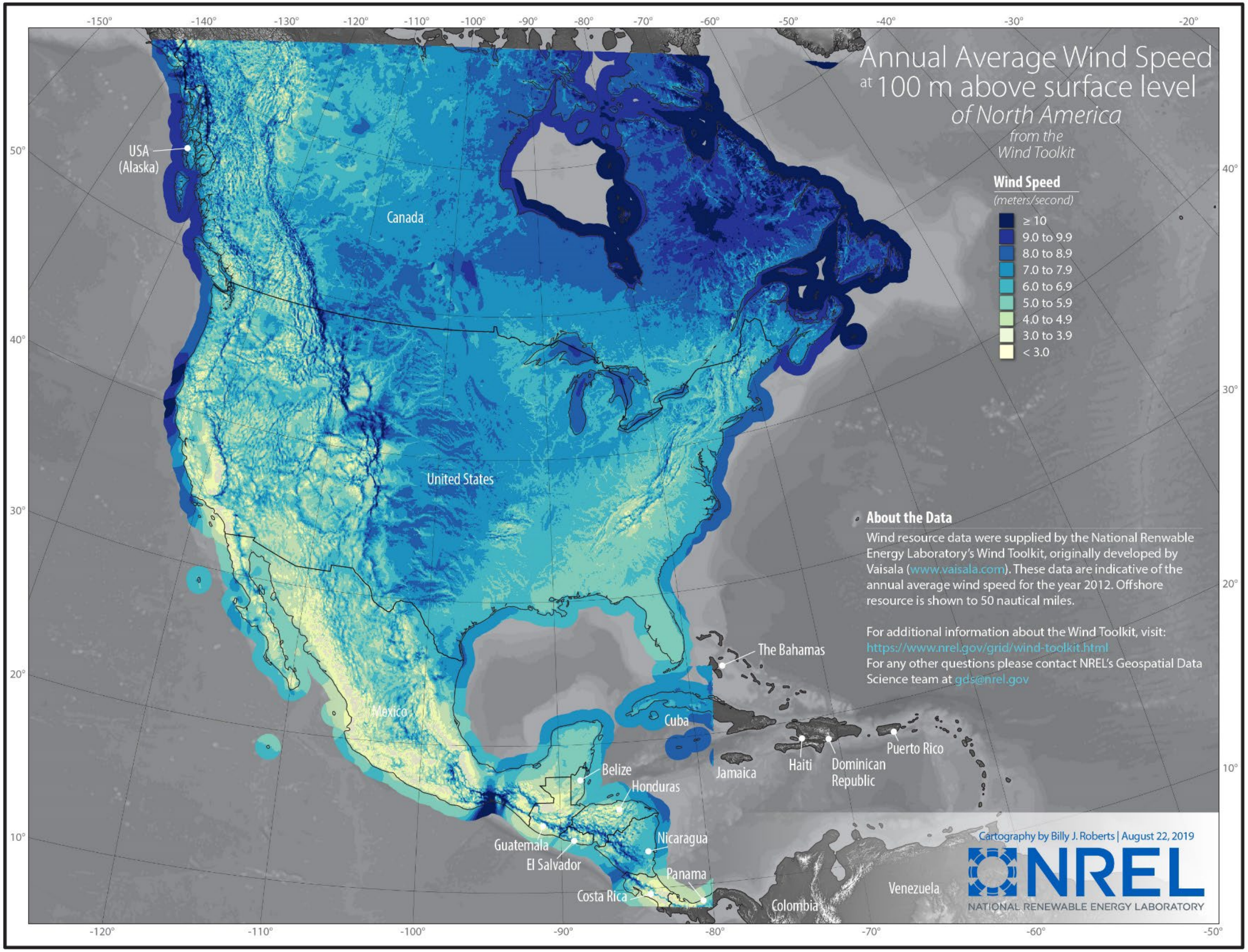

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    - New transmission lines may be needed in some areas, because most productive sites aren't near population centers
    - Continued cost reductions for offshore wind
      - Costs of installation are higher offshore
      - Becoming competitive in prime locations (e.g. U.K.)
    - Understanding extreme wind conditions, including lower wind speeds
    - Integrating wind turbines to the electric grid
    - Intermittent nature

Potential Energy Sources

- Solar
  - There are two types of solar:
    - Solar photovoltaic (PV)

    - Concentrated solar (a/k/a solar thermal)
      - Can heat steam, allowing them to store power

Potential Energy Sources

- Solar
  - Solar traditionally has been the most expensive of currently used renewable sources, but PV costs have fallen

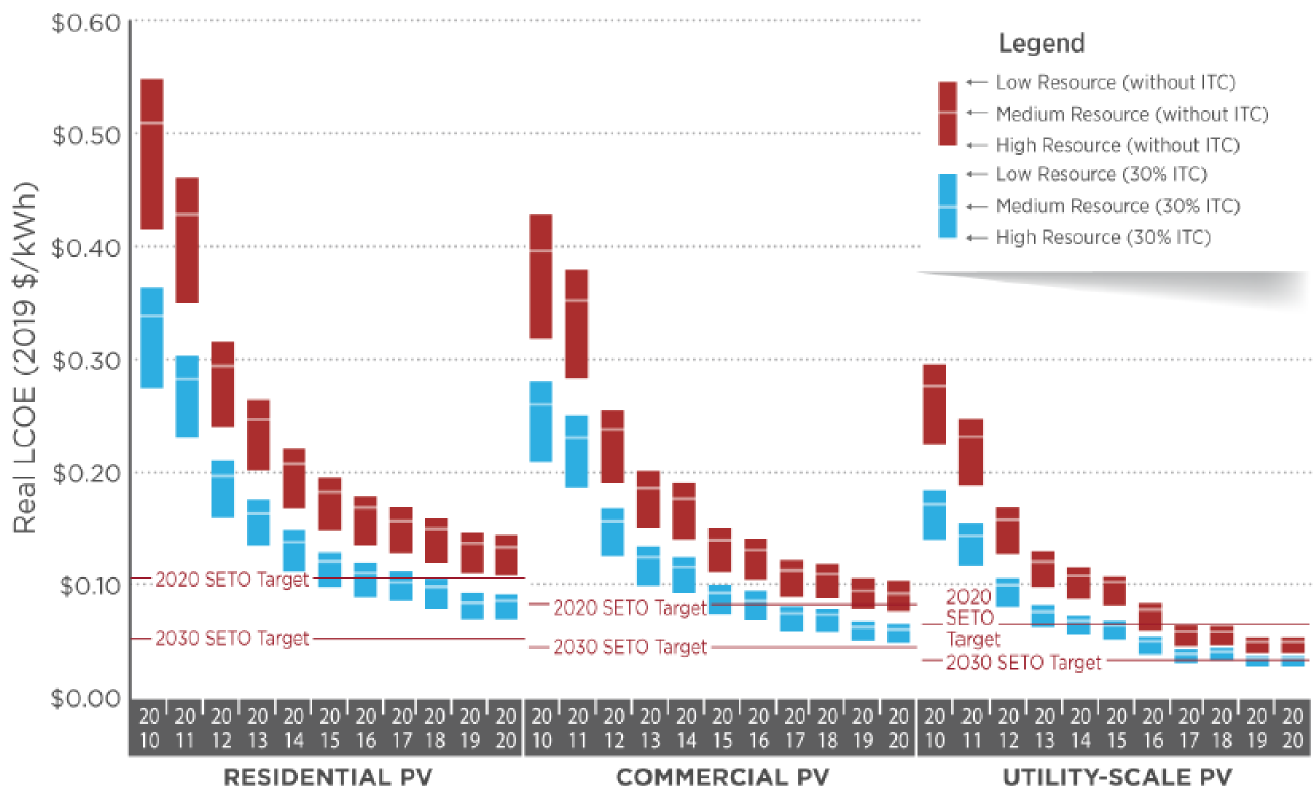
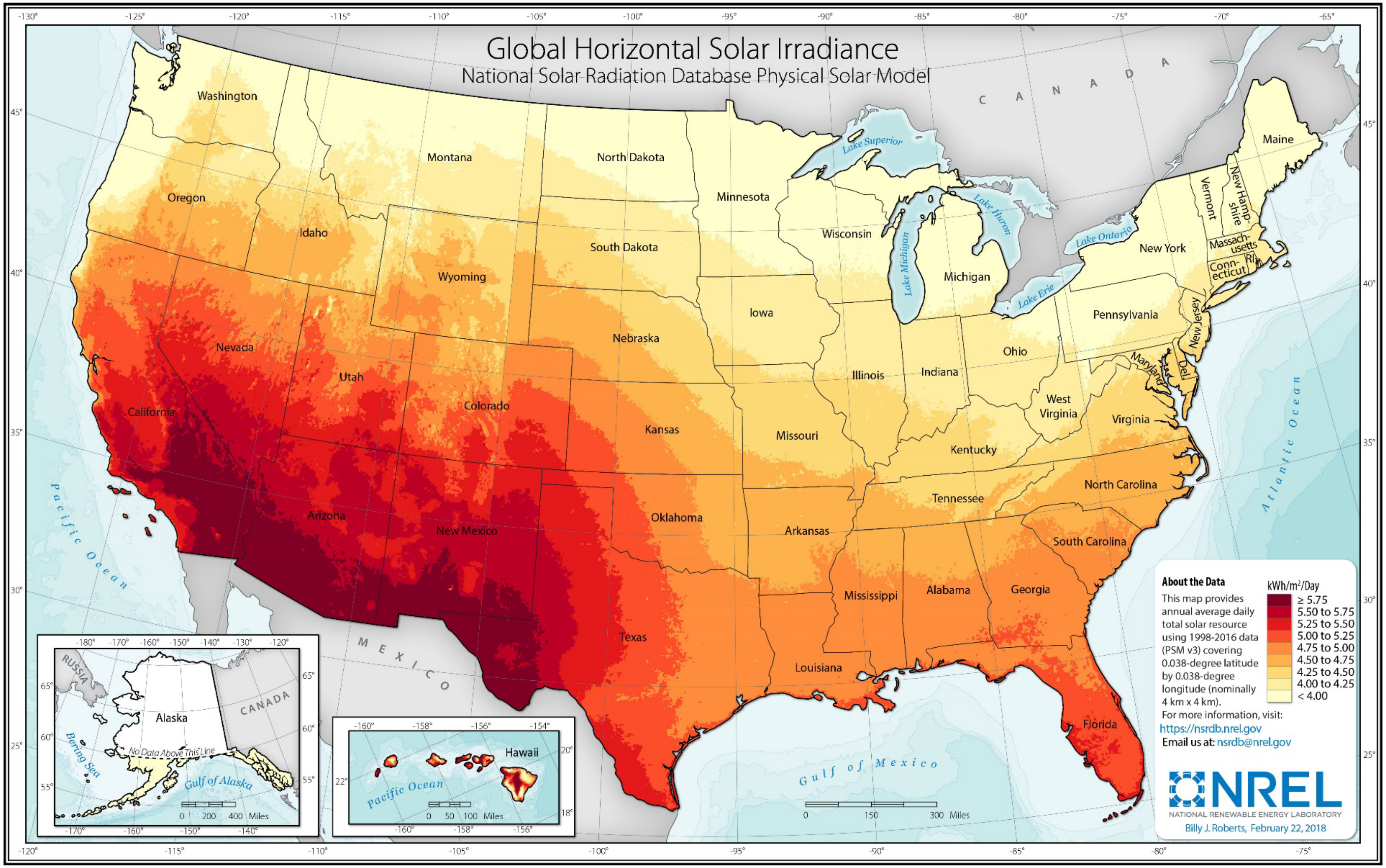


Figure ES-3. NREL PV LCOE benchmark summary (inflation-adjusted), 2010–2020

Potential Energy Sources

- Solar
  - Solar traditionally has been the most expensive of currently used renewable sources, but PV costs have fallen
    - Primarily due to lower module costs
  - Solar thermal costs still high, and fewer suitable sites
  - Storage of solar energy remains a technical challenge
  - As with wind, are there enough acceptable sites?
    - However, because high pressure areas have fewer clouds and less wind, solar is most abundant in places where wind energy is scarce
    - Many of the best locations for concentrated solar are in developing countries

Potential Energy Sources



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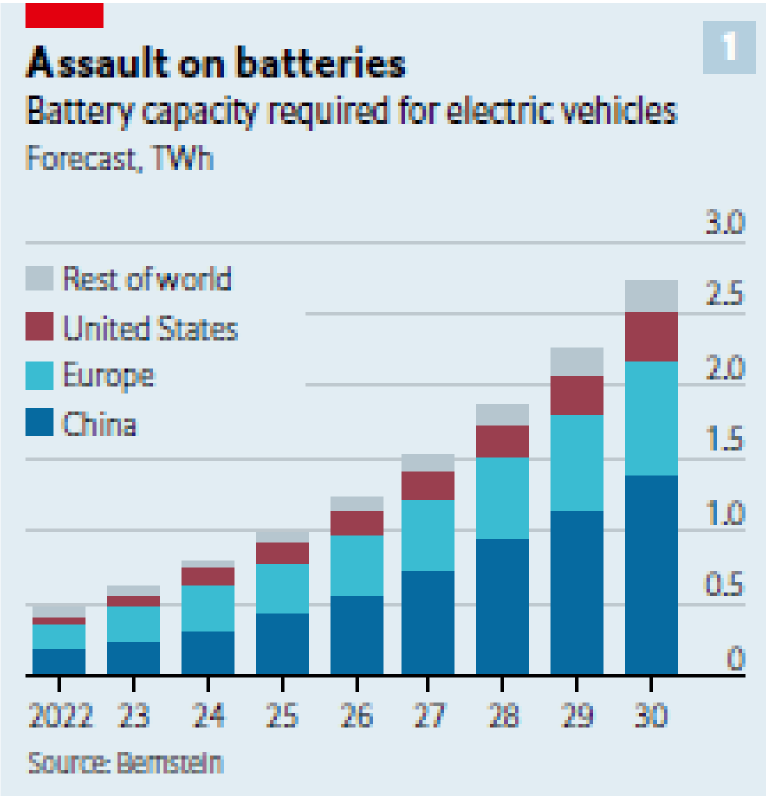
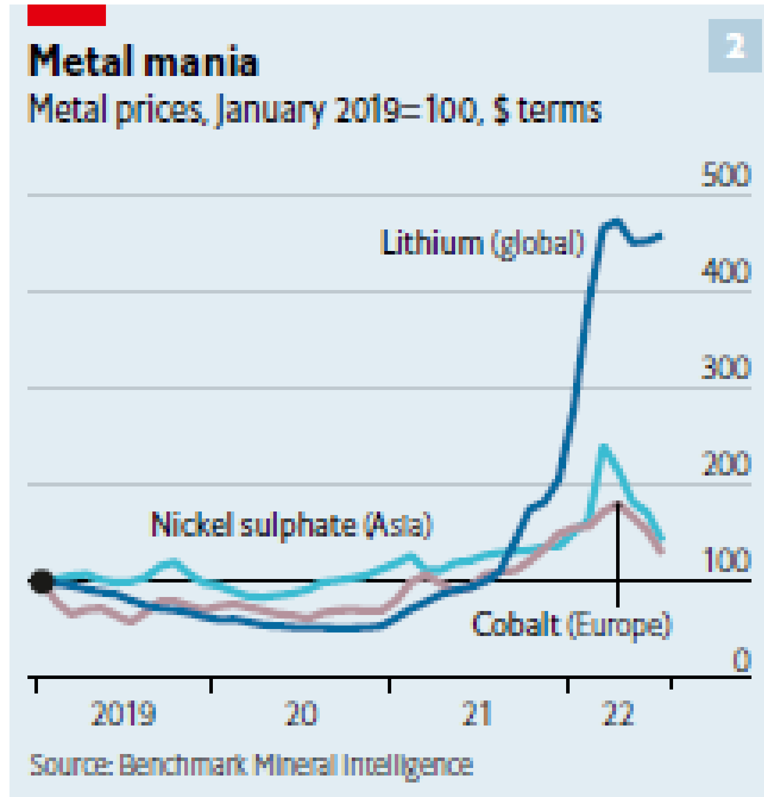
    - Many of the best locations for concentrated solar are in developing countries
  - Discuss: what made solar energy R&D successful?

Challenges to a Renewable Energy Transition

- Transportation
  - Electric motors are more efficient and simpler mechanically
  - But gasoline or diesel fuel contains 40X as much energy as current batteries
    - Usable for vehicles carrying light loads and that can charge often (e.g. passenger cars)
    - Not yet viable for long-haul trucking, aviation, or maritime shipping
  - Consumers may not see EV as perfect substitutes for gasoline-powered vehicles
    - Charging infrastructure needed
  - Prices of raw materials needed for batteries growing





Source: "Cell-side analysis," *The Economist*, August 20, 2022, 57-59.

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Challenges to a Renewable Energy Transition

- Industry
  - Not all processes can be electrified
  - Achieving very high heat for industrial processes such as steel, cement, and glass production is difficult without burning fuel

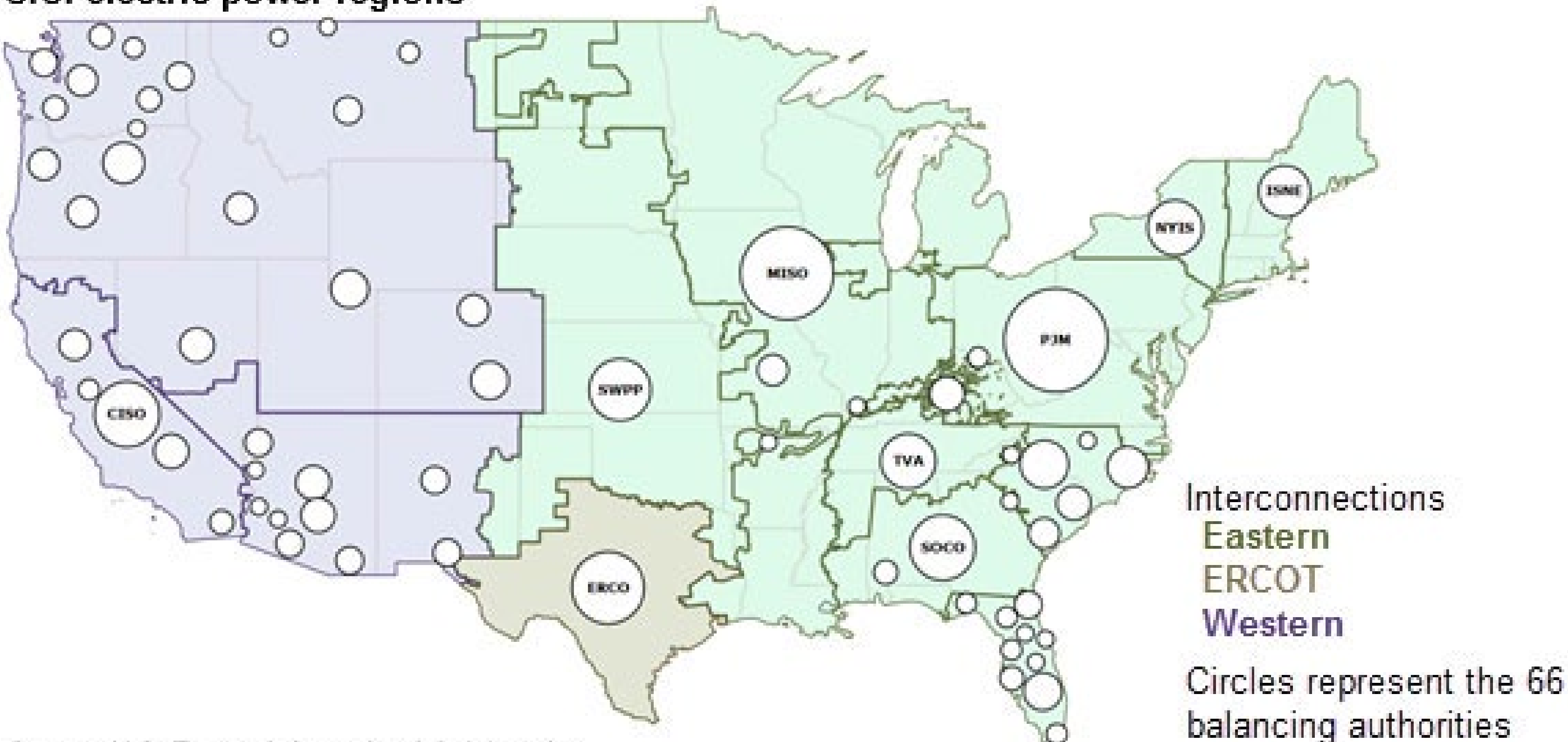
Challenges to a Renewable Energy Transition

- Electricity
  - Increased electrification is key to the renewable energy transition
  - But solar and wind are intermittent
  - To understand the potential of renewable energy for electricity generation, it is important to understand how the electric grid works

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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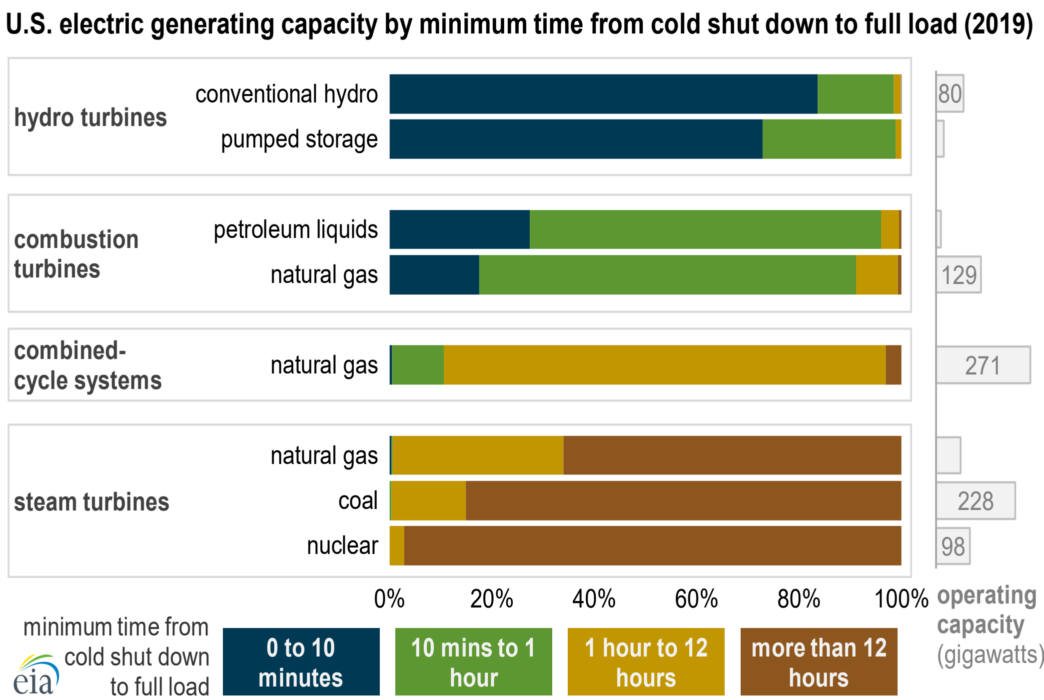
The Role of the Electricity Grid

- 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

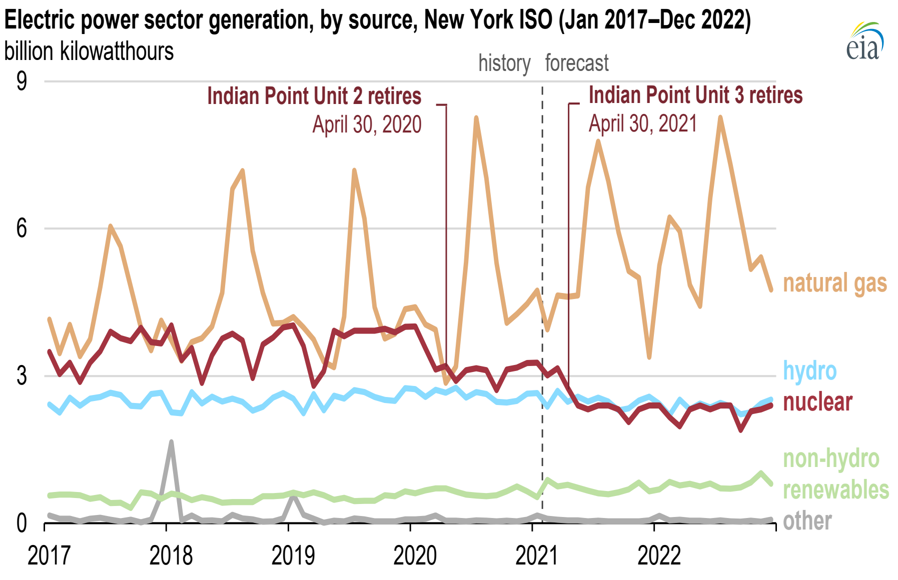
- Even when the owner has control, some plants can be switched on and off more quickly than others
  - Ramping rates: how quickly plants can change the level of output
  - Flexible sources with rapid ramping ability include:
    - Gas-fired peaker plants
      - Low fuel efficiency, but are flexible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

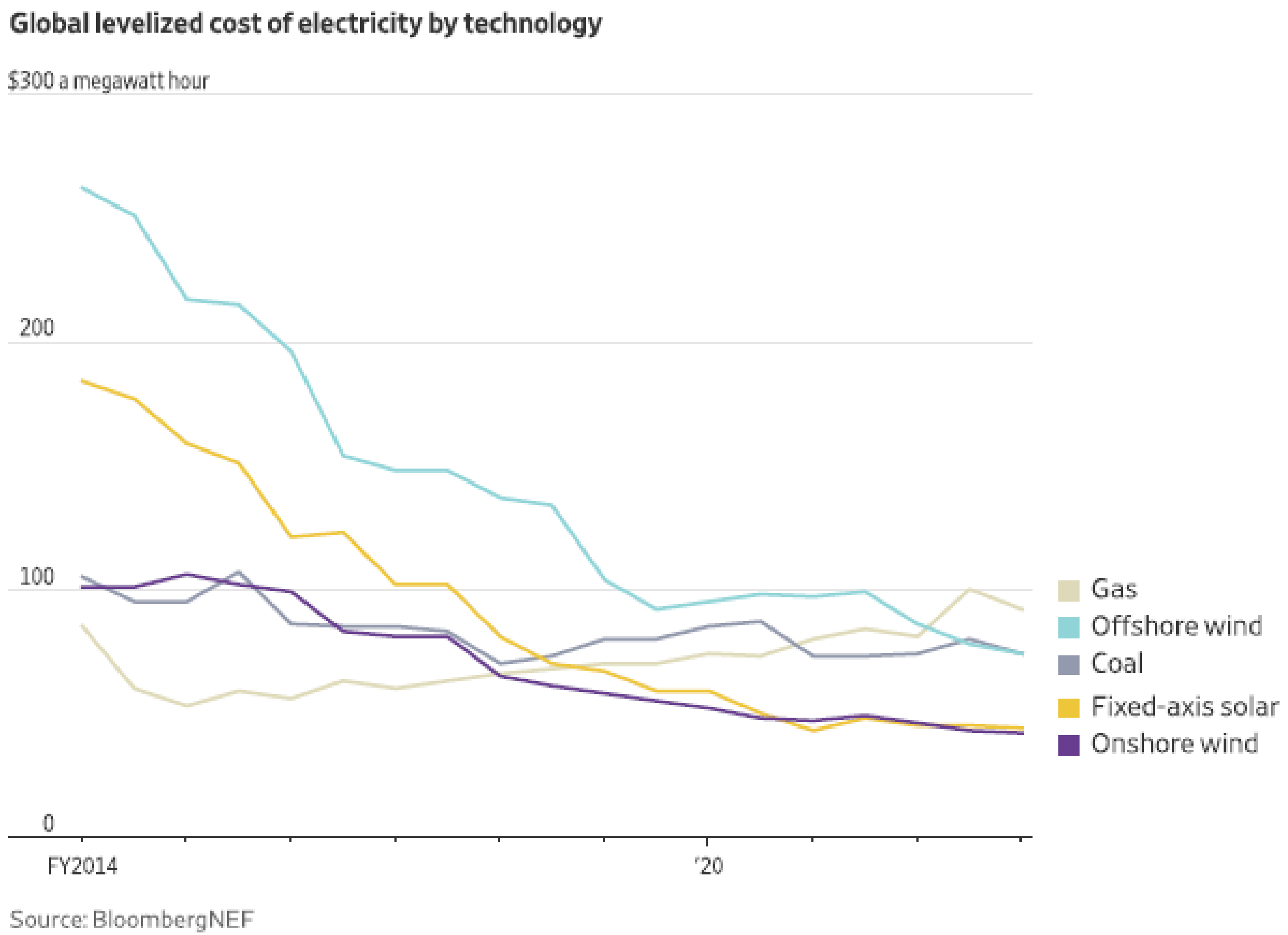
- Even when the owner has control, some plants can be switched on and off more quickly than others.
  - Ramping rates: how quickly plants can change the level of output.
  - There are also differences in often the plant must shut down for required maintenance.
  - System is designed to meet demand extremes.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

The Role of the Electricity Grid

- Generation costs
  - 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.
      - Accounts for the fact that many of the initial costs are up-front capital costs, particularly for renewables.

The Role of the Electricity Grid

- Generation costs
  - 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.
    - Key assumptions that lead to different estimates:
      - 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



Source: “Renewable-Energy Growth Explodes,” *The Wall Street Journal*, November 27, 2023

The Role of the Electricity Grid

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

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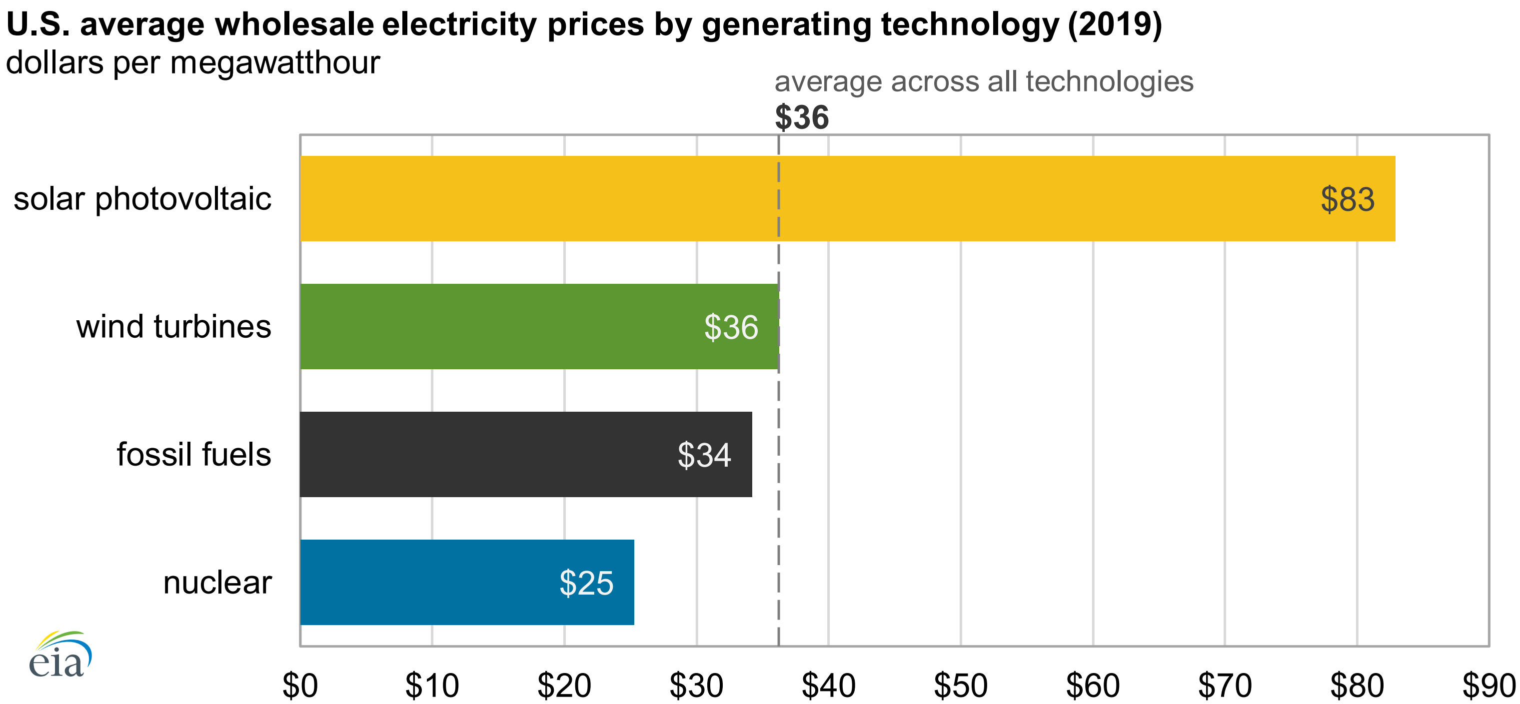
    - Value of electricity varies depending on how much and when generated
      - Consider fixed costs versus variable costs
        - » Nuclear (baseload) vs. natural gas (peak demand)
    - Renewable energy changes this
      - Because marginal cost of renewables is 0, it is offered to wholesale markets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

The Role of the Electricity Grid

- Generation costs
  - Challenges with levelized costs
    - 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

The Role of the Electricity Grid

- 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

The Role of the Electricity Grid

- 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

The Role of the Electricity Grid

- 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

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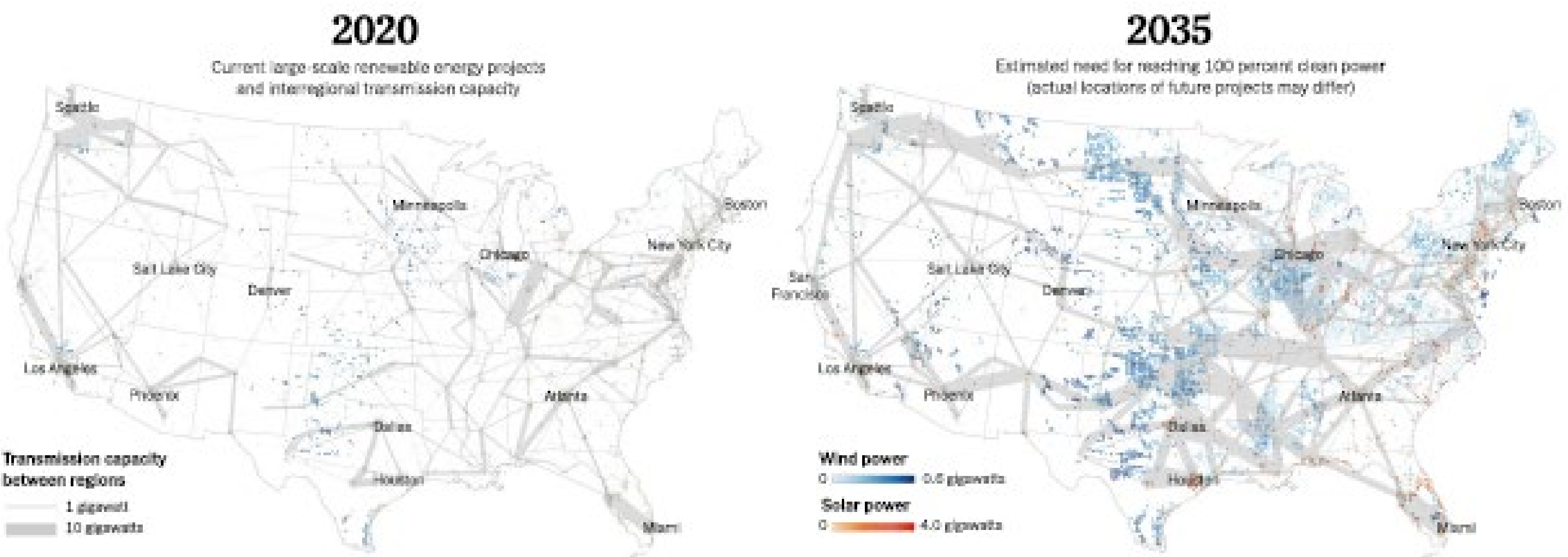
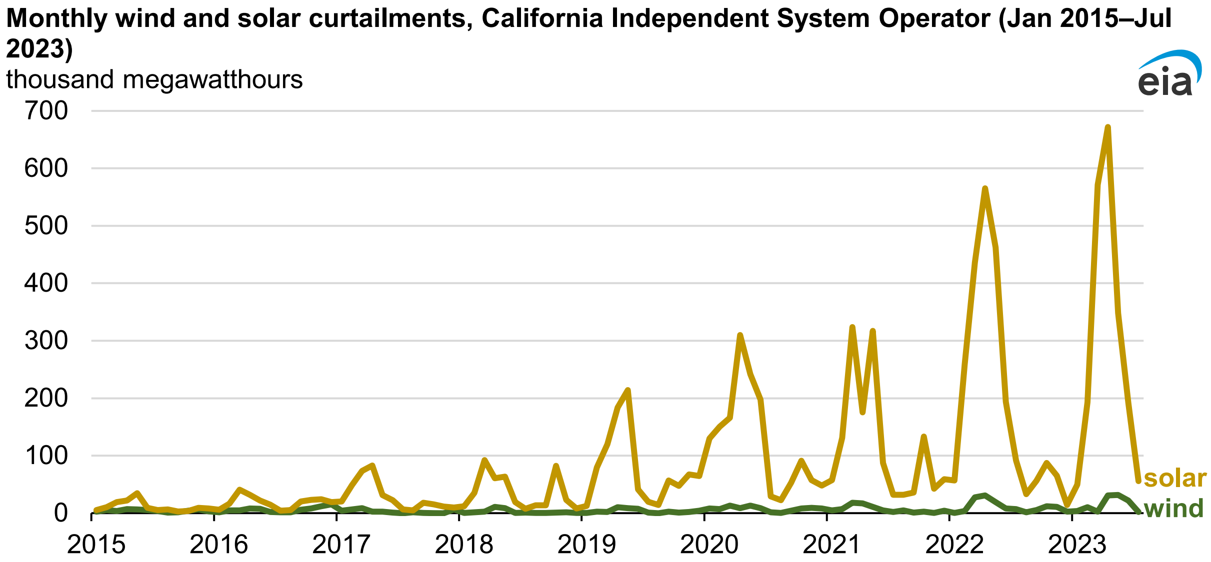


Source: National Renewable Energy Laboratory | The 2035 map is based on the "All Options" path from NREL's 100% Clean Electricity by 2035 Study. Both maps show utility-scale renewable projects, but do not include distributed installations, like rooftop solar.

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

The Role of the Electricity Grid

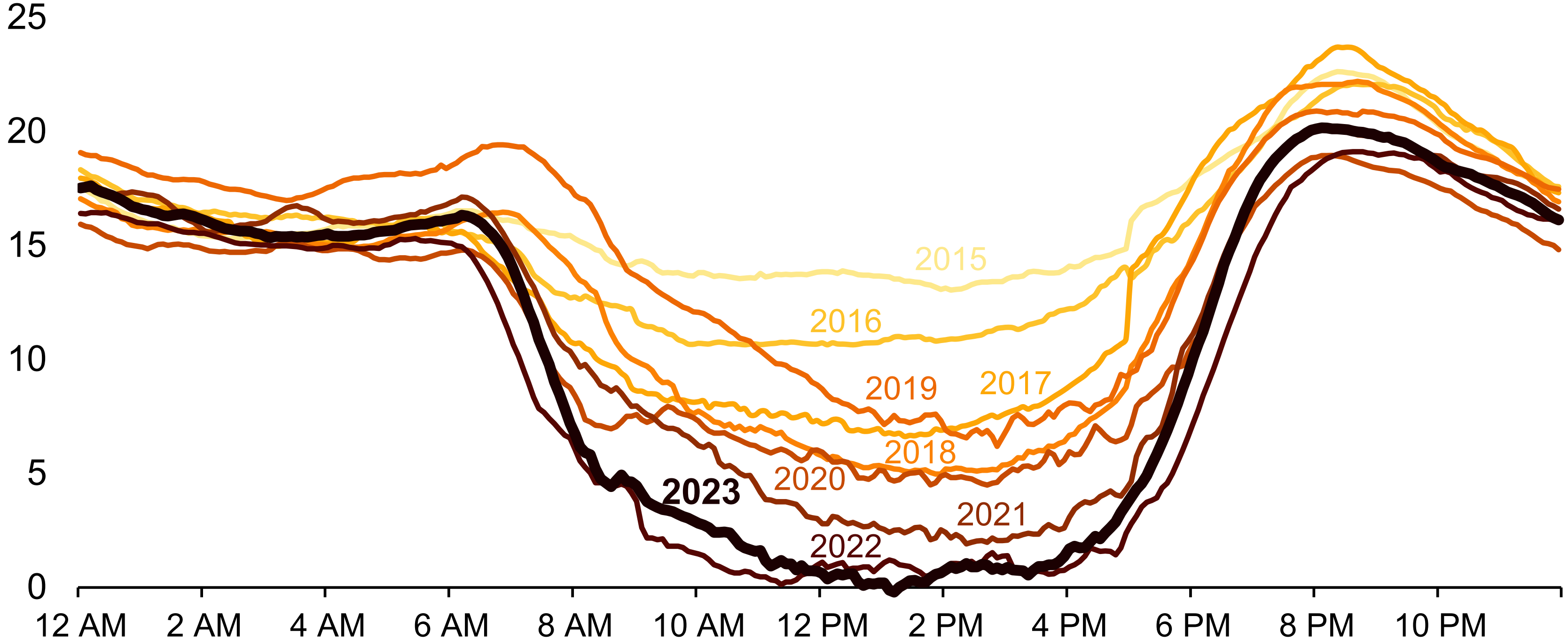
- Problems caused by inadequate transmission
  - Curtailment: quantity of electricity provided to the grid is reduced to keep in balance has been increasing



Source: EIA Today in Energy, October 30, 2023

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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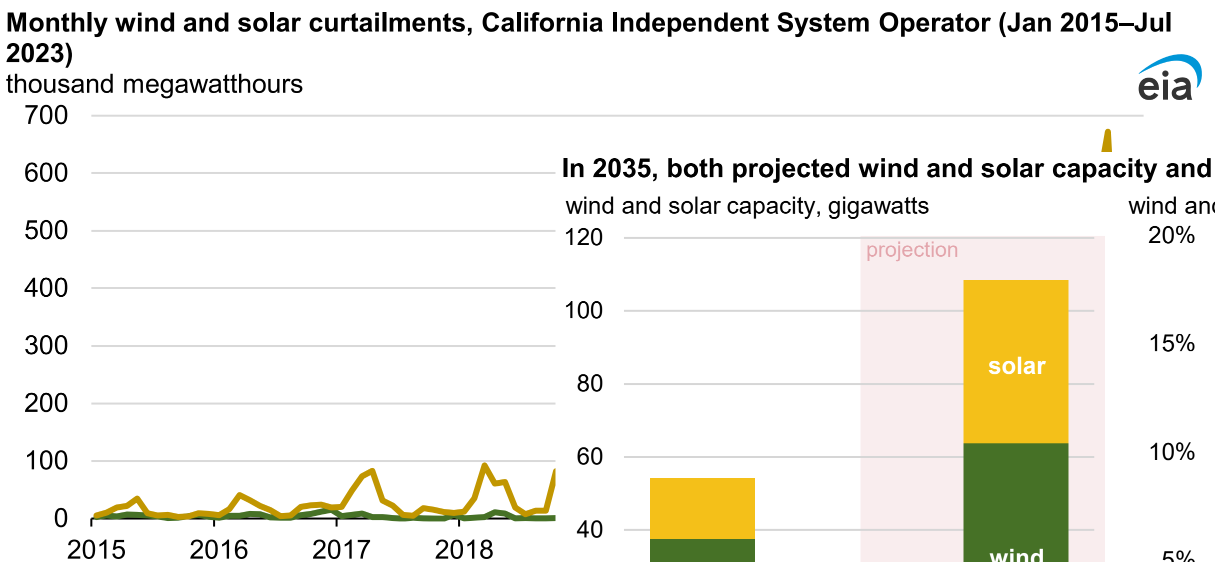
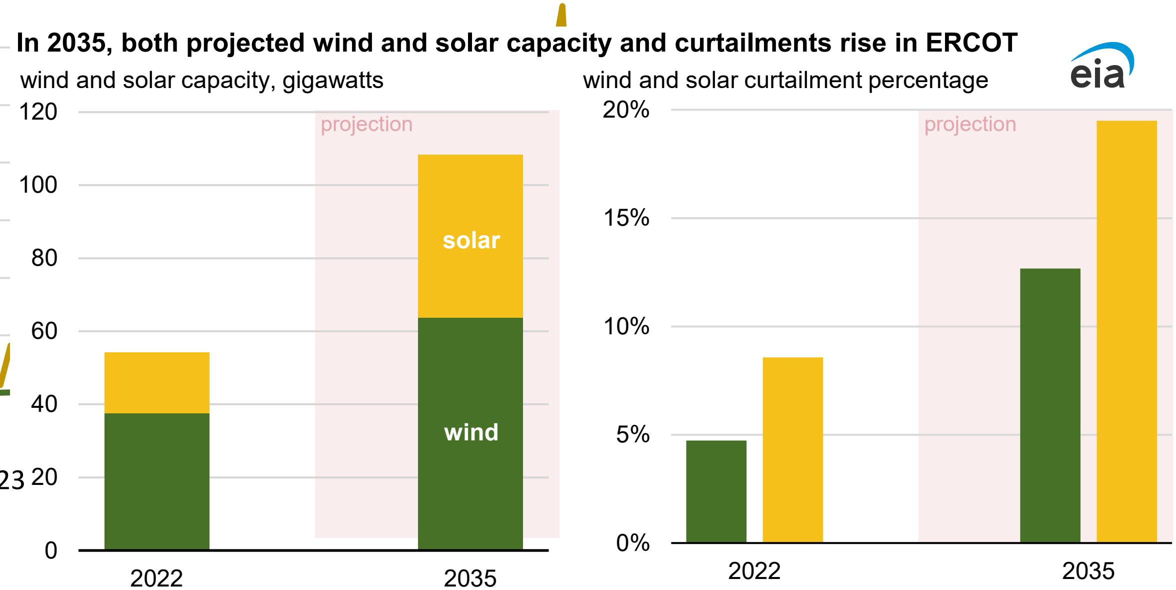


Source: EIA Today in Energy, October 30, 2023



Source: EIA Today in Energy, July 13, 2023

The Role of the Electricity Grid

- 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

The Role of the Electricity Grid

- *Question*: Why is expanding transmission difficult?

The Role of the Electricity Grid

- *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

The Role of the Electricity Grid

- *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?