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Energy transitions are complex…
And complex is, by definition, not simple.

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What the “Earth at Night” tells us…

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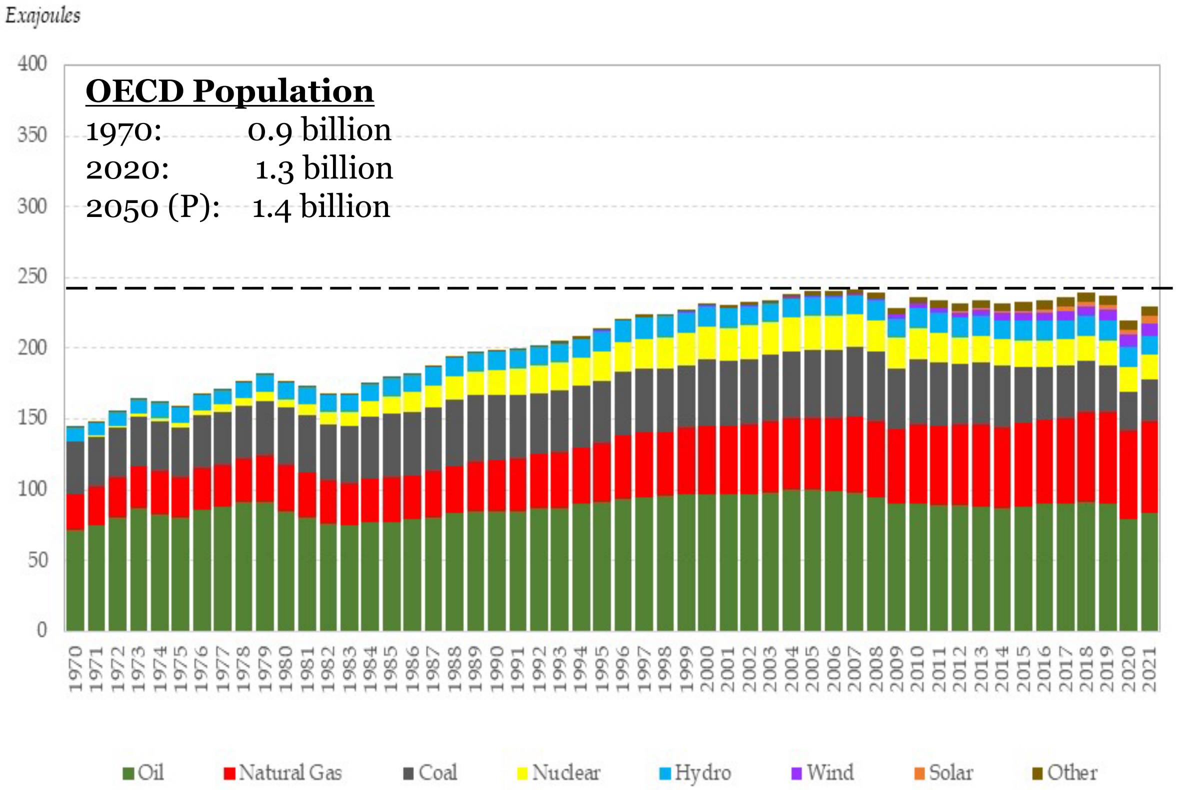
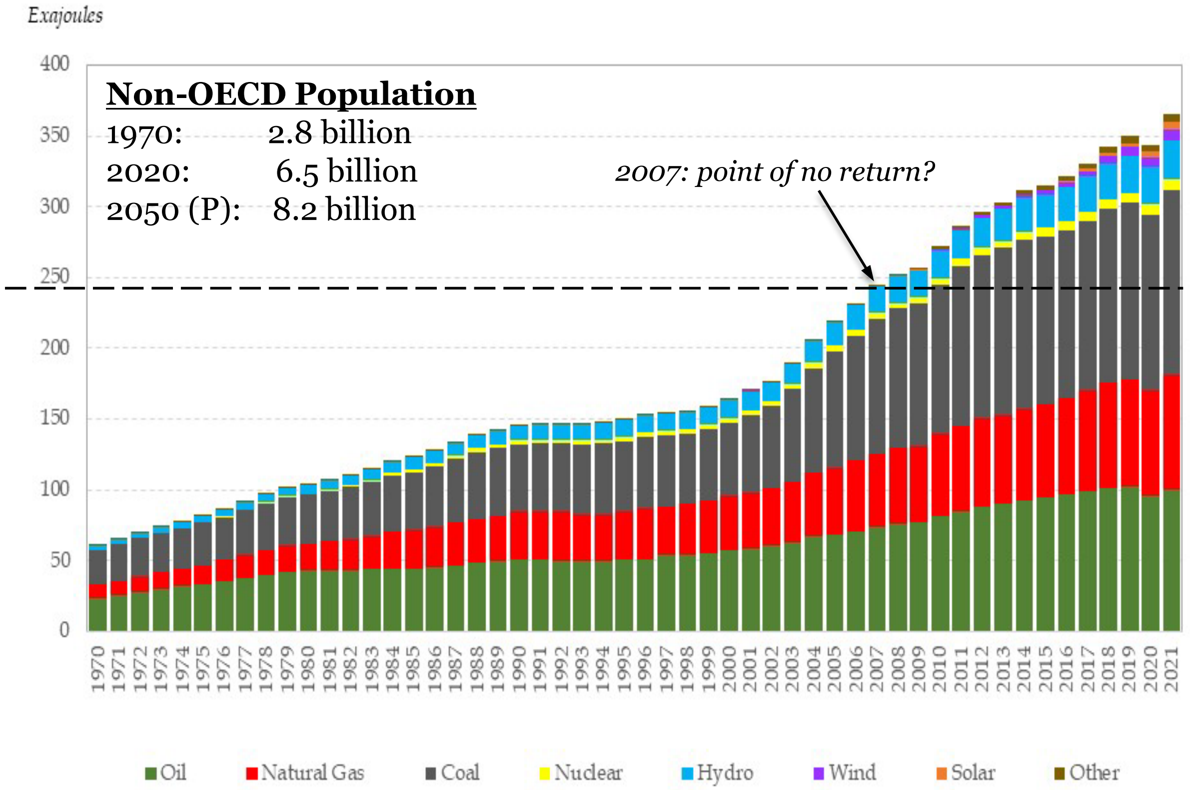
Complexity #1: Energy's future is a developing nation story

- Energy demand is rising fastest in the developing world, largely driven by hydrocarbon fuels.
  - EU is 11.8% of global demand; N. America is 20.0% of global demand; developing Asia is 36.9% of global demand.
- Projections for population and economic growth indicate this trend will likely continue.





Data Sources: BP Statistical Review, 2022; OECD.stat

Complexity #2: The reality of "scale"

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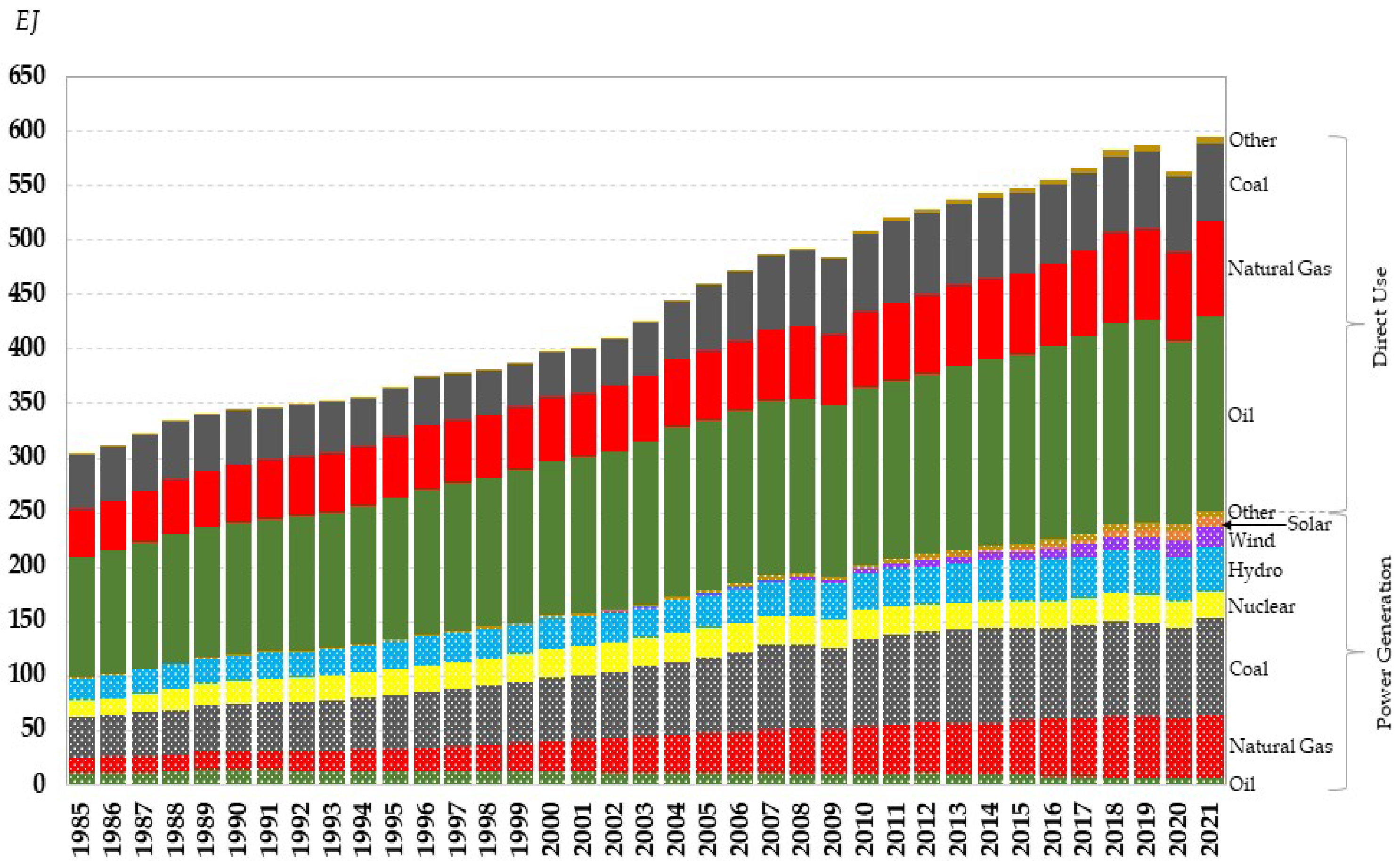
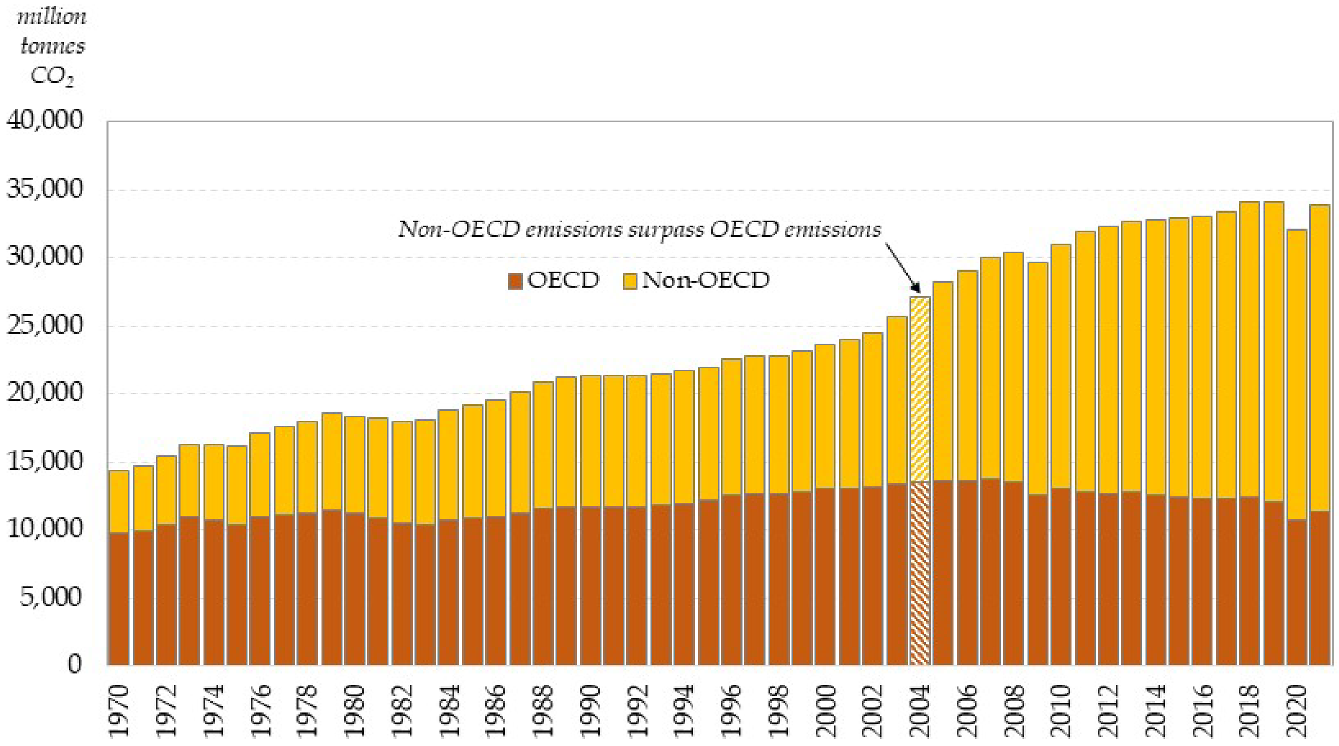
- Even with double-digit year-on-year percentage increases for wind and solar over the last 20 years, they are still a small proportion of the total energy mix, 2.5% and 1.4%, respectively, in 2020.
- Demand continues to grow.
- Electricity is about 43% of total energy. Zero-carbon generation sources: nuclear at 10%, hydro at 16%, and wind+solar at 13%... of electricity.
- Hydrocarbons account for 61% of power generation, 99% of all non-electric energy, and 82% of all energy.
- Decarbonization will require multiple solutions, and must include *net* decarbonization of incumbent supply chains. This is the reality of scale.
- The paths will look different everywhere, and will hinge on "resource" endowments – nature, minerals, energy, human capital, etc.



Data Source: BP Statistical Review of World Energy, 2022

Complexity #3: Regional CO_2 emissions

- Non-OECD emissions have grown substantially over the last 20 years. OECD emission have declined.
- Energy demand growth in developing countries will continue.
- As a matter of course, decarbonization requires a portfolio approach – carbon capture (nature-based and engineered solutions, renewables, new fuels, carbon-to-value, etc. – and there are opportunities throughout emerging value chains.



Data Source: BP Statistical Review of World Energy, 2022

Complexity abounds! What drives energy transitions?

- **Technology**, **scale** and **legacy** are each critically important.
  - Technology signals how fuels will compete. Capital is the vehicle for technology deployment!
  - Scale matters because energy systems are large and must accommodate growth and access.
  - Legacy of infrastructure and energy delivery systems is the foundation for change.
- Economics matters!
  - The ***principle of comparative advantage*** is still central to success.
  - ***Cost-benefit*** must be favorable for sustainable diffusion of new technology.
  - ***Coordination theory***: perhaps forgotten, but not gone.
    - All costs along a value chain matter, not just the energy source. Any new technology must avoid burdensome fixed costs (i.e., a barrier to entry) if it is to be successfully adopted.
- Of course, policy and geopolitics shape remain central.
  - ***Energy security*** will remain a central consideration. What's old is new again!

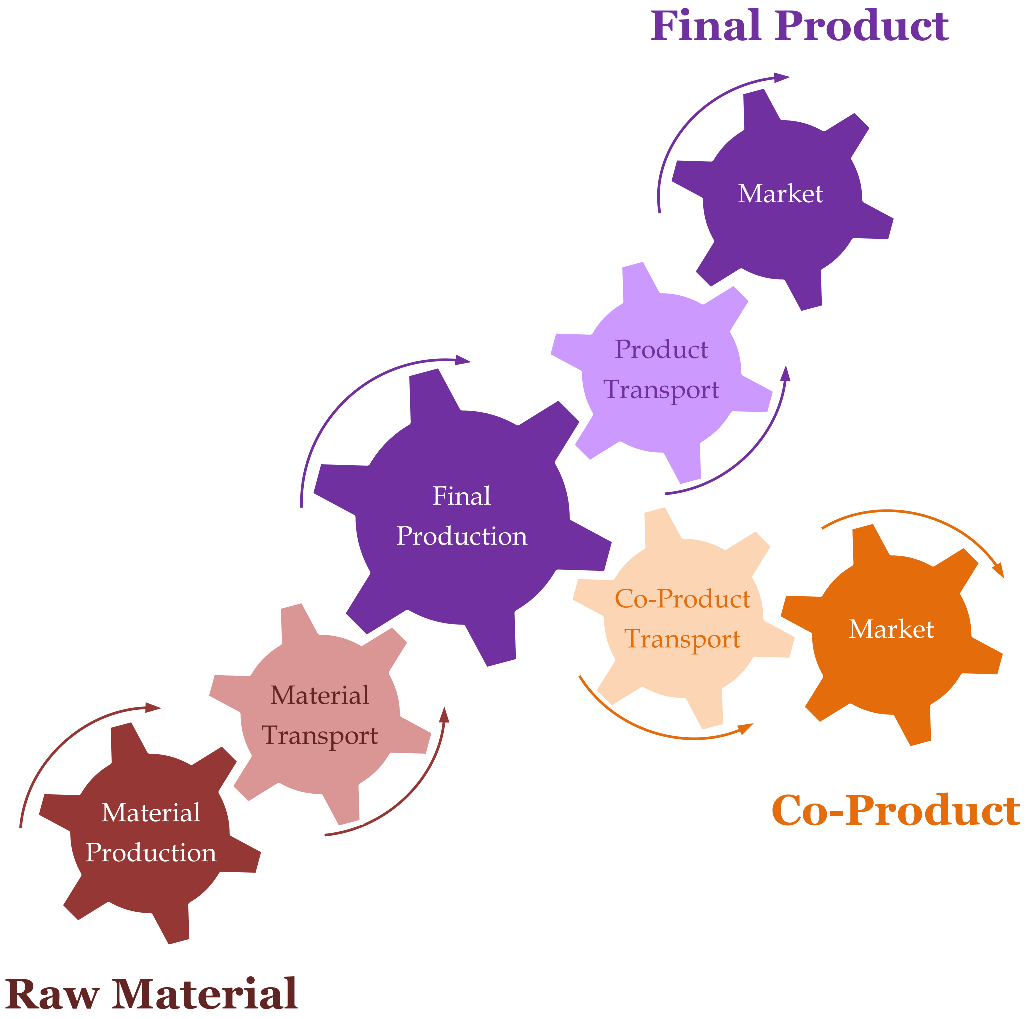
- An important lesson: The two largest drivers of "transitions" in energy markets in the last 25 years: (1) the shale revolution in the US and (2) demand growth in developing Asia.
  - (1) is technological innovation and (2) is economic growth. These two factors will shape the future as well.

Coordination Theory:

It's critical, yet oft ignored, role in energy transitions
and
a surprising example

Coordination theory and the supply chain

- Every production process involves a supply chain connecting raw material inputs to deliver a final product (and potentially a co-product) delivery.
- If any part of the supply chain breaks down, "coordination failure" ensues. Thus, it is critical that actors along the supply chain coordinate.
- The commercial viability of investments at any point along a supply chain must be positive for long-term sustainable growth. If they are not, coordination failure is inevitable, and growth is compromised. This is very relevant for the uptake of new technologies.
- The complexity of coordination along supply chains and positive value propositions can lead to the "valley of death" for new energy technologies.
- If there is value from the co-product, commercial support for all parts of the supply chain improves.
- *** - Carbon-to-value improves the economic viability and expands the portfolio of scalable low carbon energy.



Texas, known for oil and gas, leads in "green" energy. Why?

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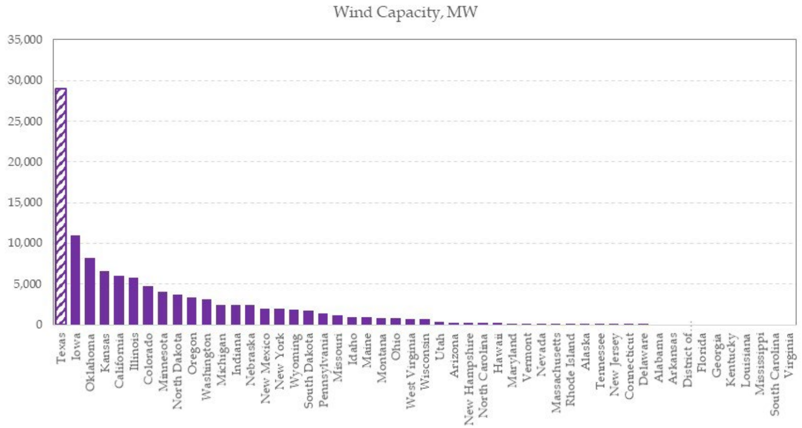
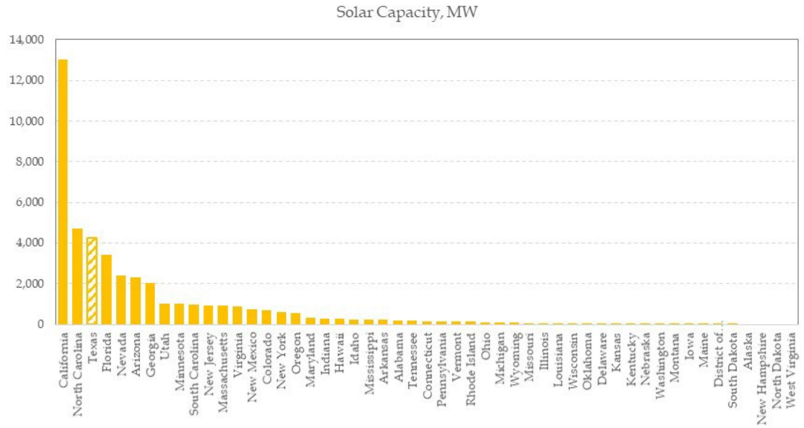
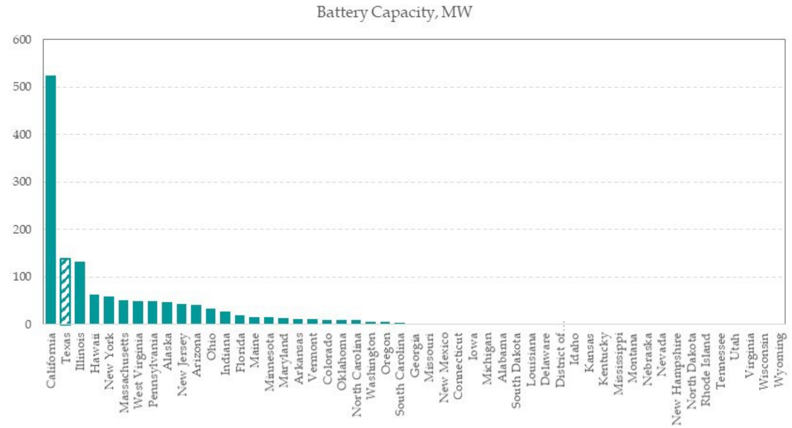
- Wind, sun, land and a business-friendly environment… the "principle of comparative advantage."

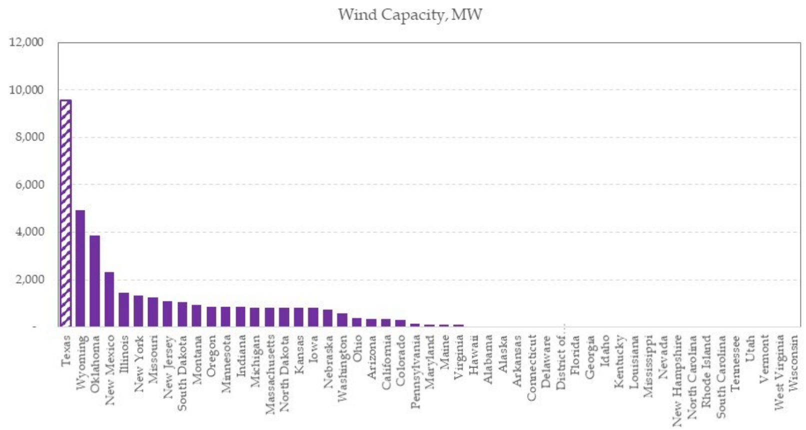
Operating Capacity

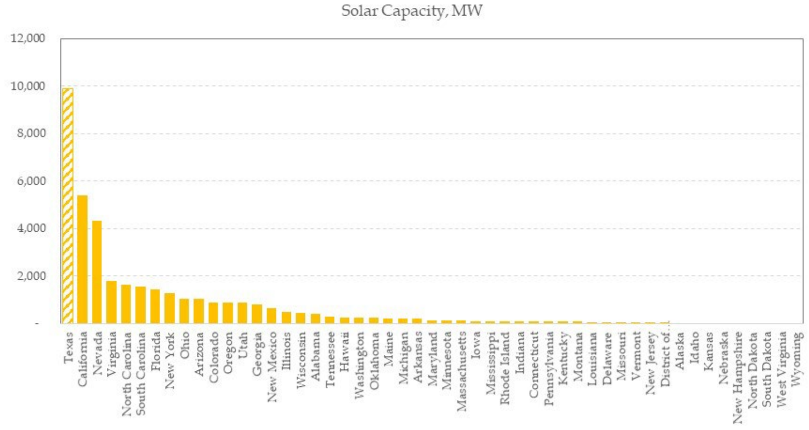


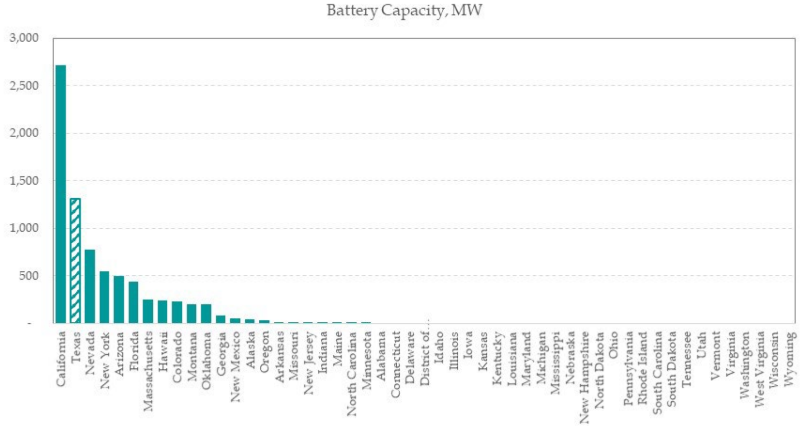




Planned Capacity



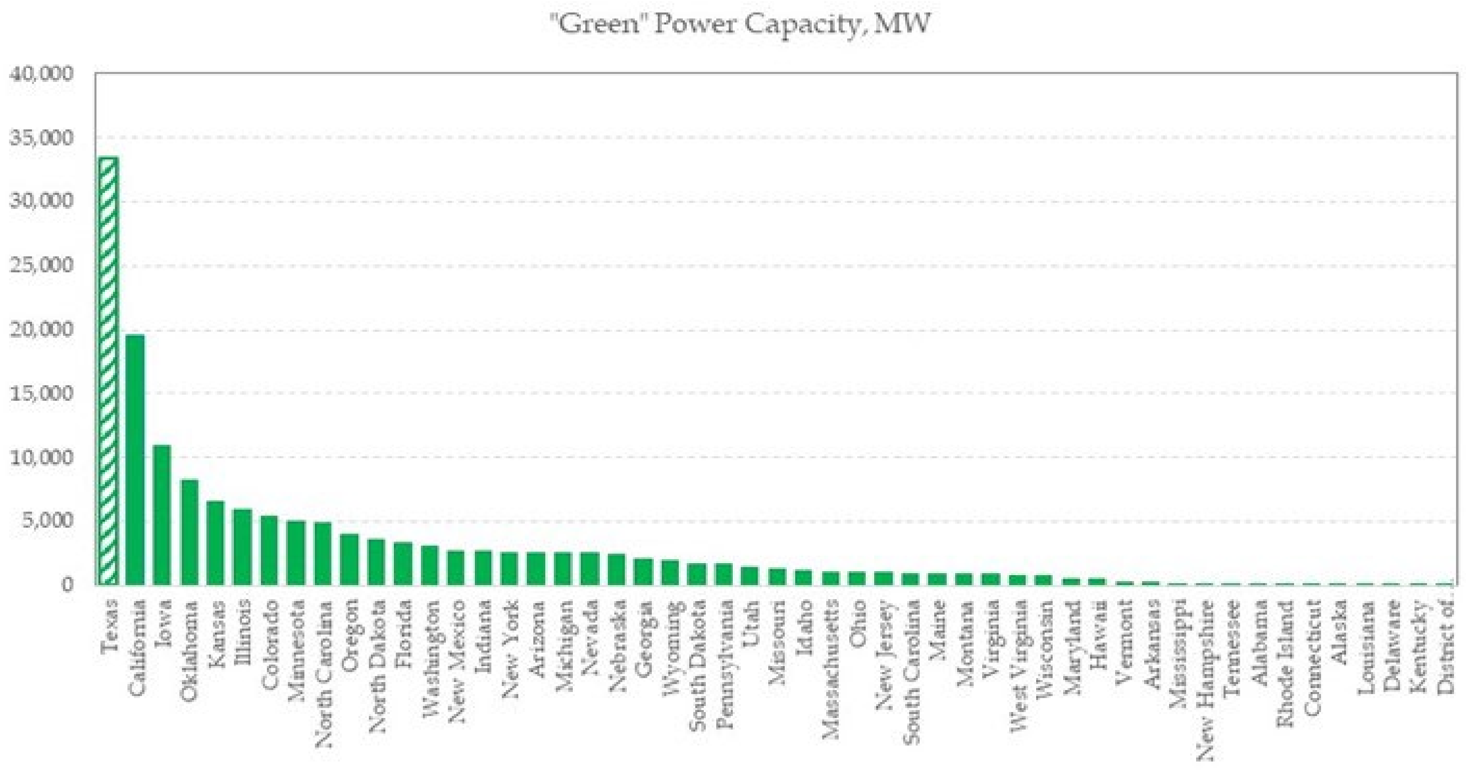




Data obtained from EIA Form 860M

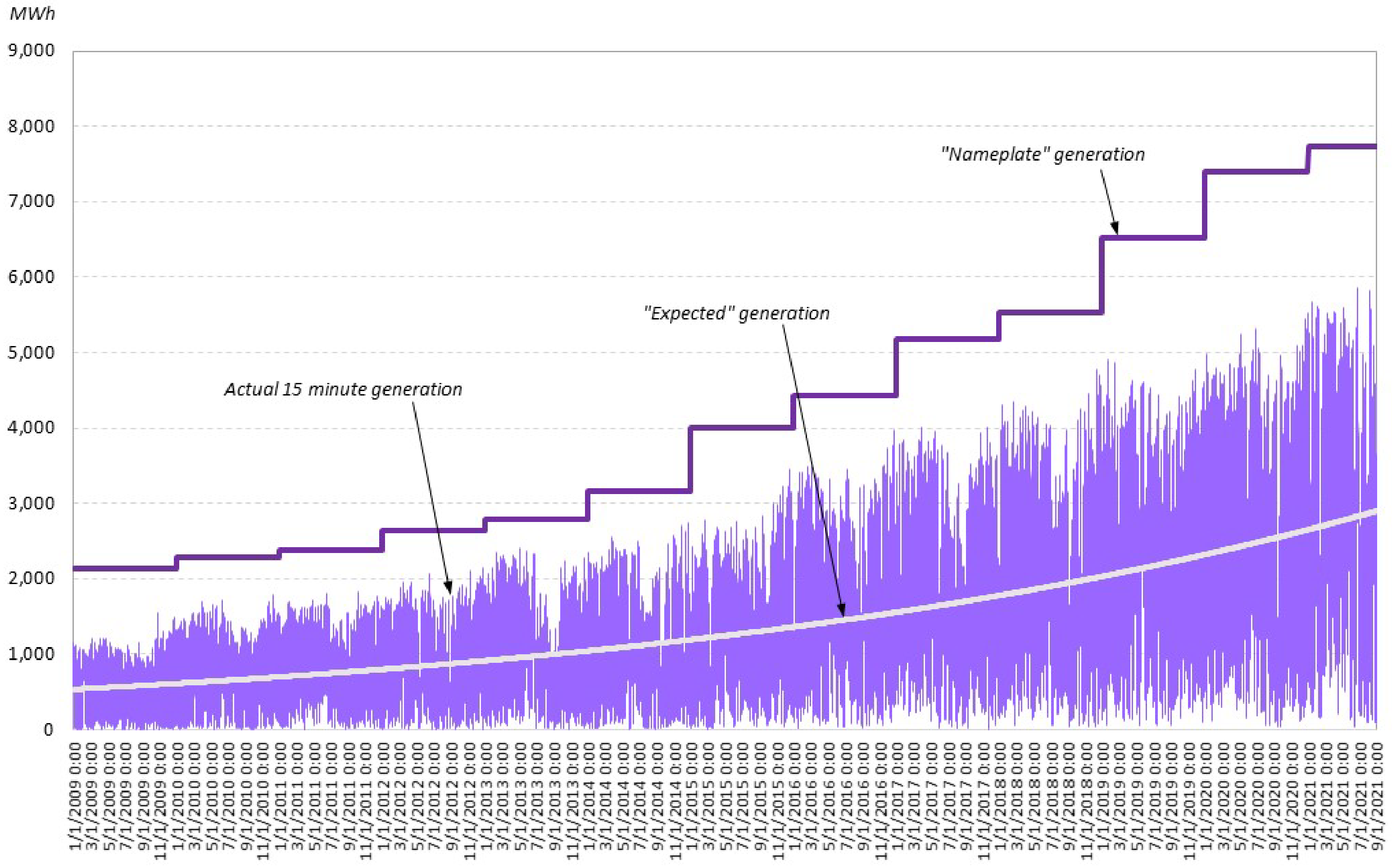
Coordination theory at work, with a policy overlay

- Texas power generation market. Total MWs of installed "green" capacity → #1 in the US.
    - Senate Bill 7 (1999), tax incentives at the Federal, State and local levels, all matter.
    - But growth was impeded until investment in the Competitive Renewable Energy Zones (CREZ) happened.
- The CREZ is a $7 billion investment approved by the Texas PUC and completed in 2013. Costs are rolled into wholesale rates.
- The CREZ allows access to a liquid market with a robust generation portfolio, which de-risks investment and supports renewables expansion.
- What does this reveal? **Renewables**, along with **transmission capacity, market liquidity, and a diverse portfolio** (i.e., Texas is also #1 in natural gas generation in the US) are **energy transition enablers**.
- An example for other energy options, such as hydrogen and CCS?



Why a portfolio? The challenge of intermittency

- As wind generation *capacity* grows, the average generation grows, which reduces emissions, all else equal.
- BUT averages are irrelevant for **reliability**. Extremes matter.
- Given the observed variability, sufficient dispatchable backup generation capacity is required… coordination for reliability!
- In the end, this raises the capital intensity of each MWh delivered, which raises an economic hurdle associated with cost.
- **Reliability matters.** Its value must be priced to ensure sufficient redundancy is available to the grid.
    - This is nothing new!



Source: Data compiled from ERCOT. "Expected" generation is the best fit over time to the actual 15-minute generation and is only for illustration. "Nameplate" generation converts the annual average wind capacity, in MWs, to MWhs assuming it is 100% utilized every 15 minutes. Resource planning utilizes seasonally rated capacity, which is different by season.

Where do we go from here?

- If transitions are to be enabled, policy must be supportive of
  - market designs that promote transparency and liquidity,
  - technological innovation,
  - a robust portfolio of energy options,
  - innovative pathways to reducing the delivered cost of energy, and
  - new infrastructure.
- Policy must take a full value chain approach and be robust in each of the above dimensions, all while fully internalizing the reliability (at a micro-level) and energy security (at a macro-level).
- Failure to do so risks coordination failure, which will be volatile as well as economically, politically and socially painful.

- A difficult question: How many policy frameworks around the world do all of the above?

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