Scenarios for Future Energy Systems

Jill Engel-Cox

Texas A&M Energy Institute Lecture Series

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Photo by Jill Engel-Cox

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Introduction and About NREL

17 U.S. Department of Energy National Laboratories

- Office of Sciece laboratory
- National Nuclear Security Administration laboratory
- Office of Fossil Energy laboratory
- Office of Energy Efficiency and Renewable Energy laboratory
- Office of Nuclear Energy, Science and Technology laboratory
- Office of Environmental Management laboratory

"Government owned, contractor operated"

U.S. DEPARTMENT OF ENERGY

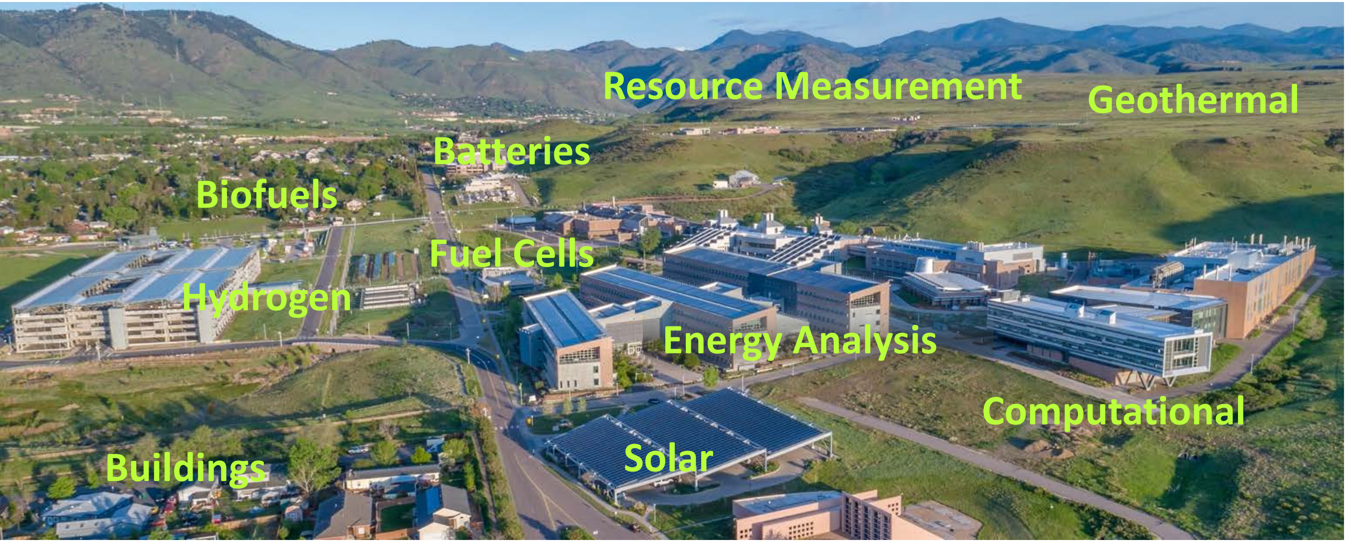
National Renewable Energy Laboratory

NREL Transforming ENERGY

Mission: NREL advances the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems.

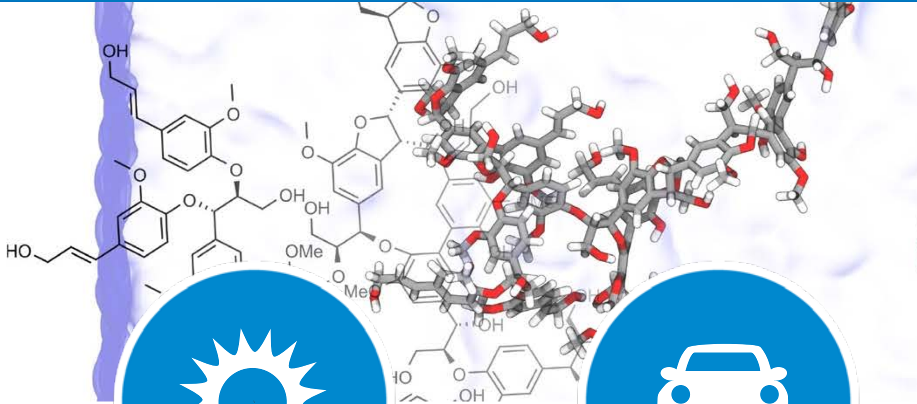
www.nrel.gov/about

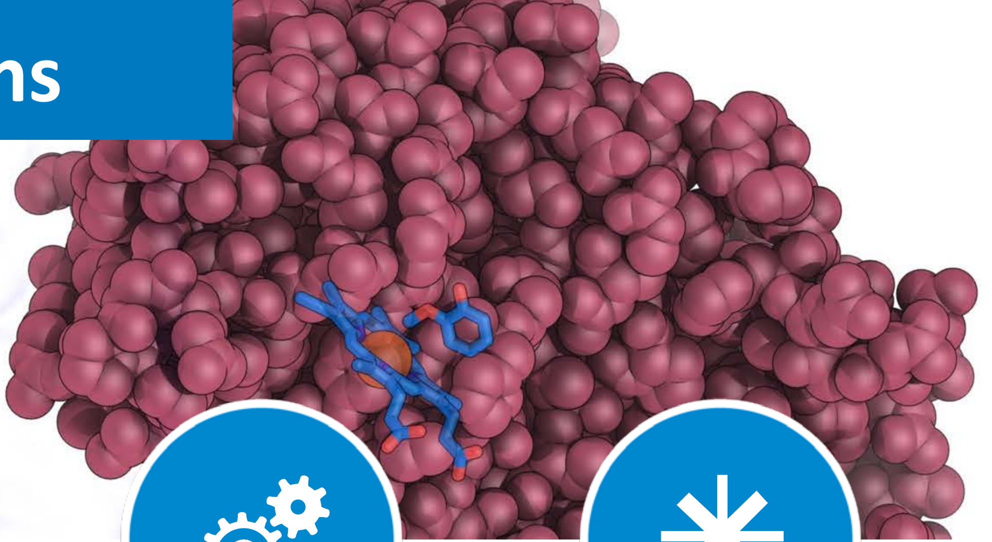
Example Technology Areas:



- 2,900 employees with 220 postdoctoral researchers, 140 interns, and many visiting professionals
- 327-acre main campus in Golden & 305-acre Flatirons Campus with National Wind Technology Center 13 miles north
- Over 70 R&D 100 awards. More than 1,000 scientific and technical materials published annually

NREL Science Programs





Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

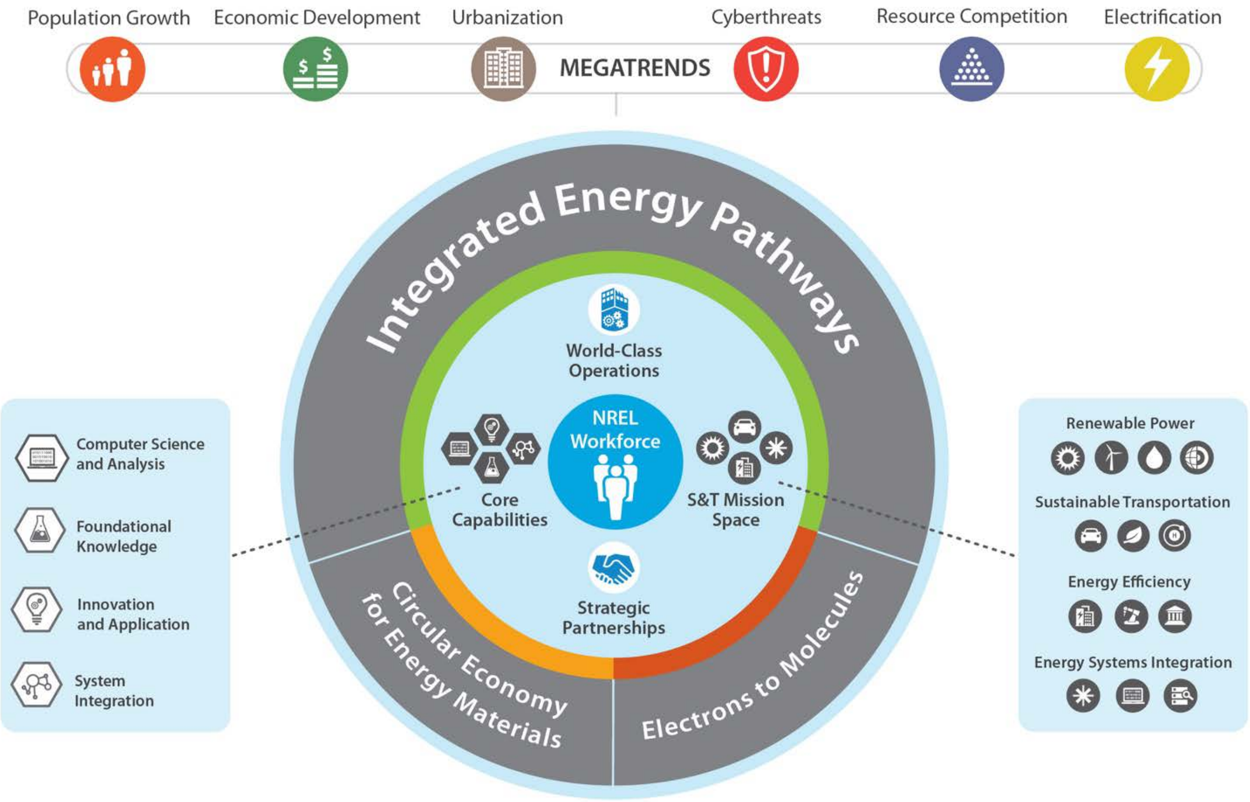
Energy Systems Integration

Grid Integration

Hybrid Systems

Security and Resilience

NREL Strategy



CRITICAL OBJECTIVES

Circular Economy for Energy Materials

Circularity for Polymers and Composites
Advanced Energy Materials and Technologies
Future Adaptive Materials for Energy Systems

Integrated Energy Pathways

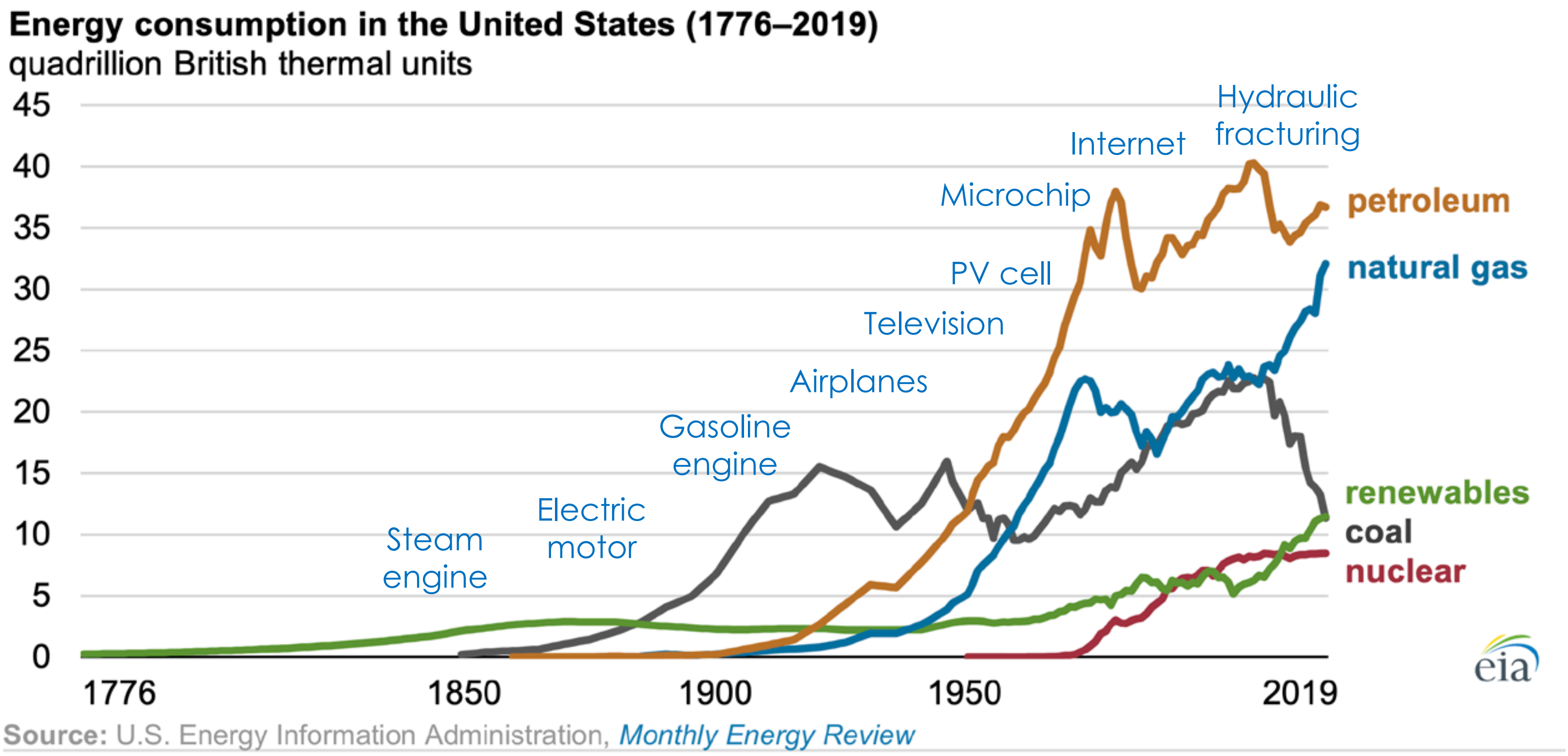
Generation, Storage, and Integration
System Security and Resilience
Advanced Mobility

Electrons to Molecules

Hybrid Approaches to CO_2 Reduction and Creating the Electron Foundry
Reactive Carbon Capture and Conversion
Novel Electricity-Driven Processes for Industrial Manufacturing

A Brief History of Energy Transitions

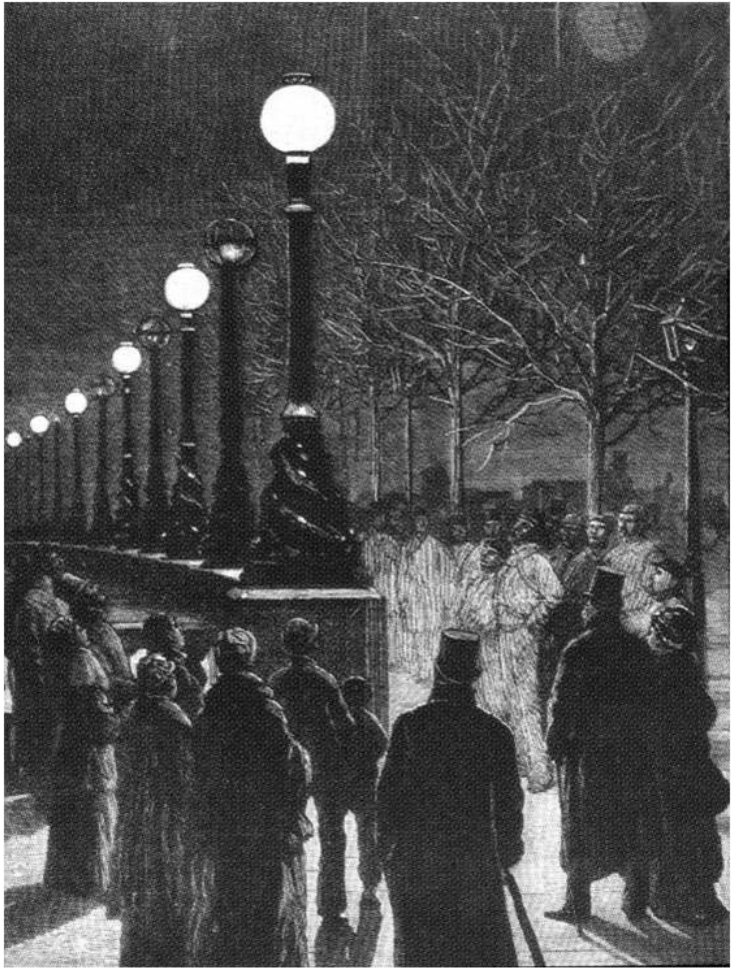
Transition of primary energy use in U.S.



Source: EIA, https://www.eia.gov/todayinenergy/detail.php?id=44277

Example: Lighting

- Lamp oil (made from plants and animals) replaced wood/candles
  - “Peak whale oil” (1846)
- Town gas (made from coal) replaced oil lamps
- Kerosene (made from oil) replaced town gas and whale oil
- Electric incandescent lights replaced gas lamps
- LED lights replacing incandescent lights



Source: Public domain, https://commons.wikimedia.org/wiki/File:Jablochkoff_Candles_on_the_Victoria_Embankment,_December_1878.jpg

Ex: Horse to Automobile

Easter morning 1900: 5th Ave, New York City. Spot the automobile.

Source: US National Archives.

Easter morning 1913: 5th Ave, New York City. Spot the horse.

Source: George Grantham Bain Collection.

Ex: Horse to Automobile: Solved one problem..

MORTON STREET, CORNER OF BEDFORD, LOOKING TOWARD BLEECKER STREET, MARCH 17, 1893.

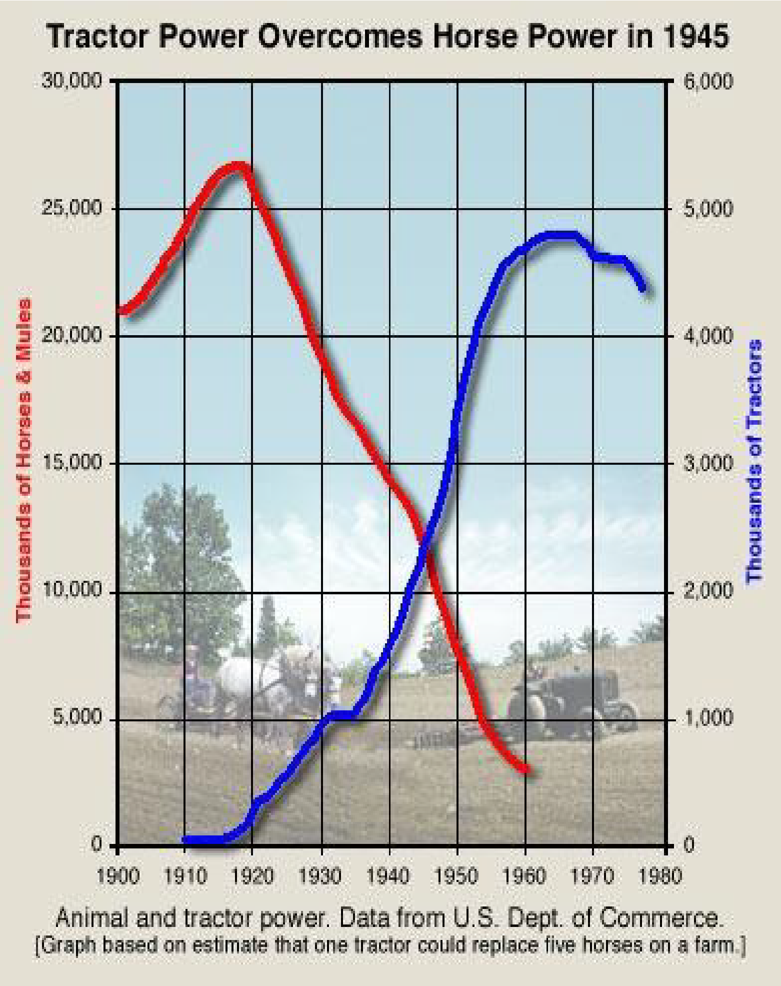
Great Horse Manure Crisis of 1894

1953 New York City Smog Event

Source: Public domain, Street-Cleaning and the Disposal of a City's Wastes, George E. Waring. 1898 ; Public domain, U.S. Library of Congress

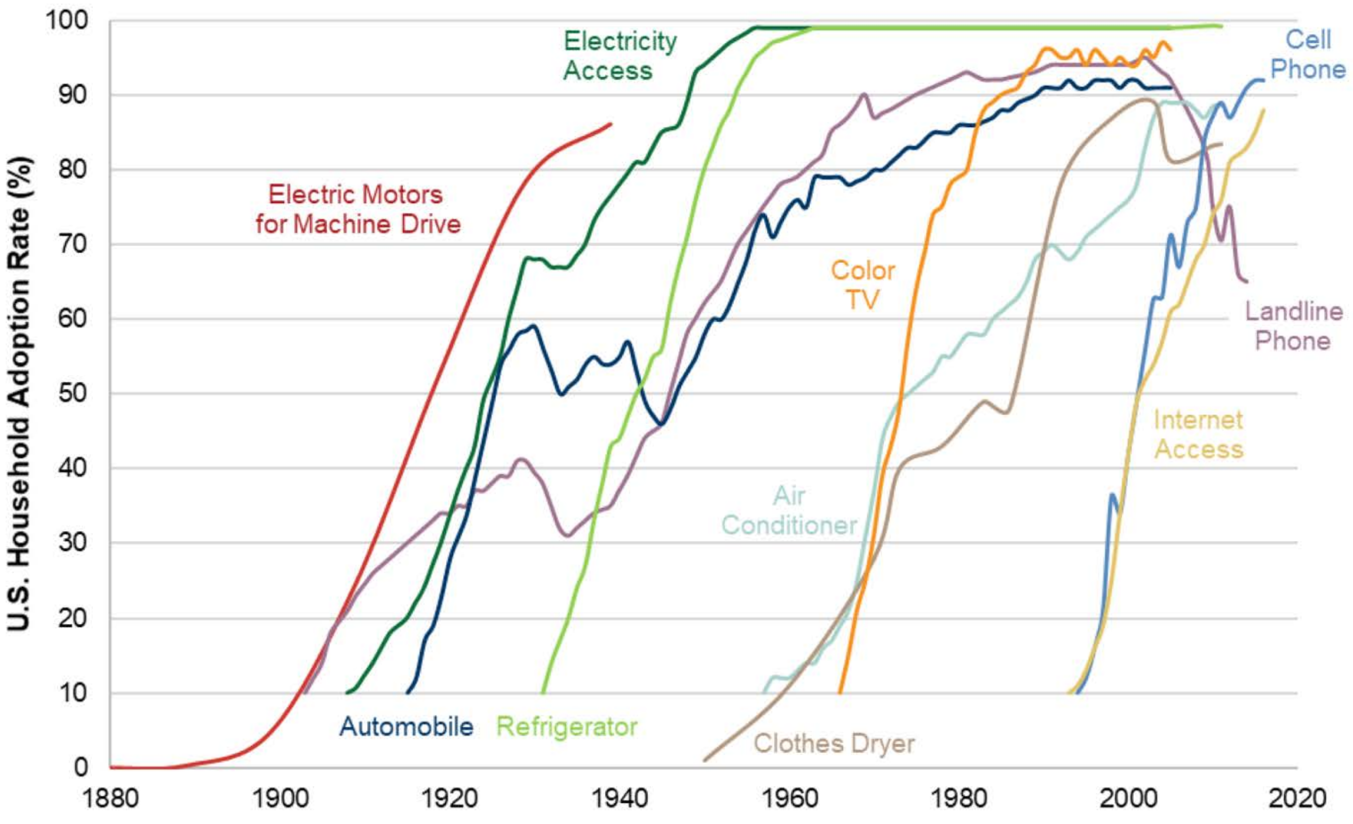
Example: Horse to Tractor

1918 Advertisement in Country Gentleman



Sources: Public domain, https://www.flickr.com/photos/dok1/2353664607; https://livinghistoryfarm.org/farminginthe40s/machines/horses-lose-their-jobs/

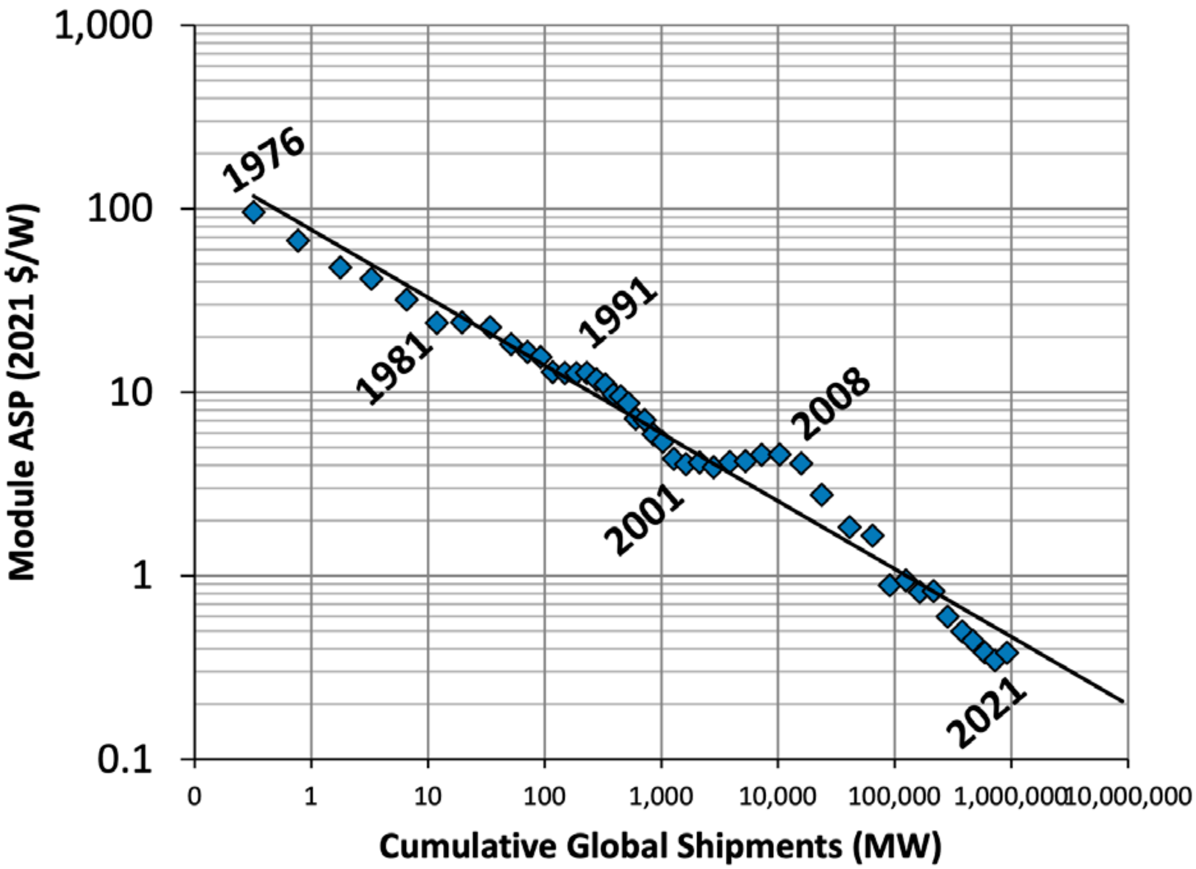
Technology Adoption Rates



Driven by:
Superior performance
Low enough cost
Meets an interest

Source: NREL’s Electrification Futures Study, www.nrel.gov/efs

PV cost has been declining dramatically



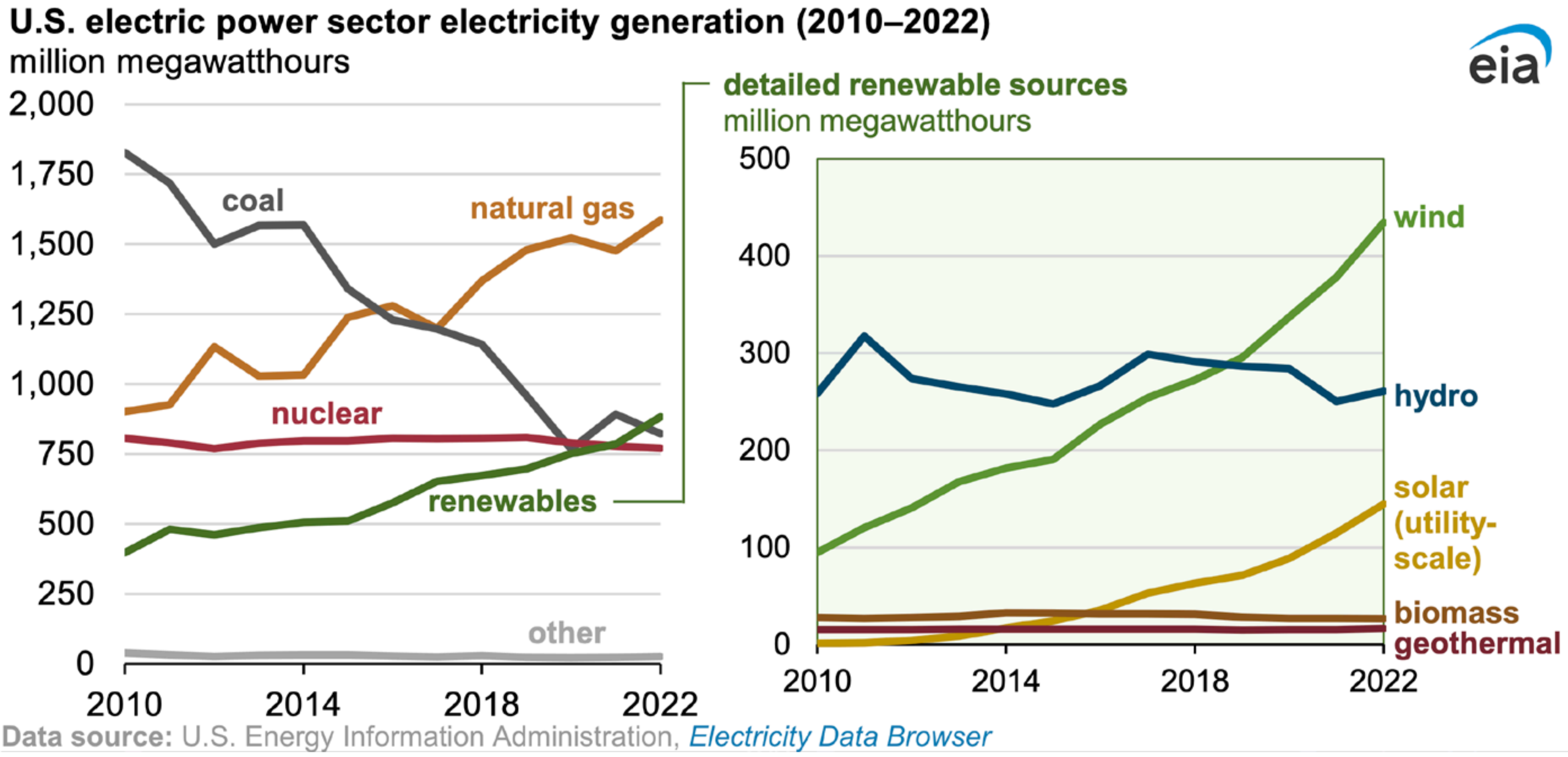
Swanson's Law: Price of PV modules decreases by 20% for every doubling of the cumulative shipped volume

Variable based on effects of silicon shortages, competition, and trade policies

Has PV reached lowest cost?

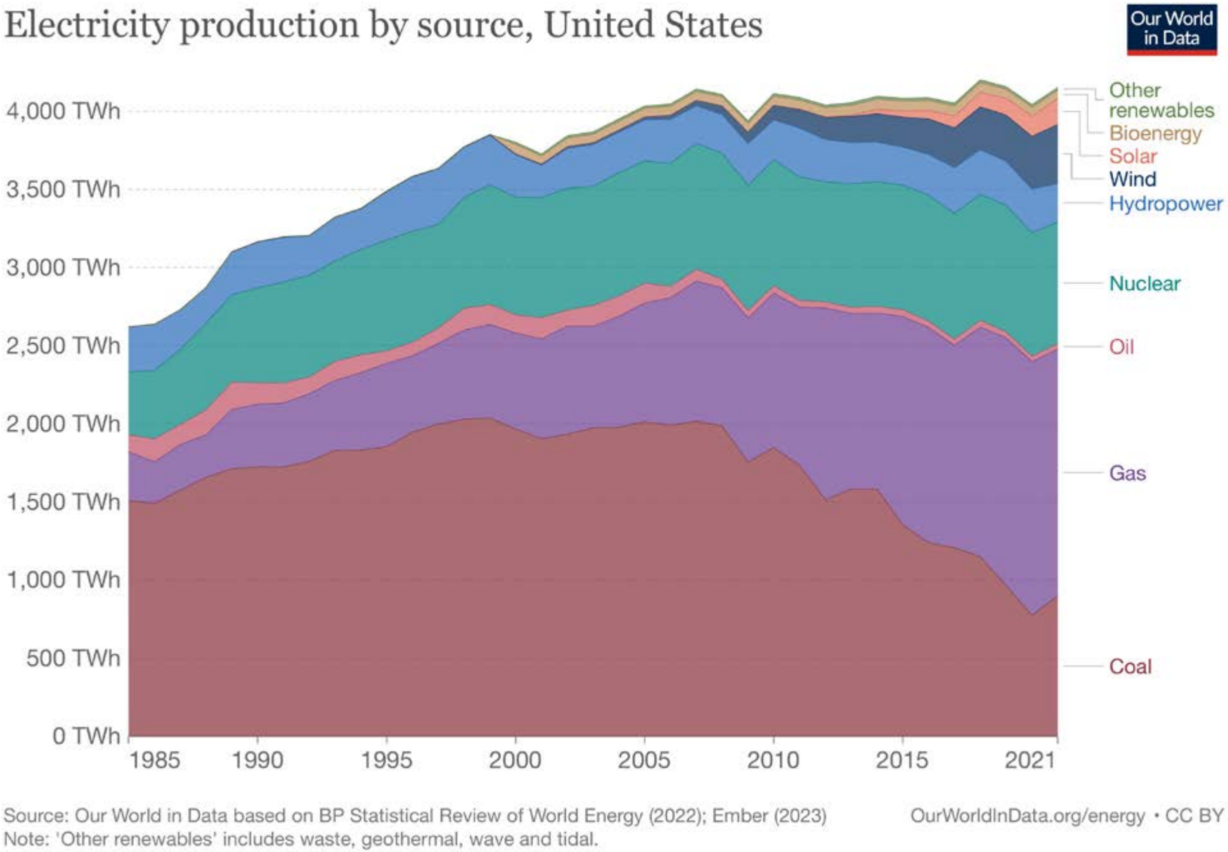
ttps://www.nrel.gov/docs/fy22osti/82854.pdf

Energy Transition: Electricity in the U.S.



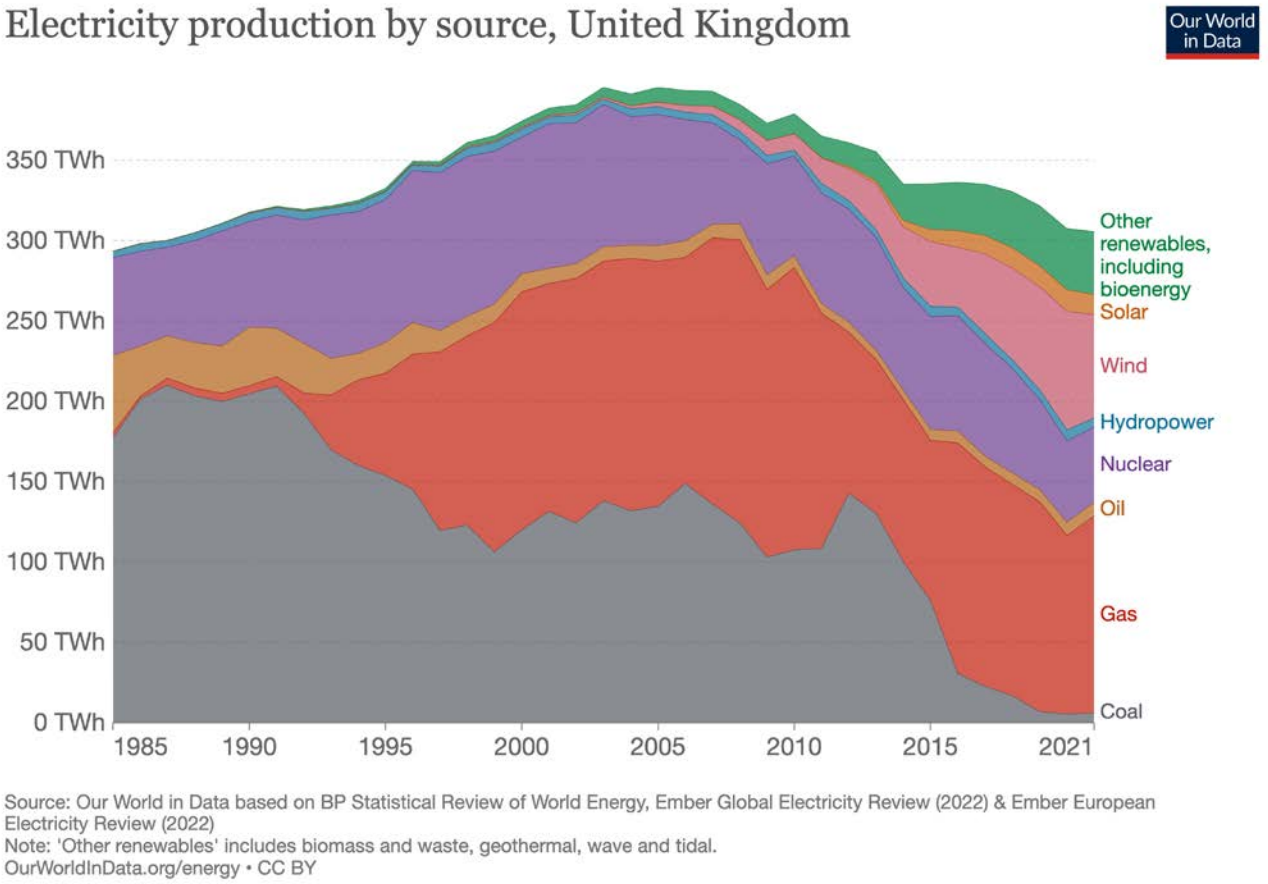
Source: EIA, https://www.eia.gov/todayinenergy/detail.php?id=55960

Energy Transition: Electricity in the U.S.



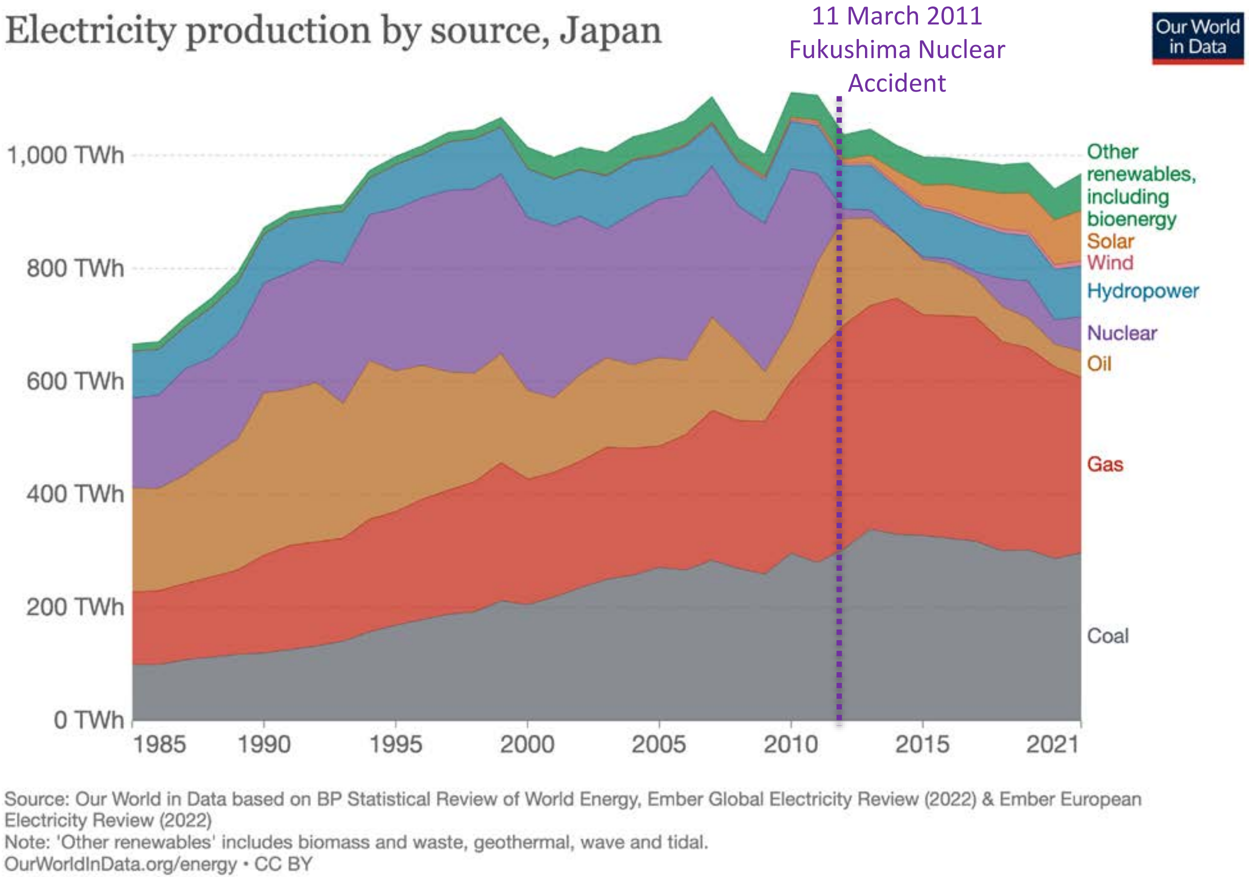
Source: https://ourworldindata.org/electricity-mix

Energy Transition: Electricity in United Kingdom



Source: https://ourworldindata.org/electricity-mix

Energy Transition: Electricity in Japan



Source: https://ourworldindata.org/electricity-mix

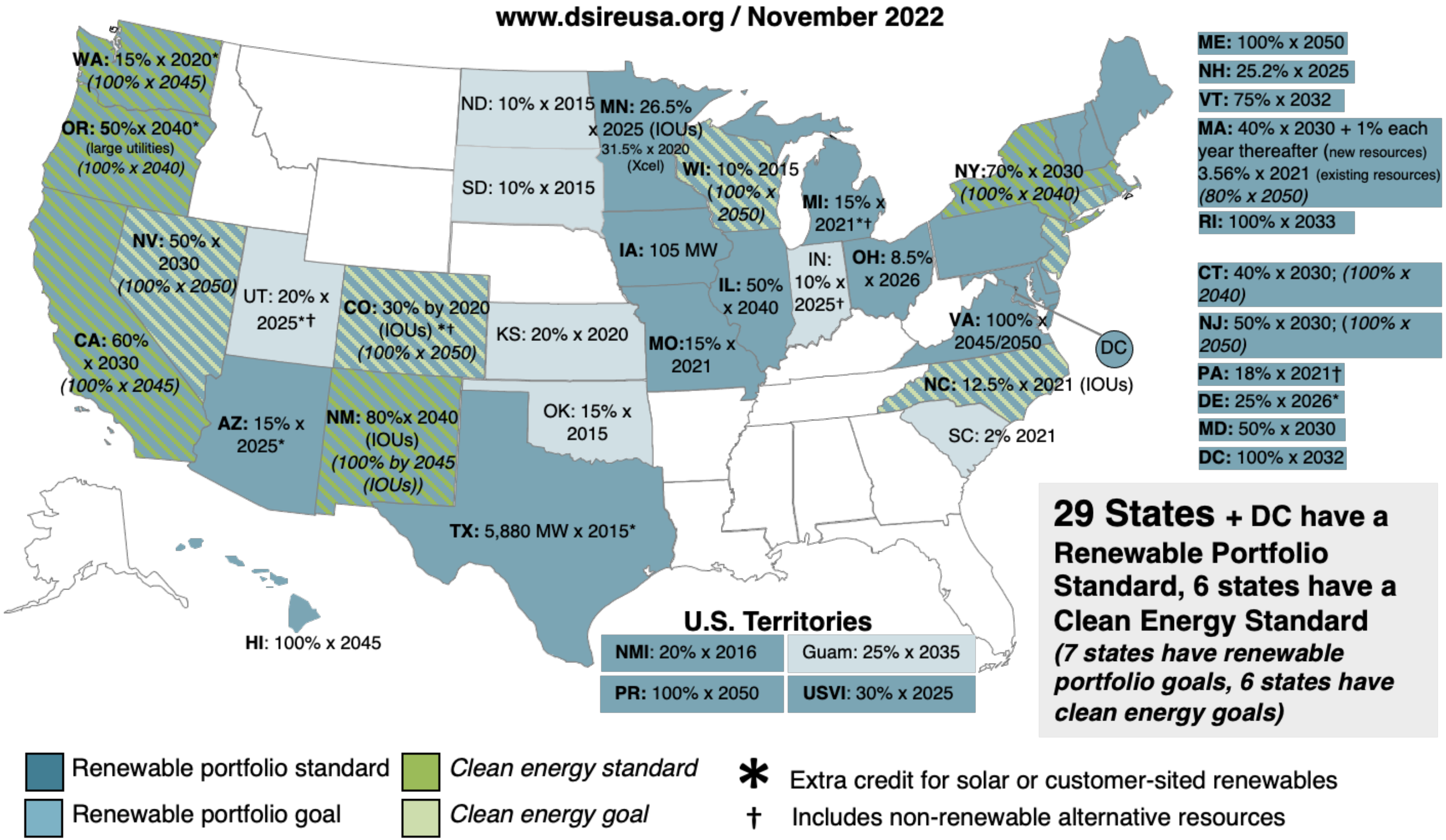
Scenarios of Future Energy Systems (100%!)

Key Future Scenario Definitions

- **Renewable energy**:
  - Energy sources that do not deplete within the timeframe of human civilizations
  - Solar, wind, geothermal, and usually biomass and hydropower
  - Goals defined by production levels (e.g., MWh) and not GHG emissions
- **Zero GHG (carbon-free) energy**:
  - Produced from sources that do not significantly generate CO_2 and other GHG
  - All renewable energy + nuclear energy
  - Goals measured by emissions from power generation and sometimes upstream/downstream life-cycle
- **Net-zero energy**:
  - Zero GHG energy and allows offsetting GHG emissions by other methods
  - Renewable + nuclear + combustion of fuels with carbon capture
  - Also direct air capture + nature-based carbon sinks, such as reforestation or regenerative agriculture
- **Clean energy and sustainable energy:**
  - Implies low levels of all types of pollution, GHG, water use, other negative environmental impacts
  - Usually some combination of renewable energy + net-zero GHG energy
  - Note: Use with care or specifically define it when used

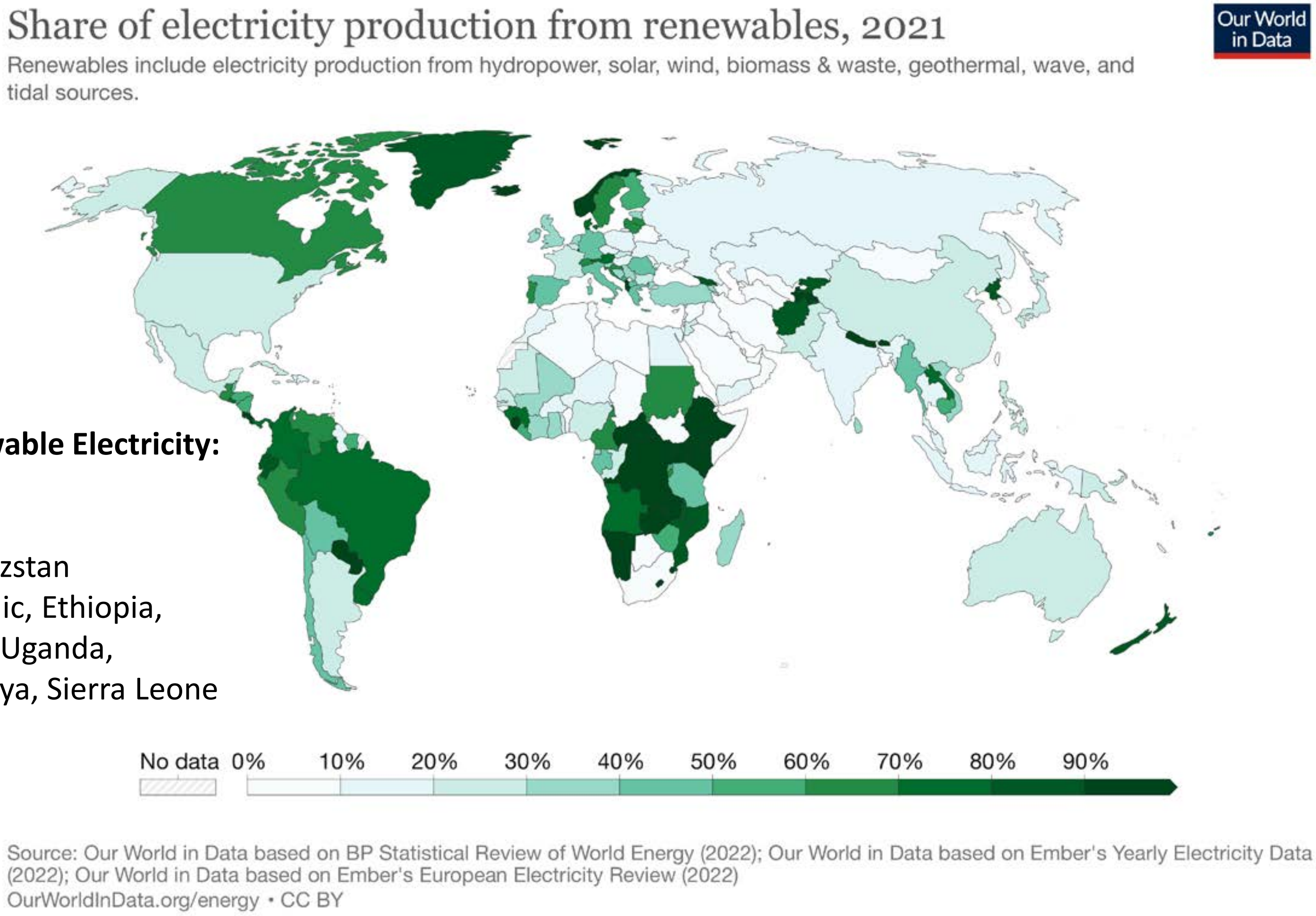
Source: Engel-Cox, J.A. and Geocaris, M. (2023), Future Low-Carbon Technology Options for a 100 Percent Decarbonized Power Sector. Climate and Energy, 39: 1-10. https://doi.org/10.1002/gas.22333

U.S. Renewable & Clean Energy Standards



Source: https://www.dsireusa.org/resources/detailed-summary-maps/

Renewable power leaders by country



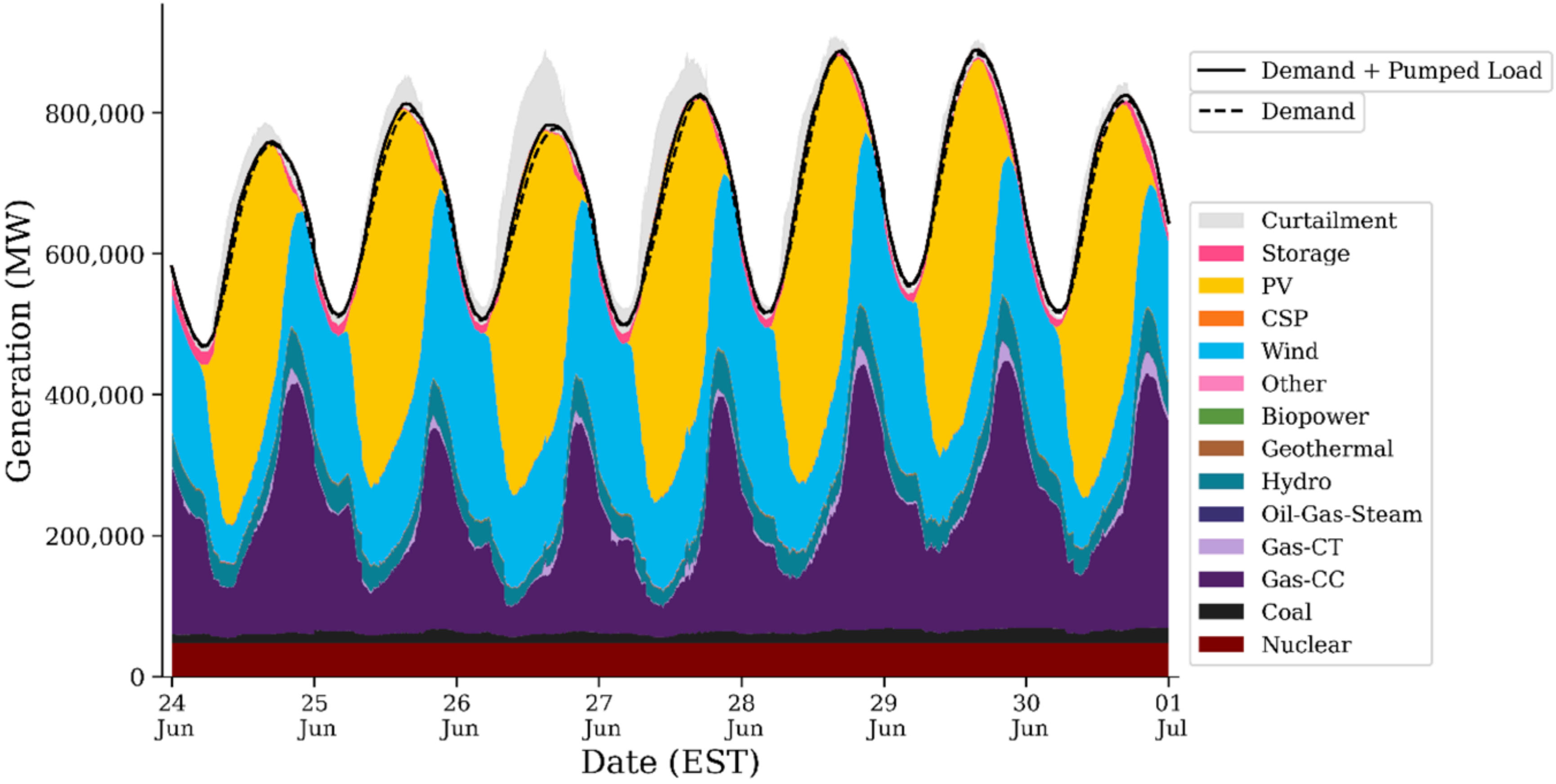
19 Countries with >90% Renewable Electricity:
Paraguay, Costa Rica
Albania, Iceland, Norway
Bhutan, Nepal, Tajikistan, Kyrgyzstan
Lesotho, Central African Republic, Ethiopia,
Democratic Republic of Congo, Uganda,
Namibia, Eswatini, Zambia, Kenya, Sierra Leone

Source: https://ourworldindata.org/renewable-energy

Priorities when running a power grid

- Reliability
- Match supply and demand
- Grid regulation
- Resource planning
  - Efficient service
  - Fair, cost-based rates
  - Investor rate of return
- Reduce emissions and waste
- Meet portfolio standards

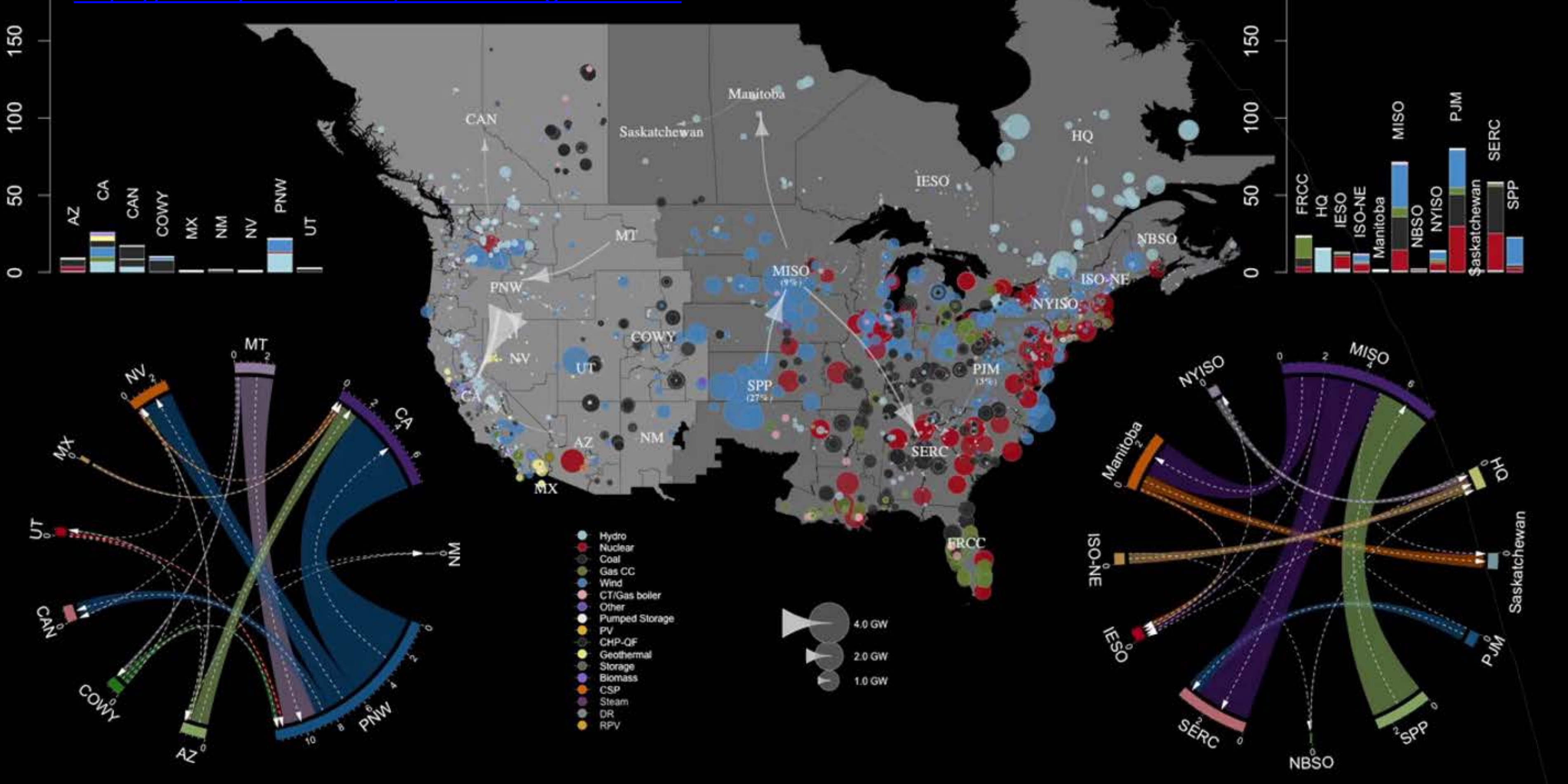
Modeled Dispatch Stack



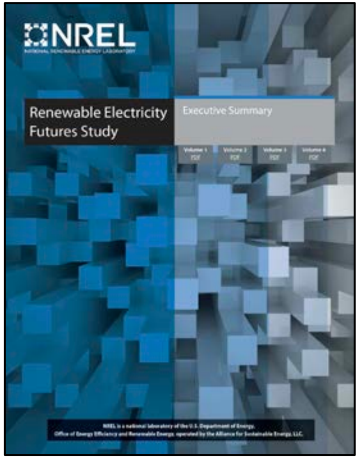
Source: Brinkman, Gregory, Dominique Bain, Grant Buster, Caroline Draxl, Paritosh Das, Jonathan Ho, Eduardo Ibanez, et al. 2021. The North American Renewable Integration Study: A U.S. Perspective Executive Summary. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-79224-ES. https://www.nrel.gov/docs/fy21osti/79224-ES.pdf

WECC (high_solar) + ERGIS (RTx30)

https://www.youtube.com/watch?v=YcgvGe2sN8Y

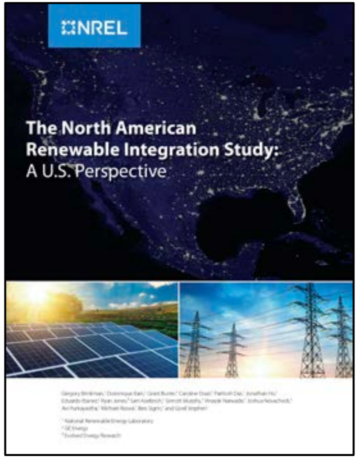


Many studies, focus on example of 100% by 2035



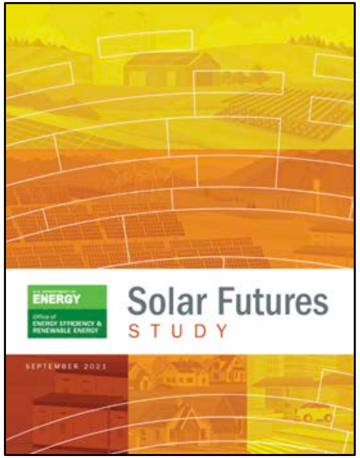
Renewable Electricity Futures Study (2012)

80% RE by 2050



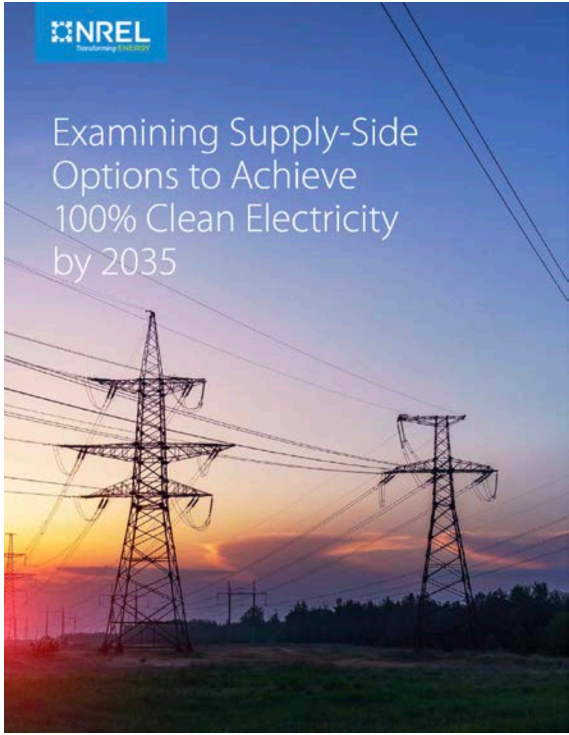
North American Renewable Integration Study (2021)

80% decarbonized by 2050



Solar Futures Study (2021)

100% decarbonized by 2050

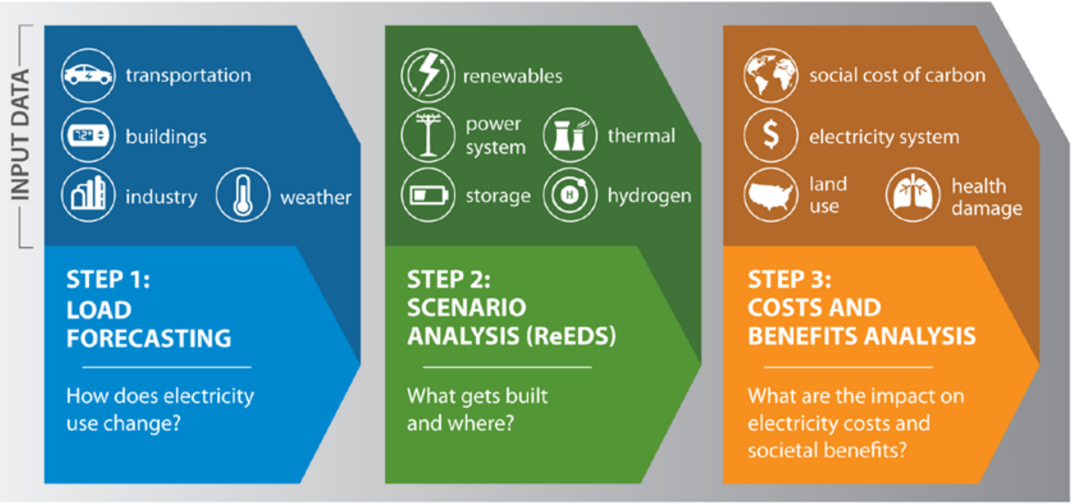


100% decarbonized by 2035

+ electrification trajectory consistent with net zero economy-wide by 2050

Credit to Paul Denholm, Trieu Mai, and colleagues. Access full report, data files, results infographics: nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

Methodology



The analysis discussed here was conducted prior to the passage of the Bipartisan Infrastructure Law of 2021 and the Inflation Reduction Act of 2022 and **does not include the effects of these policies**

	All options	Infrastructure	Constrained	No CCS
RE siting	Reference	Reference	**Limited**	Reference
CCS	Ref **+ DAC**	Ref (CCS/BECCS)	Ref (CCS/BECCS)	**No CCS**
Transmission	Reference	**+ HVDC macrogrid**	**No interregional; 5× cost**	Reference
Other	Reference	**Lower** H_2, CO_2, bio transport & storage adders	**Higher** H_2, CO_2, bio transport & storage adders	Reference

+ many sensitivities (146 total scenarios)

Nationwide Capacity Expansion Modeling: ReEDS

Objective: Minimize total **capital + operational** cost of electric power system

subject to…

Price-forming constraints: Energy balance; planning/operating reserves; RPS/carbon policies

Additional constraints: Resource availability (spatial & temporal); energy/reserve trading; generation/storage operations; fuel supply; planned builds and retirements; etc.

Inputs

- **Existing & planned** capacity
- **VRE** temporal (hourly) & spatial (11.5km × 11.5km) availability
- State & federal **policies** (current and hypothetical)
- **Load** (hourly) projections for 134 zones across contiguous U.S.
- Capital, O&M, and fuel **cost** projections
- **Technology** availability & performance projections

Regional **E**nergy **D**eployment **S**ystem

ReEDS

https://www.nrel.gov/analysis/reeds/

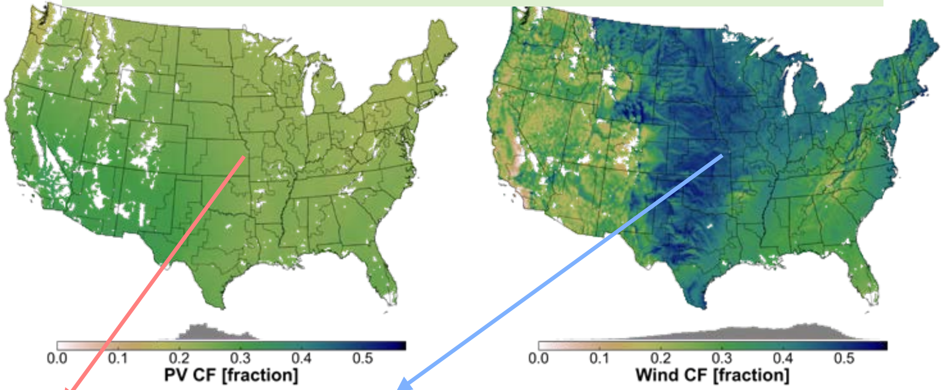
Outputs

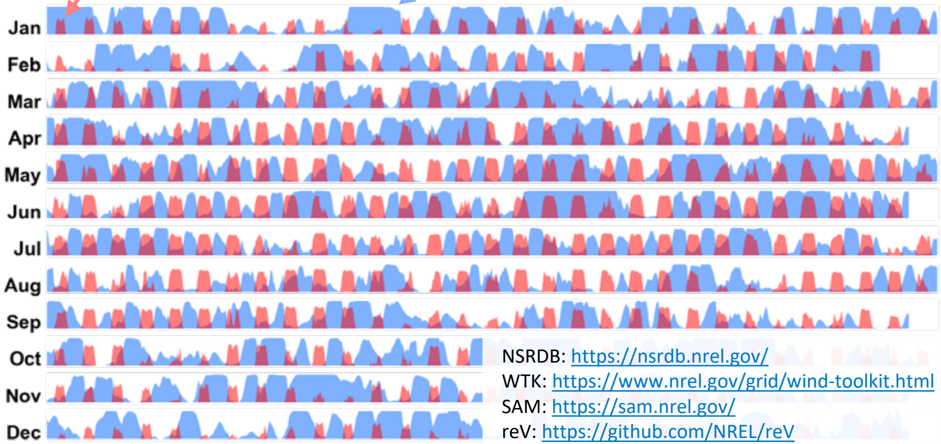
- Generation and storage **capacity** additions & retirements in each solve year
- **Transmission** capacity additions
- **Operations**: Energy generation, firm capacity, & operating reserves by tech
- CO_2, NO_x, SO_2, CH_4 **emissions**
- System **cost** [$billion], electricity **price** [$/MWh], retail **rates** [¢/kWh]

ReEDS: Key Inputs

RE temporal availability

National Solar Radiation Database + WIND Toolkit → SAM → reV model → Hourly CF profiles for >50k sites across U.S.

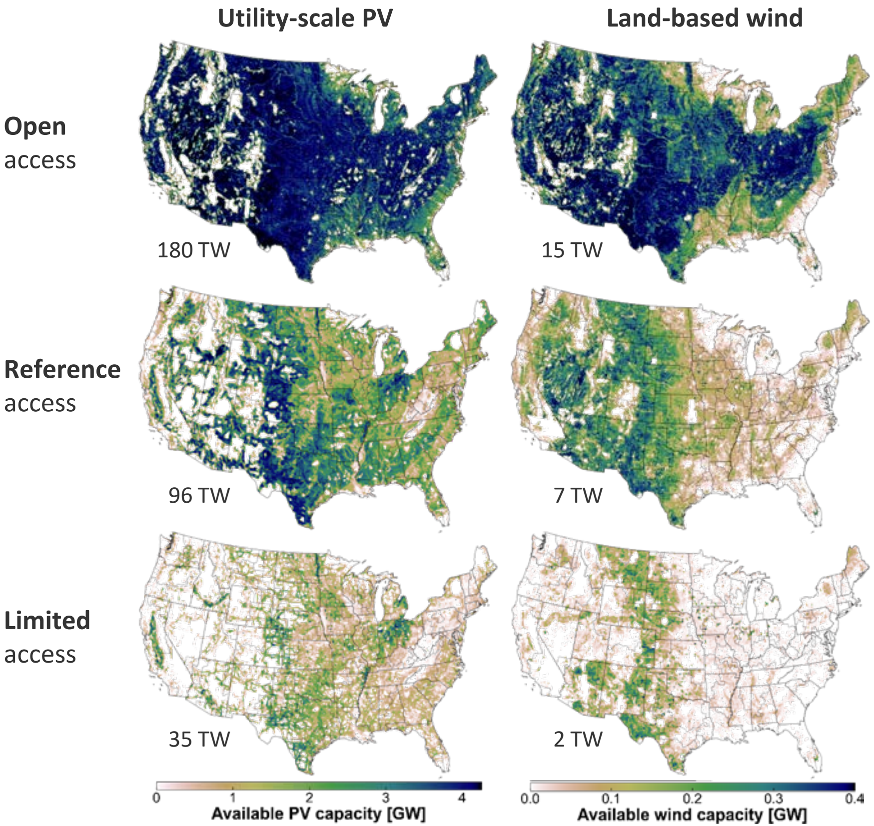




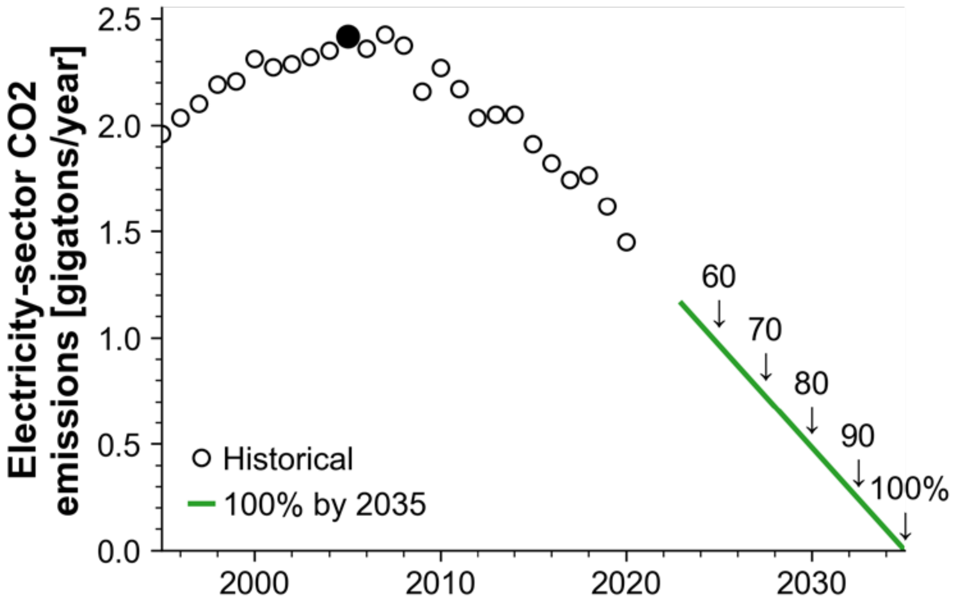
NSRDB: https://nsrdb.nrel.gov/
WTK: https://www.nrel.gov/grid/wind-toolkit.html
SAM: https://sam.nrel.gov/
reV: https://github.com/NREL/reV

RE spatial availability

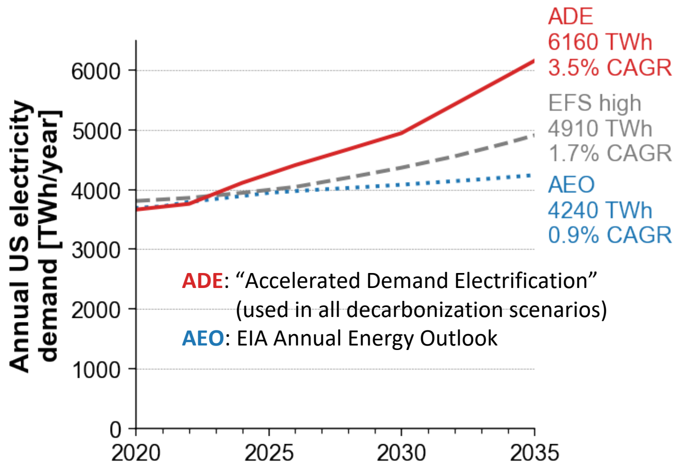
Multiple land-type exclusions ⟶ reV model ⟶ Developable wind/PV potential for same >50k sites



Finding 1. The challenge is to fully decarbonize the U.S. electricity system while meeting new and changing demand from electrified loads

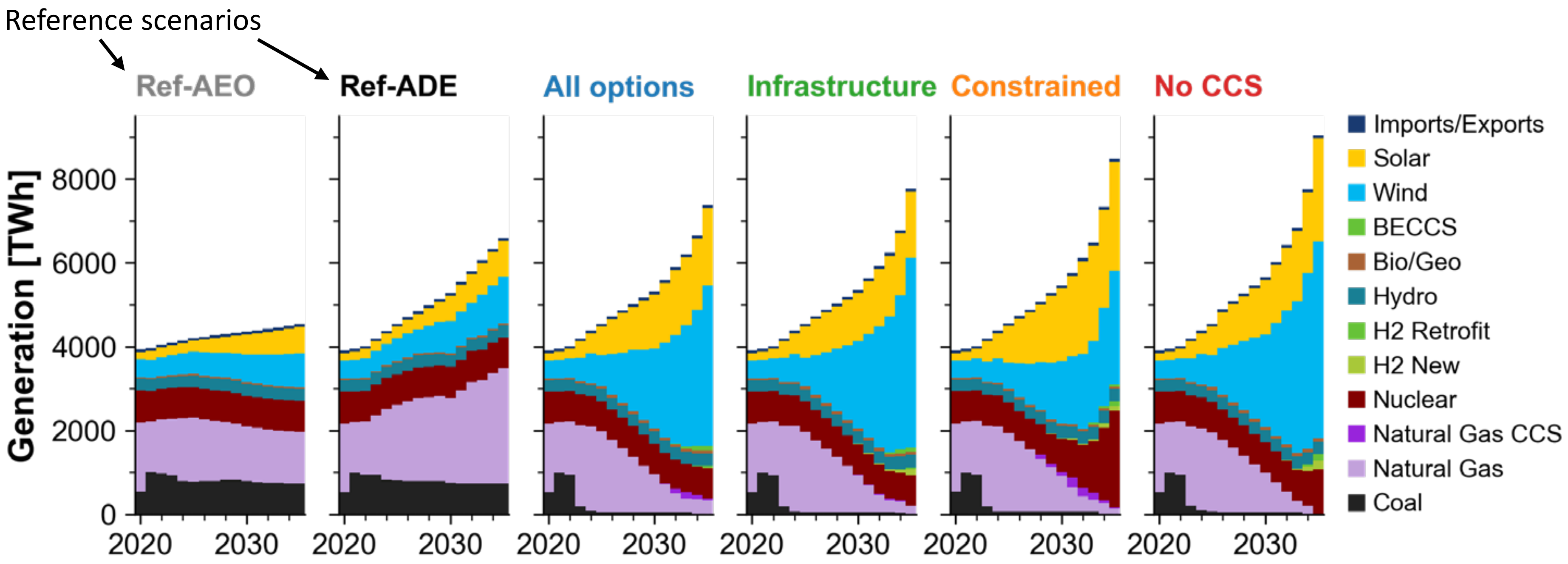


- Carbon cap trajectory
- Emissions can be offset with DAC/BECCS



% Reduction from 2005	Electricity Emissions	Energy Emissions
2020 Historical	40%	24%
2035 Ref-AEO	52%	24%
2035 Ref-ADE	31%	37%
2035 Target	100%	65%

2. Decarbonizing the grid while setting the economy on the path to net-zero emissions will require massive development of clean energy resources—particularly wind and solar



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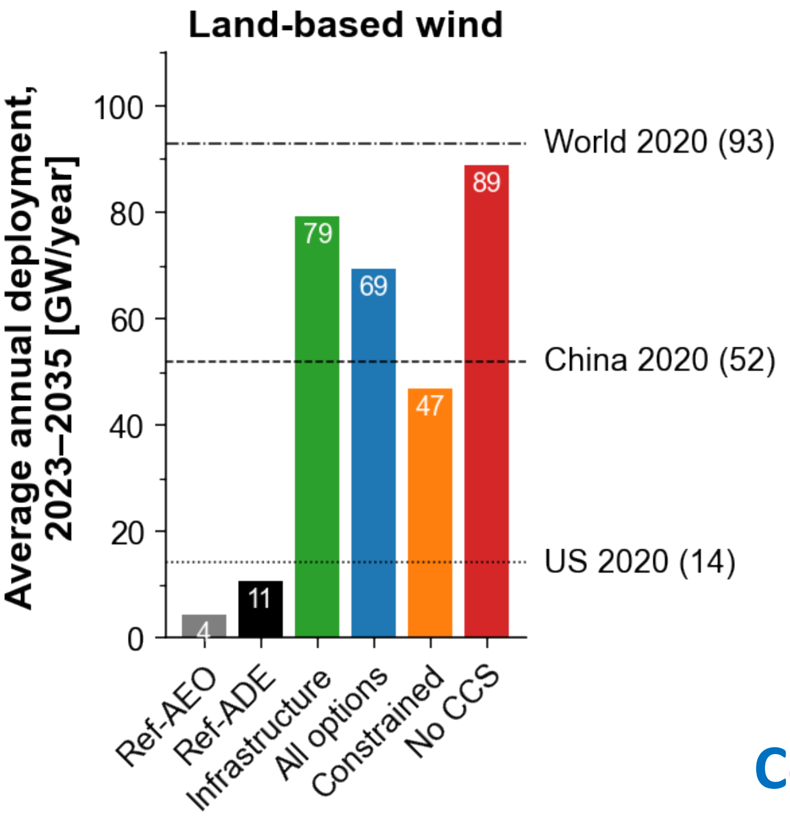
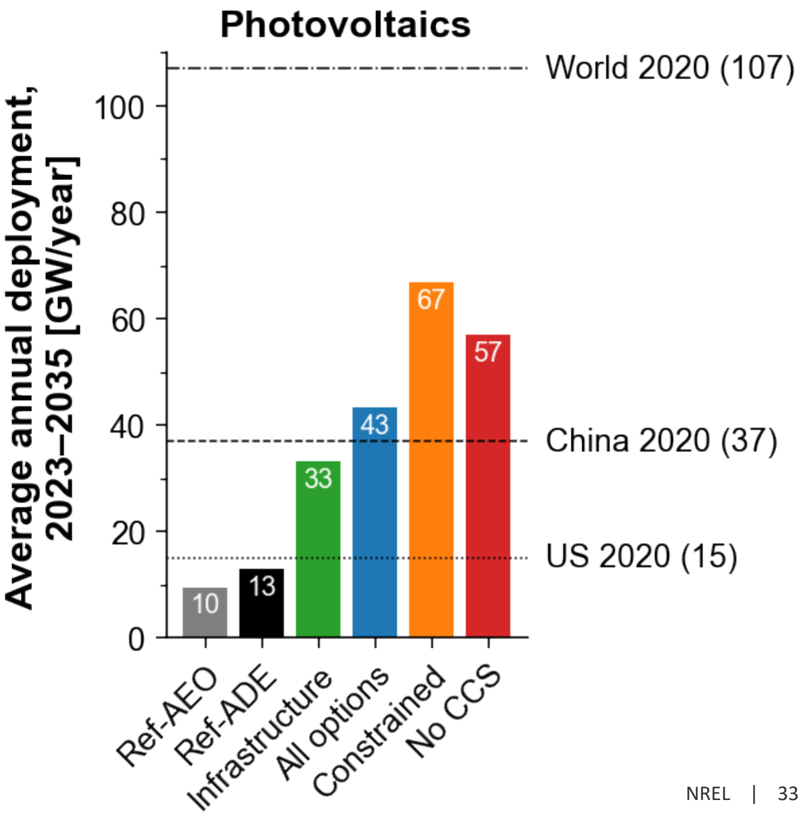
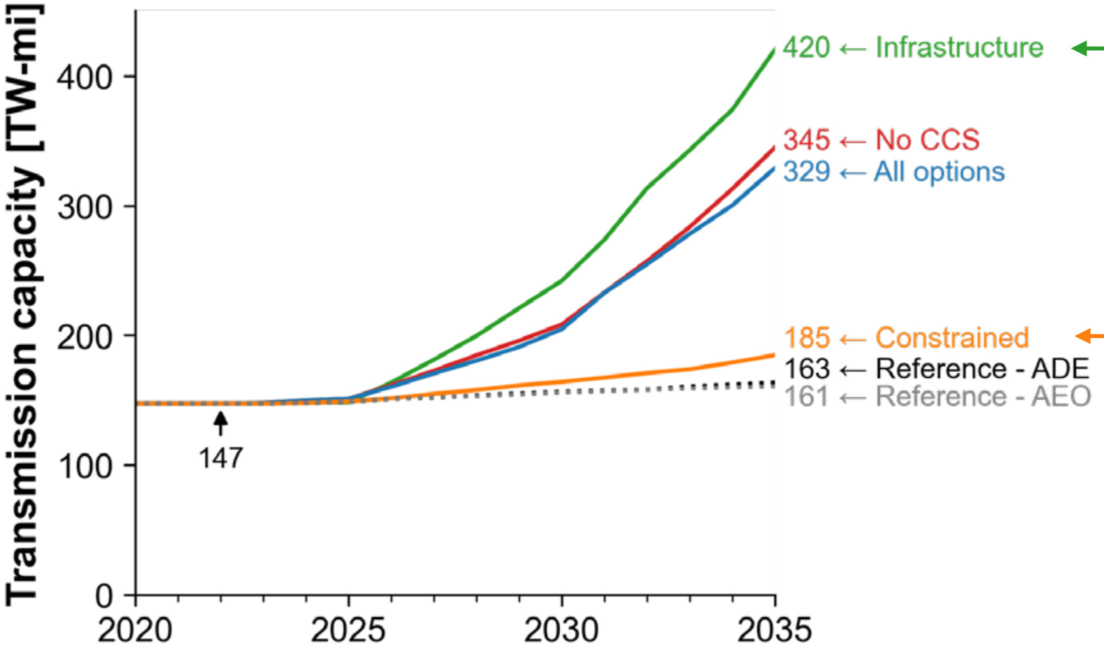




Context

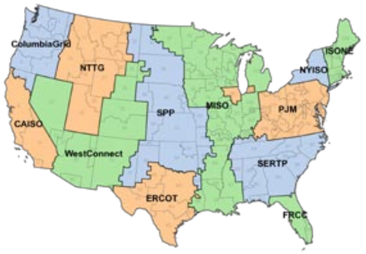
3. Transmission expansion (mainly for wind) and growth in energy storage (mainly for solar) are important enablers for a low-carbon grid



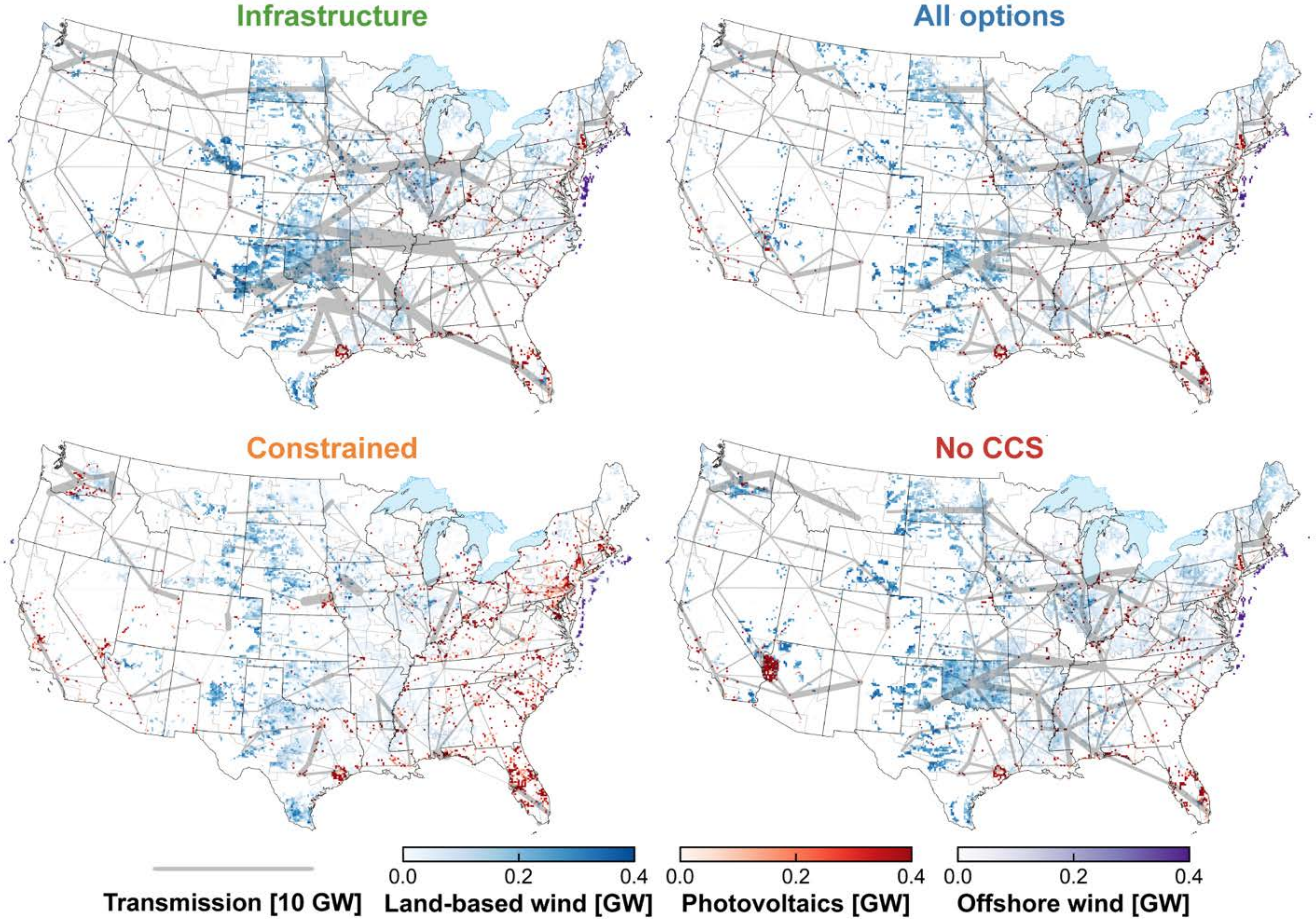
High-voltage inter-zonal transmission only

Multi-terminal HVDC macrogrid

5× transmission cost, No interregional (defined by FERC Order 1000 regions)



4. Achieving the clean energy deployment levels to reach 100% requires special attention to land use, siting, and other local factors



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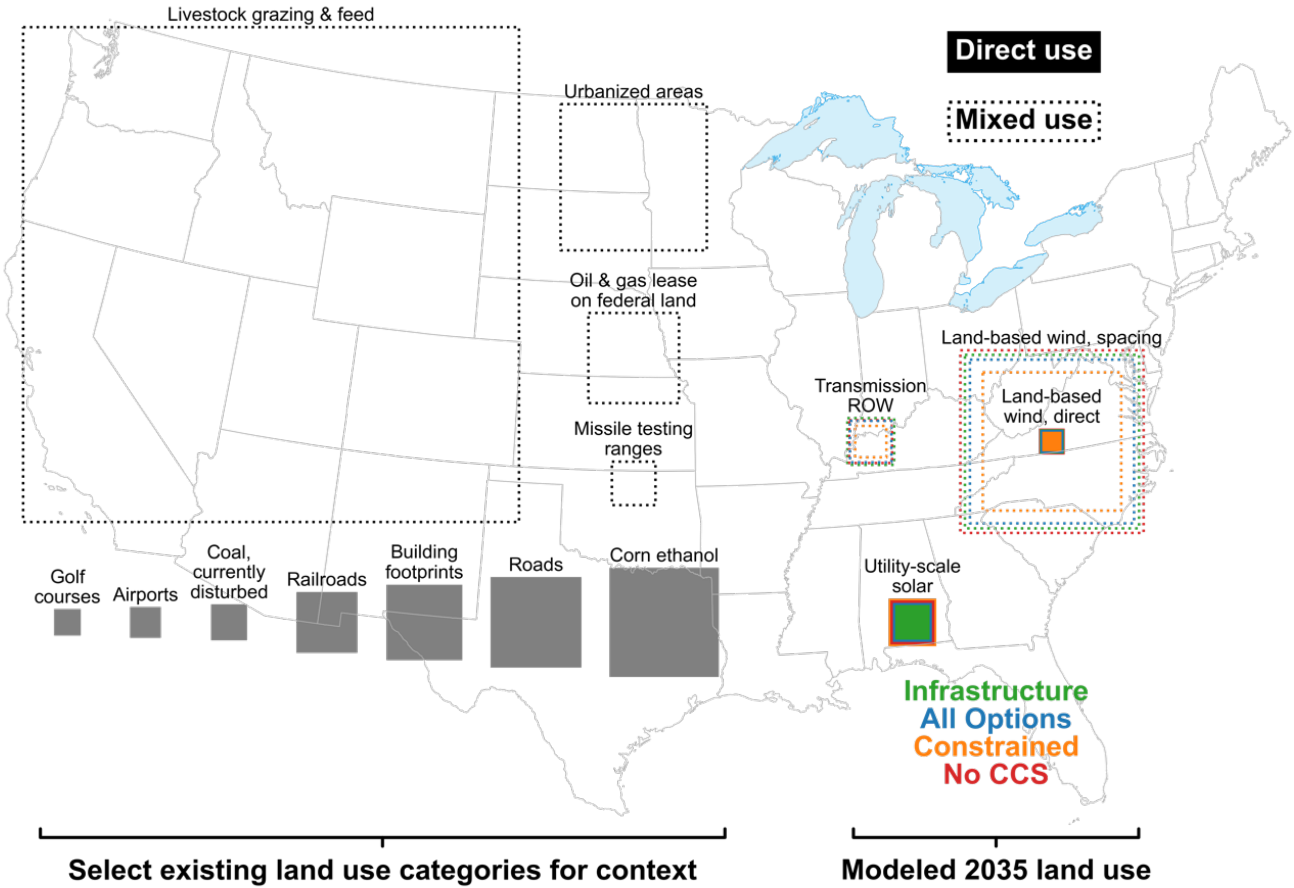
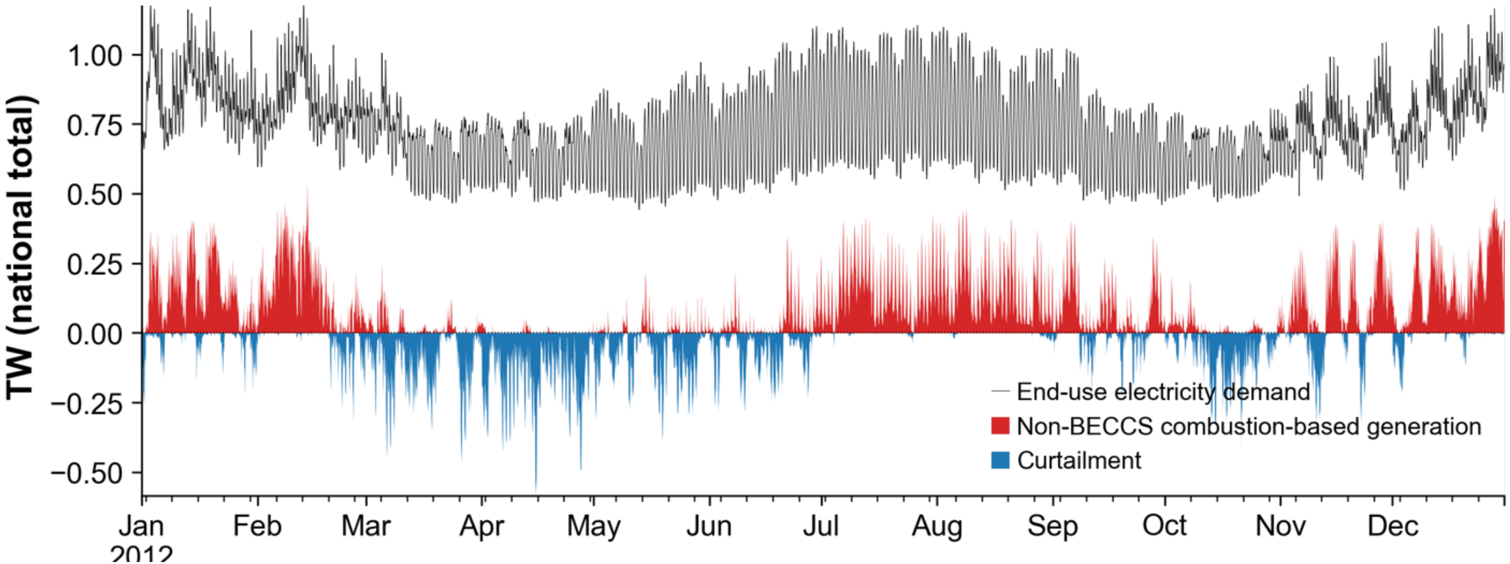
Context

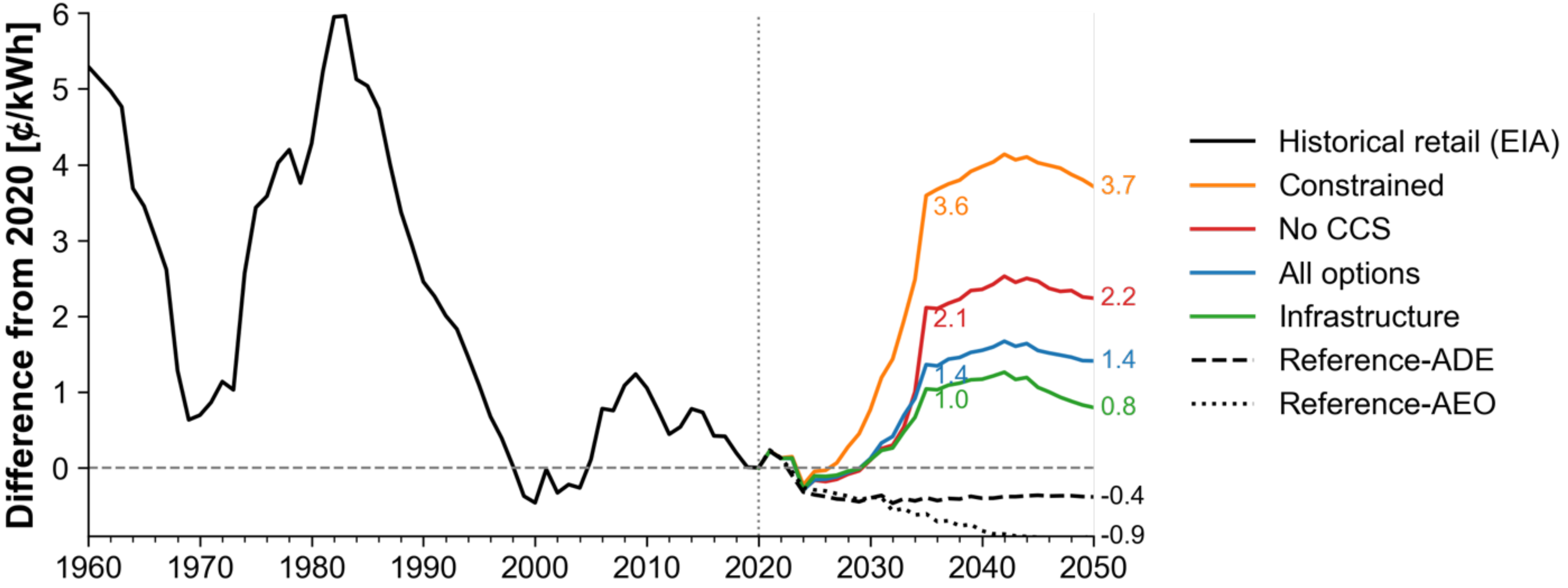


5. Getting all the way to 100% requires overcoming the seasonal imbalance challenge, but we don't yet know the optimal technology pathway to accomplish this.

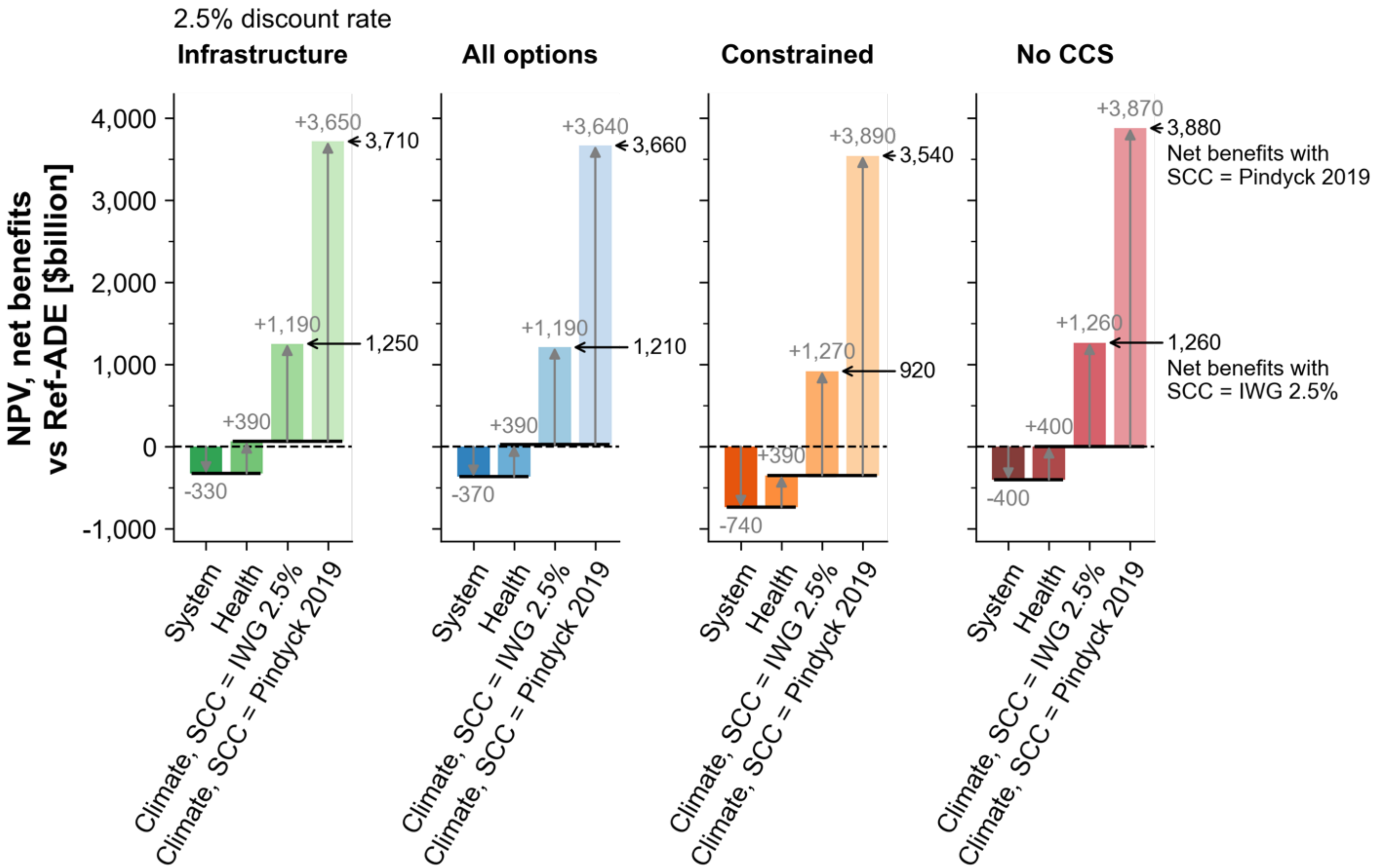


The seasonal supply/demand balance for the contiguous United States in the All Options scenario (ADE demand case) in 2035 shows the seasonal mismatch challenge.
Demand met by fossil- and hydrogen-fueled resources (red) occurs largely during periods of relatively low wind and solar output, or periods of very high electricity demand. The supply of wind and solar generally exceeds demand resulting in curtailment (blue) in the spring and fall, often for continuous periods.

6. Direct electricity system costs increase in the 100% scenarios, but these increases are well within the range of historical retail price fluctuations.



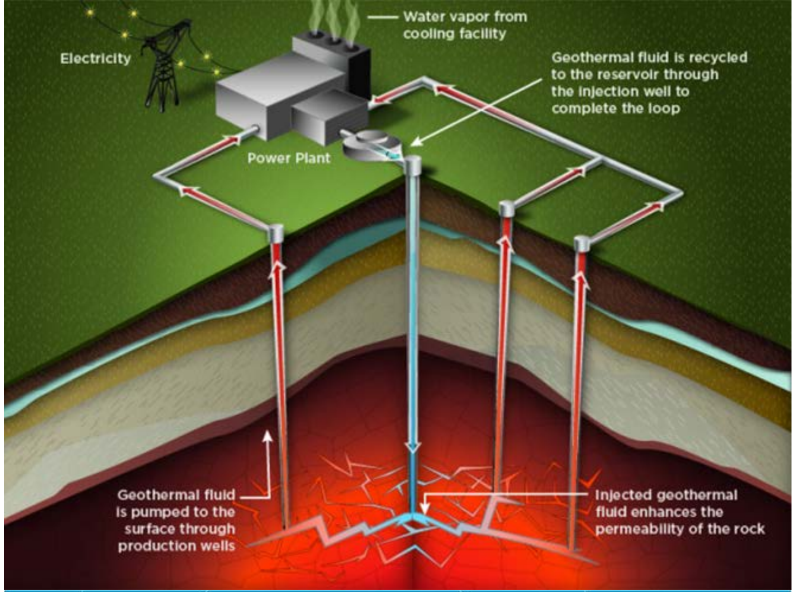
7. The benefits from improving air quality and avoided climate damages exceed the incremental costs of the 100% clean electricity.

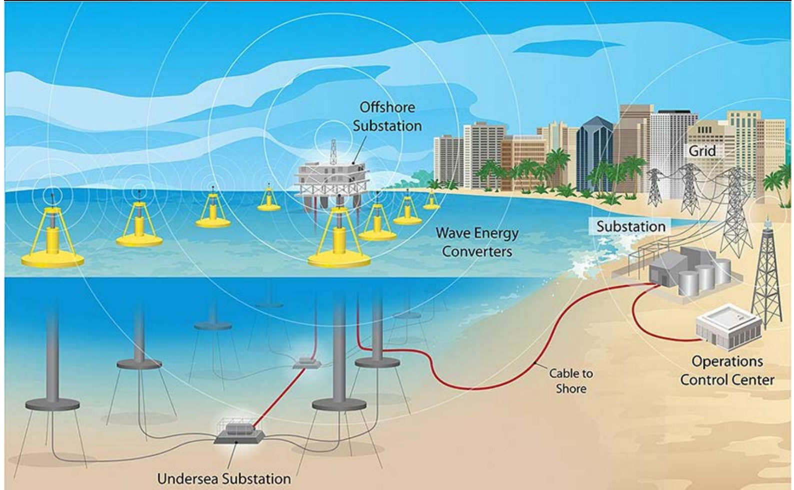


Future Technologies for Future Transitions

Renewable energy technologies with less variability + Storage

- Enhanced/Advanced Geothermal Systems
  - Dry hot rock + injected/piped fluid for heat and electricity
- Subsurface storage
  - Compressed air or gas storage
  - Heat storage
- Water energy
  - Ocean energy (wave and tidal)
  - Powering of retention dams
- Green hydrogen and other fuels
- High capacity batteries

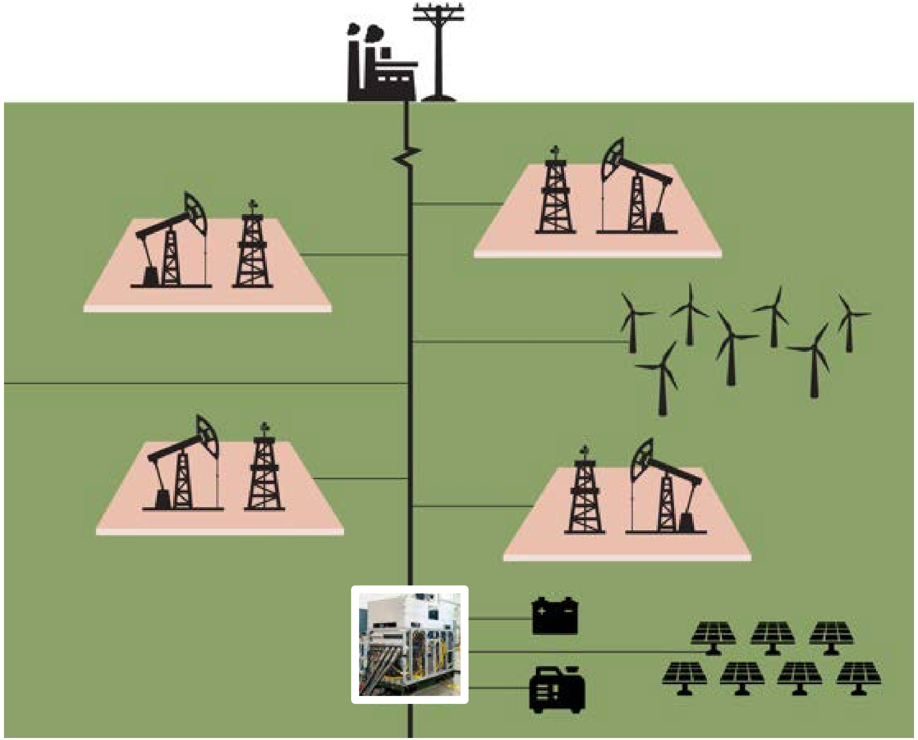




Source: NREL, https://www.nrel.gov/geothermal/sedimentary-egs.html ;
A. Hicks, https://www.nrel.gov/water/wave-array.html

Dynamic two-way distributed energy resources (DERs) and Virtual Power Plants (VPPs)

- Distributed energy
  - Multiple inter-connected energy generators near demand
  - Increased resiliency and cost savings
  - Community, campus, and industry scales
- Virtual power plants
  - Bundling and coordinated operation of small private energy generation and storage sources
  - Co-benefits to consumer, utility, and coordinator



Source: https://www.nrel.gov/docs/fy19osti/72842.pdf

Improved landuse for wind/PV with co-benefits

"Agrivoltaics"

"Floatovoltaics"

Source: NREL,
https://images.nrel.gov/

Summary and Conclusions

- **Key Challenges:** For 100% renewable/clean power, need to address…
  - Costs increase as approach 100%
  - Possible significant growth in demand from electrification
  - Expected increase in weather and climate variability
  - Generation mismatch at various timescales (hourly, seasonally)
  - Social and land-use constraints in technology acceptance, transmission, and trade
  - Definitional issues, such as inclusion of nuclear, large hydropower, and carbon capture
- **Technology Solutions**: Achieving 100% clean/renewable energy will involve a combination of technologies, existing and new, so on-going research needed
- **Anticipate and Mitigate:** All energy transitions have positive and negative effects so important to look for potential downsides and find proactive solutions.
- **Community Acceptance**: Siting and social acceptance of large-scale deployment of energy technologies and their supporting grid infrastructure must be addressed
- **Multiple Scenarios**: Solution to reach 100% <goal> energy systems will be based on state/national infrastructure, resources, and social acceptance (no one solution for all)

Thank you! Questions?

You are welcome to connect with me on LinkedIn!
Email: jill.engelcox@nrel.gov

www.nrel.gov

NREL/PR-6A50-85725

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