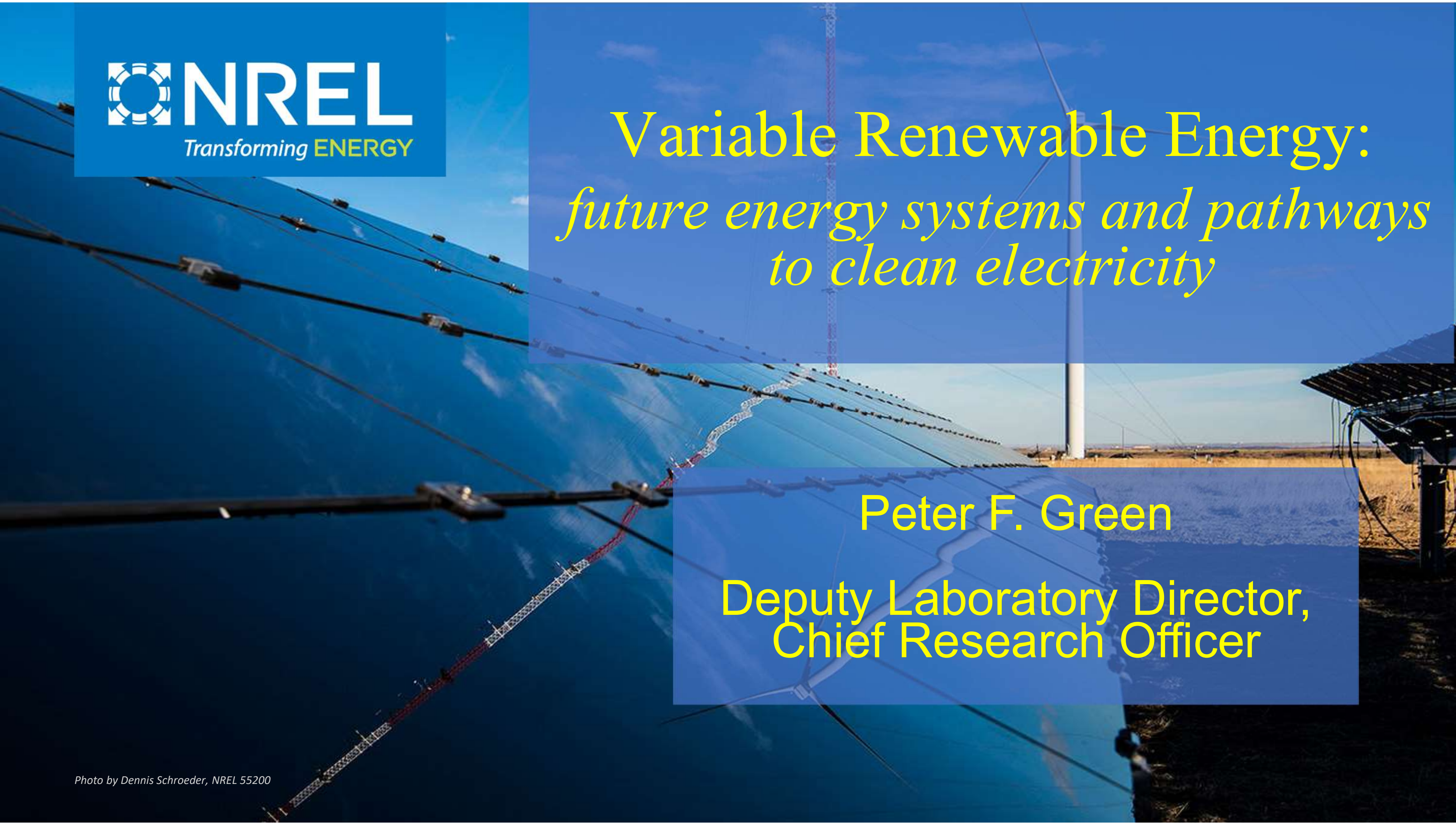


Variable Renewable Energy:
future energy systems and pathways to clean electricity

Peter F. Green

Deputy Laboratory Director,
Chief Research Officer

Photo by Dennis Schroeder, NREL 55200

OUTLINE

I. NREL –strategic directions

II. The future energy system

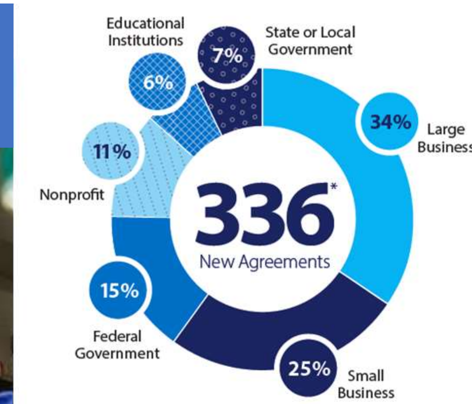
III. Scenarios and pathways –*100% carbon free electricity by 2035*

IV. Energy storage and power generation: *status*

V. Final Remarks

NREL Science Drives Innovation

3200 Employees
3 Campuses, 1000 Partnerships



Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Hydrogen and Fuel Cells

Transportation and Mobility

Energy Efficiency

Advanced Manufacturing

Buildings

State, Local, and Tribal Governments

Energy Systems Integration

Energy Security and Resilience

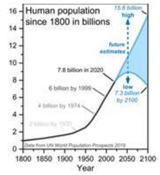
Grid Modernization

Integrated Energy Solutions

Understanding the challenge - *megatrends and mitigating major GHG contributors* -informs potential pathways and decisions

Our changing environment –*planning for a sustainable future*

Population



Economic Development

Urbanization

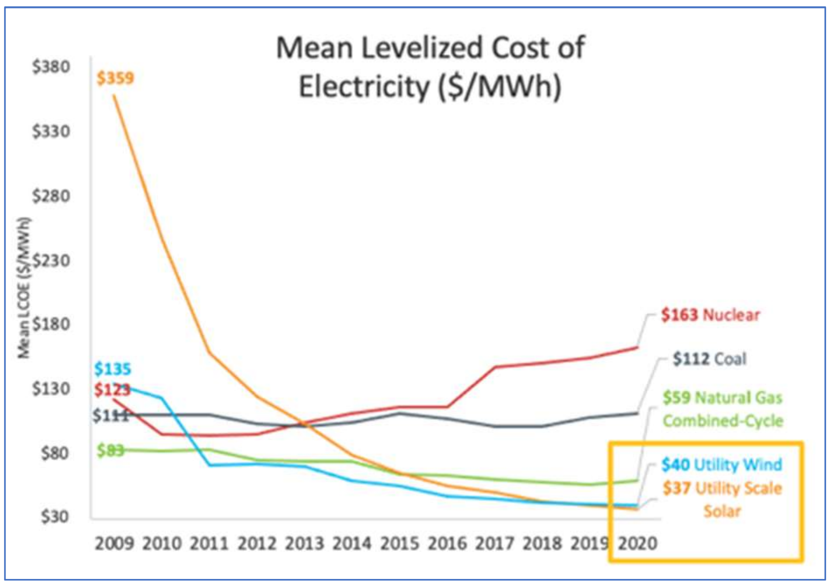
Electrification

Extreme weather events

Cyber threats

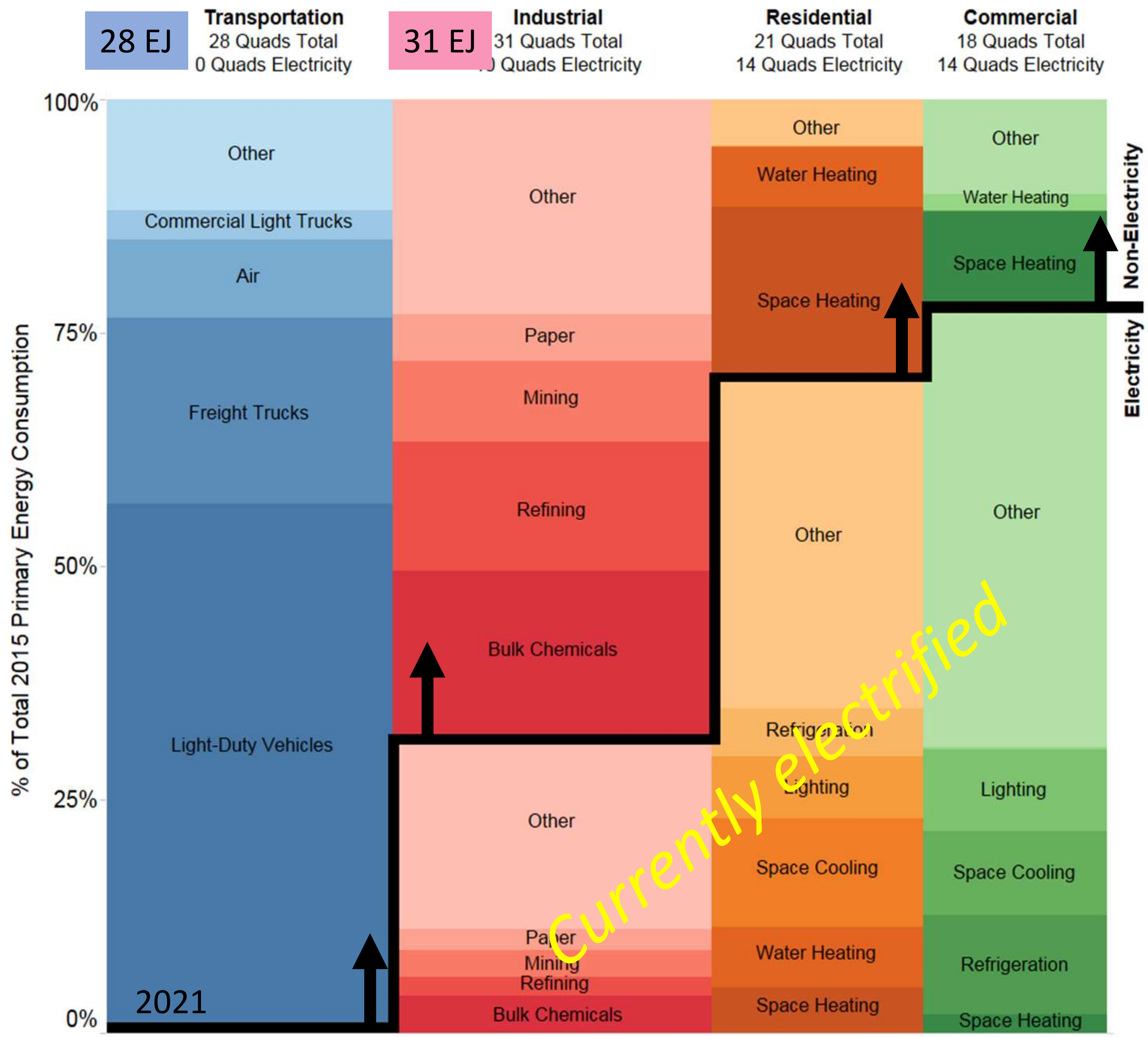
LCOEs of renewable power sources are now competitive with conventional generation

Significant reduction in LCOEs of wind and solar during the last decade



Levelized Cost of Energy Comparison—Unsubsidized 2021

The transportation and industrial sectors would benefit significantly from electrification, improved, efficiencies and decarbonization



Electrification Futures Study:
Scenarios of Electric Technology Adoption and Power Consumption for the United States

Trieu Mai, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson

How might decarbonization goals be met

1. Electrification of end-use technologies and decarbonize power generation sources
2. Energy efficiency: reducing demand
3. Using low- to zero-carbon liquid or gas fuels: hydrogen, synthetic hydrocarbon fuels, ammonia, methanol.
4. Capture, sequester and/or utilize CO_2 to reduce emissions from fossil fuel. The CO_2 could be converted to chemicals/fuels

Underpinning this effort would be: technology advances, manufacturing and deployment at scale, enabling policy

NREL's Strategic Directions

Integrated Energy Pathways

Develop the foundational knowledge and technologies to **optimize the integration of renewables, buildings, energy storage, and transportation**—modernizing our energy systems and ensuring a secure and resilient grid.

Electrons to Molecules

The **conversion of electricity and small waste gases** (e.g. CO_2, H_2O, N_2) into chemical bonds for the purposes of chemical, material, or fuel synthesis and/or energy storage.

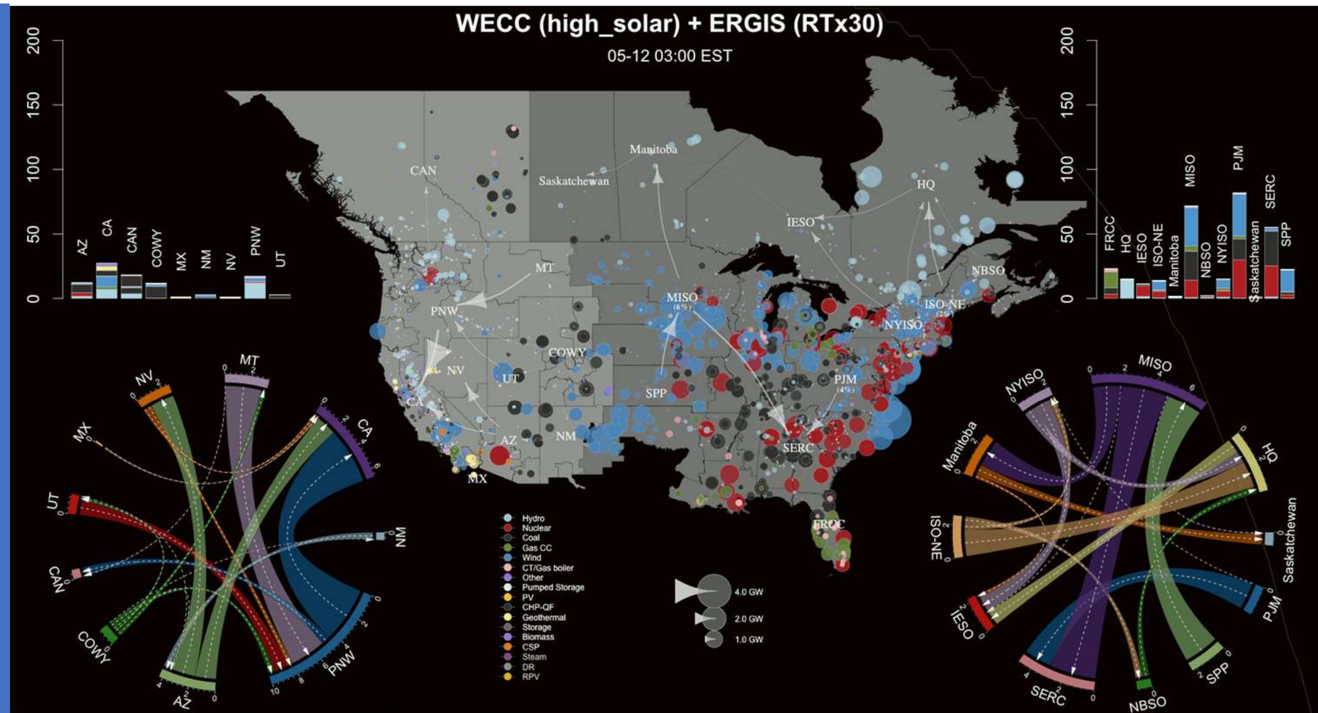
Circular Economy for Energy Materials

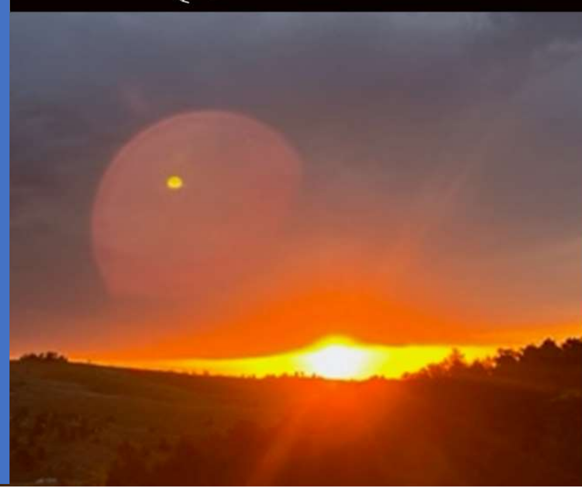
Establishing the **foundational knowledge/technology** for design, recycle, reuse, remanufacture, and reliability for **energy-relevant** materials and processes.

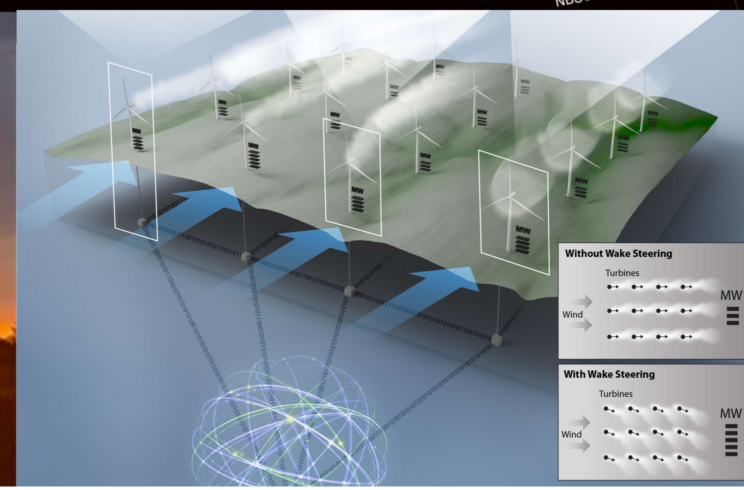
The future

Energy

system







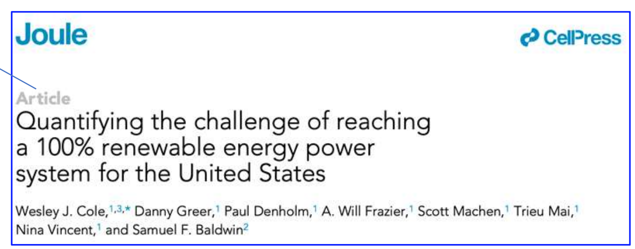
The future energy System

- Real-time control and operation of millions of distributed energy resources: EVs, distributed solar and wind, lighting, data centers, smart buildings.

- The grid must seamlessly provide power from a range of power sources, as well as:
    1. operate with high amounts of variable energy resources –wind, solar;
    2. operate under major weather disruptions -resilience;
    3. work effectively and efficiently, despite mounting cyber challenges.

- In the short term, coal/natural gas will be needed, and for long term, advances in geothermal and nuclear will enable a 100% renewable grid.

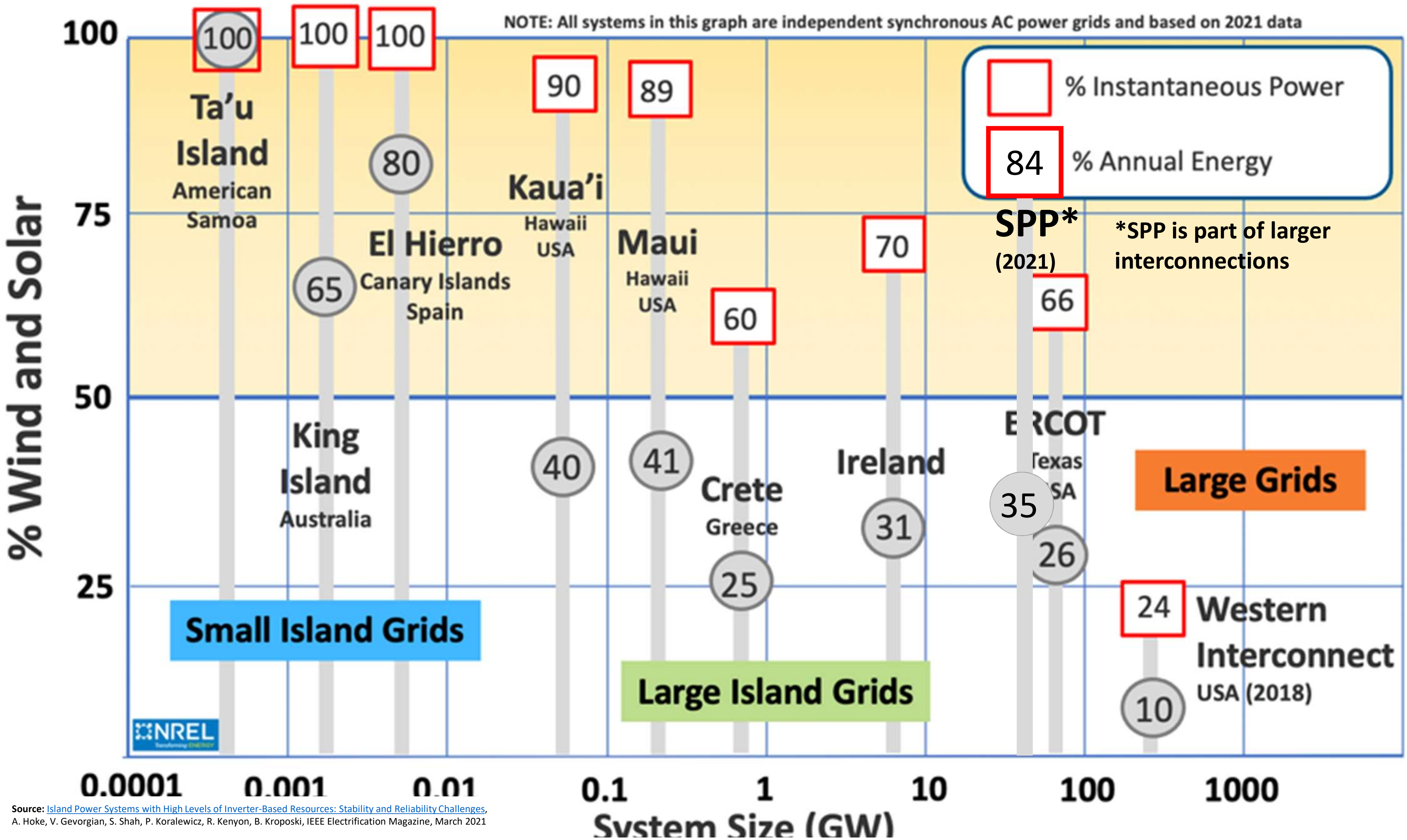
- <u>Note</u>: a 100% renewable energy grid is possible with today's technologies; some communities use 100% renewable energy grids


Joule CellPress

Article

Quantifying the challenge of reaching a 100% renewable energy power system for the United States

Wesley J. Cole,[1,3,*] Danny Greer,[1] Paul Denholm,[1] A. Will Frazier,[1] Scott Machen,[1] Trieu Mai,[1] Nina Vincent,[1] and Samuel F. Baldwin[2]



Source: Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges, A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. Kenyon, B. Kroposki, IEEE Electrification Magazine, March 2021

Energy system of the future and Decarbonization

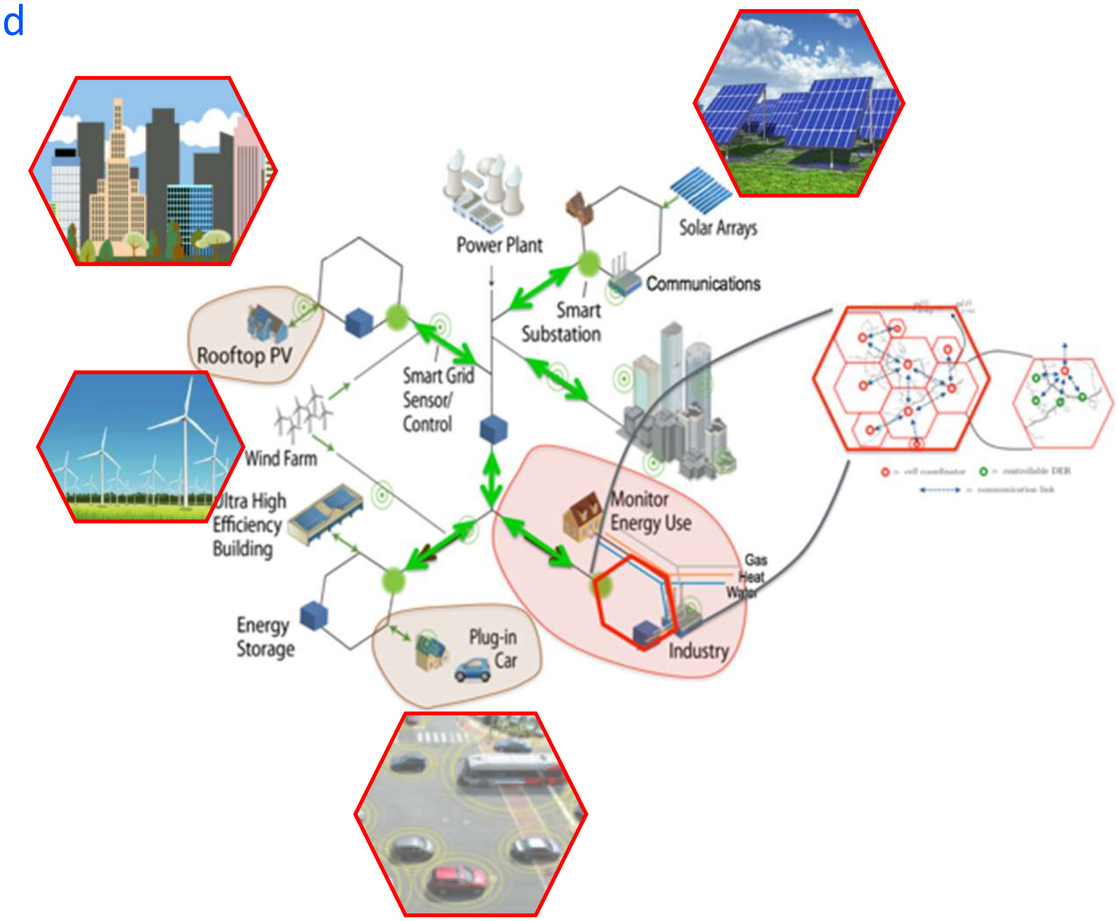
- Diverse power generation sources (inverter-based grid) -*High penetrations of wind and solar*

- Electrification –transportation, industry
  - Grid interactive buildings/communities
  - Different Storage technologies (*time scales)*
  - *Mobility…connectivity*

- Autonomous control of millions of devices
  - storage, distributed energy resources, smart appliances, EVs…

- Cyber and physical security, reliability, resilience

- **Low carbon fuels**: marine, rail, air
  - **Hydrogen infrastructure**
  - Carbon Capture, Storage
  - CO_2 conversion: Chemicals, materials, **fuels**



GRID…Office of Electricity, EERE…*examples*

Storage, Transmission…

National Transmission Planning Study

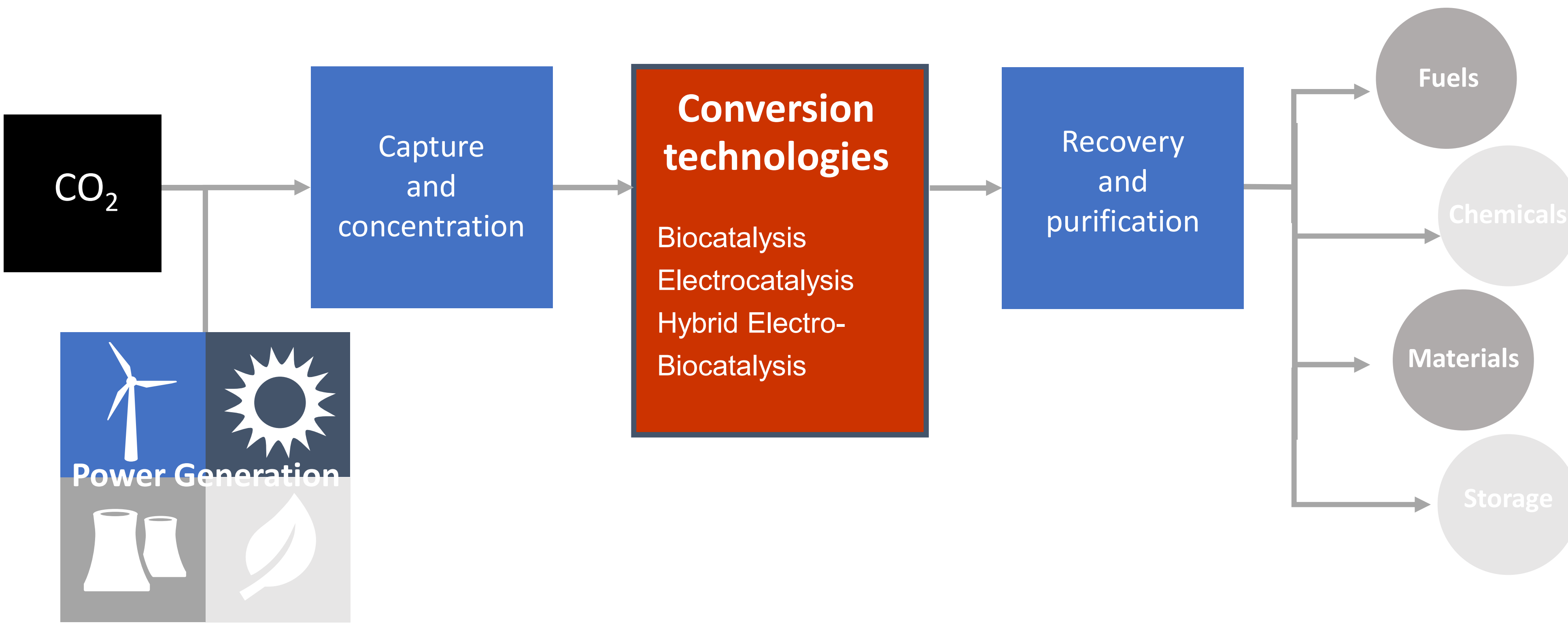
Office of Electricity

Building a Better Grid: $2.5B Transmission Facilitation Program

Grid Modernization Lab Consortium

The Grid Modernization Laboratory Consortium (GMLC) was established as a strategic partnership between DOE and the national laboratories.

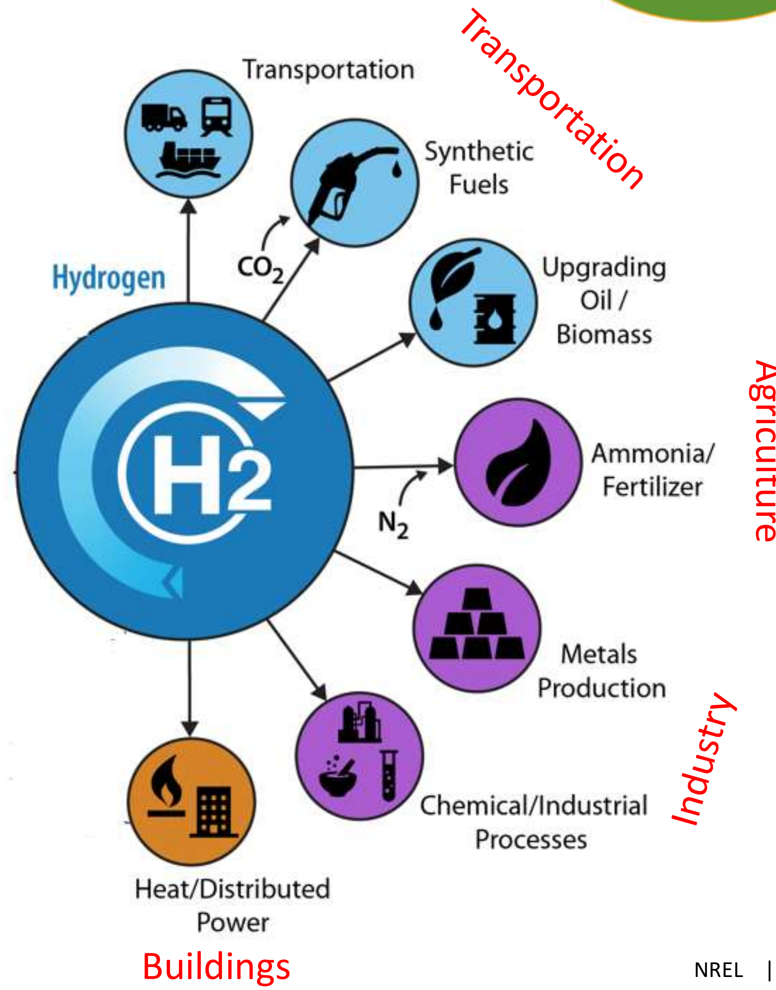
Utilizing Cheap, Abundant Electrons to Add Value to CO_2



Expand Green Hydrogen into New End-Use Cases

- There are many **end-use cases** that are hard to decarbonize with renewable power and batteries alone
- Expand hydrogen usage into **hard-to-decarbonize industrial sectors** (such as for metals production, and ammonia for fertilizer and energy storage/transport)
- Support H2-integrated **electrons-to-molecules (E2M)** research pathways, such as making net-zero-CO_2 chemicals and liquid fuels *(EXAMPLE on next slide: Biomethanation)*
- **Seasonal storage of renewable power** through hydrogen enables large penetrations to be achieved that are not possible through batteries alone
- Requires engagement and large-scale investment with these **new partners** through cost-shared public-private partnerships and demonstrations to prove value

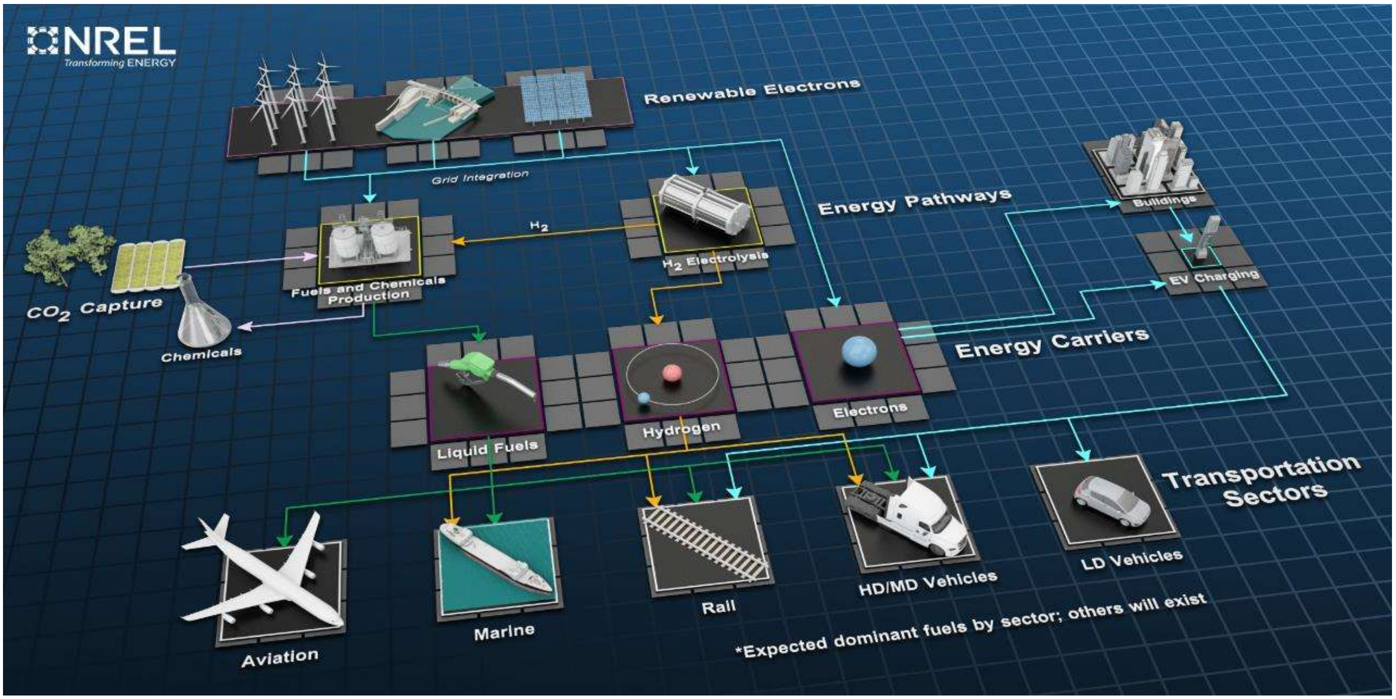
Expanding Green Hydrogen Into New End-Use Cases

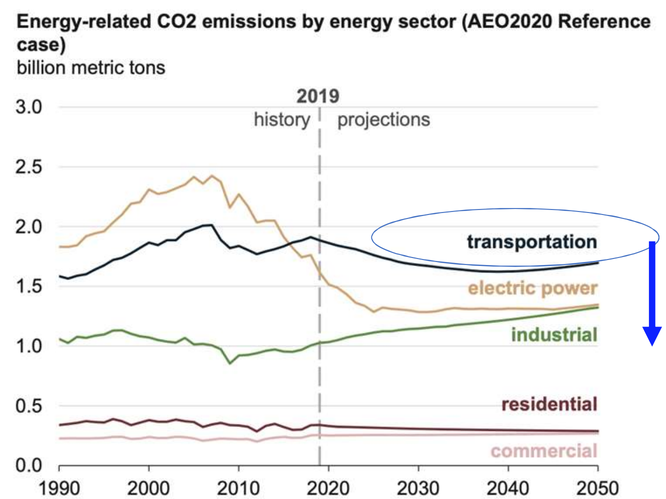


ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

NREL Decarbonization Strategy: transportation

whole system-integration approach will be key to decarbonizing transportation, shaping mobility

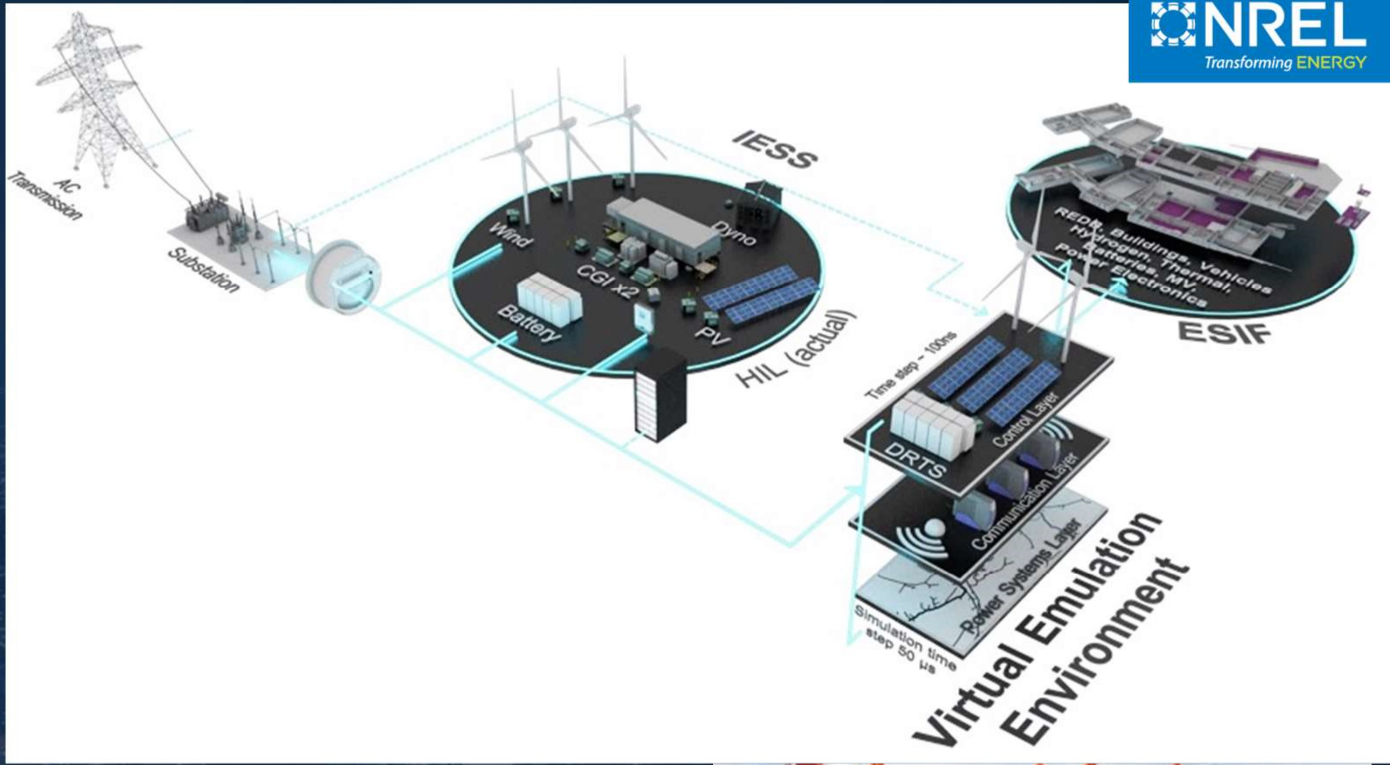




Vehicle electrification, hydrogen, low carbon fuels

ARIES

Advanced Research on Integrated Energy Systems



ARIES is a research platform developed by the National Renewable Energy Laboratory and DOE's Office of Energy Efficiency and Renewable Energy.

A research platform that can support the nation's transition to a decarbonized energy system.

Mitigating risk, vulnerability, and expense to the electric grid and customers.

Administration's and EERE Energy Goals

2035

Carbon-free U.S. electricity generation

2050

Net zero greenhouse gas (GHG) emissions—including transportation, buildings, industry, and agriculture

Environmental Justice

Diversity, equity, and inclusion for energy jobs, manufacturing, and supply chain all over the United States

OUTLINE

I. NREL –strategic directions

II. The future energy system

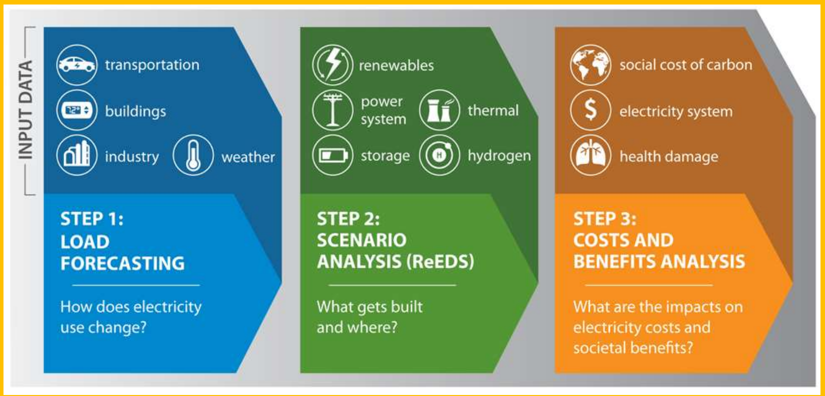
III. Scenarios and pathways –100% carbon free electricity by 2035, and subsequently net zero emissions

IV. Power Generation and Storage: *a status*

V. Final Remarks

Potential Pathways

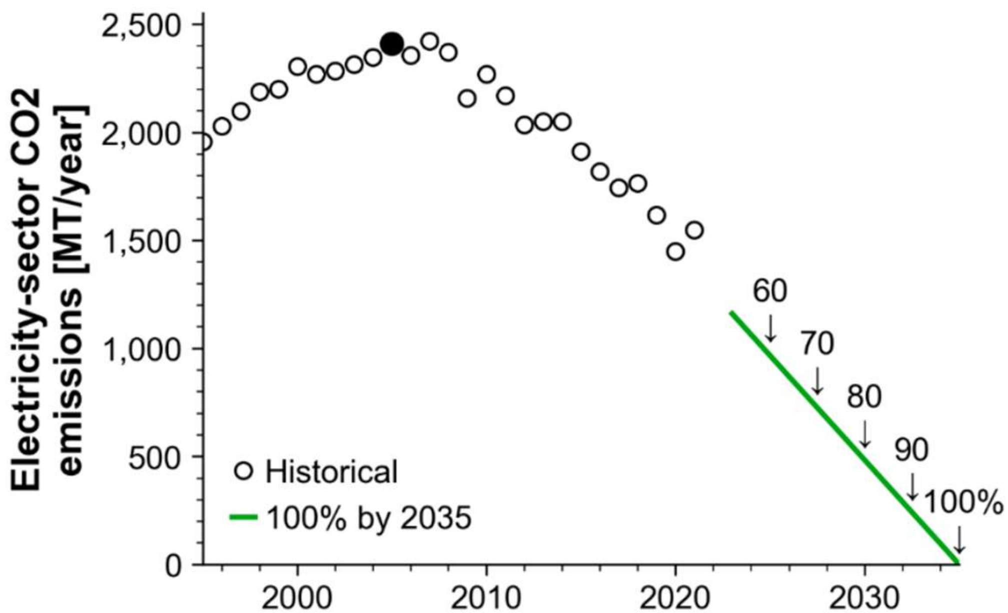
1. Electrify end-use technologies
2. Decarbonize the electric sector
3. Energy efficiency
4. Carbon capture, synthetic fuels



146 Scenarios were examined

Achieving 100% carbon free electricity by 2035

CO_2 reductions associated with achieving the 2035 carbon free electricity goal

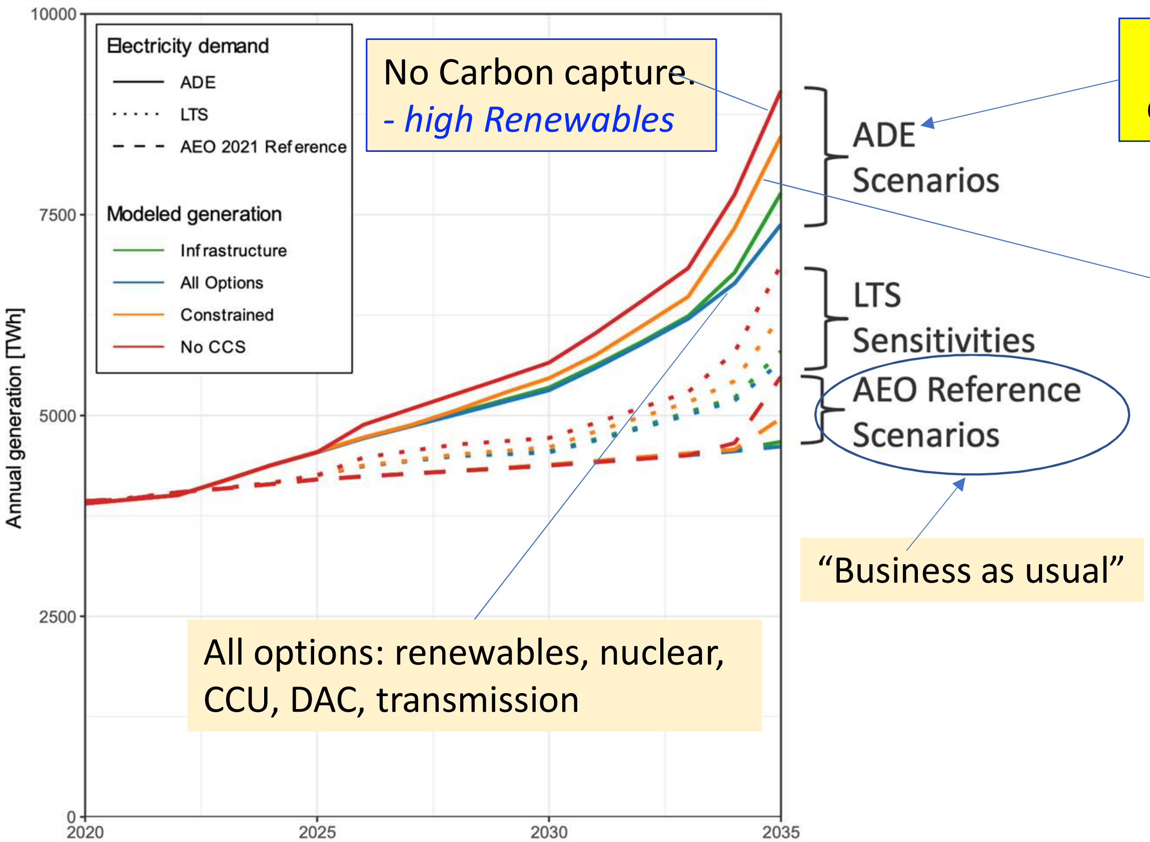


The green line represents the rate of carbon removal from the electricity sector required to reach the carbon free electricity goal by 2035

The model includes contributions from:

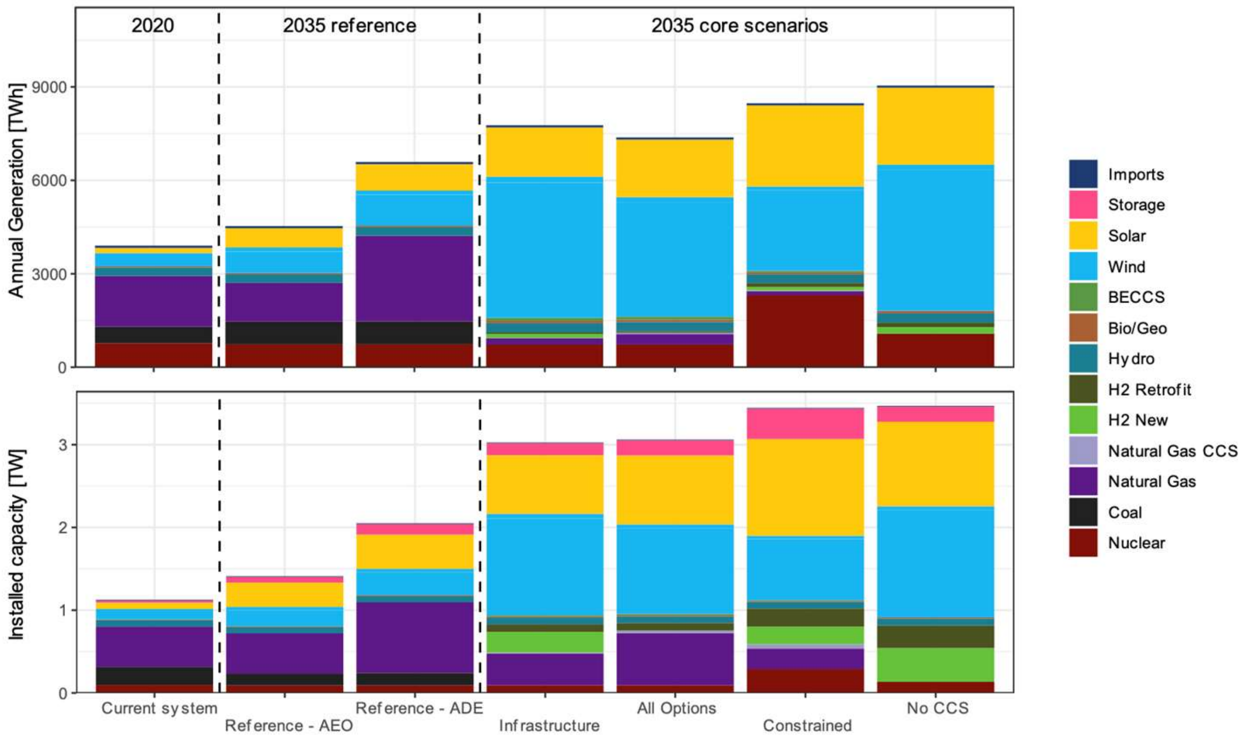
- direct combustion and global warming impacts
- methane leakage from natural gas production,
- used for electricity production
- used for hydrogen production

The projected increase in electricity generation based on different scenarios



For each scenario, the model accounts for losses

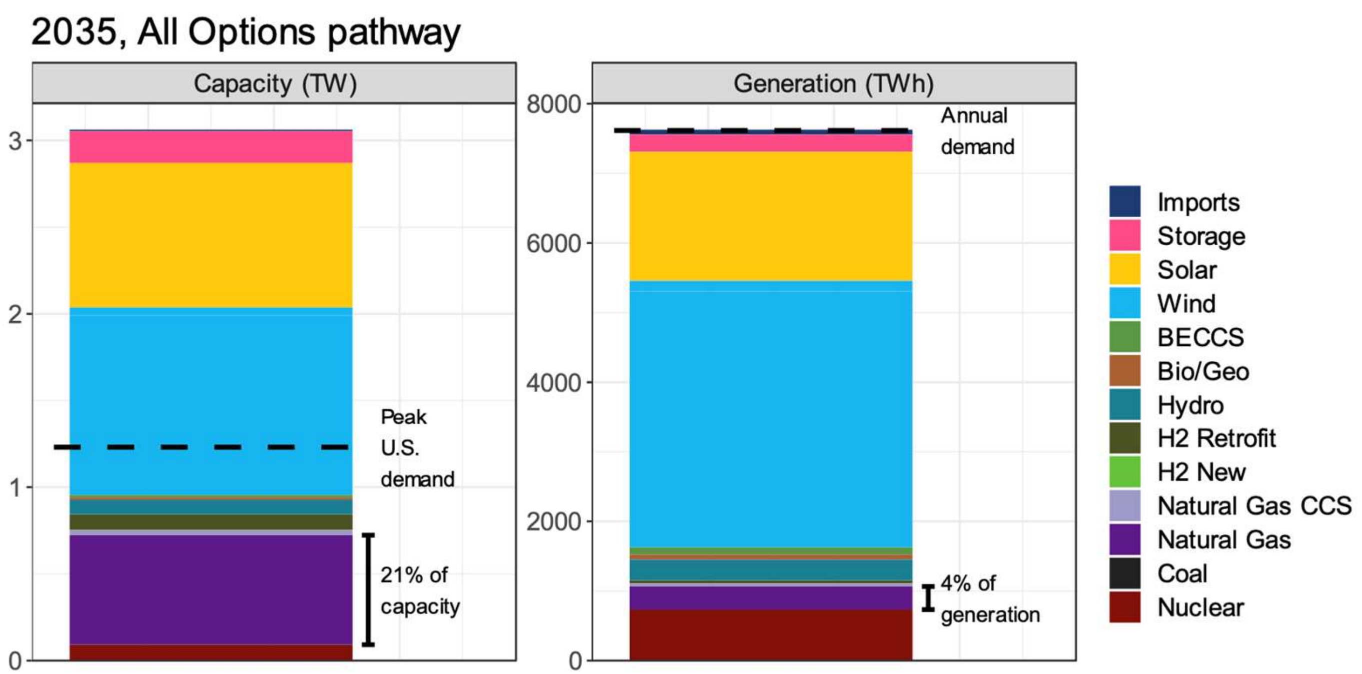
Technology Mix: Wind and Solar are most important in all scenarios (least cost assessment)



Wind and solar: 60%–80%
The wind and solar are sensitive to cost and transmission constraints.

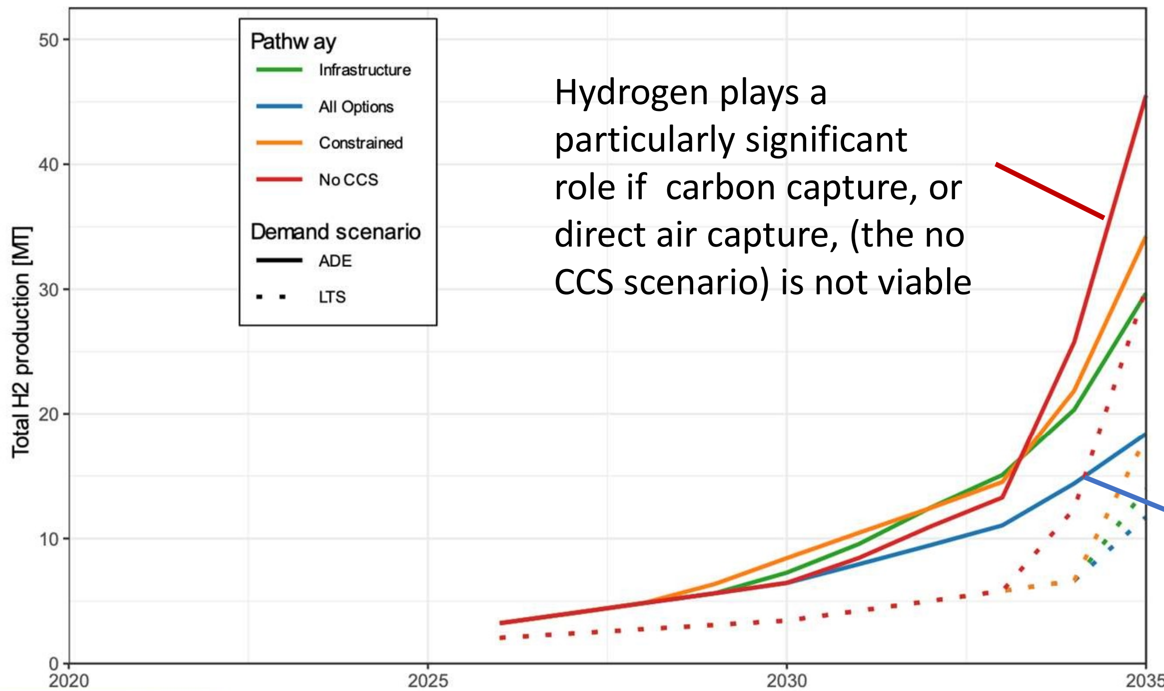
Nuclear provides 27% (Constrained scenario, but 9%–12% in the other three core scenarios)

As 100% clean electricity is approached, wind and solar will be dominant, though fossil is needed



- Fossil needed to ensure peaking capacity and resource adequacy on warm summer afternoons and cold winter days
- Electrification of space heating substantially increases peak demand in the winter, during periods of lower solar output
- BECCS and DAC will offset the CO_2 from the fossil use

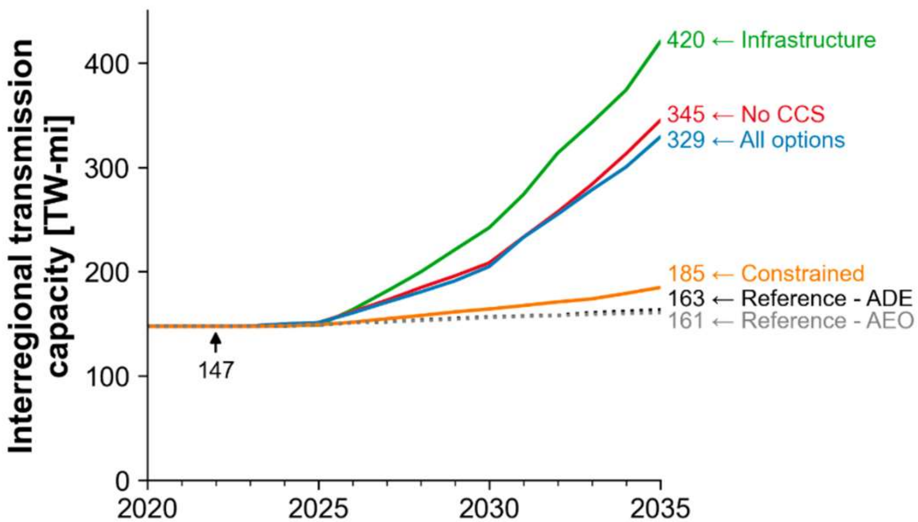
Hydrogen plays an important role toward meeting the clean energy goals



Hydrogen plays a particularly significant role if carbon capture, or direct air capture, (the no CCS scenario) is not viable

In contrast, for the ”all options” scenario, other technology advances contribute toward the clean energy goals

Interregional Transmission Capacity increases significantly, regardless of the scenario

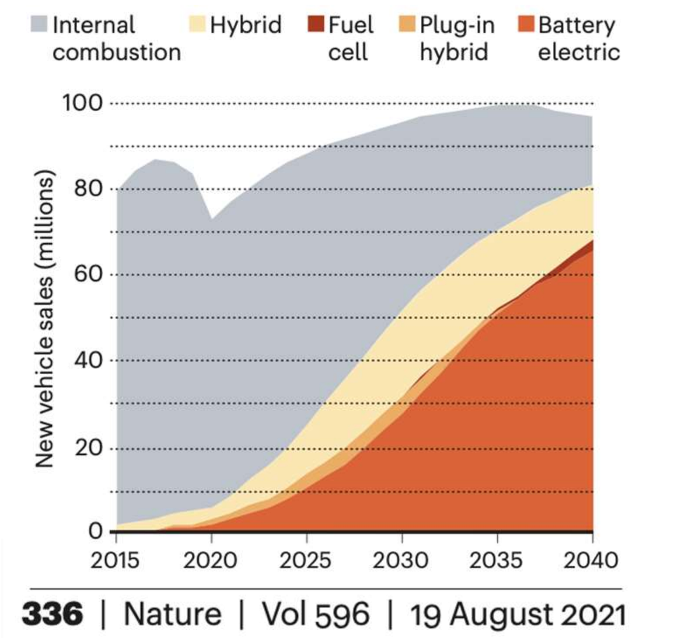


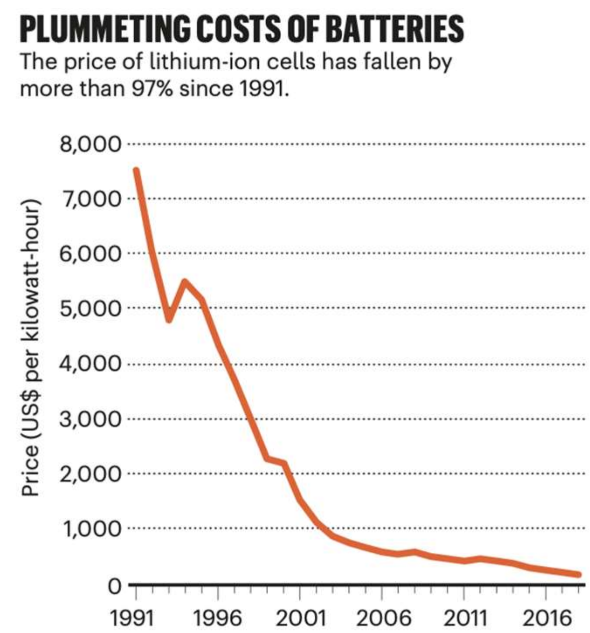
Transmission is major enabler

- Enables access to higher-quality renewable energy resources
- Better resource utilization
- reduced curtailment
- Mitigates the variability of electricity demand and variable supply across large regions across various timescales.
- Improved reliability by expanding electricity imports and exports and enhancing coordination across larger regions.

Storage and Power Generation

EV SALES INCREASE & BATTERY COSTS DECREASE

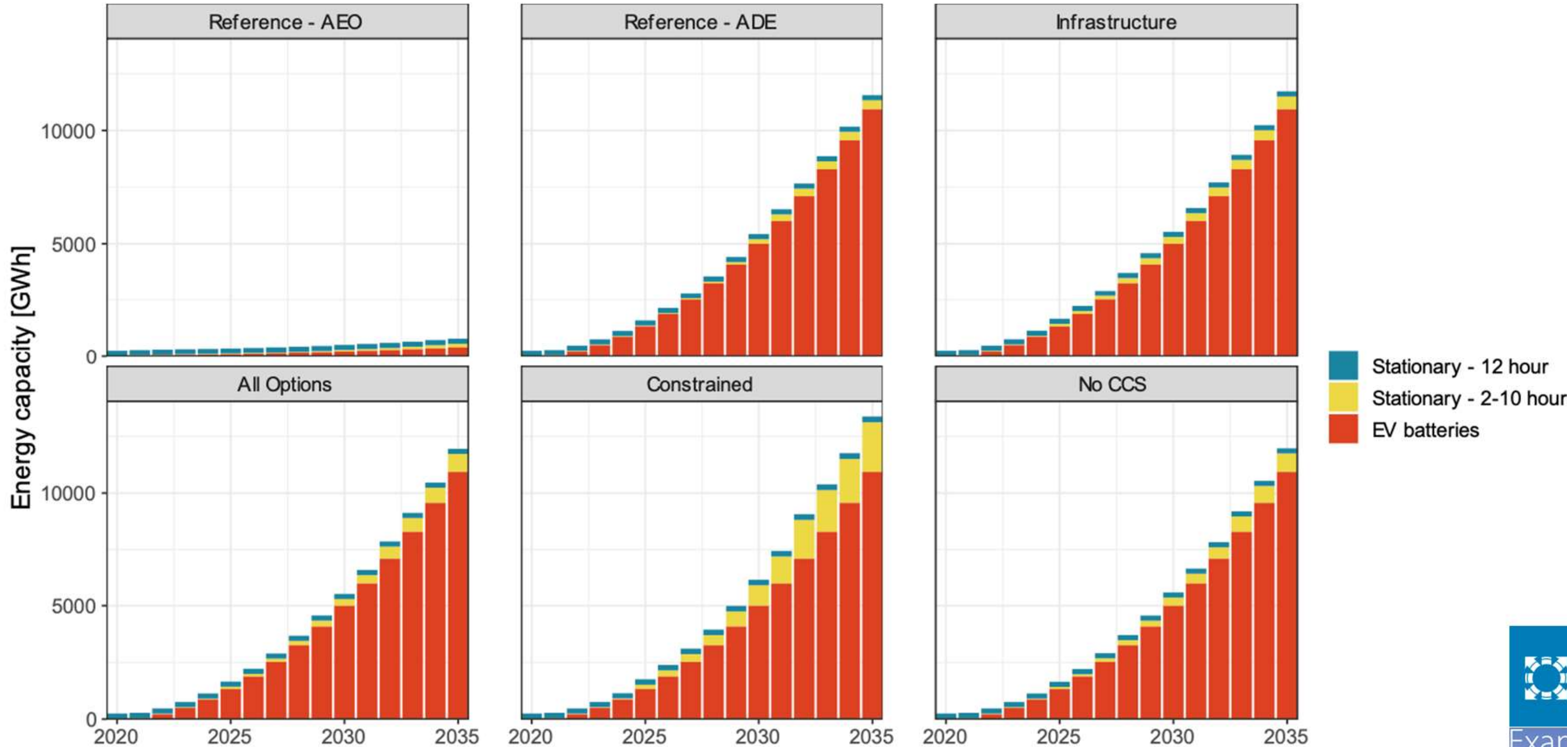




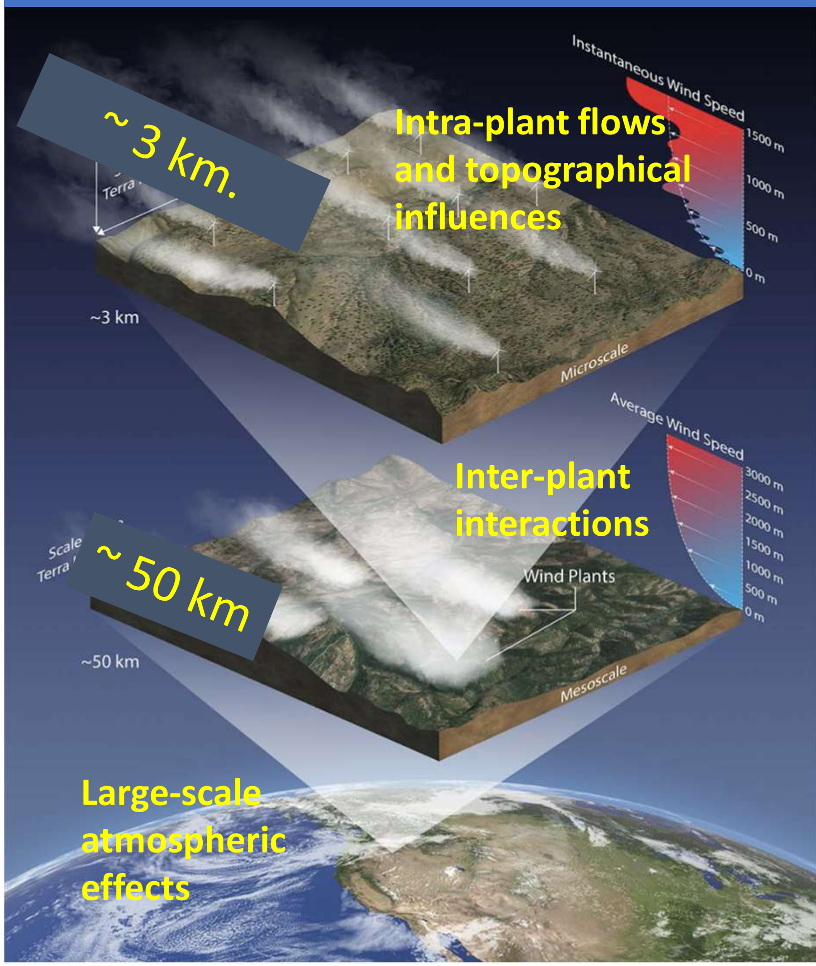
DOE Vehicle Roadmap GOAL:

- Cost of electric vehicle Battey packs <$100/KWh by 2028 to achieve parity with ICE vehicles
- the number of territories with ICE Phase Out dates continues to rise (i.e. California by 2035)

EVs are the main drivers for growth in storage

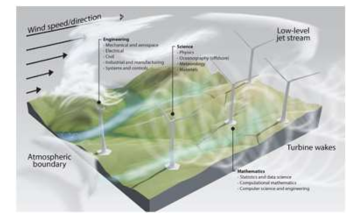


Wind energy Community knows how to meet future demands



Grand challenges

- Optimizing wind farm power production:
  - New physics associated with atmospheric resource and wind plant flow



- Off-shore wind power:
  - aerodynamics,
  - structural dynamics and
  - fluid dynamics

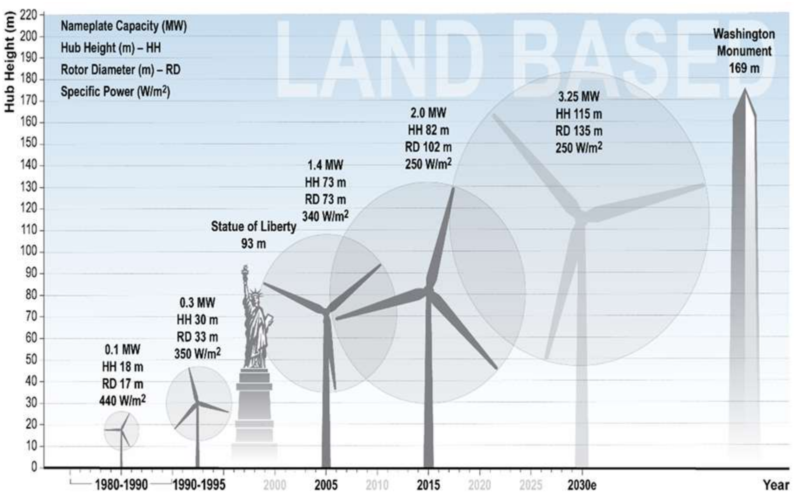
- Grid integration


Science REVIEWS

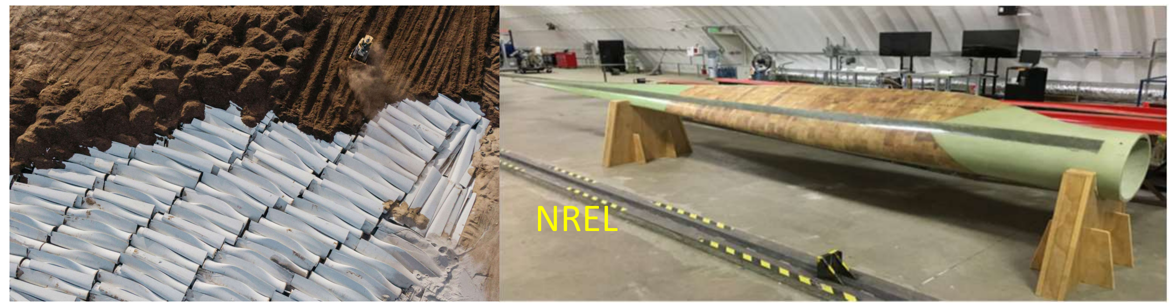
Cite as: P. Veers *et al.*, *Science* 10.1126/science.aau2027 (2019).

Grand challenges in the science of wind energy

Wind Energy Capacity (2030)~1.3 to 2.6 capacity (2022)



Circular Economy solutions



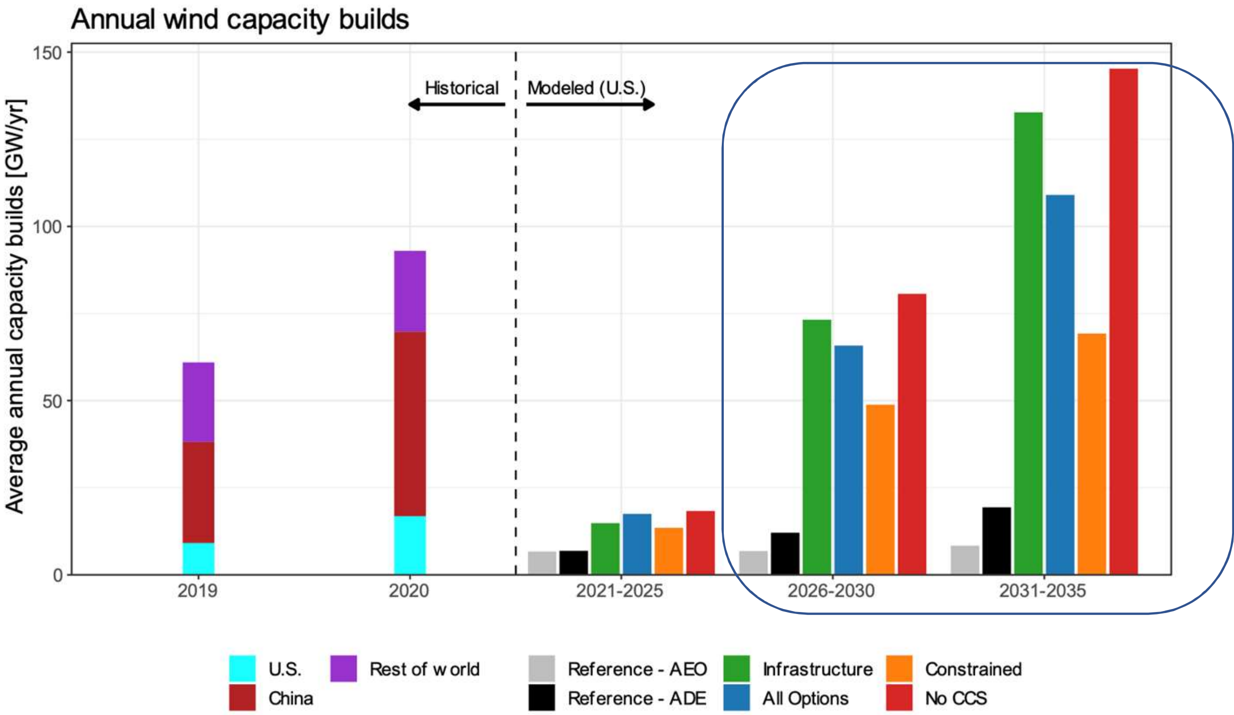
additive manufactured mold at NREL Renewable Energy 131 (2019) 111–119

- If the current funding levels remain constant, and the federal production tax credit (and investment tax credit) is allowed to expire, the goals will not be met.

- Aggressive technological and manufacturing advances will be required to meet the NREL mid projections of 400GW by 2030.

Annual Projected Growth Rate of Installed Wind Capacity

Wind *Resource potential of 4TW*
We need 1 TW



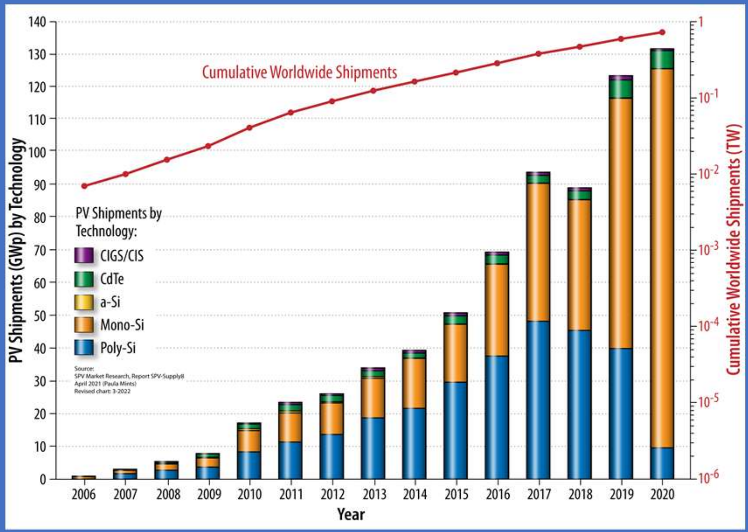
Average installation rate (2026-2035) 60 GW/year

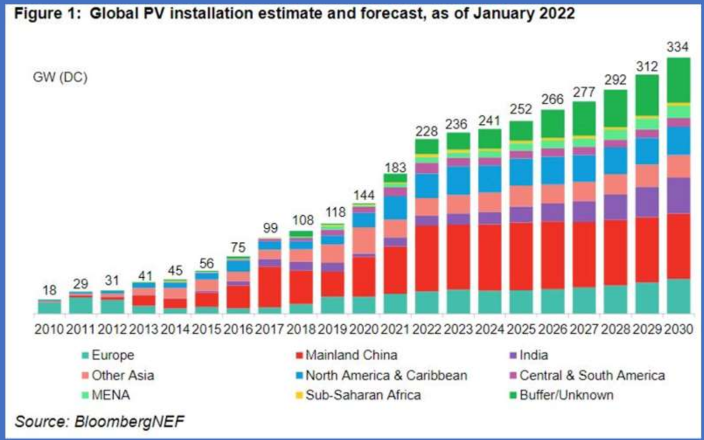
“All options” scenario its 88 GW/year

this is 6 time the installation in the US in 2020

NREL Transforming ENERGY
Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035

1 TW of solar power this year!

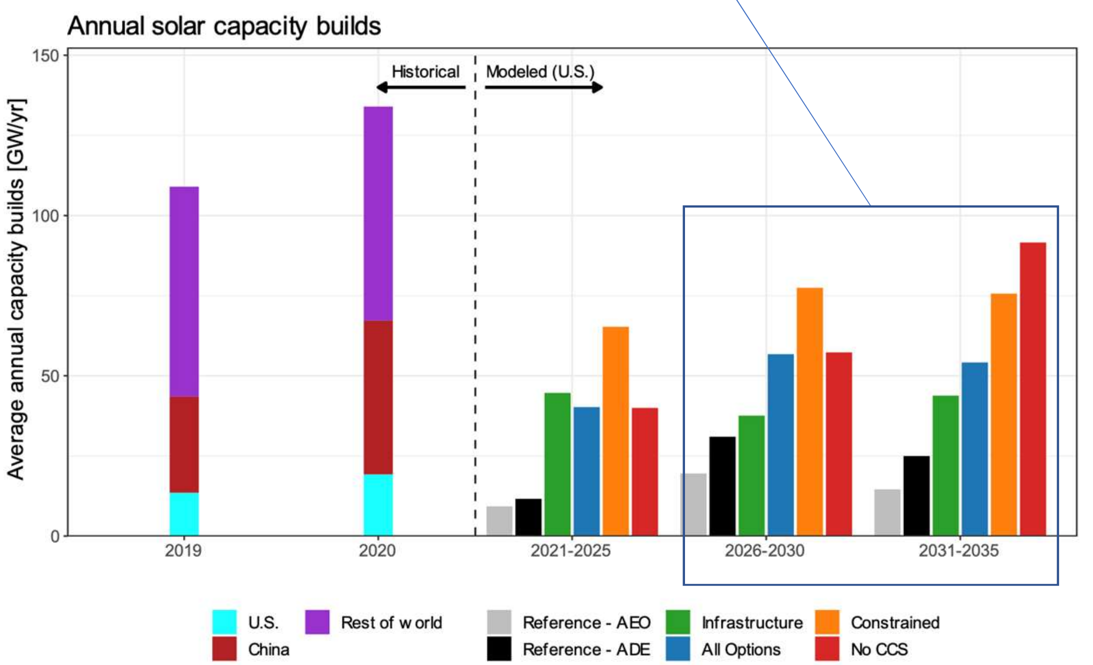




Projected Annual Installation of Utility Scale and Rooftop Solar

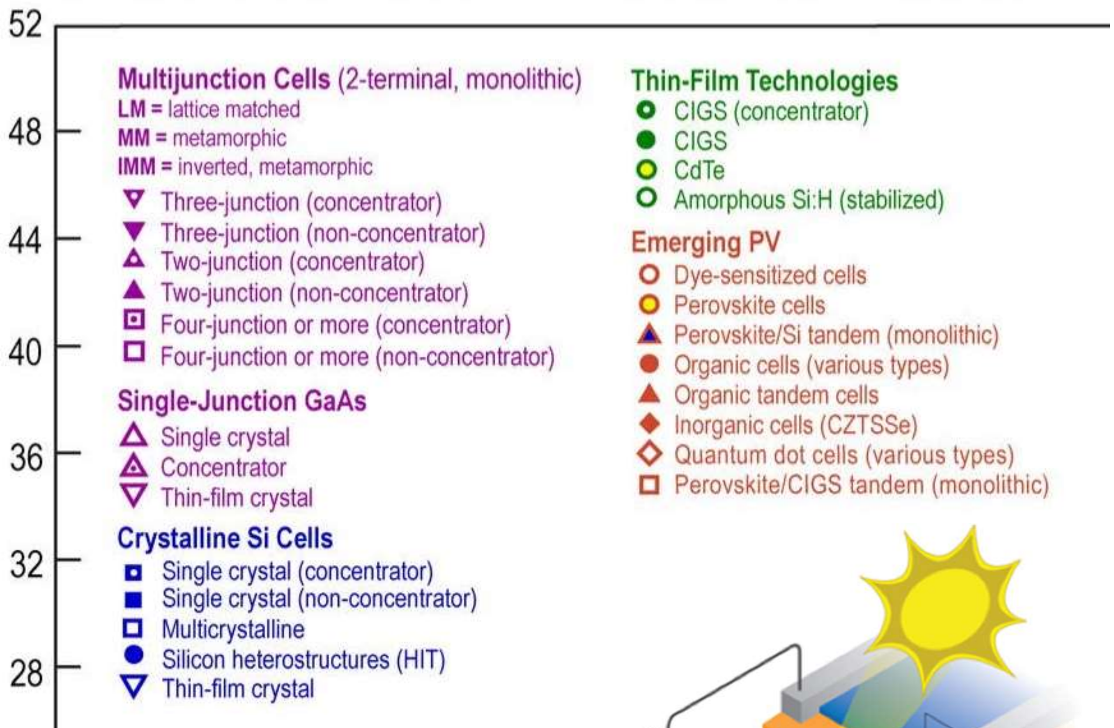
By 2035 PV contributes 20%– 36% of total electricity

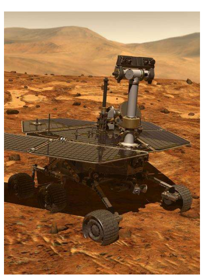
the average annual installation rate is ~40 GW/year (Range of 25 GW/year to 120 GW/year).

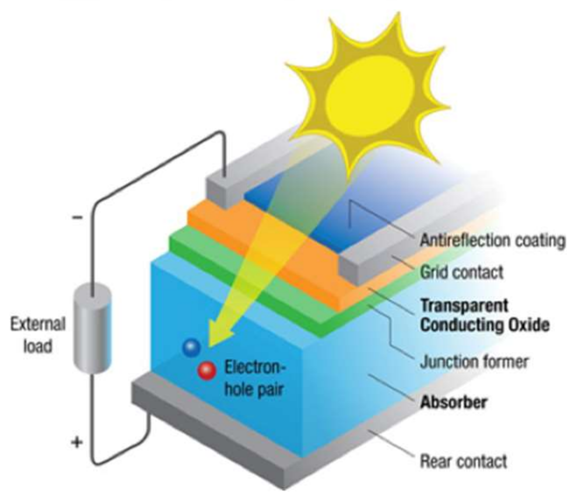


"All Options" scenario (56 GW) is nearly four times the U.S. installations in 2020 (15 GW—the highest to date)

photovoltaics=semiconductors





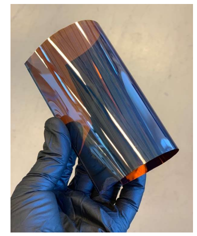


- **Challenges**
  - Dispatchability
  - Stability/durability
  - Existing electrical grid infrastructure

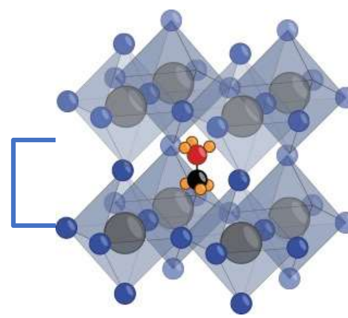
- **Research**:
  - Device physics
  - Quantum based approaches
  - **New materials**
  - System level issues
  - Specific Power = Power/Weight

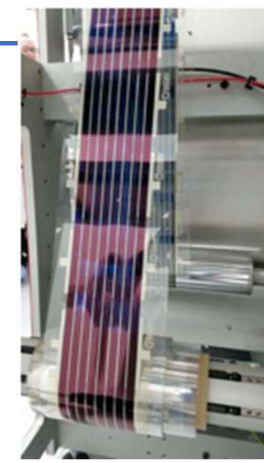
Metal Halide **Perovskites** (MHP) Semiconductors

- **Highly promising new PV material**
  - *Long term stability!*
- Domestic supply chain & manufacturing
  - Abundant materials
  - Opportunity for domestic tool manufacture
    - Additive manufacturing
    - High-speed manufacturing
    - Distributed and automated manufacturing



Scalable, *low capital cost*, domestic manufacturing based on smart materials and highly-skilled engineering workforce

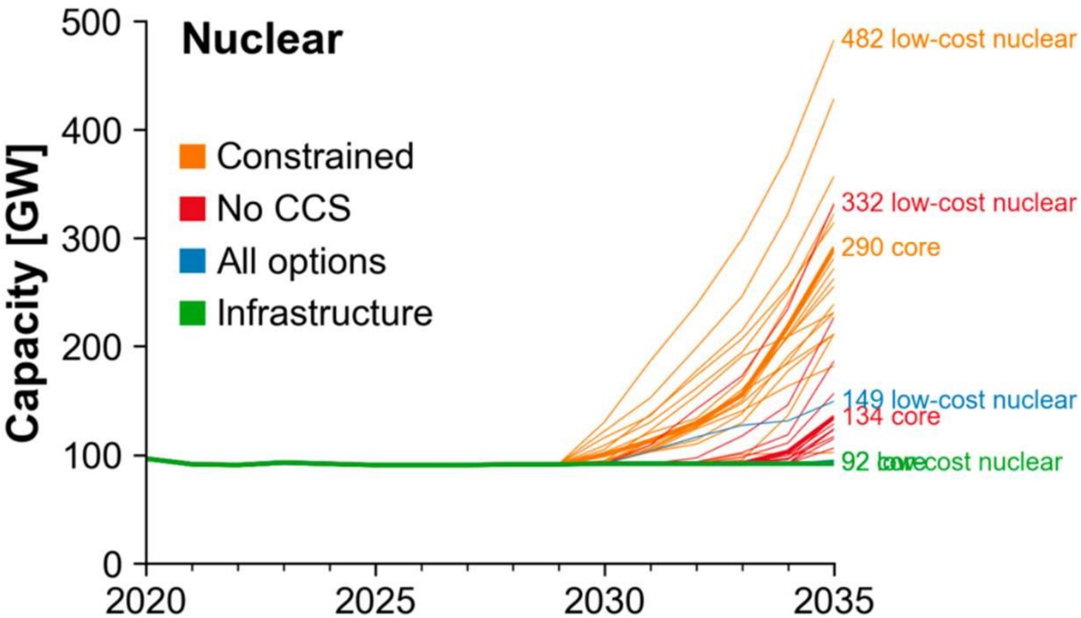




- Rapid commercialization to utility scale due to very low projected cost and capex intensity
- Scaling to Terawatts while US-manufactured
- Very high efficiency and can integrate with existing Si-PV technology

MHPs = Semiconductor Industry 4.0

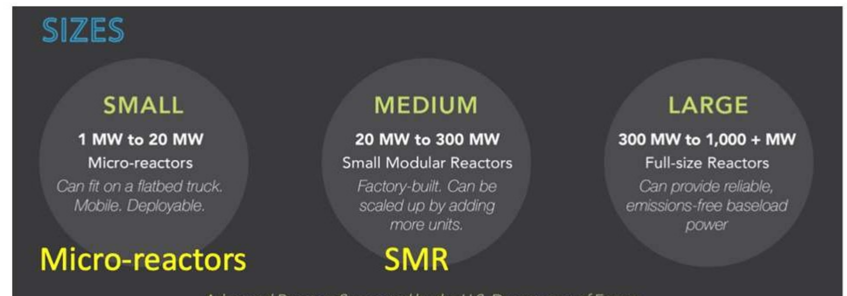
Growth of Nuclear –if VREs etc. are constrained



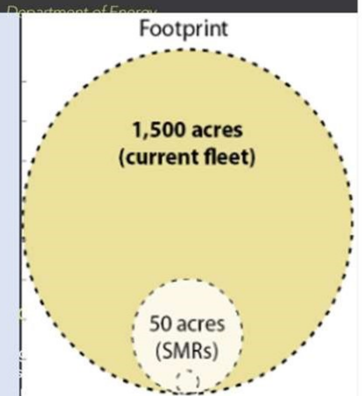
NREL Transforming ENERGY

Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035

Next Generation Nuclear Reactors



Microreactors and small modular reactors can be deployed to provide reliable energy where it is needed with a small footprint that allows for siting very near to the intended use.



Microreactor

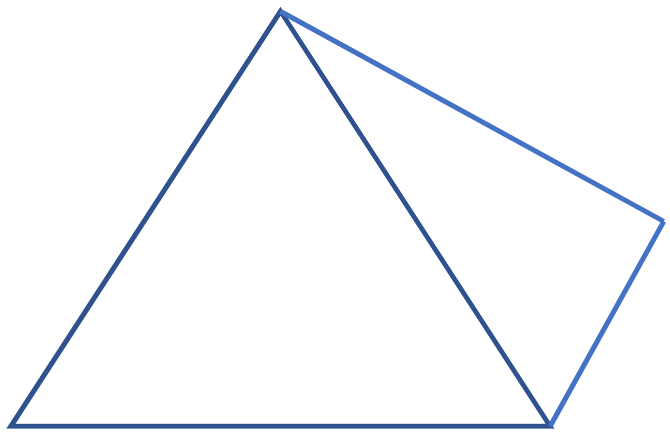
Final Remarks

- Numerous pathways, based on different scenarios, enable a future energy system, 100% RE
  a. Wind and solar power capacities will increase significantly
  b. Advances in geothermal and nuclear energy (surely by 2050) will have the added impact of eliminating the use of natural gas/coal

- New industries, manufacturing infrastructure, must be developed rapidly (H_2, carbon capture…) –deployment at scale

- All communities must be part of the solution –environmental justice (e.g.: LA 100, PR100)

Final Remarks



- Technological Advances, Markets, Investments, Policy/regulations
- Time from discovery to deployment must be accelerated
- New public-private-partnerships mechanisms

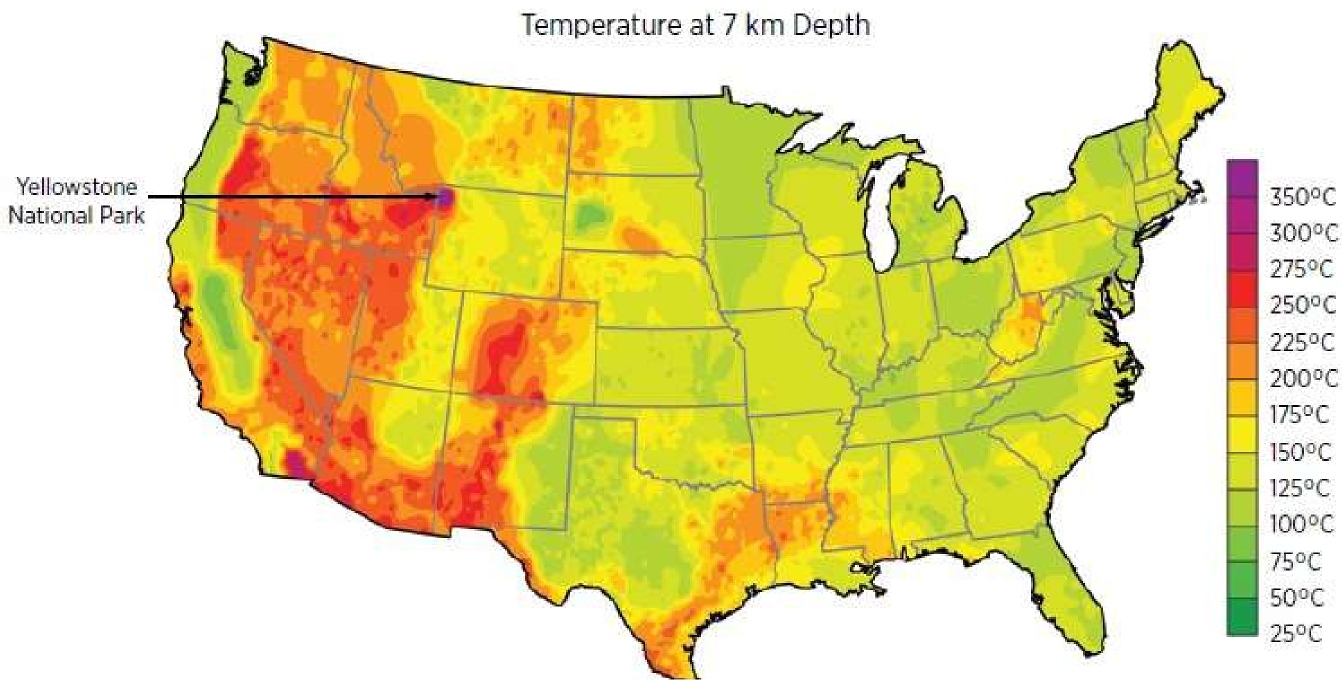

Thank you

Geothermal Energy in the United States

Technical Potential ≈ 4,200 GW_e

Economic Potential ≈ 60 GW_e

Thermal energy: Technical Potential ≈ 1200 GW_{th}



Temperatures throughout the contiguous United States at a depth of 7 km (about 4 miles). *Source: Geovision, 2019.*

Due to Geothermal's high capacity factor,

60 GW_e represents

8.5% (Currently 2.3 GW_e)

of U.S. electricity demand in 2050.

1200 GW_{th} represents

60% (Currently 16.8 GW_{th})

of the estimated heating/cooling and water heating demand in all U.S. buildings (2020).

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