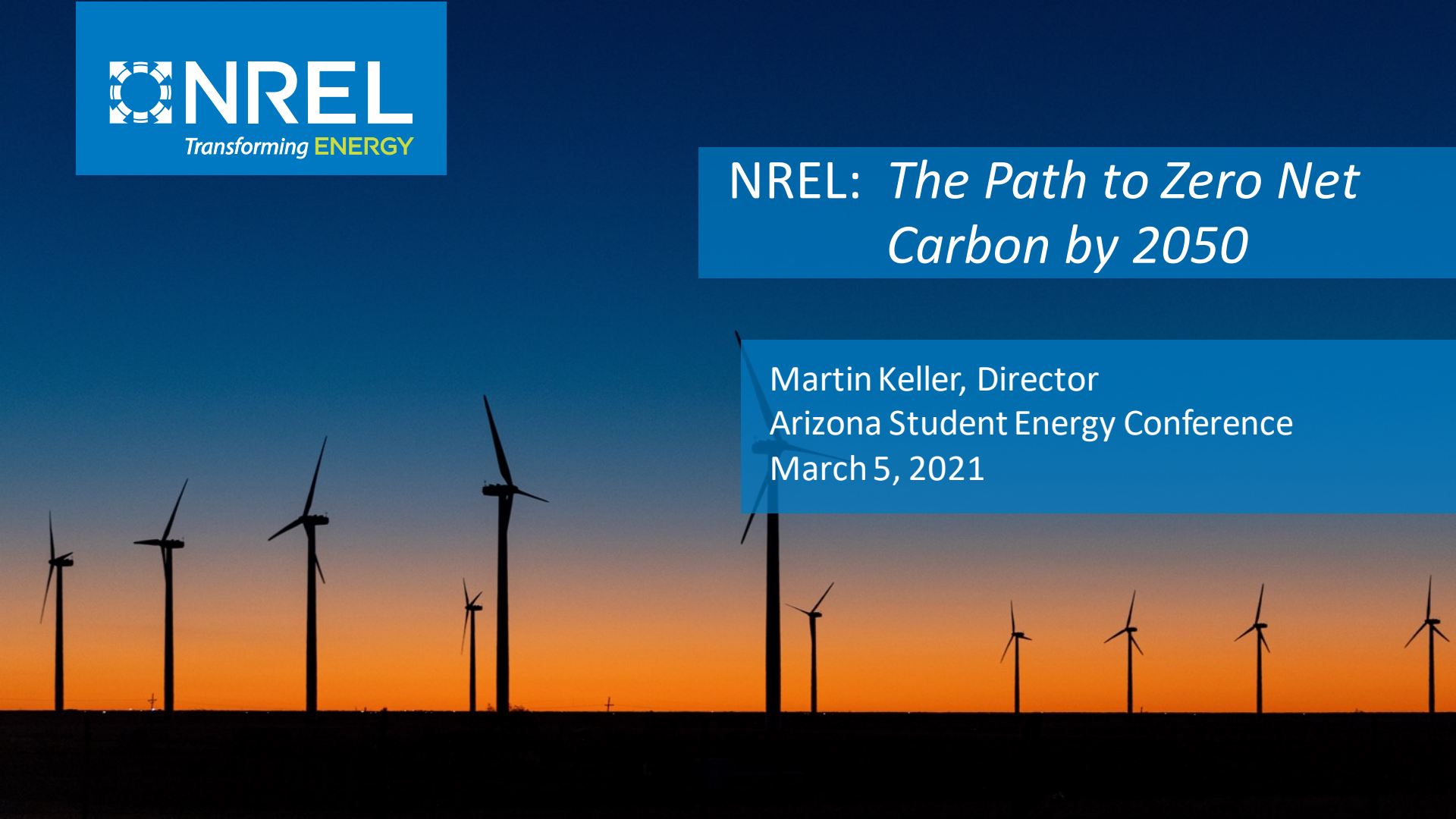


NREL: *The Path to Zero Net Carbon by 2050*

Martin Keller, Director
Arizona Student Energy Conference
March 5, 2021

ENERGY DISCOVERIES

Fire
Humans discover how to make fire

200,000 BC

Coal
Coal used for energy source

2000 BC

Natural Gas
Natural gas developed as an energy source

200 BC

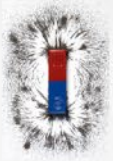
Water
Vertical water wheel invented

200 BC

Windmills
First windmills as energy source built

644

Electricity
Term first coined



1600s

Steam Engine
Creates transportation energy

1700s

Commercial Coal Mining
Begins in the U.S.

1748

Natural Gas Well
Natural gas well drilled

1821

Oil drilled
First oil well drilled

1859

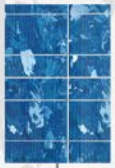
Windmill Electricity
Windmill generates electricity

1888

Nuclear Fission
Nuclear fission reaction built

1942

Silicon Solar Cell
Silicon solar cell developed



1954

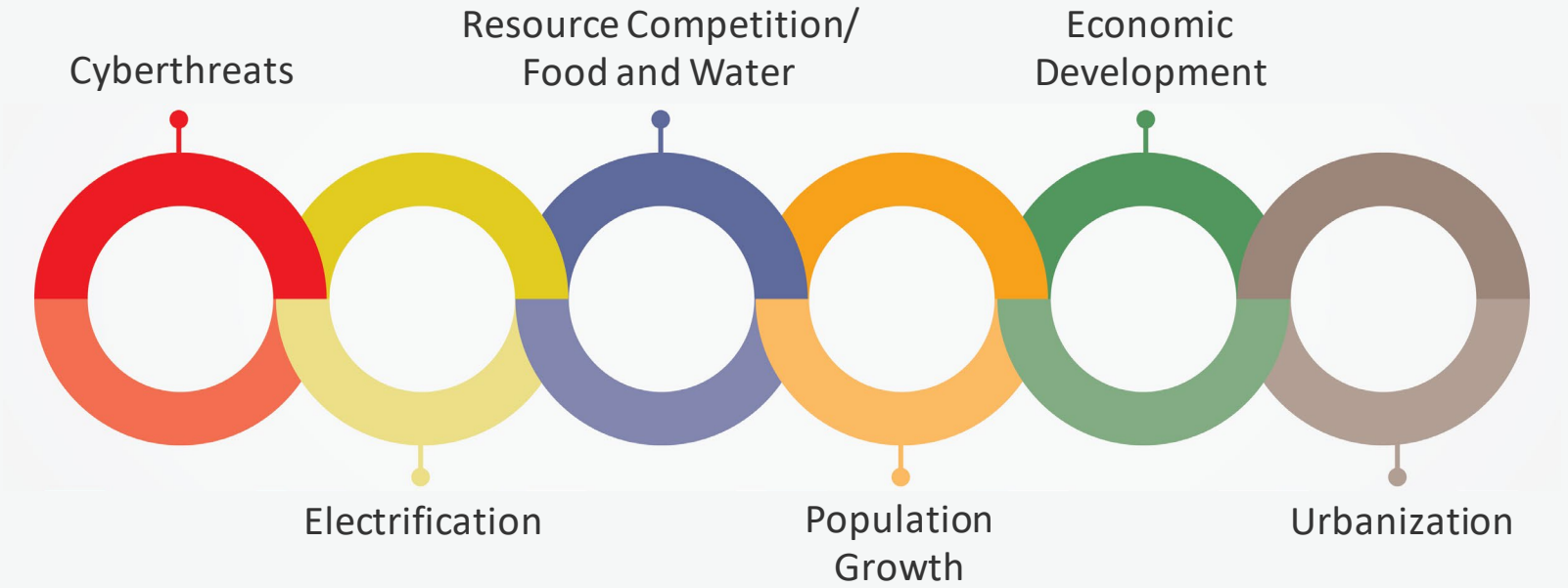
Wind Farm
First wind farm installed

1980

Fracking
Fracking becomes more common

1990s

Megatrends


Cyberthreats
Resource Competition/
Food and Water
Economic
Development
Electrification
Population
Growth
Urbanization

Population Growth

Food and Water

Urbanization

Mobility

Coast to Coast

The **17** National Laboratories have served as the leading institutions for scientific innovation in the United States for more than seventy years.

NREL Science Drives Innovation

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

NREL at-a-Glance

2,524

Workforce, including

216 postdoctoral researchers

62 graduate students

103 undergraduate students

World-class

facilities, renowned technology experts

More than 900

Partnerships

with industry, academia, and government

Campus

operates as a living laboratory

Solar Research

Areas of research include concentrating solar power, photovoltaics, grid integration, and market analysis.

Together these areas will enable reliable, low-cost solar energy at scale on the grid and beyond it.

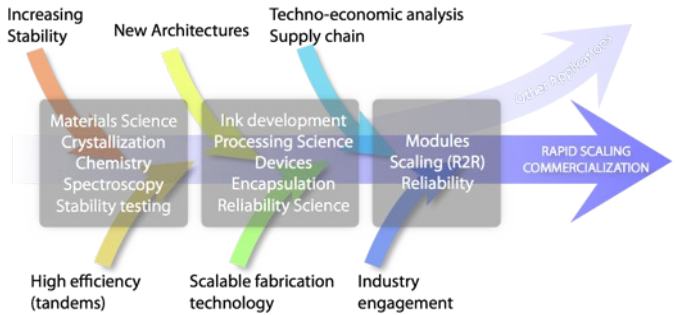
Research Challenges

- Integrate large amounts of solar energy into the power grid, while maintaining security and reliability and enhancing resilience.
- Improve the efficiency, lifetimes, and manufacturability of photovoltaic materials.
- Develop technologies for a third generation of concentrating solar power plants to further reduce costs and improve thermal storage capabilities.
- Capture surplus solar energy to provide heat and produce fuels and clean water.
- Create flexible, highly efficient solar cells that make low-cost power available without wires anywhere the sun shines
- Make solar an even better investment through work on bankability, reliability, and recyclability.

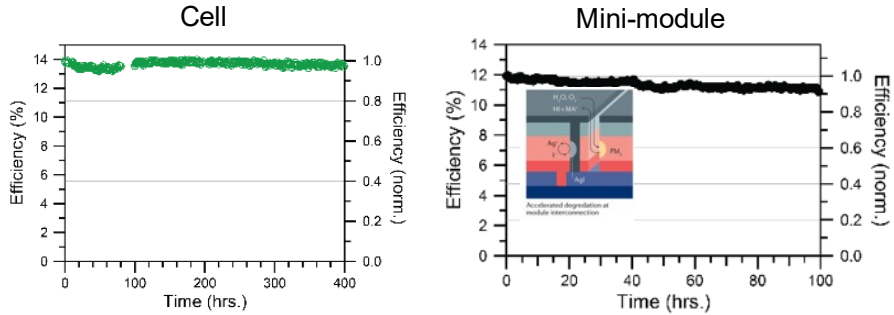
Solar Perovskite Research

NREL Addressing Commercialization Issues

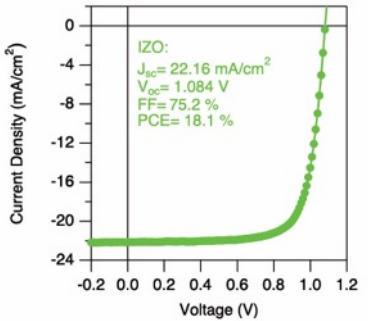
Perovskite Roadmap at NREL



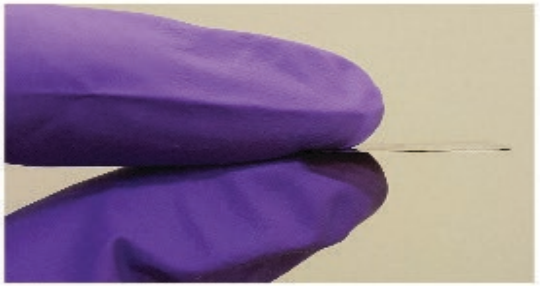
Understanding cell and module degradation



Record efficiencies



Record flexible ultralight device
Thickness <0.2mm ~148 mg/inch^2



Scalable deposition methods
– blade and roll-to-roll deposition

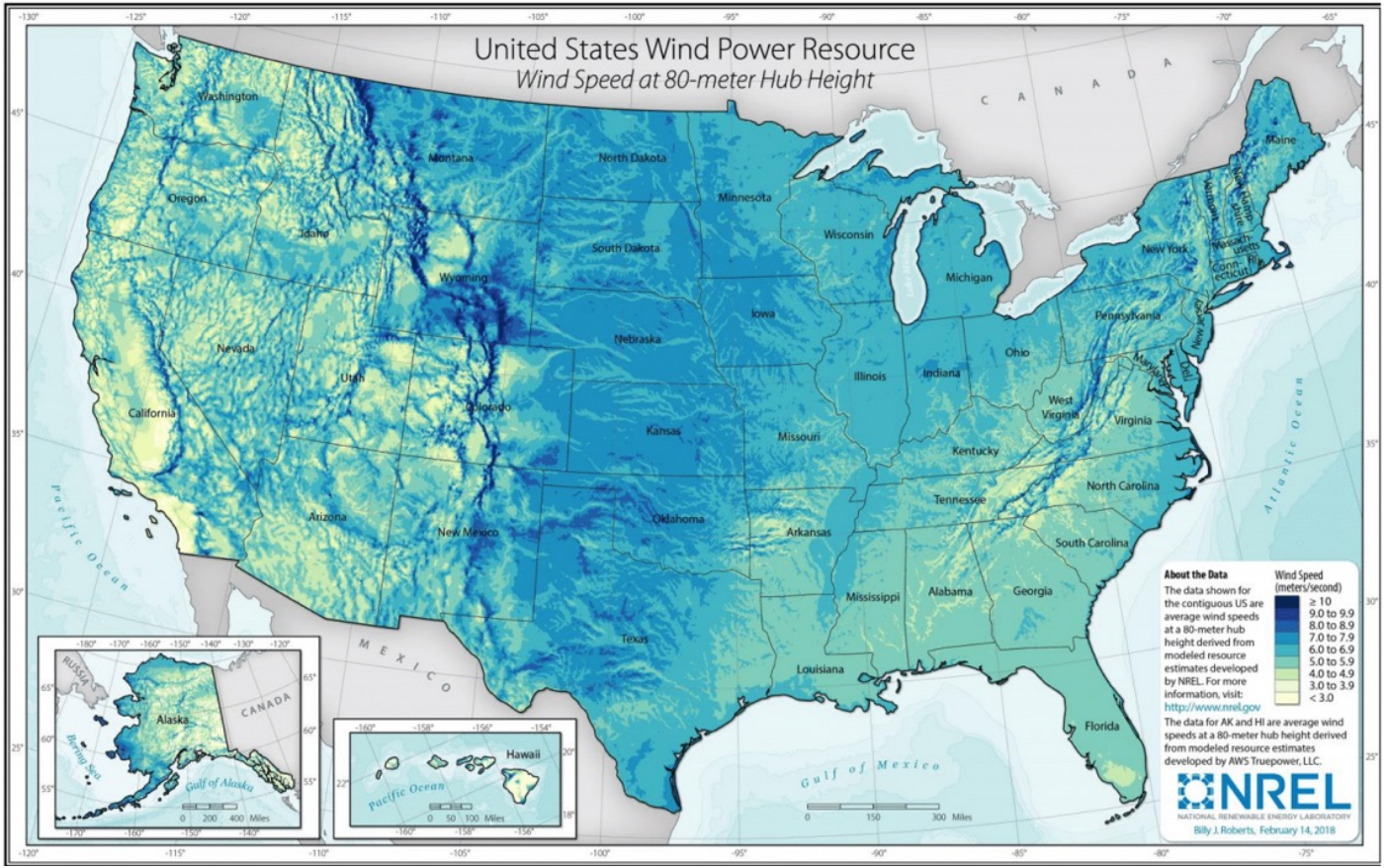
Wind Energy

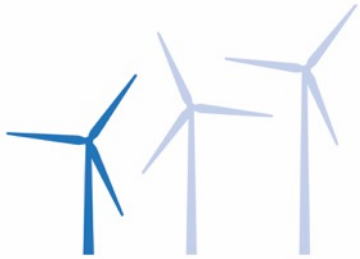
Enabling low-cost and grid-supporting wind energy by joining forces with DOE, industry, and interagency and state partners to advance scientific knowledge and technological innovation.

Research Challenges

- Validate multiple wind technologies at scale to achieve an integrated energy system that can meet the complex energy challenges of the future.
- Develop taller wind turbines with larger rotors to capture greater wind resources at higher elevations and lower the levelized cost of wind energy.
- Develop innovations for offshore wind such as floating platforms, scaling solutions for larger offshore designs, advanced turbine controls, and lightweight drivetrains.
- Optimize total power output across the entirety of a wind plant instead of at the individual-turbine level.
- Enable sustainable manufacturing through new materials and new manufacturing processes.

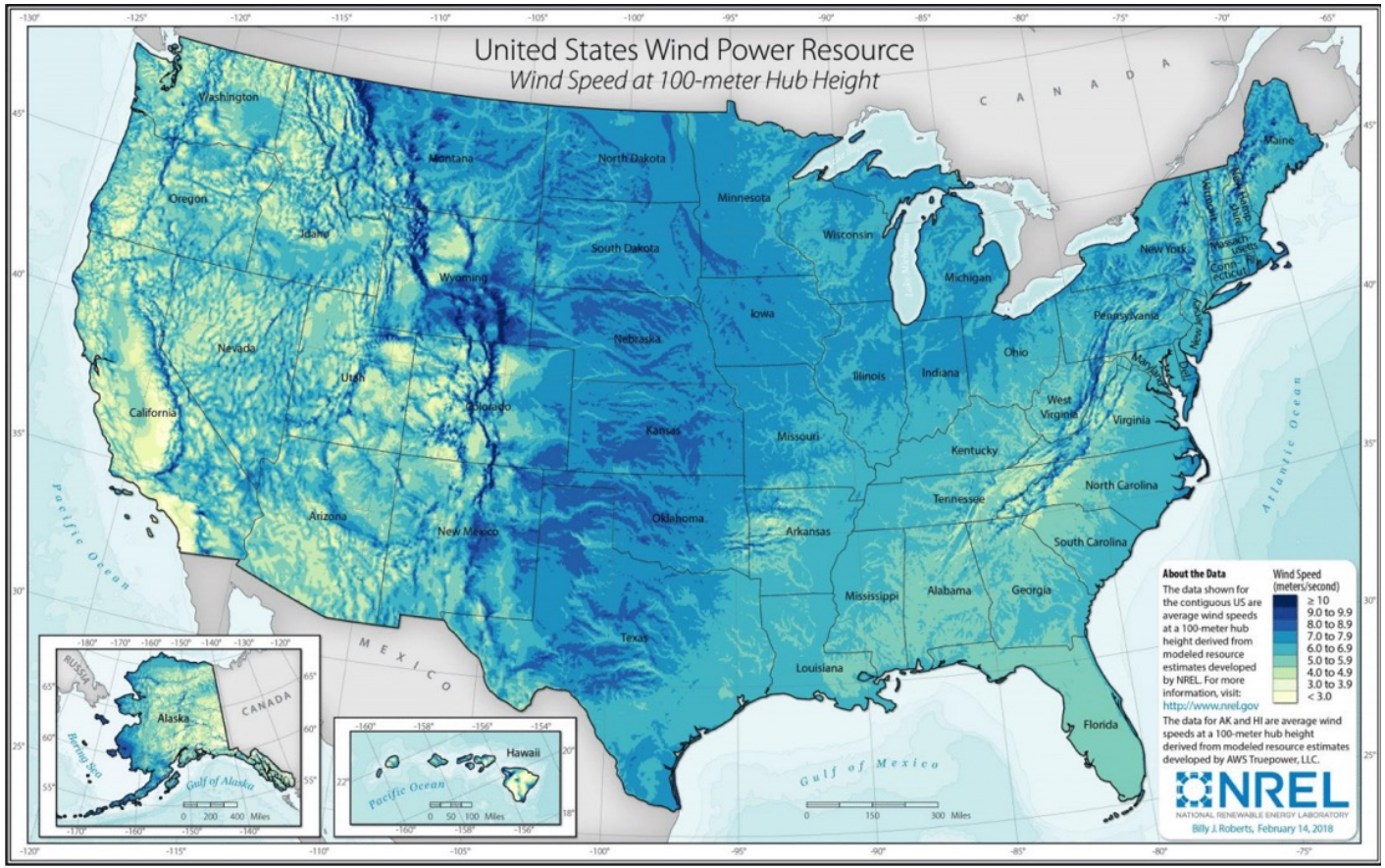
Wind Energy Potential Capacity at **80m Hub Height**





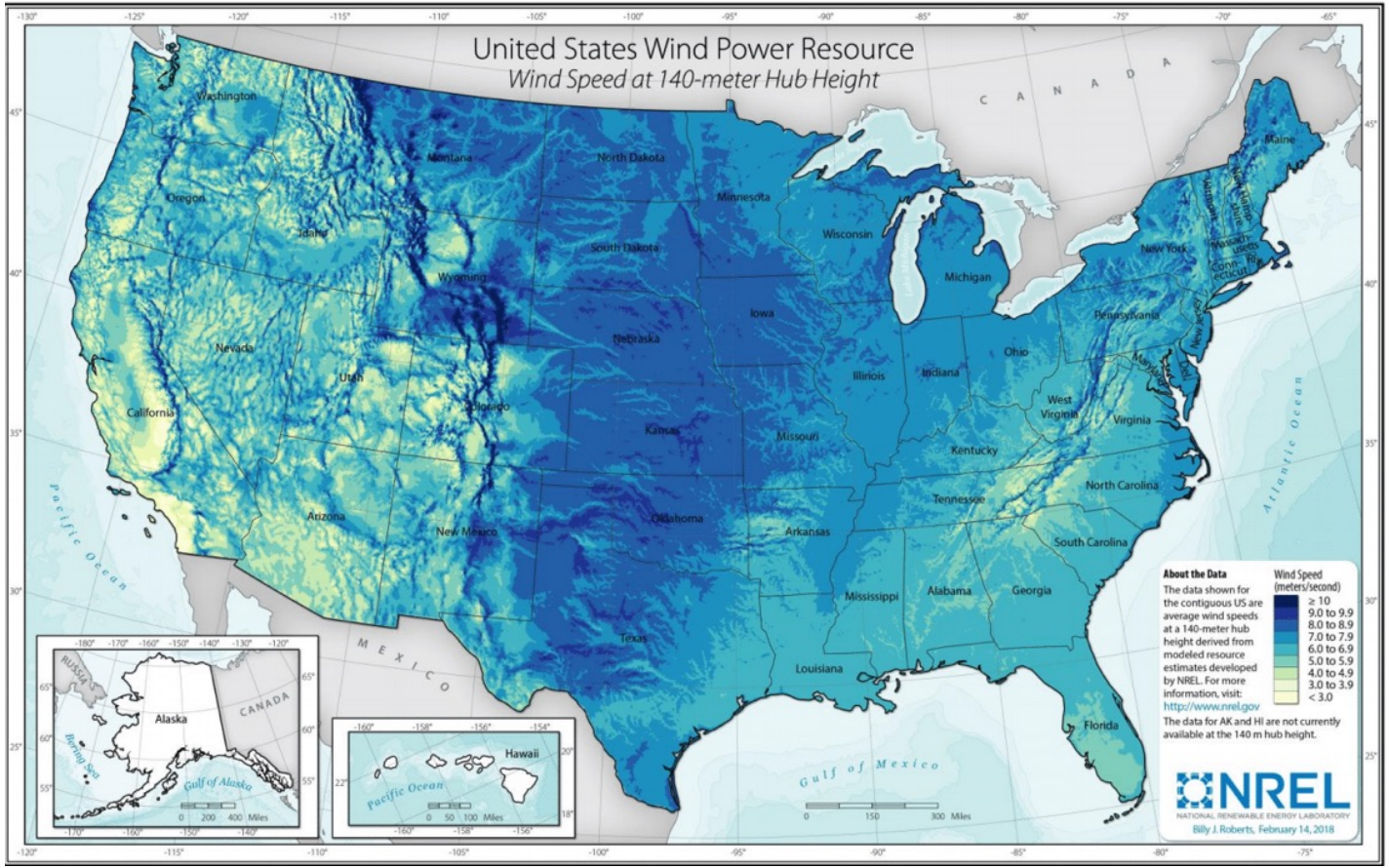
80m

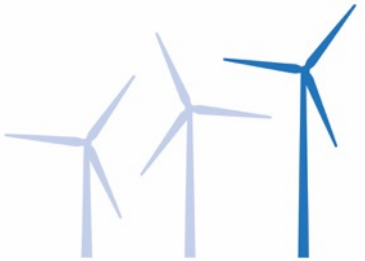
Wind Energy Potential Capacity at **110m Hub Height**



110m

Wind Energy Potential Capacity at **140m Hub Height**





140m

Energy Systems Integration Facility

Research Focus Areas

- Renewable electricity to grid integration
- Vehicle-to-grid integration
- Renewable fuels-to-grid integration
- Energy-water nexus
- High-performance computing, analytics, and visualization
- Large-scale numerical simulation
- Cybersecurity and resilience
- Smart home and building systems
- Microgrids
- Battery and thermal energy storage

Energy Security and Resilience

Now in its second year, NREL's Energy Security and Resilience (ESR) Center is implementing the strategic vision for a major lab-wide program that contributes to energy security and, more broadly, national security.

- Establishing NREL's role and presence through unique capability developments and publications
- Catalyzing energy security and resilience work in every NREL Center
- Identifying and attracting funding from new sponsors
- Engaging external advisors

Looking to the Future

Environmental Scan: Observations Toward 2040

Assumptions that Guided NREL's Strategy Formulation:

- Growth of energy use in the developing world will far outpace growth elsewhere.
- Global renewable power demand will grow.
- Urbanization trends will dominate new infrastructure growth.
- Electrification and electric vehicle adoption will grow strongly.
- Demand for high-density liquid fuels will grow.
- Digitization, data, decentralization will be strong drivers of energy transition.

NREL's Three Critical Objectives

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.

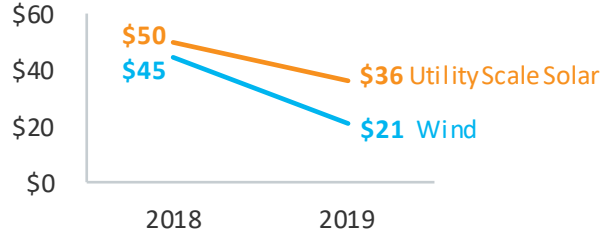
Circular Economy for Energy Materials

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

Costs for Renewables are Falling

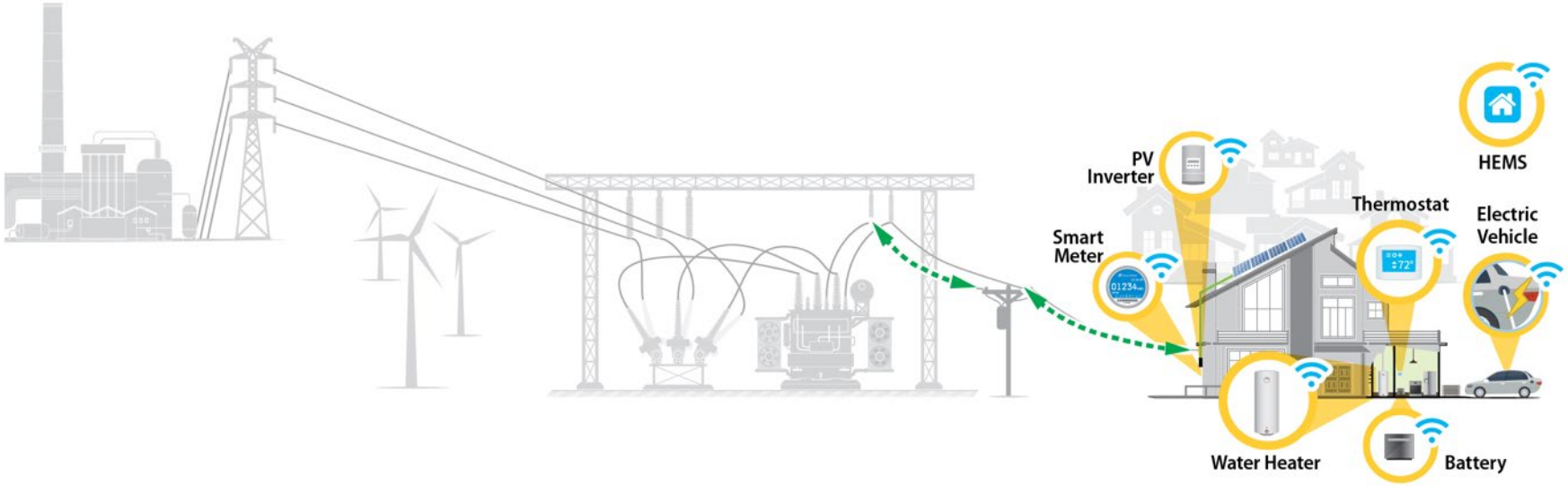
Advanced energy technologies are providing real-world solutions by:

- Becoming increasingly cost-competitive
- Boosting the U.S. energy industry
- Providing jobs for American workers



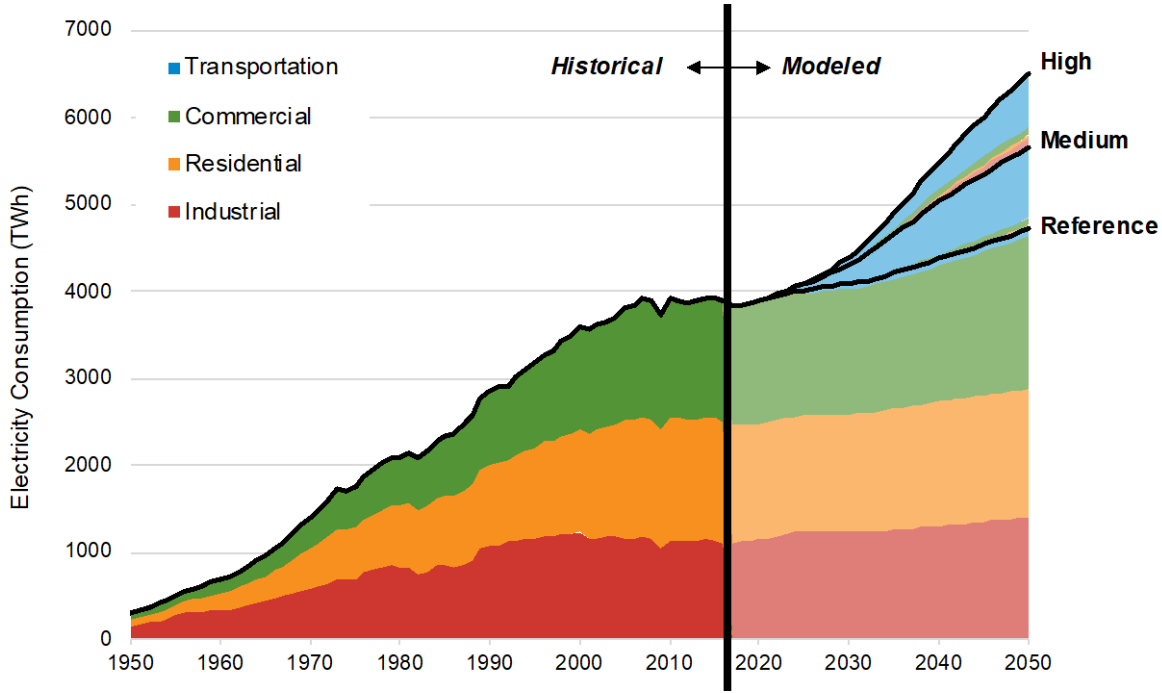
2019 Xcel pricing for projects due to go online in 2023

How We Use Electricity is Changing



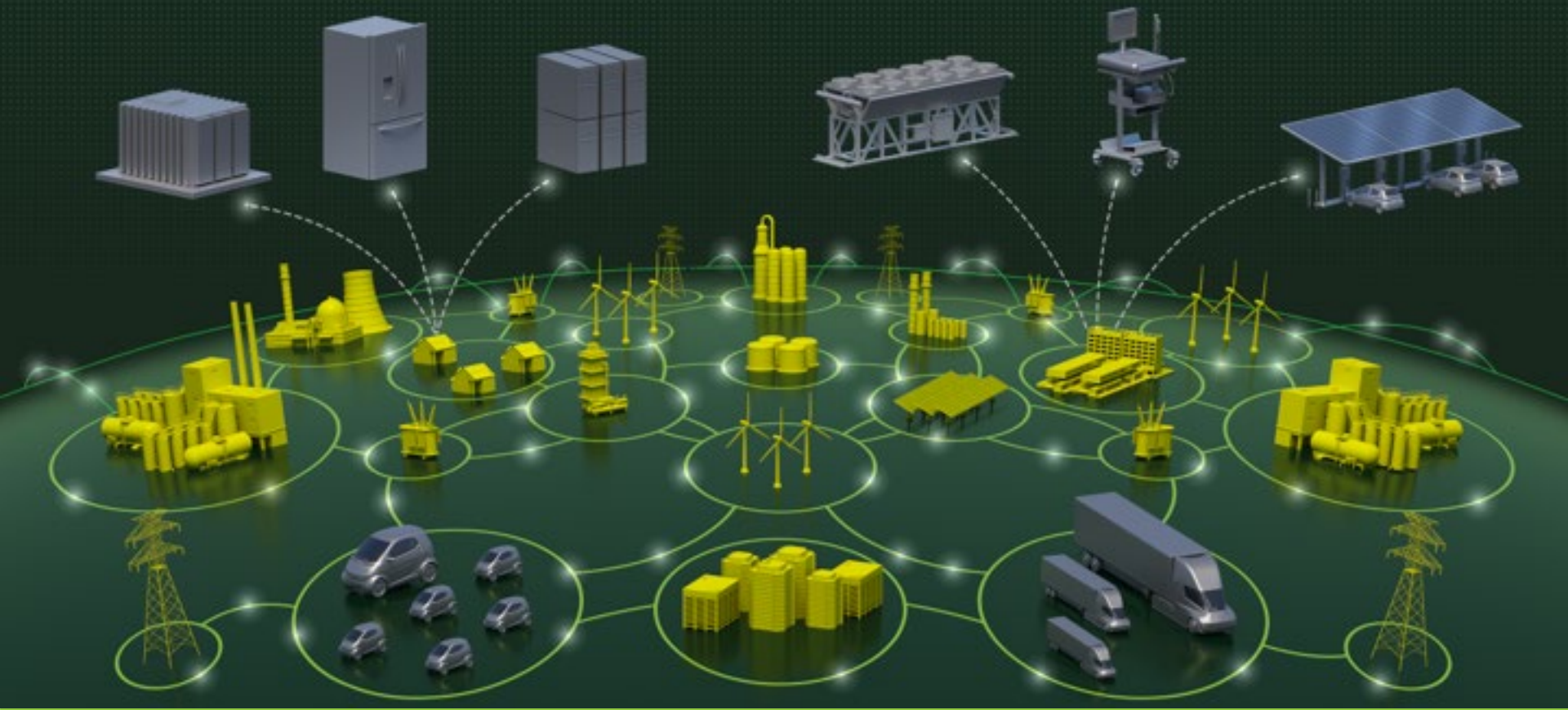
Electricity Consumption 1950–2050

Historical and Projected Annual Electricity Consumption



Moderate technology advancements are shown. Slight adjustments were made to the modeled industry consumption estimates for 2017 – 2020 to align them with available historical data.

Source: Electrification Futures Study, *NREL*, 2018



Integrated Energy Pathways

Creating Autonomous Energy Systems

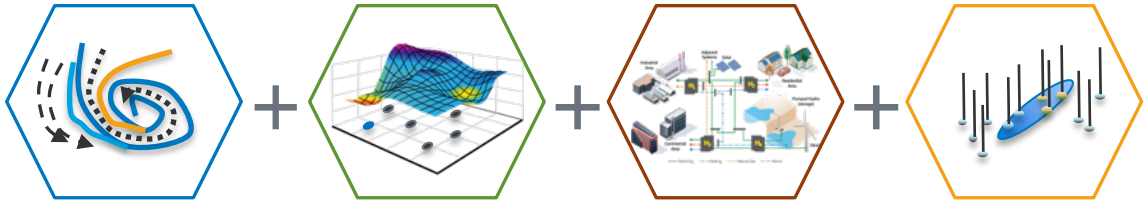
Common Problems:

- Real-time controls and optimization
- Hundreds to millions of control points
- Asynchronous data and communications
- Multi-domain systems (complex) and stochastic systems (variable renewables, consumer/occupant behavior)

APPLICATIONS

Power Grids + Transportation + Buildings + Wind Plants

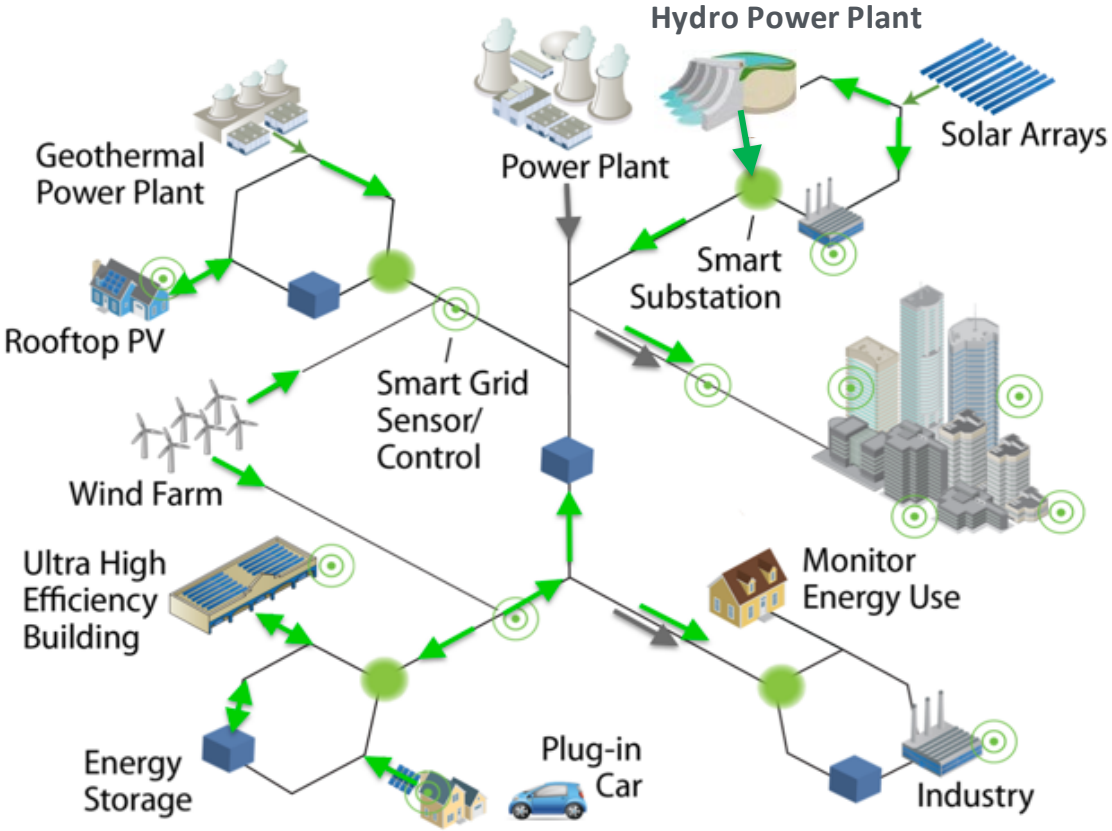
DEVELOPMENT AND OPTIMIZATION THROUGH ADVANCED SCIENCE



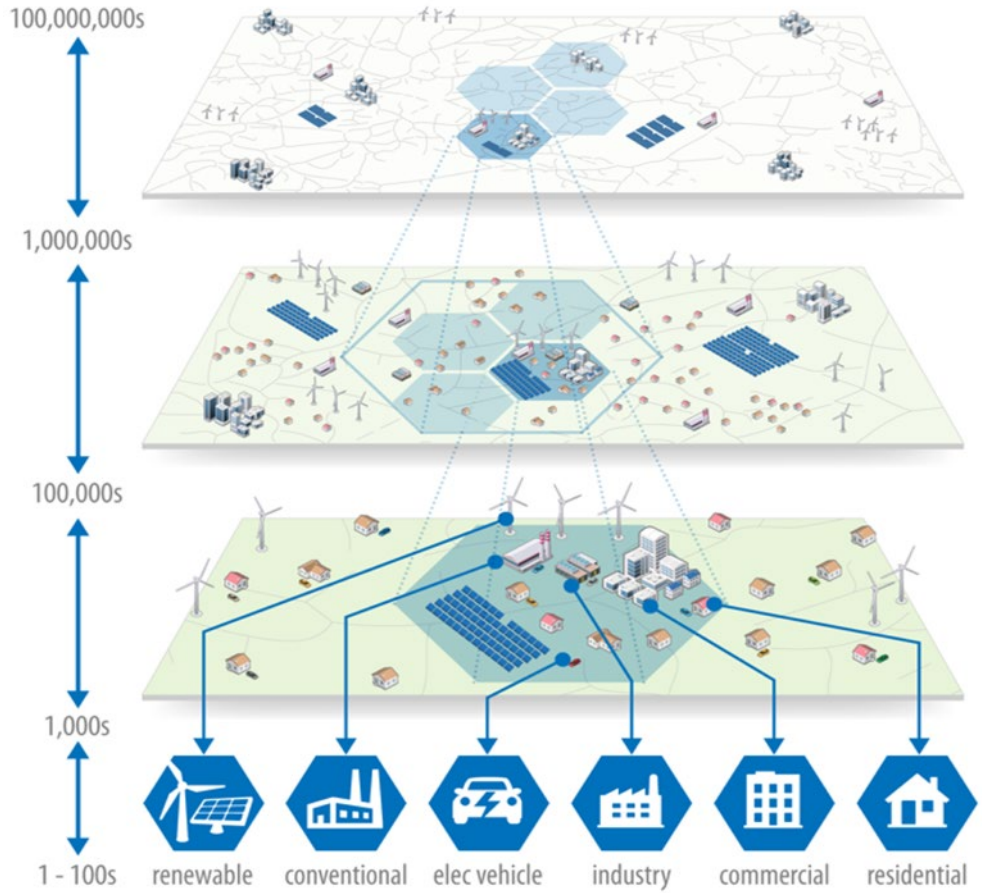
Nonlinear Control + Optimization + Complex Systems + Big Data Analytics

Future Energy System

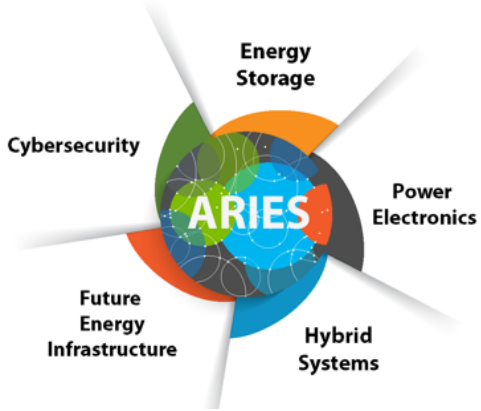
- The future energy system will integrate all types of energy systems and be more complex, distributed, and interdependent.
- If designed properly, it will also be more efficient, resilient, and affordable.



Future Grid Will Have Numerous Power Electronics Devices at All Levels

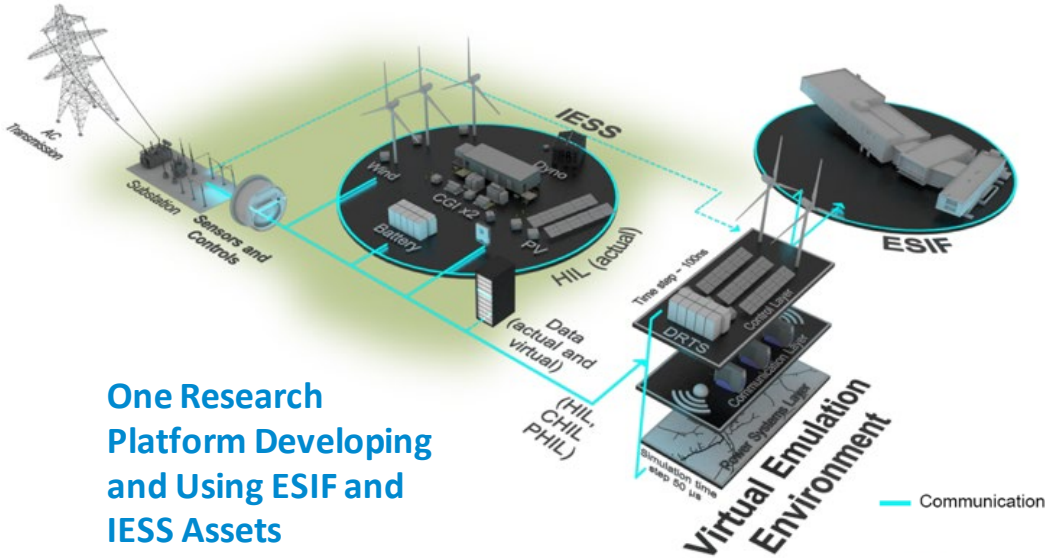


Advanced Research in Integrated Energy Systems (ARIES)



A unique research platform designed to de-risk, optimize, and secure current energy systems and provide insight into the design and operation of future energy systems. It will address the fundamental challenges of:

- Variability in the physical size of new energy technologies being added to energy systems
- Controlling large numbers (millions to tens of millions) of interconnected devices
- Integrating multiple diverse technologies that have not previously worked together.

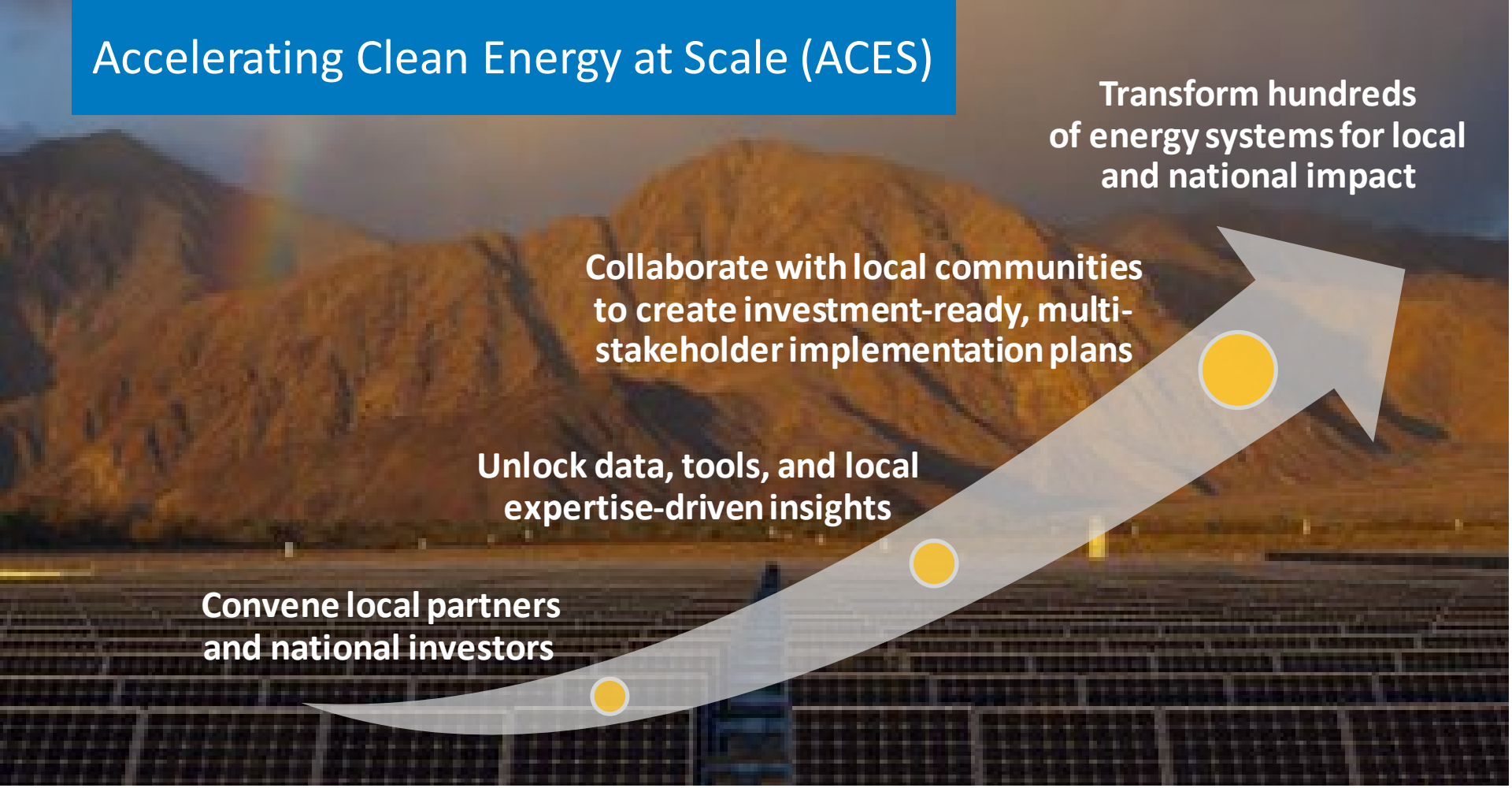


One Research Platform Developing and Using ESIF and IESS Assets

Speed Up the Process for Bringing Technologies to Scale

It took 30 years for solar panels to become one of the cheapest forms of electricity. To meet the 2050 clean energy challenge, we must speed up the process for bringing technologies to scale to 10 years.

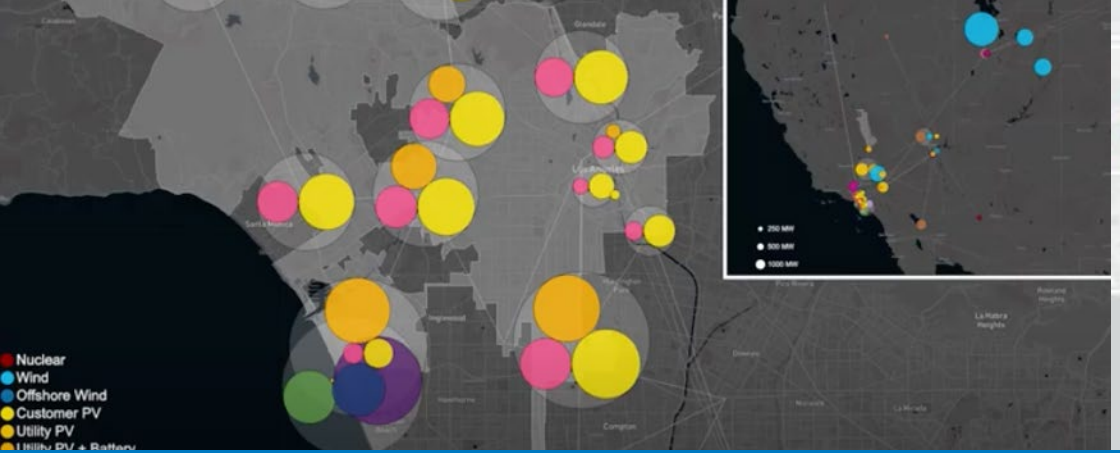
Accelerating Clean Energy at Scale (ACES)

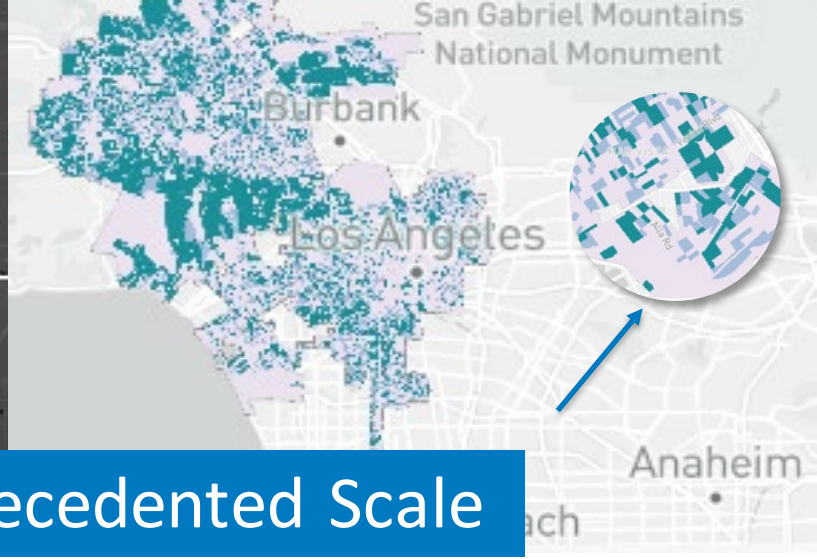


LA100 - The Los Angeles Renewable Energy Study

LA100 offers detailed, ultrahigh-resolution analysis to equip LA decision-makers to understand:

- What are the **pathways and costs to achieve a 100% renewable electricity** supply while electrifying key end uses and maintaining the current high degree of reliability?
- What are the potential **benefits to the environment and health?**
- How might local jobs and the economy change?
- How can **environmental justice** communities benefit from and be part of the solution?





LA100 Analytic Insights at an Unprecedented Scale

NREL is employing **over 100 million high performance computing simulations** to gain:

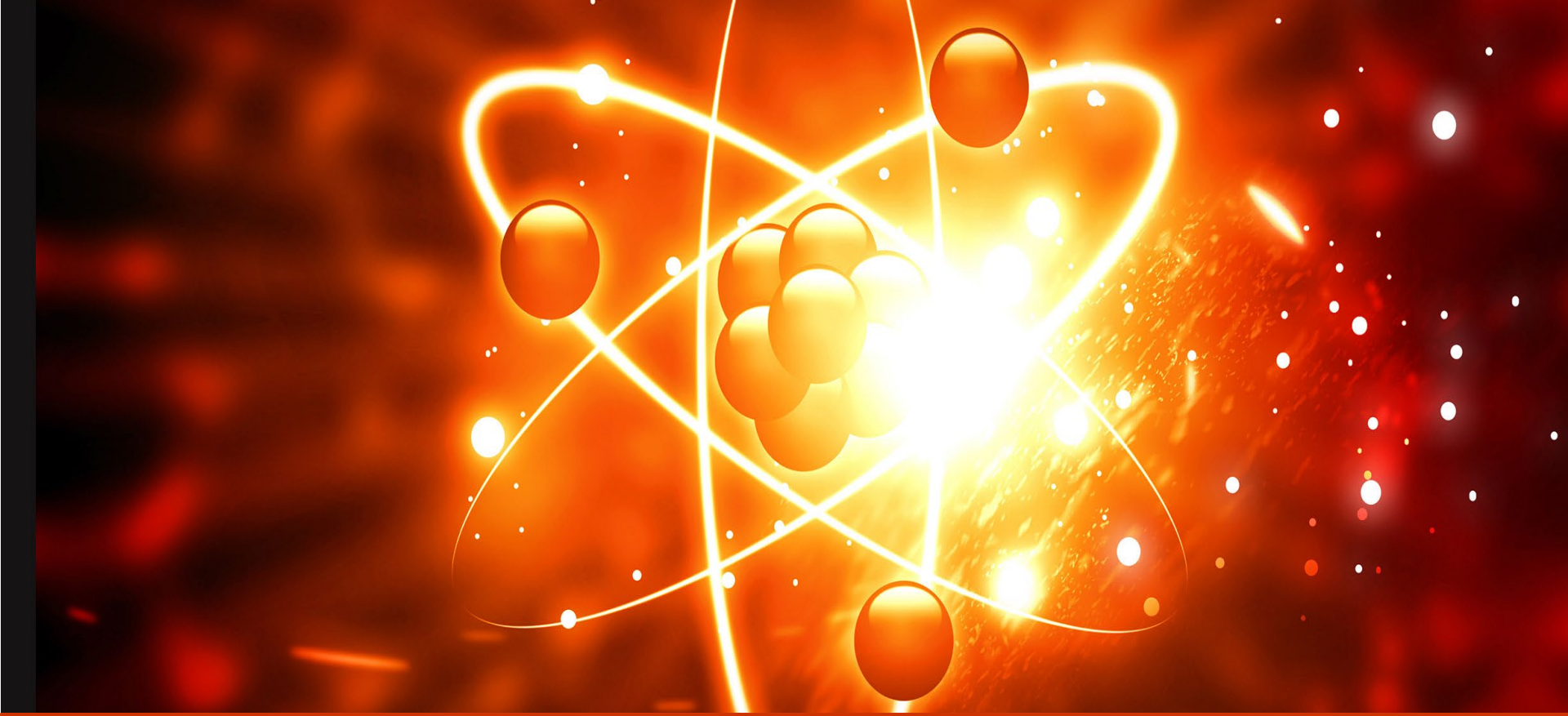
- Infrastructure level insights to realize ambitious goals
- Better understanding of the critical roles of biofuels, or RE-fueled (e.g., RNG or H2) support seasonal storage and reliability
- Best means of meeting power needs by resources across the West
- Rooftop photovoltaic details down to the building level for Los Angeles and Orange counties

Environmental Justice in Rural Communities

NREL's **Cold Climate Housing Research Center** is facilitating environmental justice for rural native Alaskans communities that were established along the coast or near rivers to facilitate commerce but are being displaced due changing ice conditions. Because fuel for power generation or heating is transported to these regions by barge or air, energy costs are exceedingly high. Some people must choose between paying energy bills or nutritious food.

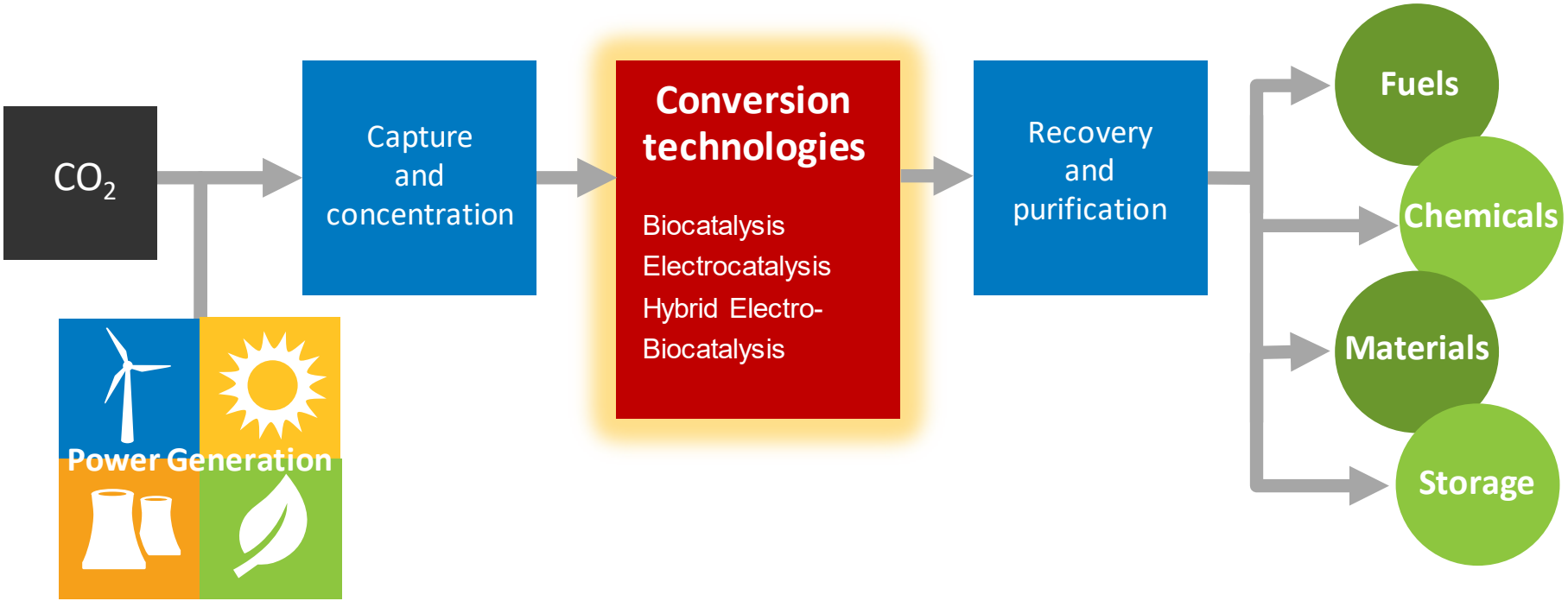
Research Challenges

- Transforming communities, strengthening economies, and enhancing resilience by blending culture, climate, and tradition with modern building science, and cutting-edge energy research.
- Developing and demonstrating appropriate housing and energy solutions that reduce energy costs, increase energy resilience, maintain healthy indoor air quality, and address water and sanitation issues.
- Developing master plans for new housing and innovating solutions to address energy burdens and health disparities in existing housing stock.



Electrons to Molecules

Utilizing Cheap, Abundant Electrons to Add Value to CO_2



Circular Economy for Energy Materials

Transitioning from a Linear to a Circular Economy

Linear

Design

Recycle
Reuse
Remanufacture

Reliability

$(D\ R^n\ R)$

Circular

Polymer Upcycling

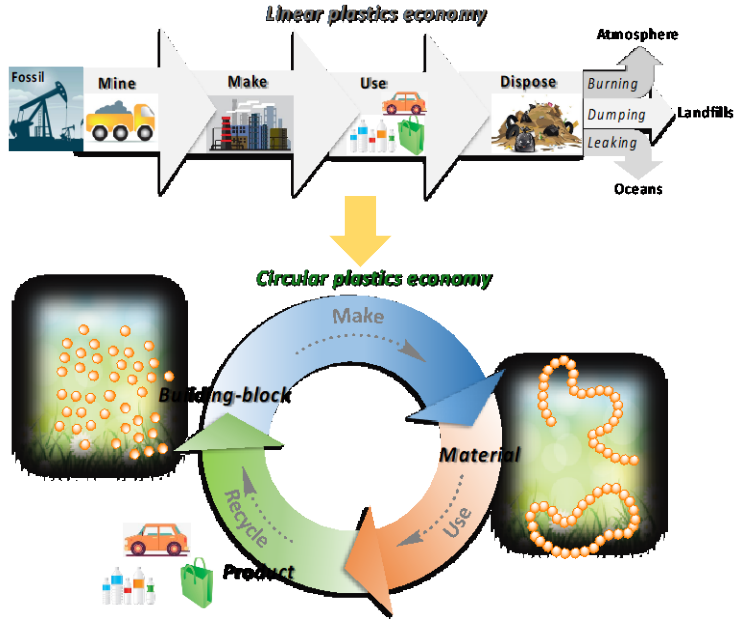
The vision for NREL in polymer upcycling is to deliver technologies that will incentivize reclamation of waste plastics to enable a circular plastics economy

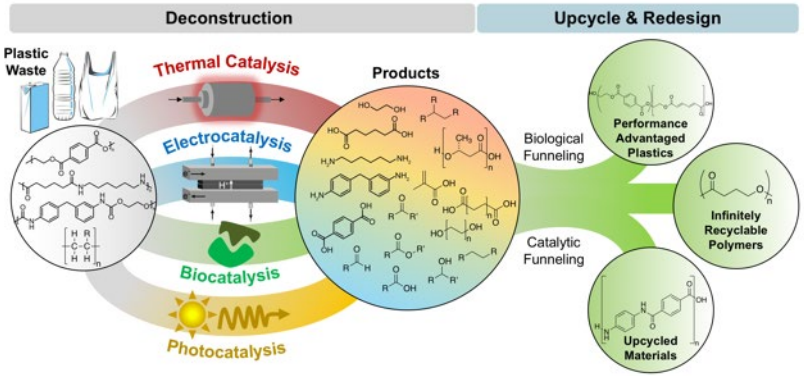
The mission is two-fold:

1) Develop robust processes to upcycle existing waste plastics
2) Develop new plastics that are recyclable-by-design

This includes chemistry, biology, material science, characterization, modeling and analysis. It also enables multi-scale, hybrid processing from g to kg scale.

bottle
changing the way we recycle
U.S. DEPARTMENT OF ENERGY





More Than 900 Partnerships

In 2020, NREL's more than 900 partnerships with industry, academia, and government included:

- 274 new partnership agreements
- $102M value of new partnerships
- 242 unique new partners
- 563 unique active partners

First Solar, an NREL partner, has now deployed 10 gigawatts of cadmium telluride (CdTe) photovoltaic (PV) panels. Manufacturing of CdTe panels is faster, cheaper, and has a lower carbon footprint than other commercial PV technologies.

FY20 Partnerships

Defense
Emphasize energy security and resiliency at installations.

Federal
Expand access to broader NREL capabilities.

International
Develop initiatives to scale-up markets for advanced energy technologies and systems.

State and Local
Help states and cities meet geographically focused energy goals.

Power
Expand work on PV materials, devices, and reliability research and grid estimation.

Chemicals
Expand current relationships and increase collaborations with industrial partners in chemical, aviation, automotive and other technologies.

Foundations
Partner to support the incubation and maturation of new energy innovations.

Manufacturing
Grow existing partnerships and execute work focused on high-impact and long-term projects.

Partnering for Impact

Through objective research and analysis, we provide the New York State Energy Research and Development Authority (NYSERDA) with resources needed for effective decision making. Our partnership will advance the use of renewable energy technologies, including options for electrifying its transportation system.

With Dallas/Fort Worth International Airport, we are using electrification, connectivity, and automation to significantly improve energy-efficient transportation of people and goods.

Our Innovation Incubator (IN_2) is expanding this scalable model to other partners and technologies and growing to a multiyear, $30 million program.

NREL and Eaton are working in the ESIF on grid intelligence, distributed energy resource management, advanced energy storage systems, virtual modeling and analysis, high-performance computing, and other research.

Thank you

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NREL
Transforming ENERGY