



The Road Ahead for Solar, Wind and Bioenergy

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The Energy and Resources Institute (TERI)
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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

40 Years of Renewable Energy Research

Nearly 1,700 employees, including more than 300 early-career researchers and visiting scientists

World-class facilities, renowned technology experts

More than 800 active partnerships

Campus operates as a living laboratory

Advancing Clean Energy Systems Globally

NREL works with partners around the world on clean energy systems analysis, research, and deployment, with the goal of accelerating global transitions to low-carbon energy systems.

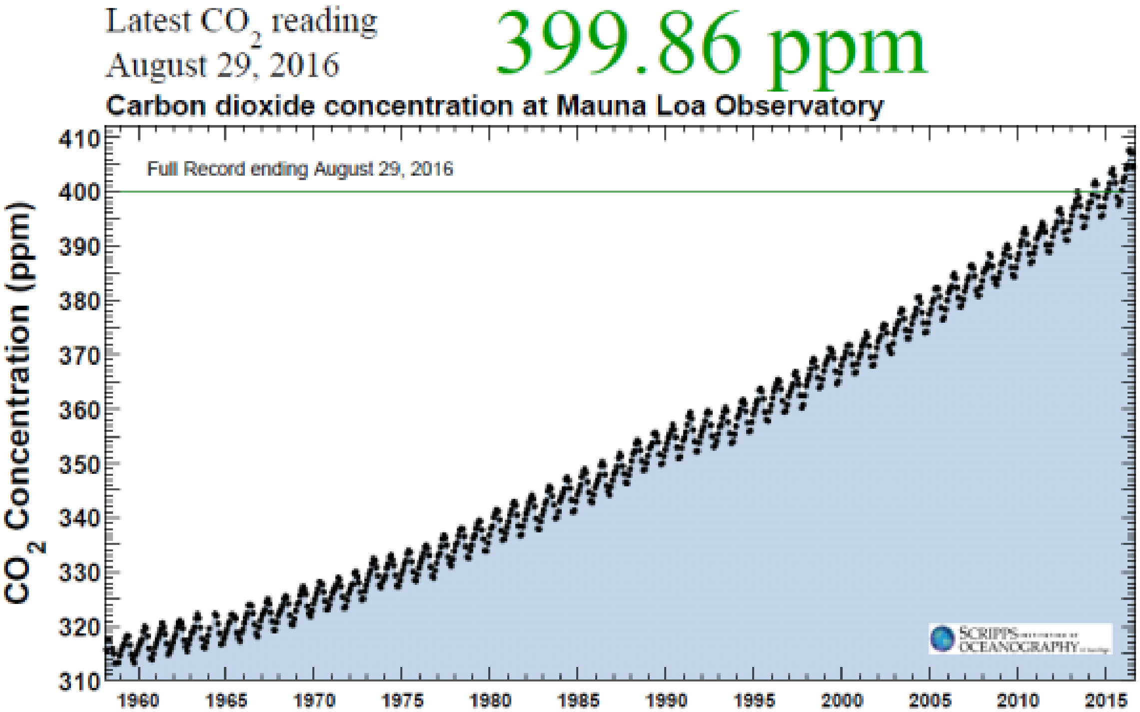
90+
Current Partner Nations

Multilateral and bilateral programs support:

Low-emissions development strategies	Energy systems integration
Grid modernization	Microgrids for isolated settings, disaster recovery

The Global Imperative for Renewables

- Rising level of carbon dioxide in the atmosphere and impact on the climate
- Growing world population with increasing needs for energy
- Volatile petroleum and gasoline prices



Keeling Curve, from 1958 to present, showing increase of carbon dioxide concentration in the atmosphere.

A Real Impact on Climate Change Requires…

Deep Decarbonization

Collaborations with India

Partnership to Advance Clean Energy – Research (PACE-R)

- Solar Energy Institute for India and the United States (SERIIUS)

  Indian Institute of Science in Bangalore and National Renewable Energy Laboratory lead development of new lower-cost solar electricity technologies and processes. (U.S. Contact: Dr. David Ginley, NREL)

- Energy Efficiency in Buildings

  Lawrence Berkeley National Laboratory and CEPT University lead effort to use information technology to accelerate implementation of cost-effective efficiency technologies. (U.S. Contact: Dr. Ashok Gadgil, LBNL)

- Second-Generation Biofuels

  Indian Institute of Chemical Technology-Hyderabad and University of Florida lead this development and optimization of non-edible feedstocks and advanced biofuels production. (U.S. Contact: Dr. Wilfrid Vermerris, University of Florida)

- Smart Grid and Grid Storage

Greening the Grid Analyses

- RE Grid Integration

  Study released July 12, 2017 shows India can integrate up to 175 GW of renewables into its electricity grid

  Grid study a collaboration of India Ministry of Power and USAID - with co-sponsorship from the World Bank (ESMAP) and the 21st Century Power Partnership - NREL; Power System Operation Corporation, Ltd. (POSOCO); and Lawrence Berkeley National Laboratory (LBNL)

  https://www.nrel.gov/docs/fy17osti/68530.pdf

- Ultra Mega Solar Parks

  Analysis of localized impacts and integration strategies of five large-scale solar parks

- Power Flow Analysis

  Analysis of system recovery from outages with high levels of renewable energy.

(U.S. Contact: Dr. Jaquelin Cochran, NREL)

Attendees of a Greening the Grid study tour to the US, May 2016.

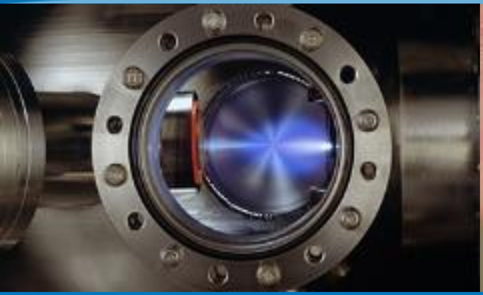
For solar technologies, a major goal is scale up to make a significant impact—

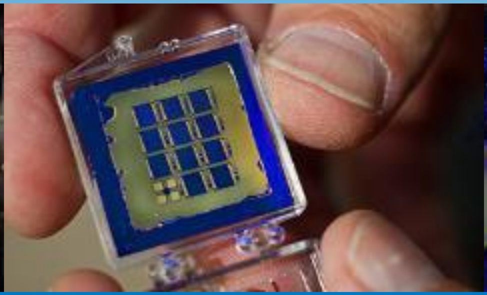
10 terawatts by **2030**,

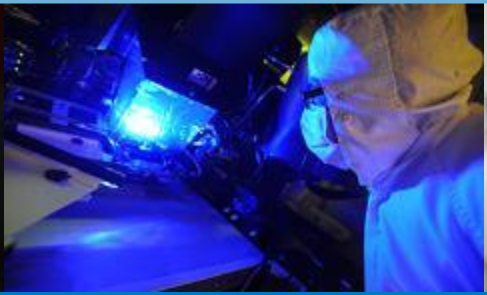
or

~50% of world electricity generation

Impact of NREL's Solar Research





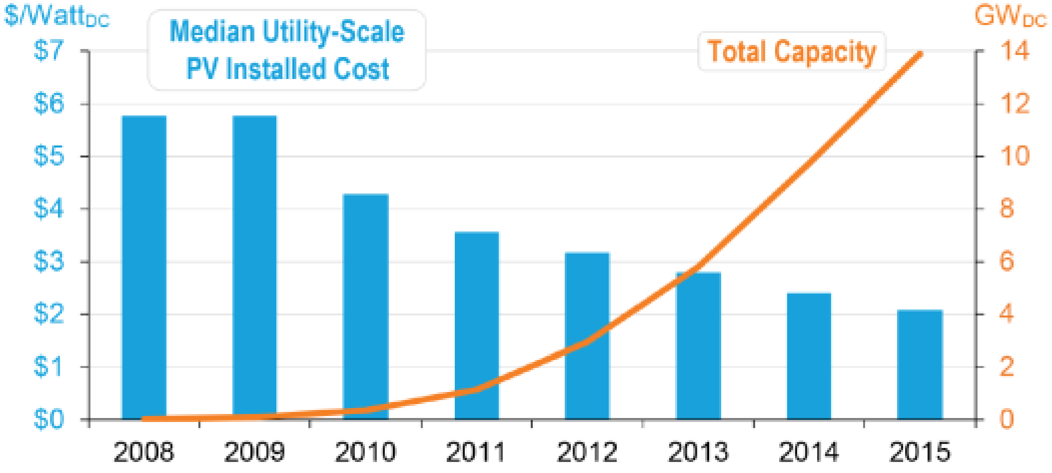


Market Impact

- U.S. Capacity:
  - 14 GW
- U.S. Forecast (through 2040):
  - ~40 GW of PV capacity in pipeline
- Costs:
  - <$2 to $6/W: *LCOE 7 to 16¢/kWhr
  - <1% of U.S. power generation

The cost of solar energy has fallen 96% and now stands at less than a dollar a watt for solar module, pre-installation.

Globally, solar energy grew by more than 50% each of the past five years (2011-2015).

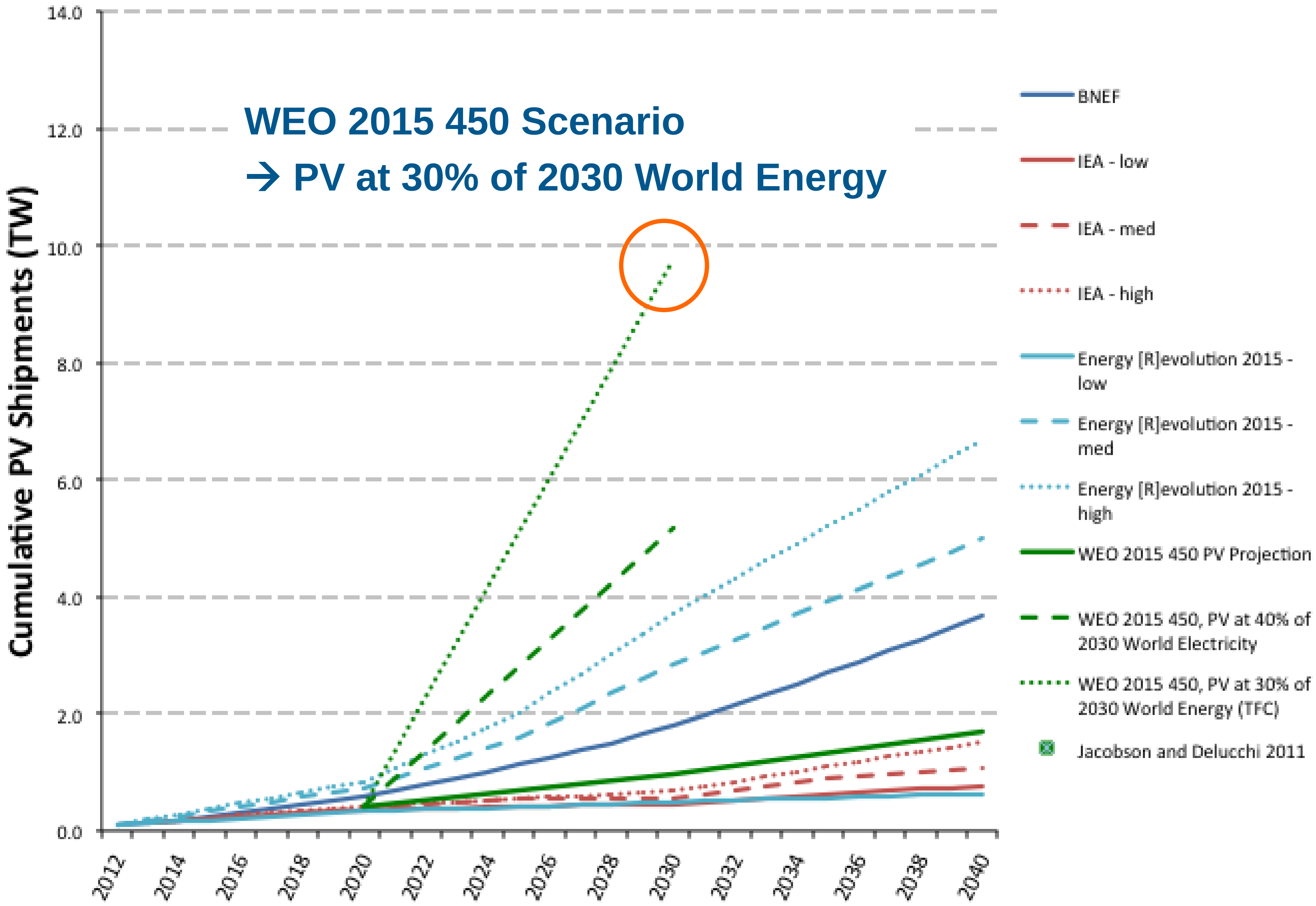


Globally, 47 GW of new photovoltaic panels were installed in 2015

That’s like building 10 averaged-sized nuclear reactors in one year

Renewable energy world.com, PV Magazine, June 2016

~10 Terawatts of PV by 2030



NREL: Materials, Manufacturing, Integration

Materials

Six-Junction Solar Device: possible >50% efficiency

Multijunction, III-V cells: efficiency >30%

Perovskite technology: efficiency of >20

Dual-junction III-V solar cell: world record 32.6% efficiency

Manufacturing

Advanced Manufacturing Office Roll-to-Roll Consortium

Perovskite inks

Thin-film manufacturing– cadmium telluride

Integration of Renewables onto the Grid

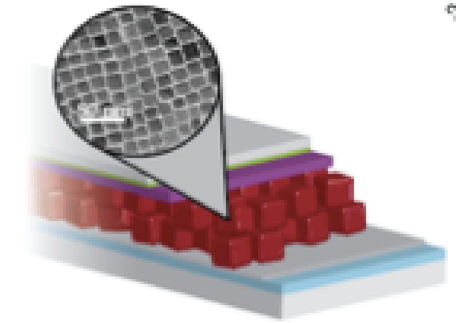
Applied Materials Science for Clean Energy

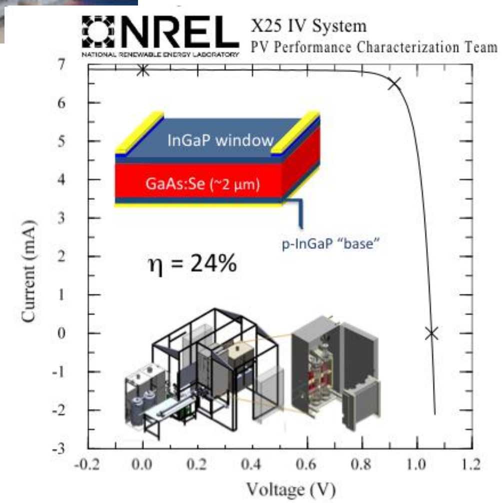
NREL's applied materials science spans materials discovery, materials processing, device fabrication, and reliability for energy generation, conversion and storage

NREL Research Leadership

- Advanced R&D for materials, concepts, devices, for photovoltaic solar conversion and solar fuels
- Leading Center for Next Generation of Materials by Design EFRC addressing metastability and synthesizability for functional materials
- NREL #1 US institution in publications and citations for perovskite PV

Current Research includes foundational R&D on silicon-based anodes for energy storage





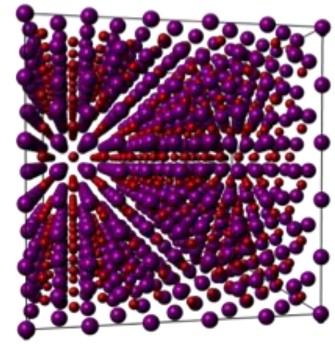
CdTe Solar Technology—Leading the Way to Grid Parity

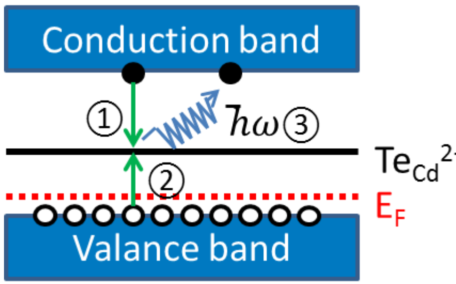
Scientific Approach

- CdTe represents the largest segment of commercial thin-film module production worldwide
- After years of empiricism by the PV community, NREL is now systematically studying the fundamentals of II-VI material
- Using atomistic calculations and experiment to indicate that Te on Cd sites limits lifetime

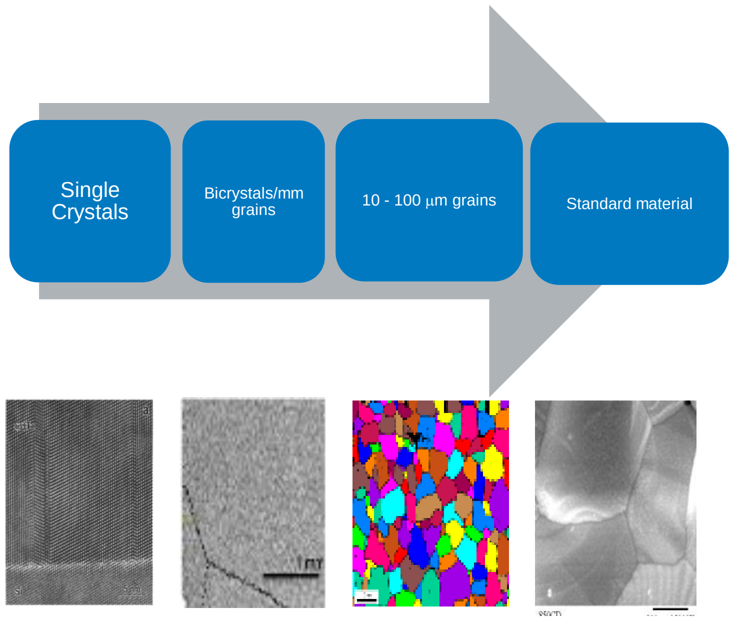
Significance and Impact

- We have attained defect-free lifetimes with ideal conductivity for solar cells
- NREL has broken the 60-year voltage barrier for CdTe devices
- A small group of companies and research groups has led to CdTe competing directly with conventional energy sources





II-VI modeling (L) and atomistic calculations (R) help to better understand CdTe behavior.



NREL is working with single crystals, large grains, and standard cells to understand and push the limits of CdTe

Burst et al., "CdTe Solar Cells with Open-Circuit Voltage Breaking the 1 V Barrier," *Nature Energy* **3** (2016)

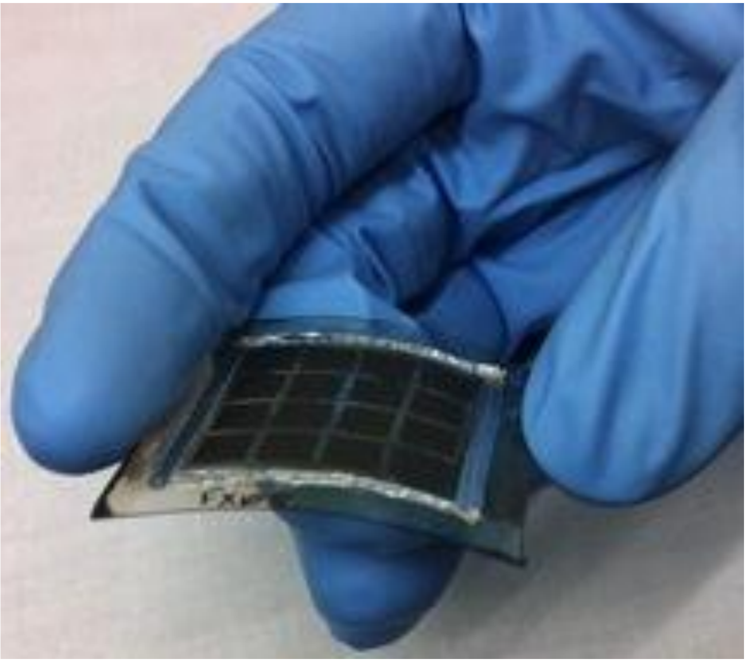
Flexible CdTe Solar Cells and Transparent Conducting Oxides

Scientific Approach

- Pursue high-efficiency CdTe cells that also have a flexible form factor.
- Develop flexible transparent conducting oxides (TCOs) for use as contacts in CdTe.

Significance and Impact

- 16.4% efficient, flexible CdTe.[1, 2] This enables lightweight, flexible, *and low-cost* PV.
- Demonstration of flexible transparent conducting oxides
- TCOs must be polycrystalline in order to maintain conductivity when flexed.[3]



Willow Glass substrate with 16 CdTe solar cells and an indium metal contact made at NREL, show the flexibility of the cells on a small piece of glass.

[1] Rance, et al., *Appl. Phys. Lett.* 2014, dx.doi.org/10.1063/1.4870834,
[2] Mahabaduge et al., *Appl. Phys. Lett.* 2015, dx.doi.org/10.1063/1.4916634,
[3] Burst et. al., submitted to *Nature Materials*, 2016

Developing World-Record GaInP/Si Dual-Junction, One-Sun Solar Cell

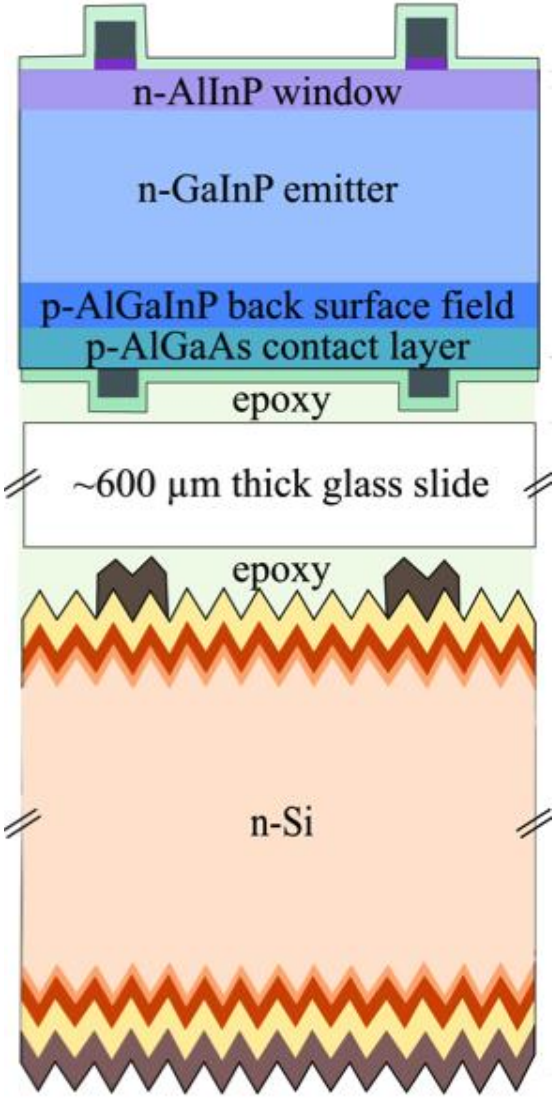
Scientific Approach

- Two-junction structure with Si bottom junction is attractive path to cost-effective solar cells with efficiency > conventional Si, enabling very large market for low-concentration PV.
- Four-terminal structure allows ease of construction, and optimal energy production under real-world operating conditions.
- Developing an improved, manufacturable bonding technique to enable transfer of this structure to industry.

Significance and Impact

- NREL developed new device structure combining a III-V Gallium-Indium Phosphide (GaInP) top junction and Si bottom junction.
- Demonstrated world-record 29.8% efficiency – significantly exceeding the best conventional Si efficiency of 25.6%.

S. Essig et al., *Energy Procedia* 77, p. 464 (2015).

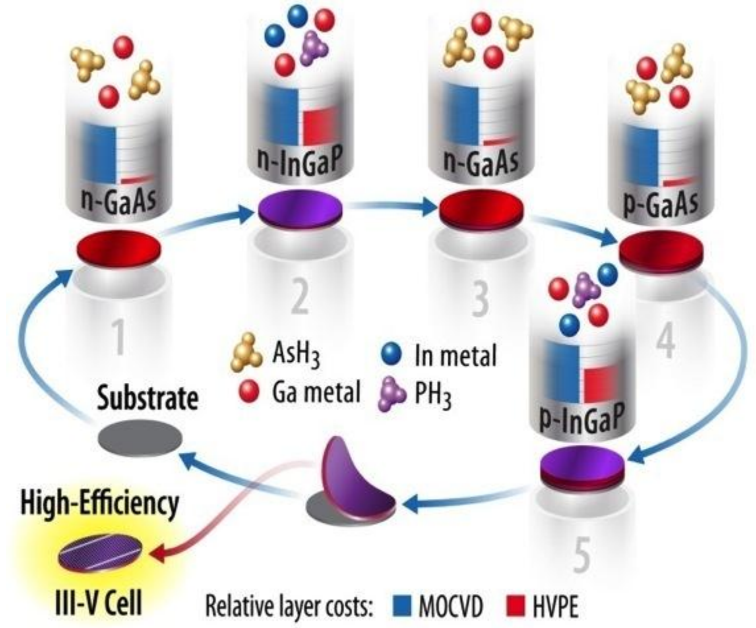


Novel tandem solar cell developed by NREL and partner CSEM with world-record efficiency at 29.8% in 2015.

High-Efficiency III-V Solar Cells at Unprecedented Low Costs

Scientific Approach

- High efficiency is critical to lowering PV costs. III-V PV is most efficient, but most expensive. Aim to radically lower III-V costs to make III-V cells the preferred PV technology.
- Use **hydride vapor-phase epitaxy** (HVPE) to drastically lower capital and materials costs while maintaining high efficiency.
- Address cost of expensive substrates through strategies for reusing them.



Schematic of in-line HVPE reactor with continual substrate reuse that eliminates metal-organic sources and uses cheap elemental metals. The bar charts show the relative materials costs for each layer.
Currently used to grow Semiconductors. Hydrogen chloride is reacted at elevated temperature with the group-III metals to produce gaseous metal chlorides, which then react with ammonia to produce the group-III nitrides

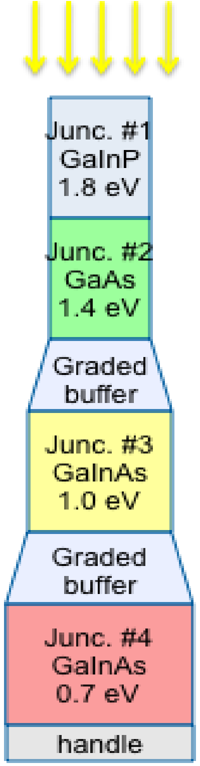
Significance and Impact

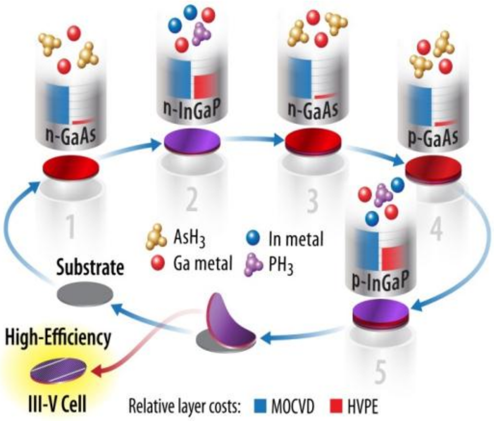
- We developed and operate a novel HVPE reactor capable of growing >25% solar cells; 20.6% already demonstrated grown at >1 micron per minute.

Simon et al., *IEEE J. Photovolt.* v.6, p. 191 (2016);
Schulte et al., *J. Cryst. Growth* v. 434 p. 138 (2016)

NREL Multijunction Solar Cells
National Security and US Manufacturing

- All modern military and commercial communications satellites are powered by multijunction (MJ) solar cells.
- Every MJ cell manufactured based on NREL inventions and technology development.
- NREL now developing low-cost MJ cells for unmanned aerial vehicles (UAVs) using a new deposition technology which has the potential to penetrate terrestrial PV markets in 5 – 10 years.

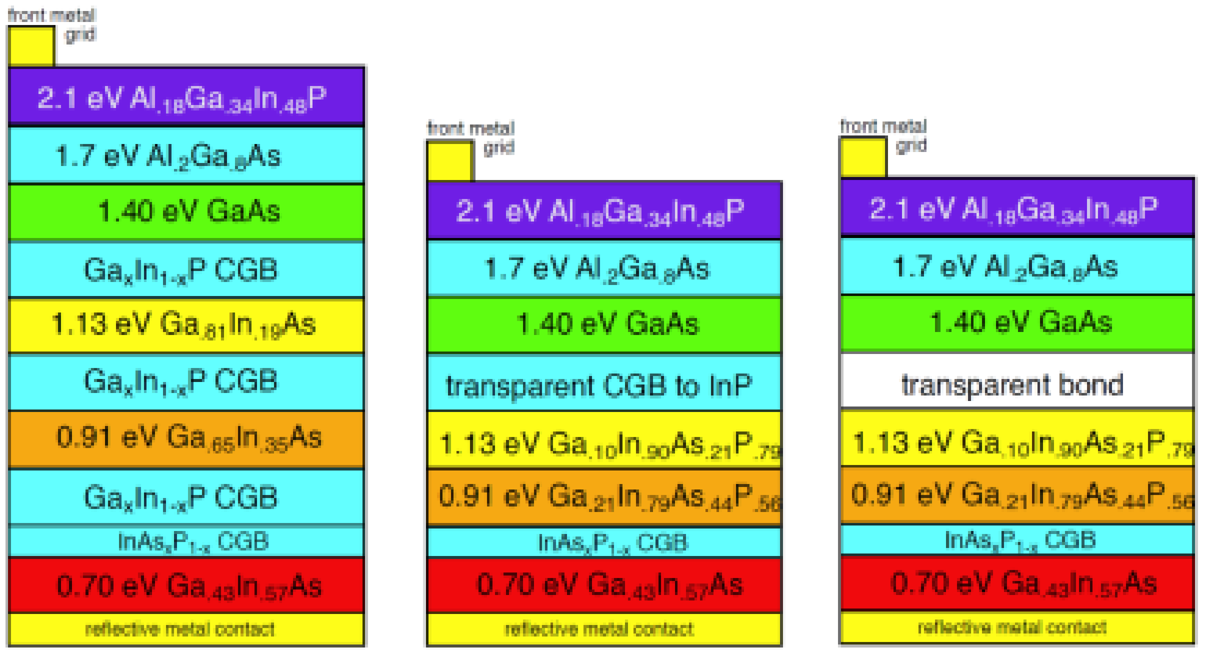




High-Efficiency Six-Junction Solar Device

More Junctions May Lead to >50% Efficiencies

- Inverted metamorphic (IMM) concentrator solar cell with up to six junctions.
- IMM cells have the potential for > 50% efficiency using moderately high-quality jct materials.



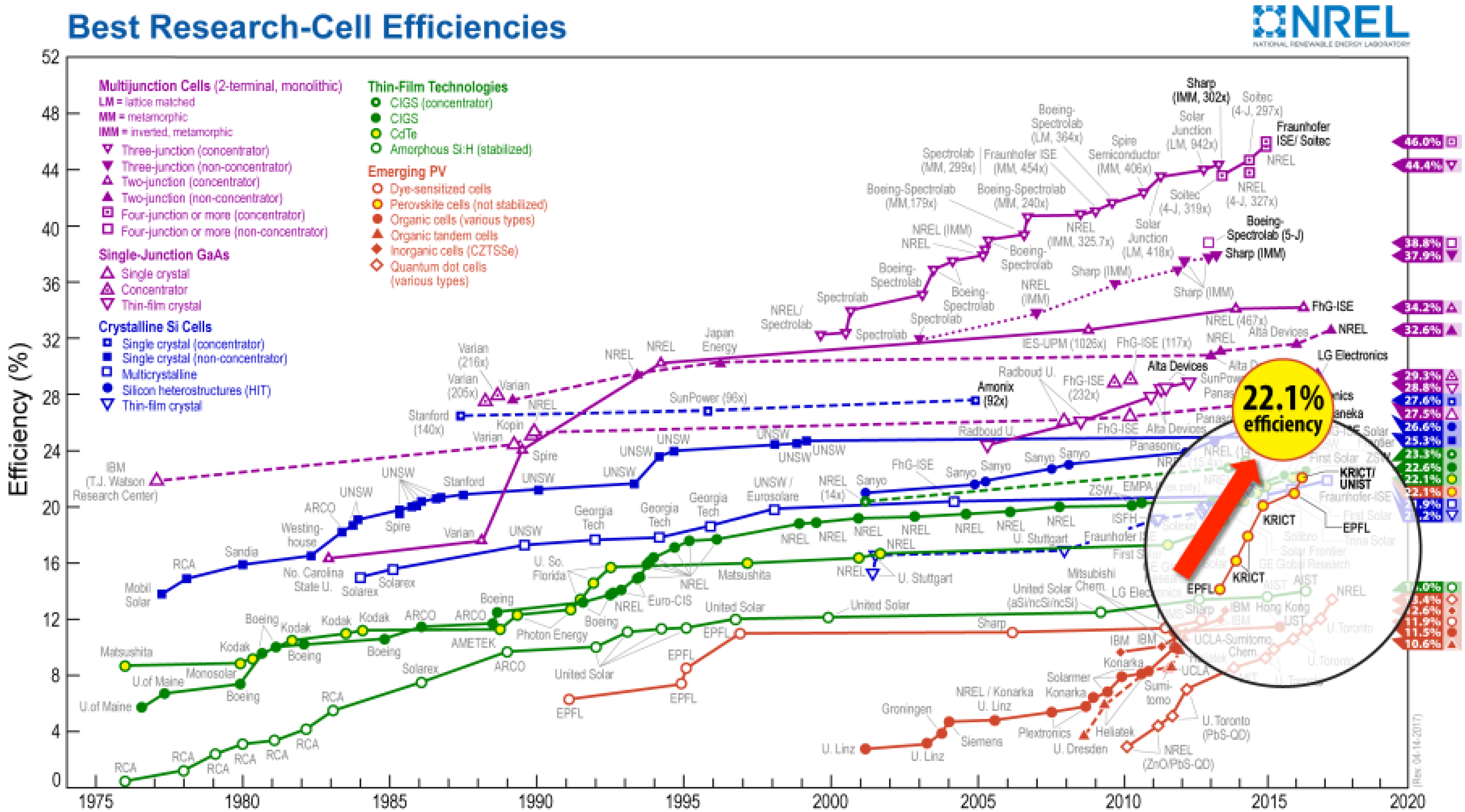
a) IMM with 3 cumulative grades

b) IMM with a single grade to InP lattice-constant

c) 3J grown on GaAs bonded to 3J grown on InP

Impact: Demonstrating that each junction has sufficient quality for a record-setting > 50% efficiency within a full 6-junction device.

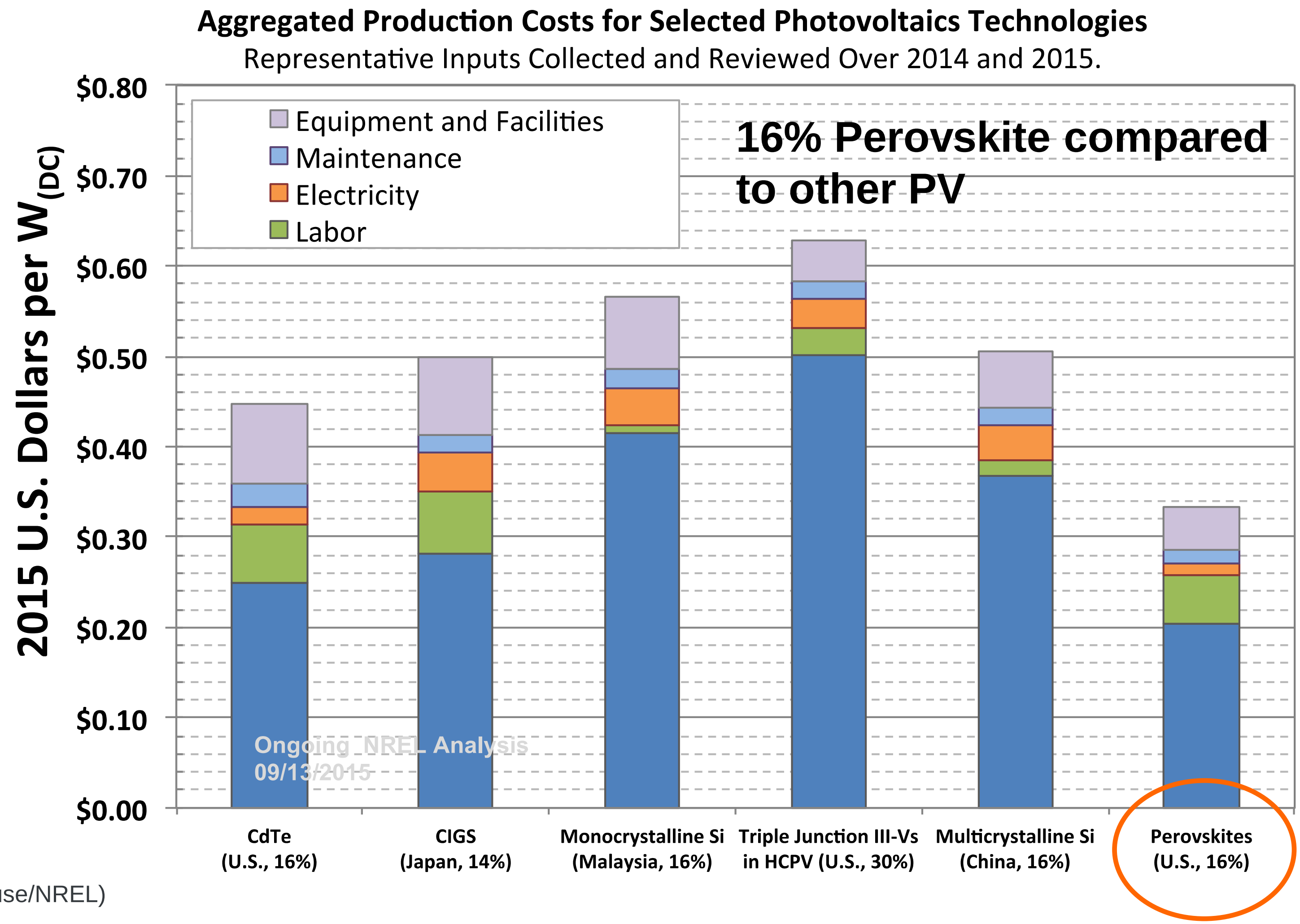
Perovskites Show Steep Climb in Efficiency



- **22.1% efficiency** for most recent lab device
- Potential for higher efficiencies and lower production costs
- Start-up companies promise modules on the market in 2017

Outlook on Cost of Perovskite Photovoltaics

Stable perovskite PV can meet 2020 cost targets

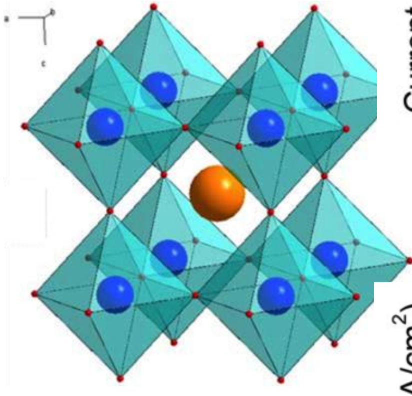


(Woodhouse/NREL)

Stabilizing Perovskite Efficiencies Using Cation Substitution

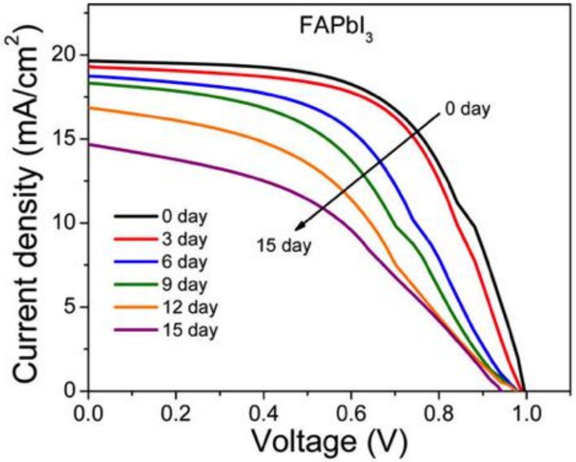
Scientific Approach

- Perovskite is a mineralogical structure typified by Calcium titanium Oxide $CaTiO_3$ (generically, ABX_3)
- Explore use of other cations in perovskite structure as means to overcome problem of current perovskite systems that degrades too quickly for commercial use.
- Use first-principles calculations coupled with experimental studies.

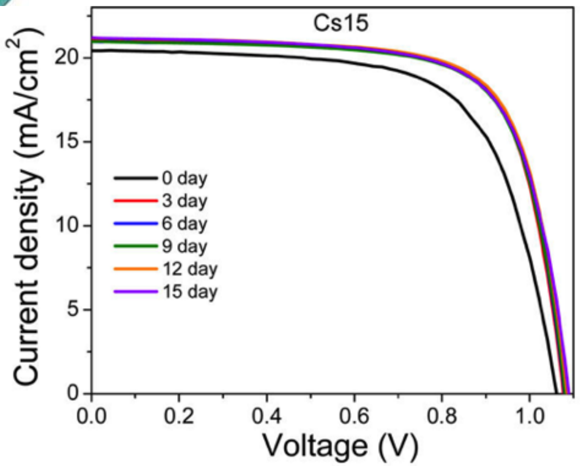


Typical perovskite structure
Formaminidium lead triiodide
$FAPbI_3$

FA cation



Cs cation



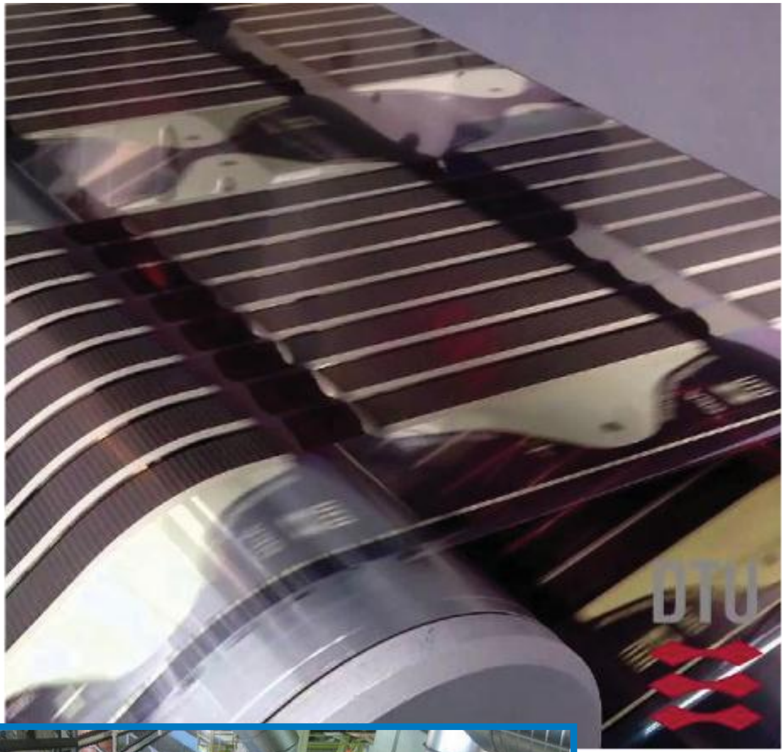
J-V curves of shelf life stability of $FAPbI_3$ (upper) and $FA_{0.85}Cs_{0.15}PbI_3$(lower) solar cells at 0−15 days of storage under 15% RH

Significance and Impact

- An alloy of FA (Formaminidium) and Cs cations increases the tolerance factor and stabilizes the perovskite structure for 100s of hours
- Results agree with first-principles calculations

Li et al. *Chem. Mater.* 2016, 28, 284, doi:10.1021/acs.chemmater.5b04107

Vision for Hybrid Perovskite Solar Cells (HPSCs)



HPSCs can be manufactured more than 50 times faster than current silicon cells

- Similar to newspaper production, HPSC manufacturing can use a roll-to-roll web printing method
- Considering the same speed as a newspaper line, it would take **~3 years** to manufacture 25 terawatts (TW) of 15%-efficient HPSCs vs. **~170 years** to manufacture 25 TW of silicon PV

Benefits of HPSCs

- Low capex, high-volume manufacturing (for PV)
- On-demand manufacturing (for LEDs/displays)
- New technologies (e.g., quantum information processing, quantum computing)

The U.S. wind industry is striving toward **supplying 20% of the nation's electrical demand in 2030**—or *four times* the current installed wind capacity.



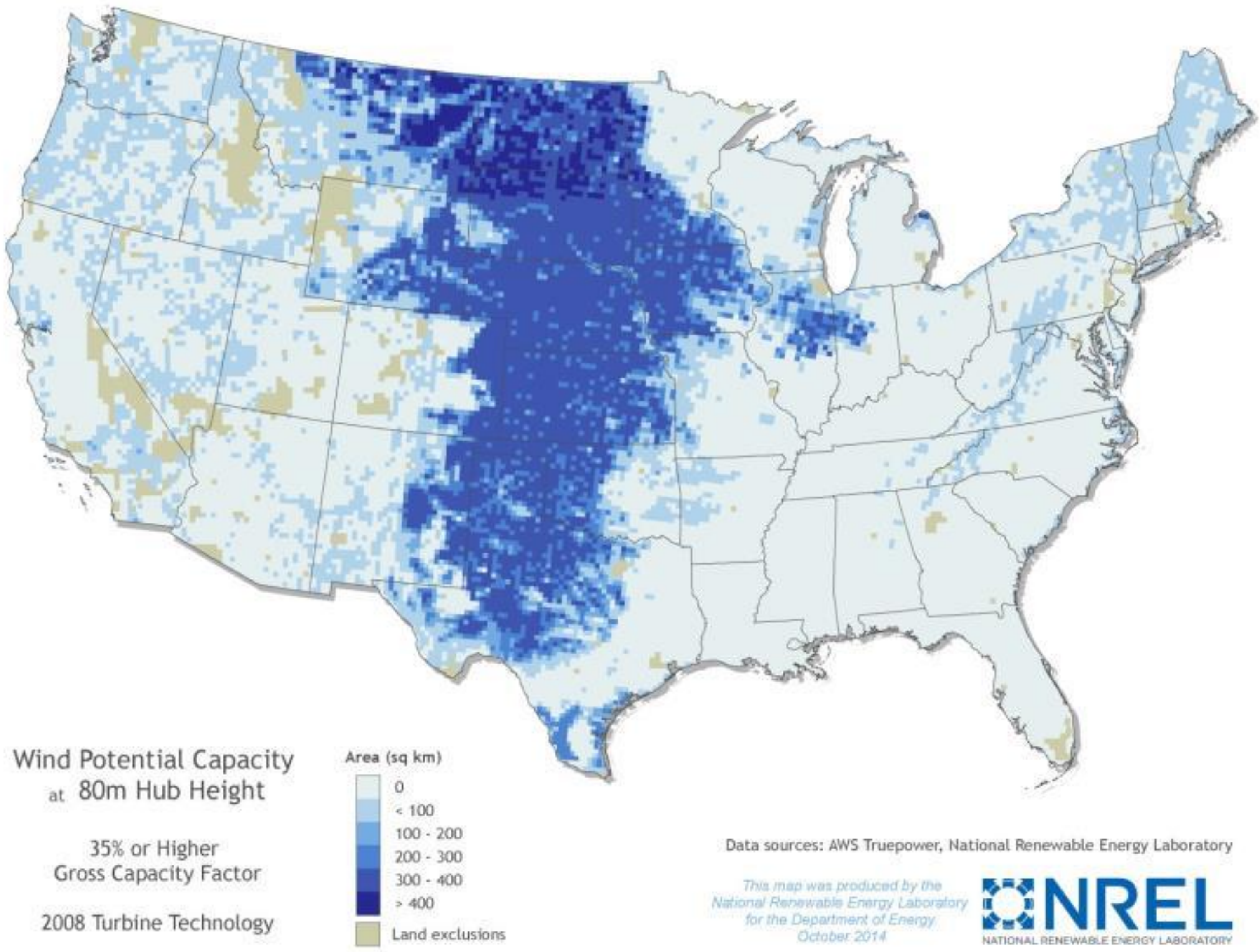

IMPACT OF NREL’S WIND RESEARCH

Innovations have driven down the cost of wind energy by 66% between 2009 and 2015, enabling industry success.

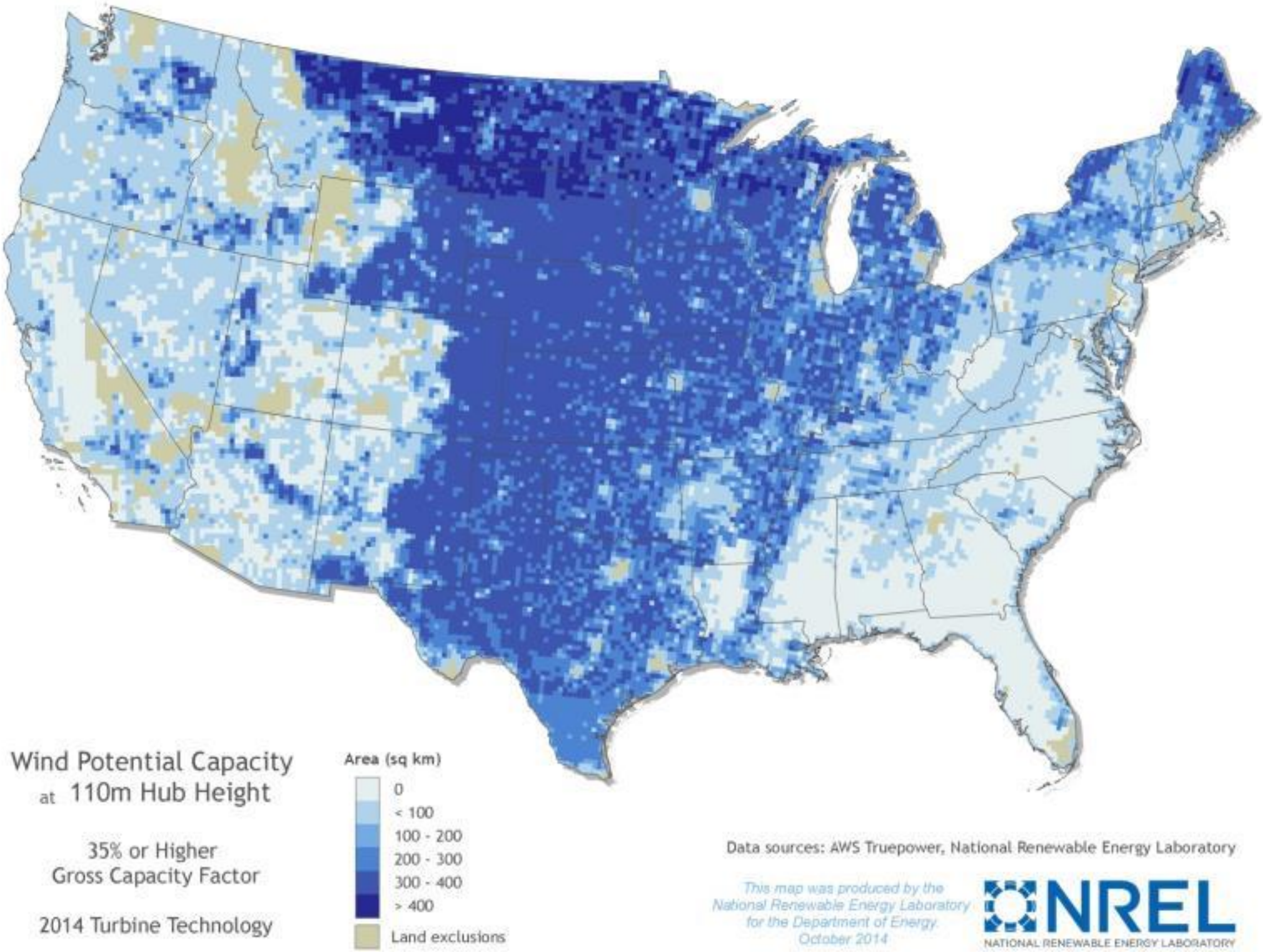
Market Impact

- Costs: 4-7 cents/kWh
- Installed capital cost between $1,300 and $1,900/kW
- U.S. ranks second in world for installed capacity at 76 GW
- Wind provides about 5.6% of U.S. electricity
- Wind power employs just more than 100,000 Americans
- More than 500 wind-related manufacturing facilities in the United States

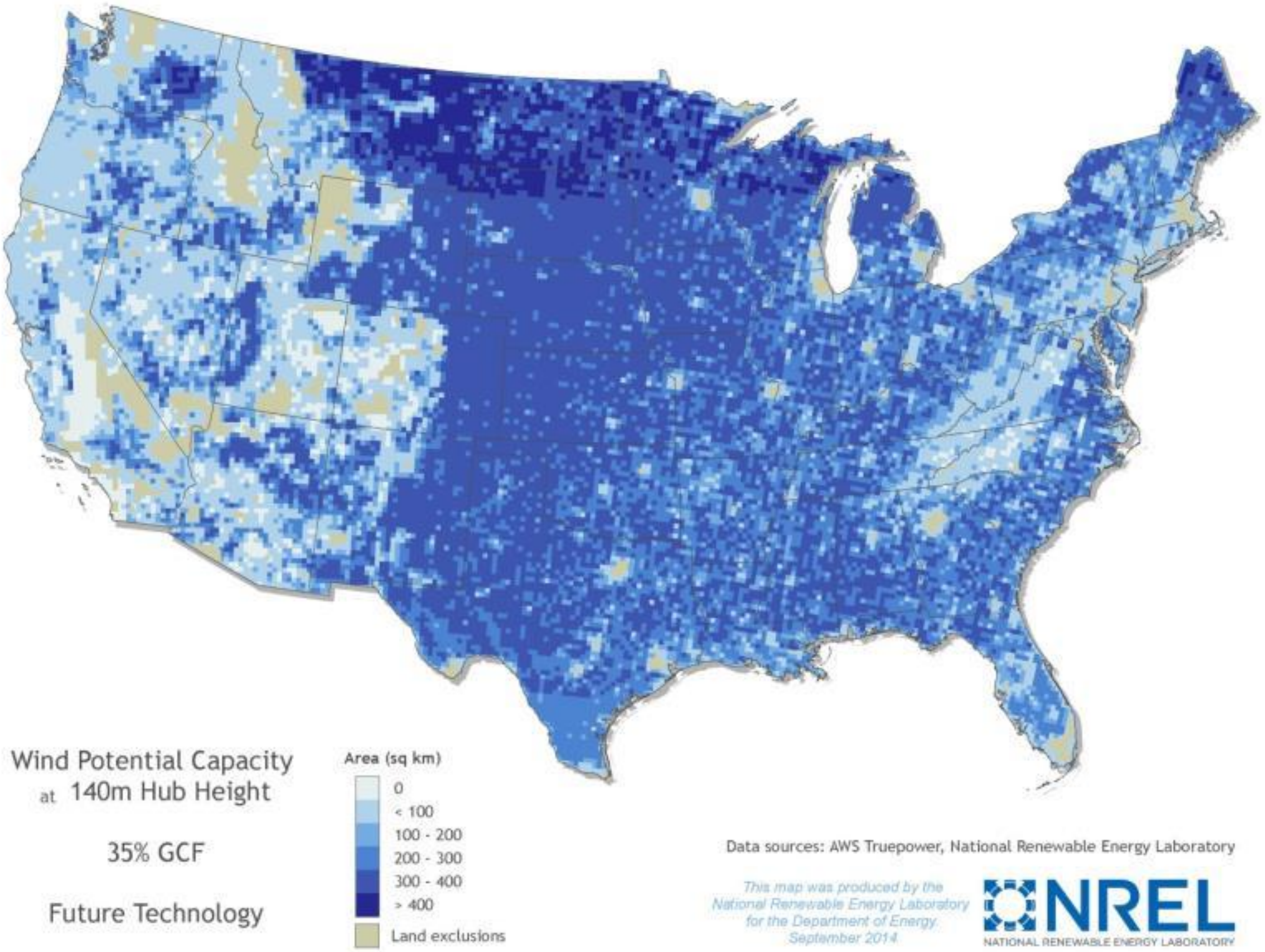
Wind Energy Potential Capacity at 80m Hub Height
2008 Turbine Technology



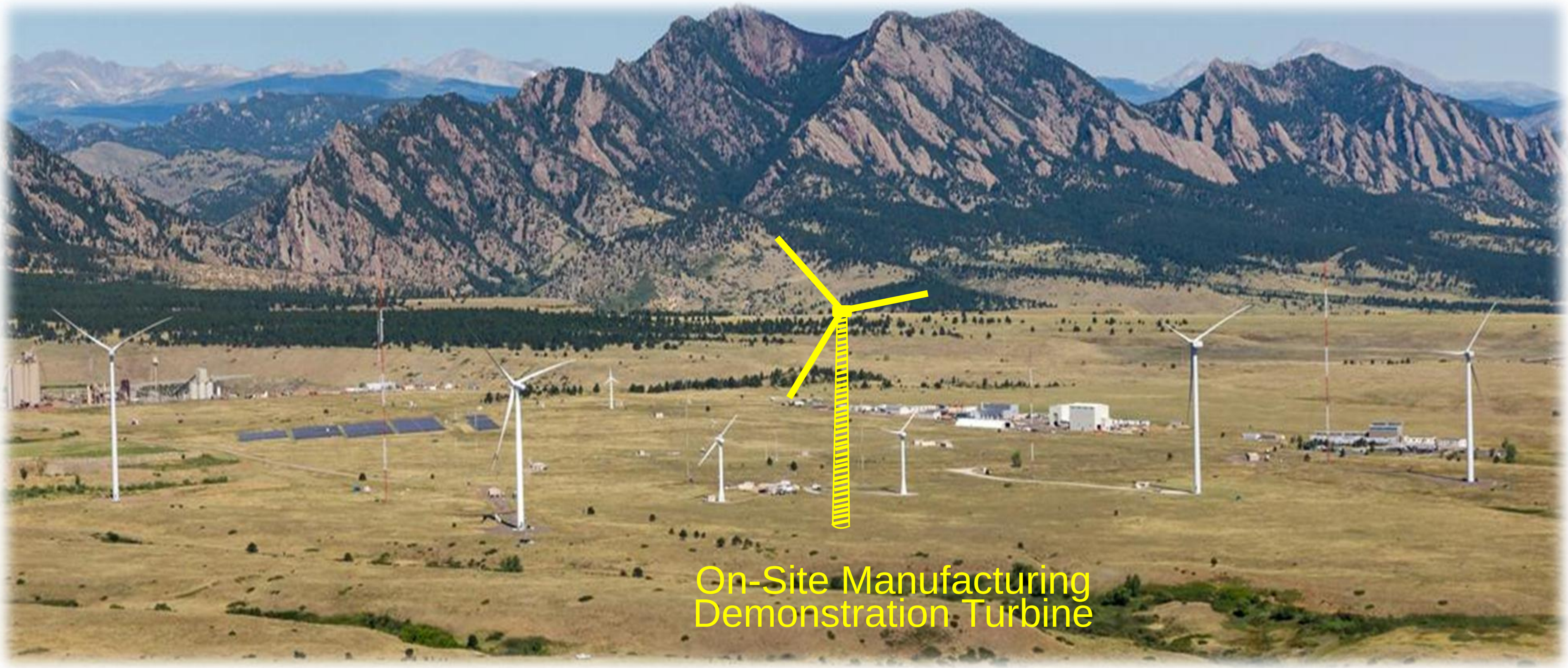
Wind Energy Potential Capacity at 110m Hub Height
2014 Turbine Technology



Wind Energy Potential Capacity at 140m Hub Height 'Near Future' Turbine Technology (150W/m^2)

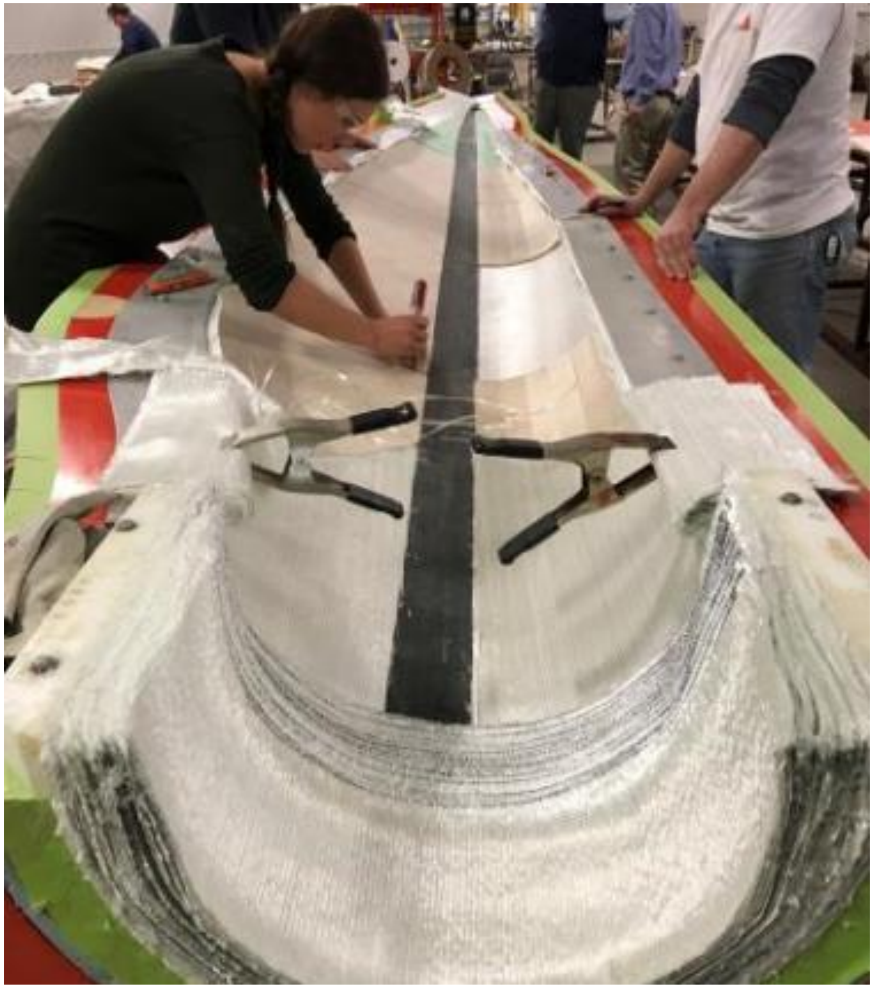


NREL's National Wind Technology Center



- Leading national wind energy research in next-generation turbine manufacturing
- 140m tower manufactured on-site
- ~60-70m blade manufactured on site with 3D-printed blade molds
- Possibly other components manufactured on-site
- Project risk mitigated by on-site NWTC materials and component validation
- Tallest turbine in U.S.

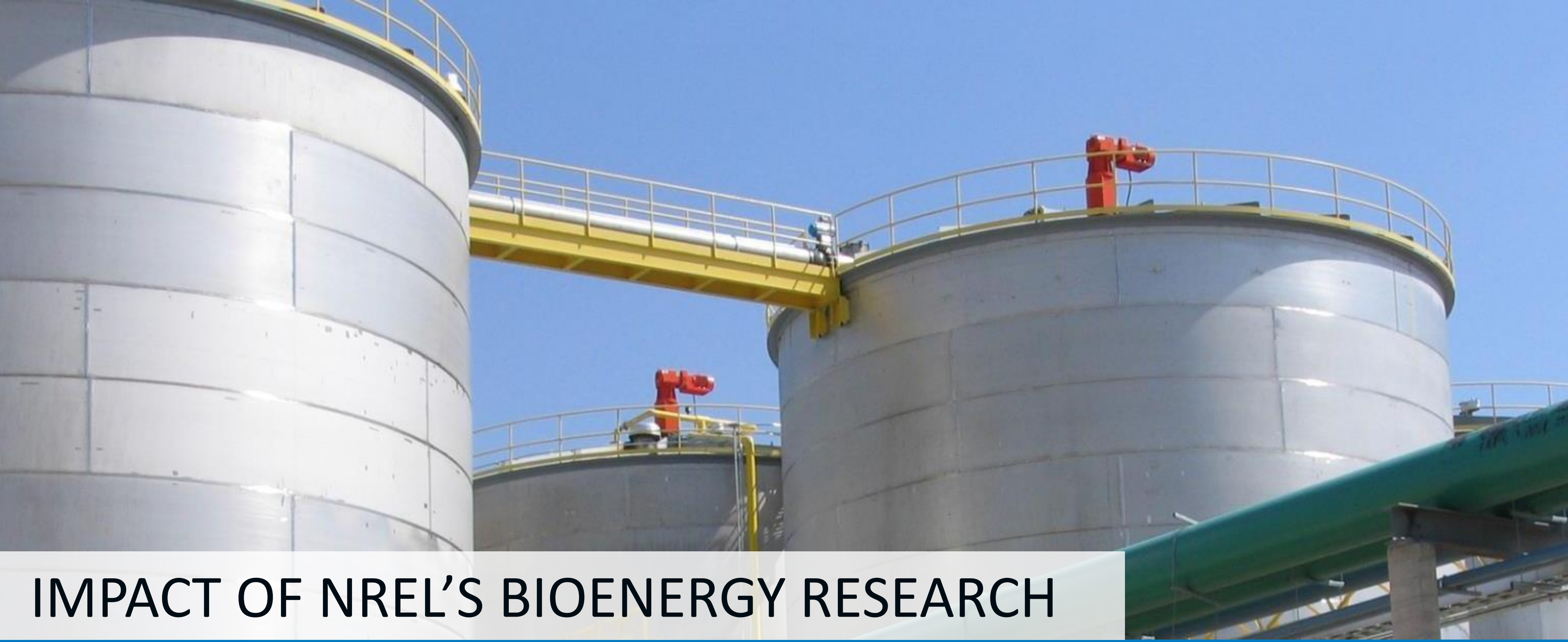
Path to Advanced Composites for Wind Energy



NREL's Composites Manufacturing Education and Training (CoMET) Facility:

- **Accelerating the manufacture** of advanced wind turbine components
- Driving **composites science and education**
- Demonstrating initial work on the Manufacturing USA **Institute for Advanced Composites Manufacturing Innovation** (IACMI)
- Providing a real-world classroom to educate tomorrow's **highly trained advanced composites workforce**
- Increasing partnering with **research universities** and **industry**

Bioenergy, like solar,
has a major push to scale up the technology—
to **60 billion gallons** biofuel by **2030**



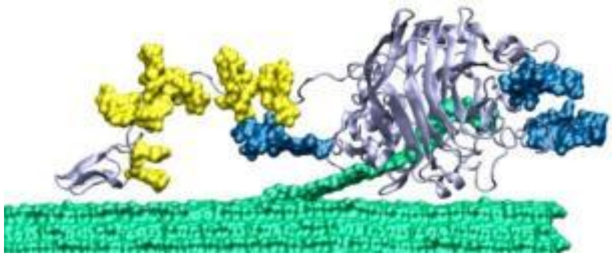
IMPACT OF NREL’S BIOENERGY RESEARCH

NREL contributed to first-of-a-kind commercialization of cellulosic ethanol technologies in the United States.

Market Impact

- NREL’s work on enzymes contributed to a 78% reduction in the cost of converting biomass into cellulosic ethanol
- NREL’s pilot plant integrated and scaled up bioconversion technology
- NREL R&D directly contributed to DuPont and POET cellulosic ethanol biorefineries
- 2012 analysis modeled cost-competitive production of cellulosic ethanol

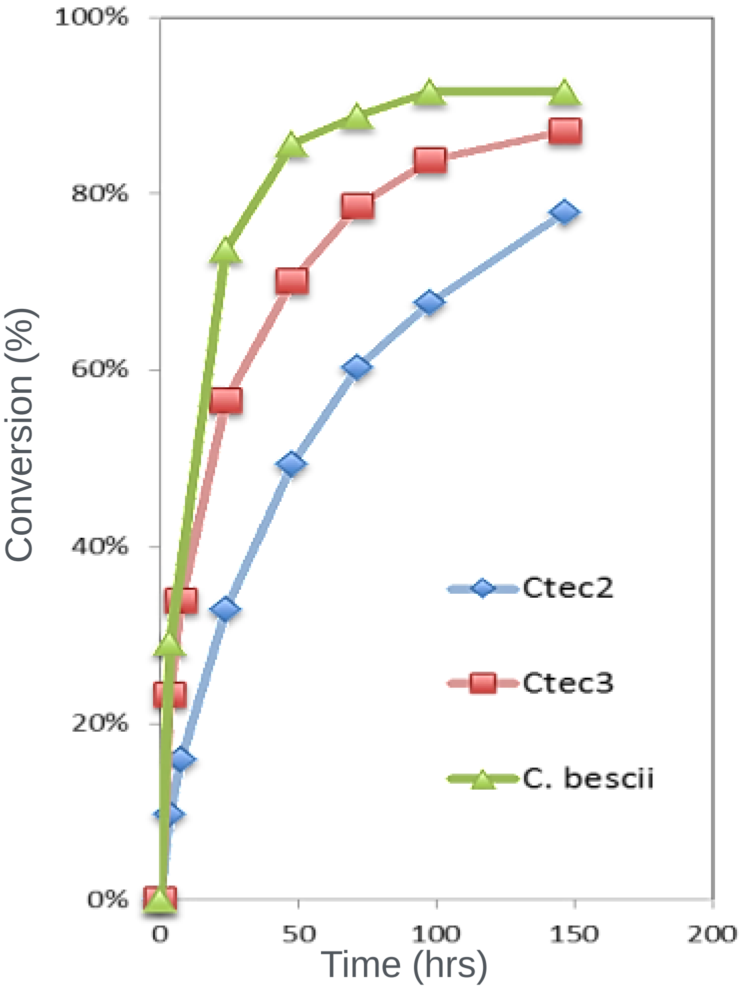
Enzyme Engineering and Optimization



CBH1 enzyme depolymerizing cellulose

Scientific Approach

- Use high-resolution microscopy and computational modeling to understand, predict behavior of natural and/or genetically modified enzymes
- use rational design principles to develop next generation enzymes with superior performance



Next-gen enzyme vs commercial preps

Significance and Impact

- NREL has a long history of improving cellulases and decreasing the cost of sugar production
- We work in industrially relevant host strains that easily translate to commercial processes

Bioeconomy

Key Research Areas

- **Using refinery infrastructure that already exists** – feasibility of co-processing pyrolysis oil (drop-in hydrocarbons) with Ensyn Corporation
- **Producing natural bioplastics, acids, and alkanes** – pathway found in nature (lignin valorization) uses “waste” lignin
- **Developing new chemicals and materials** – includes renewable carbon fiber, sustainable ammonia production, ethylene via sunlight, bioconversion of methane to lactate

Lignin Utilization

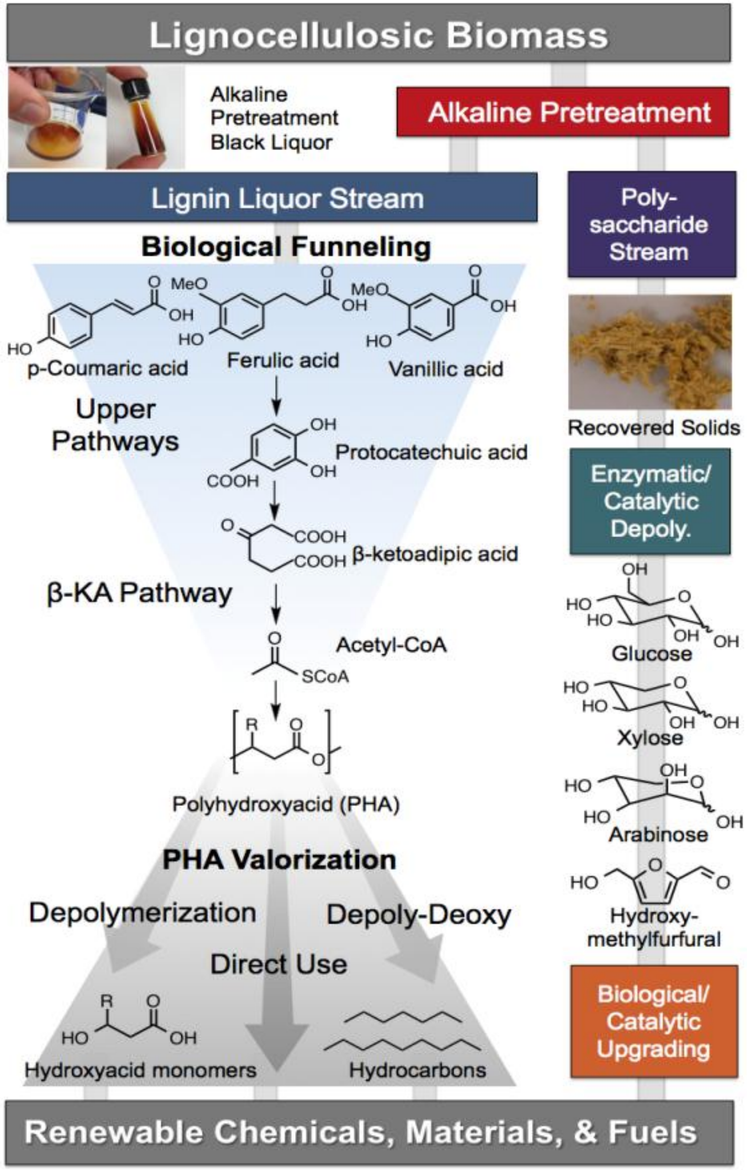
Scientific Approach

- Utilization of alkaline pretreatment isolates soluble lignin derivatives upstream
- Novel biological funneling concept converts heterogeneous mix to key platform intermediates
- NREL ideally suited to perform tandem biological – catalytic hybrid processes
- Subsequent sugar streams more amenable to downstream fuel / product conversion

Significance and Impact

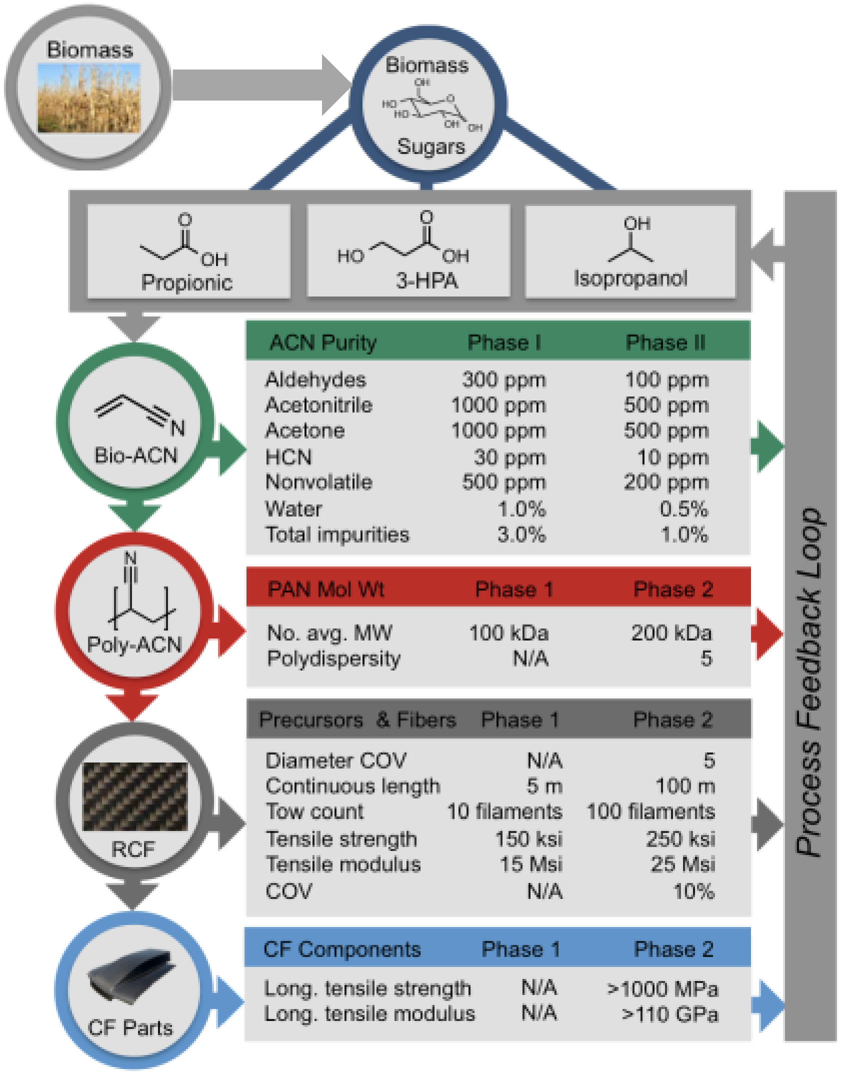
- Can significantly improve economics (~$1.00/gal) of finished fuel
- Can significantly improve LCA of process (depending on product choice)

Ragauskas, Beckham, Biddy, et al., *Science* 2014
Linger, Vardon, Guarnieri, Karp, et al., *PNAS* 2014



Renewable Carbon Fiber

- **Consortium Partners –** NREL (Lead), INL, Biochemtex, Johnson Matthey, CU-Boulder, CSM, ORNL, MATRIC, DowAksa, Ford, MSU
- **Objective –** Cost-effective production of renewable carbon fibers from lignocellulosic biomass
- **Strategy –**
  - Deconstruction of biomass to sugars/lignin
  - Biological production of key intermediates
  - Chemical catalysis to acrylonitrile (ACN)
  - Polymerization of Acrylonitrile to carbon fiber for industrial testing and validation



ACN Purity	Phase I	Phase II
Aldehydes	300 ppm	100 ppm
Acetonitrile	1000 ppm	500 ppm
Acetone	1000 ppm	500 ppm
HCN	30 ppm	10 ppm
Nonvolatile	500 ppm	200 ppm
Water	1.0%	0.5%
Total impurities	3.0%	1.0%

PAN Mol Wt	Phase 1	Phase 2
No. avg. MW	100 kDa	200 kDa
Polydispersity	N/A	5

Precursors & Fibers	Phase 1	Phase 2
Diameter COV	N/A	5
Continuous length	5 m	100 m
Tow count	10 filaments	100 filaments
Tensile strength	150 ksi	250 ksi
Tensile modulus	15 Msi	25 Msi
COV	N/A	10%

CF Components	Phase 1	Phase 2
Long. tensile strength	N/A	>1000 MPa
Long. tensile modulus	N/A	>110 GPa

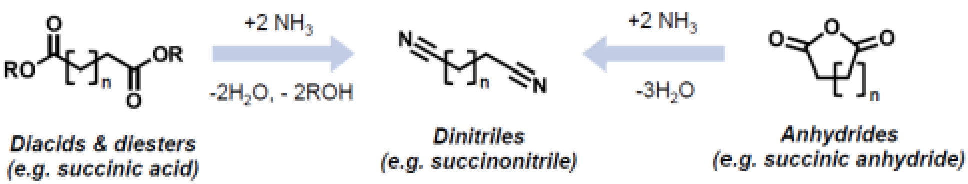
Significance and Impact

- First example of “homogeneous” renewable carbon fiber
- Potential for cheaper route to acrylonitrile

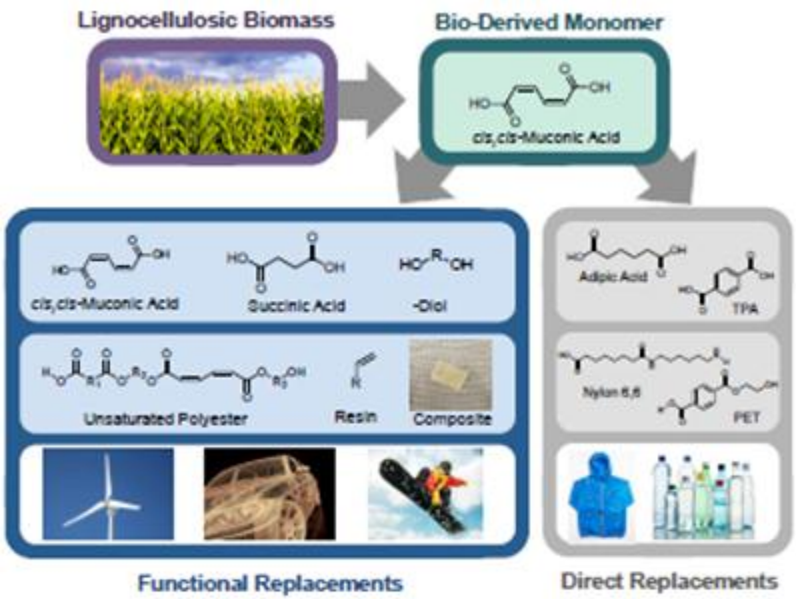
Other Examples of Innovation in Biochemicals

Other Nitrilation Applications

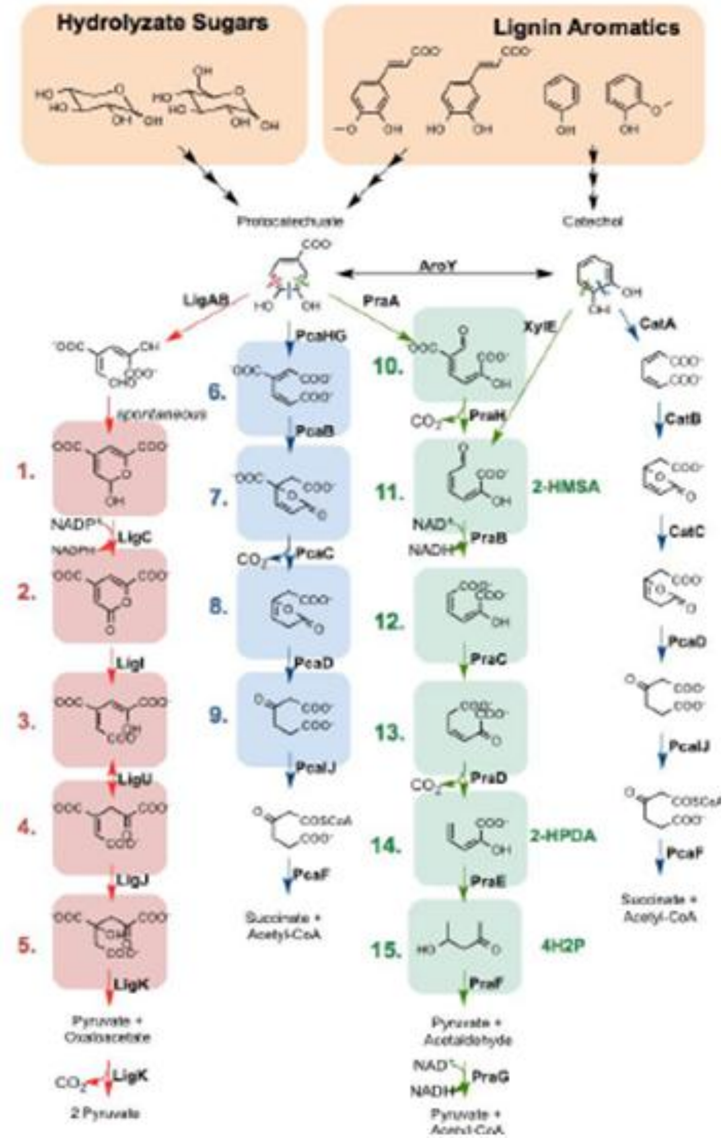
Precursors to diamines (used in nylon synthesis)



Muconic Acid as a Platform Chemical



Expanding Functional Replacements



Rorrer et al., *Green Chemistry* 2017; Advance Article (DOI: 10.1039/C7G0032OJ)
Rorrer et al., *ACS Sustainable Chem &Eng* 2016, 4(12) pp 6867-6876

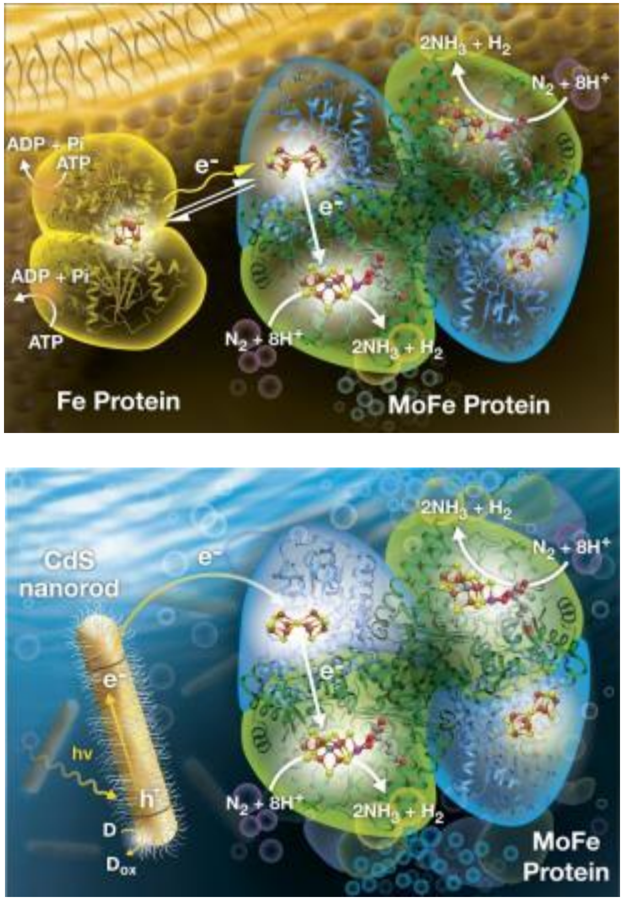
Hybrid Solar/Biology Process to Drive N_2 Reduction

Scientific Approach

- Demonstrated that cadmium sulfide (CdS) nanocrystals can be used to harvest light and energize electrons with sufficient potential to propel the reduction of N_2 into ammonia, which takes place within the nitrogenase molybdenum iron (MoFe) protein
- Rates of ammonia production were shown to be a good approximation to those of the ATP-dependent reaction

Significance and Impact

- Novel hybrid nanocrystal / protein approach to drive difficult chemical reactions
- N2 to NH3 example has huge environmental implications (vs Haber-Bosch)



Biological (top) and photobiohybrid (bottom) processes for the reduction of N_2 to ammonia by nitrogenase.

Brown, King et al., *Science* 22 Apr 2016; Vol 352, Issue 6284, pp 448-450

Energy Systems Integration

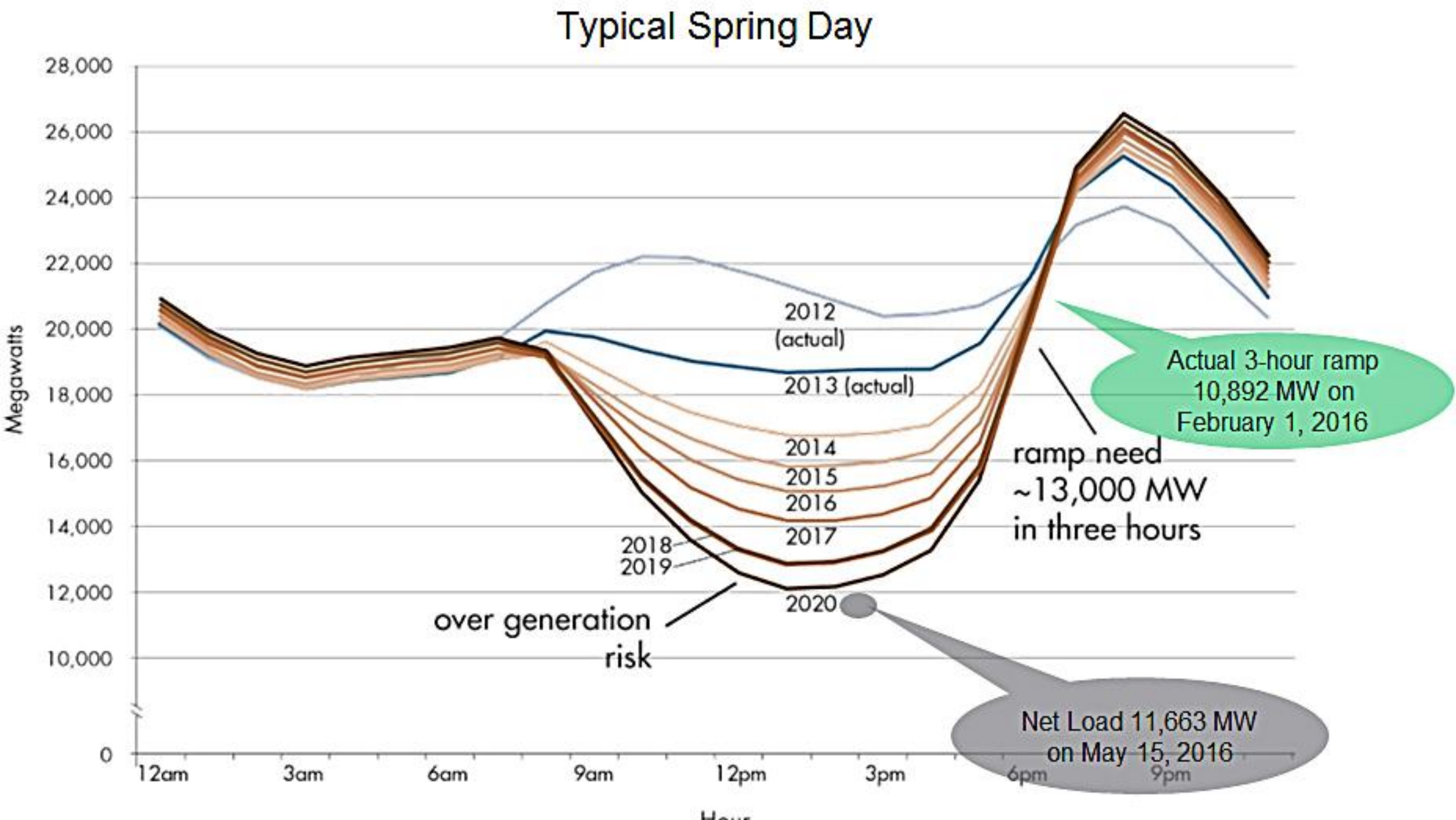
Fortifying U.S. energy infrastructure at a ***pace and scale that matters***.

ENERGY SYSTEMS INTEGRATION

Research Focus Areas

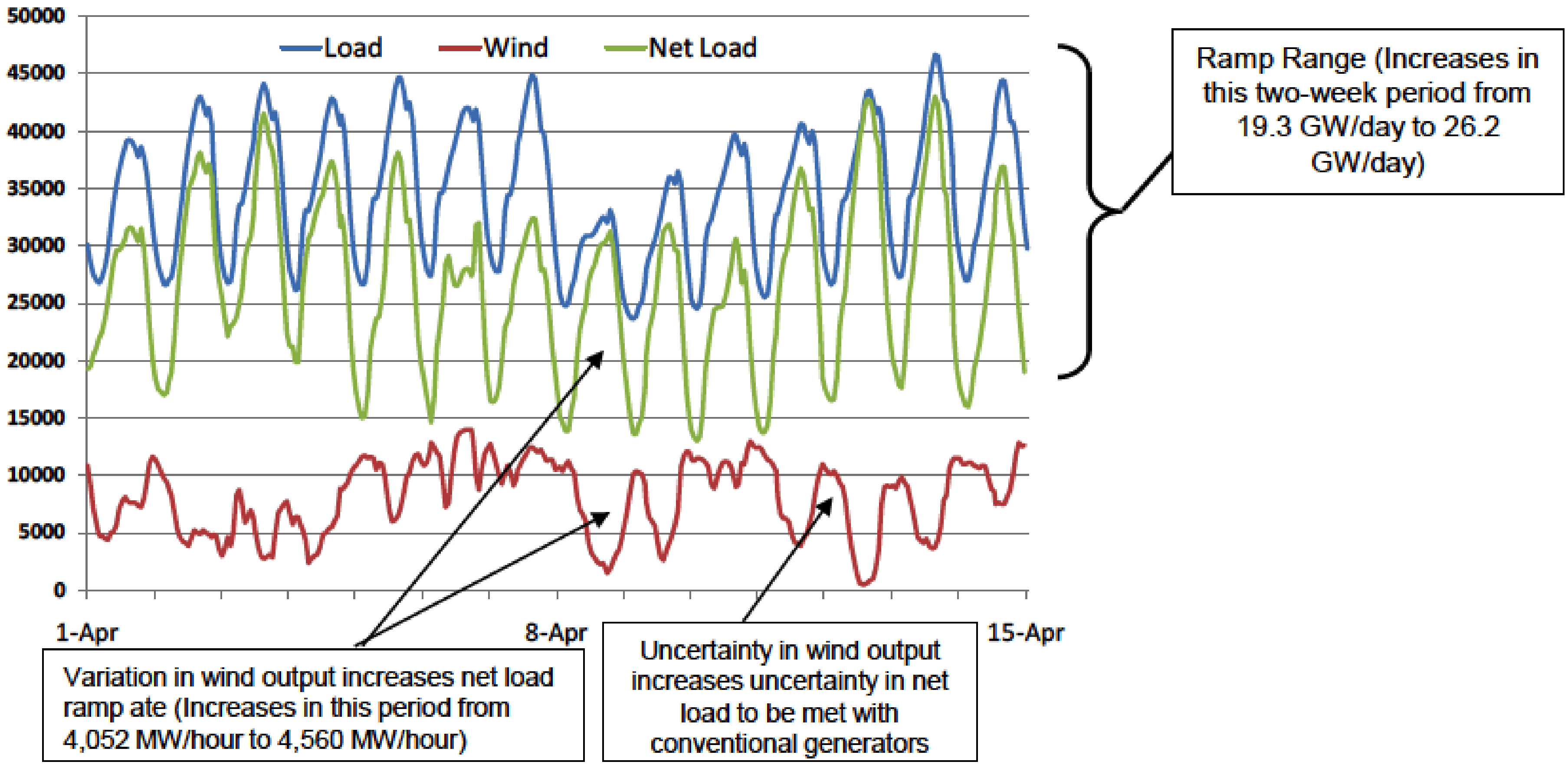
- Renewable electricity to grid integration
- Vehicle-to-grid integration
- Renewable fuels to grid integration
- Battery and thermal energy storage
- Microgrids
- Large-scale numerical simulation
- Cybersecurity and resilience
- Smart home and building systems
- Energy-water nexus
- High-performance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

High PV Penetrations Can Result in the "Duck Curve"



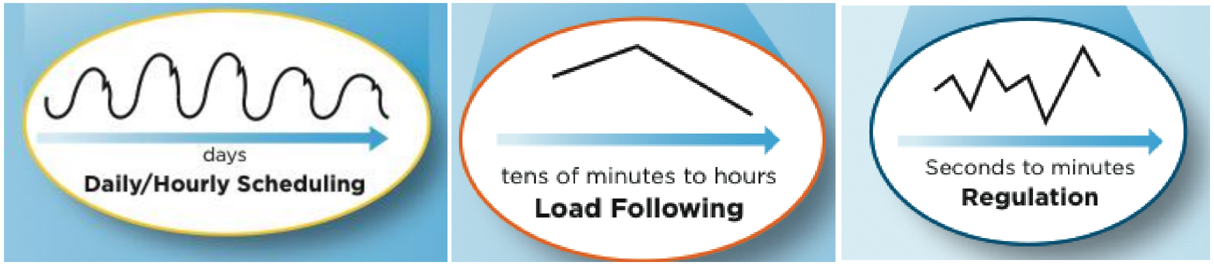
Credit: CAISO

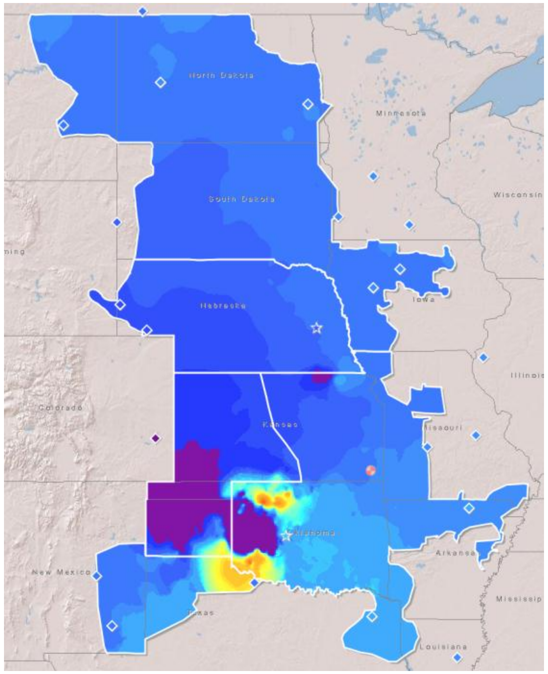
Wind and Solar Add Variability to Supply Side



Wind and solar add variability and uncertainty to the generation supply, increasing the need for grid flexibility.

Flexibility Essential to Maintaining Balance





Supply-Side Flexibility

Storage

RE Forecasts

Flexible Generation

Demand-Side Flexibility

Storage

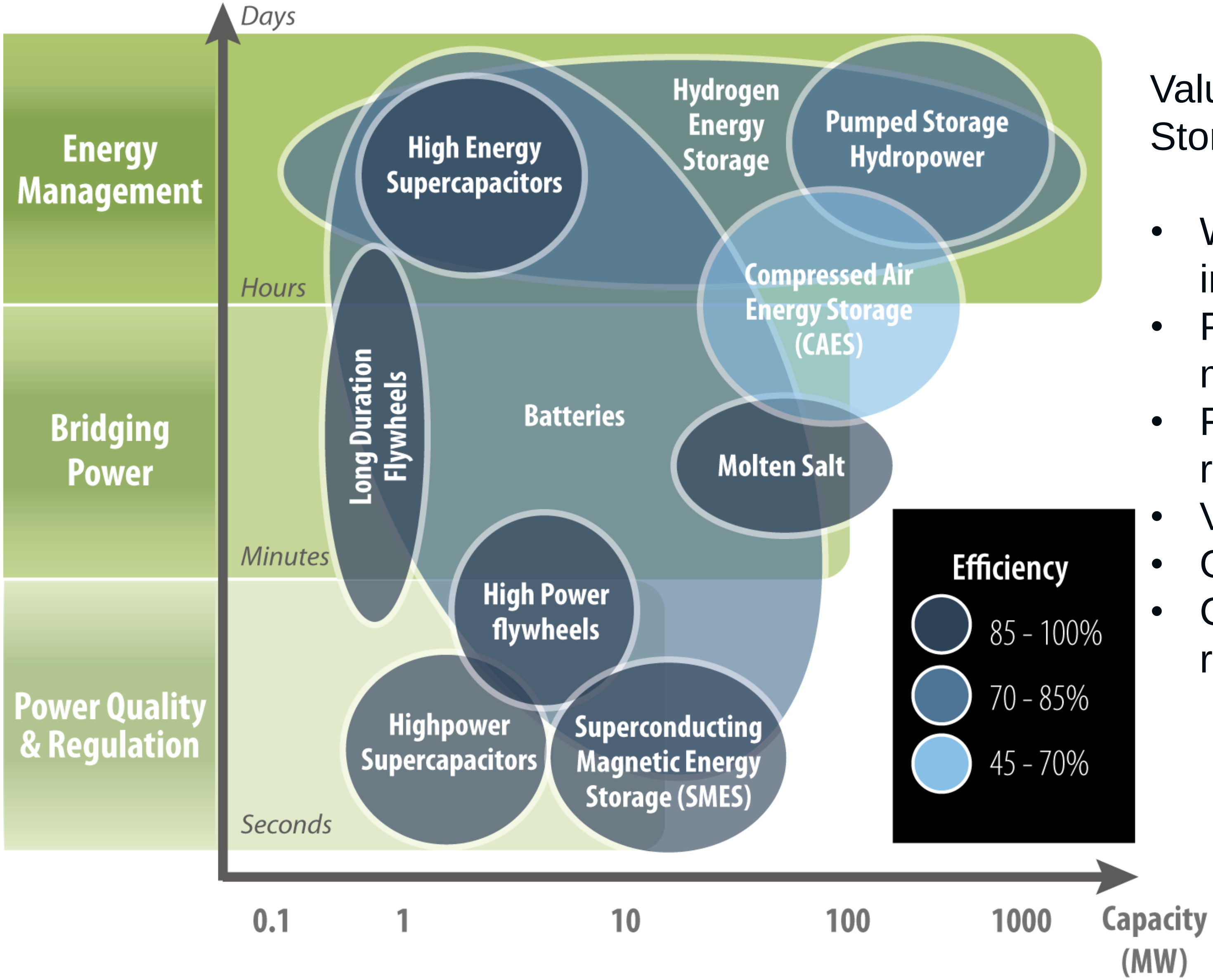
Demand Response

Smart Loads

Storage is one of many *options for providing more flexible supply and demand at multiple timescales.*

Energy storage technologies can smooth out RE supplies

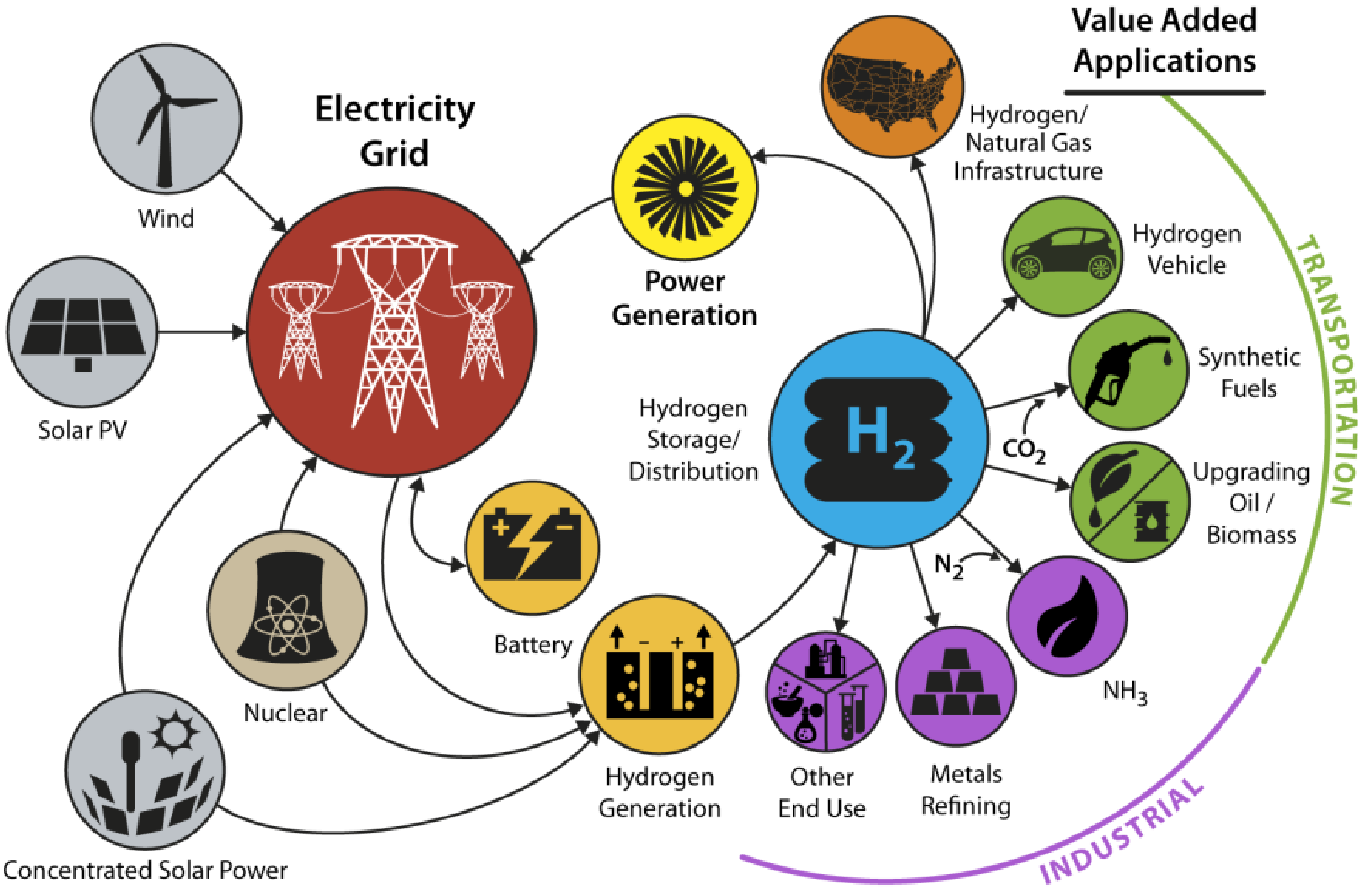
Storage Technologies and Applications



Value Streams of Storage

- Wind and solar integration
- Peak demand management
- Frequency regulation
- Voltage regulation
- Operating reserves
- Contingency reserves

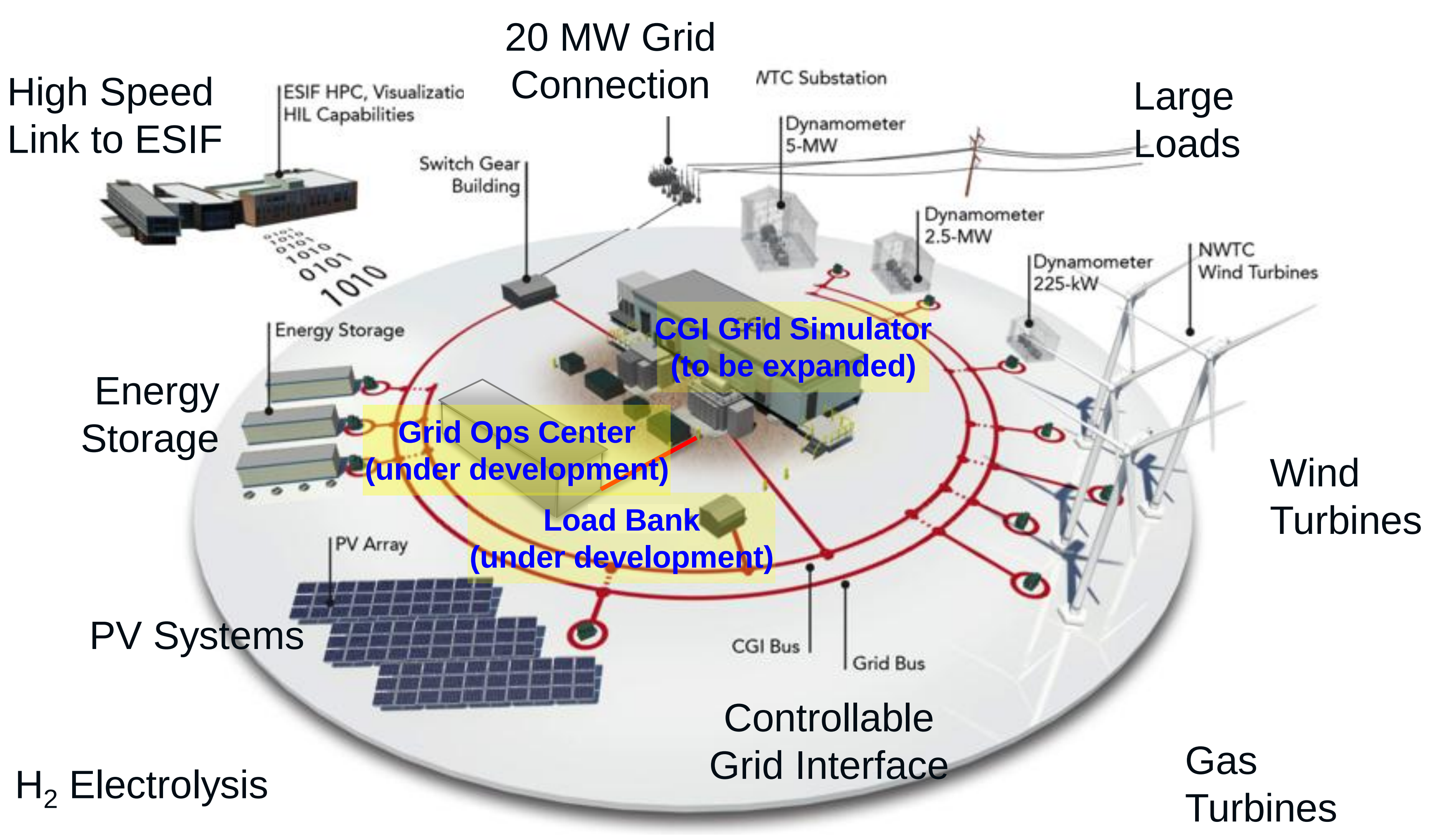
Future H2@Scale Energy System



Grid Storage Research: The Challenge of PV and PEVs

- High penetration distributed solar power and plug-in electric vehicles (PEVs) pose a integration challenge
- Storage is technically capable of solving these problems, but it's expensive and unproven
- Better tools are needed to accurately assess and validate the capabilities, effects, and value of energy storage in distributed deployments operated under different control strategies

Multi-Source Grid Integration Research



Staff expertise and research facilities enabling full-scale (1-10 MW) testing of energy systems at transmission and distribution grid levels

Advanced Energy Systems Design

What we need
for
TOMORROW

What we
have
TODAY

1MW
Island, Village

10MWs
Campus

100MWs
Community

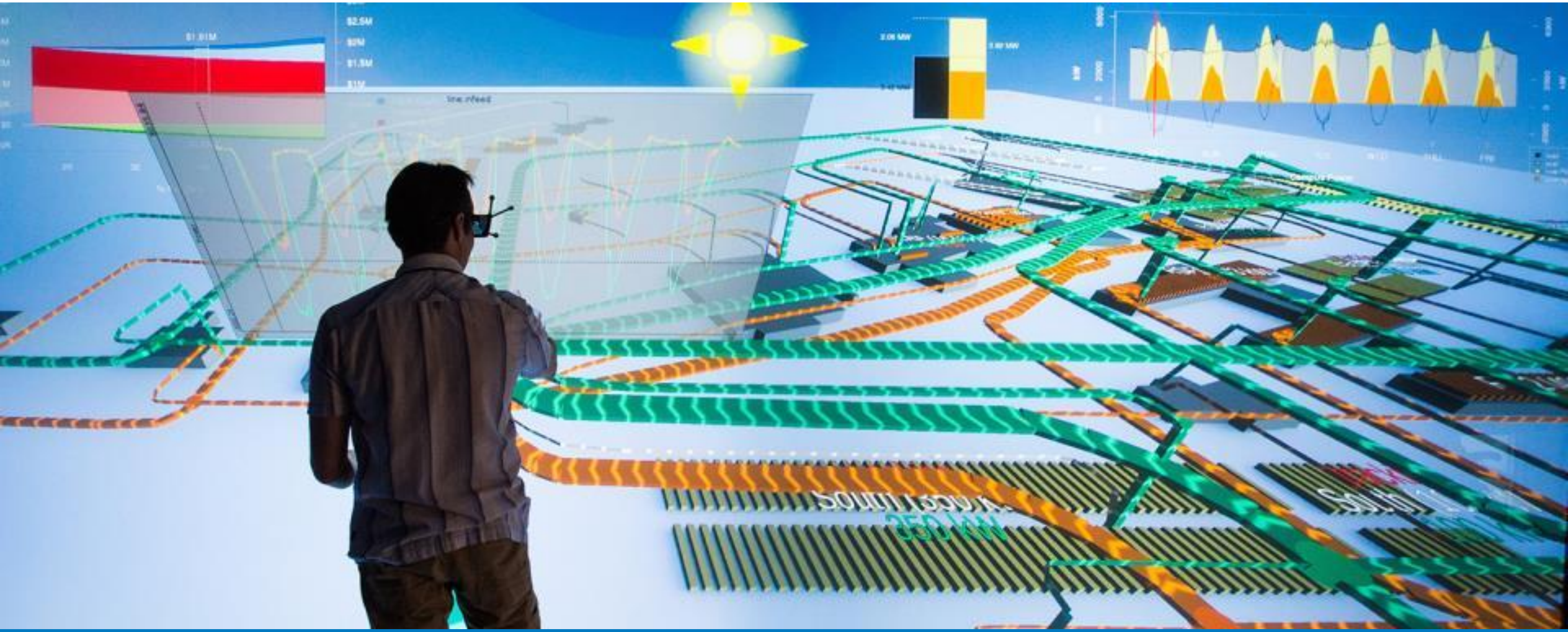
1GW
City

A systems approach to energy transformation: applicable at multiple scales, different levels of maturity

Net-zero energy communities

NREL, Panasonic & Xcel Energy Partnership

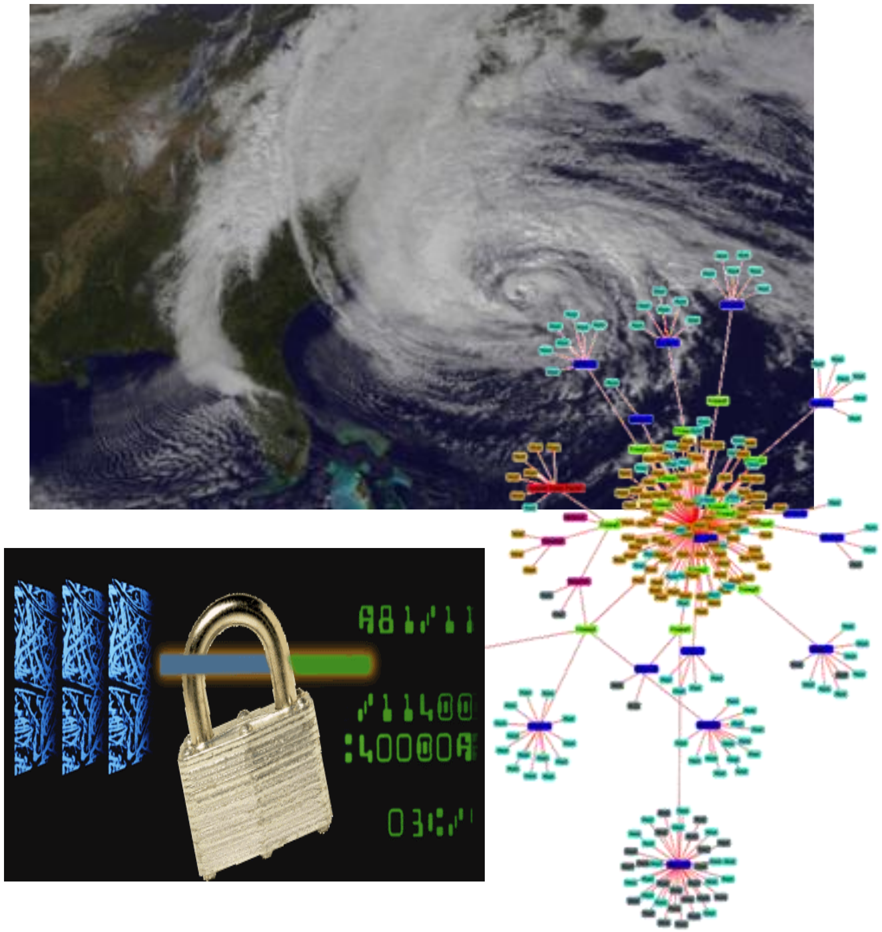
- Planned net-zero, transit-oriented community, Peña Station NEXT, near Denver International Airport
- Utilizing NREL's URBANopt system to analyze the dynamic energy consumption of corporate office and retail space, multifamily dwellings, hotel, parking, and street lighting in the planned development.
- This project will result in tools that can be applied for utility business models, demonstrate the use of multiple distributed energy resources, and create a proven model for smart city design.



Grid Security and Resilience

Improve ability to identify, protect, respond and recover from hazards and threats potentially impacting grid function

- Holistic grid security and resilience, from devices to micro-grids to systems
- Inherent security designed into components and systems, not security as an afterthought
- Security and resilience addressed throughout system lifecycle including legacy and emerging technologies
- Threat detection and response with data analytics;
- Cyber security approaches for renewables, DER and smart inverters;
- Distribution system restoration tools for natural disaster recovery; and
- Tools for improved outage forecasting from tropical cyclones and other weather events.



"The best way to predict your future is to create it."

–Abraham Lincoln