U.S. Energy Transition
Dr. Martin Keller
Director, National Renewable Energy Laboratory
40 Years of Clean Energy Research

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

World-class facilities, renowned technology experts

Nearly 750 partnerships

Campus operates as a living laboratory

National economic impact of $872 million annually
Integrated Approach to Market-Relevant Solutions

Three Pillars

- Analysis & System Integration
  - Provides market insight and informs landscape

- Innovation & Application
  - Responds to market challenges with solutions and identifies knowledge gaps

- Foundational Knowledge
  - Scientific discovery that fills gaps and disrupts current-generation technology

Market-Relevant Solutions

Impact
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.

Multilateral and bilateral programs support:

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

Lessons from international experience benefit our research and work at home.

90+ Current Partner Nations
Making Progress on a Global Scale Requires…

Investment in innovation
Integration of renewables and efficiency
Partnering across political and socio-economic barriers
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
A Real Impact on Climate Change Requires…

Deep Decarbonization
The Need is Great, and Renewables are Helping

- Energy consumption is predicted to grow **56%** by **2040**
- Energy needs are spread across many end-use sectors

In the U.S., more than half of CO₂ emissions come from industrial and transportation sectors

- Renewables are providing energy and cutting emissions, but there are challenges

Total Emissions in 2014 = 6,870 Million Metric Tons of CO2 equivalent
www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
The Changing U.S. Energy Landscape
Energy Use in the United States

U.S. Energy Consumption (2015): 97.7 Quadrillion Btu

Overall challenge: How we use energy
U.S. Energy Production and Consumption

U.S. Energy Production (2015): 83.5 Quadrillion Btu
- 21.5% Coal
- 33.4% Natural Gas
- 10.0% Nuclear
- 11.5% Renewables
- 23.6% Crude Oil

U.S. Renewable Energy Production: 9.6 Quadrillion Btu
- 2.9% Hydropower
- 2.2% Wind
- 0.5% Solar
- 0.3% Geothermal
- 5.6% Biomass

U.S. Energy Consumption (2015): 97.7 Quadrillion Btu
- 16.0% Coal
- 29.1% Natural Gas
- 8.6% Nuclear
- 9.8% Renewables
- 36.3% Petroleum

U.S. Renewable Energy Consumption: 9.6 Quadrillion Btu
- 2.5% Hydropower
- 1.9% Wind
- 0.4% Solar
- 0.2% Geothermal
- 4.8% Biomass
U.S. Energy Mix has Shifted

- In 2016, the use of natural gas and renewable energy increased in the United States:
  - Natural gas provided 29.6% of total energy supply
  - Renewable energy provided 10.4% of total energy supply

Renewables Growing Share of U.S. Generation

Renewables as a Percentage of Total U.S. Generation

Renewable Generation

GWh


Percent of Total Generation

14% 12% 10% 8% 6% 4% 2% 0%

300,000 350,000 400,000 450,000 500,000 550,000 600,000
Advanced energy technologies are providing real-world solutions. They drive a domestic energy economy with technologies that are increasingly cost-competitive with existing conventional technologies. Advanced energy manufacturing and installations also have become major opportunities for American workers in the 21st century.
Deeply Decarbonized Energy System - 2050

Deeply Decarbonized Energy System

2050 Mixed Case

- Geothermal
- Solar
- Wind
- Nuclear
- Hydro
- Biomass
- Natural Gas
- Coal
- Petroleum
- Electricity Generation
- Grid Electricity
- Power-to-Gas SNG
- Pipeline Gas
- Hydrogen Production
- Combined Heat and Power
- Biofuel Production
- Fuel Cells
- Buildings
- Industry
- Transportation
- Liquid Fuels
- Petroleum Refining
Light Duty Vehicle

Light Duty Vehicle Stock, Mixed Case

- Gasoline ICE
- Diesel ICE
- Other
- PHEV
- EV
- Hydrogen FCV

Years: 2014 to 2046

Millions of Light Duty Vehicles (LDVs)
Freight and Aviation Grow with the Economy

If Freight and Aviation Dominate Transportation Energy, Liquid Hydrocarbon Will Dominate Transportation Fuel!
Long haul transport will need low carbon fuels

Electric Vehicles likely attractive for some light duty applications but long haul will need low carbon fuels

Source: Ricard research & US DoE
80% of total U.S. electricity generation in 2050 can be sourced from renewable technologies

- Commercially available today
- In combination with a more flexible electric system.

This scenario looks at very high renewable electricity penetrations.

2014 paper follow up to Renewable Energy Futures Study:

Total U.S. electricity generation in 2015 was 1,168 GW.

<table>
<thead>
<tr>
<th>Theoretical Potential of Resources</th>
<th>Percent of Theoretical Potential of Current Installed Capacity (2015)</th>
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</thead>
<tbody>
<tr>
<td>Solar PV/CSP</td>
<td>.0073%</td>
</tr>
<tr>
<td>155,000 GW (PV)</td>
<td></td>
</tr>
<tr>
<td>38,000 GW (CSP)</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>.48%</td>
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<tr>
<td>11,000 GW (onshore)</td>
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<tr>
<td>4,200 GW (offshore to 50nm)</td>
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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.
For solar technologies, a major goal is scale up to make a significant impact—

10 terawatts by 2030,

or

~50% of world electricity 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).

**Market Impact**

- Costs: From less than $2 to $6/W
- Levelized cost of energy at 7-16 cents/kWhr
- Solar provides nearly 1% of U.S. power generation
- U.S. installed capacity at 14.8 GW
- Solar power employs more than 260,000 U.S. workers
- U.S. forecast (through 2040) is for nearly 40 GW of PV capacity in pipeline
~10 Terawatts of PV by 2030

WEO 2015 450 Scenario
→ PV at 30% of 2030 World Energy
Globally, 47 GW of new photovoltaic panels were installed in 2015.

That’s like building 10 averaged-sized nuclear reactors in one year.
U.S. Solar PV Technical Potential Nearly Double Previous Estimates

- The question: How much energy could be generated if we installed PV on all existing, suitable roof area in the US?
- Lidar-based GIS analysis, statistical modeling, and PV-generation simulations used in analysis

The total nationwide technical potential of PV from buildings of all sizes 1,118 GW of installed capacity and 1,432 TWh of annual energy generation, which equates to 39% of total national electric sales.
Research Yields Record Solar Efficiency

All multi-junction commercial cells for space and concentrator PV build on NREL inventions.

Devices with “engineered” multilayered structures have ~46% conversion efficiency.
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.
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 Potential Capacity at 110m Hub Height

35% or Higher Gross Capacity Factor
2014 Turbine Technology

Area (sq km)
- 0
- < 100
- 100 - 200
- 200 - 300
- 300 - 400
- > 400

Data sources: AWS Truepower, National Renewable Energy Laboratory

This map was produced by the National Renewable Energy Laboratory for the Department of Energy,
October 2014
Wind Energy Potential Capacity at 140m Hub Height
‘Near Future’ Turbine Technology (150W/m²)
• 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.
On-site Manufacturing

Major development for wind energy through elimination of transportation barriers

• Enables more efficient turbine design
  • Broader tower base (4.3m → 7m)
  • Larger blade root diameter

• Efficient tall towers and long blades are very difficult to achieve without on-site manufacturing

• Eliminates significant transportation costs for components for large turbines

• Leverage recent advantages in manufacturing

• Leverage National Wind Technology Center (NWTC) validation capabilities to demonstrate part quality

• Eliminates safety issues from component transport
Bioenergy, like solar, has a major push to scale up the technology—to 60 billion gallons biofuel by 2030.
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 67% 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
NREL’s Role Across the Bioenergy Value Chain

**Feedstock Supply and Logistics**
- Developing commodity-scale feedstock supply and logistics systems

**Conversion Technology Development**
- Improving conversion efficiencies, yields, and costs; demonstrating process integration

**Integrated Biorefinery Deployment**
- Systematically validating and deploying technology at first-of-a-kind facilities

**Infrastructure and End-Use**
- Evaluating vehicle emissions, performance, and deployment options

**Economic and Sustainability Analysis**
- Developing approaches to sustainability and providing public economic analyses
Impact of NREL’s Bioenergy Research

Market Impact

- U.S. produced 13.3 billion gallons of ethanol and 1.34 billion gallons of biodiesel in 2013
- Biorefineries:
  - 211 commercial corn ethanol plants
  - 115 biodiesel refineries
  - 3 commercial cellulosic ethanol plants
- Cellulosic ethanol cost parity with gasoline demonstrated by NREL/EERE at pilot scale in 2012

The cost of converting biomass into cellulosic ethanol has fallen by 67% due in part to NREL’s enzymes research and development.
Integrating Capabilities to Create Sustainable Liquid Fuels

Scientific Approach

- Fundamental understanding of protein-substrate interactions allows for rational design of superior cellulase enzymes
- Fundamental understanding of protein-substrate interactions allows for rational design of superior cellulase enzymes

Significance and Impact

- Partnered to develop, integrate, and validate technologies that enabled first-of-a-kind commercialization of cellulosic ethanol in the U.S.
Producing Carbon Fiber from Biomass

**Objective:** Cost effective production of renewable carbon fibers from lignocellulosic biomass
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
NREL Explores Integrating A Broad Portfolio of Energy Sources

NREL research shows that nuclear-renewable systems can:

- Provide clean energy to industry.
- Produce high-value goods like synthetic gasoline or desalinated water.
- Improve the operation of the electric grid.

A nuclear-renewable hybrid energy system can provide high-value goods like desalinated water.


Advanced Energy Systems Design

What we have TODAY

1MWs Island, Village

10MWs Campus

What we need for TOMORROW

100MWs Community

1GWs City

A systems approach to energy transformation: applicable at multiple scales, different levels of maturity
Future H2@Scale Energy System

- Electricity Grid
  - Wind
  - Solar PV
  - Nuclear
  - Concentrated Solar Power

Power Generation
- Hydrogen Storage/Distribution
- Battery

Hydrogen
- Other End Use
- Metals Refining
- Upgrading Oil / Biomass
- Synthetic Fuels
- Hydrogen Vehicle
- Hydrogen/Natural Gas Infrastructure

Value Added Applications
- NH₃
- N₂
- CO₂
Many Storage Technologies and Applications

Value Streams of Storage
- Wind and solar integration
- Peak demand management
- Frequency regulation
- Voltage regulation
- Operating reserves
- Contingency reserves
“The best way to predict your future is to create it.”

Abraham Lincoln
IMPACT OF NREL’S VEHICLES RESEARCH

R&D breakthroughs provide a range of efficient, high-performance, and market-viable transportation options for consumers and industry

Market Impact

- Per capita consumer fuel economy savings of $600/year
- A potential annual supply of more than 30 billion gallons of fuel from domestic biomass feedstocks.
- Electric vehicle battery cost 70% less than 2008
- Fuel efficiency standards with potential for $170 billion cost savings for commercial truck operators
- Fuel cell electric vehicle range of more than 300 miles
NREL expertise and technical innovations have developed physics-based modeling and advanced analytics to greatly improve building energy efficiency and so contribute to a doubling of U.S. energy productivity (dollars of GDP per unit of energy) during the past four decades.

**IMPACT OF NREL’S BUILDINGS RESEARCH**

- **1980s** – Modeling
- **1990s** – Codes and standards
- **2000s** – Zero-energy buildings/campuses (technology demonstration)
- **2020+** – Zero-energy districts (scale)