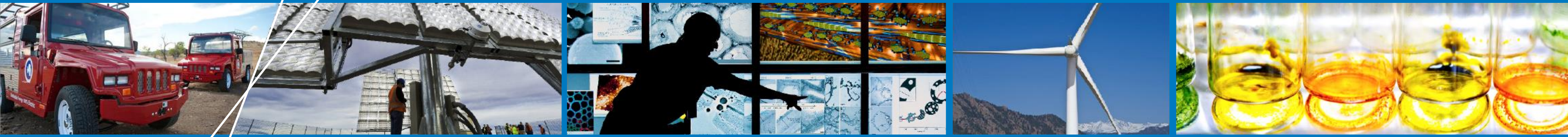
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Introduction to H2@Scale



2017 DOE Hydrogen and Fuel Cells Program Review

Bryan Pivovar (PI)

June 9, 2017

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Downtown Denver from NREL

27 September 2016 | GENEVA - A new WHO air quality model confirms that 92% of the world's population lives in places where air quality levels exceed WHO limits.

More than half US population lives amid dangerous air pollution, report warns

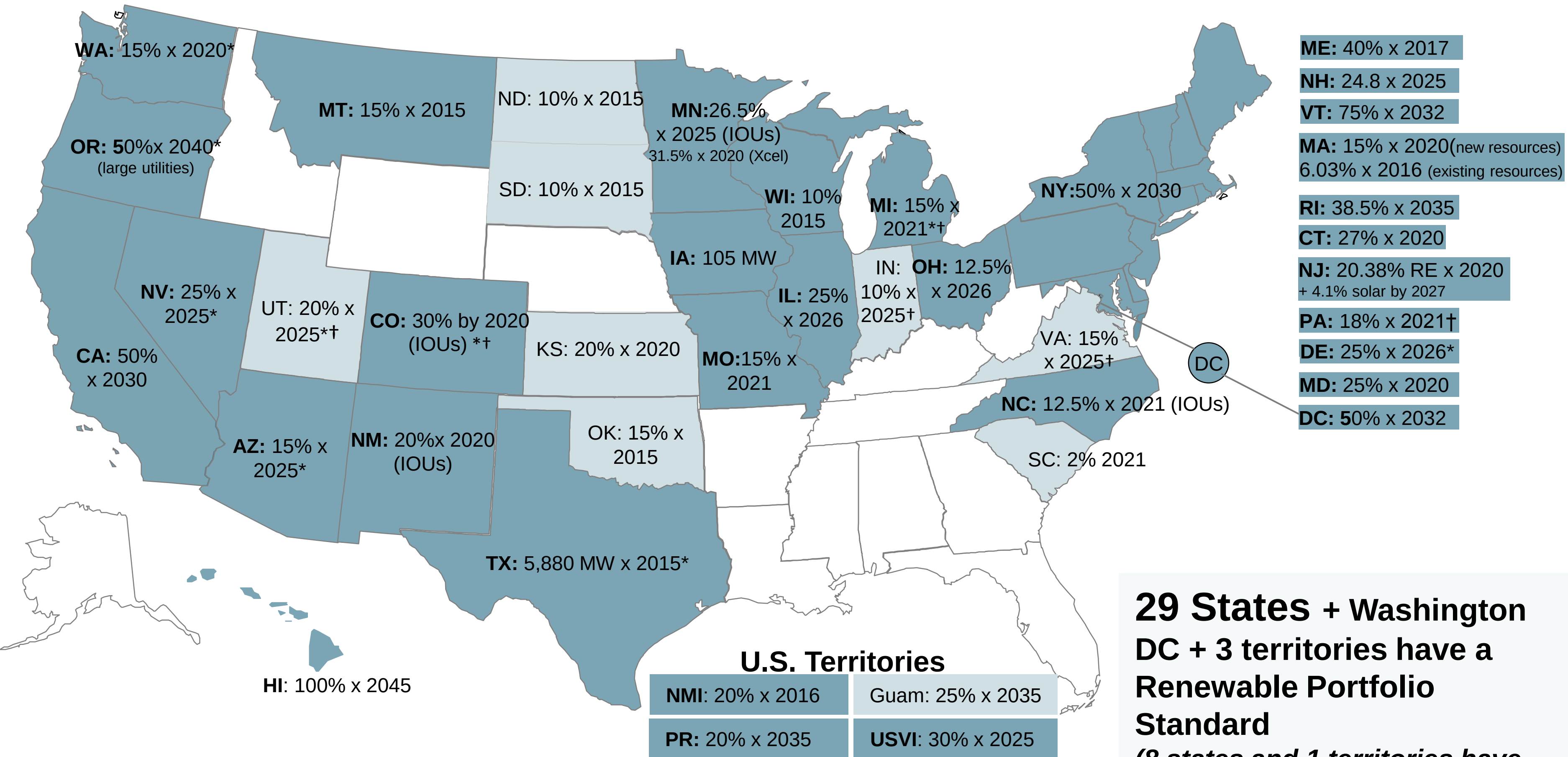
https://www.theguardian.com/environment/2016/apr/20/dangerous-air-pollution-us-population-report

Energy System Challenge

- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

How do we supply all these services in the most beneficial manner?

Changing Landscape - RPS



29 States + Washington DC + 3 territories have a Renewable Portfolio Standard

(8 states and 1 territories have renewable portfolio goals)

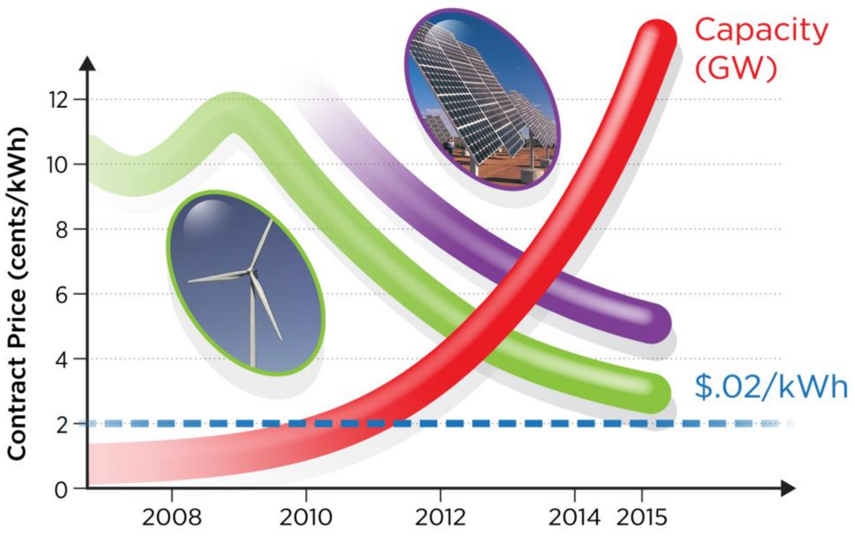
Renewable portfolio standard

Renewable portfolio goal

* Extra credit for solar or customer-sited renewables

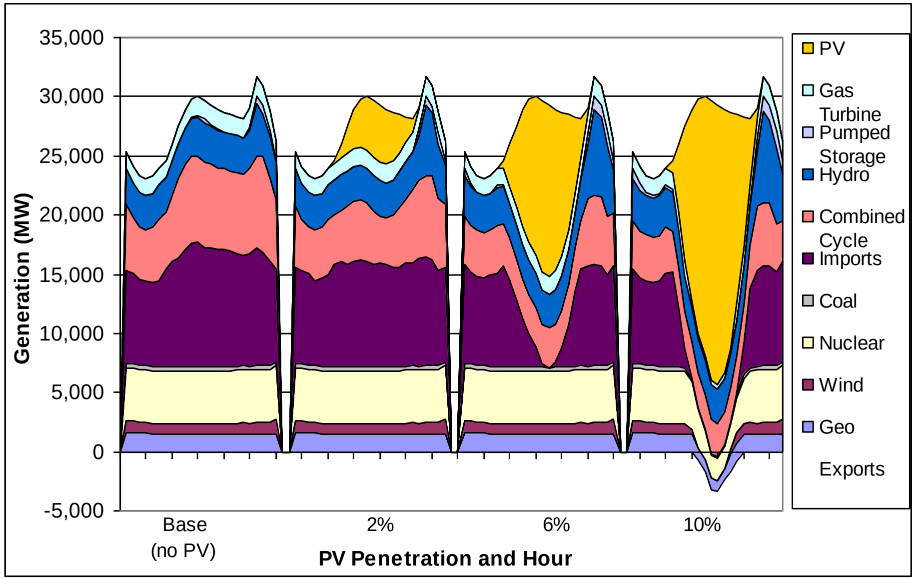
† Includes non-renewable alternative resources

Renewable Energy Impacts



Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1'15 Report, 2. DOE EERE Wind Report, 2015

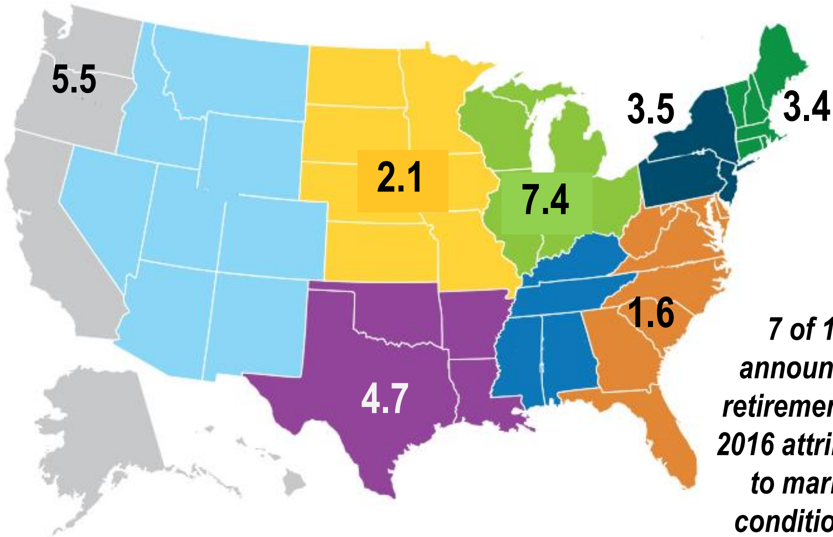
Denholm et al. 2008



Renewable Energy Impacts

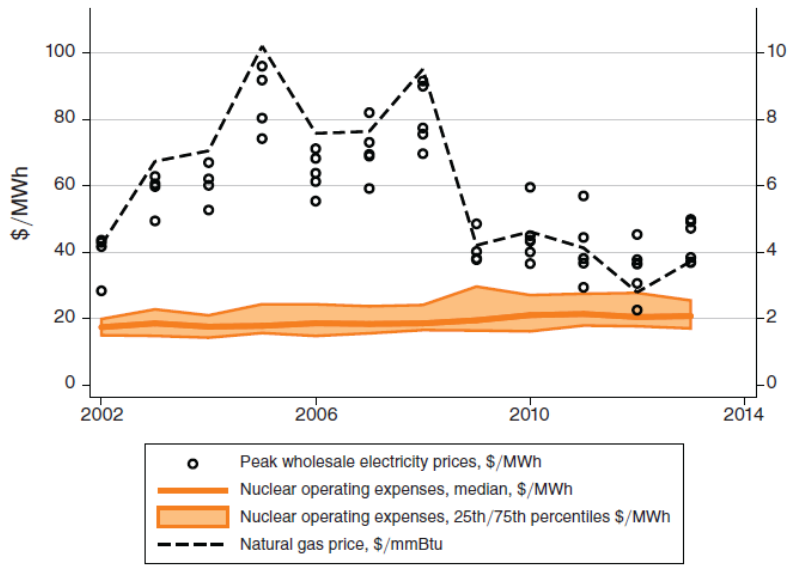
Nuclear Plants at Risk by 2030, or Recently Retired (GW) [1]

1. Source: U.S. DOE Quadrennial Energy Review, 01/2017



7 of 10 announced retirements in 2016 attributed to market conditions.[1]

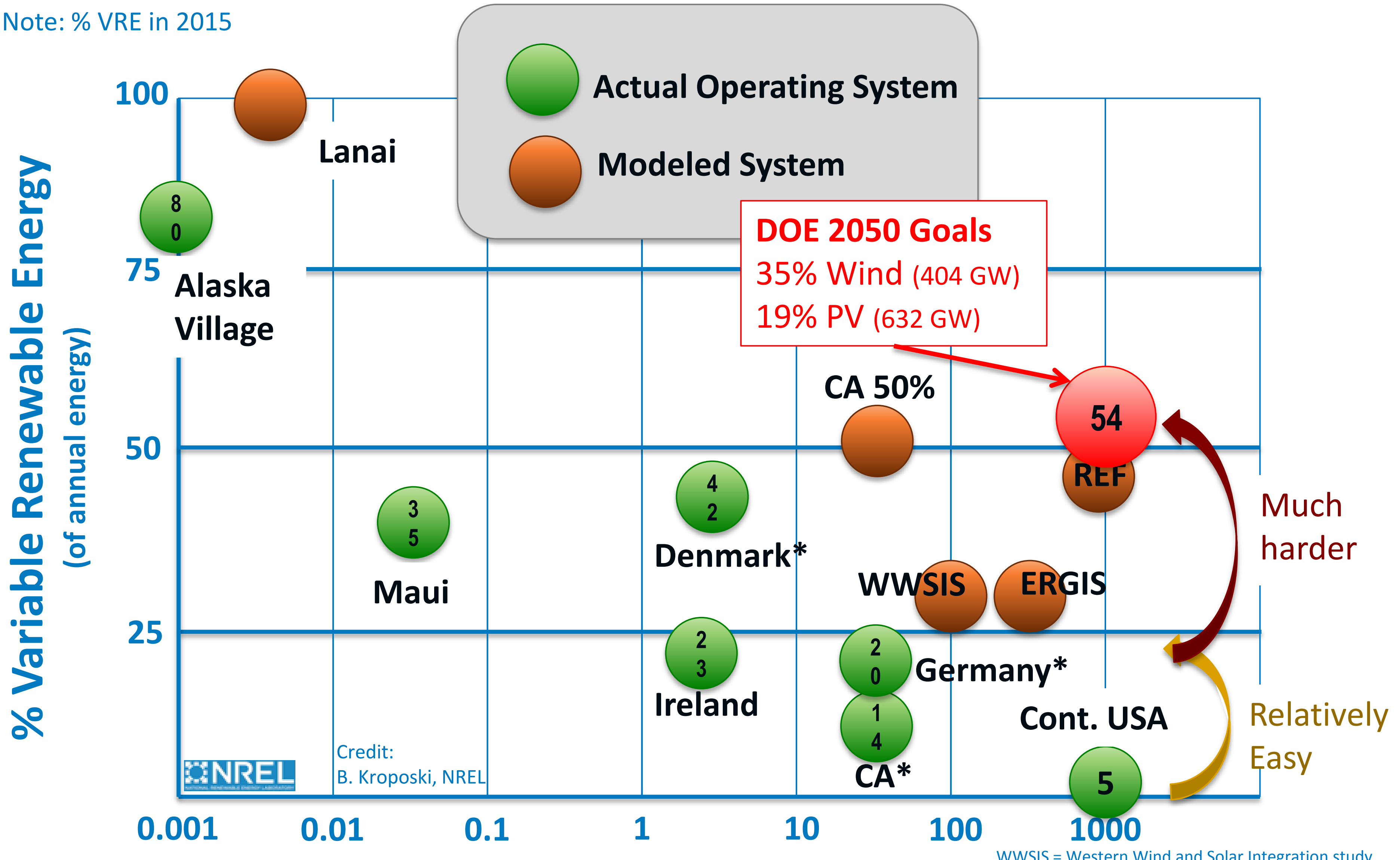
Source: L. Davis and C. Hausman, American Economic Journal, Applied Economics, 2016
Market Impacts of a Nuclear Power Plant Closure



Actual cost of electricity production by nuclear plants in the United States

What constitutes "a pace and scale that matters" for our efforts to transform clean energy systems?

Note: % VRE in 2015



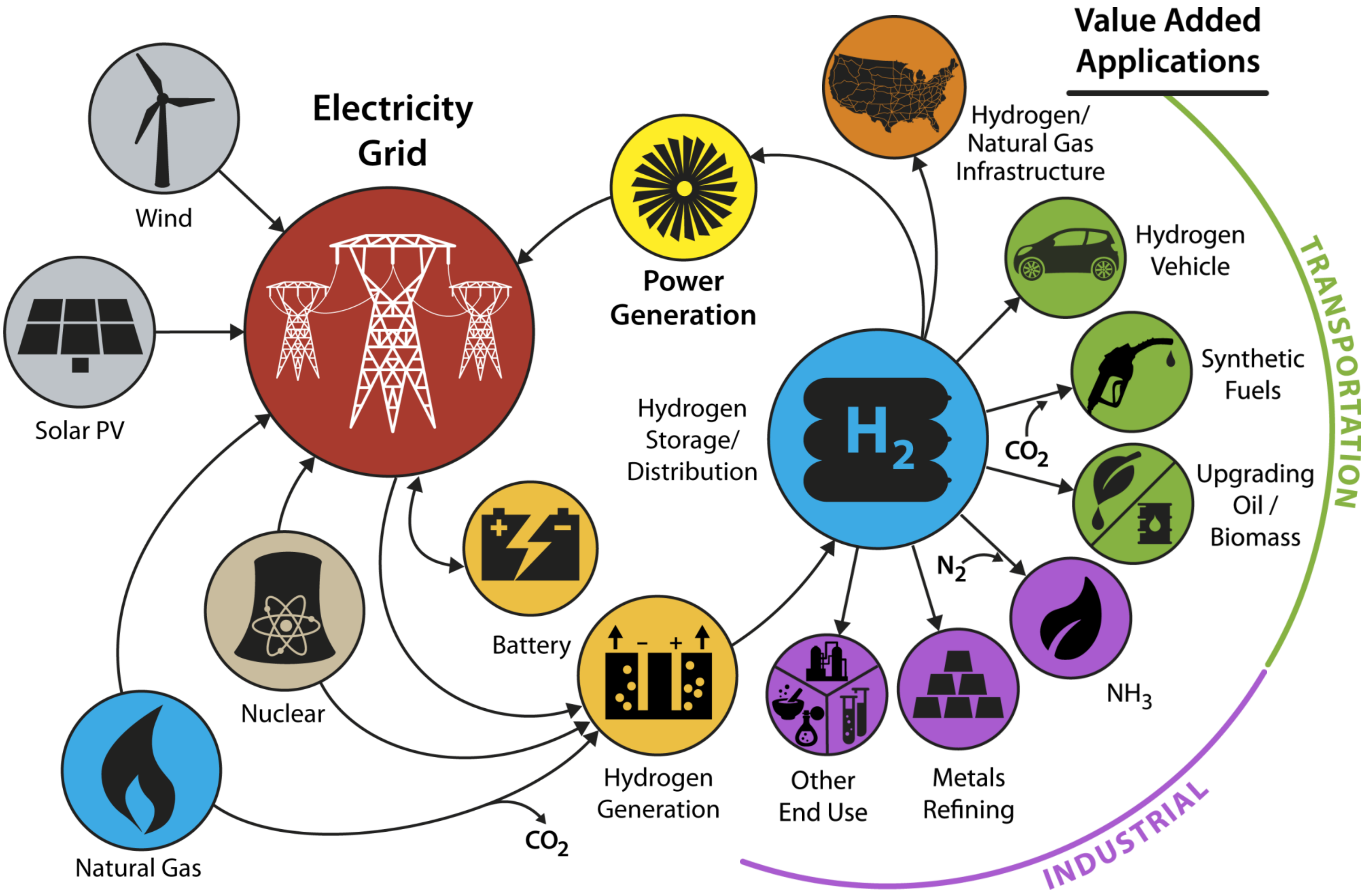
* Part of a larger synchronous AC power system

WWSIS = Western Wind and Solar Integration study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study

- **Dwight D. Eisenhower**

"If you can't solve a problem, enlarge it"

Conceptual H2@Scale Energy System*



*Illustrative example, not comprehensive

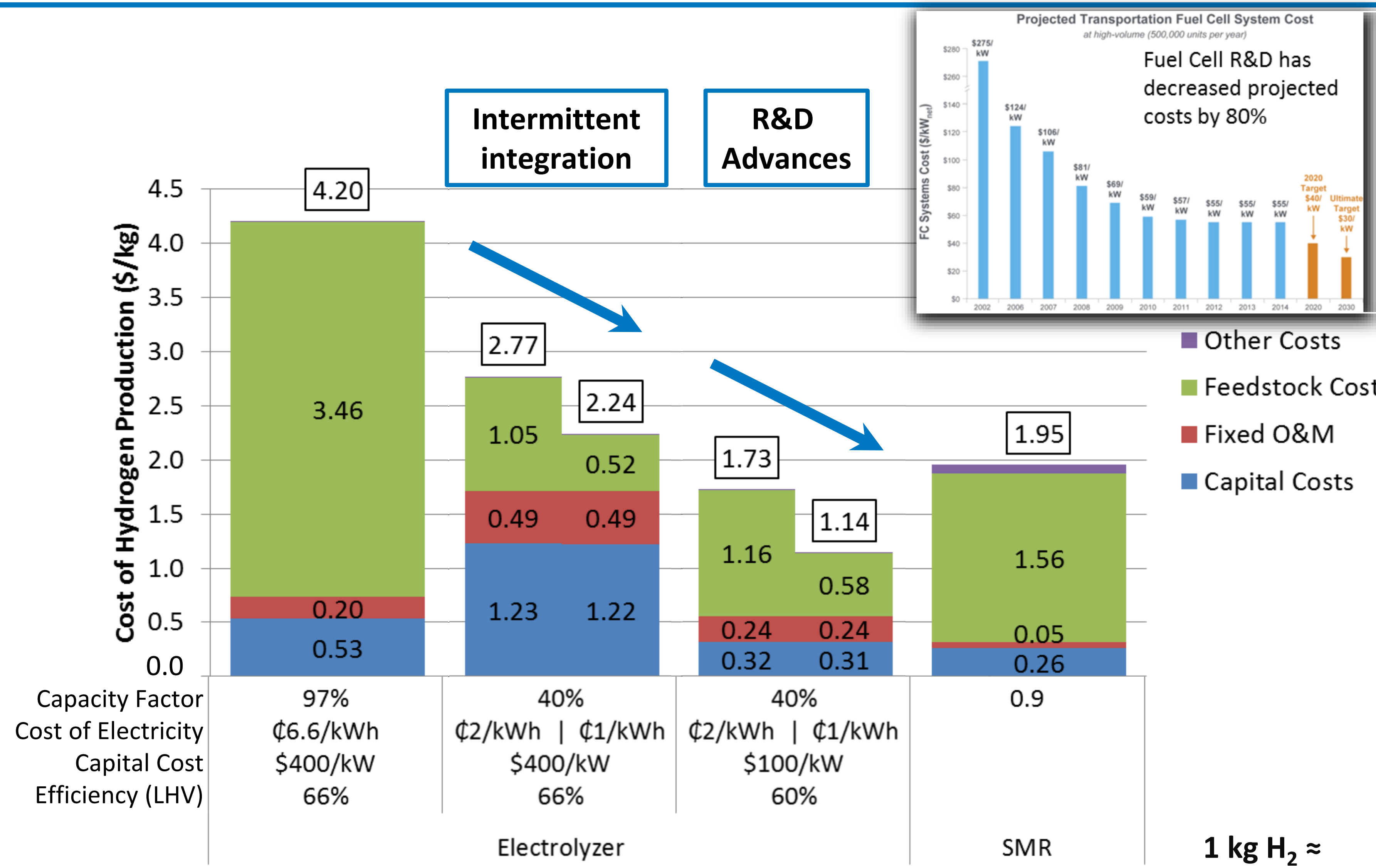
H2@Scale Vision

- **Attributes**
  - Large-scale, clean, energy-carrying intermediates for use across energy sectors
  - Increased penetration of variable renewable power and nuclear generation
  - Expanded thermal generation (nuclear, CSP, geothermal) through hybridization
  - Increased H2 from methane (carbon capture/use potential)

- **Benefits**
  - Increased energy sector jobs (GDP impact)
  - Manufacturing competitiveness (low energy costs)
  - Enhanced energy security (reduced imports, system flexibility/resiliency)
  - Enhanced national security (domestic production (metals), local resources)
  - Improved air(water) quality via reduced emissions (criteria pollutants, GHGs)
  - Decreased energy system water requirements.

Getting <u>all</u> these benefits in a single energy system significantly enhances value.

Conceptual H_2 at Scale Energy System*



1 kg H_2 ≈ 1 gallon of gasoline equivalent (gge)

H2@Scale Big Idea Teams/Acknowledgement

H2@Scale has moved beyond this National Lab team to include DOE offices, and other stakeholders.

DOE - FCTO: Neha Rustagi, John Stevens, Fred Joseck, Eric Miller, Jason Marcinksoski, Dave Peterson, James Kast, Leah Fisher; NE: Carl Sink

Steering Committee:

Bryan Pivovar (lead, NREL), Amgad Elgowainy (ANL), Richard Boardman (INL), Shannon Bragg-Sitton (INL); Adam Weber (LBNL), Rod Borup (LANL), Mark Ruth (NREL), Jamie Holladay (PNNL), Chris Moen (SNL), Don Anton (SRNL)

Low T Generation:

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High T Generation:

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Storage and Distribution:

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Utilization:

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Future Electric Grid:

Charles Hanley (lead, SNL); Art Anderson (NREL); Bryan Hannegan (NREL); Chris San Marchi (SNL); Ross Guttromson (SNL); Michael Kintner-Meyer (PNNL); Jamie Holladay (PNNL); Rob Hovsapian (INL)

Foundational Science:

Adam Weber (lead, LBNL); Voja Stamekovic (ANL); Nenad Markovic (ANL); Frances Houle (LBNL); Morris Bullock (PNNL); Aaron Appel (PNNL); Wendy Shaw (PNNL); Tom Jaramillo (SLAC); Jens Norskov (SLAC); Mark Hartney (SLAC), Vitalij Pecharsky (Ames); Alex Harris (BNL)

Analysis:

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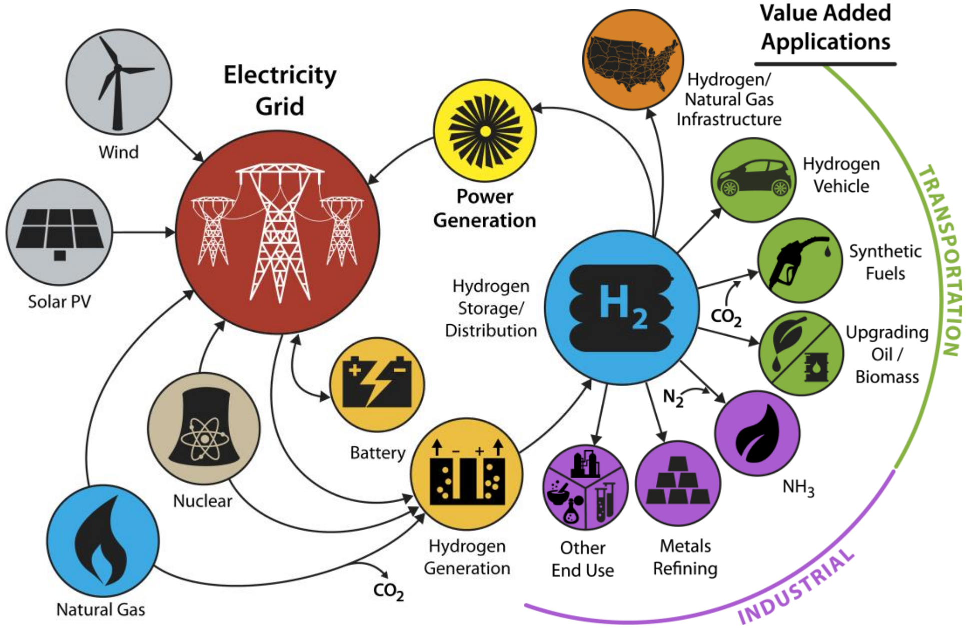
Stakeholder Groups - Workshops - Roadmaps

- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Regulators
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Big Oil, Biomass)
- Metals/Steel
- Ammonia

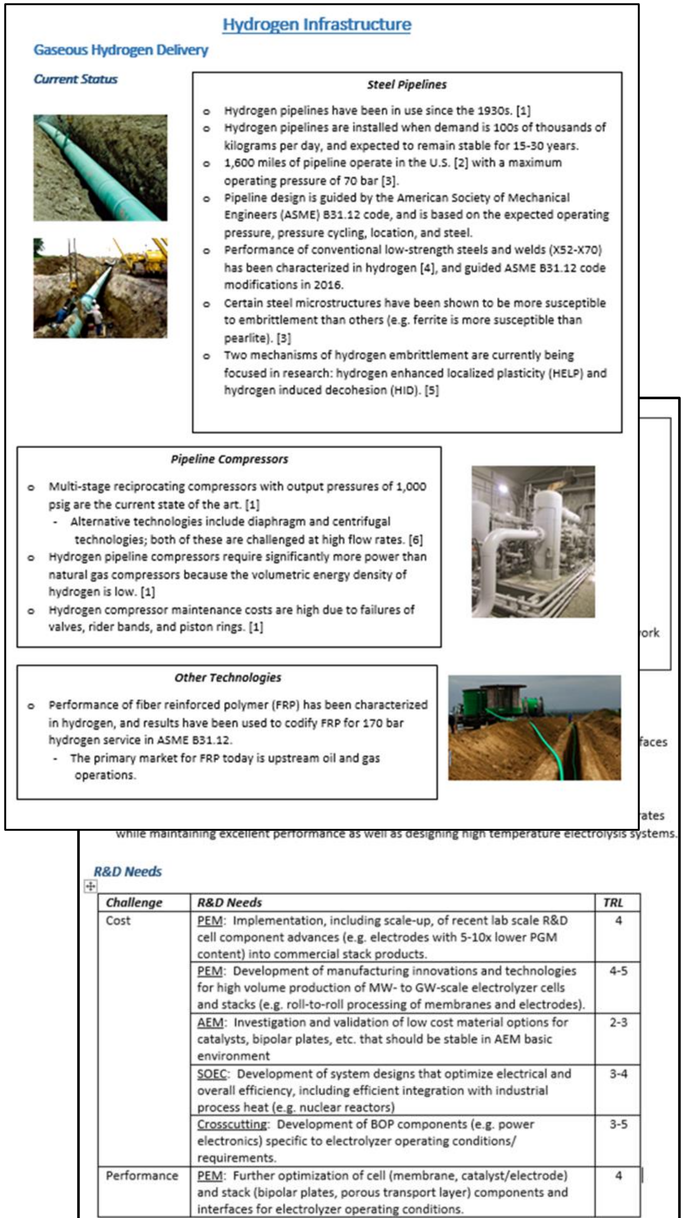
- Analysis
- Investors



Blue: High engagement and support
Green: Engaged with interest/support
Orange: Limited engagement
Black: Little engagement

H2@Scale Workshop Report available at
http://www.nrel.gov/docs/fy17osti/68244.pdf

Key Current/Next Steps



Hydrogen Infrastructure

Gaseous Hydrogen Delivery

Current Status

Steel Pipelines

- Hydrogen pipelines have been in use since the 1930s. [1]
- Hydrogen pipelines are installed when demand is 100s of thousands of kilograms per day, and expected to remain stable for 15-30 years.
- 1,600 miles of pipeline operate in the U.S. [2] with a maximum operating pressure of 70 bar [3].
- Pipeline design is guided by the American Society of Mechanical Engineers (ASME) B31.12 code, and is based on the expected operating pressure, pressure cycling, location, and steel.
- Performance of conventional low-strength steels and welds (X52-X70) has been characterized in hydrogen [4], and guided ASME B31.12 code modifications in 2016.
- Certain steel microstructures have been shown to be more susceptible to embrittlement than others (e.g. ferrite is more susceptible than pearlite). [3]
- Two mechanisms of hydrogen embrittlement are currently being focused in research: hydrogen enhanced localized plasticity (HELP) and hydrogen induced decohesion (HID). [5]

Pipeline Compressors

- Multi-stage reciprocating compressors with output pressures of 1,000 psig are the current state of the art. [1]
  - Alternative technologies include diaphragm and centrifugal technologies; both of these are challenged at high flow rates. [6]
- Hydrogen pipeline compressors require significantly more power than natural gas compressors because the volumetric energy density of hydrogen is low. [1]
- Hydrogen compressor maintenance costs are high due to failures of valves, rider bands, and piston rings. [1]

Other Technologies

- Performance of fiber reinforced polymer (FRP) has been characterized in hydrogen, and results have been used to codify FRP for 170 bar hydrogen service in ASME B31.12.
  - The primary market for FRP today is upstream oil and gas operations.

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faces

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while maintaining excellent performance as well as designing high temperature electrolysis systems.

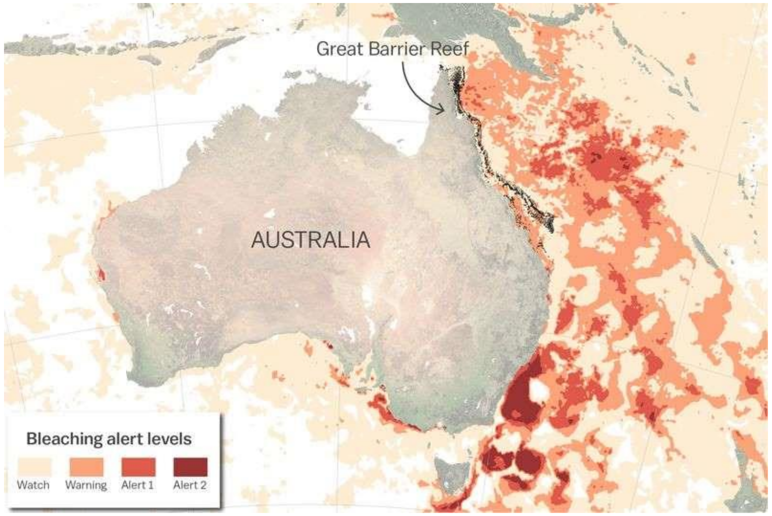
R&D Needs

Challenge	R&D Needs	TRL
Cost	PEM: Implementation, including scale-up, of recent lab scale R&D cell component advances (e.g. electrodes with 5-10x lower PGM content) into commercial stack products.	4
	PEM: Development of manufacturing innovations and technologies for high volume production of MW- to GW-scale electrolyzer cells and stacks (e.g. roll-to-roll processing of membranes and electrodes).	4-5
	AEM: Investigation and validation of low cost material options for catalysts, bipolar plates, etc. that should be stable in AEM basic environment	2-3
	SOEC: Development of system designs that optimize electrical and overall efficiency, including efficient integration with industrial process heat (e.g. nuclear reactors)	3-4
	Crosscutting: Development of BOP components (e.g. power electronics) specific to electrolyzer operating conditions/ requirements.	3-5
Performance	PEM: Further optimization of cell (membrane, catalyst/electrode) and stack (bipolar plates, porous transport layer) components and interfaces for electrolyzer operating conditions.	4

- **FY16-FY17**
  - H2@Scale Workshop to obtain feedback that guided roadmap development
  - Preliminary analysis to determine technical potential of hydrogen supply and demand
- **FY17-FY18**
  - H2@Scale Workshop to solicit feedback on draft RD&D roadmap, and identify regional and near-term opportunities to advance H2@Scale
  - H2@Scale Roadmap identifying and prioritizing RD&D needs
  - Analysis to assess potential supply and demand of H2@Scale under future market scenarios
- **June 10, 2017**
  - Review session at FCTO's Annual Merit Review to obtain feedback on technoeconomic analysis, and roadmap

Future Impact

The Great Barrier Reef's catastrophic coral bleaching, in one map



Mysterious Whale Swarms Perplexing Scientists

"Super-groups" of up to 200 humpback whales—a normally solitary species—are gathering off South Africa.

Images:
1. http://www.msn.com/en-gb/travel/news/the-great-barrier-reef%e2%80%99s-catastrophic-coral-bleaching-in-one-map/ar-BBA1t2n?li=BBoPU0T
2. http://news.nationalgeographic.com/2017/03/humpback-whales-swarms-south-africa/

Technical Backup Slides

Key H2@Scale Events - Timeline

2015

Jan — Precursor to H2@Scale focused on Hybrid Energy Systems

June — 1st Meeting of what would become H2@Scale National Lab team

Aug-Dec — Initial development of H2@Scale Vision and value proposition. Championed through Transportation Working group.

2016

Jan-Mar — H2@Scale development through NL CRO Working Group and through DOE program offices.

Apr —
1st HTAC Briefing

National Lab Chief Research Officer Meetings

Big Idea Summit

May-Oct — Engagement with various (industry) stakeholder groups.

Nov —
H2 at Scale Workshop

National Lab H2@Scale Analysis funding

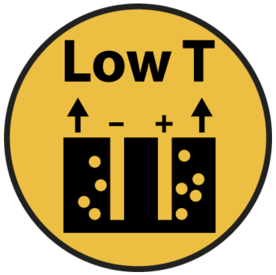
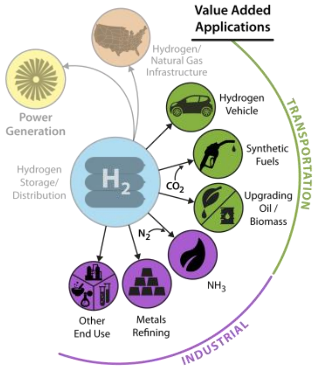
2017

Dec-Apr — Continued outreach, analysis, and focus on Roadmap development

May — **H2 at Scale Workshop**

H2@Scale webinar available at
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

What is needed to achieve H_2 at Scale?

Low and High Temperature H_2 Generation		H_2 Storage and Distribution	H_2 Utilization
 Development of **low cost, durable, and intermittent H_2** generation.	 Development of **thermally integrated, low cost, durable, and variable H_2** generation.	 Development of **safe, reliable, and economic storage and distribution** systems.	 **H_2 as game-changing energy carrier,** revolutionizing energy sectors.

Analysis

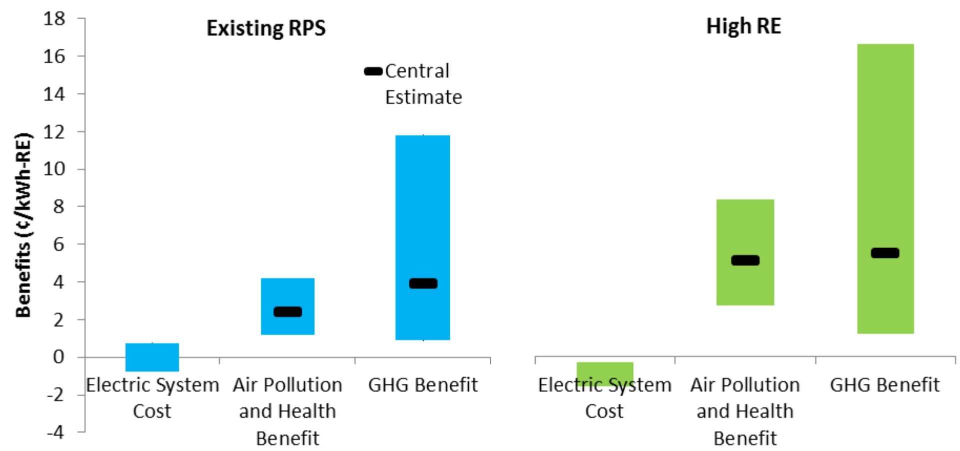
Foundational Science

Future Electrical Grid

Value Proposition Development

- **Trying to build off/follow in tracks of others**

		EXISTING RPS		HIGH RE	
RENEWABLE ENERGY IN 2050		increased by ↑ 122 GW | 296 TWh		increased by ↑ 331 GW | 765 TWh	
COSTS	ELECTRIC SYSTEM COSTS	range from -0.7% to 0.8%	equivalent to +/– $31 billion *estimates span +/- 0.75¢/kWh-RE*	range from 0.6% to 4.5%	equivalent to $23 billion– $194 billion *estimates span 0.26-1.5¢/kWh-RE*
COSTS	ELECTRICITY PRICES	range from -2.4 cents/kWh to 1 cent/kWH		range from -1.9 cents/kWh to 4.2 cents/kWH	
BENEFITS	SULFUR DIOXIDE	reduced by ↓ 6% | 2.1 million metric tons SO_2		reduced by ↓ 29% | 11.1 million metric tons SO_2	
BENEFITS	NITROGEN OXIDES	reduced by ↓ 6% | 2.5 million metric tons NO_x	equivalent to $97 billion (2.4¢/kWh-RE) *estimates span $48 billion-$175 billion (1.2-4.2¢/kWh-RE)*	reduced by ↓ 29% | 12.8 million metric tons NO_x	equivalent to $558 billion (5.0¢/kWh-RE) *estimates span $303 billion-$917 billion; 2.7-8.2¢/kWh-RE*
BENEFITS	PARTICULATE MATTER 2.5	reduced by ↓ 5% | 0.3 million metric tons $PM_{2.5}$		reduced by ↓ 29% | 1.8 million metric tons $PM_{2.5}$	
BENEFITS	GREENHOUSE GAS EMISSIONS	reduced by ↓ 6% | 4.7 billion metric tons CO_2e	equivalent to $161 billion (3.9¢/kWh-RE) *estimates span $37 billion-$487 billion (0.9-11.8¢/kWh-RE)*	reduced by ↓ 23% | 18.1 billion metric tons CO_2e	equivalent to $599 billion (5.4¢/kWh-RE) *estimates span $132 billion-$1,821 billion (1.2-16.3¢/kWh-RE)*
BENEFITS	WATER USE	reduced by ↓ 4% consumption | 3% withdrawal		reduced by ↓ 18% consumption | 18% withdrawal	
IMPACTS	NATURAL GAS	reduced by ↓ 35 quads (3.3%)	equivalent to $78 billion impact 1.9¢/kWh-RE	reduced by ↓ 46 quads (4.3%)	equivalent to $99 billion impact 0.9¢/kWh-RE
IMPACTS	RE JOB NEEDS	increase in ↑ 19% RE-employment	equivalent to 4.7 million RE job-years	increase in ↑ 47% RE-employment	equivalent to 11.5 million RE job-years



[A Prospective Analysis of the Costs, Benefits, and Impacts of U.S. Renewable Portfolio Standards](http://www.nrel.gov/docs/fy17osti/67455.pdf)
NREL/TP-6A20-67455
http://www.nrel.gov/docs/fy17osti/67455.pdf