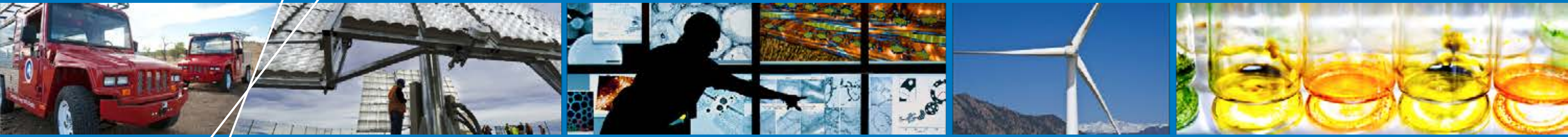
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Introduction to H2@Scale



2017 DOE Hydrogen and Fuel Cells Program Review

Bryan Pivovar (PI)

June 8, 2017

TV044

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

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.

Overview

- While H2@Scale analysis is currently being funded (FCTO/NE) it will be presented by Mark Ruth in next talk (TV045).
- Focus of this talk (which is not a currently funded project and not being reviewed – although input is always solicited) is an overview/introduction to the continually evolving H2@Scale vision.
- H2@Scale: Providing Energy System-Wide (Economic, Security, and Environmental) Benefits through Increased Hydrogen Implementation

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

Background

H_2 at Scale a National Lab led 'Big Idea'

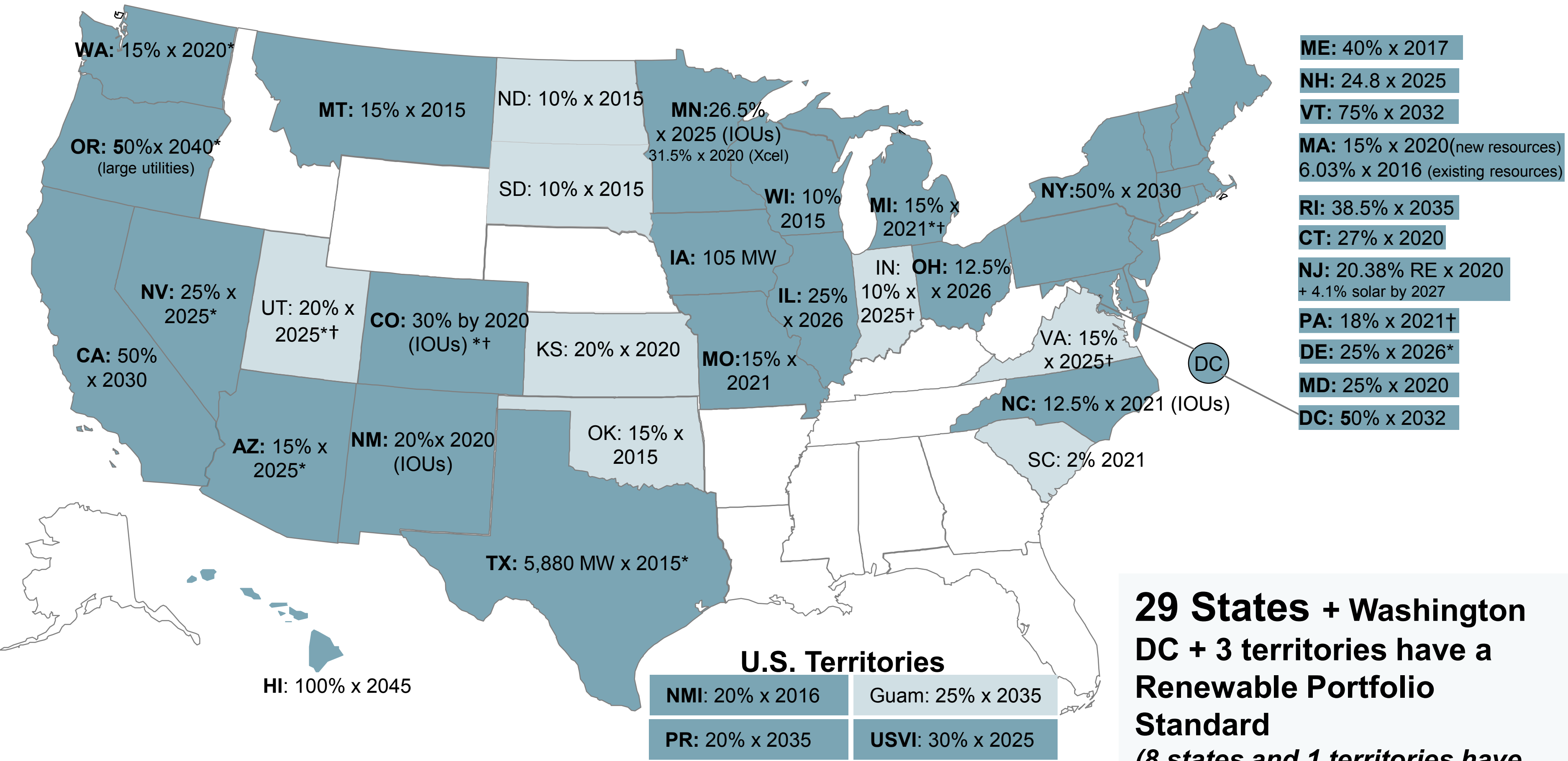
- 'Big Ideas' are identified by National Lab teams as high impact areas that are currently underemphasized or missed within DOE portfolio
- Culminate in a DOE/National Lab Big Idea Summit (H2@Scale presented April 22, 2016)
- Have led to large programs, increased visibility for specific topics

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

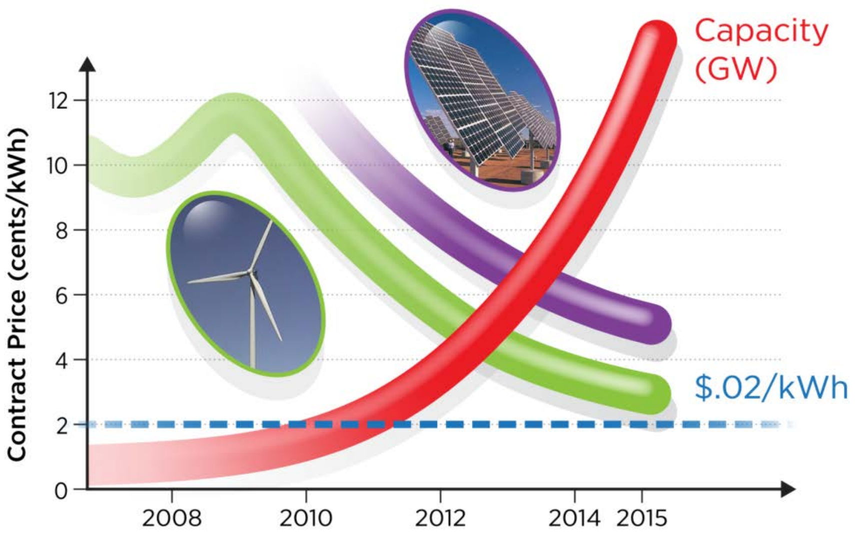
(8 states and 1 territories have renewable portfolio goals)

- Renewable portfolio standard
- Renewable portfolio goal

* Extra credit for solar or customer-sited renewables

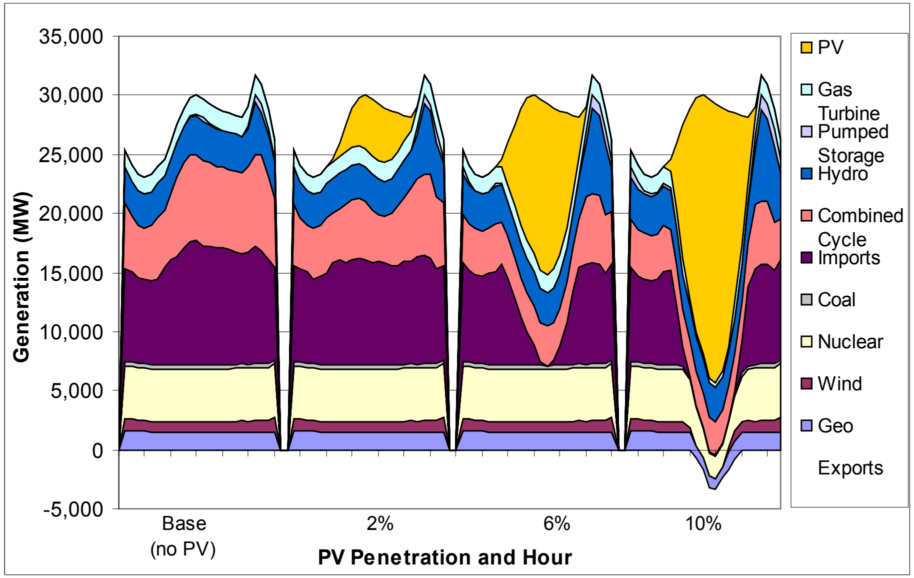
† Includes non-renewable alternative resources

Renewable Energy Impacts



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

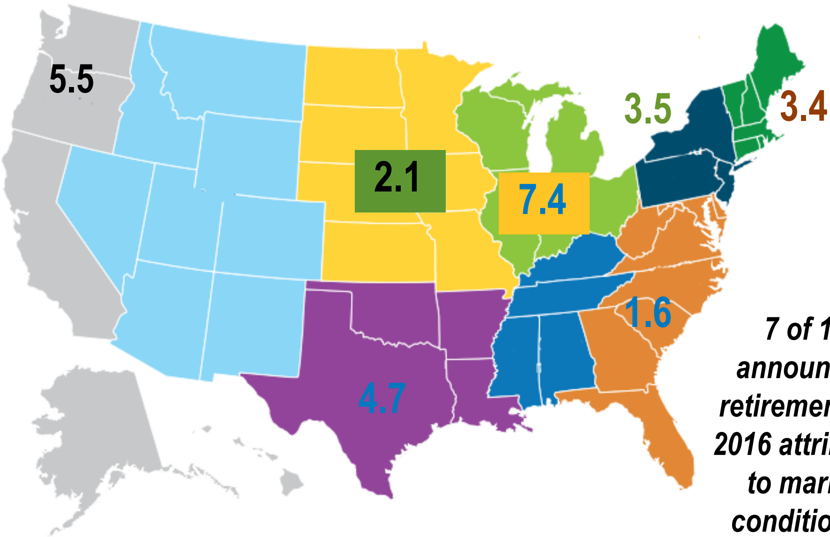
Denholm et al. 2008



Renewable Energy Impacts

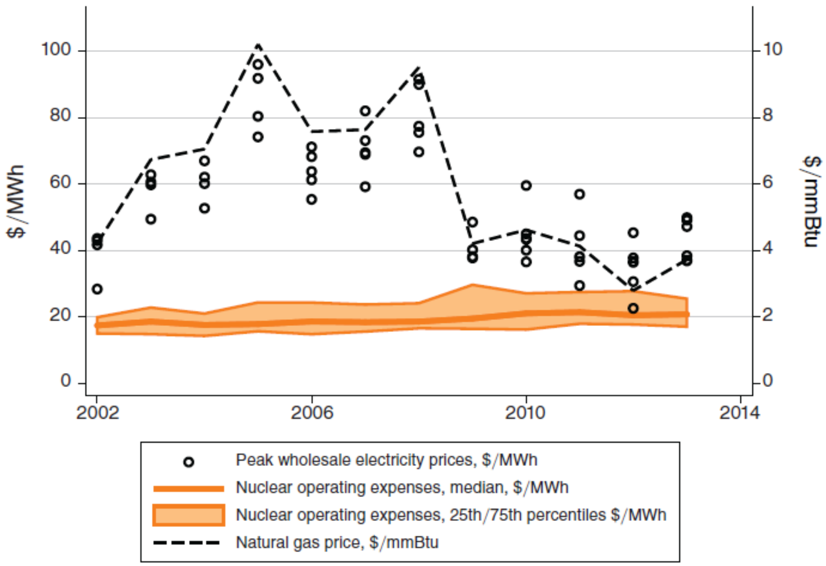
Nuclear Plants at Risk by 2030, or Recently Retired (GW) [1]

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



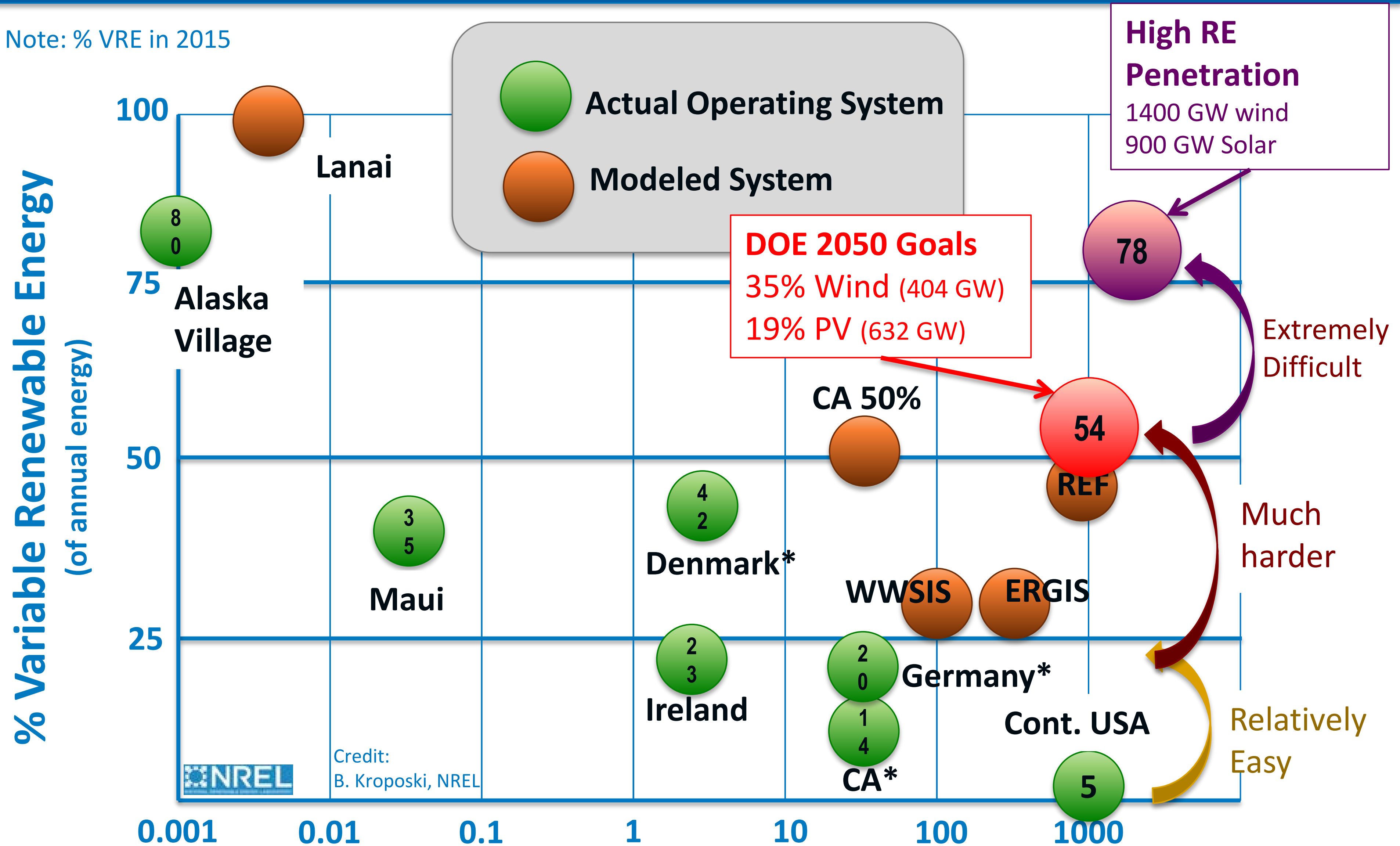
7 of 10 announced retirements in 2016 attributed to market conditions.[1]

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?



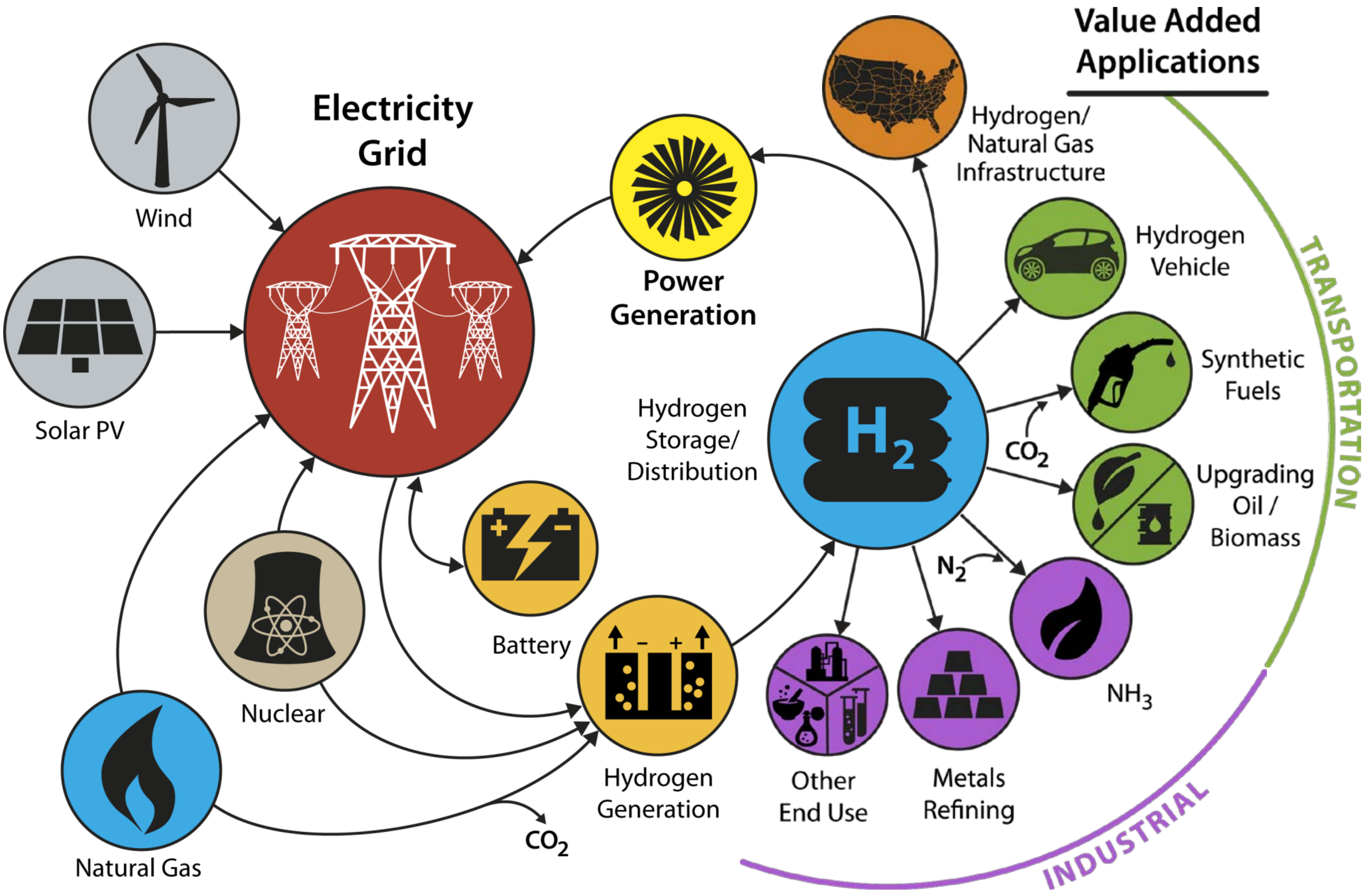
* Part of a larger synchronous AC power system

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

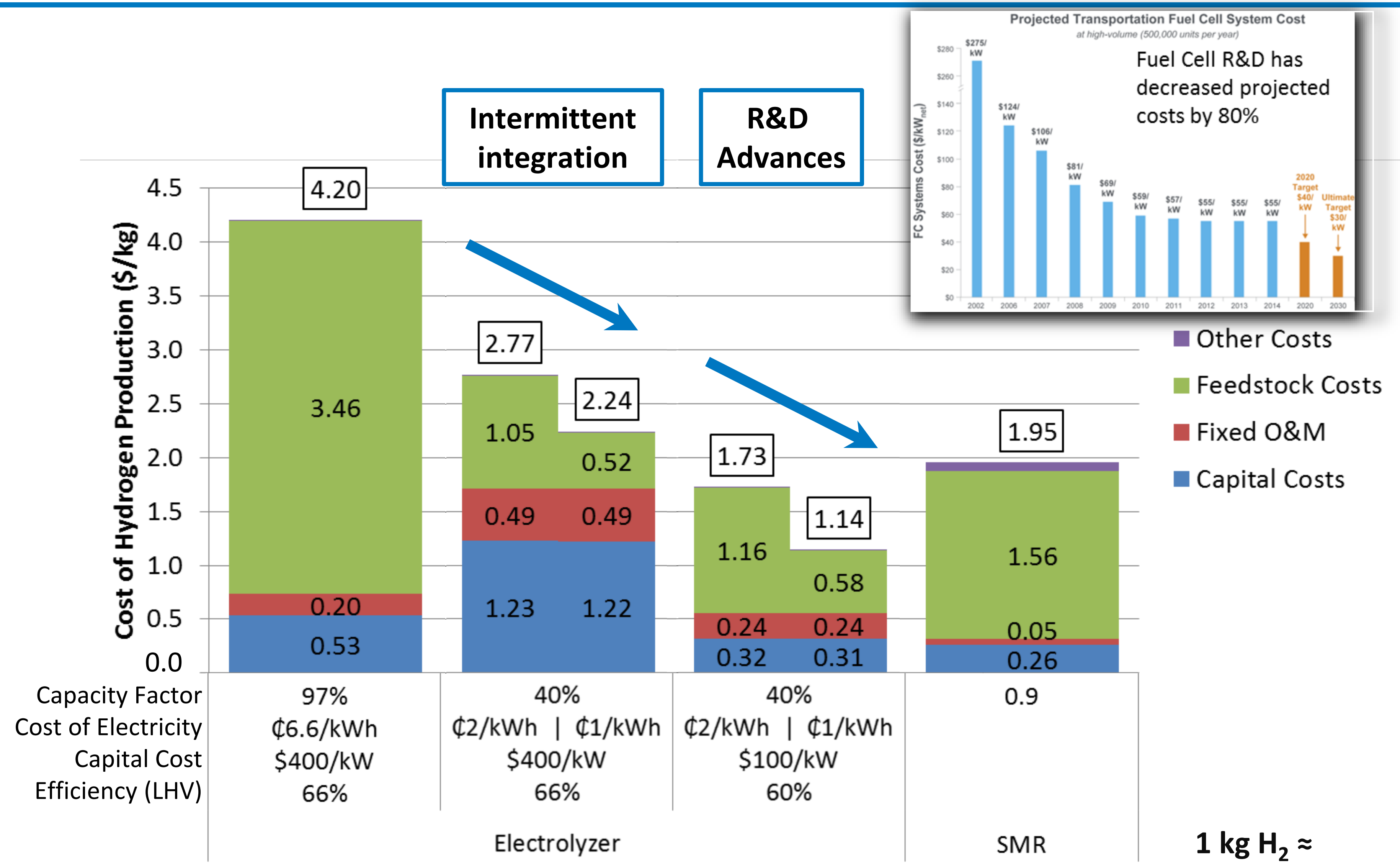
H2@Scale Vision

- **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 all 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:

Rod Borup (lead, LANL); Jamie Holladay (PNNL); Christopher San Marchi (SNL); Hector Colon Mercado (SRNL); Kevin Harrison (NREL); Ted Krause (ANL); Adam Weber (LBNL); David Wood (ORNL)

High T Generation:

Jamie Holladay (lead, PNNL); Jim O'Brien (INL); Tony McDaniel (SNL); Ting He (INL); Mike Penev (NREL); Bill Summers (SRNL); Maximilian Gorensek (SRNL); Jeffery Stevenson (PNNL); Mo Khaleel (ORNL)

Storage and Distribution:

Don Anton (lead, SRNL); Chris San Marchi (SNL); Kriston Brooks (PNNL); Troy Semelsberger (LANL); Salvador Aceves (LLNL); Thomas Gennett (NREL); Jeff Long (LBNL); Mark Allendorf (SNL); Mark Bowden PNNL; Tom Autrey PNNL

Utilization:

Richard Boardman (lead, INL); Don Anton (SRNL); Amgad Elgowainy (ANL); Bob Hwang (SNL); Mark Bearden (PNNL); Mark Ruth (NREL); Colin McMillan (NREL); Ting He (INL); Michael Glazoff (INL); Art Pontau (SNL); Kriston Brooks (PNNL); Jamie Holladay (PNNL); Christopher San Marchi (SNL); Mary Biddy (NREL) ; Geo Richards (NETL)

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)

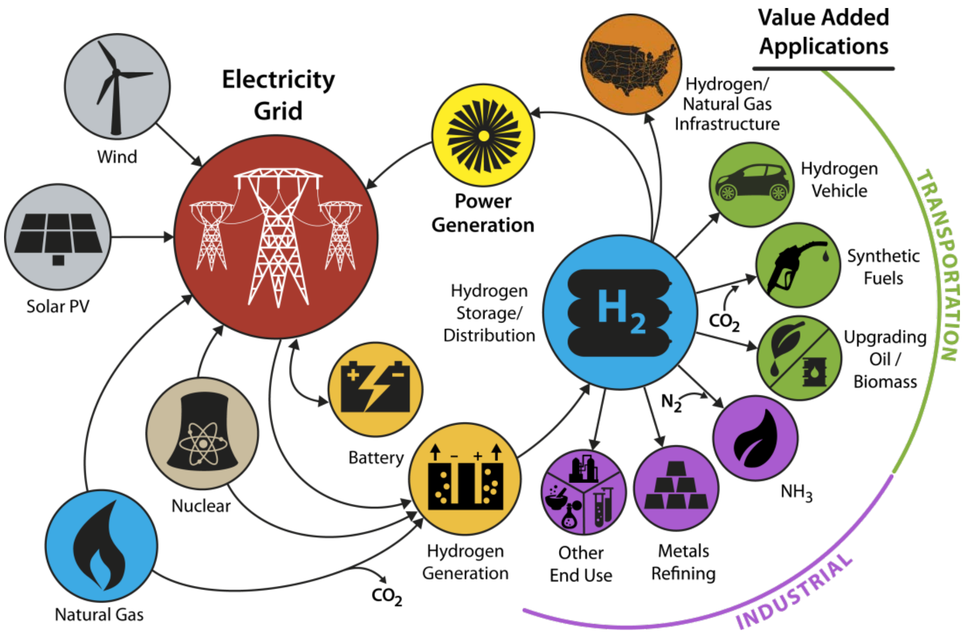
Analysis:

Mark Ruth (lead, NREL); Amgad Elgowainy (co-lead, ANL); Josh Eichman (NREL); Joe Cordaro (SRNL); Salvador Aceves (LLNL); Max Wei (LBNL); Karen Studarus (PNNL); Todd West (SNL); Steve Wach (SRNL); Richard Boardman (INL); David Tamburello (SRNL); Suzanne Singer (LLNL)

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

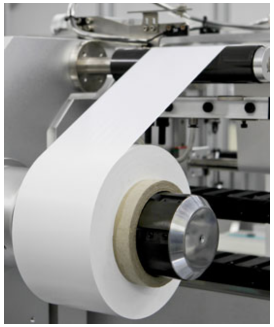
H2@Scale 2016 Workshop

Nuclear

Hybridization with electrolyzers to improve economics

Solar Power

Storage of heat in metal hydride beds



Manufacturing

Lower cost of H_2 production, and develop value-add applications

Fossil Energy

H_2 can be produced through coal gasification and chemical looping

Bioenergy

H_2 is necessary for biofuel production, and can also be produced from bio-oil and biogas

Geothermal Power

H_2 can be recovered from geothermal steam, and electrolyzers can be integrated with geothermal power

Low and High Temperature Hydrogen Production

Low T Foundational Research Needs

- Discovery and development of membranes and catalysts that minimize the use of precious metals
- Determination of impact of intermittent operation on electrolyzers with low PGM loading
- Development of manufacturing technologies (e.g. roll-to-roll processing) and balance of plant components (e.g. electronics)

Workshop Findings

- Expected use profiles and scales of electrolyzers for grid stability should be defined
- Regulatory framework necessary to value electrolyzers in grid services
  - ✓ Stakeholder education is important
  - ✓ Value proposition over conventional solutions must be more specifically defined

High T Foundational Research Needs

High-temperature Electrolysis

- Elucidation of degradation mechanisms
- Development of materials for durable high current density operation
- Determination and improvement of load following capability

Thermochemical

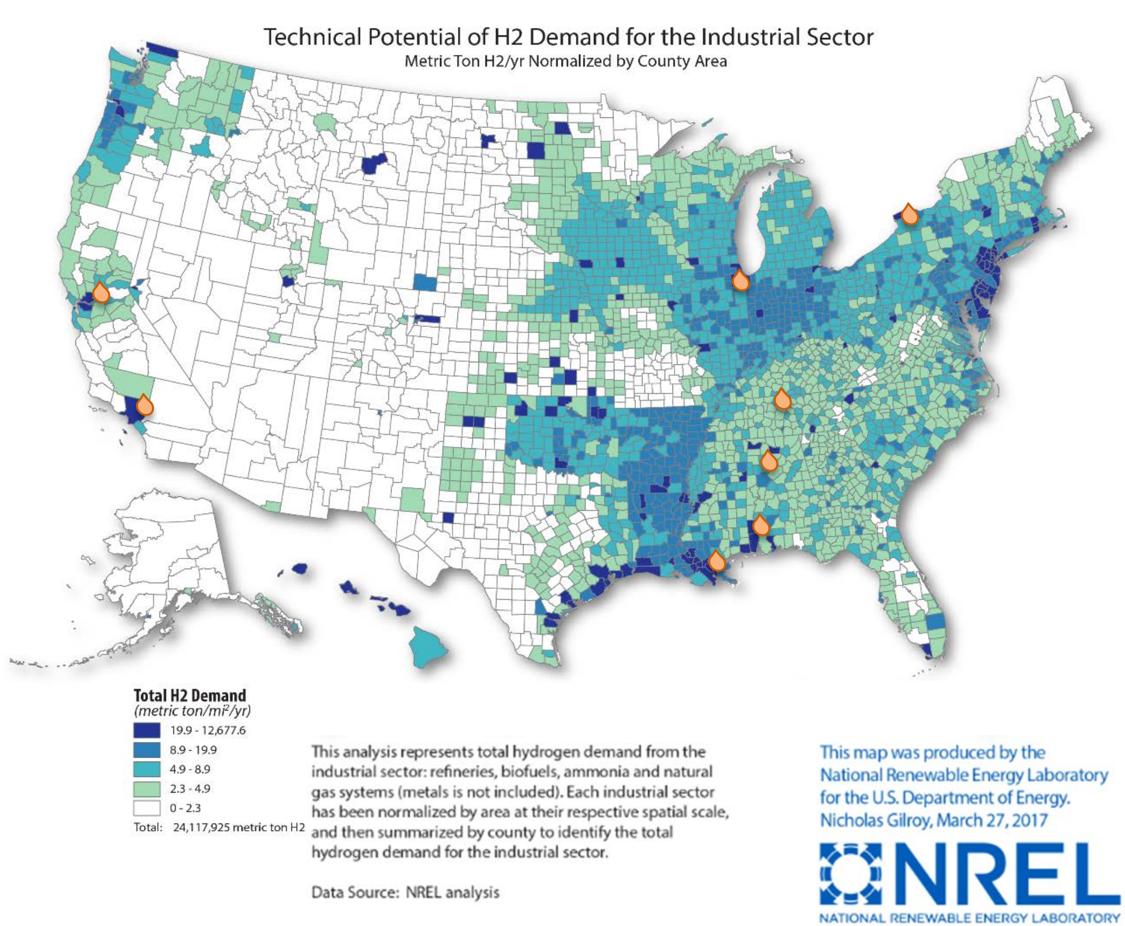
- Discovery of redox materials capable of efficient H_2 production
- Development of high-temperature materials for thermochemical reactors

Hydrogen Storage and Distribution

Examples of Research Needs

- **Delivery and Storage**
  - ✓ High-throughput compression for pipelines
  - ✓ Purification technologies to enable co-leveraging of infrastructure
  - ✓ Liquid carriers
- **Liquefaction**
  - ✓ Advanced expanders and compressors for mixed refrigerants
  - ✓ Non-mechanical approaches (e.g. magneto-caloric materials, thermo-acoustics)
  - ✓ Small-scale technologies
- **Cross-Cutting**
  - ✓ Capture of H_2 from existing process streams (e.g. chlor-alkali plants)
  - ✓ Development of skilled workforce

Current Status



Hydrogen End Use Applications

Drivers for Demand

Oil Refining

- Quality of crudes
- Air quality (removal of sulfur and aromatics)
- Demand for gasoline

Ammonia

- Demand for food crops
- Demand for biofuels
- Emerging applications, such as NOx control
- Demand for liquid carriers

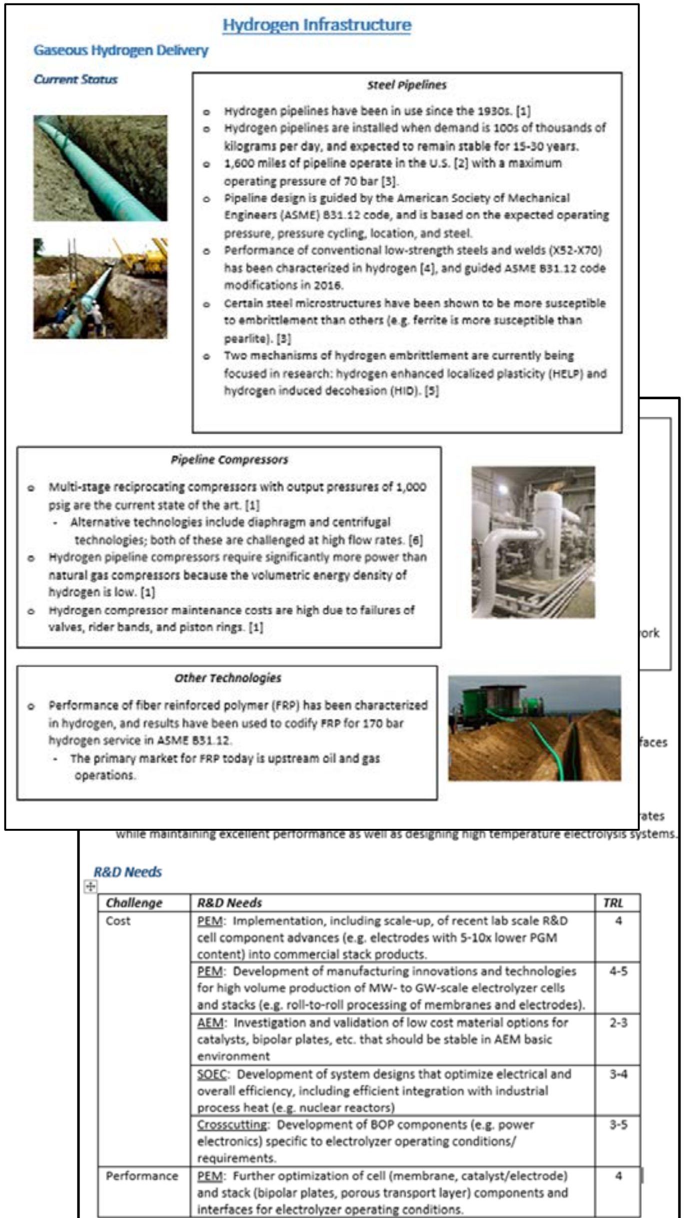
Metal Refining

- Lower cost feedstock (recycled scrap)
- Cyclability
- Scalability
- Purity of resulting iron

Technical and Market Needs

- Low-cost distributed H_2 production
- Co-electrolysis for methanol synthesis
- Identification of opportunities to use O_2 from electrolysis
- Valuation of renewable H_2 in regulatory frameworks
- Creation of "Sustainability Index" for investors
- Engineering of DRI reactors to manage kinetics in H2
(e.g. flash ironmaking technology)

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

ates

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

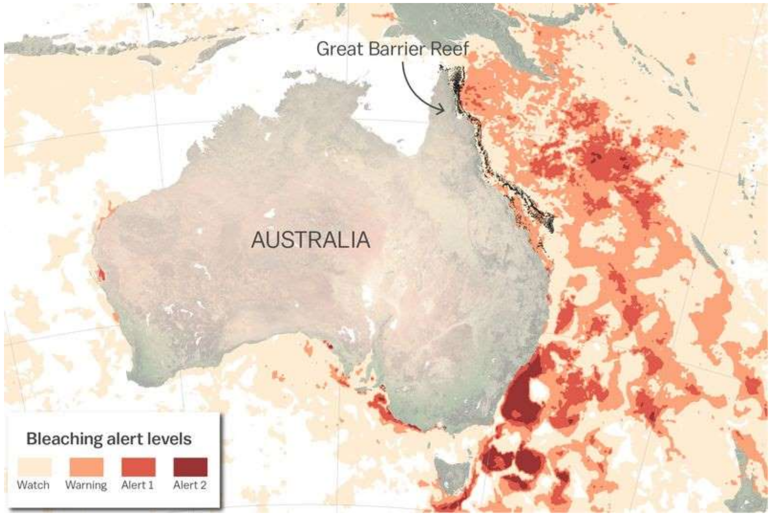
R&D Needs

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 Roadmap identifying and prioritizing RD&D needs
  - Analysis to assess potential supply and demand of H2@Scale under future market scenarios
- **May 23-24, 2017**
  - H2@Scale workshop in Houston, TX to assess regional challenges, and obtain feedback on draft sections of roadmap
- **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

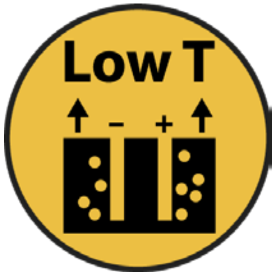
Dec-Apr – Continued outreach, analysis, and focus on Roadmap development

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



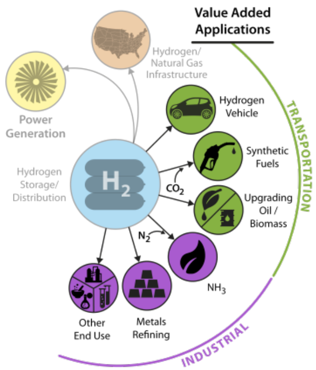
Development of **low cost, durable, and intermittent H_2** generation.

Development of **thermally integrated, low cost, durable, and variable H_2** generation.

H_2 Storage and Distribution

Development of **safe, reliable, and economic storage and distribution** systems.

H_2 Utilization



H_2 as game-changing energy carrier, revolutionizing energy sectors.

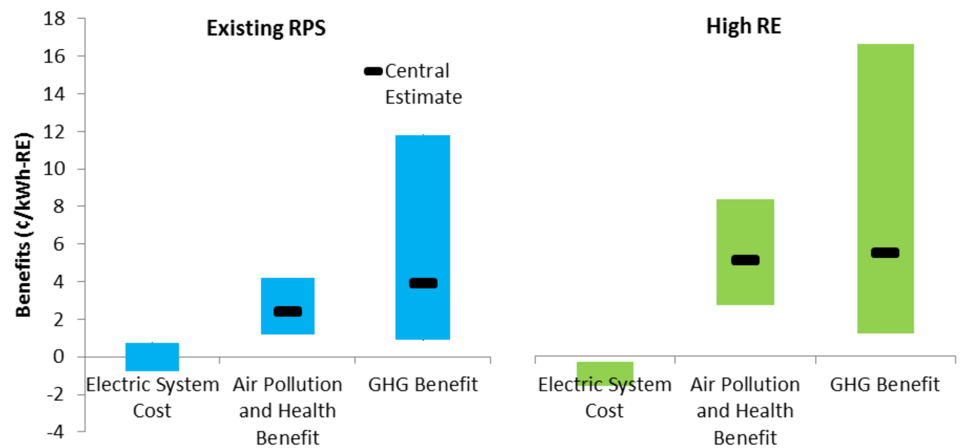
Analysis

Foundational Science

Future Electrical Grid

Value Proposition Development

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

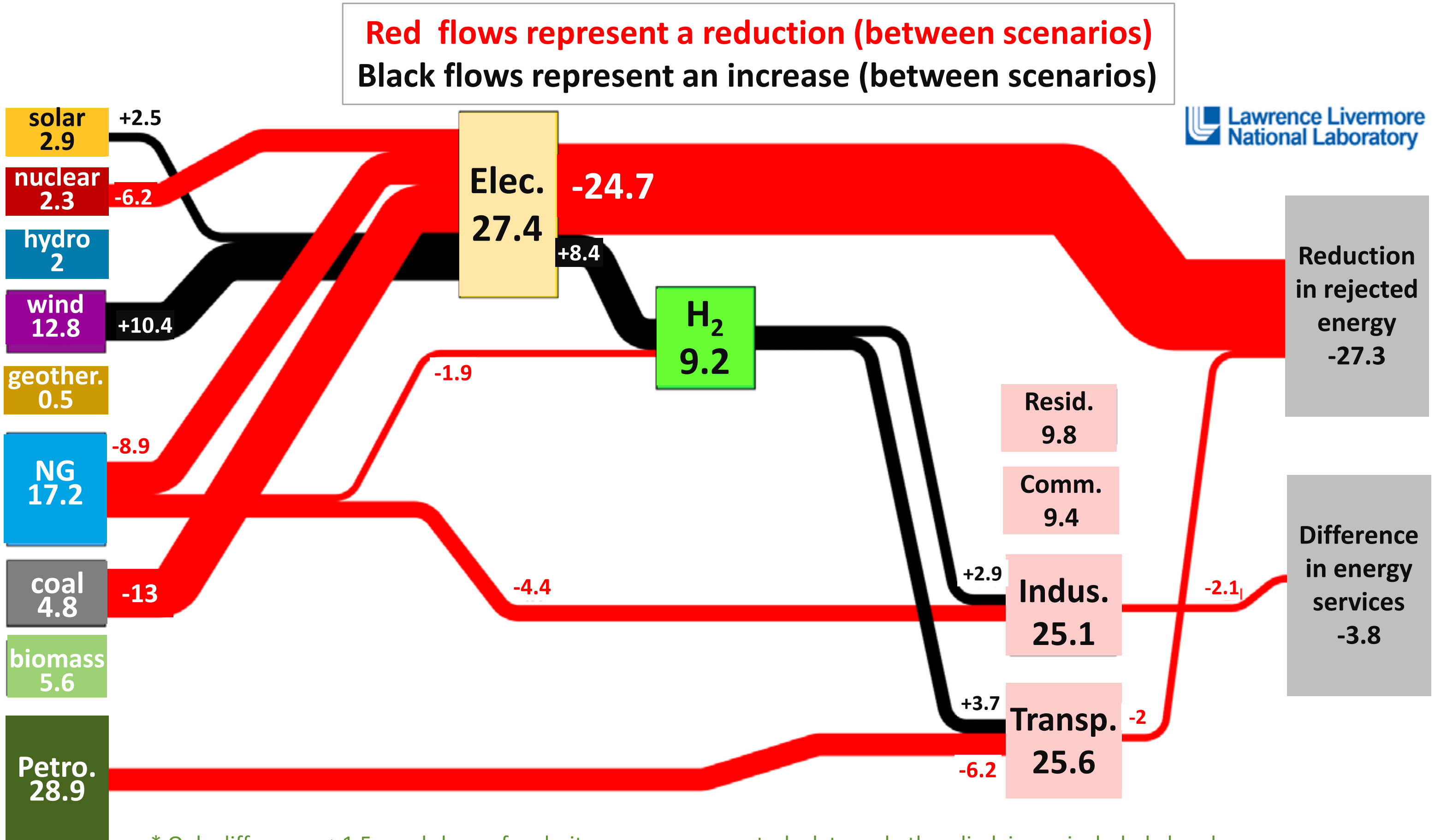


A Prospective Analysis of the Costs, Benefits, and Impacts of U.S. Renewable Portfolio Standards
NREL/TP-6A20-67455
http://www.nrel.gov/docs/fy17osti/67455.pdf

Evolving H_2@Scale vision/message

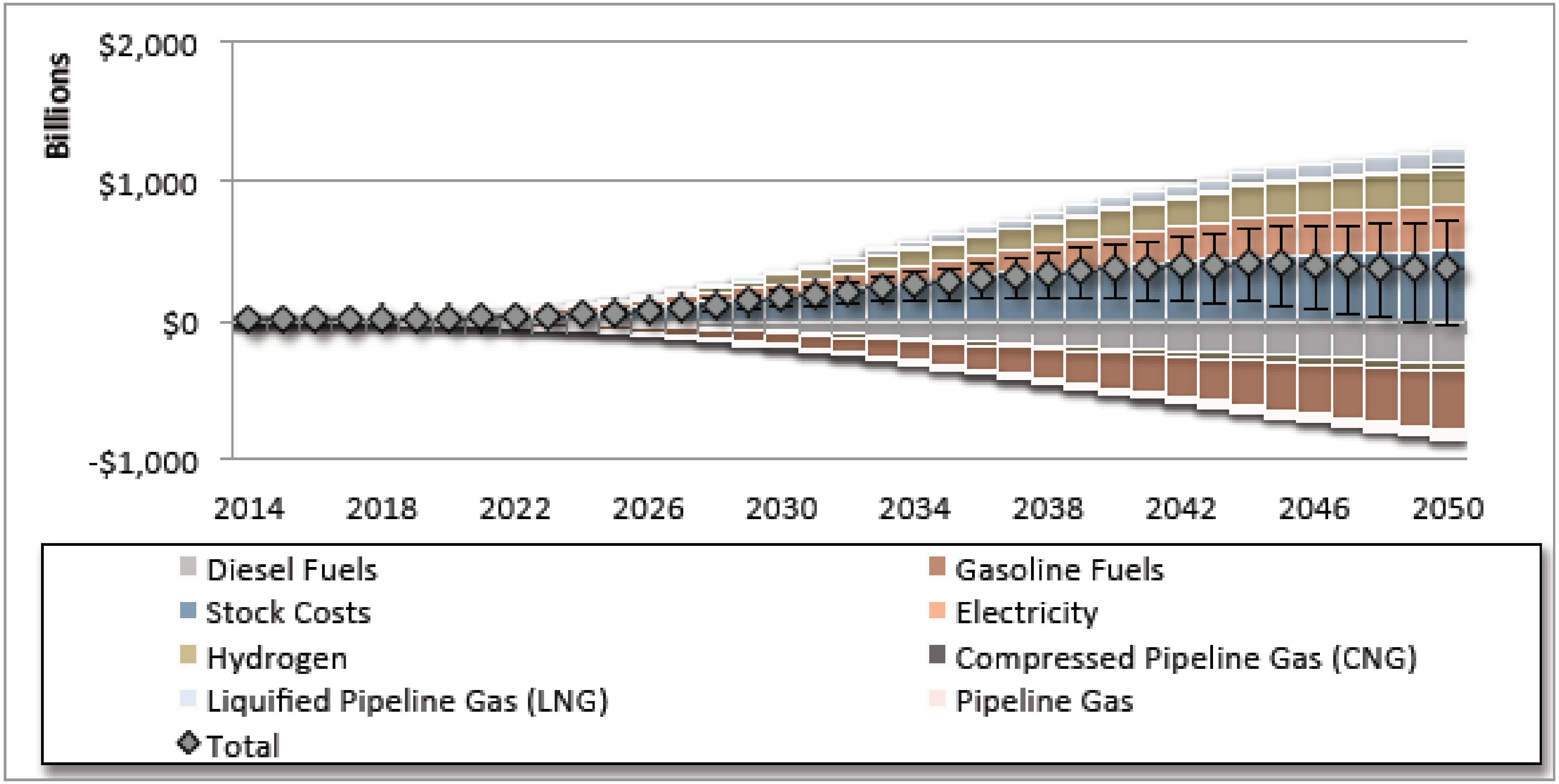
- **Quantifying energy-system wide value proposition**
  - Based on Scenario Development (like that shown below)

Energy Use difference between 2050 high-H_2 and AEO 2040 scenarios (Quad Btu)



* Only differences >1.5 quad shown for clarity purposes, case study data and other disclaimers included elsewhere

Energy System-Wide Models (E3)



There are a lack of energy system-wide models.
Hydrogen tends to be prominent.
High cost uncertainties exist, but costs don't appear prohibitive.

Assessing Economic Impact

ICF Results using E3 inputs

RESULTS SUMMARY: NATIONAL IMPACTS

National Level GDP ($ Billion)

	2020	2025	2030	2040	2050
Reference Case	**$18,745**	**$20,708**	**$22,765**	**$26,746**	**$31,317**
High Renewables	$18,772	$20,760	$22,910	$26,959	$31,607
Difference	**26**	**52**	**145**	**213**	**290**
% Change	**0.1%**	**0.3%**	**0.6%**	**0.8%**	**0.9%**
Mixed Case	$18,770	$20,777	$22,909	$26,921	$31,500
Difference	**24**	**69**	**144**	**175**	**183**
% Change	**0.1%**	**0.3%**	**0.6%**	**0.7%**	**0.6%**

- **GDP impact trends are similar to the employment results**
  - Impacts comparable across both scenarios around 2030
    - About a half percentage point increase over the Reference Case
  - High RE Case shows more pronounced impacts in the long run
    - Close to a full percentage point more than the Reference Case