H_2 @Scale:

Energy system-wide benefits of increased H2 implementation

UC Riverside Renewable Natural Gas Meeting

May 17, 2017
Riverside, CA

Keith Wipke, NREL

Adapted from Bryan Pivovar's H2@Scale Presentations

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

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

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

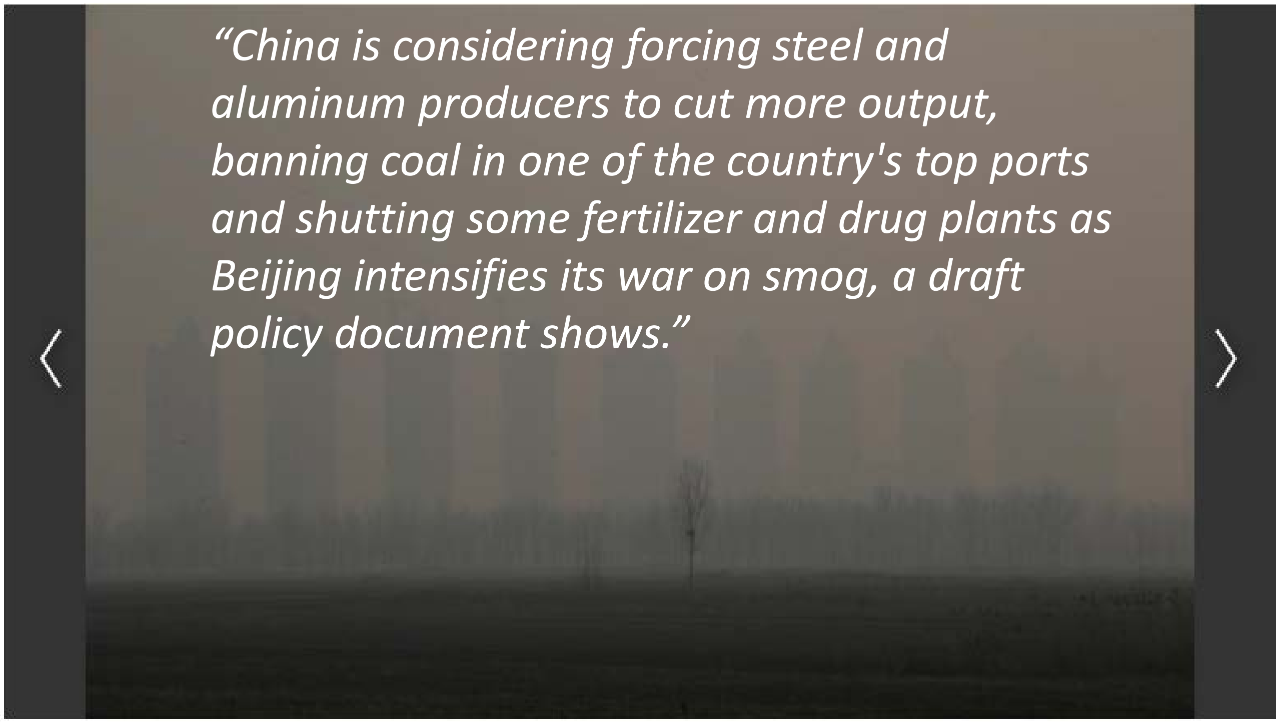
https://www.theguardian.com/environment/2016/apr/20/dangerous-air-pollution-us-population-report

Air Quality Still a Multi-Sector Issue Worldwide

REUTERS — Exclusive: China mulls radical output cuts, port coal ban in war on smog -...

COMMODITIES | Mon Feb 13, 2017 | 2:32am EST

Exclusive: China mulls radical output cuts, port coal ban in war on smog - document

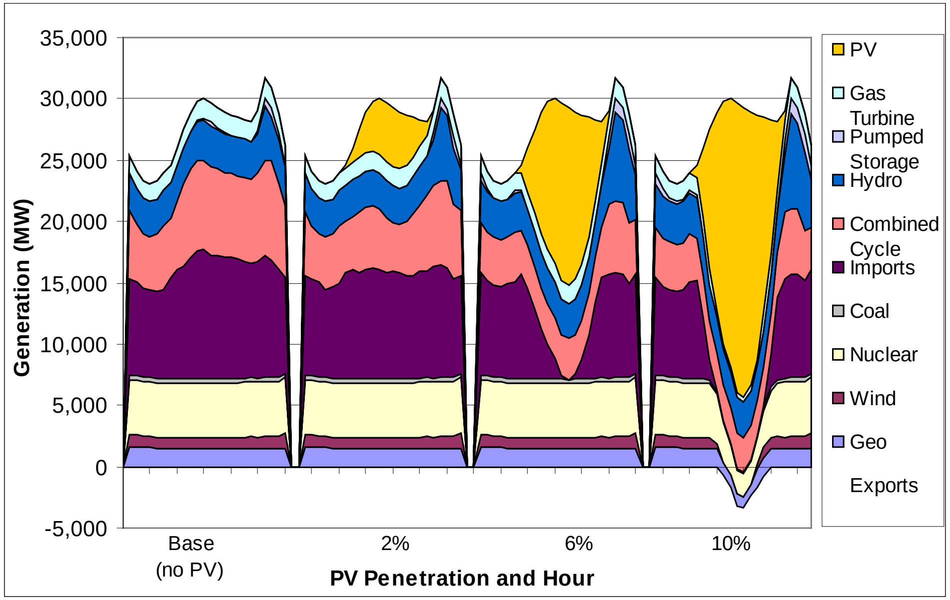


FILE PHOTO: Residential buildings under construction are pictured on a polluted day after the Chinese Lunar New Year holidays on the outskirts of Langfang, Hebei province, China, February 3, 2017. REUTERS/Jason Lee/File Photo 2/2

Source: Reuters 2/14/17 -- http://www.reuters.com/article/us-china-pollution-idUSKBN15S0ET

Current/Future Energy System Challenges

- **Multi-sector requirements not going away**
  - o Transportation
  - o Industrial
  - o Grid
- **Renewable energy challenges increasing with time**
  - o Variable
  - o Concurrent generation
  - o Traditional baseload being removed



Dwight D. Eisenhower:

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

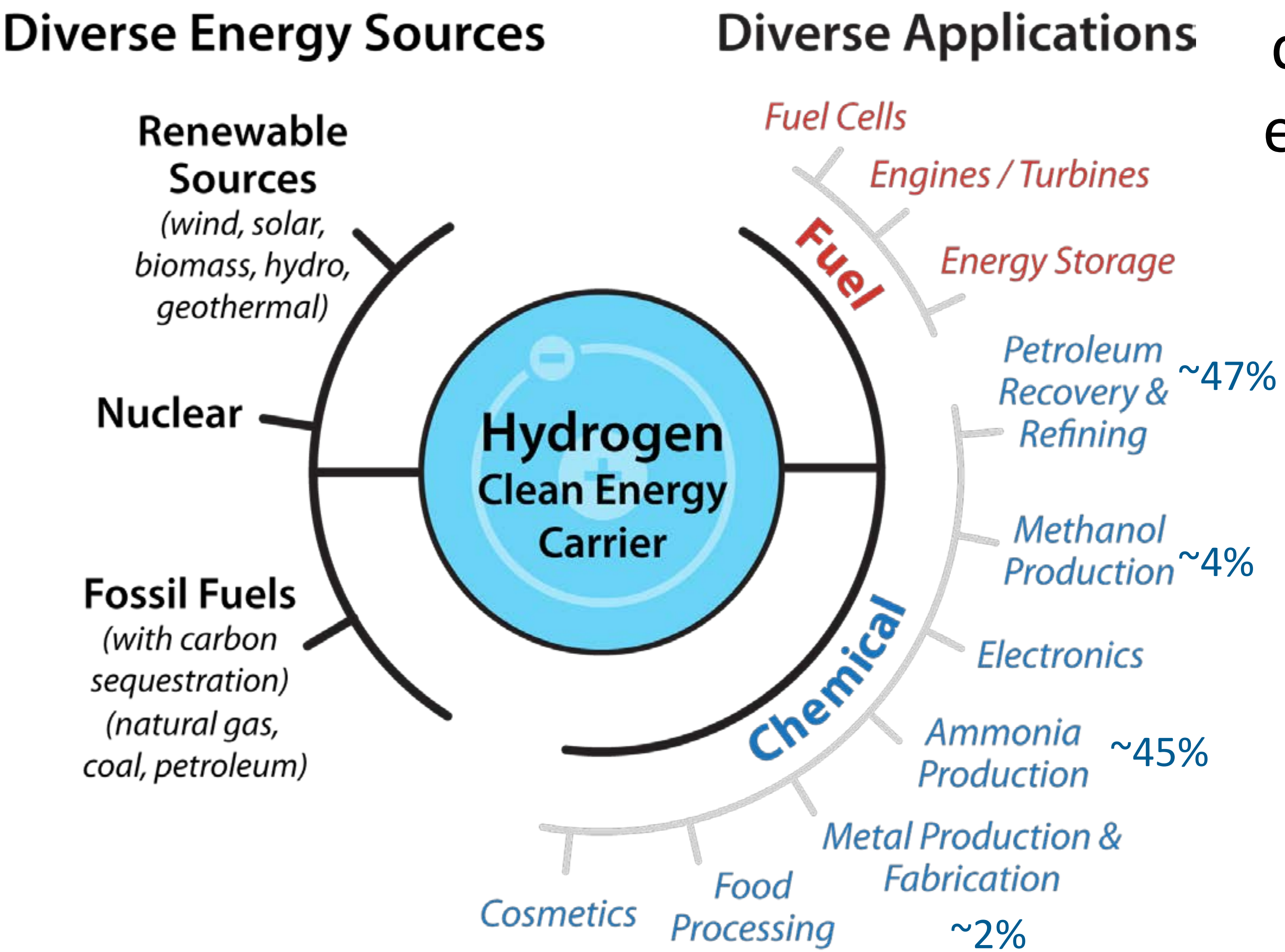
H2@Scale Vision

- **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 proposition.

Hydrogen, the Clean, Flexible Energy Carrier

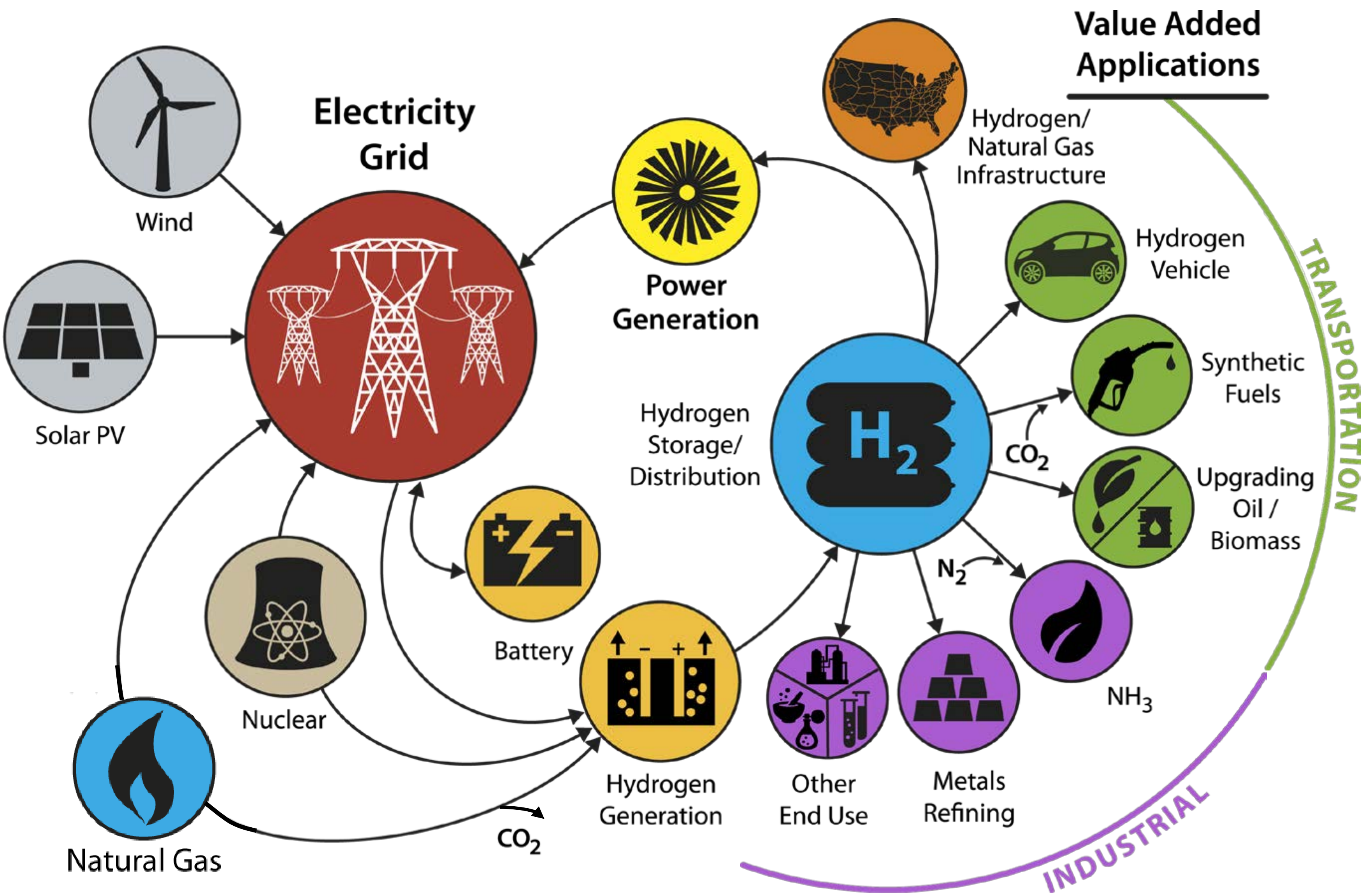


can service all energy sectors plus improve

Energy Security and **Domestic Economy**

The numbers indicate where H2 is used today

Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

Hydrogen is a worldwide race to capture new jobs

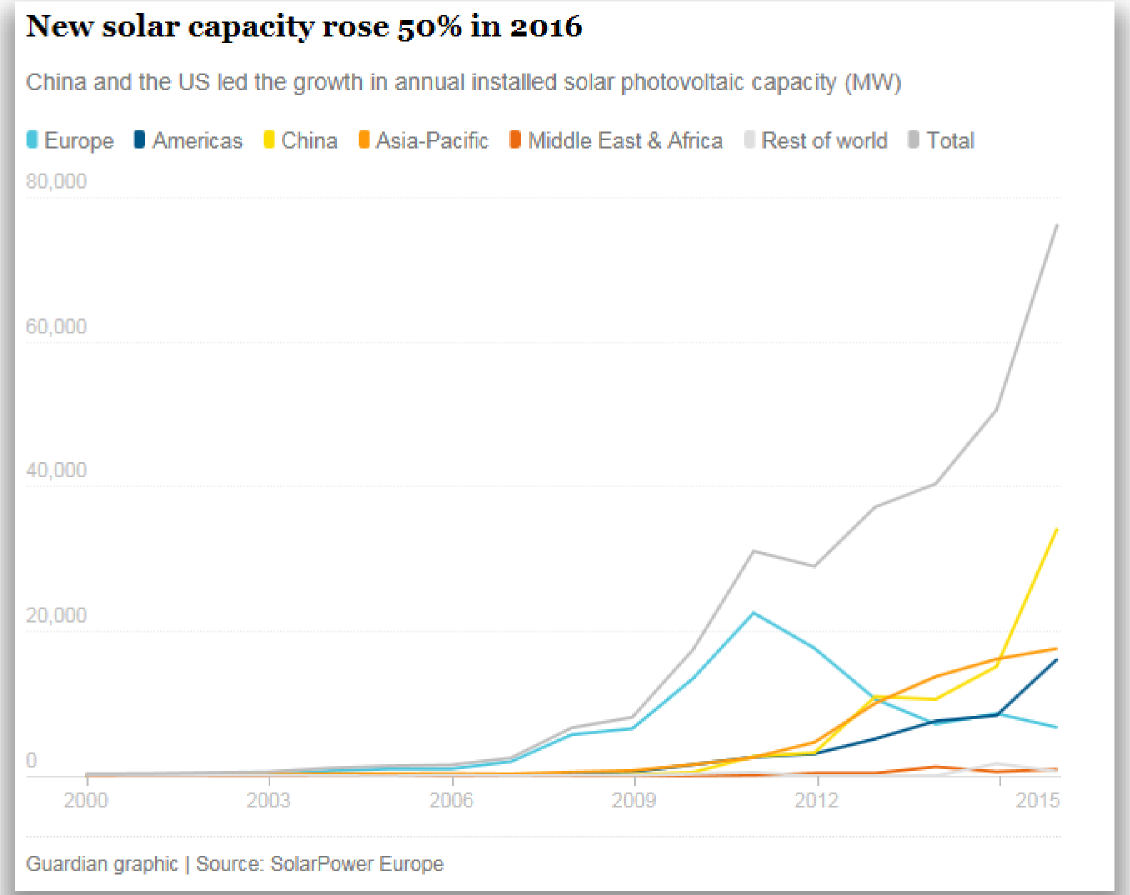
"It's not until 2020 before we figure out how much we can increase hydrogen power generation," said Hiroshi Katayama, deputy director of the hydrogen and fuel cells strategy office at the trade ministry, referring to an ongoing study on hydrogen supply chain. "There is a lot to do until 2020."

The industry's value worldwide is forecast to grow by 46 times in the next 15 years to 4.9 trillion yen ($44 billion) from about 106 billion in the year through March 2016, according to Fuji Keizai Co., a Tokyo-based research company.

Translation: growth in "industry value" = **JOBS**

Source: https://www.bloomberg.com/news/articles/2017-02-09/japan-makes-big-push-for-hydrogen-fuel-cells-rubbished-by-musk

Renewables taking on a life of their own…



Interpretation: China growing renewables for their own benefit vs. just an export to others

Source: https://www.theguardian.com/environment/2017/mar/07/solar-power-growth-worldwide-us-china-uk-europe

Renewables taking on a life of their own…

A worker maintains photo-voltaic panels at Xinyi station in Songxi, China. Photograph: Feature China/Barcroft Images

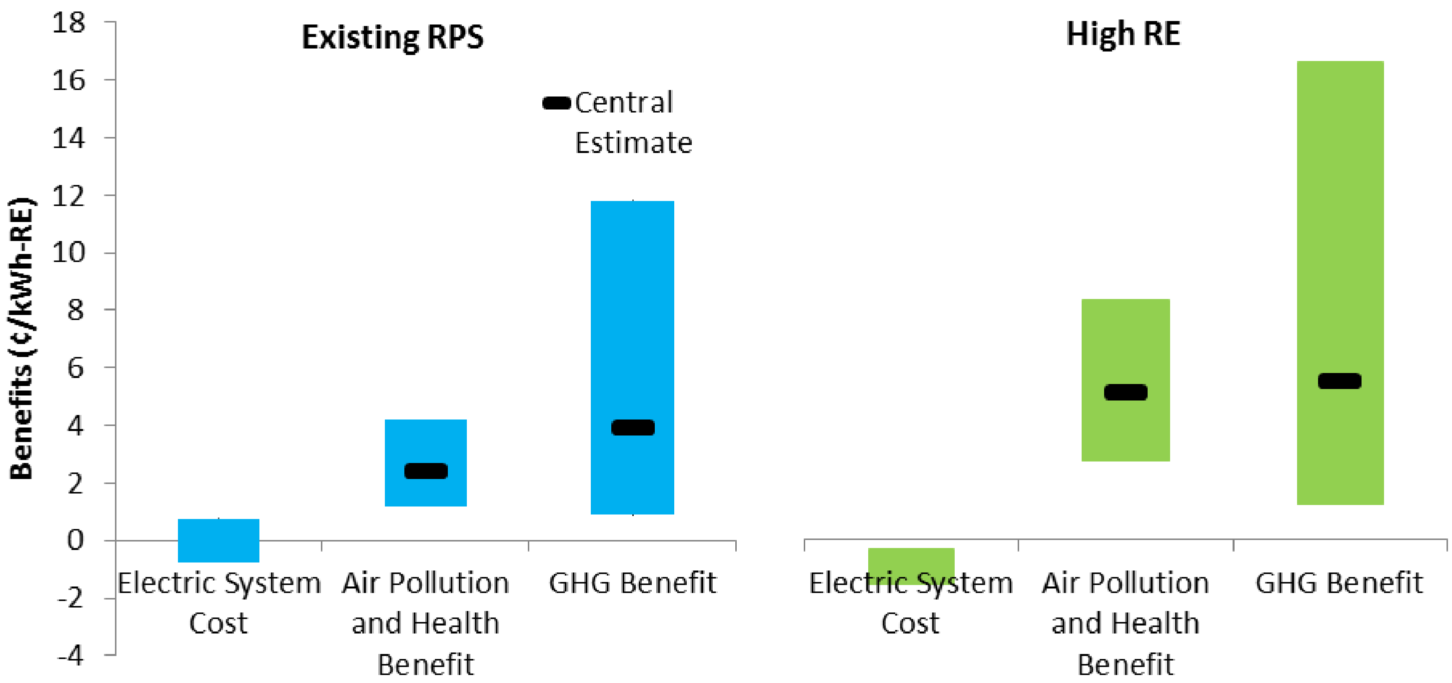
Summary of Prospective Costs, Benefits, and Impacts of RE Supported by State RPS Policies

		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	equivalent to $97 billion (2.4¢/kWh-RE) (estimates span $48 billion-$175 billion (1.2-4.2¢/kWh-RE))	reduced by ↓ 29%; 11.1 million metric tons SO_2	equivalent to $558 billion (5.0¢/kWh-RE) (estimates span $303 billion-$917 billion; 2.7-8.2¢/kWh-RE)
BENEFITS	NITROGEN OXIDES	reduced by ↓ 6%; 2.5 million metric tons NO_x		reduced by ↓ 29%; 12.8 million metric tons NO_x	
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

- Incremental RE generation offsets fossil fuel generation leading to environmental benefits such as a reduction in air and water pollution and GHG emissions.
- Incremental RE generation has monetary impacts such as the potential economic savings for companies and consumers and stimulation of job growth
- Overall, with existing RPS and high RE targets, benefits of investing in renewables exceeds the costs

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

Comparison of Costs and Monetized Benefits



- When comparing the costs and monetized benefits, we find that the benefits exceed the costs, even when considering the highest cost and lowest benefit outcomes

  Existing RPS: Costs are <0.75 cents/kWh-RE vs. >1.2 cents/kWh-RE air pollution and >0.9 cents/kWh-RE GHG NET benefits

  High RE: Costs are <1.5 cents/kWh RE vs. >2.7 cents/kWh-RE air pollution and >1.2 cents/kWh-RE GHG benefits

- Additional benefits occur from water savings, an increase in demand for gross RE workforce needs, and a reduction in natural gas prices

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

Current/Future Energy System Challenges

Bloomberg Markets Tech Pursuits Politics Opinion Businessweek

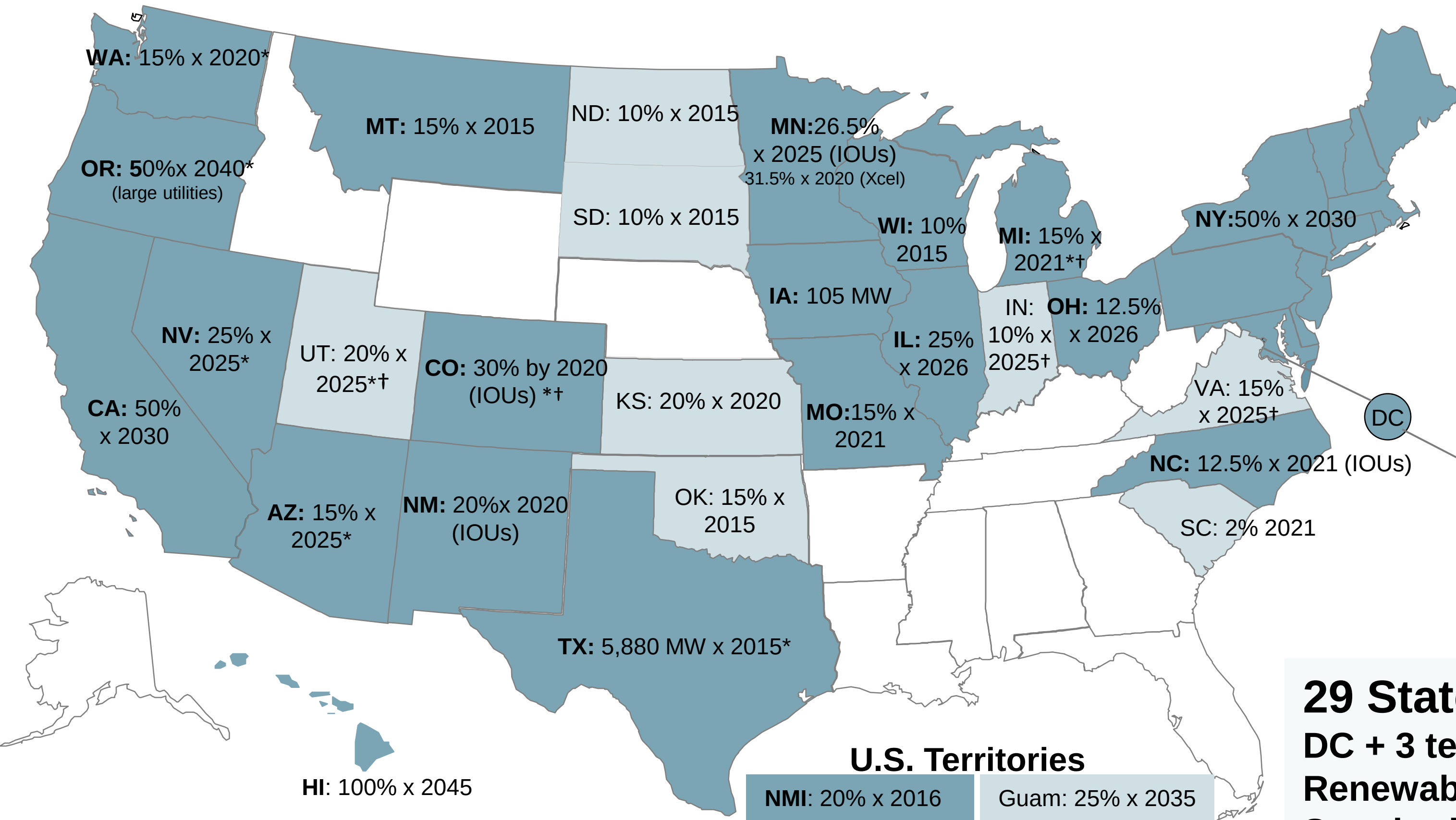
For the First Time, Wind on the Plains Supplied More Than Half Region's Power

by Chris Martin
February 13, 2017 2:39 PM

Wind turbines in Milford, Iowa, on Sept. 15, 2016. Photographer: Daniel Acker/Bloomberg

Source: Bloomberg 2/13/17
https://www.bloomberg.com/news/articles/2017-02-13/wind-on-the-plains-supplied-more-than-half-region-s-power-needs

Drivers: Status of State RPS as of August 2016



ME: 40% x 2017
NH: 24.8 x 2025
VT: 75% x 2032
MA: 15% x 2020(new resources) 6.03% x 2016 (existing resources)
RI: 38.5% x 2035
CT: 27% x 2020
NJ: 20.38% RE x 2020 + 4.1% solar by 2027
PA: 18% x 2021†
DE: 25% x 2026*
MD: 25% x 2020
DC: 50% x 2032

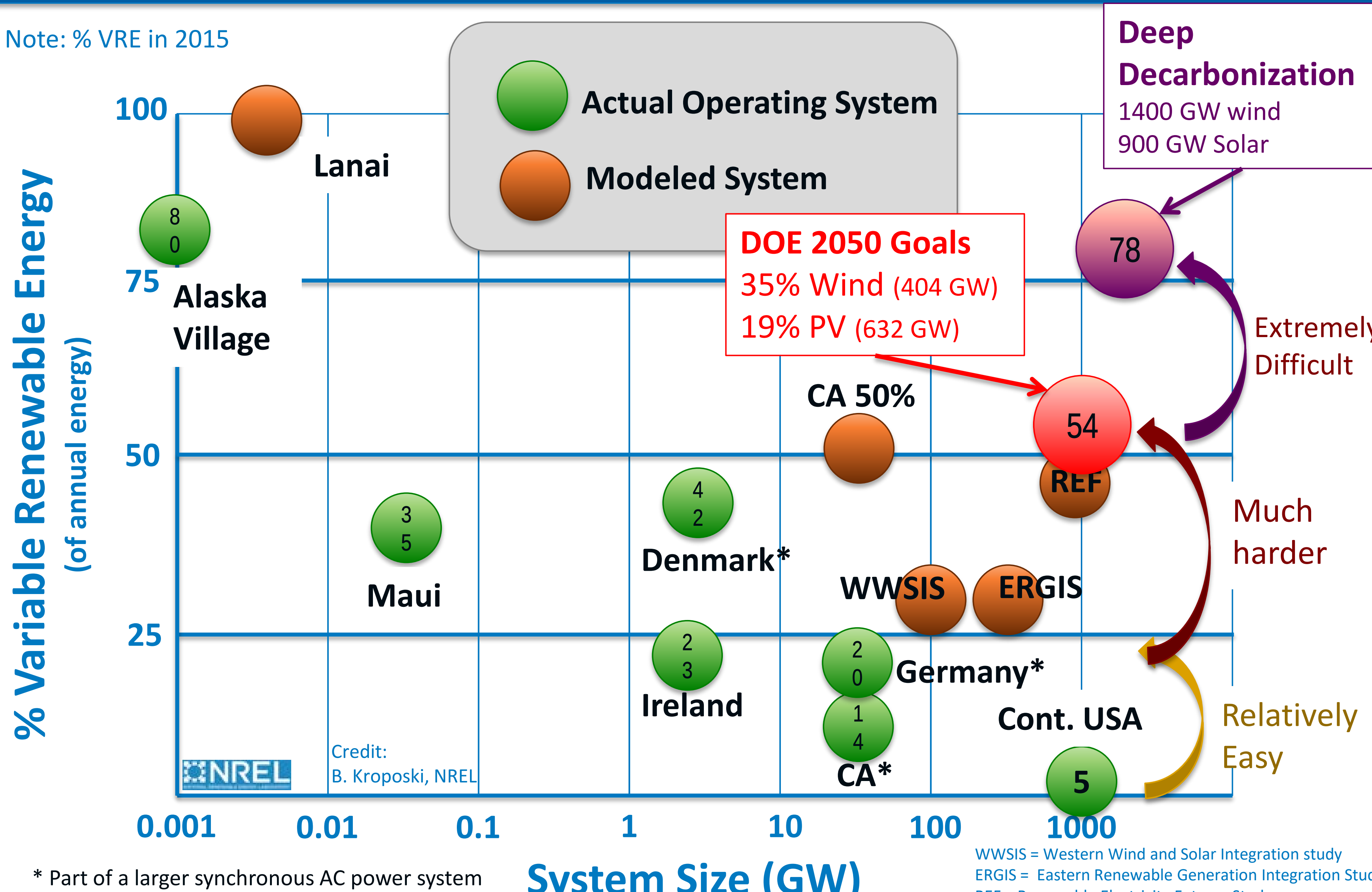
U.S. Territories

NMI: 20% x 2016	Guam: 25% x 2035
PR: 20% x 2035	**USVI**: 30% x 2025

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

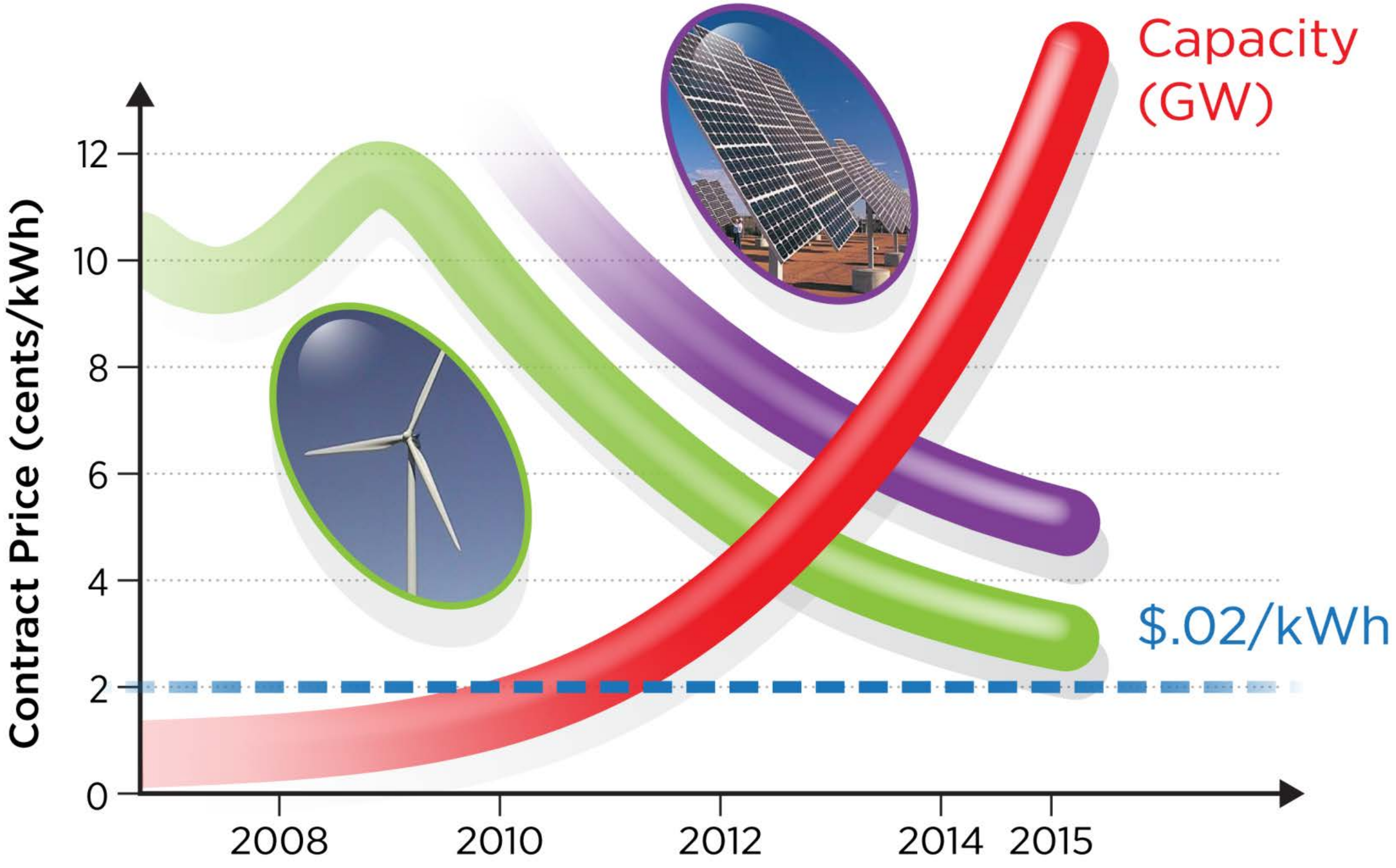
What constitutes “a pace and scale that matters” for our efforts to transform clean energy systems?



* Part of a larger synchronous AC power system

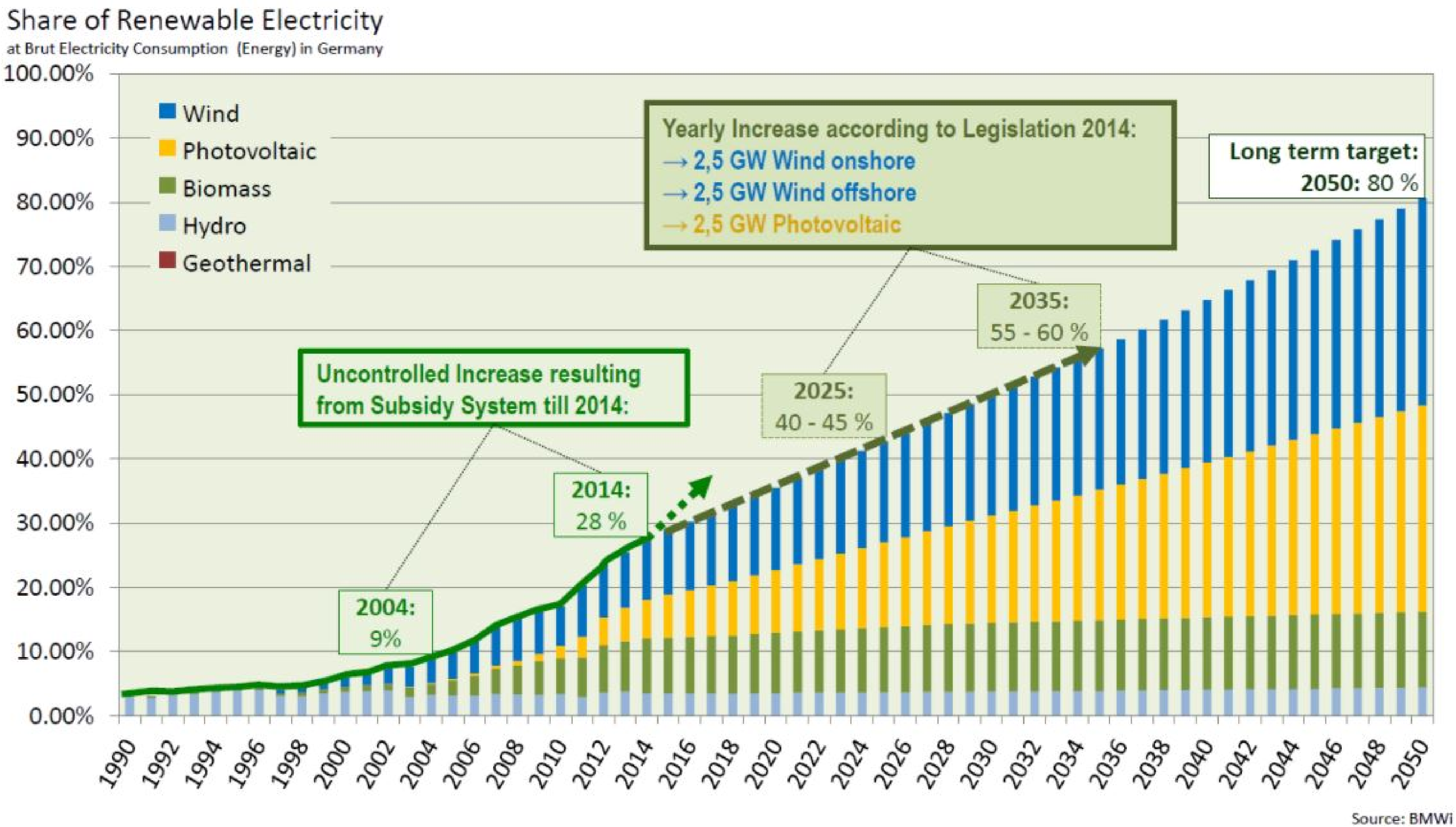
WWSIS = Western Wind and Solar Integration study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study

Drivers: Cheaper renewable electricity



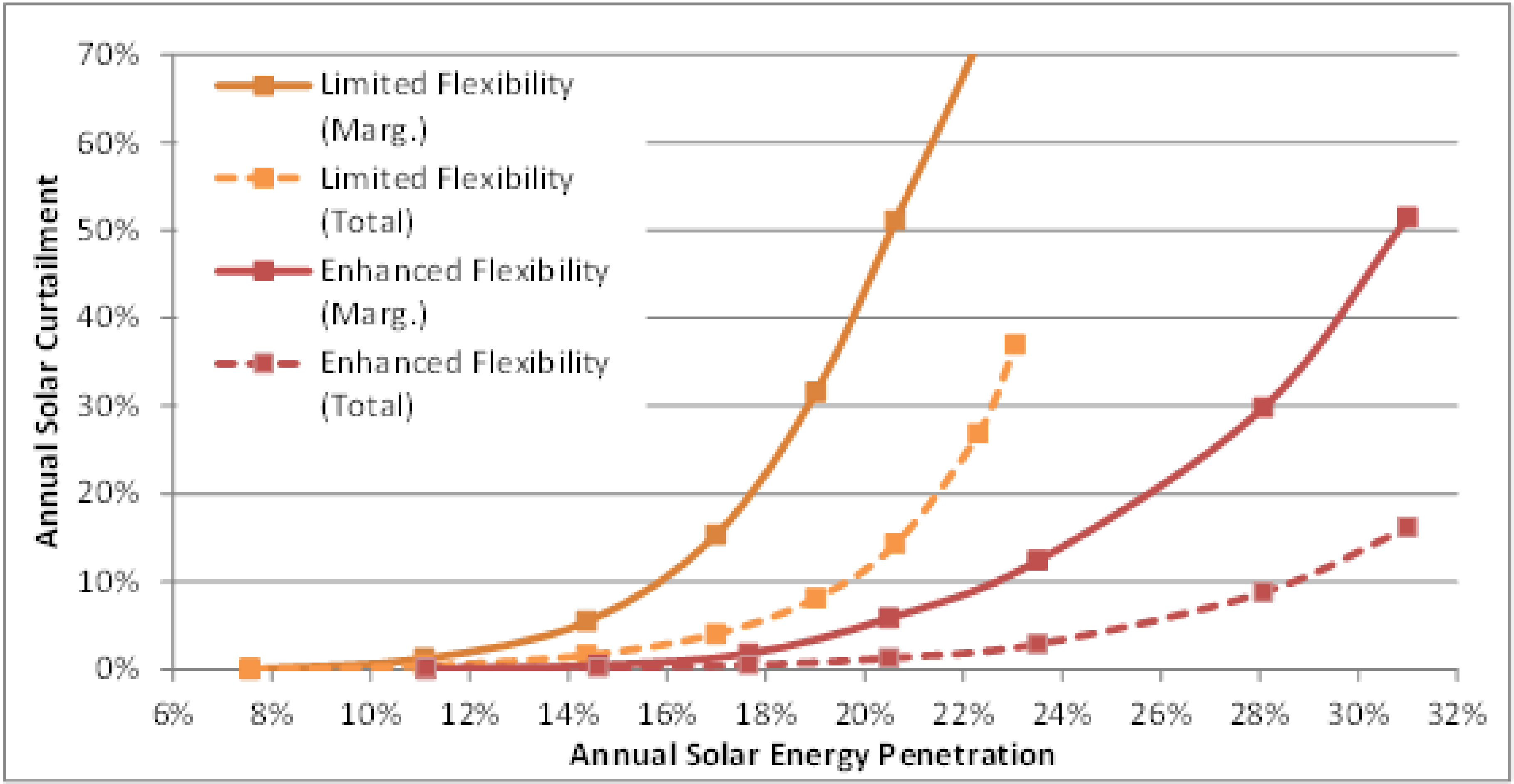
Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1’15 Report, 2. DOE EERE Wind Report, 2015

Drivers: Germany already limiting RE penetration rate



Drivers: Limitations of Mismatched Load/Generation

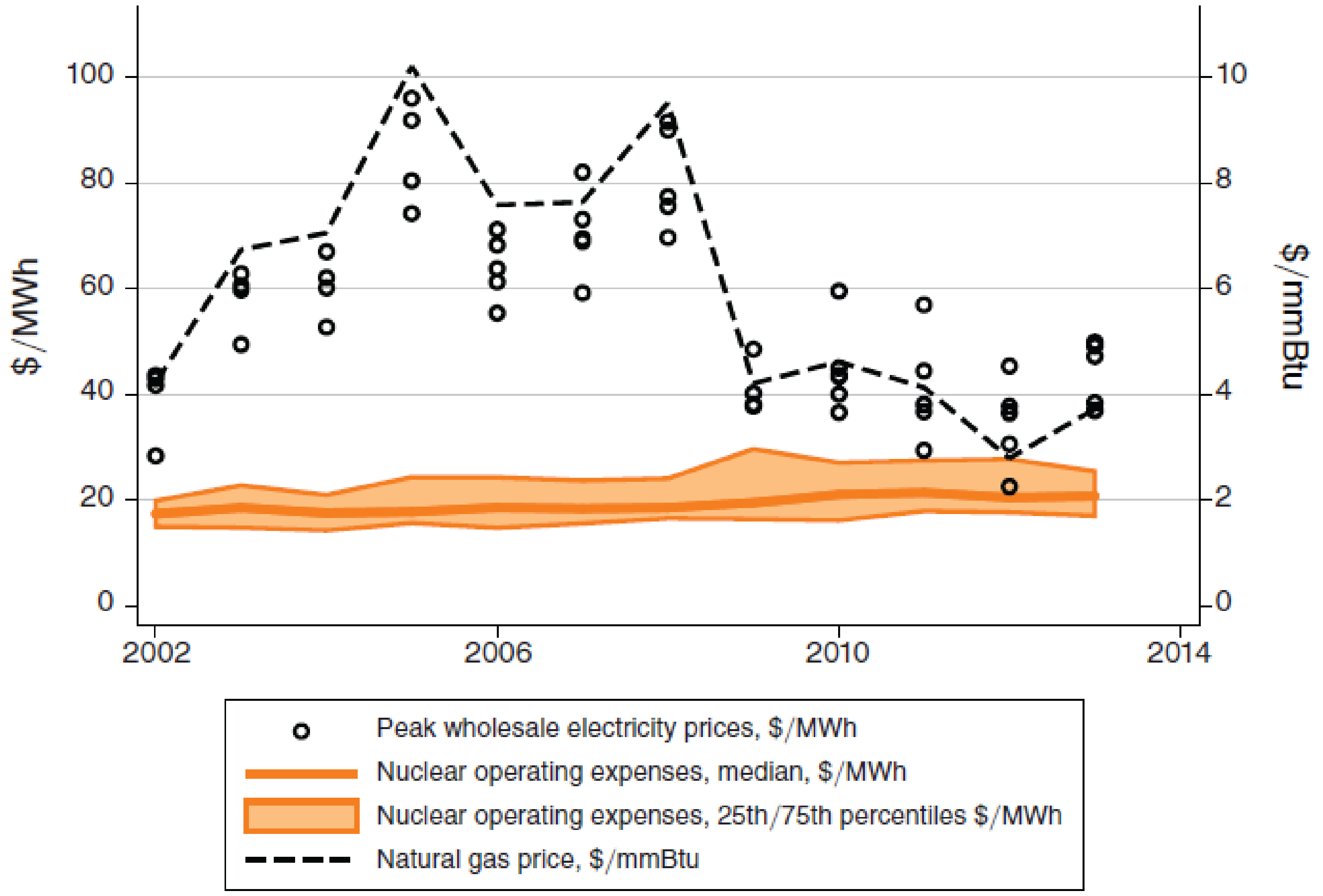
Denholm, P.; M. O'Connell; G. Brinkman; J. Jorgenson (2015) Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart. NREL/TP-6A20-65023



Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

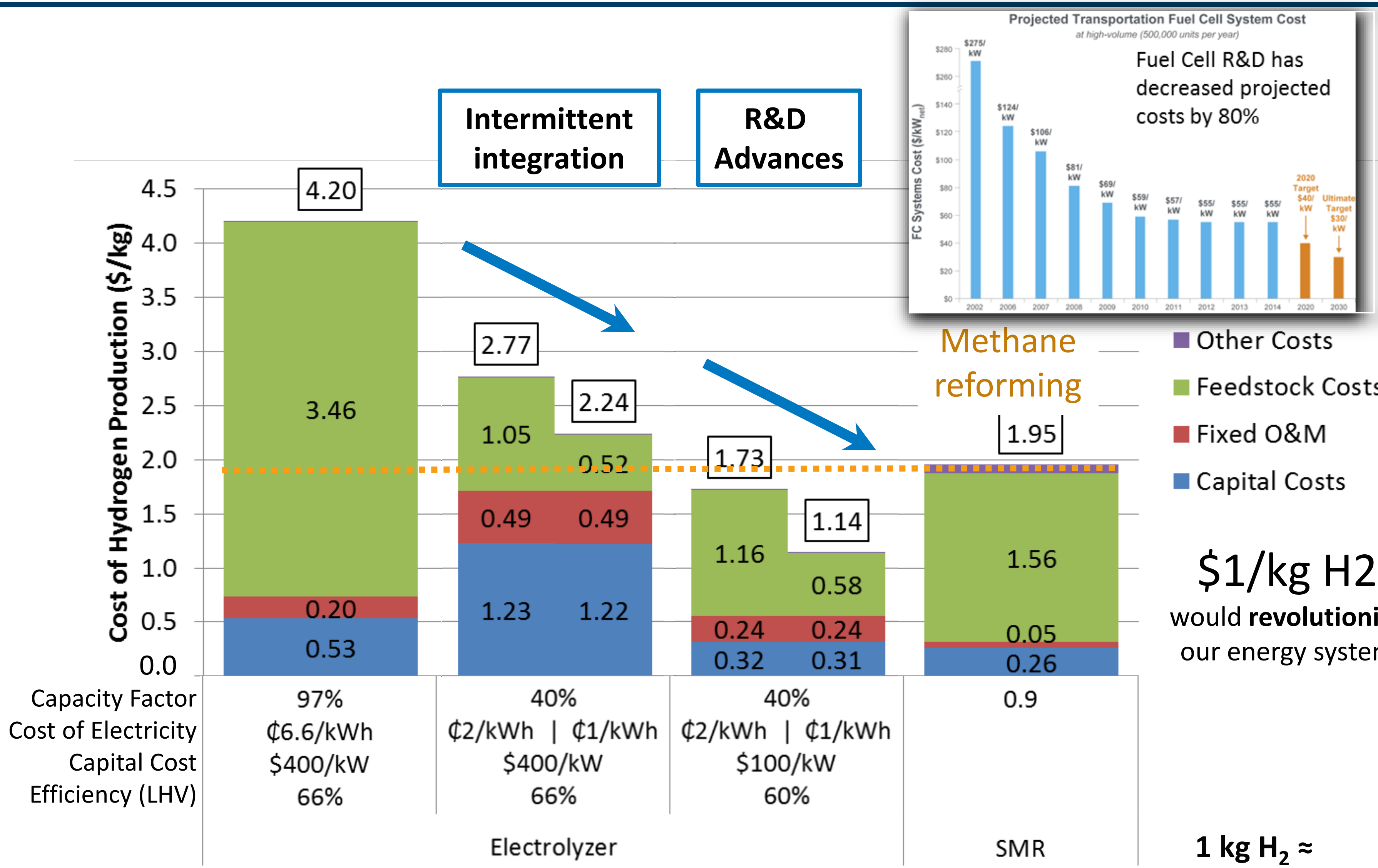
Drivers: Electricity from NG approaching nuclear operating costs

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

Improving the Economics of Hydrogen

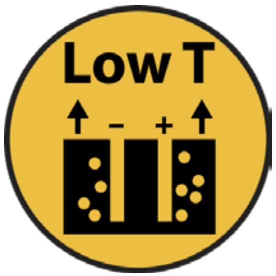
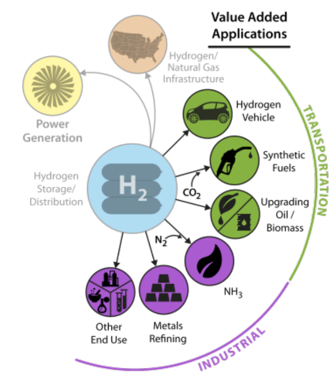


$1/kg H2

would **revolutionize** our energy system

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

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

H_2 at Scale Workshop (November 16-17)

Credit: Mark Ruth

About 170 attendees from DOE, states, industry, and academia

Solicited input for roadmap

Key focus areas:

- **Additional opportunities for technologies, markets, education, and demonstrations**
- **Integration with power generation**
- **Infrastructure needs and challenges on regional, national, and global scales**
- **Policy and market drivers for fuels and natural gas system as end uses**
- **Challenges competing in commodity markets for chemical and metals**

H_2 at 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)

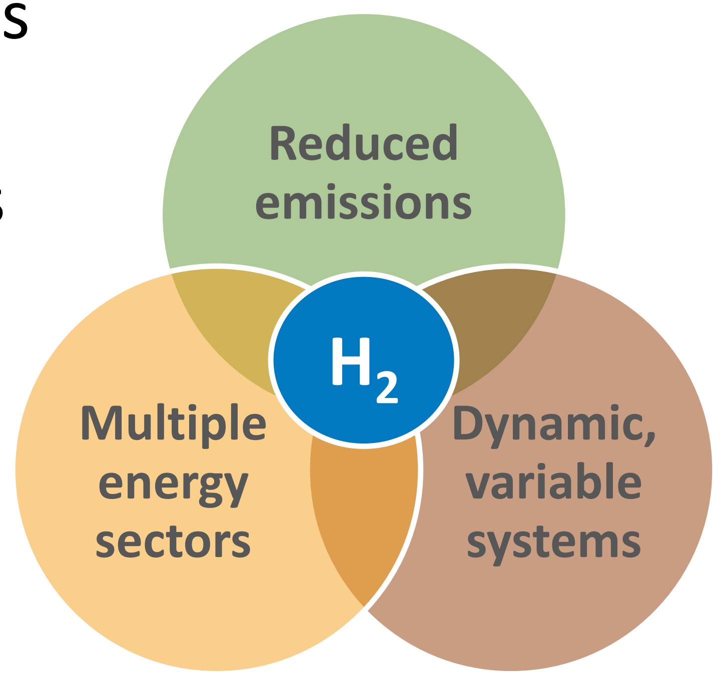
Analysis:

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)

What does success look like?

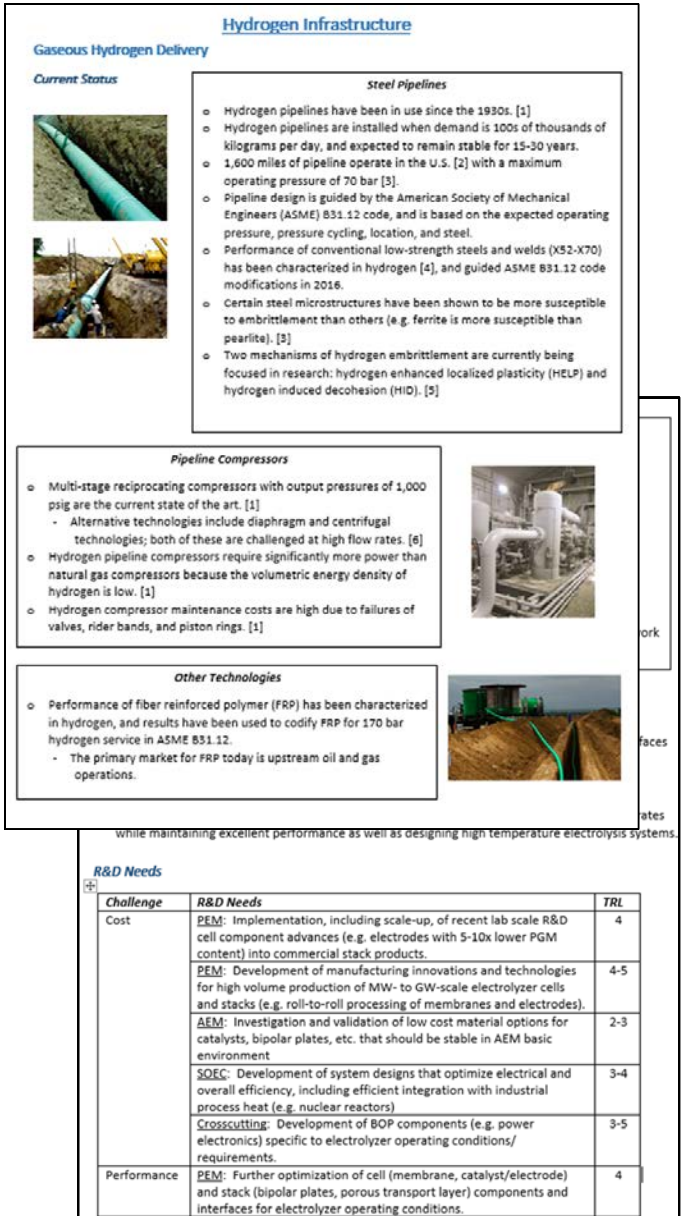
- Reduced emissions across sectors
- Future energy system needs are met
- Improved Energy security
  - Diversity/resiliency/domestic
- Manufacturing competitiveness
  - Job creation
- Decreased water requirements

Unique potential of H_2 to positively impact all these areas



What does success look like?

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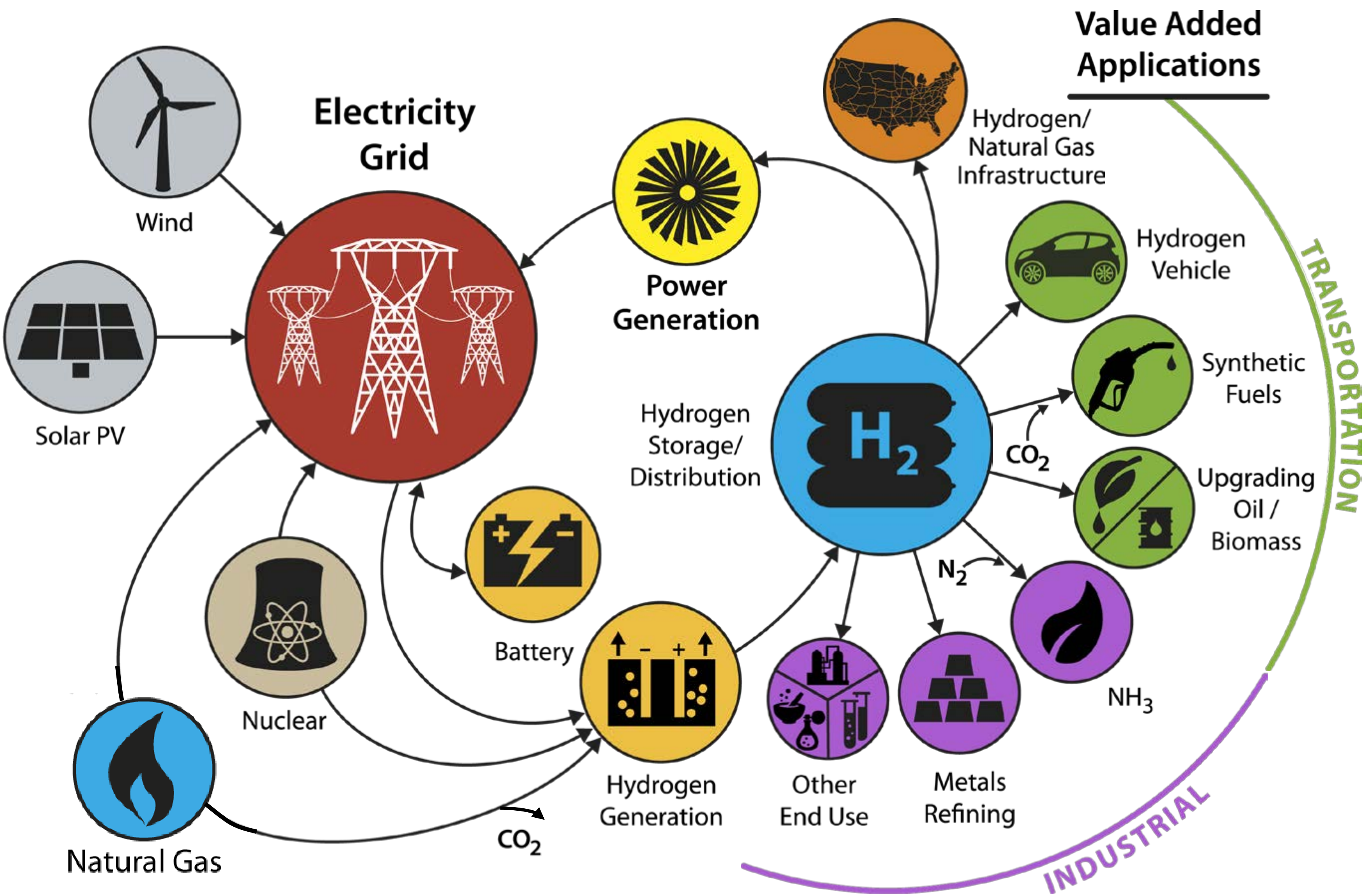
while maintaining excellent performance as well as designing high temperature electrolysis systems.

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

Conceptual H_2 at Scale Energy System*

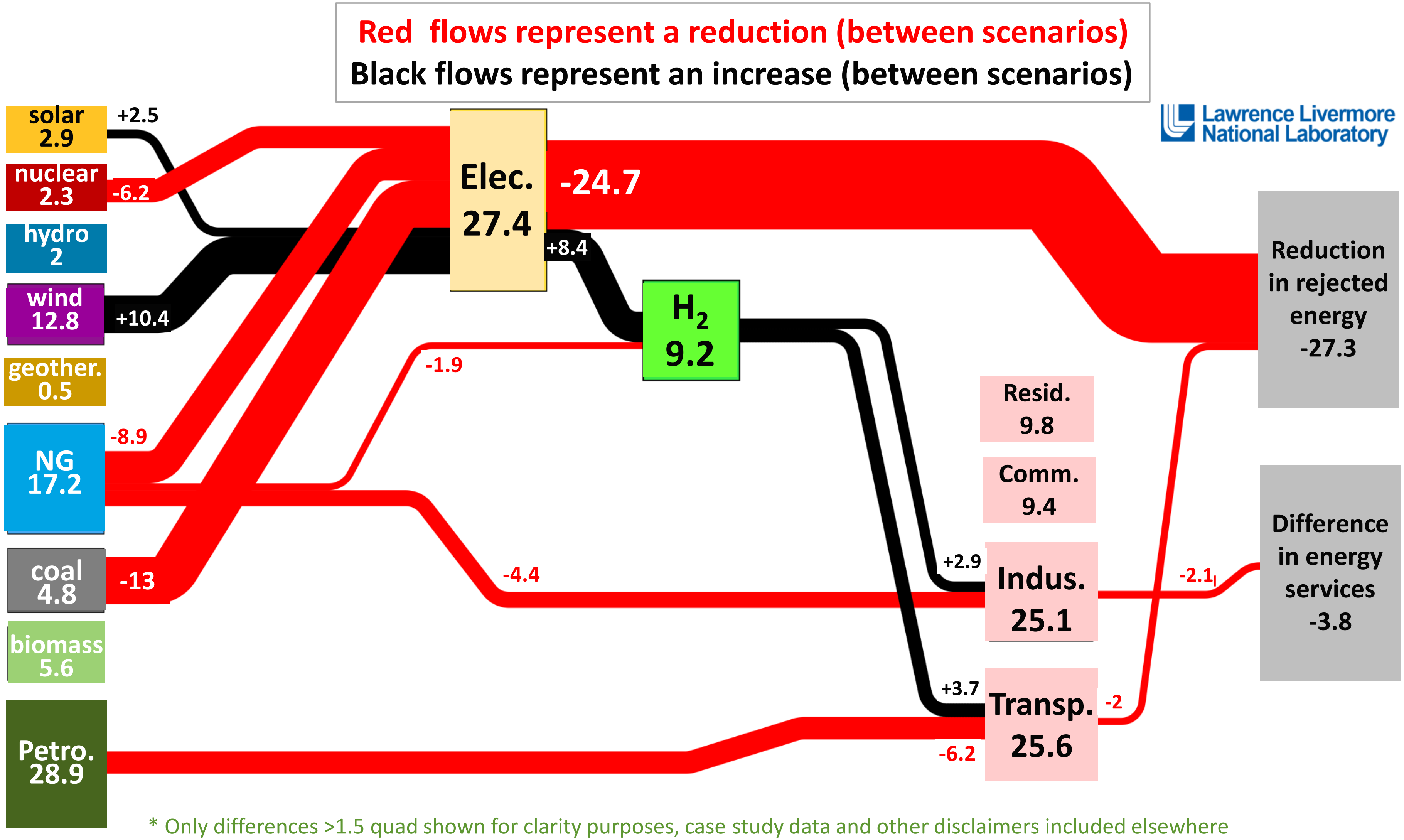


*Illustrative example, not comprehensive

Questions/Discussion

Energy reductions possible from high H2 & RE usage

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

Key 2016 H2@Scale Events

April
- 1st HTAC Briefing
- National Lab Chief Research Officer Meetings
- DOE Program Office Briefing
- **Big Idea Summit**

May
- Utility Workshops (Colorado & California)
- International Partnership for the Hydrogen Economy meeting

June
- Fuel Cells Technology Office / Vehicle Technologies Office Annual Merit Review

July
- Southwest Regional Energy Innovation Forum
- Sustainable Transportation Summit
- FCTO Webinar

Aug.
- Intermountain Energy Summit
- New Mexico Regional Energy Storage and Grid Integration Meeting

Sept.
- Colorado School of Mines Steel Center Biennial Meeting
- Electric Power Research Institute Power Delivery and Utilization Conference

Oct.
- California Hydrogen Business Council Fall Summit
- National Press Club Event

Nov.
- **H2 at Scale Workshop**
- **National Lab H2@Scale Analysis funding**

Dec.
- 2nd Hydrogen and Fuel Cells Technology Advisory Committee Briefing