

# H<sub>2</sub>

## HTAC Meeting

### @Scale:

Energy system-wide  
benefits of increased  
H<sub>2</sub> implementation

May 4, 2017

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>

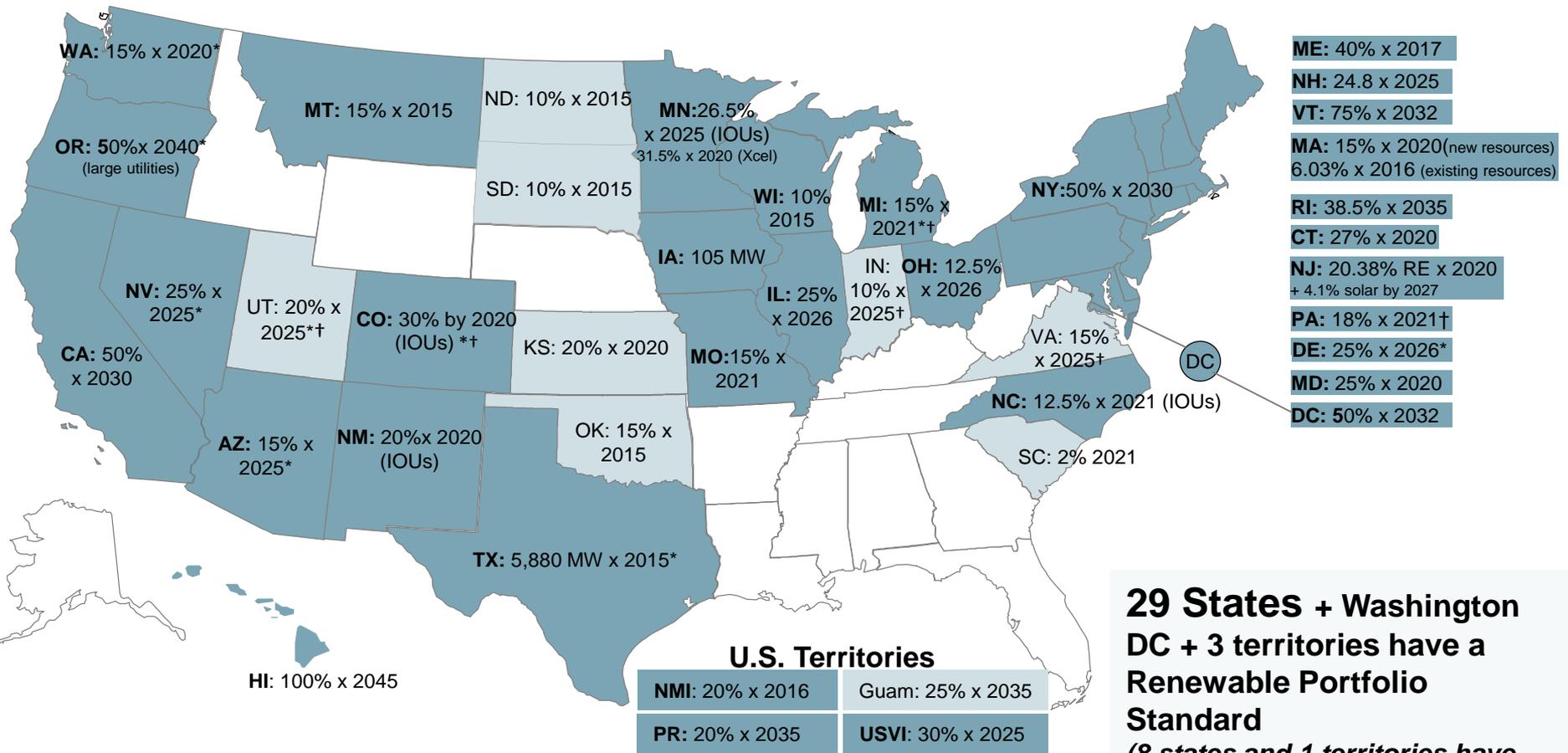
# Energy System Challenge

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

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

# Changing Landscape - RPS

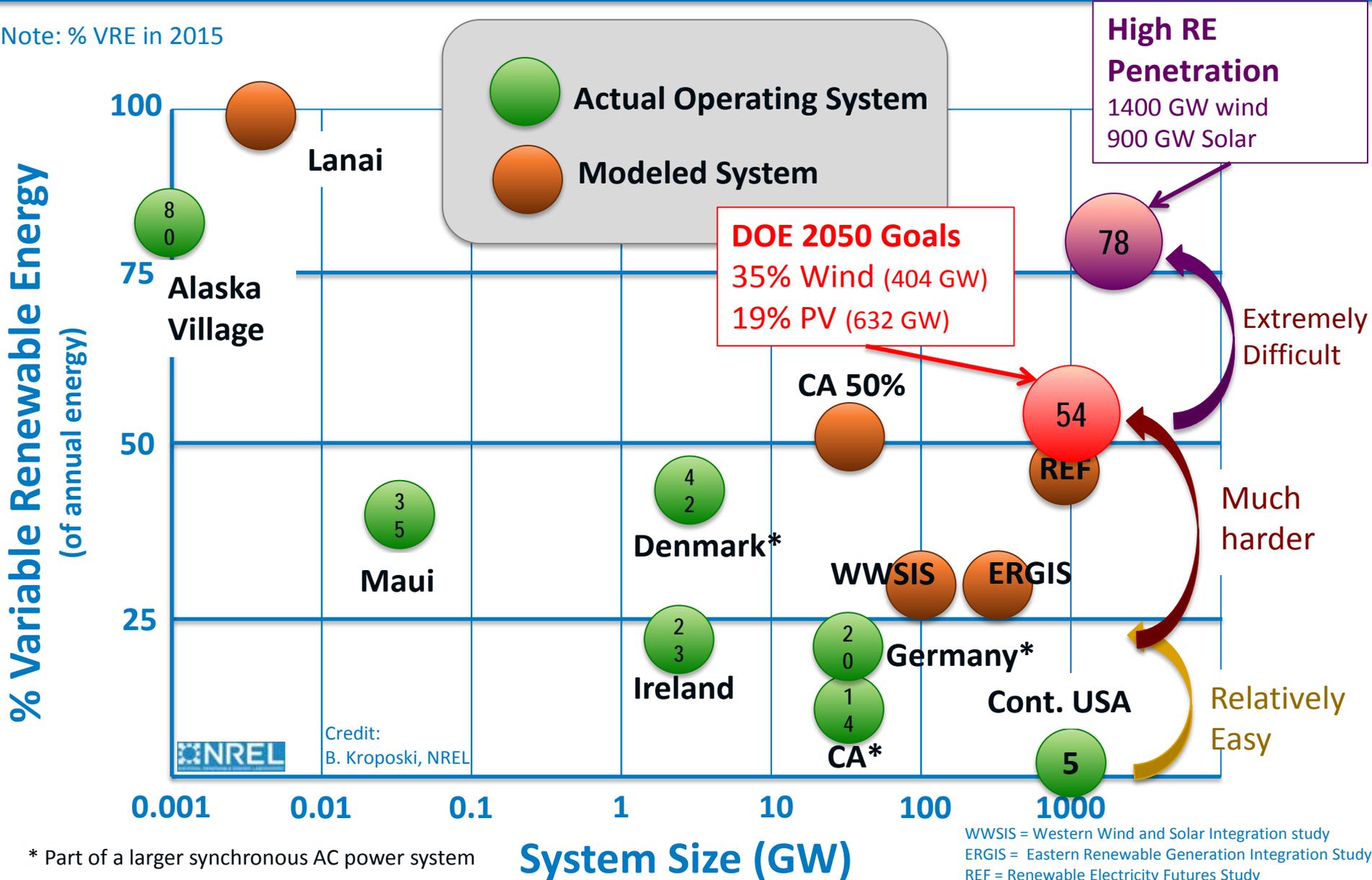


**29 States + Washington DC + 3 territories have a Renewable Portfolio Standard**  
*(8 states and 1 territories have renewable portfolio goals)*

Renewable portfolio standard  
 Renewable portfolio goal  
\* Extra credit for solar or customer-sited renewables  
† Includes non-renewable alternative resources

# 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

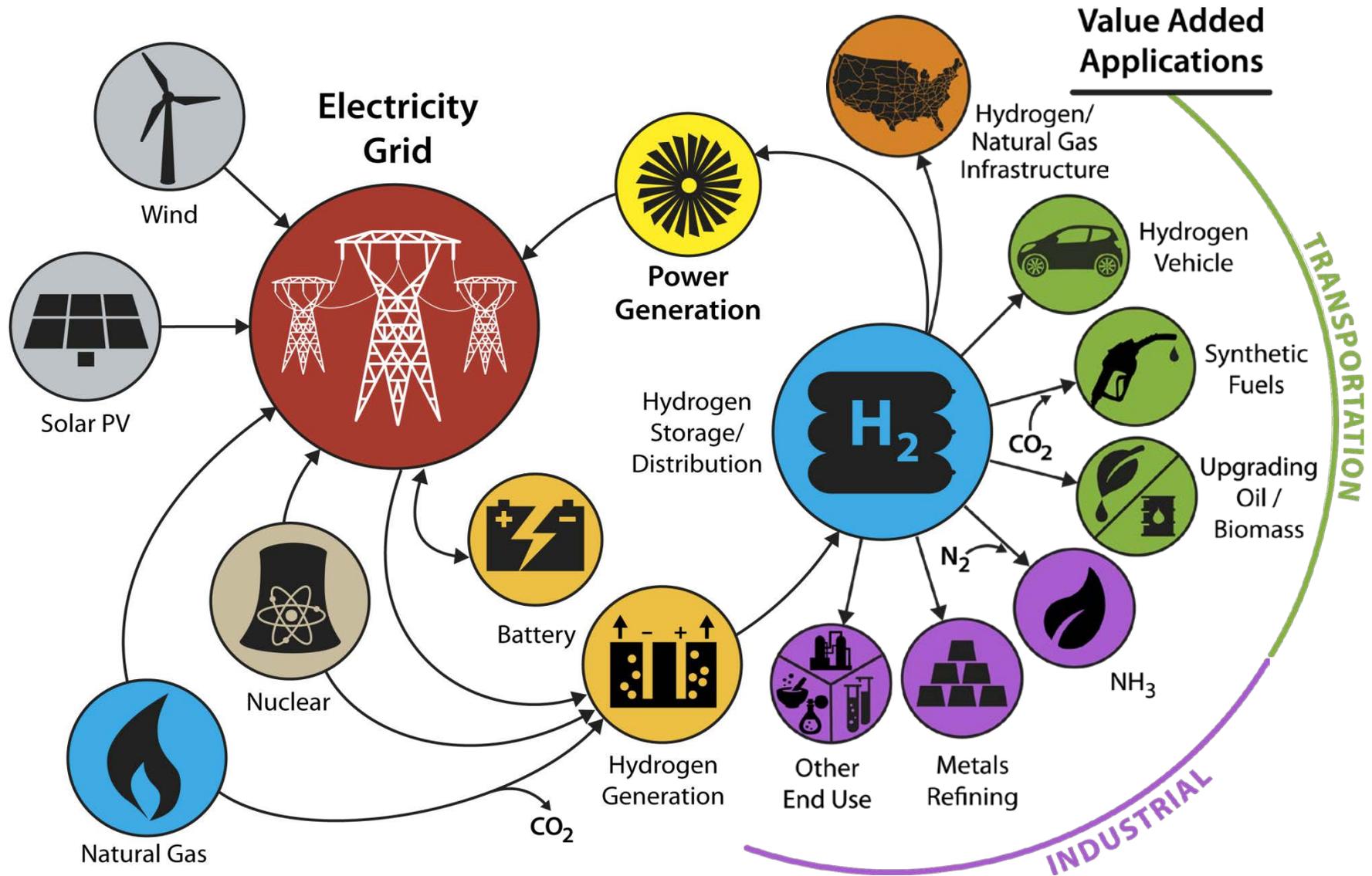
WWSIS = Western Wind and Solar Integration study  
 ERGIS = Eastern Renewable Generation Integration Study  
 REF = Renewable Electricity Futures Study

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- **Dwight D. Eisenhower**

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

# Conceptual H<sub>2</sub> at 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)

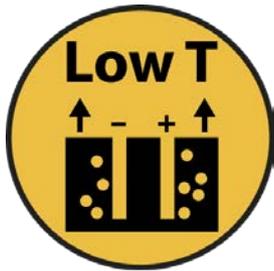
- **Benefits**

- 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 proposition.

# What is needed to achieve H<sub>2</sub> at Scale?

## Low and High Temperature H<sub>2</sub> Generation



Development of **low cost, durable, and intermittent H<sub>2</sub> generation.**



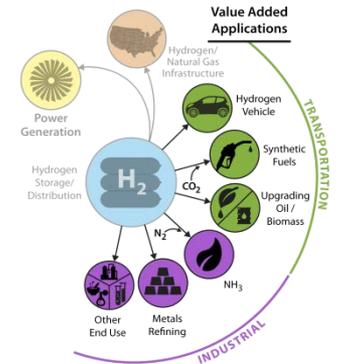
Development of **thermally integrated, low cost, durable, and variable H<sub>2</sub> generation.**

## H<sub>2</sub> Storage and Distribution



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

## H<sub>2</sub> Utilization



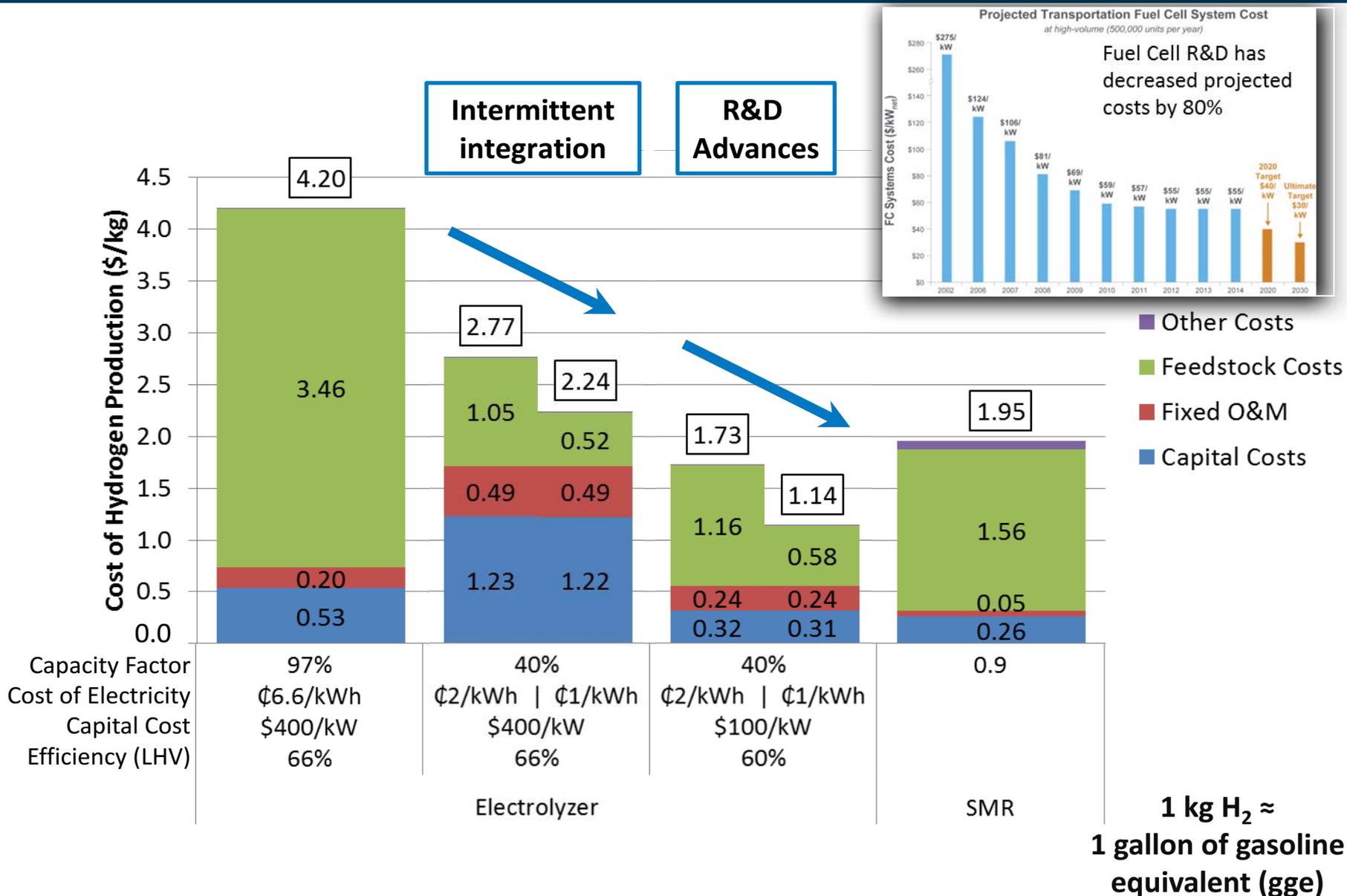
**H<sub>2</sub> as game-changing energy carrier, revolutionizing energy sectors.**

Analysis

Foundational Science

Future Electrical Grid

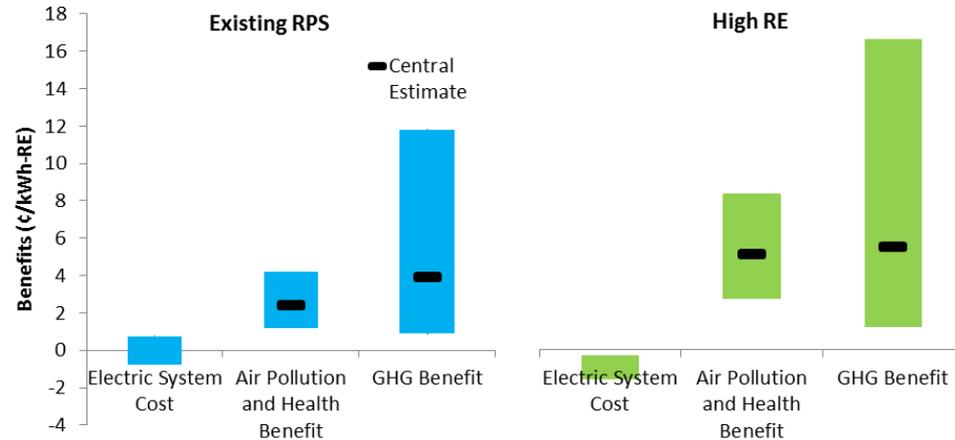
# Improving the Economics of Renewable H<sub>2</sub>



# Value Proposition Development

- Trying to build off/follow in tracks of others

	EXISTING RPS	HIGH RE
<b>RENEWABLE ENERGY IN 2050</b>	increased by ↑ <b>122</b> GW   <b>296</b> TWh	increased by ↑ <b>331</b> GW   <b>765</b> TWh
<b>COSTS</b>	<b>ELECTRIC SYSTEM COSTS</b> range from <b>-0.7% to 0.8%</b> equivalent to <b>+/- \$31 billion</b> <small>estimates span +/- 0.75¢/kWh-RE</small>	range from <b>0.6% to 4.5%</b> equivalent to <b>\$23 billion - \$194 billion</b> <small>estimates span 0.26-1.5¢/kWh-RE</small>
	<b>ELECTRICITY PRICES</b> range from <b>-2.4 cents/kWh to 1 cent/kWh</b>	range from <b>-1.9 cents/kWh to 4.2 cents/kWh</b>
<b>BENEFITS</b>	<b>SULFUR DIOXIDE</b> reduced by <b>↓ 6%</b>   <b>2.1 million</b> metric tons SO <sub>2</sub>	reduced by <b>↓ 29%</b>   <b>11.1 million</b> metric tons SO <sub>2</sub>
	<b>NITROGEN OXIDES</b> reduced by <b>↓ 6%</b>   <b>2.5 million</b> metric tons NO <sub>x</sub>	reduced by <b>↓ 29%</b>   <b>12.8 million</b> metric tons NO <sub>x</sub>
	<b>PARTICULATE MATTER 2.5</b> reduced by <b>↓ 5%</b>   <b>0.3 million</b> metric tons PM <sub>2.5</sub>	reduced by <b>↓ 29%</b>   <b>1.8 million</b> metric tons PM <sub>2.5</sub>
	<b>GREENHOUSE GAS EMISSIONS</b> reduced by <b>↓ 6%</b>   <b>4.7 billion</b> metric tons CO <sub>2e</sub>	reduced by <b>↓ 23%</b>   <b>18.1 billion</b> metric tons CO <sub>2e</sub>
	<b>WATER USE</b> reduced by <b>↓ 4%</b> consumption   <b>3%</b> withdrawal	reduced by <b>↓ 18%</b> consumption   <b>18%</b> withdrawal
	<b>NATURAL GAS</b> reduced by <b>↓ 35</b> quads (3.3%) equivalent to <b>\$78 billion</b> impact 1.9¢/kWh-RE	reduced by <b>↓ 46</b> quads (4.3%) equivalent to <b>\$99 billion</b> impact 0.9¢/kWh-RE
<b>RE JOB NEEDS</b>	increase in <b>↑ 19%</b> RE-employment equivalent to <b>4.7 million</b> RE job-years	increase in <b>↑ 47%</b> RE-employment equivalent to <b>11.5 million</b> RE job-years



**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>

# H<sub>2</sub> at Scale Big Idea Teams/Acknowledgement

## 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)

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

### 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 Gorenssek (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 Bidy (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 Hovsopian (INL)

### Foundational Science:

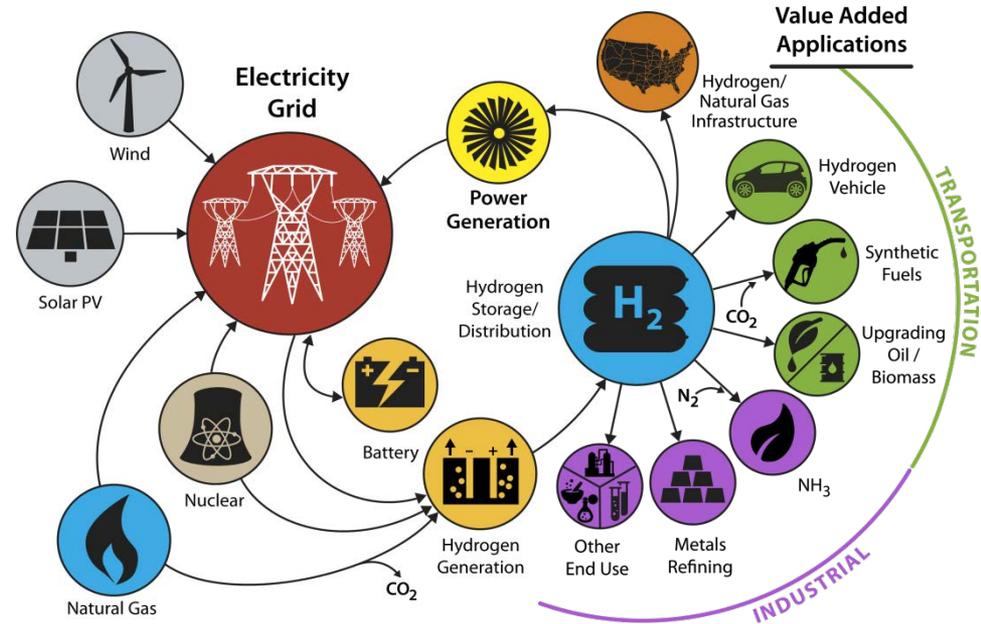
Adam Weber (lead, LBNL); Voja Stamekovic (ANL); Nenad Markovic (ANL); Frances Houle (LBNL); Morris Bullock (PNNL); Aaron Appel (PNNL); Wendy Shaw (PNNL); Tom Jaramillo (SLAC); Jens Norskov (SLAC); Mark Hartney (SLAC); Vitalij Pecharsky (Ames); Alex Harris (BNL)

### 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

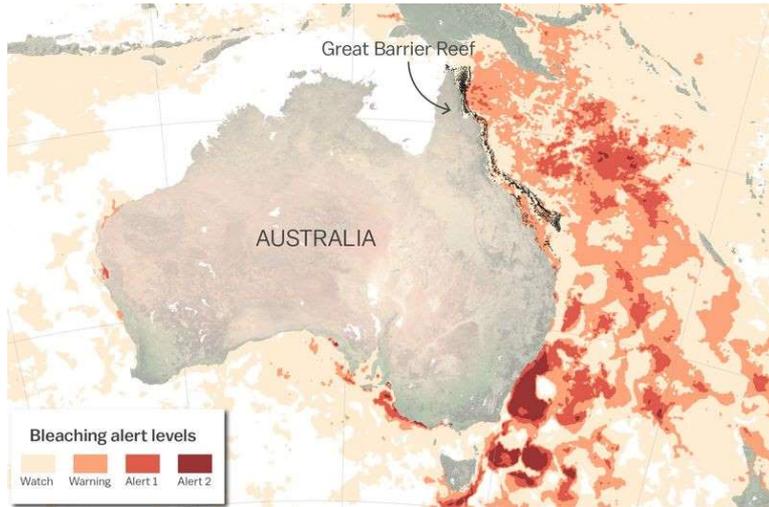


**Blue:** High engagement and support  
**Green:** Engaged with interest/support  
**Orange:** Limited engagement  
**Black:** Little engagement

Next Workshop Houston May 23-24, 2017

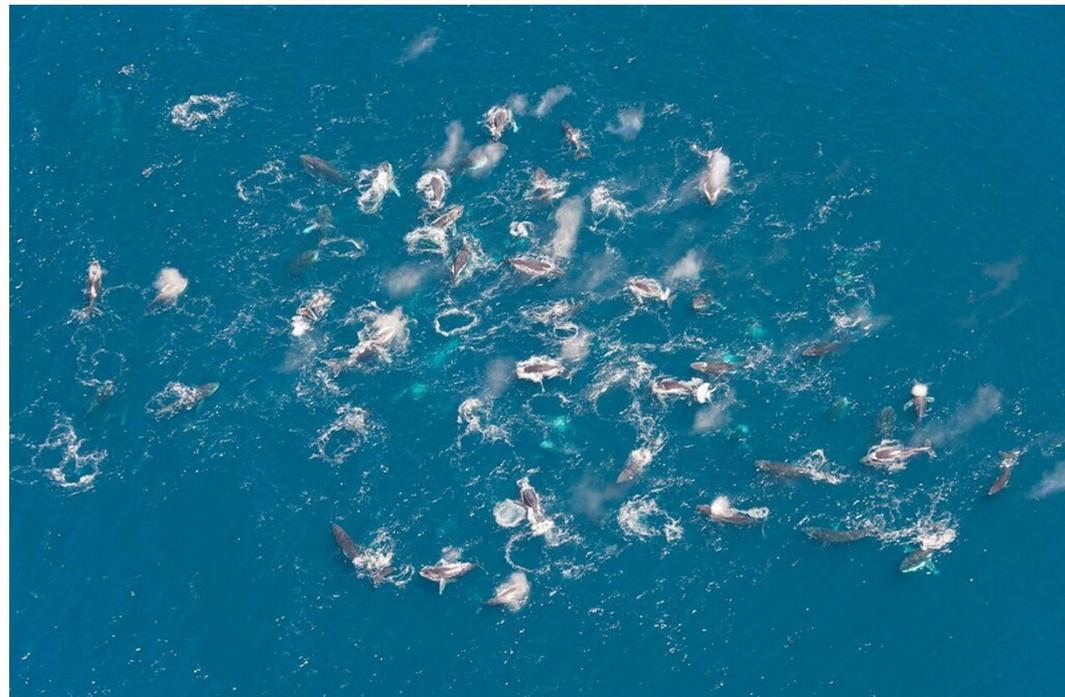
# Future Impact?

## 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=BB0PU0T>
2. <http://news.nationalgeographic.com/2017/03/humpback-whales-swarms-south-africa/>

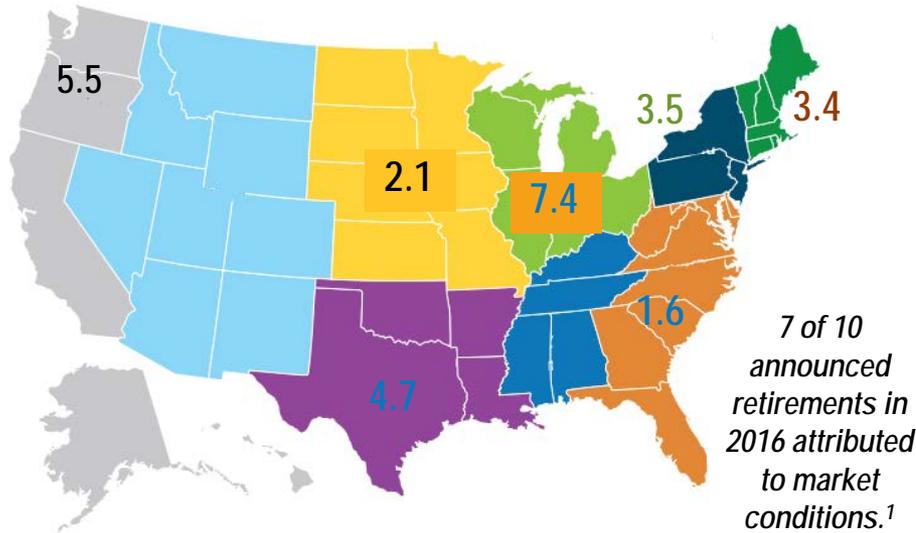
# Back up slides

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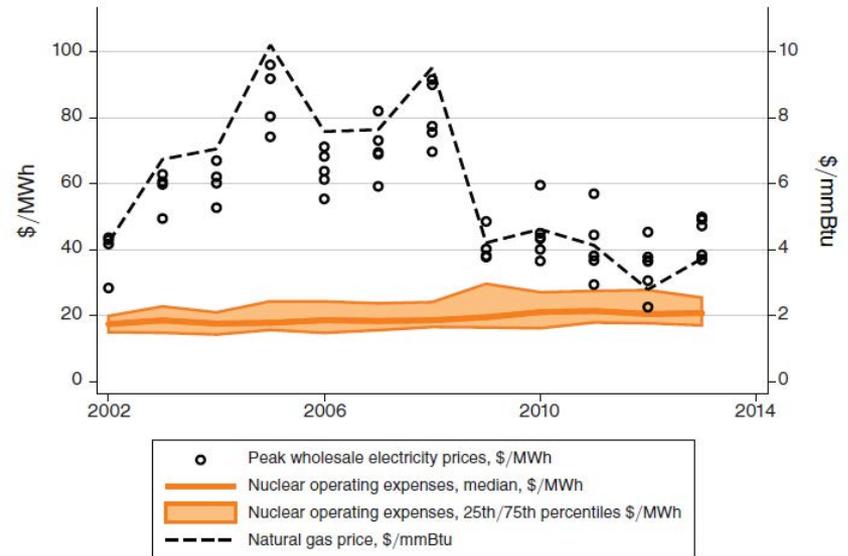
# Nuclear Energy Impacts

## Nuclear Plants at Risk by 2030, or Recently Retired (GW) <sup>1</sup>

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

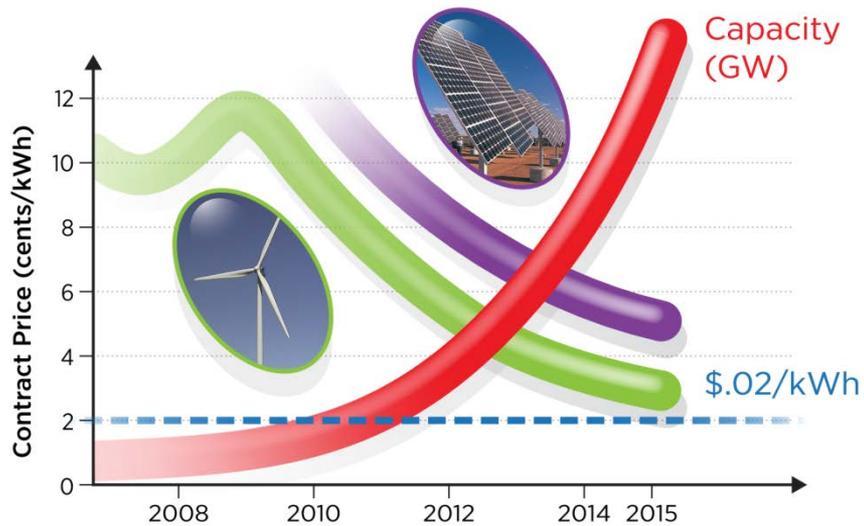


Source: L. Davis and C. Hausman, *American Economic Journal, Applied Economics*, 2016  
Market Impacts of a Nuclear Power Plant Closure



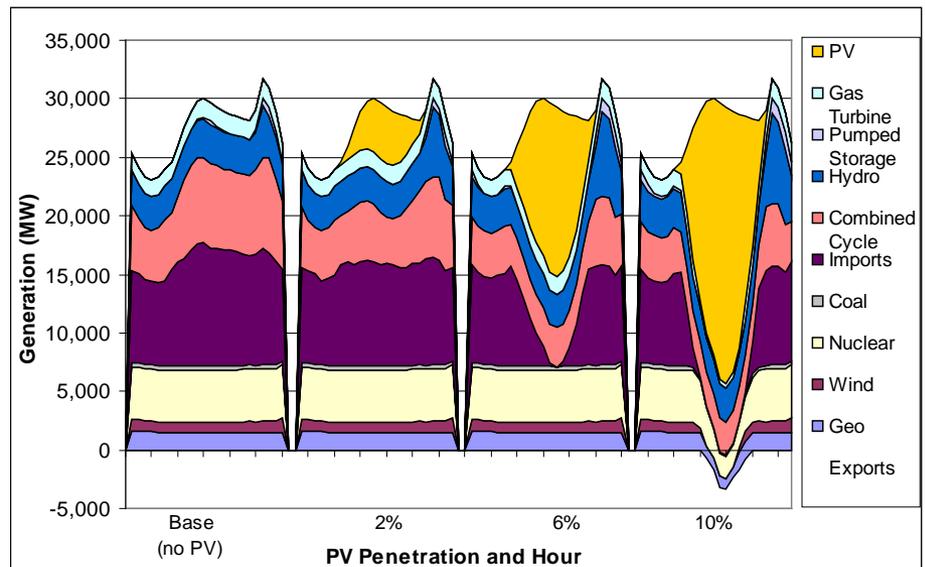
*Actual cost of electricity production by nuclear plants in the United States*

# Renewable Energy Impacts



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

Denholm et al. 2008



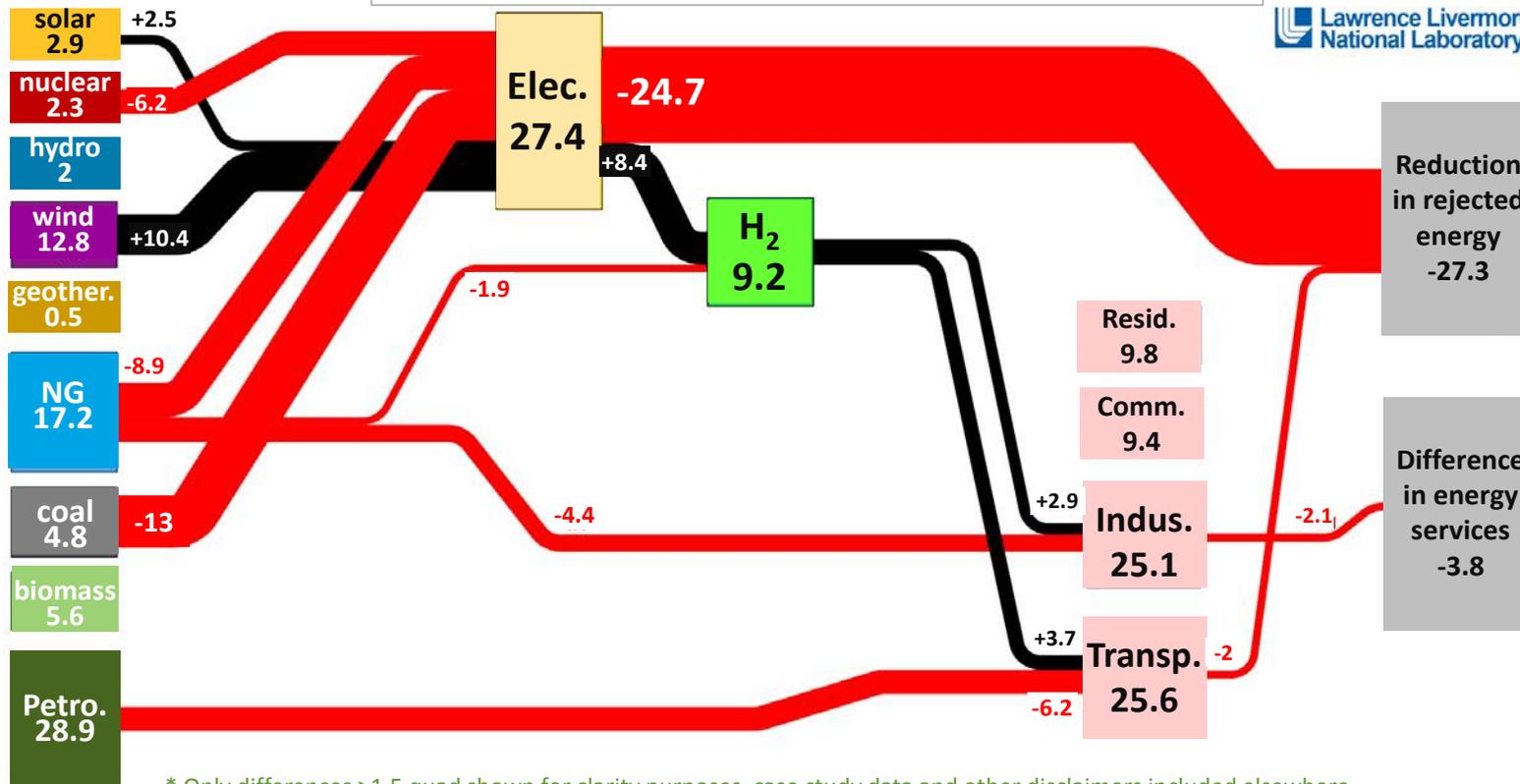
# Evolving H<sub>2</sub>@Scale vision/message

- Quantifying energy-system wide value proposition

- o Based on Scenario Development (like that shown below)

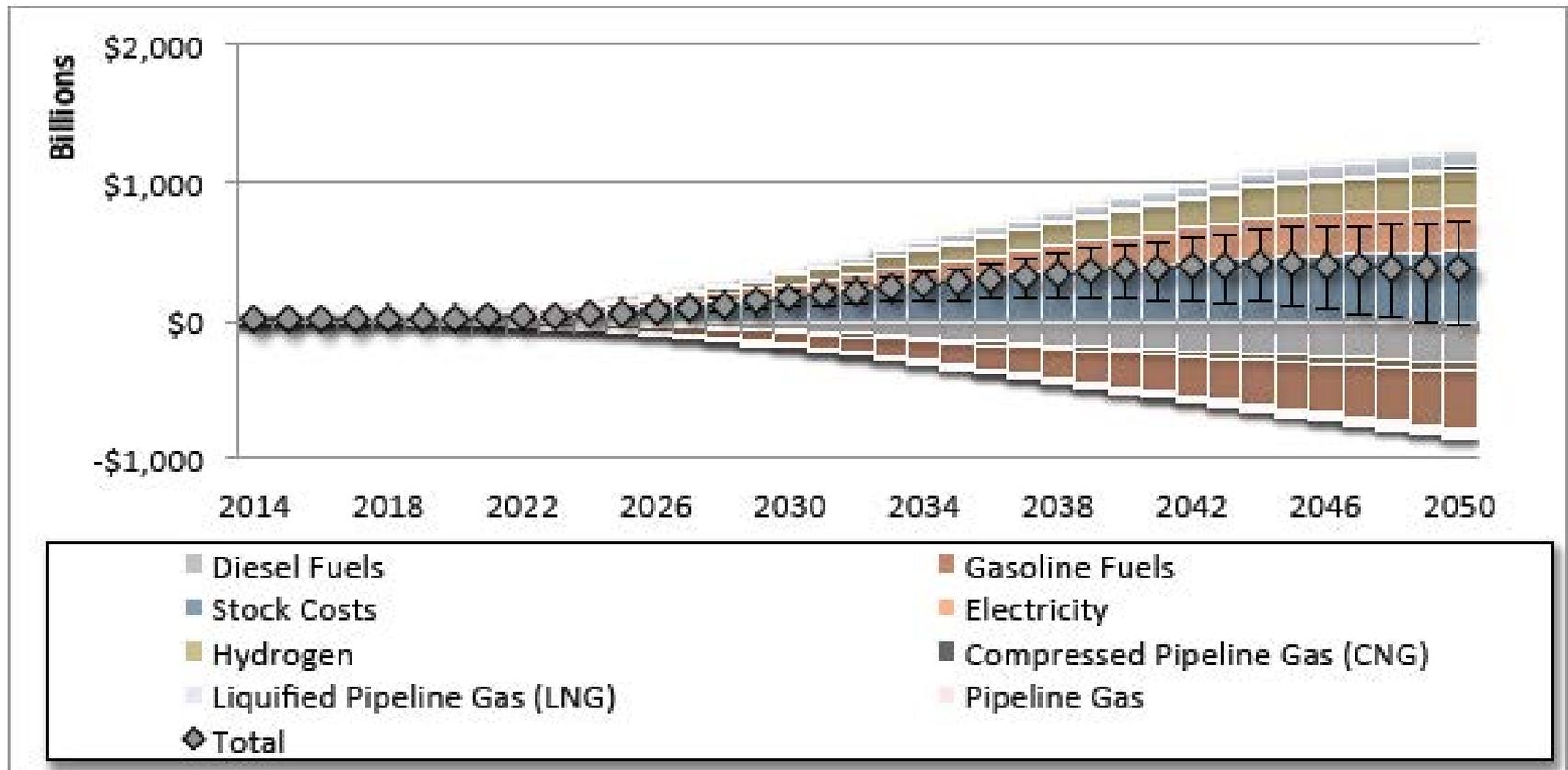
Energy Use difference between 2050 high-H<sub>2</sub> and AEO 2040 scenarios (Quad Btu)

Red flows represent a reduction (between scenarios)  
Black flows represent an increase (between scenarios)



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

#### ▪ 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