



## H2@Scale Analysis

### Hydrogen and Fuel Cells AMR and Peer Evaluation Meeting

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Project ID #TV045

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

## Timeline and Budget

- Project Type: Lab Call
- Project start date: 1/1/17
- FY17 planned DOE funding: \$1,267K
  - NREL: \$667K
  - ANL: \$500K
  - LBNL: \$50K
  - PNNL: \$50K
  - INL: Funded by DOE's Office of Nuclear Energy

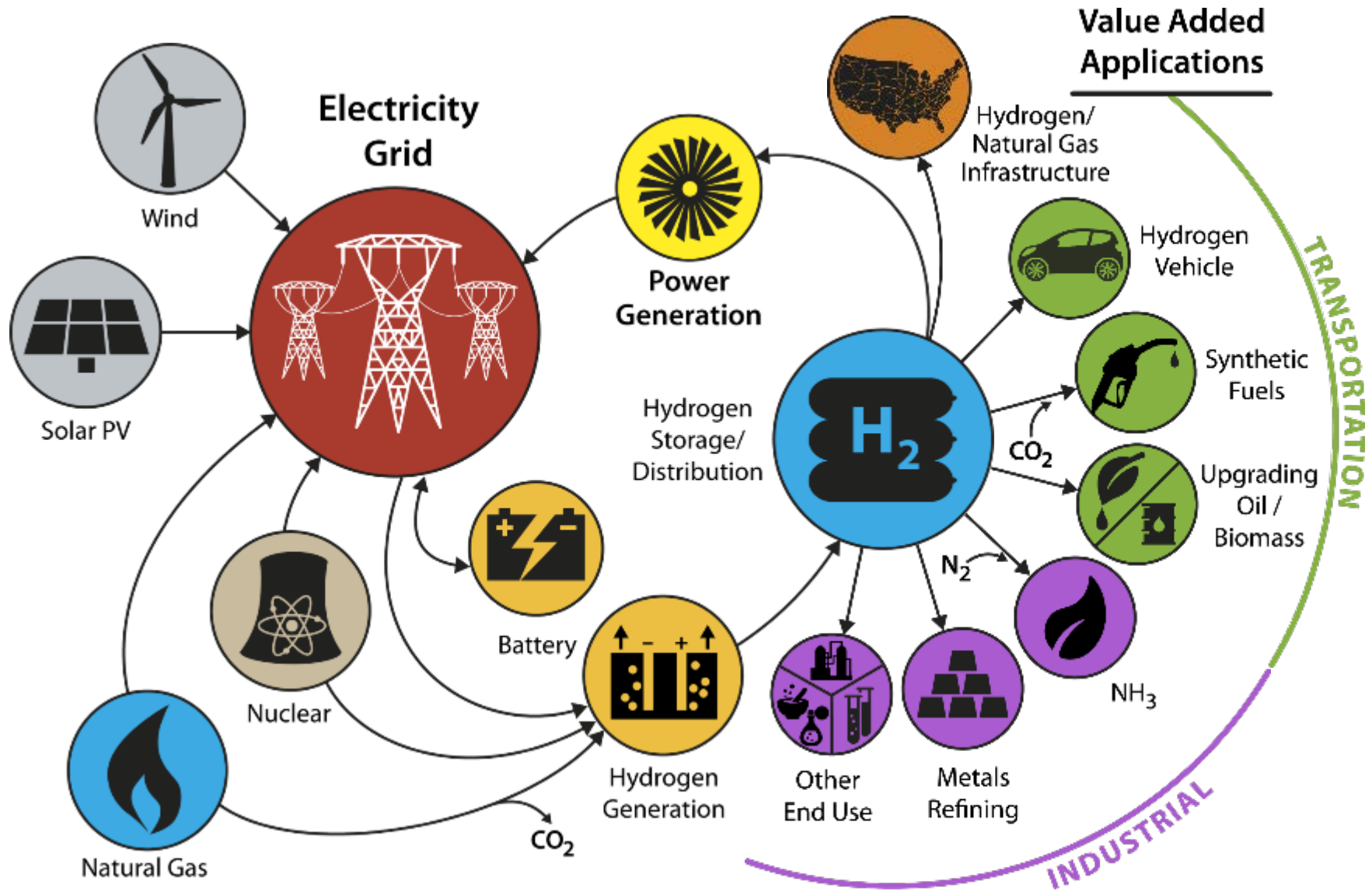
## Partners

- Project lead: NREL
- Lab partners: ANL, LBNL, PNNL, INL, LLNL
- DOE partners: Nuclear Energy
- Industry and academia reviewers

## Barriers (Systems Analysis)

- A: Future Market Behavior
  - Potential market for low value energy and potential hydrogen markets beyond transportation
- D: Insufficient Suite of Models & Tools
  - Tools integrating hydrogen as an energy carrier into the overall energy system and quantifying the value hydrogen provides
- E: Unplanned Studies and Analysis
  - H2@Scale is a new concept and requires analysis of its potential impacts for input in prioritizing R&D

# Relevance: Conceptual H2@Scale Energy System\*



\*Illustrative example, not comprehensive

# Relevance: Analysis Objectives

## Objective: Improve fidelity of H2@Scale value proposition

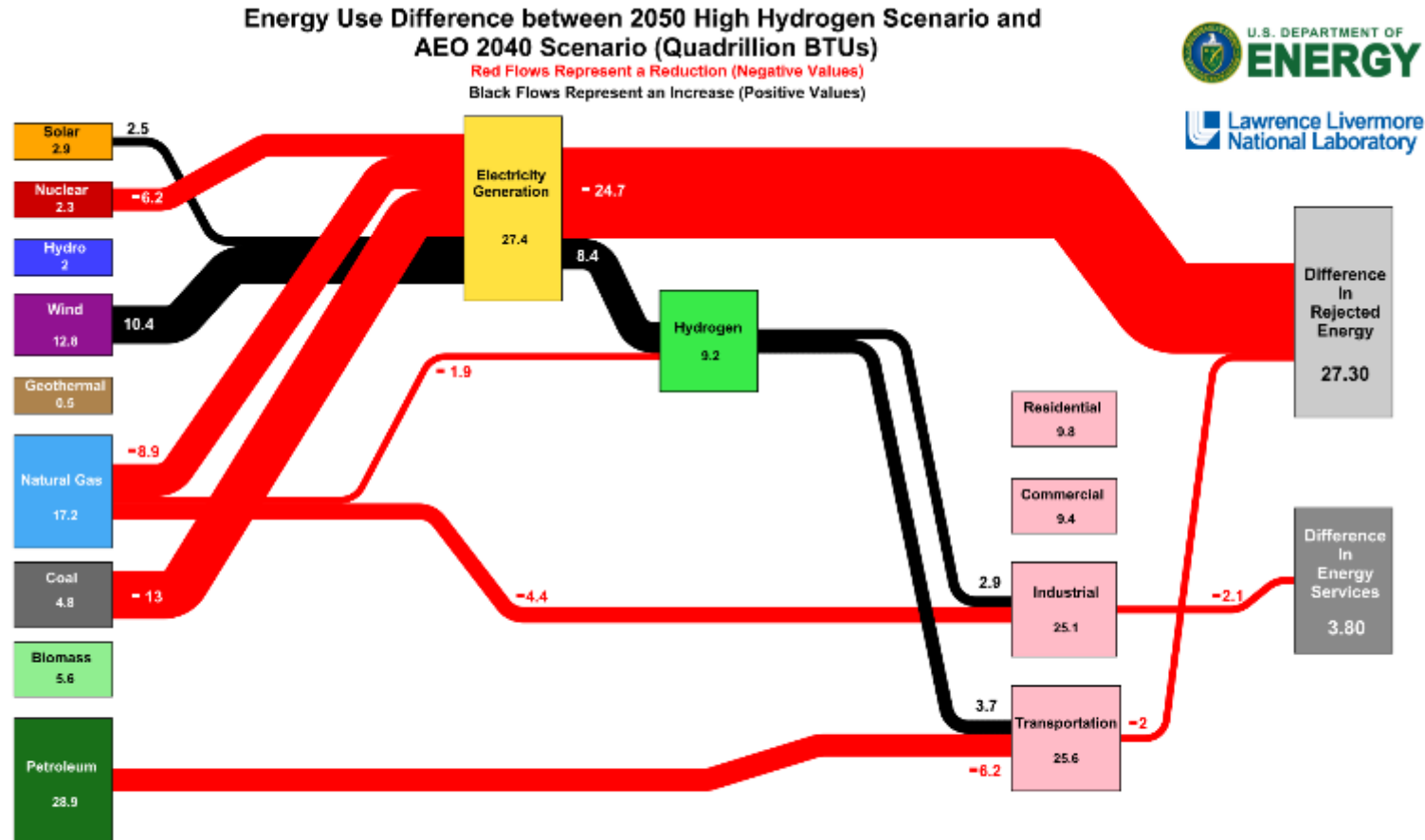


Figure 101 March 2016. Data is based on Final Hydrogen Roadmap (DOE-HQ-2016-0001) and (DOE-HQ-2016-0001). All data information is a projection and is subject to change. This analysis was performed by the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only central electricity plants and does not include wind-generation. The response optimization of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in 2050 equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the ratio of electricity delivered to the grid to the primary energy input into electricity generation. Fuel use efficiency is calculated as 100% for the residential sector, 80% for the commercial sector, 80% for the industrial sector, and 80% for the transportation sector. Values may not equal sum of components due to independent rounding. Negative values between 3 and -2.5 are not shown. LBNL-50-67667

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A preliminary analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.

Source: Pivovar, Bryan. "H2@Scale: Deeply Decarbonizing Our Energy System HTAC Presentation" April 6, 2016.

[https://www.hydrogen.energy.gov/pdfs/htac\\_apr16\\_10\\_pivovar.pdf](https://www.hydrogen.energy.gov/pdfs/htac_apr16_10_pivovar.pdf)

# Relevance: Analysis Objectives

## Objective: Improve fidelity of H2@Scale value proposition

Energy Use Difference between 2050 High Hydrogen Scenario and  
AEO 2040 Scenario (Quadrillion BTUs)  
Red Flows Represent a Reduction (Negative Values)  
Black Flows Represent an Increase (Positive Values)



- Provide results that are supported by in-depth analysis of market potential and economics
- Quantify potential impacts
  - Economics
  - Resources
  - Emissions
- Identify regional opportunities and challenges

Petroleum

28.9

-8.2

25.6

Figure 101 March 2016. Data is based on High Hydrogen Scenario and AEO2040-08102015. If data information is a dependent on it, it is only result and is given in the scenario document National Laboratory and the department of energy, under where scenario the work was performed. Distributed electricity represents only total electricity value and does not include wind-generation. Also reports optimization of resource resources in U.S. Hydro, wind, geothermal and solar for electricity in 100 equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total value of electricity delivered divided by the primary energy input from electricity generation. Fuel use efficiency is calculated as 100% for the natural gas and 80% for the coal-fired power, 85% for the industrial sector, and 90% for the transportation sector. Values may not equal sum of components due to independent rounding. Negative values between 3 and -2.5 are not shown. 1481-20-07067

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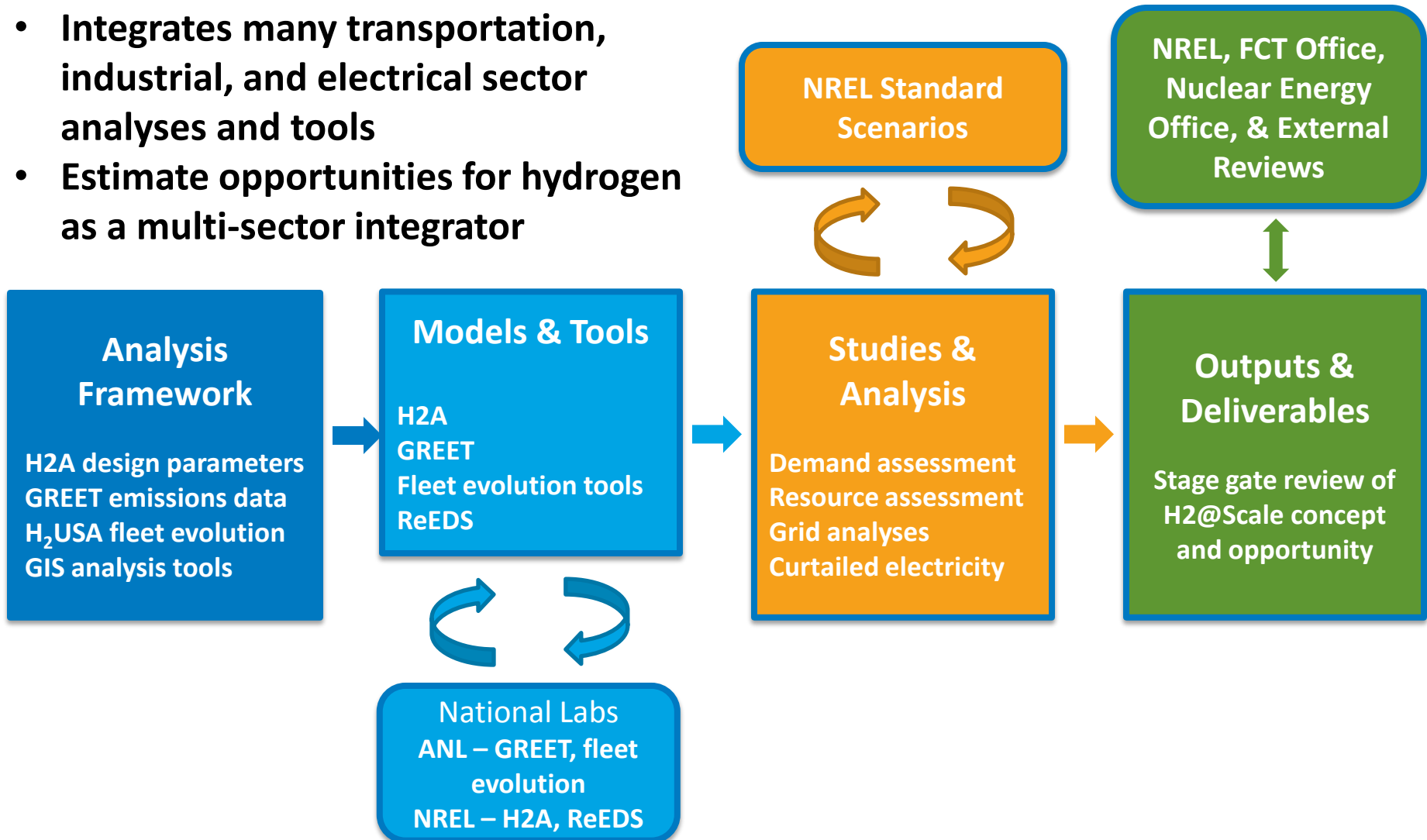
Source: Pivovar, Bryan. "H2@Scale: Deeply Decarbonizing Our Energy System HTAC Presentation" April 6, 2016.

[https://www.hydrogen.energy.gov/pdfs/htac\\_apr16\\_10\\_pivovar.pdf](https://www.hydrogen.energy.gov/pdfs/htac_apr16_10_pivovar.pdf)

# Approach: FCTO Systems Analysis Framework

## *H2@Scale Analysis*

- Integrates many transportation, industrial, and electrical sector analyses and tools
- Estimate opportunities for hydrogen as a multi-sector integrator



# Approach: Staged Analysis

## Technical Potential

- Potential demand
- Supply resources
- Impact potential (limited)
- Infrastructure Issues

## Economic Potential

- H<sub>2</sub> price requirements
- Supply options and costs
- Scenarios
- Impact potential

## Additional analysis needs

- Additional scenarios
- Economic inertia
- Economic externalities
- Spatial issues

Milestone	Date
Presentation summarizing potential demand, resources, and infrastructure issues	3/31/2017
Demand and supply curves	6/30/2017
Stage gate review of potential for H2@Scale concept	9/30/2017

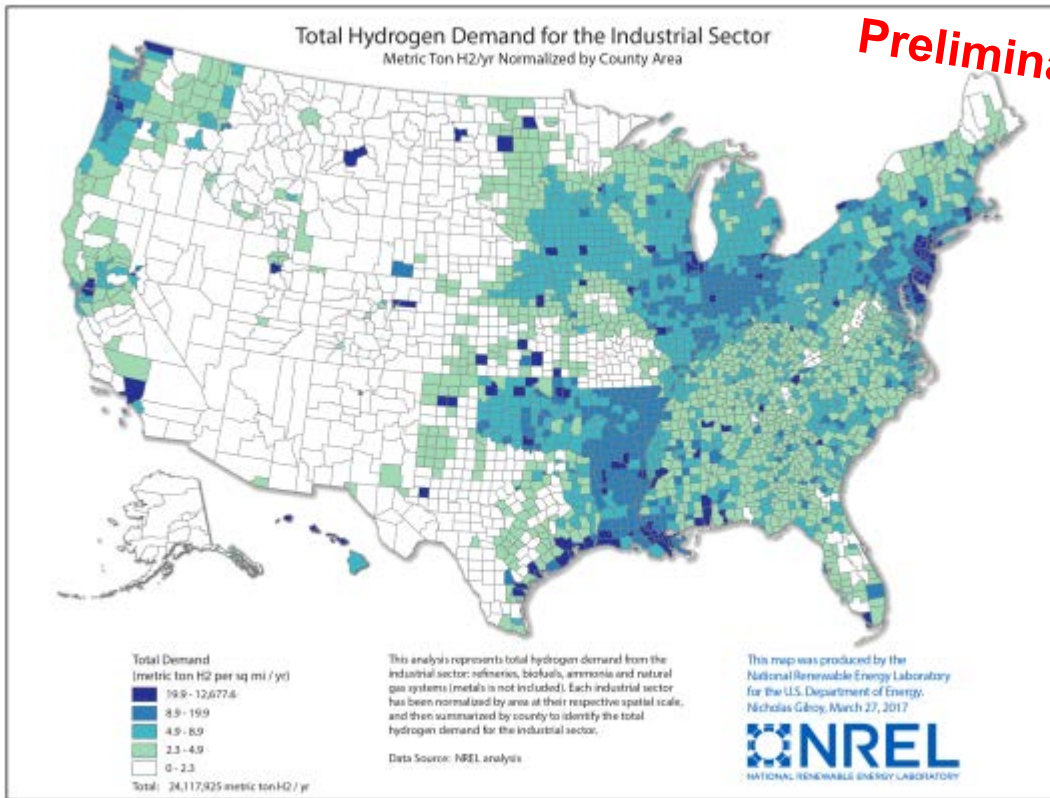


# Approach: Analysis of Technical Potential

Analysis Issue / Gap	Approach
National <b>demand estimates</b>	Identify <b>existing studies</b> , review results, and estimate demand in mature markets
National <b>resource estimates</b>	Review existing resource studies and hydrogen yields <b>estimate requirements for hydrogen production</b>
<b>Value proposition</b> for producing hydrogen via electrolysis	Identify drivers for and implications of <b>increased opportunity for responsive load</b>
Impacts of electrolytic hydrogen on <b>emissions and resource use</b>	Assess impacts using <b>GREET</b>
<b>Potential impacts on infrastructure</b>	Assess <b>increased electricity load</b> and identify <b>locations</b> where demands exceed potential production



# Accomplishment: Technical Potential for H<sub>2</sub> Demand



**Preliminary Results**

Use	Market potential (million metric tonne H <sub>2</sub> / year)
<b>Industrial Use</b>	
Refineries & CPI <sup>§</sup>	8*
Metals	5
Ammonia	5
Natural Gas	7
Biofuels	4
Light Duty Vehicles	28
Other Transport	3
<b>Total</b>	<b>60</b>

**Total market potential:**  
**60 MMT/yr**

**Current U.S. market: ≈ 10 MMT/yr**

**Global H<sub>2</sub> production revenue:**  
**6% CAGR, 2009-2016<sup>1</sup>**

<sup>§</sup> CPI: Chemical Processing Industry not including metals, biofuels, or ammonia

\* Current potential used due to lack of consistent future projections

Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from <http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels>

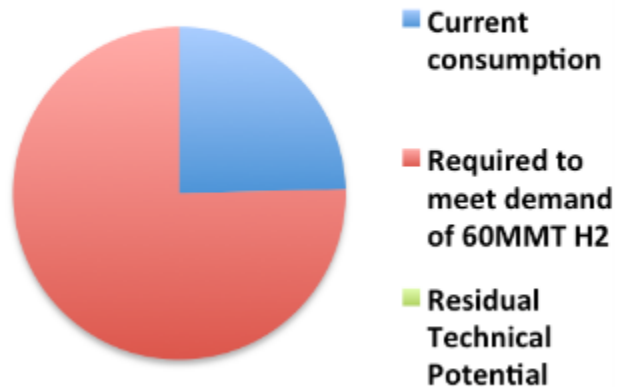
1. Global hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology- Trends & Forecasts (2011-2016)

# Accomplishment: Utilization of Renewable Resources

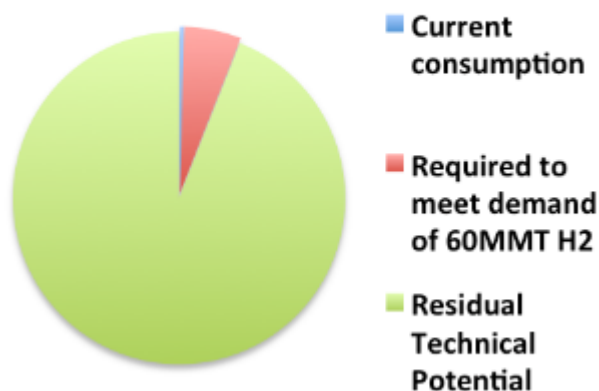
	EIA 2015 current consumption (quads/yr)	Required to meet demand of 60 MMT / yr (quads/yr)	Technical Potential (quads/yr)
Solid Biomass	4.7	15	20
Wind Electrolysis	0.7	9	170
Solar Electrolysis	0.1	9	1,364

*Preliminary Results*

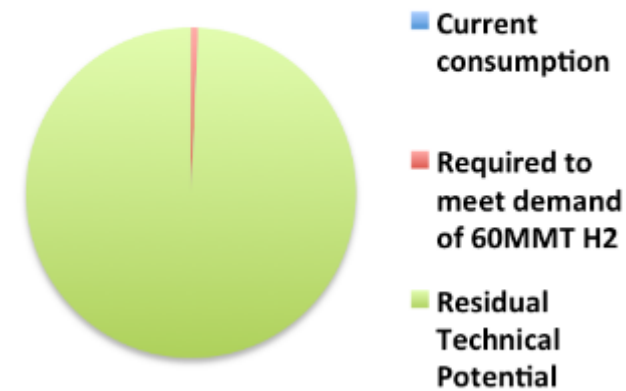
**Biomass Technical Potential**



**Wind Technical Potential**

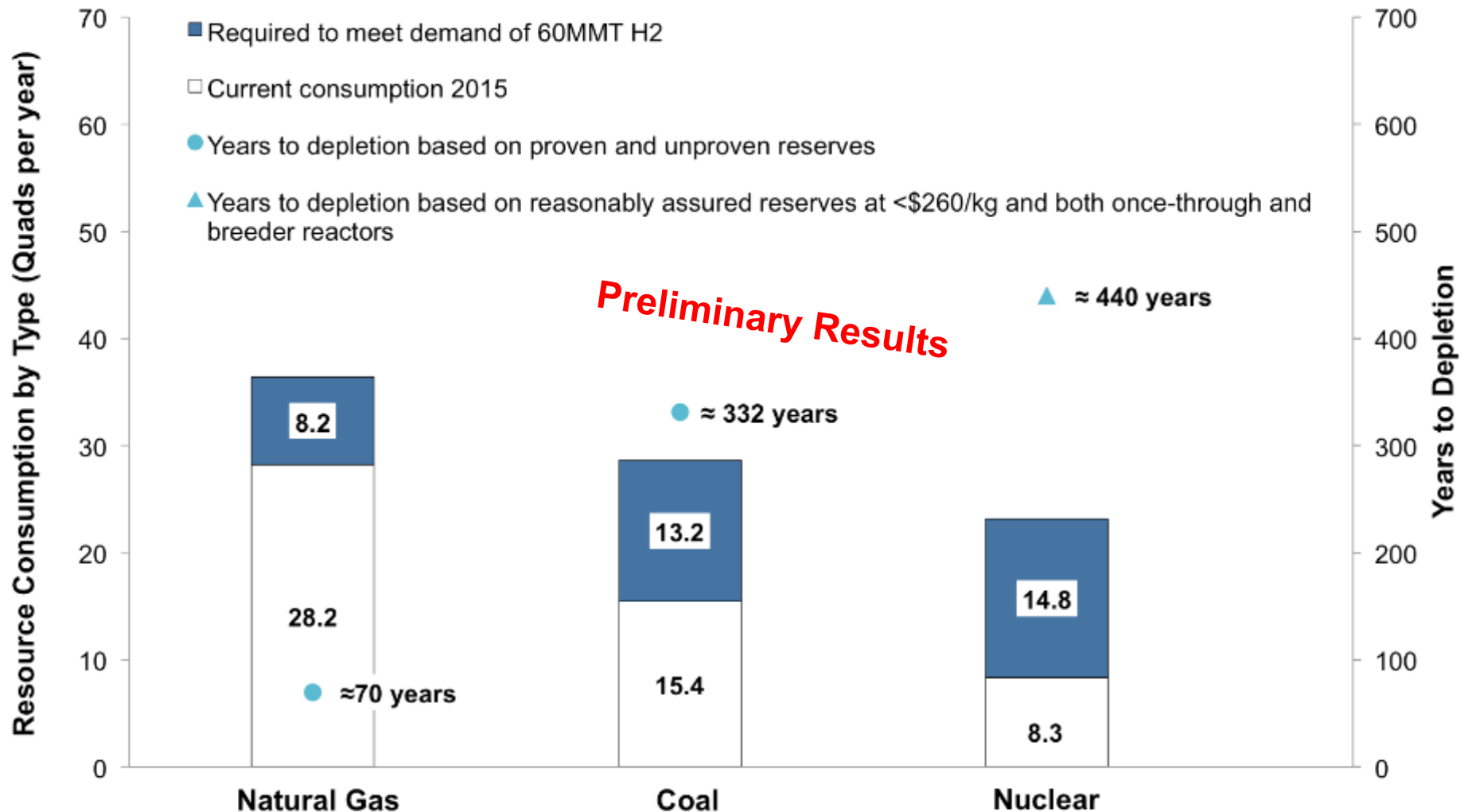


**Solar Technical Potential**



**Total demand including hydrogen is satisfied by  $\approx 6\%$  of wind,  $<1\%$  of solar, and  $\approx 100\%$  of biomass technical potential**

# Accomplishment: Utilization of Fossil & Nuclear Resources

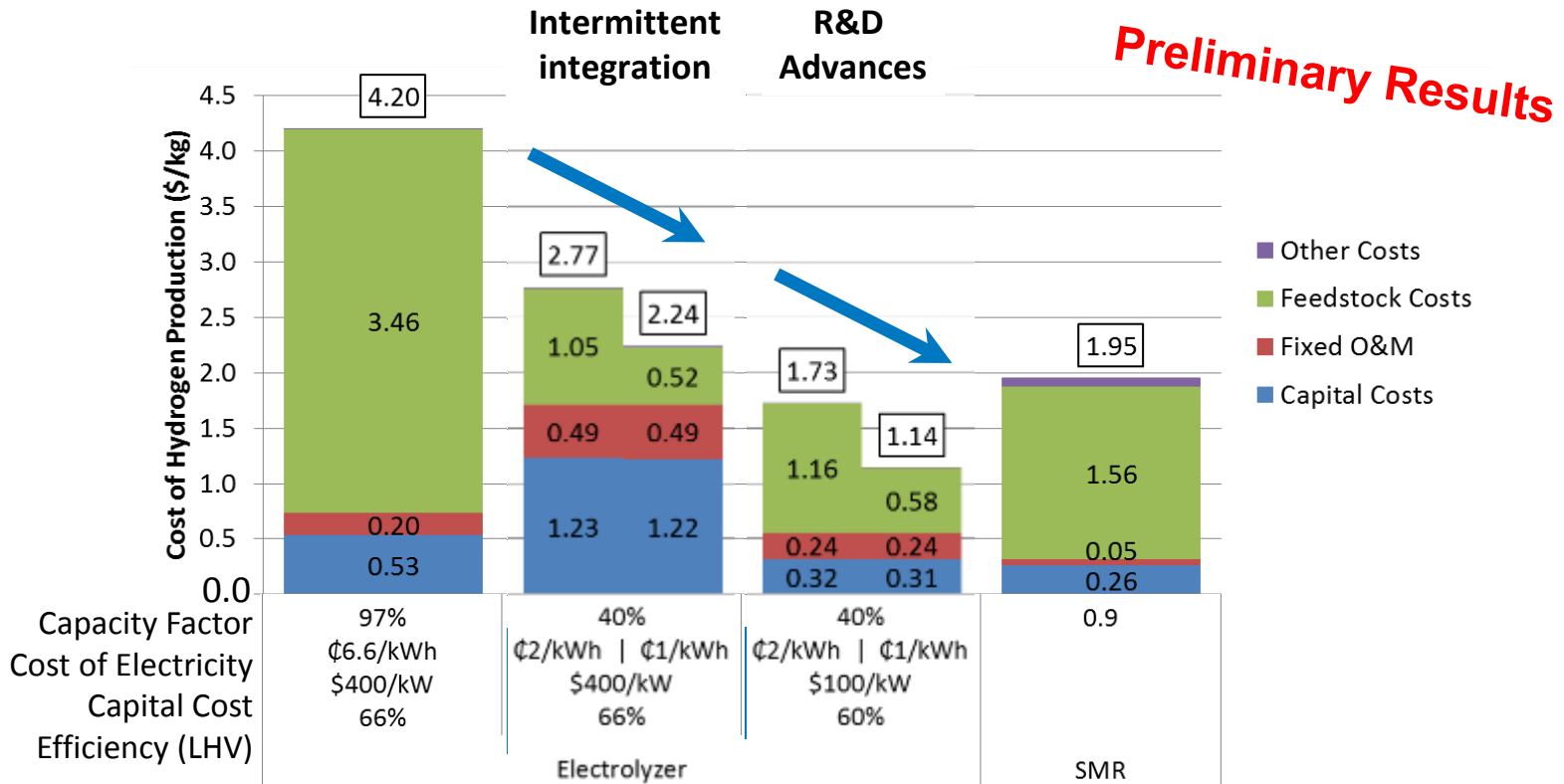


**Hydrogen can be produced from diverse domestic resources to meet aggressive growth in demand**

# Accomplishment: Potential for Use of Low-Cost Electricity

Increased renewable electricity generation likely to

- lead to increased curtailment and intermittent low-cost electricity
- drive out nuclear power generation



Intermittent low-cost electricity can enable low-cost hydrogen production and also support clean electricity generation

# Accomplishment: Potential Impacts on Emissions and Resources

Use	MMT / yr	GHG Reduction (million metric ton CO <sub>2</sub> /yr)	Petroleum Reduction (bbl/yr)	NG Reduction (mmBtu/yr)
Refineries	8	87	900,000	1,332,000,000
Metals	5	78	0	365,000,000
Ammonia	5	54	500,000	833,000,000
Natural Gas System	7	63	700,000	923,000,000
Biofuels <sup>§</sup>	4	28	77,500,000	-26,000,000*
Light Duty Vehicles	28	469	1,017,600,000	629,000,000
Other Transport	3	50	113,400,000	51,000,000
<b>Total</b>	<b>60</b>	<b>830 Million MT</b>	<b>1.2 Billion bbl</b>	<b>4.1 Quads</b>

**Preliminary Results**

~16% of U.S. energy-related emissions in 2016

~17% of U.S. petroleum consumption in 2016 – potential savings of over \$50 billion

~14% of U.S. natural gas consumption in 2016

**Hydrogen alone has the potential to reduce emissions and fossil use by ~15%. The ability to enable higher penetrations of renewable energy can further reduce emissions and fossil use.**

\*Negative values represent increase in use due to fertilizer production  
<sup>§</sup> 12% of the benefits of hydrogenated biofuels are credited to hydrogen

# Accomplishment: Estimate of Impacts on Grid

## How much electricity would H2@Scale require?

$$60\text{B kg H}_2 \text{ per year} \times 55 \text{ kWh per kilogram} = 3,300 \text{ TWh per year}$$



## How does that compare with our current electricity use?

$$\text{U.S. Electricity Consumption} = \text{Approximately } 3,900 \text{ TWh per year}^*$$

*Preliminary Results*

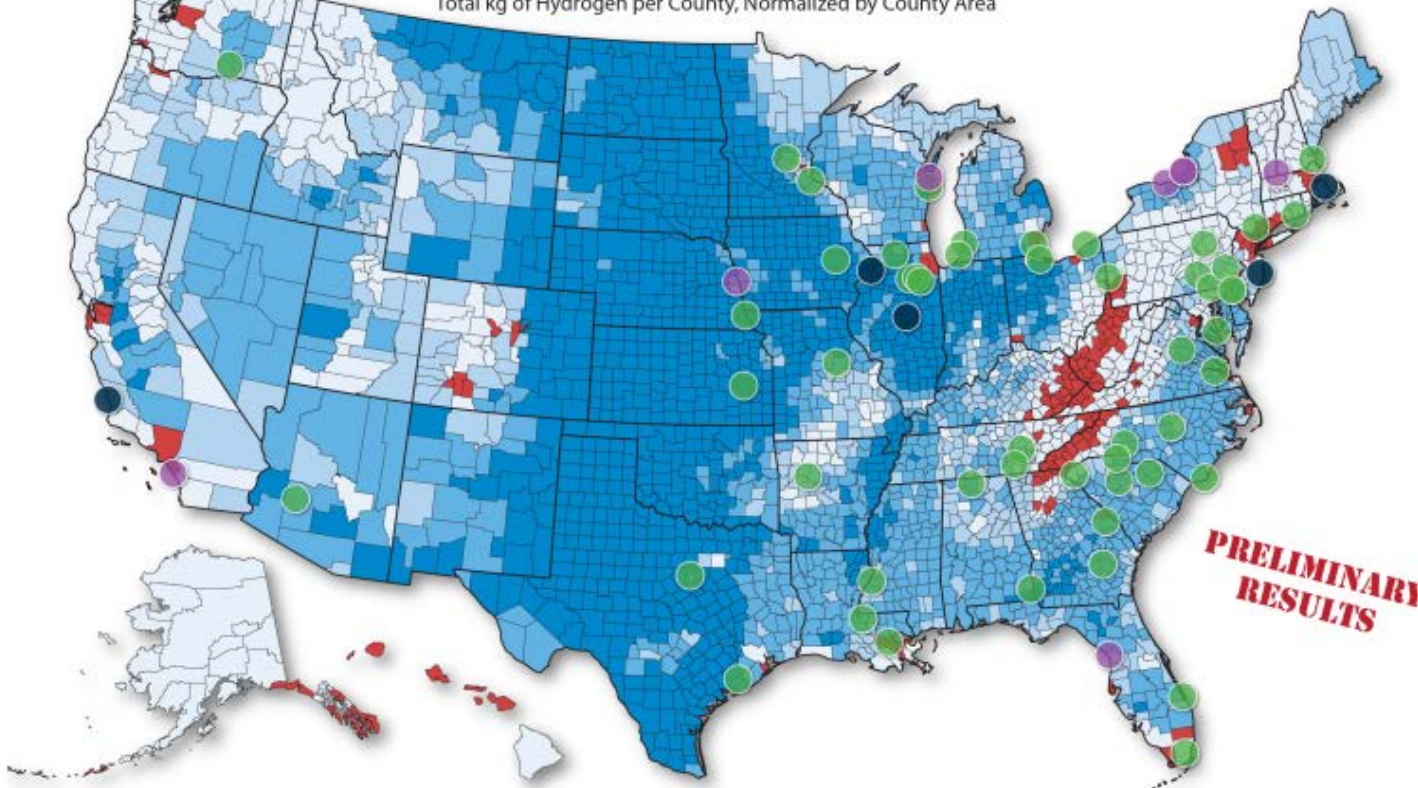
**~85% of current U.S.  
electricity demand**

\*2015 consumption. Source: EIA AEO 2016

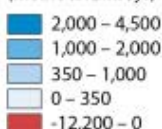


# Accomplishment: Where Resources are Sufficient

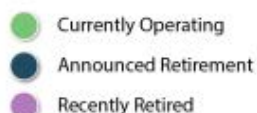
Hydrogen Potential From Photovoltaic and Onshore Wind Resources Minus  
Total Hydrogen Demand for the Industrial & Transport Sectors  
Total kg of Hydrogen per County, Normalized by County Area



## Hydrogen (metric ton/m<sup>2</sup>/yr)



## Nuclear Energy Plants



This analysis represents potential generation from utility-scale photovoltaics and onshore wind resources minus total hydrogen demand from the industrial sector: refineries, biofuels, ammonia and natural gas systems (metals are not included) and the transport sector: light duty vehicles and other transport. The data has been normalized by area at their respective spatial scales, and then summarized by county.

Data Source: NREL analysis  
Robson, A. Preserving America's Clean Energy Foundation. Retrieved March 23, 2017, from <http://www.thirdway.org/report/preserving-americas-clean-energy-foundation>

This map was produced by the  
National Renewable Energy Laboratory  
for the U.S. Department of Energy.  
Nicholas Gilroy, March 27, 2017

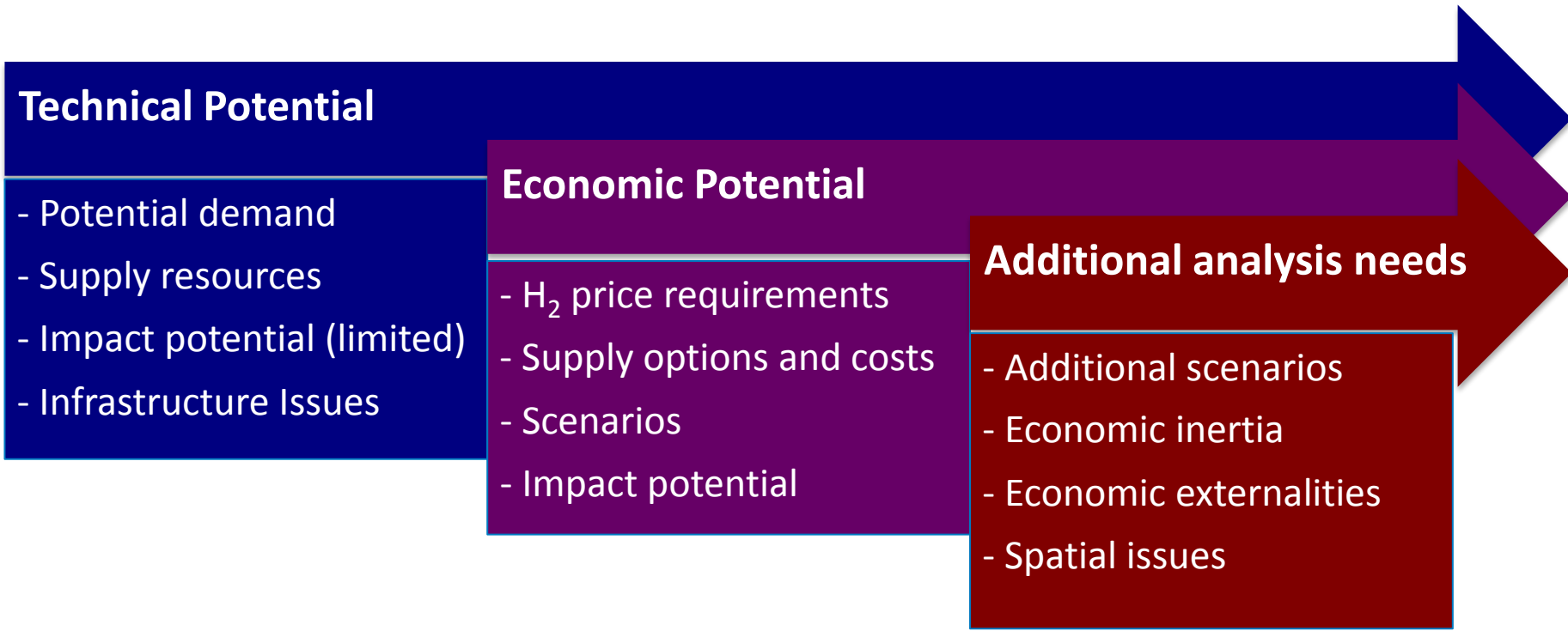


- PV and wind resources exceed industrial + transportation demand (not including metals) in **counties colored blue**
- Industrial + transportation demand is greater than resources **only in counties colored red**
- Nuclear production could provide the necessary additional generation

**Most counties have sufficient renewable resources. Those that do not have renewable or nuclear resources nearby.**

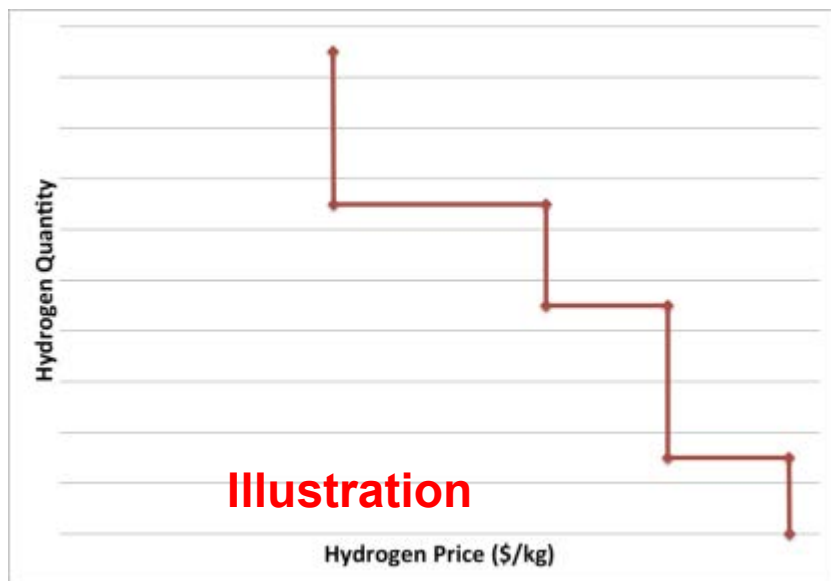


# Remaining Challenges and Barriers



- Economic potential of H<sub>2</sub>@Scale is not known
- Impacts on economics, resources, and emissions at potential market sizes are not known with high fidelity
- Barriers to market entry and growth are poorly characterized
- Regional and spatial issues have not been identified

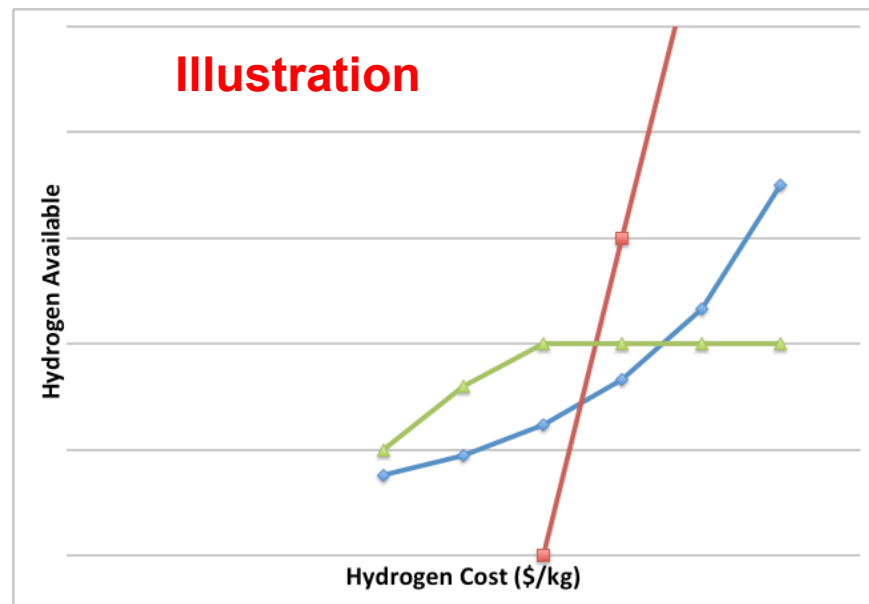
## Price requirements and demand curves



- Bottom-up demand estimates
- Technical, inertia, and resource constraints
- Includes demand aggregation to avoid double counting

## Production cost estimates

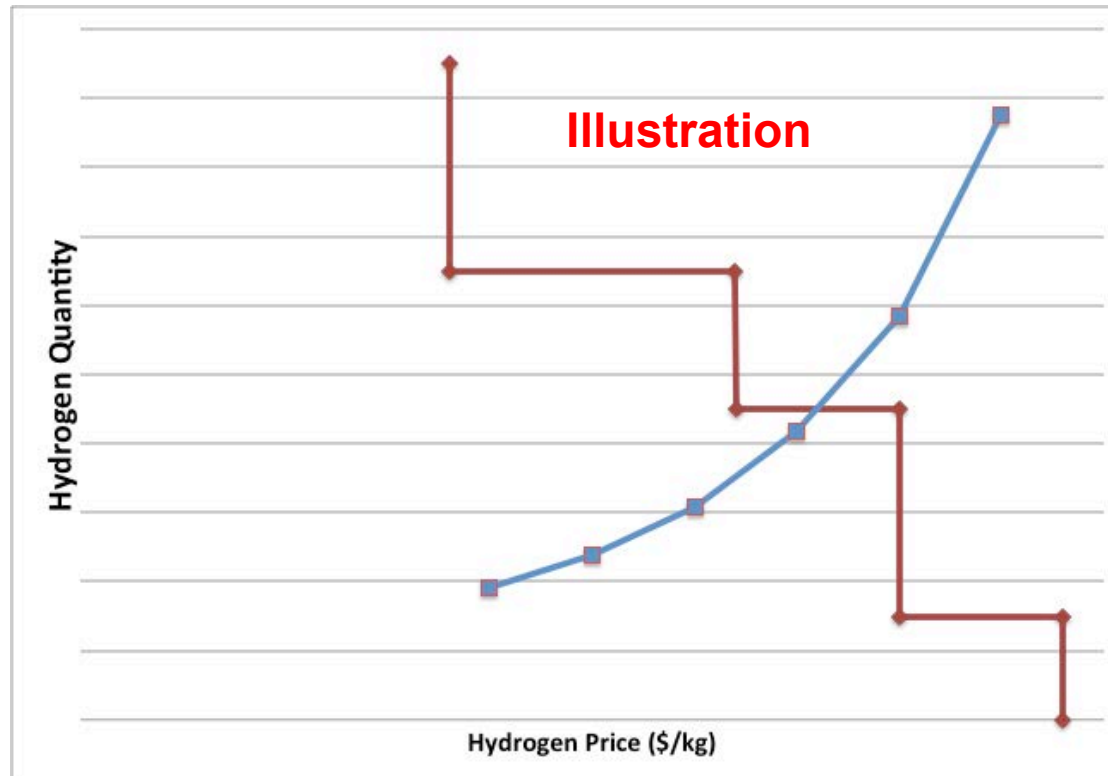
- Steam methane reforming (SMR)
- Nuclear generation
- Otherwise curtailed electricity with high penetrations of variable renewable generators on the grid



**Any proposed future work is subject to change based on funding levels**

Curves on this slide are illustrative and are not based on analysis. Development of supply and demand curves is proposed.

# Proposed Future Work: Scenario Generation & Impact Analysis



- Supply and demand curves will be used to develop several scenarios
  - Crossover point identifies scenario's market size and hydrogen prices
- For each scenario, economic impacts (including jobs), resource use, and emissions will be estimated using tools developed for other analyses
  - Benefits provided by supporting the grid will be included

**Any proposed future work is subject to change based on funding levels**

Curves on this slide are illustrative and should only be used for those purposes.

# Proposed Future Work: Stage Gate Review

Review by External Experts Planned for September 2017

## Present

- Analysis results to external experts
- Draft roadmap

## Review

- Analysis results and implications
- Plans in roadmap

## Identify & Prioritize

- Future directions and needs for analysis and R&D

## Plan

- Additional analysis efforts possibly including additional scenarios, economic inertia, economic externalities, spatial issues

**Any proposed future work is subject to change based on funding levels**

# Collaborations

Collaborator	Role
NREL	Lead; production cost estimates, supply-demand scenarios, impact assessments
ANL	Deputy lead; hydrogen demand analysis, emission and water use impact analysis
LBNL	Support scenario development; identify barriers to H2@Scale implementation including supply chain issues
PNNL	Support scenario development; identify barriers to H2@Scale implementation including supply chain issues
INL	Funded by DOE's Office of Nuclear Energy. Analyze potential hydrogen use for metals industry; identify opportunities to use nuclear energy
LLNL	Develop visualizations including Sankey diagrams
DOE's Office of Nuclear Energy	Identify opportunities to use nuclear energy
Industry	Providing input on scenarios, production opportunities, and alternative H <sub>2</sub> uses through workshops and advisory committees.

**This project involves multiple labs performing analysis and industry providing insights and feedback.**

# Technology Transfer Activities

- Industry is involved in workshops and reviews especially the Stage Gate review
- Opportunities to develop scenarios that are interesting to industry will be investigated

# Responses to Last Year's Reviewer Comments

This project began in January 2017, hence it was not reviewed previously



# H<sub>2</sub>

## @Scale:

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

- Technical potential demand = 60 MMT / yr
- Domestic resources are sufficient
- Using renewable electrolytic hydrogen would reduce emissions and fossil use by  $\approx 15\%$
- Further reductions are likely when considering grid impacts
- Economic potential will be analyzed
- Future work includes barriers to market entry, regional and spatial issues, and economic feedback effects

# Technical Back-Up Slides

# Acronyms

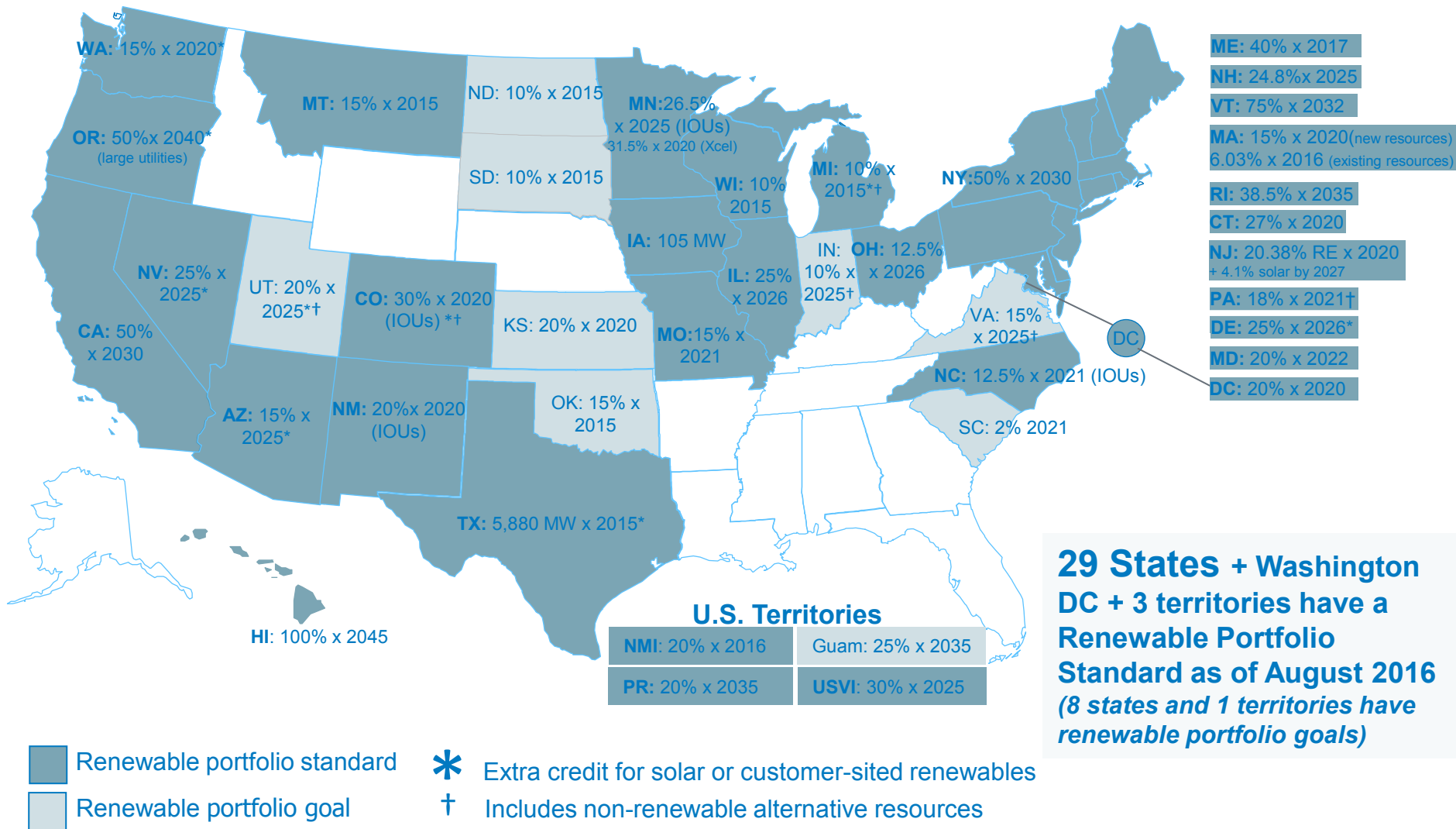
- AEO – Annual Energy Outlook
- ANL – Argonne National Laboratory
- Btu – British Thermal Unit
- bbl - barrel
- CAGR – Compound Annual Growth Rate
- CO<sub>2</sub> – Carbon Dioxide
- CPI – Chemical Processing Industry
- DOE – Department of Energy
- EIA – Energy Information Agency
- FCEV – Fuel Cell Electric Vehicle
- FCT – Fuel Cell Technologies
- FY – Fiscal year
- GIS – Geographic Information System
- GREET - Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- H<sub>2</sub> – Hydrogen
- H<sub>2</sub>A – Hydrogen Analysis
- HTAC – Hydrogen Technical Advisory Committee
- INL – Idaho National Laboratory
- kg - kilogram
- kW – kilowatt
- kWh – kilowatt hour
- LBNL – Lawrence Berkeley National Laboratory
- LHV – Lower Heating Value
- LLNL – Lawrence Livermore National Laboratory
- Marg. – On the margin
- Mi - mile
- mmBtu – million British thermal units
- MMT – million metric tonne
- NH<sub>3</sub> - Ammonia
- NREL – National Renewable Energy Laboratory
- O&M – Operating and Maintenance
- PNNL – Pacific Northwest National Laboratory
- PV – Photovoltaic
- Quad – Quadrillion Btu
- R&D – Research and Development
- RE – Renewable Energy
- ReEDS - Regional Energy Deployment System
- RPS – Renewable Portfolio Standard
- SMR – Steam Methane Reforming
- TWh – terawatt hour
- U.S. – United States
- yr - year

# Definition of Technical and Economic Potential

- Theoretical Potential
  - Total use or production based on changes in technology utilization (e.g., travel patterns changed to light duty vehicles exclusively) and assuming all land is available for production. Theoretical potential is not reported in this presentation.
- Technical Potential
  - Subset of theoretical potential. Potential market or resource size with respect to constraints including current market size and land use issues.
- Economic Potential
  - Subset of technical potential. Includes screens based on price points to compete in markets, cost of hydrogen generation, and energy transmission costs.

Definitions adapted from Milbrandt, Anelia. "A Geographic Perspective on the Current Biomass Resource Availability in the United States" December 2005. <http://www.nrel.gov/docs/fy06osti/39181.pdf>

# RPSs are Popular and Drive Increased Curtailment and Price Volatility

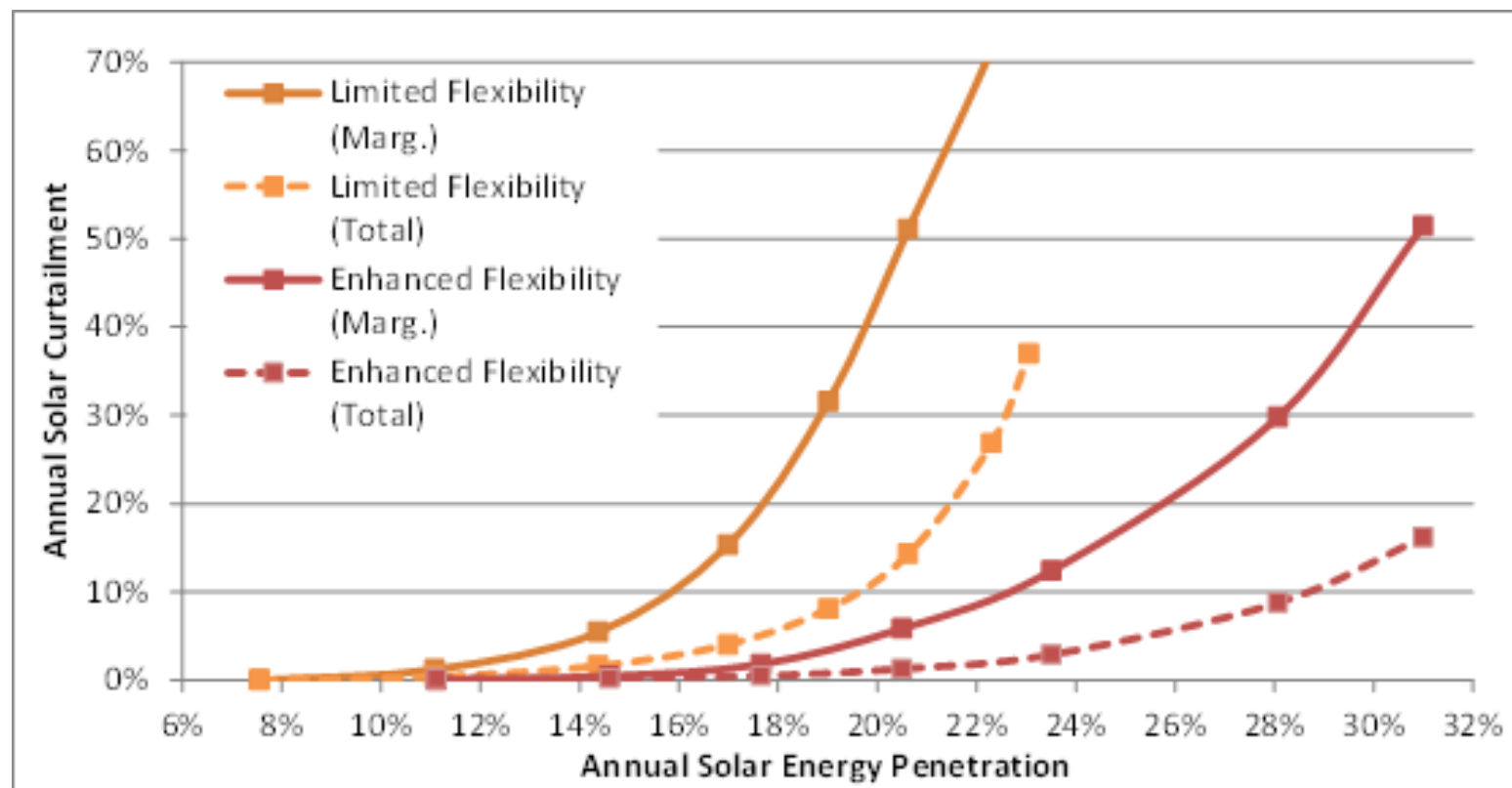


**29 States + Washington DC + 3 territories have a Renewable Portfolio Standard as of August 2016 (8 states and 1 territories have renewable portfolio goals)**

Source: www.dsireusa.org

# High Variable Renewable Penetration Can Result in Curtailment

As penetrations of solar PV increase, curtailment increases, reducing the value proposition for solar PV. Increased grid flexibility helps but does not solve issues.



Source: 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

# Impact Estimate Tools

Impact estimates will utilize tools developed for other analyses including those used to develop this Renewable Portfolio Standard Analysis

		EXISTING RPS		HIGH RE		
<b>RENEWABLE ENERGY IN 2050</b>		increased by ↑ <b>122 GW</b> <b>296 TWh</b>		increased by ↑ <b>331 GW</b> <b>765 TWh</b>		
<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 0.2¢-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>2</sub> e	equivalent to <b>\$161 billion</b> <small>(3.9¢/kWh-RE) estimates span \$17 billion - \$487 billion (0.9¢-17.8¢/kWh-RE)</small>	reduced by ↓ <b>23%</b>	<b>18.1 billion</b> metric tons CO <sub>2</sub> e
	 <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>IMPACTS</b>	 <b>NATURAL GAS</b>	reduced by ↓ <b>35 quads (3.3%)</b>	equivalent to <b>\$78 billion</b> <small>impact 1.0¢/kWh-RE</small>	reduced by ↓ <b>46 quads (4.3%)</b>	equivalent to <b>\$99 billion</b> <small>impact 0.9¢/kWh-RE</small>	
	 <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	

- Renewable (RE) and nuclear use offsets fossil fuel use leading to environmental benefits such as a reduction in air and water pollution and GHG emissions.
- Also 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](http://www.nrel.gov/docs/fy17osti/67455.pdf)  
NREL/TP-6A20-67455 <http://www.nrel.gov/docs/fy17osti/67455.pdf>