NREL
NATIONAL RENEWABLE ENERGY LABORATORY

H2@Scale Analysis

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Overview

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

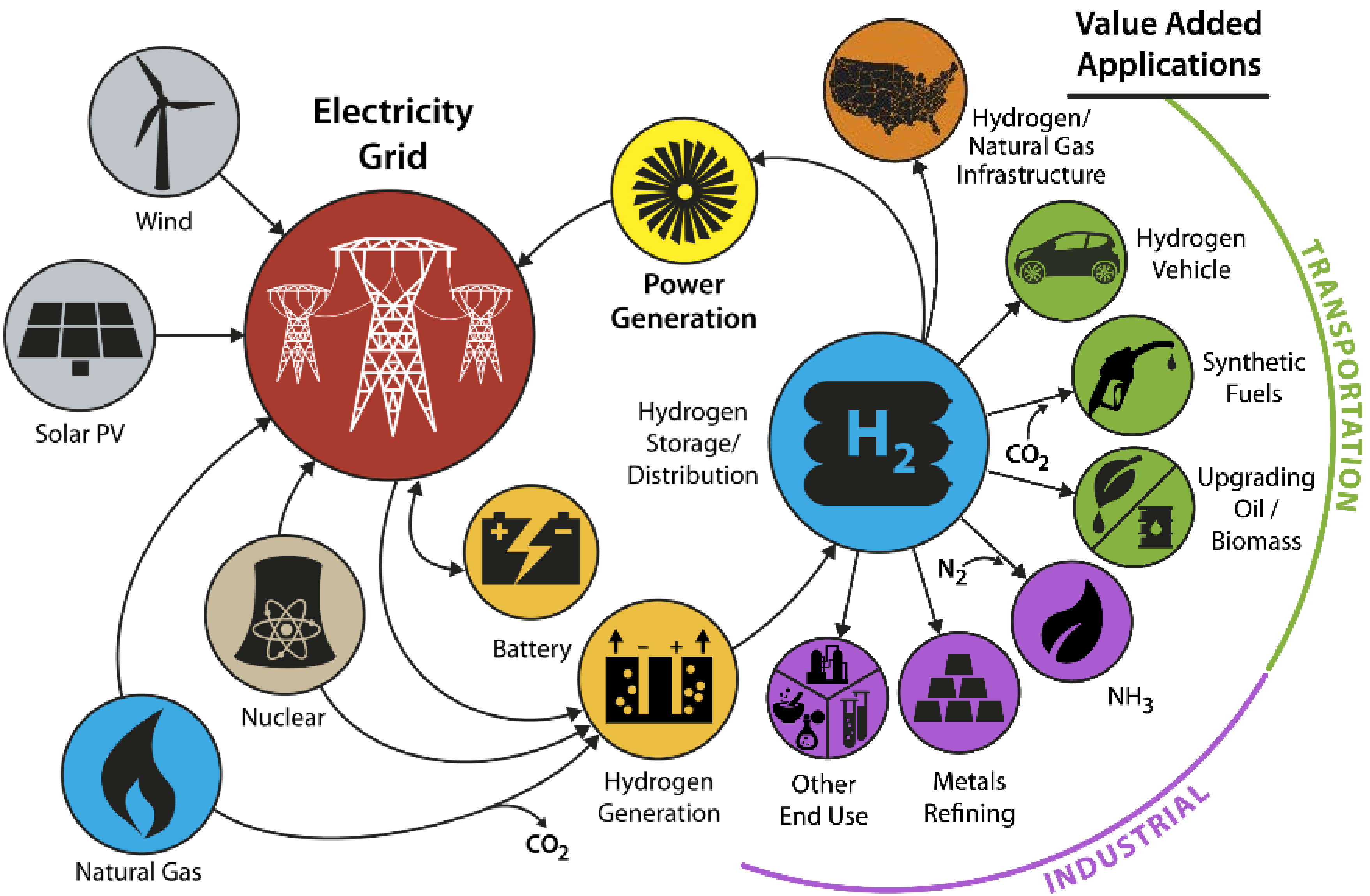
Partners

- 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*



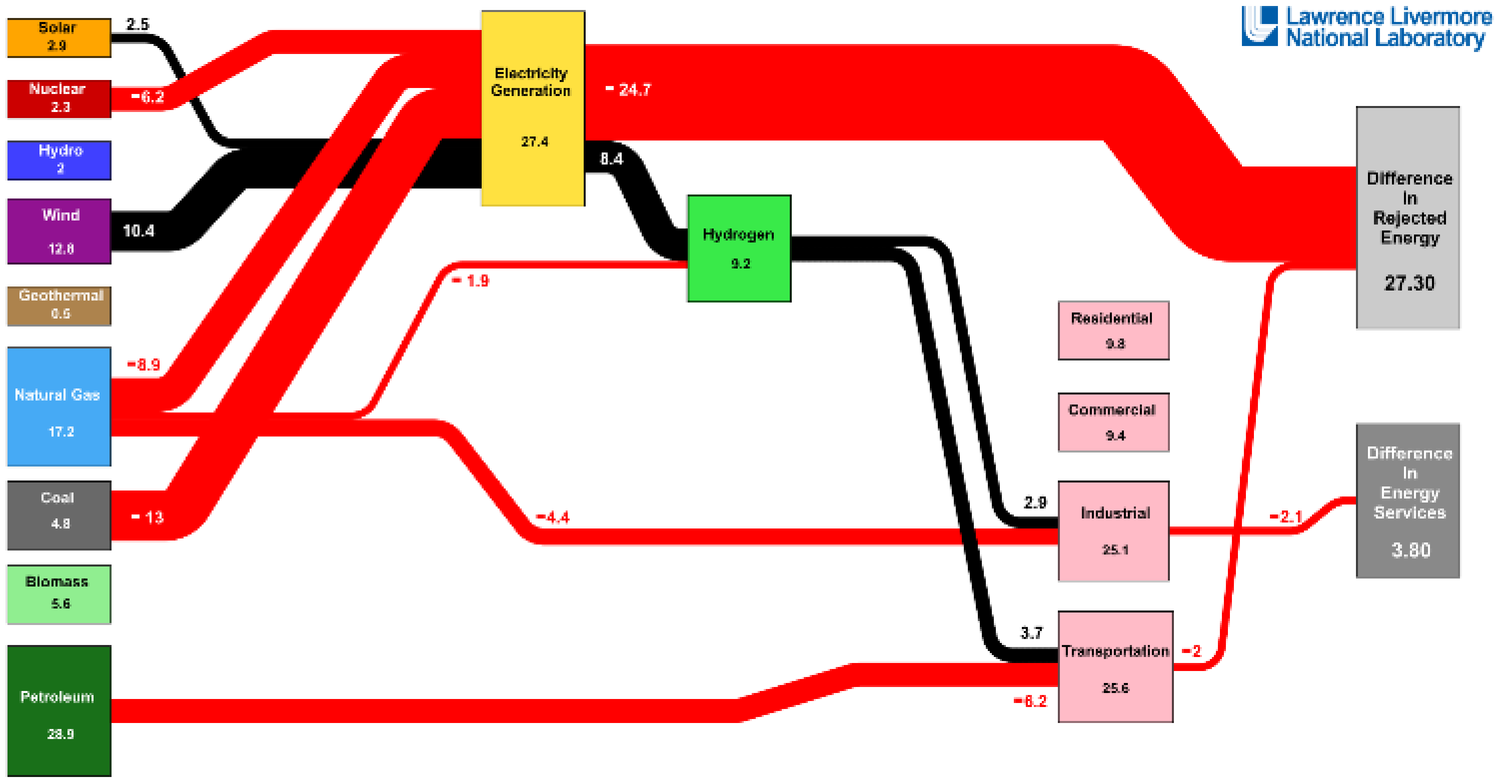
*Illustrative example, not comprehensive

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)



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

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

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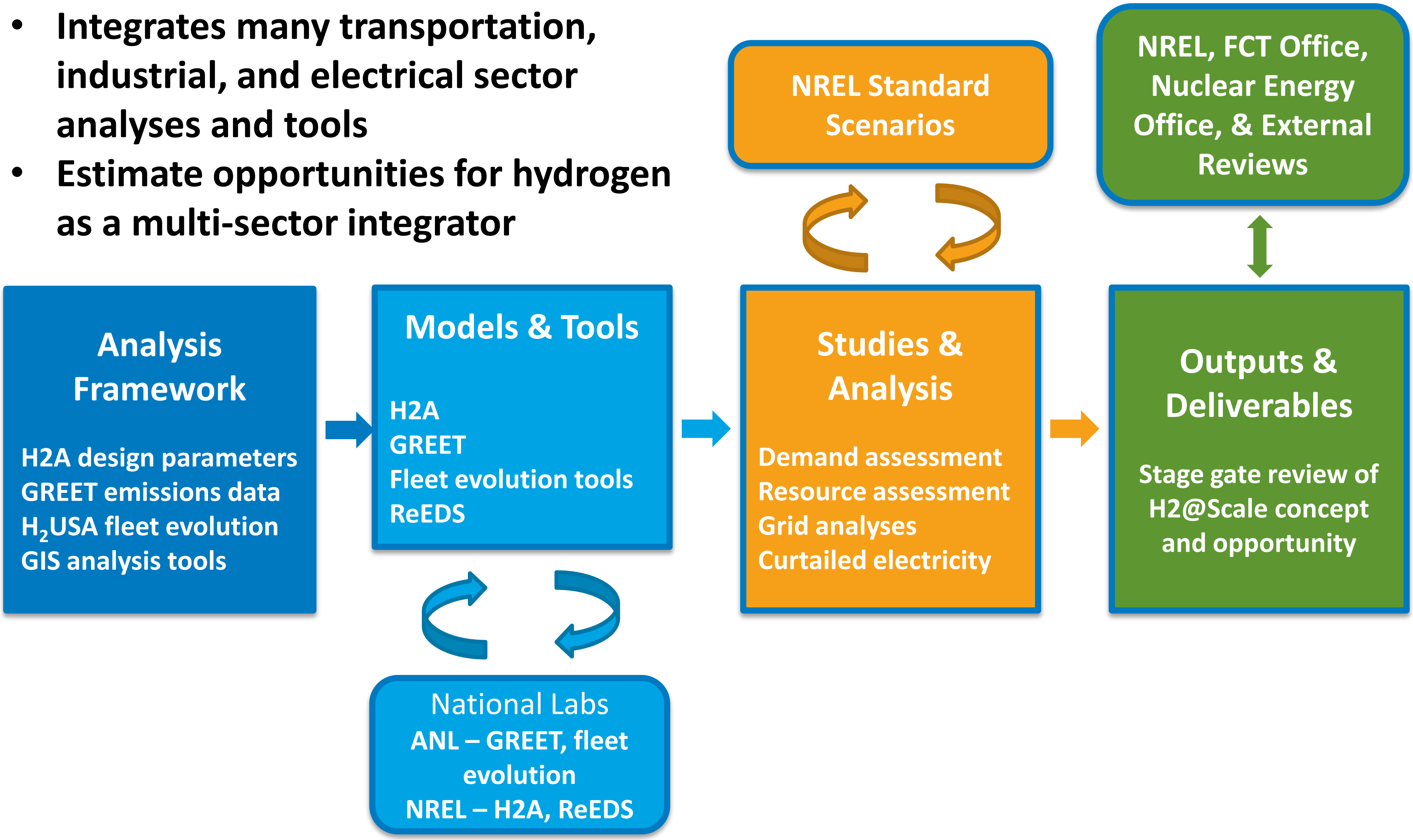
Approach: FCTO Systems Analysis Framework

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_2 price requirements
- Supply options and costs
- Scenarios
- Impact potential

Additional analysis needs

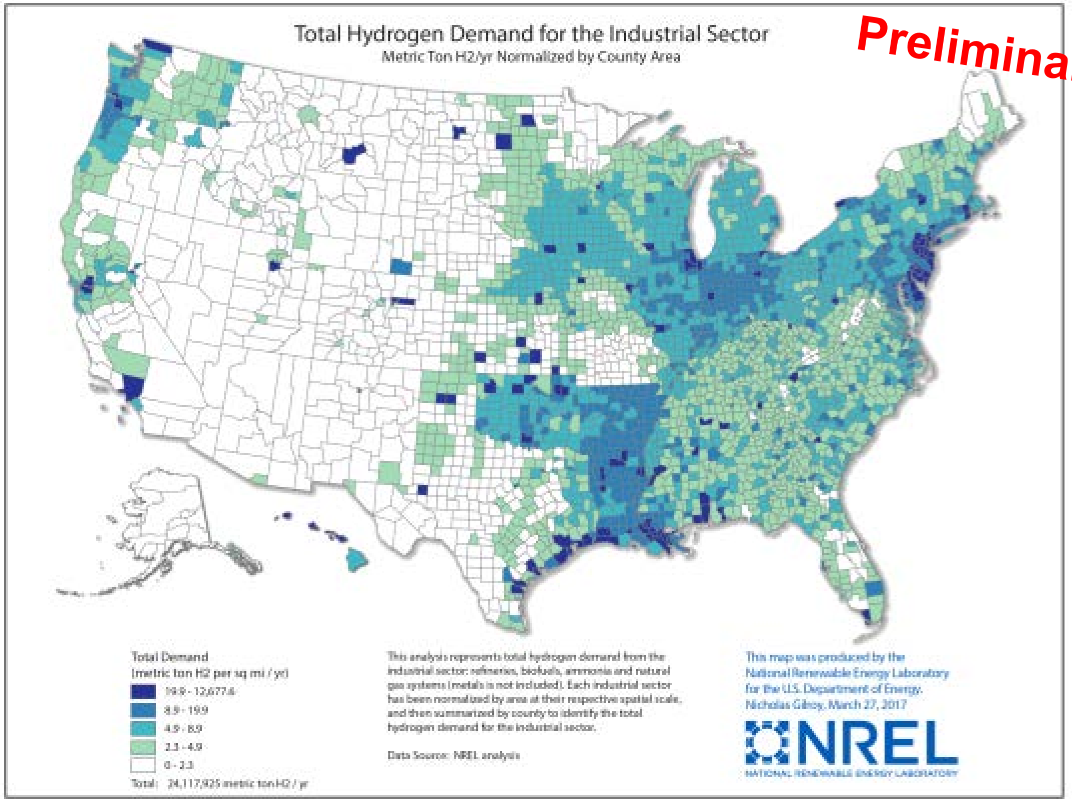
- Additional scenarios
- Economic inertia
- Economic externalities
- Spatial issues

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

Accomplishment: Technical Potential for H_2 Demand



Preliminary Results

Use	Market potential (million metric tonne H_2 / year)
Industrial Use	
Refineries & CPI§	8*
Metals	5
Ammonia	5
Natural Gas	7
Biofuels	4
Light Duty Vehicles	28
Other Transport	3
Total	**60**

Total market potential: 60 MMT/yr

Current U.S. market: ≈ 10 MMT/yr

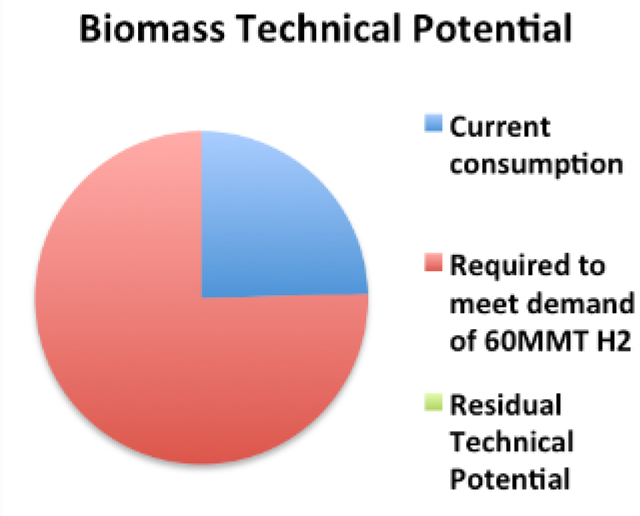
Global H_2 production revenue: 6% CAGR, 2009-2016[1]

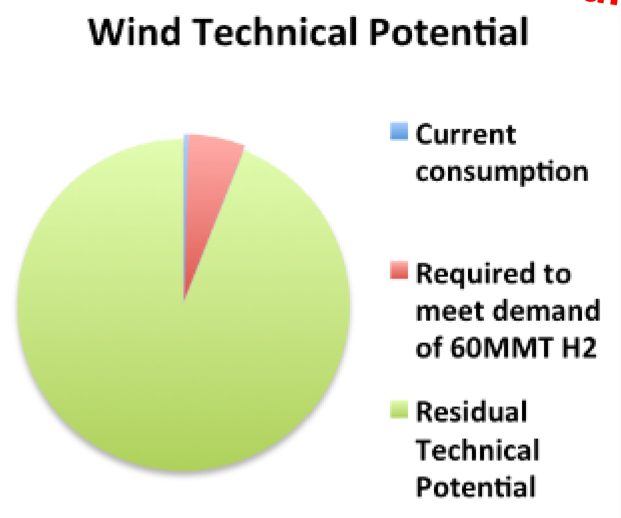
§ CPI: Chemical Processing Industry not including metals, biofuels, or ammonia
* Current potential used due to lack of consistent future projections
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
1. Global hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology- Trends & Forecasts (2011-2016)

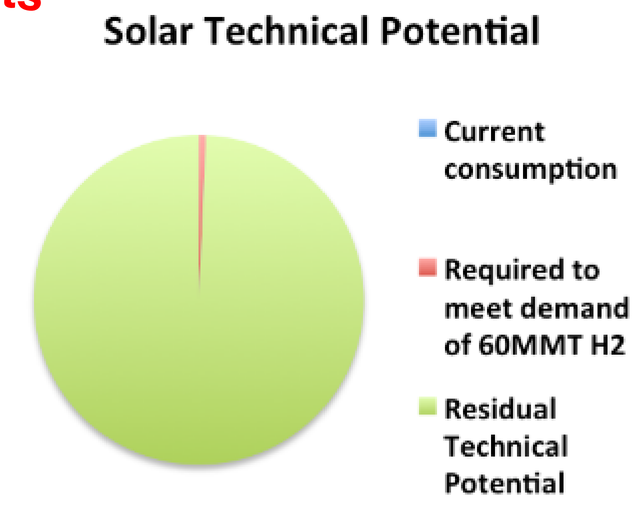
Accomplishment: Utilization of Renewable Resources

	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

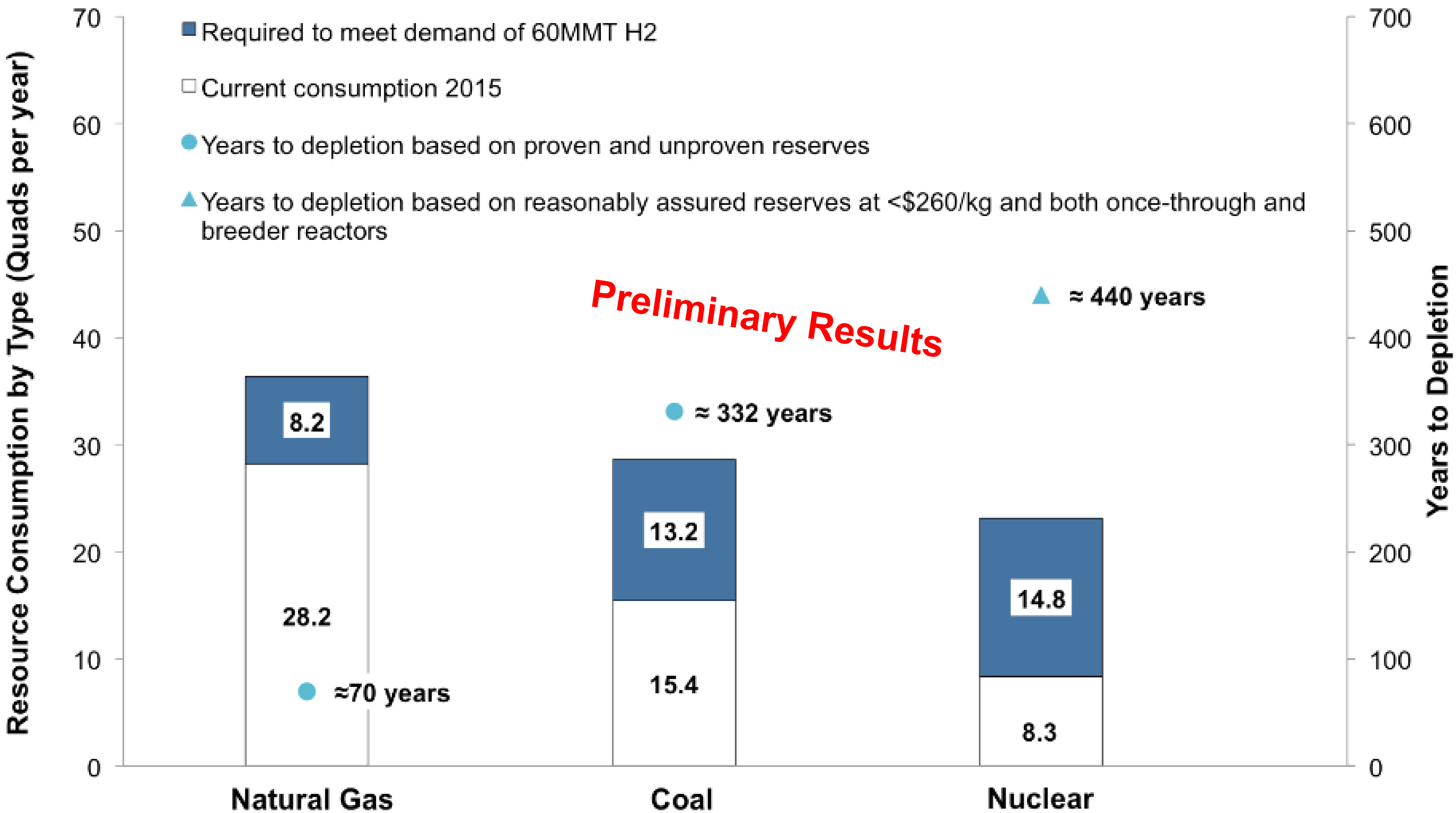






Total demand including hydrogen is satisfied by ≈6% of wind, <1% of solar, and ≈100% of biomass technical potential

Accomplishment: Utilization of Fossil & Nuclear Resources

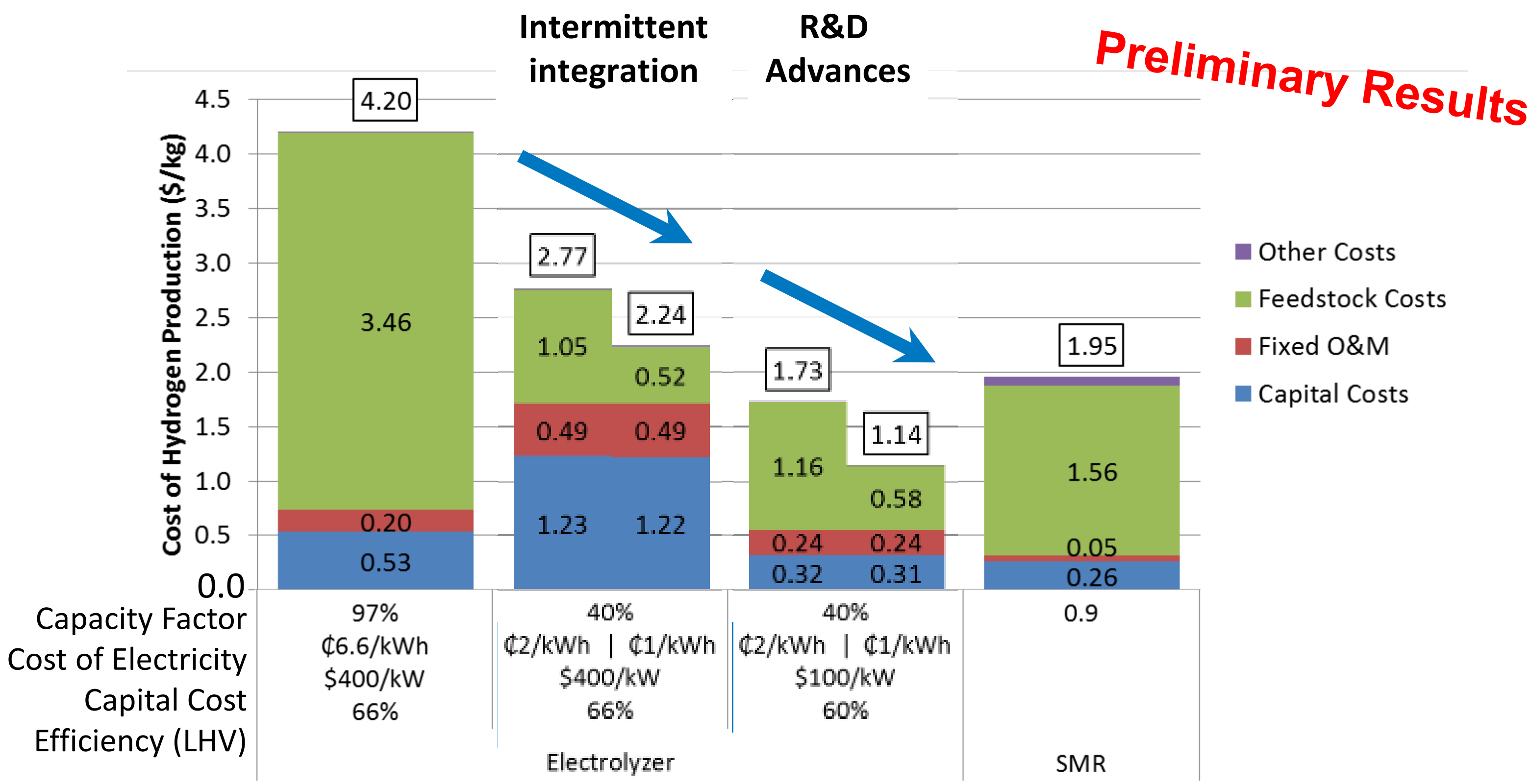


Hydrogen can be produced from diverse domestic resources to meet aggressive growth in demand

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_2/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§	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
Total	**60**	**830 Million MT**	**1.2 Billion bbl**	**4.1 Quads**

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

§ 12% of the benefits of hydrogenated biofuels are credited to hydrogen

Accomplishment: Estimate of Impacts on Grid

How much electricity would H2@Scale require?

60B kg H_2 per year **X 55 kWh** per kilogram **=** **3,300 TWh** per year

How does that compare with our current electricity use?

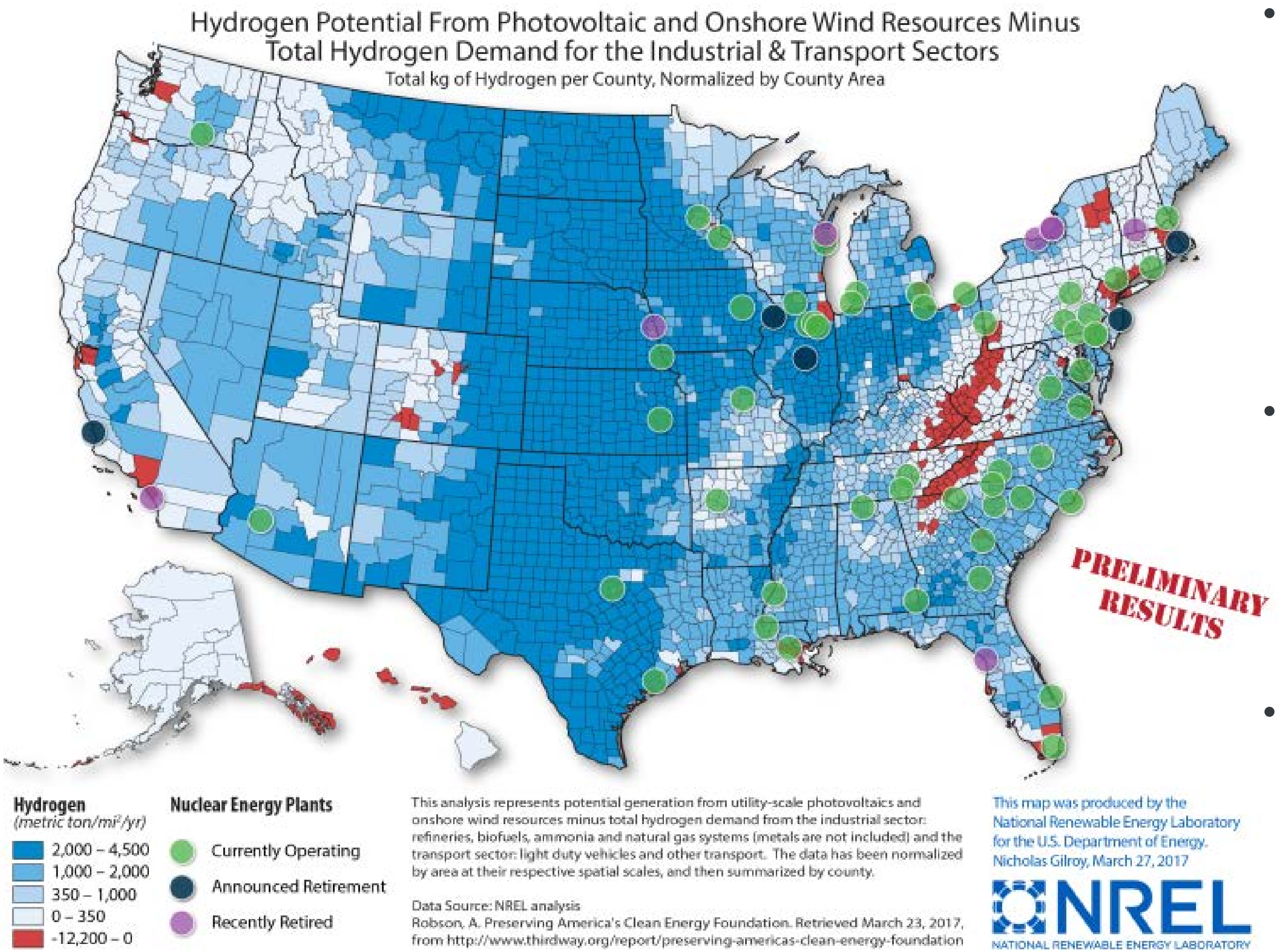
U.S. Electricity Consumption **=** Approximately **3,900 TWh** per year*

Preliminary Results

~85% of current U.S. electricity demand

*2015 consumption. Source: EIA AEO 2016

Accomplishment: Where Resources are Sufficient



- 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

Technical Potential

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

Economic Potential

- H_2 price requirements
- Supply options and costs
- Scenarios
- Impact potential

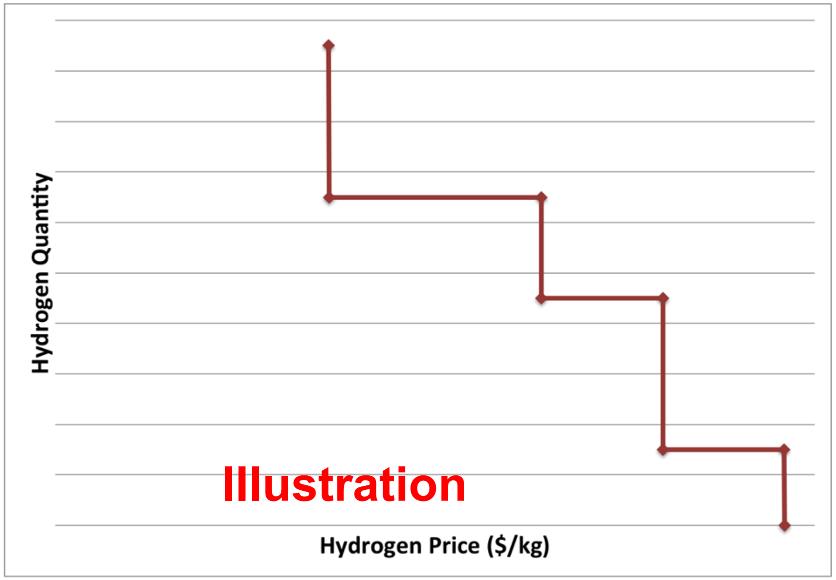
Additional analysis needs

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

- Economic potential of H2@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

Proposed Future Work: Price Requirements & Supply Options

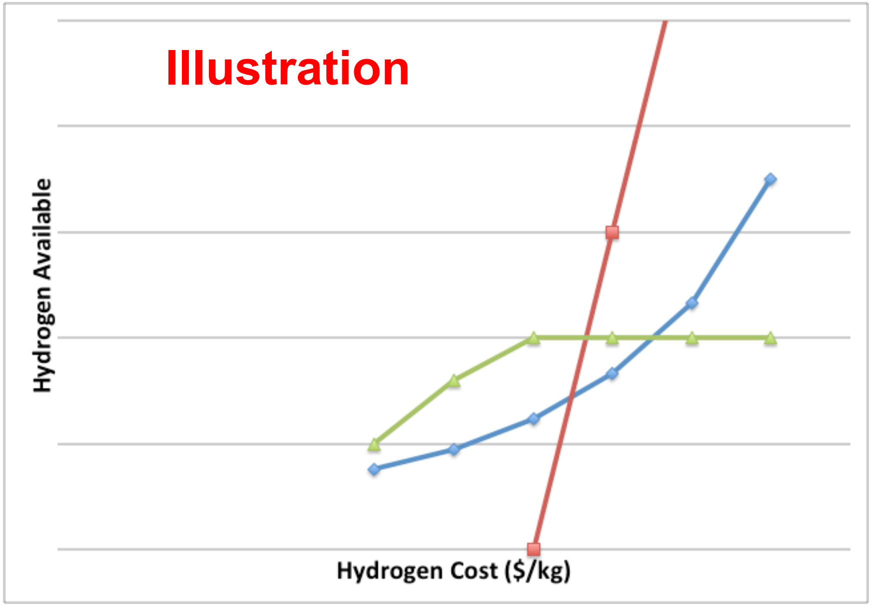
Price requirements and demand curves



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

Production cost estimates

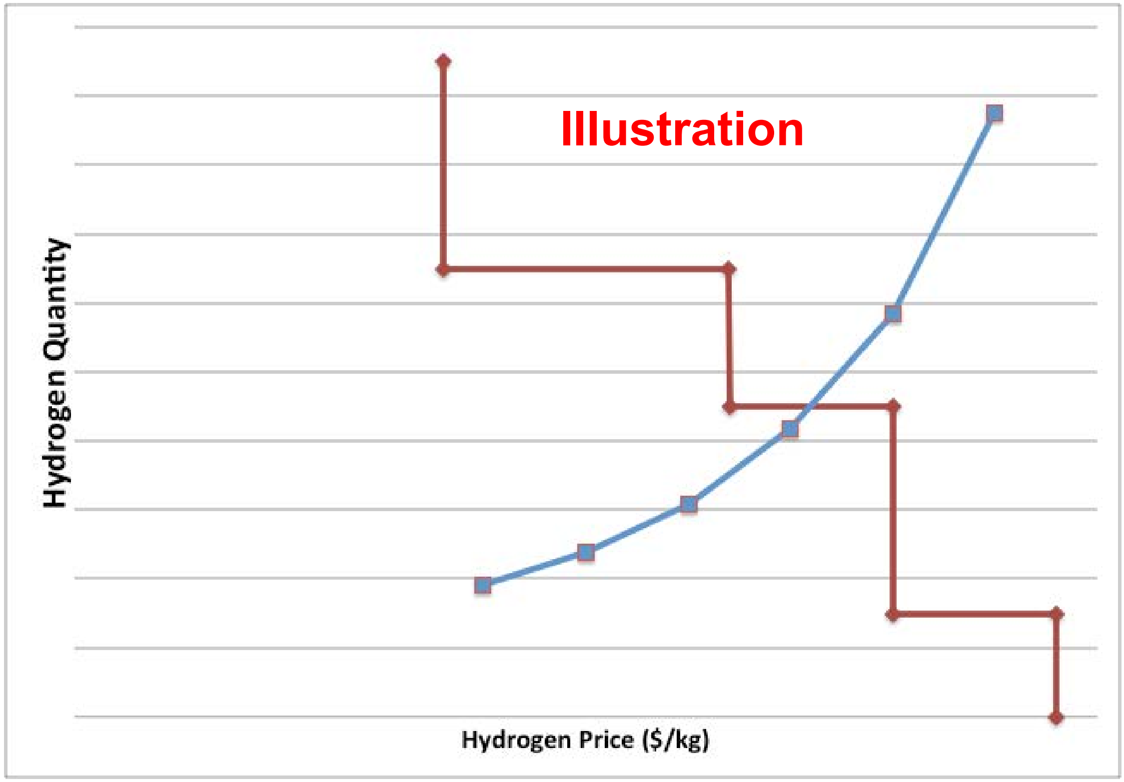
- Steam methane reforming (SMR)
- Nuclear generation
- Otherwise curtailed electricity with high penetrations of variable renewable generators on the grid



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_2 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

Summary

H_2 @Scale:

Energy system-wide benefits of increased H_2 implementation

- Technical potential demand = 60 MMT / yr
- Domestic resources are sufficient
- Using renewable electrolytic hydrogen would reduce emissions and fossil use by ≈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

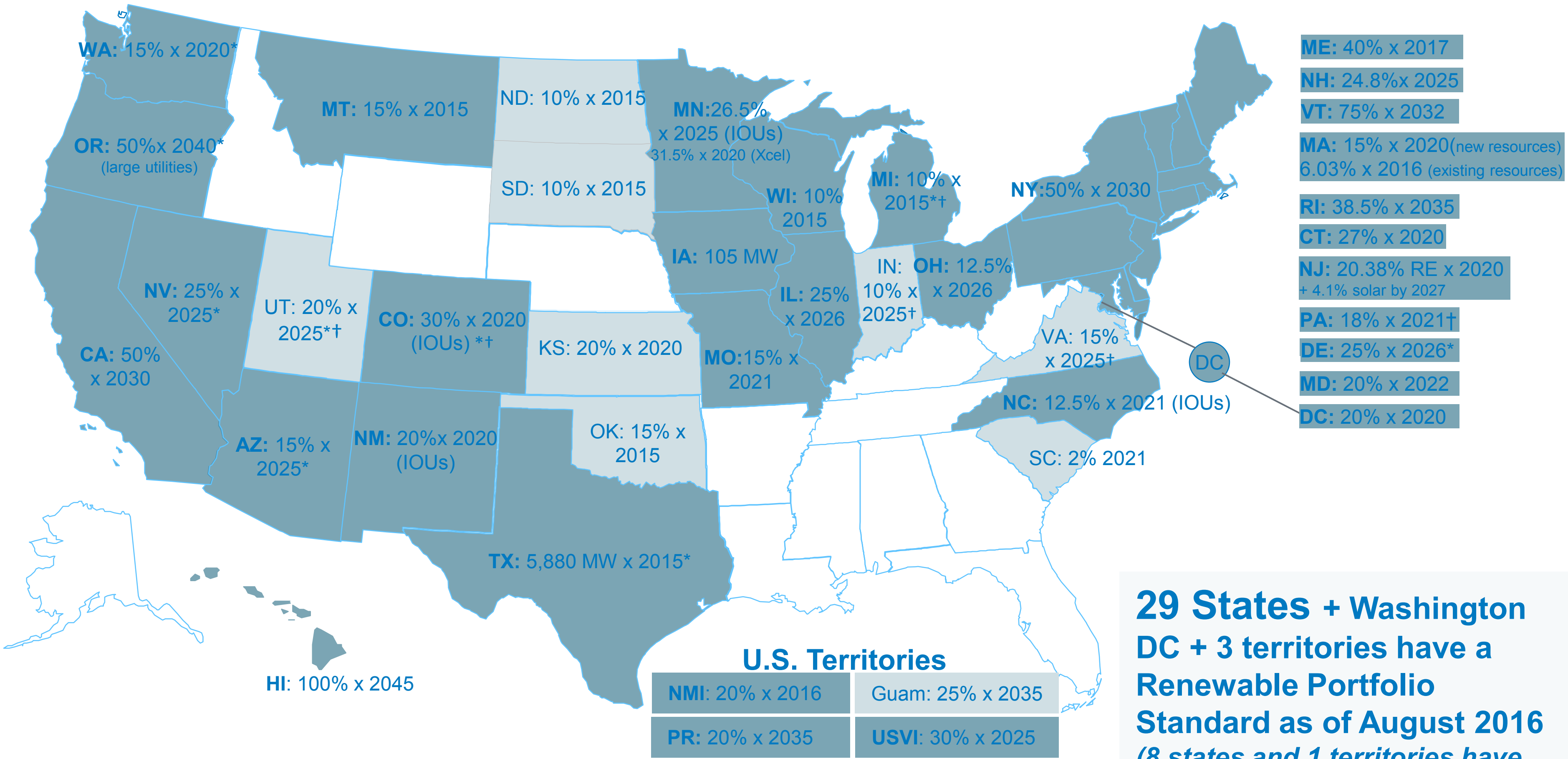
- AEO – Annual Energy Outlook
- ANL – Argonne National Laboratory
- Btu – British Thermal Unit
- bbl - barrel
- CAGR – Compound Annual Growth Rate
- CO_2 – Carbon Dioxide
- CPI – Chemical Processing Industry
- DOE – Department of Energy
- EIA – Energy Information Agency
- FCEV – Fuel Cell Electric Vehicle
- FCT – Fuel Cell Technologies
- FY – Fiscal year
- GIS – Geographic Information System
- GREET - Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- H2 – Hydrogen
- H2A – 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_3 - 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)

Renewable portfolio standard

Renewable portfolio goal

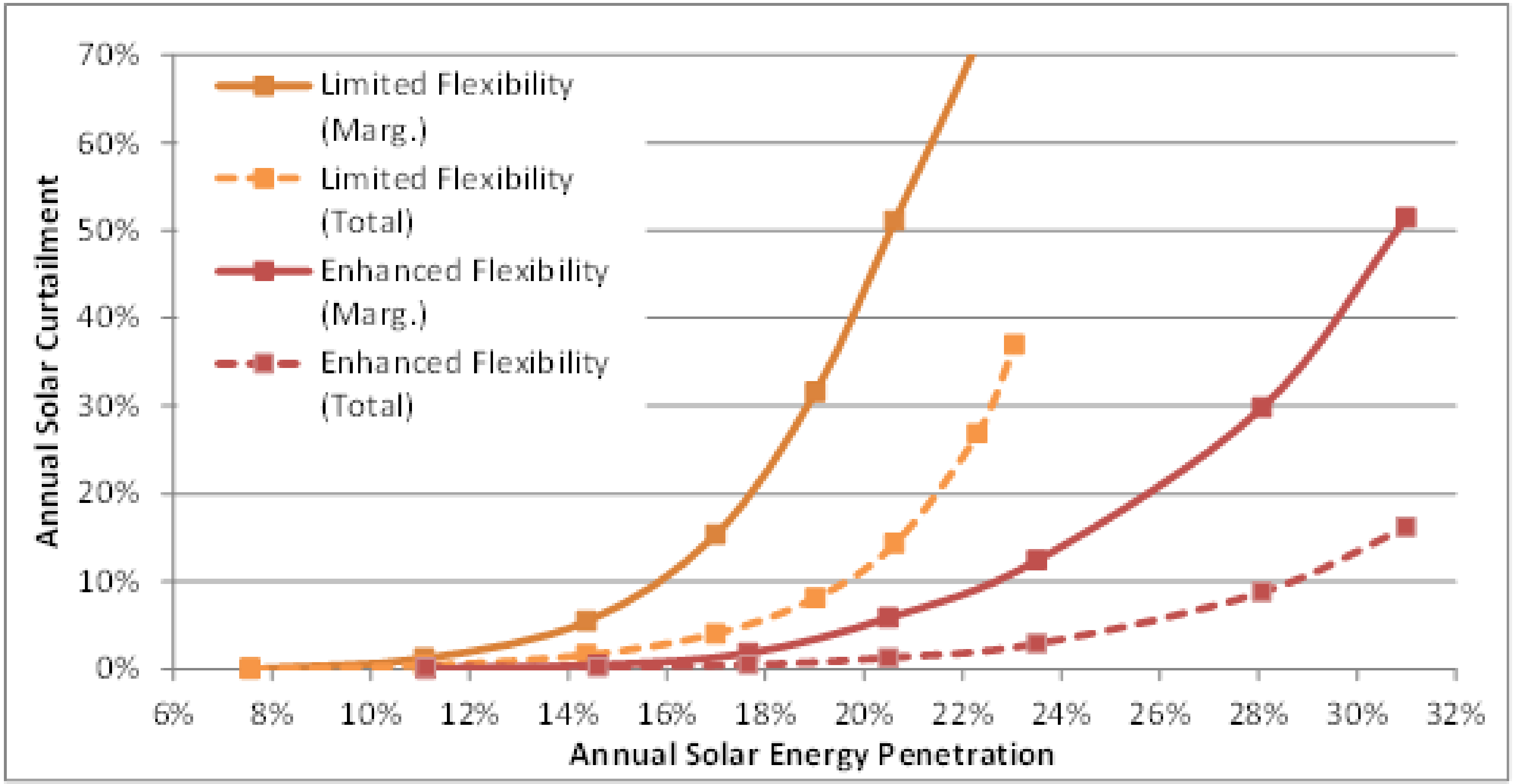
* Extra credit for solar or customer-sited renewables

† Includes non-renewable alternative resources

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	
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	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	SULFUR DIOXIDE, NITROGEN OXIDES, PARTICULATE MATTER 2.5	equivalent to $97 billion (2.4¢/kWh-RE) (estimates span $48 billion–$175 billion (1.2–4.2¢/kWh-RE))		equivalent to $558 billion (5.0¢/kWh-RE) (estimates span $207 billion–$917 billion; 2.7–8.2¢/kWh-RE)	
BENEFITS	GREENHOUSE GAS EMISSIONS	reduced by ↓ 6%	4.7 billion metric tons CO_2e	reduced by ↓ 23%	18.1 billion metric tons CO_2e
BENEFITS	GREENHOUSE GAS EMISSIONS	equivalent to $161 billion (3.9¢/kWh-RE) (estimates span $37 billion–$487 billion (0.9–11.8¢/kWh-RE))		equivalent to $599 billion (5.4¢/kWh-RE) (estimates span $132 billion–$1,821 billion (1.7–16.3¢/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

- 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
NREL/TP-6A20-67455 http://www.nrel.gov/docs/fy17osti/67455.pdf