



H2@Scale Resource and Market Analysis

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Acknowledgements

- NREL: Lori Bird, Wesley Cole, Elizabeth Connelly, Josh Eichman, Nicholas Gilroy, Bryan Pivovar, Keith Wipke
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Analysis Objectives

- Improve fidelity of H2@Scale value proposition
 - Provide results that are supported by in-depth analysis and can be used to
- Quantify potential impacts
 - Resource use
 - Emissions
 - Economic
- Identify regional opportunities and challenges
- Perform by a multilab team with support from DOE's Fuel Cell Technologies Office (FCTO) and DOE's Nuclear Energy Office

Overview of Analysis Effort

Initial (Complete)

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

In-depth (FY17)

- H₂ price requirements
- Supply options and costs
- Scenarios
- Impact potential
- Stage-gate review

Additional analysis needs

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

Initial Analysis

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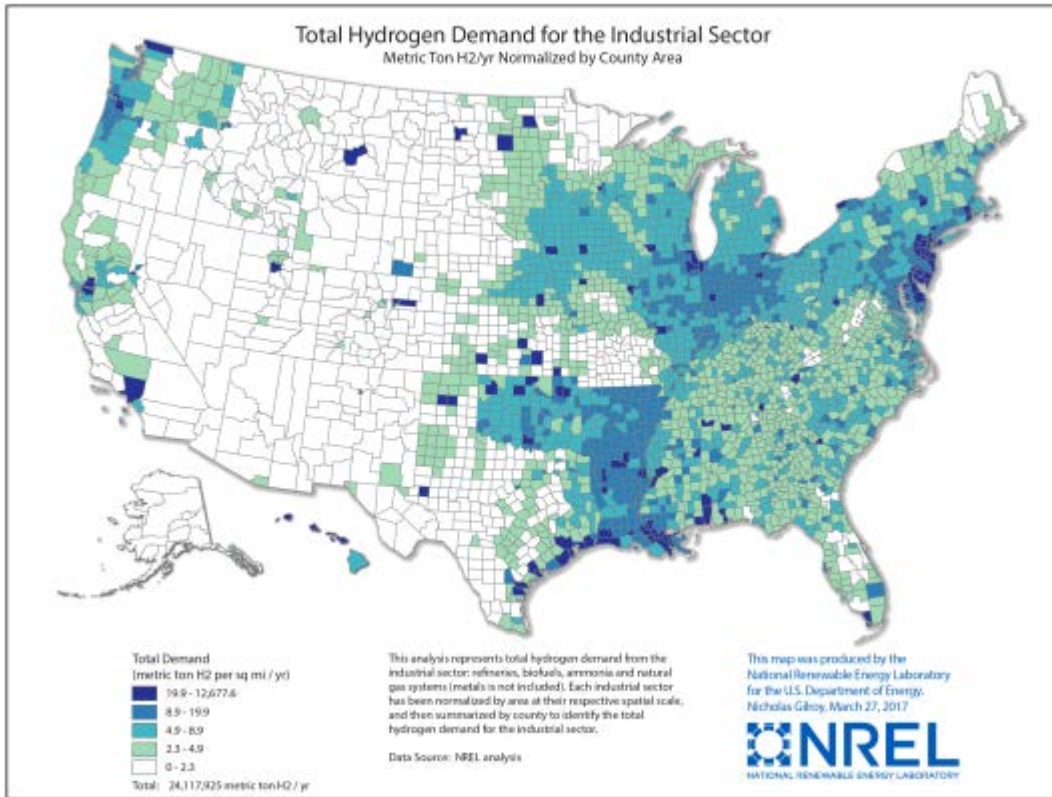
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Initial Analysis: U.S. Hydrogen Demand Potential



Total market potential:

60 MMT/yr

Preliminary Results

Current U.S. market: \approx 10 MMT/yr

**Global H₂ production revenue:
6% CAGR, 2009-2016¹**

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

[§] CPI: Chemical Processing Industry not including metals, biofuels, or ammonia

* Current potential used due to lack of consistent future projections

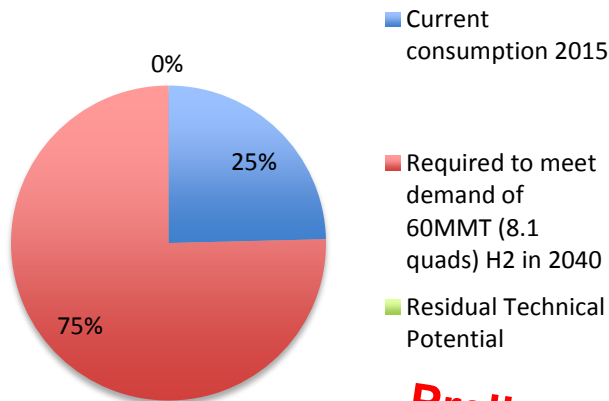
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from <http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels>

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

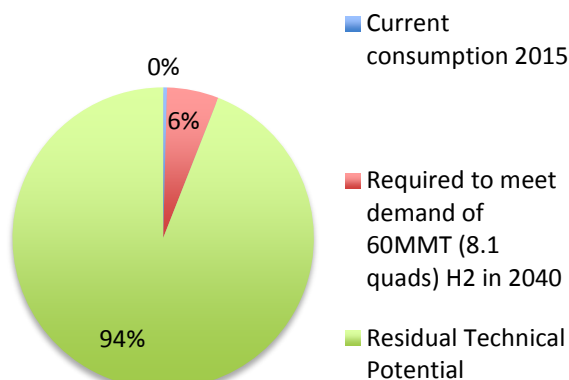
Initial Analysis: Resource Availability for Hydrogen

	EIA 2015 current consumption (quads/yr)	Required to meet demand of 60 MMT (8.1 quads) / yr H ₂ (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

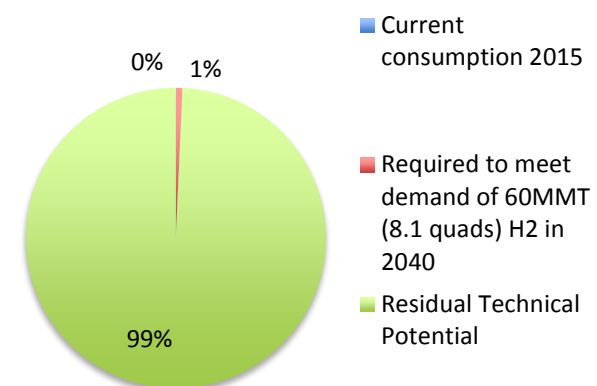
Biomass Technical Potential (quads/yr)



Wind Technical Potential (quads/yr)



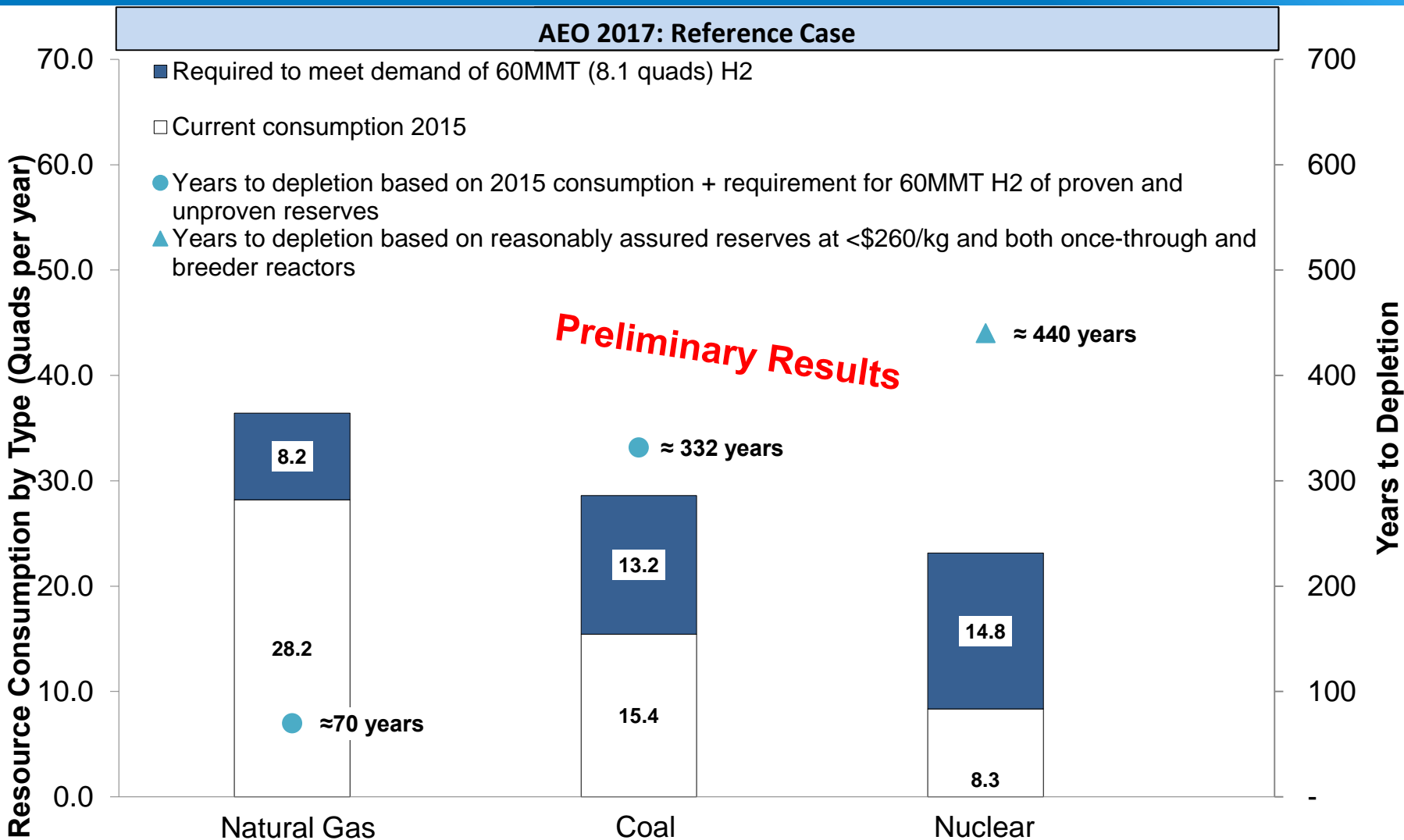
Solar Technical Potential (quads/yr)



Preliminary Results

Technical potential for wind and solar are much greater than potential demand. Biomass potential equals demand.

Initial Analysis: Nuclear & Fossil Resources for Hydrogen



Hydrogen production from grid electricity can be supplemented by diverse domestic resources to meet aggressive growth in demand

Coal estimate based on demonstrated recoverable reserves

Initial Analysis: GHG Emissions, Petroleum Use, and NG Use Reductions

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		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

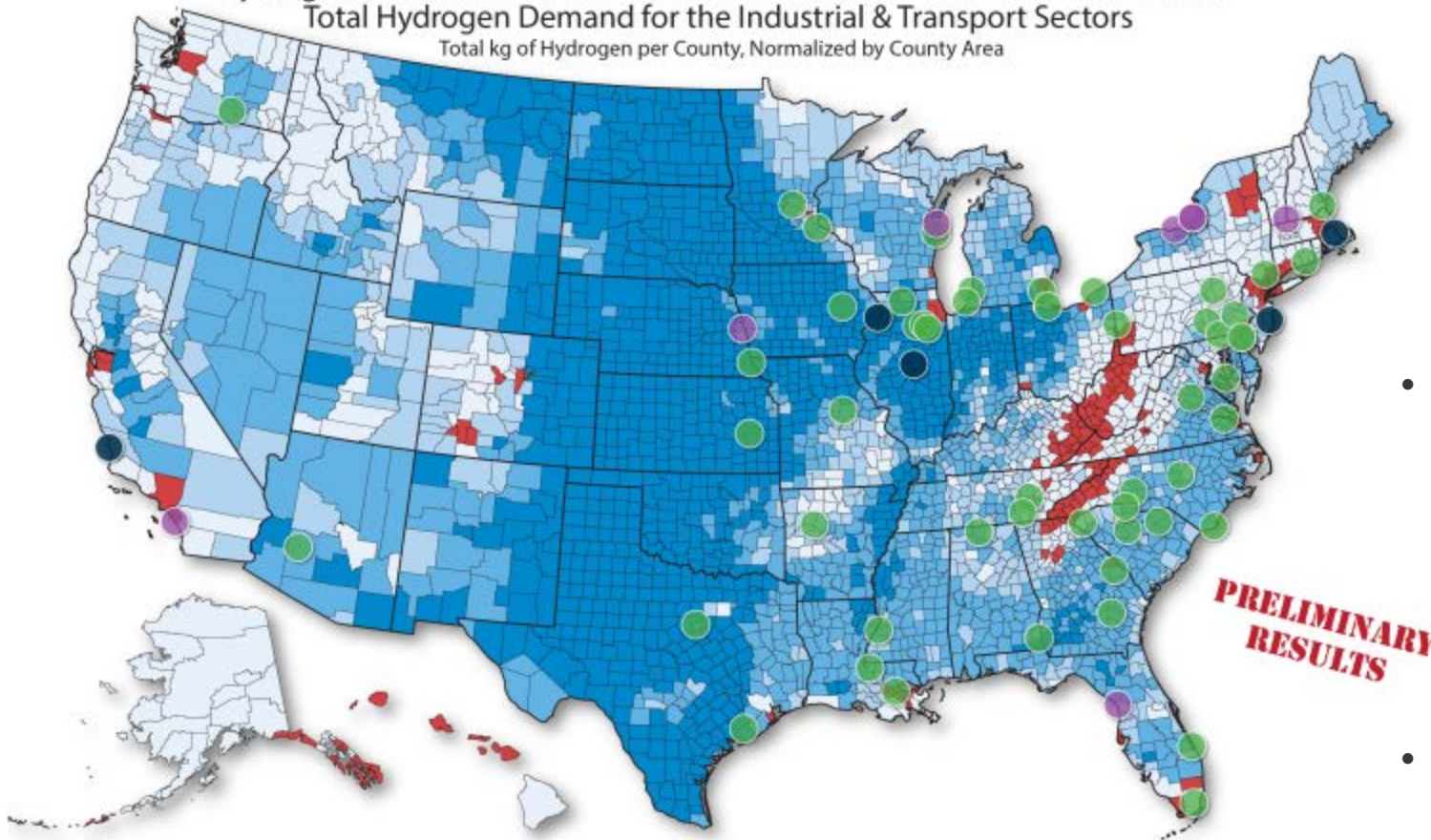
Hydrogen alone has the potential to reduce emissions and fossil use by ≈15%. The ability to enable higher penetrations of renewable energy can further reduce emissions and fossil use.

*Negative values represent increase in use due to natural gas use for hydrogen production

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

Initial Analysis: 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/m²/yr)

- 2,000 – 4,500
- 1,000 – 2,000
- 350 – 1,000
- 0 – 350
- 12,200 – 0

Nuclear Energy Plants

- Currently Operating
- Announced Retirement
- Recently Retired

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

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

In-Depth Analysis

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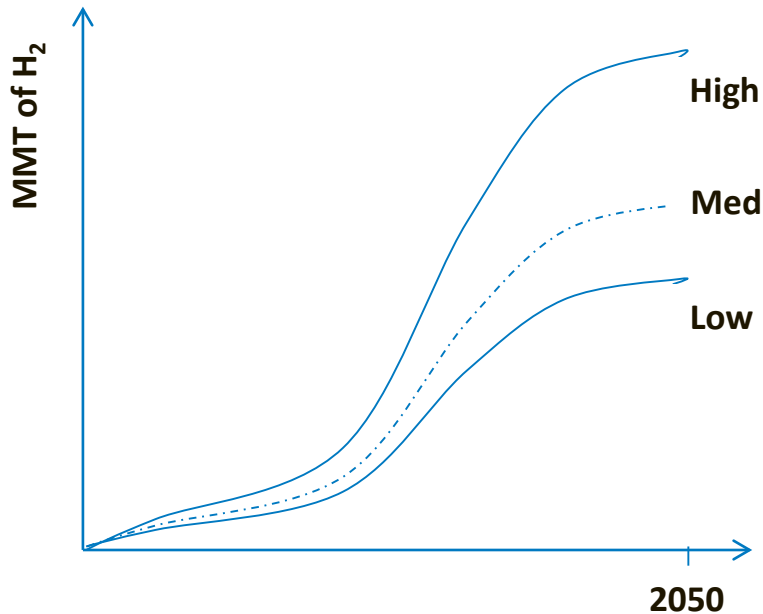
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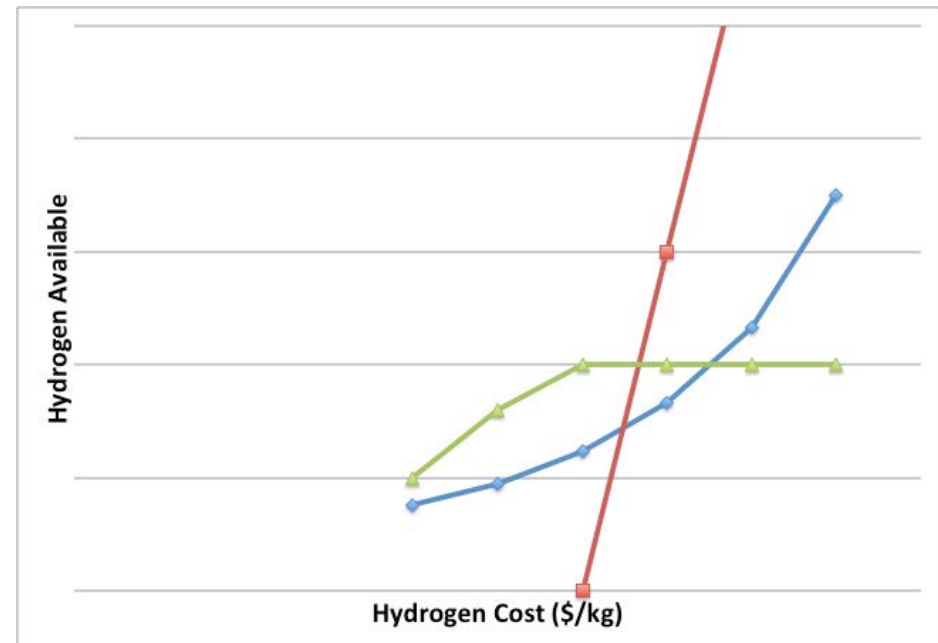
Price requirements and demand curves



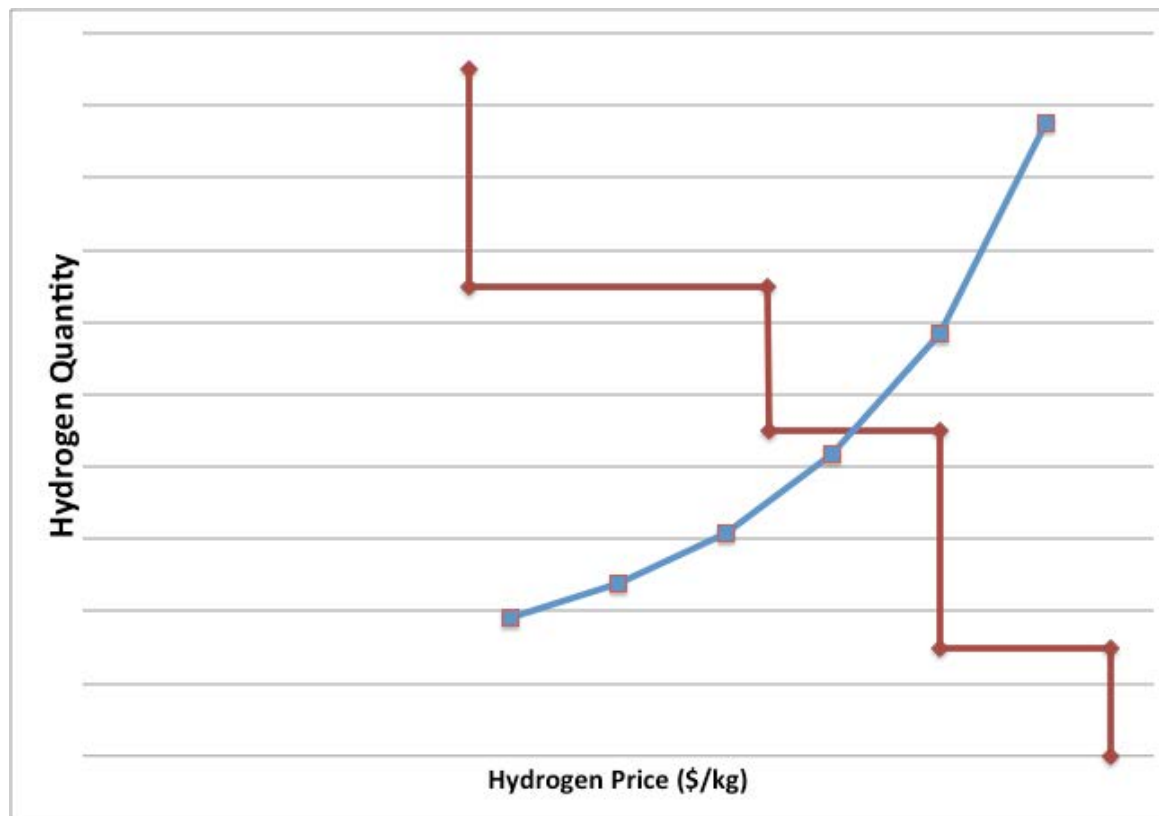
- Bottom-up demand estimates
- Technical, inertia, and resource constraints
- Includes demand aggregation to avoid double counting

Production cost estimates for several scenarios

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



In-Depth: Scenario Generation (Underway)



- Supply and demand curves can provide estimates of market size for many possible scenarios
 - Cross point identifies the amount of hydrogen generated and used as well as the hydrogen demand markets
- With that information we can estimate impacts

Building off 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 <small>estimates span +/- 0.5 CAGR-RE</small>	range from 0.6% to 4.5%	equivalent to \$23 billion - \$194 billion <small>estimates span 0.29-1.31 CAGR-RE</small>
	 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 <small>metric tons SO₂</small>		reduced by ↓ 29% 11.1 million <small>metric tons SO₂</small>	
	 NITROGEN OXIDES	reduced by ↓ 6% 2.5 million <small>metric tons NO_x</small>	equivalent to \$97 billion <small>(2.4¢/kWh-RE) estimates span \$48 billion - \$173 billion (1.7-4.2 CAGR-RE)</small>	reduced by ↓ 29% 12.8 million <small>metric tons NO_x</small>	equivalent to \$558 billion <small>(5.0¢/kWh-RE) estimates span \$203 billion - \$917 billion (2.7-8.2 CAGR-RE)</small>
	 PARTICULATE MATTER 2.5	reduced by ↓ 5% 0.3 million <small>metric tons PM_{2.5}</small>		reduced by ↓ 29% 1.8 million <small>metric tons PM_{2.5}</small>	
	 GREENHOUSE GAS EMISSIONS	reduced by ↓ 6% 4.7 billion <small>metric tons CO₂e</small>	equivalent to \$161 billion <small>(3.9¢/kWh-RE) estimates span \$37 billion - \$487 billion (1.9-17.8 CAGR-RE)</small>	reduced by ↓ 23% 18.1 billion <small>metric tons CO₂e</small>	equivalent to \$599 billion <small>(5.4¢/kWh-RE) estimates span \$131 billion - \$1,821 billion (1.7-16.1 CAGR-RE)</small>
	 WATER USE	reduced by ↓ 4% 3% <small>consumption withdrawal</small>		reduced by ↓ 18% 18% <small>consumption withdrawal</small>	
IMPACTS	 NATURAL GAS	reduced by ↓ 35 quads (3.3%)	equivalent to \$78 billion <small>impact: 1.5¢/kWh-RE</small>	reduced by ↓ 46 quads (4.3%)	equivalent to \$99 billion <small>impact: 0.9¢/kWh-RE</small>
	 RE JOB NEEDS	increase in ↑ 19% <small>RE-employment</small>	equivalent to 4.7 million <small>RE job-years</small>	increase in ↑ 47% <small>RE-employment</small>	equivalent to 11.5 million <small>RE job-years</small>

- 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>

In-Depth: Stage-Gate Review

Planning for September 2017

Present

- Analysis results to external experts
- Roadmap and R&D plans

Review

- Analysis results and implications
- Plans in roadmap

Identify & Prioritize

- Future directions and needs for R&D & analysis

Plan

- Additional R&D & analysis efforts

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- FY18 efforts based on feedback from stage-gate review
- Potential opportunities
 - Additional demands or supply options
 - Improved understanding of economic inertia
 - Impact on macro-economics and feedback loops
 - Regional and spatial issues

Concluding Remarks

- Hydrogen demand of 60 MMT / yr is possible when transportation and industry are considered
- Resources are available to meet that demand
- Using renewable resources would reduce emissions and fossil use by over 15%
- Further impacts are possible when considering synergistic benefits
- Additional analysis is underway to improve understanding of potential markets and synergistic impacts
- Further analysis will be necessary to estimate impacts due to spatial characteristics, feedback effects in the economy, and inertia characteristics

Questions

- What key impacts would you like to see as the focus of our analysis?
- Are there non-policy impacts that we should consider? If so, which ones?
- What additional aspects would analysis be useful to address?

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