NATIONAL RENEWABLE ENERGY LABORATORY

Resource Availability for Hydrogen Production

Marc Melaina, Michael Penev, Elizabeth Connelly, Donna Heimiller, Anelia Milbrandt

National Renewable Energy Laboratory

DOE Hydrogen and Fuel Cells Program
2017 Annual Merit Review and Peer Evaluation Meeting
June 6, 2017

Project ID
SA067

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

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

Start: October, 2016
End: September, 2017*

Status: 40% complete

* Project continuation determined by DOE

Barriers

4.2 Technical Approach:
Infrastructure Analysis

4.5 A. Future Market Behavior:
Scenarios to understand vehicle-fuel demand and supply

4.5 E. Unplanned Studies and Analysis
Response to DOE Request

Budget

FY17 Planned DOE Funding: $50K
Total Funds Received to Date: $50K

Partners

Primary Data Sources

- U.S. Geological Survey
  - Updated uranium resource estimates
- Idaho National Laboratory
  - Uranium consumption per kg hydrogen

Systems Analysis Framework Components

- Analysis estimates total resource availability, including geographic distributions for renewable resources.
- Potential resource stress is estimated with comparisons to forecasts of future consumption.

- Resource and consumption updates (NREL, USGS, EIA)
- H2@Scale

- Fuel Cell Technologies Office
- General audience

Analysis Framework

Resource estimation and hydrogen production potential

Data Sources

- H2A Production Case Studies
- EIA 2017 Annual Energy Outlook

Models & Tools

- H2A Production Case Studies
- SERA vehicle stock model

H2A Model Updates

Studies & Analysis

- Hydrogen Resource Potential
- Long-term analysis
- Environmental analysis

Outputs & Deliverables

- Resource report
- Reference for other publications (e.g. Posture Plan)

Acronyms

H2A: Hydrogen Analysis Model

EIA: Energy Information Administration

SERA: Scenario Evaluation and Regionalization Analysis model

USGS: United States Geological Survey

Improving Energy Security, Economic Resilience, and the Market Competitiveness of Hydrogen

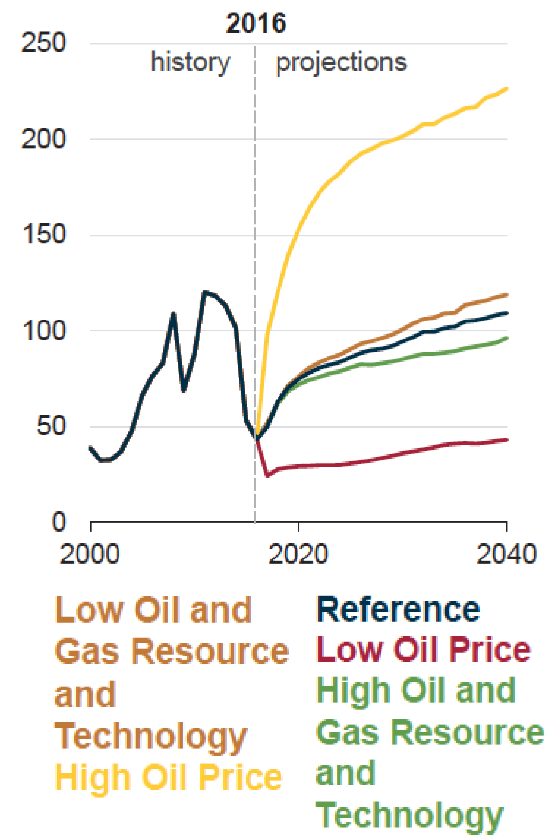
Relevance/Impact 2

- **The transportation sector is dominated by petroleum fuels dependent upon a volatile global market**
  - Studies suggest a significant economic penalty due to continued reliance on imported petroleum, on the order of $100 billion to $400 billion per year (Liu, Greene and Lin, 2015 AMR Presentation)
- **Producing hydrogen from domestic energy resources should increase U.S. economic resilience by reducing dependence on imported oil**
- **The ability to rely on a variety of energy resources should result in a more robust and competitive future hydrogen market**

Project Goal: An improved understanding of energy resource availability and diversity provides insights into the long-term potential to develop a hydrogen infrastructure system that is robust, resilience, and economically competitive

The scale and diversity of resource availability informs the potential for future hydrogen market competitiveness

The wide range in oil price projections ($2016/bbl) in the near-term suggests volatility will persist into the future

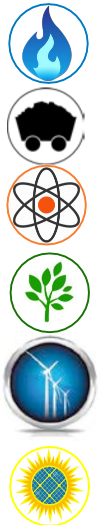


Annual Energy Outlook 2017
https://www.eia.gov/outlooks/aeo/

Resources needed for future hydrogen demand compared to projected resource consumption without FCEV fuel demands

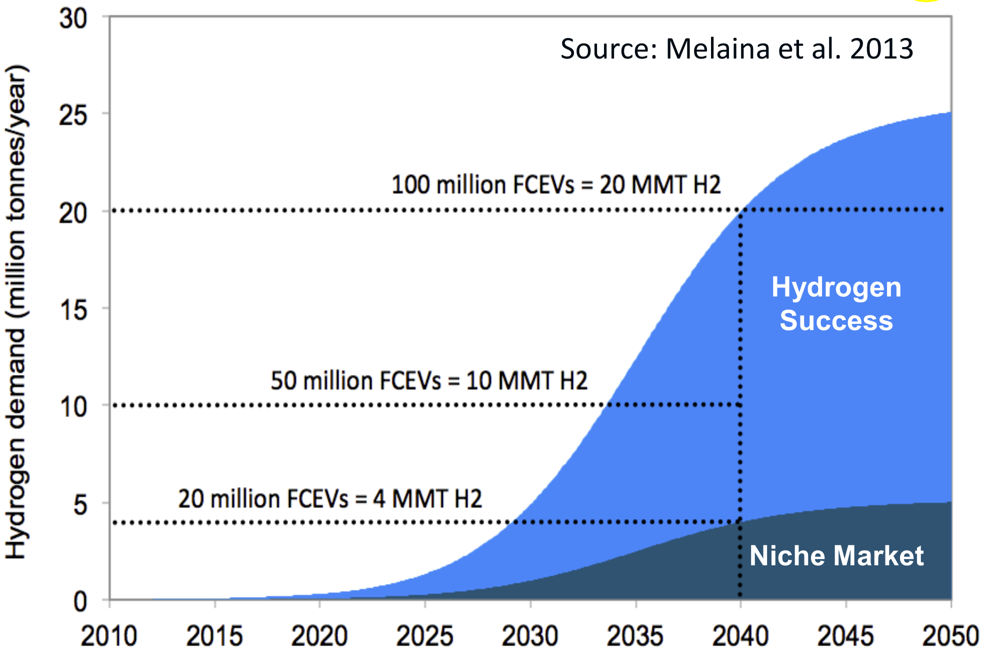
Project Objectives

- Estimate hydrogen production required for potential future FCEV demand
- Provide updated estimates of hydrogen production potential from a wide range of energy resources: natural gas, coal, uranium, biomass, wind, solar
- Compare resource requirements for hydrogen to projected consumption in a future without significant FCEVs (EIA's Annual Energy Outlook)
- Determine resource availability spatially and on a per kg of hydrogen basis



Comparisons are made to a range of hydrogen supply levels: 4-10 million metric tonnes (MMT) of hydrogen per year. This supply range is tested for EACH resource type.

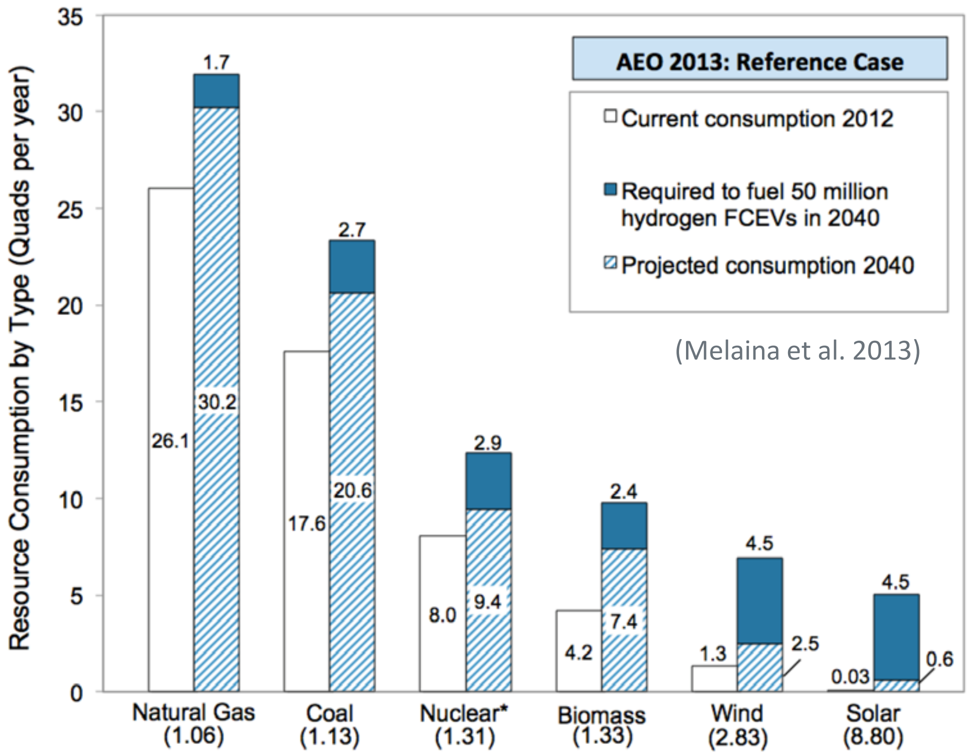
- **Demand assumes an average of 12,000 miles driven per year per vehicle and an average FCEV fuel economy of 60 mpgge**
- **Any given resource is assumed to supply 4-10 MMT of a total potential demand of 20 MMT in the Hydrogen Success case**



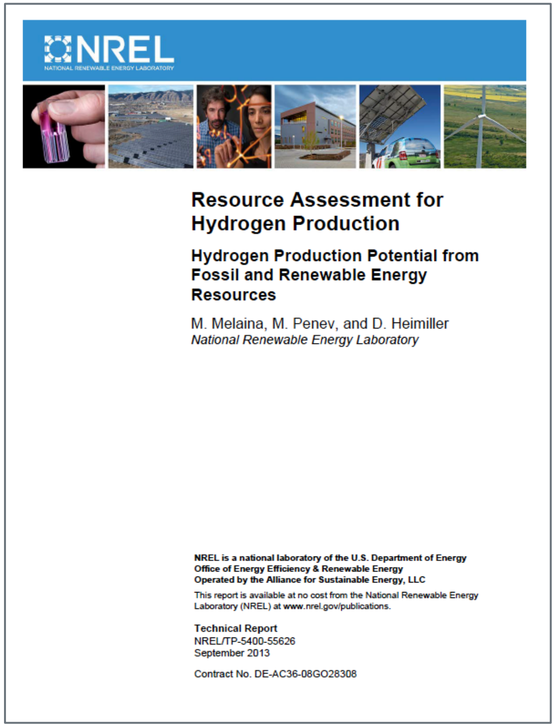
Update to previous resource assessment (2013)

Approach 1

- Approach relies upon the same basic analytic methods used in the 2013 report (right)
- Updates are made to key input parameters where new information or improved assumptions are available
- Comparisons to projected consumption depend upon new Annual Energy Outlook cases (results from the 2013 report are shown below)



(Melaina et al. 2013)


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Resource Assessment for Hydrogen Production

Hydrogen Production Potential from Fossil and Renewable Energy Resources

M. Melaina, M. Penev, and D. Heimiller
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5400-55626
September 2013

Contract No. DE-AC36-08GO28308

Dark blue bars show additional resource consumption for hydrogen production (for 50 million FCEVs) compared to projected resource consumption in 2040 without significant FCEV market growth (blue hatched bars are AEO 2013 Reference Case)

Resource requirements: Production Efficiency

Approach 2

Production efficiencies are key input assumptions in estimating future resource requirements

	Resource	Quantity per kg hydrogen
	Natural Gas	156,000 Btu (HHV)
	Coal (with CCS)	7.9 kg
	Uranium	*to be updated*
	Solid Biomass	13.0 kg
	Wind	46 kWh electricity
	Solar	46 kWh electricity

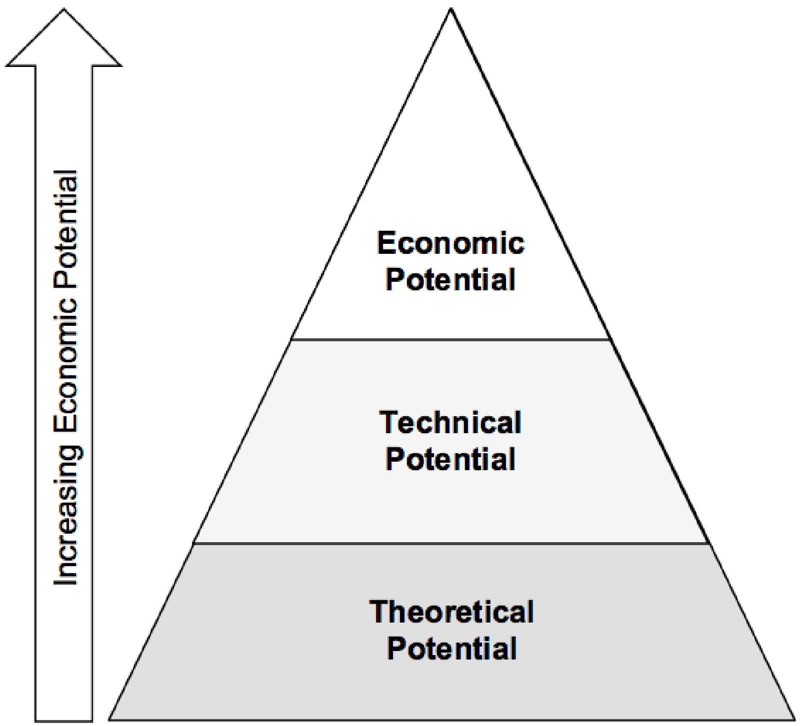
HHV: higher heating value; CCS: Carbon capture and storage

- Most values are based upon H2A production model conversion efficiencies
- Uranium conversion rate is being updated in coordination with the H2@Scale team
- Improved future conversion rates would reduce reliance on any particular resource

Resource requirements are estimated through simple energy balance calculations, and do not take into account future policies or market competition

Characterizing energy resource availability

A clear and consistent approach is needed to characterize and compare different estimates of fossil and renewable energy resources



Energy Resource Type			
Coal	**Natural Gas**	**Uranium**	**Renewable**
Estimated Recoverable Reserves (ERR)	Proved Reserves	RAR Estimates at <$50/lb U_3O_8	Projections of Supply in a High Demand Scenario
Demonstrated Reserve Base (DRB)	Unproved Resources	RAR Estimates at <$100/lb U_3O_8	Current Technical Potential
Other Occurrences	Other Occurrences	Total Undiscovered Resources	Higher Technical Performance

(Melaina et al. 2013)

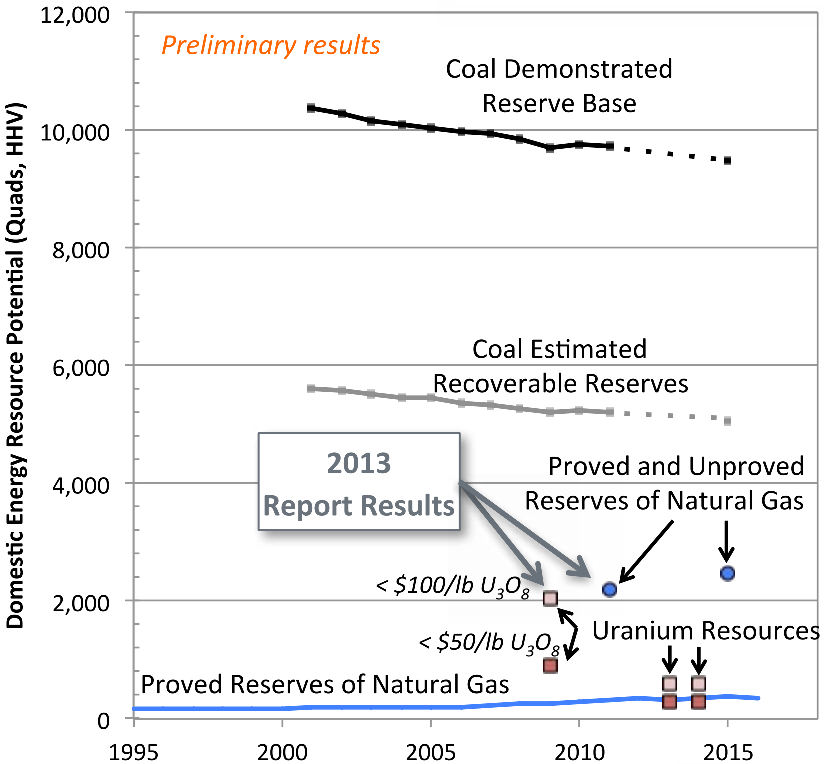
The economic potential estimates for renewables from Lopez et al. (2012) will be updated to reflect improved resource potentials for biomass, wind, and solar

Updated fossil and nuclear energy resource estimates

Proved and unproved reserves of natural gas have increased significantly.

New estimation methods for uranium resources result in lower values.

- Coal resource estimates have continued downward trend over time
- Table below shows total resource and hydrogen production potential
  - EP = Economic Potential
  - TRR = Technically Recoverable Resources



Sources: EIA 2016a,b; EIA 2017a,b.

Resource	Resource Potential			Hydrogen Production Potential		
Fossil and Nuclear	**Physical Resource**		**Quads**	**Hydrogen Potential**		**Quads H2**
Natural Gas (EP)	340	Trillion cubic feet	350	2,030	MMT H2	270
Natural Gas (TRR)	2,500	Trillion cubic feet	2,500	14,700	MMT H2	2,000
Coal (EP)	250	Billion short tons	5,100	29,500	MMT H2	4,000
Coal (TRR)	480	Billion short tons	9,500	55,100	MMT H2	7,400
Uranium (EP)	200	Million lbs U_3O_8	300	900	MMT H2	100
Uranium (TRR)	400	Million lbs U_3O_8	600	2,100	MMT H2	300

2017 Updates

U_3O_8 estimates will be updated with H2@Scale

Preliminary results

Updated hydrogen potential from fossil and nuclear

Accomplishments 2

Resources required to produce hydrogen for 20-50 million FCEVs by 2040 are compared to total resource estimates and projected consumption in two AEO cases:

(1) Reference Case

(2) Low Oil and Gas Resource and Technology Case

The percent increase in resource use due to FCEVs is shown in the bottom section of table at right.

Resource Metric		Fossil and Nuclear Pathways [a]			
		Natural gas [b]	**Coal** [c] (with CCS)	**Nuclear** [d] (high temp. electrolysis)	**Nuclear** [d] (thermo-chemical)
Resource Availability					
Economic Resource Potential		338 Tcf	255 B tons	166 M lb U_3O_8	
Technically Recoverable Resource		2,474 Tcf	477 B tons	362 M lb U_3O_8	
Resource Consumption (without hydrogen for FCEVs) [e]					
Current [2015]		27.2 Tcf	727 M tons	797 TWh	
Reference Case: 2040		31.7 Tcf	492 M tons	702 TWh	
Low Oil and Gas Resource and Technology Case: 2040		24.2 Tcf	445 M tons	759 TWh	
Resource to Produce Hydrogen for 20 & 50 million FCEVs [f]					
50 M FCEVs		1.7 Tcf	79 M tons	278 TWh	292 TWh
20 M FCEVs		0.7 Tcf	31 M tons	111 TWh	117 TWh
Percent Increase in 2040 Resource Consumption for 20 & 50 million FCEVs					
Reference Case	20 M FCEVs	2%	6%	16%	17%
	50 M FCEVS	5%	16%	40%	42%
Low Oil and Gas Resource and Technology Case	20 M FCEVs	3%	7%	15%	15%
	50 M FCEVS	7%	18%	37%	38%

Preliminary results

Resource consumption increase required to supply 20-50 million FCEVs is modest for natural gas (2%-7%) and coal (6%-18%), and significant for uranium (15%-42%)

U_3O_8 estimates will be updated

Updated hydrogen potential from renewables

Renewable resources required to produce hydrogen are compared to the same AEO cases.

Compared to the 2013 report:

- AEO 2017 Reference Case consumption in 2040 is 32% lower for biomass, 109% higher for wind, and 97% higher for solar
- High end of TRR for biomass is about 10% larger than in 2013 report.

Resource Metric		**Renewable Pathways**		
		Biomass [a]	**Wind** [b] (on/offshore)	**Solar** [c] (PV & CSP)
Resource Availability				
Economic Resource Potential		900 M tons	2,000 TWh	1,000 TWh
Technically Recoverable Resource		417–1,192 M tons	50,000 TWh	400,000 TWh
Resource Consumption (without hydrogen for FCEVs) [d]				
Current [2015]		279 M tons	193 TWh	48.9 TWh
Reference Case: 2040		295 M tons	526 TWh	408 TWh
Low Oil and Gas Resource and Technology Case: 2040		313 M tons	696 TWh	617 TWh
Resource to Produce Hydrogen for 20 & 50 million FCEVs [e]				
50 M FCEVs		144 M tons	460 TWh	460 TWh
20 M FCEVs		57 M tons	184 TWh	184 TWh
Percent Increase in 2040 Resource Consumption for 20 & 50 million FCEVs				
Reference Case	20 M FCEVs	19%	35%	45%
	50 M FCEVS	49%	87%	113%
Low Oil and Gas Resource and Technology Case	20 M FCEVs	18%	26%	30%
	50 M FCEVS	46%	66%	75%

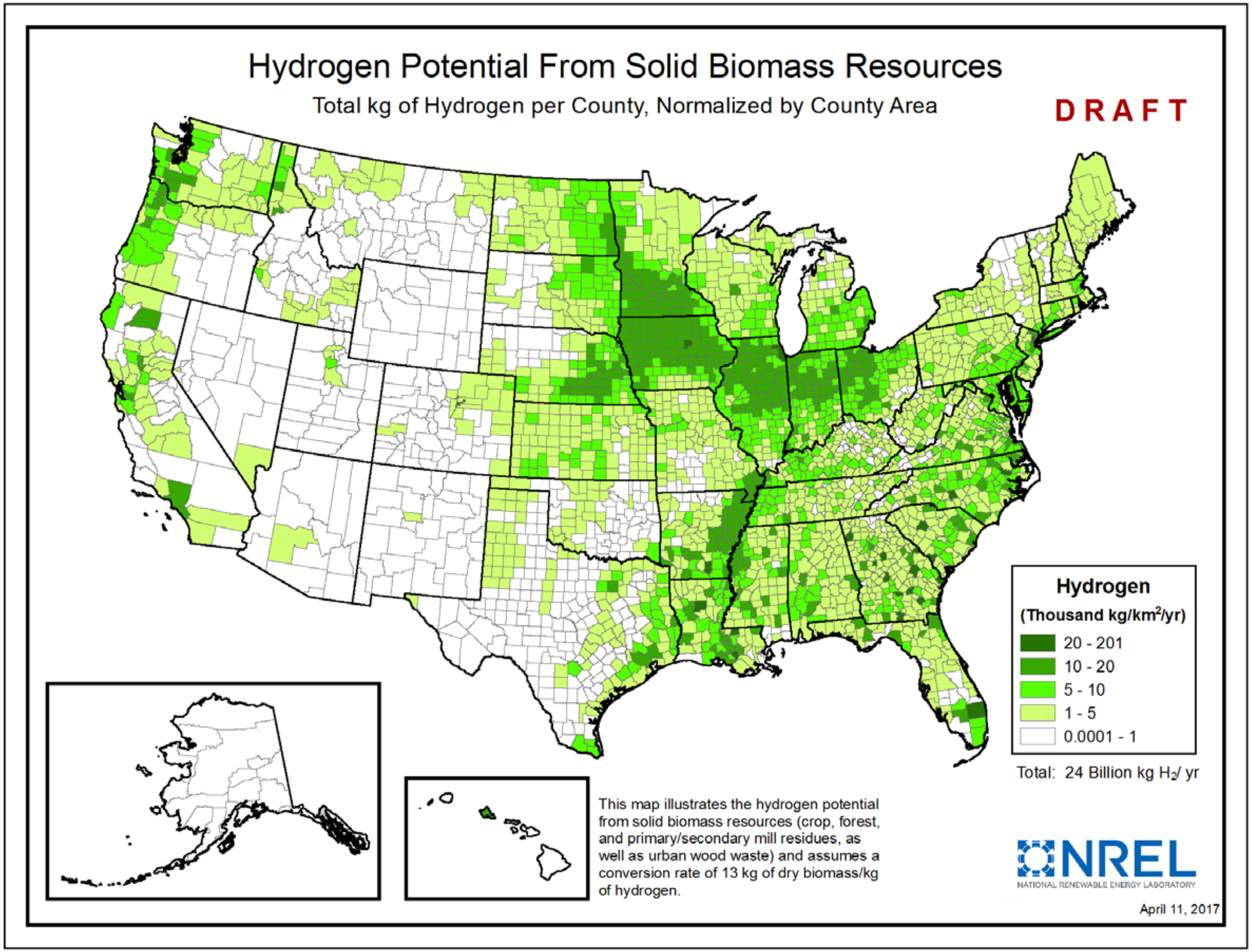
Preliminary results

Resource consumption increase required to supply 20-50 million FCEVs in 2040 is significant for biomass (18%-49%), wind (26%-87%) and solar (30%-113%)

Compared to 2013, these percentages are higher for biomass and lower for wind and solar

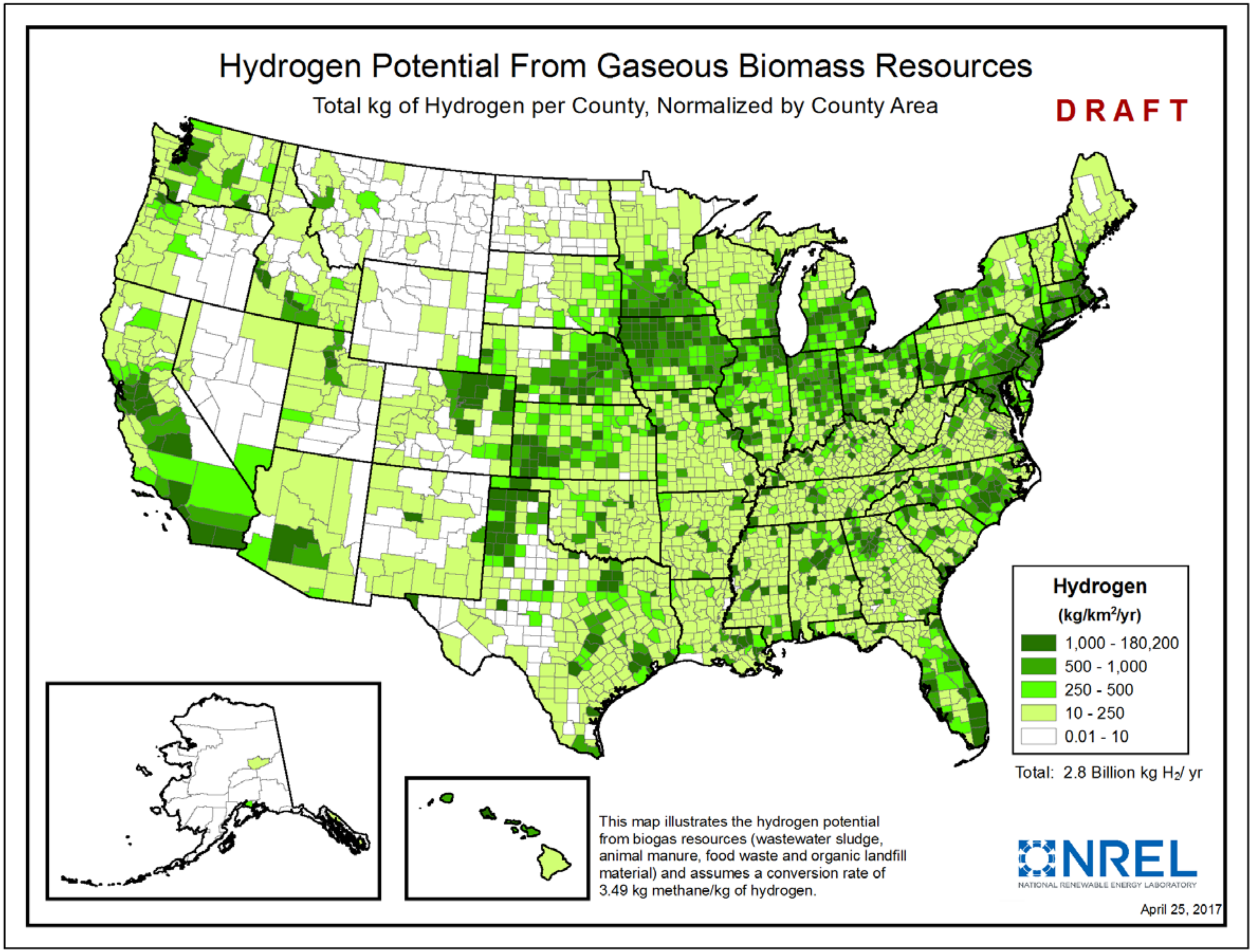
Updated map of hydrogen production potential from solid biomass resources

Accomplishments 4

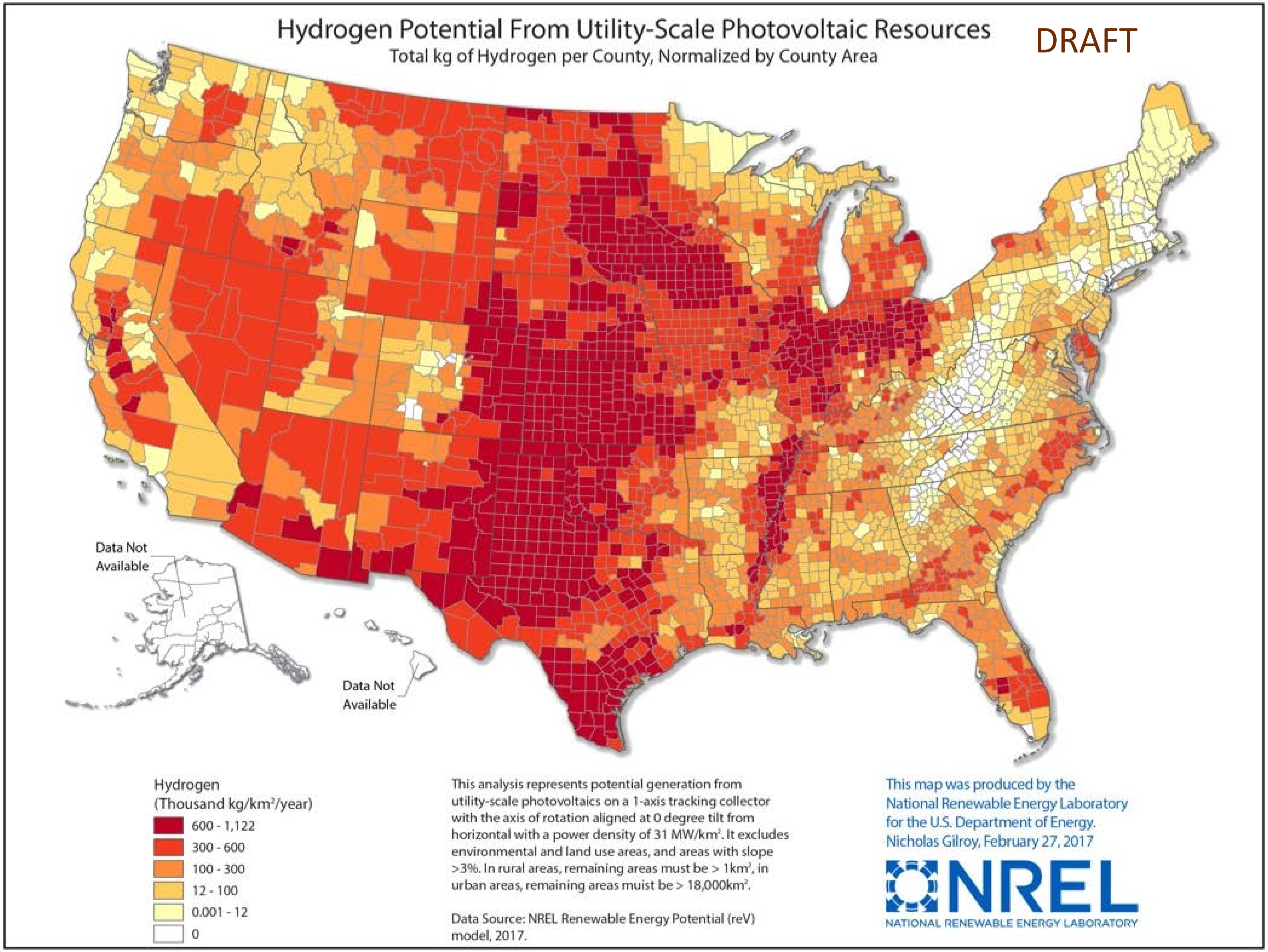


Updated map of hydrogen production potential from gaseous biomass resources

Accomplishments 5



Updated map of hydrogen production potential from solar resources (updated threshold of 31 MW/km^2)

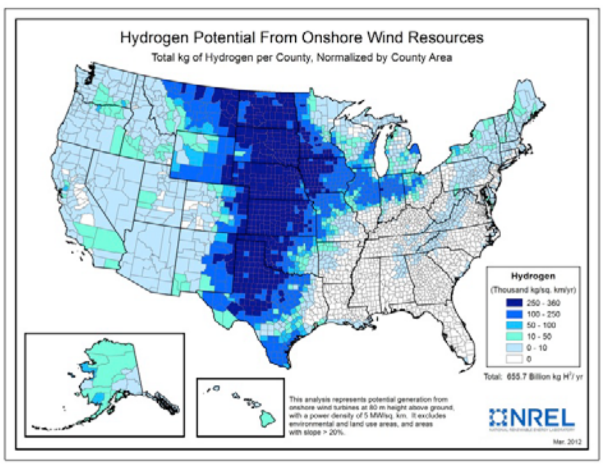


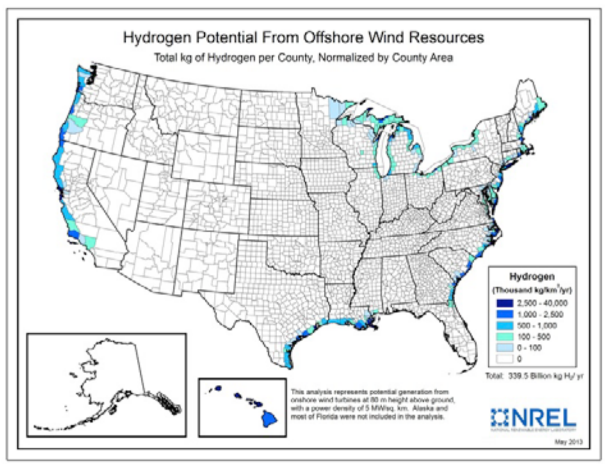
Updated total renewable production potentials

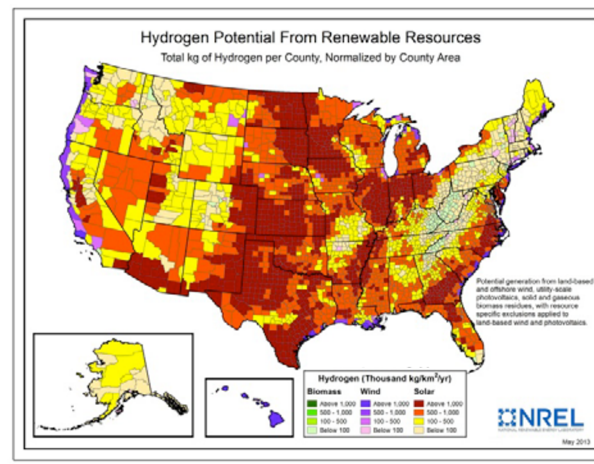
Renewable	Physical Resource	Quads/yr	Hydrogen Potential	Quads H2/yr
Biomass (EP)	900 Million tons eq.	15	60 MMT H2/yr	8
Biomass (moderate)	400 Million tons eq.	7	30 MMT H2/yr	4
Biomass (high)	1,100 Million tons eq.	19	80 MMT H2/yr	10
Wind (EP)	2,000 TWh electricity	20	40 MMT H2/yr	6
Wind (TRR)	50,000 TWh electricity	500	1,100 MMT H2/yr	150
Solar (EP)	1,000 TWh electricity	10	20 MMT H2/yr	3
Solar (TRR)	400,000 TWh electricity	3,900	8,700 MMT H2/yr	1,200

Notes: EP = Economic Potential, TRR = Technically Recoverable Resource. Biomass TRR is shown as a moderate to high range. Conversions to quads are on a higher heating basis; EIA thermal equivalent of 9760 Btu/kWh is used for wind and solar. Sums are rounded.

Preliminary results







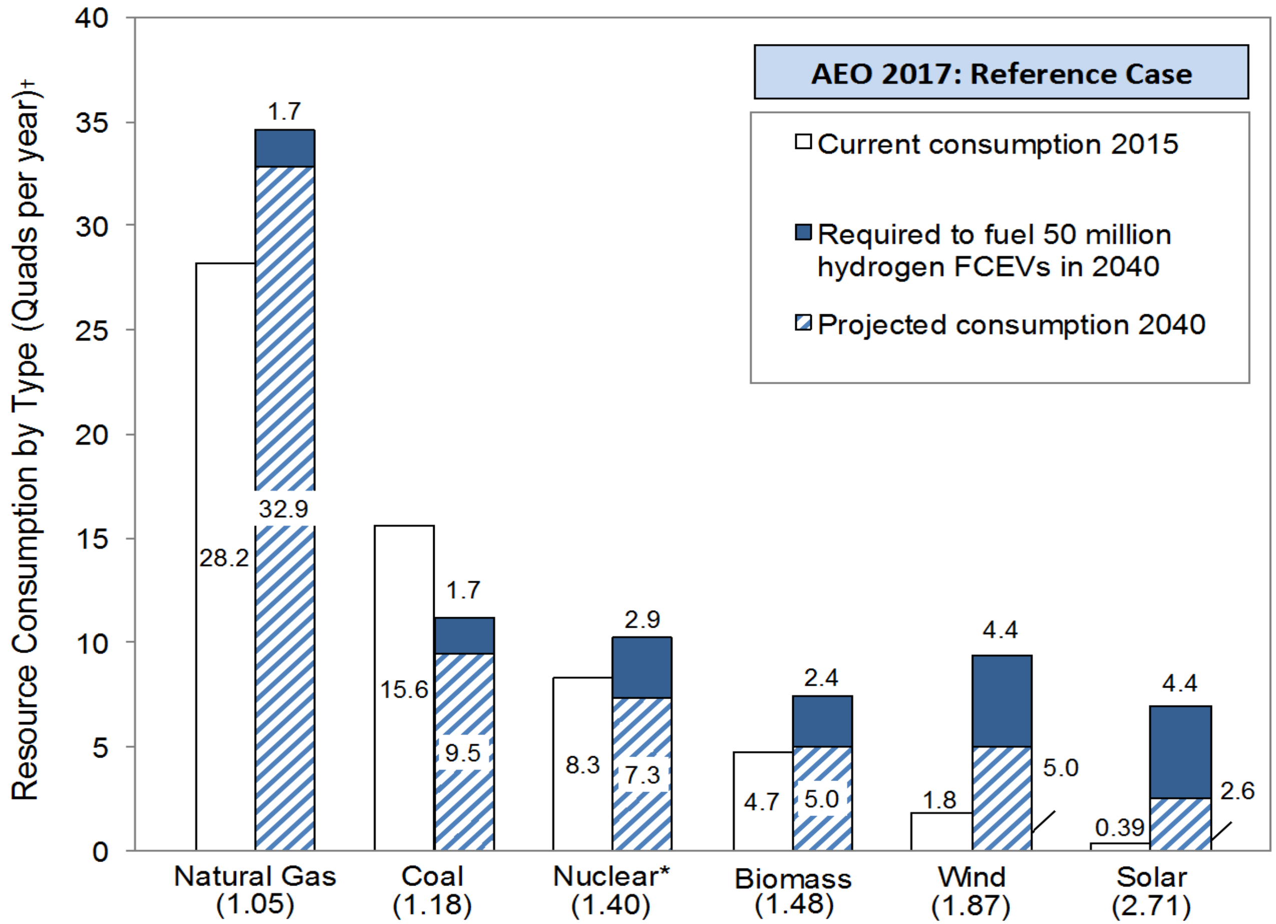
Additional updates will be made for wind and total renewable hydrogen potential maps

Updated comparison to current 2015 and future consumption in 2040: AEO Reference Case

Ratio of projected 2040 consumption and additional resource needed to supply 50 million FCEVs is shown as a factor in parenthesis below each resource label at left.

Highest factors are for wind (1.87) and solar (2.71).

However, these factors are much lower than 2013 results for wind (2.83) and solar (8.80)



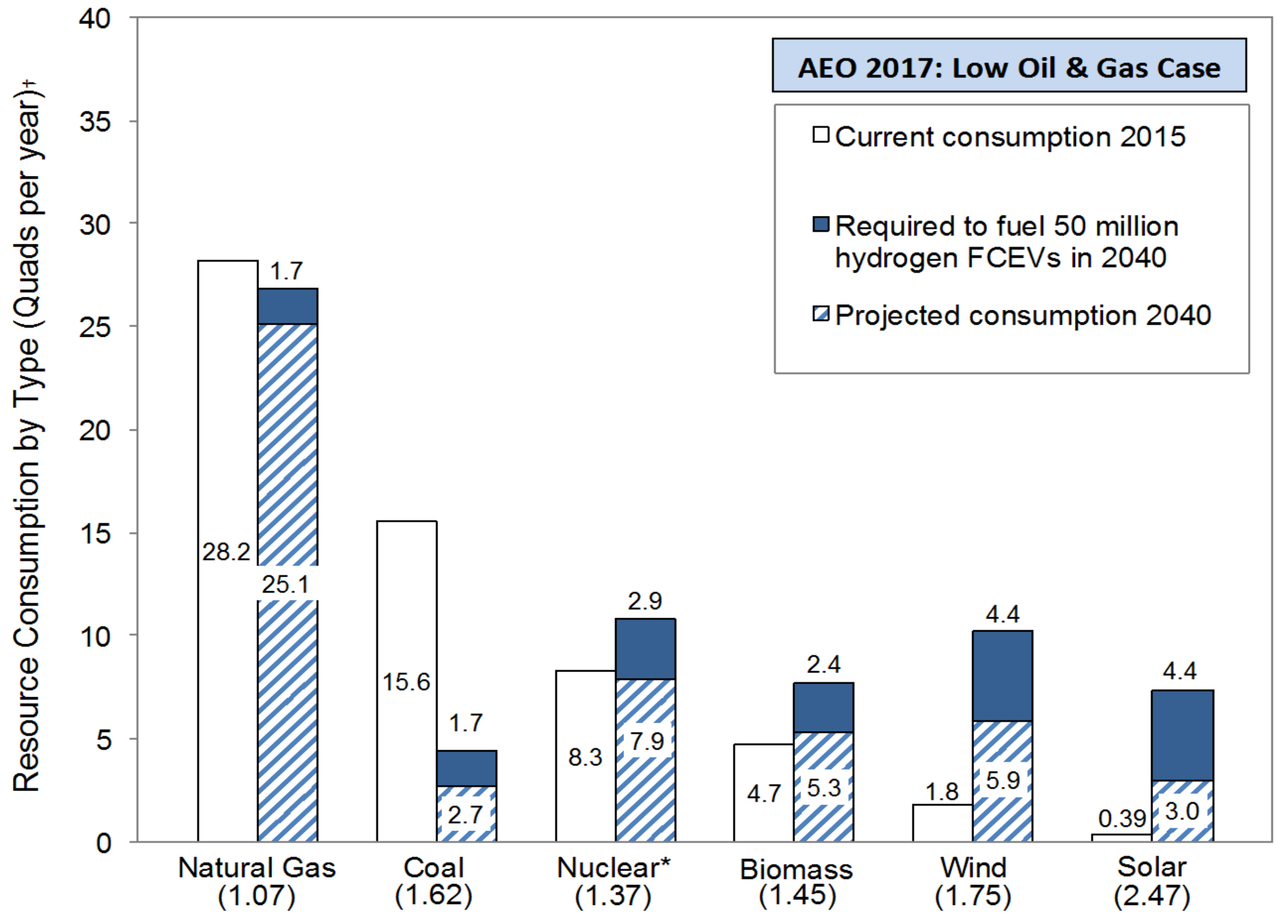
NOTE: Wind and solar resource requirements are calculated using a thermal equivalent value of 9,510 Btu per kWh, following the convention used by EIA (see AEO 2017, Table A17)

Increased resource consumption to supply 50 million FCEVs in 2040 varies significantly by resource type, from natural gas at 5% to solar at 171%

Updated comparison to current 2015 and future consumption in 2040: AEO Reference Case

The AEO 2017 **Low Oil and Gas Case** includes limited domestic fossil resources and future consumption, resulting in greater reliance on nuclear, biomass, wind and solar resources.

Differences suggests hydrogen production would likely be more diversified under the Low Oil and Gas Case market conditions.



Projected consumption in the AEO 2017 Low Oil and Gas Case has significant impact on percent increase in natural gas (5% to 7%) and coal (18% to 62%) due to FCEVs.

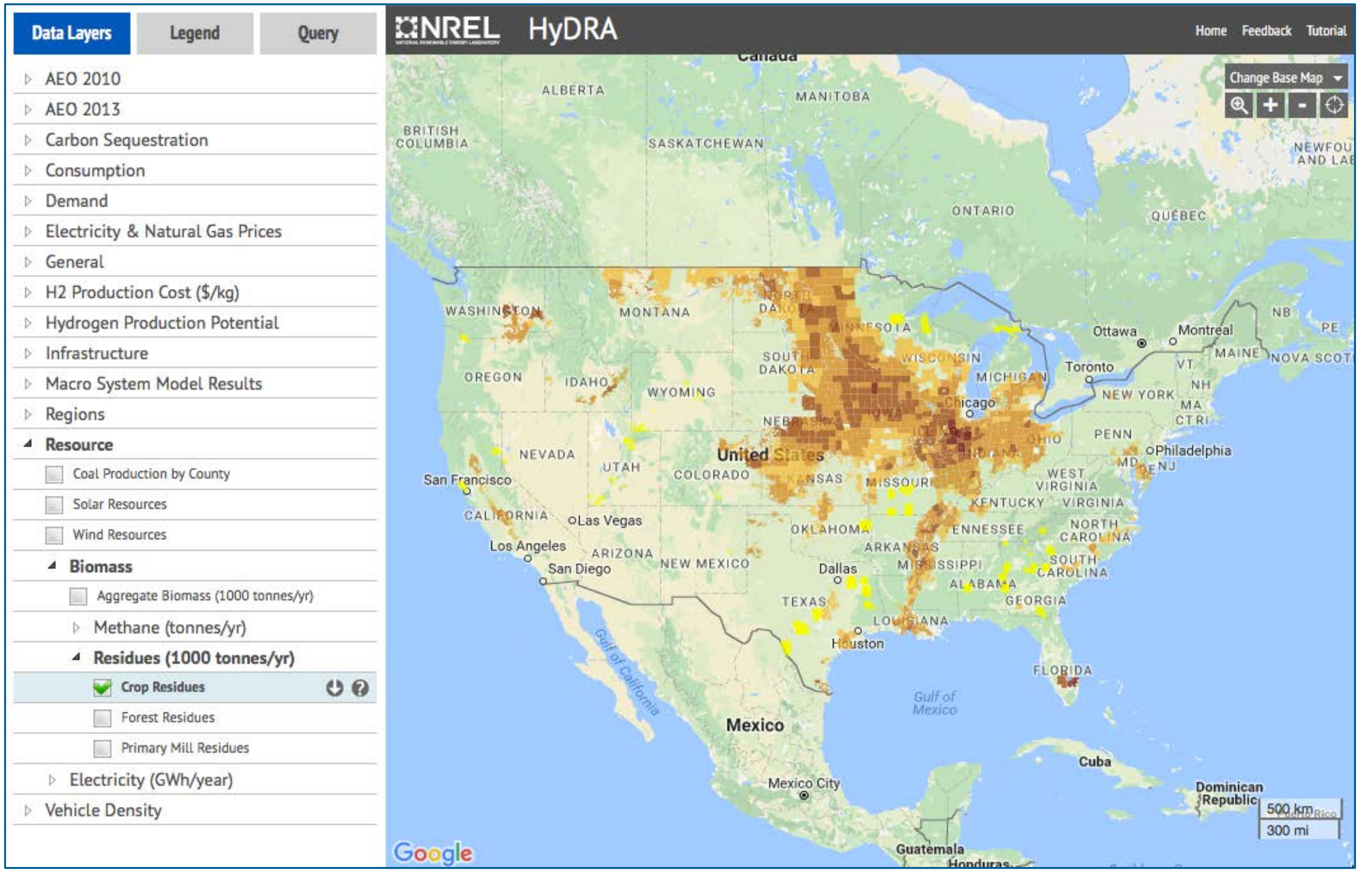
Projected market success of wind and solar suggest increased viable for hydrogen production

Results will be conveyed in updated HyDRA Tool

HyDRA is an online data sharing and visualization tool, providing access to spatial data from a variety of studies

The present project will result in updated estimates of resource potentials within HyDRA

Image at right is a screenshot of the enhanced HyDRA tool to be released later in FY 2017. Update includes new resource data and enhanced end-user capabilities.



HyDRA can be accessed at: https://maps.nrel.gov/hydra/

Resource potential results will be loaded into the HyDRA tool to provide public access

Response to previous year’s AMR comments

This project was not reviewed at the 2016 AMR

Comments from the 2012 AMR were addressed in the final 2013 Resource Report

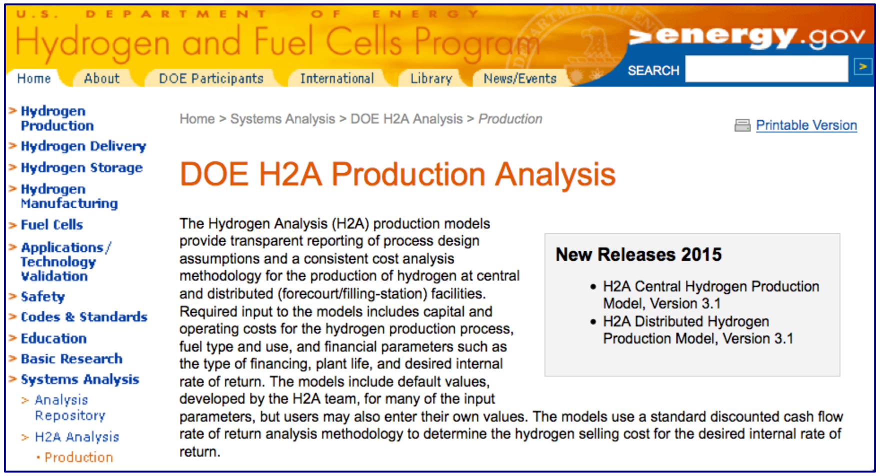
Collaboration: Sources and proper use of data

Collaboration 1

- Conversion efficiencies from H2A have been vetted in the process of updating the H2A Production Case Studies (separate project)
- Uranium resource estimates from USGS and conversion efficiencies for nuclear production systems from Idaho National Laboratory will be verified through direct discussion with topic experts
- Results will be coordinated with the H2@Scale project team
- Final report will be peer reviewed

USGS
science for a changing world

INL Idaho National Laboratory



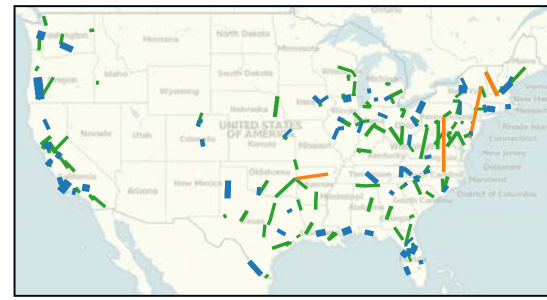
https://www.hydrogen.energy.gov/h2a_production.html

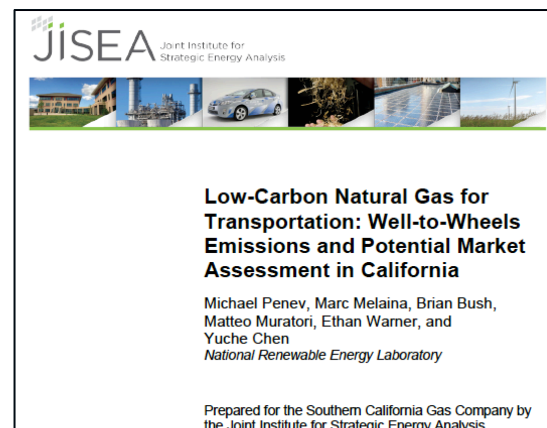
Remaining Challenges and Barriers

- No major challenges or barriers pose a risk to this project
- Efforts will continue to make consistent comparisons across different resource potential types (e.g., new uranium estimates)

Proposed Future Work

- The resource report is the main project deliverable
- Resource potential estimates will be used as inputs to the ***Scenario Evaluation and Regionalization Analysis (SERA)*** cost optimization routine
  - Including spatial resource availability constraints will improve the realism of hydrogen supply chain cost estimates by generating more realistic depictions of:
    - Production facility scales and locations
    - Delivery distances between production facilities and demand centers (urban areas)
- Examples of supply curves resulting from these types of spatial constraints in the SERA model can be found in a recent JISEA report on low-carbon natural gas potential in southern California (shown at right)
- Any proposed future work is subject to change based on funding levels





JISEA Joint Institute for Strategic Energy Analysis

Low-Carbon Natural Gas for Transportation: Well-to-Wheels Emissions and Potential Market Assessment in California

Michael Penev, Marc Melaina, Brian Bush, Matteo Muratori, Ethan Warner, and Yuche Chen
National Renewable Energy Laboratory

Prepared for the Southern California Gas Company by the Joint Institute for Strategic Energy Analysis

http://www.nrel.gov/docs/fy17osti/66538.pdf

Summary

Relevance

- Hydrogen production for FCEVs can reduce reliance on imported petroleum, improving national energy security and economic resilience
- Energy resource diversity should improve hydrogen's economic competitiveness

Approach

- Establish framework to draw comparisons across different resource estimate types
- Estimate total potential to produce hydrogen from major energy resources
- Test each major resource in potential to supply 4 to 10 MMT of hydrogen per year; compare to expected consumption in 2040 without significant FCEV market share

Technical Accomplishments and Progress

- Updated hydrogen production potential for natural gas, coal (with CCS), nuclear, biomass (solid and gaseous), wind, and solar resources
- Compared results to future 2040 consumption as percent increase due to FCEVs
- Results will be captured in final report and made available through HyDRA tool

Collaboration

- Major reliance on external sources; discussions with INL and USGS on uranium

Proposed Future Research

- Final report; use in improving hydrogen supply curves for future SERA simulations

Acronyms

AEO	Annual Energy Outlook
CSP	Concentrated solar power
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EP	Economic Potential
FCEV	Fuel cell electric vehicle
H2A	Hydrogen Analysis Model
HHV	Higher heating value
MMT	Million metric tons
PV	Photovoltaic
SERA	Scenario Evaluation and Regionalization Analysis model
TRR	Technically Recoverable Resources
TWh	Terawatt hours
USGS	United States Geological Survey

References

- Melaina, M., M. Penev, and D. Heimiller, 2013. Resource Assessment for Hydrogen Production, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-55626. Available at: http://www.nrel.gov/docs/fy13osti/55626.pdf
- Liu, Changzheng, David Greene, and Zhenhong Lin, 2015. *Assessing the Outlook for U.S. Oil Dependence Using Oil Security Metrics Model (OSMM)*, 2015 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, June 11, 2015. Available at: https://energy.gov/sites/prod/files/2015/07/f24/van010_liu_2015_p.pdf
- Penev, M., M. Melaina, B. Bush, M. Muratori, E. Warner and Y. Chen, 2016. *Low-Carbon Natural Gas for Transportation: Well-to-Wheels Emissions and Potential Market Assessment in California*, Joint Institute for Strategic Energy Analysis, National Renewable Energy Laboratory, Technical Report NREL/TP-6A50-66538. Available at: http://www.nrel.gov/docs/fy17osti/66538.pdf
- EIA. (2016a). Annual Coal Report 2015. Table 15. Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, 2015. https://www.eia.gov/coal/annual/pdf/table15.pdf
- EIA. (2016b). 2015 Domestic Uranium Production Report. Table 10. Uranium reserve estimates at the end of 2014 and 2015. https://www.eia.gov/uranium/production/annual/pdf/dupr.pdf
- EIA. (2017a). Assumptions to the Annual Energy Outlook. Table 9.2 Technically recoverable U.S. dry natural gas resources as of January 1, 2014. https://www.eia.gov/outlooks/aeo/assumptions/pdf/0554(2016).pdf
- EIA. (2017b). Annual Energy Outlook 2017. Table: Energy Consumption by Sector and Source. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2017&region=1-0&cases=ref2017~lowrt&start=2015&end=2050&f=A&sourcekey=0