U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Resource Assessment for Hydrogen Production

Elizabeth Connelly, Ph.D.

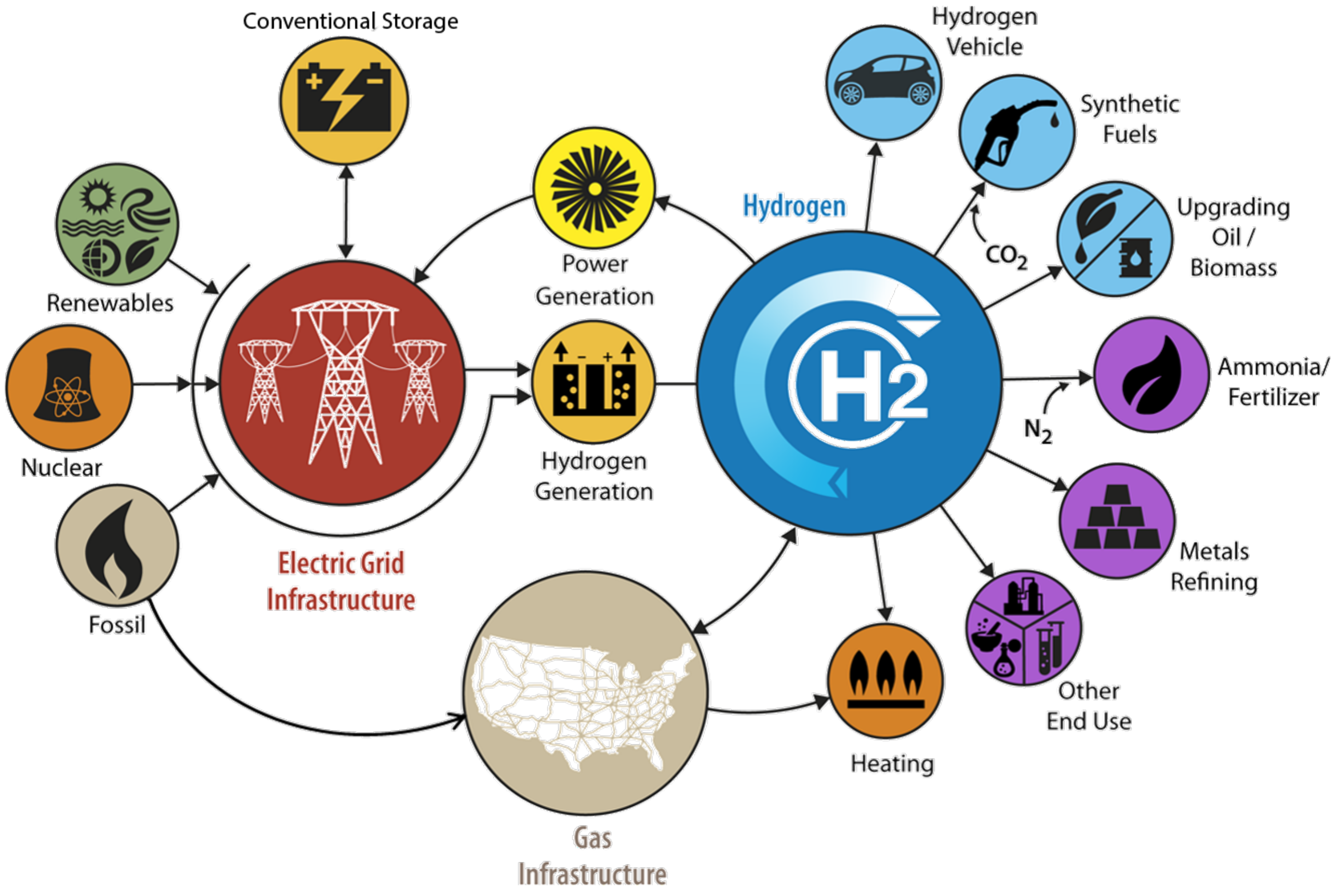
June 10, 2020


Outline

- Background
- Objectives
- Assumptions and Data Sources
- Results
  - Technical Potential
  - Electricity Consumption
  - Water Consumption
- Future Work

Background – H2@Scale

H2@Scale concept: enabling affordable, reliable, clean, and secure energy across sectors



More information at: www.energy.gov/eere/fuelcells/h2-scale

H2@Scale Analysis:

National Laboratory (NREL, ANL, INL) effort

1. **Resource Assessment for Hydrogen Production**
2. **Hydrogen Demand Analysis**
3. **Analysis of Economic Potential of Hydrogen Production and Utilization**

Resource Assessment Objectives

- **Inform H2@Scale analysis on technical resource potential**
  - Estimate total hydrogen production potential from multiple energy resources
  - Are there sufficient domestic resources to be able meet the technical hydrogen demand (estimated in the H2@Scale analysis)?

- **Estimate the quantity of domestic energy resources required to meet** an incremental increase in hydrogen demand in the future of **10 MMT of hydrogen** annually
  - Represents a doubling of annual hydrogen consumption by 2040 [additional 10 MMT/yr]
  - Compare those requirements to the projected future consumption of each resource

Summary of Results

Resource	Hydrogen Production Potential (MMT)*	Percent of Resource Potential to Produce 10 MMT H_2
Natural Gas	17,800	0.06%
Coal	50,100	0.02%
Nuclear (Uranium)	2,900	0.4%

Resource	Hydrogen Production Potential (MMT/yr)*	Percent of Annual Resource Potential to Produce 10 MMT H_2/yr
Biomass	50	17.5%
Wind	800	1.4%
Solar	5,200	0.2%
Water Power	50	20.5%
Geothermal	490	2.1%

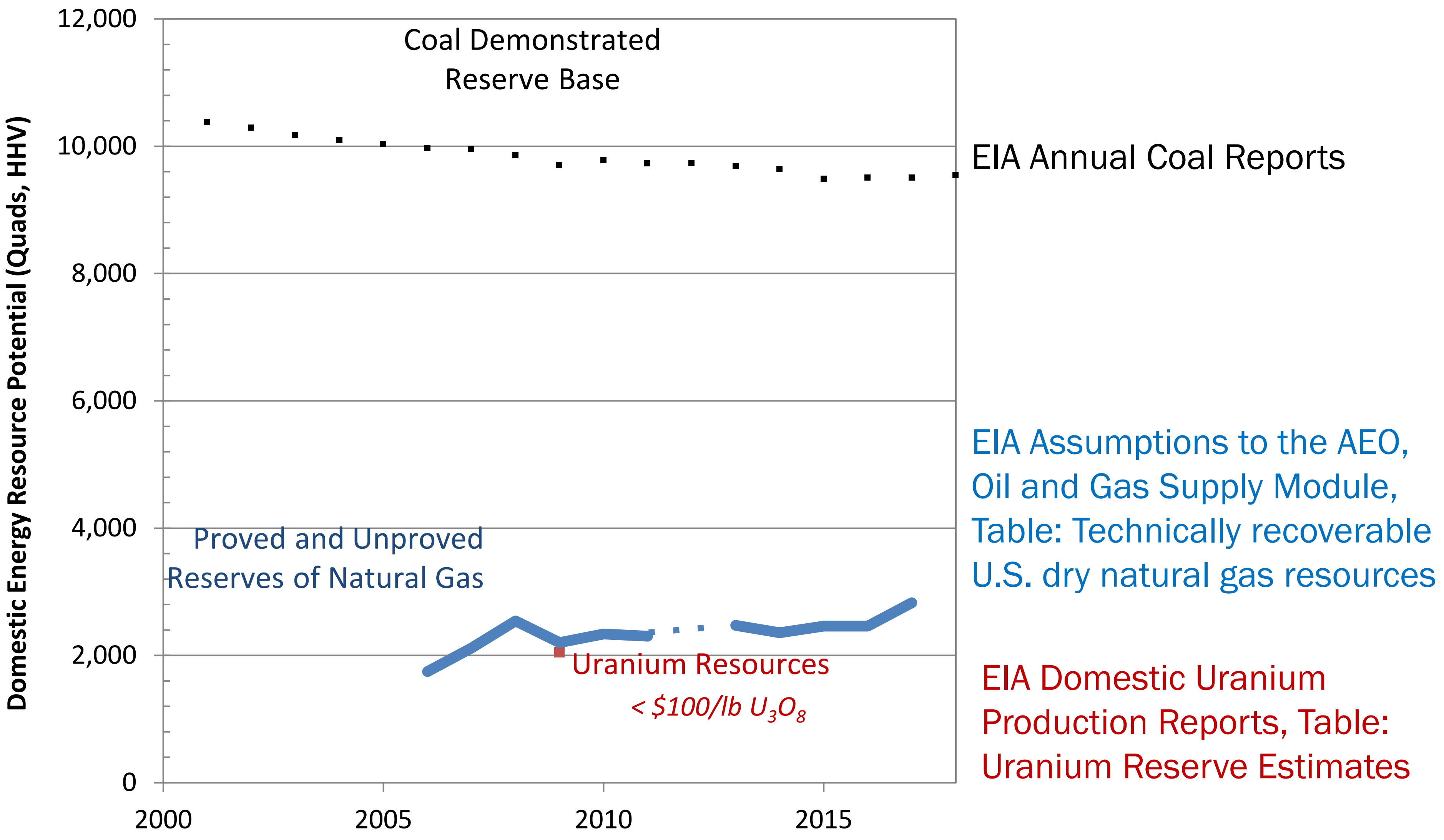
* Fossil and uranium production potentials are based on reserves; renewable production potentials are based on previous analyses of technical potential. There is some inherent variability among the underlying data sources used for these calculations.

Assumptions & Data Sources

Summary of Data Sources

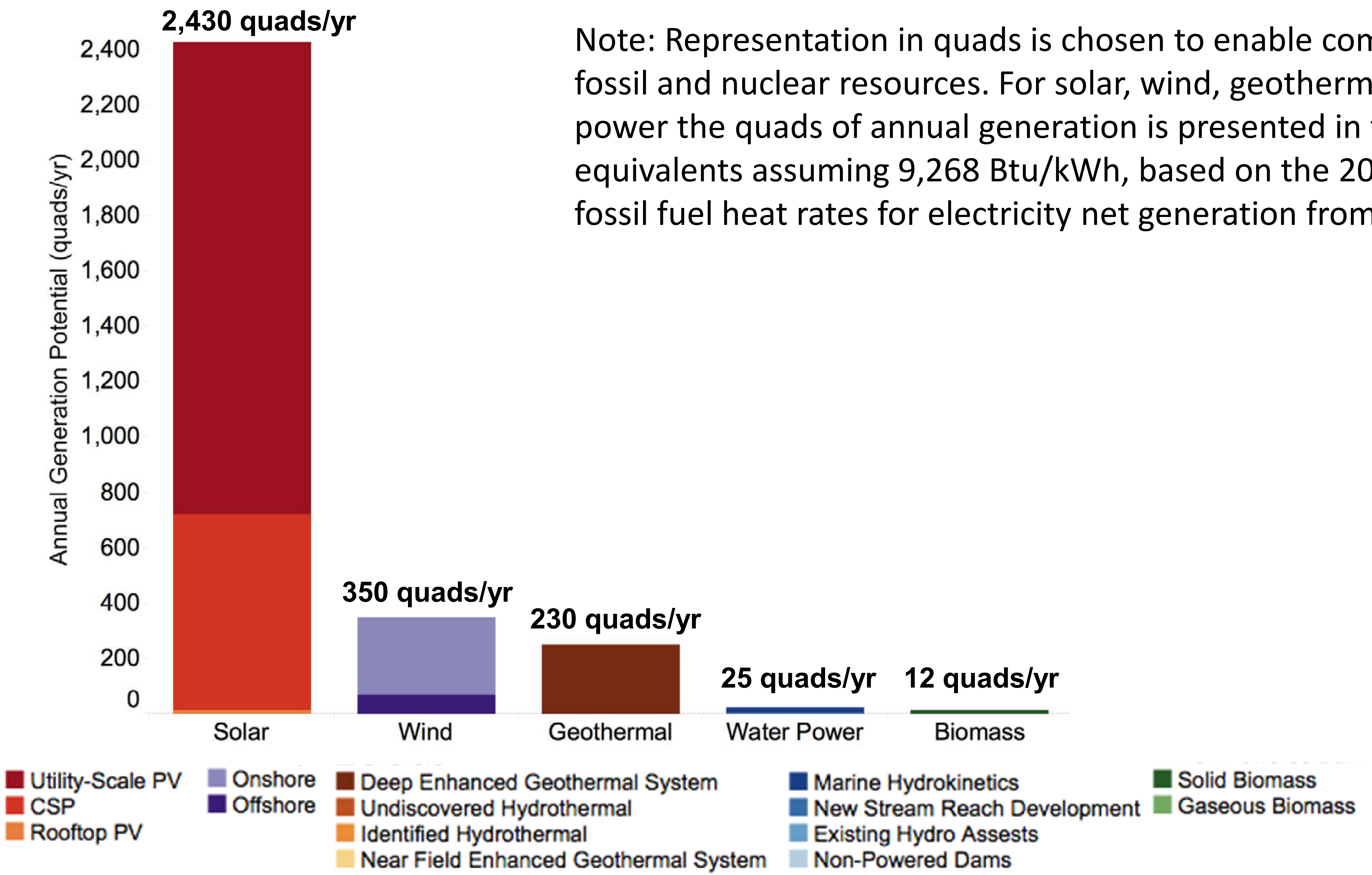
	Current and Future Consumption	Technical Potential	Hydrogen Conversion Rate
Natural Gas	2019 EIA Annual Energy Outlook 1) *Reference Case* 2) *Low Oil and Gas Resource and Technology Case*	EIA AEO Assumptions (2019) Proved + Unproved Reserves	H2A
Coal		EIA Annual Coal Report (2019) Demonstrated Reserve Base	NETL (2010) Case Study
Nuclear (Uranium)		EIA Uranium Production Report (2019) <$100/lb U_3O_8	Jim O'Brien (INL) – systems modeling of HTGR
Biomass		Solid biomass: Billion-Ton Report (DOE 2016) Gaseous biomass: NREL analysis (Milbrandt et al. 2018)	H2A (solid) NREL (biomethane)
Wind		Land-based: NREL reV model Offshore: NREL 2016 Offshore Wind Energy Resource Assessment	H2A
Solar		UPV: NREL reV model Rooftop PV: NREL analysis (Gagnon et al. 2016) CSP: NREL Potential Role of CSP (Murphy et al. 2019)	H2A
Water Power		EHA: ORNL Hydrosource NPD: ORNL Non-Powered Dam Assessment NSD: ORNL New Stream Reach Development Assessment MHK: Table 4.N.2, Quadrennial Technology Review (2015)	H2A
Geothermal		GeoVision Analysis Supporting Task Force Report	H2A

Comparison of Fossil and Uranium Reserves



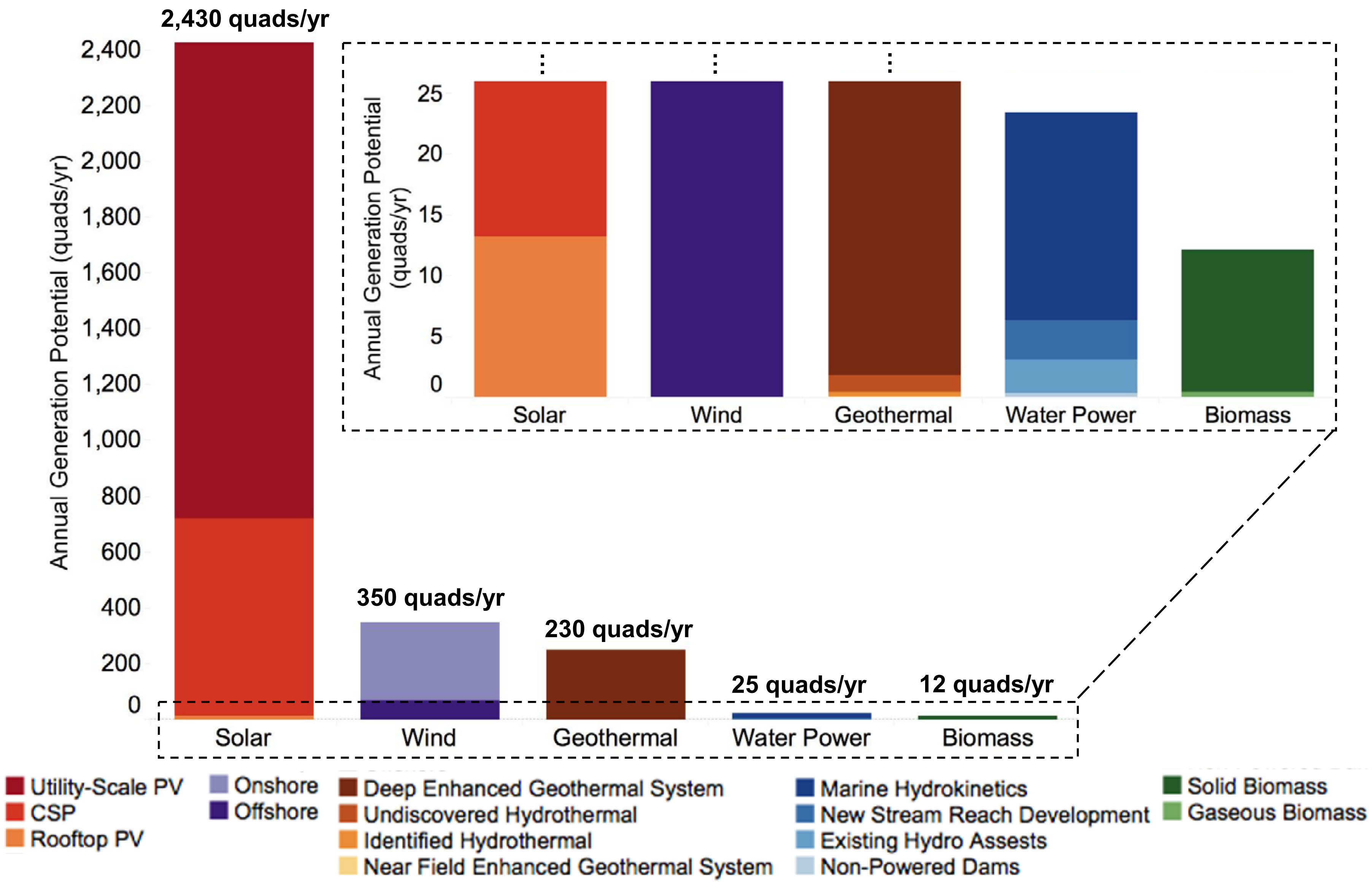
Reserve estimates are uncertain and are likely to increase as technology develops, industry practices improve, and the understanding of the geology increases. In particular, uranium reserves at < $100/lb U_3O_8 is likely a significant underestimate of actual uranium resource

Comparison of Renewable Resource Technical Potentials



Note: Representation in quads is chosen to enable comparison with fossil and nuclear resources. For solar, wind, geothermal, and water power the quads of annual generation is presented in thermal equivalents assuming 9,268 Btu/kWh, based on the 2017 approximate fossil fuel heat rates for electricity net generation from EIA.

Comparison of Renewable Resource Technical Potentials



Technology Assumptions

Resource	Conversion Pathway	Amount to Produce 1 kg Hydrogen[a]		Production Efficiency[b] (E_{out}/E_{in}, LHV)
Natural gas	Steam methane reforming	167 scf	165 MJ	73.0%
Coal (bituminous)	Coal gasification	8.6 kg	226 MJ	53.3%
Nuclear (uranium)	High-temperature electrolysis	4.62×10^{-5} kg U	240 MJ	50.2%
Biomass	Biomass gasification	13.0 kg bone dry biomass	242 MJ	48.3%
Biomethane	Steam methane reforming	3.29 kg methane	165 MJ	73.0%
Wind power **Solar power** **Water power** **Geothermal**	Low temperature electrolysis	51.3 kWh	185 MJ	64.9%

MJ = megajoule

[a] Values are derived from H2A Current or Future Central Case Studies for each resource type and from the central electrolysis case study for wind, solar, geothermal, and water power. The 167 scf per kg for steam methane reforming is derived from the future central steam methane reforming case study, assuming the GREET LHV/HHV ratio of 0.903 and EIA HHV of 1,036 Btu/scf. The coal requirement is based on NETL (2010) case 2.2, and the GREET (2018) LHV of bituminous coal of 22.6 MMBtu/ton. Uranium consumption for the nuclear high-temperature electrolysis production pathway is from personal communication with Jim O'Brien (INL). The 13.0 kg bone dry biomass is from the future central biomass gasification case study. Biomethane is assumed to have an LHV of 50 MJ/kg (Saur and Milbrandt 2014). The H2A case studies are available from the DOE H2A website: http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] Production efficiency is defined as the energy of the hydrogen out of the production process (on an LHV basis) divided by the sum of the energy into the process from the feedstock. The production efficiencies in this table do not account for any additional input feedstock consumption or electricity byproduct credits. Efficiency definitions are distinct in that resource "energy in" is in different forms, as noted in the column indicating MJ of resource required. Production efficiencies indicated for low temperature electrolysis are based on system electrical energy input (51.3 kWh, including electricity requirements for balance of plant) and nuclear efficiency is on a heat input basis.

Results

Availability, Current Consumption, and Projected Consumption for Fossil and Nuclear Resources

Resource Metric	Fossil and Nuclear Pathways [a]		
	Natural gas [b]	**Coal** [c]	**Nuclear** [d] (high temp. electrolysis)
Resource Availability			
Technical Resource Potential	2,829 Tcf	473 B tons	353 M lb U_3O_8
Resource Consumption (without an additional 10 MMT of hydrogen production) [e]			
Current [2017]	27.1 Tcf	642 M tons	885 TWh
Reference Case: 2040	33.3 Tcf	487 M tons	728 TWh
Low Oil and Gas Resource and Technology Case: 2040	26.5 Tcf	582 M tons	798 TWh
Required Resource for Hydrogen Production			
10 MMT of Hydrogen	1.7 Tcf	78 M tons	256 TWh
Percent of Technical Potential	0.06%	0.02%	0.4%
Percent Increase in 2040 Resource Consumption to Produce 10 MMT of Hydrogen			
Reference Case	5%	20%	39%
Low Oil and Gas Resource and Technology Case	6%	17%	35%

[a] Calculations were made to determine the hydrogen quantity required. Some systems require input energy such as electricity or produce useful byproducts such as heat or electricity.

[b] Natural gas technical potential is based on *Total Technically Recoverable Resources* estimates at the beginning of 2018 (Assumptions to the Annual Energy Outlook 2020, Table 2).

[c] Coal technical potential is from the Demonstrated Reserve Base from the 2018 Annual Coal Report. Consumption, provided in quads by EIA, was converted to million tons using 19.44 MMBtu/ton for 2017 consumption and 19.82 MMBtu/ton for 2040 consumption (EIA 2020).

[d] The nuclear production pathway for high temperature electrolysis is described above. Uranium resource technical potential is from 2018 uranium reserves at a forward-cost category of up to but less than \$100/lb U_3O_8 (2018 Domestic Uranium Production Report, Table 10).

[e] Current (2017) and projected (2040) resource consumption values are from the *Reference Case* and *Low Oil and Gas Resource and Technology* scenario from the 2019 Annual Energy Outlook.

Hydrogen Production Potential from Fossil and Nuclear Resources

Resource	Resource Potential			Hydrogen Production Potential		
Fossil and Nuclear	**Physical Resource**		**Quads**	**Hydrogen Potential**		**Quads H2**
Natural Gas	2,800	Trillion cubic feet	2,600	17,800	MMT H2	2,100
Coal	470	Billion short tons	9,500	50,100	MMT H2	6,800
Uranium	400	Million lbs U_3O_8	700	2,900	MMT H2	300

- Coal reserves show the highest hydrogen production potential: >50,000 MMT
- **Technical potential of natural gas has increased by 35%** since 2013 due to increase in EIA natural gas reserve estimates
- **Uranium reserves estimate decreased by 65%** since 2009 due to smaller set of properties covered by EIA survey (see backup slide for more information)
- **Combined fossil and nuclear hydrogen production potential is >70,000 MMT**

Nuclear Technical Potential

- There are **major uncertainties associated with U.S. uranium resource estimates**, and a thorough evaluation of the U.S. uranium resource base has not been conducted since 1980.
- It is estimated that uranium technical resource potential might increase by 10% if inferred resources were added to reasonably assured resource (RAR).
- New ore processing and fuel fabrication techniques may lead to increases in RAR.
- Advanced reactor designs could improve the efficiency of uranium use.
- **Nuclear energy resources could be increased by reprocessing of spent uranium fuel**, since the spent fuel retains about 96% of the fissile material from the original fuel.

The technical potential of nuclear resources presented in this report is likely an underestimate of long-term potential

Availability, Current Consumption, and Projected Consumption for Renewable Resources

Resource Metric	Renewable Pathways				
	Biomass	**Wind**	**Solar**	**Water Power**	**Geothermal**
Resource Availability					
Annual Technical Resource Potential	800 M tons	38,000 TWh	260,000 TWh	2,500 TWh	25,000 TWh
Resource Consumption (without an additional 10 MMT of hydrogen production) [a]					
Current [2017]	292 M tons	254 TWh	87 TWh	298 TWh	16 TWh
Reference Case: 2040	329 M tons	382 TWh	547 TWh	307 TWh	56 TWh
Low Oil and Gas Resource and Technology Case: 2040	337 M tons	564 TWh	885 TWh	310 TWh	58 TWh
Required Resource for Hydrogen Production					
10 MMT of Hydrogen	143 M tons	513 TWh	513 TWh	513 TWh	513 TWh
Percent of Annual Technical Potential	17.5%	1.4%	0.2%	20.5%	2.1%
Percent Increase in 2040 Resource Consumption to Produce 10 MMT of Hydrogen					
Reference Case	44%	134%	94%	167%	916%
Low Oil and Gas Resource and Technology Case	42%	91%	58%	165%	884%

[a] Resource consumption values are from the *Reference Case* and *Low Oil and Gas Resource and Technology* scenario from the Annual Energy Outlook 2019 (EIA 2019 *Renewable Energy Consumption by Sector and Source* table 17). Conversion to TWh is based on EIA average fossil fuel heat rates for electricity generation (EIA 2019f). Biomass consumption converted from quads to million short tons assuming 8,500 Btu/lb (HHV) (Lopez et al. 2012).

Technical Hydrogen Production Potential from Renewable Resources

Resource	Resource Potential			Hydrogen Production Potential	
Renewable	**Annual Physical Resource**		**Quads/yr**	**Annual Hydrogen Potential**	**Quads H2/yr**
Biomass	800	Million tons eq./yr	12	50 MMT H2/yr	7
Wind	37,800	TWh electricity/yr	400	700 MMT H2/yr	100
Solar	261,800	TWh electricity/yr	2,400	5,100 MMT H2/yr	700
Hydropower (conventional)	690	TWh electricity/yr	6	14 MMT H2/yr	2
Water Power (including MHK)	2,500	TWh electricity/yr	20	50 MMT H2/yr	7
Geothermal (conventional)	180	TWh electricity/yr	2	4 MMT H2/yr	1
Geothermal (including EGS)	24,800	TWh electricity/yr	230	480 MMT H2/yr	60

Notes: Conversions to quads are on a higher heating basis; EIA fossil fuel heat rate of 9,268 Btu/kWh (for 2017) is used to calculate quads of physical resource for wind, solar, water power, and geothermal (this does not impact hydrogen potential). Sums are rounded. The technical potential of conventional hydropower represents existing hydropower assets, non-powered dams, and new stream-reach development, but does not include marine hydrokinetic power. The technical potential of conventional geothermal represents identified and undiscovered hydrothermal, but not enhanced geothermal systems.

- Enhanced geothermal systems (EGS) increases the resource potential by >100x
- Solar energy offers the highest hydrogen production potential: >5,000 MMT/yr
- **Combined renewable hydrogen production potential is over 6,500 MMT/yr**

Biomass Technical Potential

The biomass technical potential relies on the following two data sets:

1. **Solid biomass** from the Billion-Ton Report (2016): non-waste resources in 2040 base-case scenario estimated at ~680 million dry tons
   - Converts to 47 MMT of hydrogen per year
2. **Gaseous biomass** from NREL analysis (Milbrandt et al. 2018; Saur and Milbrandt 2014): gaseous biomass estimated at about 11 million tons of CH_4
   - Converts to 2.8 MMT of hydrogen per year

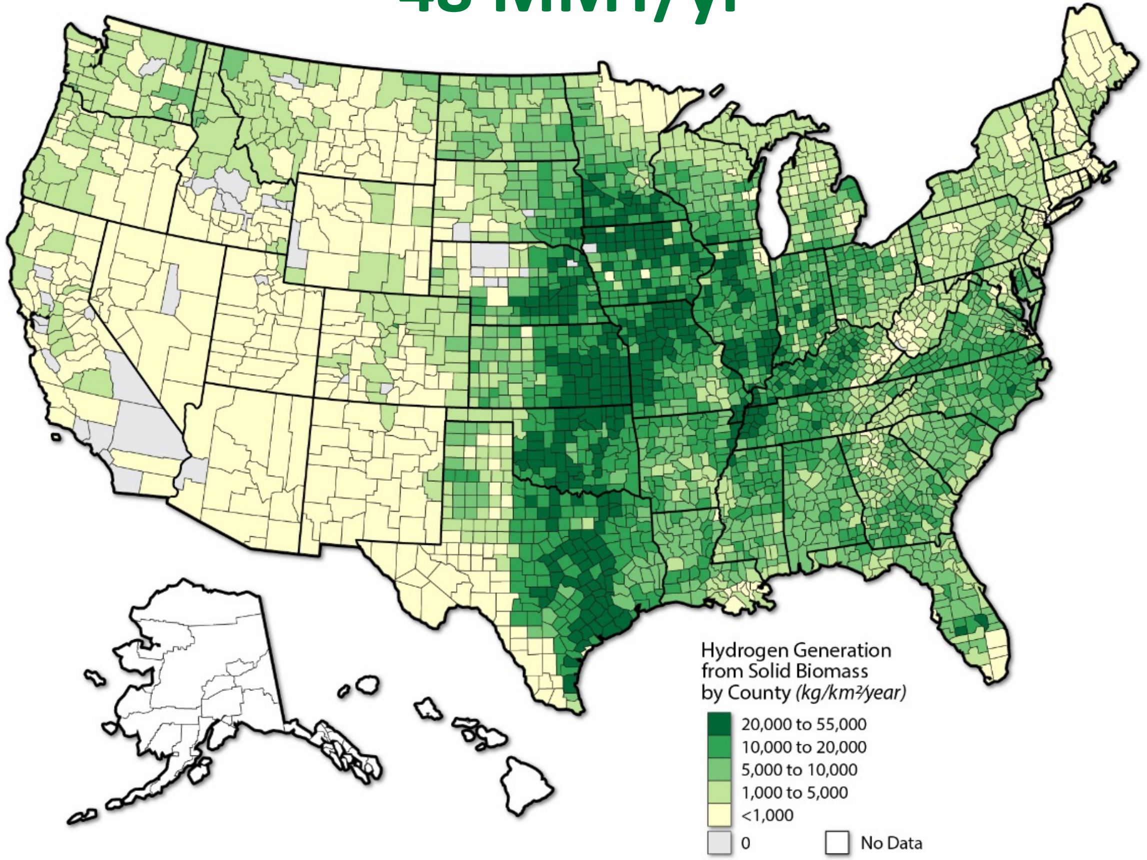
Biomass Feedstocks

BTS 2016	
Forestry Resources	**Energy Crops**
Logging Residues	Switchgrass
Thinnings	Miscanthus
Other Removals	Biomass Sorghum
Whole Trees	Energy Cane
Agricultural Residues	Coppice Wood
Corn Stover	Noncoppice wood
Wheat Straw	
Oats Straw	
Barley Straw	
Sorgham Stubble	

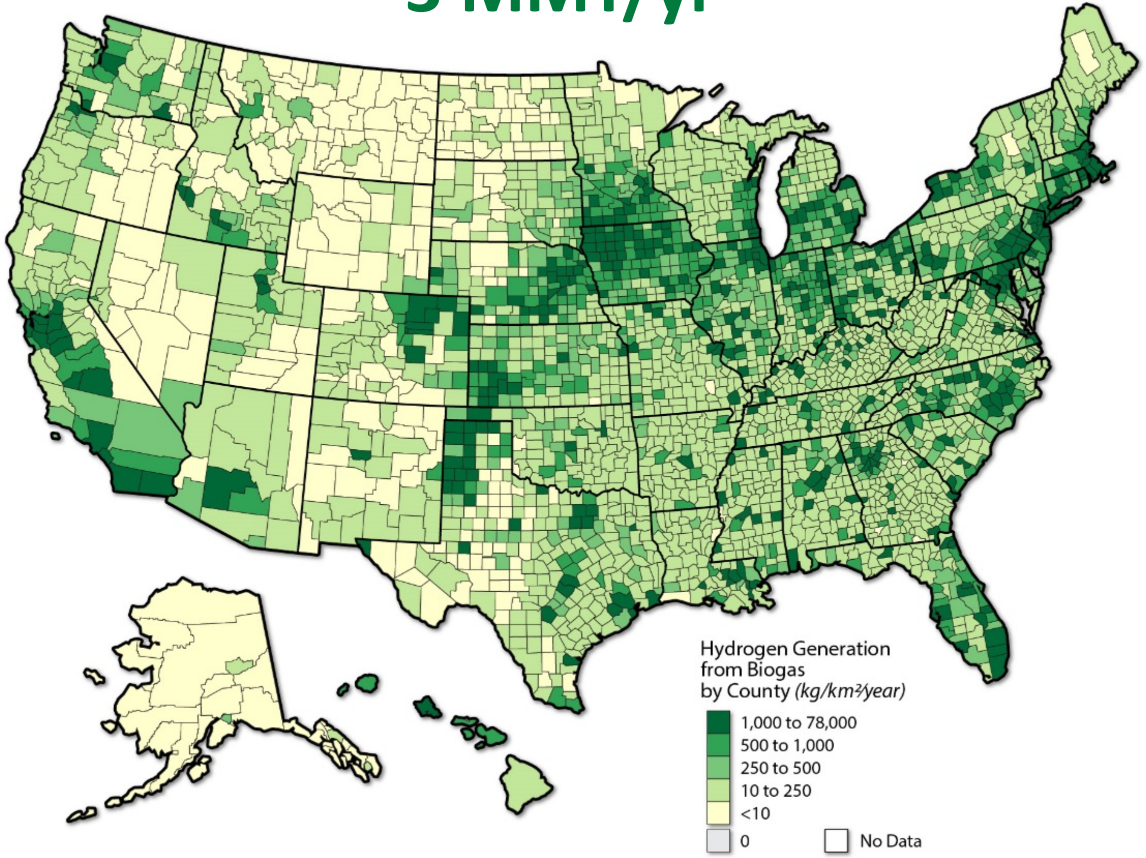
Milbrandt et al. (2018) Wet Waste
Wastewater Sludge
Animal Manure
Food Waste
Fats, Oils, and Greases

Maps of Hydrogen Potential from Biomass

H_2 production potential from solid biomass resources: 48 MMT/yr



H_2 production potential from gaseous biomass resources: 3 MMT/yr



Wind Potential

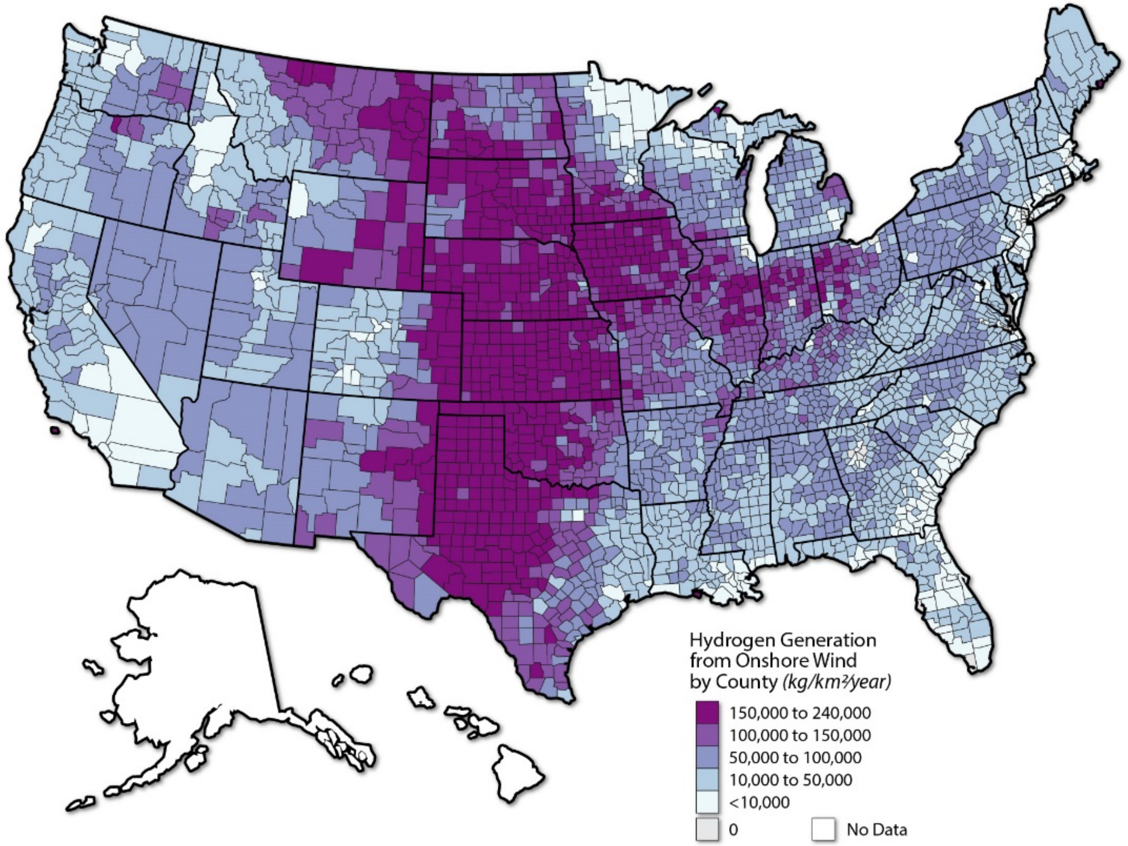
- **Offshore wind** technical potential (Musial et al. 2016): 7,203 TWh/yr
- **Land-based wind** technical potential (reV Model: Maclaurin et al. 2019): 30,564 TWh/yr

⇒ Wind resource technical potential: **~38,000 TWh/yr**

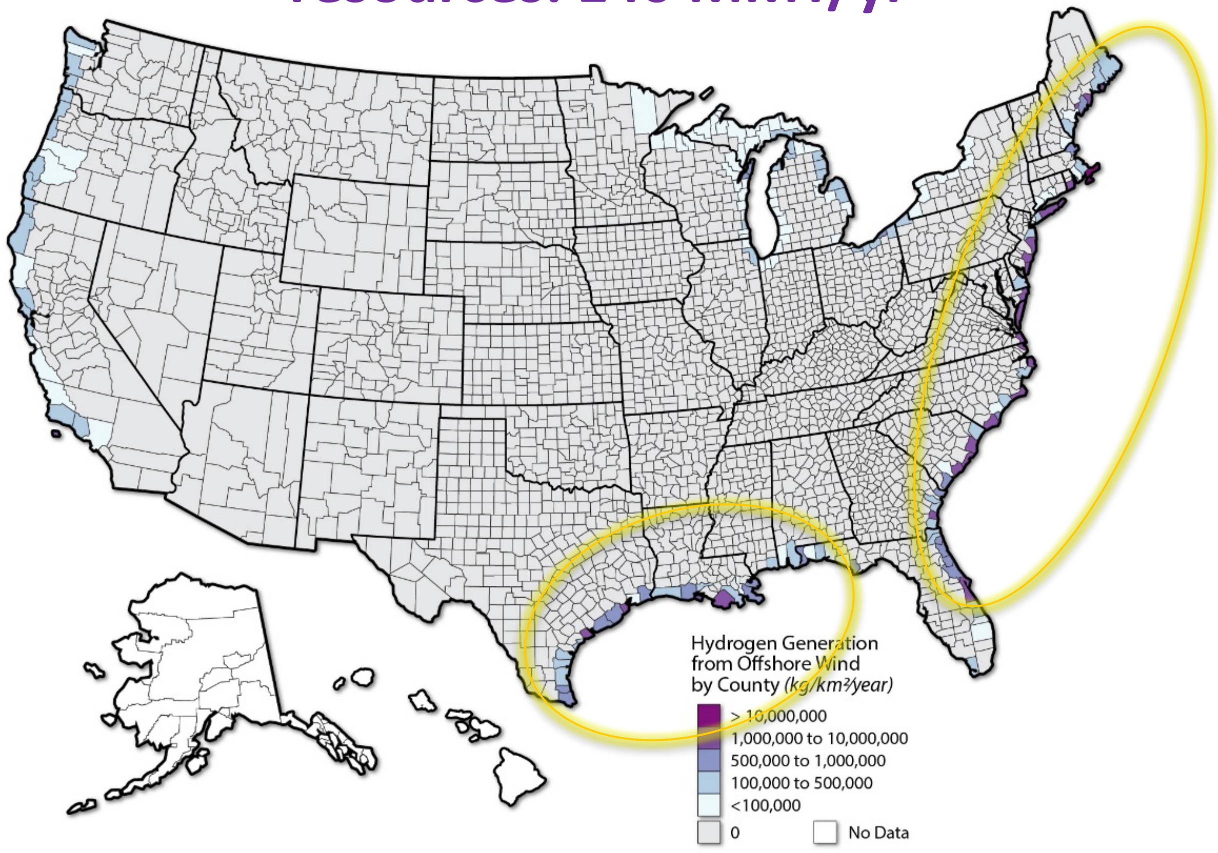
- Both offshore and land-based technical potentials are expected to be updated in 2020

Maps Hydrogen Potential from Wind Resources

H_2 production potential from land-based wind resources: 600 MMT/yr



H_2 production potential from offshore wind resources: 140 MMT/yr



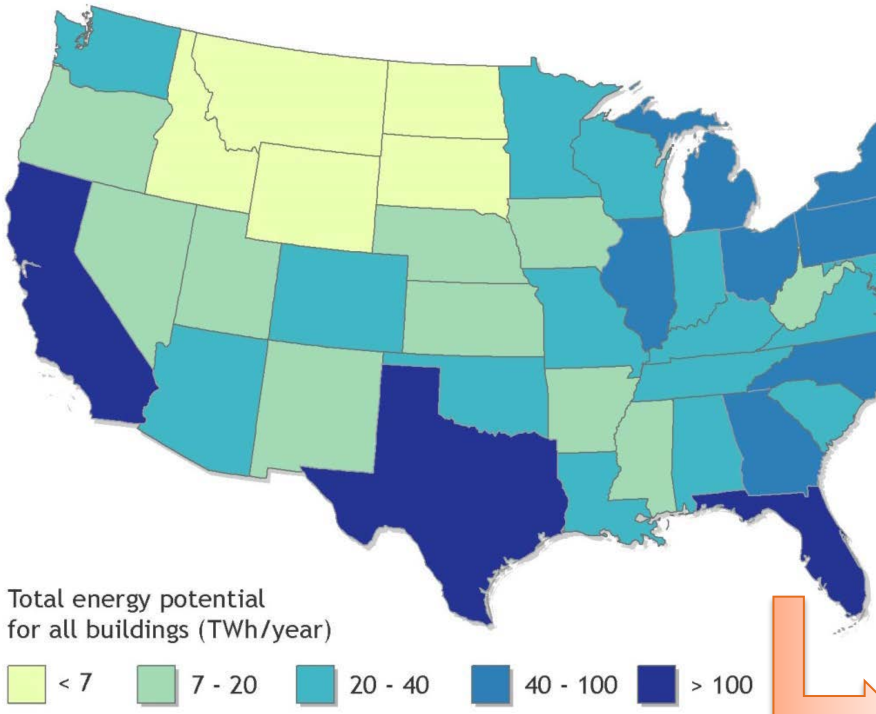
Hawaii not included in map – represents ~100 TWh/yr (or 2 MMT H_2/yr)

Solar Potential

- **Rooftop PV** technical potential (Gagnon et al., 2016): 1,432 TWh/yr
- **Utility-scale PV** technical potential (reV Model: Maclaurin et al. 2019): ~184,000 TWh/yr
- **Concentrated solar power (CSP)** technical potential (Murphy et al. 2019): 17,000 GW converting to ~76,000 TWh/yr

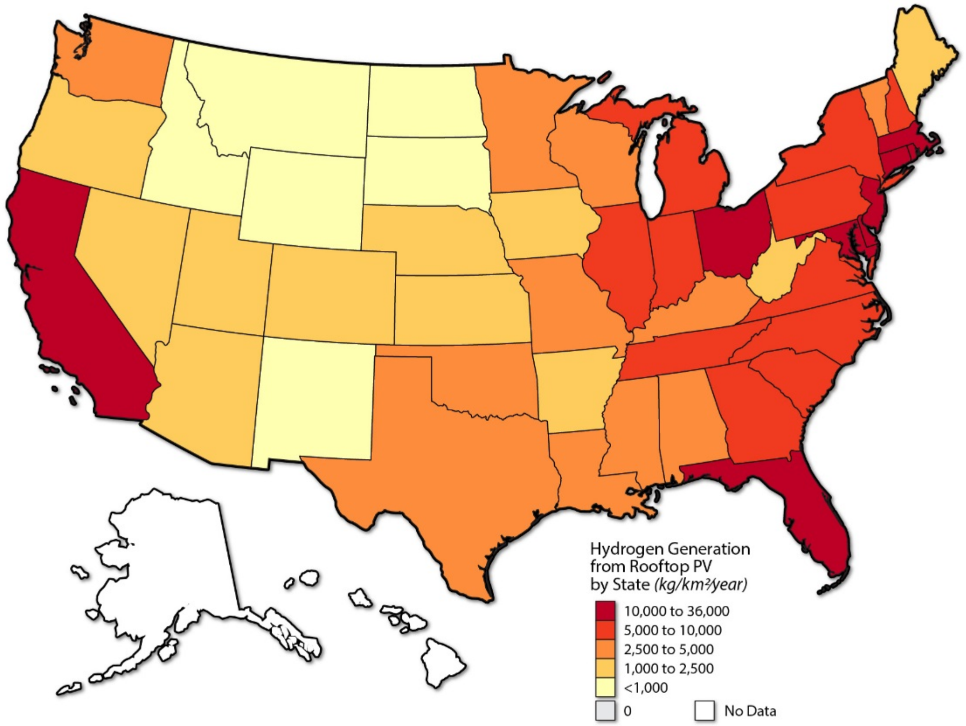
⇒ Solar resource technical potential: **~261,000 TWh/yr**

Map of Hydrogen Potential from Rooftop PV by State



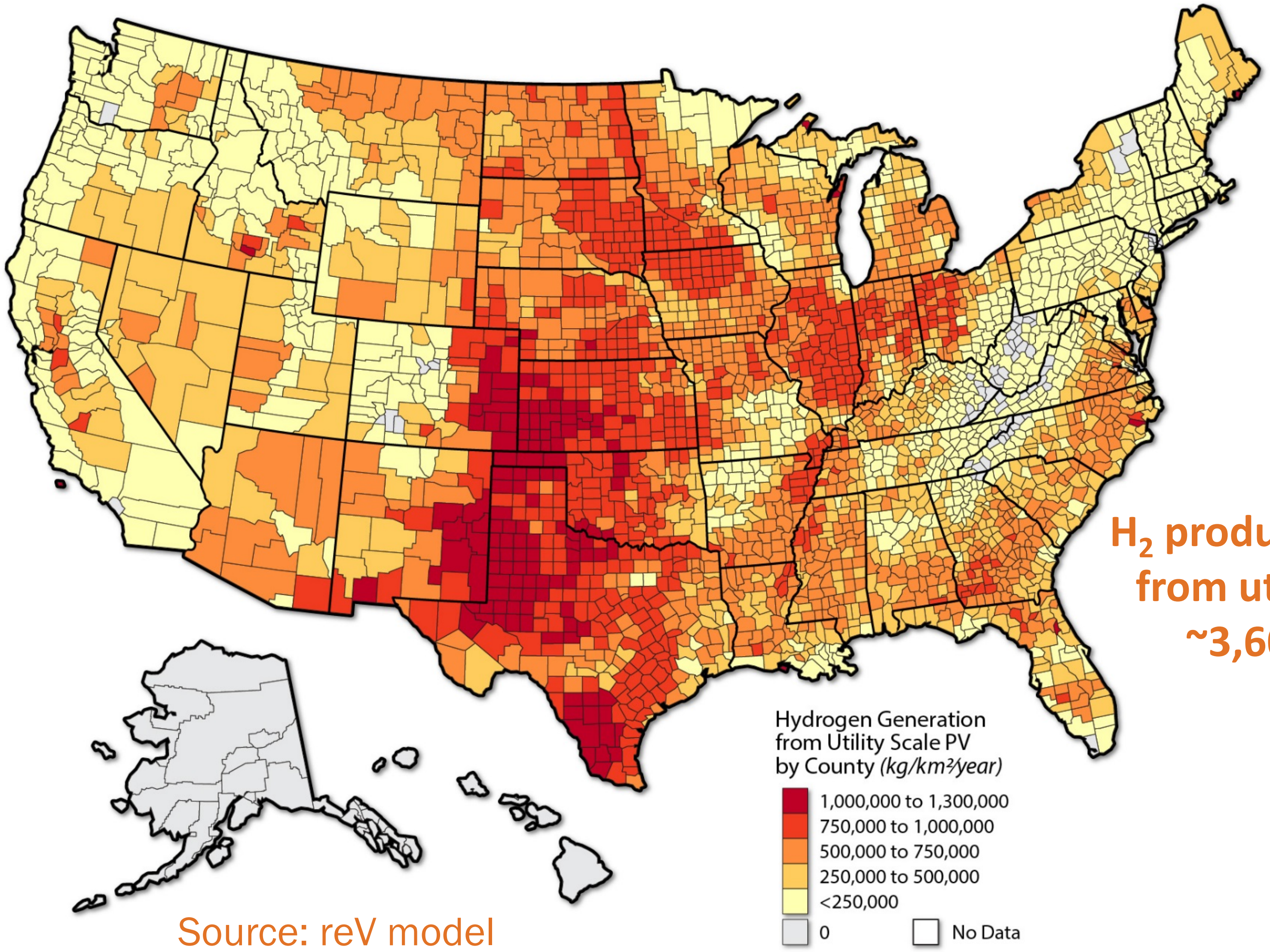
Estimated National PV Technical Potential for All Buildings from Gagnon et al. (2016)

H_2 production potential from rooftop PV: 38 MMT/yr



Hydrogen potential normalized by area

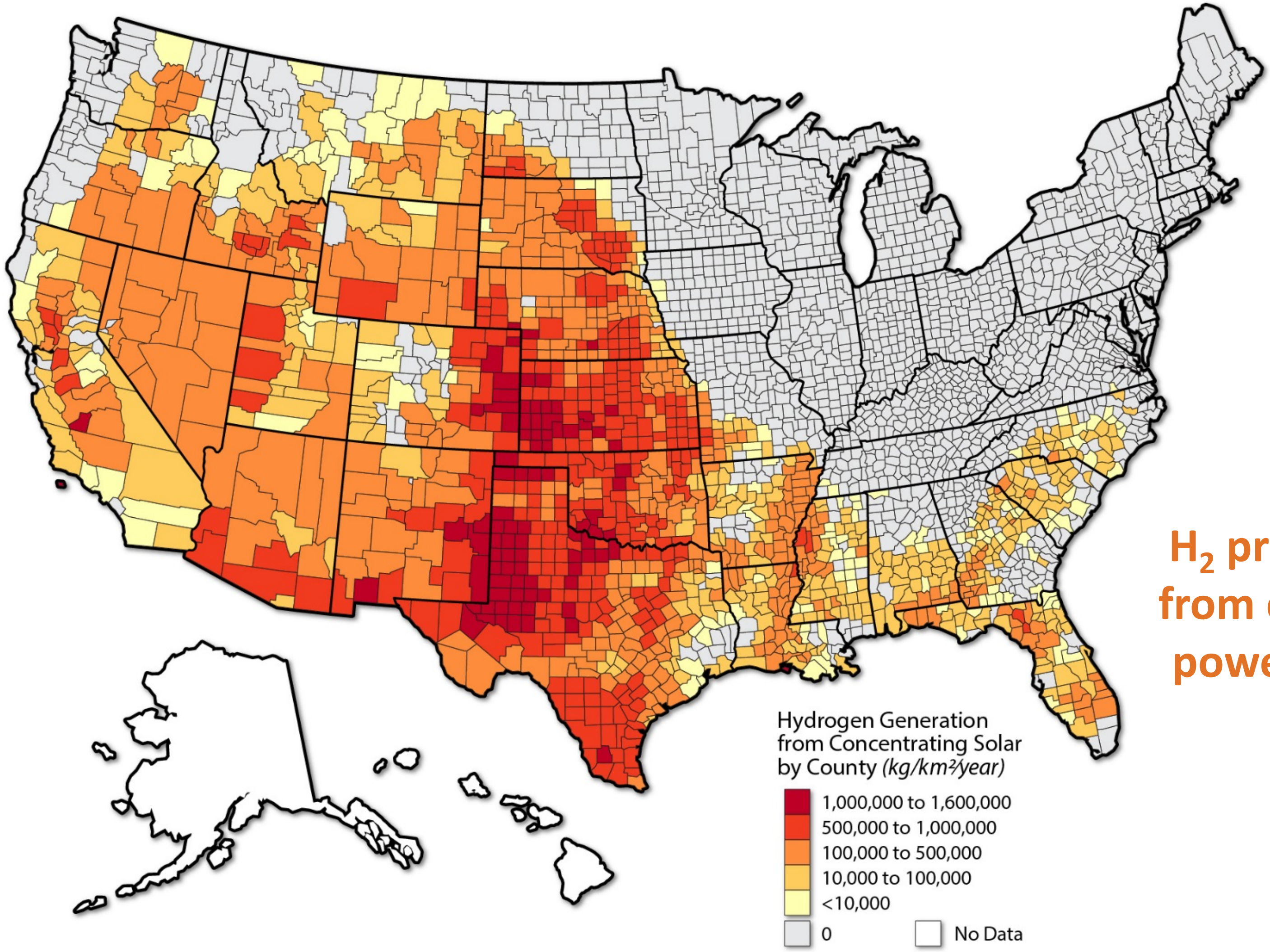
Map of Hydrogen Potential from Utility-Scale PV



H_2 production potential from utility-scale PV: ~3,600 MMT/yr

Source: reV model

Map of Hydrogen Potential from CSP



H_2 production potential from concentrating solar power: ~1,500 MMT/yr

Source: Murphy et al. (2019). "The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets." National Renewable Energy Laboratory

Water Power Potential

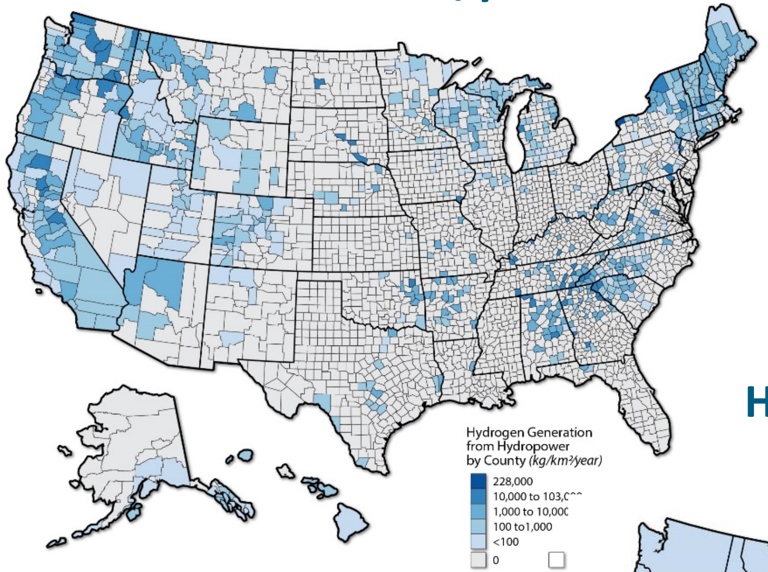
- Current (2017) capacity and generation of **existing hydropower assets** (EIA 2019; Johnson et al. 2019): 79 GW and ~300 TWh/yr
- **Non-powered dams (NPD)** technical potential (Hadjerioua et al., 2012): 45 TWh/yr
- **New stream-reach development (NSD)** technical potential (Kao et al., 2014): 347 TWh/yr
- **Marine Hydrokinetic (MHK)** technical potential (Table 4.N.2, QTR, 2015): relatively new technology that could increase energy production potential, but is relatively uncertain

MHK Resource	Technical Resource (TWh/yr)	
	Total US	*Continental US*
Wave Energy	898–1,229	378–472
Tidal Current Energy	222–334	15–22
Ocean Current Energy	45–163	45–163
River Current Energy	120	100
TOTAL	1,285–1,846	538–757

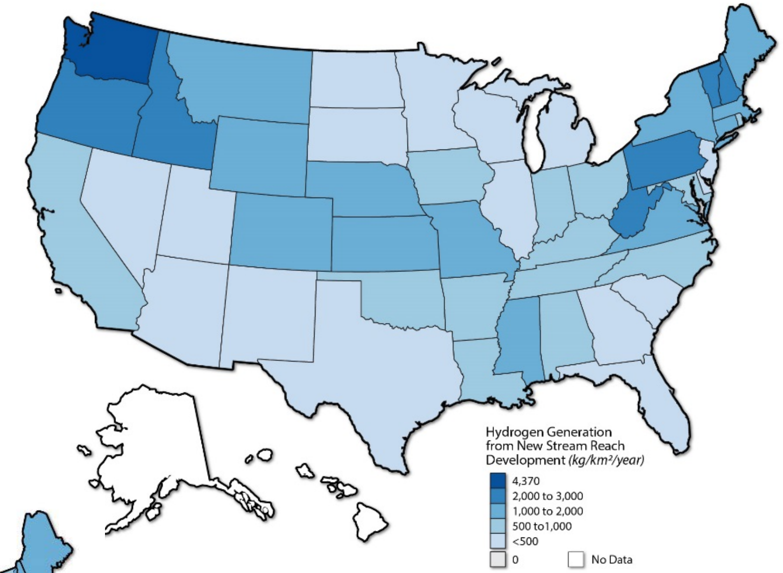
Water power resource technical potential:
~690 TWh/yr (excl. MHK) to 2,500 TWh/yr (incl. MHK)

Maps of Hydrogen Production Potential from Hydropower

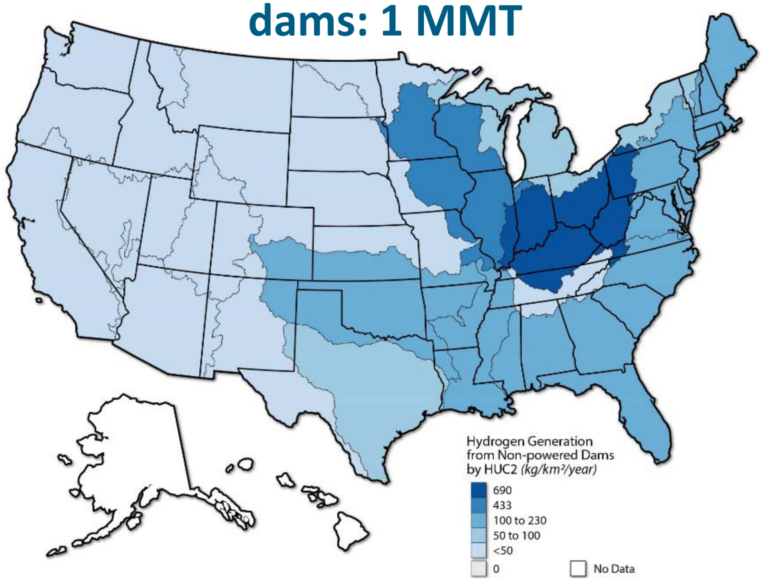
H_2 production potential from existing hydropower assets: 5.8 MMT/yr



H_2 production potential from new stream-reach development: 6.8 MMT/yr



H_2 production potential from non-powered dams: 1 MMT



Total Hydrogen Production Potential (from conventional hydropower):
15 MMT/yr
to
50 MMT/yr
(including MHK)

Geothermal Potential

- Technical potential based on BAU scenario of geothermal resource capacity (Table 4, Augustine et al., 2019)
- Capacity factor of 90% for flash plants, 80% for binary

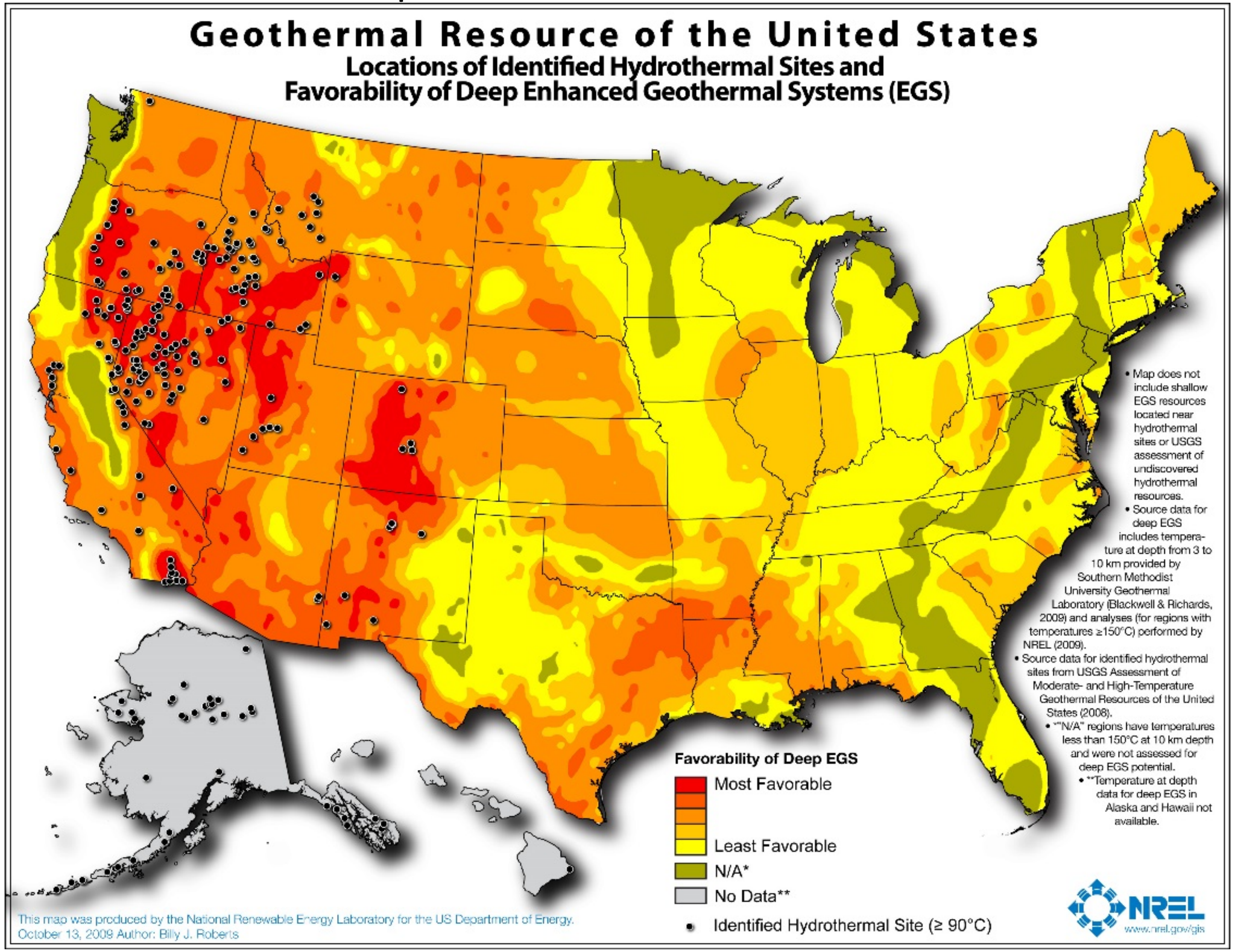
	Flash	Binary
Hydrothermal	64.2%	35.8%
NF EGS	56.9%	43.1%
Deep EGS	32.9%	67.1%

Geothermal Resources	BAU Scenario Availability (MW_e)	Estimated Power Generation Potential (TWh/yr)	Estimated Hydrogen Production Potential (MMT/yr)
Identified Hydrothermal	5,078	38	0.7
Undiscovered Hydrothermal	18,830	143	2.8
Near Field Enhanced Geothermal System	1,382	10	0.2
Deep Enhanced Geothermal System	3,375,275	24,628	480.1
TOTAL	**3,400,565**	**24,819**	**483.8**

Hydrogen production potential from geothermal is
~3.5 (excluding EGS) to >480 MMT/yr

Geothermal Maps

2009 Map of Geothermal Resources



Map not included in report

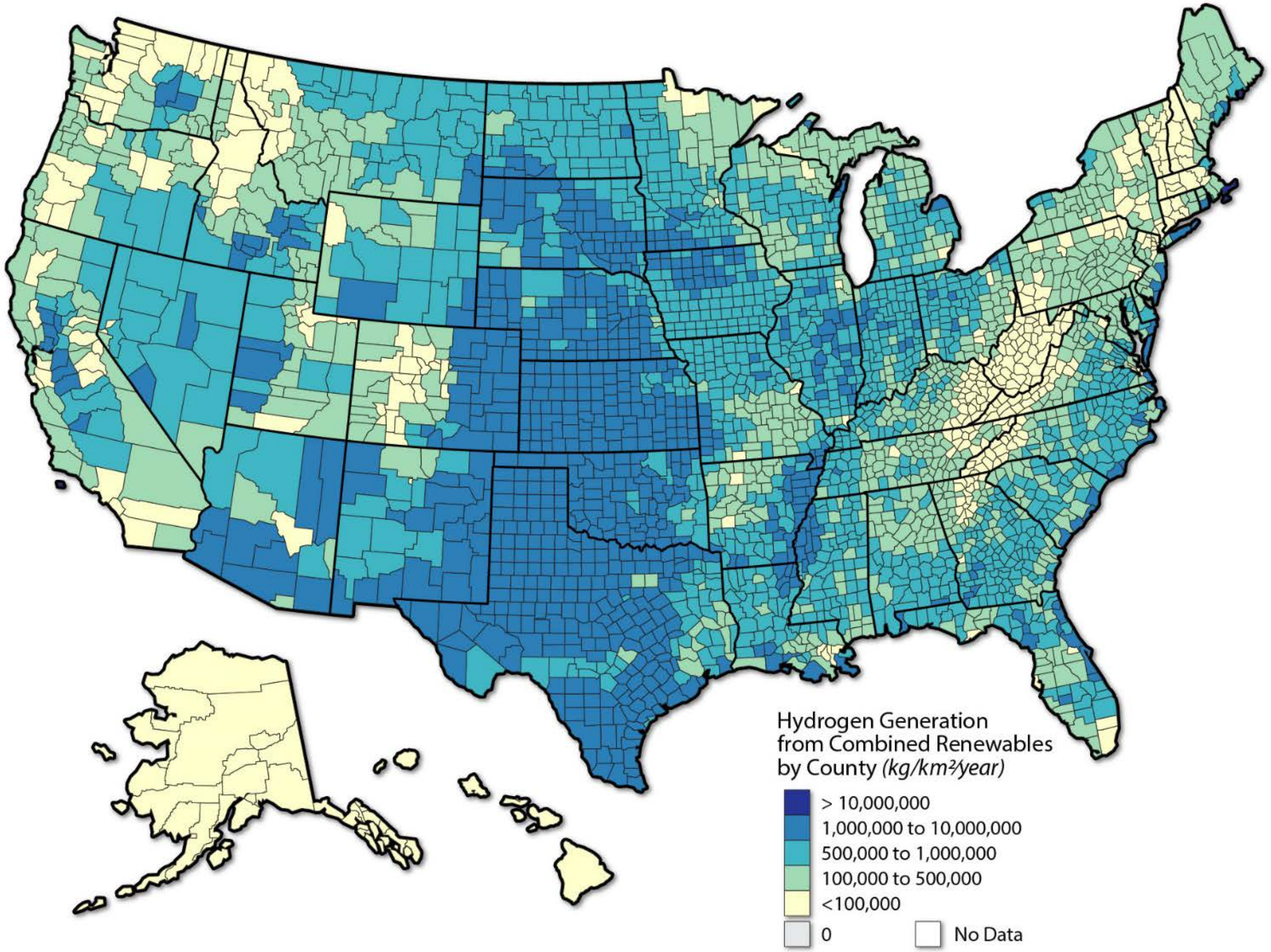
Combined Renewable Technical Potential Map

Map includes only the renewable resources for which county-level data was available:

- **Biomass**
- **Wind**
- **Solar (CSP and UPV)**
- **Hydro (EHA)**

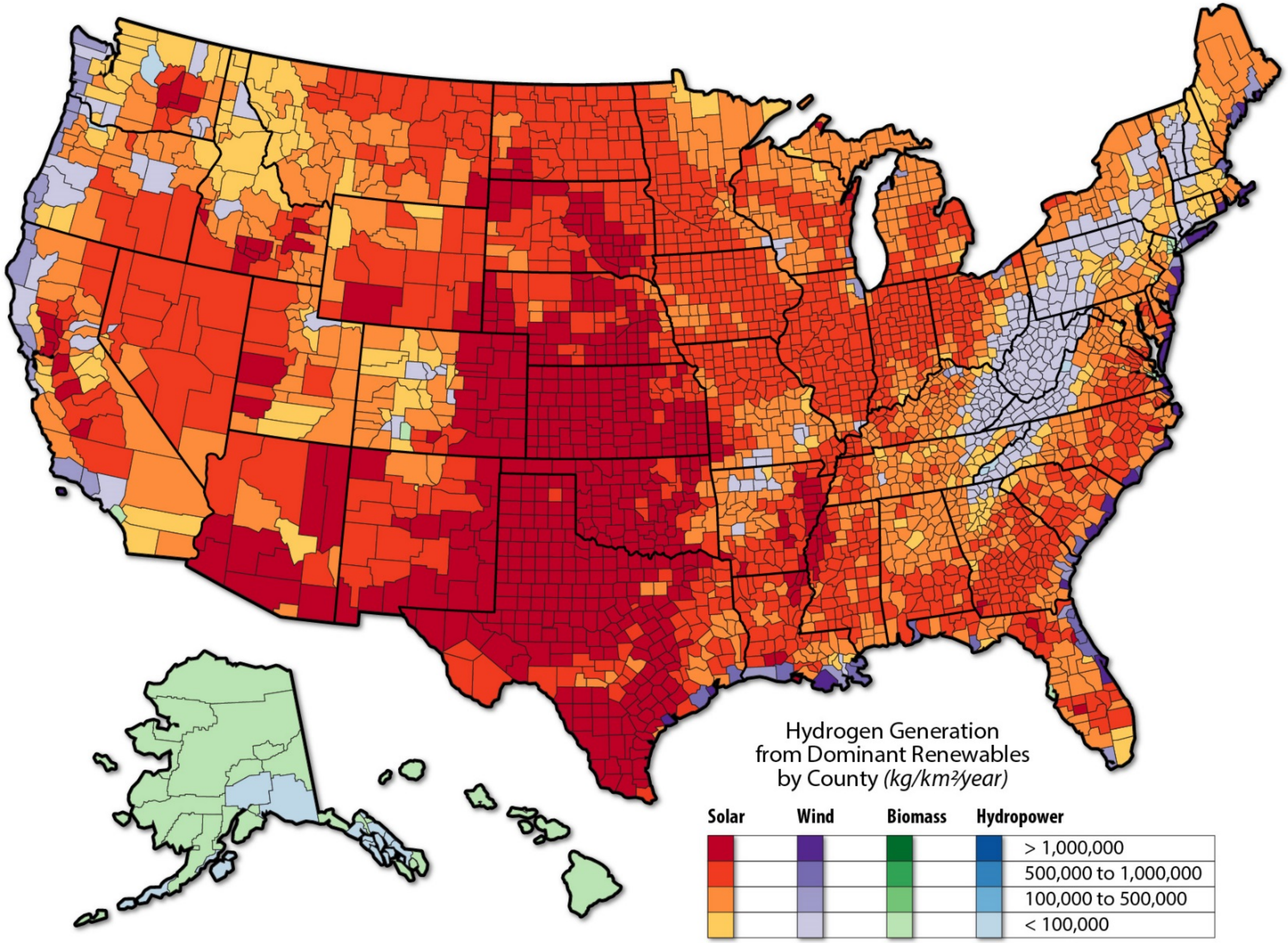
DOES NOT INCLUDE:

- Solid biomass for AK or HI
- Offshore wind for HI
- Rooftop PV
- Non-powered dams, new stream-reach development, or marine hydrokinetics
- Geothermal



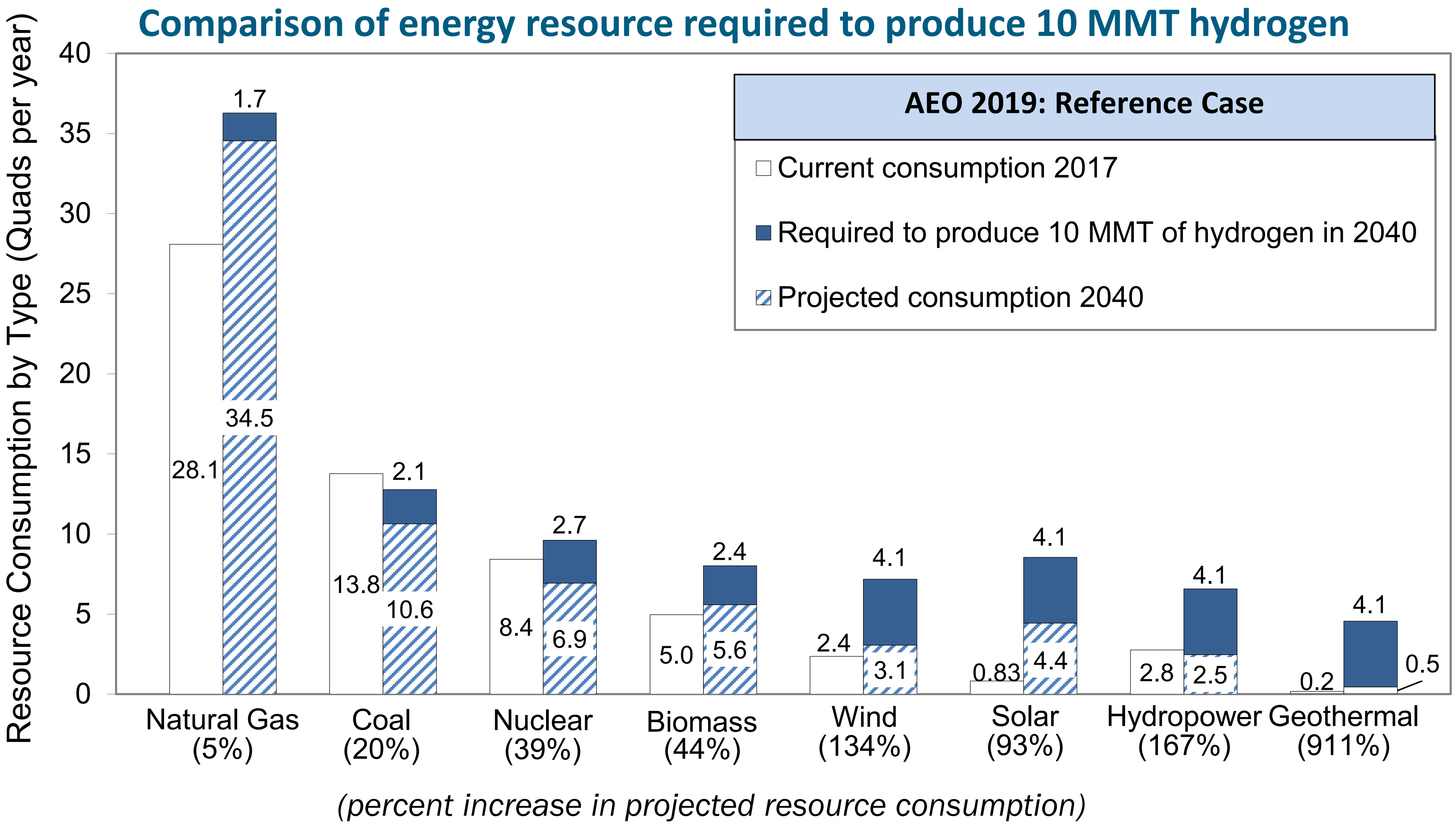
Map shows **5,900 MMT** (90%) of hydrogen production potential, out of an estimated total technical potential from renewable resources of ~**6,500 MMT**

Revision of Map of Dominant Renewable Resource Potential



Resource	Number of Counties as Dominant
Solar	2724
Wind	347
Biomass	65
Hydro	17

Comparison Across Energy Resources



Note: The demand for wind, solar, hydropower, and geothermal resources to produce 10 MMT of hydrogen is 513 TWh, which is converted to quads using the EIA fossil fuel heat rate of 8,017 Btu/kWhe in 2040, to enable comparison with the EIA projected resource consumption estimates. As a result, the energy requirements for the low-temperature electrolysis pathways appear higher than coal and biomass gasification, despite having a higher conversion efficiency.

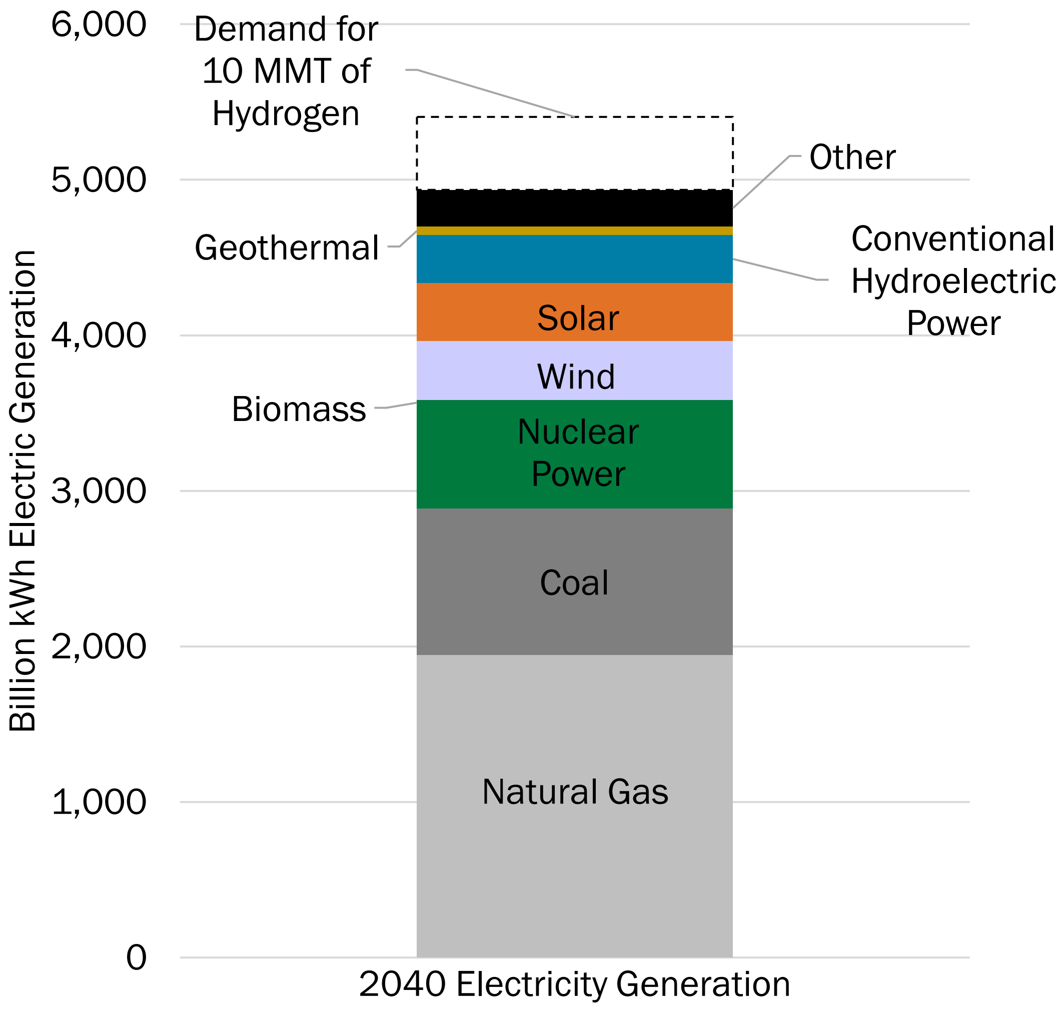
Contextualized with Projected Electricity Generation

- For electricity LTE, 513 TWh will be required to meet demand of 10 MMT H_2 in 2040
- Total projected net electricity generation: 4,936 TWh

Demand for 10 MMT of electrolytic hydrogen would result in a **10% increase** in electricity generation in 2040

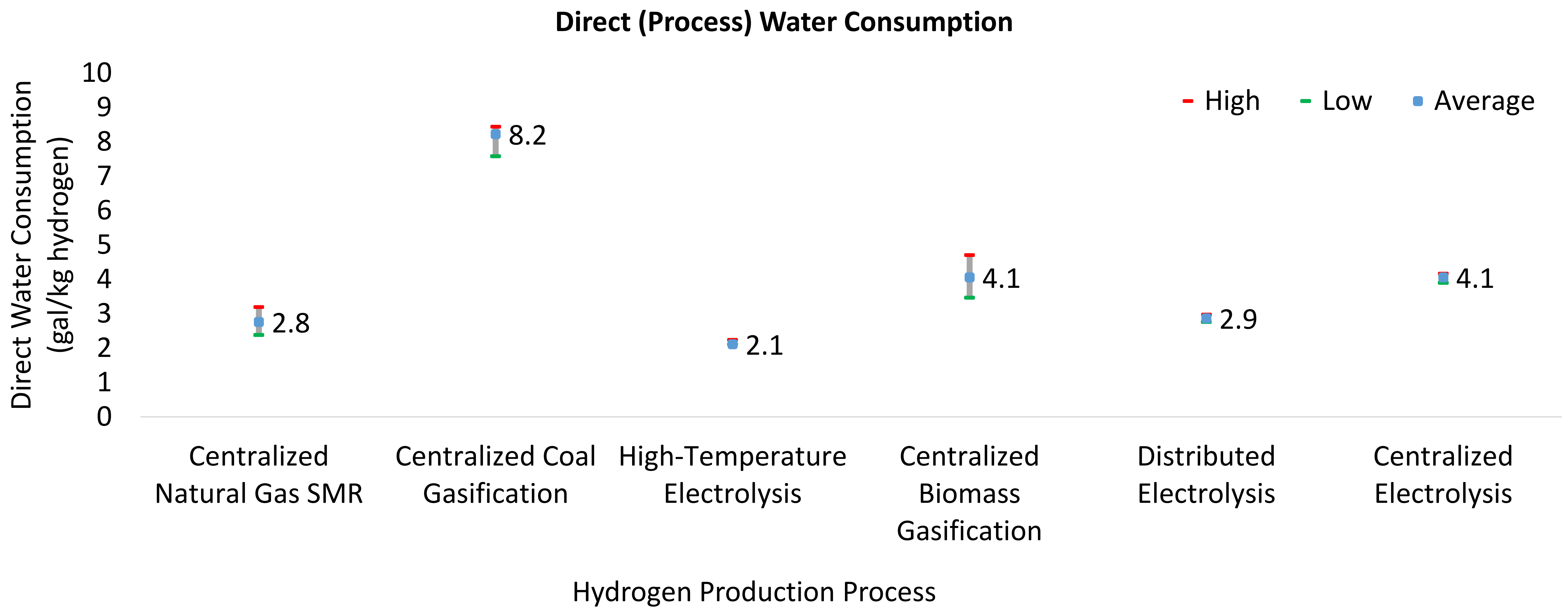
- Projected renewable electricity generation: 1,356 TWh

Producing 10 MMT of electrolytic hydrogen from renewables would increase projected renewable power generation by 38%

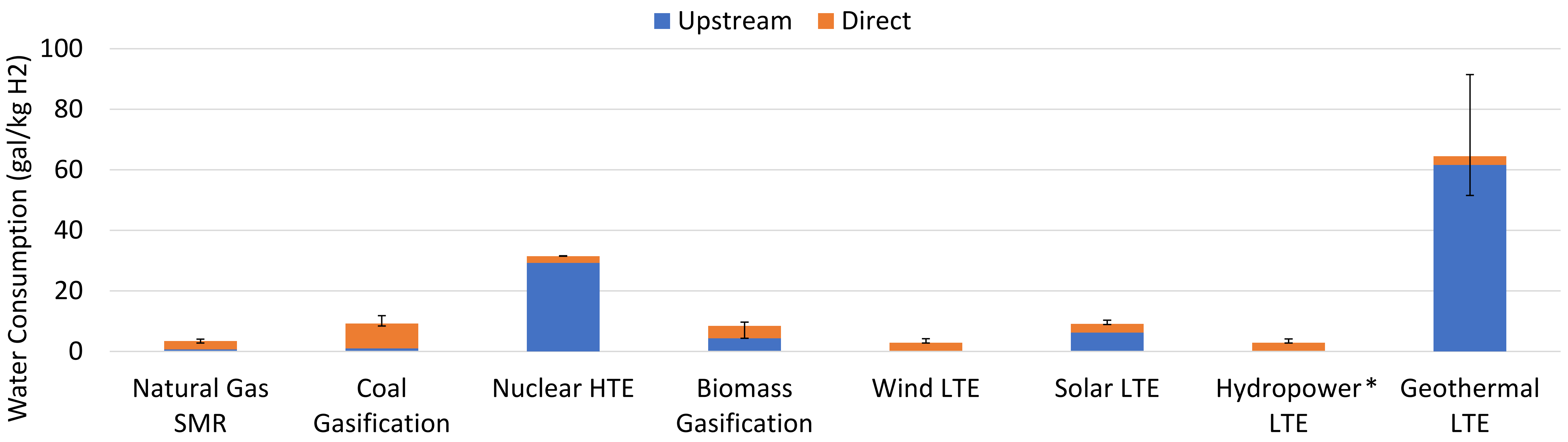


Water Consumption by Technology

Based on ANL's GREET model and EERE Program Record (#17005) on water consumption associated with hydrogen production for each pathway



Water Consumption by Technology (cont.)



* Note: upstream water consumption does not include evaporative losses, which can be significant for hydropower

- Comparison of water consumption requirement to produce 10 MMT hydrogen: approximately 29 billion gallons (if produced exclusively from wind or hydropower) to 645 billion gallons (if produced exclusively from geothermal) [based on average water consumption factors from the GREET model]
- Freshwater withdrawals in the US in 2015 was over 100 trillion gallons (Dieter et al. 2018) **-> water requirement to produce 10 MMT of hydrogen would range from <0.03% to 0.6% of the US freshwater withdrawals** [not considering displacement]

Future Work

- Upcoming H2@Scale analysis report will address **economic potential** of hydrogen production from domestic energy resources

- Resource potential estimates can be incorporated into the Scenario Evaluation and Regionalization Analysis (SERA) model (Bush et al. 2013) for cost-based **optimization of hydrogen supply chains considering geospatial resource constraints**

- Analysis addressing the geospatial **water availability constraints**

Acknowledgments

DOE Offices
Office of Fossil Energy
Office of Nuclear Energy
Bioenergy Technologies Office
Wind Energy Technologies Office
Solar Energy Technologies Office
Water Power Technologies Office
Geothermal Technologies Office

National Laboratories
National Energy Technology Laboratory
Idaho National Laboratory
National Renewable Energy Laboratory
Oak Ridge National Laboratory
Argonne National Laboratory

This work was funded by the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy

Report will soon be available online: https://www.nrel.gov/research/publications.html

For more information on H2@Scale: www.energy.gov/eere/fuelcells/h2-scale

Backup Slides

Co-Authors & Reviewers

Co-Authors

- Michael Penev (NREL) – H2A model developer; author on 2013 Report
- Anelia Milbrandt (NREL) –Biomass resource expert
- Nick Gilroy & Billy Roberts (NREL) – GIS expert, reV modeling of solar
- Marc Melaina (previously NREL) – Hydrogen expert, author on 2013 Report

Reviewers

- Tom O’Connor (NE), Richard Boardman (INL), Jim O’Brien (INL)
- Zia Haq (BETO)
- Christopher Munson and Peter Balash (NETL)
- Chad Hunter (NREL), Mark Ruth (NREL), Tim Brown (First Element), Manussawee Sukunta (U.S. EIA), Michael Scott (U.S. EIA), and Susan Schoenung (Longitude 122 West)

References

- Argonne National Laboratory (2019). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model v 2019. https://greet.es.anl.gov/index.php
- Augustine, Ho, and Blair (2019). "GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration." National Renewable Energy Laboratory https://www.nrel.gov/docs/fy19osti/71833.pdf
- DOE. (2015). "Quadrennial Technology Review 2015." Chapter TA 4.N: Marine and Hydrokinetic Power. https://www.energy.gov/sites/prod/files/2015/12/f27/QTR2015-4N-Marine-and-Hydrokinetic-Power.pdf
- EIA (2019). "Annual Energy Outlook 2019" https://www.eia.gov/outlooks/archive/aeo19/
- Gagnon et al. (2016). "Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment." National Renewable Energy Laboratory https://www.nrel.gov/docs/fy16osti/65298.pdf
- Hadjerioua, Wei, and Kao (2012). "An Assessment of Energy Potential at Non-Powered Dams in the United States." Oakridge National Laboratory https://hydrosource.ornl.gov/sites/default/files/NHAAP_NPD_FY11_Final_Report.pdf
- Han, J. and Elgowainy, A. (2017). "Water Consumption for Light-Duty Vehicles' Transportation Fuels." Program Record 17005. https://www.hydrogen.energy.gov/pdfs/17005_water_consumption_ldv_fuels.pdf
- Johnson et al. (2019). "Existing Hydropower Assets." HydroSource. Oak Ridge National Laboratory, Oak Ridge, TN. https://hydrosource.ornl.gov/market-info-and-data/existing-hydropower-assets
- Kao et al. (2014). "New Stream-reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States." Oakridge National Laboratory https://hydrosource.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf
- Lee et al. (2017) "Regional water consumption for hydro and thermal electricity generation in the United States." *Applied Energy* http://dx.doi.org/10.1016/j.apenergy.2017.05.025
- Lopez et al. (2012). "U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis." National Renewable Energy Laboratory https://www.nrel.gov/docs/fy12osti/51946.pdf
- Maclaurin et al. (2019). "The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling". National Renewable Energy Laboratory https://www.nrel.gov/docs/fy19osti/73067.pdf
- Milbrandt, A., Seiple, T., Heimiller, D., Skaggs, R., Coleman, A., 2018. Wet waste-to-energy resources in the United States. *Resources, Conservation and Recycling* 137, 32–47. https://www.sciencedirect.com/science/article/pii/S0921344918301988
- Murphy, Sun, col, Maclaurin, Turchi, Mehos (2019). "The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets." National Renewable Energy Laboratory https://www.nrel.gov/docs/fy19osti/71912.pdf
- Musial, Heimiller, Beiter, Scott, and Draxl (2016). "2016 Offshore Wind Energy Resource Assessment for the United States." National Renewable Energy Laboratory https://www.nrel.gov/docs/fy16osti/66599.pdf
- National Energy Technology Laboratory (NETL). (2010). Assessment of Hydrogen Production with CO_2 Capture – Volume 1: Baseline State-of-the-Art Plants. DOE/NETL-2010/1434. http://www.canadiancleanpowercoalition.com/pdf/SMR9%20-%20H2_Prod_Vol1_2010.pdf
- Saur, G. and Milbrandt, A. "Renewable Hydrogen Potential from Biogas in the United States". NREL. July 2014. NREL/TP-5400-60283.https://www.nrel.gov/docs/fy14osti/60283.pdf
- US DOE (2015). "Quadrennial Technology Review 2015." Chapter TA 4.N: Marine and Hydrokinetic Power. https://www.energy.gov/sites/prod/files/2015/12/f27/QTR2015-4N-Marine-and-Hydrokinetic-Power.pdf

Conversion Assumptions

Metric	Value	Units	Source
Coal (Bituminous)			
Required coal	8.6	kg coal/kg hydrogen	NETL (2010) Case 2.2
Coal energy content	22.6	MMBtu/ton (HHV)	GREET (2018)
Natural Gas			
Required natural gas	156,000	Btu natural gas/kg hydrogen	H2A Future Case Study
Gas Btu content	1,036	Btu per scf (HHV)	March 2020 Monthly Energy Review (EIA 2020b)
Solid Biomass			
Required biomass	13.0	kg biomass/kg hydrogen	H2A Future Case Study
Biomass energy content	18.6	MJ/kg biomass (LHV)	H2A Conversion Factor, (Biomass MYPP Feedstock)
	19.7	MJ/kg biomass (HHV)	Lopez et al. (2012)
Biomethane			
Required biomethane	3.29	kg biomethane/kg hydrogen	Saur and Milbrandt (2014)
Biomethane energy content	50.0	MJ/kg biomethane (LHV)	Saur and Milbrandt (2014)
	56.4	MJ/kg biomethane (HHV)	Lopez et al. (2012)
Wind, Solar, Hydro, and Geothermal Power			
System electricity requirement	51.3	kWh/kg hydrogen	H2A Future Case Study
Nuclear Power			
High temperature electrolysis	50.2%	Thermal conversion	O’Brien (2017)
Uranium use	$4.62*10^{-5}$	kg uranium per kg hydrogen	O’Brien (2017)

Changes in Uranium Technical Potential

Independent Statistics & Analysis

U.S. Energy Information Administration

2015 Domestic Uranium Production Report

May 2016

The uranium reserve estimates presented here cannot be compared with the much larger historical data set of uranium reserves published in the July 2010 report *U.S. Uranium Reserves Estimates*. Those reserve estimates were made by EIA based on data collected by EIA and data developed by the National Uranium Resource Evaluation (NURE) program, operated out of Grand Junction, Colorado, by DOE and predecessor organizations. The EIA data covered approximately 200 uranium properties with reserve estimates, collected from 1984 through 2002. The NURE data covered approximately 800 uranium properties with reserve estimates, developed from 1974 through 1983. Although the data collected by the Form EIA-851A survey covers a much smaller set of properties than the earlier EIA data and NURE data, EIA believes that within its scope the EIA-851A data provides more reliable estimates of the uranium recoverable at the specified forward cost than estimates derived from 1974 through 2002. In particular, this is because the NURE data has not been comprehensively updated in many years and is no longer a current data source.

EIA Note on Fossil Fuel Heat Rates

Average Fossil Fuel Heat Rates for Electricity Generation

Release date: January 29, 2019

The fossil fuel heat rate is used as the thermal conversion factor for electricity generation from noncombustible renewable energy (hydro, geothermal, solar thermal, solar photovoltaic, and wind) to estimate the amount of fossil fuels replaced by these renewable sources. EIA uses this data to report the primary energy content of generation from noncombustible renewable energy. EIA does not collect data on the heat or energy input into noncombustible renewable generators because this information is not something that plant operators would typically know, and it has little use in electric power markets.

The displaced fossil fuel energy for each unit (e.g., kilowatthours) of electricity generated from noncombustible renewables varies over time and across cases within the AEO as the composition, operation, and efficiency of the fossil generation fleet changes over time in response to market and policy conditions. The primary energy content of renewables generation reported in EIA's *Annual Energy Outlook 2019* uses the average fossil fuel heat rates contained in the file on the right.

Reporting conventions for the primary energy content of renewables generation vary across sources, and different approaches may serve different analytic, policy, or statistical needs. Users who need renewable primary energy in terms of final energy consumed should multiply the annual generation (in kWh) for the wind, solar, hydro, or geothermal resource of interest by 3,412 Btu/kWh to obtain an estimate of primary energy consumption for renewables.