H_2 @Scale:

Energy System-Wide Benefits of Increased H_2 Implementation

Concept Overview & Preliminary Analysis

Mark Ruth

May 23, 2017
Houston, Texas

November 2016 Workshop Report available at
http://www.nrel.gov/docs/fy17osti/68244.pdf
H2@Scale webinar available at
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

NREL/PR-6A20-68629
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.

Energy System Challenges

- **Evolving multi-sector requirements**
  - Transportation
  - Industrial
  - Electricity

U.S. uses 3700 TWh electricity and 7.2 billion barrels oil annually

Air pollution causes 200,000 premature deaths annually in the U.S.

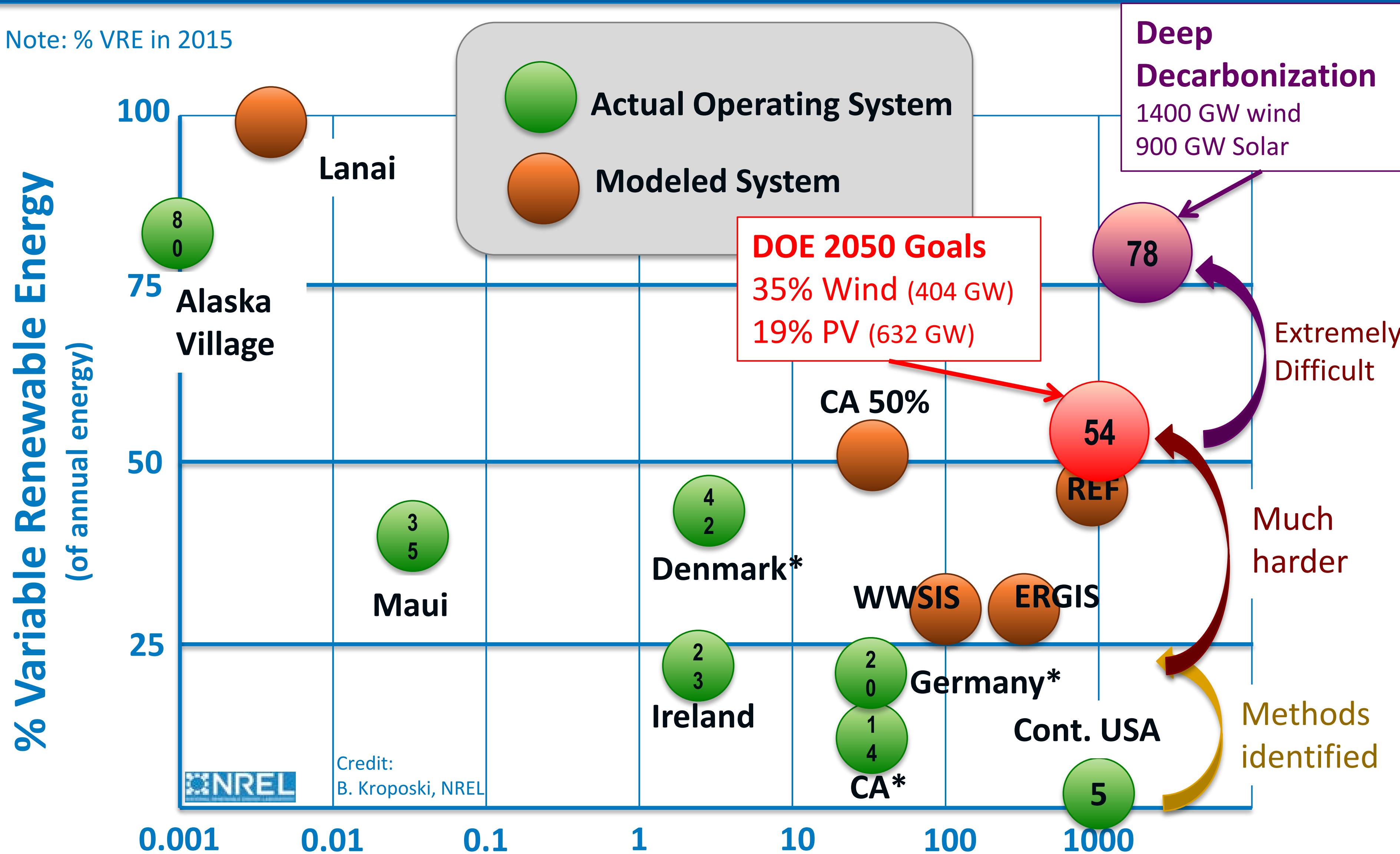
Over 6 million Americans work in the energy sector

U.S. oil Imports in 2016 > $100 billion

How do we supply all these services in the most beneficial manner?

Electricity Use: AEO 2016
Oil Use: https://www.eia.gov/tools/faqs/faq.php?id=33&t=6
Oil import costs: https://www.census.gov/foreign-trade/statistics/historical/petr.txt
Energy Sector Jobs: https://energy.gov/sites/prod/files/2017/01/f34/2017%20US%20Energy%20and%20Jobs%20Report_0.pdf
Air pollution deaths: Fabio Caiazzo, Akshay Ashok, Ian A. Waitz, Steve H.L. Yim, Steven R.H. Barrett, Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005, *Atmospheric Environment*, Volume 79, November 2013, Pages 198-208

Where is the Grid Headed? How Will It Get There?



* Part of a larger synchronous AC power system

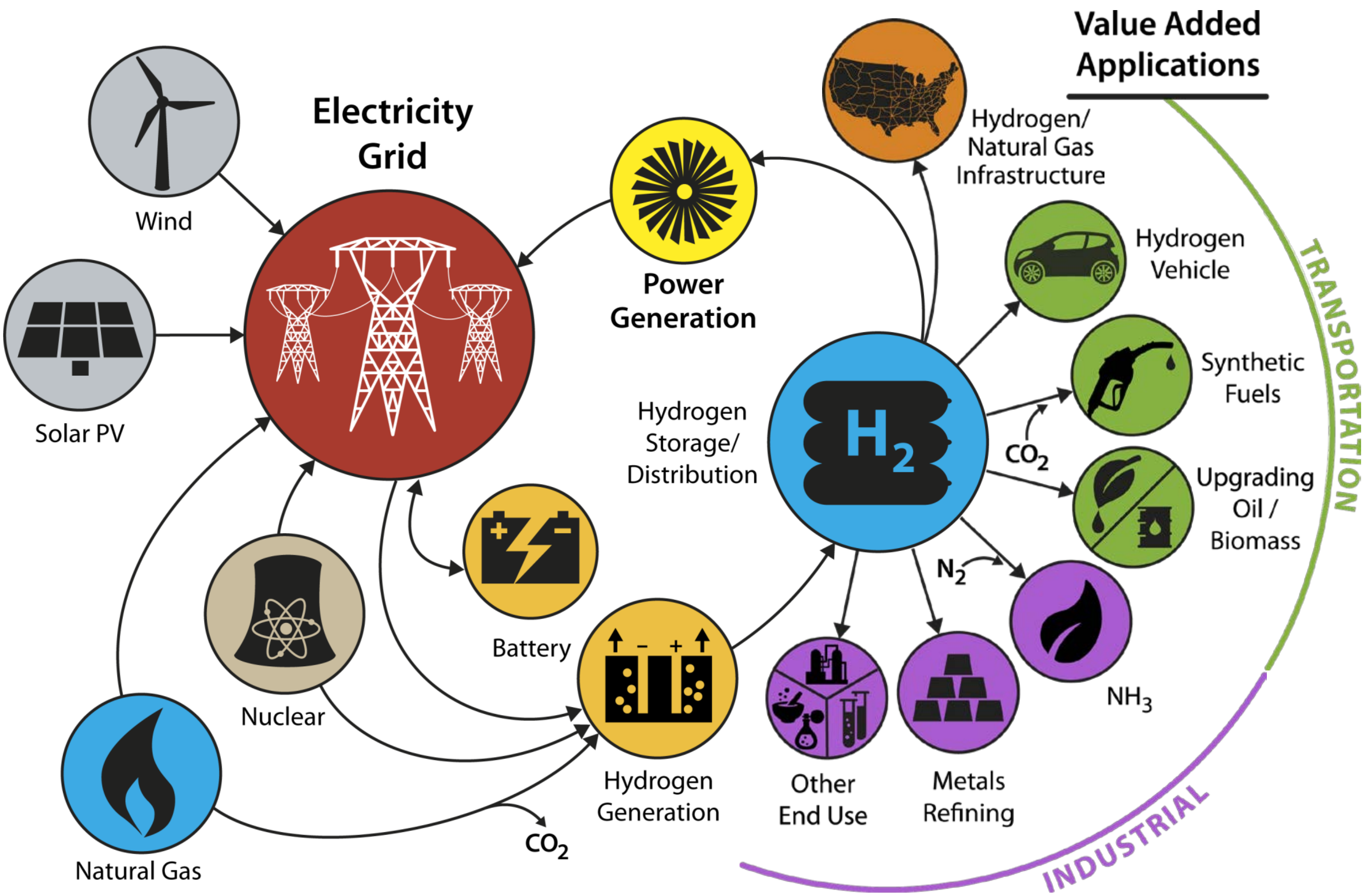
WWSIS = Western Wind and Solar Integration study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study

"If you can't solve a problem, enlarge it"

President Dwight D. Eisenhower

Source: https://www.whitehouse.gov/sites/whitehouse.gov/files/images/first-family/34_dwight_d_eisenhower%5B1%5D.jpg

Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

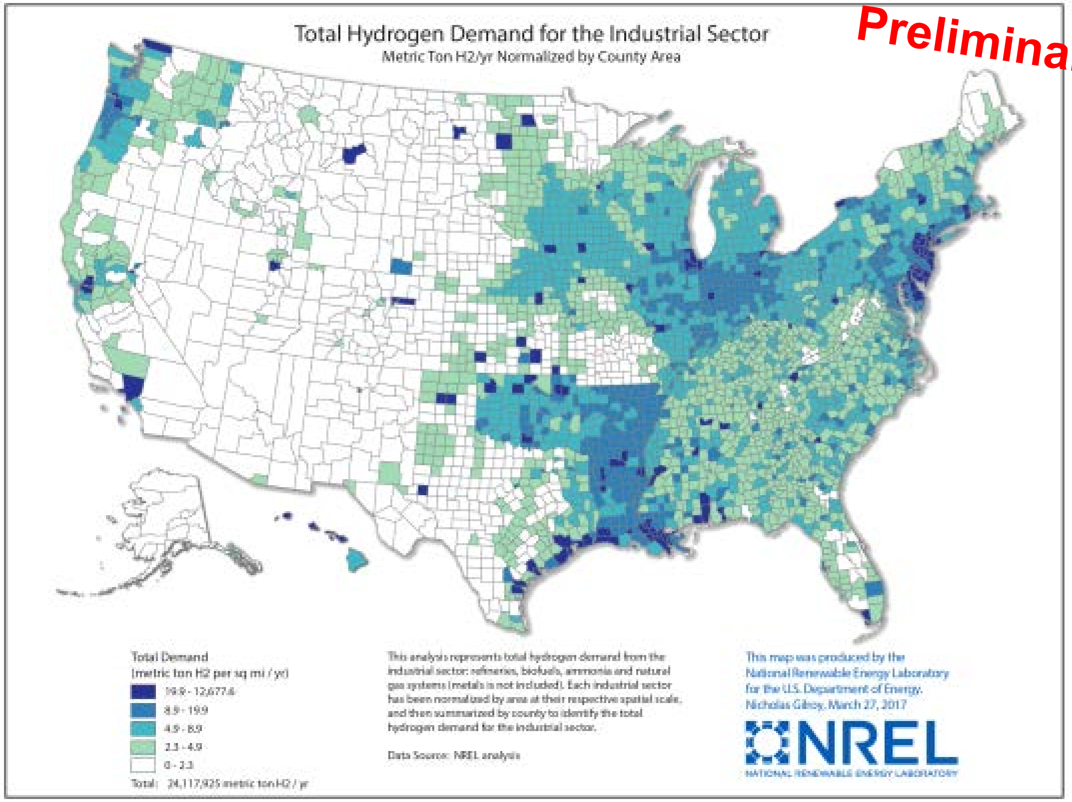
H2@Scale Vision

- **Attributes**
  - Large-scale, clean, energy-carrying intermediate for use across energy sectors
  - Increased penetration of variable renewable power and nuclear generation
  - Improved economics of thermal power generation (nuclear, CSP, geothermal) through hybridization
  - Increased H2 from methane (carbon capture/use potential)

- **Benefits**
  - Increased energy sector jobs (GDP impact)
  - Manufacturing competitiveness (low energy costs)
  - Enhanced energy security (reduced imports, system flexibility/resiliency)
  - Enhanced national security (domestic production (metals), local resources)
  - Improved air(water) quality via reduced emissions (criteria pollutants, GHGs)
  - Decreased energy system water requirements.

Getting all these benefits in a single energy system significantly enhances value proposition.

H_2 Demand Technical Potential



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

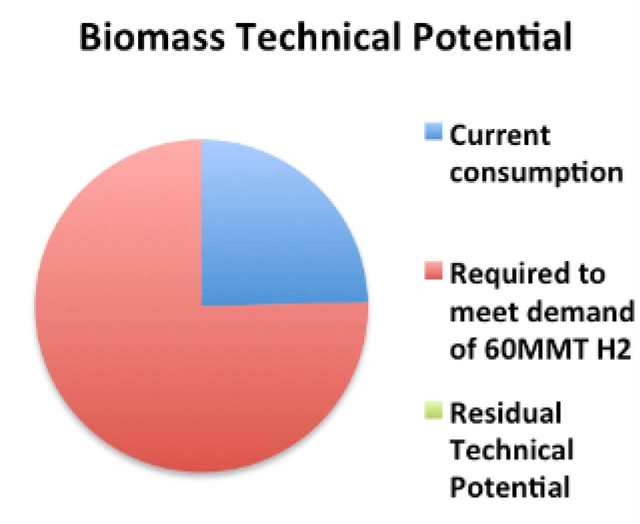
Global H_2 production revenue: 6% CAGR, 2009-2016[1]

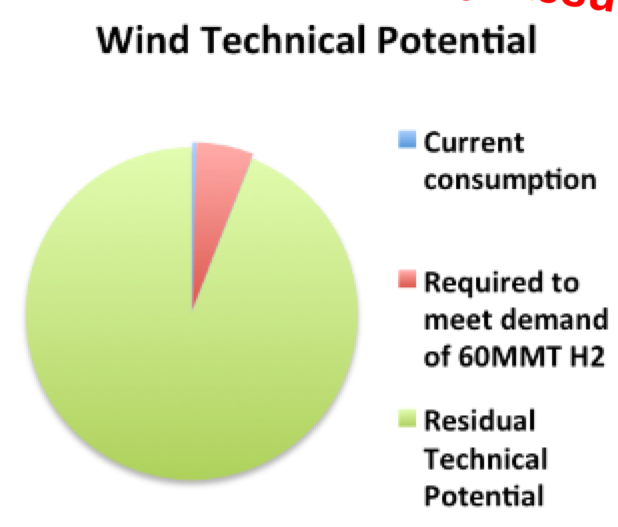
§ CPI: Chemical Processing Industry not including metals, biofuels, or ammonia
* Current potential used due to lack of consistent future projections
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
1.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

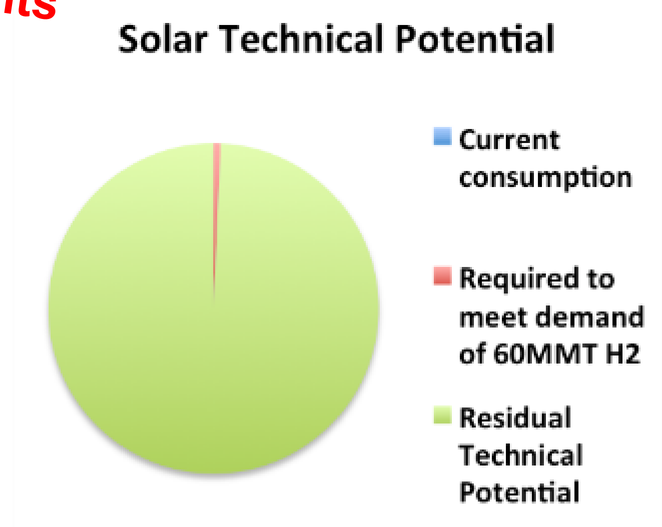
Technical Potential Supply from Renewables

	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

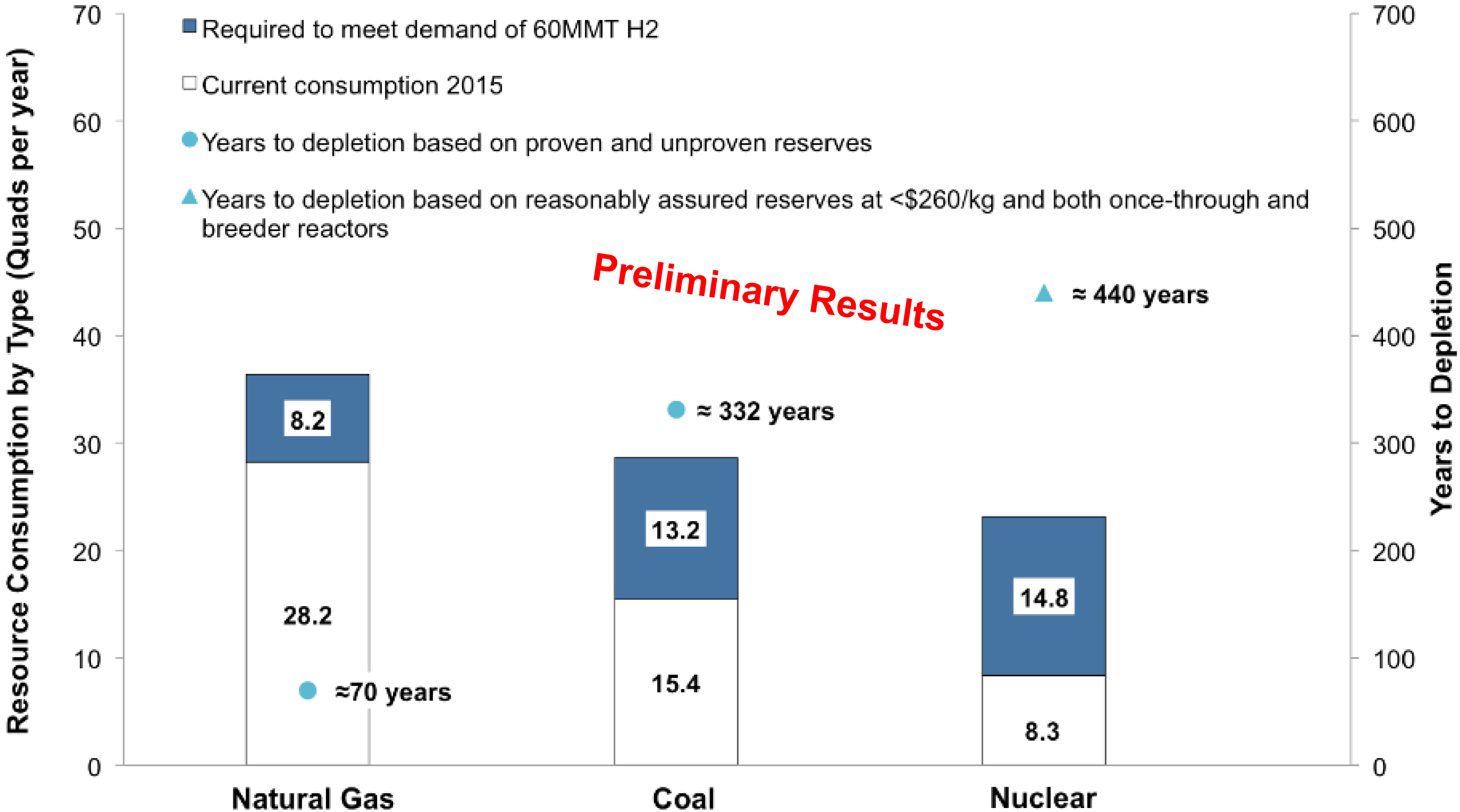






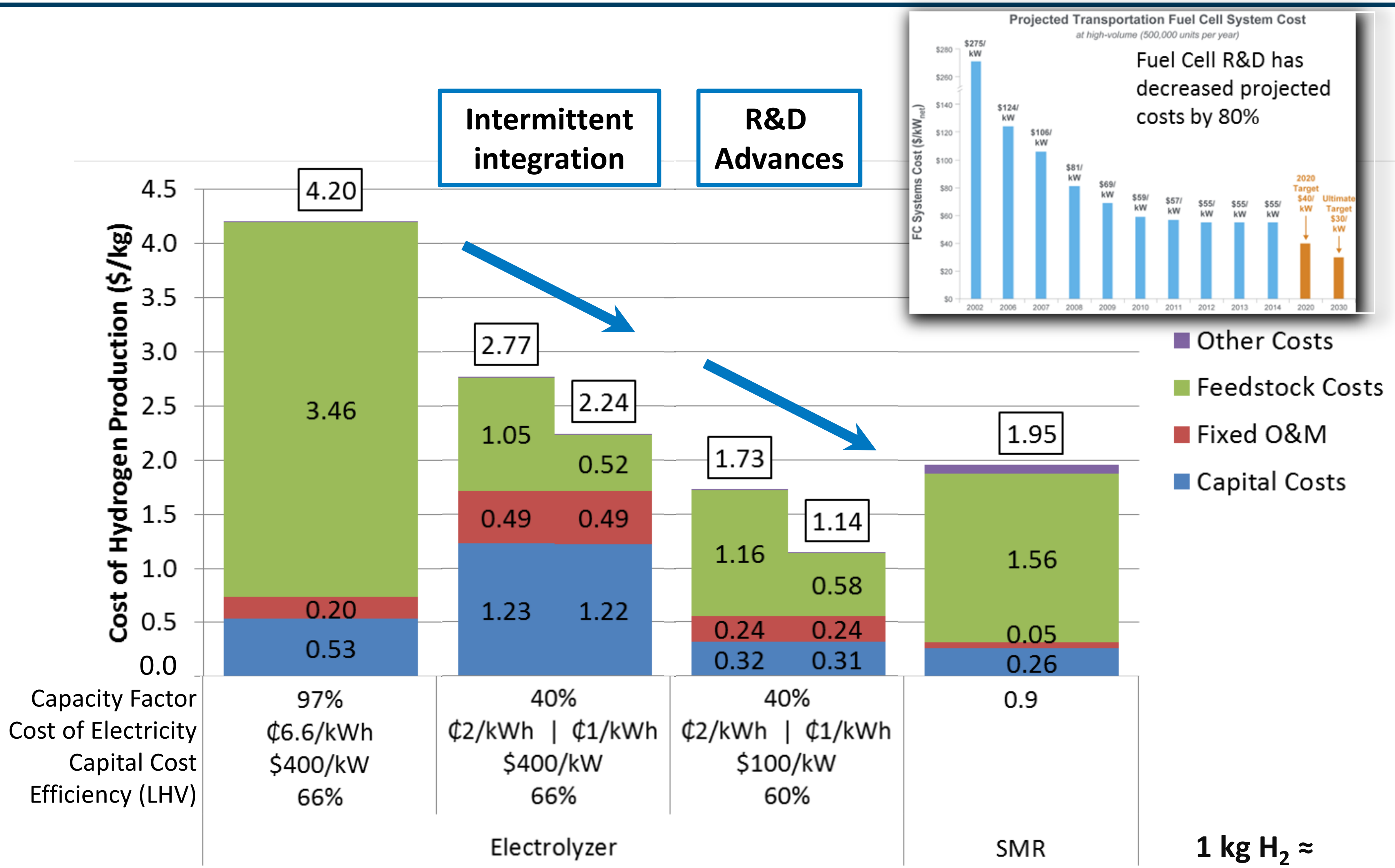
Total demand including hydrogen is satisfied by ≈6% of wind, <1% of solar, and ≈100% of biomass technical potential

Potential Supply from Fossil & Nuclear Resources



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

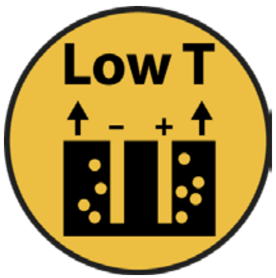
Improving the Economics of Elecrolytic H_2



1 kg H_2 ≈ 1 gallon of gasoline equivalent (gge)

What is needed to achieve H_2 at Scale?

Low and High Temperature H_2 Generation



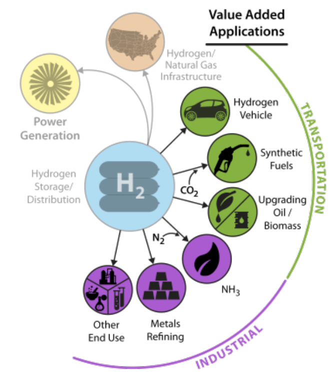
Development of **low cost, durable, and intermittent H_2** generation.

Development of **thermally integrated, low cost, durable, and variable H_2** generation.

H_2 Storage and Distribution

Development of **safe, reliable, and economic storage and distribution** systems.

H_2 Utilization



H_2 as game-changing energy carrier, revolutionizing energy sectors.

Analysis

Foundational Science

Future Electrical Grid

H_2@Scale Big Idea National Laboratory Team

H2@Scale has moved beyond this National Lab team to include DOE offices, and industrial/other stakeholders.

Steering Committee:

Bryan Pivovar (lead, NREL), Amgad Elgowainy (ANL), Richard Boardman (INL), Shannon Bragg-Sitton (INL); Adam Weber (LBNL), Rod Borup (LANL), Mark Ruth (NREL), Jamie Holladay (PNNL), Chris Moen (SNL), Don Anton (SRNL)

Low T Generation:

Rod Borup (lead, LANL); Jamie Holladay (PNNL); Christopher San Marchi (SNL); Hector Colon Mercado (SRNL); Kevin Harrison (NREL); Ted Krause (ANL); Adam Weber (LBNL); David Wood (ORNL)

High T Generation:

Jamie Holladay (lead, PNNL); Jim O'Brien (INL); Tony McDaniel (SNL); Ting He (INL); Mike Penev (NREL); Bill Summers (SRNL); Maximilian Gorensek (SRNL); Jeffery Stevenson (PNNL); Mo Khaleel (ORNL)

Storage and Distribution:

Don Anton (lead, SRNL); Chris San Marchi (SNL); Kriston Brooks (PNNL); Troy Semelsberger (LANL); Salvador Aceves (LLNL); Thomas Gennett (NREL); Jeff Long (LBNL); Mark Allendorf (SNL); Mark Bowden PNNL; Tom Autrey PNNL

Utilization:

Richard Boardman (lead, INL); Don Anton (SRNL); Amgad Elgowainy (ANL); Bob Hwang (SNL); Mark Bearden (PNNL); Mark Ruth (NREL); Colin McMillan (NREL); Ting He (INL); Michael Glazoff (INL); Art Pontau (SNL); Kriston Brooks (PNNL); Jamie Holladay (PNNL); Christopher San Marchi (SNL); Mary Biddy (NREL) ; Geo Richards (NETL)

Future Electric Grid:

Charles Hanley (lead, SNL); Art Anderson (NREL); Bryan Hannegan (NREL); Chris San Marchi (SNL); Ross Guttromson (SNL); Michael Kintner-Meyer (PNNL); Jamie Holladay (PNNL); Rob Hovsapian (INL)

Foundational Science:

Adam Weber (lead, LBNL); Voja Stamekovic (ANL); Nenad Markovic (ANL); Frances Houle (LBNL); Morris Bullock (PNNL); Aaron Appel (PNNL); Wendy Shaw (PNNL); Tom Jaramillo (SLAC); Jens Norskov (SLAC); Mark Hartney (SLAC), Vitalij Pecharsky (Ames); Alex Harris (BNL)

Analysis:

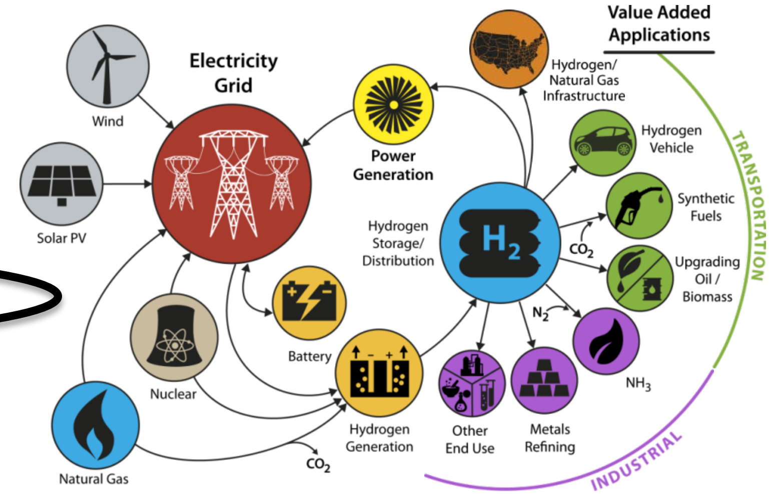
Mark Ruth (lead, NREL); Amgad Elgowainy (co-lead, ANL); Josh Eichman (NREL); Joe Cordaro (SRNL); Salvador Aceves (LLNL); Max Wei (LBNL); Karen Studarus (PNNL); Todd West (SNL); Steve Wach (SRNL); Richard Boardman (INL); David Tamburello (SRNL); Suzanne Singer (LLNL)

H2@Scale Involves Many Stakeholders

- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Oil, Biomass)
- Metals/Steel
- Ammonia

- Regulators
- Analysis
- Investors

Blue: High engagement and support
Green: Engaged with interest/support
Orange: Limited engagement
Black: Little engagement



Stakeholder groups presenting at this workshop are identified with ovals.

Motivation for Future Impact

27 September 2016 | GENEVA - A new WHO air quality model confirms that 92% of the world's population lives in places where air quality levels exceed WHO limits.

More than half US population lives amid dangerous air pollution

https://www.theguardian.com/environment/2016/apr/20/dangerous-air-pollution-us-population-report

Credit: Warren Gretz – NREL Pix 07070.jpg

Credit: Bryan Pivovar

Energy and environmental challenges grow as the population grows and economies advance

H2@Scale would help meet challenges