H_2 at Scale:

Deeply Decarbonizing our Energy System

HTAC Presentation

April 6, 2016

Steering Committee:
Bryan Pivovar (lead, NREL), Amgad Elgowainy (ANL), Richard Boardman (INL), Adam Weber (LBNL), Salvador Aceves (LLNL), Rod Borup (LANL), Mark Ruth (NREL), David Wood (ORNL), Jamie Holladay (PNNL), Art Pontau (SNL), Don Anton (SRNL)

Advanced Generation:
Rod Borup (lead, LANL); Jamie Holladay (co-lead, PNNL); Christopher San Marchi (SNL); Hector Colon Mercado (SRNL); Jim O'Brien (INL); Kevin Harrison (NREL); Ted Krause (ANL); Adam Weber (LBNL); David Wood (ORNL)

Industrial Utilization:
Richard Boardman (lead, INL); Don Anton (co-lead, 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);

Modeling/Analysis:
Mark Ruth (lead, NREL); Amgad Elgowainy (co-lead, ANL); Rob Hovsapian (INL); 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)

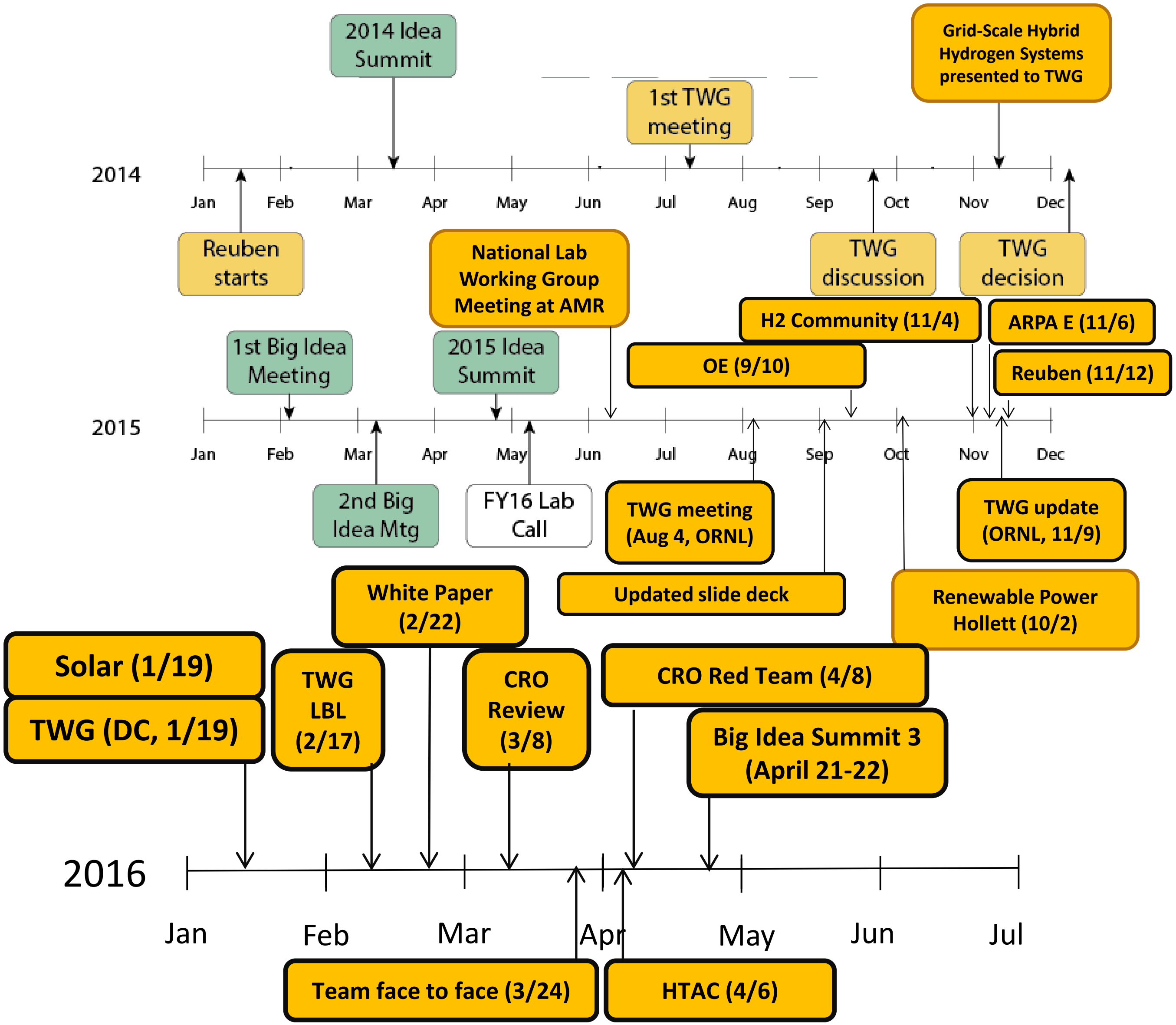
Overview of Talk

- **Provide 'Big Idea' perspective**
- **Describe current vision on H2 @ Scale as a 'Big Idea'**
  - What we've learned
  - Challenges encountered
  - Momentum gained
- **Solicitation of support to/from HTAC/ individual entities**
  - Industry engagement

H_2 at Scale a National Lab led 'Big Idea'

- 'Big Ideas' are identified by National Lab teams as high impact areas that are currently underemphasized or missed within DOE portfolio
- Culminate in a DOE/National Lab Big Idea Summit
- Have led to large programs, increased visibility for specific topics

H_2 at Scale Big Idea Timeline



Motivation - Major Administration Energy Goals

1. Reduce GHG emissions by 17% by 2020, 26-28% by 2025 and 83% by 2050 from 2005 baseline Climate Action Plan
2. Reduce net oil imports by half by 2020 from a 2008 baseline Blueprint Secure
3. Double energy productivity by 2030 Department of Energy
4. By 2035, generate 80% of electricity from a diverse set of clean energy resources Blueprint Secure Energy Future
5. Reduce CO_2 emissions by **3 billion metric tons** cumulatively by 2030 through efficiency standards set between 2009 and 2016 CAP Progress Report

H_2 at Scale strongly impacts 1 and 4, also impacts 2.

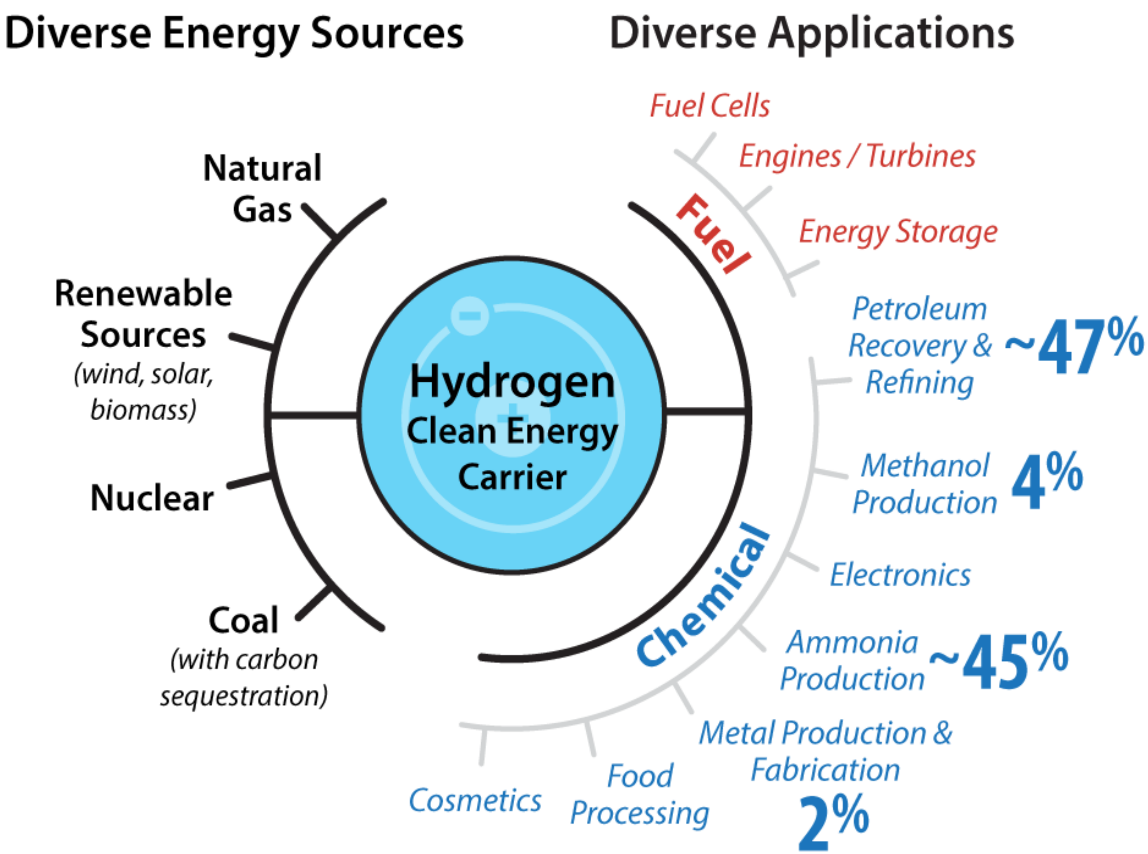
Problem

- **Climate change ⇒ deep decarbonization**
  - Limited options
- **Multi-sector challenges**
  - Transportation
  - Industrial
  - Grid

Over half of U.S. CO_2 emissions come from the industrial and transportation sectors

- **Renewable challenges**
  - Variable
  - Concurrent generation

Impact

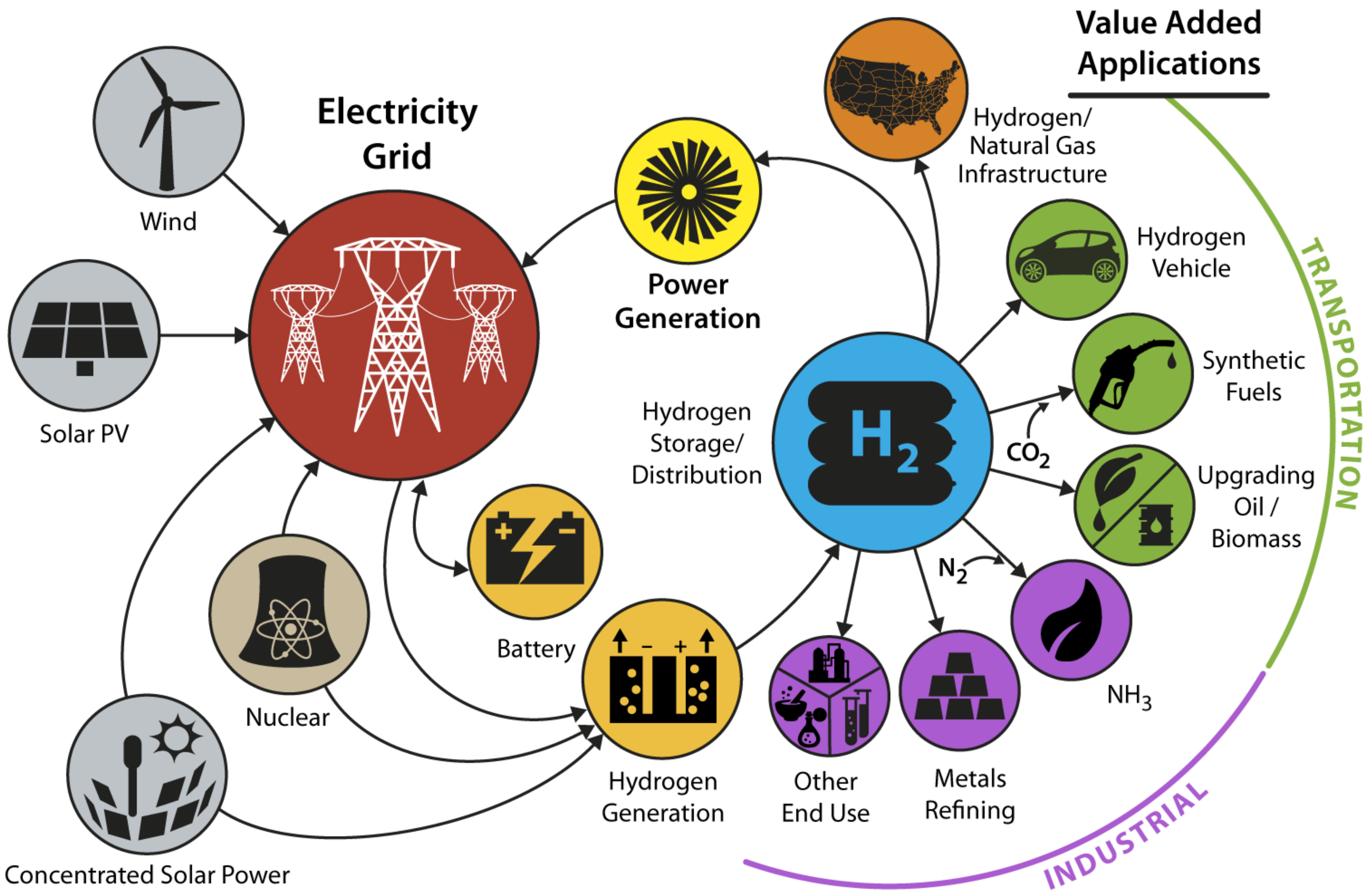


H_2 at scale can enable increased renewable penetration that results in a:

45% reduction in total U.S. carbon emissions by 2050*

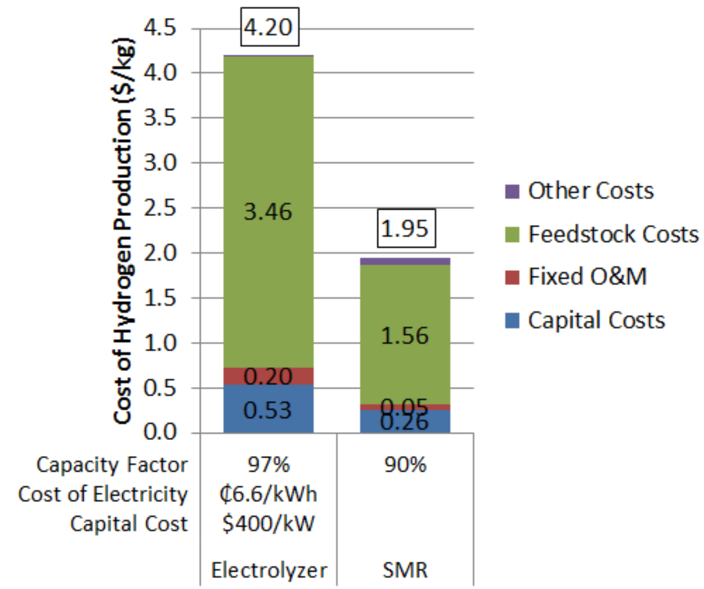
*compared to EIA AEO 2040 "Business as usual" case

Future H_2 at Scale Energy System

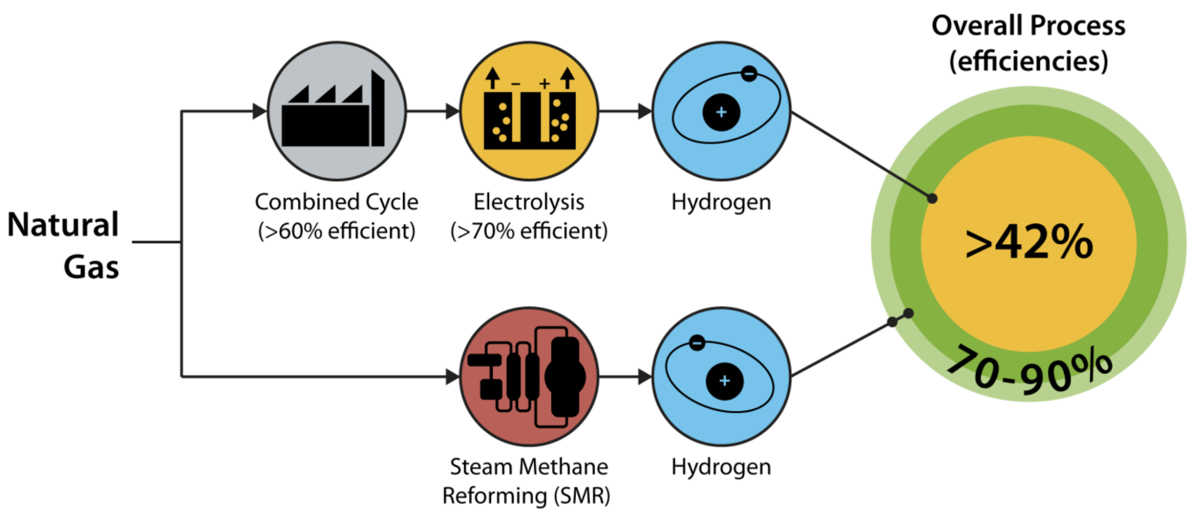


Hydrogen Production (Current)

- Today's electrolysis technology (scaled up) is not cost competitive with today's SMR.
- This is expected—it's driven by electricity cost tied to burning fossil fuels and two inefficient processes.



H2A Analysis, Josh Eichman, NREL



Clean Power Plan
reduce carbon dioxide emissions by 32% by

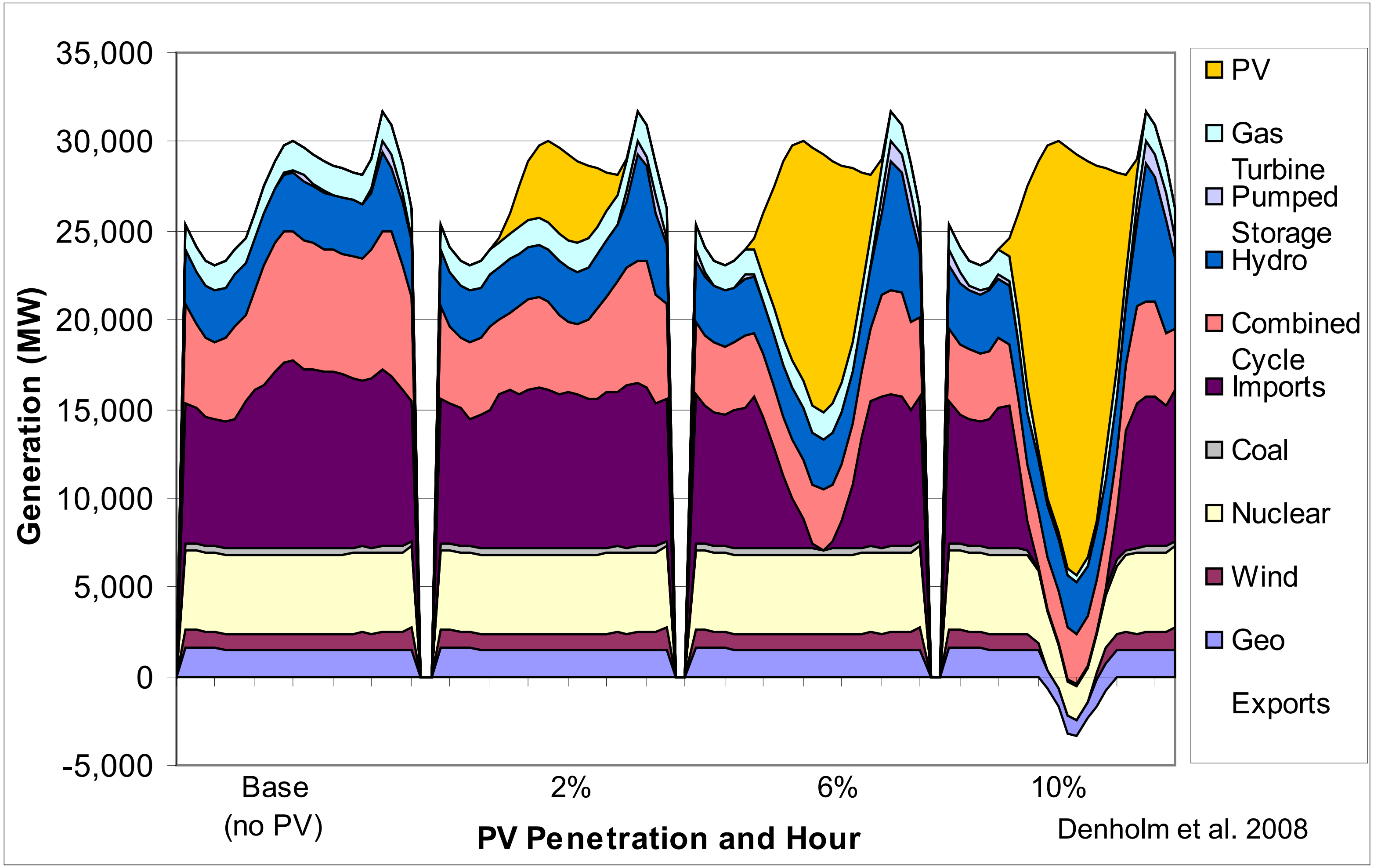
President's Climate Action Plan
80% reduction in transportation GHG by 2050

What has changed, is changing, or will change that has an impact

Renewable Energy Standards
37 states with renewable portfolio standards or goals

Growing Renewable Energy Penetration
Since 2008, US solar >20x increase, wind >3x increase.
Other countries >30% total RE penetration.

Solar PV in the Spring

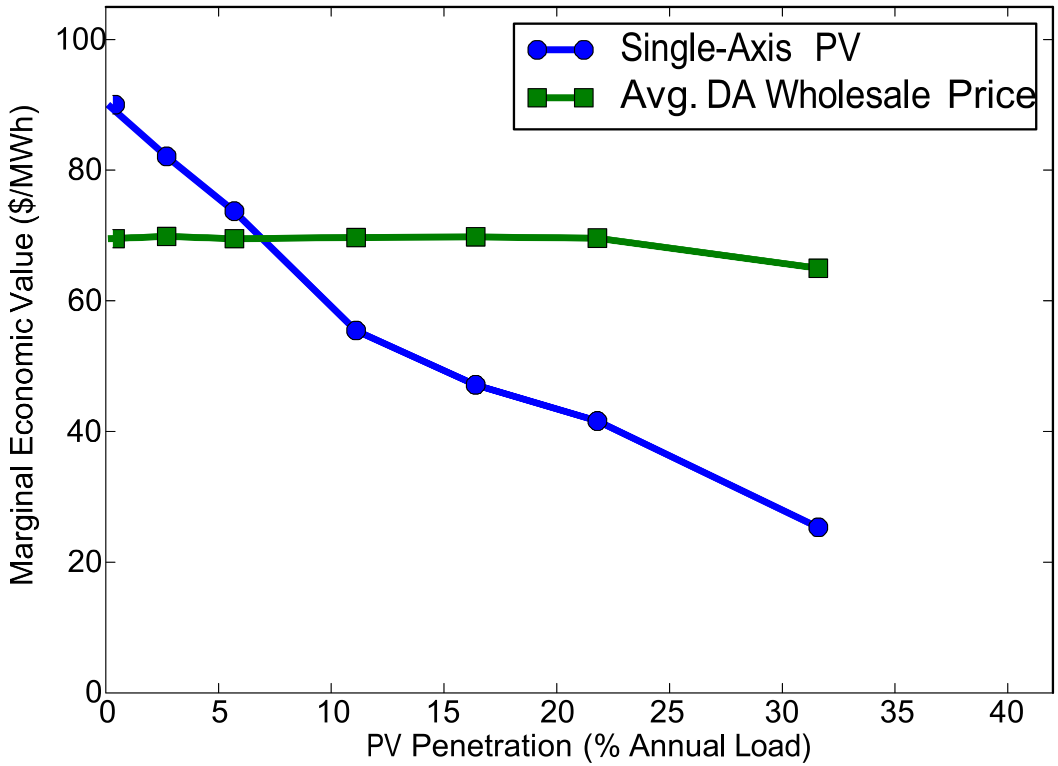


Simulated dispatch in California for a spring day with PV penetration from 0-10%

Even at low penetrations, instantaneous demand can be met by solar power

Hydrogen Value Proposition for RE Penetration

PV has decreasing value with increased penetration.

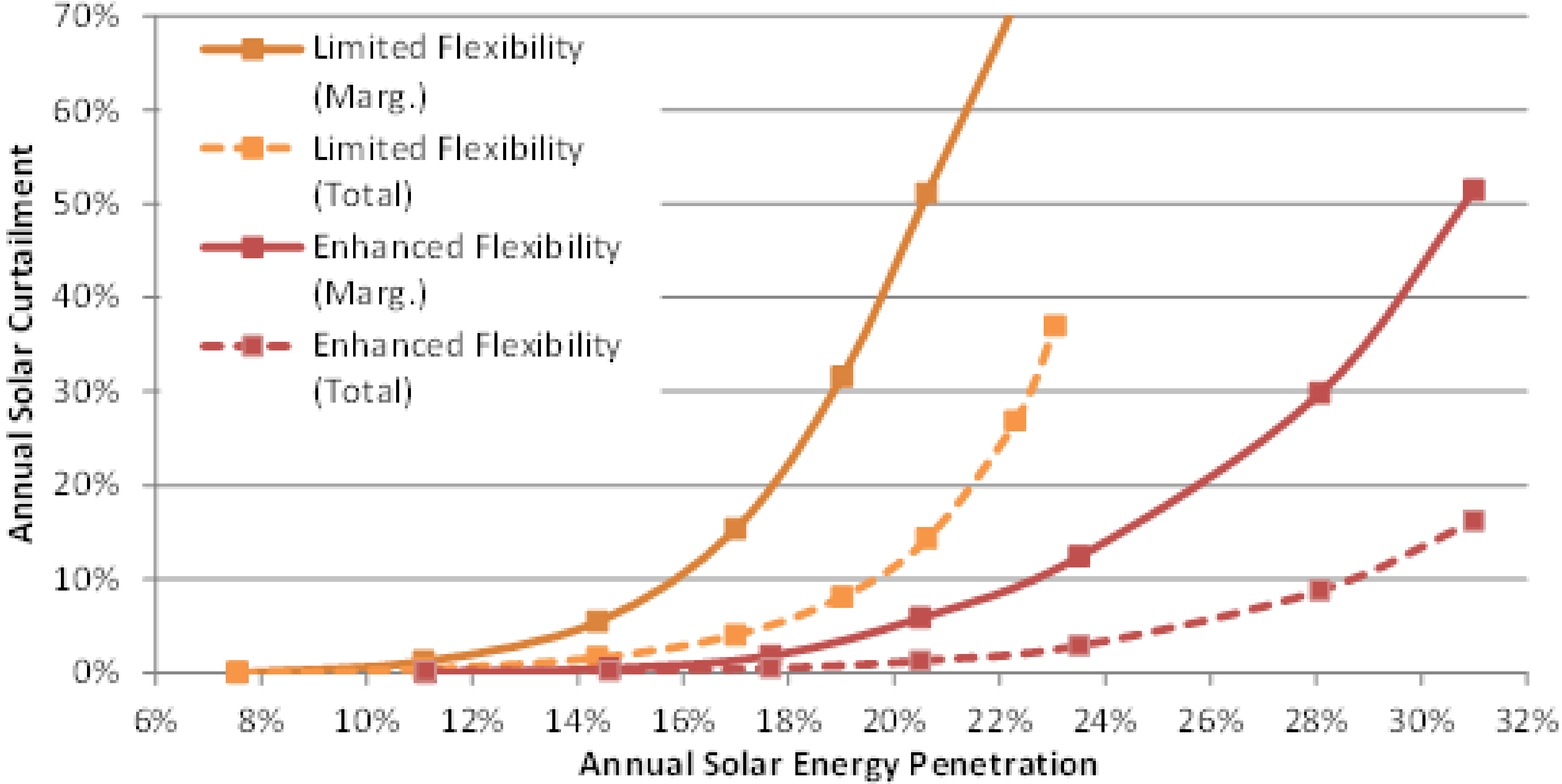


Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California Andrew Mills and Ryan Wiser, June 2012, http://eetd.lbl.gov/EA/EMP

An increased value proposition is needed for higher market penetration of variable renewables.

RE Penetration - Curtailment

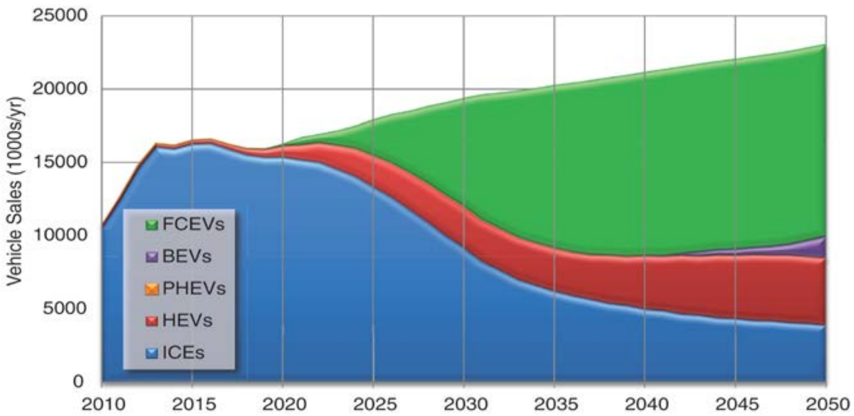
Denholm, P.; M. O'Connell; G. Brinkman; J. Jorgenson (2015) Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart. NREL/TP-6A20-65023



- A tipping point is reached due to increased use of low cost renewable energy
- Curtailment will lead to an abundance of low value electrons, and we need solutions that will service society's multi-sector demands

Future H_2 Demand

The H_2 at Scale team projects a 5x increase in H_2 use could be achieved by 2050 with high renewable penetration.

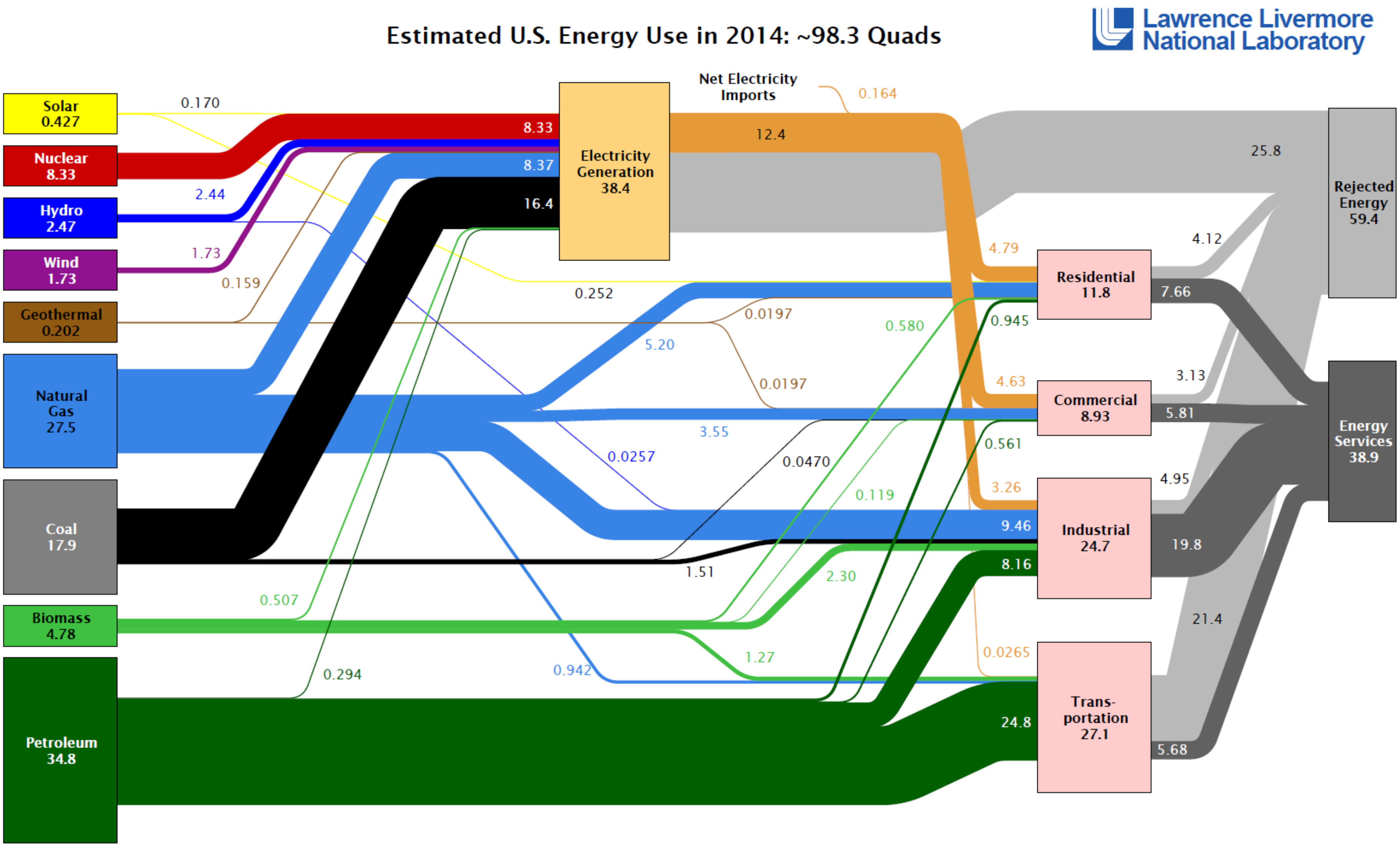


Vehicle sales by vehicle technology with midrange technology assumptions and low-carbon production of hydrogen, fuel cell vehicle subsidies, and additional incentives.
http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

Potential Hydrogen Demand in 2050*	
	Quads
Hydrogen for direct use in LDVs	3.2
Hydrogen for direct use in HDVs	0.5
Hydrogen for biofuel upgrading	0.4
Hydrogen for oil refining	0.4
Ammonia production	2.5
Steel refining	1.0
Total	7.9

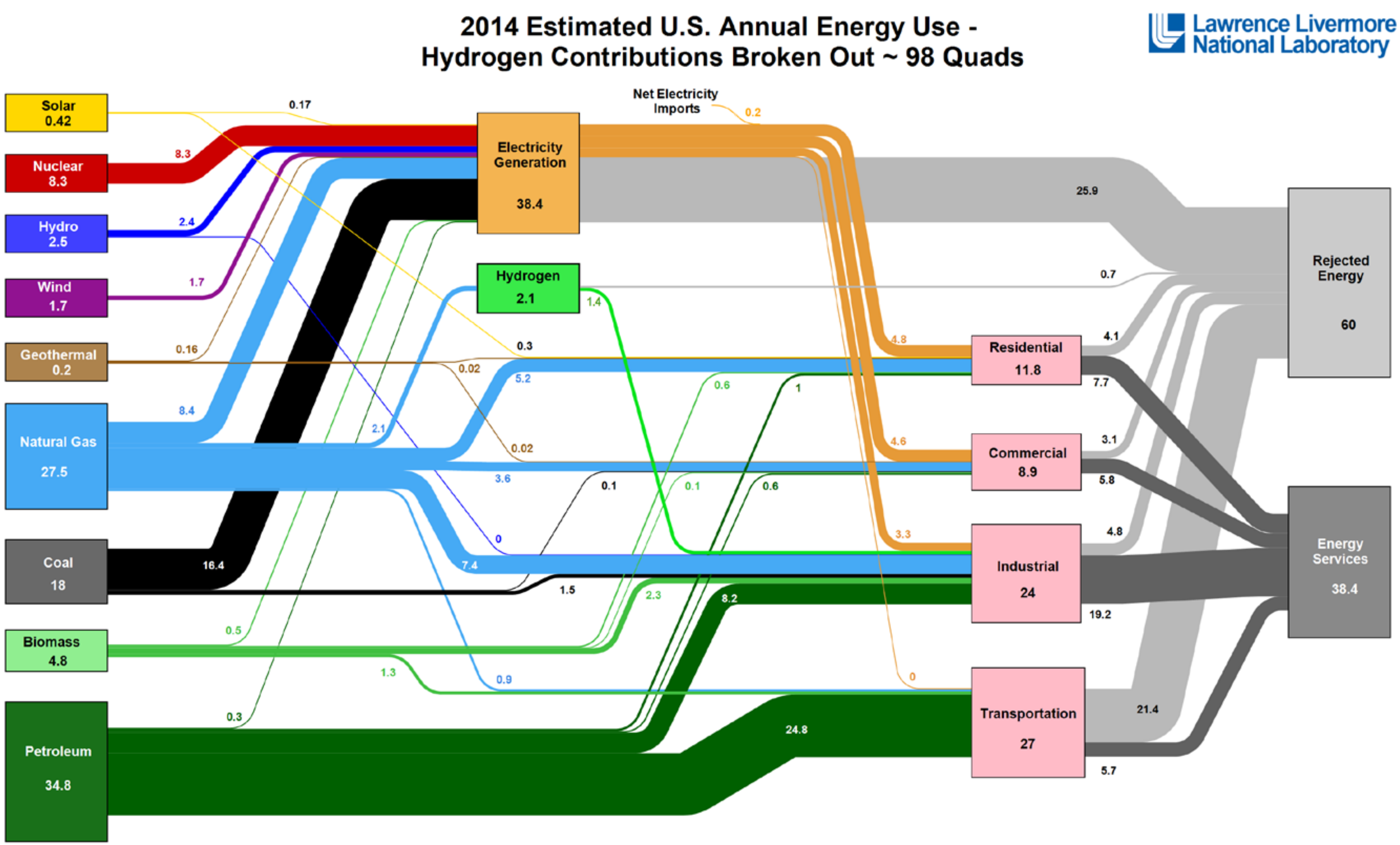
* Based on H2 at Scale Analysis Team projections

Current Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Current Energy Flow – w/Hydrogen



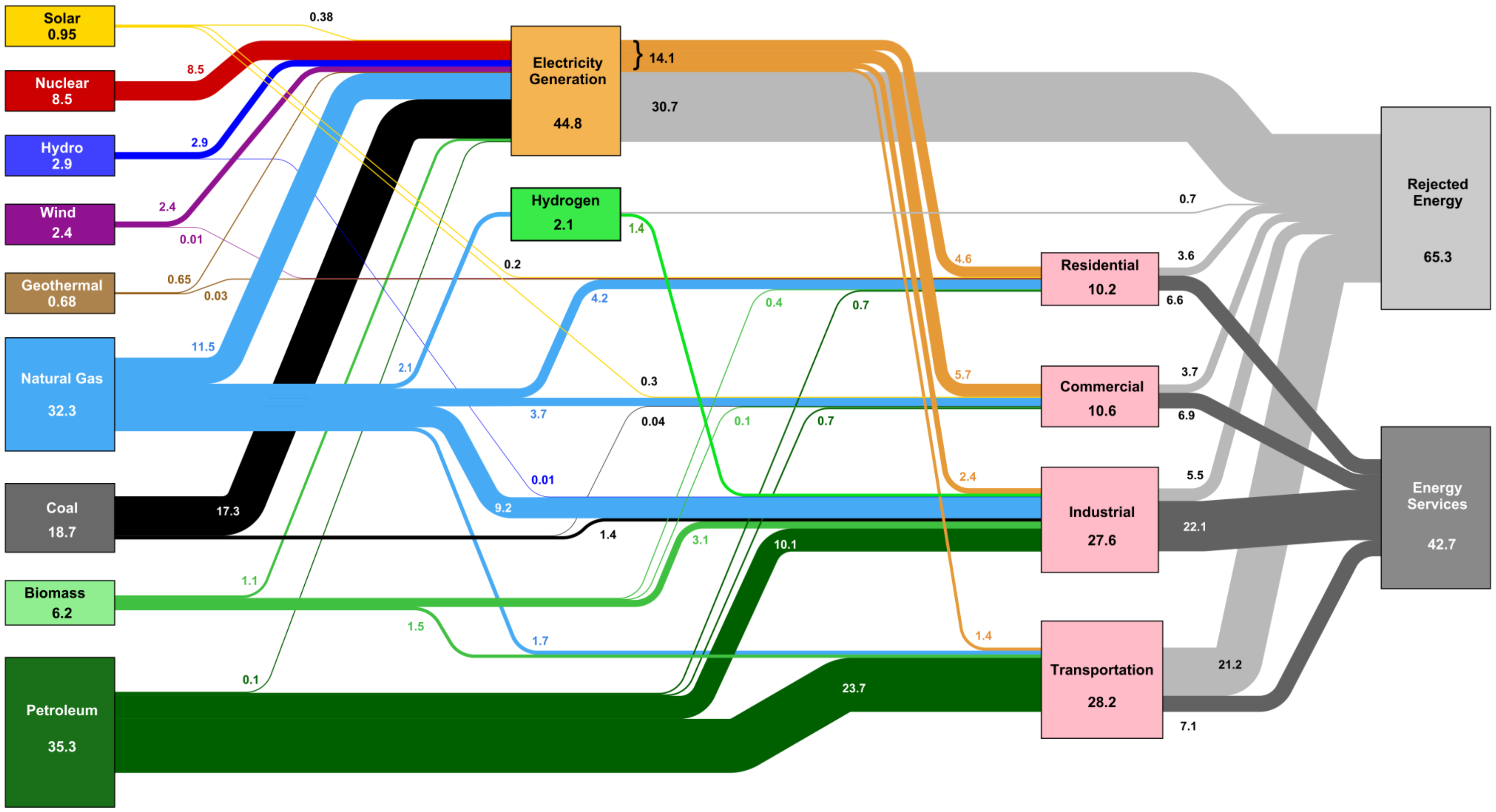
Source: LLNL September 2015. Data is based on DOE/EIA-0035(2015-03) and Annual Energy Outlook DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.

Energy Flow 2040 Business as Usual

2040 EIA AEO Estimated U.S. Annual Energy Use - Hydrogen Contributions Broken Out ~ 108 Quads

Lawrence Livermore National Laboratory



Source: LLNL March 2016. Data is based on DOE/EIA-0035(2015-03) and Annual Energy Outlook DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

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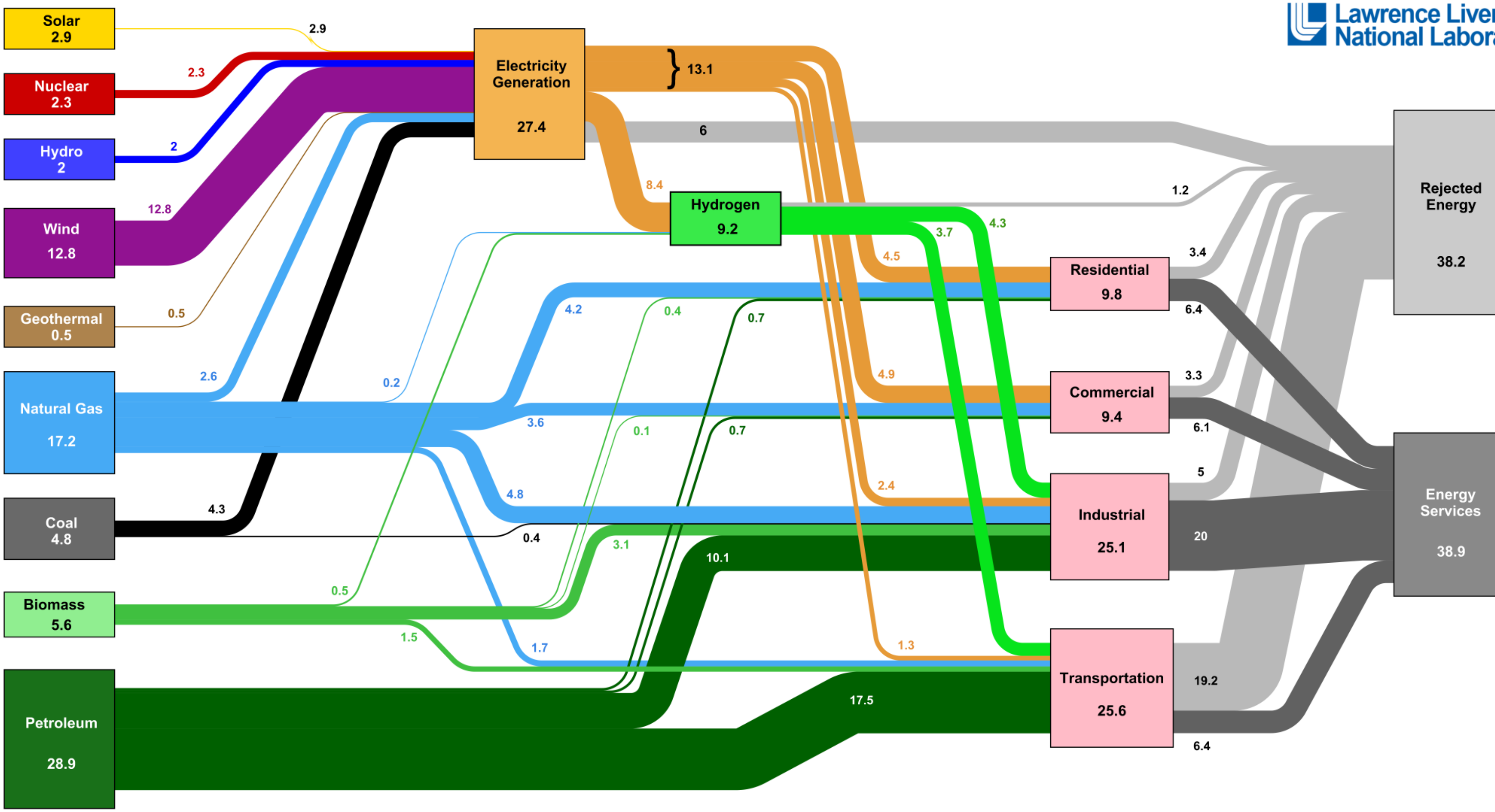
Energy Flows – 2050 High RE/H_2

U.S. DEPARTMENT OF ENERGY

Lawrence Livermore National Laboratory

2050 Estimated U.S. Annual Energy Use with High Hydrogen Contributions Broken Out ~ 77 Quads



Source: LLNL September 2015. Data is based on High Hydrogen Estimations and DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

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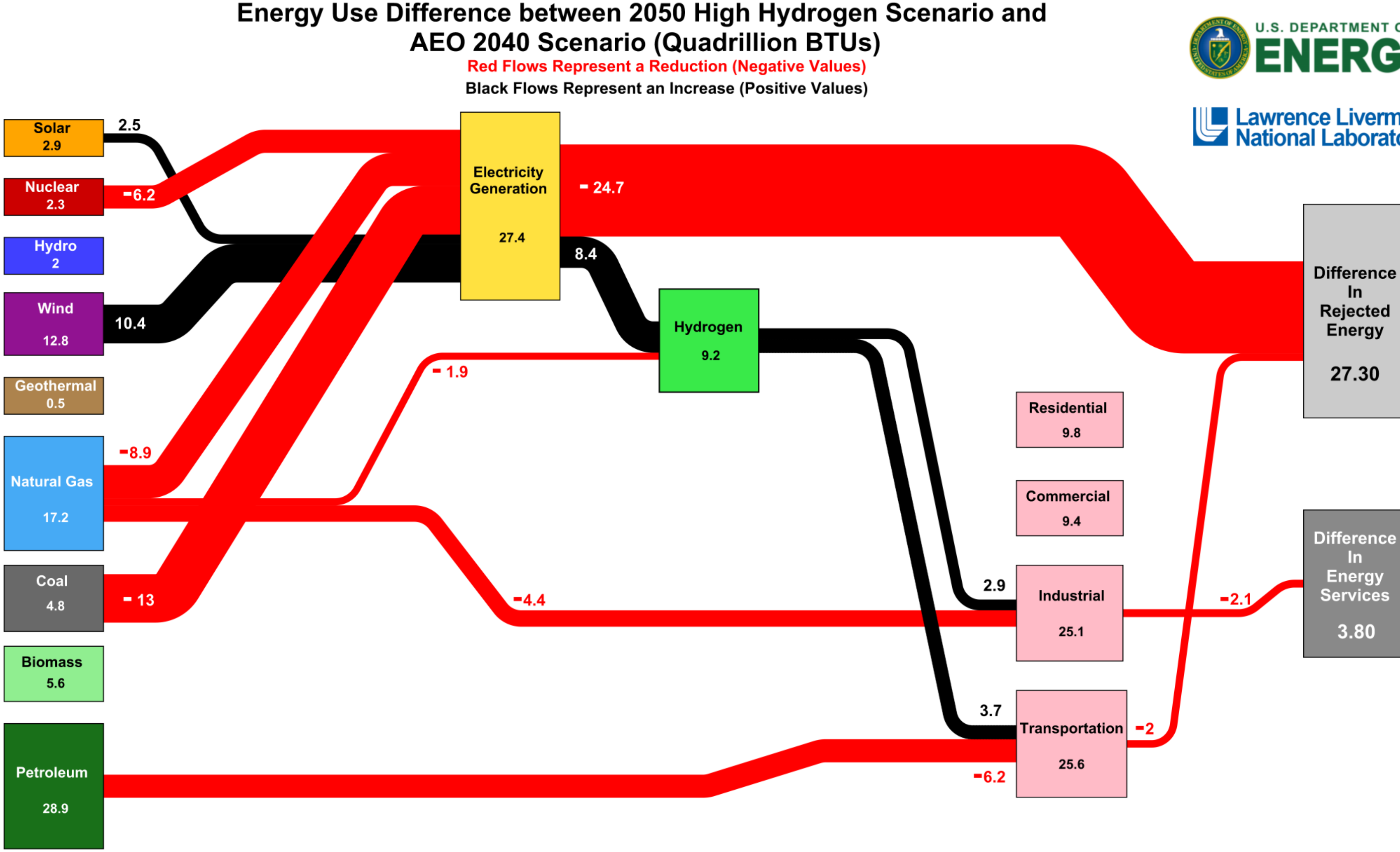
BAU vs. High RE/H_2 – Energy Differences*



* Only differences >1.5 quad shown for clarity purposes, case study data included in backup slides

Source: LLNL March 2016. Data is based on High Hydrogen Estimations and DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. Negative Values between 0 and -0.5 are not shown. LLNL-MI-676987

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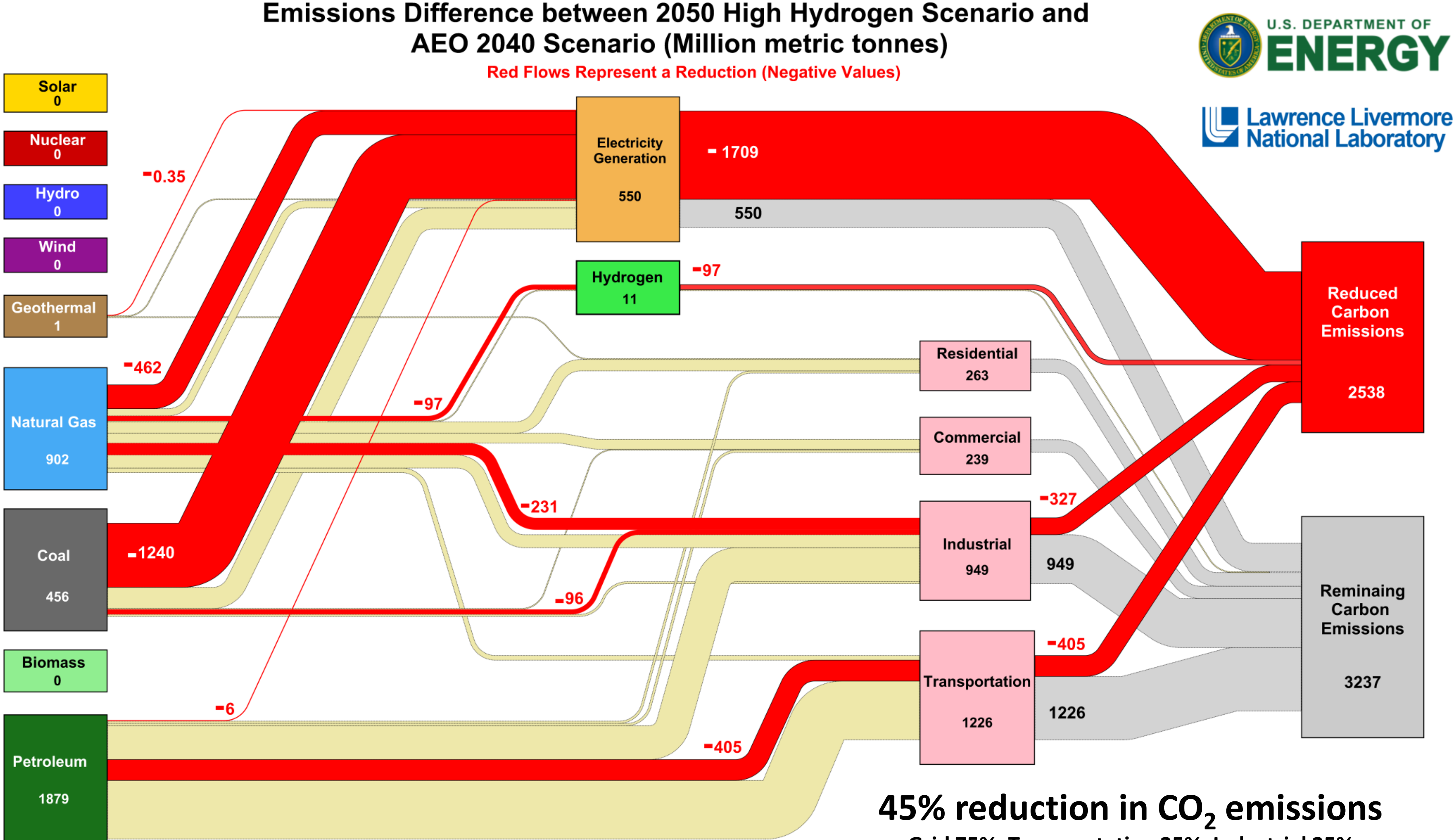
BAU vs. High RE/H_2 – CO_2 Emissions

Emissions Difference between 2050 High Hydrogen Scenario and AEO 2040 Scenario (Million metric tonnes)

Red Flows Represent a Reduction (Negative Values)



45% reduction in CO_2 emissions

Grid 75%, Transportation 25%, Industrial 25%

Source: LLNL March 2016. Data is based on High Hydrogen Estimations and DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

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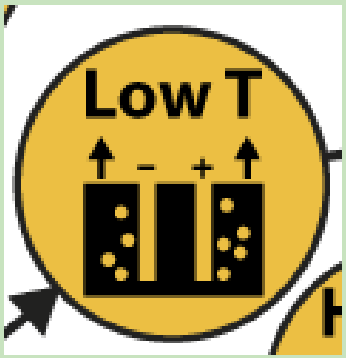
H2 @ Scale Technical Framework

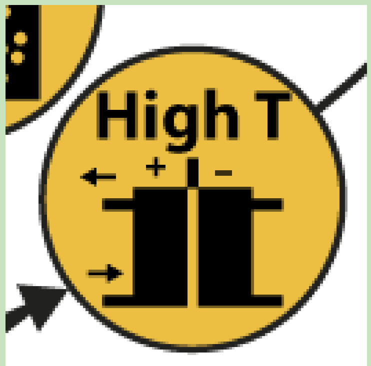
Renewable Energy Conversion, Storage, and Use

Low T H_2 Generation



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

High T H_2 Generation

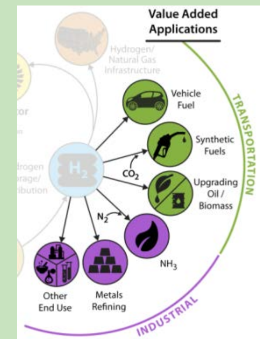


Development of thermally integrated, low cost, reliable, and efficient H_2 generation.

Hydrogen Storage and Distribution

Development of reliable, efficient, and economic storage and distribution of hydrogen (energy).

H2 End Use



H2 as a game changing energy carrying currency, revolutionizing industry and the energy sector.

H2 at Scale Framework

Intermittent Hydrogen Deeply Decarbonizing our Energy System

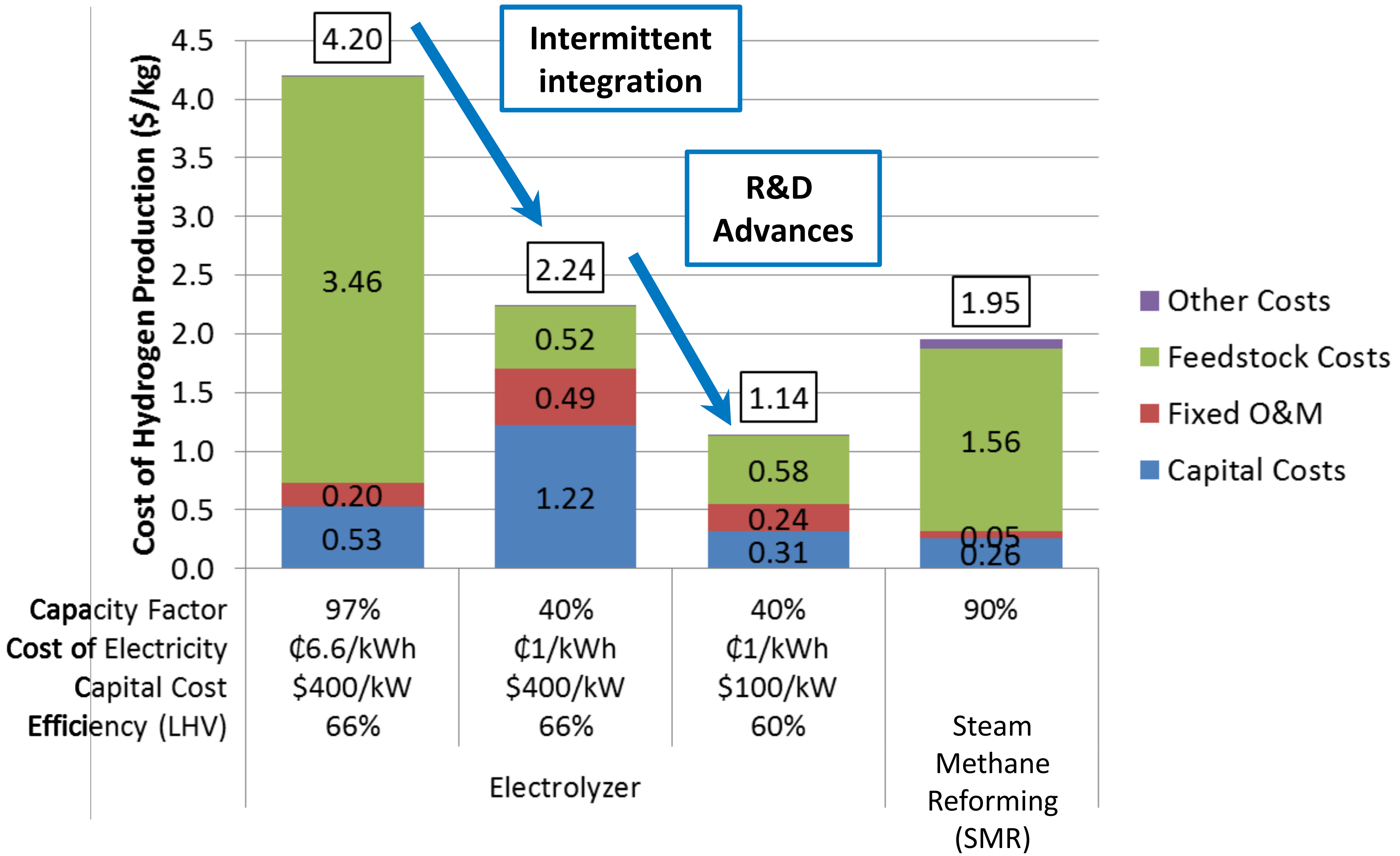
Low T generation	High T generation	Storage and Distribution	Industrial/End use
Develop non-noble metals OER catalyst	Durable corrosion resistant conductive materials	GWh-month scale geologic storage	Process heat integration with intermittent hydrogen generation
Low-cost durable high-conductivity membranes	Front end controls for thermal management with cyclic operation	Develop novel materials and processes for chemical Storage	New process chemistry with hydrogen as reductant
Develop alkaline membranes enabling noble metal replacement	Technologies for high temperature thermal storage	Integration with renewable grid/System optimization	Ammonia production beyond Haber Bosch
Low-cost, corrosion resistant, thin film metal coatings	CO2 electrochemical reduction	Novel compression/liquefaction technologies	Hydrogen/ hydrogen-rich combustion
Develop durable systems for intermittent operation	Material systems for advanced redox cycles	Leak Detection/ Purification	
	System integration	Material compatibility for pipelines and compressors	

Analysis

Fundamental Science

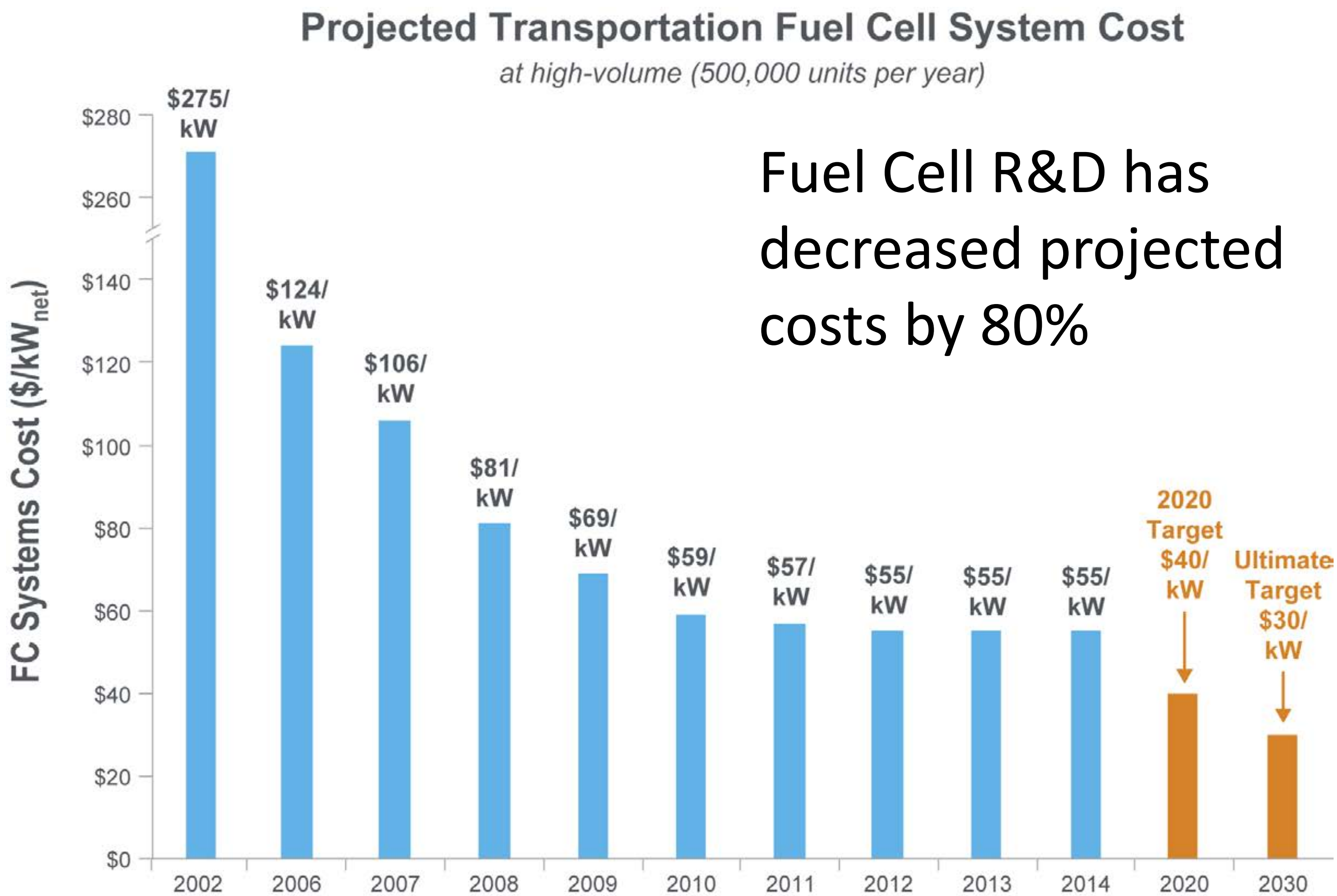
Grid Connection/Integration

Improving the Economics of Renewable H_2



Investments to Enable H_2 at Scale

R&D Impact on Fuel Cell Costs



Fuel Cell R&D has decreased projected costs by 80%

Data from FCTO AMR presentations.

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- **Provide 'Big Idea' perspective**
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  - What we've learned
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H_2 at Scale Summary

- Reducing emissions (GHG, criteria pollutants)
- Cross-energy-sector synergetic opportunities (electricity, industrial, transportation)
- Support needs of dynamic, variable power systems

Unique potential of H_2 to positively impact all these areas

- Other benefits
  - Energy security (diversity/domestic)
  - Manufacturing competitiveness/job creation