H_2 at Scale:

Enhance the U.S. energy portfolio through sustainable use of domestic resources, improvements in infrastructure, and increase in grid resiliency.

NREL Workshop

November 16, 2016

Presented by Bryan Pivovar
National Renewable Energy Lab
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H2@Scale webinar available at
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

Beijing 2016

Pittsburgh Today

http://www.pittsburghmagazine.com/Best-of-the-Burgh-Blogs/The-412/August-2013/This-is-What-Pittsburgh-Looked-Like-at-Noon-73-Years-Ago/

Energy System Challenge - Sustainability

- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

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

- **Decarbonization has limited options**
  - Renewables, Nuclear, and CCS
  - Intense electrification or carbon-neutral fuels

Changing Landscape

- **Environmental Impacts**
- **Policy (RPS, ZEV)**

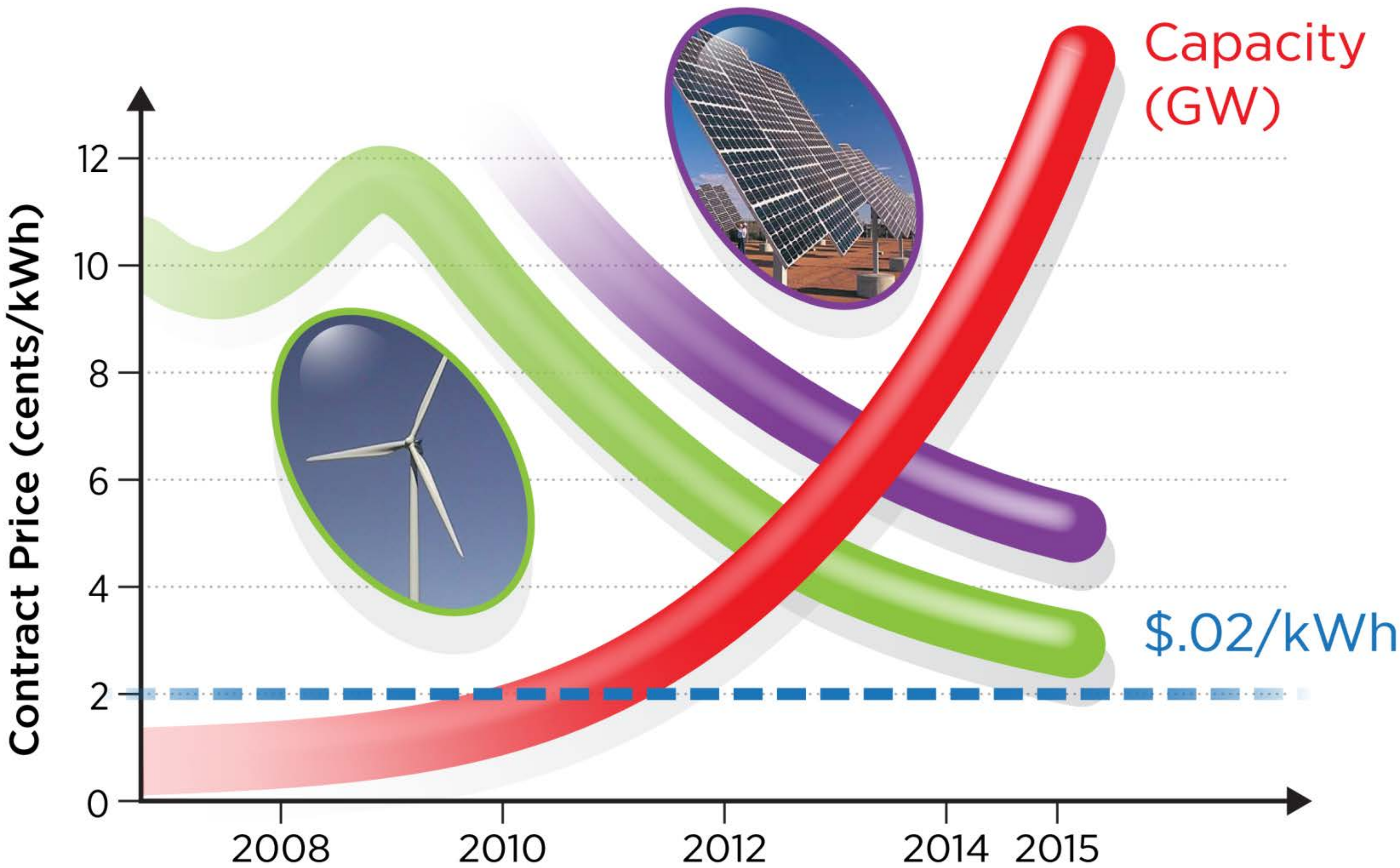
German Government Votes to Ban Internal Combustion Engines by 2030

The German Bundesrat has voted to ban new gasoline- or diesel-powered vehicles from EU roads starting in 2030.

By Bob Sorokanich Oct 8, 2016

http://www.roadandtrack.com/new-cars/future-cars/news/a31097/german-government-votes-to-ban-internal-combustion-engines-by-2030/

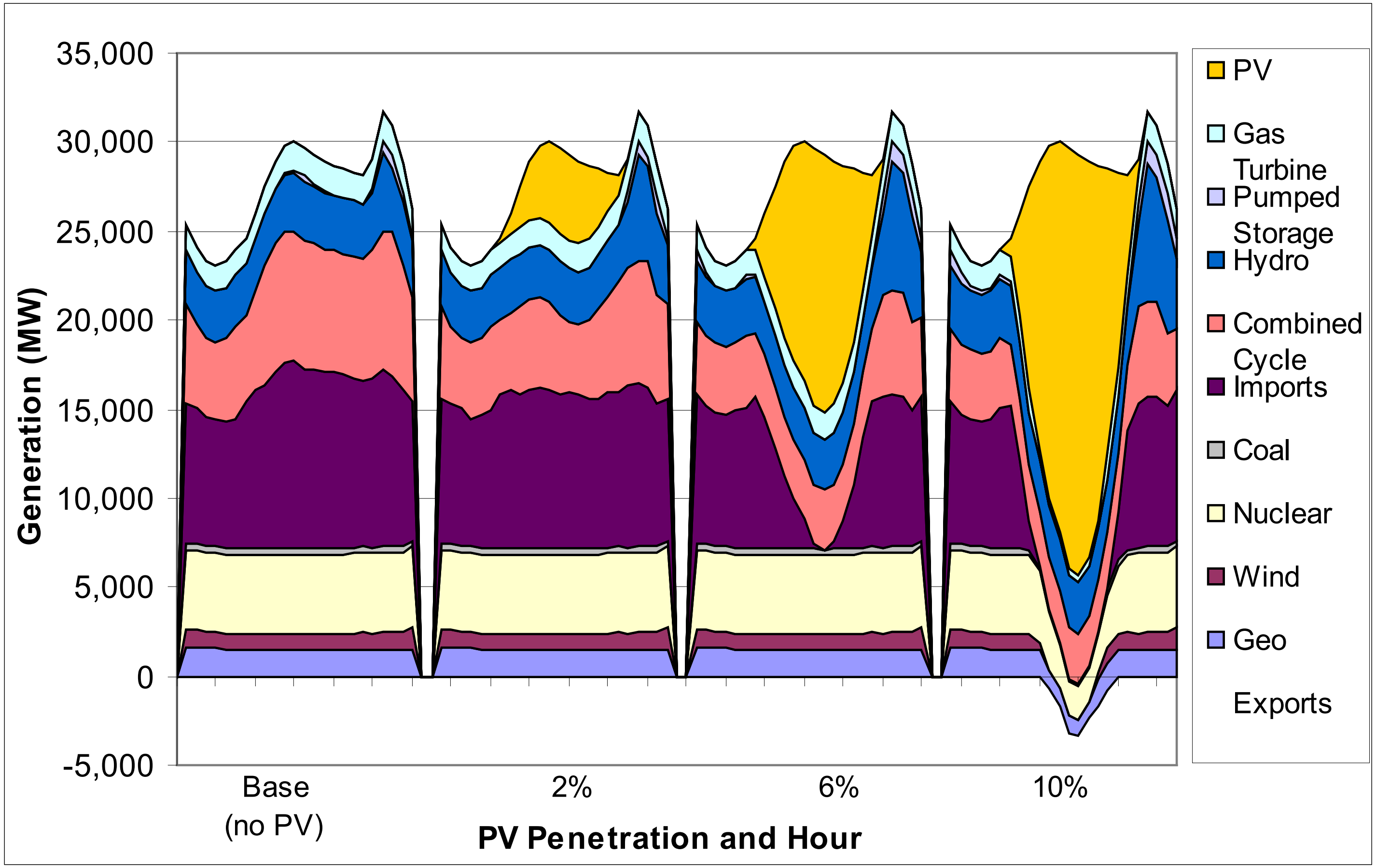
Carbon-free electricity prices



Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1'15 Report, 2. DOE EERE Wind Report, 2015

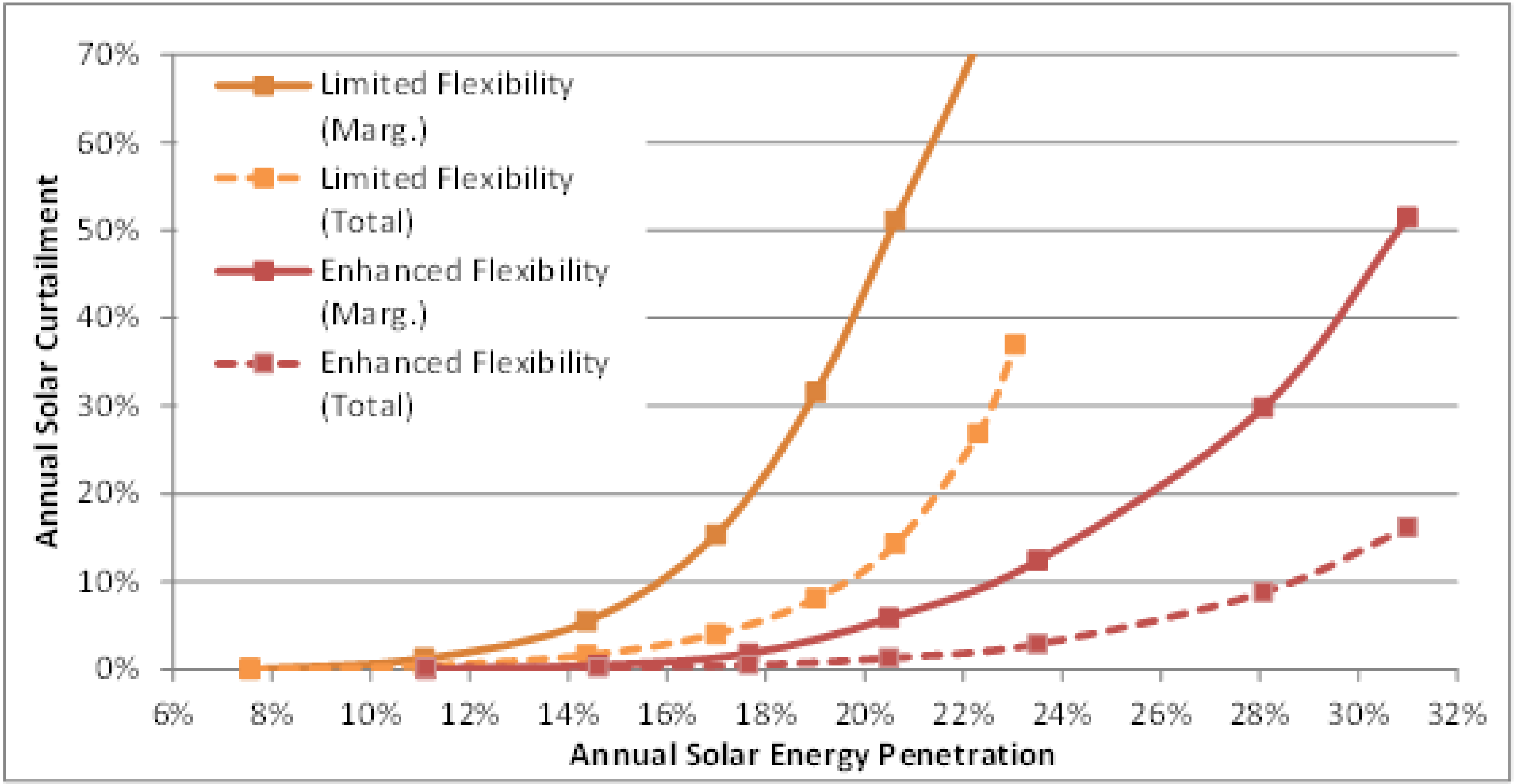
Renewable Challenges

Denholm et al. 2008



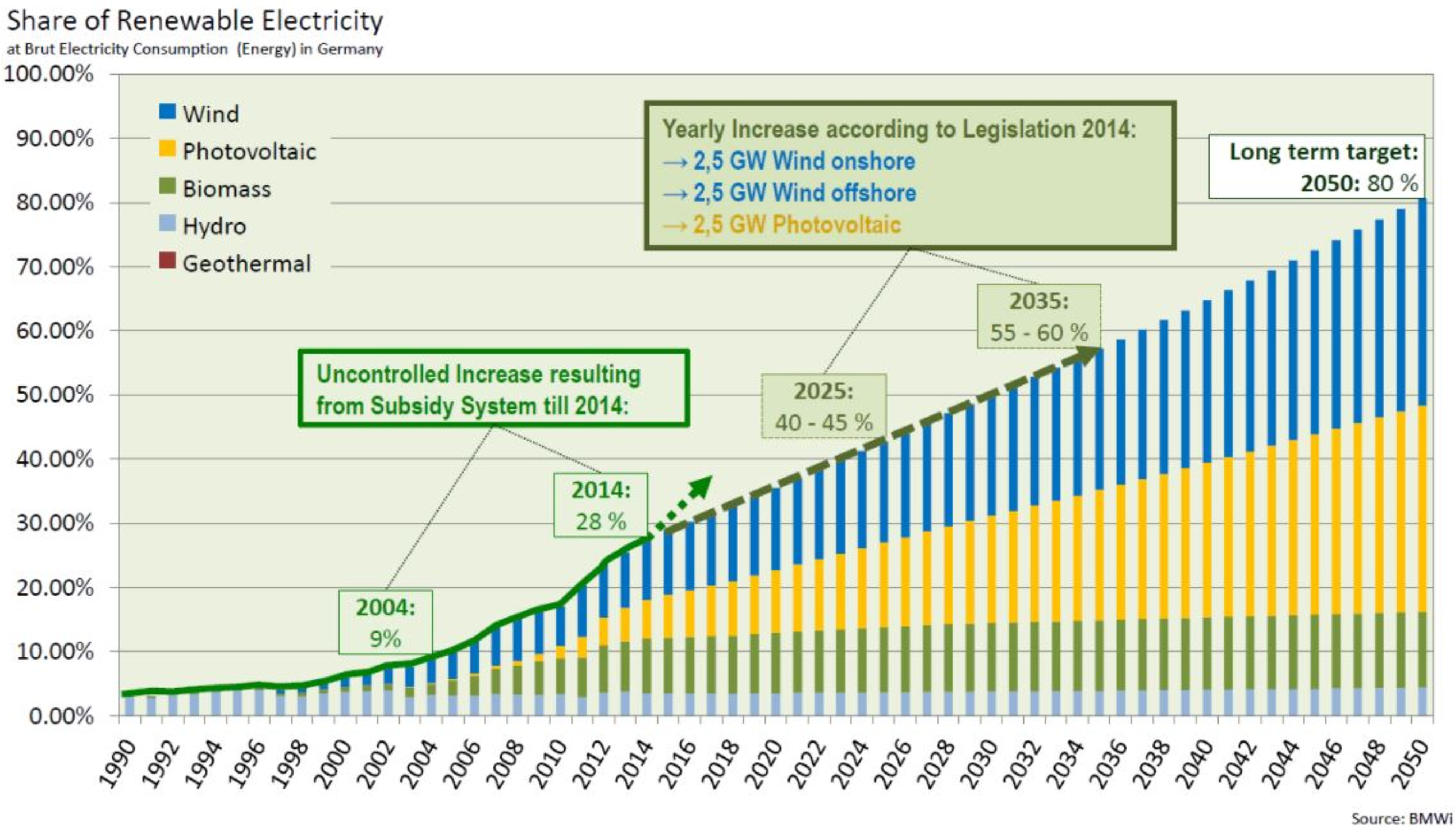
Limitations of Mismatched Load/Generation

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



Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

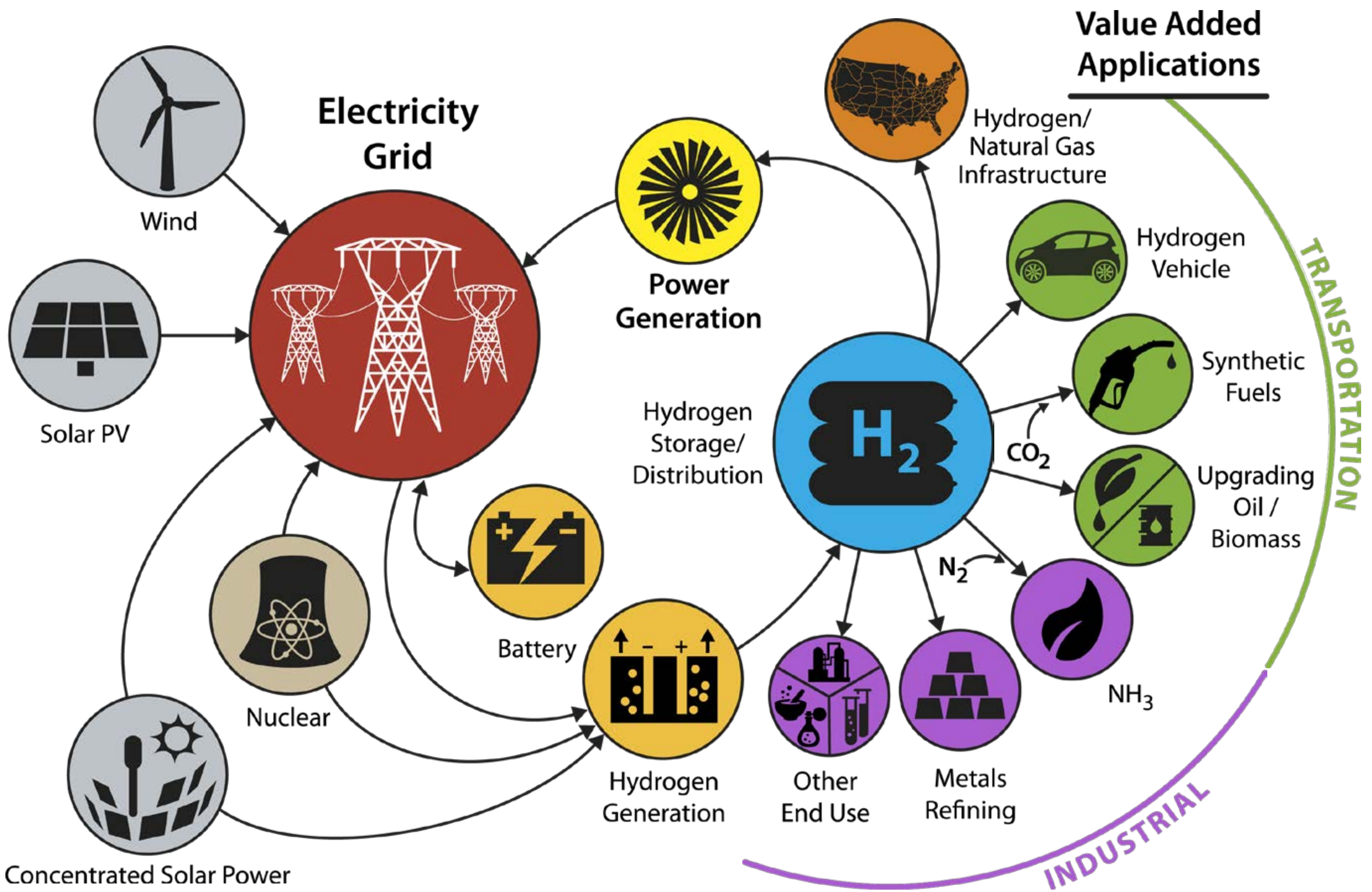
Example: Germany already limiting RE penetration rate



- **Dwight D. Eisenhower**

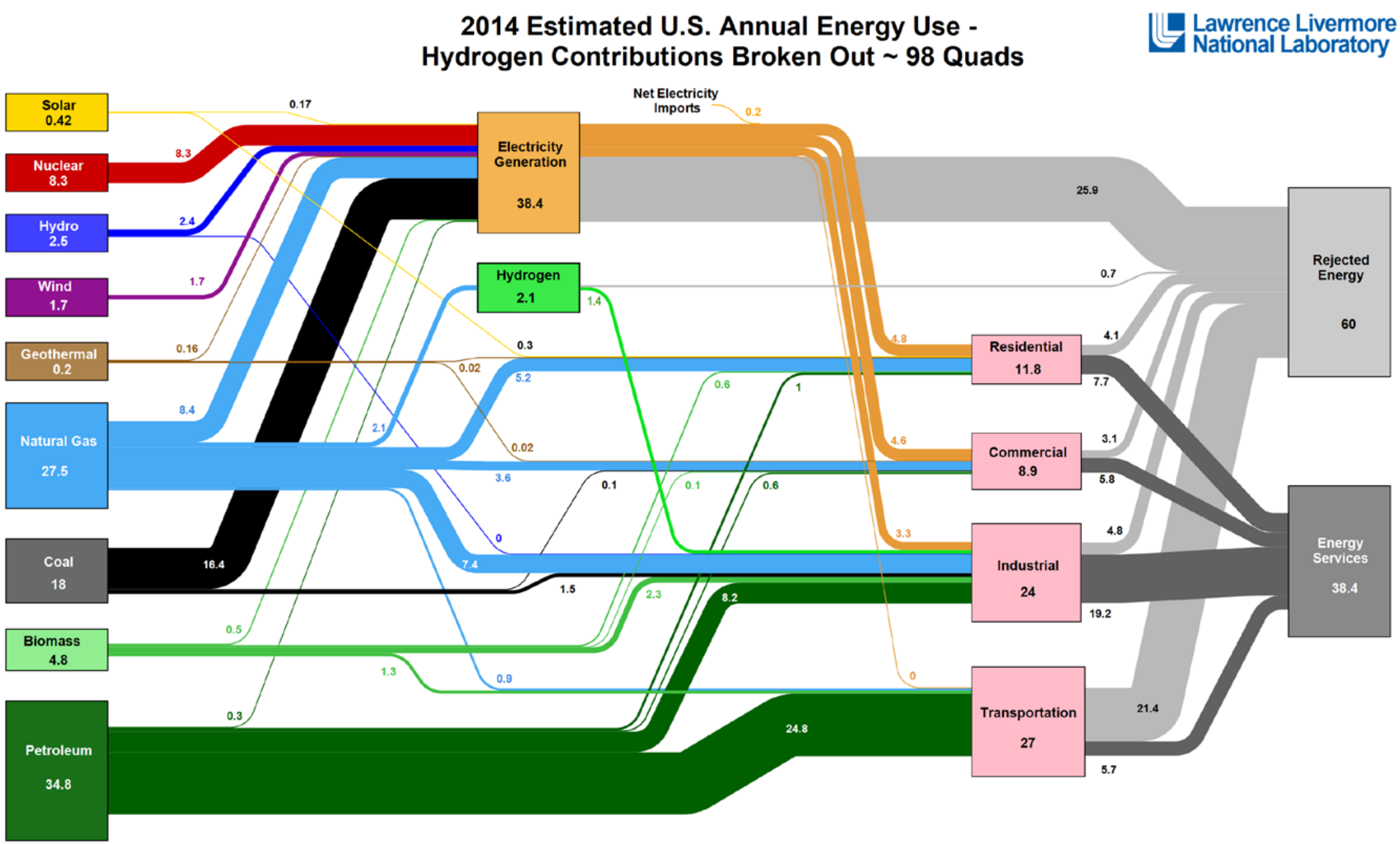
"If you can't solve a problem, enlarge it"

Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

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

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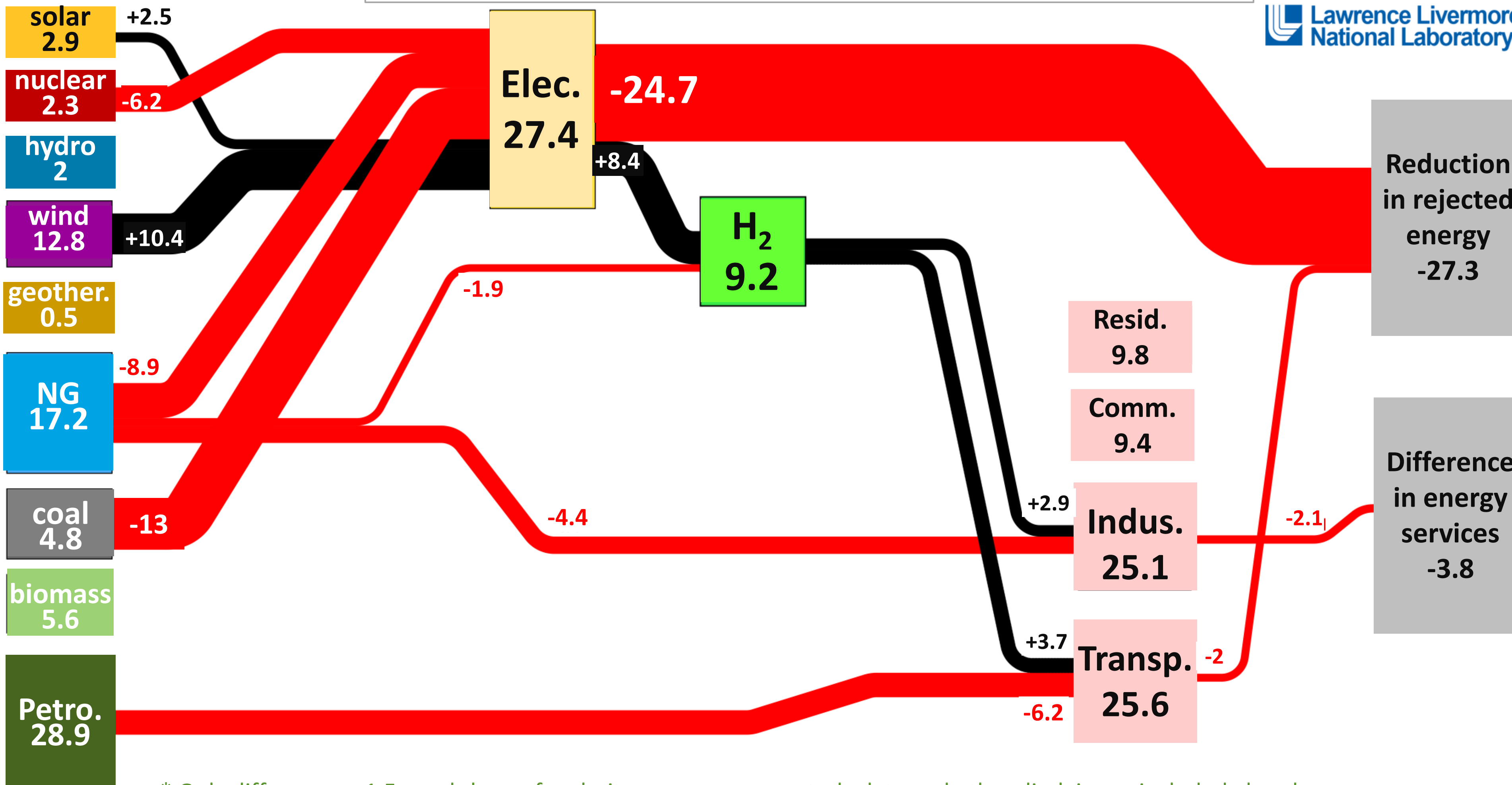
BAU (Business As Usual) vs. High H_2 – Energy Difference*

Energy Use difference between 2050 high-H_2 and AEO 2040 scenarios (Quad Btu)

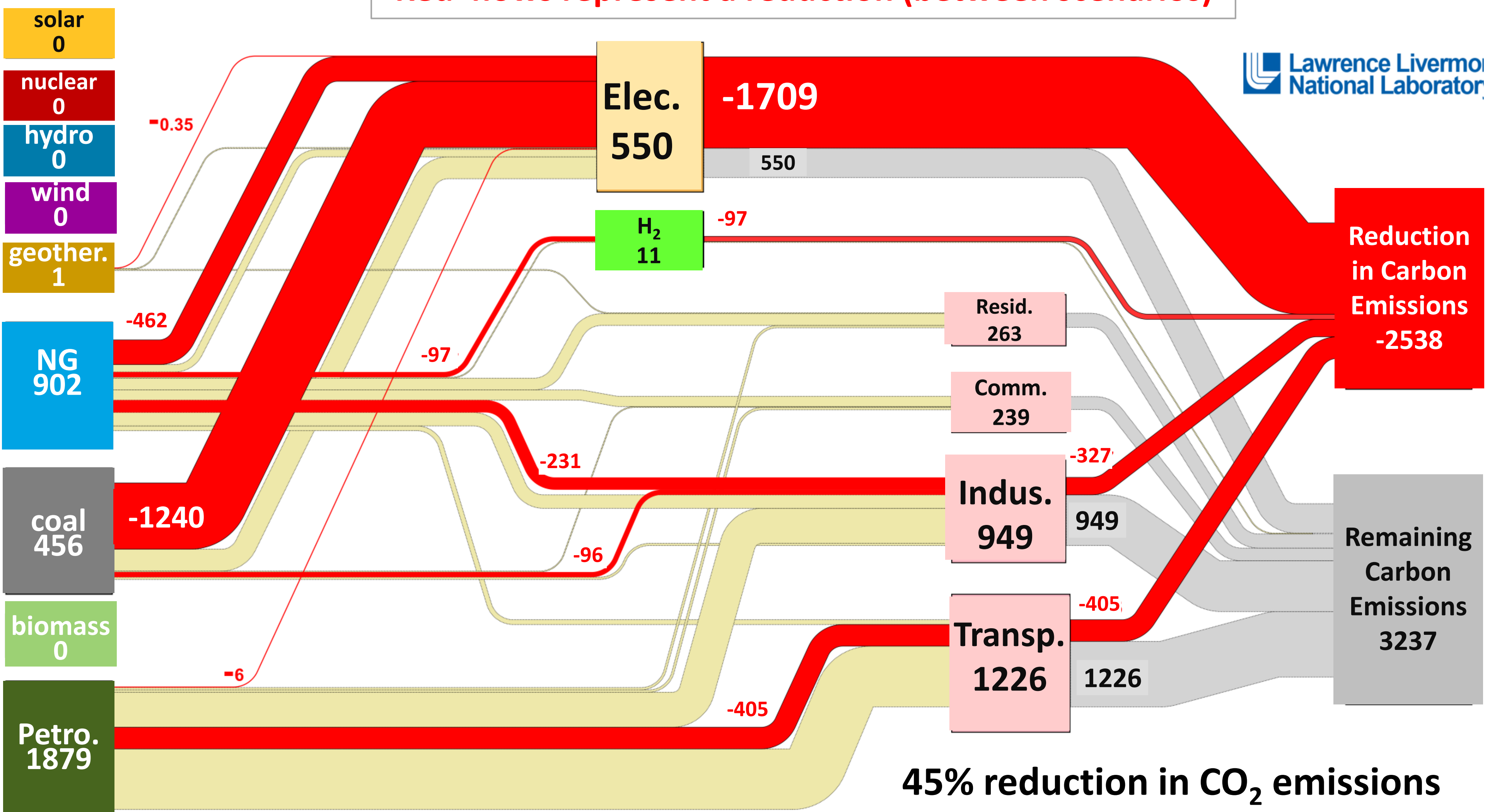
Red flows represent a reduction (between scenarios)
Black flows represent an increase (between scenarios)



* Only differences >1.5 quad shown for clarity purposes, case study data and other disclaimers included elsewhere

BAU (Business As Usual) vs. High H_2 – CO_2 Difference*

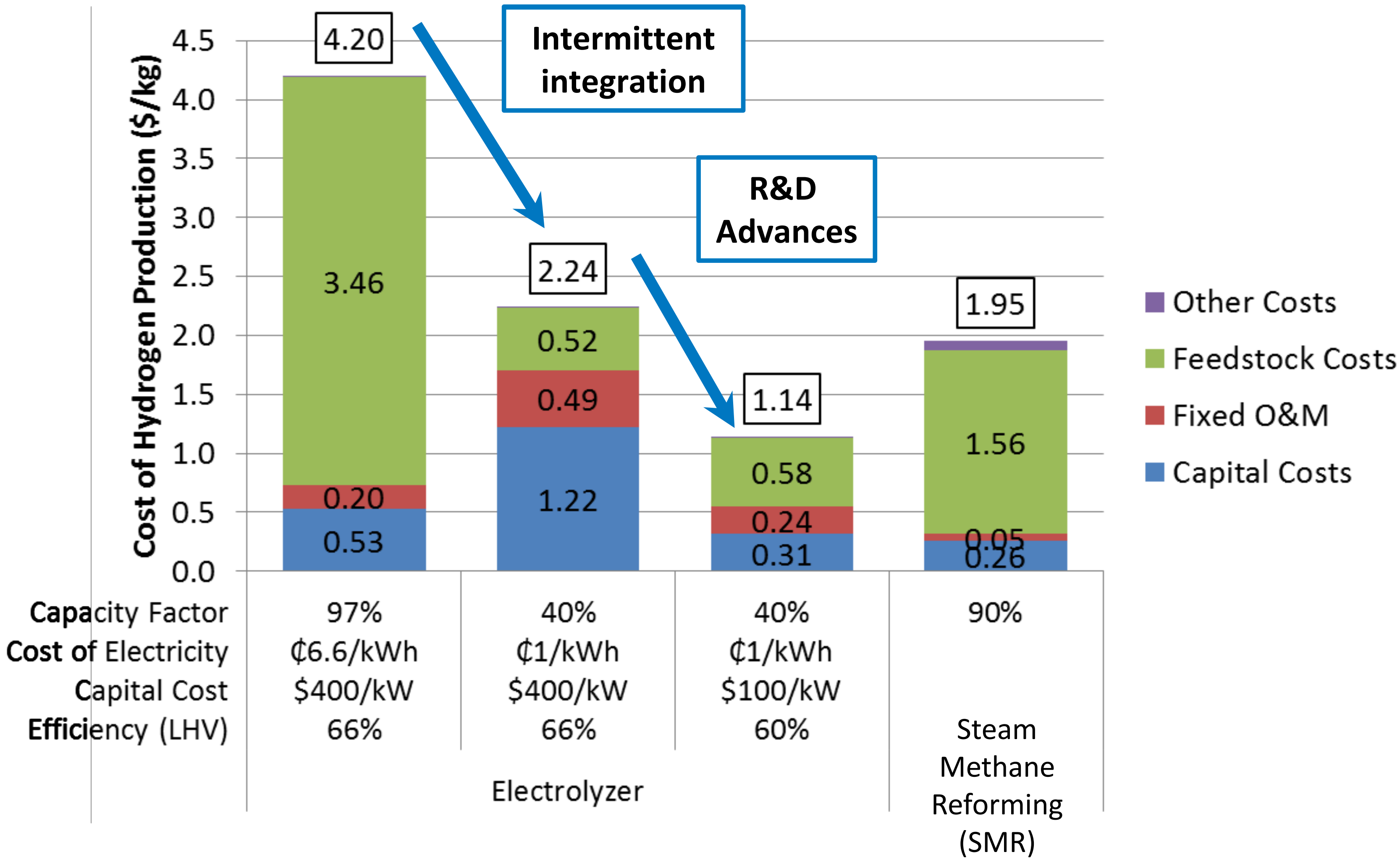
Emissions difference between 2050 high-H_2 and AEO 2040 scenarios (million MT)



45% reduction in CO_2 emissions

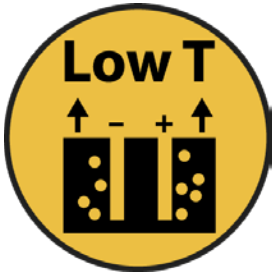
Grid 75%, Transportation 25%, Industrial 25%

Improving the Economics of Renewable H_2



What is needed to achieve H_2 at Scale?

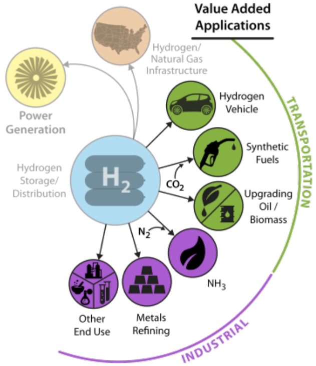
Low and High Temperature H_2 Generation		H_2 Storage and Distribution	H_2 Utilization



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

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

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



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

Analysis

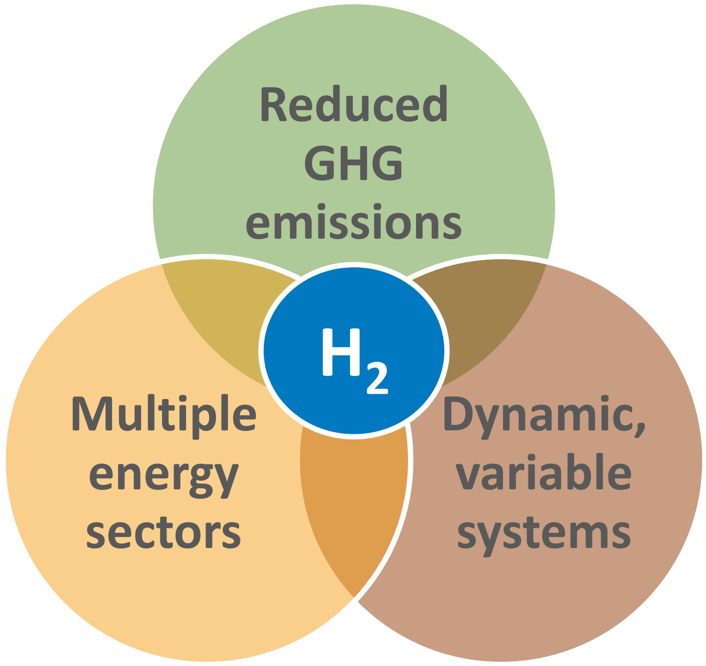
Foundational Science

Future Electrical Grid

H_2 at Scale Value Summary

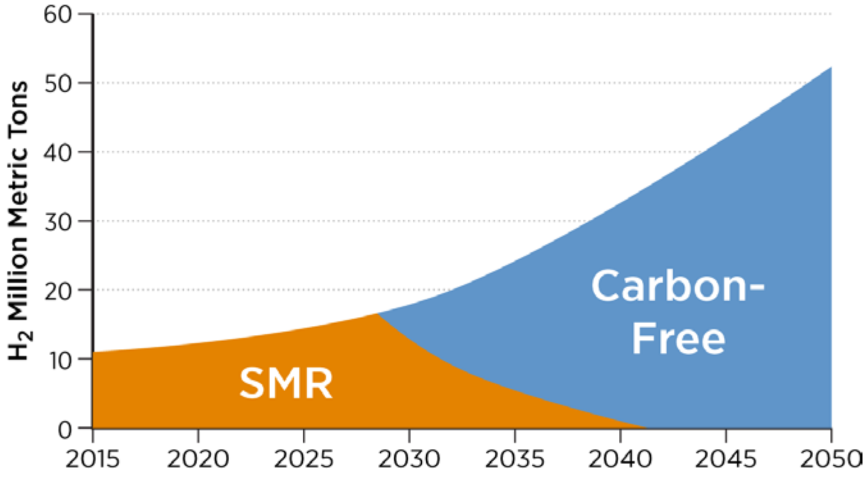
- Reducing emissions across sectors (GHG, criteria pollutants)
- Support needs of future energy system

Unique potential of H_2 to positively impact all these areas



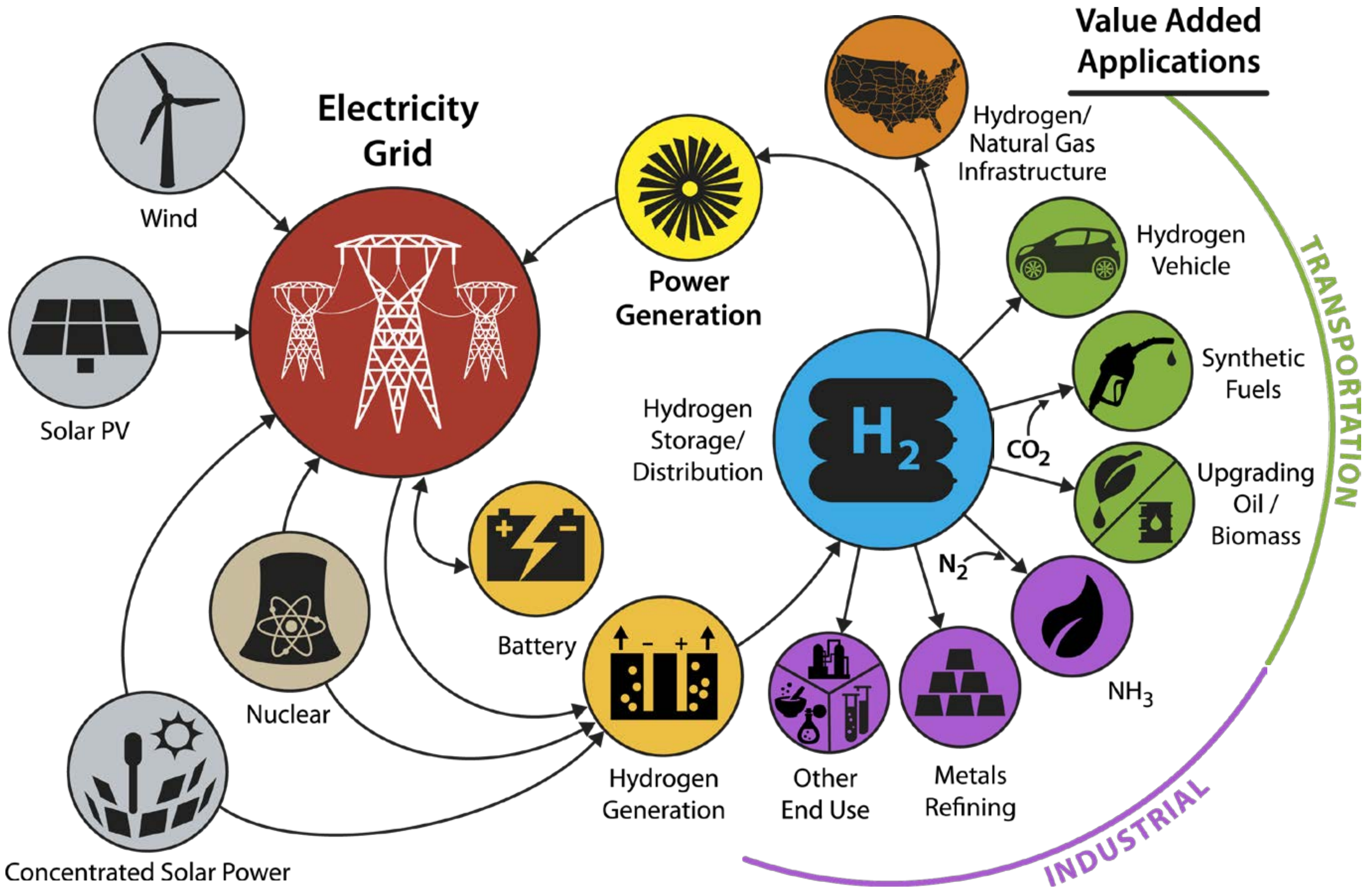
- Other benefits
  - Energy security (diversity/resiliency/domestic)
  - Manufacturing competitiveness/ job creation
  - Decreased water requirements

What does success look like?



- **Back up slides**

Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

H_2 at Scale Big Idea Teams/Acknowledgement

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), Adam Weber (LBNL), Rod Borup (LANL), Mark Ruth (NREL), Jamie Holladay (PNNL), Chris Moen (SNL), Don Anton (SRNL)

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High T Generation:

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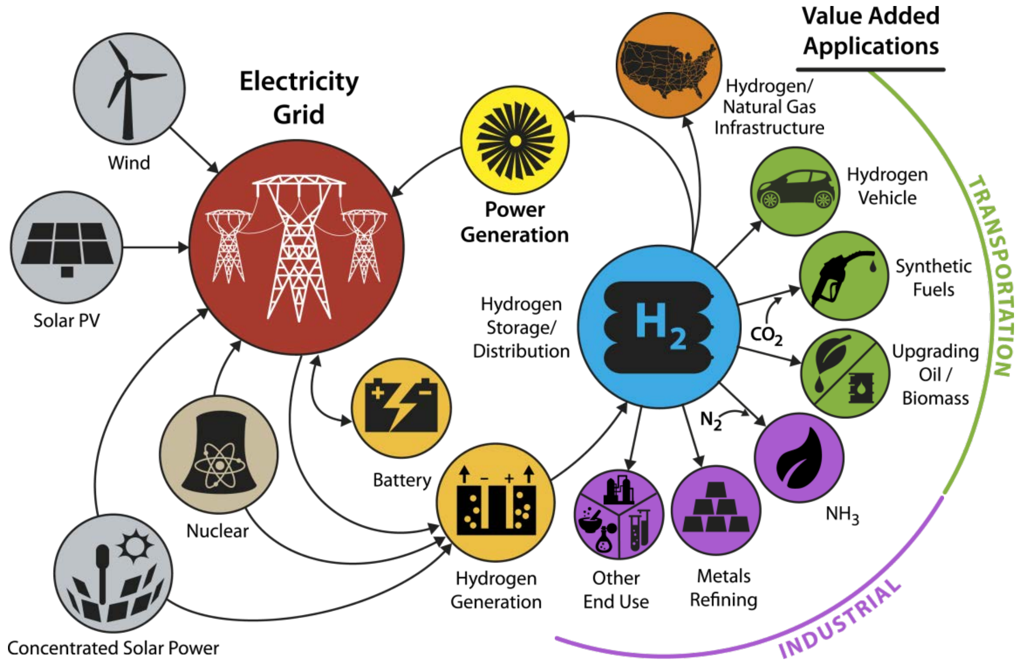
  - Fuel Cell Technologies Office
  - Transportation Working Group
- **Office of Nuclear Energy**
- **Office of Electricity Delivery and Energy Reliability**

- **Engagement with**
  - Office of Fossil Energy
  - Office of Science

Stakeholder Groups

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

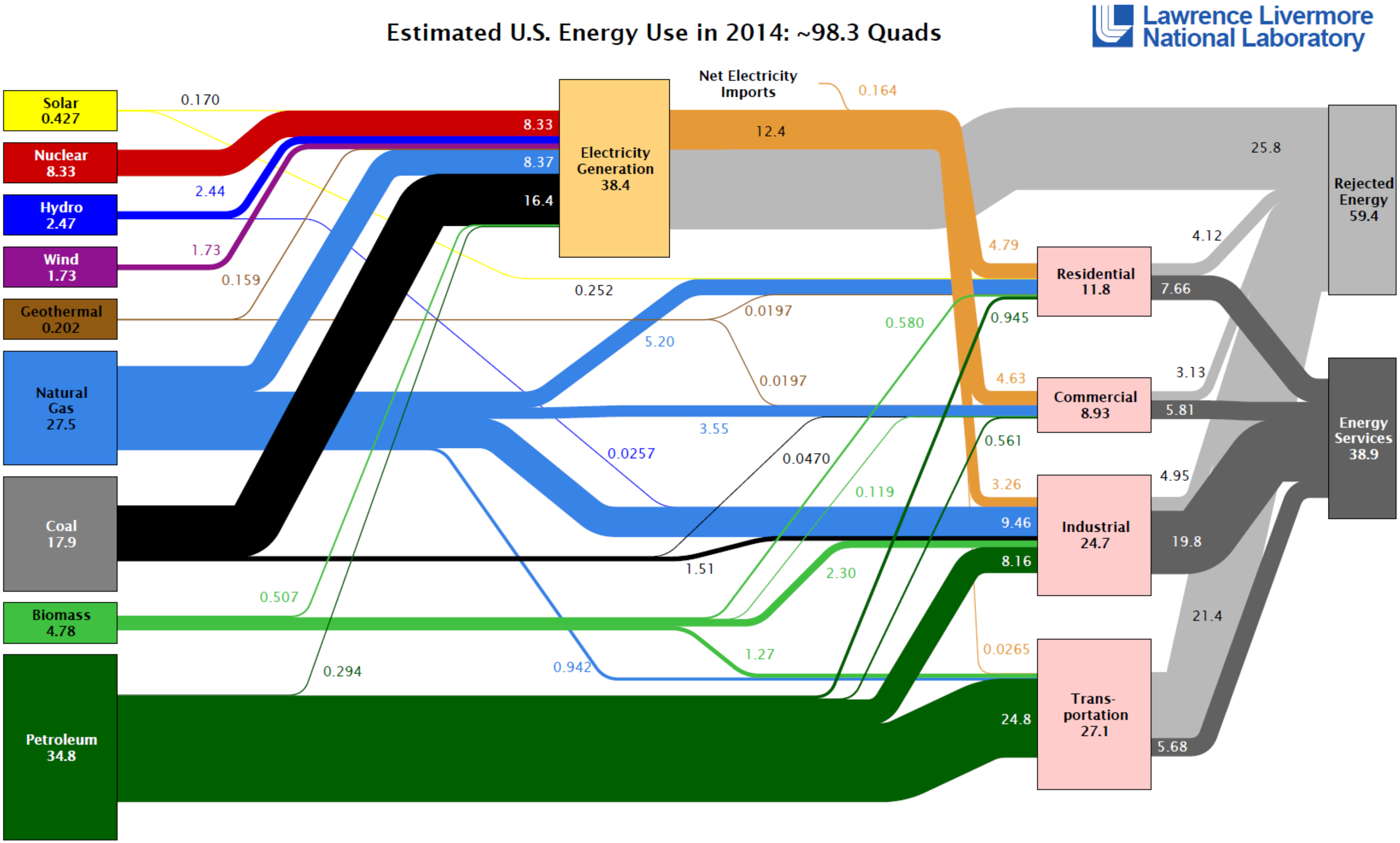
- Analysis
- Investors



H_2 at Scale Roadmap

duce intermittent H_2
production capital to \$300/kW
(\$3-8/kg H_2)

Current Energy Flow



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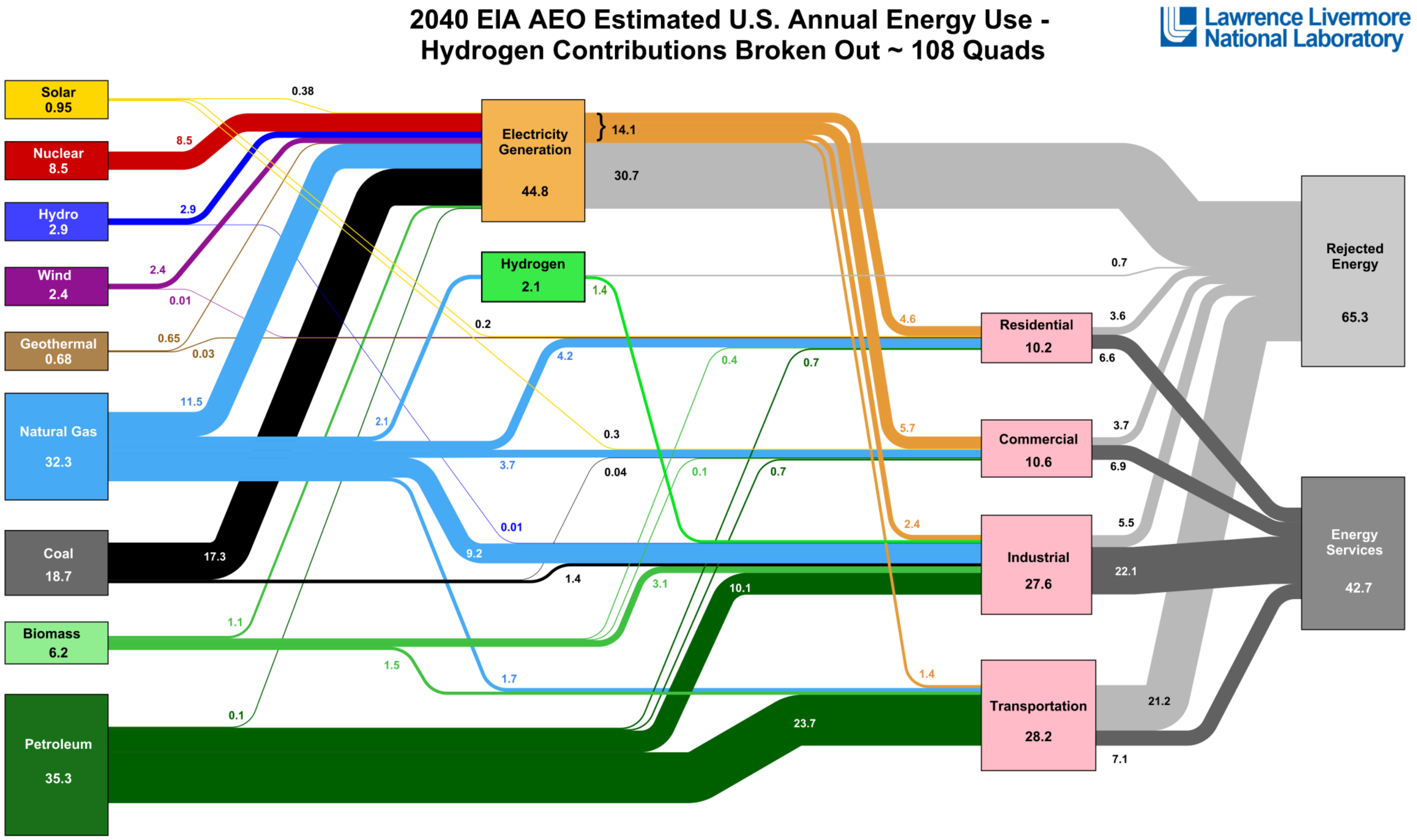
Energy Flow 2040 Business as Usual



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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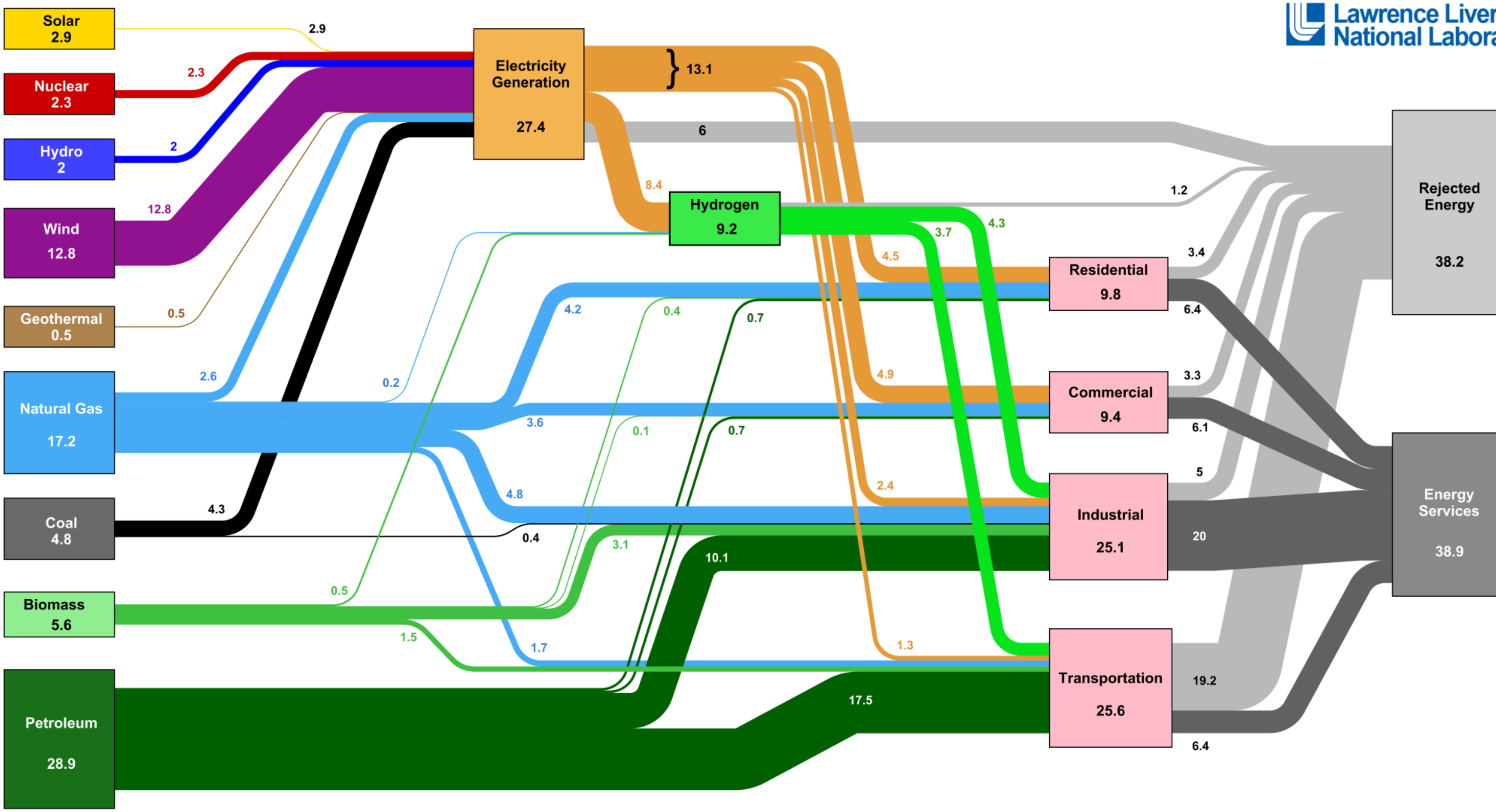
Energy Flows – 2050 High RE/H_2

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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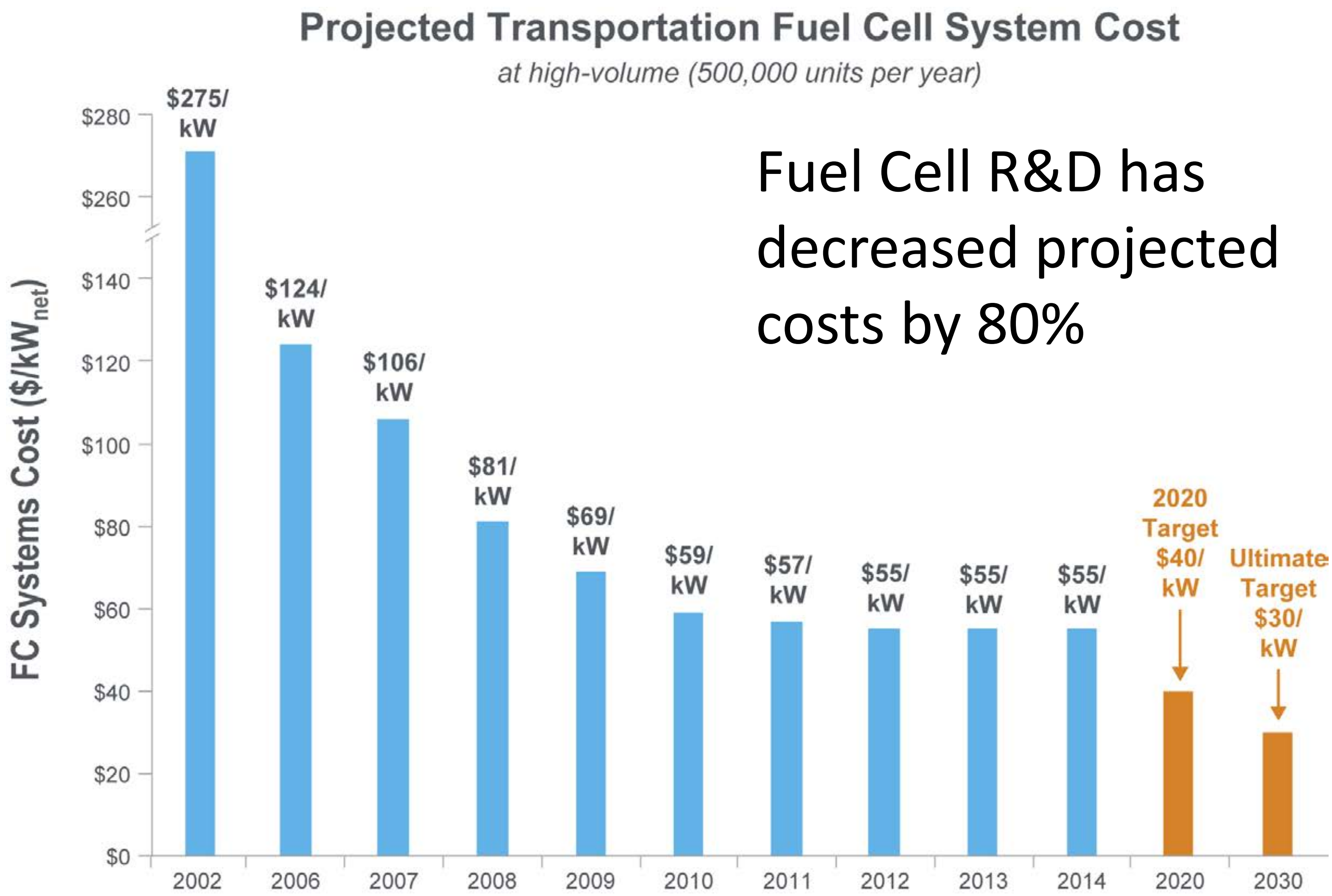
Investments to Enable H_2 at Scale

R&D Impact on Fuel Cell Costs



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

Data from FCTO AMR presentations.