H2@SCALE : Deeply Decarbonizing our Energy System

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Presenter:
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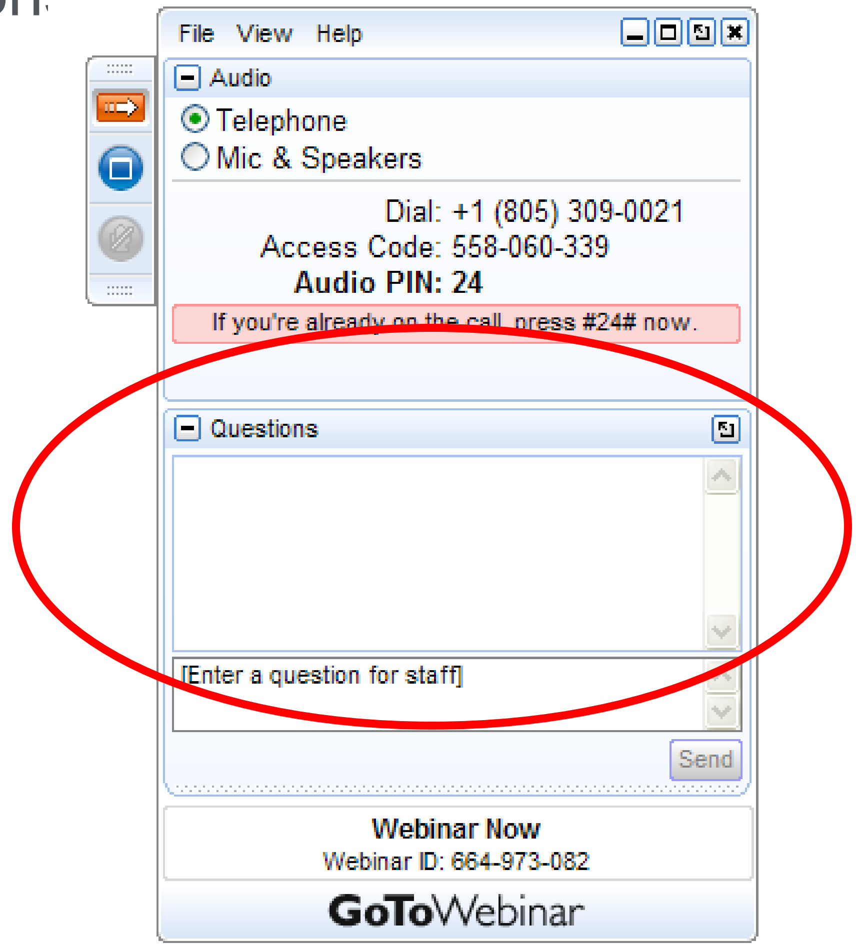
DOE Host:
Erika Gupta : Fuel Cell Technologies Office

U.S. Department of Energy
Fuel Cell Technologies Office
July 28th, 2016

Question and Answer

- Please type your questions into the question box



H_2 at Scale:

Deeply Decarbonizing our Energy System

Webinar

July 28, 2016

Presented by Bryan Pivovar
National Renewable Energy Lab
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Acknowledgements

- **Department of Energy (DOE), Energy Efficiency and Renewable Energy (EERE)**
  - 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

Webinar content

- What is hydrogen at scale?
- Why is it needed?
- Why now/today?
- What can it accomplish?
- How will it be accomplished?
- Why government, national labs, academia, and industry are all needed?
- What does success look like?

Several factors impacting ‘status’ of H2

- **Hydrogen is not new.**
  - Has seen ups and downs
  - Most have a preconceived opinion, but complexity of hydrogen and changing environment present challenges
- **Hydrogen is different**
  - Perception (incl. Safety)
  - Infrastructure (cost)
- **Lack of champion(s) (established revenue)**

H_2 "Fun Facts"

- H_2:
  - Has 10 million metric tons of domestic production (gasoline, fertilizer)
  - This is 2% of US energy and is approximately equal to solar and wind combined today.
  - Has over 1600 miles of pipelines in the US
  - Has been used in over 1000 fuel cell vehicles with several million miles of vehicle travel
  - Has fueling stations for vehicles open to the public in the US today

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 lacking within DOE portfolio
- Culminated in a DOE/National Lab Big Idea Summit (April 21-22, 2016).
- Major opportunity for H_2 visibility and applications across sectors aligned with Climate goals

H_2 at Scale Big Idea Teams/Acknowledgement

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), Mark Hartney (SLAC), Vitalij Pecharsky (Ames); Alex Harris (BNL); Geo Richards (NETL)

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

Low T Generation:

Rod Borup (lead, LANL); Jamie Holladay (co-lead, 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)

Future Electric Grid:

Art Pontau (lead, SNL); Art Anderson (NREL); Bryan Hannegan (NREL); Chris San Marchi (SNL); Charles Hanley (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); Vitalij Pecharsky (Ames)

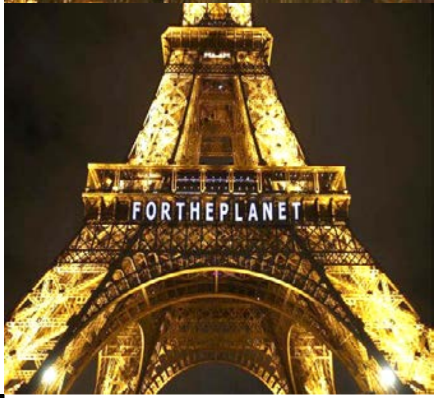
Analysis:

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)

Key Driver- Paris Agreement at COP 21

"Let that be the common purpose here in Paris. A world that is worthy of our children. A world that is marked not by conflict, but **by cooperation**; and not by human suffering, but by human progress. A world that's safer, and more prosperous, and more secure, and more free than the one that we inherited. **Let's get to work**."

- President Barack Obama at the launch of COP21

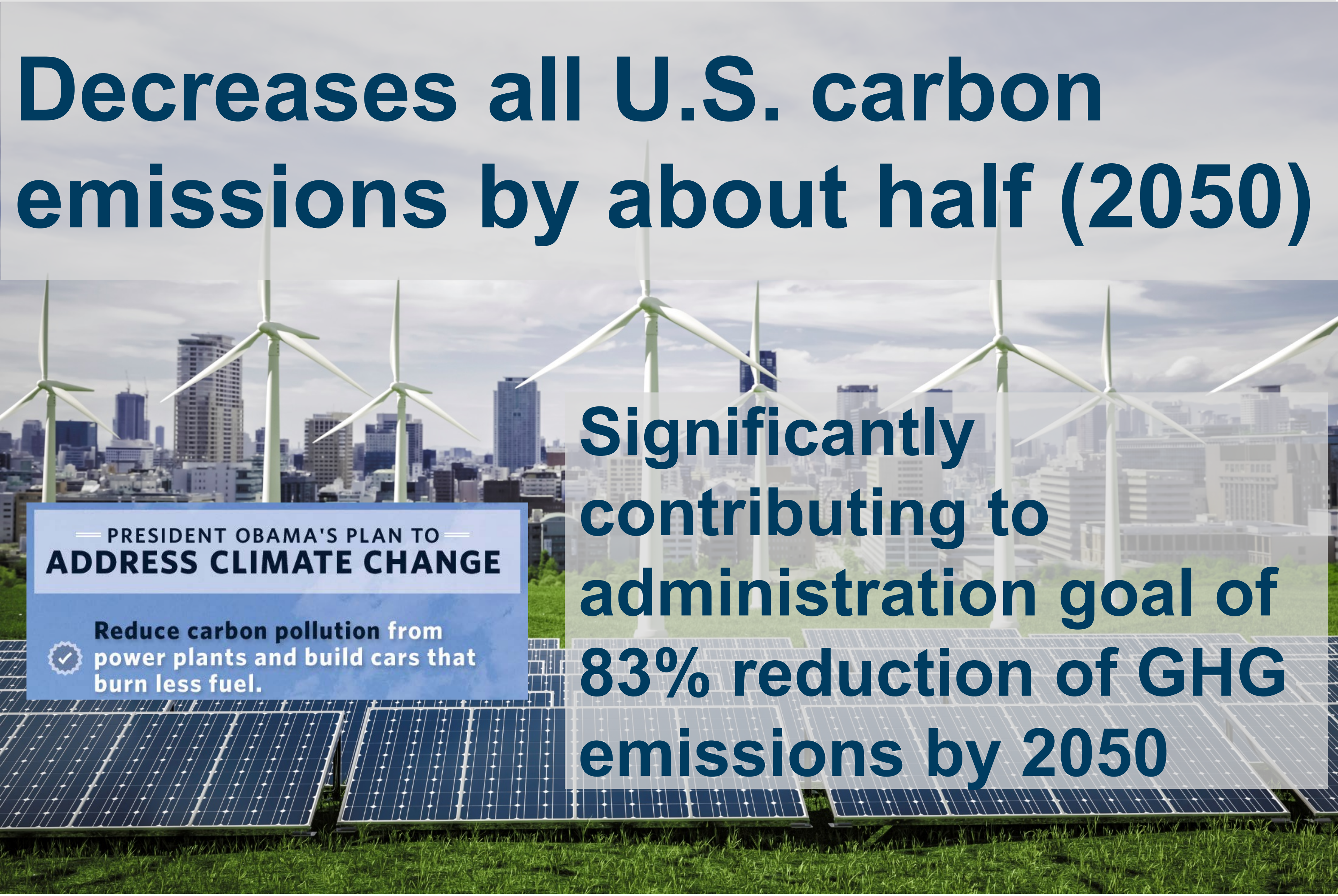


PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Why hydrogen?.....Our Energy System

H_2@Scale enables green processes and increased renewable penetration that

Decreases all U.S. carbon emissions by about half (2050)



Significantly contributing to administration goal of 83% reduction of GHG emissions by 2050

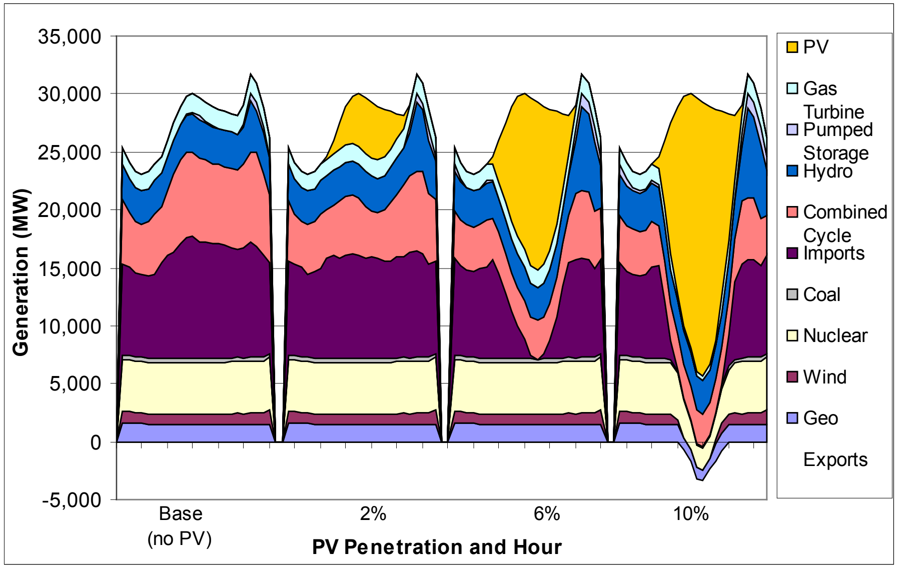
Energy System Challenges

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

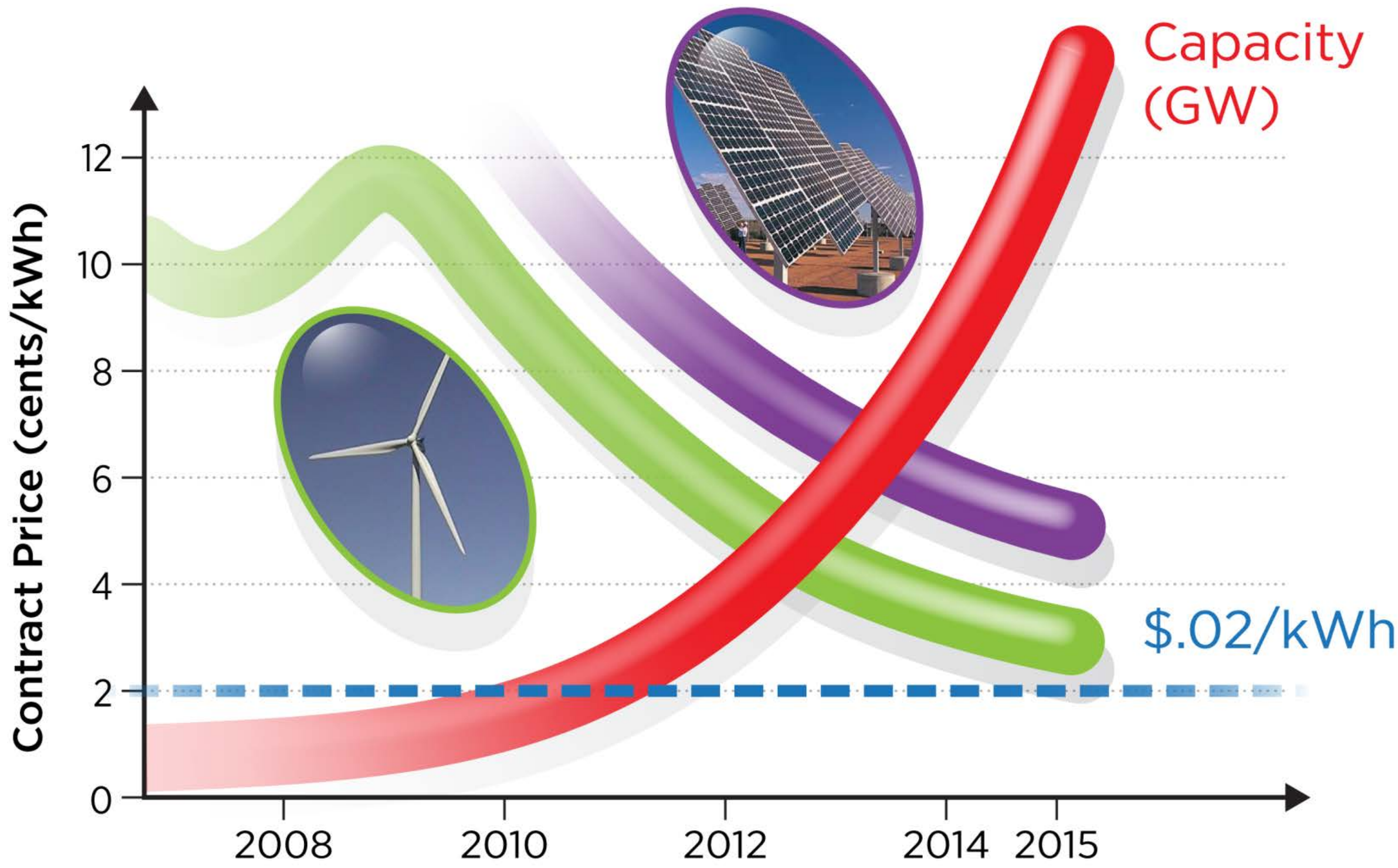
Over half of U.S. CO_2 emissions come from the industrial and transportation sectors

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

Denholm et al. 2008



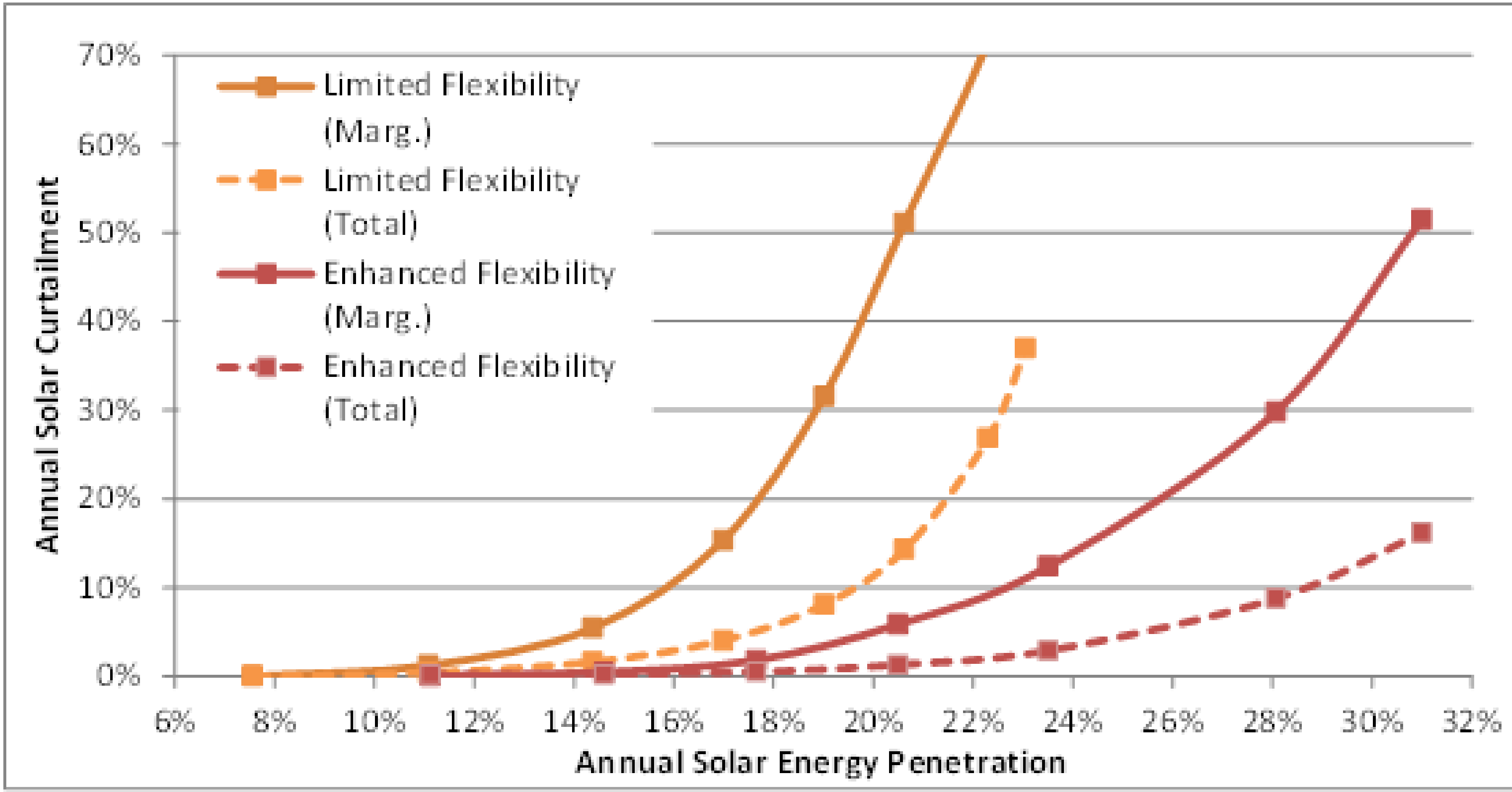
Why now? Carbon-free electricity prices



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

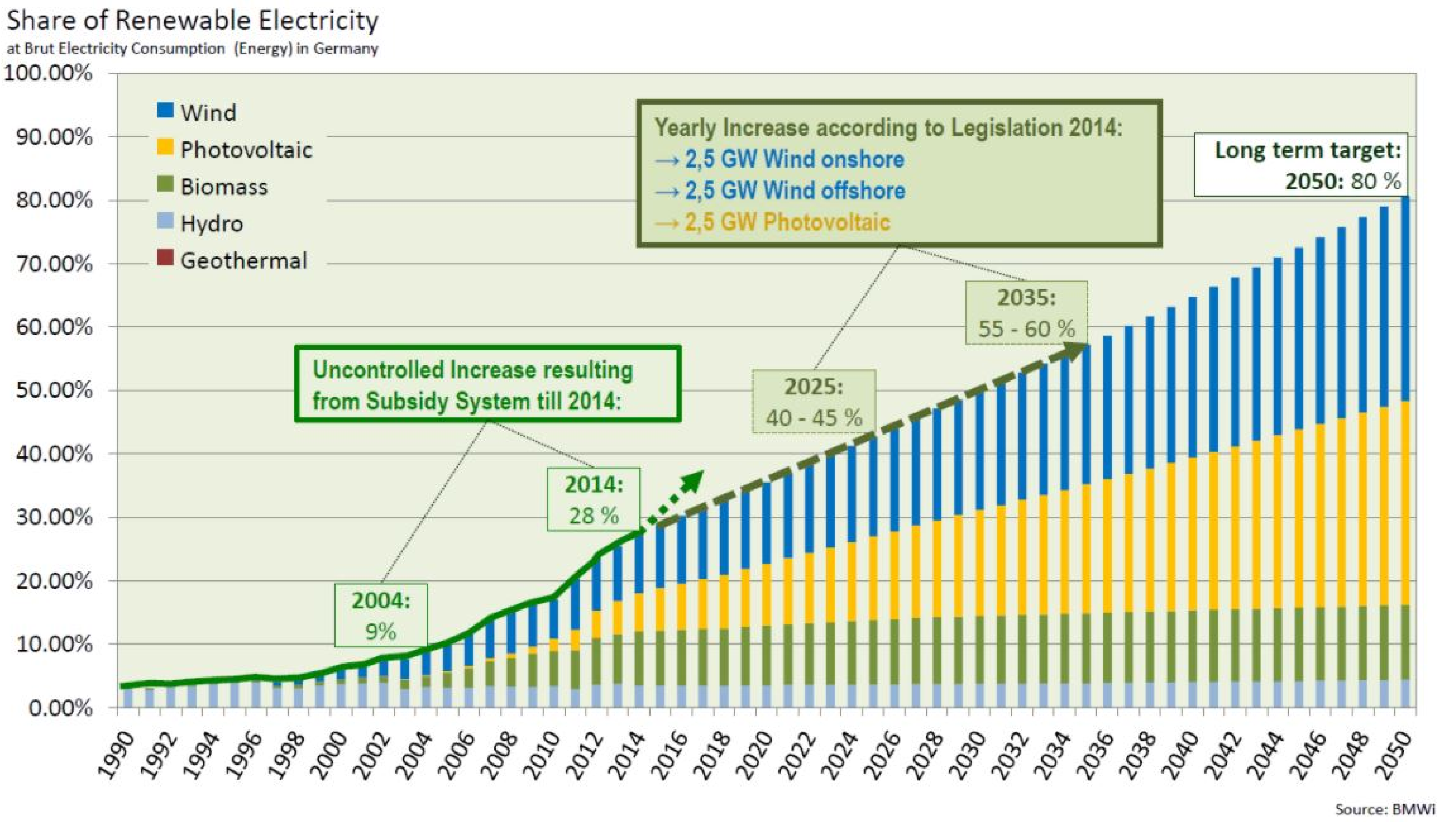
Limitations of Mismatched Load/Generation

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

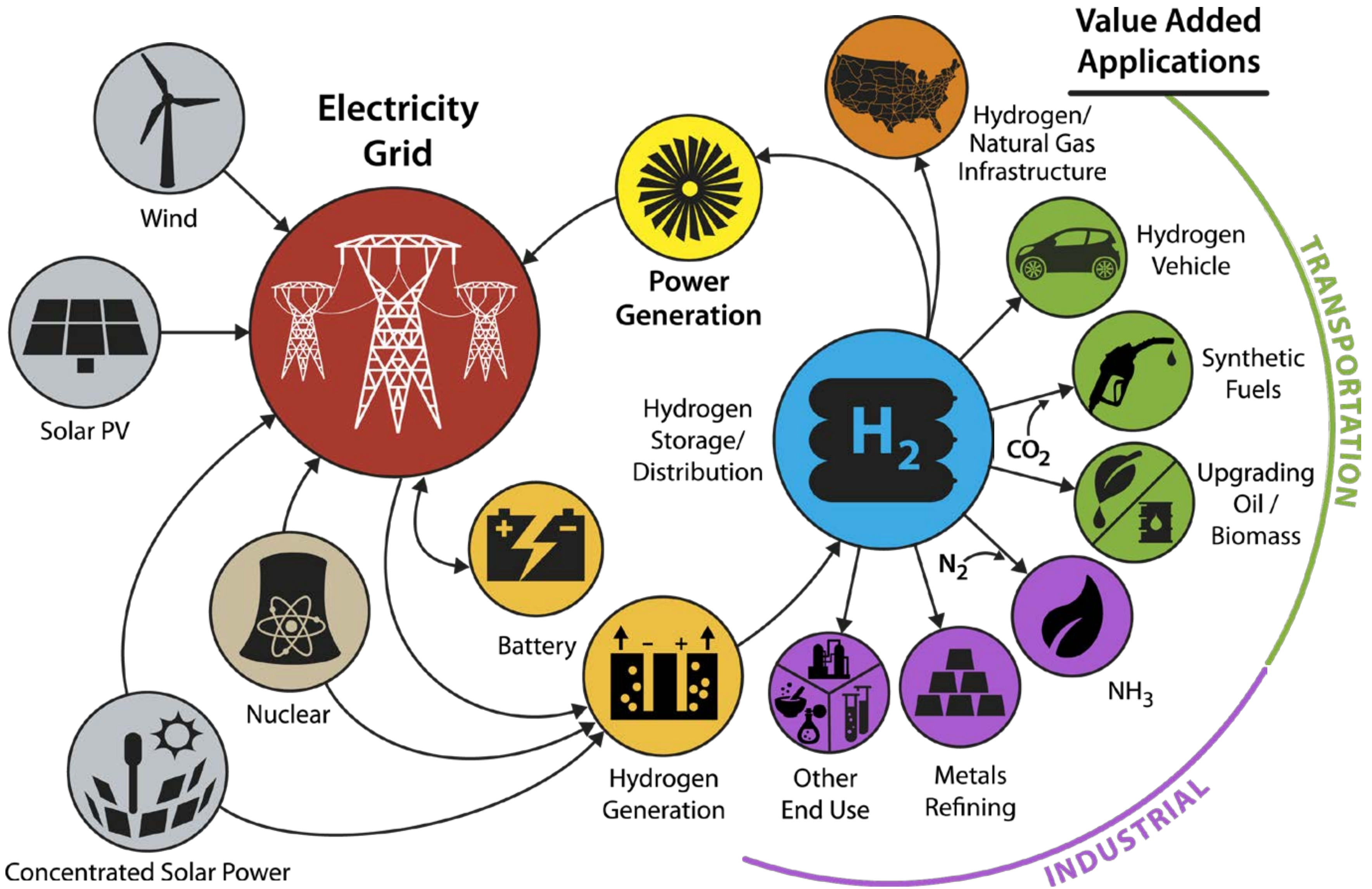


Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

Example: Germany already limiting RE penetration rate

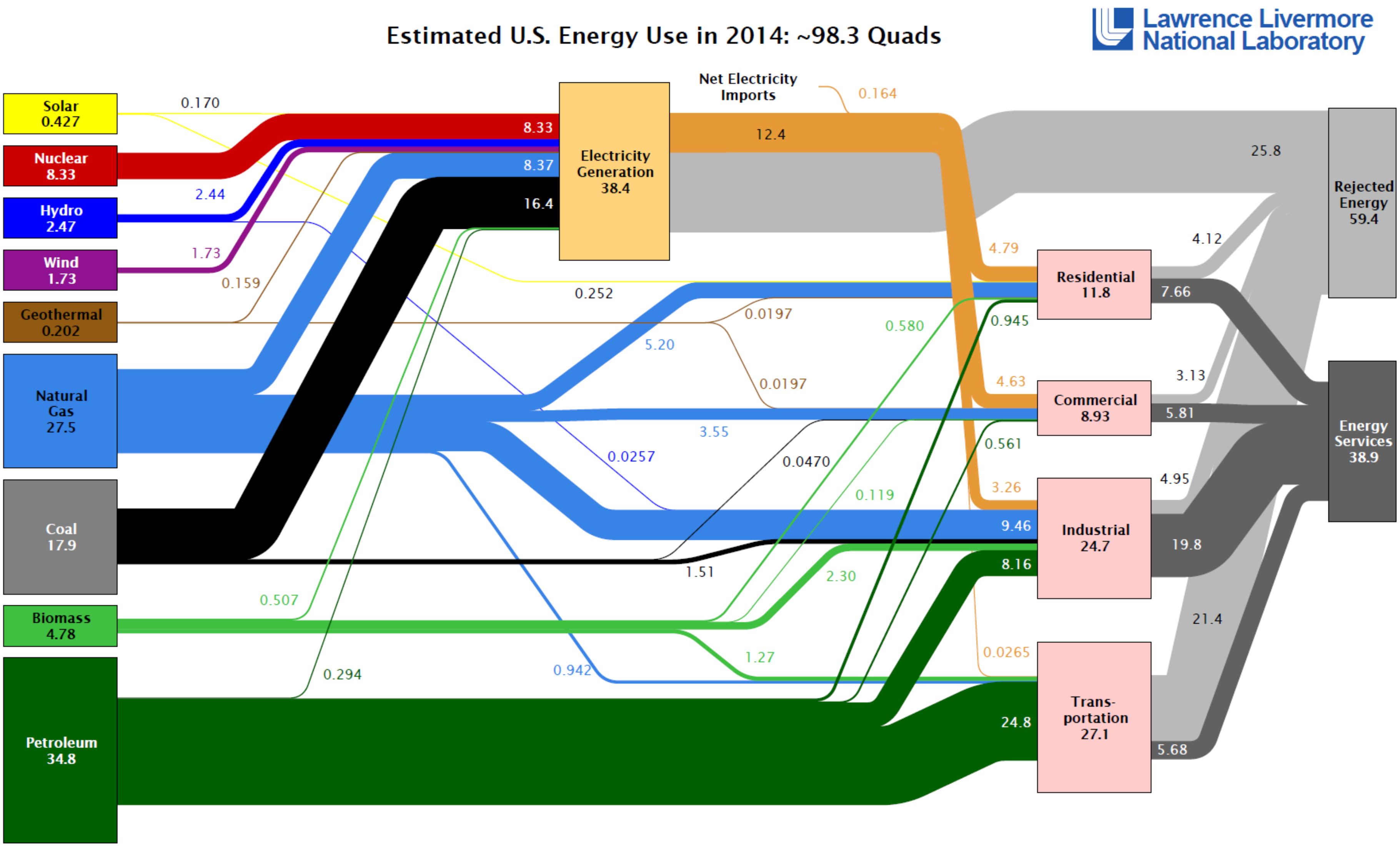


Conceptual H_2 at Scale Energy System*



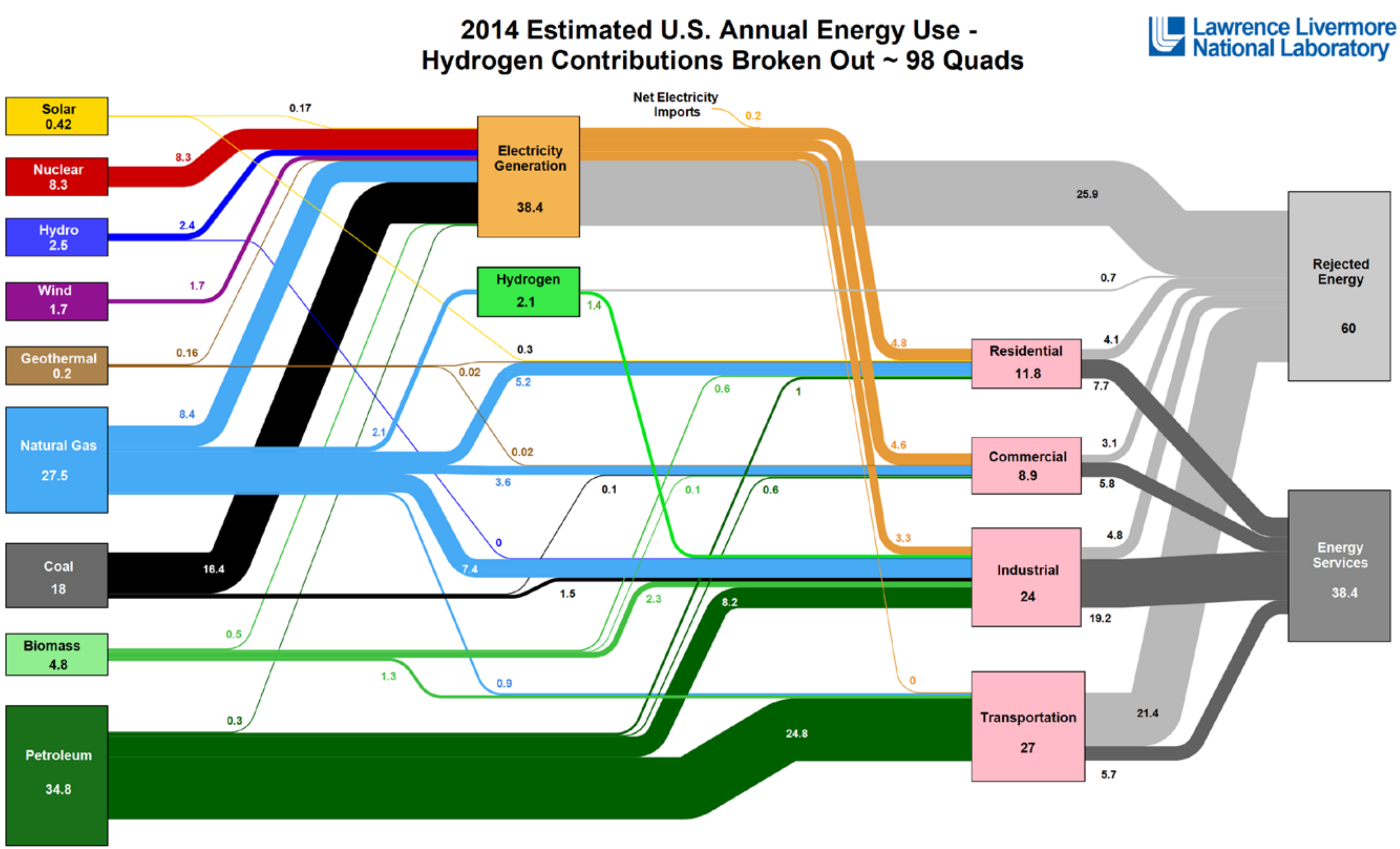
*Illustrative example, not comprehensive

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

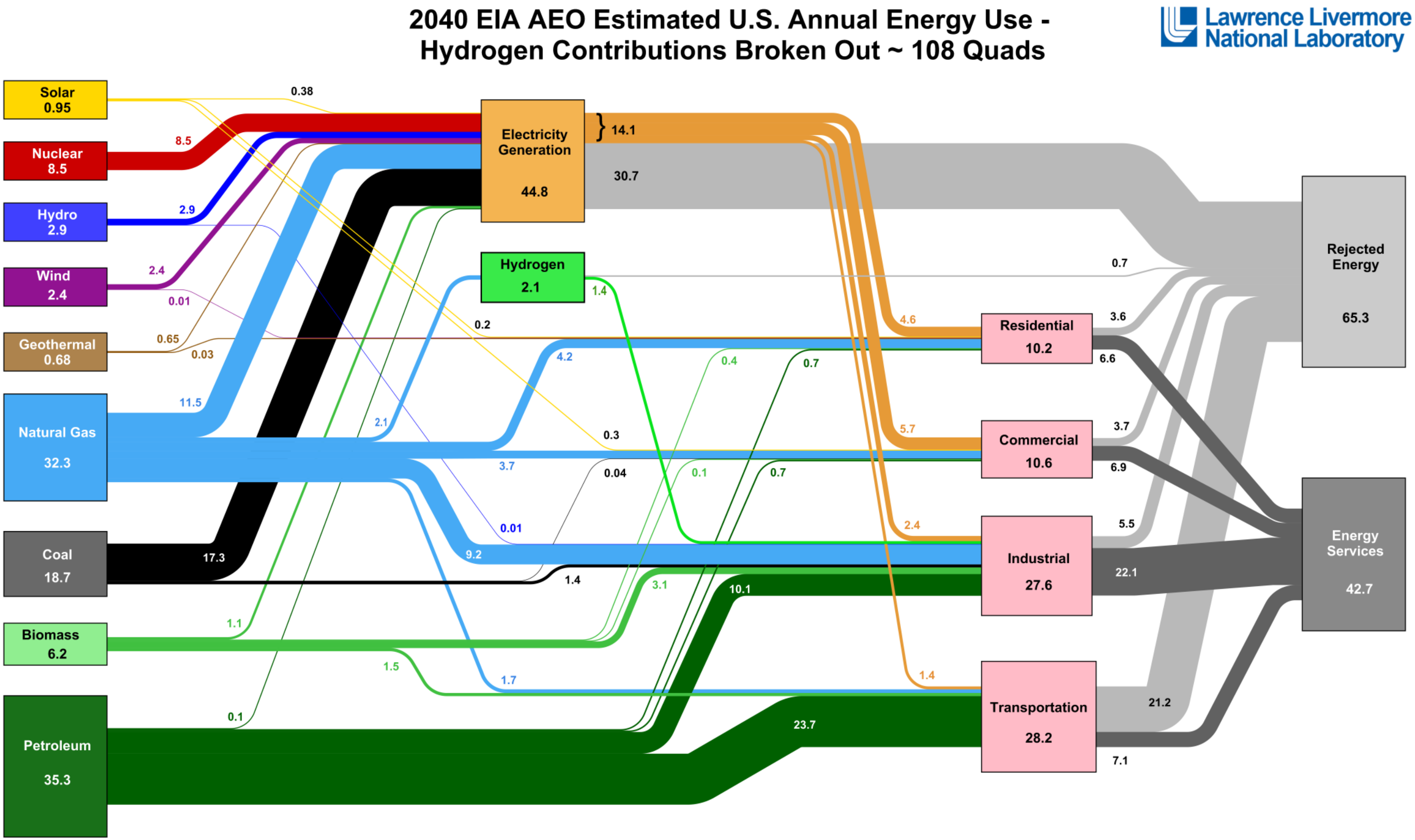
Current Energy Flow – w/Hydrogen



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



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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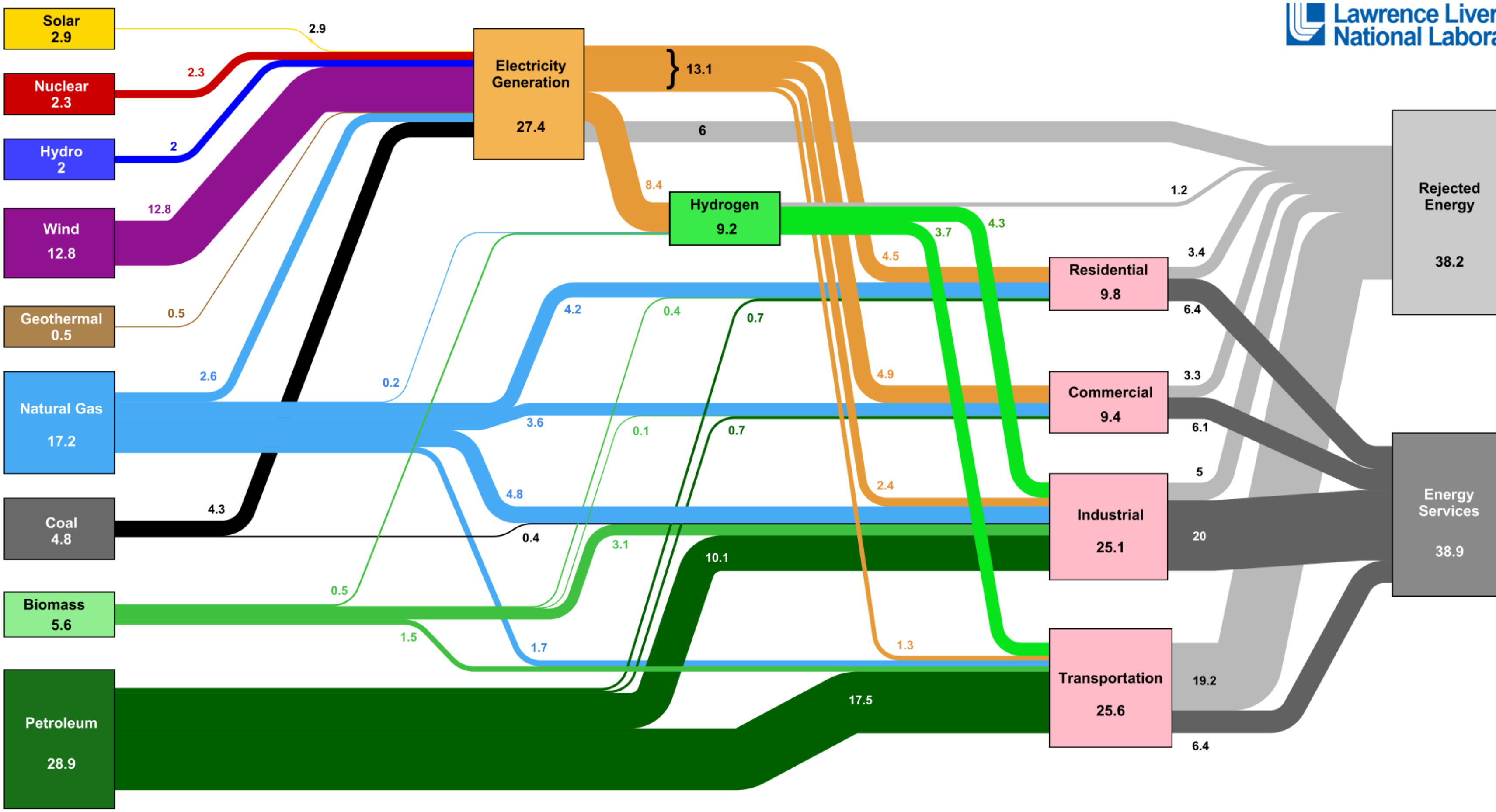
Energy Flows – 2050 High RE/H_2

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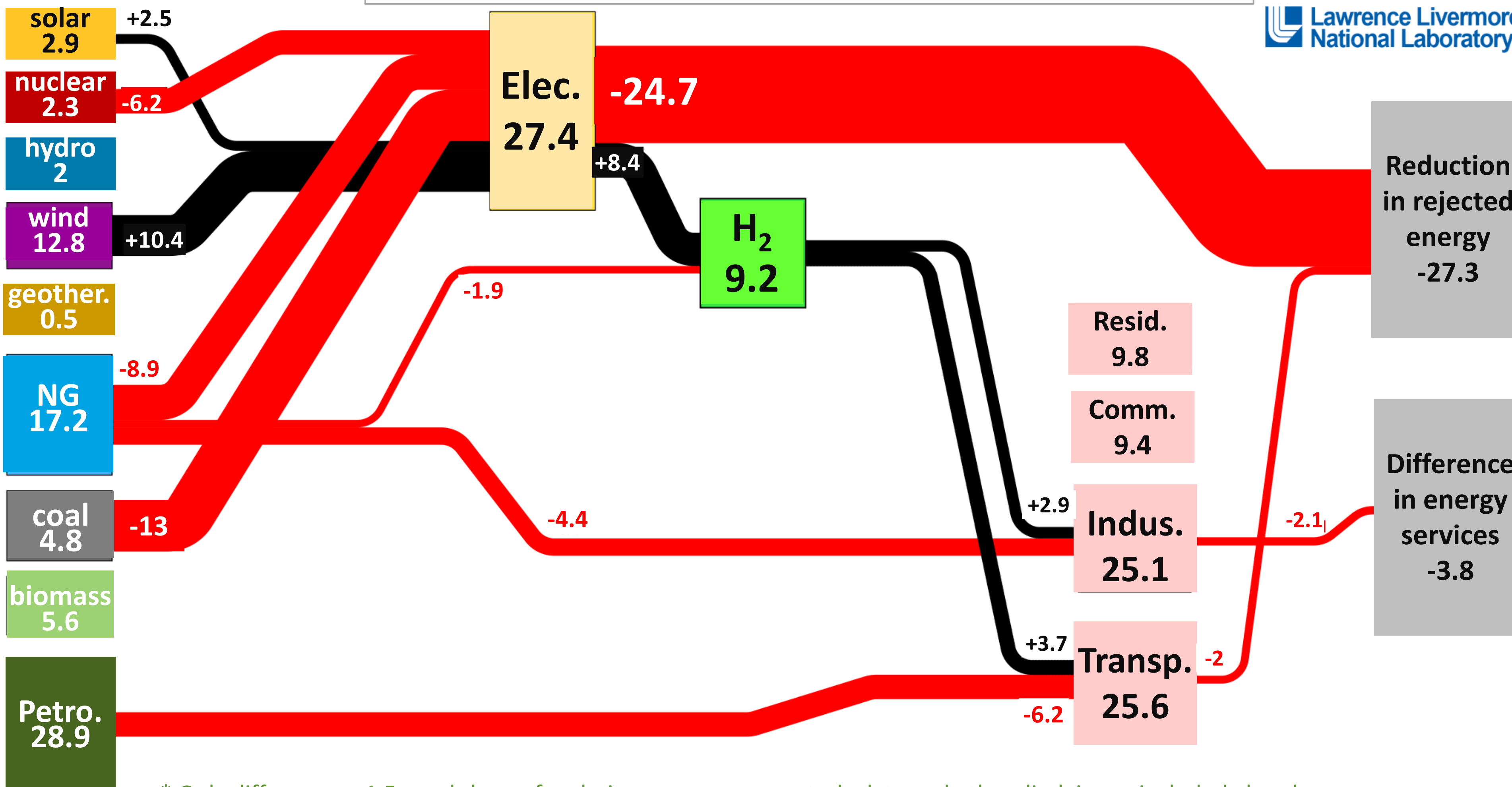
BAU(Business As Usual) vs. High H_2 – Energy Difference*

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)

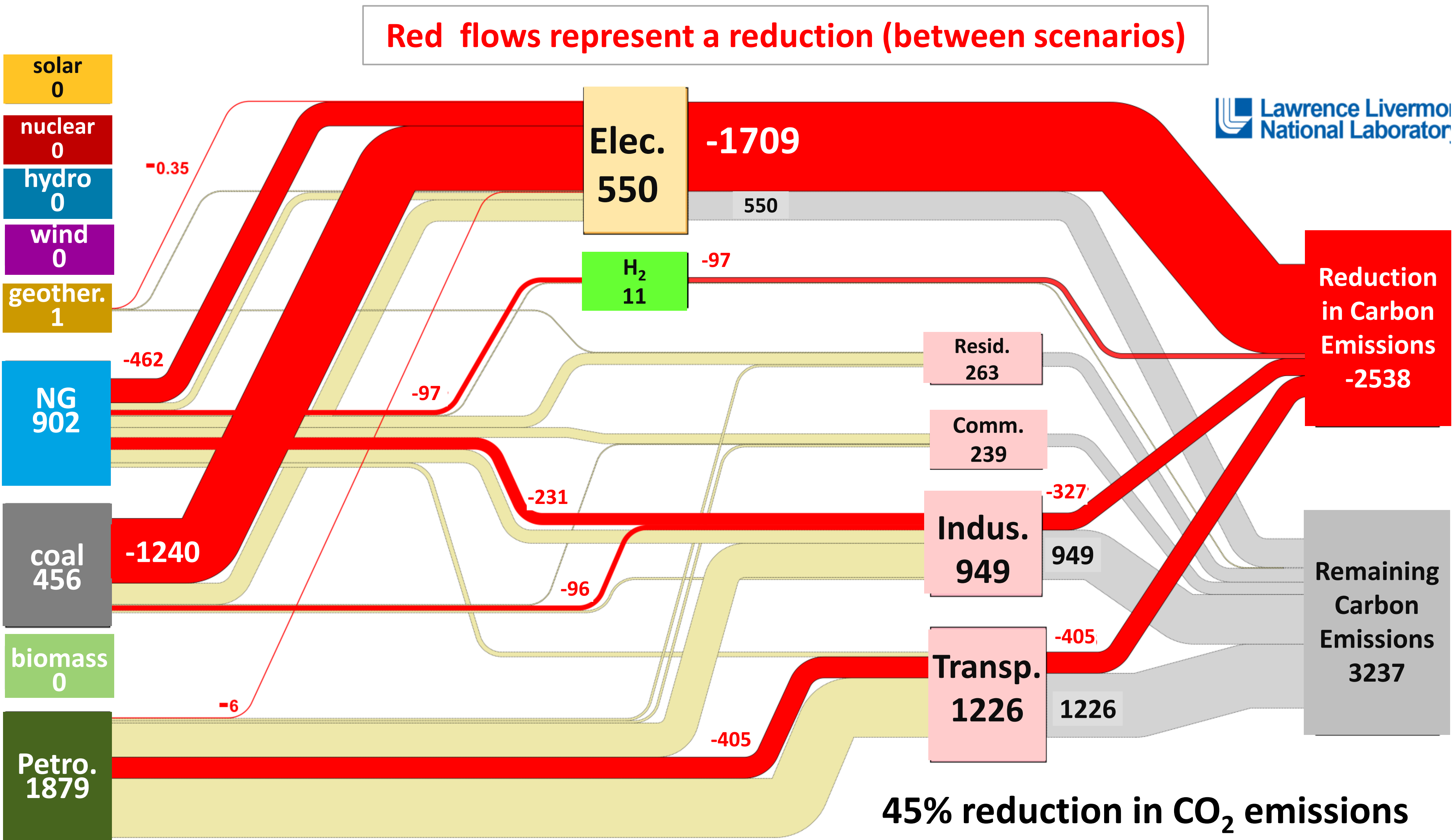
Lawrence Livermore National Laboratory



* 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*

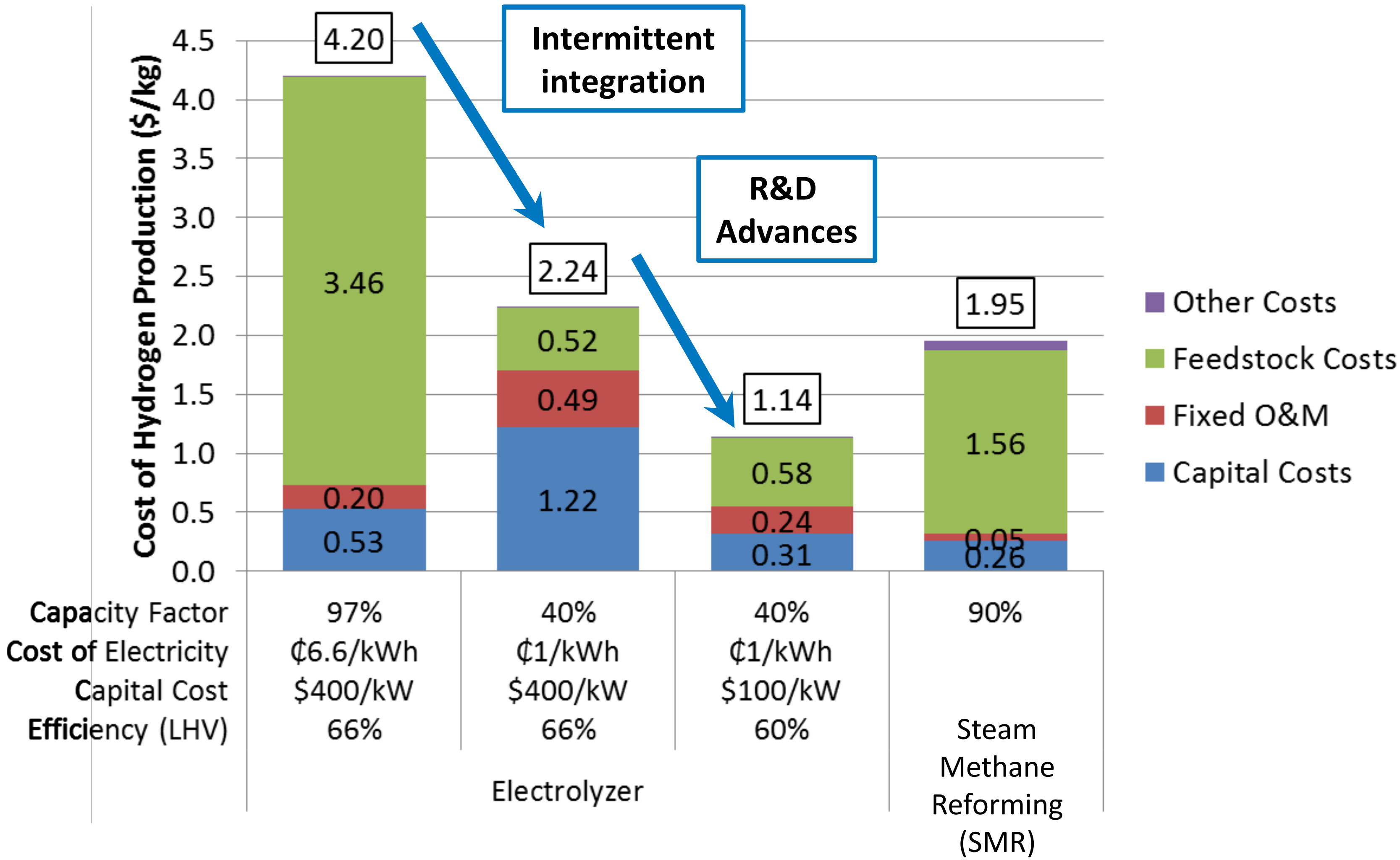
Emissions difference between 2050 high-H_2 and AEO 2040 scenarios (million MT)



45% reduction in CO_2 emissions

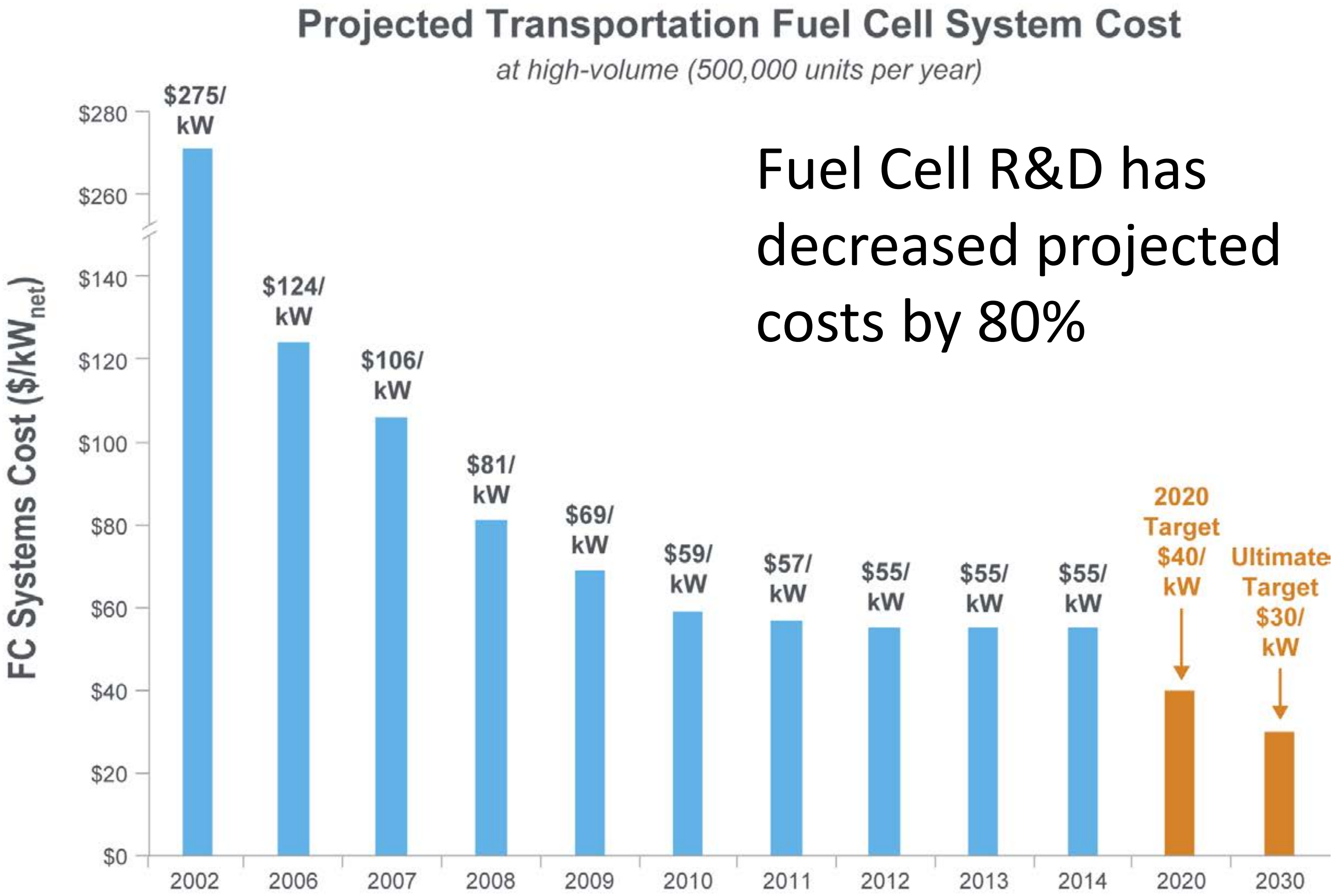
Grid 75%, Transportation 25%, Industrial 25%

Improving the Economics of Renewable H_2



Investments to Enable H_2 at Scale

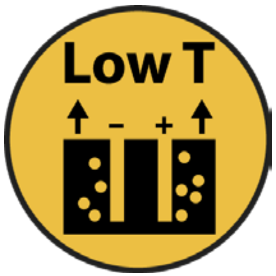
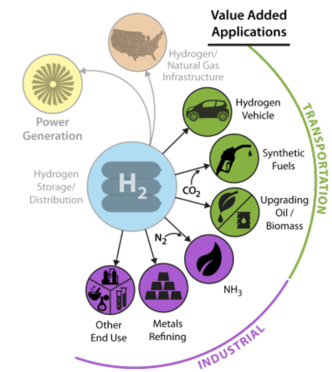
R&D Impact on Fuel Cell Costs



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

Data from FCTO AMR presentations.

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

Initial Research Priorities

Low T generation	High T generation	H_2 Storage and Distribution	H_2 End use
• Develop and test durable systems for variable operation • Develop and integrate new cell component materials	• Thermal system integration • Material systems for advanced redox cycles	• Examine grid-scale hydrogen storage technologies • Material compatibility for pipelines and compressors	• Process heat integration with variable hydrogen generation • New process chemistry with hydrogen as reductant

Analysis

- Comparison between several internally-consistent, deeply-decarbonized futures
- Technoeconomic and life-cycle analysis to support R&D directions

Foundational Science

- Understand chemical-bond energy-storage mechanisms and interactions
- Discover new materials for efficient energy-conversion

Future Electrical Grid

- Analysis and design for reliable and resilient grid interactions

Stakeholder Engagement

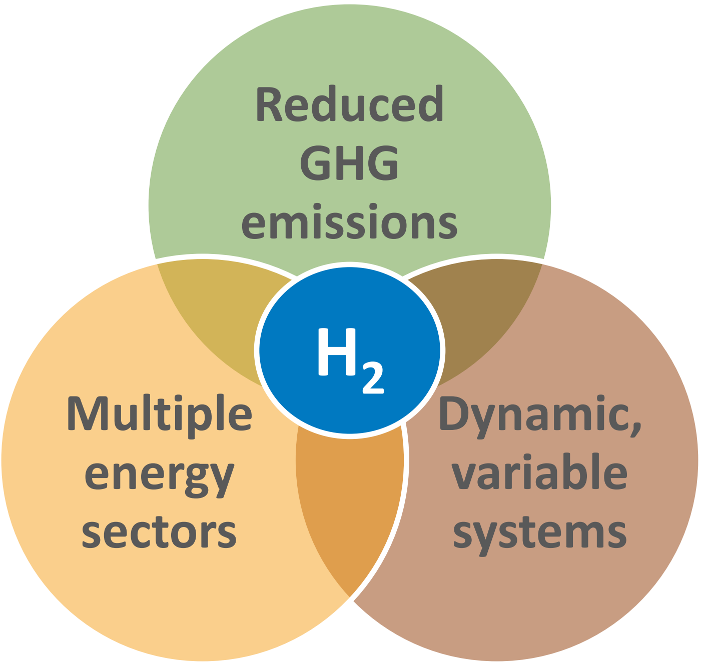
- **Utilities/Regulators**
- **Industrial Gas**
- **Big Oil**
- **OEMs/supply chain**
- **Metals**
- **Ammonia**
- **Biomass upgrading**
- **Investment community**

Presentations
Workshops
Working groups

H_2 at Scale Value Summary

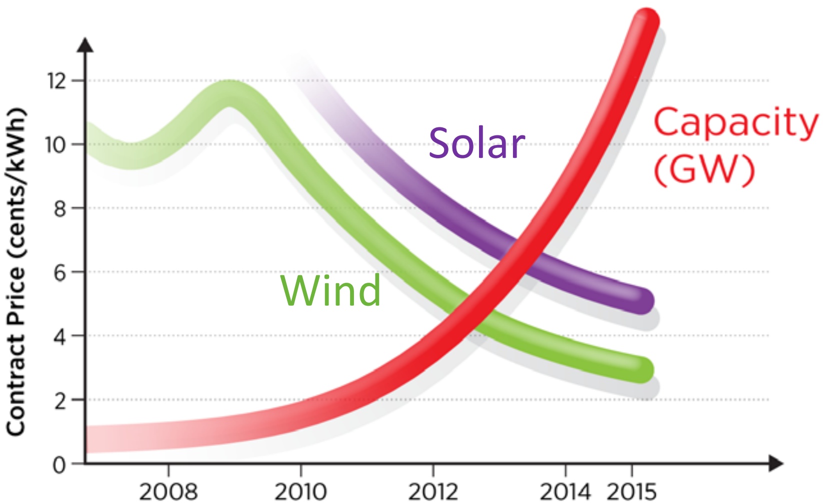
- Reducing emissions across sectors (GHG, criteria pollutants)
- Support needs of dynamic, variable power systems (dispatchable, scalable, ‘one-way’ storage)

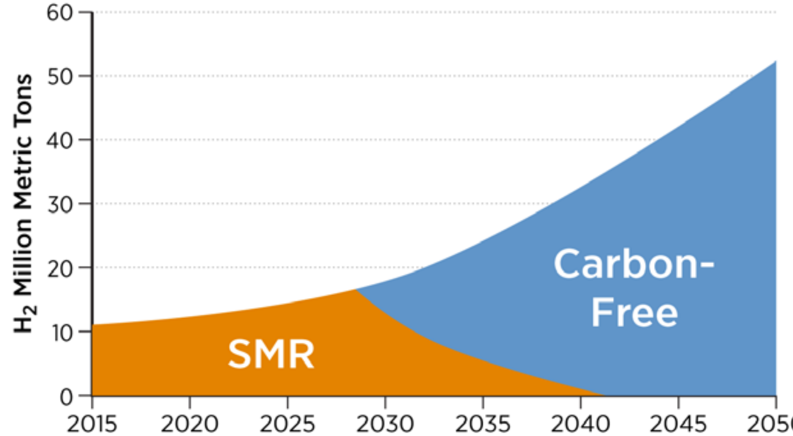
Unique potential of H_2 to positively impact all these areas



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

What does success look like?





H_2 @ Scale

Reduction by Sector

75%
Grid

25%
Transportation

25%
Industrial

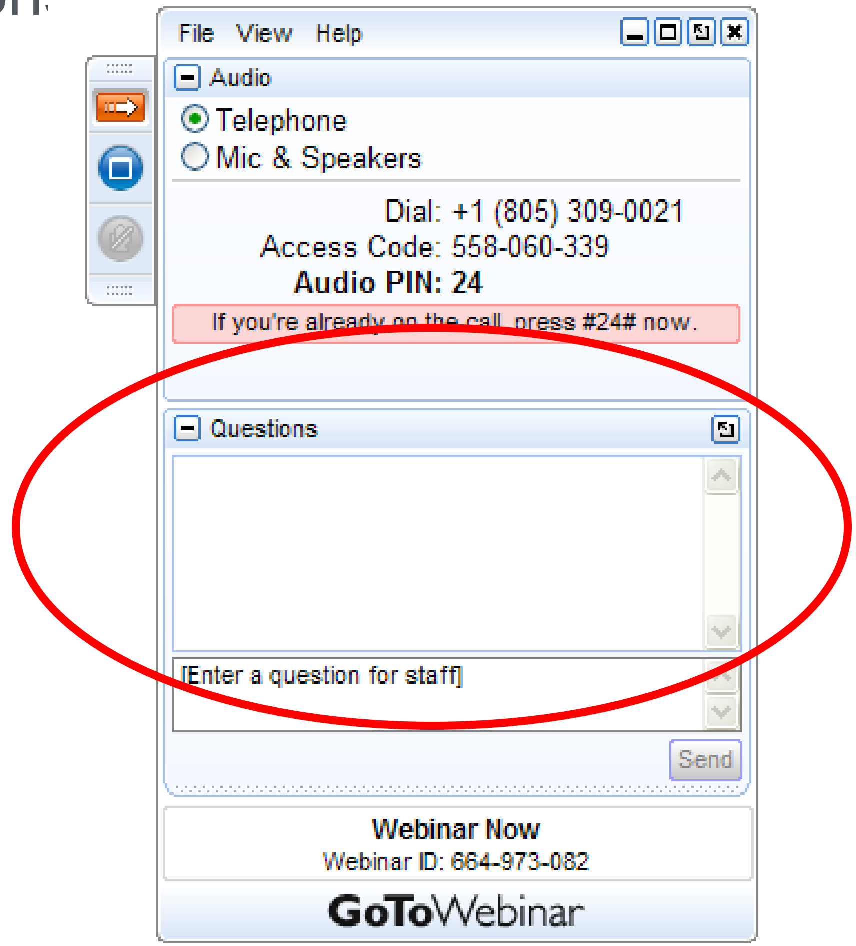
Creating a sustainable future

50% **fewer GHG emissions** than today . . . by **2050**

MORE
Jobs
Security
Resiliency

Question and Answer

- Please type your questions into the question box



Thank You

Presenter(s):

•Bryan Pivovar : Fuel Cell Group Manager - NREL

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DOE Host:

•Erika Gupta : Technology Manager - Fuel Cell Technologies Office

Questions? - DOEfuelcellwebinars@EE.Doe.Gov

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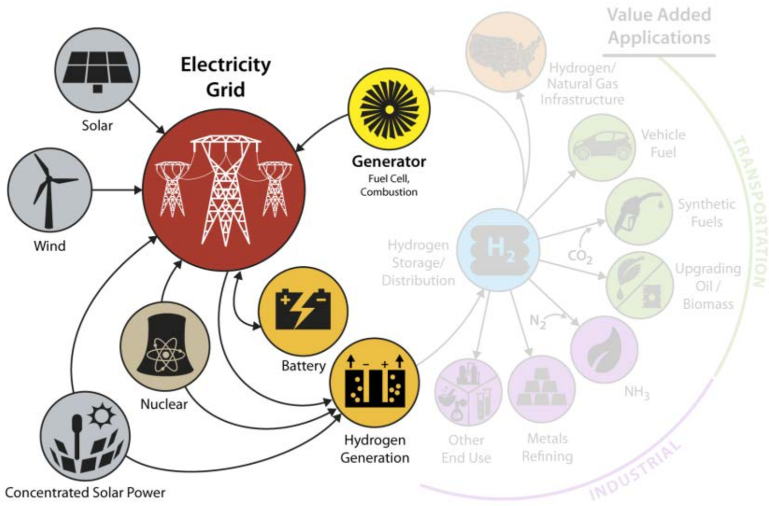
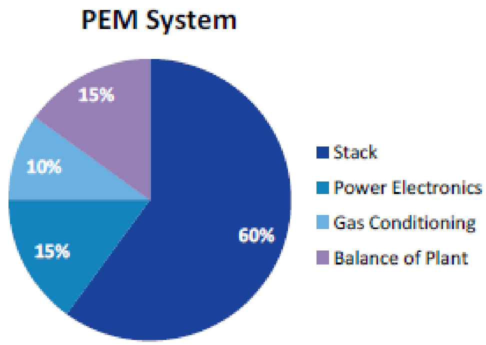
Back-up Slides

Low and High T H_2 Generation



Cost Distribution



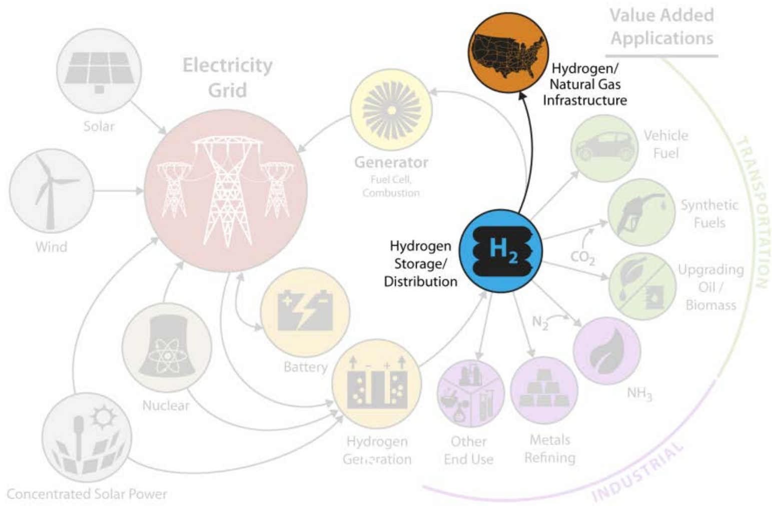
<u>Research Priorities</u>

- Durability for intermittent operation
- Lower cost electrolysis
- Manufacturing at scale
- Thermal integration

<u>Specific H_2 Production Technology Needs</u>

- PEM electrolysis
  - Cell/Stack Components
  - Power electronics/BOP
- Advanced alkaline electrolysis (membranes)
- Solid oxide electrolysis/thermal chemical
  - Oxide conducting materials
  - Thermal integration

H_2 Storage and Distribution



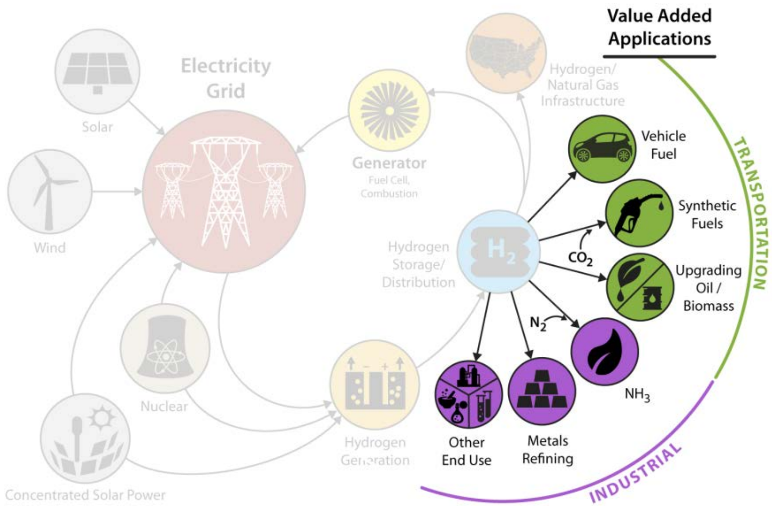
Specific Technology Needs

- Hydrogen Storage
  - Chemical/metal hydrides
    - Materials systems
    - Catalysis
  - Physical Storage
    - Geologic
    - Manufactured
- Direct Electro-Chemical Hydride Conversion
- Distribution
  - Compression
  - Liquefaction
  - Materials Compatibility *(Hydrogen Embrittlement)*
  - Leak Detection/Repair
  - Hydrogen Contamination/Purification
  - Materials Compatibility
  - Grid Integration/Optimization

Research Priorities

- Development of storage/delivery systems for large-scale grid and industrial use
- Assessment of potential for integration with existing technology and infrastructure
- System analysis, integration and optimization

H_2 Utilization



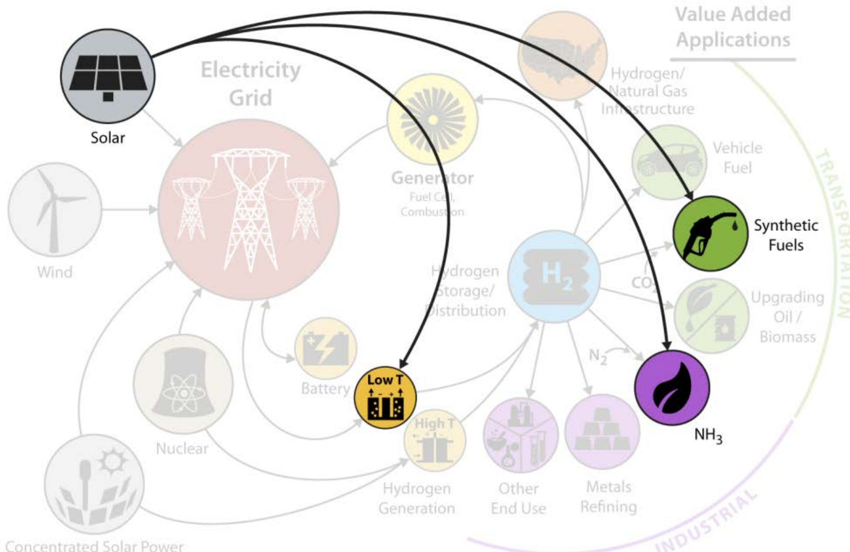
<u>Research Priorities</u>

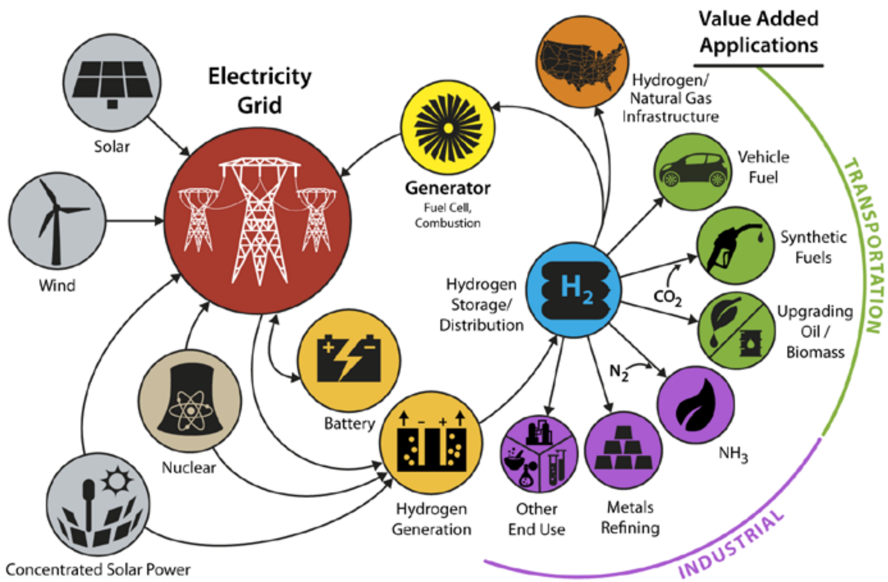
- New process chemistry with H_2 used as a reductant
  - Chemical, Fuels, Metals Production
- Process efficiency improvement
  - Industry and power systems
- Process heat integration with intermittent H_2 generation
- H_2 / H_2-rich flame modeling

<u>Specific H_2 Utilization Technology Needs</u>

- Ammonia production
  - Distributed/modular
- Refineries and Biofuels
  - Process integration
- Metals and glass making
  - Game changing direct reduction
  - Reducing gases for annealing/
  - tempering
- Combustion Processes
  - Burner design and testing
  - Flame chemistry impacts
  - Use of oxygen
- H_2 Heat Pumps
  - Waste heat recovery
  - Heat amplification / cooling

Foundational Science





Fundamental understanding of potentially revolutionary technologies for other chemical bond energy storage/conversion.

Numerous chemistry/ materials issues:

Catalysis/Reactions

Systems far from equilibrium

Confined catalysis

Corrosion

Detection and understanding of rare events

Material interactions (Embrittlement)

ser facilities

SNS, light sources, nanocenters, microscopy

CSR and advanced computing

Big data

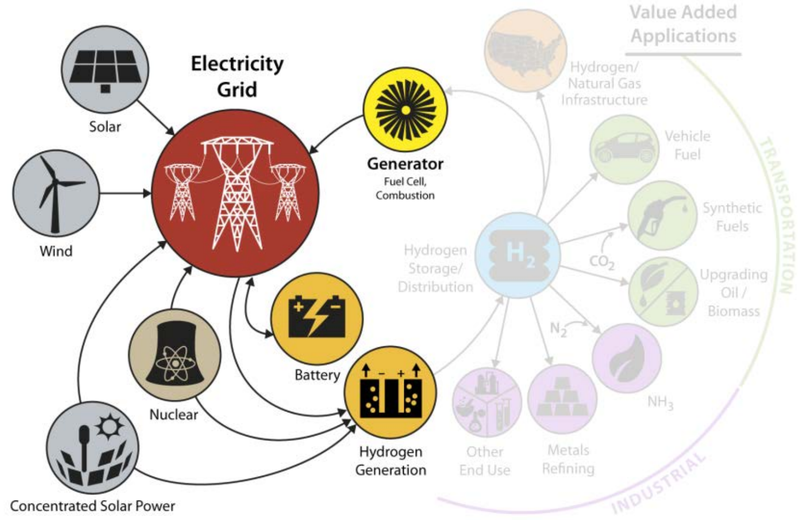
Algorithms for prediction multiscale physics

:AP leveraged science

IGI (expansion)

dissolution, kinetics, solvents

Grid Integration



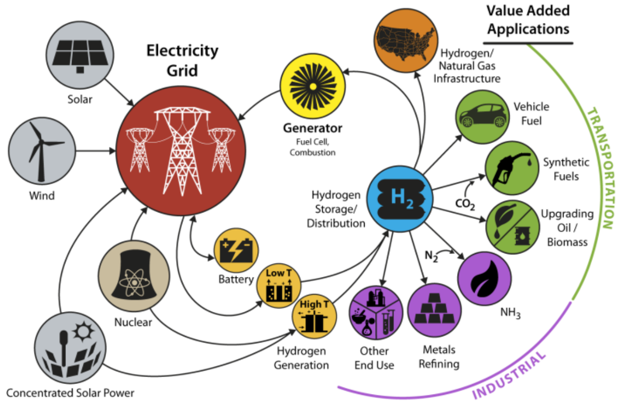
Research & Development Priorities

- Systems analysis
- Systems engineering
- Systems design and demo

Specific Grid Integration Technology Needs

- Affordability
  - Modest capital investment for production and storage
  - Renewable hydrogen source for marketplace revenue
- Flexibility- Scalable, deployable, multiple renewable hydrogen markets
- Reliability
  - Stable, sufficient power source
  - Inherently integrated element of grid
- Resilience- Distributed production and storage systems—large storage options
- Sustainability- Enable stable grid with abundant renewables-demand/response
- Security- Enable domestic, renewable energy resource

Analysis



Analysis Priorities

- Specifying the role of hydrogen in deep decarbonization of the U.S. energy sector
- Understanding of drivers impacting energy sector evolution
- Quantification of hydrogen potential to meet seasonal electricity storage requirements
- Technoeconomic analysis
- Life cycle analysis

Specific Analysis Needs

- Role of hydrogen within energy sector
  - Energy sector evolution / capacity expansion analysis to identify key opportunities for hydrogen to support power, gas, industrial, and transportation sectors
  - Grid operations co-optimization with hydrogen providing grid support on short and long time-frames and on regional and national scales
  - Analysis of the hydrogen’s benefits resilience, reliability, and robustness
- Technoeconomic analysis to support R&D directionin hydrogen generation, storage & distribution, and end use
- Life cycle analysis to identify opportunities to reduce GHG and criteria pollutant emissions