H_2 at Scale:

Deeply Decarbonizing our Energy System

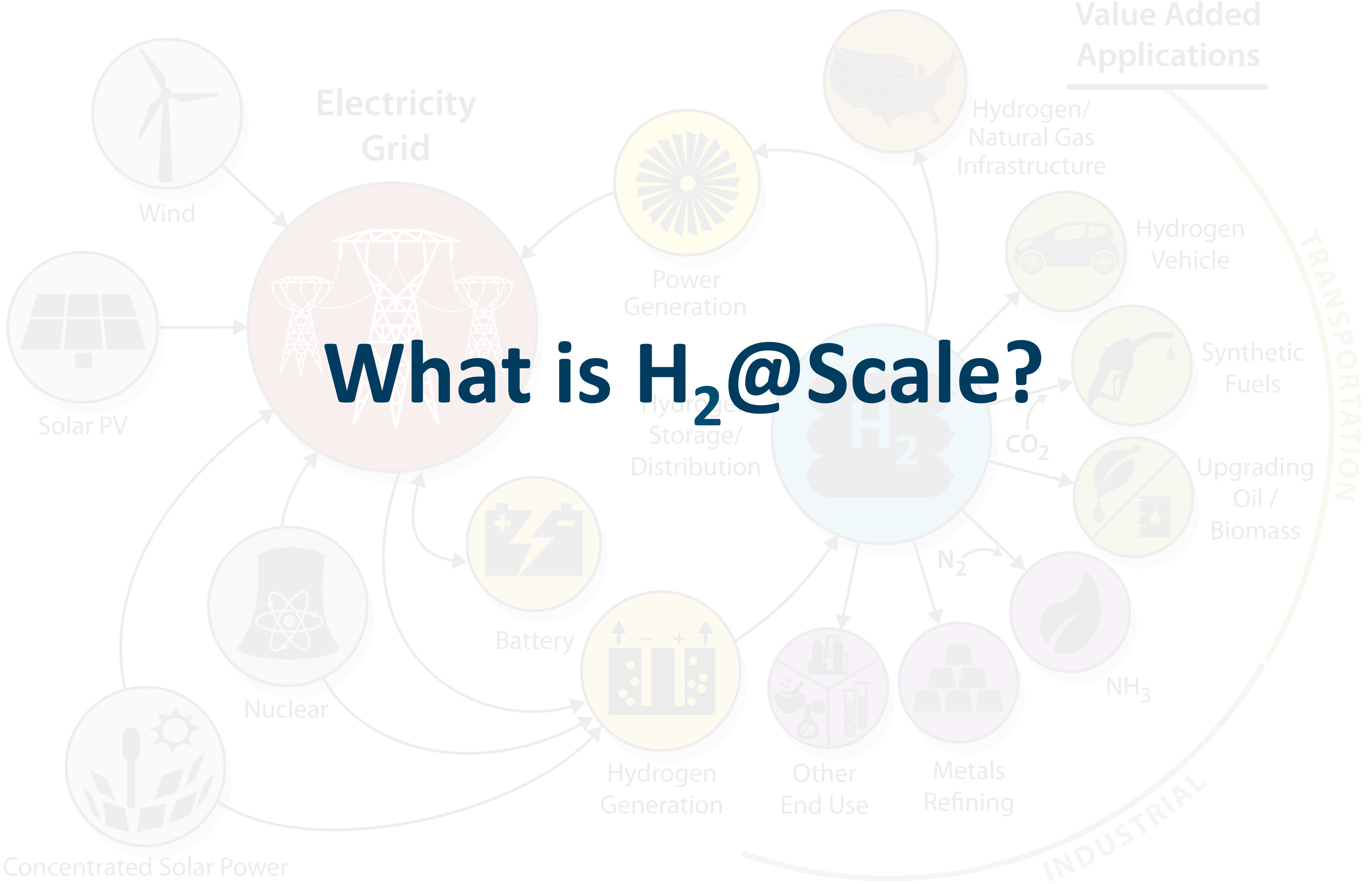
Touch Screen Presentation at AMR

Wardman Park Marriott
June 6–10, 2016

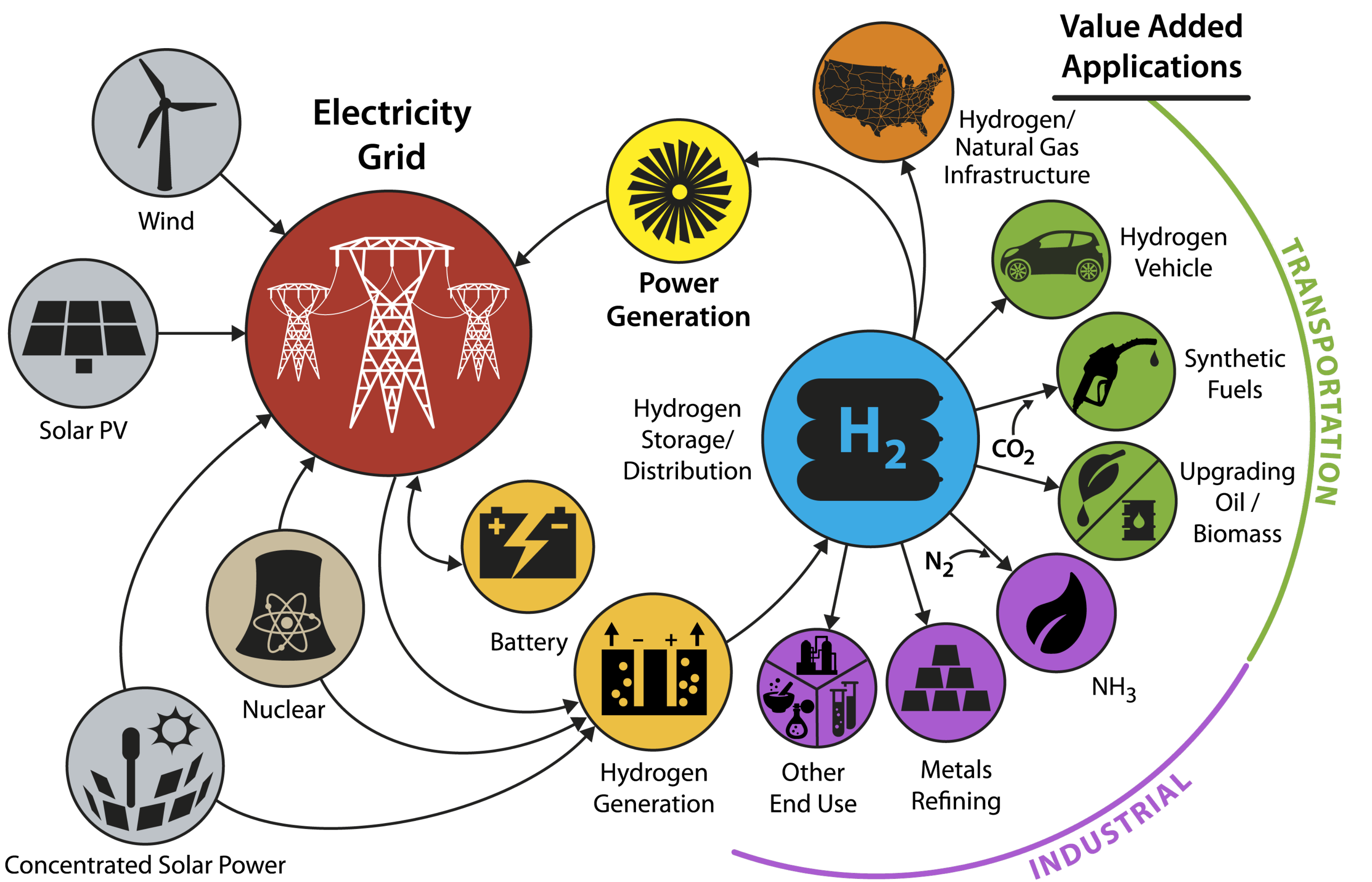
H_2 at Scale: Deeply Decarbonizing our Energy System

- What is Hydrogen at Scale?
- Why is it needed?
- Why now/today?
- What can it accomplish?
- How will it be accomplished?
- Who is the team?
- Why national labs along with industry?
- What does success look like?
- Additional content/backup slides

What is H_2@Scale?



Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

Why is it needed?

Why?.....Our Cities/Energy System

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

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

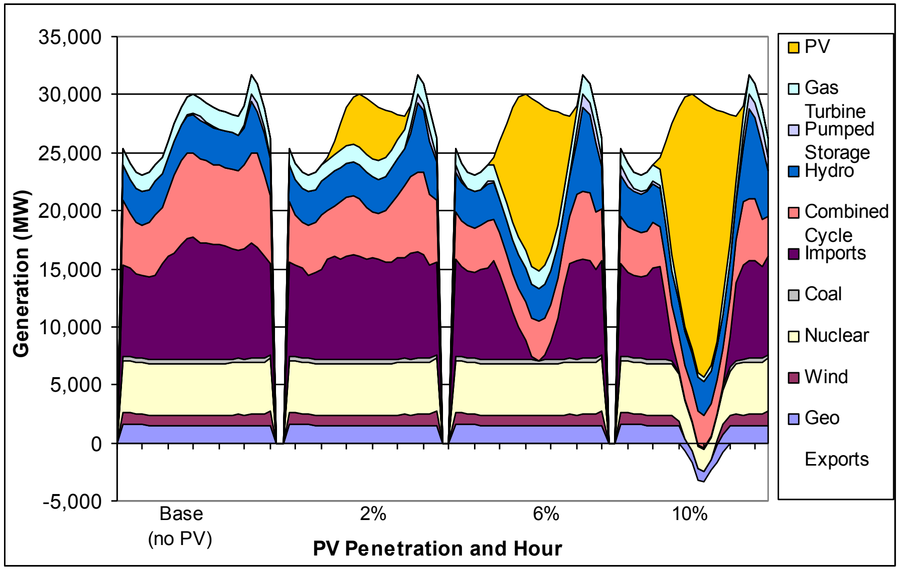
Energy System Challenges

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

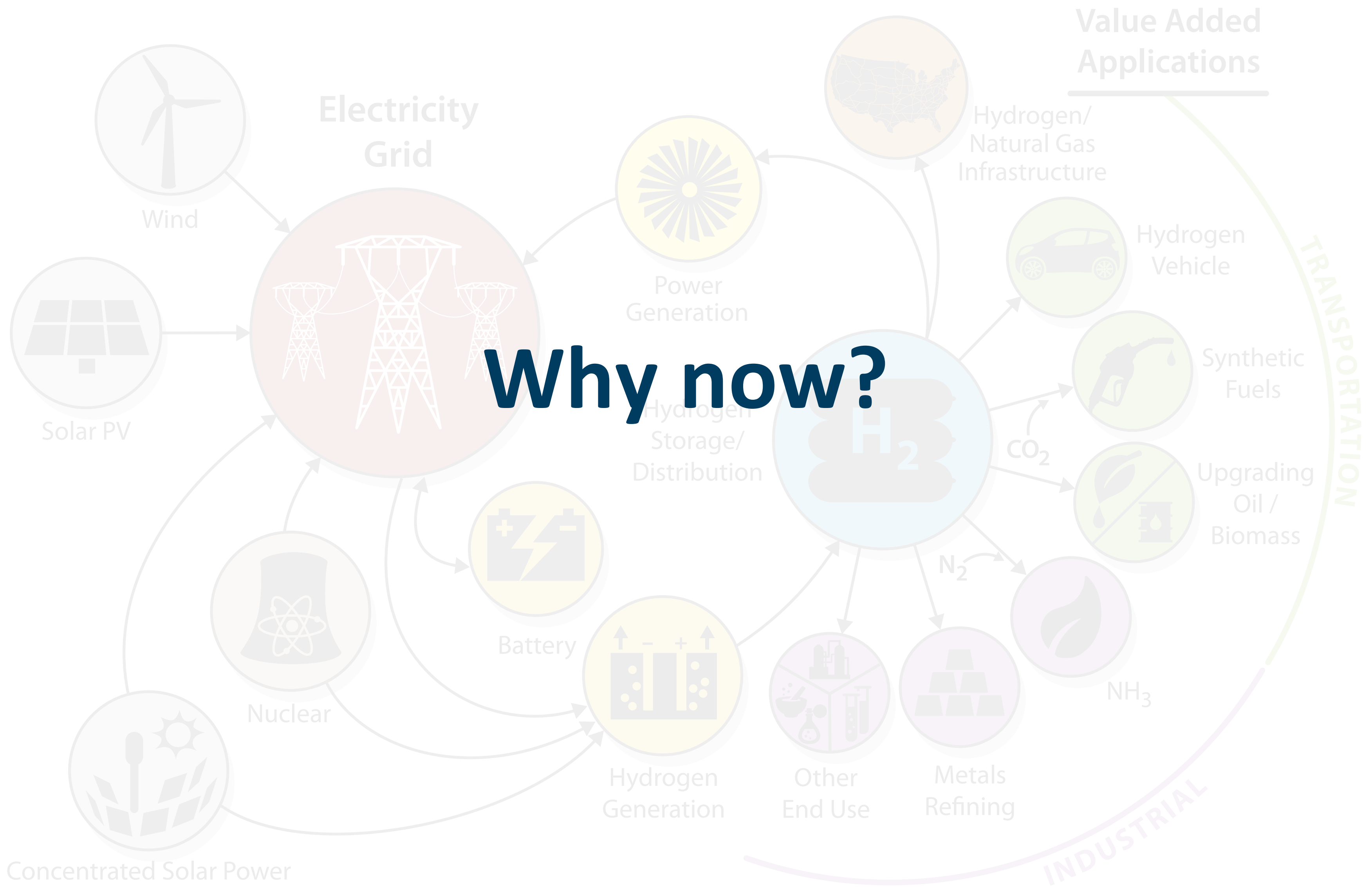
Over half of U.S. CO_2 emissions come from the industrial and transportation sectors

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

Denholm et al. 2008



Why now?


Electricity Grid
Value Added Applications
Wind
Solar PV
Power Generation
Hydrogen/ Natural Gas Infrastructure
Hydrogen Vehicle
Synthetic Fuels
Upgrading Oil / Biomass
Hydrogen Storage/ Distribution
H_2
CO_2
N_2
NH_3
Battery
Nuclear
Hydrogen Generation
Other End Use
Metals Refining
Concentrated Solar Power
TRANSPORTATION
INDUSTRIAL

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.

Clean Power Plan
reduce carbon dioxide emissions by 32% by

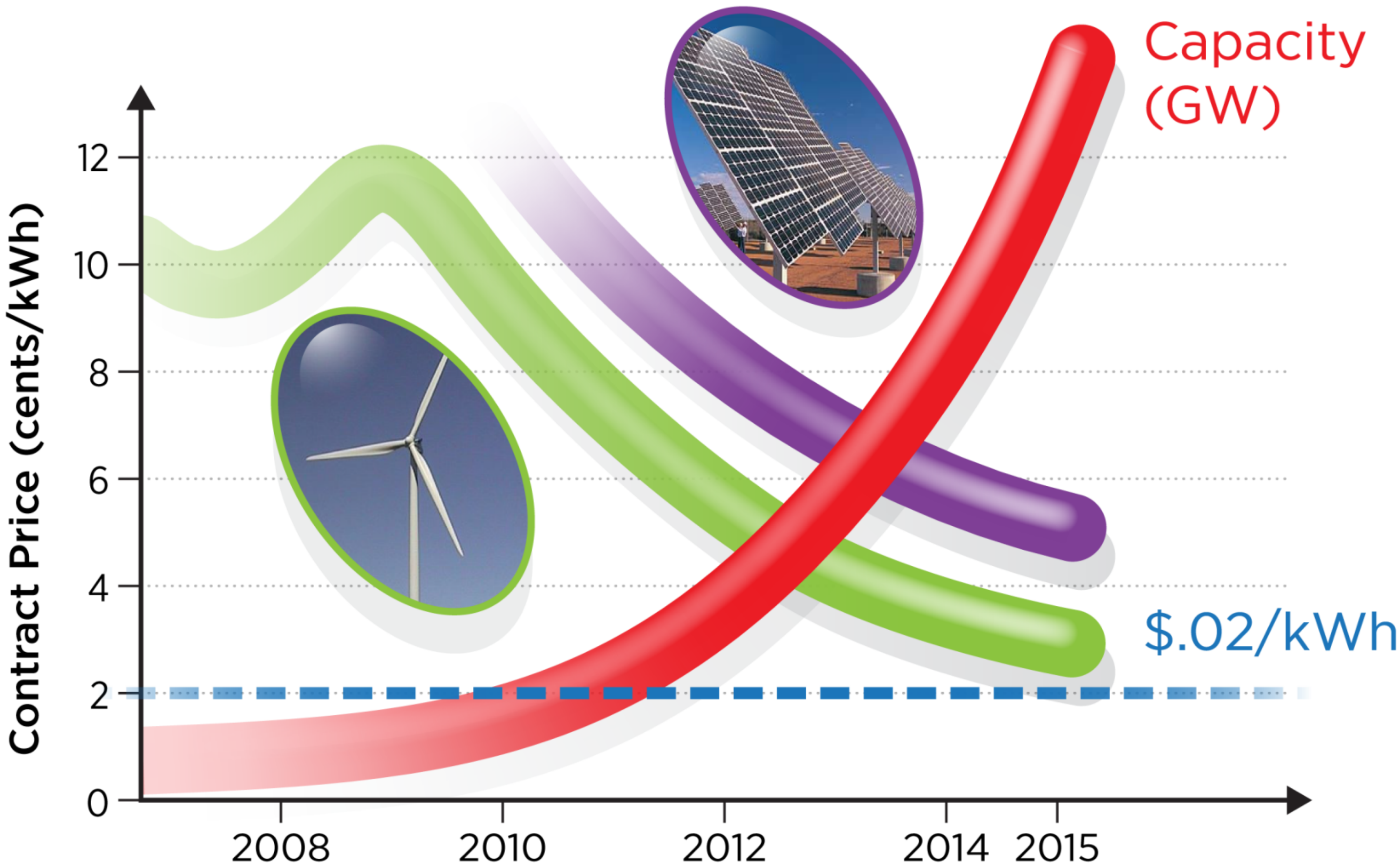
President's Climate Action Plan
80% reduction in transportation GHG by 2050

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.

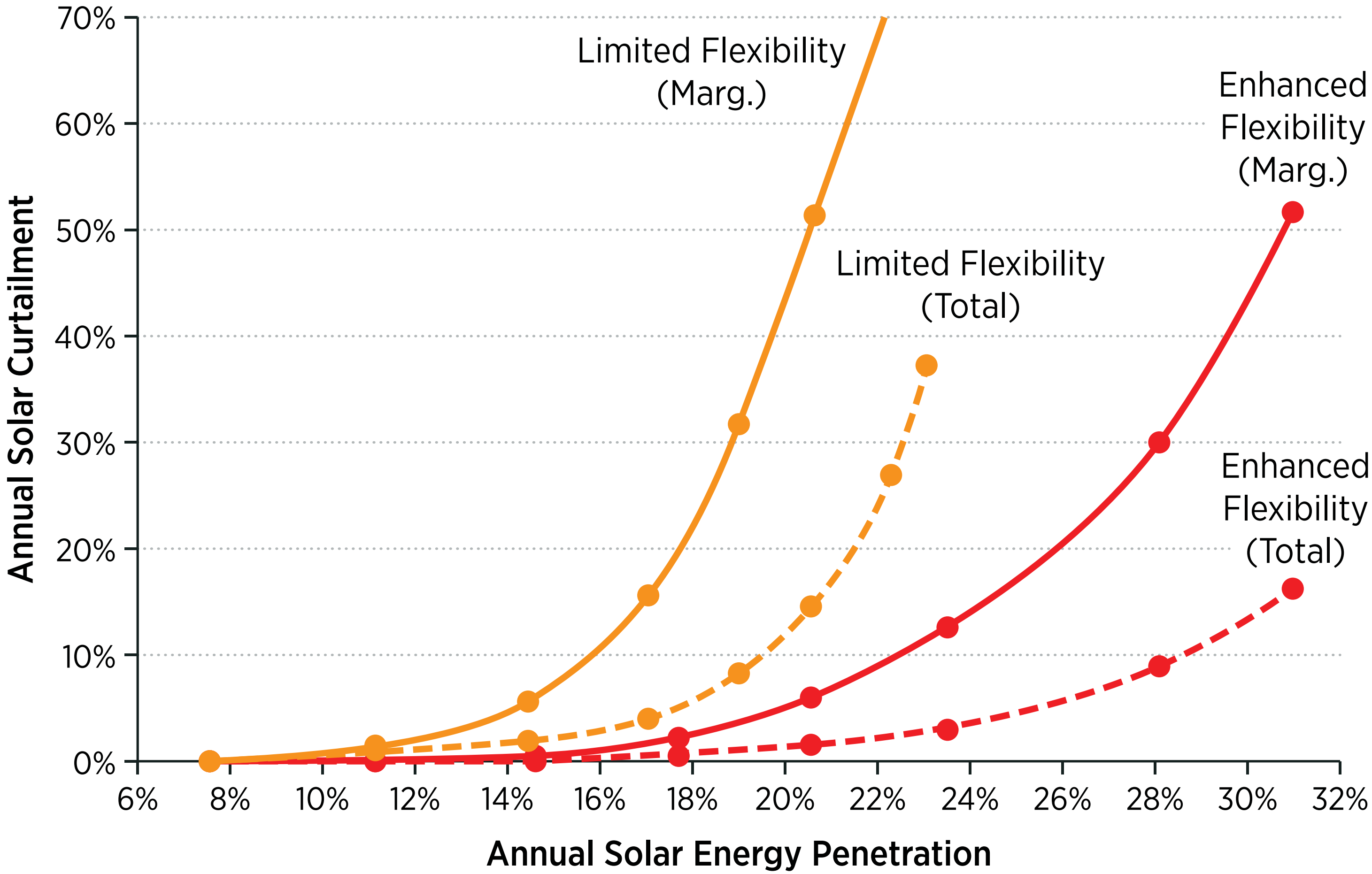
Carbon-Free Electricity Prices



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

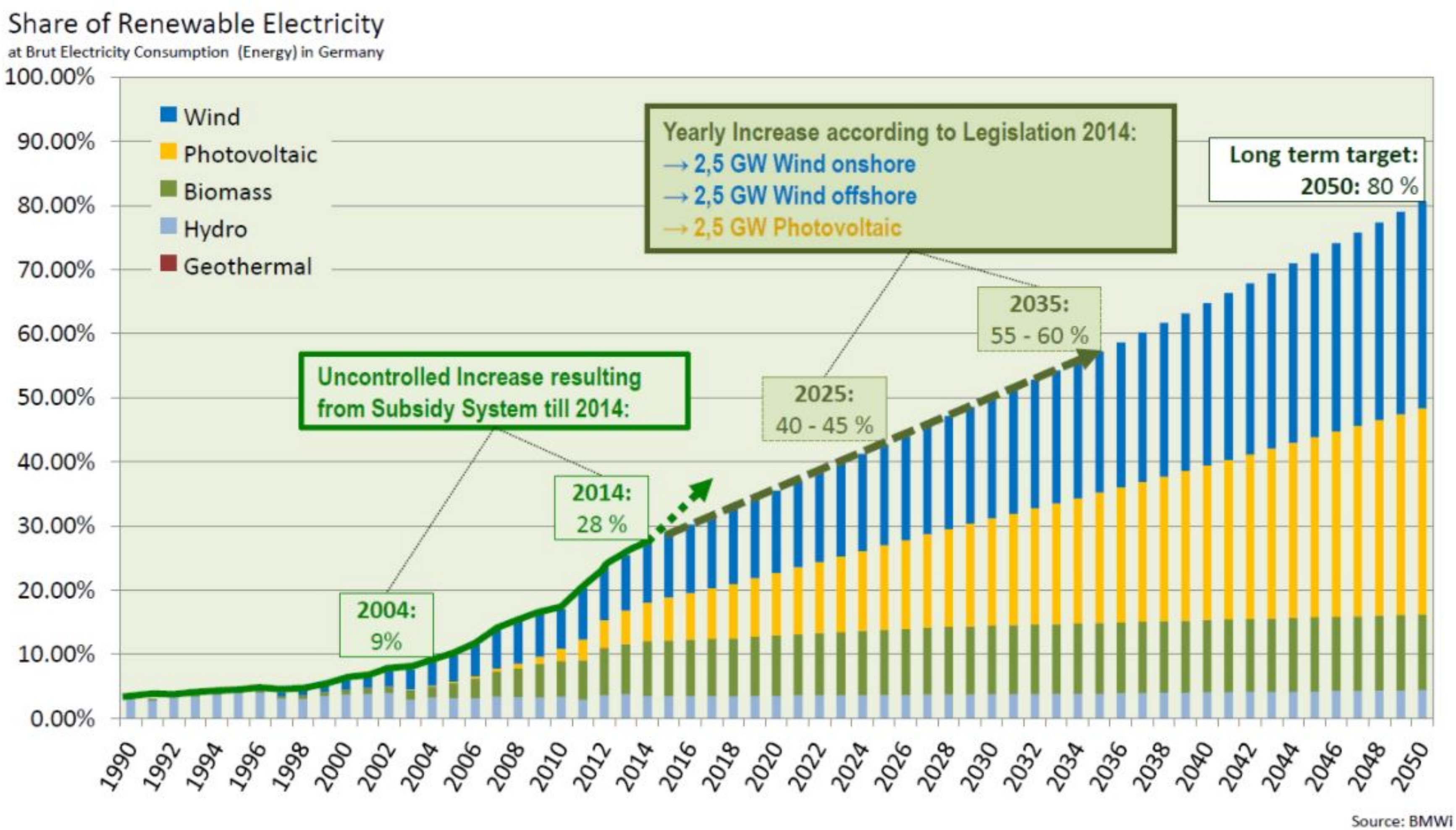
Limitations of Variable Inputs

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



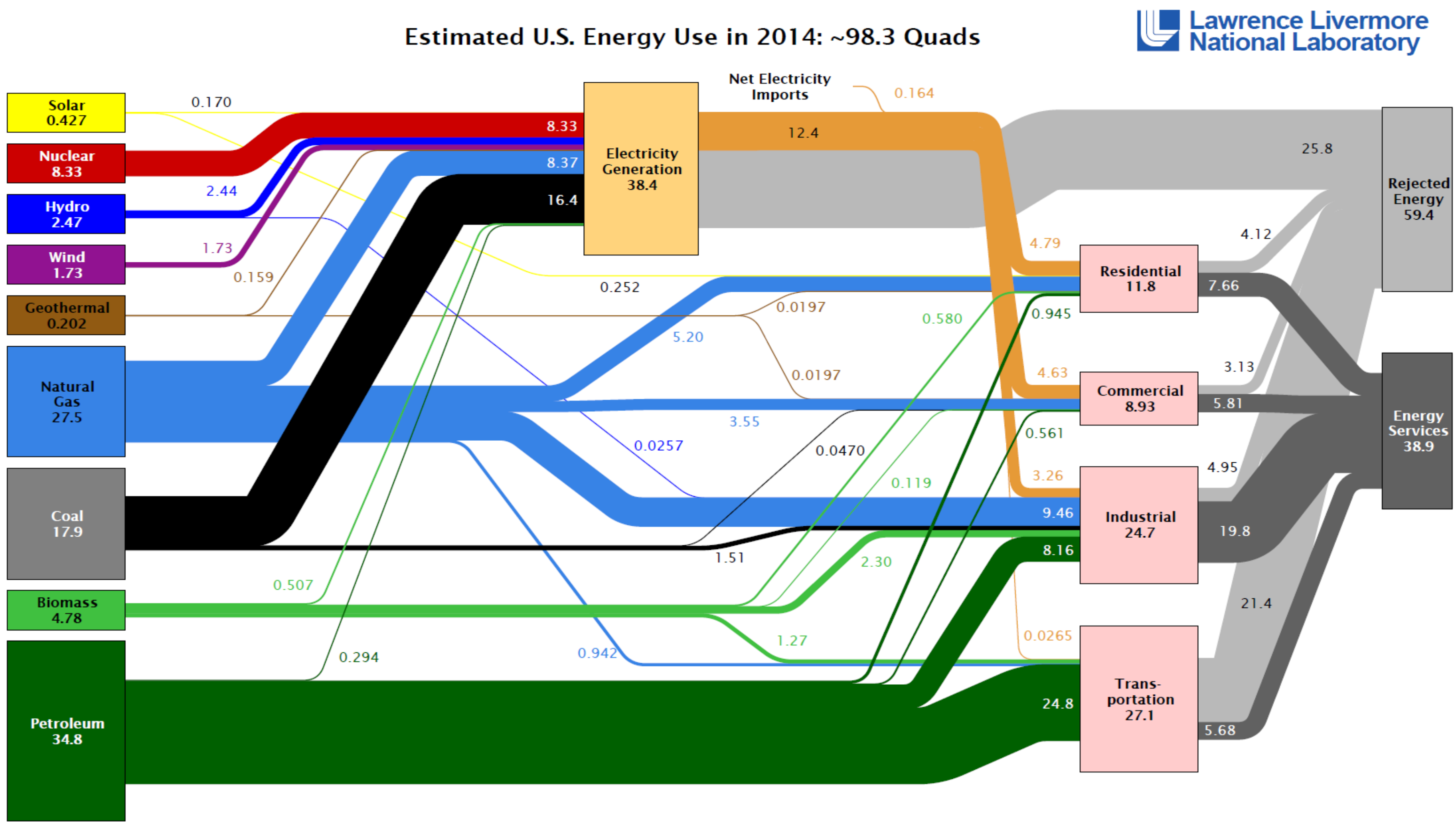
Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

Example: Germany Already Limiting RE Penetration Rate



What can it accomplish?

Current Energy Flow

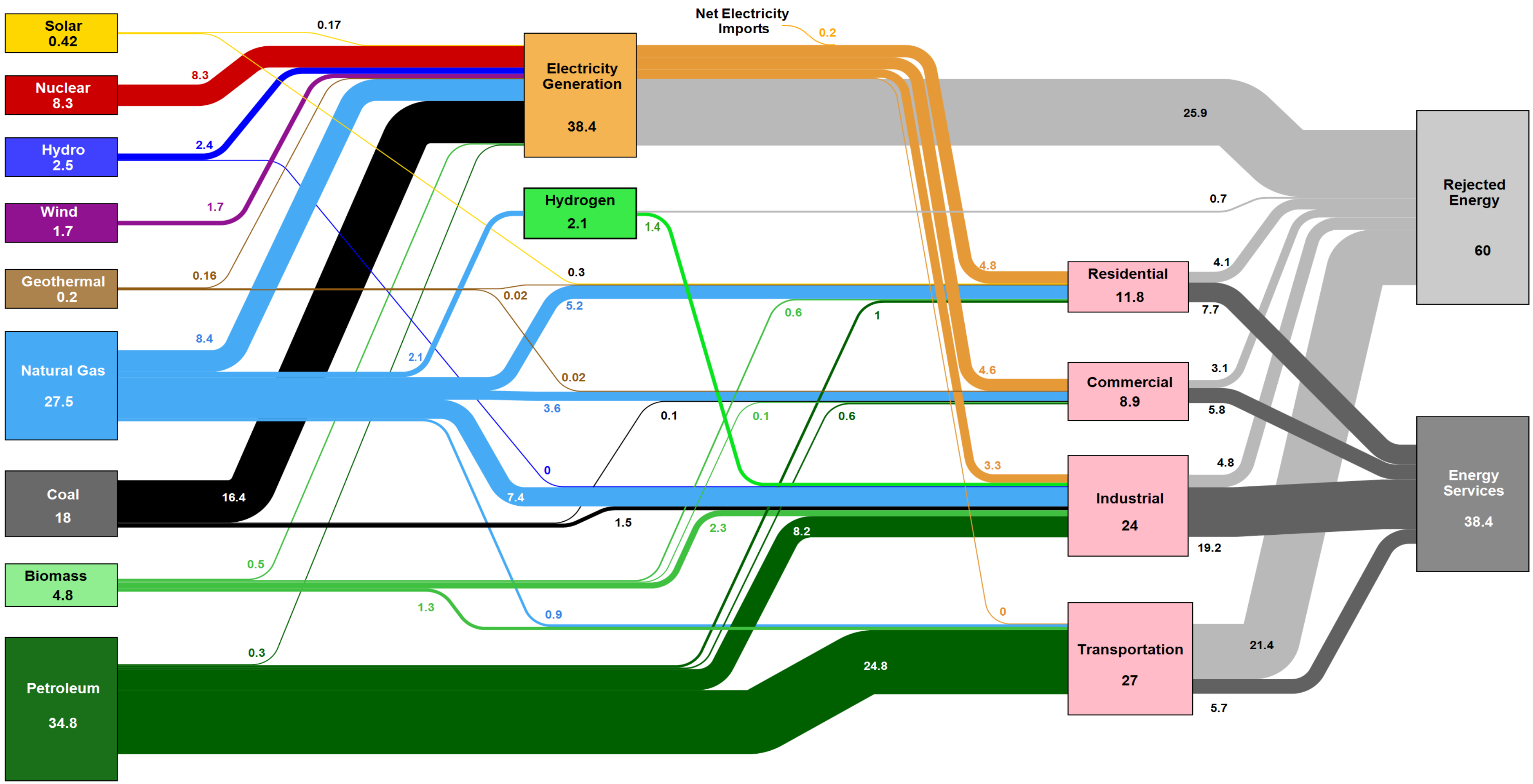


Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents 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

2014 Estimated U.S. Annual Energy Use - Hydrogen Contributions Broken Out ~ 98 Quads

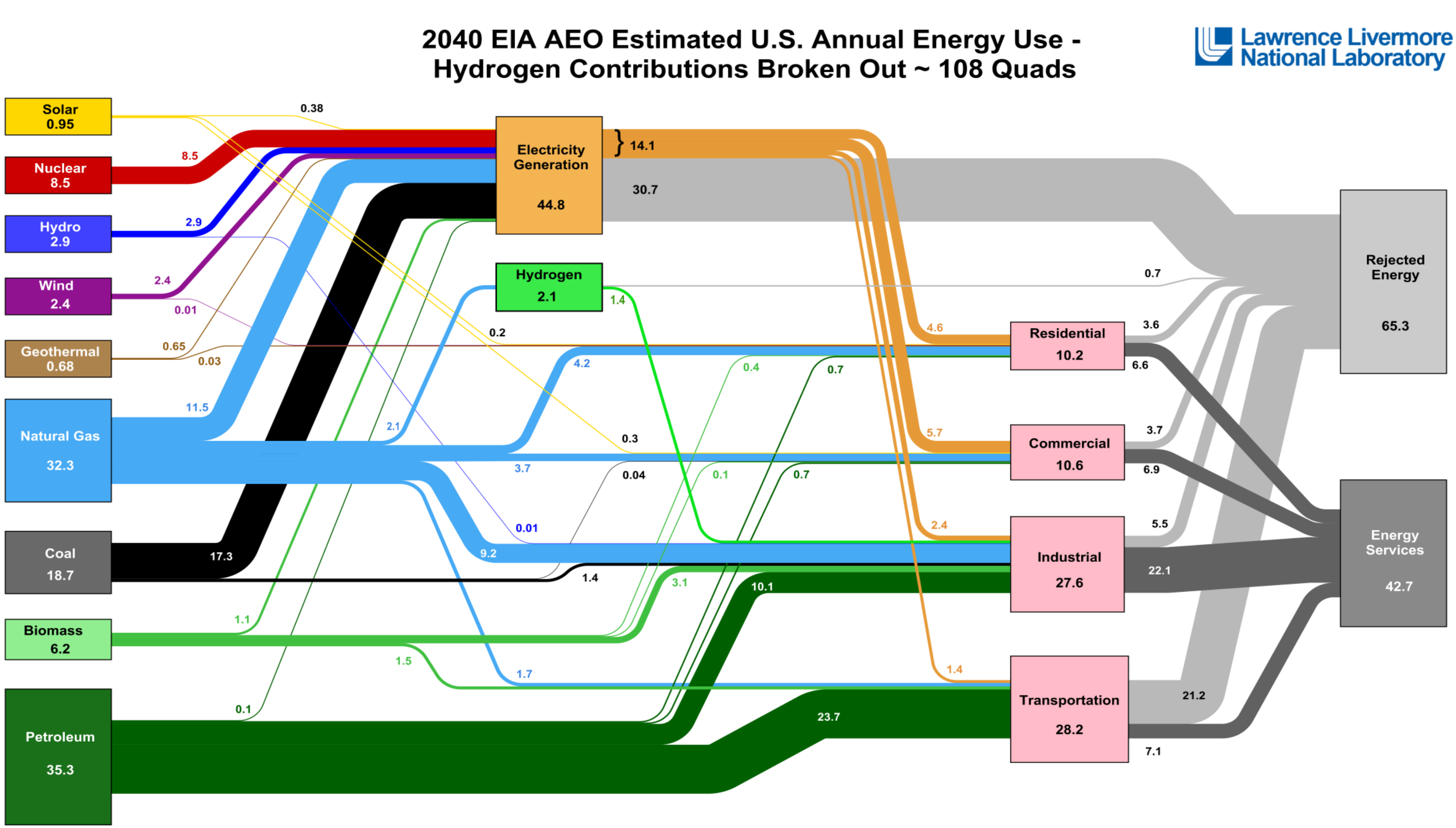
Lawrence Livermore National Laboratory



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



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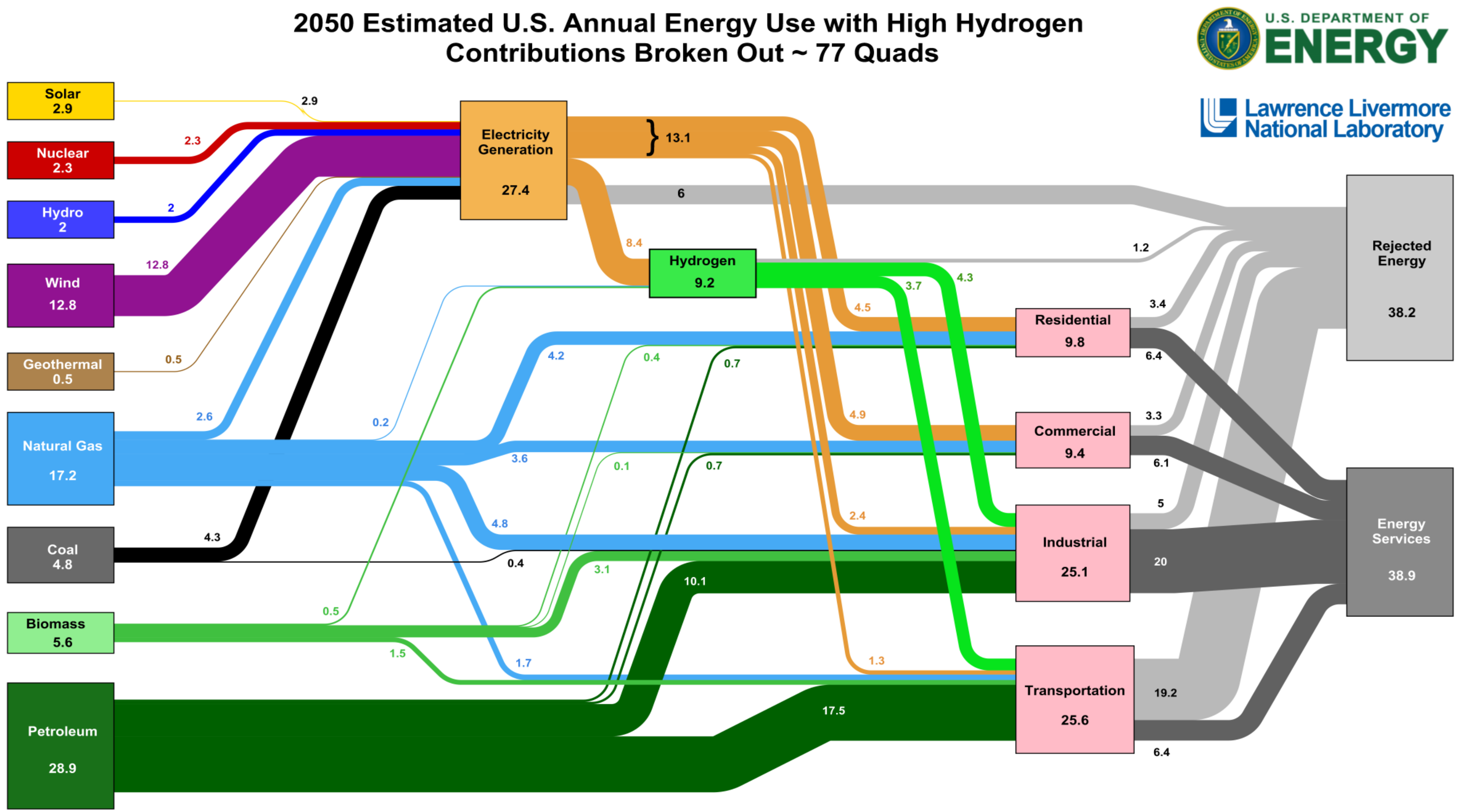
Energy Flows – 2050 High RE/H_2



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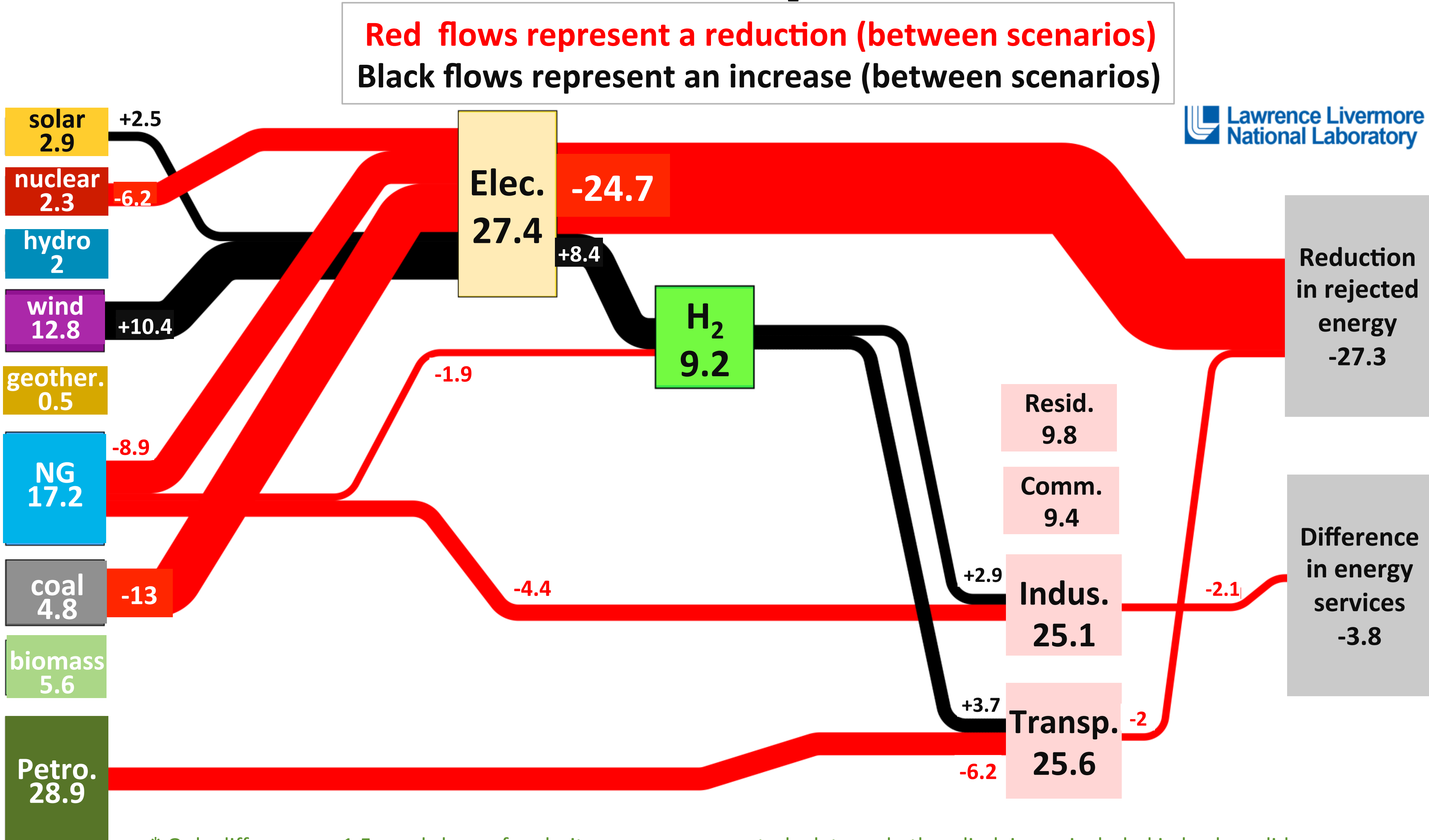
BAU (Business As Usual) vs. High H_2 – Energy Difference*

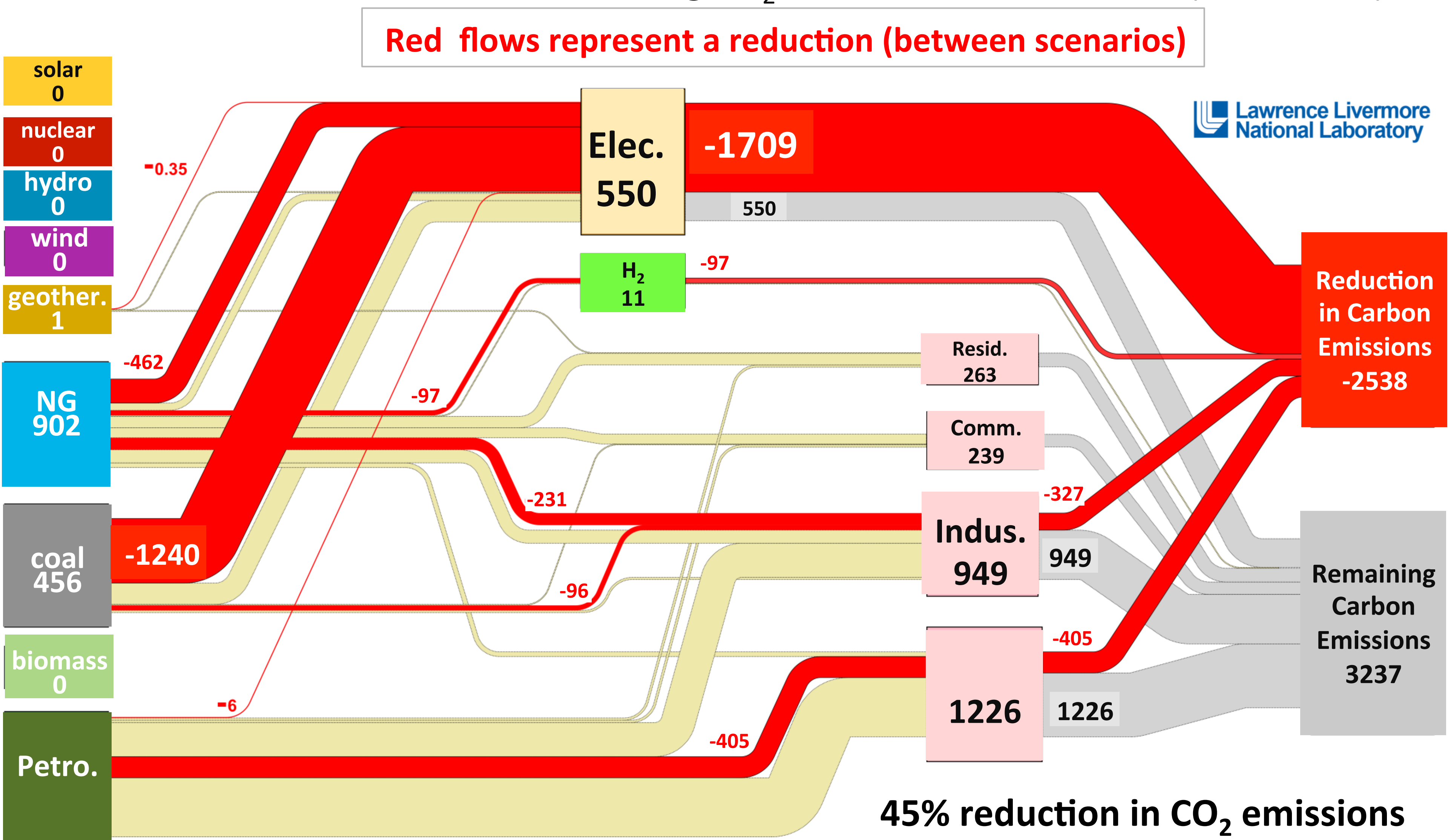
Energy Use difference between 2050 high-H_2 and AEO 2040 scenarios (Quad Btu)



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

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

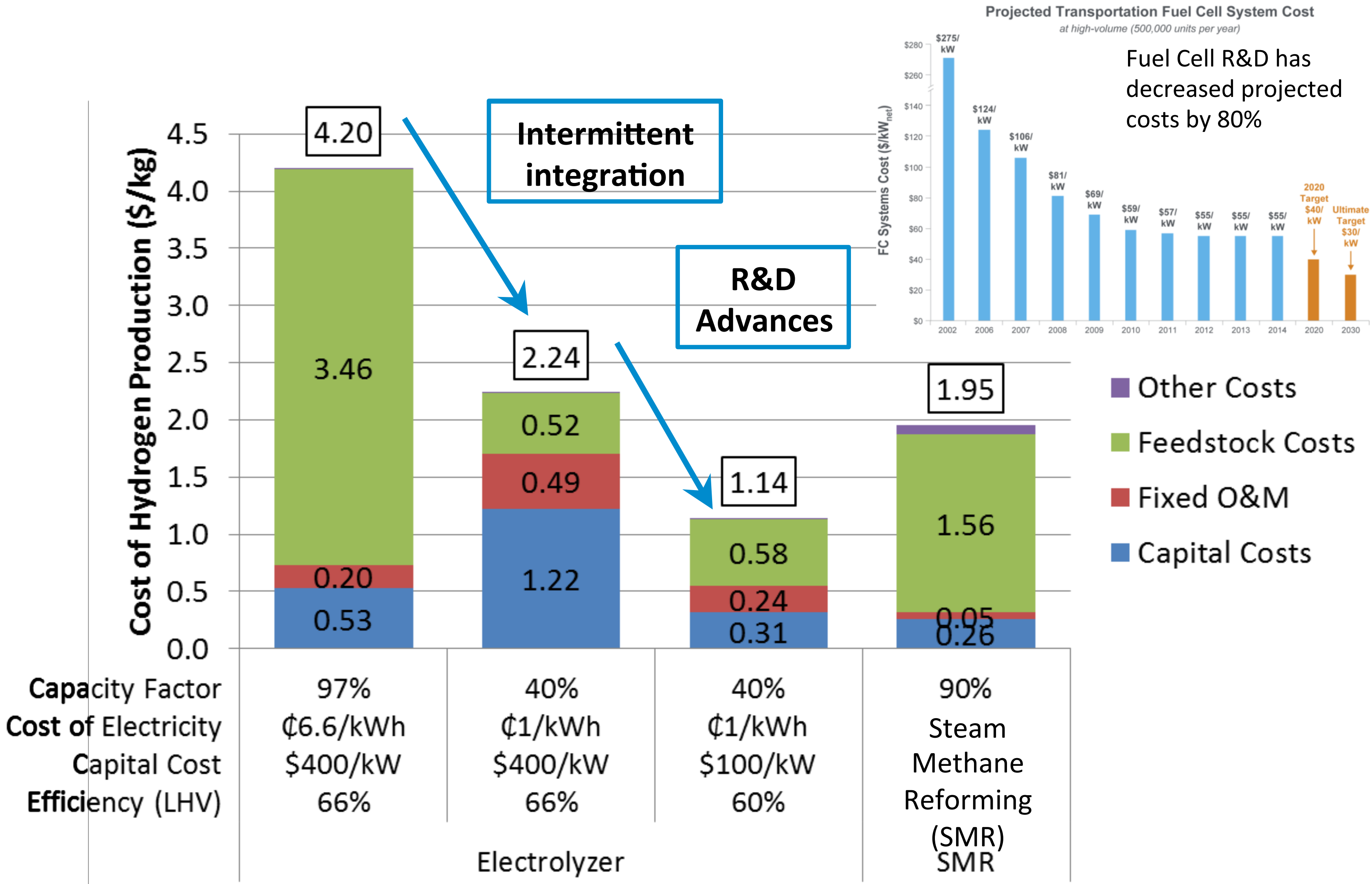
Emissions difference between 2050 high-H_2 and AEO 2040 scenarios (million MT)



45% reduction in CO_2 emissions

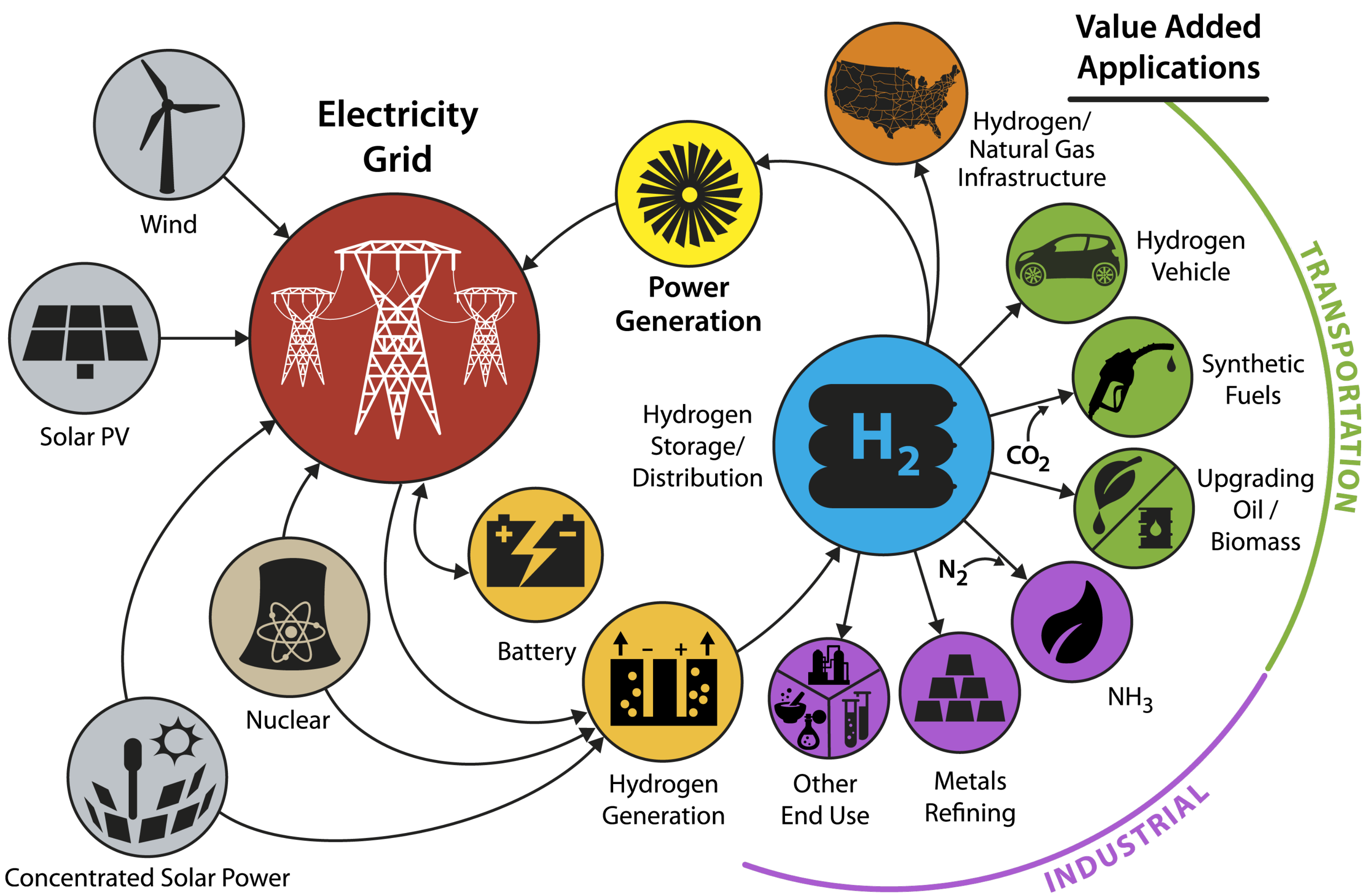
Grid 75%, Transportation 25%, Industrial 25%

Improving the Economics of Renewable H_2



How will it be accomplished?

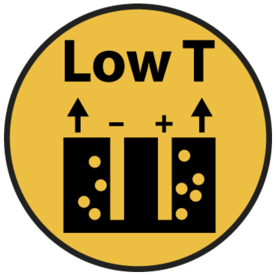
Conceptual H_2 at Scale Energy System*



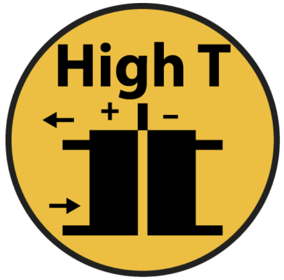
*Illustrative example, not comprehensive

What is Needed to Achieve H_2 at Scale?

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

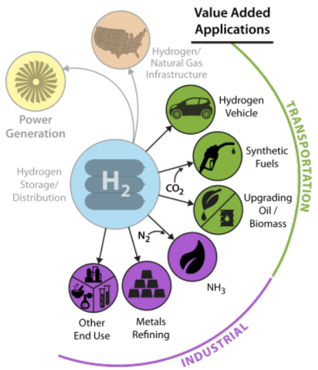


Development of **low cost, durable, and intermittent H_2** generation.



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

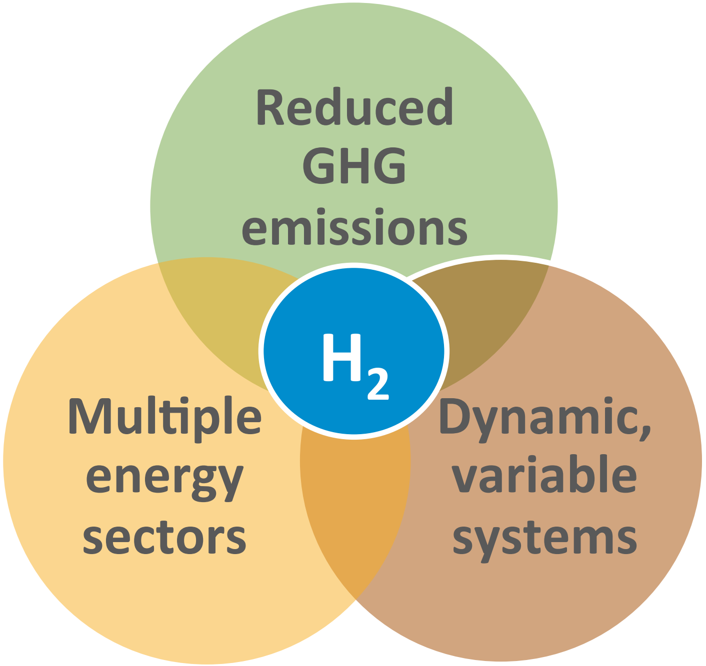
Foundational Science

Future Electrical Grid

H_2 at Scale Value Summary

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

Unique potential of H_2 to positively impact all these areas



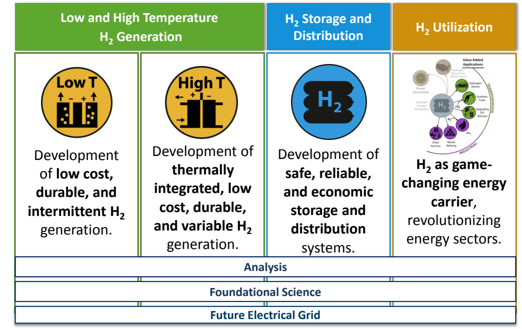
- Other benefits
  - Energy security (diversity/ resiliency/domestic)
  - Manufacturing competitiveness/ job creation
  - Decreased water requirements

Who is the team?

H_2 at Scale Big Idea Team

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 (NREL)



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)

Why national labs along with industry?

Why National Labs Along with Industry?

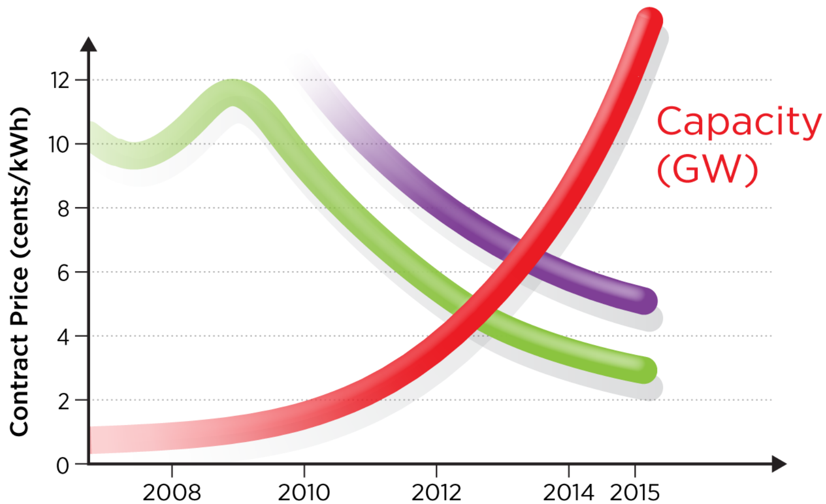
- **NLs**: Unique skills/capabilities, ideally suited for addressing the challenges of tomorrow's energy system. H2@Scale vision only possible through the NL efforts.

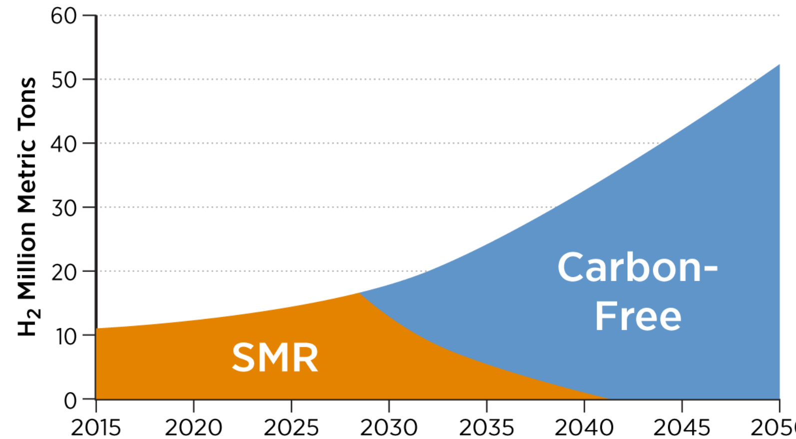
- **Gov't**: No profit in developing this system in today's market, but needs to be ready for future energy systems needs. Consideration of societal impacts/costs. Both global and local. Can enable or derail potentially.

- **Commercial/industrial engagement critical**: Focus on enabling the vision of the long-term, through the short-term and mid-term steps.

What does success look like?

What Does Success Look Like?





Going from 10 million MT of H_2 from SMR to 50 million MT from carbon-free sources, will enable a 50 % decrease in CO_2 emissions by 2050

H_2 @ Scale

Reduction by Sector

75%
Grid

25%
Transportation

25%
Industrial

Creating a sustainable future

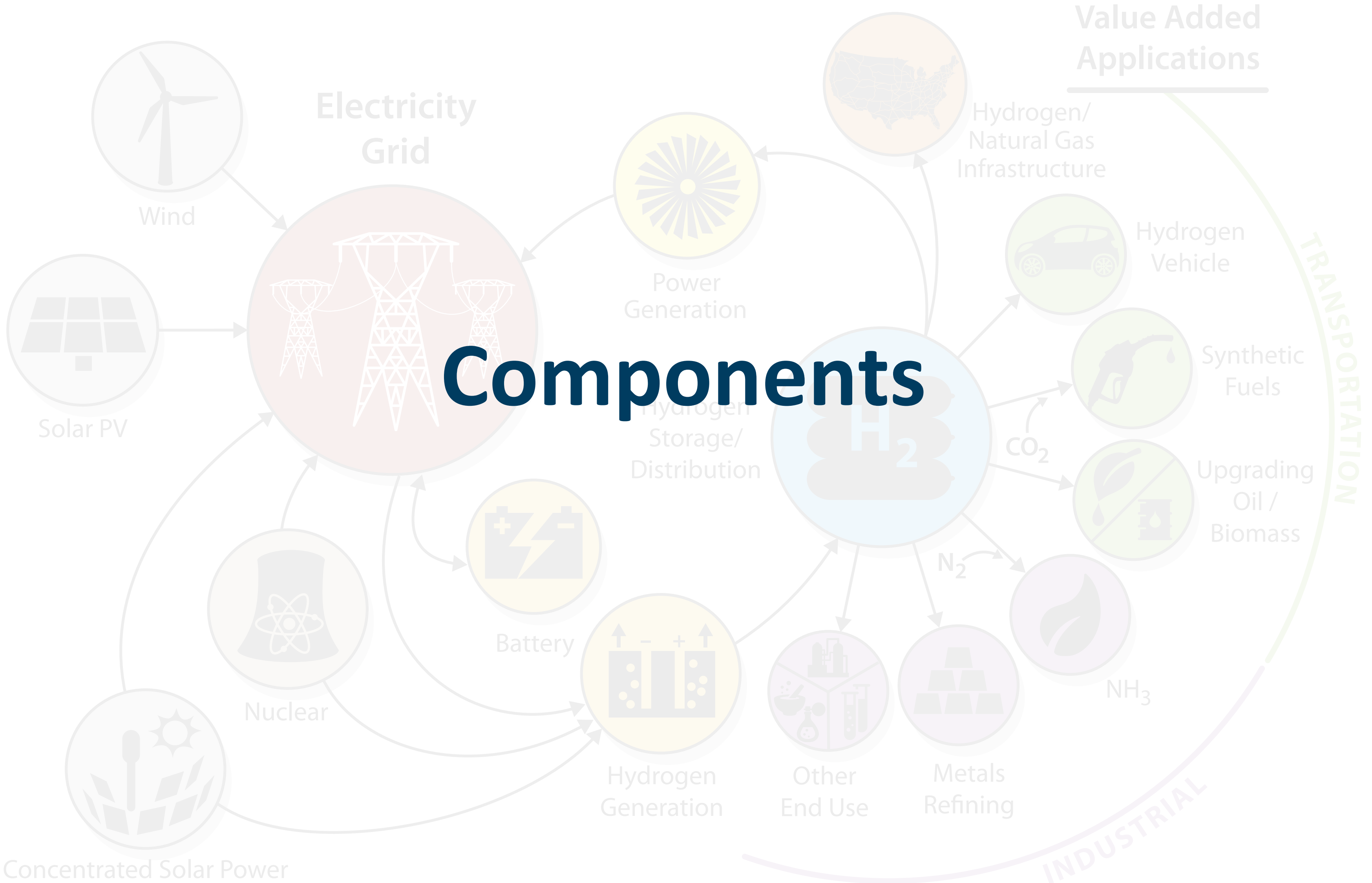
50% **fewer GHG emissions** than today . . . by **2050**

MORE
Jobs
Security
Resiliency

Additional Content/Backup Slides

- H_2@Scale components
- H_2@Scale history/timeline
- H_2@Scale connection to energy storage
- H_2@Scale safety perceptions/concerns
- H_2@Scale connection to grid
- Cross-DOE-office connections
- QTR connections

Components



Wind
Electricity Grid
Solar PV
Power Generation
Hydrogen/ Natural Gas Infrastructure
Value Added Applications
Hydrogen Vehicle
Synthetic Fuels
Upgrading Oil / Biomass
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CO_2
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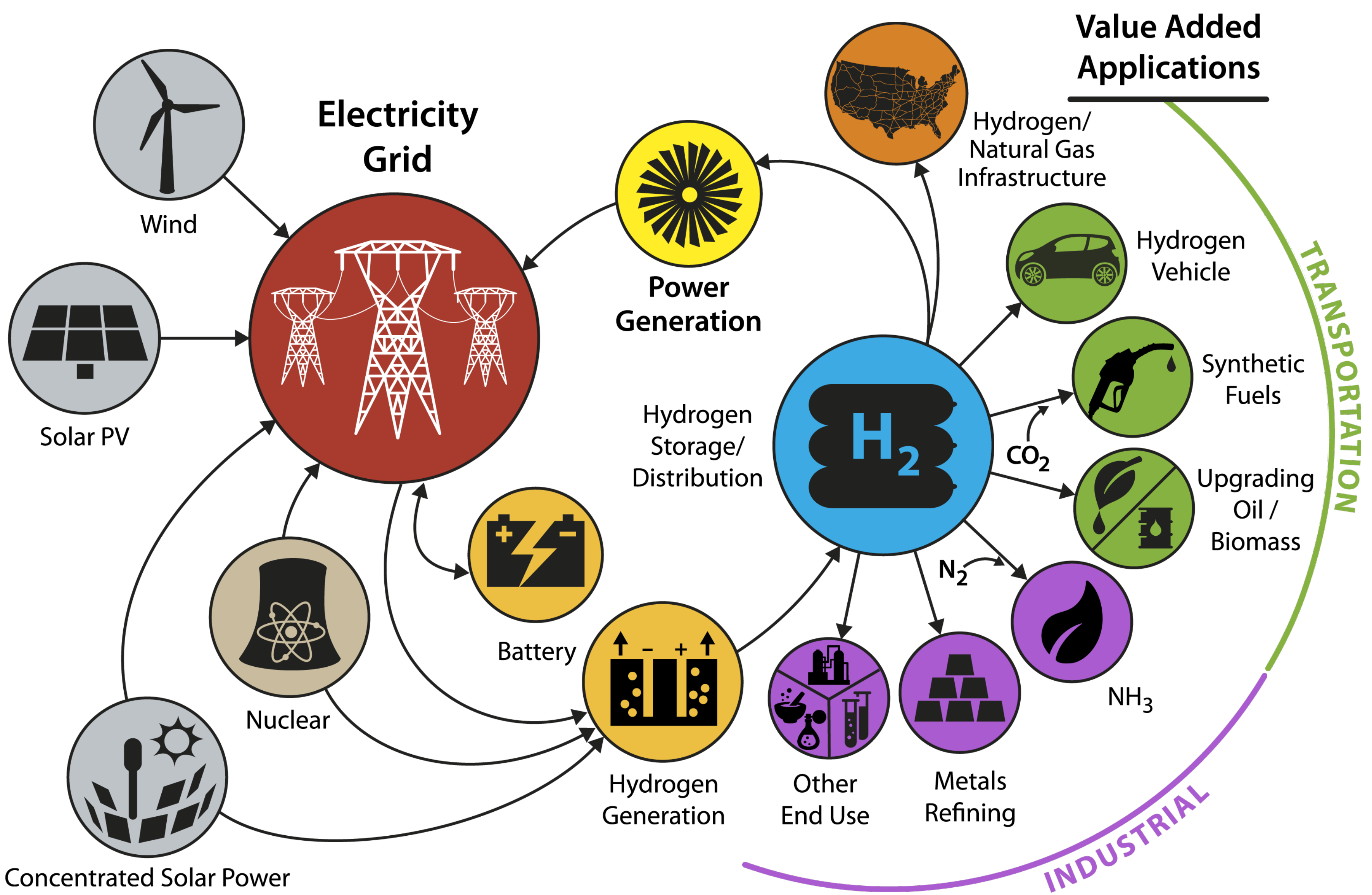
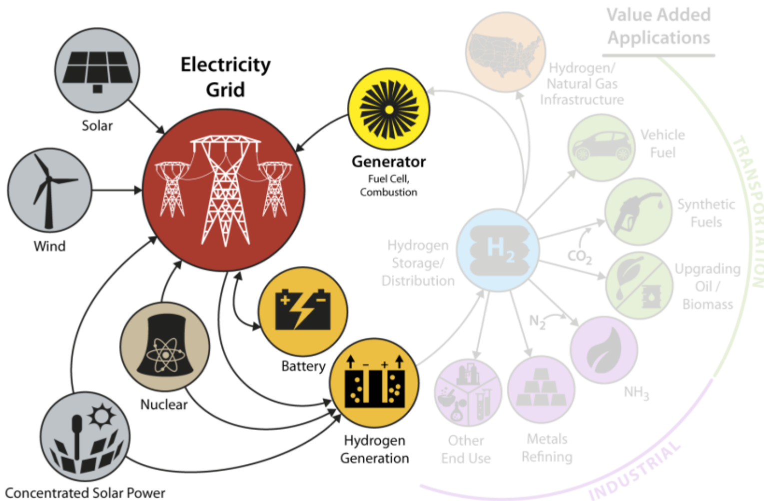
Metals Refining
INDUSTRIAL
Concentrated Solar Power

Conceptual H_2 at Scale Energy System*

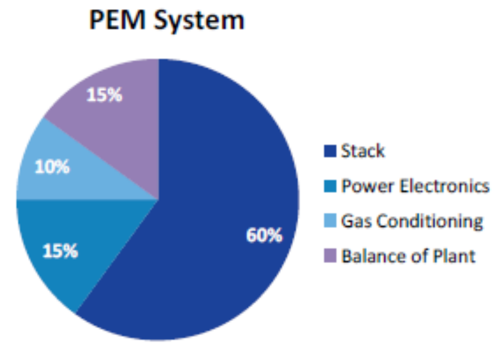


*Illustrative example, not comprehensive

Low- and High-T H_2 Generation



Cost Distribution



Research Priorities

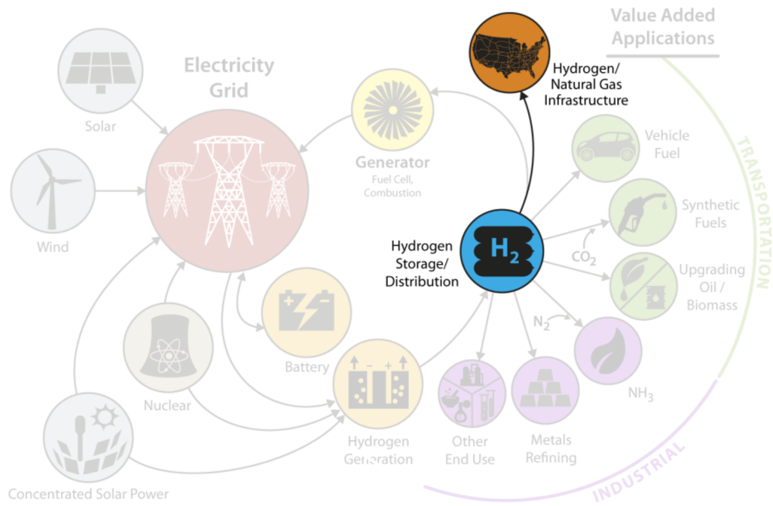
- Durability for intermittent operation
- Lower cost electrolysis
- Manufacturing at scale
- Thermal integration

Specific H_2 Production Technology Needs

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

DOE Programs Impact: EERE (FCTO, Solar, Wind, AMO); OE/Grid; NE; FE; SC

H_2 Storage and Distribution



Specific Technology Needs

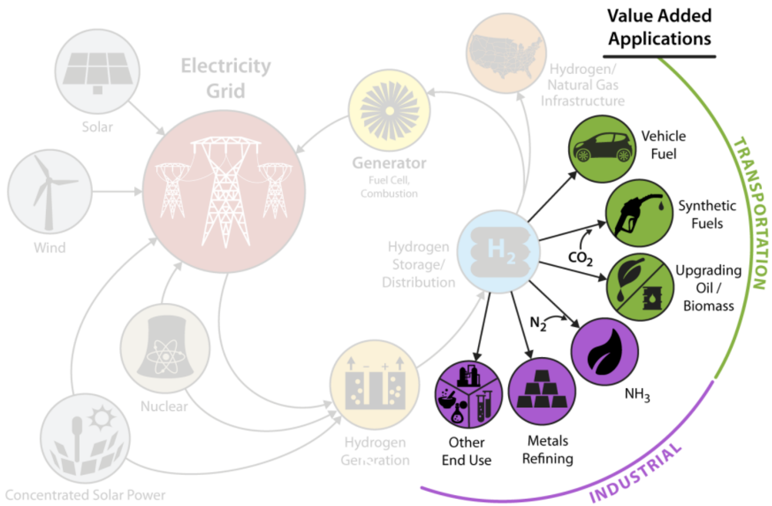
- Hydrogen Storage
  - Chemical/metal hydrides
    - Materials systems
    - Catalysis
  - Physical Storage
    - Geologic
    - Manufactured
- Direct Electro-Chemical Hydride Conversion
- Distribution
  - Compression
  - Liquefaction
  - Materials Compatibility *(Hydrogen Embrittlement)*
  - Leak Detection/Repair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

DOE Programs Impact: EERE (FCTO, AMO); OE, FE; SC

H_2 Utilization



Research Priorities

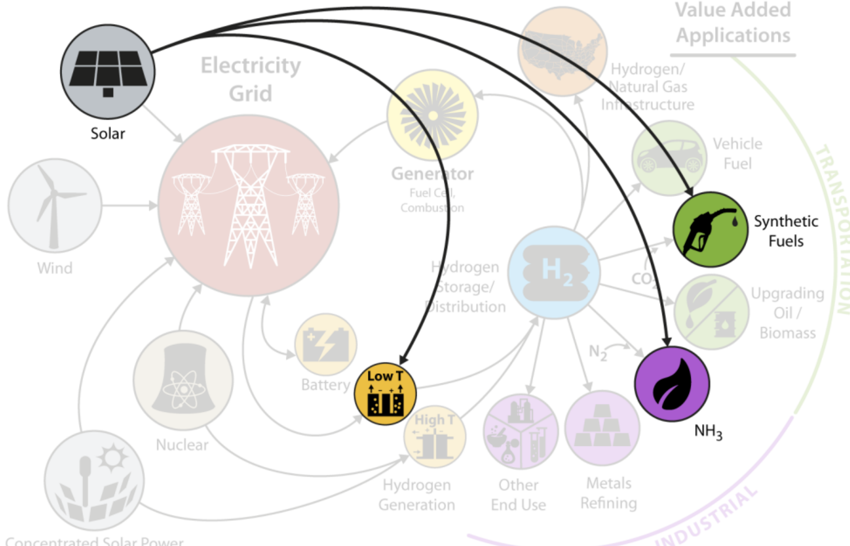
- New process chemistry with H_2 used as a reductant
  - Chemical, Fuels, Metals Production
- Process efficiency improvement
  - Industry and power systems
- Process heat integration with intermittent H_2 generation
- H_2 / H_2-rich flame modeling

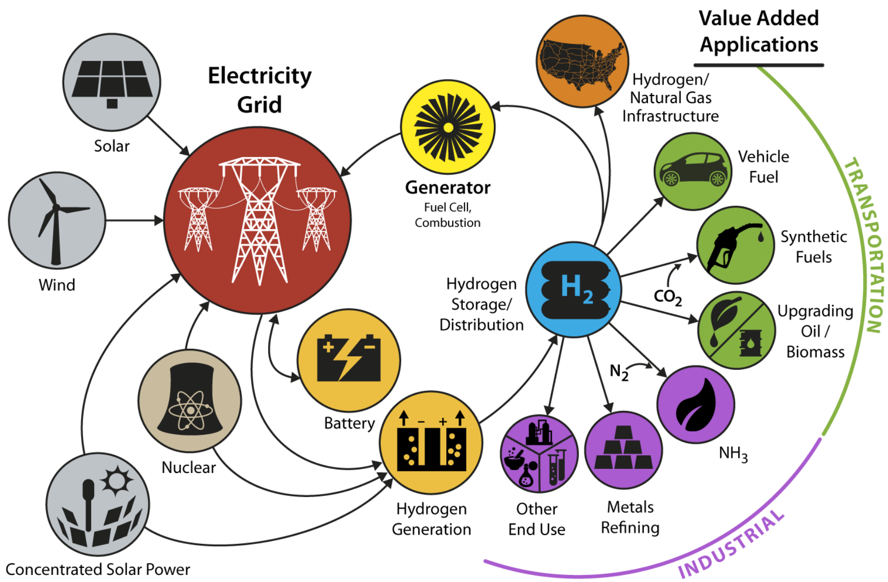
Specific H_2 Utilization Technology Needs

- 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

DOE Programs Impact: EERE (AMO, FCTO, Wind/Solar); NE; FE; ARPA-E; SC

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)

User facilities

SNS, light sources, nanocenters, microscopy

ACSR and advanced computing

Big data

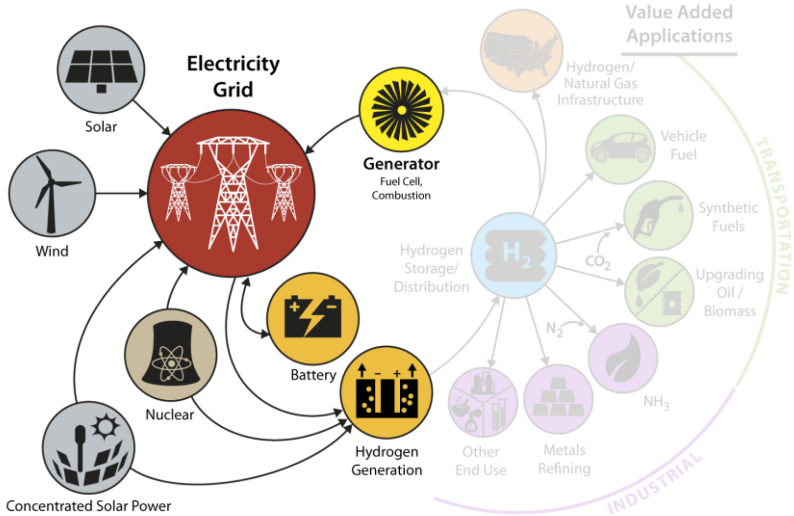
Algorithms for prediction multiscale physics

JCAP leveraged science

MGI (expansion)

dissolution, kinetics, solvents

Grid Integration



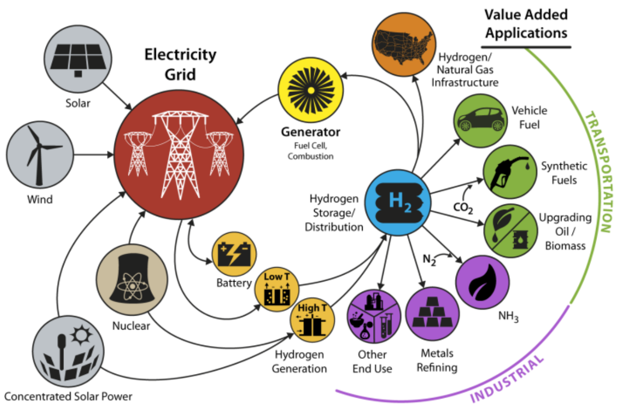
Specific Grid Integration Technology Needs

- 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

Research & Development Priorities

- Systems analysis
- Systems engineering
- Systems design and demo

Analysis



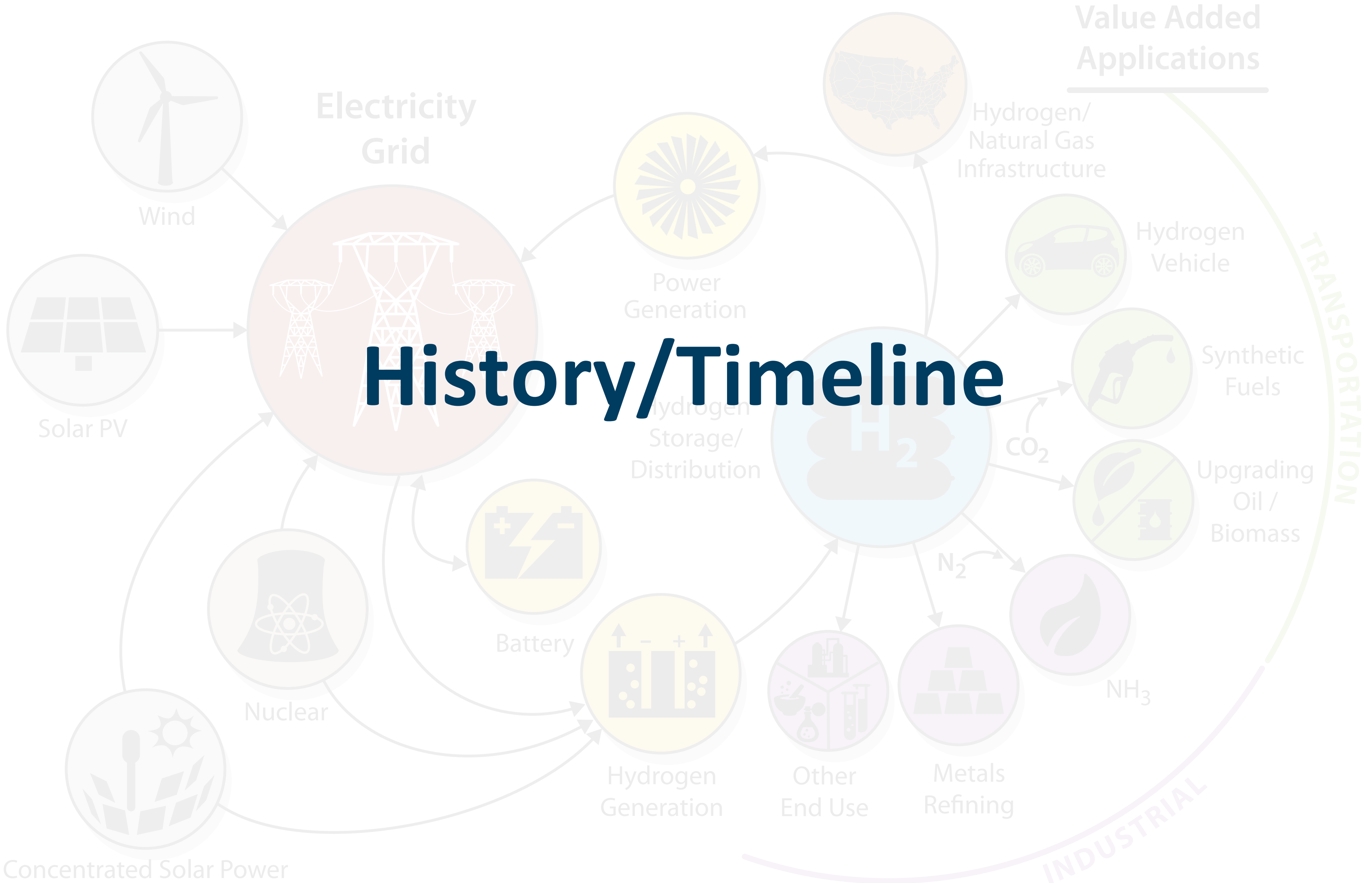
<u>Analysis Priorities</u>

- 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

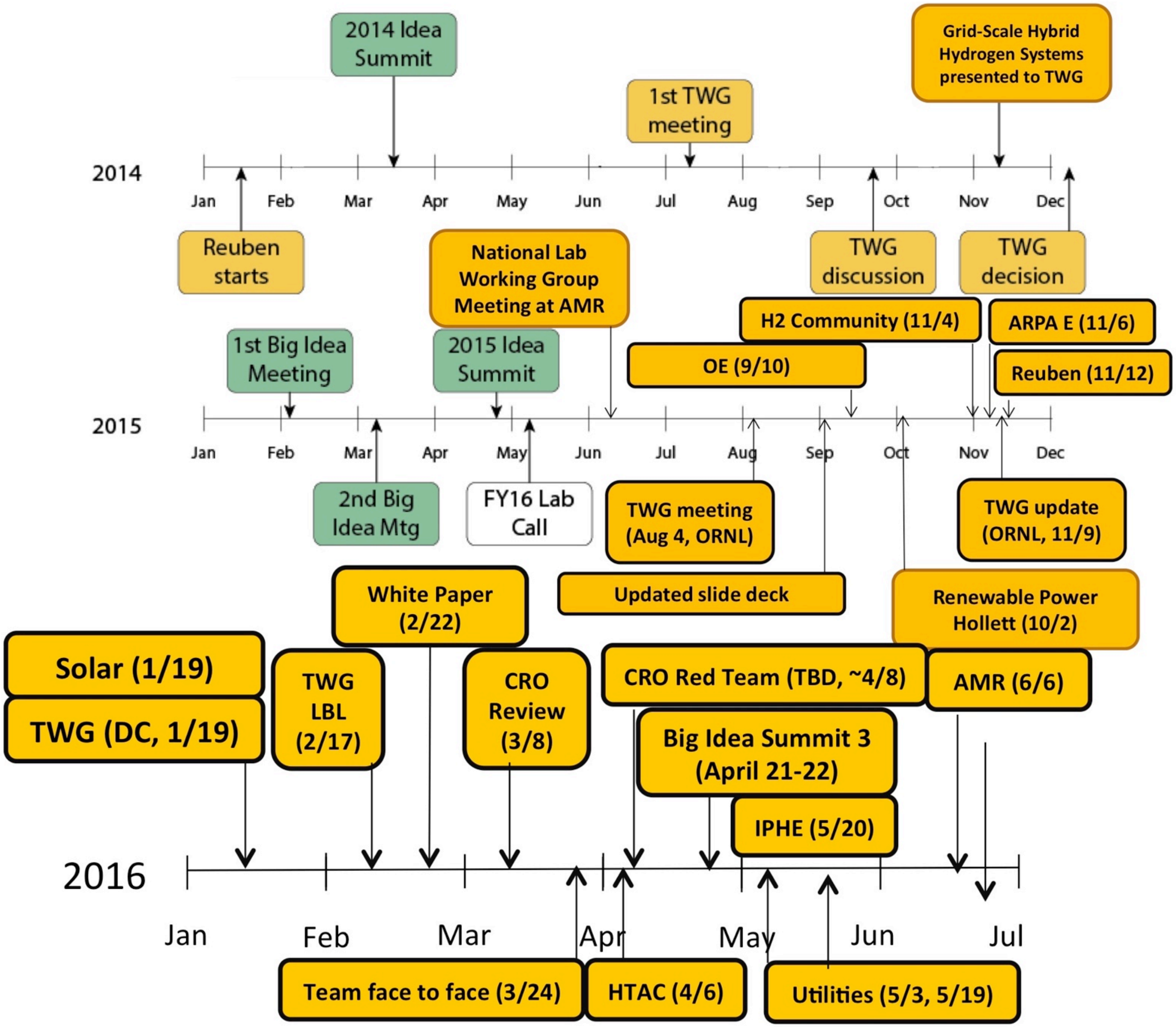
<u>Specific Analysis Needs</u>

- 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

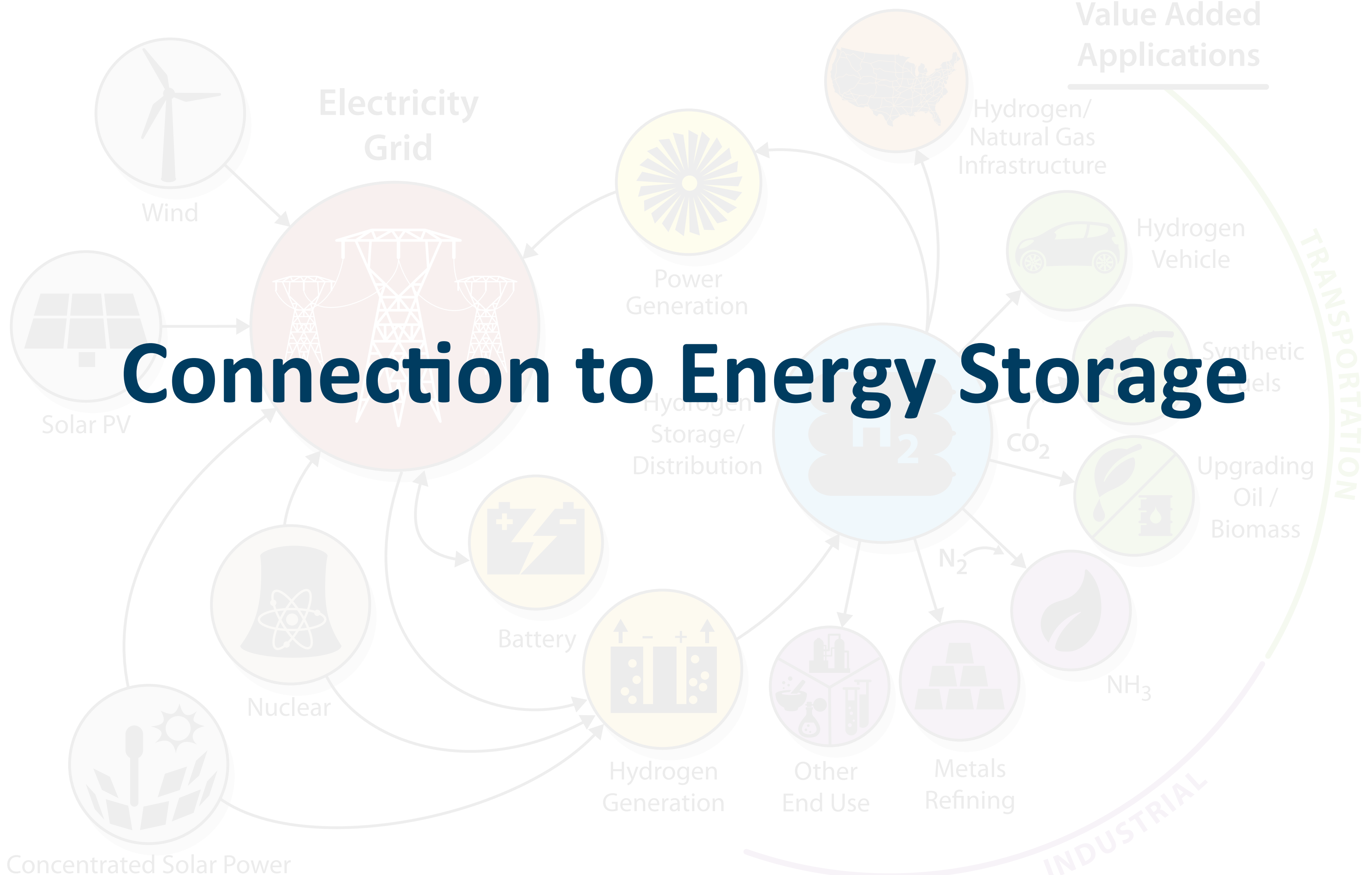
History/Timeline



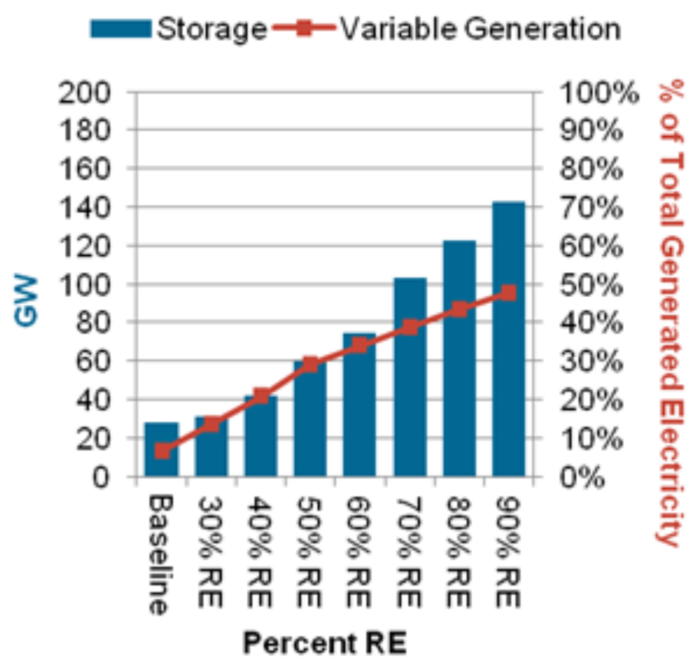
H_2 Big Idea Timeline

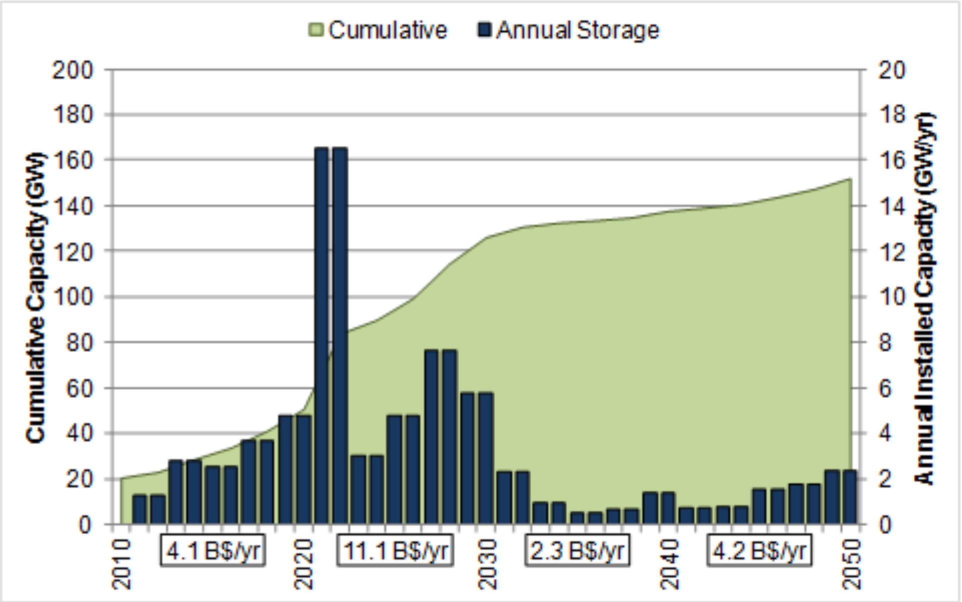


Connection to Energy Storage

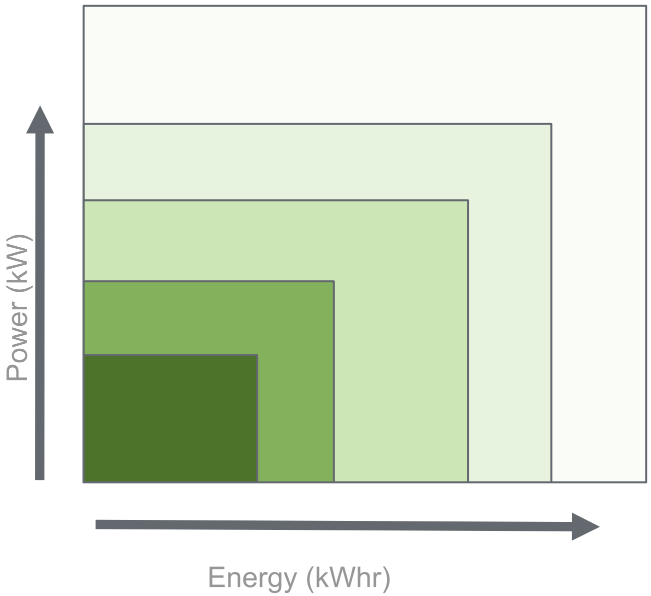


Storage Needs with Increased RE Penetration





RE Futures Study

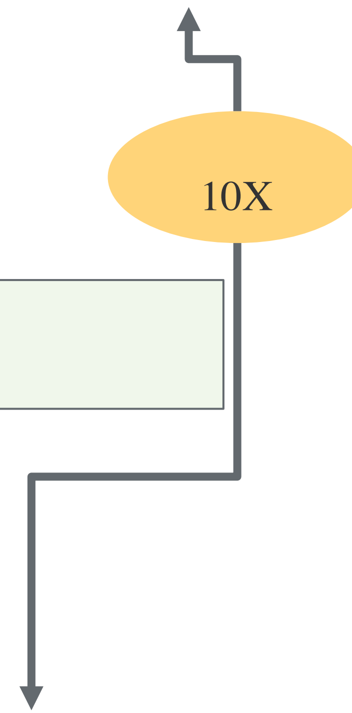


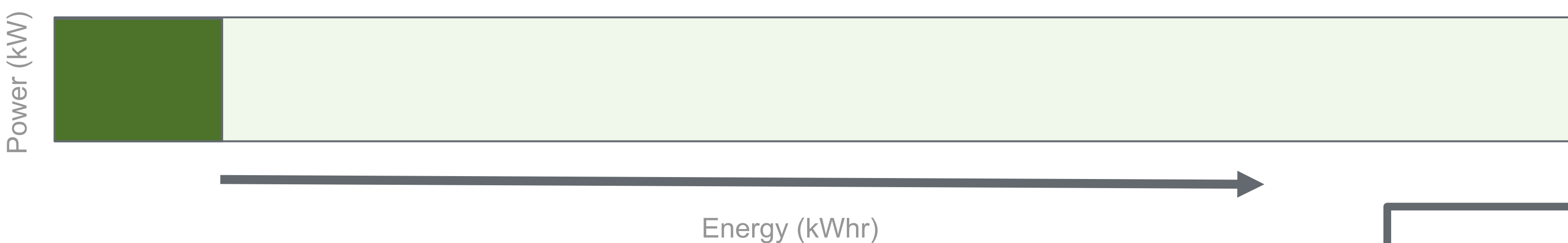
Battery systems

Power and Energy scale together

More energy storage = more batteries

Marginal cost of storage capacity is $1400/kWh





Hydrogen systems

Power and energy scale separately

More energy storage = more tanks only $140/kWh

Source: Hydrogenics

Examples – Hydrogen vs. Batteries

Competitive Analysis vs. Battery Storage

Attributes	Pilot Project – Hydrogen Energy System	Pilot Project – Battery System	Full-Scale Project – Hydrogen Energy System	Full-Scale Project – Battery System
Favorable Total Cost of Ownership	△	△	●	✖
Technical Scalability	●	●	●	△
Modularity	●	●	●	△
Maintenance Requiements	●	●	●	●
Capital System Cost	△	△	●	✖
Environmental Attributes/Disposal	●	△	●	✖
Conditioned Footprint	●	●	●	✖
Reliability	●	●	●	●
Expected Lifetime of Electrochemical Core	●	△	●	✖

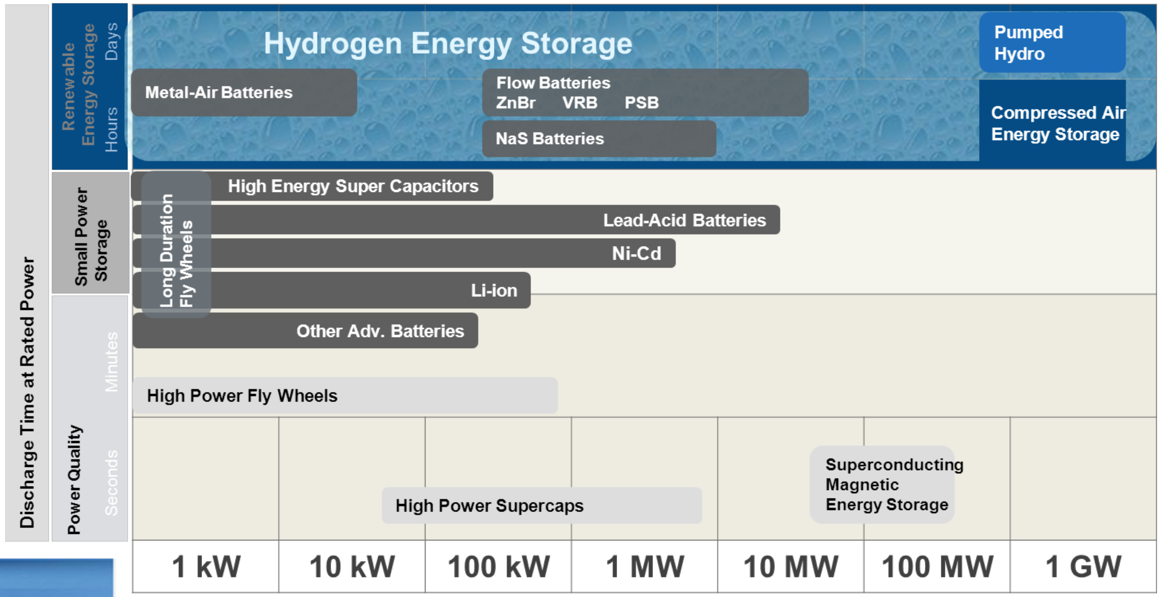
Good = ●; Concern = △; Not Good = ✖

Hydrogen vs. LiOH Battery Solution

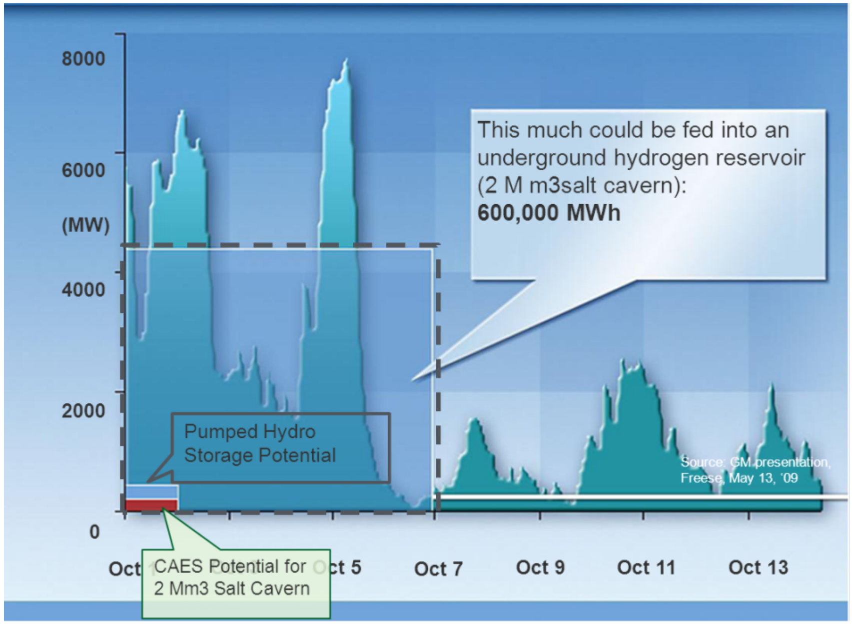
Factor	Battery System	Difference	Hydrogen System
Net Energy Cost	$1.69	2.5X +	$0.68
Incremental Storage Cost	$1400 - $850/kWh	10x +	$50-140/ kWh
% of Time Full	71%	1.6x +	43%
Wind Energy Wasted (1)	7.9/12.3 (64%)	2.6x +	2.8/10.9 (25%)
Capital Cost	69M$	2.5x +	28M
Total Life Cycle Cost	91M$	2.6x +	36.5M$
Net System Efficiency	35%	8% +	39%
Environmental Impact	D	+	O

Source: Hydrogenics

Many Jobs, Many Solutions



Source: Electricity Storage Association



Capacity, Not Efficiency a Larger Driver for Renewable Storage

Only hydrogen offers storage capacity for several days or weeks

Source: Hydrogenics

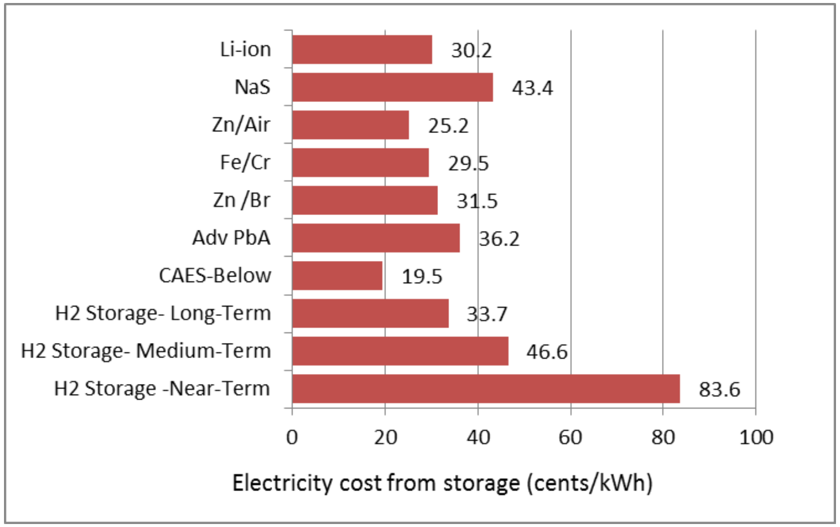
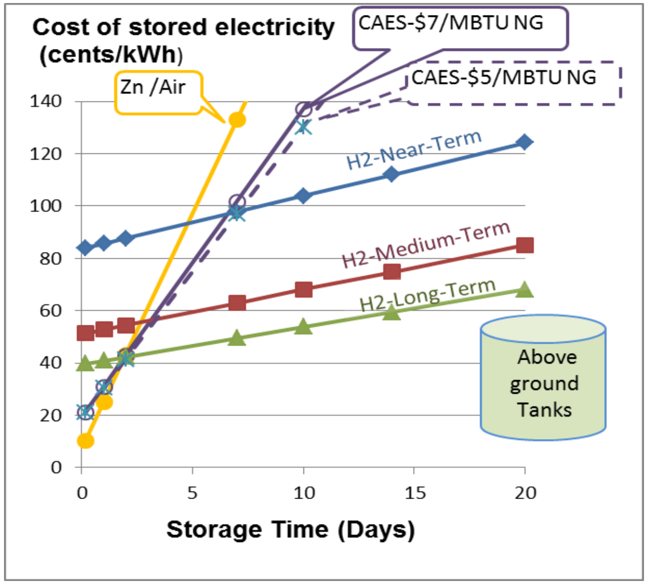


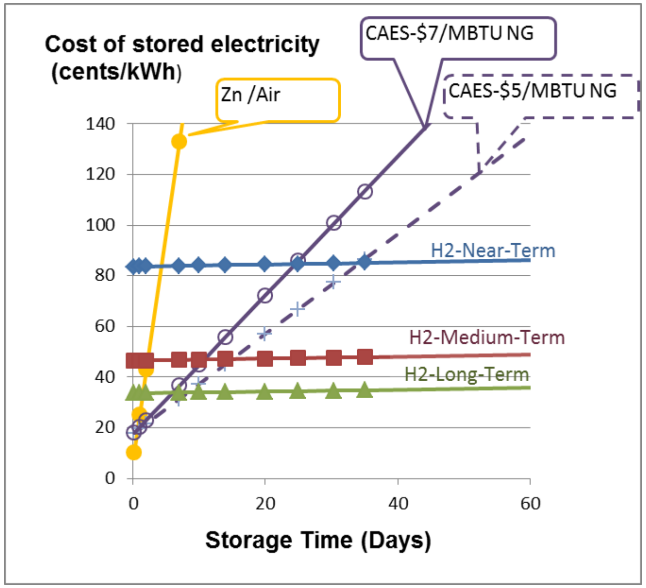
Figure 1. Price of on-Peak electricity for various below-ground H2 & CAES storage and battery storage options with one-day storage and 10% "free" (stranded) energy for a 10MW output over 4 hours (40MWh/day) & NG = $5/MBTU (for CAES) [All battery & CAES costs are based on the lower EPRI estimates.]

Only Long-Term H_2 Storage competes in single day cycling

But multi-day energy storage will likely be necessary in a high renewables penetration scenario, if there is more value placed on otherwise curtailed renewable resources due to:

- Higher Renewable Portfolio Standards
- Carbon Dioxide Emission Controls

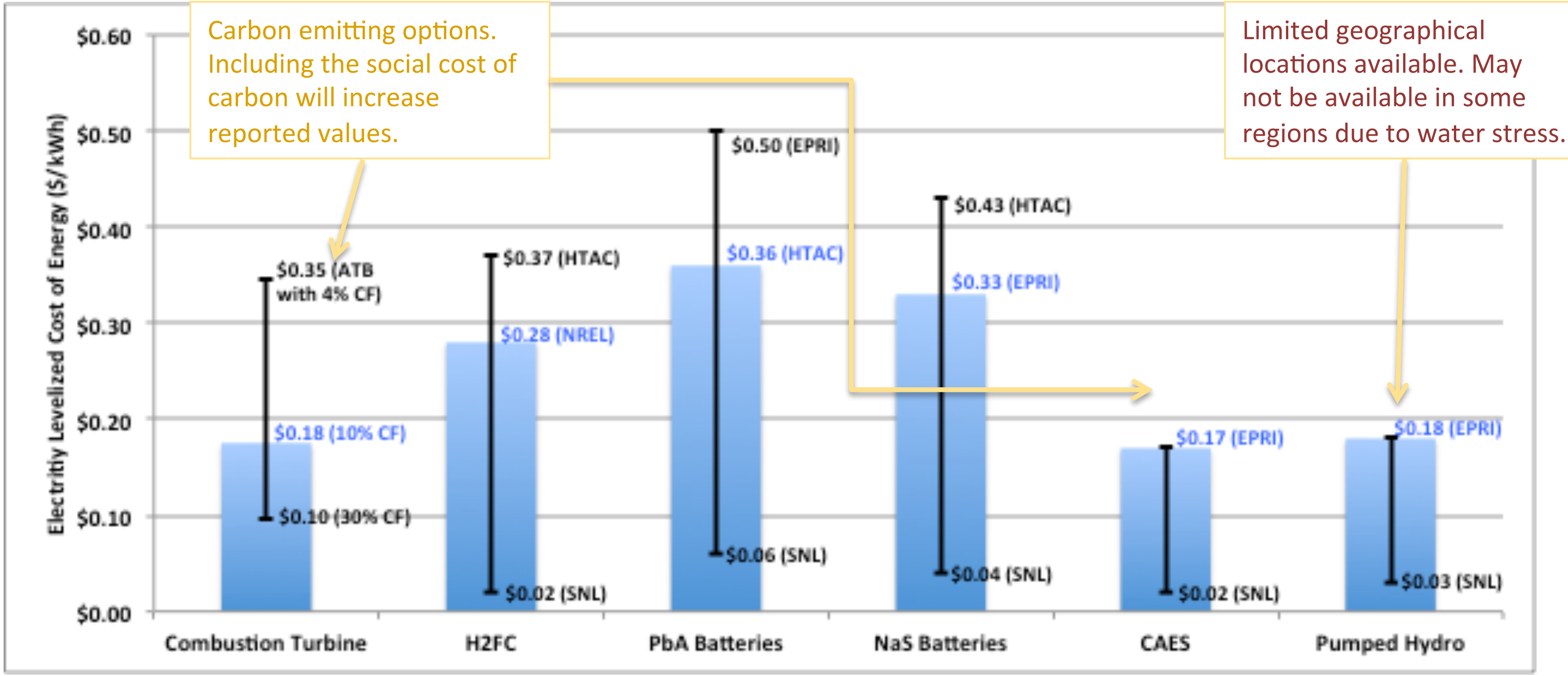




Need to understand when there is economic value for longer storage times under high penetration renewables scenarios

Source: Sandy Thomas

Energy "Storage"



Storage will need to compete with flexible generation on economics and probably emissions. Efficiency challenges exist, but when considering renewable electrons, it is economics, not efficiency, that is the critical metric.

Hydrogen goes beyond other technologies by providing a sink for grid electrons rather than a just a capacitor.

Non-energy values (e.g., ancillary services, capacity) are not included in these analyses but are likely to benefit storage as compared to combustion turbines (see Denholm, et all "The Relative Economic Merits of Storage and Combustion Turbines for Meeting Peak Capacity Requirements under Increased Penetrations of Solar Photovoltaics" (2015).

ATB: Annual Technology Baseline; CF: Capacity Factor; H2FC: Hydrogen Fuel Cell; CAES: Compressed Air Energy Storage

Safety Perceptions/Concerns

Hydrogen Safety

What is the first thing you think of when "Hydrogen Safety" is mentioned?

The flames observed are actually the burning aluminum powder, and lacquer applied to the canvas skin to mitigate against lightning strikes, not the hydrogen inside the airship. [1]

[1] *The Freedom Element, Living with Hydrogen*, Dr. A. Bain, Blue Note Publications, Cocoa Beach, FL, USA, 2004.

Hindenburg Disaster: May 6, 1937
Lakehurst, NJ

Fuel Flamability Comparison

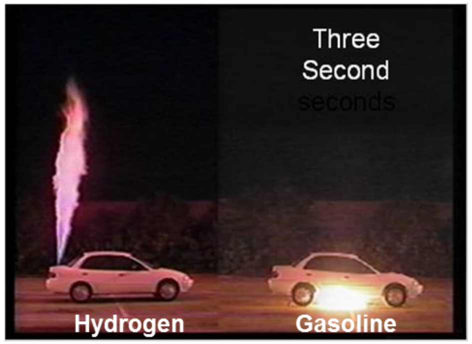
	Hydrogen	Gasoline Vapors	Natural Gas
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14.0%
Ignition Energy (MJ)	0.02	0.2	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited)	29%	2%	9%

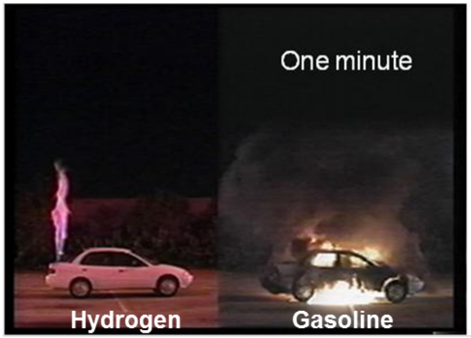
"Hydrogen safety concerns are not cause for alarm; they simply are different than those we are accustomed to with gasoline or natural gas."
AirProducts and Chemicals, Inc.

Fuel Leak Simulation

Punctured tank and ignition

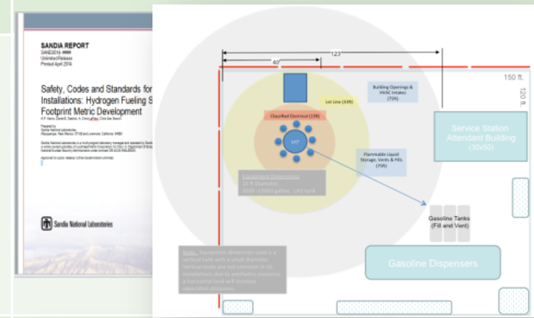
with equivalent energy release

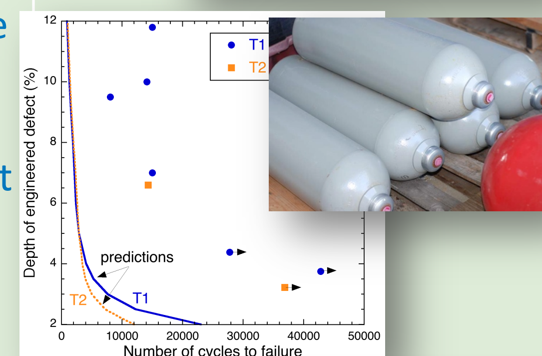


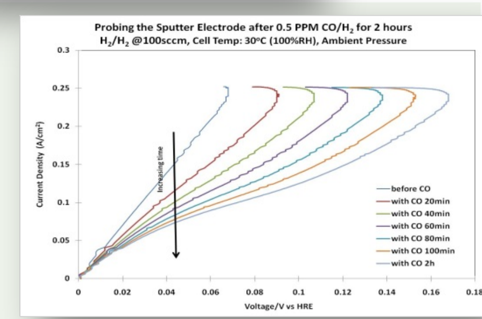


H_2 Safety

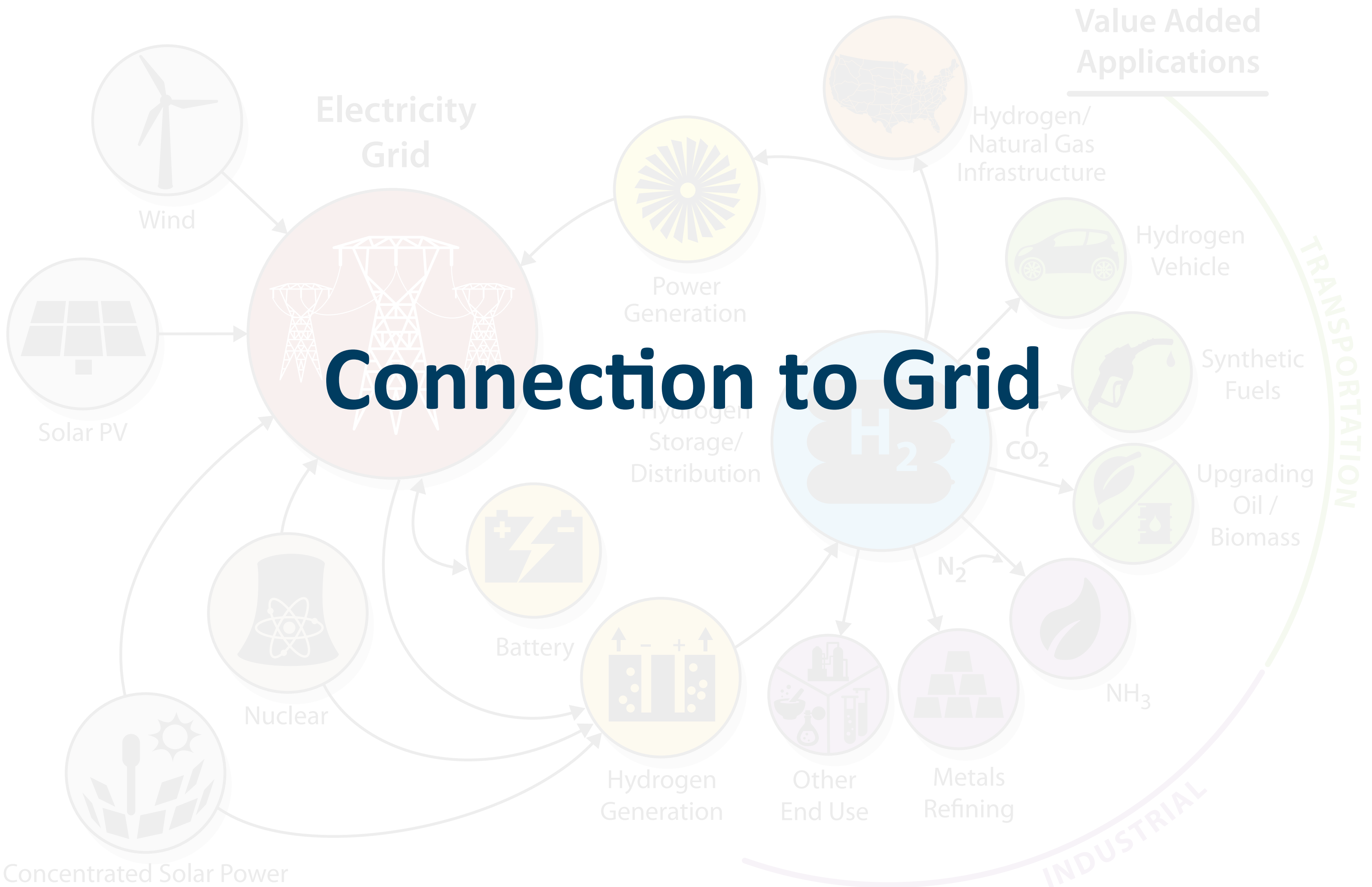
Hydrogen Risk Assessment Models (HyRAM)	Developed a tool to enable integrated probabilistic and deterministic modeling (Quantitative Risk Assessment) for end users.
LH2 Reduced Separation Distances	Use of performance-based design to reduce separation distance and overall station footprint. Published report on ongoing research and research gaps in liquid hydrogen models (http://prod.sandia.gov/techlib/access-control.cgi/2014/1418776.pdf)
Materials Compatibility	Testing of hydrogen compatibility of materials. Use of austenitic stainless steel provides life-time cost reductions (High fatigue stress can be achieved with cycles to failure >10,000 cycles). Development of high-pressure hydrogen materials testing protocol. (www.sandia.gov/matlsTechRef/)
Fuel Quality	• Developing a concept inline hydrogen analyzer to continuously monitor impurities and alert the user to any fuel quality issues at the station. • Investigating effect of performance at low Pt (toward DOE target) loadings.



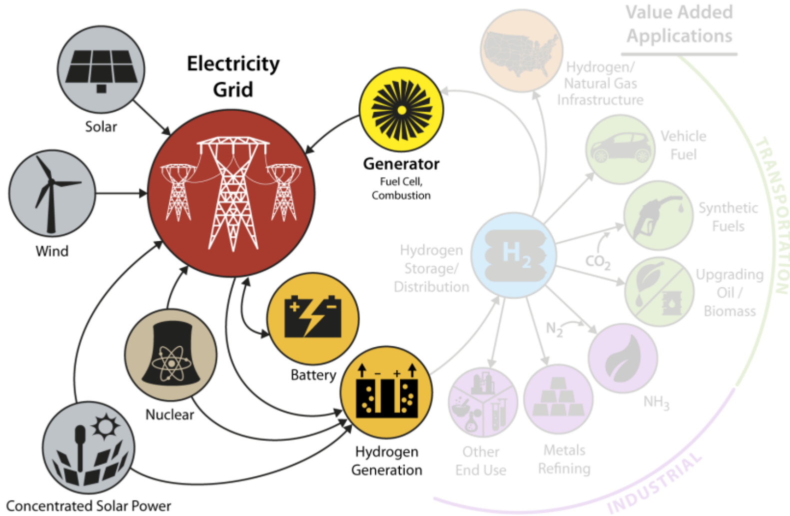




Connection to Grid



Future Electric Grid



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

Grid Support

- **How does H_2 impact Reliability, Resiliency, Security?**
  - We're not sure and need your help, but there are specific features that are likely to have impact, there is also the ability to control (improve) impacts
- **Ancillary services (including fast dynamic response)**
- **Large scale potential**
  - Scalability
  - Flexibility (sighting and integration)
  - Energy storage

Resiliency

- Blackouts cost economy $billions annually.
- H_2 can provide resiliency (how is H_2 impact quantified, validated, and/or monetized?)

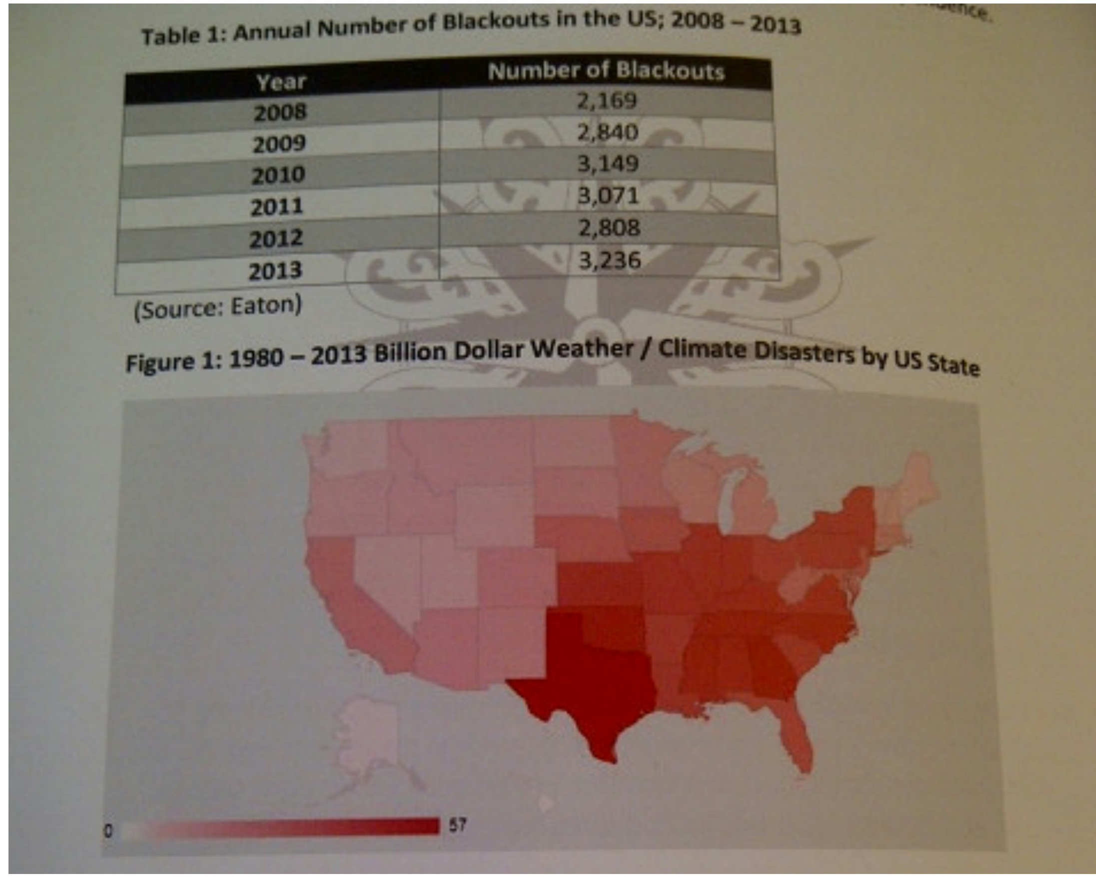


Table 1: Annual Number of Blackouts in the US; 2008 – 2013

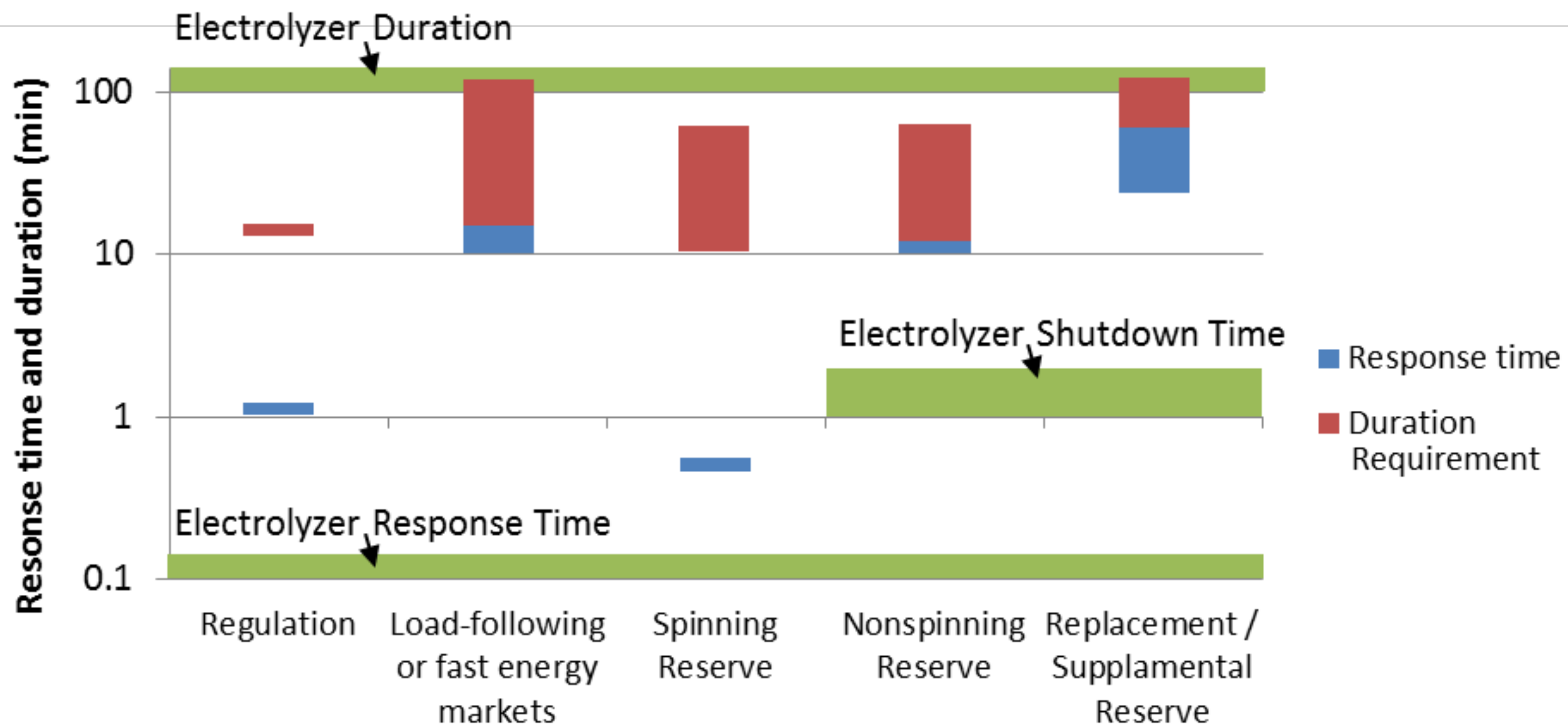
Year	Number of Blackouts
2008	2,169
2009	2,840
2010	3,149
2011	3,071
2012	2,808
2013	3,236

(Source: Eaton)

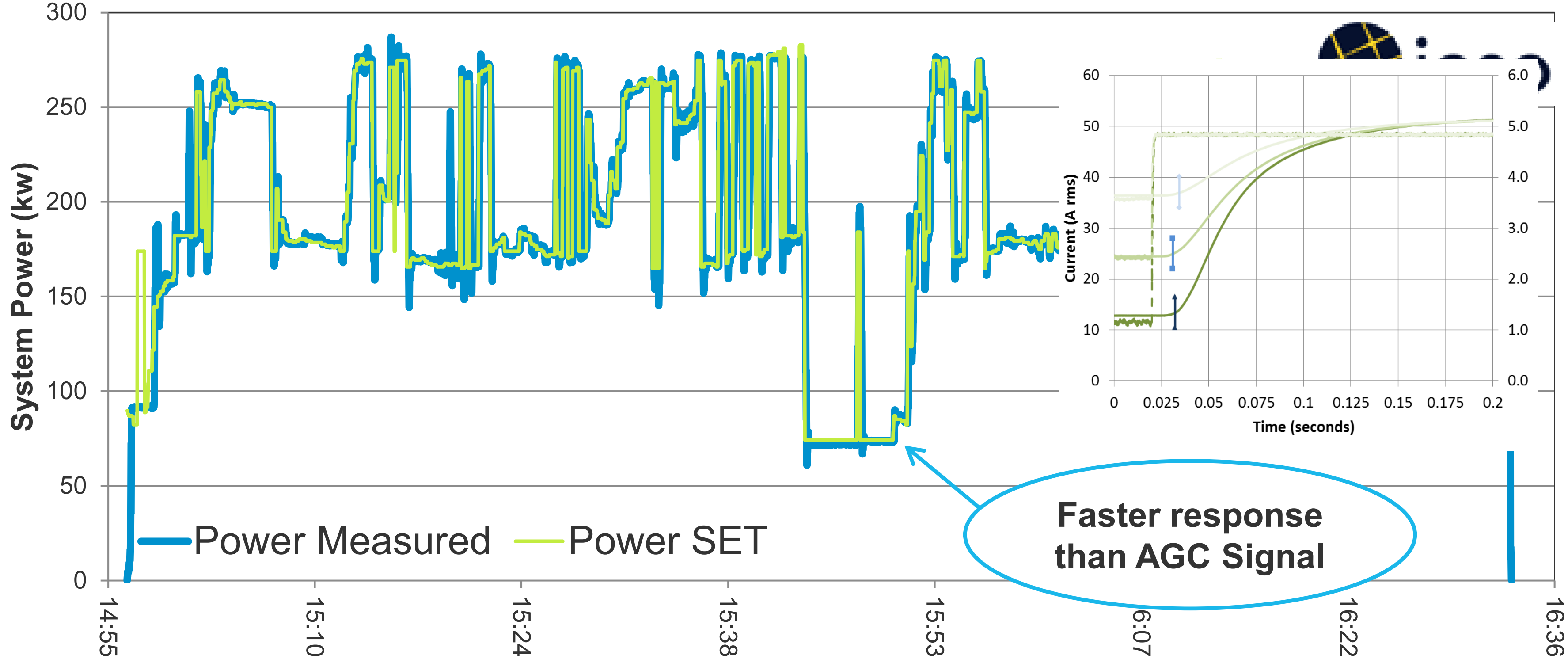
Figure 1: 1980 – 2013 Billion Dollar Weather / Climate Disasters by US State

Grid Support

- Ancillary services (response time/duration)



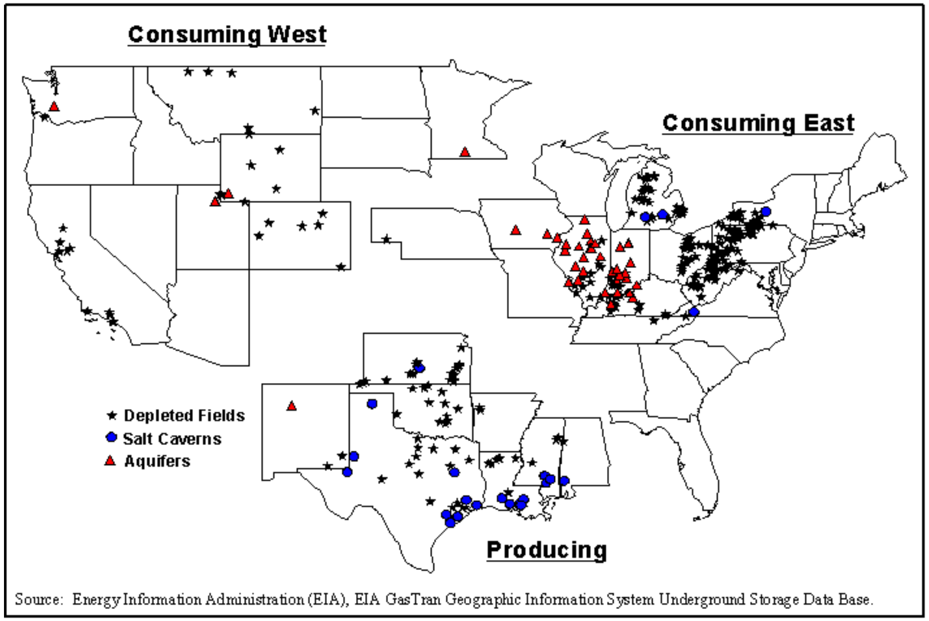
Exceptional Energy Storage Capability *and* Real Time Dynamic Response



Note: IESO signal test completed June 2011 – AGC (Automatic Generation Control)

H_2 Storage Potential

- Current natural gas system
  - 305,000 miles of transmission pipelines
  - 400 underground natural gas storage facilities
  - 3.9 Bcf underground storage working gas capacity
- If transitioned to H_2 equates to…
  - 38 billion kg of H_2



H_2 storage capacity
~2 months energy needs potentially available
Does this reflect resiliency or security?

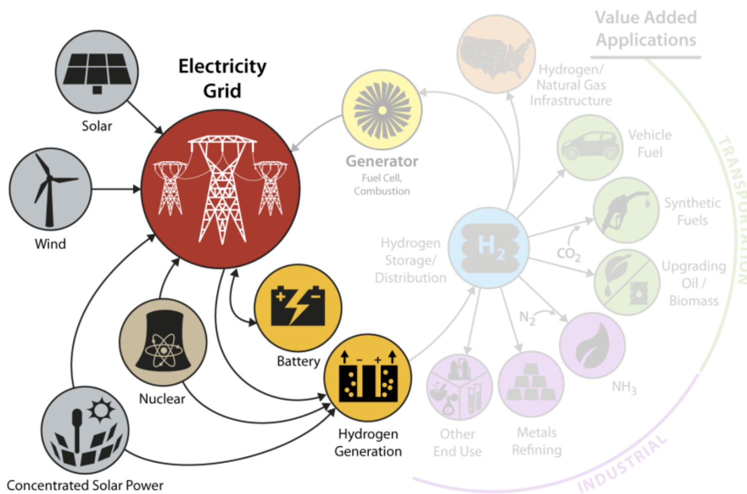
Source: www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html

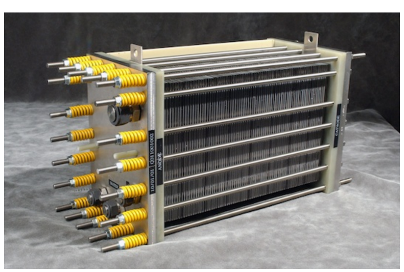
Scalability/Flexibility

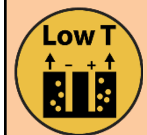
- Distributed options vs. centralized options
  - From sub-MW to GW scale
  - Coupling with local generation (wind, PV, CSP, NE)
  - Electricity transmission vs. hydrogen distribution
  - On-sight consumption or conversion

Cross-DOE-Office Connections

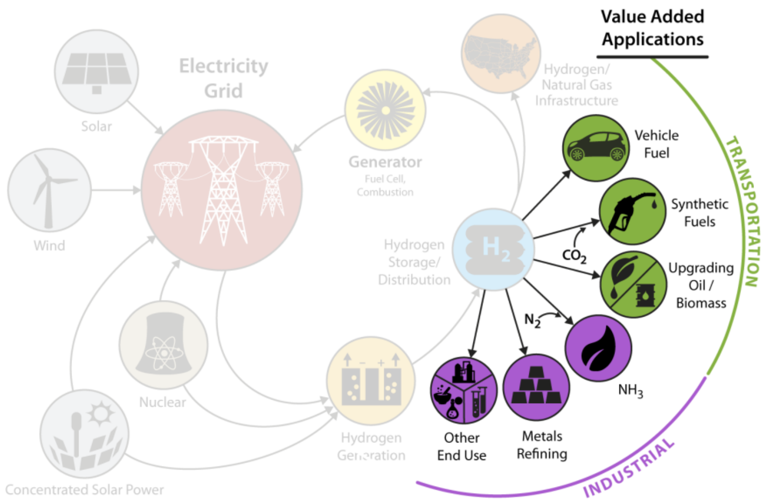
Cross-Office Collaborations

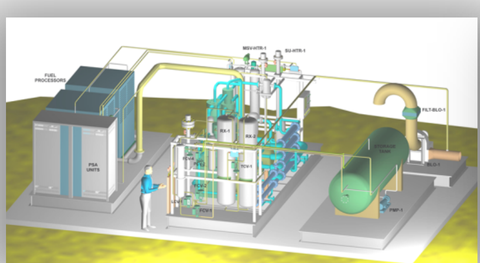


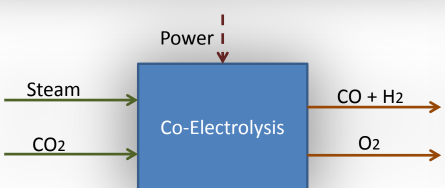


R&D Focus	Research Activities	DOE Programs	Impact
Low T H_2 Production 	• Reduce precious metal loadings on electrolyzer electrodes • Low-cost, durable high-conductivity membranes • Low-cost, corrosion resistant, thin film protective coatings • Develop durable systems for intermittent operation • Develop transformational technologies for water splitting from renewable feedstock	ARPA-E BES SETO Wind OE FCTO	✓ Increase the value of renewable electrons ✓ Enable high penetration of renewables on the grid ✓ Improve efficiency and stability of electrochemical and photoelectrochemical technologies ✓ Decrease the cost of H_2 at high volume by 5X
High T H_2 Production 	• Materials discovery and development for high T electrolyzers (e.g. SOEC) • Component durability in intermittent heat sources • Develop transformational high-temperature redox redox materials and reactor components for hydrogen generation	NE BES SETO FCTO	✓ Reduce electricity consumption of electrolysis by leveraging waste heat ✓ New materials discovery ✓ Improve thermochemical/ concentrated solar system design and components including materials, heliostat, and power electronics
H2 Storage and Distribution 	• Polymer and steel compatibility with H2 • Advanced liquefaction and refrigeration • Materials for harsh environments • Reduce moving parts, and improve efficiency of pipeline and forecourt compressors • Use of fiber reinforced composite polymers in pipelines	NNSA BES ARPA-E AMO FE FCTO	✓ Develop physics-based understanding of hydrogen embrittlement ✓ Improve hydrogen liquefaction efficiency by > 60% ✓ Improve reliability and efficiency of gas compression ✓ Lower cost of high-pressure pipelines ✓ Enable over 2X reduction in cost of hydrogen delivery and dispensing

Cross-Office Collaborations

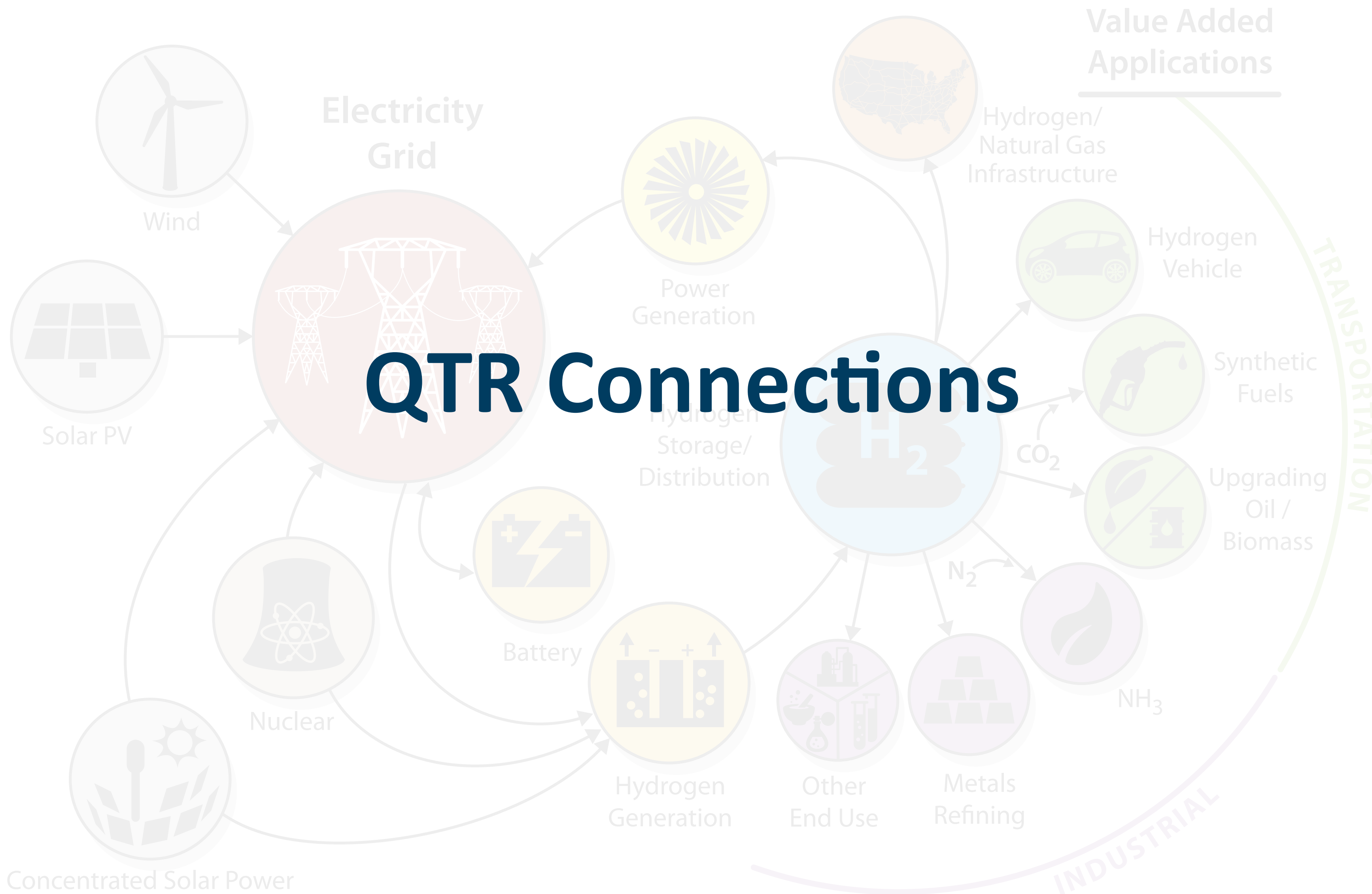






R&D Focus	Research Activities	DOE Programs	Impact
Ammonia	• Modular Plants • Catalyst R&D • Process intensification • Ammonia Fuel Cells	ARPA-E AMO FCTO FE SC	✓ Decrease cost of NH_3 production >25% ✓ Improve process efficiency ✓ Improve NH_3 handling safety
Refineries	• Electrolysis and refinery heat integration • H_2 and O_2 combustion • Integrated coke gasification • NE &RE energy utilization	FE FCTO AMO SC NE & RE	✓ >75% GHG footprint reduction ✓ Facilitate heavy crude refining ✓ Coke by-product management ✓ Expand markets for RE & NE
Chemicals	• Catalyst R&D for H_2-dependent chemicals • CO_2 reduction chemistry • Process intensification • Hybrid electricity/chemicals	ARPA-E AMO SC NE & RE FCTO	✓ Sustainable chemicals production ✓ Pathway to CO_2 utilization ✓ Domestic workforce with competitive manufacturing
Biofuels	• Modular plants for distributed production • H_2 (and O_2) incorporation in bio-refineries	BETO VTO SC NE & RE FCTO	✓ Increase biofuels potential production >30% ✓ 100% zero-emissions biofuels ✓ Expand markets for local RE
Metals & Glass Refining	• Direct reduction of iron process development • Metals annealing/tempering • Materials codification	ARPA-E AMO SC	✓ 10x increase in U.S. steel production with associated heavy manufacturing ✓ >5% impact on world GHG
Combustion Processes	• Flame chemistry and heat transfer studies • Burner and turbine testing	ARPA-E AMO FE SC	✓ Movement toward Zero-emissions process heating ✓ Clean power generation
H2 Heat Pumps	• Low temperature heat use • Industrial and residential energy efficiency studies • Power systems integration	ARPA-E AMO BTO FE SC	✓ 5% efficiency improvement for manufacturing industries ✓ 10% efficiency improvement for power generation turbines ✓ >50% cooling water reduction

QTR Connections

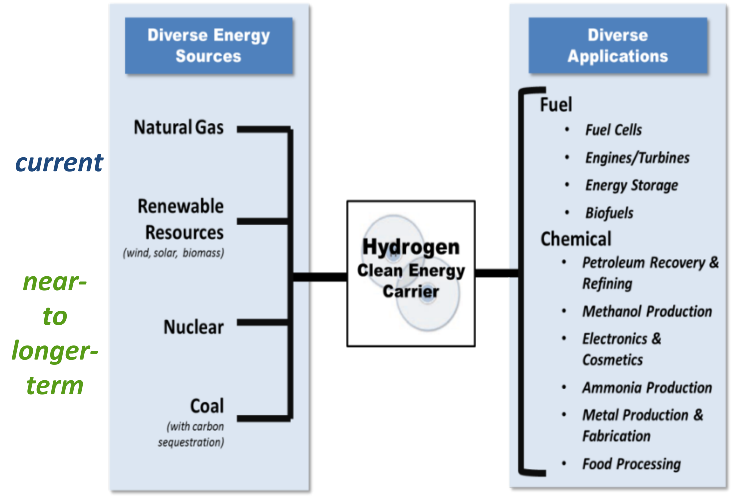


QTR Feedback

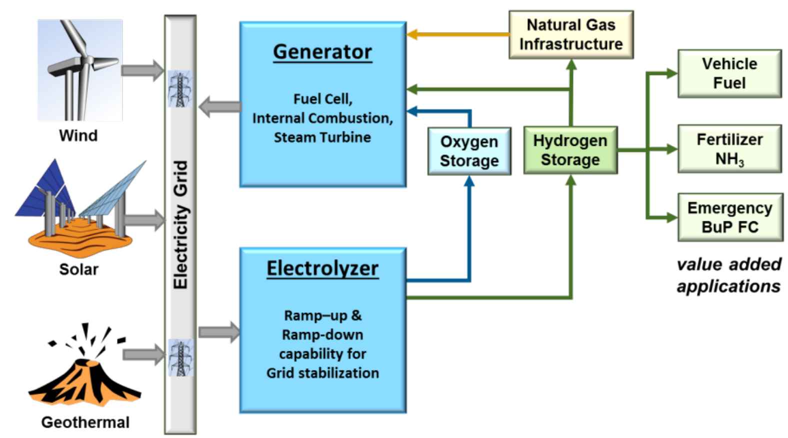
- **Major challenges:**
  Reduce the cost of producing and delivering H_2 from renewable/low-carbon sources for FCEV and other uses (capex, O&M, feedstock, infrastructure, safety, permitting, codes/standards)

- **Factors driving change in the technologies:**
  - FCEVs are driving requirements (e.g. high P tanks)
  - Need to reduce cost of 700 bar refueling stations for near-term FCEV roll-out

- **Where the technology R&D needs to go:**
  - Materials innovations to improve efficiencies, performance, durability and cost, and address safety (e.g. embrittlement, high pressure issues)
  - System-level innovations including renewable integration schemes, tri-generation (co-produce power, heat and H_2), energy storage balance-of-plant improvements, etc.
  - Cost reductions in H_2 compression, storage and dispensing components
  - Continued resource assessments to identify regional solutions to cost-competitive H_2



H_2 offers important long-term value as a clean energy carrier



Renewable energy integration options with hydrogen

QTR - Hydrogen Analysis and Research Goals

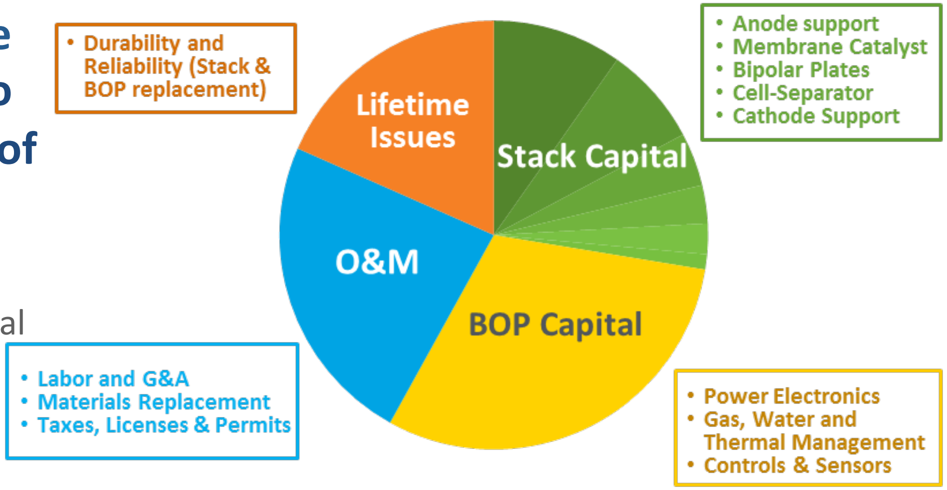
- **Reduce the cost of H_2 from renewable and low-carbon domestic resources to achieve a delivered & dispensed cost of <\$4/gge** **(Note: 1 kg H_2 ~ 1 gge)**

  Pathways:
  - Electrolysis, high temperature thermochemical (solar/nuclear), biomass gasification/bio-derived liquids, coal gasification with CCS, biological & photoelectrochemical

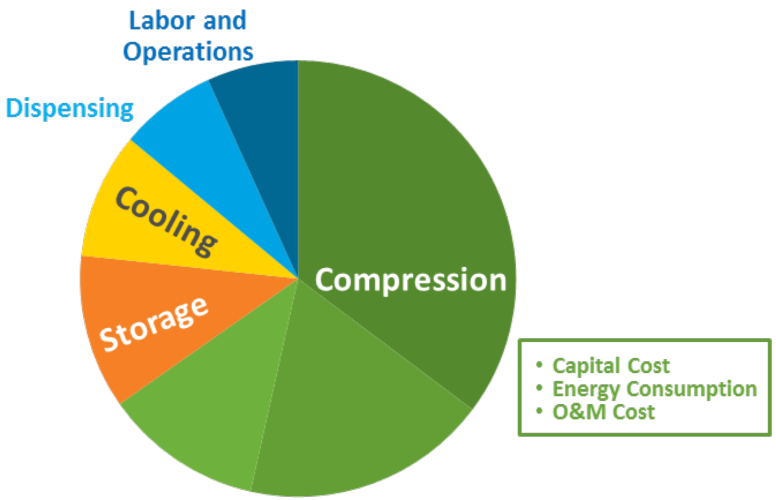
- **Need R&D in materials and components to improve efficiency, performance, durability, and reduce capital and operating costs for all pathways**
  - For many pathways, feedstock cost is a key driver of H_2 cost

- **Need strong techno-economic and regional resource analysis**

- **Opportunities for energy storage (e.g. curtailed wind for electrolyzing water)**



H_2 Production Example- Cost Breakdowns for PEM electrolysis, (excluding electricity feedstock costs)



H_2 Delivery Example- Compression, Storage and Dispensing (CSD) Cost Breakdown for the Pipeline Delivery Scenario