H_2 at Scale:

Deeply Decarbonizing Our Energy System

Briefing to Deputy Under Secretary Adam Cohen

Forrestal Building
April 4, 2016
Washington, D.C.

Bryan Pivovar: NREL

NREL/PR-5900-66246
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Motivation - Major Administration Energy Goals

Reduce GHG emissions by 17% by 2020, 26-28% by 2025 and 83% by 2050 from 2005 baseline Climate Action Plan

Reduce net oil imports by half by 2020 from a 2008 baseline Blueprint Secure

Double energy productivity by 2030 Department of Energy

By 2035, generate 80% of electricity from a diverse set of clean energy resources Blueprint Secure Energy Future

Reduce CO_2 emissions by **3 billion metric tons** cumulatively by 2030 through efficiency standards set between 2009 and 2016

CAP Progress Report

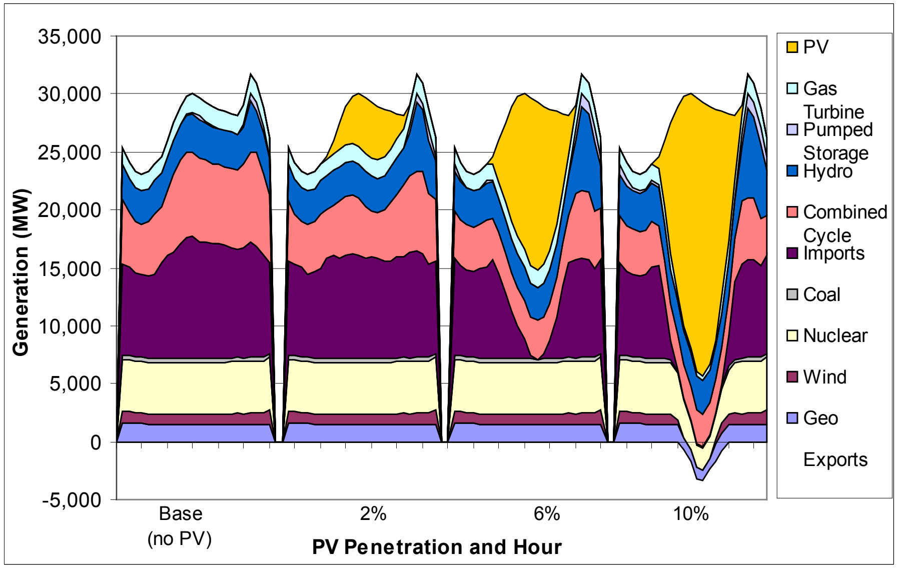
Problem

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

Over half of CO_2 emissions from industrial and transportation sectors

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

Denholm et al. 2008



Real Climate Change Impact Requires

Deep Decarbonization

H_2@scale can enable increased renewable penetration that:

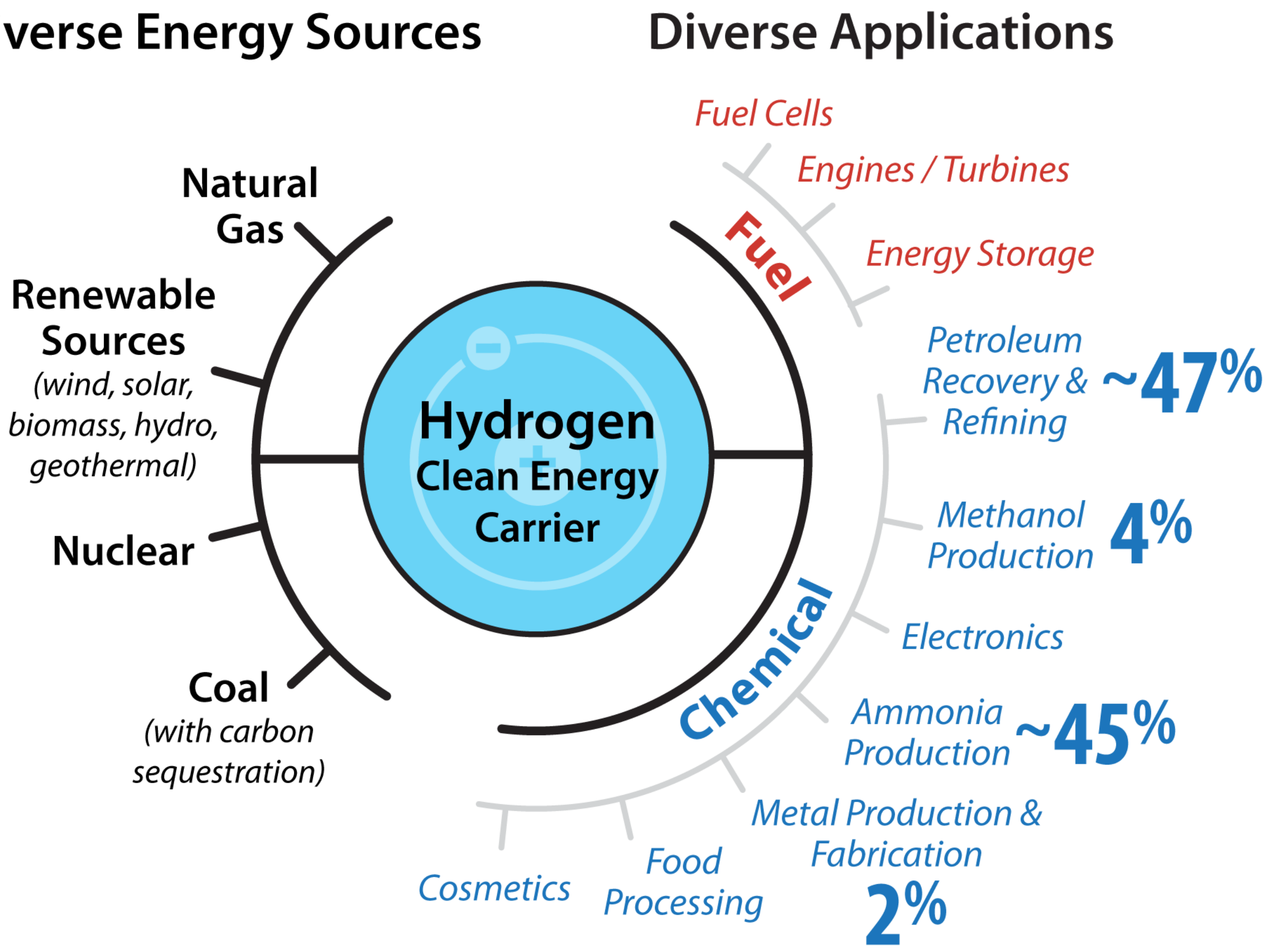
Decreases 45% of all U.S. carbon emissions by 2050

Broad Cross-Sector Impacts

- **Grid**
- **Transportation**
- **Industrial Applications**
- **Buildings**

While also improving **Energy Security** and **Domestic Economy**

Hydrogen, the Clean, Flexible Energy Carrier



Diverse Energy Sources

Natural Gas

Renewable Sources *(wind, solar, biomass, hydro, geothermal)*

Nuclear

Coal *(with carbon sequestration)*

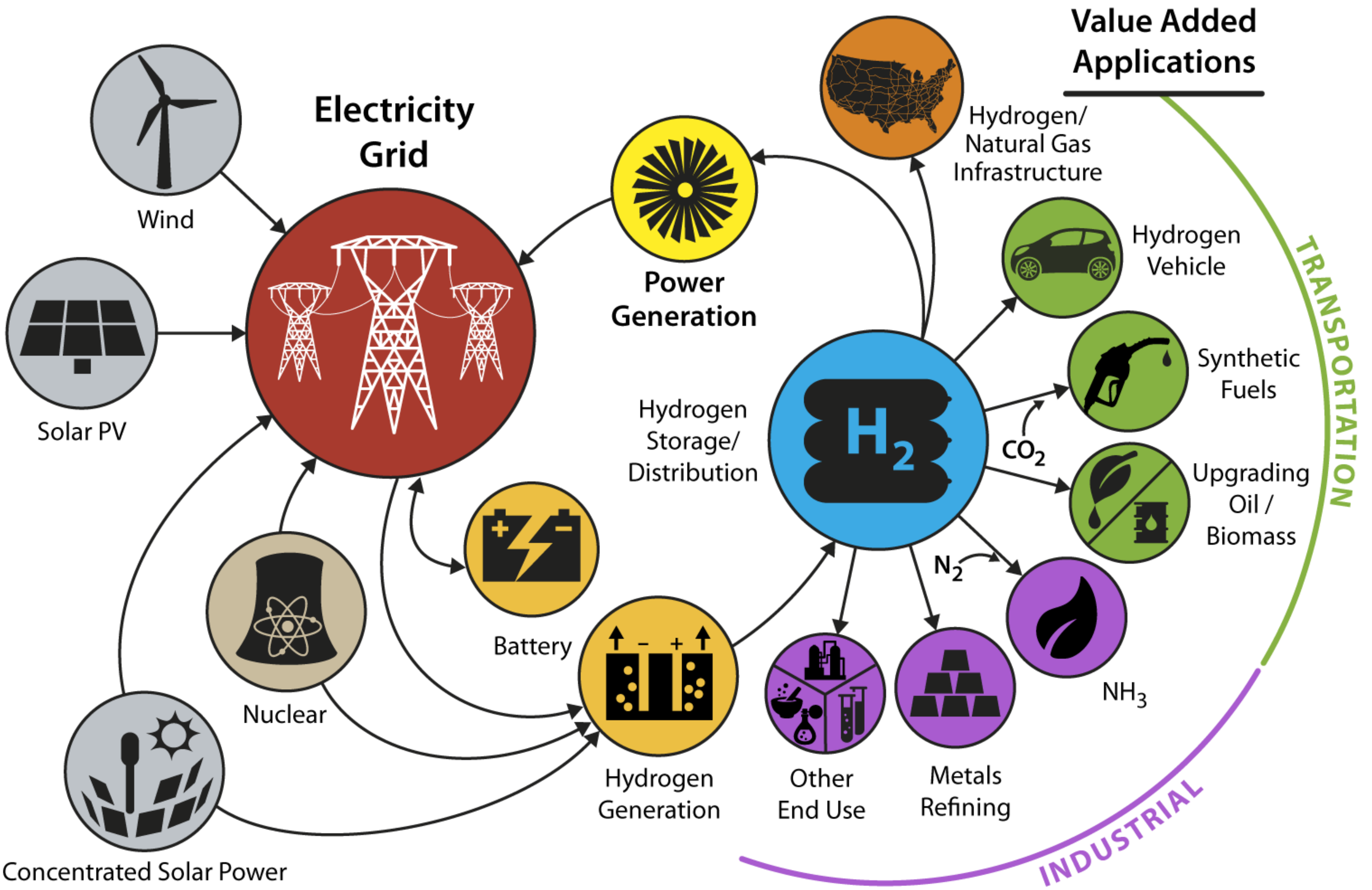
Hydrogen
Clean Energy Carrier

Diverse Applications

Fuel
- *Fuel Cells*
- *Engines / Turbines*
- *Energy Storage*

Chemical
- *Petroleum Recovery & Refining* ~47%
- *Methanol Production* 4%
- *Electronics*
- *Ammonia Production* ~45%
- *Metal Production & Fabrication* 2%
- *Food Processing*
- *Cosmetics*

Future H_2 at Scale Energy System



BAU vs. High RE/H_2 – Energy Differences*

Energy Use Difference between 2050 High Hydrogen Scenario and AEO 2040 Scenario (Quadrillion BTUs)

Red Flows Represent a Reduction (Negative Values)

Black Flows Represent an Increase (Positive Values)

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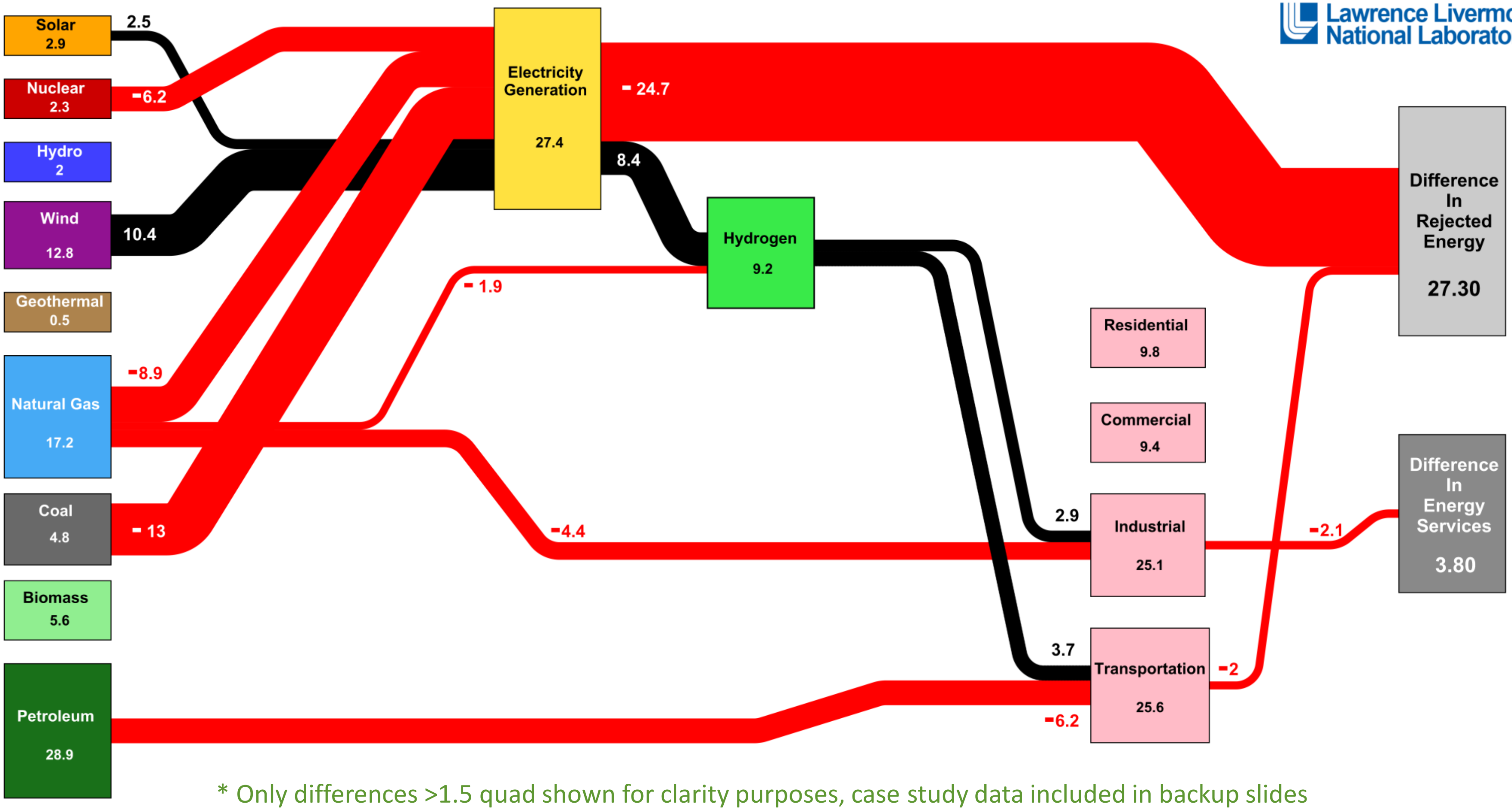

* Only differences >1.5 quad shown for clarity purposes, case study data included in backup slides

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

BAU vs. High RE/H_2 – CO_2 Emissions

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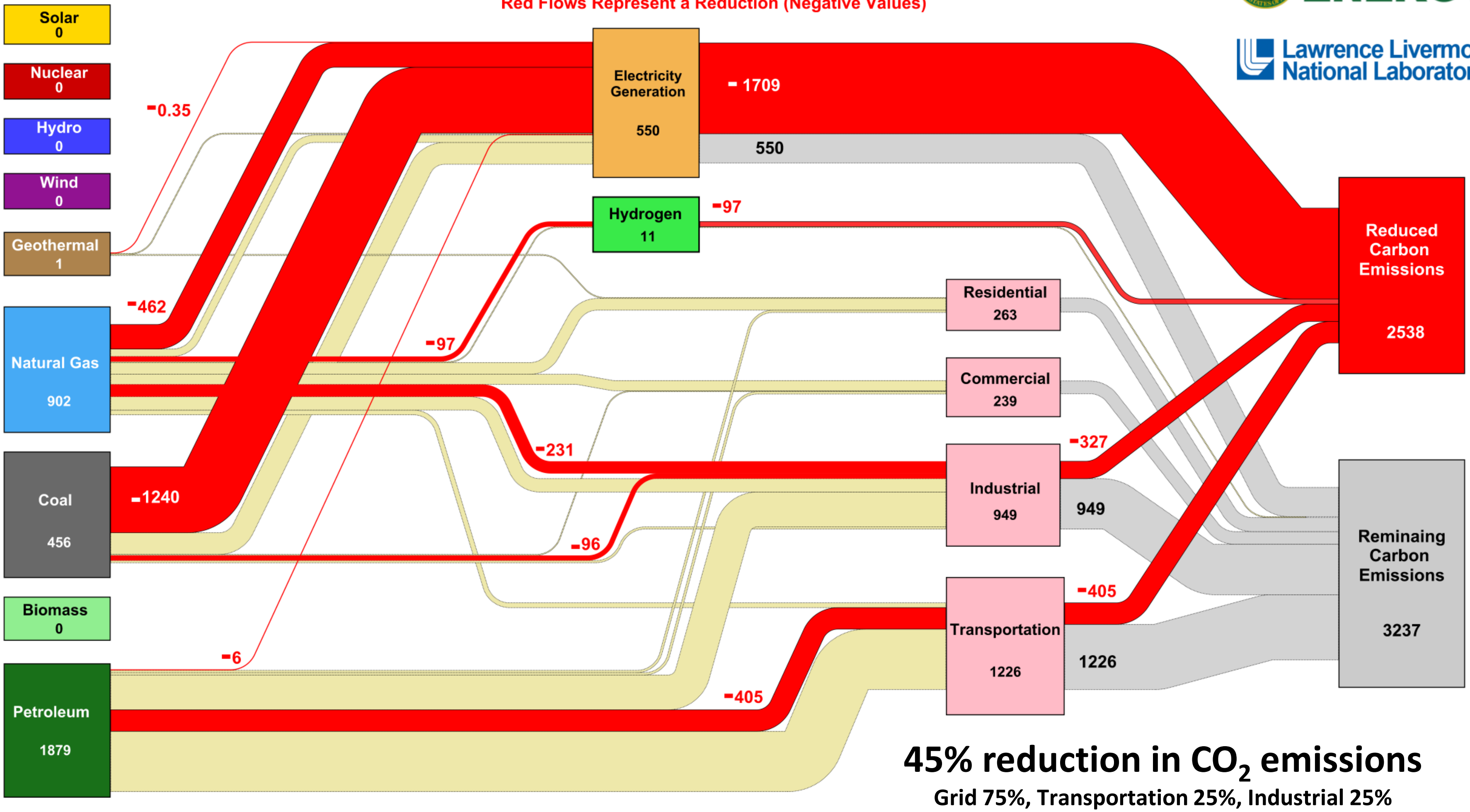


Emissions Difference between 2050 High Hydrogen Scenario and AEO 2040 Scenario (Million metric tonnes)

Red Flows Represent a Reduction (Negative Values)

45% reduction in CO_2 emissions

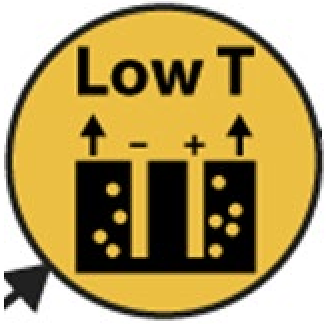
Grid 75%, Transportation 25%, Industrial 25%

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

H2 @ Scale Technical Framework

Renewable Energy Conversion, Storage, and Use

Low and High Temperature H_2 Generation



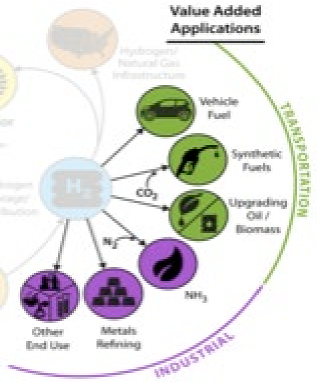
Development of **low cost, durable, and intermittent H_2** generation.

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

H_2 Storage and Distribution

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

H_2 End Use



H_2 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

- Develop non-noble metals OER catalyst
- Low-cost durable high-conductivity membranes
- Develop alkaline membranes enabling noble metal replacement
- Low-cost, corrosion resistant, thin film metal coatings
- Develop durable systems for intermittent operation

High T generation

- Durable corrosion resistant conductive materials
- Front end controls for thermal management with cyclic operation
- Technologies for high temperature thermal storage
- CO2 electrochemical reduction
- System integration

H_2 Storage and Distribution

- GWh-month scale geologic storage
- Develop novel materials and processes for chemical Storage
- Integration with renewable grid/System optimization
- Novel compression/liquefaction technologies
- Leak Detection/ Purification
- Material compatibility for pipelines and compressors

H_2 End use

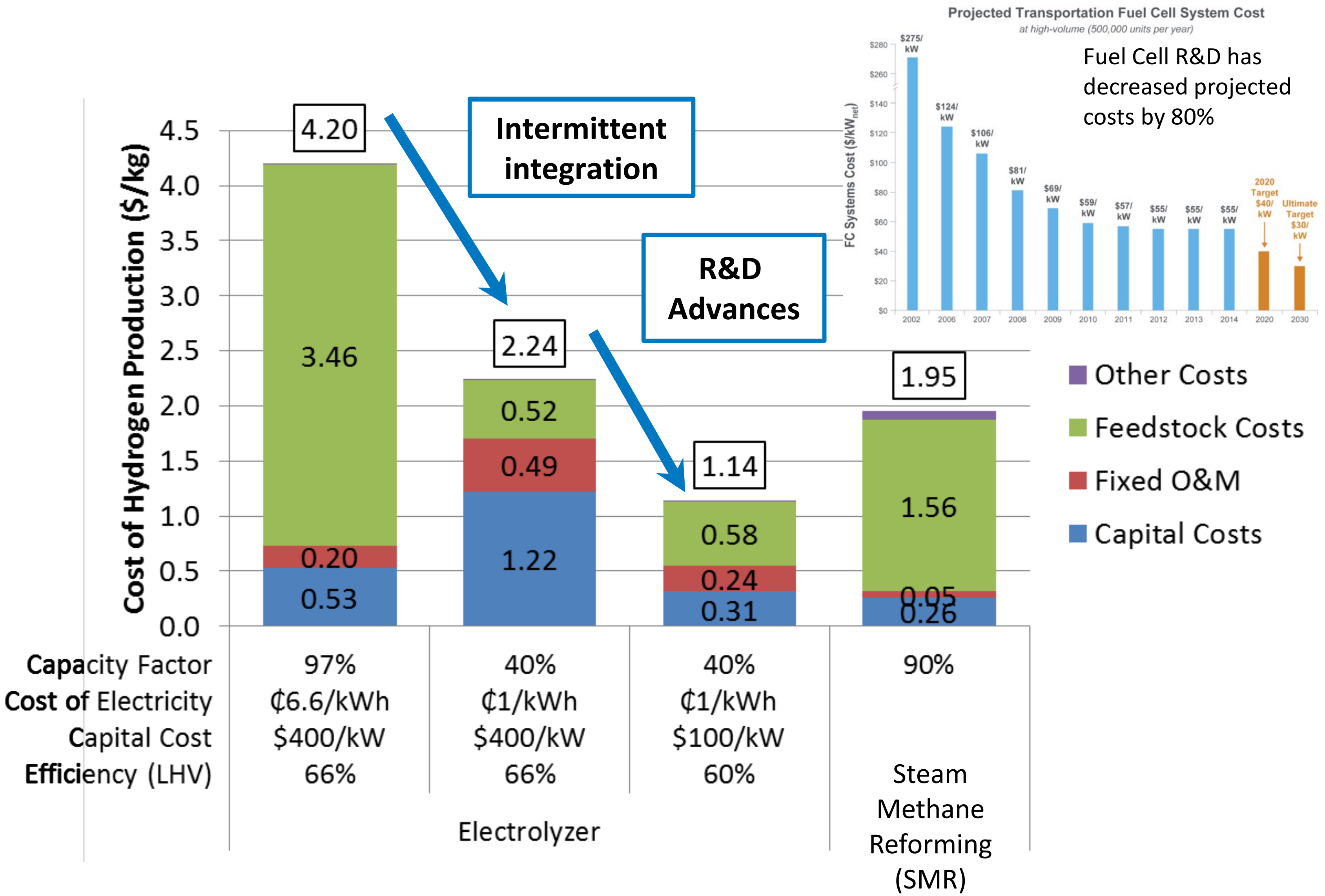
- Process heat integration with intermittent hydrogen generation
- New process chemistry with hydrogen as reductant
- Ammonia production beyond Haber Bosch
- Hydrogen/ hydrogen-rich combustion

Analysis

Foundational Science

Future Electrical Grid

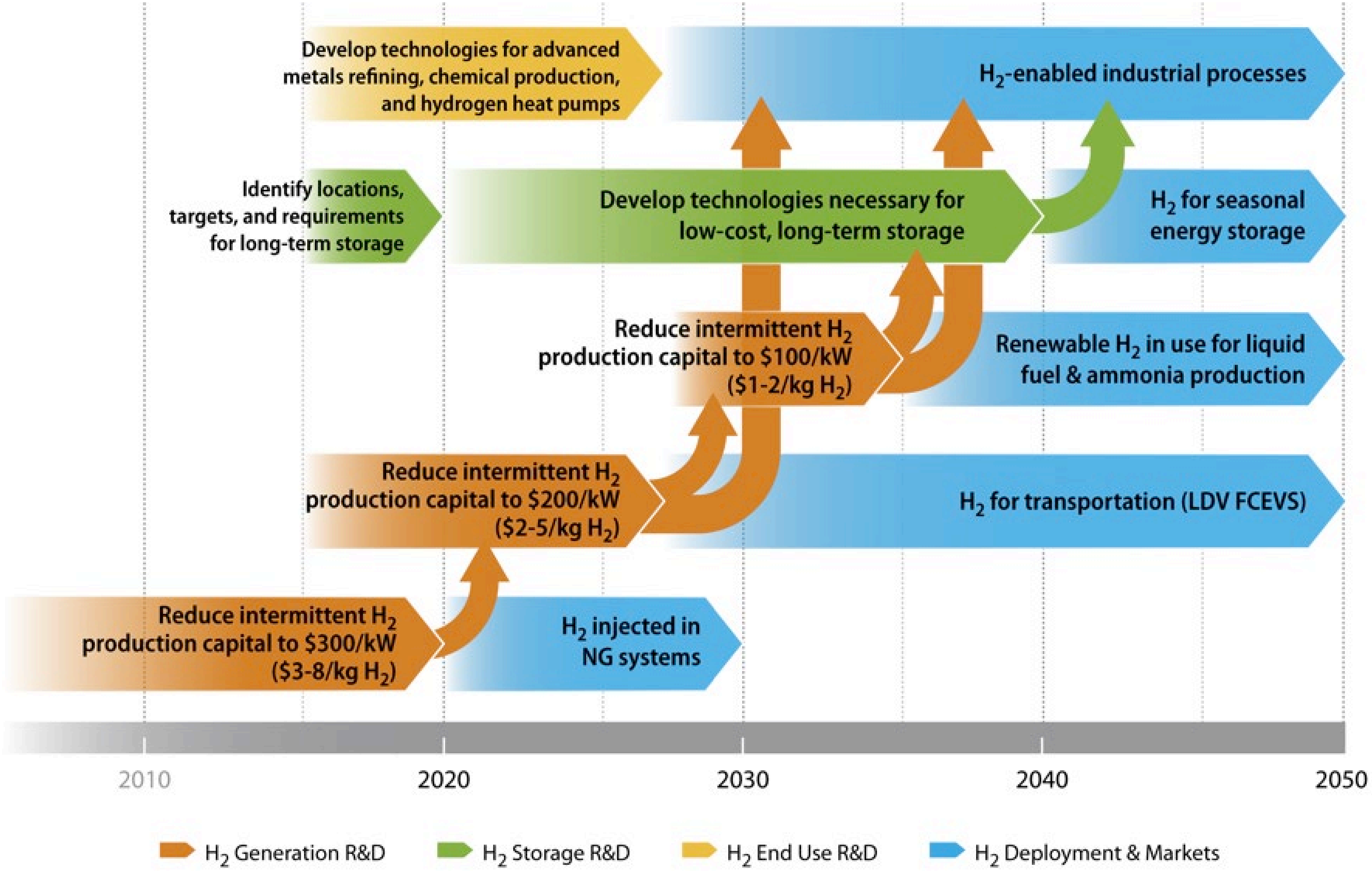
Improving the Economics of Renewable H_2



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

	Electrolyzer			Steam Methane Reforming (SMR)
Capacity Factor	97%	40%	40%	90%
Cost of Electricity	₵6.6/kWh	₵1/kWh	₵1/kWh	
Capital Cost	$400/kW	$400/kW	$100/kW	
Efficiency (LHV)	66%	66%	60%	

H_2 at Scale Roadmap



Develop technologies for advanced metals refining, chemical production, and hydrogen heat pumps

H_2-enabled industrial processes

Identify locations, targets, and requirements for long-term storage

Develop technologies necessary for low-cost, long-term storage

H_2 for seasonal energy storage

Reduce intermittent H_2 production capital to \$100/kW (\$1-2/kg H_2)

Renewable H_2 in use for liquid fuel & ammonia production

Reduce intermittent H_2 production capital to \$200/kW (\$2-5/kg H_2)

H_2 for transportation (LDV FCEVS)

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

H_2 injected in NG systems

🟧 H_2 Generation R&D 🟩 H_2 Storage R&D 🟨 H_2 End Use R&D 🟦 H_2 Deployment & Markets

How much will we need?

37¢

per taxpayer*

$100M	**R&D for Foundational Technologies**
$200M	**Development & Demonstration: 2 approaches**
$200M	**Pilot Scale Systems Integration & Demonstration**

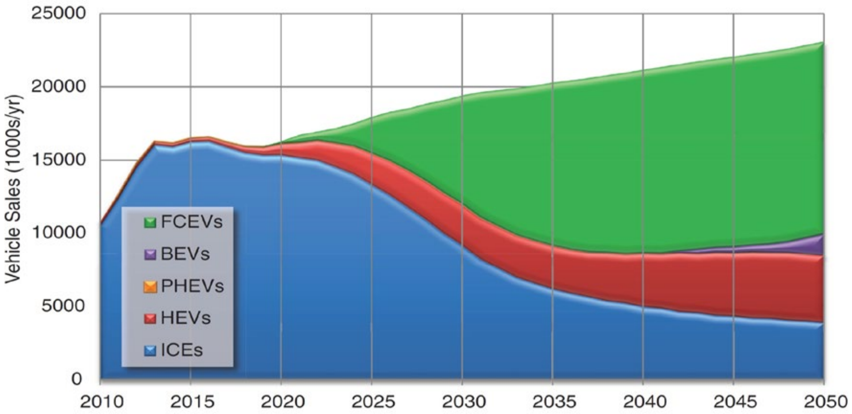
Phase	Funding	Activities
I	$100M/3 yrs	R&D and systems solutions development for foundational technologies (H_2 generation including basic and applied science, industrial process opportunities for clean H_2 utilization)
II	$200M/4 yrs	Development and demonstration of at least 2 viable approaches
III	$200M/4 yrs	Systems integration and demonstration at scale enabling renewables (pilot scale/equivalent to BETO IBR or battery manufacturing plant funding)

*Based on 122M taxpayers in the U.S.

Back Up Slides

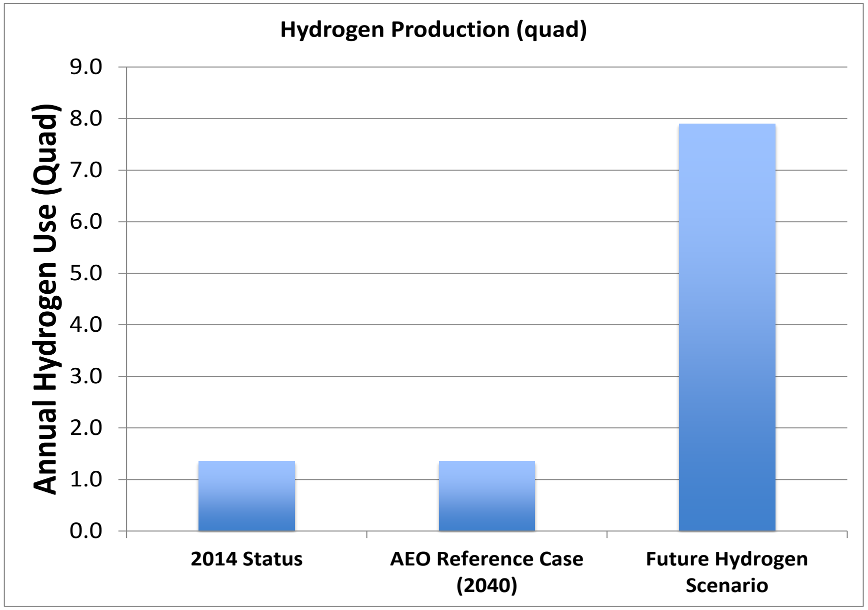
H_2 Demand

Potential growth of hydrogen markets, increasing importance in the future (chicken and egg problem)

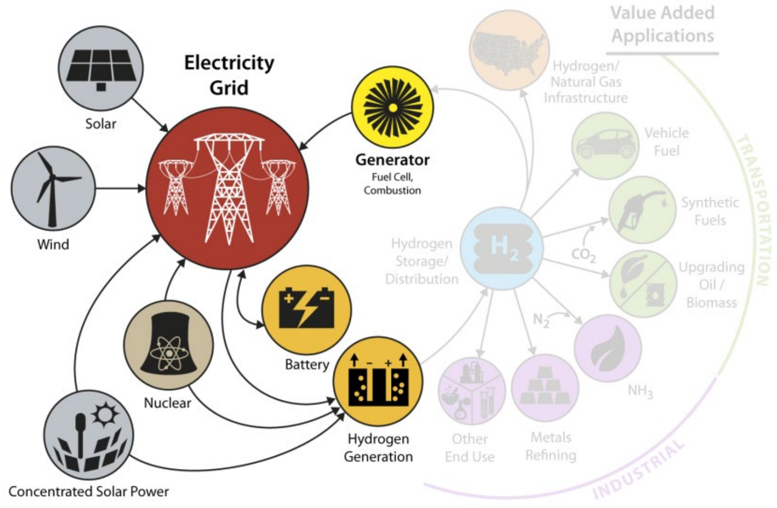


Vehicle sales by vehicle technology with midrange technology assumptions and low-carbon production of hydrogen, fuel cell vehicle subsidies, and additional incentives. http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

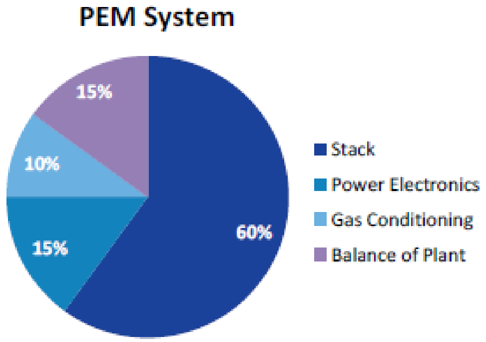
Hydrogen Demand Estimates in 2050	
	Quads
Hydrogen for direct use in LDVs	3.2
Hydrogen for direct use in HDVs	0.5
Hydrogen for biofuel upgrading	0.4
Hydrogen for oil refining	0.4
Ammonia production	2.5
Steel refining	1.0
Total	7.9



Low and High T H_2 Generation



Cost Distribution



Research Priorities

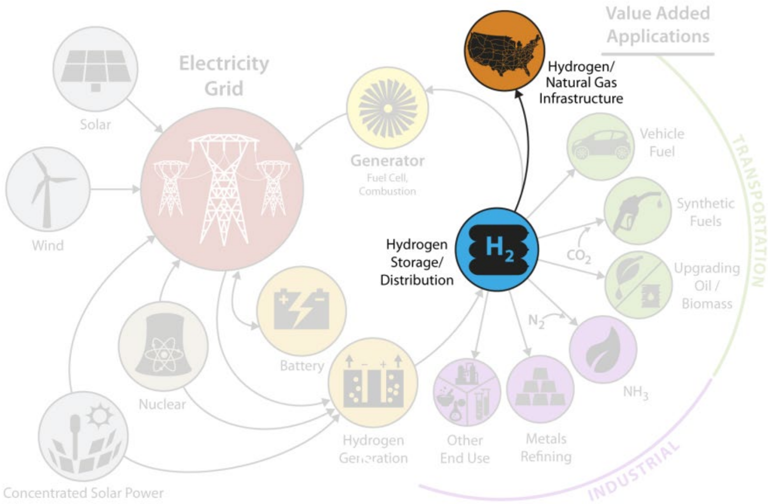
- Durability for intermittent operation
- Lower cost electrolysis
- Manufacturing at scale
- Thermal integration

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



<u>Specific Technology Needs</u>

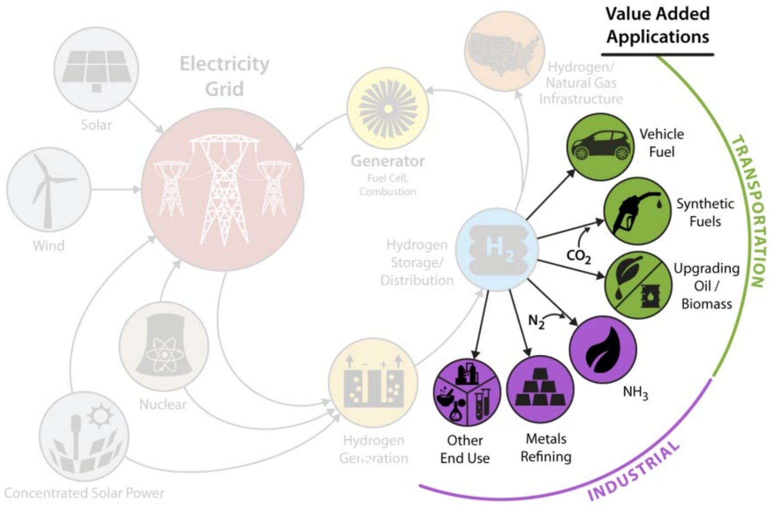
- Hydrogen Storage
  - Chemical/metal hydrides
    - Materials systems
    - Catalysis
  - Physical Storage
    - Geologic
    - Manufactured
- Direct Electro-Chemical Hydride Conversion
- Distribution
  - Compression
  - Liquefaction
  - Materials Compatibility *(Hydrogen Embrittlement)*
  - Leak Detection/Repair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

<u>Research Priorities</u>

- 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 End Use



<u>Research Priorities</u>

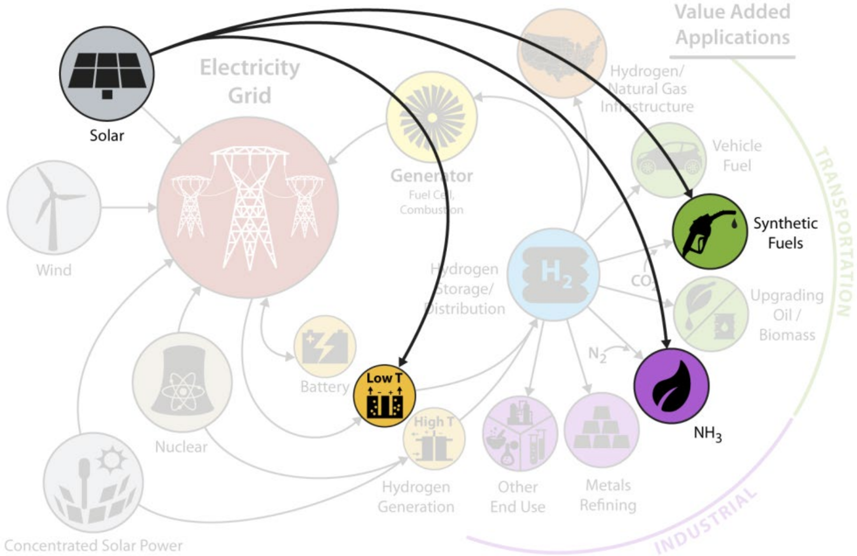
- New process chemistry with H_2 used as a reductant
  - Chemical, Fuels, Metals Production
- Process efficiency improvement
  - Industry and power systems
- Process heat integration with intermittent H_2 generation
- H_2 / H_2-rich flame modeling

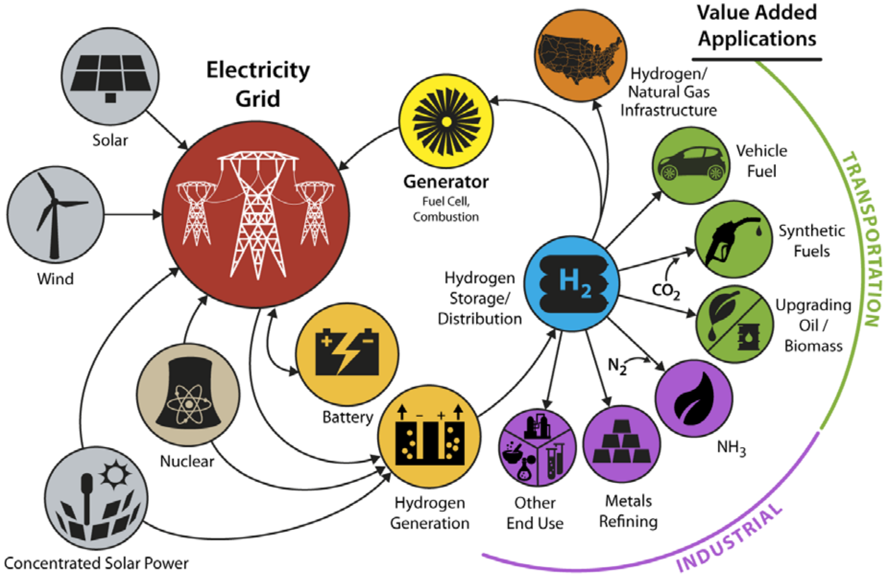
<u>Specific H_2 Utilization Technology Needs</u>

- 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

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)

ser facilities

SNS, light sources, nanocenters, microscopy

CSR and advanced computing

Big data

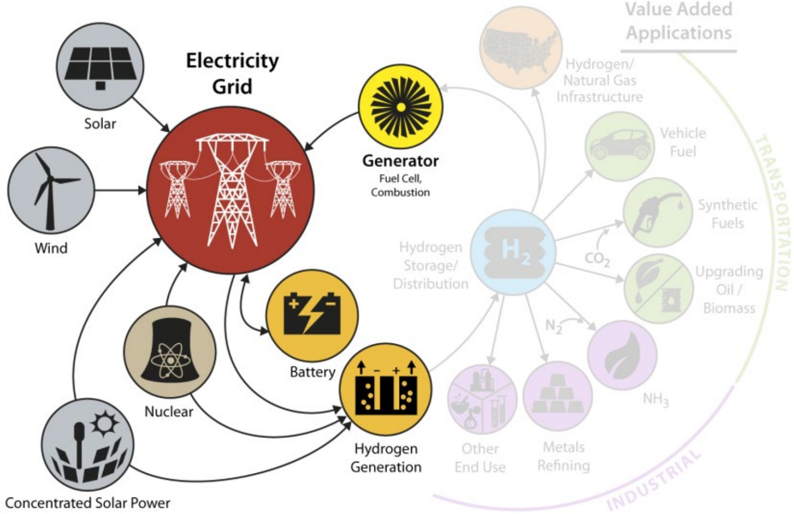
Algorithms for prediction multiscale physics

AP leveraged science

IGI (expansion)

dissolution, kinetics, solvents

Grid Integration



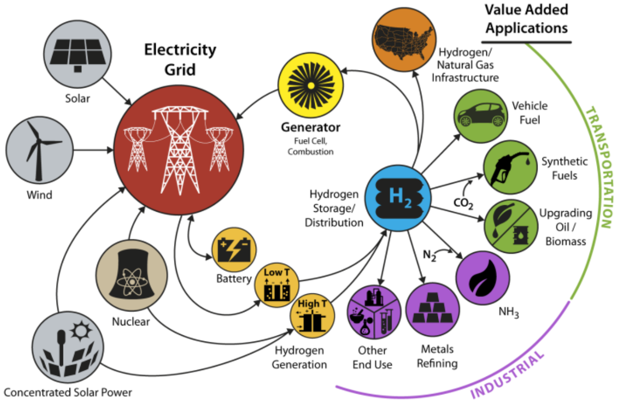
Research & Development Priorities

- 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



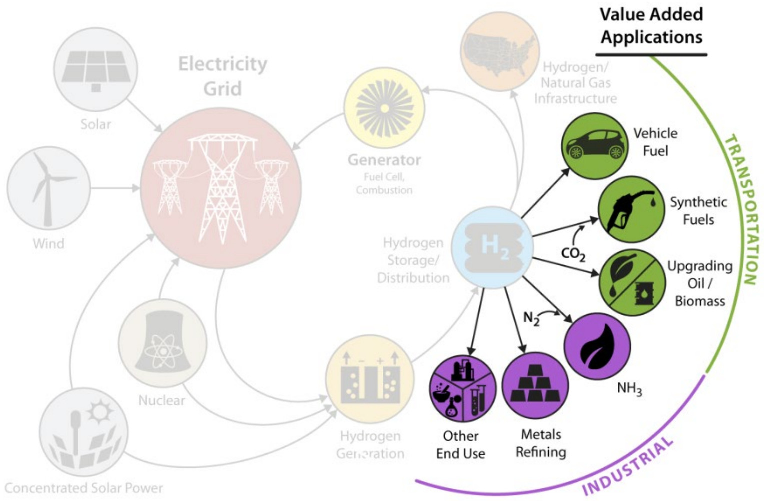
Analysis Priorities

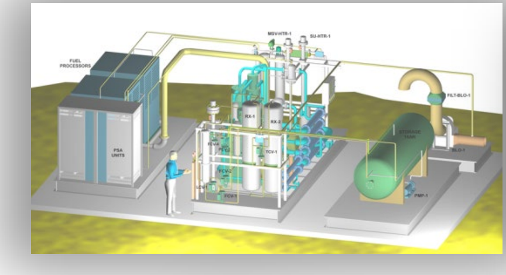
- Specifying the role of hydrogen in deep decarbonization of the U.S. energy sector
- Understanding of drivers impacting energy sector evolution
- Quantification of hydrogen potential to meet seasonal electricity storage requirements
- Technoeconomic analysis
- Life cycle analysis

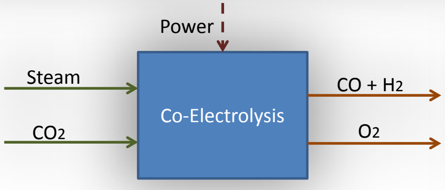
Specific Analysis Needs

- 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

Cross-Office Collaborations



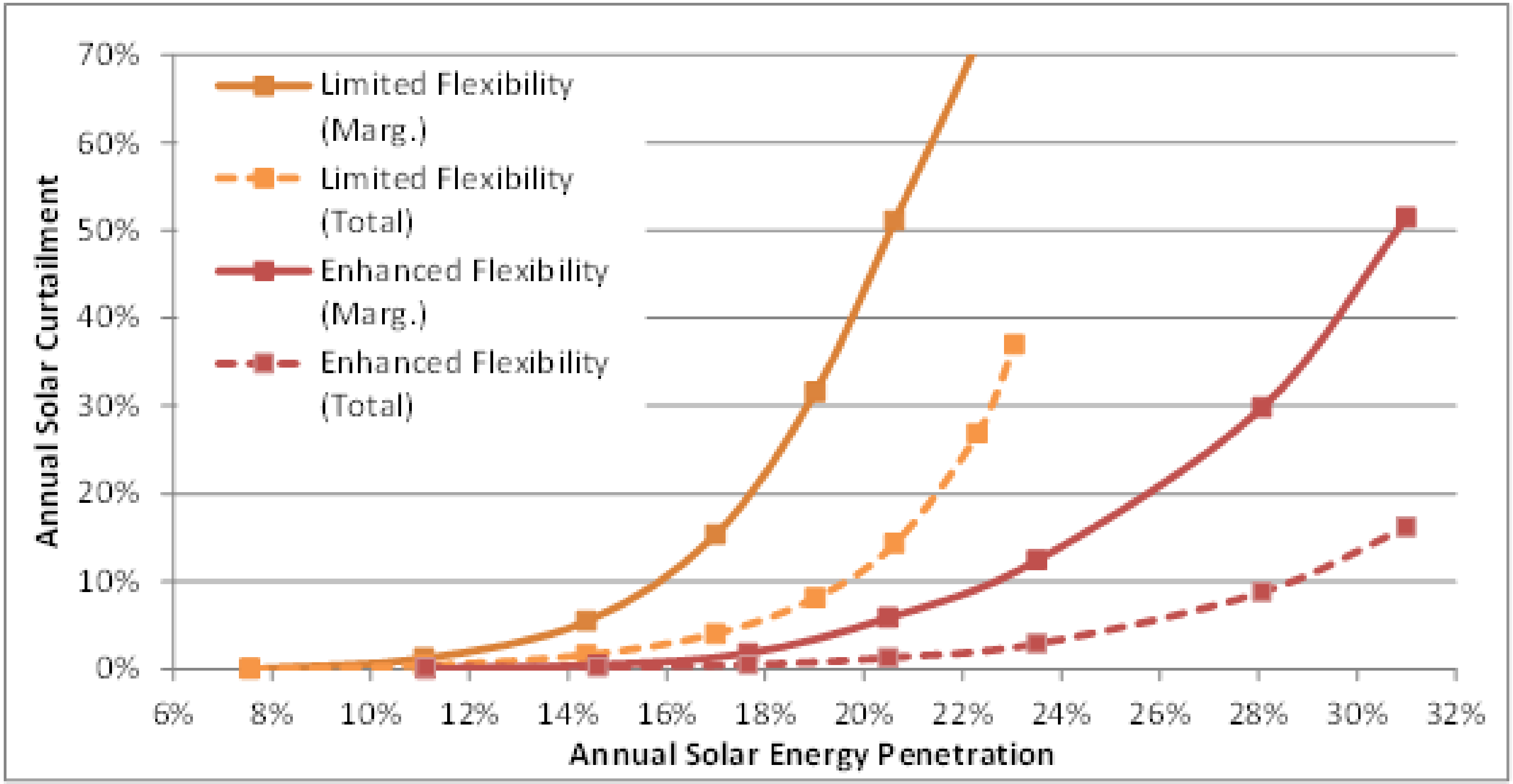




R&D Focus	Research Activities	DOE Programs	Impact
Ammonia	• Modular Plants • Catalyst R&D • Process intensification • Ammonia Fuel Cells	ARPA-E AMO FCTO FE	✓Decrease cost of NH_3 production >25% ✓Improve process efficiency ✓Improve NH_3 handling safety
Refineries	• Electrolysis and refinery heat integration • H_2 and O_2 combustion • Integrated coke gasification • NE &RE energy utilization	FE FCTO AMO 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 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	BTO VTO 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	✓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 FE	✓5% efficiency improvement for manufacturing industries ✓10% efficiency improvement for power generation turbines ✓>50% cooling water reduction

Why Now?

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



Renewable energy cheaper, use increasing, running into a tipping point
Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

Updated H_2 at Scale Big Idea Teams/Structure

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)

SLAC and Ames have expressed desire to be added. BNL?

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); Carl Stoots (INL); Mike Penev (NREL); TBD

Storage and Distribution:

Don Anton (lead, SRNL);
TBD: San Marchi SNL
Brooks PNNL
Genet NREL
Semelsberger LANL
Aceves LLNL
Gennett, Thomas NREL ; jeff long LBL; Craig Brown NIST; Allendorf, Mark SNL; Mark Bowden PNNL; tom autrey PNNL

Industrial 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)

Grid:

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

Fundamental Science:

Adam Weber(lead, LBL); Voja Stamekovic (ANL)

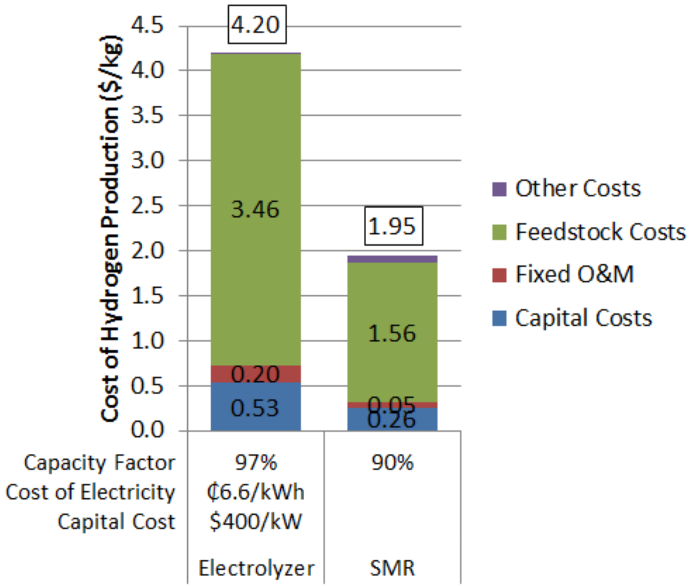
TBD (SLAC); TBD (Ames)

Analysis:

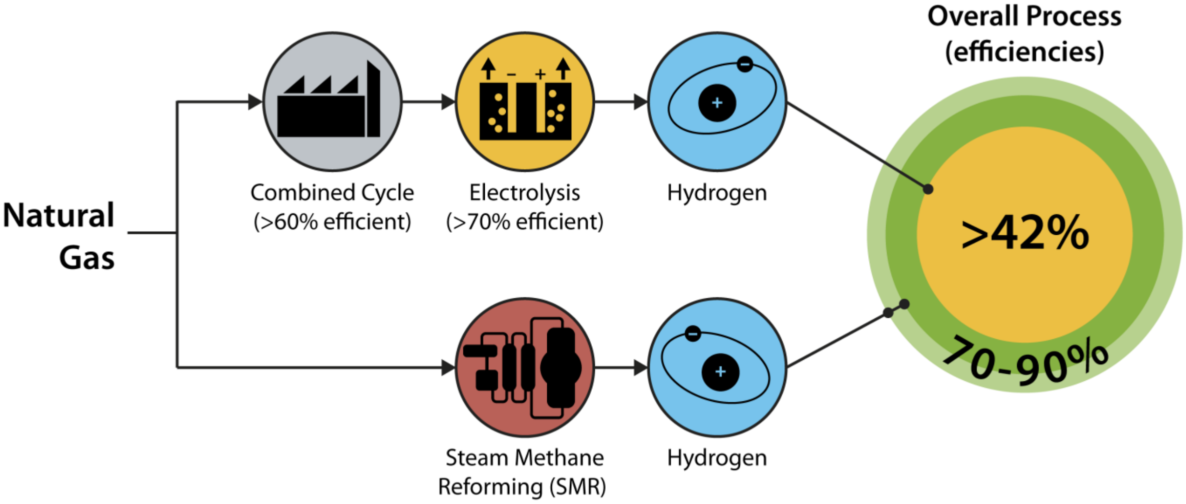
Mark Ruth (lead, NREL); Amgad Elgowainy (co-lead, ANL); Josh Eichman (NREL); Joe Cordaro (SRNL); Salvador Aceves (LLNL); Max Wei (LBNL); Karen Studarus (PNNL); Todd West (SNL); Steve Wach (SRNL); Richard Boardman (INL); David Tamburello (SRNL); Suzanne Singer (LLNL)

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.



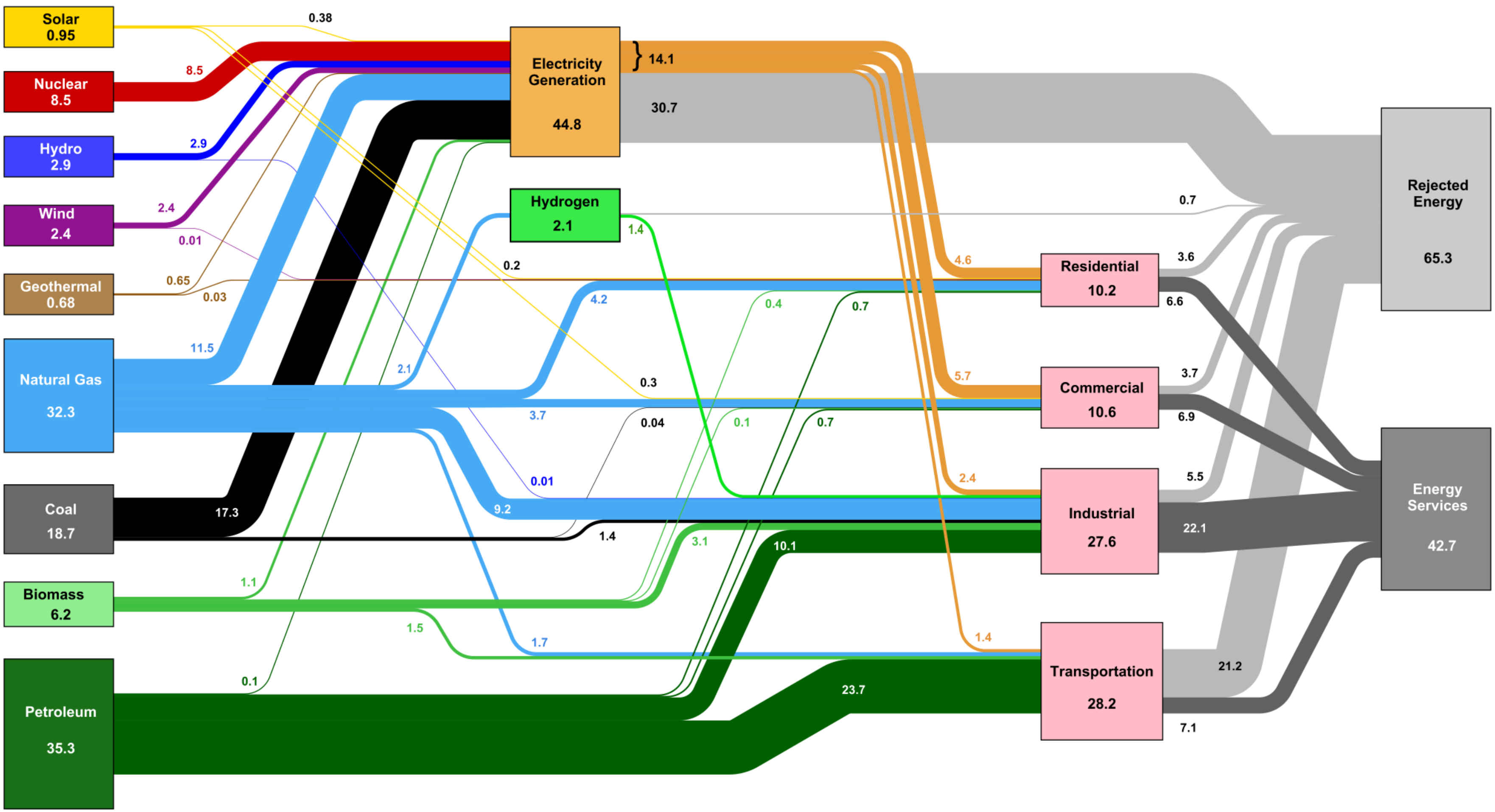
H2A Analysis, Josh Eichman, NREL



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

Energy Flows – 2050 High RE/H_2

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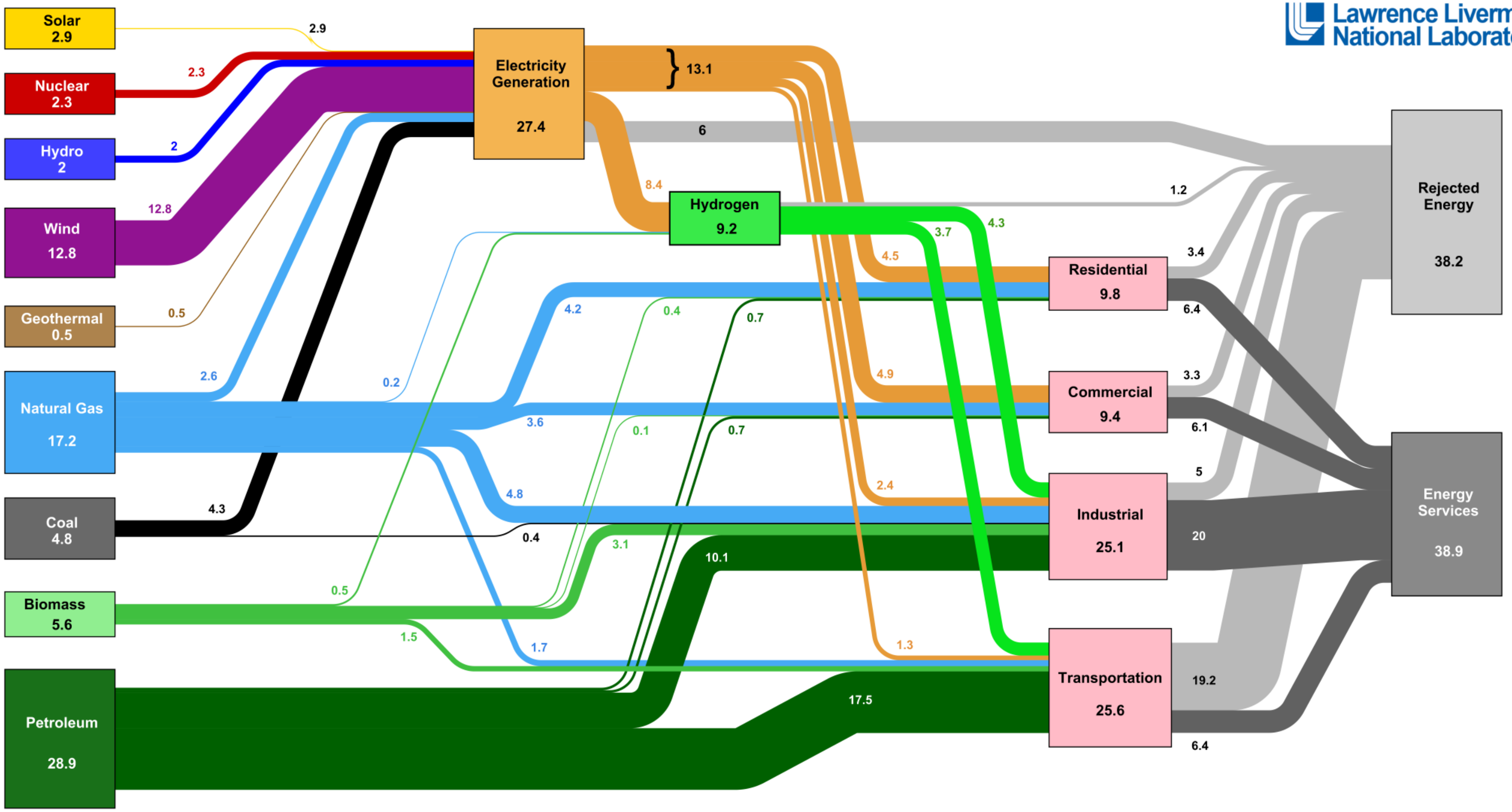
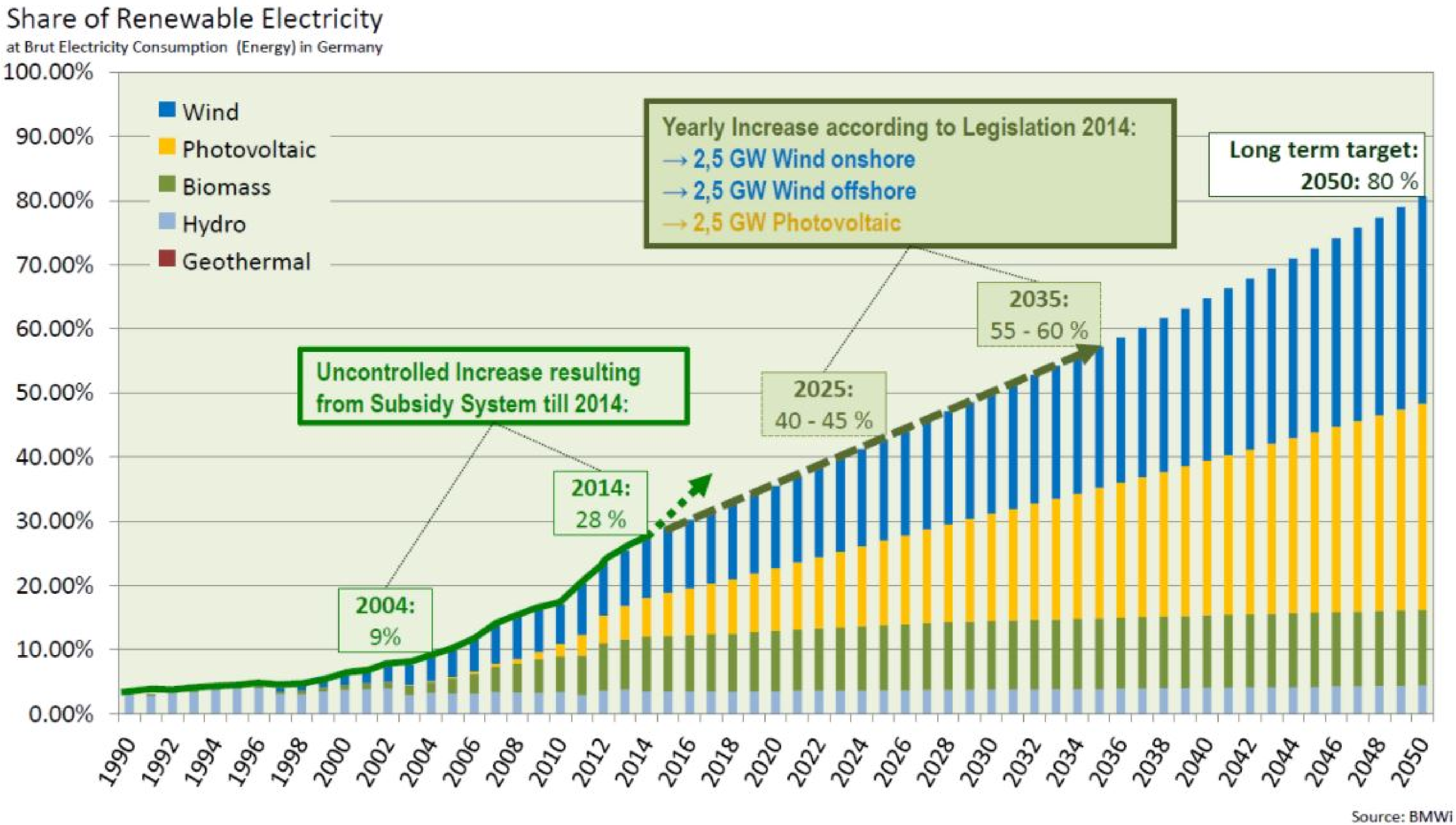
2050 Estimated U.S. Annual Energy Use with High Hydrogen Contributions Broken Out ~ 77 Quads



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

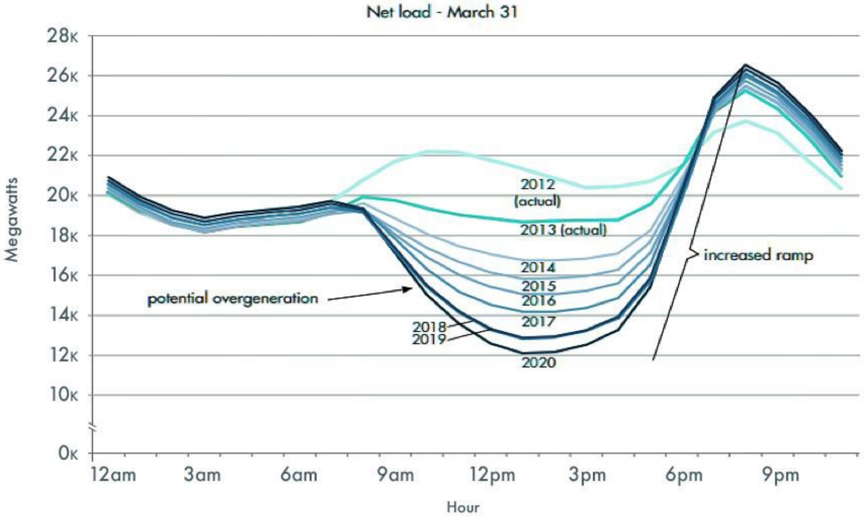
Germany already limiting RE penetration rate



Source: BMWi

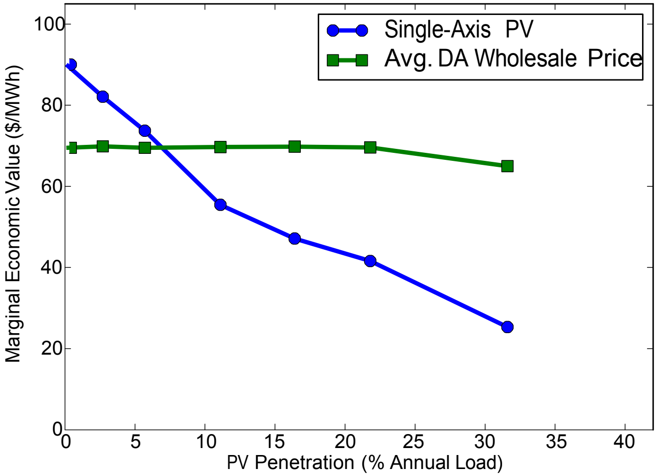
Hydrogen Value Proposition for RE Penetration

- Transient concerns.



DEMAND RESPONSE AND ENERGY EFFICIENCY ROADMAP, CAISO, 2013

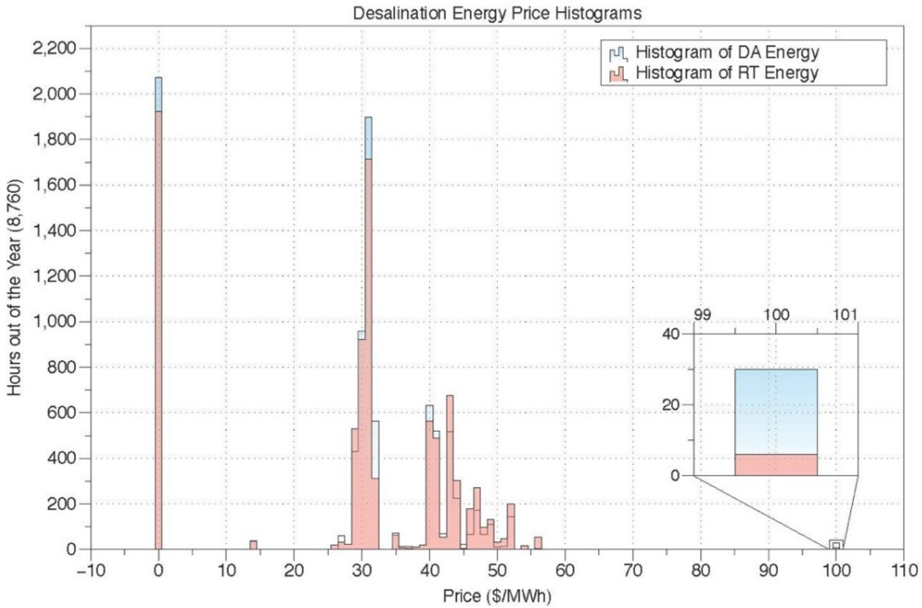
- Decreasing value with penetration.



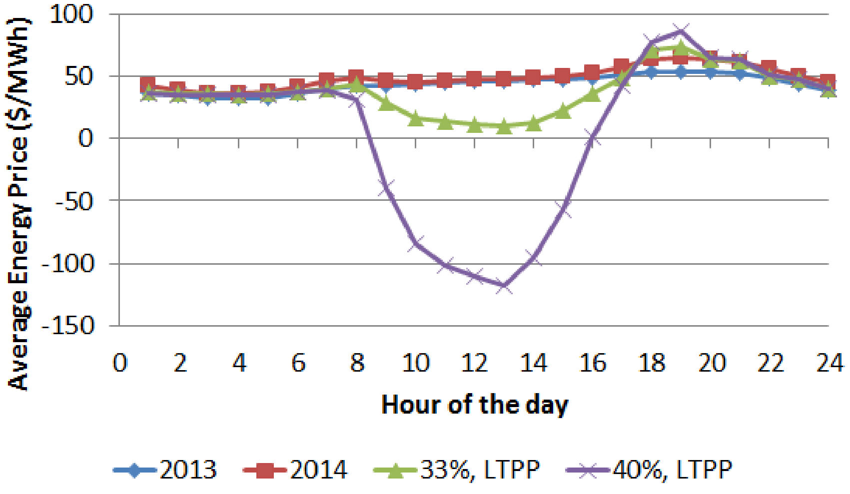
Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California Andrew Mills and Ryan Wiser, June 2012, http://eetd.lbl.gov/EA/EMP

What happens to time of day pricing

- More low value electrons than high need costs
- Negative pricing of electrons can occur.



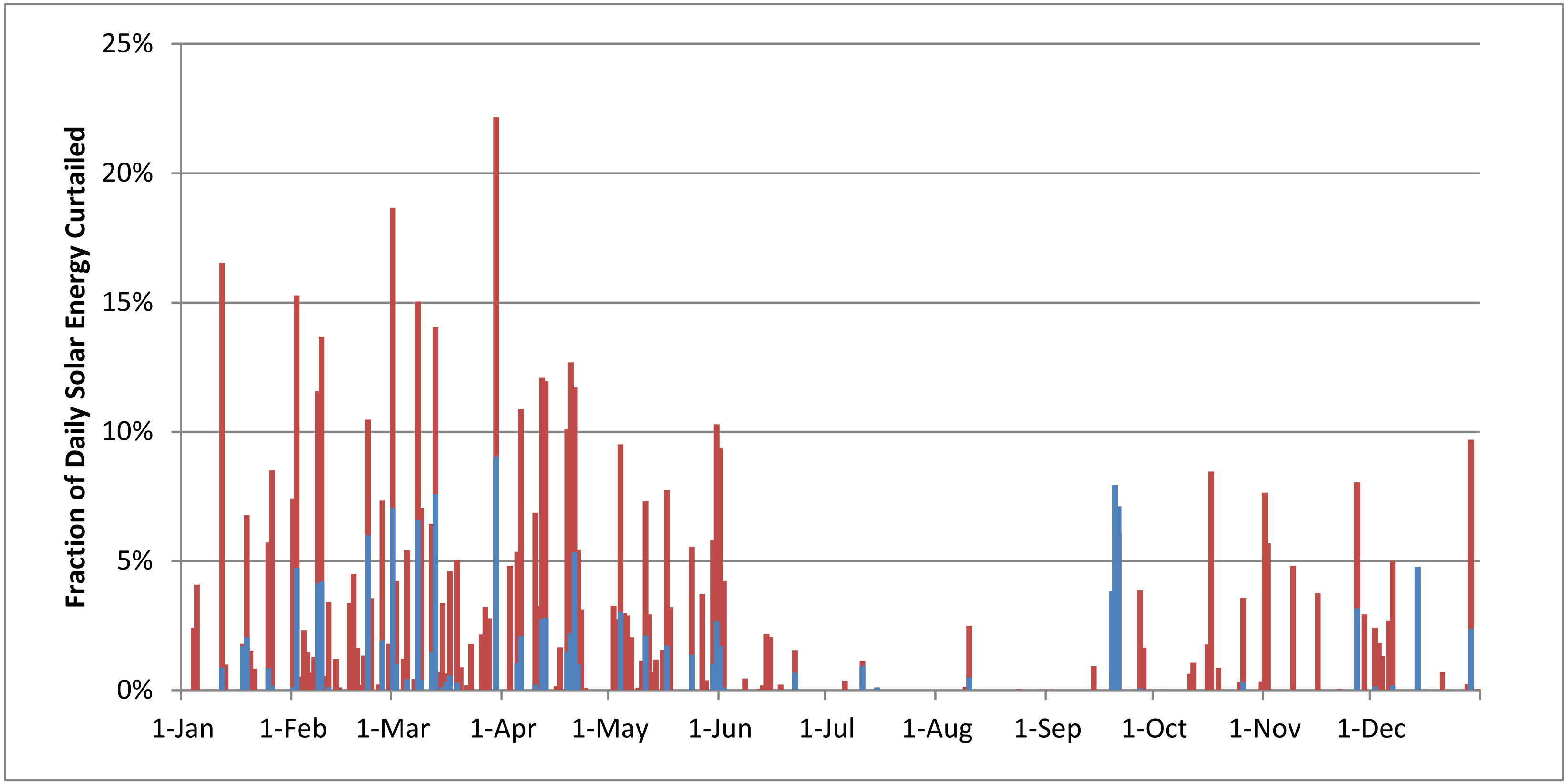
Source: Mark Ruth, NREL (PLEXOS: 22% PV, 11% wind)



DA – Day Ahead
RT – Real Time
LTPP - Long Term Procurement Plan

Source: Josh Eichman, NREL

Resulting variable generation curtailment

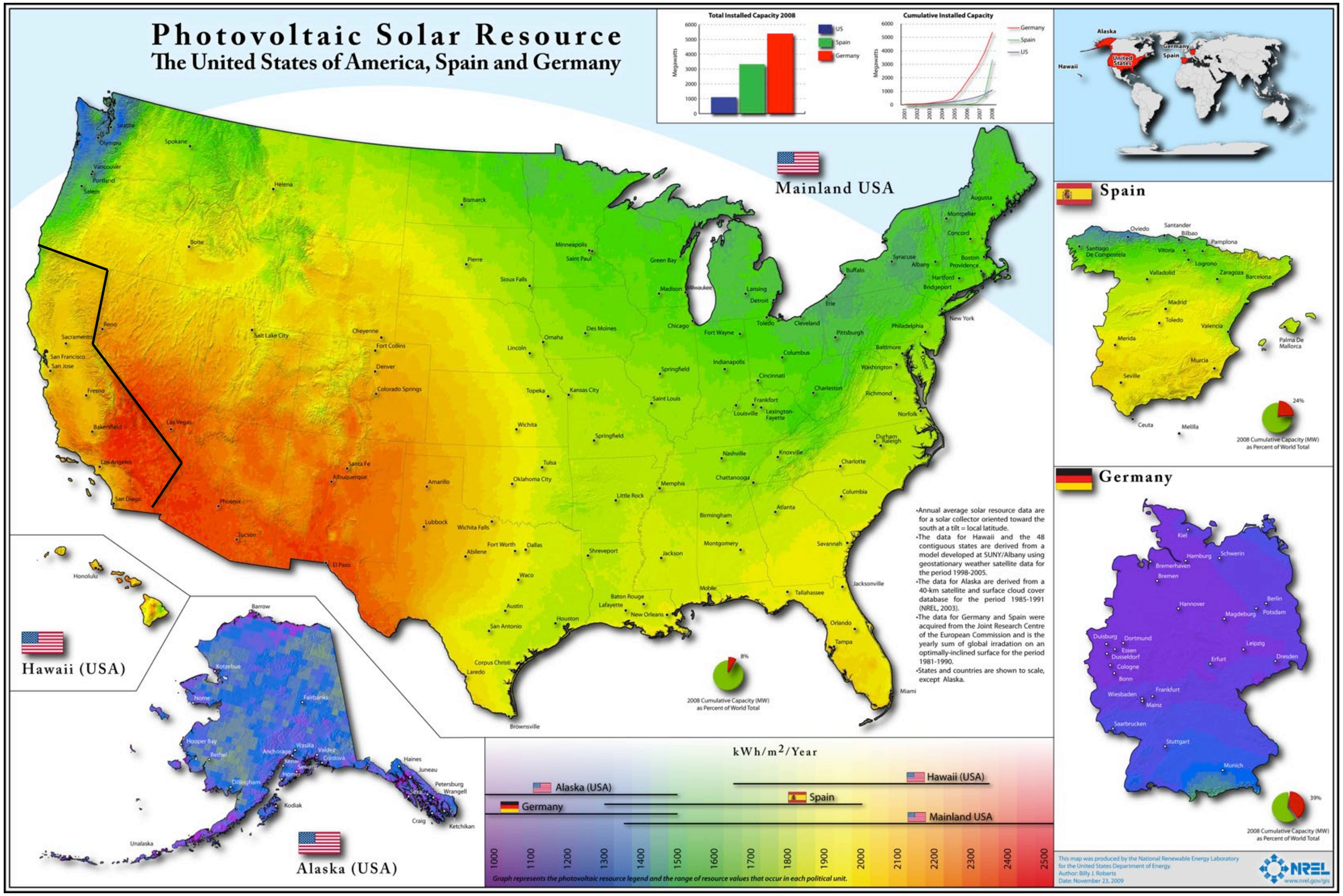


Used and curtailed VG in California on March 29
in a scenario with 11% annual wind and 11% annual solar

California and Germany

California

- 400 km^2
- 40 million people
- 46GW Peak Load
- 10GW Solar
- 6GW Wind
- 18% solar capacity factor



- Annual average solar resource data are for a solar collector oriented toward the south at a tilt = local latitude.
- The data for Hawaii and the 48 contiguous states are derived from a model developed at SUNY/Albany using geostationary weather satellite data for the period 1998-2005.
- The data for Alaska are derived from a 40-km satellite and surface cloud cover database for the period 1985-1991 (NREL, 2003).
- The data for Germany and Spain were acquired from the Joint Research Centre of the European Commission and is the yearly sum of global irradiation on an optimally-inclined surface for the period 1981-1990.
- States and countries are shown to scale, except Alaska.

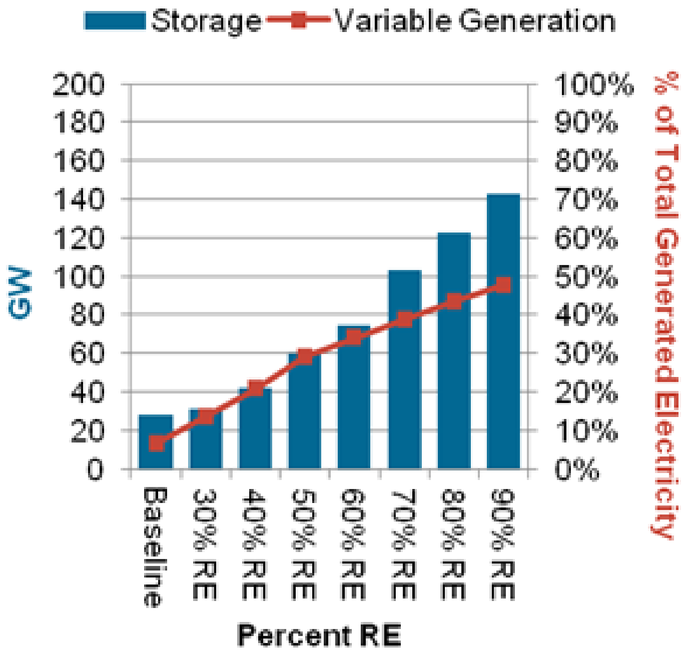
Graph represents the photovoltaic resource legend and the range of resource values that occur in each political unit.

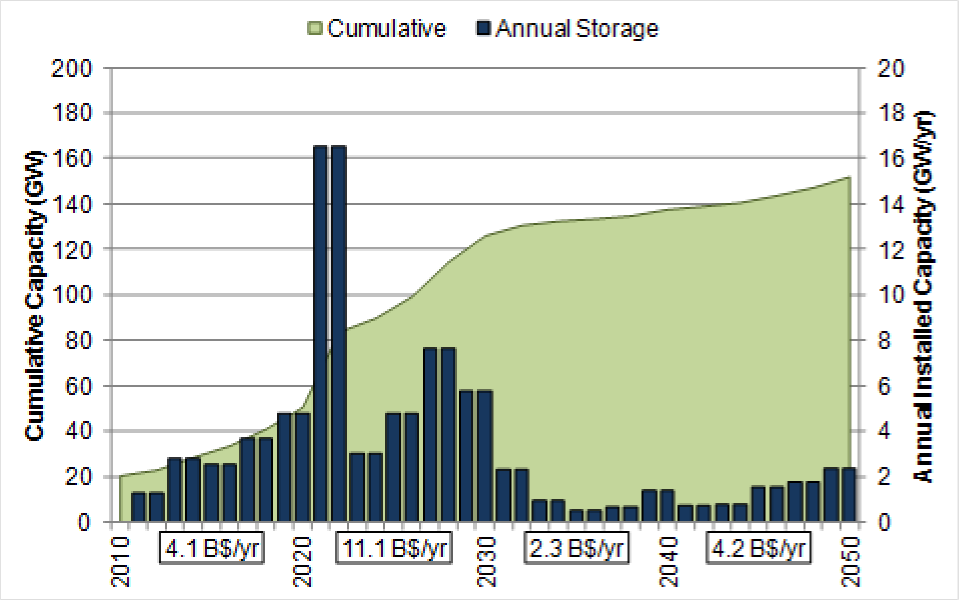
This map was produced by the National Renewable Energy Laboratory for the United States Department of Energy.
Author: Billy J. Roberts
Date: November 23, 2009
www.nrel.gov/gis

Germany

- 357 km^2
- 80 million people
- 75GW Peak Load
- 38GW Solar
- 32GW Wind
- 10% Solar capacity factor

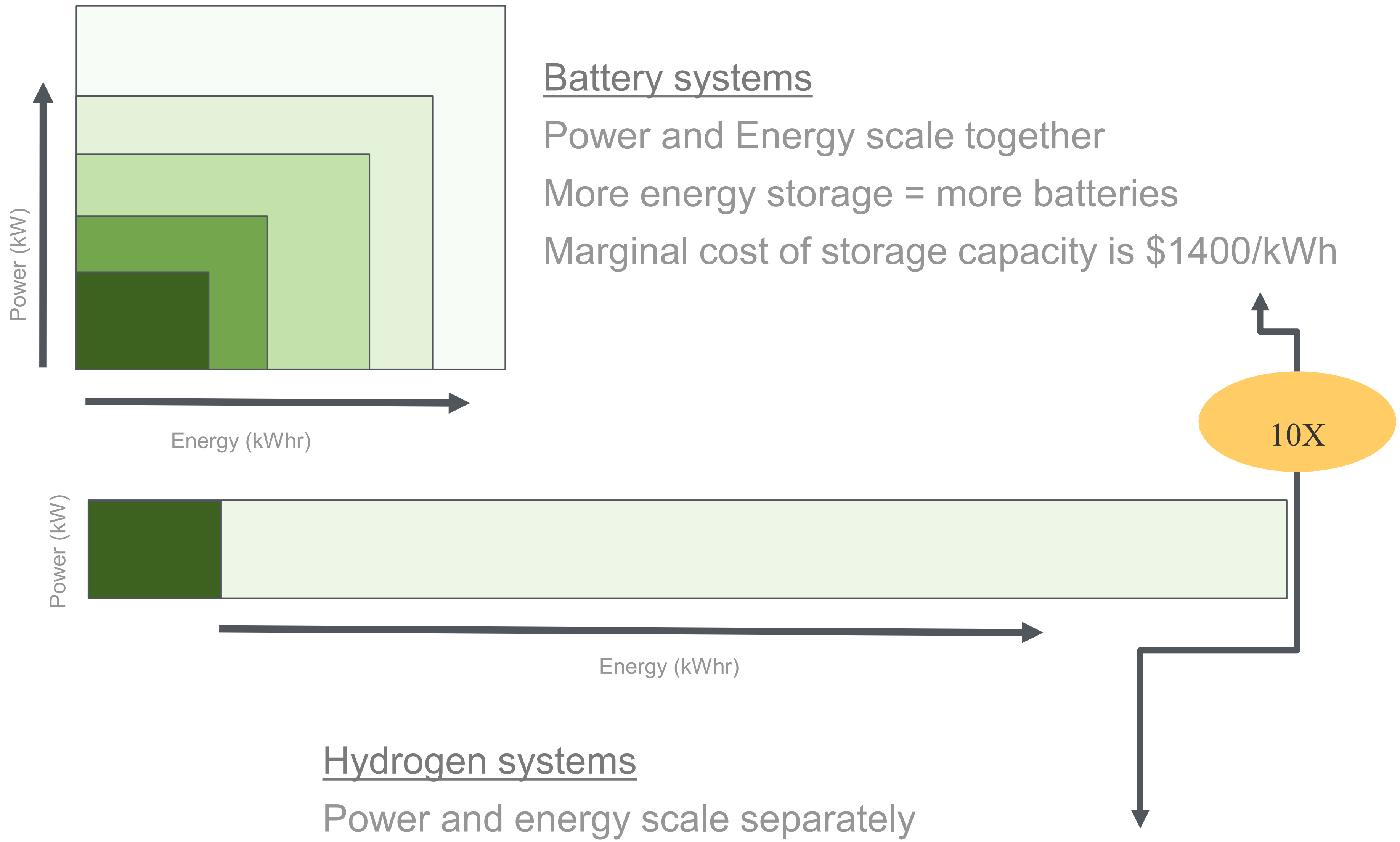
Storage needs with increase RE penetration





RE Futures Study

Comparison between Energy Storage Options



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 = ✖

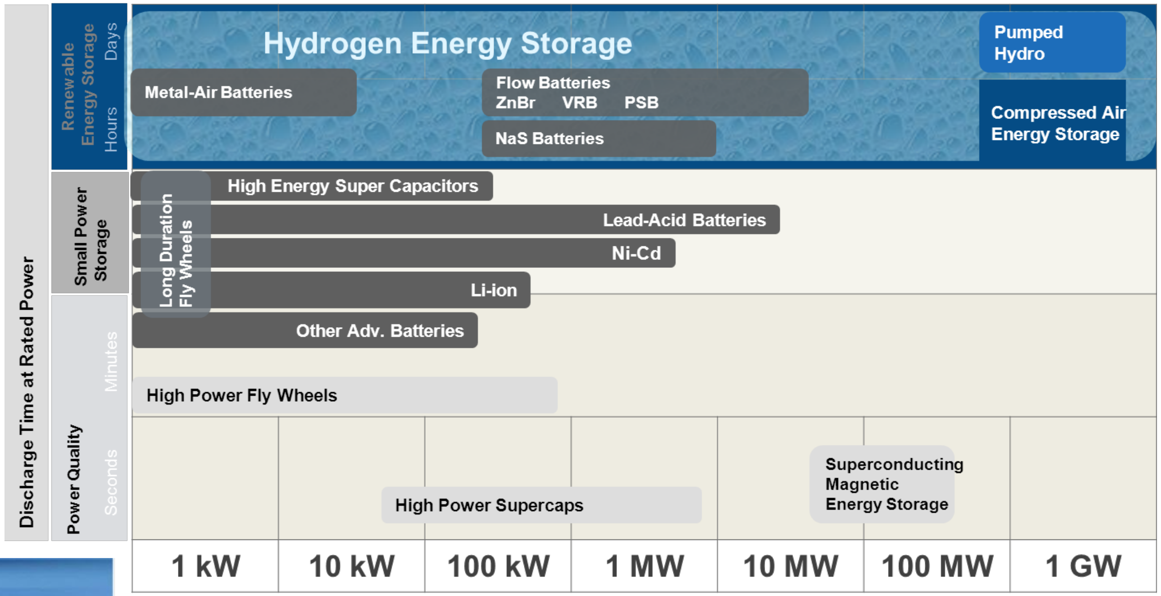
Hydrogen vs. LiOH Battery Solution

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

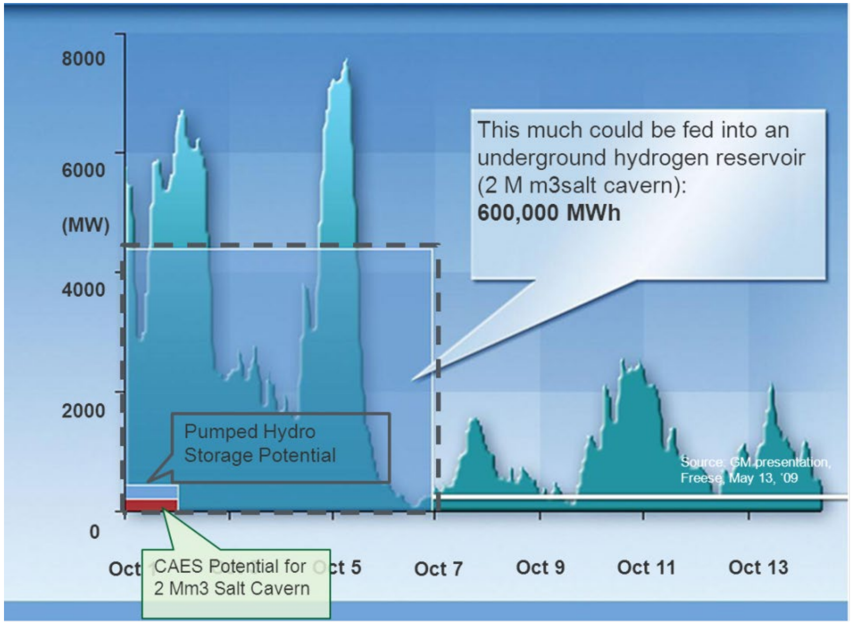
Source: Hydrogenics

Energy Storage

Many Jobs, Many Solutions



Source: Electricity Storage Association



This much could be fed into an underground hydrogen reservoir (2 M m3salt cavern): **600,000 MWh**

Source: GM presentation, Freese, May 13, '09

Only hydrogen offers storage capacity for several days or weeks

Capacity, Not Efficiency a Larger Driver for Renewable Storage

Source: Hydrogenics

Energy Storage Preliminary Analysis

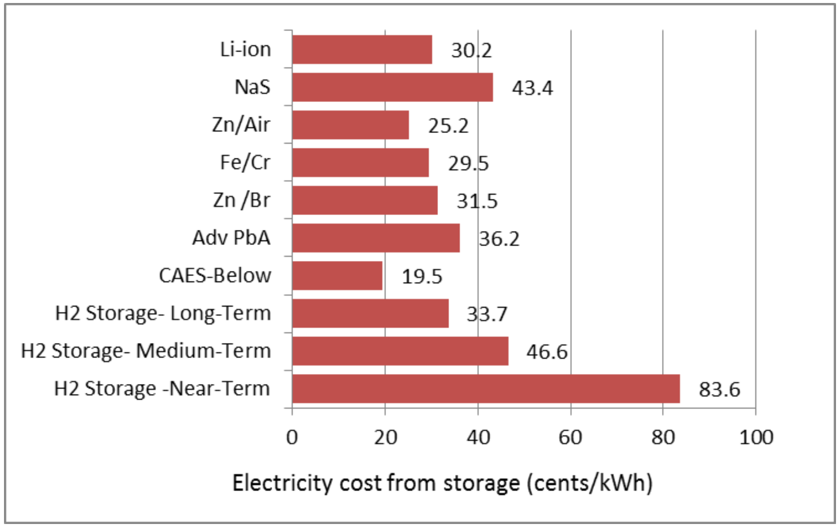
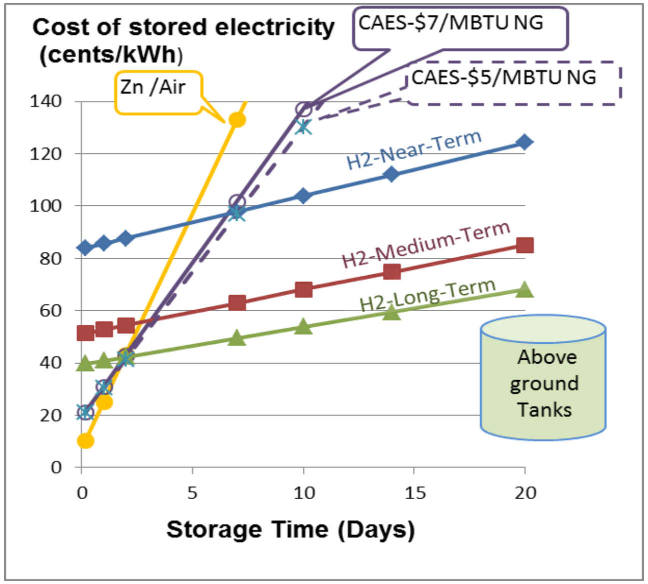


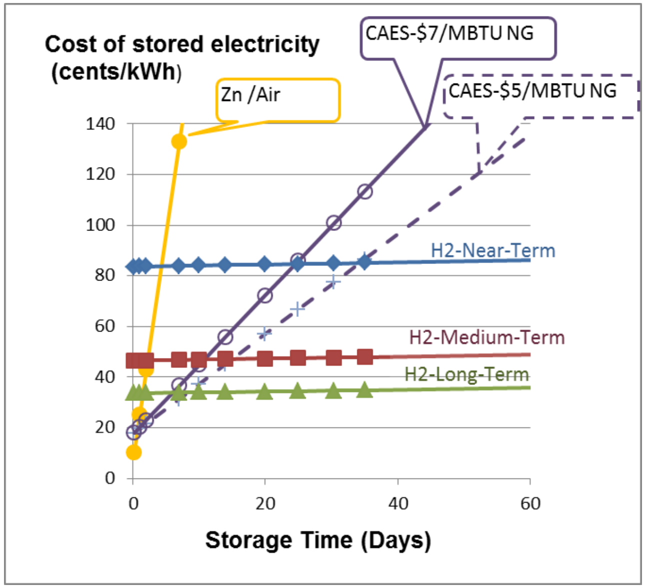
Figure 1. Price of on-Peak electricity for various below-ground H2 & CAES storage and battery storage options with one-day storage and 10% "free" (stranded) energy for a 10MW output over 4 hours (40MWh/day) & NG = $5/MBTU (for CAES) [All battery & CAES costs are based on the lower EPRI estimates.]

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

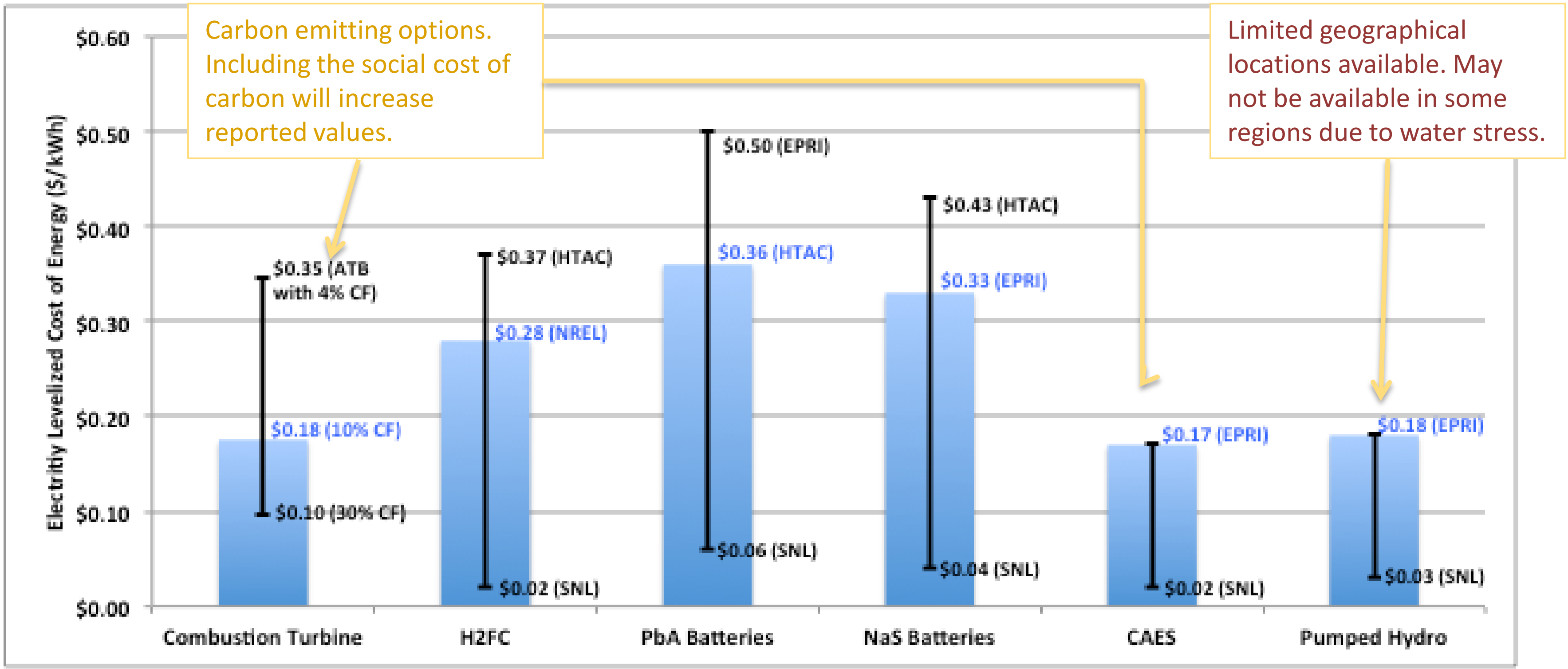




Need to understand when there is economic value for longer storage times under high penetration renewables scenarios

Source: Sandy Thomas

Energy "Storage"



Carbon emitting options. Including the social cost of carbon will increase reported values.

Limited geographical locations available. May not be available in some regions due to water stress.

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

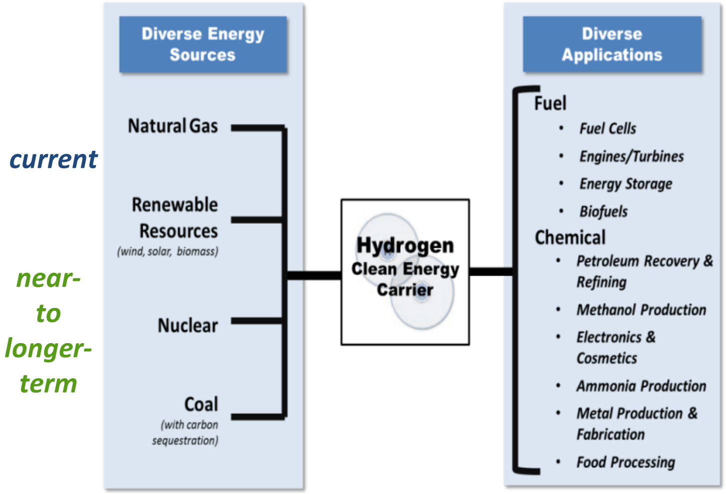
QTR Feedback

- **Major challenges:**

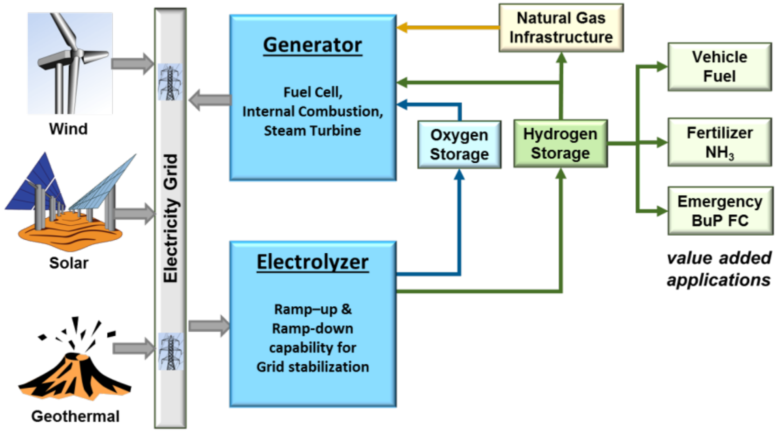
  Reduce the cost of producing and delivering H_2 from renewable/low-carbon sources for FCEV and other uses (capex, O&M, feedstock, infrastructure, safety, permitting, codes/standards)

- **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



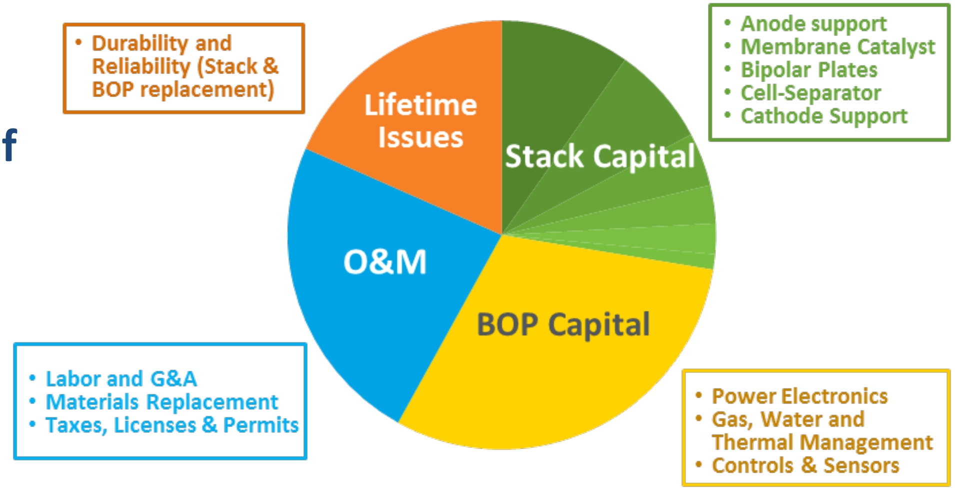
Renewable energy integration options with hydrogen

Note: H2 storage on-board FCEVs is addressed in Ch. 8

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)**



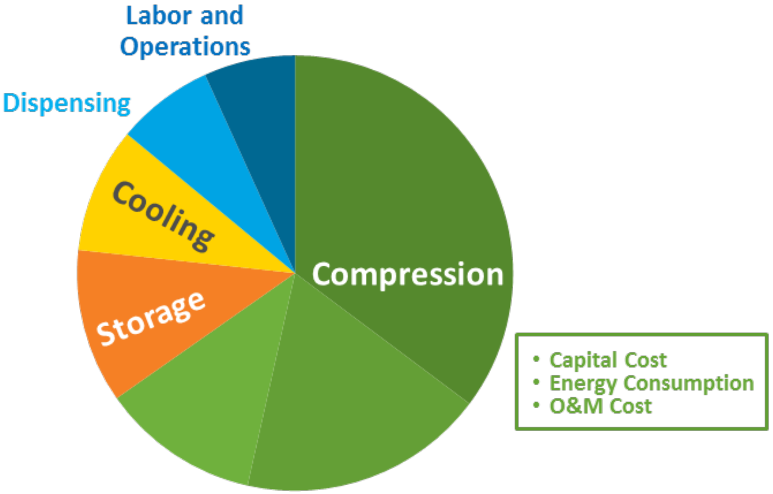
- Durability and Reliability (Stack & BOP replacement)

- Anode support
- Membrane Catalyst
- Bipolar Plates
- Cell-Separator
- Cathode Support

- Labor and G&A
- Materials Replacement
- Taxes, Licenses & Permits

- Power Electronics
- Gas, Water and Thermal Management
- Controls & Sensors

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



- Capital Cost
- Energy Consumption
- O&M Cost

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