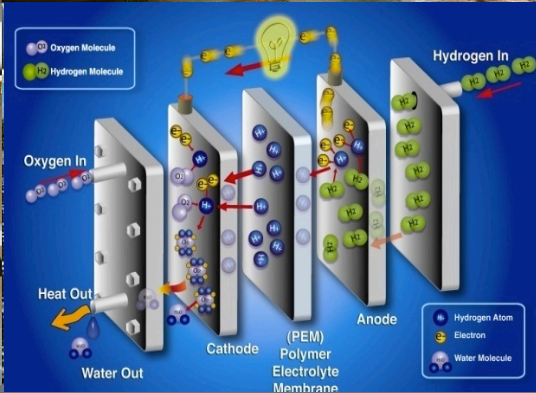
DOE Fuel Cell Technologies Office Hydrogen for Energy Storage

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



Workshop on Hydrogen Energy Storage

Grid and Transportation Services

Sacramento, California

May 14th & 15th 2014 at the Grand Sheraton Hotel

Dr. Monterey R. Gardiner

Technology Manager

Monterey.Gardiner@ee.doe.gov

Fuel Cell Technologies Office

U.S. Department of Energy

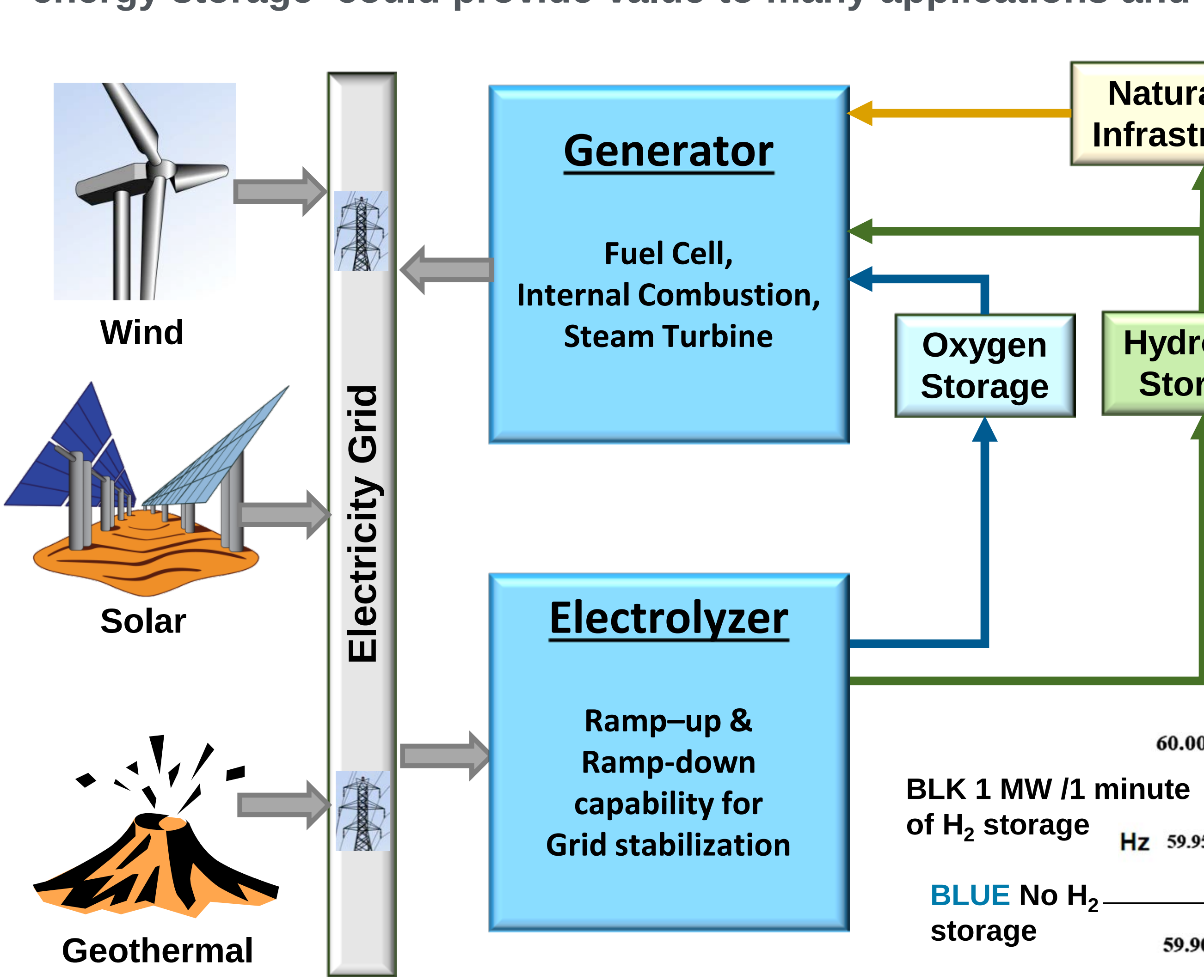
Outline

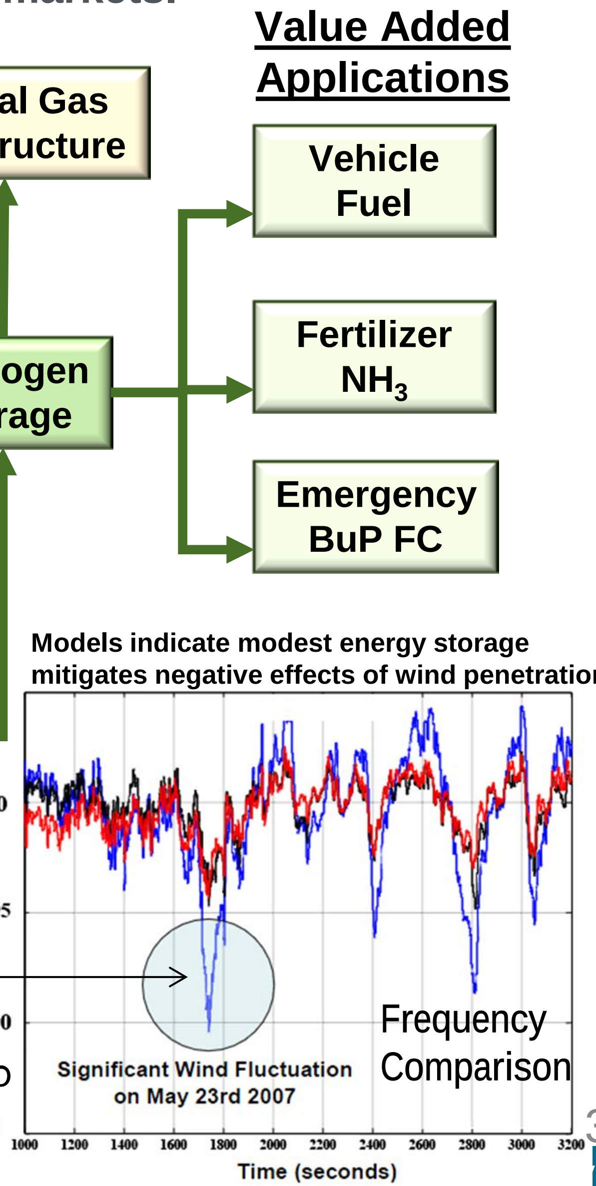
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Previous Analysis Efforts by DOE
  - National Laboratories, Hydrogen Technical Advisory Committee
- Past Workshops
  - Flow Cells, Electrolyzers R&D Needs, International
- Energy Systems Integration Facility
  - National Renewable Energy Laboratory
- Workshop Goals and Objectives

H_2 for Energy Storage

Hydrogen may be produced from a variety of renewable resources, and hydrogen-based energy storage could provide value to many applications and markets.

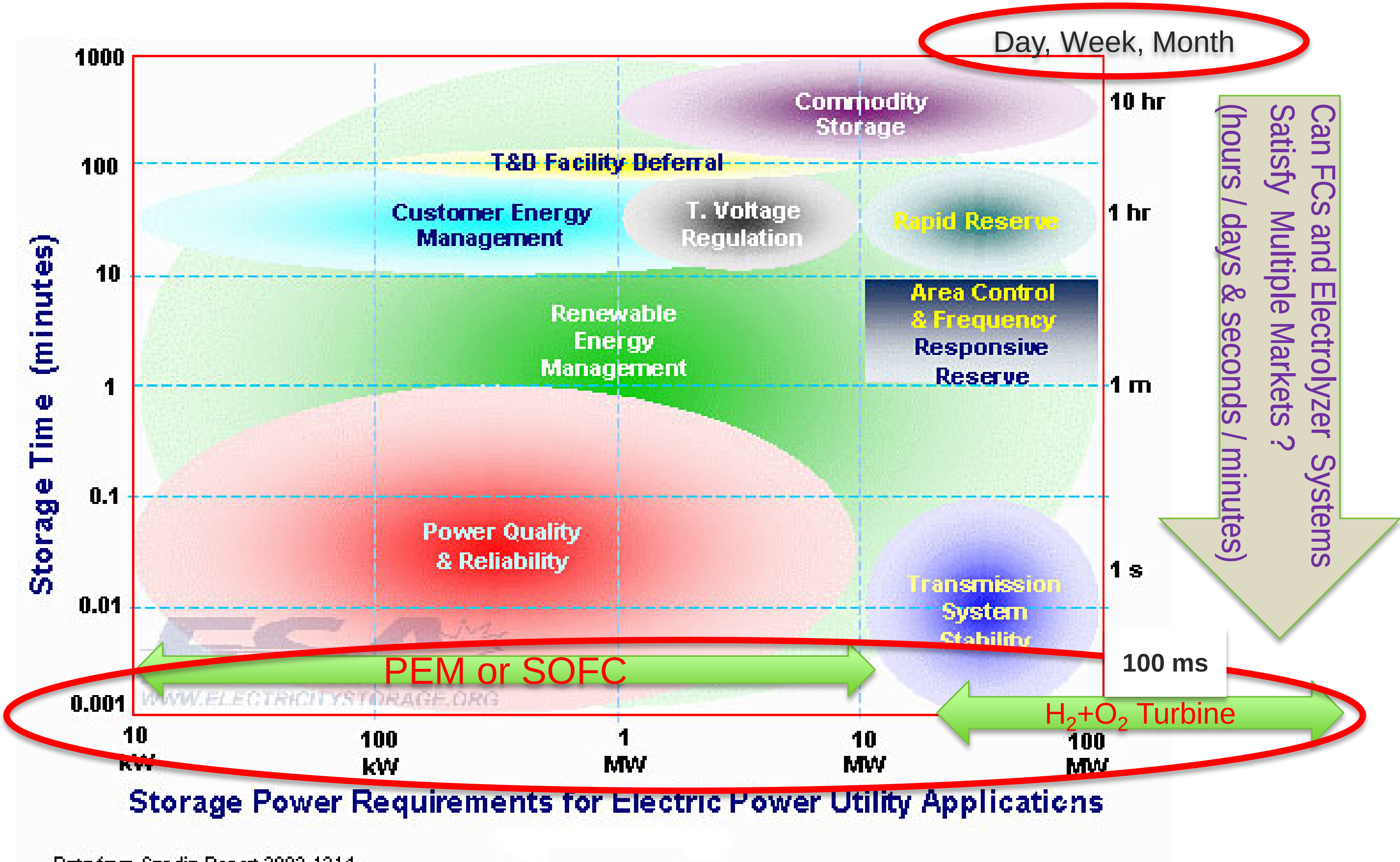




Source: www.hydrogen.energy.gov/pdfs/review12/mt008_ewan_2012_o.pdf
Hawaii Natural Energy Institute Mitch Ewan, GE Transient PSLF™

Hydrogen is a flexible energy storage option and Power Generation spans the range of *microwatts to GW* with *Hours to Months* of Storage Capacity

Quiet, low emission, low maintenance fuel cells to provide onsite heat and power for easy siting



Electrolyzers respond quickly and could provide valuable grid stabilization services
Currently ancillary services have low market values, and low utilization rates
As societies become more dependent on variable generation, the value will likely increase

Ancillary Service Requirements

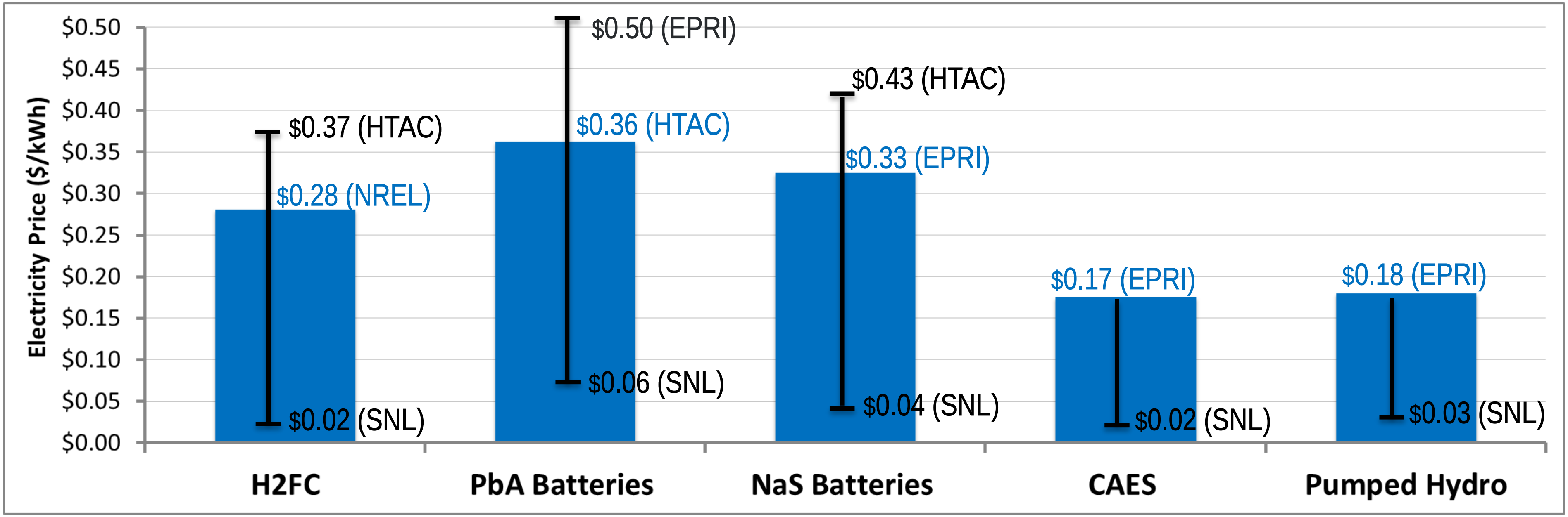
Response time	How quickly can you begin responding?
Ramp-rate	How fast can you change your response?
Energy capacity	(duration) For how long can you respond?
Power capacity	How much can you provide in response?
Min. turndown	What is your lowest operating point?
Startup time	How long does it take to start up?
Shutdown time	How long does it take to shutdown?

Source: Josh Eichman NREL Fellow

LCOE ($/kWh) from multiple studies: H_2, PbA, NaS, CAES & Pumped Hydro

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

A wide range of costs have been presented in the past, primarily due to market assumptions and methodology: arbitrage, financials, technology maturity, market type



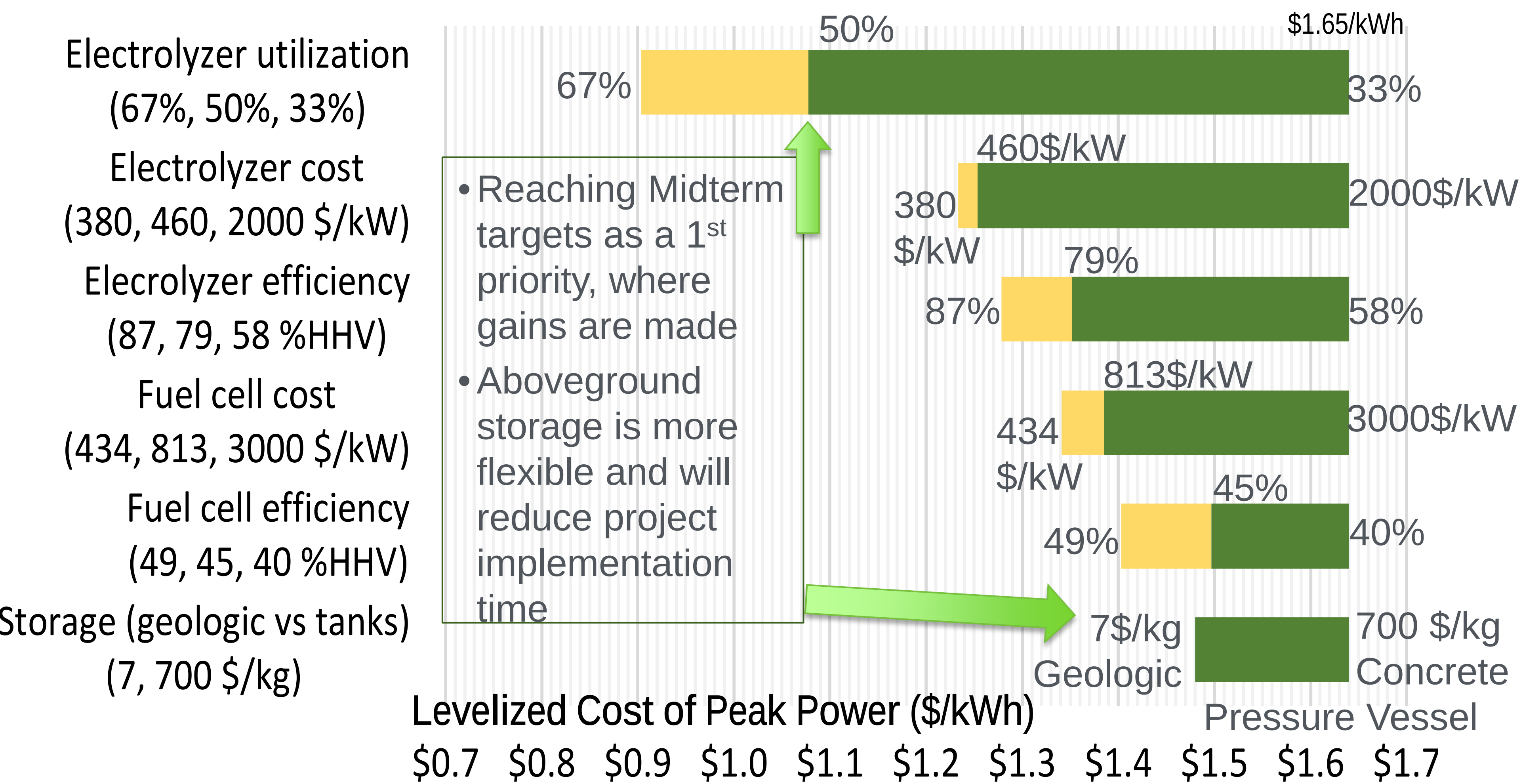
Sources:

- NREL: D. Steward, G. Saur, M. Penev, and T. Ramsden, "Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage," National Renewable Energy Lab , Technical Report (NREL/TP-560-46719), November 2009.
- SNL: S. Schoenung, "Economic Analysis of Large-Scale Hydrogen Storage for Renewable Utility Applications," Sandia National Lab report (SAND2011-4845), August 2011.
- HTAC: S. Thomas, "Estimates of Electricity Costs from Battery and Hydrogen Storage Systems," paper describing HTAC model.
- EPRI: D. Rastler, "Electricity Energy Storage Technology Applications: A White Paper Primer on Applications, Costs, and Benefits," Electric Power Research Institute, Technical Update (1020676), December 2010.

PRELIMINARY Analysis LCOE Sensitivity Analysis for Pure Arbitrage with 24 hours of Storage (NREL)

Electrolyzer Improvements Provide the Largest Benefit: Utilization, Capital Cost, Efficiency

From Left to Right Targets: Long, Mid, Near Term FCTO Technology Targets



Challenges

- Improved stack performance
- High pressure stack/system components/membranes
- Increase stack size
- Market issues (balance of manufacturing investment and market size)
- Grid integration

RD&D Needs

- Improved catalysts
- Improved membranes
- Better anode support media
- Studies of high P electrolysis vs. compression
- Demonstrate large scale viability (MEA, power conversion, etc.)
- Low cost hardware
- Studies determining best markets for electrolysis
- Value proposition for oxygen?
- MW scale demonstration
- Market acceptance of electrolysis

Additional Market Opportunities (ranked by order of votes)

1. Power to gas
2. Ancillary grid services (frequency/voltage regulation)
3. Renewable H2 for petroleum refining
4. Forklifts

RD&D Needs Near Term

- Study what the additional market opportunities are worth (and size) now and later.
- Create MW scale development program including large scale testing & MW scale test lab w/ low cost or curtailed electricity
- Definition of electrolyzer requirements across applications
- Education (of stakeholders)
- MW-Scale pilots to provide services (regional grids)
- Develop electrolyzer roadmap – prove out costs and critical elements
- Forklifts – Material handling projects don't have funding for onsite hydrogen production

Workshop Summary Report (March 2012)

by Adam Z. Weber,Lawrence Berkeley National Laboratory
http://energy.gov/eere/fuelcells/flow-cells-energy-storage-workshop

Organizing Committee:
Industry, National Laboratories and DOE:
EERE, ARPA-E, and the Office of Electricity Delivery & Energy Reliability

Reversible flow cell advantages: energy storage:

- **High round-trip efficiency (60 – 90%)**
- **Power and energy capacity are large and decoupled**
- **Long cycle life**
- **Low self-discharge**
- **Reliable and stable performance**

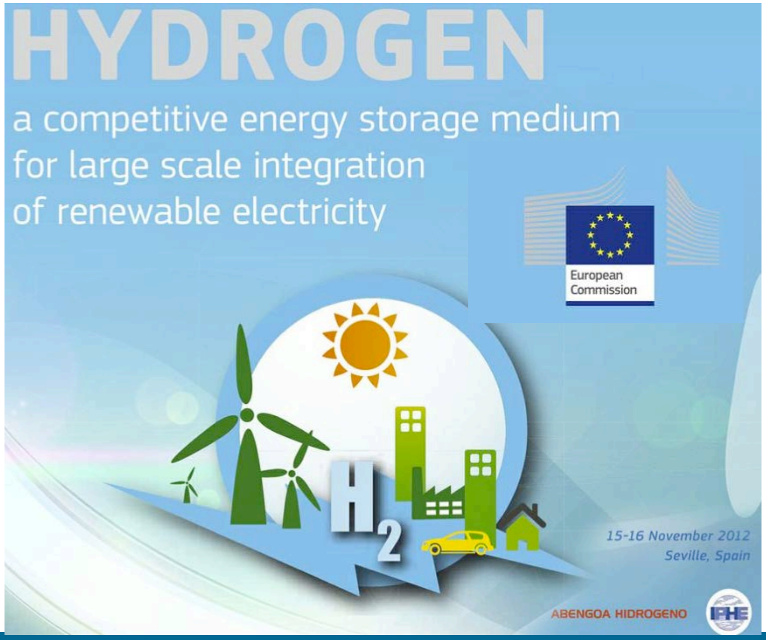
Applying breakthroughs from core fuel cell technologies to improve efficiency, performance, durability, and cost

International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) – Hydrogen Storage Workshop November 2012

-Over 100 participants from more than 20 countries

-Provided high level recommendations for hydrogen to be an economic solution to over-generation

-Focus on policy and requirement for multidisciplinary expertise to evaluate and communicate benefits



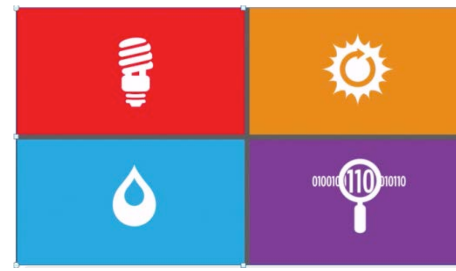
www.iphe.net/events/workshops/workshop_2012-11.html

DOE Initiatives Supporting a Modern Grid

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

Future directions include increased cross-cutting activities and collaboration such as through DOE's new national asset for energy systems integration research, development, and testing

Future Directions- Energy Systems Integration Facility (ESIF)



www.nrel.gov/esif

Quadrennial Energy Review Established January 2014

-Four year Cross Federal Agency Effort

-First year will focus on Energy Infrastructure & will Develop a Road map to modernize U.S. Energy Infrastructure

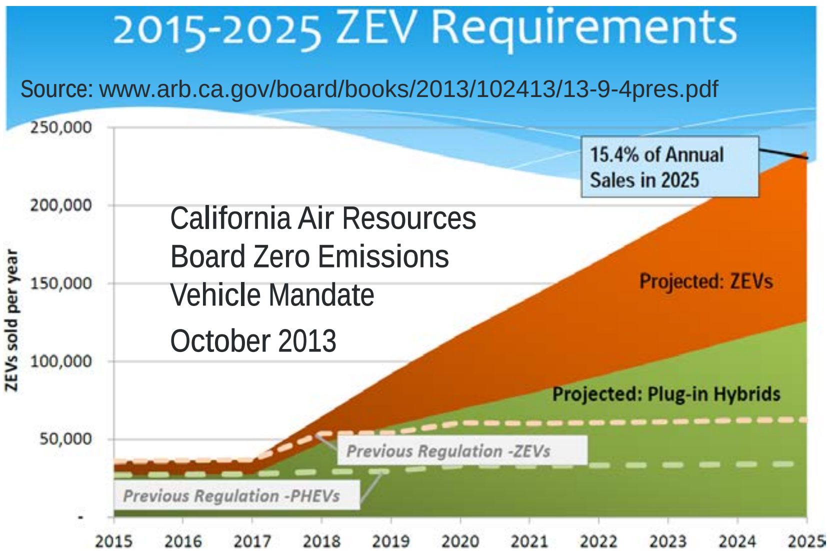
-Part of the Presidents Climate Action Plan

http://energy.gov/epsa/initiatives/quadrennial-energy-review-qer

California Zero Emission Vehicle Mandate & Renewable Energy Portfolio Standards

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

California has aggressive zero emission vehicle and renewable energy generation goals:
→ 1.5M zero emission vehicles by 2025, with infrastructure to support 1M by 2020
→ CA is planning for next steps beyond 33% REPS in 2020 , for 2030 (~40% or some other scheme)



California Utilities Commissioned Study

–by Energy & Environmental Economics (E3)

Overgeneration Statistics	33% RPS	40% RPS	50% RPS Large Solar
Total Overgeneration			
GWh/yr.	190	2,000	12,000
Percent of RPS energy	0.2%	1.8%	8.9%
Overgeneration frequency			
Hours/yr.	140	750	2,000
Percent of hours	1.6%	8.6%	23%
Extreme Overgeneration Events			
99th Percentile (MW)	610	5,600	15,000
Maximum Observed (MW)	6,300	14,000	25,000

Challenge

Source: www.ethree.com/documents/California_Utility_Brief_E3_Study_Final.pdf

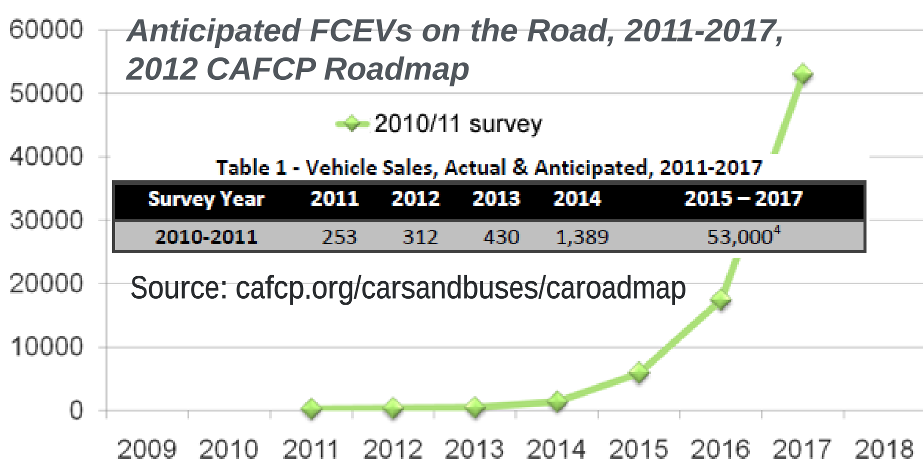


Table 1 - Vehicle Sales, Actual & Anticipated, 2011-2017

Survey Year	2011	2012	2013	2014	2015 – 2017
2010-2011	253	312	430	1,389	53,000[4]

Electric drive transportation fuel demand can support a grid with high variable generation

- Ca-SB1505 requires 33% RE H2 for state funded stations, & all infrastructure after 3500 tons/y (~18K FCEV)
- 33% RPS ~1.3GW electrolyzer with 1.5% CF & Storage!
- 190GWh results in 8.5 Ton/d or 3.1M kg/y (60kWh/kg)
- 16K FCV- 200 kg/yr (50 mi/kg), ~50K FCV with 33% RE H2
- Electric drive- EV 0.25 kWh/mi & FCV 0.8-1.2 kWh/mi
    - 2.5 MWh/EV-year & ~ 10 MWh/FCV-year

Identify benefits & opportunities for commercial hydrogen energy storage applications which support: *Grid Services, Variable Electricity Generation, Hydrogen vehicles*

Key topics: (1) Business models and early applications, (2) Specific policy barriers and incentives, (3) Modeling and econometric approaches, and (4) Potential opportunities for effective demonstrations

Thank you!

Fuel Cell Technologies Office

http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

Monterey R. Gardiner

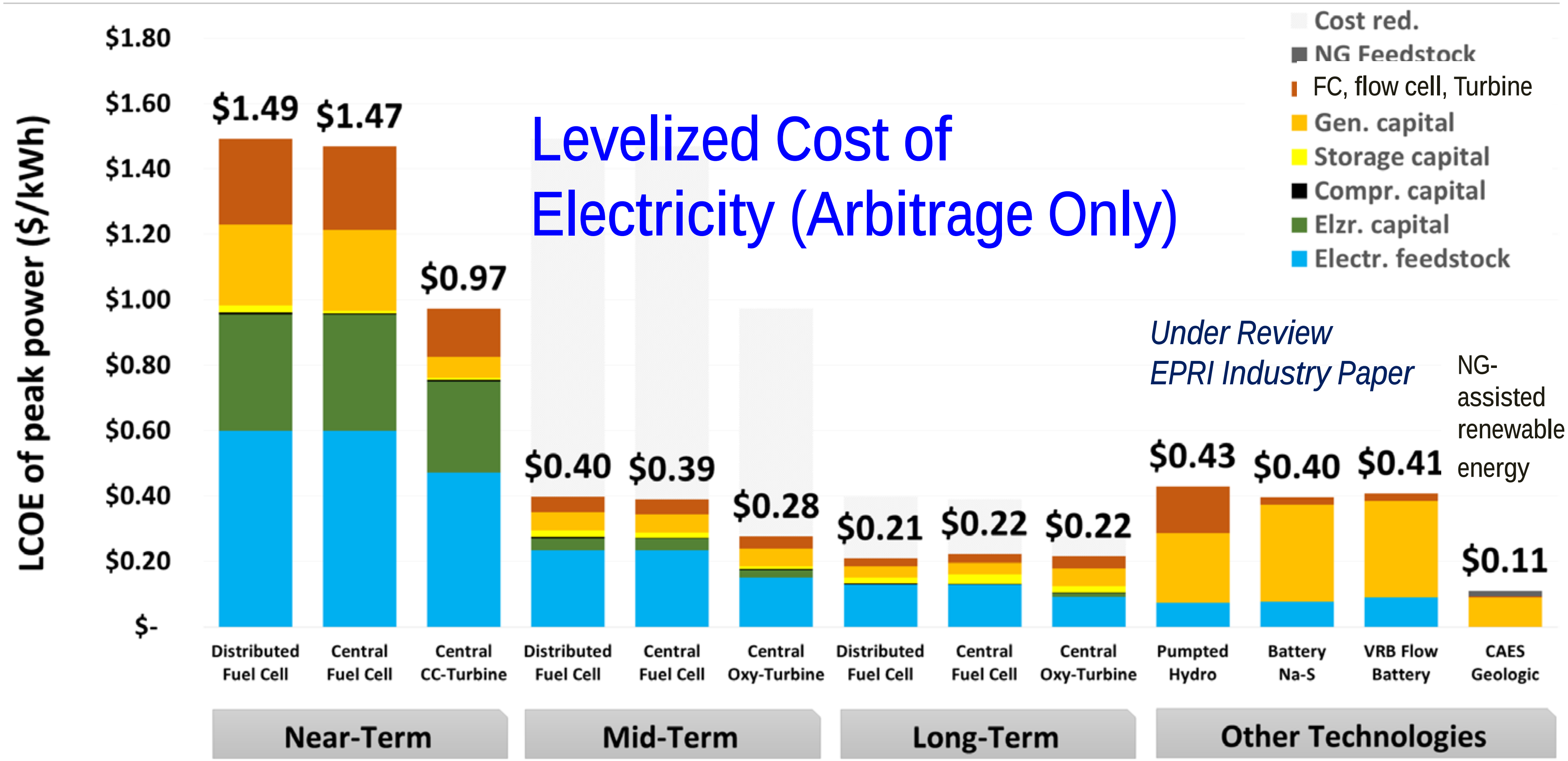
Monterey.Gardiner@ee.doe.gov

202-586-1758

PRELIMINARY Analysis LCOE Waterfall Technology Improvements

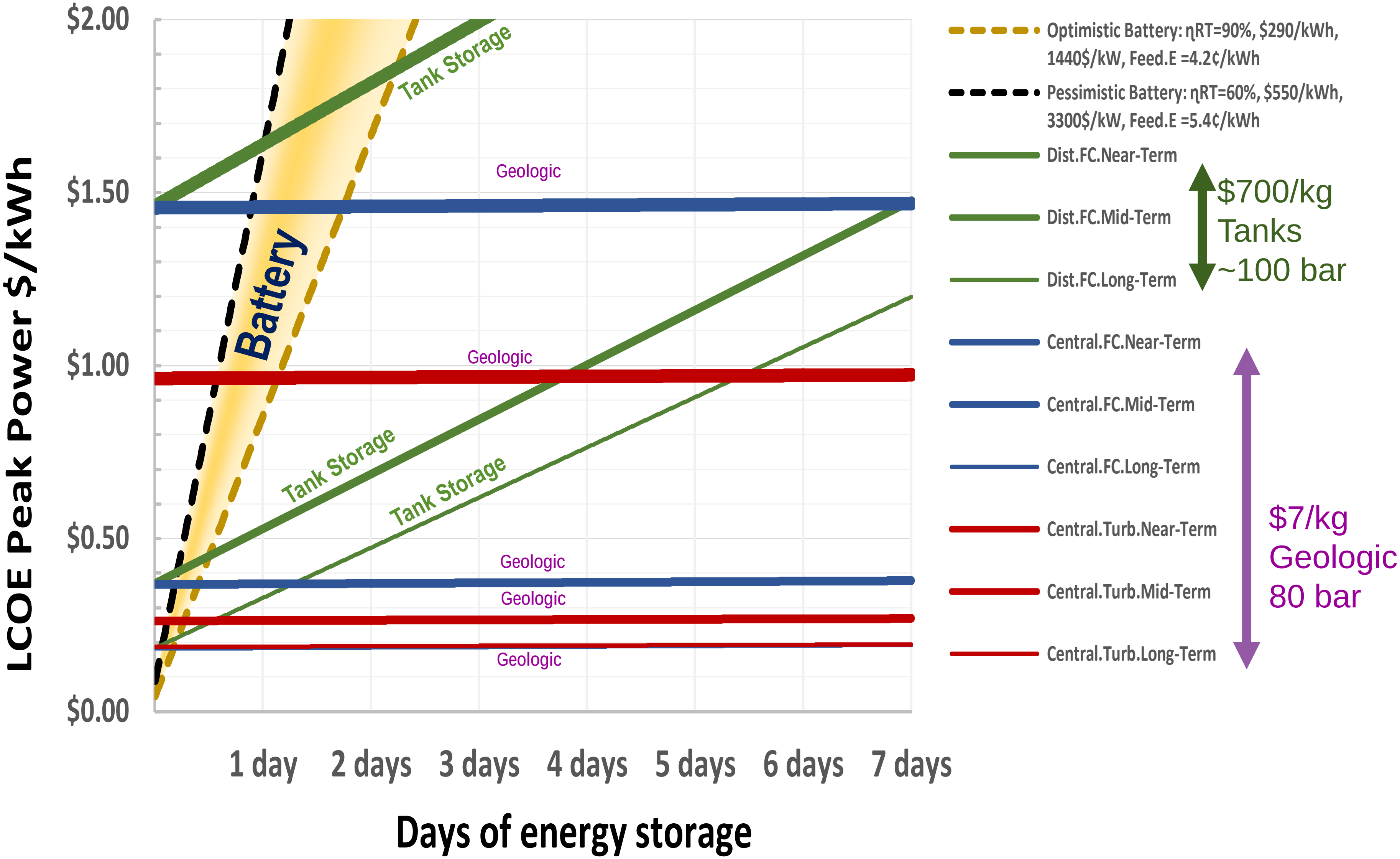
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Reaching long term technology targets shows levelized cost of electricity could be ½ of new pumped hydro or advanced batteries e.g. Na-S battery



Source: NREL Model Mike Penev

Using static market assumptions, H_2-storage costs are competitive to battery systems for long duration storage needs, costs increase at a slower rate (compared to battery systems).

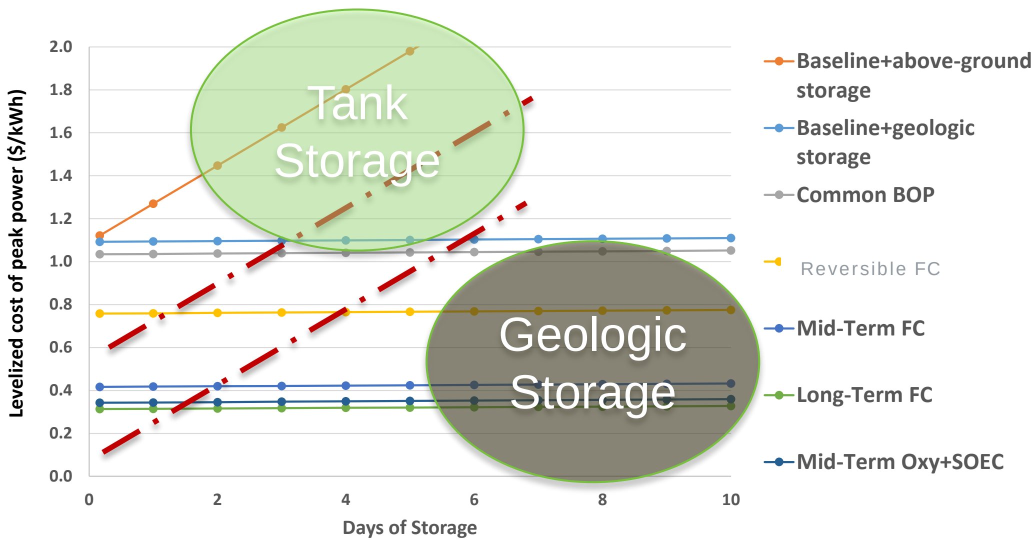


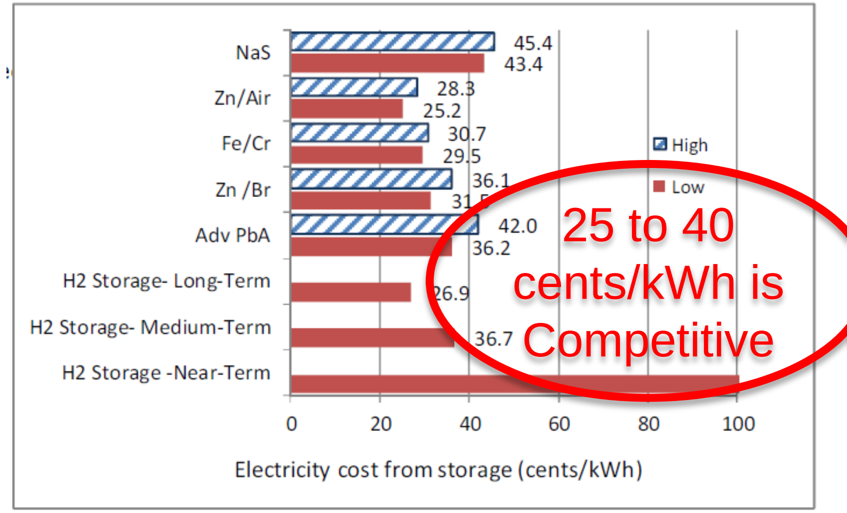
Storage Capacity (40 MWh/ day)

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

Costs increase rapidly with above ground storage ($700/kg vs. $7/kg)

Additional Storage capacity is extremely low cost and the main strength





HTAC simple model EPRI test case.XLS, WS 'DashBoard' AG-312;4/7/2012

Figure 1. Estimated costs of electricity from storage using the HTAC /NREL model & EPRI battery $/kWh cost estimates

<u>Underground</u> hydrogen storage is competitive with most battery options at medium and long term

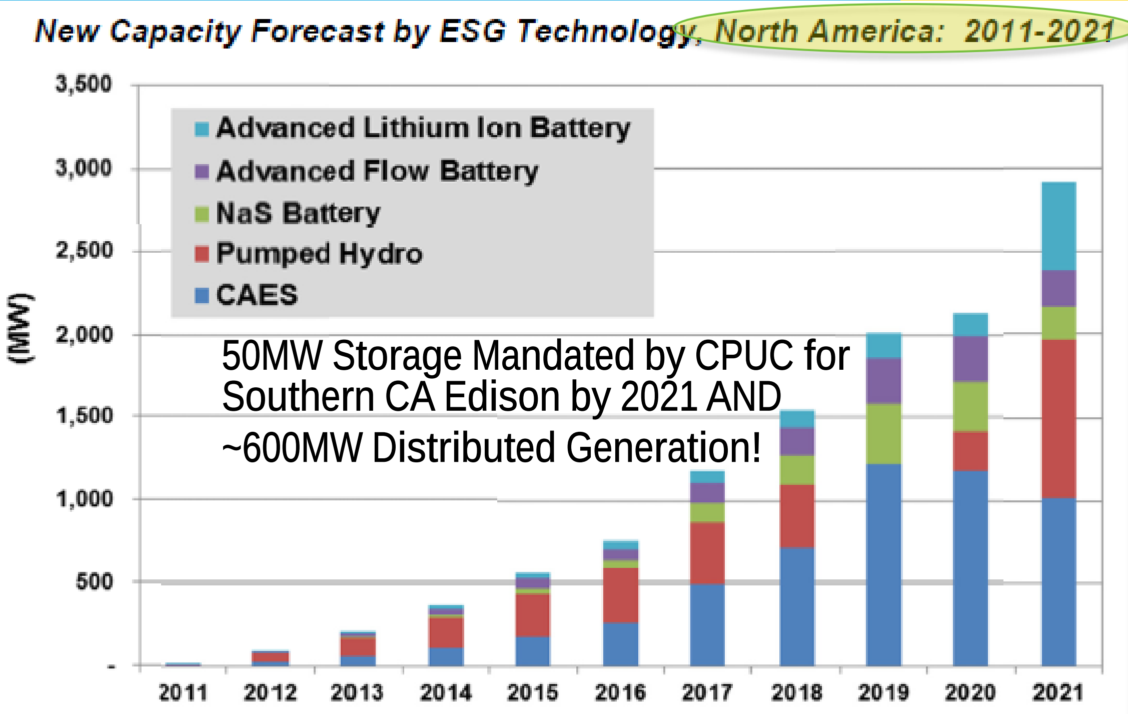
Assumptions:

10MW FC, 40 MWhr storage, %10 free electricity, 33.3% capacity factor electrolyzer (8 hr/d), FC operating 4 hr/d

Storage Times		Near-term H2	Medium-Term H2	Long-term H2	Adv PbA	Zn/Br	FeCr	Zn/Air	NaS
4 hours	Capex ($M)	$ 75.9	$ 16.9	$ 10.9	$ 3.1	3.2	$ [illegible]	$ 2.6	$ 4.6
	Cents/kWh	121.1 c/kWh	36.6 c/kWh	26.8 c/kWh	11.0 c/kWh	12.7 c/kWh	10.9 c/kWh	10.2 c/kWh	13.2 c/kWh
1 day	Capex ($M)	75.9	16.9	10.[illegible]	18.9	19.3	19.2	15.5	27.[illegible]
	Cents/kWh	121.1 c/kWh	36.7 c/kWh	26.9 c/kWh	36.2 c/kWh	31.5 c/kWh	29.5 c/kWh	25.2 c/kWh	43.4 c/kWh
2 days	Capex ($M)	75.9	16.9	10.[illegible]	37.8	38.7	38.4	30.9	55.[illegible]
	Cents/kWh	121.1c/kWh	36.7c/kWh	26.9c/kWh	66.3c/kWh	53.9c/kWh	51.8c/kWh	43.1c/kWh	79.5c/kWh
1 week	Capex ($M)	76.0	17.0	11.0	132.[illegible]	135.3	134.4	[illegible]	194.1
	Cents/kWh	121.4 c/kWh	36.9 c/kWh	27.1 c/kWh	217.1 c/kWh	166.2 c/kWh	163.3 c/kWh	132.9 c/kWh	260.3 c/kWh
2 weeks	Capex ($M)	76.1	17.1	11.1	264.4	270.7	268.8	216.5	388.3
	Cents/kWh	121.7c/kWh	37.2c/kWh	27.3c/kWh	428.2c/kWh	323.4c/kWh	319.4c/kWh	258.7c/kWh	513.5c/kWh
1 month	Capex ($M)	76.4	17.3	11.3	574.5	588.1	584.0	470.4	843.6
	Cents/kWh	122.4c/kWh	37.8c/kWh	27.9c/kWh	923.3c/kWh	692.0c/kWh	685.5c/kWh	553.6c/kWh	1107.1c/kWh
2 months	Capex ($M)	76.9	17.8	11.8	1149.1	1176.1	1168.0	940.9	1687.1
	Cents/kWh	123.7 c/kWh	38.9 c/kWh	29.0 c/kWh	1841 c/kWh	1375 c/kWh	1364 c/kWh	1100 c/kWh	2207 c/kWh

HTAC simple model EPRI test case.XLS, WS 'Storage Time' K-19;4/11/2012

PROJECTED New Storage Capacity Addition by Technology: NORTH AMERICA



http://www.energymanagertoday.com/energy-storage-gets-big-boost-in-los-angeles-089232/

(Source: Pike Research)

California Public Utilities Commission

AB 2514 (2010)

1. To open a proceeding to determine appropriate targets, if any, for each load-serving entity to procure viable and cost-effective energy storage systems.
2. By October 1, 2013, adopt an energy storage procurement target, if determined to be appropriate, to be achieved by each LSE by December 31, 2015, and a 2nd target to be achieved by December 31, 2020.
3. "[T]he commission may consider a variety of possible policies to encourage the cost-effective deployment of energy storage systems, including refinement of existing procurement methods to properly value energy storage systems."

- **Rice Project: 150 MW CSP plant in Sonoran Desert, CA**
  - Developer (SolarReserve LLC) will sell power to PG&E for 25 years (beginning June 1, 2016).
  - 10 hours of energy storage.
  - **Cost = $600 million.**
  - First commercial-scale system in CA to include energy-storage capability.
- **Similar project (Crescent Dunes) by SolarReserve, near Tonopah, NV- operational 2013**
  - 110 MW molten salt power tower. (+$10 million per year in salaries and operating costs)
  - Will provide energy for NV Energy, Inc.
  - First commercial-scale molten salt power tower in the world. www.solarreserve.com/what-we-do/csp-projects/crescent-dunes/

Molten Salt Storage

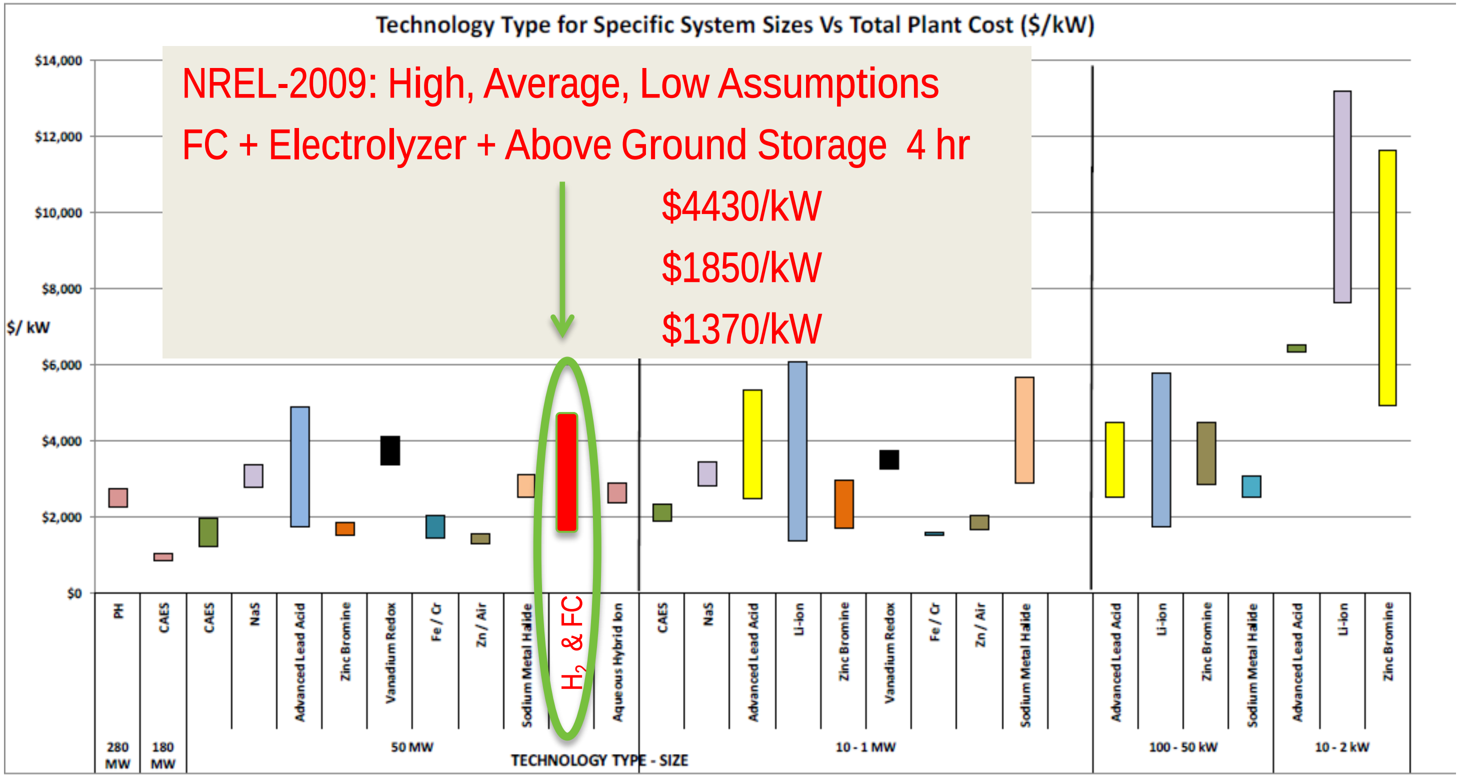
Source: http://www.renewableenergyworld.com/rea/news/article/2013/01/pg-e-approved-to-buy-power-from-solarreserve-csp-project-with-molten-salt-

Fuel Cells vs. Other Storage Technologies

Hydrogen Installed Capital Costs Are Comparable

Summary -Total Installed Cost $ / kW

BULK ENERGY STORAGE | SUBSTATION/ FEEDER GRID SUPPORT | END-OF LINE GRID AND END-USER ENERGY MANAGEMENT



Range of Costs Due to: 1. Technology; 2. Hours of Storage; 3. Maturity

EPRI ELECTRIC POWER RESEARCH INSTITUTE

 15

Hydrogen & Fuel Cells for Energy Storage

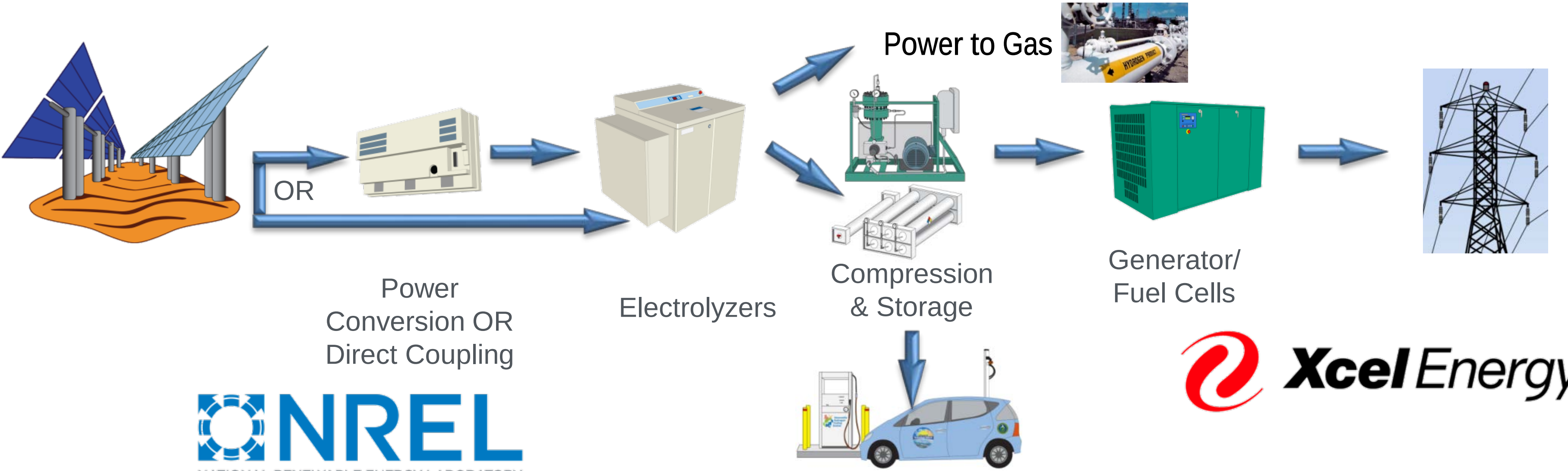
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Increasing renewable energy utilization while supporting the grid!

Alternative Storage Technologies and Necessary Assumptions

- **Battery Storage Systems (near 90% efficiency)**
  - Power conditioning system: AC-DC rectifier, DC-AC output switchgear
  - Battery bank, and balance of plant
- **Hydrogen Storage Systems**
  - Electrolyzer, underground storage cavern, compressor system
  - Fuel cell plus DC-AC inverter

- Common Model Assumptions
  - e^-. stored 8 hr/d, 10 MW power 4 hr/ 40 MWhr,
  - 10% e^- "free" balance at 6c/kwh for 8 hr,
  - Battery/electrolyzer sized to meet storage needs
- Financial Assumptions: 10% ROI and …:
  - Battery O&M 2% of Capital cost
  - 2.5%/y compressors, 2.2%/y electrolyzer, 2%/y FC
  - Storage time varied from 4 hr to 2 months
  - Component replacement fund 6.2%/yr interest



NREL NATIONAL RENEWABLE ENERGY LABORATORY

Xcel Energy®

LCOE Cost Assumptions used by NREL

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

-Assumptions follow FCTO MYRDD goals, with more aggressive metrics Long-Term
-Long-Term R&D could allow Reversible FC's achieving high efficiency and low cost

	Near-Term			Mid-Term			Long-Term		
System Description	**Distributed Fuel Cell**	**Central Fuel Cell**	**Central CC-Turbine**	**Distributed Fuel Cell**	**Central Fuel Cell**	**Central Oxy-Turbine**	**Distributed Fuel Cell**	**Central Fuel Cell**	**Central Oxy-Turbine**
Power rating (MW)	10	150	150	10	150	150	10	150	150
Energy storage capacity	4 hours	1 week	1 week	4 hours	2 weeks	2 weeks	4 hours	4 weeks	4 weeks
H2 Storage type	Terrestrial	Salt-dome	Salt-dome	Terrestrial	Salt-dome	Salt-dome	Terrestrial	Salt-dome	Salt-dome
Operation									
Electrolyzer efficiency (% HHV)	58%	58%	58%	79%	79%	79%	87%	87%	87%
Generator efficiency (% HHV)	40%	40%	51%	45%	45%	70%	49%	49%	70%
Discharge hours (hours/day)	4	4	4	4	4	4	4	4	4
Charge hours (hours/day)	8	8	8	12	12	12	16	16	16
Installed Capital Costs									
Electrolyzer ($/kW)	2,000	2,000	2,000	460	460	460	-	-	380
Power generation ($/kW)	3,000	3,000	783	677	677	655	434	434	655
H2 Storage ($/kg)	700	7	7	700	7	11	700	7	11
Total system cost ($000)	76,668	1,120,286	645,614	14,035	199,941	161,900	6,847	121,345	161,283
Feedstock Cost									
Cost of electricity ¢/kWh	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Percent of free electricity	10%	10%	10%	20%	20%	20%	30%	30%	30%
Blended cost of electricity ¢/kWh	5.4	5.4	5.4	4.8	4.8	4.8	4.2	4.2	4.2

NREL Model: capital recovery factor 12%, maintenance 5% of capital cost,~5 cents/kWh e-

Reversible Flow Cells

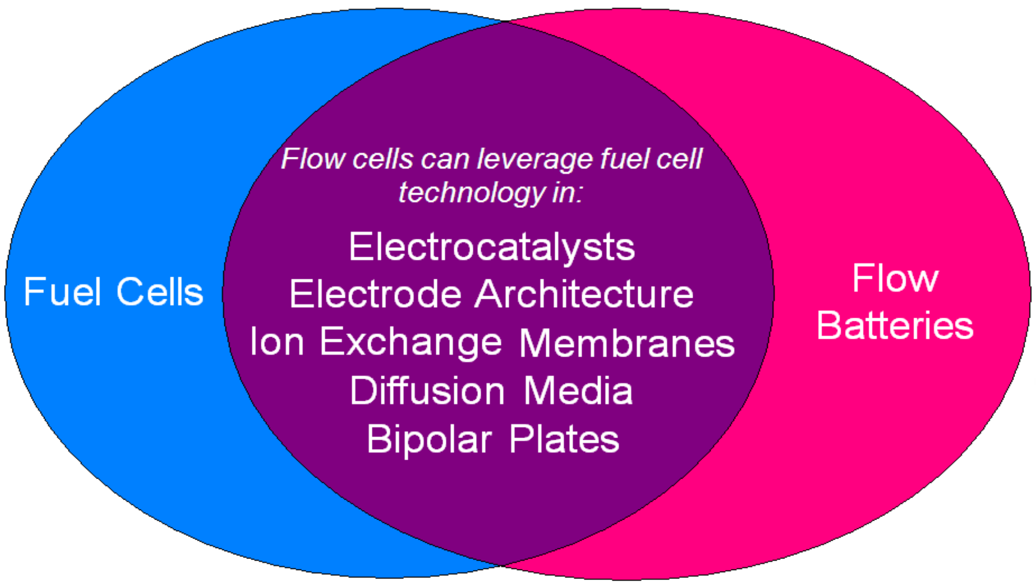
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

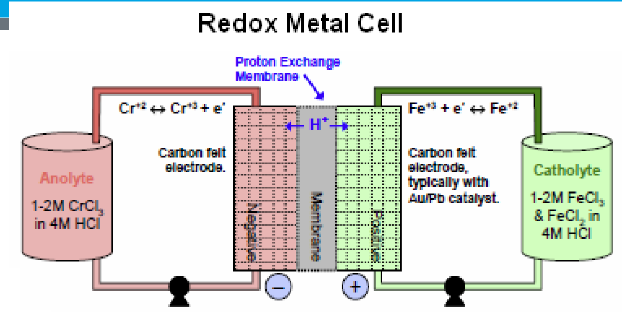
High efficiency energy storage that leverages existing fuel cell technology

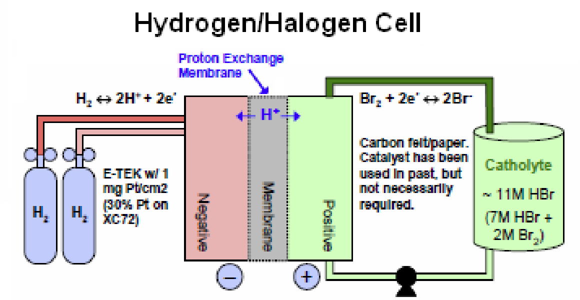
Advantages of reversible flow cells for energy storage:

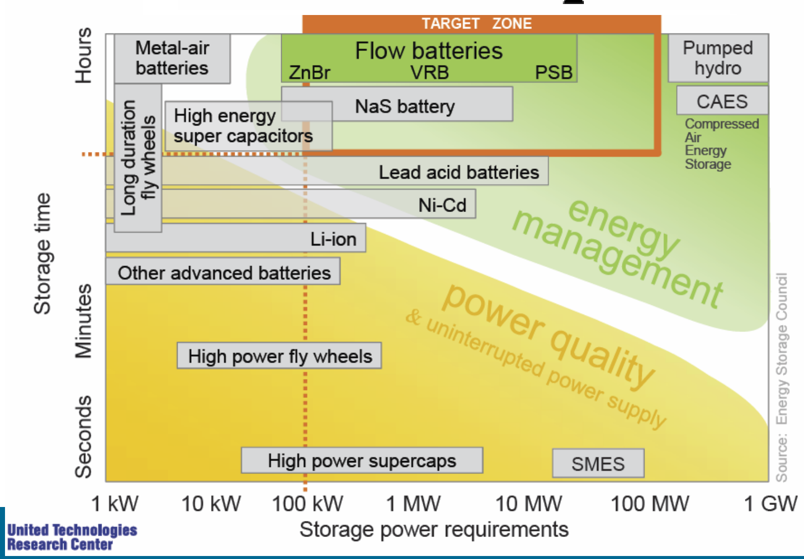
- **High round-trip efficiency (60 – 90%)**
- **Power and energy capacity are large and decoupled**
- **Long cycle life**
- **Low self-discharge**
- **Reliable and stable performance**

Applying breakthroughs from core fuel cell technologies would improve efficiency, performance, durability, and cost







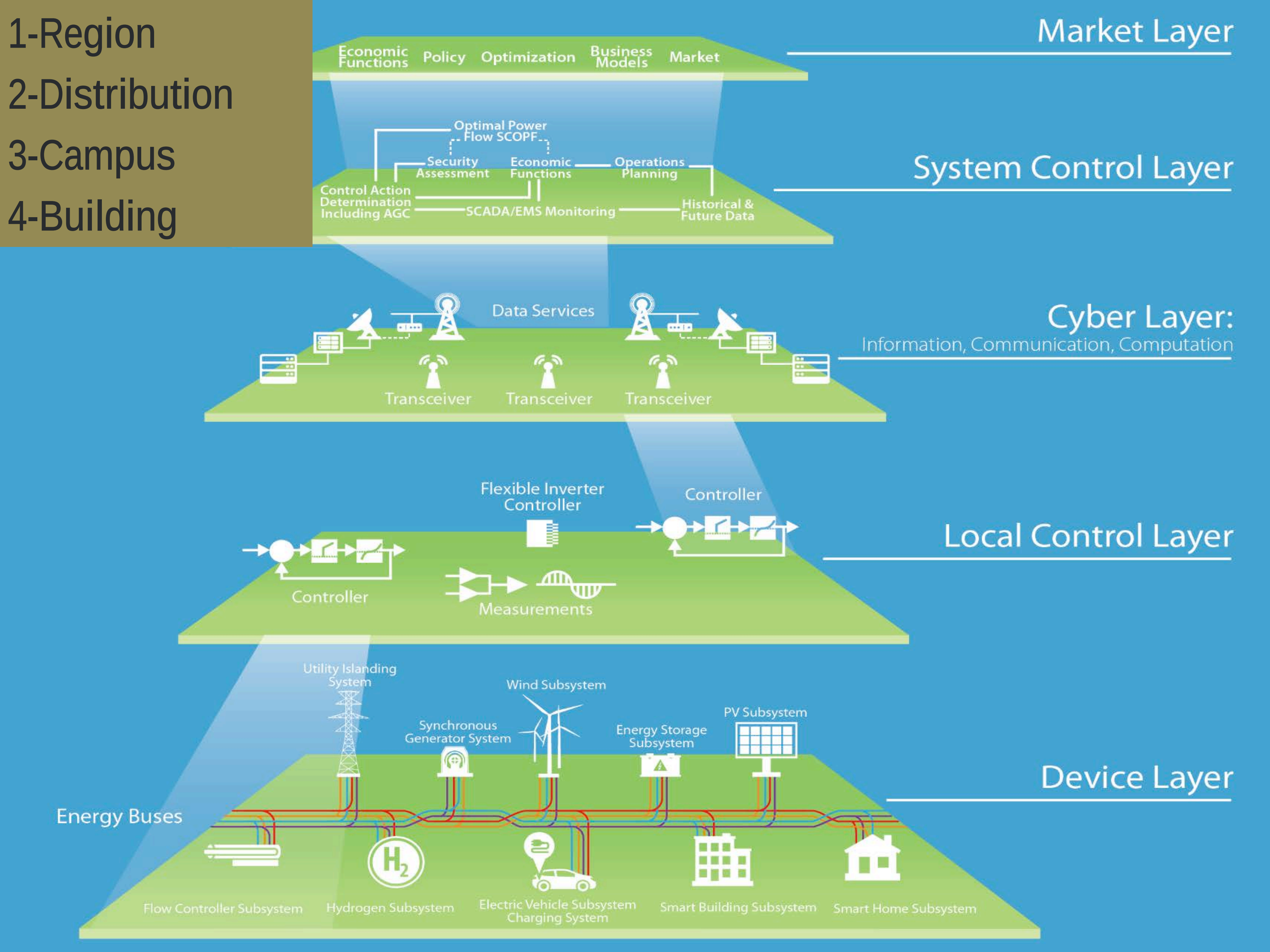


1-Region

2-Distribution

3-Campus

4-Building

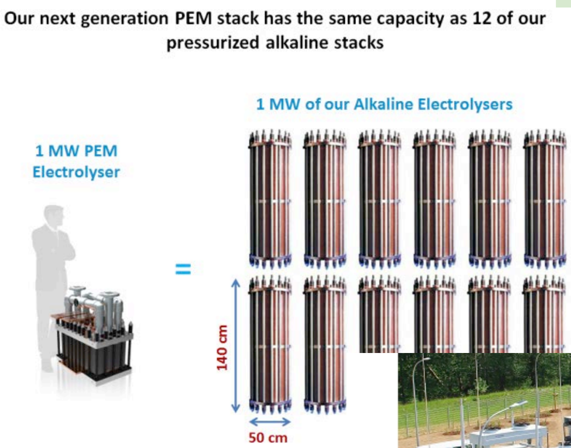


Foot Print Hydrogen & 1-2 MW electrolyzer: 24 to 2000 MWh (1-90 d) [e⁻ consumption]

~24 MWh day input capacity for electrolyzer (1MW, ~50 kWh/kg) ~450 kg/day (430 - 480 kg)
30 MW wind farm, 33% Capacity Factor ~24MWh average output, Liquefaction +10-15 kWh/kg

Olympic Swimming pool 50M X 25M X 2M 2500 M^3, (~2XISO 170 M^3) 40 days@100bar

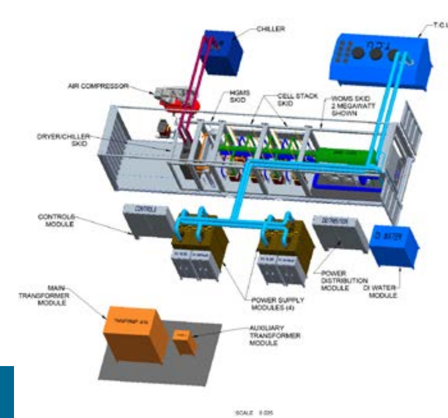
24 MWh/d	10 bar	50 bar	100 bar (+~1 kwh/kg)	350 bar (+2-3 kwh/kg)	Liquid (+10-15 kwh/kg)
~kg/m^3 / M^3	0.8	4.5	8	24	70
1 day	562	100	56	19	6
10 day	5625	1000	562	188	64
40 day	22500	4000	2250	750	257
90 day	50625	9000	5063	1688	579



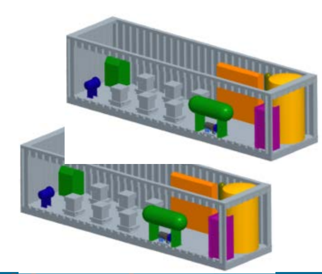
Proton: Open-frame skid modular plant configuration, Transition from previous fully-packaged designs

1MW ~2X 40 ft iso container (40X8X8.5 feet) Metric-Meter (12.2X2.4X2.9) plus set back

Aug. 2013- Hydrogenics 2MW Power-to-Gas Demonstration Plant Falkenhagen, Germany



Large Active Area PEM Stack

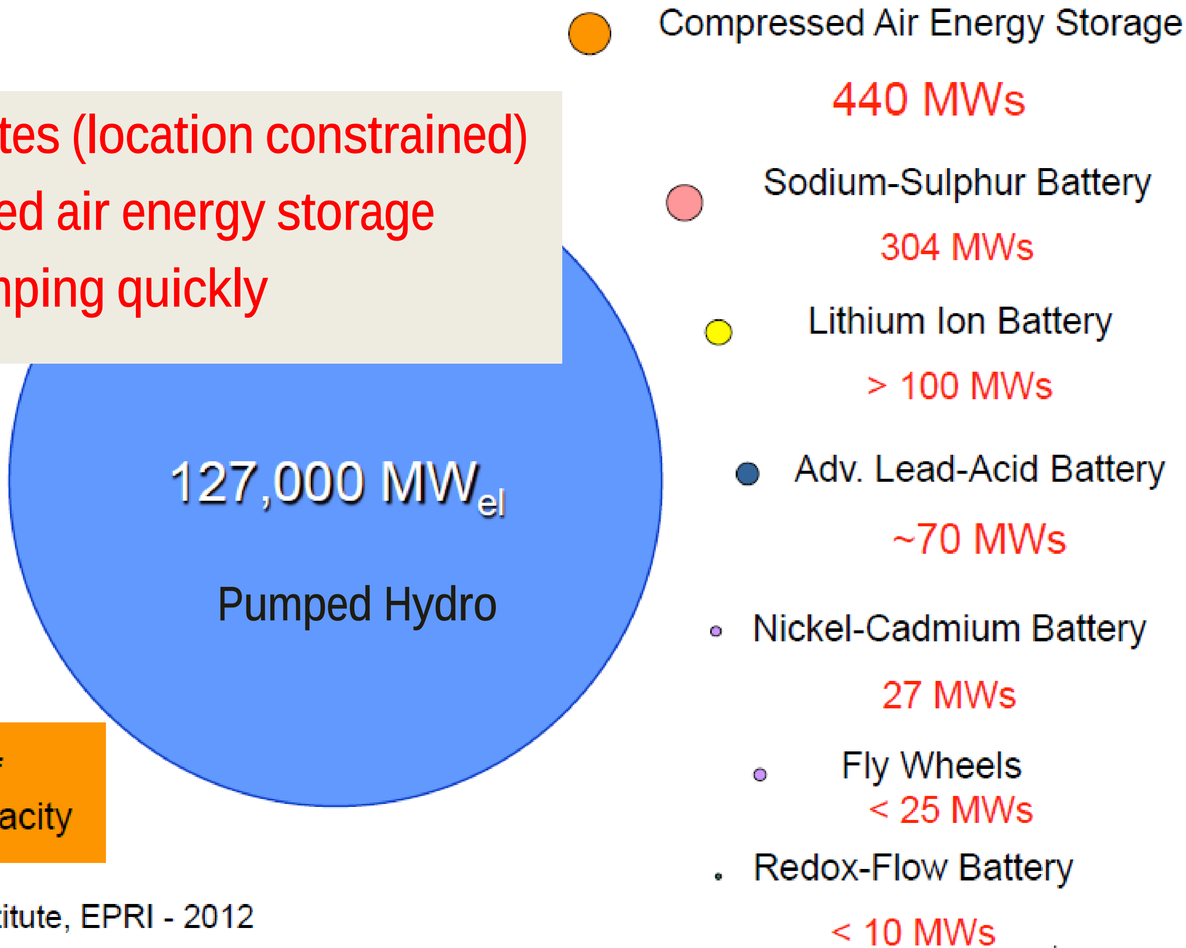


MW-scale concep

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

Worldwide installed storage capacity for electrical energy

- Pumped hydro dominates (location constrained)
- Followed by compressed air energy storage
- Other technologies ramping quickly



U.S. Pumped Hydro:

19 GW Installed

31 GW Planned

Versus ~250MW Other Storage

Over 99% of total storage capacity

Source: Fraunhofer Institute, EPRI - 2012

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

 4

EERE Energy Systems Integration

ESI Vision

- EE and RE technologies are integrated into the energy system in a safe, reliable, and cost effective manner at a relevant scale to support the nation's goals of 80% clean electricity by 2035 and reducing oil imports by 33% by 2025.

Project Goal

- Conduct research and testing to characterize the building and grid services related to building loads, electric vehicles, and DER,
- Develop holistic approaches to increasing the hosting capacity of EE and RE technologies on the grid.

1.0 Physical Characterization of EE & RE Technologies → 2.0 Comm., Information, Computation Infrastructur e → 3.0 Developing Holistic Grid Services → Increasing & Enhancing the Hosting Capacity

Physical Characterization of FCT technologies for Grid Services

Physical Characterization of Electrolyzer Capabilities: What ancillary services can electrolyzers provides to the grid and to microgrid control entities? What range of responses or other characteristics do stakeholders (utilities, utility commissions, others) need? How can these responses be prioritized for grid services?

DOE ACTIVITIES – Develop a cost reduction road map for FCTO based energy storage technologies:

1. Workshop on Electrolyzer R&D gaps and new market opportunities (February)
2. Workshop on FCTO Opportunities for Energy Storage (March)
3. Present results of Workshop-ES at FCTO Annual Merit Review (June)
4. Q3 Draft FCTO Hydrogen for Energy Storage R&D Roadmap

NREL ACTIVITIES – Support development of and characterize MW scale electrolyzer

1. Develop characterization protocols to evaluate electrolyzers response to grid signals and load-following renewable electricity inputs
2. Physically test devices to determine impact to durability under variable operation
3. Develop models of electrolyzers for high penetration simulations
4. Report baseline characterization of specific grid support capabilities
5. Develop transition plan for test equipment utilization in FY15 with a minimum 50% industry cost share

INDUSTRY –

1. Provides 125 kW electrolyzer stack installed at 250 kW (capable) test bed
2. Review characterization protocols with utilities
3. Demonstrate capabilities of electrolyzers to utilities and regulators

Activities outlined in the INTEGRATE AOP (FCTO)

1.0 Physical Characterization- establish a flexible, testing environment for variable-powered stack operation and advanced R&D on electrolyzer balance of plant (BoP) components. With a goal of plug-n-play installations to reduce cost and added value to grid services market. This pre-solicitation effort establishes a functional electrolyzer test bed for utility and industry, and other national laboratory grid integration RD&D efforts.
1.2 -Conduct stack- and system-level testing to demonstrate stack operation and recommend BoP optimization to aid in the monetization of ancillary services for electrolyzer systems with utility stakeholders to gain confidence and industry buy-in of capabilities.
1.3 -Report detailed characterization of large-scale electrolyzers for providing grid services. As part of this task, utilities and regulators will be invited to ESIF to witness first hand how these technologies can be used to provide grid services.

Activities Proposed in Area 2 for Lab Directed Work, Lab Call, or Industry Solicitation

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

1.0 Physical Characterization of EE & RE Technologies → **2.0 Comm., Information, Computation Infrastructure** → 3.0 Developing Holistic Grid Services → Increasing & Enhancing the Hosting Capacity

Development of Data, Communication, and IT "standards" to Support Open Integration

<u>Communications, Information, and Computational Interface:</u> What data are available and needed? How can we standardize data communication and leverage existing work in this area? How do we verify that the devices are able to share and act on data transmitted?

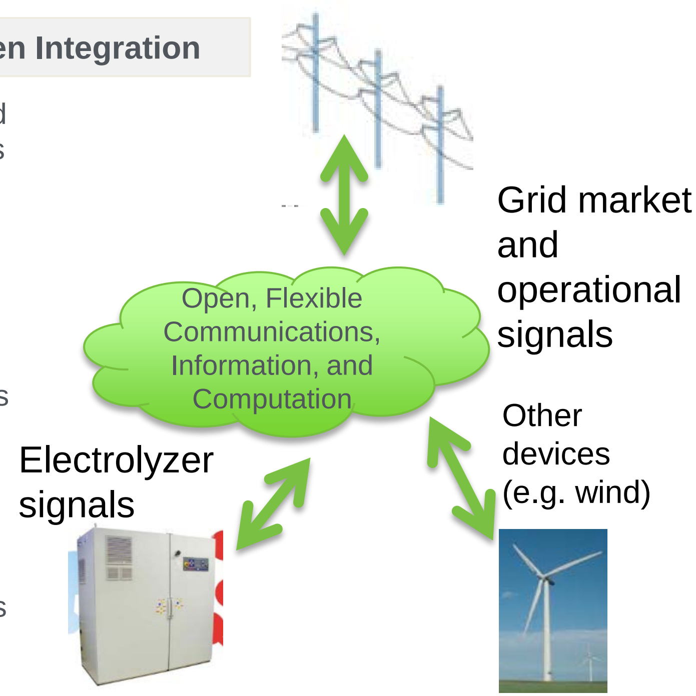
DOE ACTIVITIES –Support development of common data interoperability/ taxonomies-classifications. Collaborate with industry to develop standard data maps, interoperability protocols for the various market structures. Hydrogen provides three energy vectors: electricity, vehicle fuel and thermal energy. We will identify opportunities at the boundaries of these vectors, e.g. leveraging energy storage at refueling-charging stations and the high value of transportation fuel.

NREL ACTIVITIES

1. Develop Communications, Information, and Computational connections (communication layer) for integrated system experimentation
2. Develop an advanced utility interface (AUI) to accept communication signals, process and deliver control commands to electrolyzer stack and BoP subsystems.
3. ($100K)Support Virtual connection between ESIF and INL Real-time digital simulator (RTDS) – allows integration of ESIF RTDS to much larger RTDS in order to simulate much larger power systems

Industry

1. Provide input regarding the interoperability of technologies
2. Provide input on cross industry communications structures while defining value streams resulting from repurposing equipment and increasing asset utilization



2.0 C. Communication (link INL's RTDS systems) - connect to INL's 138kV loop and 3 region utility intersection, further discussion with other Offices anticipated

Activities Proposed in Area 3 for Lab Directed Work, Lab Call, or Industry Solicitation

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

1.0 Physical Characterization of EE & RE Technologies → **2.0 Comm., Information, Computation Infrastructure** → **3.0 Developing Holistic Grid Services** → **Increasing & Enhancing the Hosting Capacity**

Evaluation and demonstration of intelligent, integrated system to provide grid services -

DOE ACTIVITIES

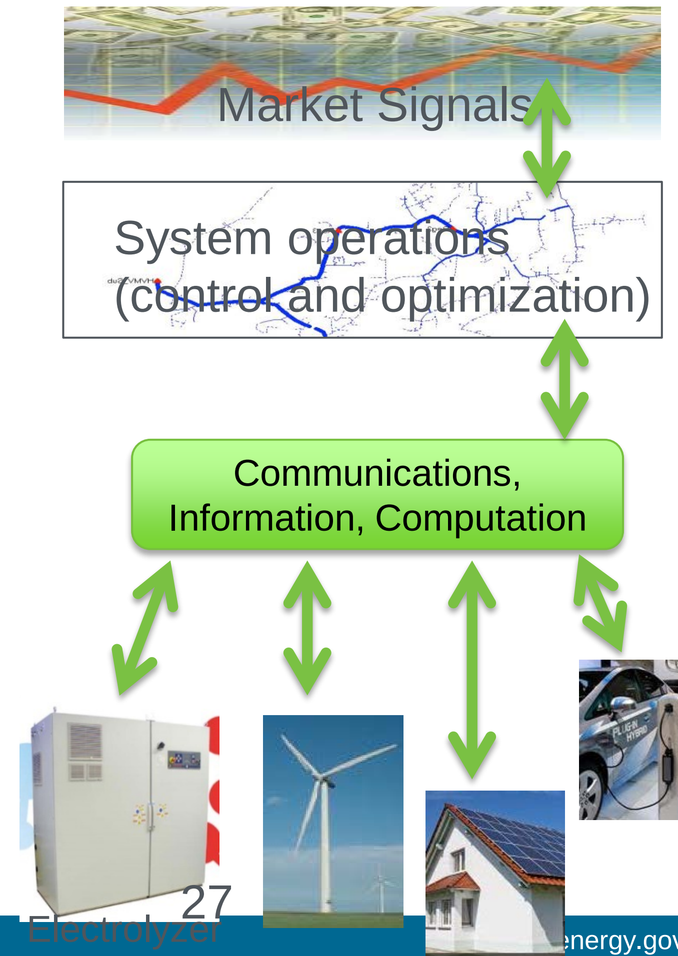
1. Develop use cases and needs (e.g. residential scale energy system, distribution systems with high penetrations of renewable energy, integrated wind/hydrogen system) for deployments of electrolyzers and fuel cells at scale

NREL ACTIVITIES

1. Implement and demonstrate supervisory communication/control platform to optimize electrolyzers with multiple EERE technologies; includes a customer (energy manager) friendly interface
2. Analyze and refine (at ~1/8 scale) the value preposition of MW electrolyzers and provide a prioritized list of grid services and other energy vectors (vehicle fuel, thermal- power to gas H_2 + natural gas pipelines)
3. Under Discussion: Demonstrate & describe capabilities of integrated systems to utilities and regulators
    1. Explore gas storage cost reduction where applicable
    2. Stand alone wind and large scale electrolyzers for vehicle fuel
    3. Opportunities for refueling station operation or multiple small scale (~kW range) FCs to support the grid

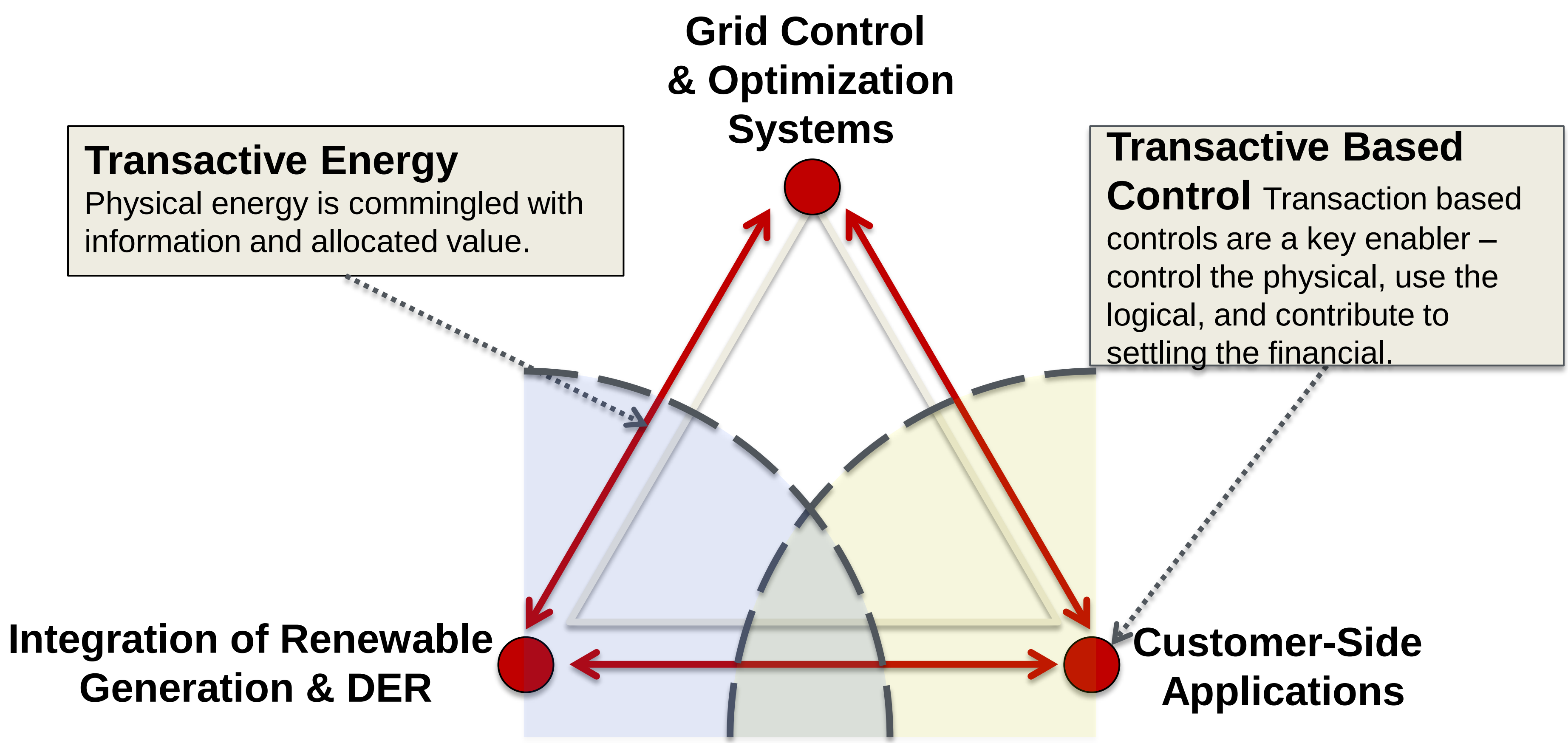
INDUSTRY

1. Provide constraints and parameters for value stream proposals
2. Review use cases and results (especially electrolyzer performance)
3. Recommend demonstration sites and potential projects in FY15



Control and Optimization at ESIF

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



INTEGRATED DER REFERENCE DOCUMENT + TRANSACTIVE REFERENCE DOCUMENT

AGREEMENT ON INTEGRATED INTEROPERABILITY

Electrolyzer, Storage, and Fuel Cell Foot Print

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

Hydrogen-based storage systems can provide storage at costs that are 10x less than battery systems, because power and energy scale separately.

Liquid tanker 4,000 kg, 60 MWh final electricity via fuel cell, $20,000 vehicle fuel at $5/kg or $3000 of electricity at 0.05$/kWh. 280 MWh with transmission(without line losses or opportunity costs or congestion uncertainty) is $14,000 at $0.05/kWh).

280 MWh of partially curtailed electricity to provide:
$20,000 of hydrogen vehicle fuel at $5/kg, 1 kWh/mile
$14,000 of electricity sold via transmission line using 280 MWh at $0.05/kWh, and $28,000 at 0.10/kwh
$3000 (60 MWh at $0.05/kWh) with added value of very high power-quality, and reliable electricity that is quiet and has zero local emissions produced onsite.

~$9000 at $0.15/kWh Provided via hydrogen and liquefaction and back to electricity (Backup power, resiliency, high density energy storage applications)
*does not take into account production costs, only target sales cost.

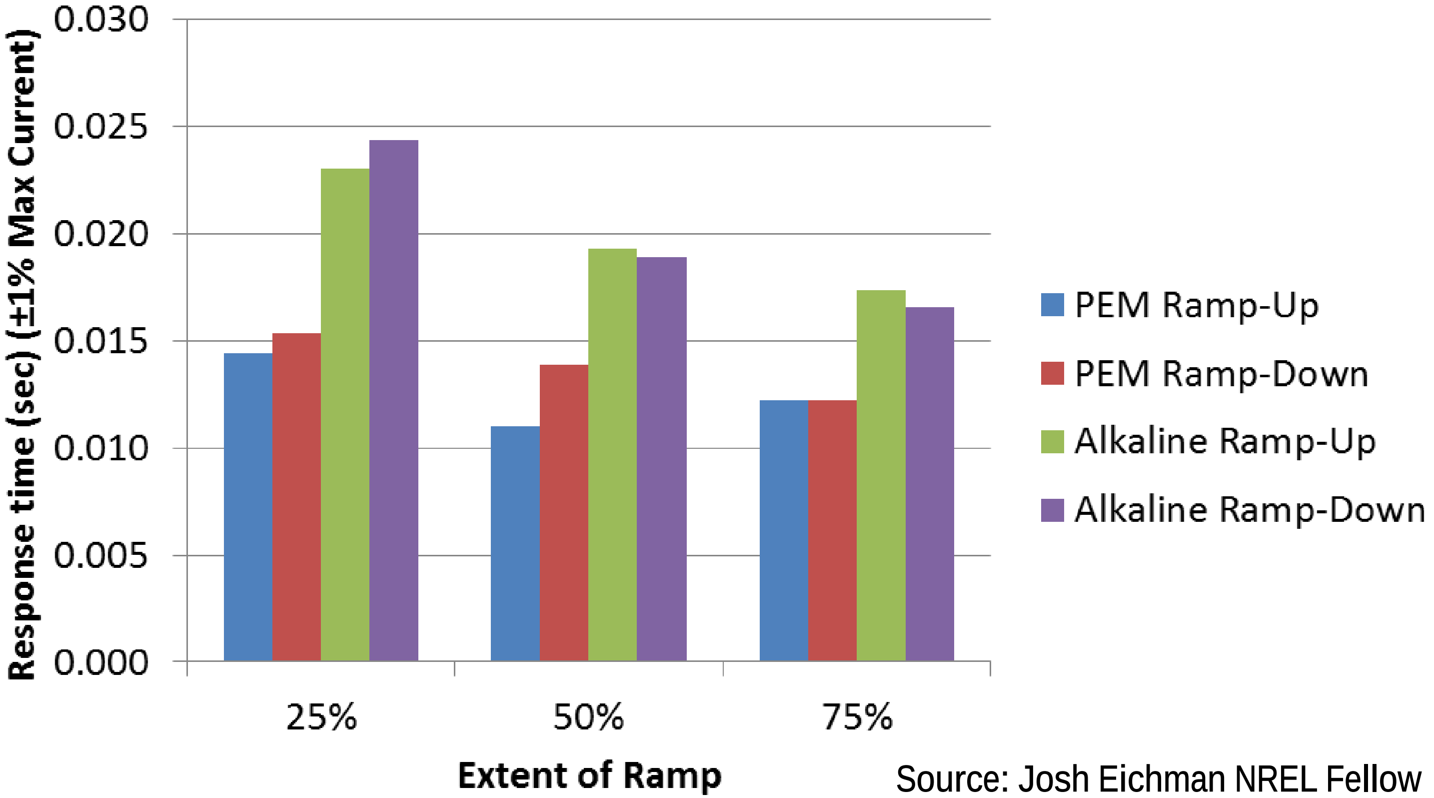
Battery systems: Power and Energy scale together; More energy storage = more batteries; Marginal cost of storage $1400/kWhr

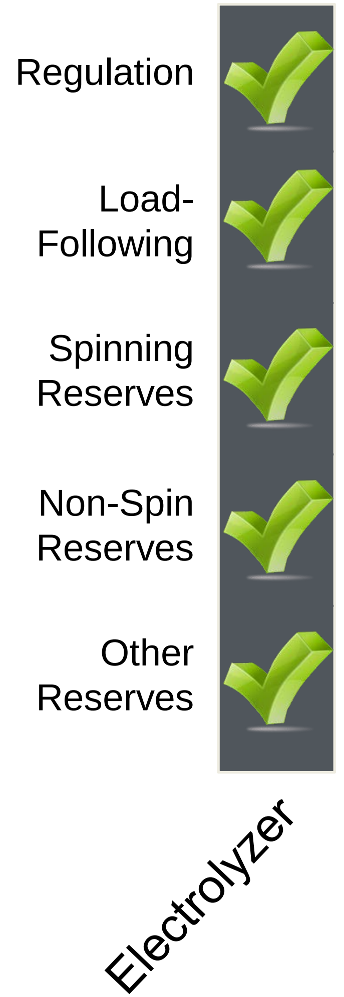
Electrolyzer Response Time Testing

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

All devices are VERY responsive, and will meet ancillary service needs

- **Resulting Response time for ramp-up and ramp-down tests for both PEM and Alkaline units at NREL**





Source: Josh Eichman NREL Fellow

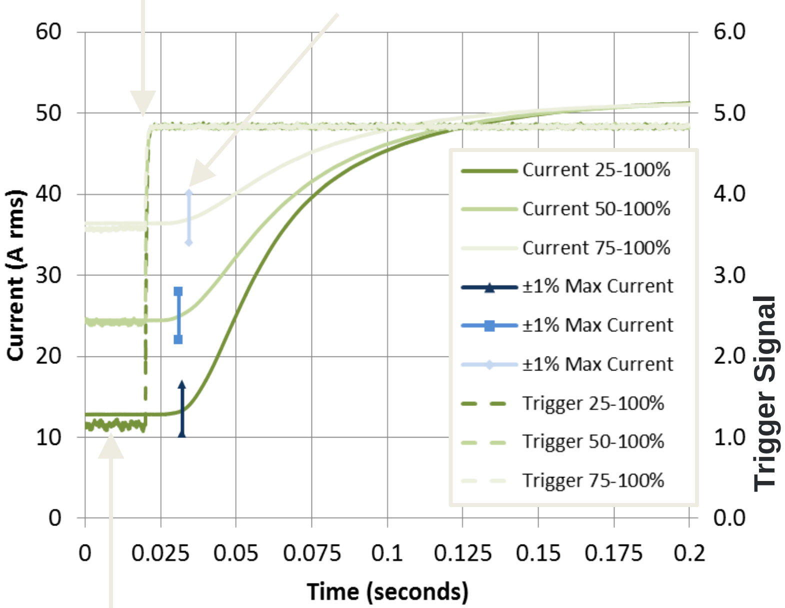
Electrolyzer Response Time Testing

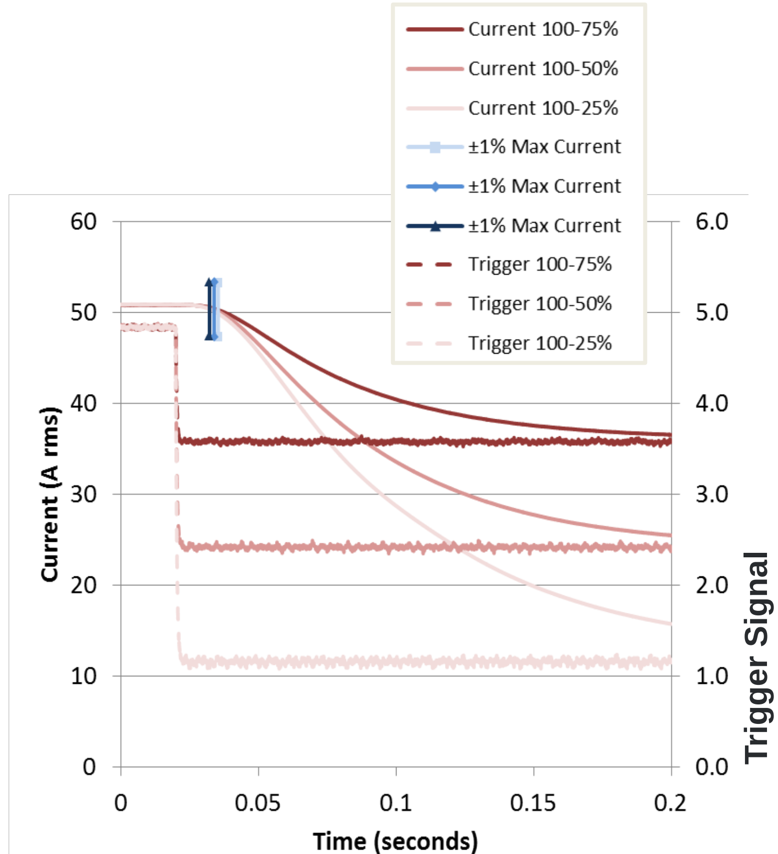
Power set-point was changed (PEM unit shown below)

– Ramp Up: 25%, 50%, and 75% →100%
– Ramp Down: 100% → 75%, 50% and 25%

Trigger at 0.02 seconds

Response (±1% max current)





Regulation

Load-Following

Spinning Reserves

Non-Spin Reserves ✓

Other Reserves ✓

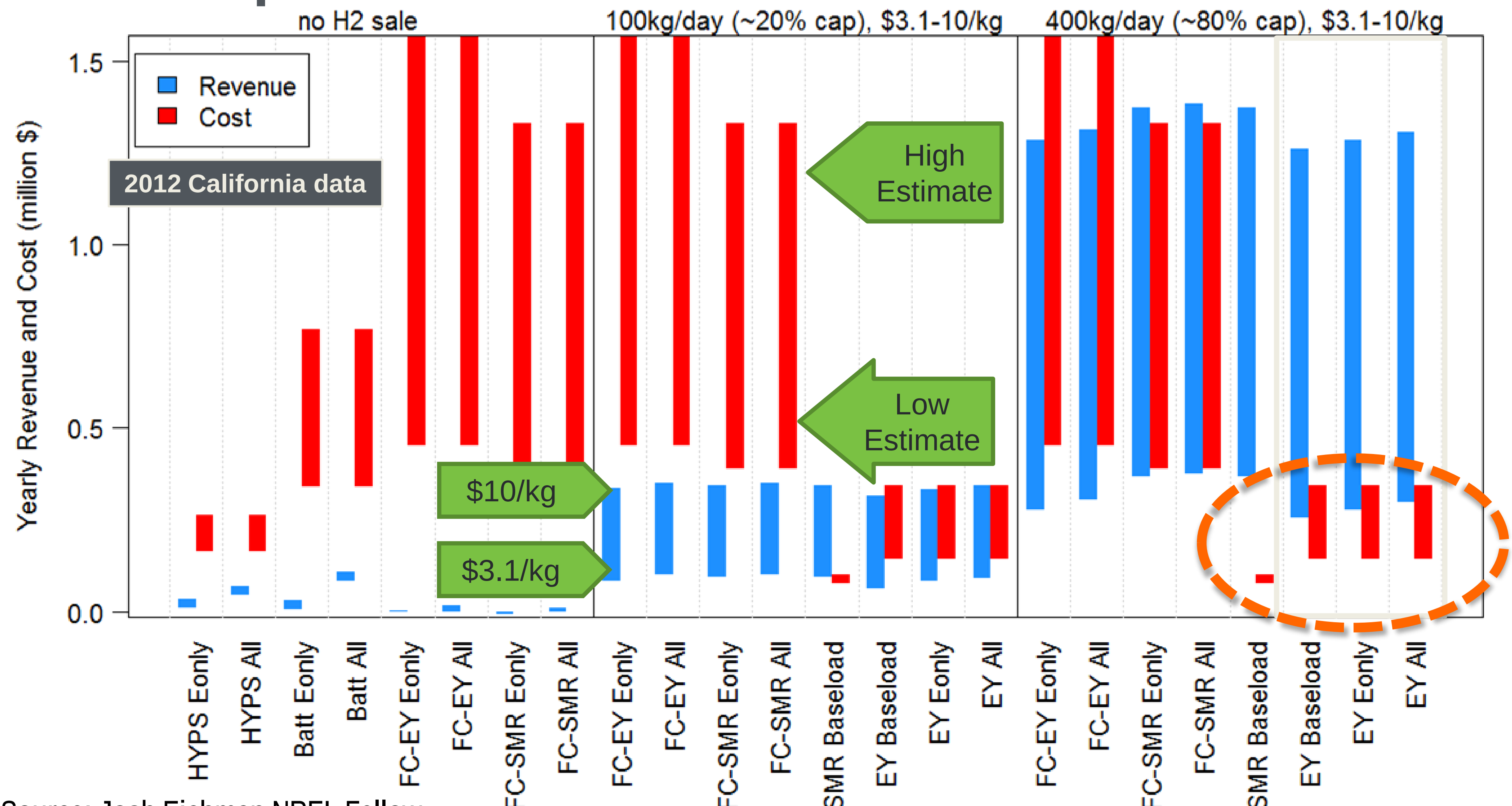
Electrolyzer

Samples taken every 0.0002 seconds

Source: Josh Eichman NREL Fellow

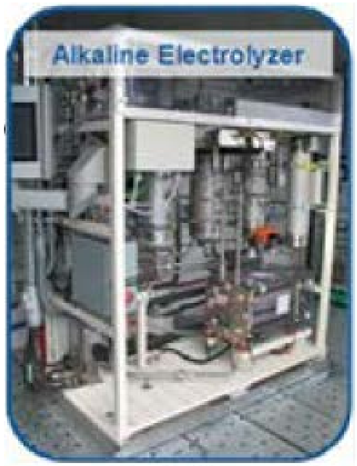
Larger hydrogen refueling station capacities (100 kg to 400 kg) and lower costs
Result in much higher revenues & a near market case for Electrolyzers to support the grid

- **Comparison of annual revenue and cost**



Source: Josh Eichman NREL Fellow

- **Electrolyzers testing at the National Wind Technology Center**
  - Startup and Shutdown
  - Minimum Turndown
  - Response Time
    - Ramp Rate
    - Frequency Response



	PEM	Alkaline
Manufacturer	Proton OnSite	Teledyne Technologies
Electrical Power	50kW (208VAC)	40kW (480VAC)
Rated Current	155A per stack	220A 75 cell stack
Stack Count	3	1
Hydrogen Production	12 kg/day	13 kg/day
System Efficiency at Rated Current	68.6 (kWh/kg)	95.7 (kWh/kg)

ESIF Opportunities (SMART Milestones under development)

1. Lessons learned and data from Canada others regarding wind curtailment and power to gas opportunities
2. DC-DC efficiency gains (~15% inverter loss DC-AC-DC)
3. Real time digital simulator-INL-NREL
4. NG-FC-PV Synergies
5. Investigate business case for residential FCs (60K 750W sold in Japan)
6. ESIF as test bed for qualified H-Prize entries
7. H2 infrastructure with disaster resilience to provide EV charging and H2 refueling
8. MW scale biomass fed electrolyzer development (Proton)

http://orbit.dtu.dk/en/publications/isolated-full-bridge-boost-dcdc-converter-designed-for-bidirectional-operation-of-fuel-cellselectrolyzer-cells-in-gridtie-applications%28a0fd2812-53ed-49c8-9668-e1019bd6a8c7%29.html

CA Public Utilities Commission Rate Making Order R10-12-007

Barriers to Energy Storage Development- A Lack of:

1. Definitive System Need
2. Cohesive Regulatory Framework
3. Evolving Markets and Market Product Definitions
4. Resource Adequacy Accounting
5. Cost Effectiveness Evaluation Method
6. Cost Recovery Policy (cost /market based)
7. Cost Transparency and Price Signals
8. Commercial Operating Experience
9. Well-defined Interconnection Processes

BARRIERS TO ENERGY STORAGE DEPLOYMENT

	BARRIER	Energy Storage Sec. 2835, 9620 R.10-12-007
[1]	Lack of definitive system need	Considers setting a storage "need" or procurement target per AB 2514
[2]	Lack of cohesive regulatory framework	Identify regulatory barriers; encourage collaboration across proceedings
[3]	Evolving markets and market product definitions	Identify proceedings affecting storage market participation
[4]	Resource Adequacy (RA) accounting	Determine uses where storage can be eligible for RA and collaborate with RA proceeding
[5]	Lack of cost-effectiveness (C/E) evaluation method	Determin a cost-effectiveness framework for energy storage
[6]	Lack of cost recovery policy (cost- vs. market-based)	Consider how storage uses can inform CPUC cost recovery policies and consider revisions to allow multi-use storage
[7]	Lack of cost transparency and price signals	Identify regulatory forums for improving cost & price signals, including within rate design
[8]	Lack of commercial operating experience	Considers targeted RD&D; coordinate with R.11-03-012 and R.11-10-003
[9]	Lack of well-defined interconnection processes	Interconnection of dis

Power Generation (Fuel Cell)

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

1.1 MW Hydrogen Plant

Plant Total = 250 m^2 230 m^2/MW

Combine Cycle Turbine Plant

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

600 MW Natural Gas plant

Plant	= 50,000 m^2	83 m^2/MW
Ponds	= 120,000 m^2	200 m^2/MW
Total	= 170,000 m^2	283 m^2/MW

Combine Cycle Turbine Plant

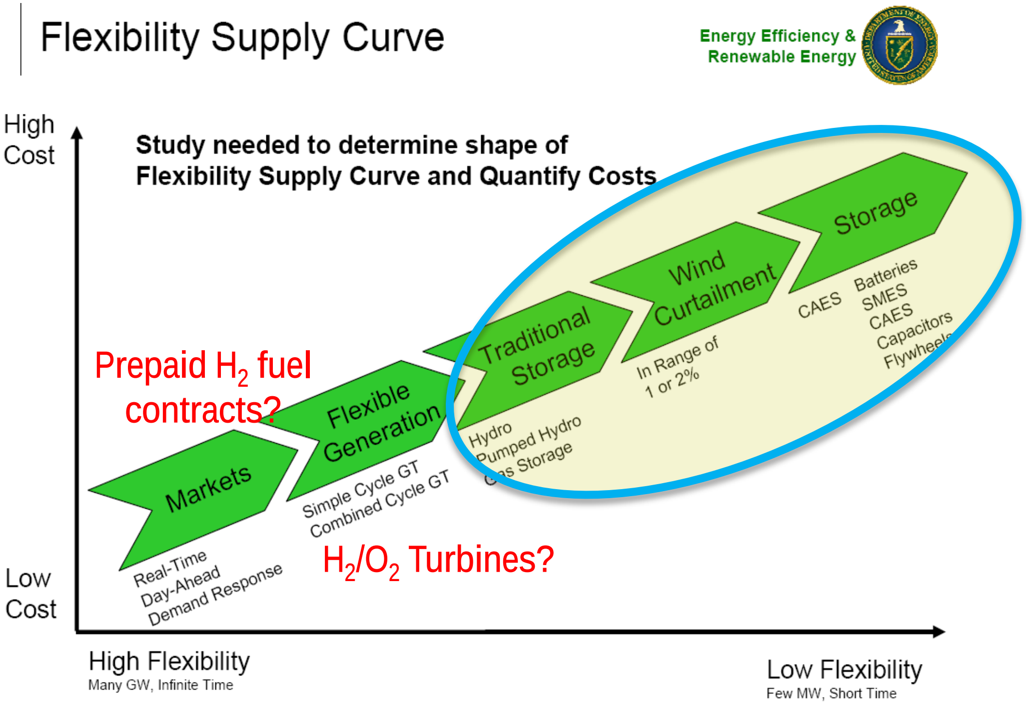
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

89 MW Natural Gas plant

Plant	= 17,000 m^2	190 m^2/MW
Ponds	= 30,000 m^2	340 m^2/MW
Total	= 170,000 m^2	530 m^2/mW

Managing Expectations

- **Utility Owner's focus on cost**
  - **Consumers: resilience, reliability & cost of outages or poor quality electricity**
- **Storage is one of the last options for supporting the electric grid**



Soirce: "Wind Dispatchability and Storage: Interconnected Grid Perspective, presentation by Barry Nickell, http://old.nationalwind.org/pdf/Nickellstoragestory-Public.pdf

Task	Period
Output smoothing	Intermittent ~ second
Load-levelling	Daily 4-12 h Weekly 40-60 h Seasonal 3 month
Peak Shaving	180-10000 s
Spinning reserve	30-300 s
Voltage stabilisation, frequency regulation	0.5-120 s
Countermeasure against supply disruption	0.12-0.2 s
Improvement of stability	0.02-0.2 s

H_2 Storage

FC/Electrolyzer

Source: European Wind Energy Association, "Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations," Table 13, pp. 104, December 2005, www.ewea.org/fileadmin/ewea_documents/documents/publications/grid/051215_Grid_report.pdf

In 2011, U.S. consumed 3,856 TWh of electricity (10.5 TWh/day).

Source: U.S. Energy Information Administration

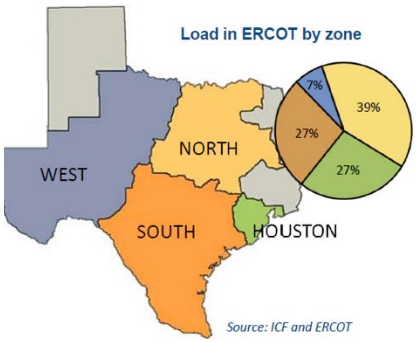
Storage amounted to ~23 GW, at ~24 hours ~ 550 GWh (4% is ~30 M kg H_2).

Source: Electricity Advisory Committee, "Energy Storage Activities in the United States Electricity Grid," Mayy 2011.

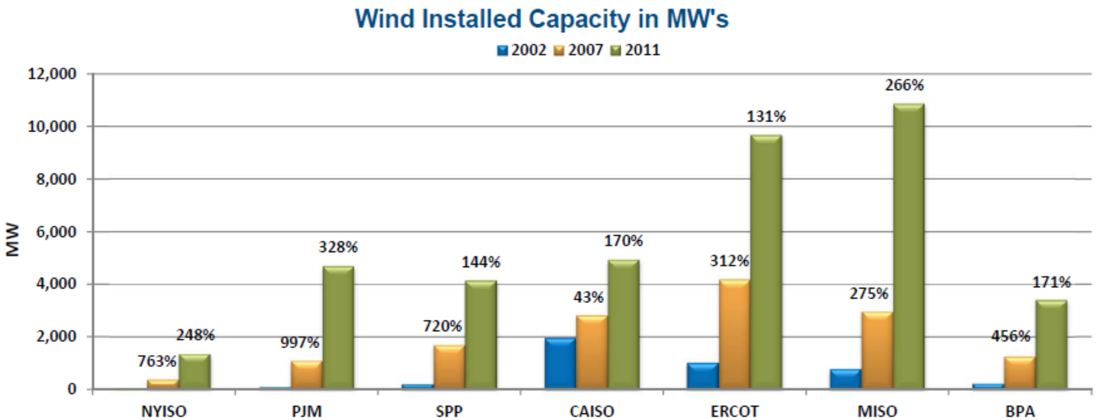
Curtailed Wind: 10% assumption is too low

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

- Wind growth has been rapid ('07-'11)
  - NYISO, PJM, MSIO more than 250%, SPP, CAISO, ERCOTT, BPA ~150%
- ERCOTT has ~2500GWh/ yr curtailed
  - Western portion generation, eastern portion demand
  - Transmission under construction, Dispatchable Intermittent Resources will alleviate this

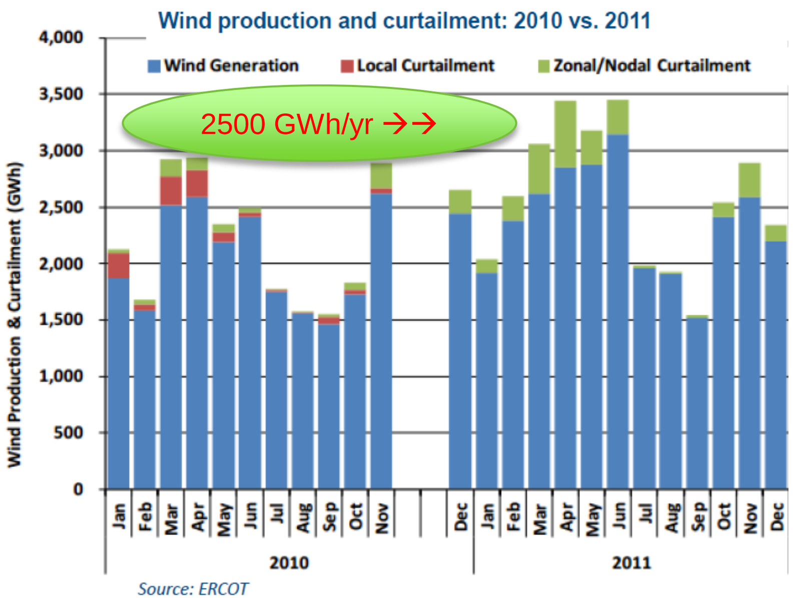


Wind production in ERCOT tripled from 2007 to 2011
Total curtailments increased in each year from 2008 to 2011



Source: SNL

U.S Total Installed Capacity of Wind in the year 2002 : **4,822 MW**
U.S Total Installed Capacity of Wind in the year 2007 : **17,135 MW**
U.S Total Installed Capacity of Wind in the year 2011 : **46,440 MW**
Growth rates shown for each region is % growth from the previous reported year.



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

Hydrogen technologies could provide many ancillary services for grid stability
Barriers remain: further technical validation and monetizing value to the grid through market mechanisms (FERC, CA Energy Commission)

	Backup Power (In aggregate)	Tri Gen. (waste-water/sofc -mcfc)	Stationary PEM	Electrolyzers	Bulk H_2 Storage 10MW (4 to 168 hr)	Vehicle+ Fuel Demand (100 to 1000 kg/d)
	5-10 kW	1-3MW	1-10MW	1-10MW	1-6MWh	3-33MWh
Spinning/Non-Spinning Reserves	✓	✓	✓	✓		TBD
Load Leveling (storage)	TBD		✓	✓	✓	
Peak Shaving (gen)			✓	✓		
Voltage Stabilization	TBD	TBD	TBD	TBD		
Frequency Regulation	TBD		✓	✓		
Black Start	TBD	TBD	TBD			
T&D Deferral	TBD		TBD		✓	
Resilience/ Backup Power	✓	TBD	✓	✓		TBD