Comparison of Electrical Energy Storage Options

Presented to the
Hydrogen Technical Advisory Committee
Washington, DC NREL Offices
November 15, 2012

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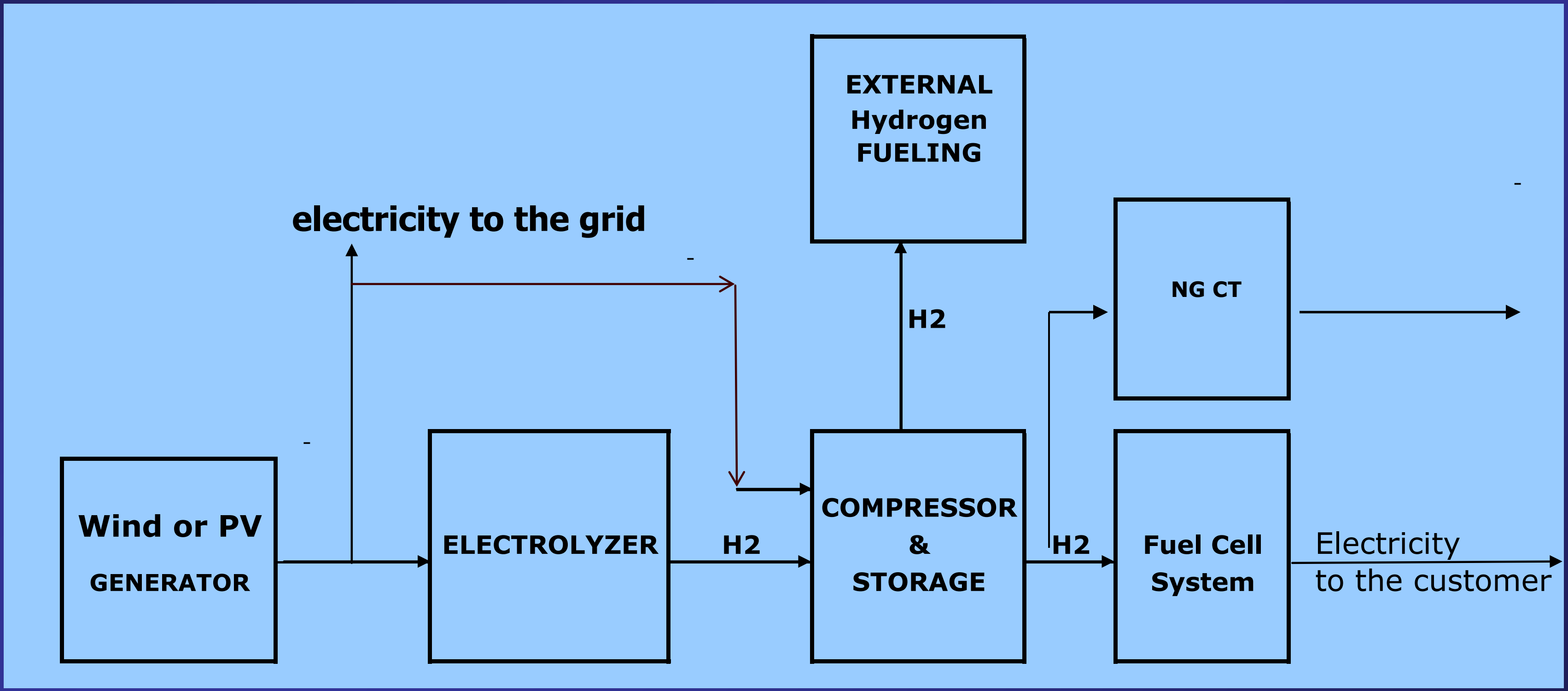
Intermittent Renewable Electricity Sources Require Storage at times due to

- Limited Electric transmission capability
- Insufficient electrical loads
- To reduce the environmental impact of burning fossil fuels (Mainly natural gas) to firm intermittent renewable sources

Electrical Energy Storage Options include

- Pumped Hydro (not considered here)
- Batteries
- Compressed Air Energy Storage (CAES)
- Hydrogen storage

Hydrogen Storage System



electricity to the grid

EXTERNAL Hydrogen FUELING

NG CT

H2

Wind or PV GENERATOR

ELECTROLYZER

H2

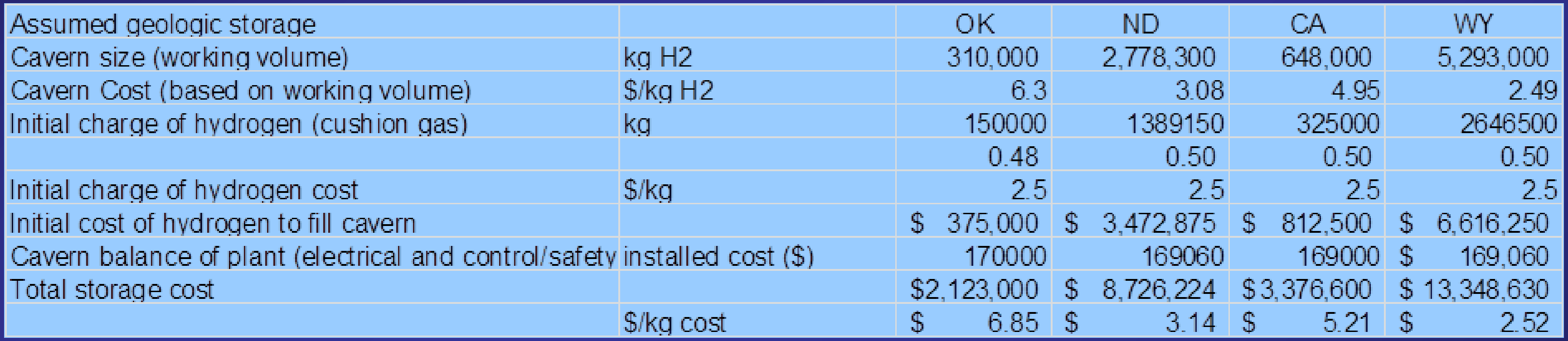
COMPRESSOR & STORAGE

H2

Fuel Cell System

Electricity to the customer

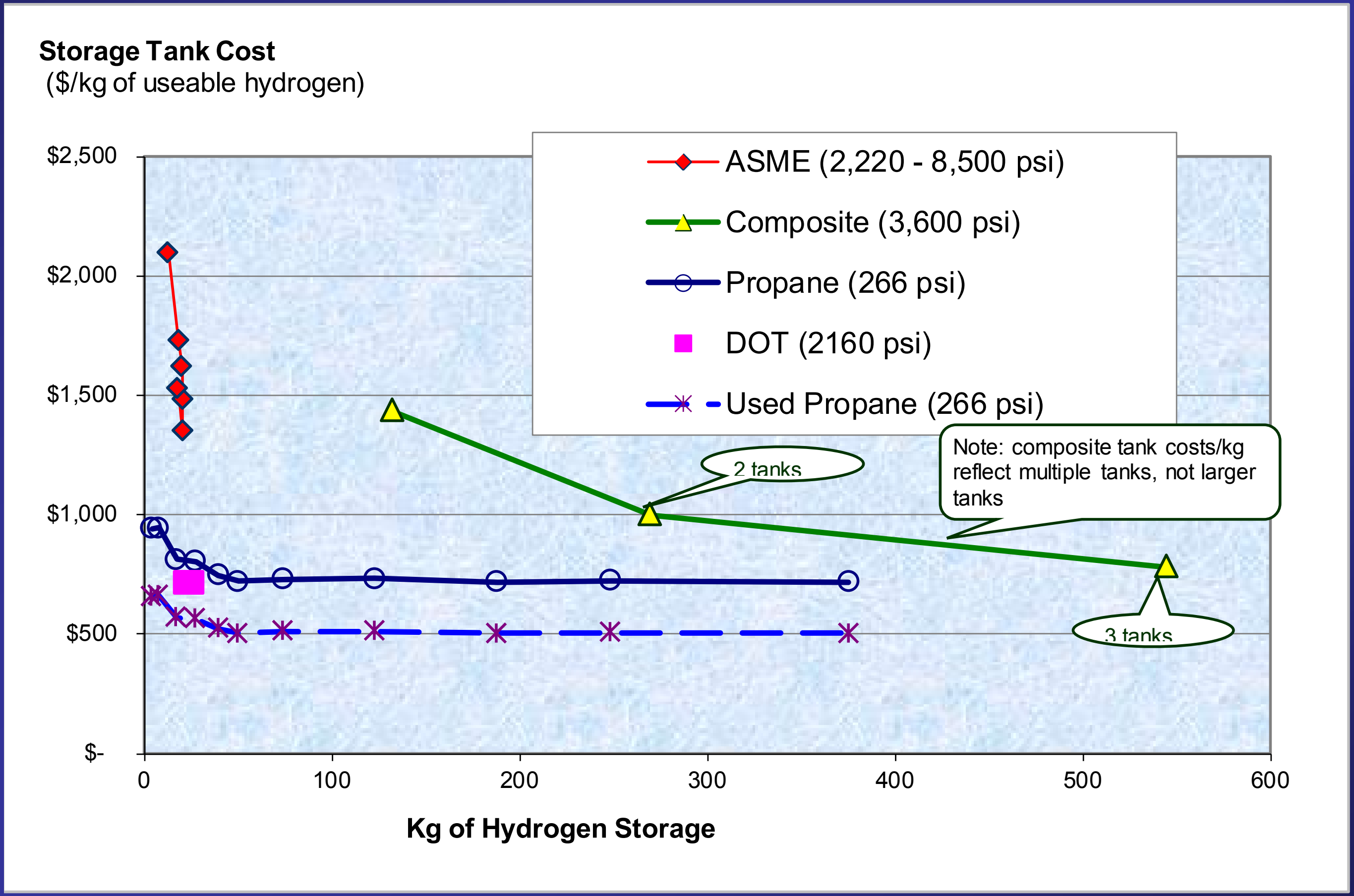
NREL Underground H2 Storage Costs



Assumed geologic storage		OK	ND	CA	WY
Cavern size (working volume)	kg H2	310,000	2,778,300	648,000	5,293,000
Cavern Cost (based on working volume)	$/kg H2	6.3	3.08	4.95	2.49
Initial charge of hydrogen (cushion gas)	kg	150000	1389150	325000	2646500
		0.48	0.50	0.50	0.50
Initial charge of hydrogen cost	$/kg	2.5	2.5	2.5	2.5
Initial cost of hydrogen to fill cavern		$ 375,000	$ 3,472,875	$ 812,500	$ 6,616,250
Cavern balance of plant (electrical and control/safety	installed cost ($)	170000	169060	169000	$ 169,060
Total storage cost		$2,123,000	$ 8,726,224	$ 3,376,600	$ 13,348,630
	$/kg cost	$ 6.85	$ 3.14	$ 5.21	$ 2.52

Source :Darlene Steward, the National Renewable Energy Laboratory

Above Ground H2 Storage Costs



Note: composite tank costs/kg reflect multiple tanks, not larger tanks

H2 Storage Tank Costs.XLS; I85 10/12 /2

Battery Cost Data for 50- to 100- MW storage systems*

Although Zn/Air is in the R&D stage and is not commercially available

EPRI paper shows that Zn/Air may be the lowest cost option in the long-run

			$/kWh			
		gh	Low	Hig		
[illegible]	[illegible]	1590	425	475	90%	85%
Zn /Br	[illegible]	1750	290	35	60%	60%
Fe/Cr	1800	1900	360	380	75%	75%
Zn/Air	1440	1700	290	340	75%	75%
NaS	3100	3300	520	550	75%	75%
CAES-Above	800	900	200	240	90%	90%
CAES-below	640	730	1	2	90%	90%
Li-Ion	1085	1550	900	1700	92%	87%

From EPRI: D. Rastler, "Electricity Energy Storage Technology Options" a white paper primer on applications, costs & benefits, Electric Power Research Institute, 1020676 (2010); Li-Ion data are for energy storage for Utility T&D support applications (EPRI estimates for Li-ion for megawatt-scale for ISO fast response and renewables integration are even higher at $4,340/kWh to $6,200/kWh.)

Hydrogen/FC System cost & Efficiency assumptions

	Near- term	medium-term	Long-term
Electrolyzer HHV efficiency*	79.3%	81.7%	87.7%
Electrolyzer Capex**	$1500 /kW	$1000 /kW	$380 /kW
Compressor efficiency	92%	92%	92%
Compressor Capex ($/kg/day)	232	232	232
FC HHV efficiency	39.7%	44.8%	49.0%
FC capex***	$1000 /kW	$750 /kW	$500 /kW
H2 (above ground) tank capex	$807 /kg	$760 /kg	$700 /kg
H2 Dispenser Capex	$ 75,000	$ 60,259	$ 50,216

* Norsk Hydro 50.7 kWh/kg = 77.7% HHV eff.; Giner/ProtonOnsite: 88.9%

** NREL Independent Panel Review; (BK-6A1-46676; Sept 2009)

***DOE Targets: $750/kW (2008); $650/kW (2012); $550/kW(2015); $450/kW (2020)

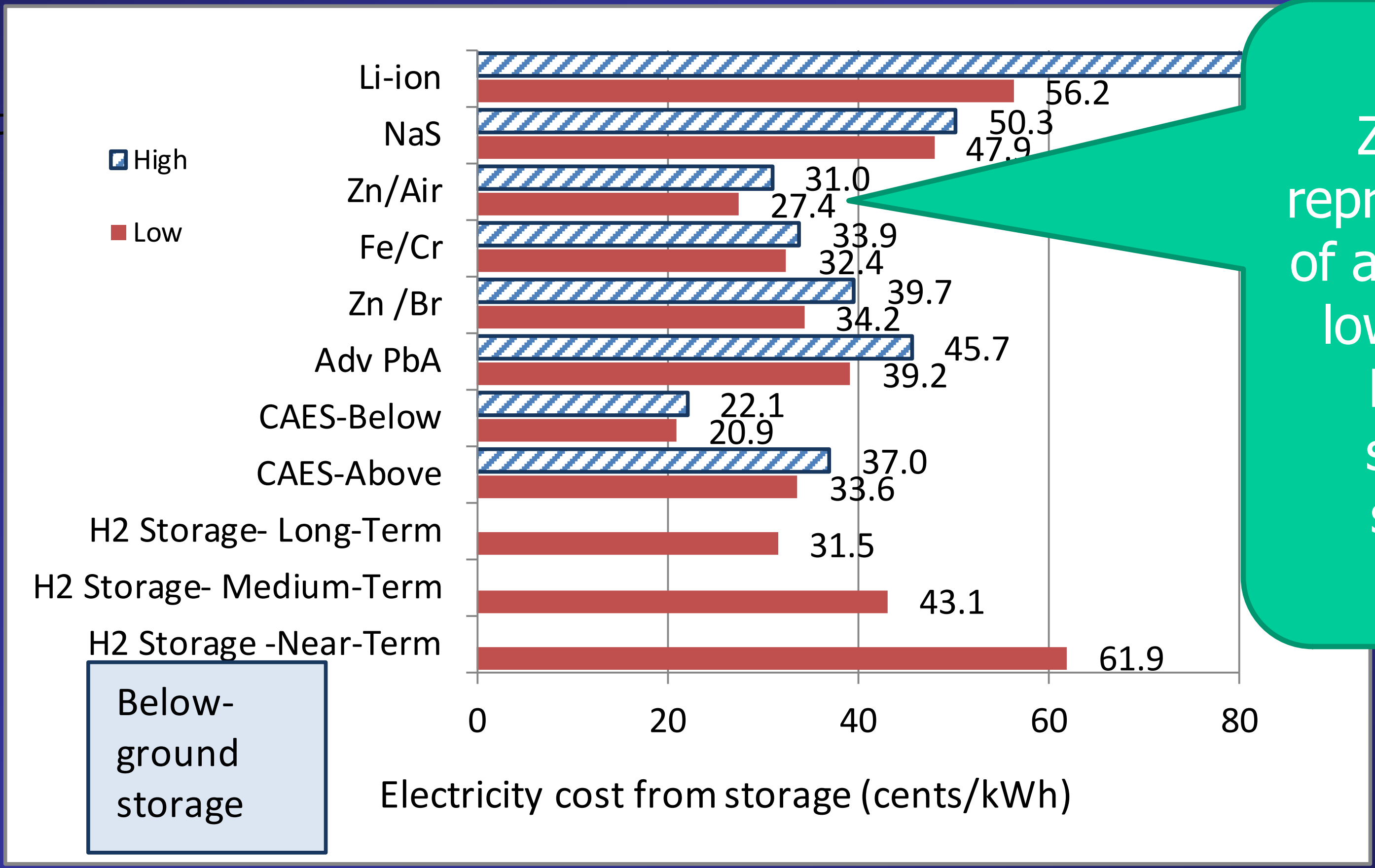
HTAC ERWG simple model EPRI (Rev 10-9-12 -25MW).XLS, WS Assumptions D15;10/12

O&M and Replacement cost Assumptions

	Replacement Costs		
	Replacement Interval	Fraction Replaced	Annual O&M
	(Years)		(% of Capex)
Electrolyzer	7	25%	2.18%
Compressor	10	100%	2.50%
Storage System			0.02%
Fuel Cell System	15	30%	2.00%
Dispenser System			0.90%

HTAC simple model EPRI (Rev 10-9-12--25MW).XLS, WS 'O&M' D-13;11/11

Cost of Stored Electricity for one day's storage
(below-ground hydrogen storage)

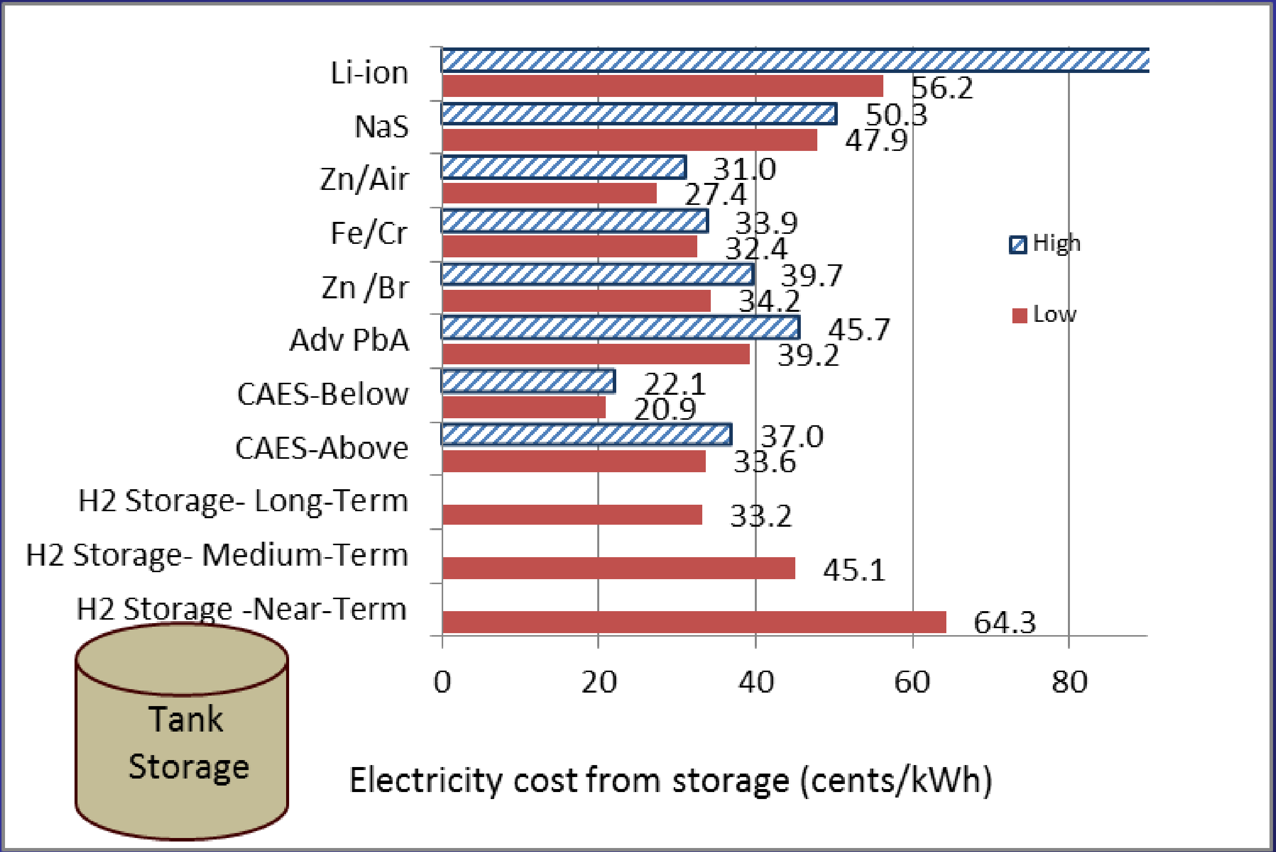


Zn/air is representative of a projected lowest cost Battery storage system

HTAC simple model EPRI(Rev10-9-12-25MW).XLS, WS 'DashBoard' AM-315;11/1

Wind energy purchased at 5.4 cents/kWh;
Natural Gas at $7/MBTU (needed for CAES systems)

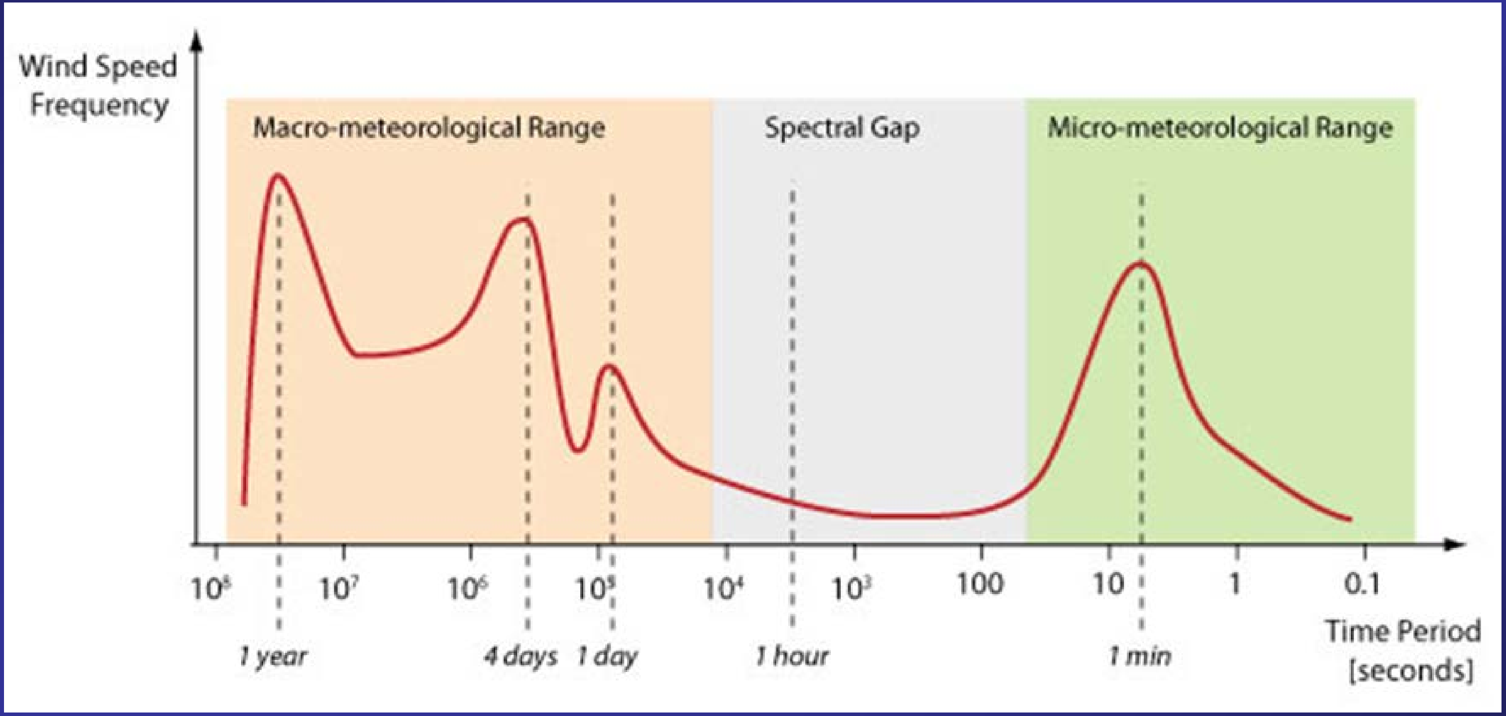
Cost of Stored Electricity for one day's storage (Above-ground hydrogen storage)



Natural Gas at $7/MBTU (needed for CAES systems)

Wind Spectral Data

(Peaks at one day; four days & one year)



Source: Green Rhino Energy

http://www.greenrhinoenergy.com/renewable/wind/wind_characteristics.php

Seasonal Wind Energy production in Lake Benton, Minnesota- (104 MW)

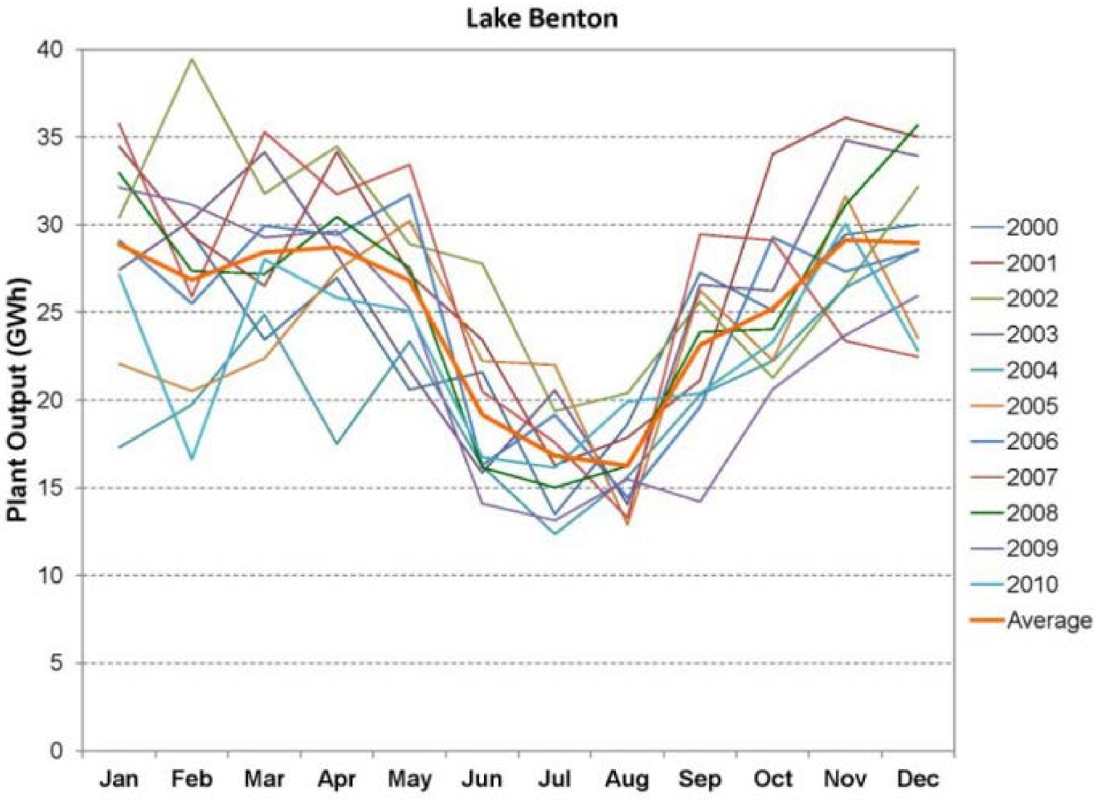


Figure 3. Monthly wind energy production from Lake Benton

Winter average energy is 1.64 times average Summer Energy

Source: Y. H. Wan, "Long-term Wind Power Variability", Report # NREL/TP-5500-53637, January 2012

Seasonal Wind Energy production in Blue Canyon, Oklahoma- (75 MW)

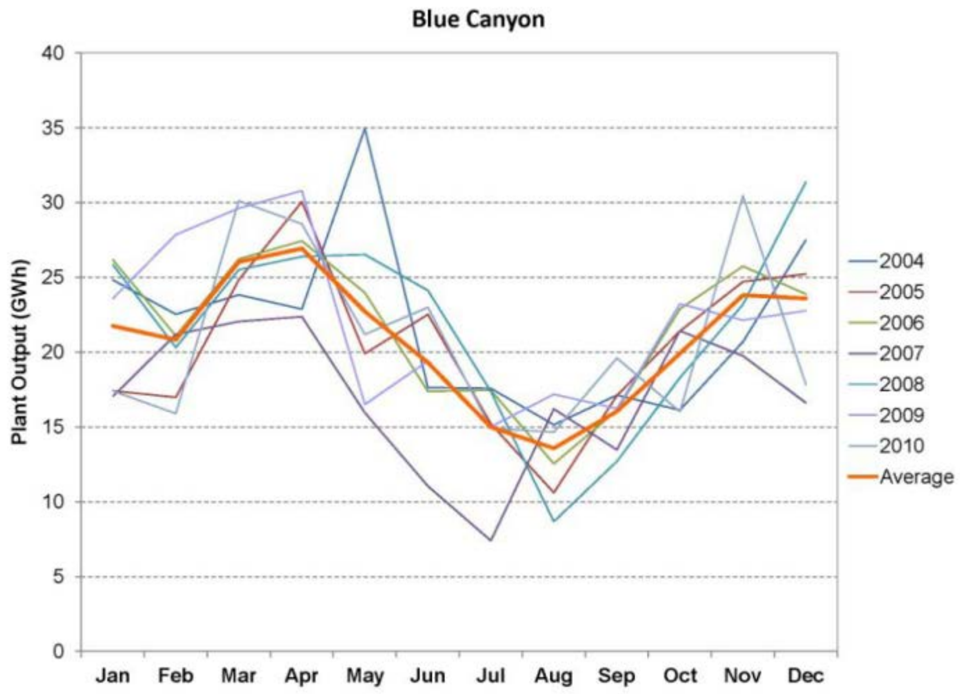


Figure 5. Blue Canyon monthly production

Winter average energy is 2 times average Summer Energy

Source: Y. H. Wan, "Long-term Wind Power Variability", Report # NREL/TP-5500-53637, January 2012

Seasonal Wind Energy production in Storm Lake, Iowa- (113 MW)

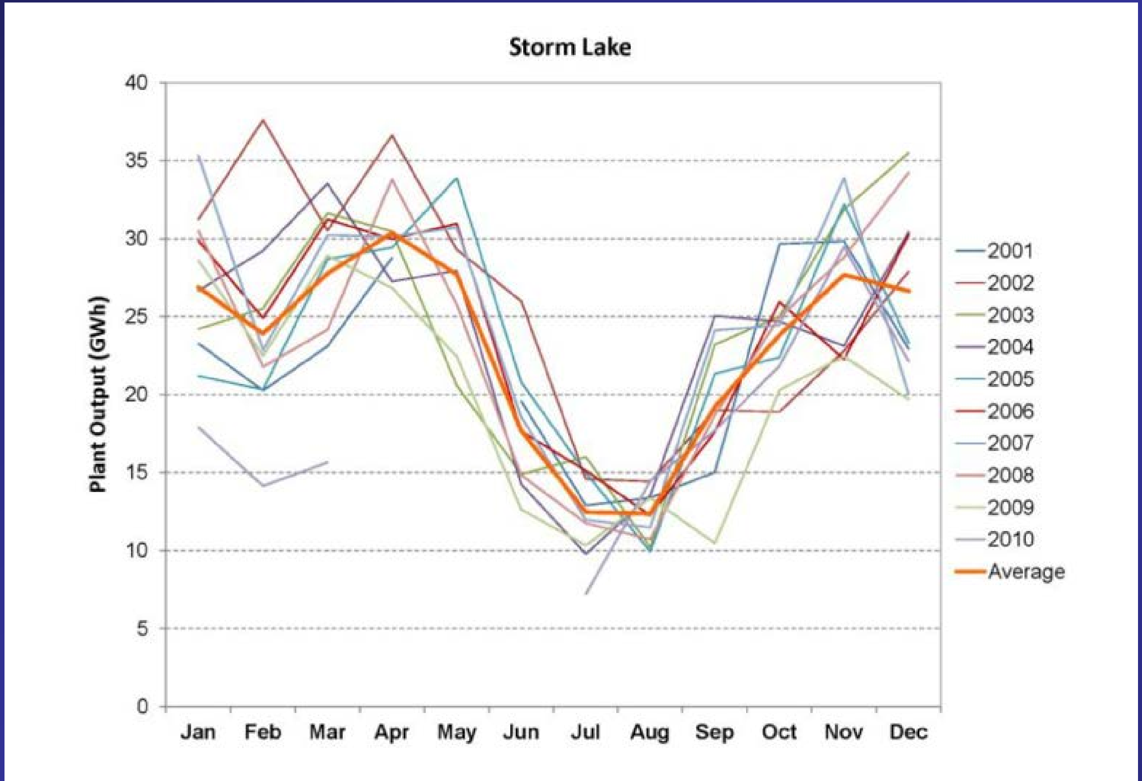


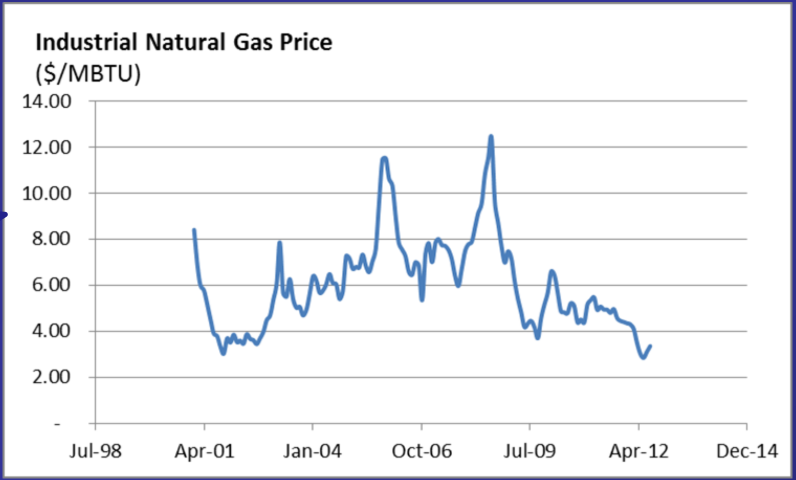
Figure 4. Storm Lake monthly production

Winter average energy is 2.4 times average Summer Energy

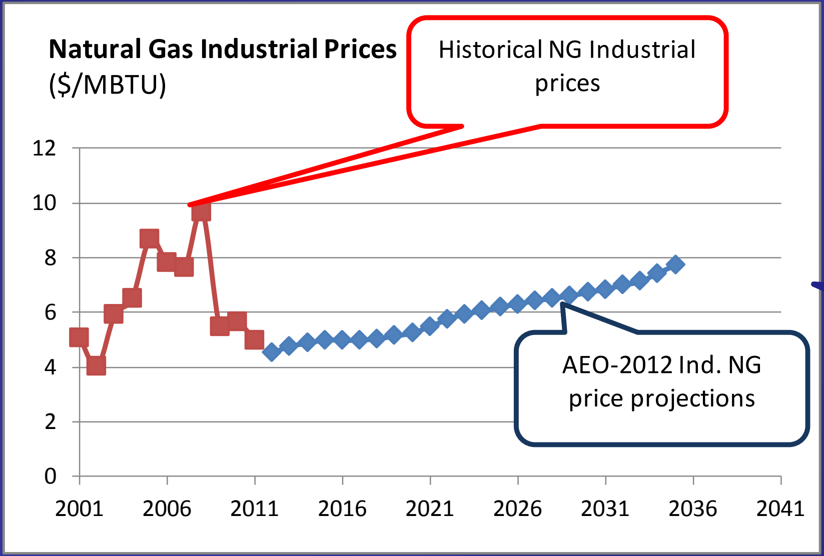
Source: Y. H. Wan, "Long-term Wind Power Variability", Report # NREL/TP-5500-53637, January 2012

Industrial Natural Gas Prices

Monthly NG Prices



Industrial Natural Gas Price
($/MBTU)



Natural Gas Industrial Prices
($/MBTU)

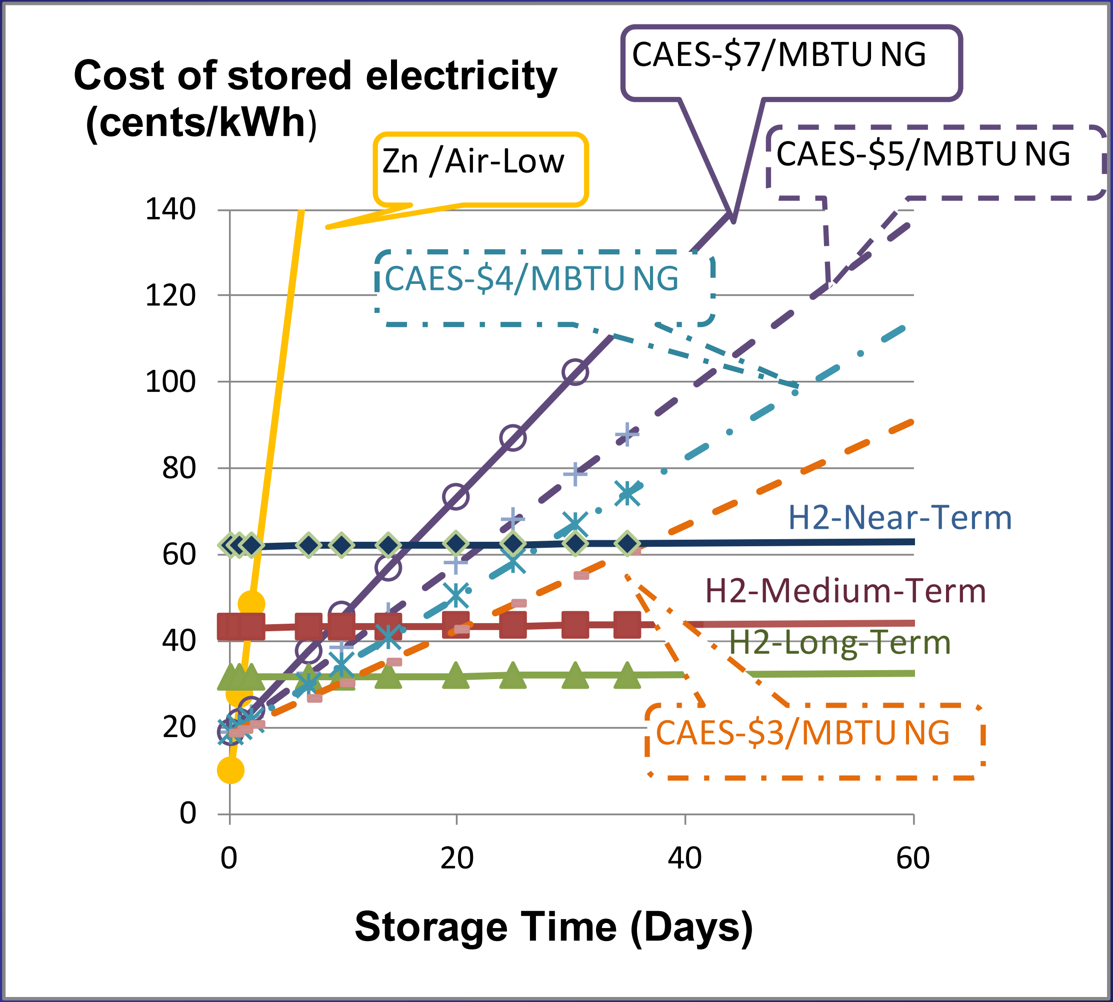
Historical NG Industrial prices

AEO-2012 Ind. NG price projections

Annual Prices & AEO projections

Story Economics.XLS; Tab 'AEO 2012 Fuel costs'; - 40 10/5 /2012

CAES cost depends on Natural Gas cost



HTAC_simple model EPRI (REV 7-5-12-Energy only).XLS, WS 'DashBoard' AH-410:11/11

Acknowledgments

- HTAC Enabling Renewables Subcommittee members*:
  - **Frank Novachek**, Chairman-Xcel Energy
  - Darlene Steward-NREL
  - Charlie Freese-GM
  - Daryl Wilson-Hydrogenics
  - Rob Friedland- Proton Onsite
  - Robert Shaw – Arête
  - Todd Ramsden-NREL
  - George Sverdrup- NREL (ret.)
  - Fred Joseck- DOE EERE
  - Hal Koyama – Idatech
  - Levi Thompson -U. of Michigan
  - Jason Marcinkoski- DOE EERE
  - Peter Bond – Brookhaven Nat'l Lab
  - Maurice Kaya – Hawaii Renewable Energy Development Venture

*While subcommittee members contributed to much of the information is this presentation, they have not endorsed the conclusions presented here, which are the sole responsibility of the author.

Disclaimer: EPRI has neither reviewed nor endorsed the conclusions of this presentation.

Storage Volume Required

Energy Storage Volume: German Case Study:

Storage Volume required for:

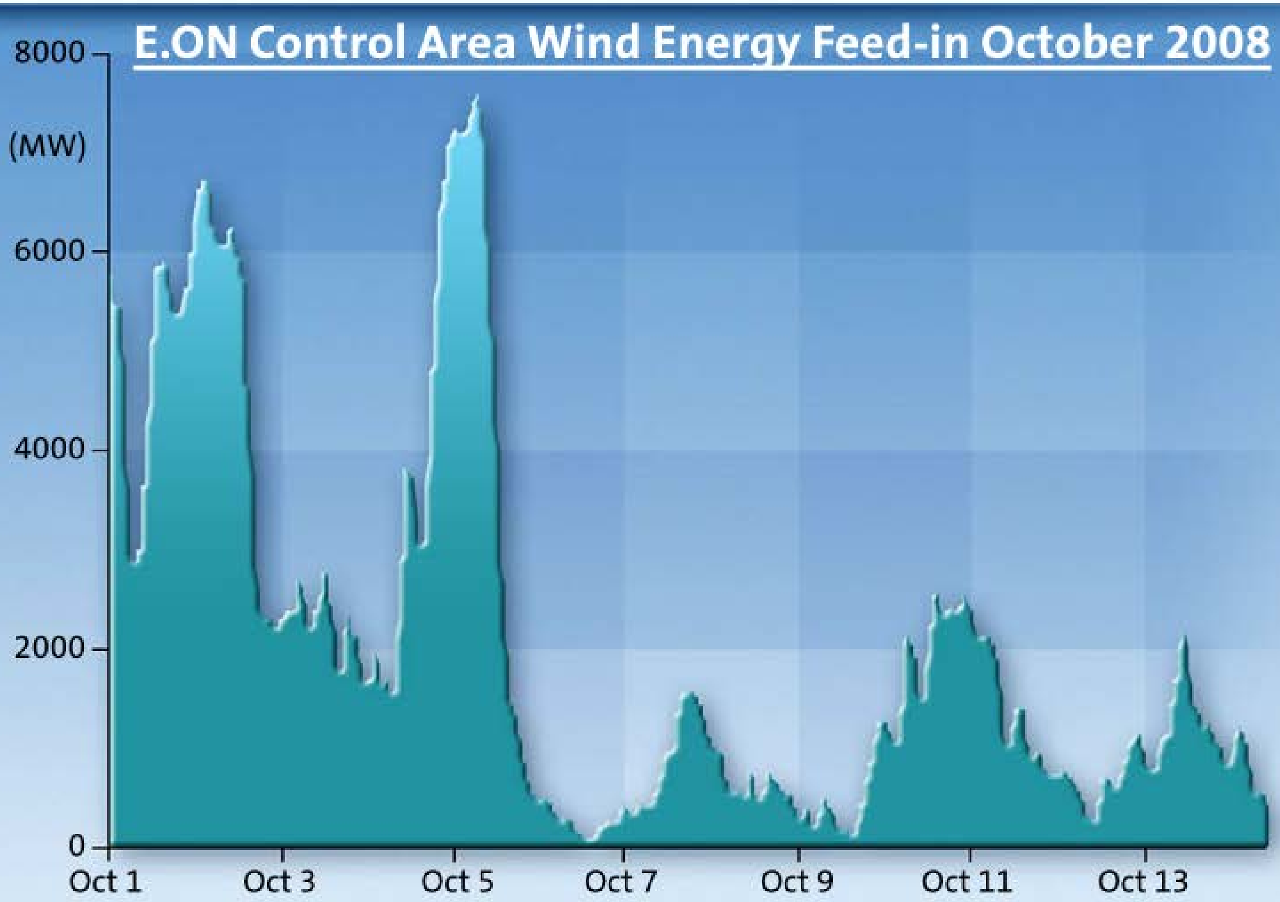
- Pumped hydro
- CAES
- Hydrogen

Source: Charlie Freese (GM) : “GM Powertrain Strategy- Electrification of the Vehicle” Hydrogen conference, April 1, 2009

Case Study

Sustainables & Fluctuating Energy Availability

E.ON Control Area Wind Energy Feed-in October 2008



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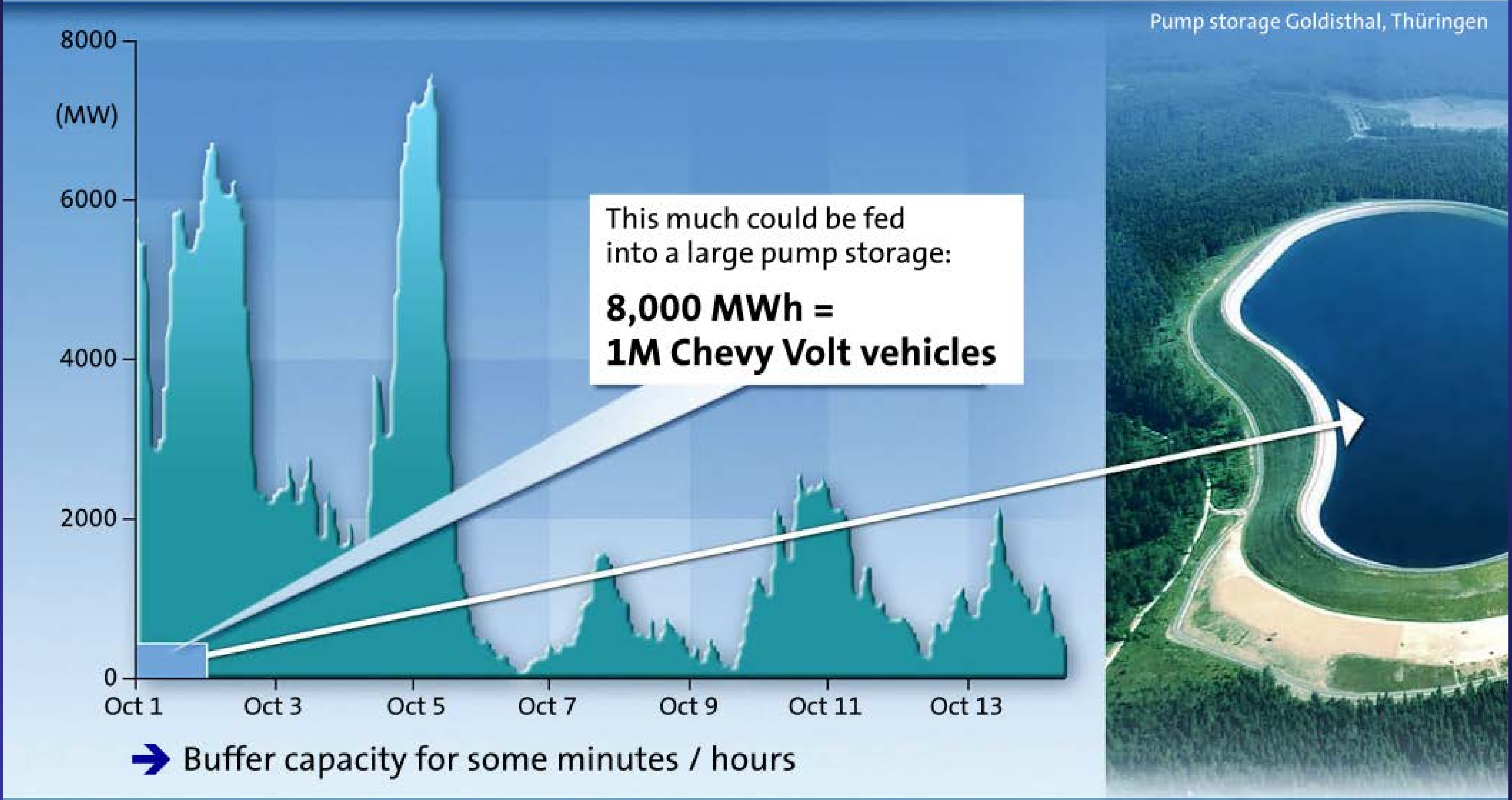
Fluctuating Wind Energy

Compared to Conventional Pump Storage Capacity



Pump storage Goldisthal, Thüringen

This much could be fed into a large pump storage:

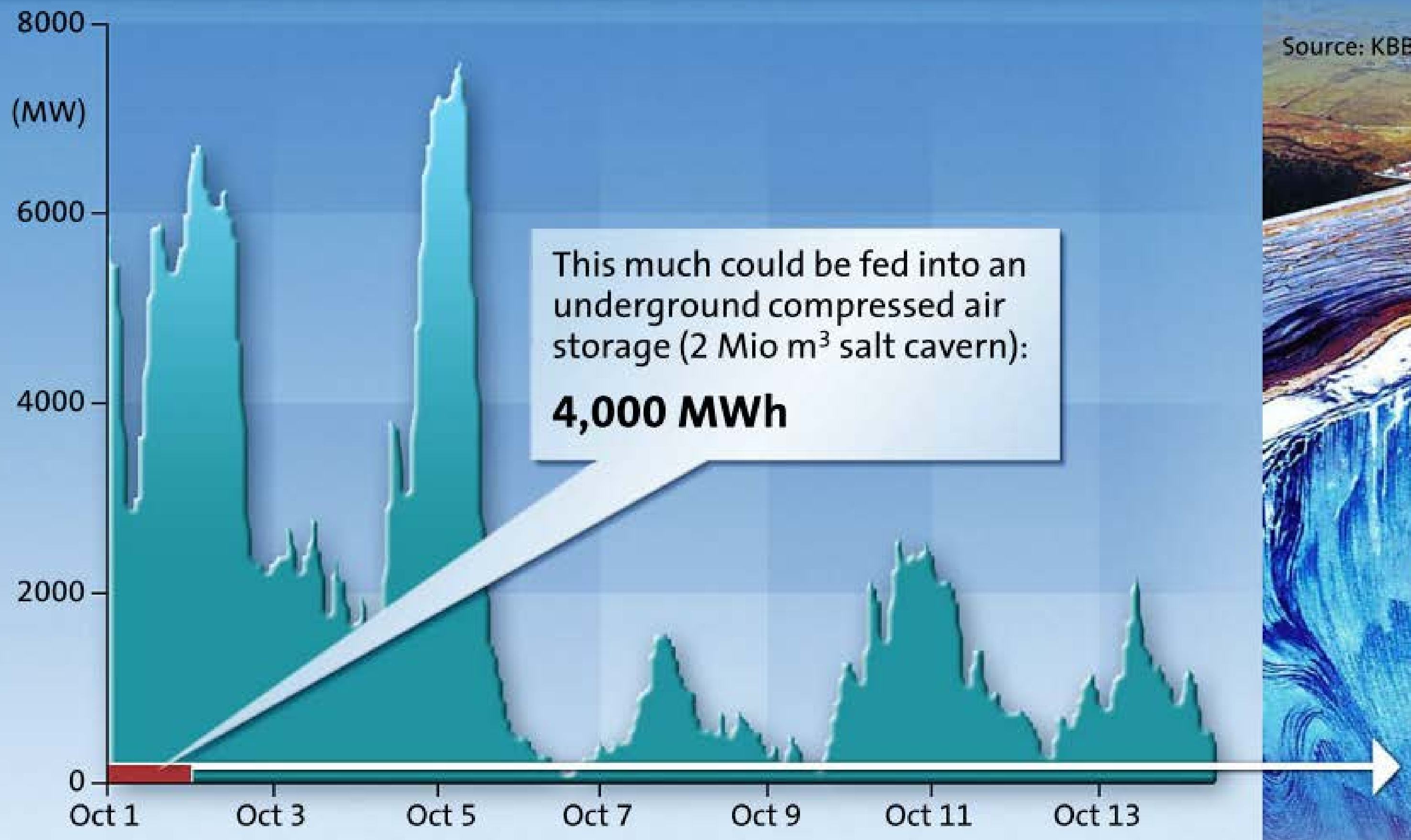
8,000 MWh =
1M Chevy Volt vehicles

→ Buffer capacity for some minutes / hours

Used with permission

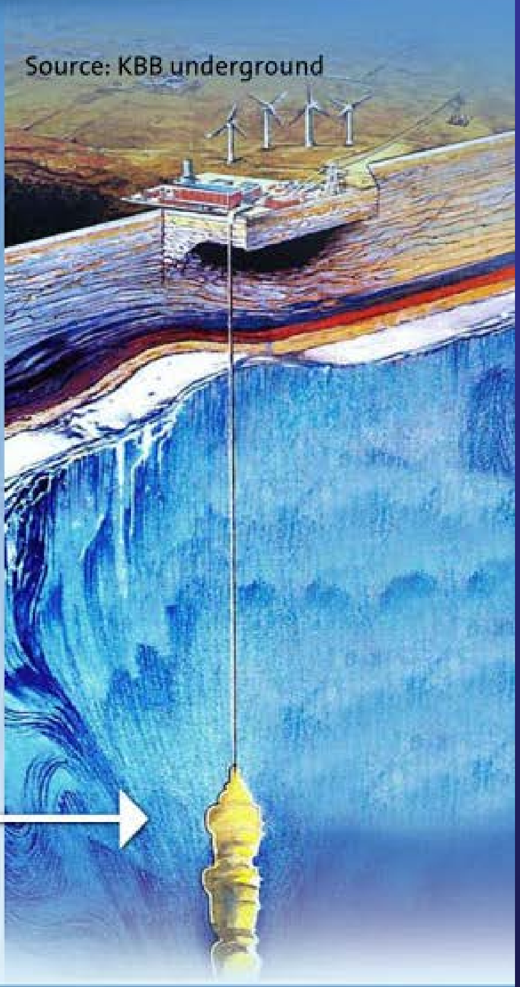
Store Fluctuating Wind Energy:

Storage of Compressed Air in Salt Caverns



This much could be fed into an underground compressed air storage (2 Mio m³ salt cavern):

4,000 MWh



Source: KBB underground

➔ Buffer capacity for some minutes / hours

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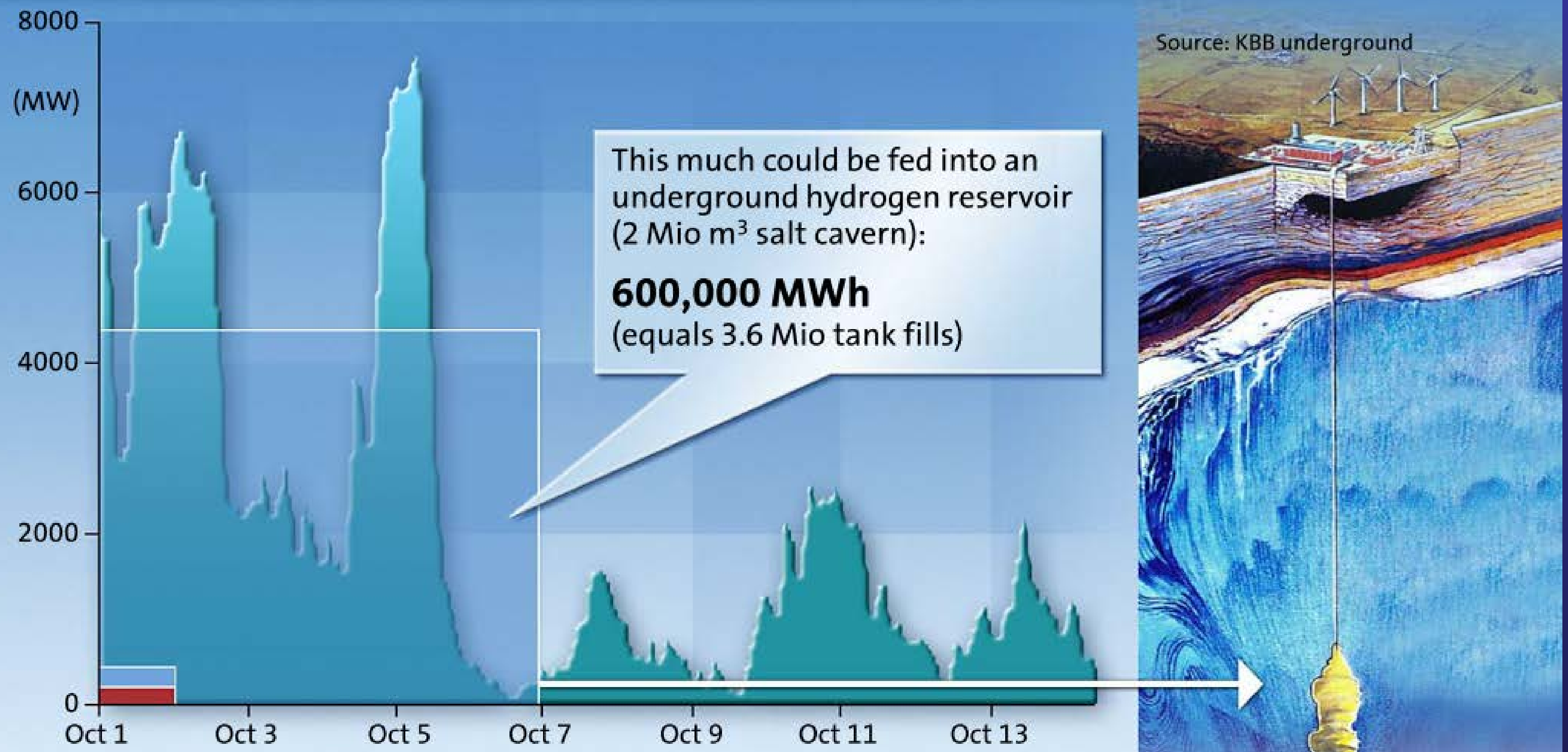
Hydrogen

The Energy Buffer in the Renewable Energy System



This much could be fed into an underground hydrogen reservoir (2 Mio m^3 salt cavern):

600,000 MWh

(equals 3.6 Mio tank fills)

Source: KBB underground

➔ Only hydrogen offers storage capacity for several days

Used with permission

Storage Potential

- Storage Energy Potential from:
- Pumped hydro – 8,000 MWh
- CAES- 4,000 MWh
- Hydrogen – 600,000 MWh

H2 = 75X

H2 = 150X

Future Advanced SOFC Systems

Capex projections

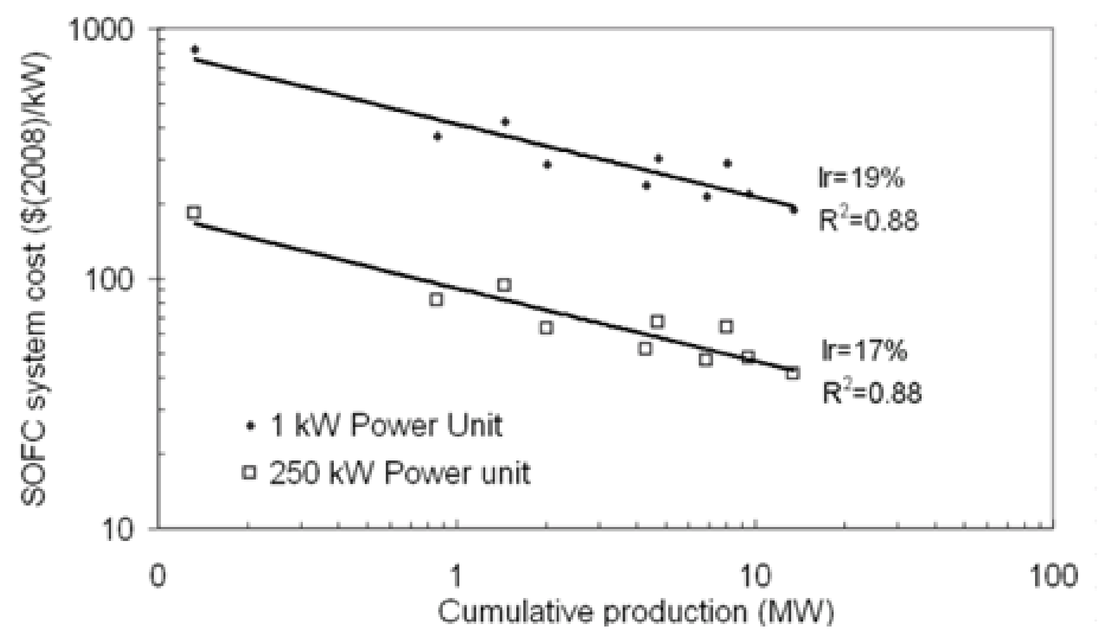
- FC capex projections:
  - $1,000/kW near-term
  - $750/kW mid-term
  - $500/kW long-term

Future SOFC Systems

- SA* Estimate: $700/kW
- HTAC subcommittee: $500/kW
- SECA** Goal: $400/kW
- ERCN*** Estimate: $150/kW

*SA = Strategic Analysis (Brian James et al. formerly from DTI);
**SECA = Solid State Energy Conversion Alliance;
***ERCN = Energy Research Center of the Netherlands

Long-Term SOFC Production Cost Estimate*



R. Rivera-Tinoco, K. Schoots & B.C.C. van der Zwaan, Learning Curves for Solid Oxide Fuel Cells (Energy Research Center of the Netherlands.), Figure 4; available at: http://www.energy.columbia.edu/sitefiles/file/Learning%20Curves%20for%20Solid%20Oxide%20Fuel%20Cells.pdf *(cost based on SOFC data from HC Starck, Topsoe & Versa)

Cost to Price Markup

- Labor
  - 20% of cost
  - 25% G&A
  - 40% OH
  - 15% profit
- Material
  - 80% of cost
  - 20% G&A
  - 15% Profit

Labor Markup:
0.2 x 1.25 x1.4 x1.15 =1.1

Material Markup:
0.8 x 1.2 x1.15 =0.4

Total markup = 1.1 +0.4 =1.5

SOFC Price:
$100/kW x 1.5 = $150/kW

Long-Term Electrolyzer Price

- Construction Cost: $213/kW*
- Electrolyzer Price: $213 x 1.5 = $320/kW

Long-Term Hydrogen Assumptions	Base Case	SOFC-Low	SOFC-High
FC Capex	$500 /kW	$150 /kW	$700 /kW
FC HHV Efficiency	49.0%	55.0%	55.0%
Electrolyzer HHV Efficiency	87.7%	87.7%	87.7%
Electrolyzer Capex	$380 /kW	$320 /kW	$320 /kW

HTAC simple model EPRI (Rev 10-9-12 -25MW).XLS, WS Assumptions D47;11/11

*Genovese, K. Harg, M. Paster, & J. Turner, Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis, NREL/BK-6A1-46676, September 2009

Additional Revenue to Storage system operator (CHHP)

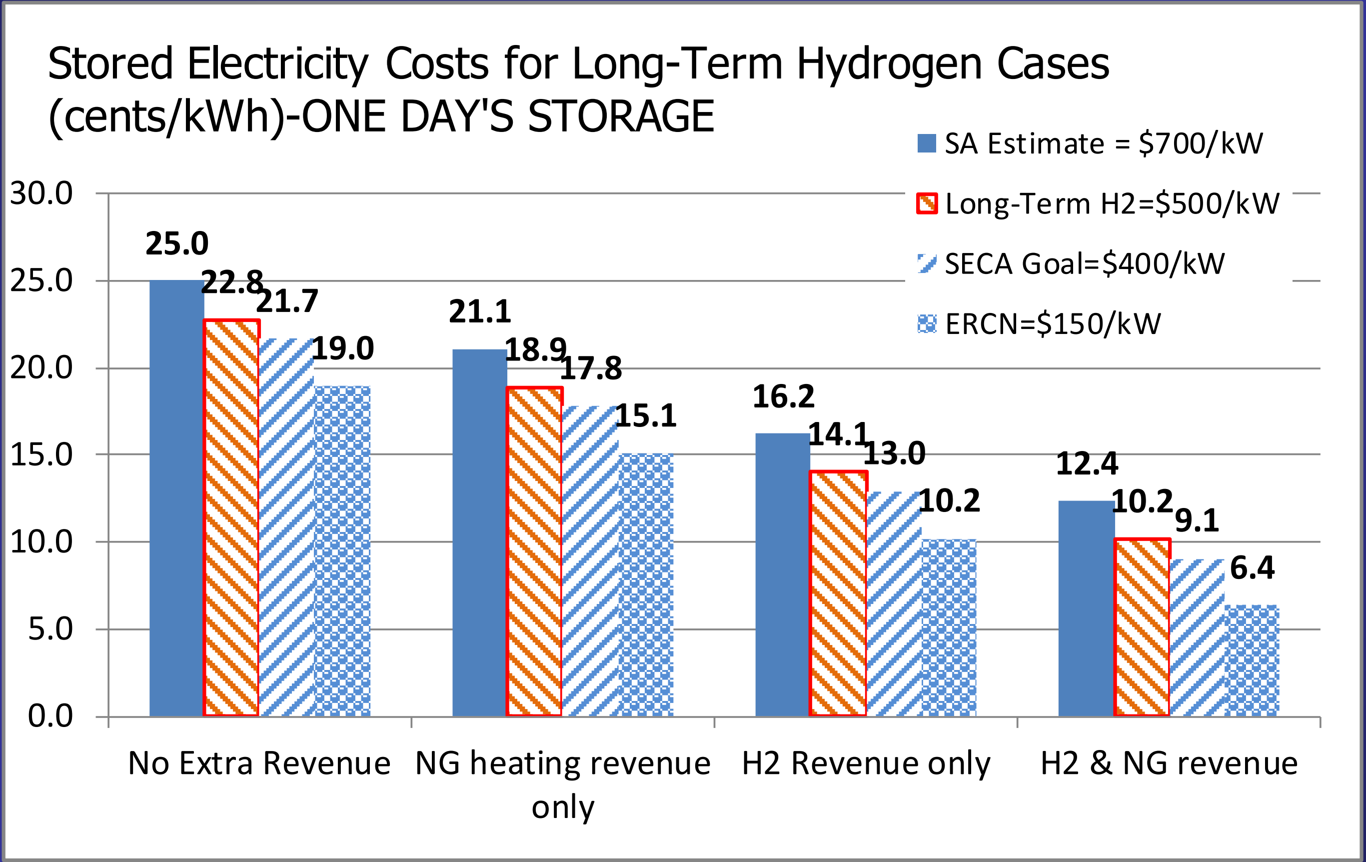
- Hydrogen Fuel (1530 kg/day* sold at a same price per mile as gasoline at $3.81/gallon untaxed with 50/50 split of HEVs and ICVs)
- Displacement of natural gas heating @ $6.30/MBTU using SOFC waste heat (30% heat recovery)

[Total efficiency = 30% + 55% = 85%]

* Assumes 13,000 miles/yr; 68.3 miles/kg; 300 cars/day; & 8 days average time between fill-ups.

Long-Term Stored Electricity Prices to Yield 10% ROI

(for one day's storage time)

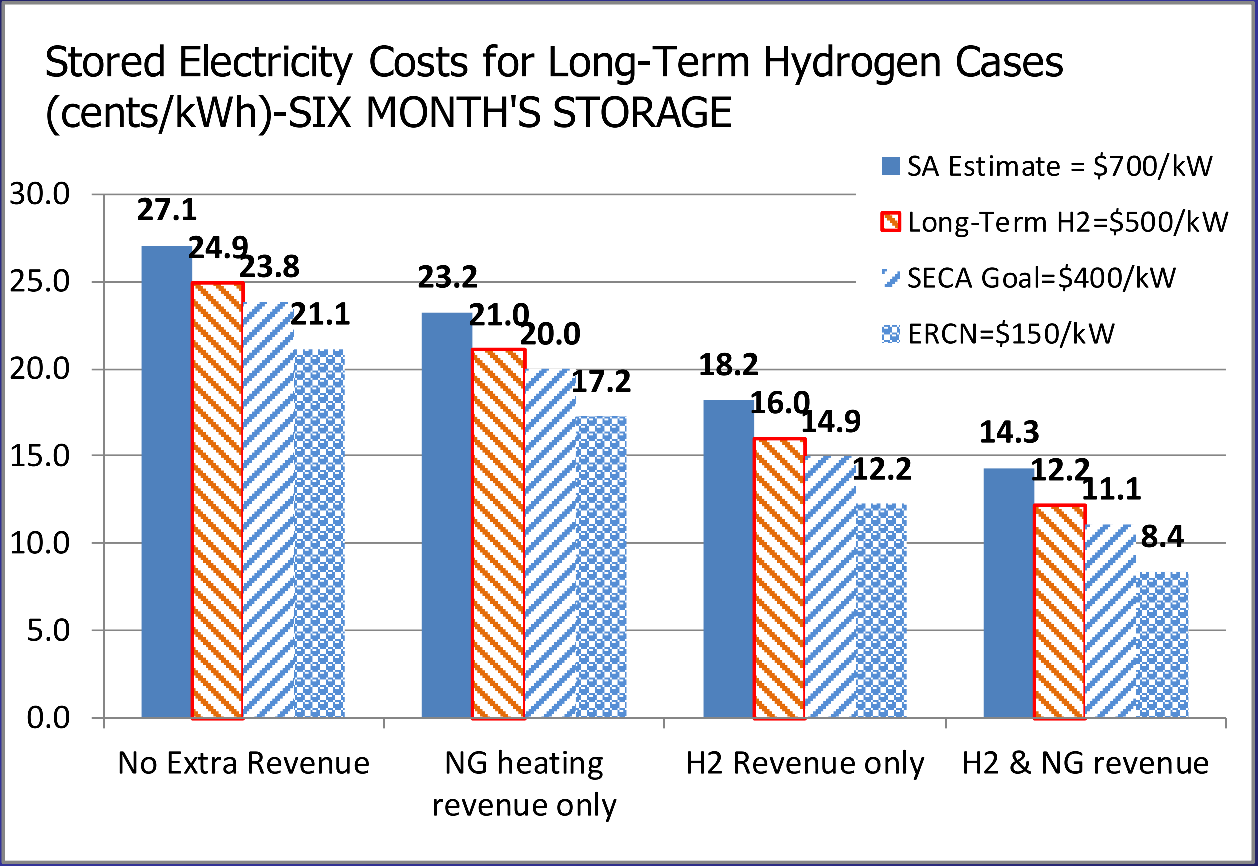


HTAC simple modelEPRI (Rev 10-9-12-25 MW).XLS, WS H2 Value T-46;11/11

SA = Strategic Analysis (Brian James et al. formerly from DTI);
SECA = Solid State Energy Conversion Alliance;
ERCN = Energy Research Center of the Netherlands

Long-Term Stored Electricity Prices to Yield 10% ROI

(for six month's storage time)

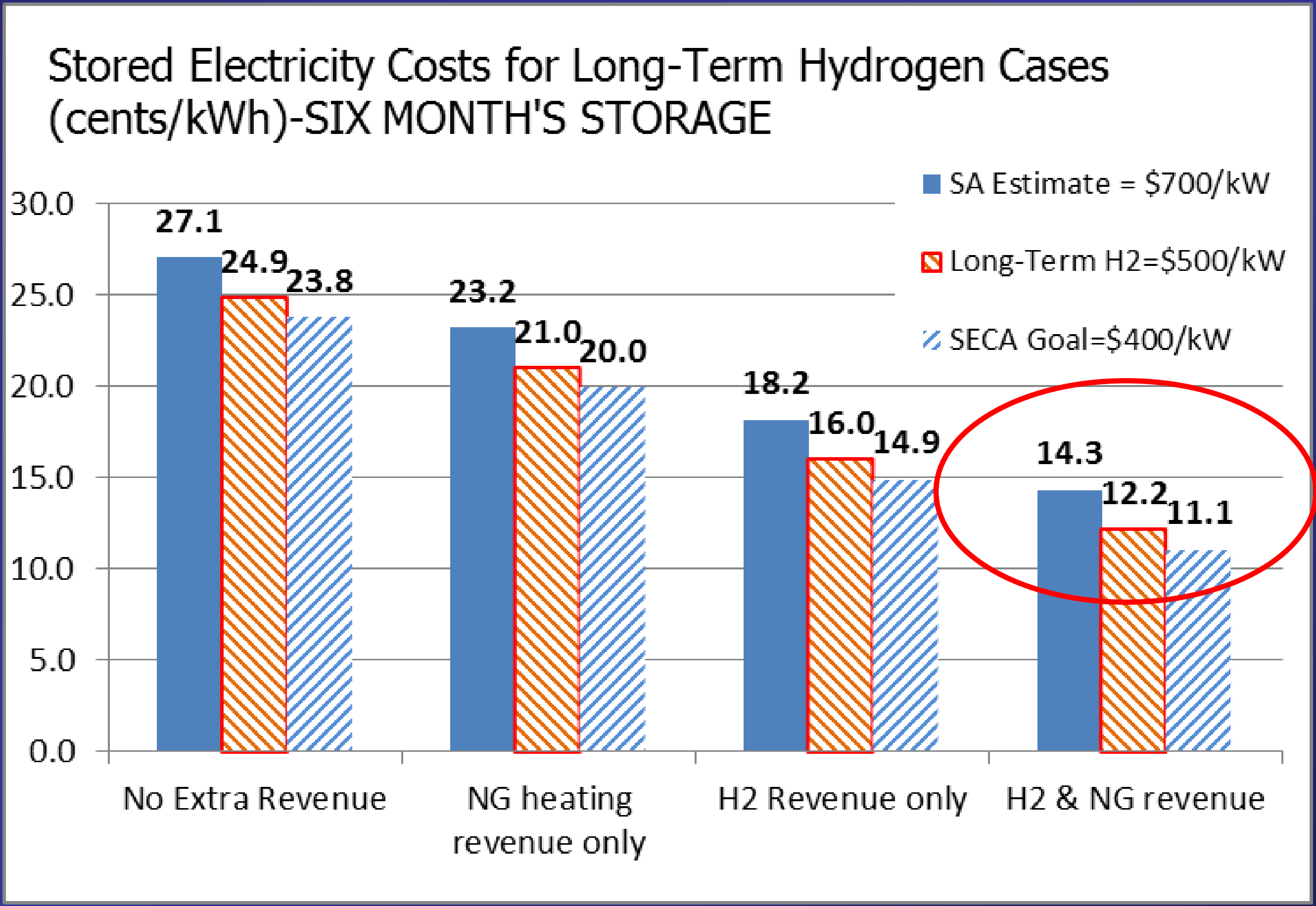


HTAC simple model SPRT (Rev 10-9-12-25 (vw)).XLS; WS H2 Value AA-46;11/11

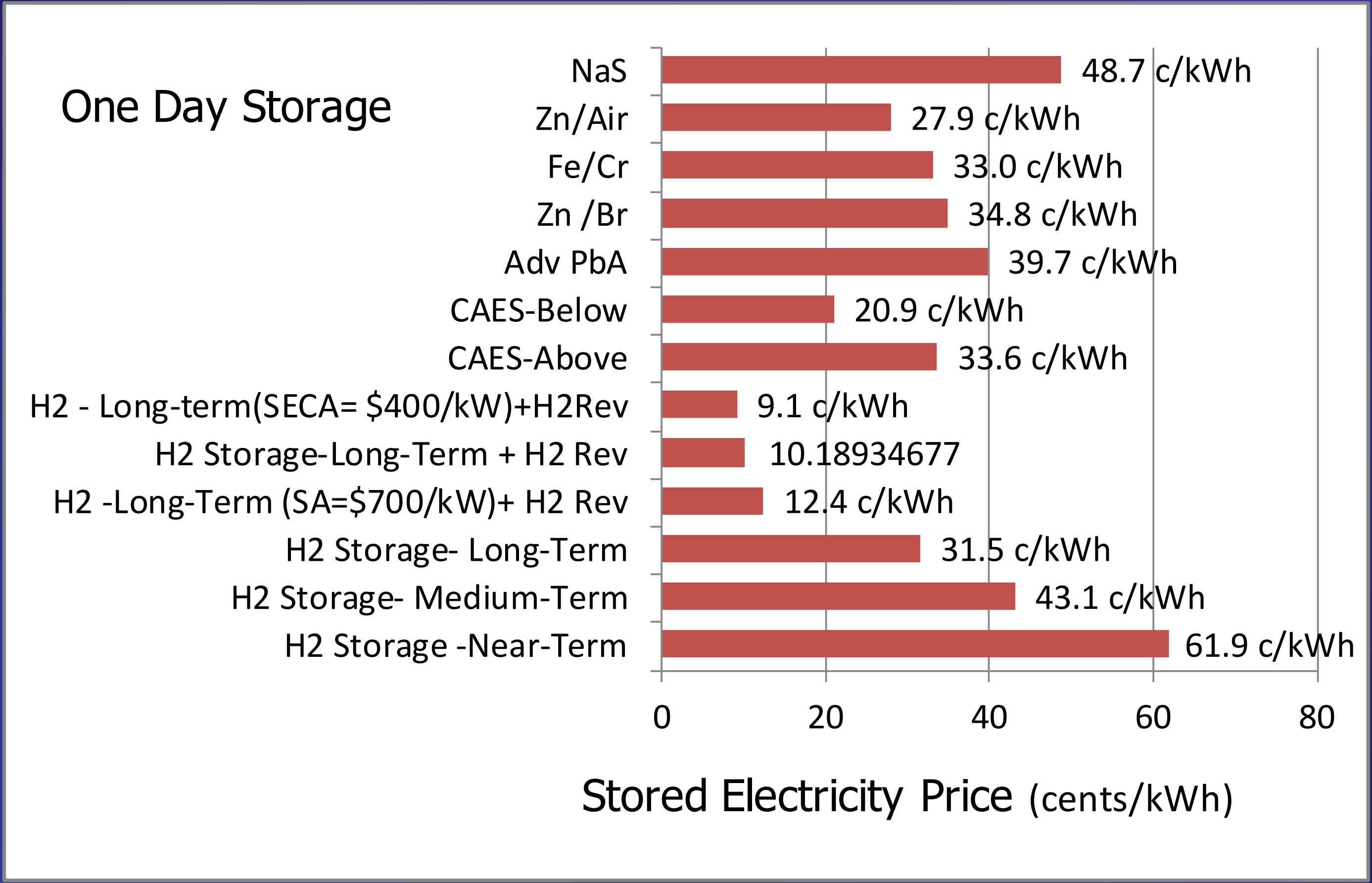
SA = Strategic Analysis (Brian James et al. formerly from DTI);
SECA = Solid State Energy Conversion Alliance;
ERCN = Energy Research Center of the Netherlands

Electricity Costs for SIX MONTH'S (SEASONAL) STORAGE

(without the $150/kW option)



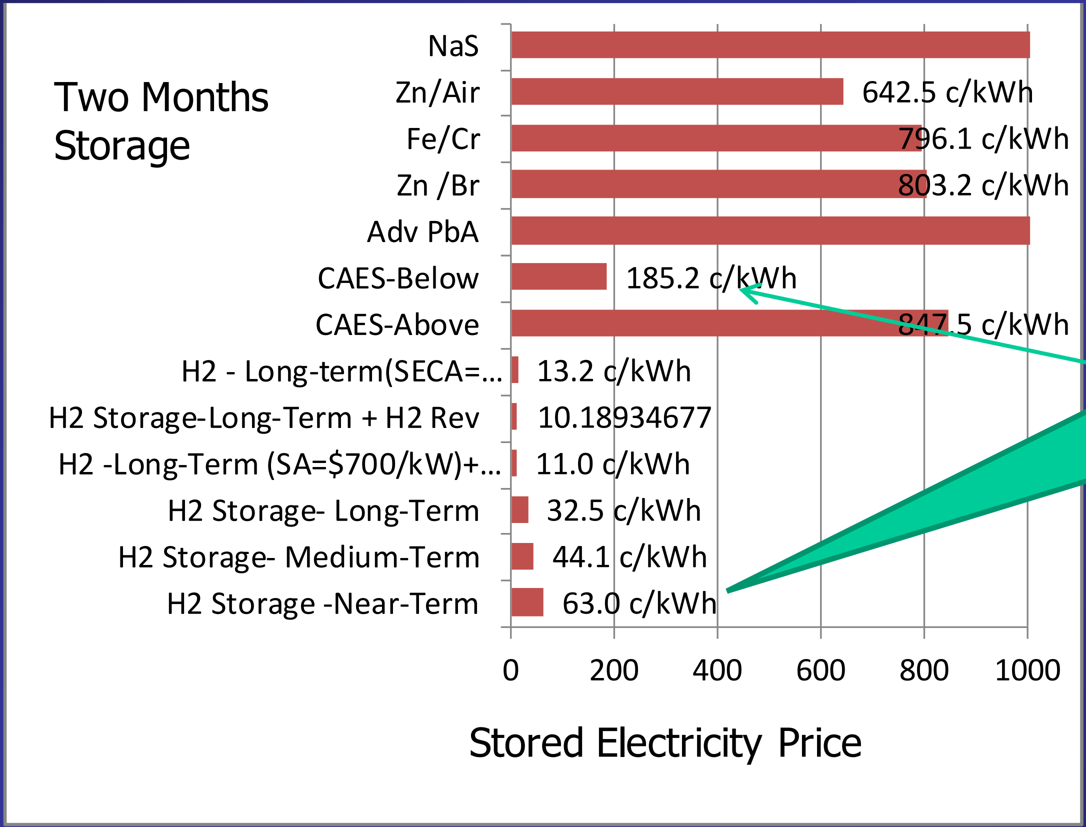
Summary of stored Electricity Prices for one day’s storage



HTAC simple model EPRI (Rev 10-9-12-25MW).XLS, WS 'Dashboard' AW-323;3/19/

SOFC systems include H2 Revenue and NG Heating credits;
Low cost estimates only for battery & CAES systems

Summary of stored Electricity Prices for Two Month's underground storage

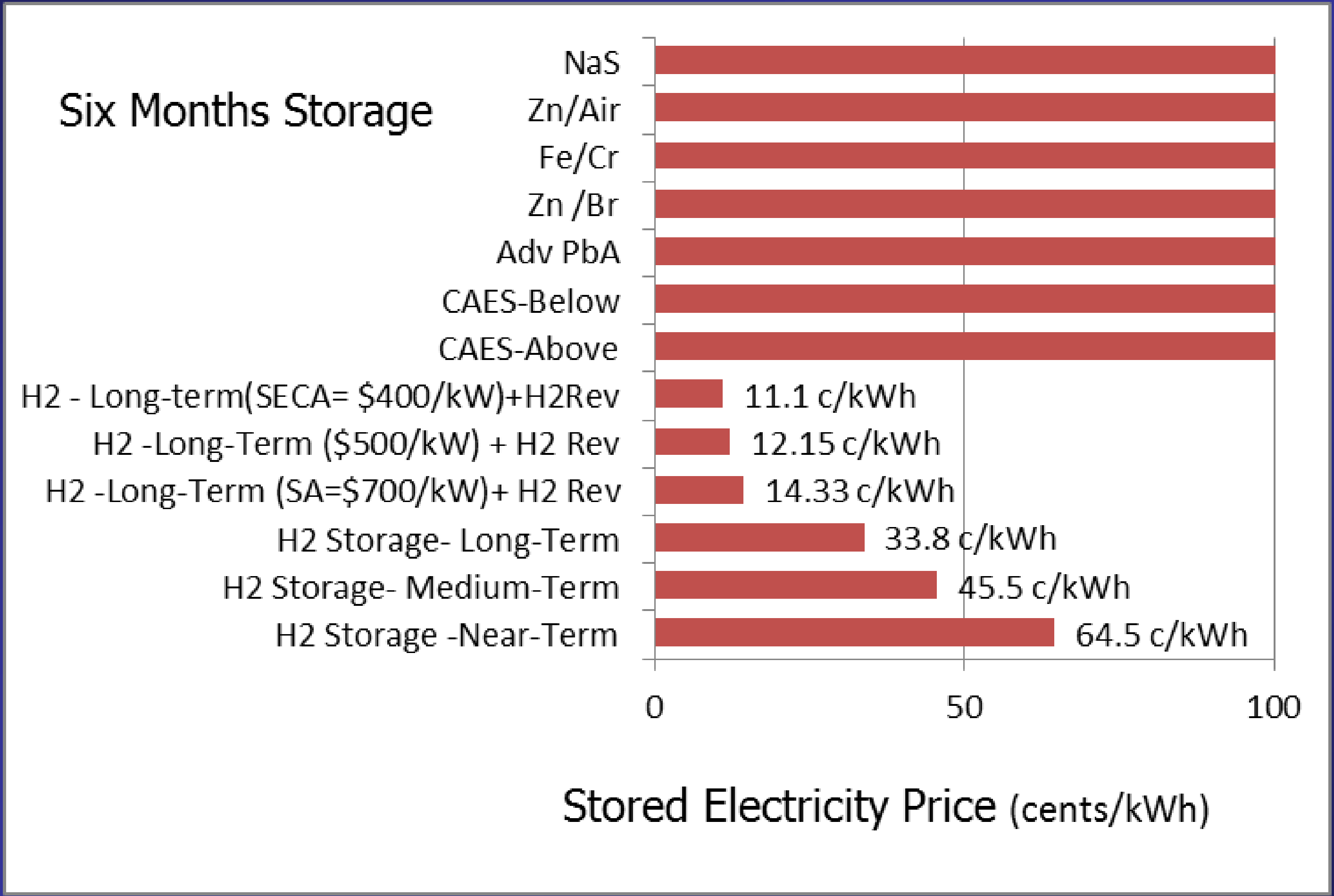


Even Near-term hydrogen storage is 3 times less expensive than underground CAES

HTAC simple model EPRI (Rev 10-9-12-25MW).XLS, WS 'Dashboard' BC-323;3/19/

SOFC systems include H2 Revenue and NG Heating credits

Summary of stored Electricity Prices for Six Month's (Seasonal) underground storage



SOFC systems include H2 Revenue and NG Heating credits

Conclusions

- Energy Storage may be needed to enable significant renewable electricity market penetration
- Storage will be required to avoid the negative environmental impact* of natural gas (or Coal) “firming” of intermittent renewables

*Even natural gas turbines used to “firm” intermittent renewables may increase greenhouse gas emissions and local air pollution compared to running those turbines 100% of the time without any renewables.

Conclusions (cont.)

- Hydrogen Storage is economic for one-day storage at 9.1 to 12.4 cents/kWh.
- For two month's storage, even near-term hydrogen storage is 3 times less expensive than the next lowest option: CAES
- For Seasonal (6-months) storage, hydrogen is the only viable option at 11.1 to 14.3 cents/kWh
  - [no other option is less than $1/kWh]

Thank You

- Contact Information:

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  thomas@cleancaroptions.com
  - Simulation details at:
  - **http://www.cleancaroptions.com**

Back-Up Slides

Financial Assumptions

- Storage system owner purchases wind energy at 5.4 cents/kWh (with 10% free to represent stranded wind)
- Owner charges enough for peak electricity to make a 10% real, after-tax ROI.

Other Financial Assumptions

Inflation rate	1.9%
Marginal income tax rate	38.9%
Real, after-tax Rate of return required	10%
Depreciation schedule	Declining balance
Annual capital recovery factor	11.79%
Taxes & Insurance	2%

HTAC simple model EPRI (Rev 10-9-12--25MW).XLS, WS 'Dashboard (Flow Diagram) D-95;11/1

Wind + NG turbine worse than 100% NG turbine?

- Wind + NG turbine balancing plant increases:
  - GHGs
  - NOx &
  - SOx
  - (Due to part-power operation of NG turbine)

See, for example, Willem Post, “Wind energy does little to reduce GHG emissions,” available at http://theenergycollective.com/willem-post/64492/wind-energy-reduces-co2-emissions-few-percent

Simple-cycle NG Turbine efficiency

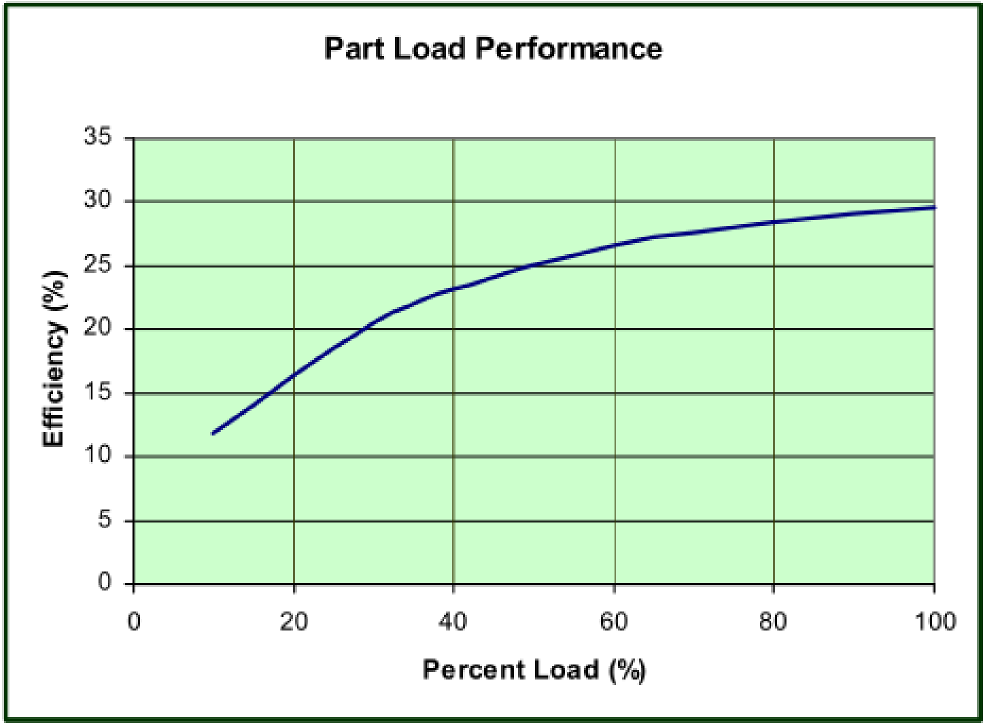


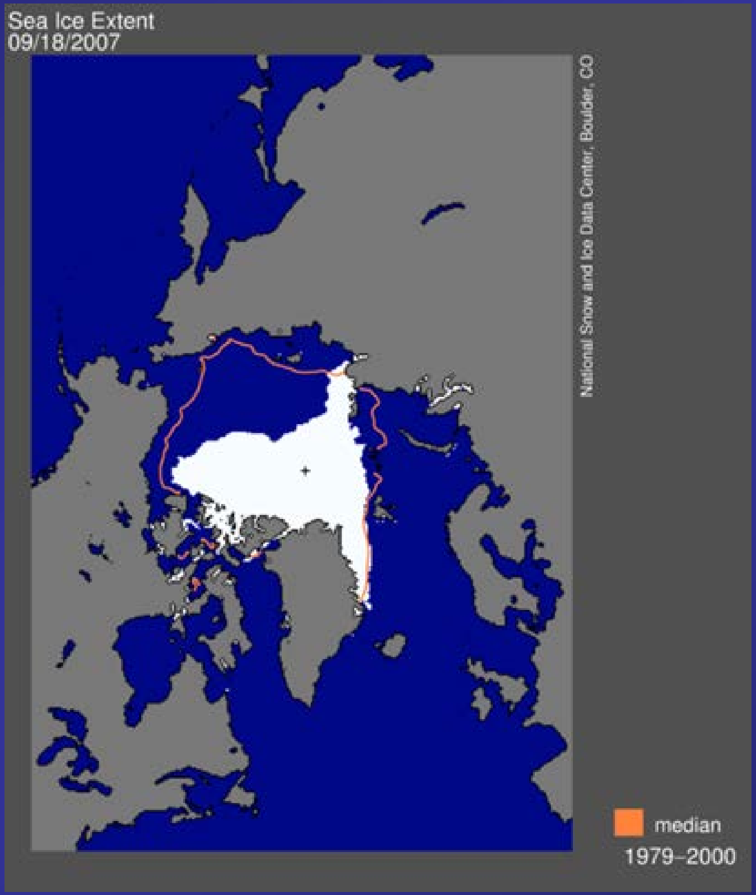
Figure 2. Part Load Power Performance

Source: EEA/ICF

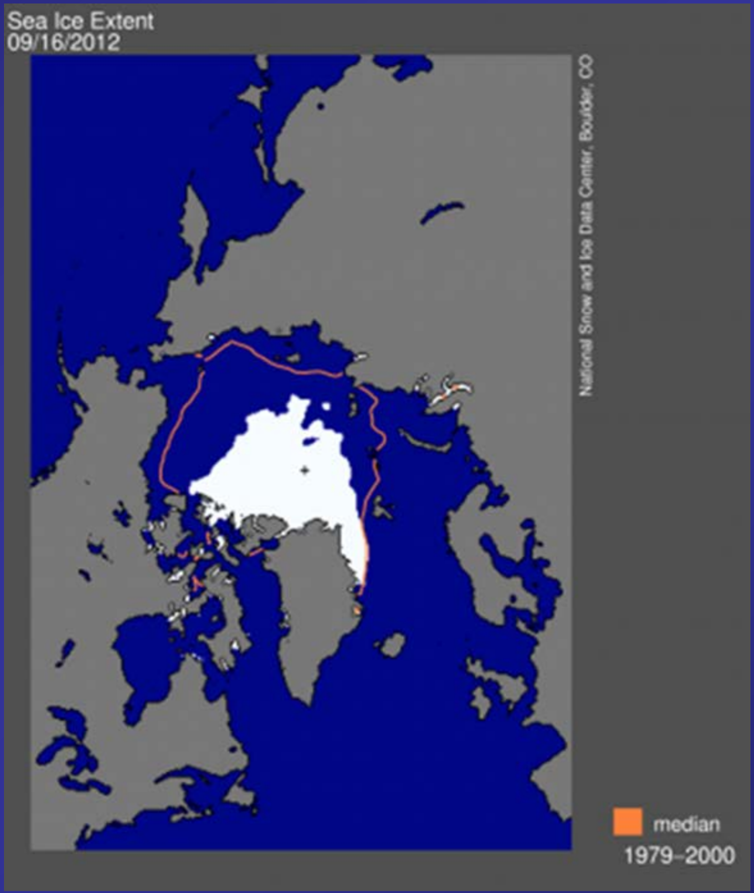
New Motivation to curb greenhouse gases

ARCTIC ICE Extent

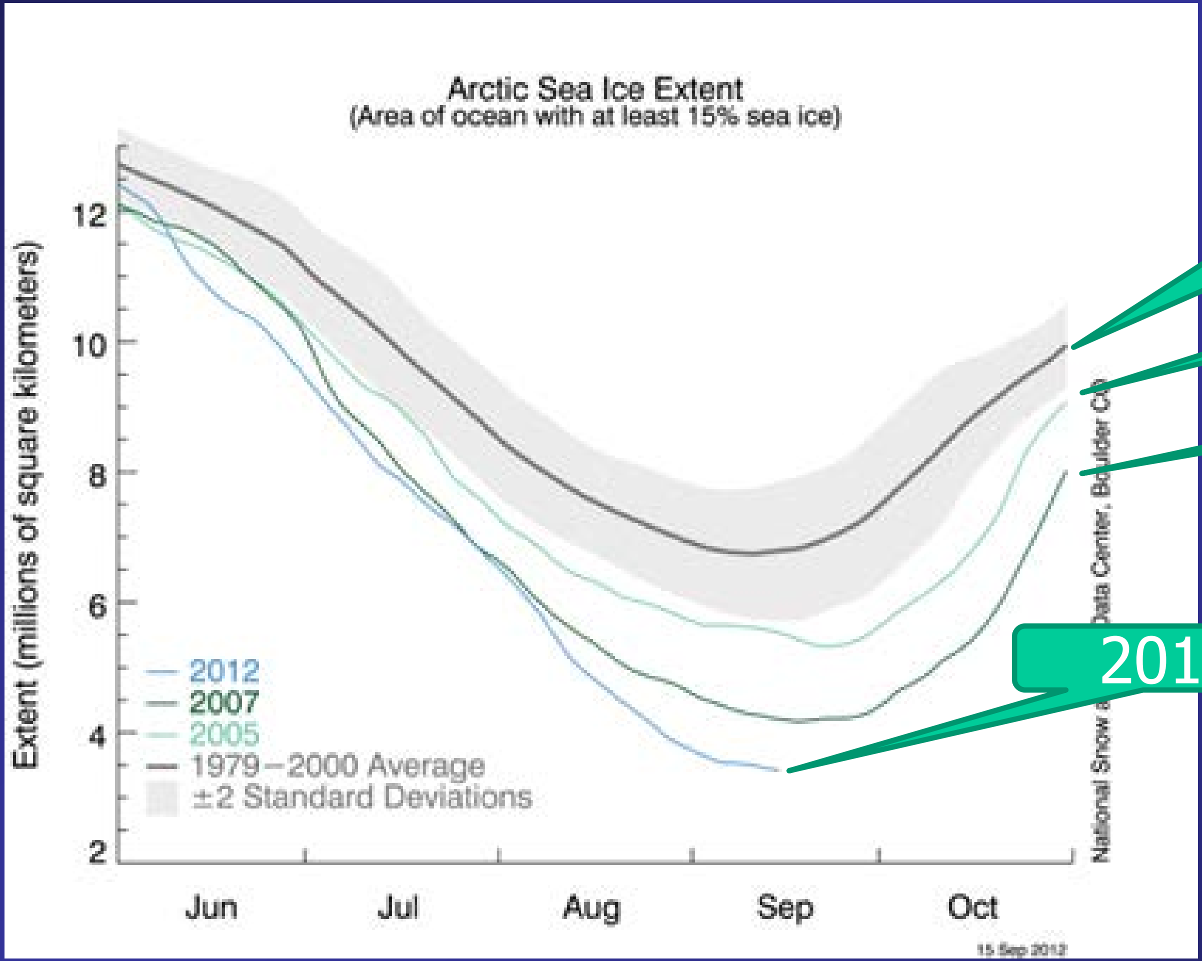
Previous Low Ice
extent: 2007



New Lowest Arctic Ice Extent; Sept 16, 2012:



Graph of Arctic Ice Extent



21-year average: 1979-2000

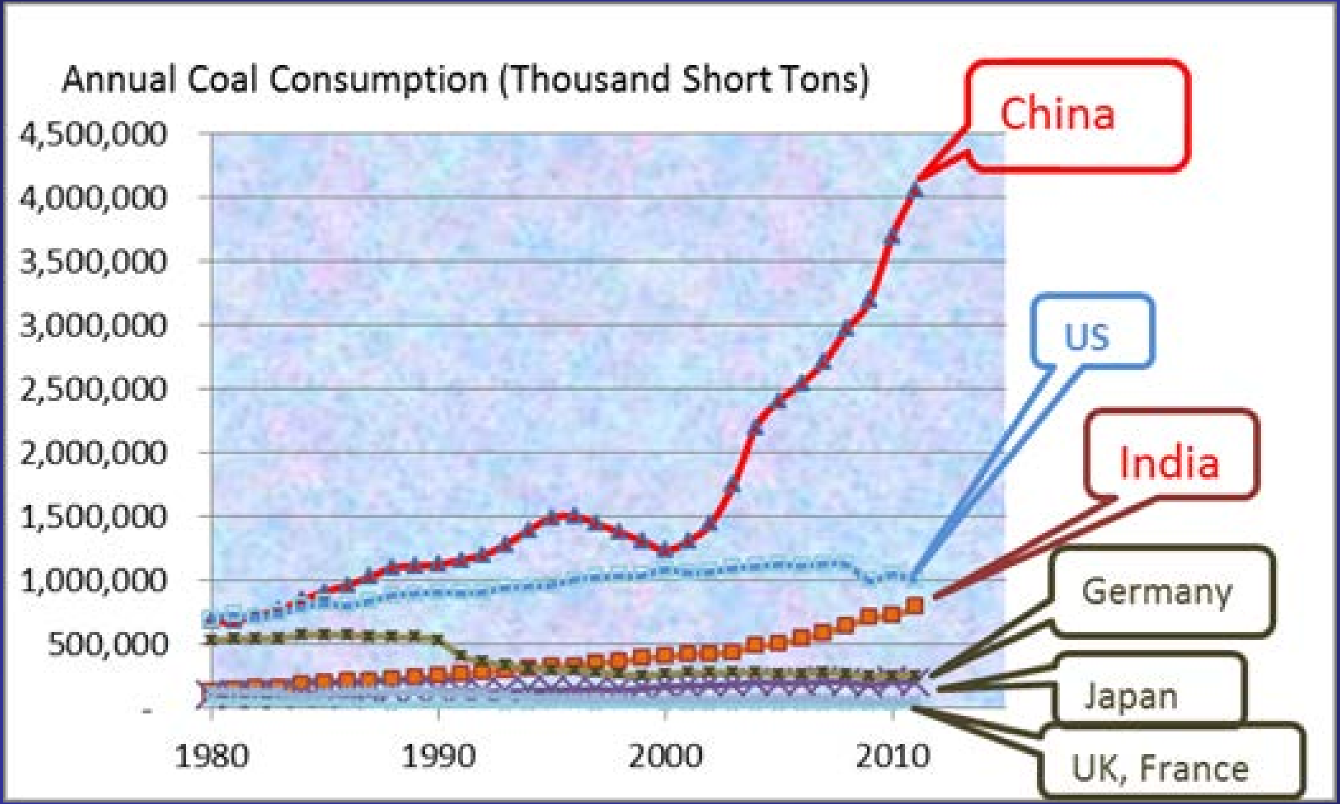
2005

2007

2012

Source: National snow & ice data center; http://nsidc.org/arcticseaicenews/

Global Coal Consumption Rising Fast



Average hourly wind power

at Trent Mesa, Texas -150 MW peak

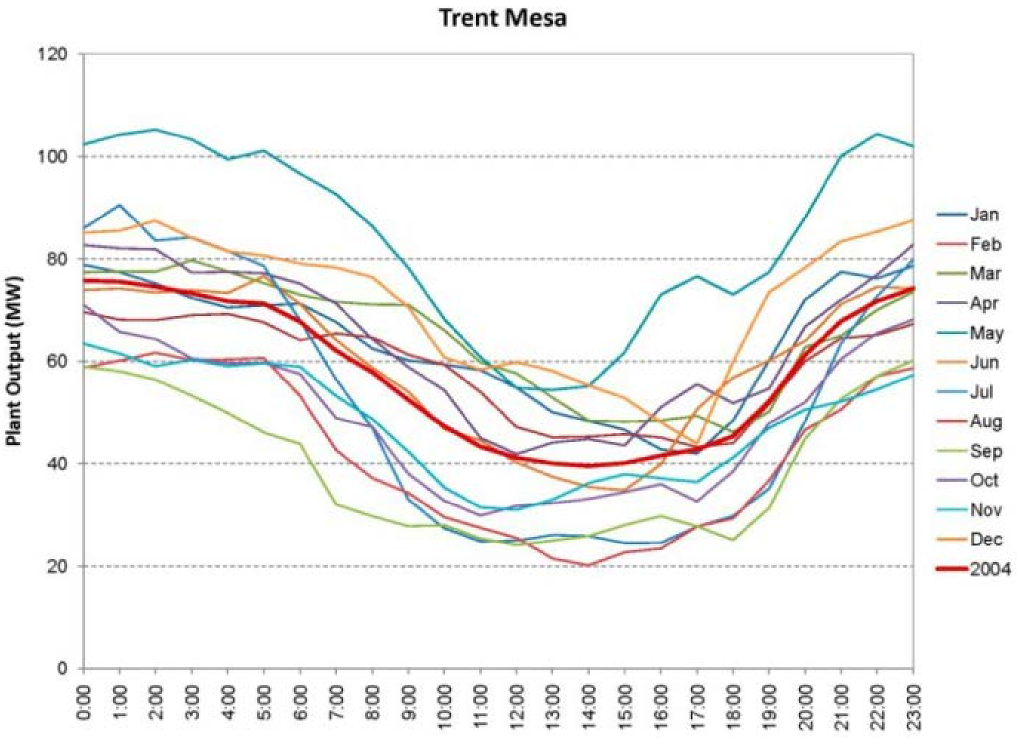
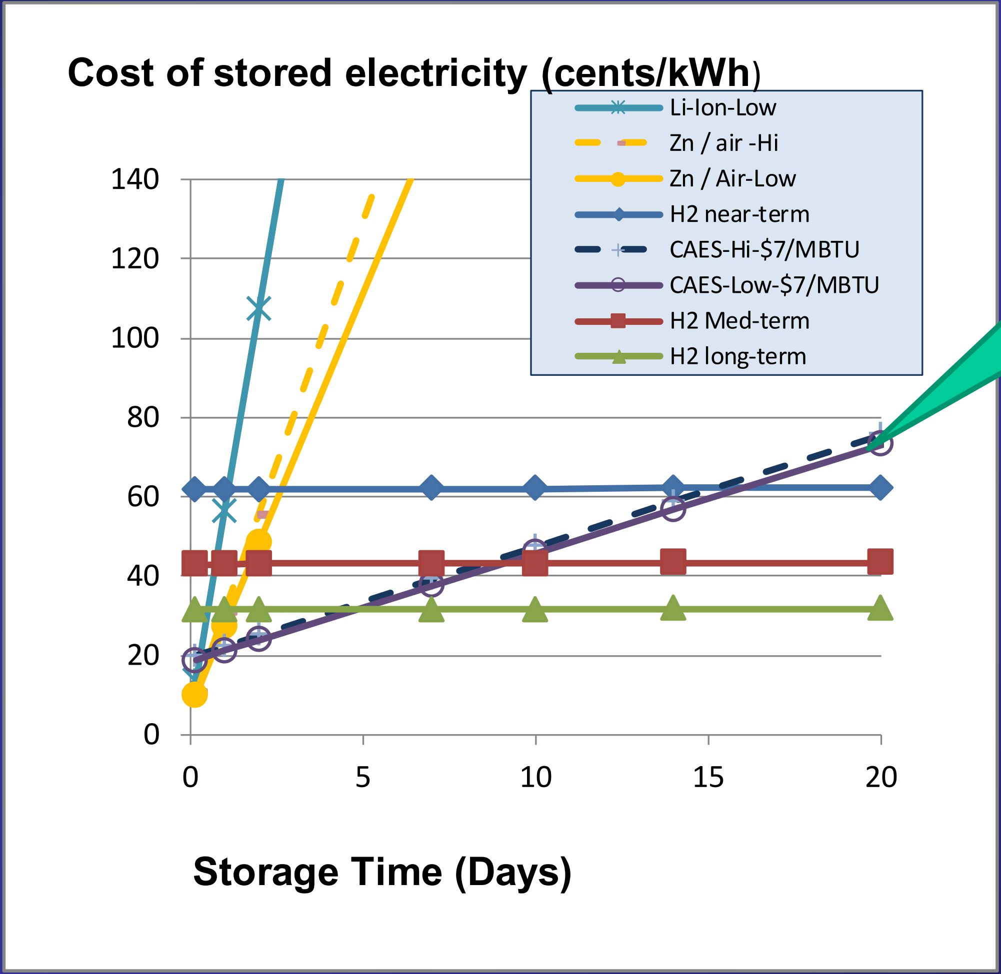


Figure 10. 2004 average hourly wind power profiles by month from Trent Mesa

Longer-Term (Below-Ground) Storage



Natural Gas = $7/MBTU

HTAC simple model EPRI (Rev 10-9-12 - 25MW.XLS, WS 'DashBoard' AK-355;11/11