Variable Renewable Generation & Storage—Are We On the Right Road?

"Accelerating Climate Action"
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Stanford
Steyer Taylor Center for
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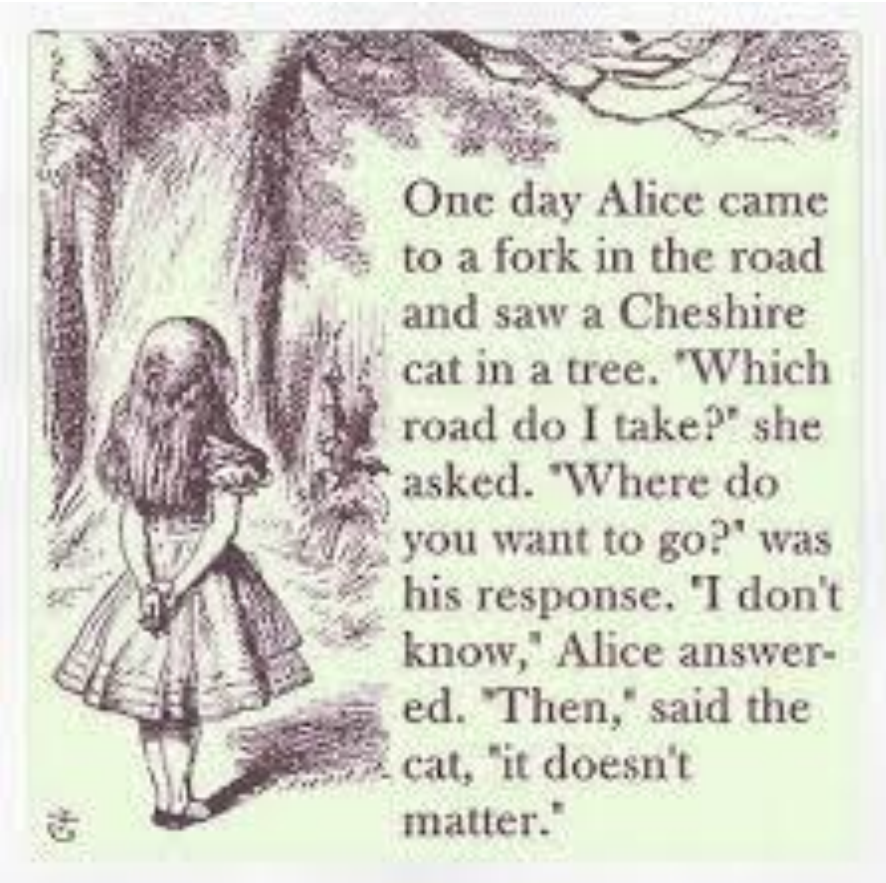
Thesis of Presentation

- Variable Generation (VG) renewables—wind and PV, look like the perfect solution these days:
  - Low “headline numbers” in bids in utility RFPs (Xcel)
  - Low Levelized Cost of Electricity (LCOE) if you *include* tax credits and *disregard* cost of backup capacity and low capacity factor utilization of transmission
  - At low levels of penetration, using VG to partially turn down spinning fossil plants is easy and uncomplicated.
- The elephant in the room is the need to have 100% backup of the VG—either fossil or still-expensive storage
- State regulators typically use entirely different proceedings to procure “renewables” vs. “reliability.” Should be combined, not separate.
- Deep decarbonization is different than “decarbonization lite.” And policy makers should, *but don’t*, optimize carbon emissions and reliability coherently.

CPUC Staff Says Same Thing to Their Bosses



"First, the siloed procurement structure created by governing statutes and policies makes it difficult to identify the most efficient and cost-effective solutions to grid integration. Staff observes that policies directing resource procurement should consider costs and benefits from a system perspective.

"Second, the CPUC's current approach of opening proceedings and developing programs to address one emerging technology area may not invite analysis that can consider the interrelationships holistically with other technologies or policy goals."*

*Source: Beyond 33% Renewables: Grid Integration Policy for a Low-Carbon Future," CPUC Staff, November 25, 2015, page 14.

VG: Super Cheap Carbon Abatement in Early Going

1MW Solar	
Construction Cost in-svc.	$1.30 million
Less ITC @ 30% of cost	(0.39)
Net Capital Cost	$0.91 million
Annual Cost @ 10% CRF	$90,000
Annual O&M	$ 15,000
Total/yr	$105,000/yr
MWh @ 30% Cap. Factor	2,628 MWh/yr
Cost per MWh	**$40/MWh**
less NGCC fuel credit	($20)
Net Cost per MWh	$20
÷ 0.4 ton CO2/MWh	**$50 per avoided ton**

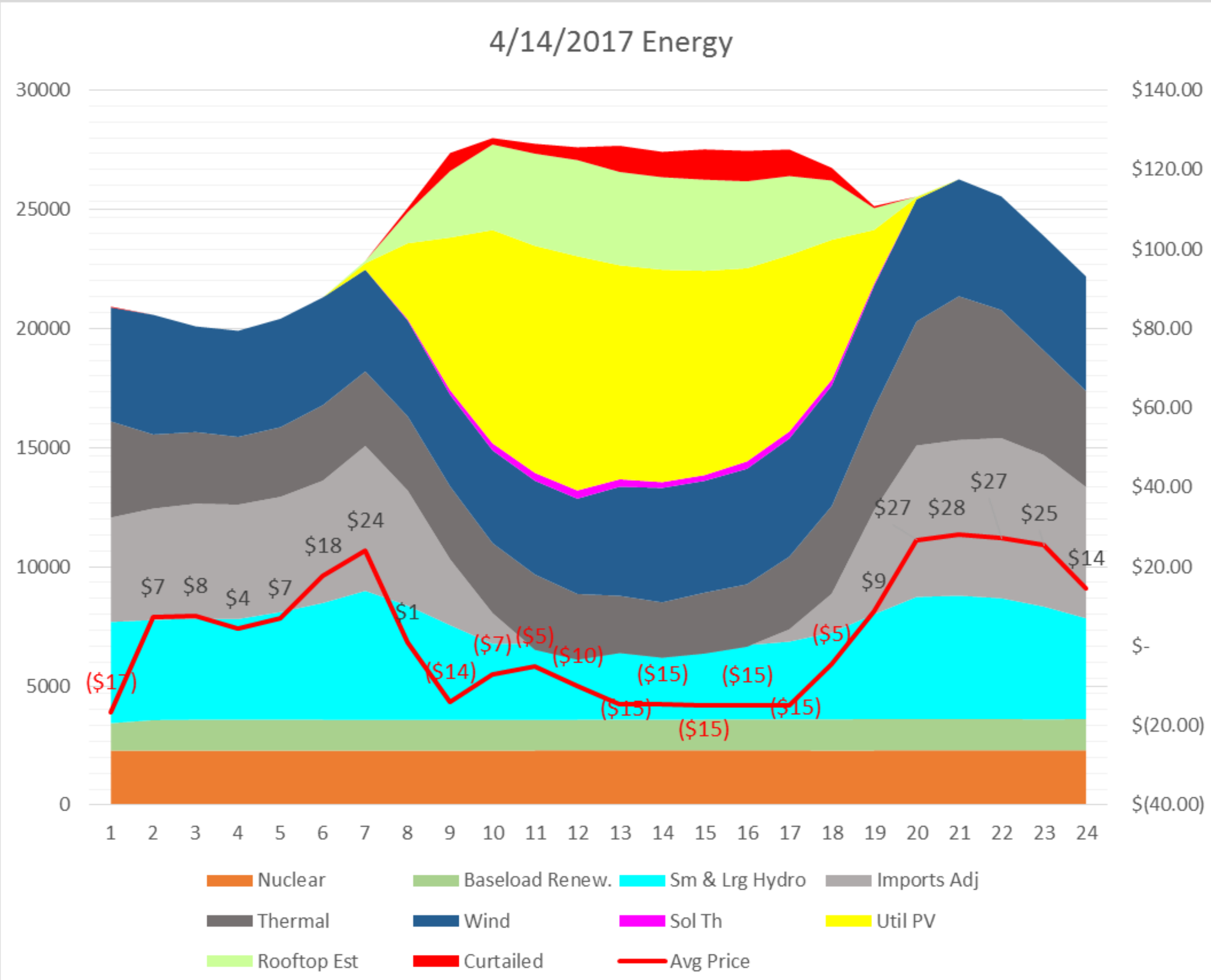
1MW Wind	
Construction Cost in svc.	$1.1 million
Less NPV of PTC*	(0.6)
Net Capital Cost	$0.5million
Annual Cost @ 10% CRF	$50,000
Annual O&M	$ 40,000
Total/yr	$90,000/yr
MWh @ 40% Cap. Factor	3,504 MWh/yr
Cost per MWh	**$26**
less NGCC fuel credit	($20)
Net Cost per MWh	$6
÷ 0.4 ton CO2/MWh	**$15 per avoided ton**

* $24/MWh x 3504MWh/yr = $84k/yr. NPV of $84k/yr, increasing 2% w/ inflation, for 10 yrs at 8% = $609k

VG Eliminates Some Fossil MWh but not the Fossil Generators Themselves

- **Can't stop <u>running</u> gas plants even if available VG exceeds load.** Need to have already hot, spinning turbines that are operating at part capacity that you can ramp up and down when VG fluctuates. See slide #6.
  - At any instant, CAISO won't let VG be more than ~5x spinning fossil generation (i.e., if you have 20,000 MW of VG on line they want 4,000 MW of upward flexibility in gas plants).
  - Emitting carbon every minute so you can quickly emit more if the wind or sun falls off or if load spikes.
- **Can't <u>decommission</u> gas plants even if they don't get used that much.** There's no solar at night, and wind can be zero or near zero so you have to have firm resources (excluding wind and PV) equal to annual peak at 5pm in August.
  - California PUC concluded you need 8MW of wind to replace 1MW of gas backup. See slide # 7.
  - They concluded 2MW of PV to replace 1MW of gas backup—*but only during the daytime in the summer*, which seems like a poor comparison.

Curtailing VG While Still Running Fossil



Source: CAISO generation and curtailment data, Bonneville Power Administration hydro export data, CEC rooftop solar installation and generation data, CAISO price data reported by independent market makers.

"RPS"* energy 42% for the day.

Solar PV 22% of daily energy.

Curtailment as % of Solar PV was 7%, 9,000 MWh.

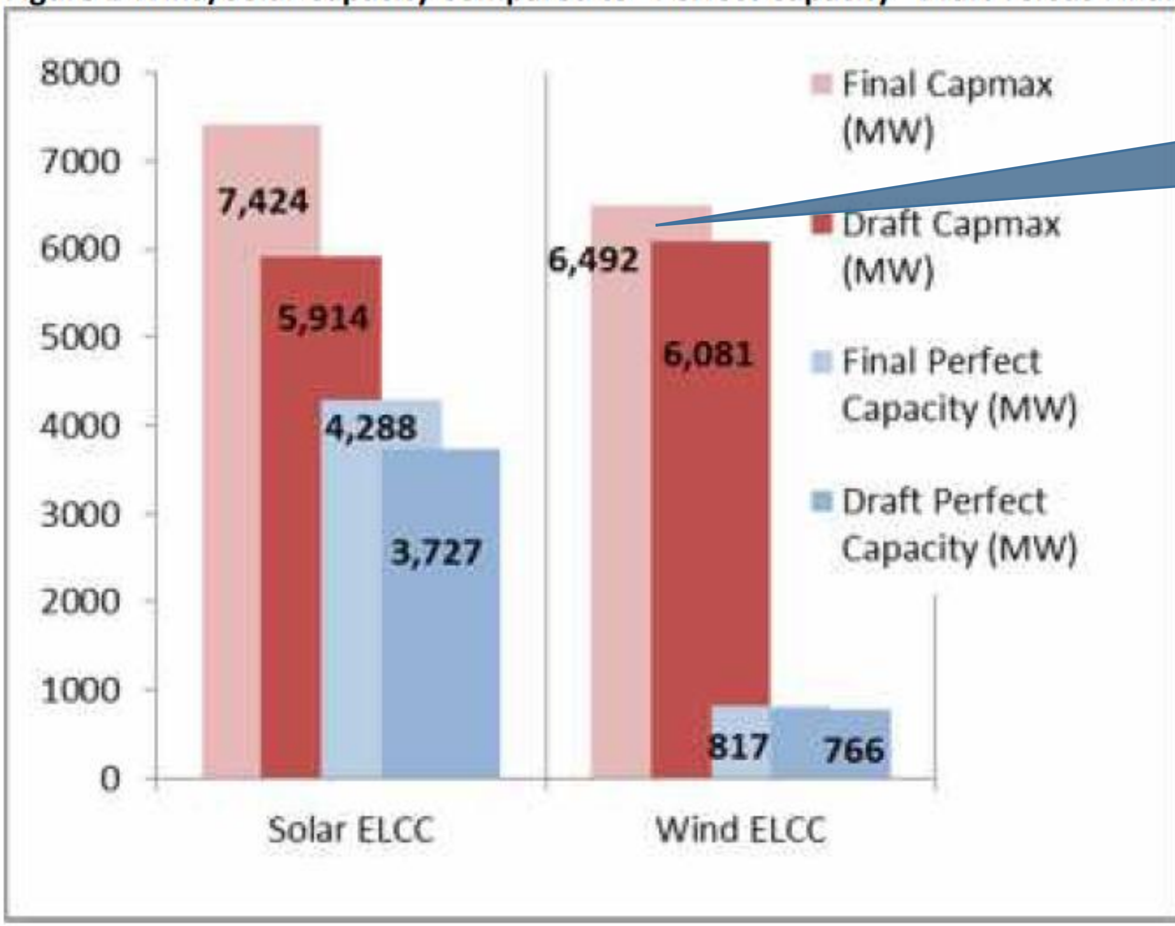
Evening thermal in excess of spinning reserves 15x daytime thermal.

* "RPS" excludes large hydro & rooftop.

Variable Generation is Truly Variable

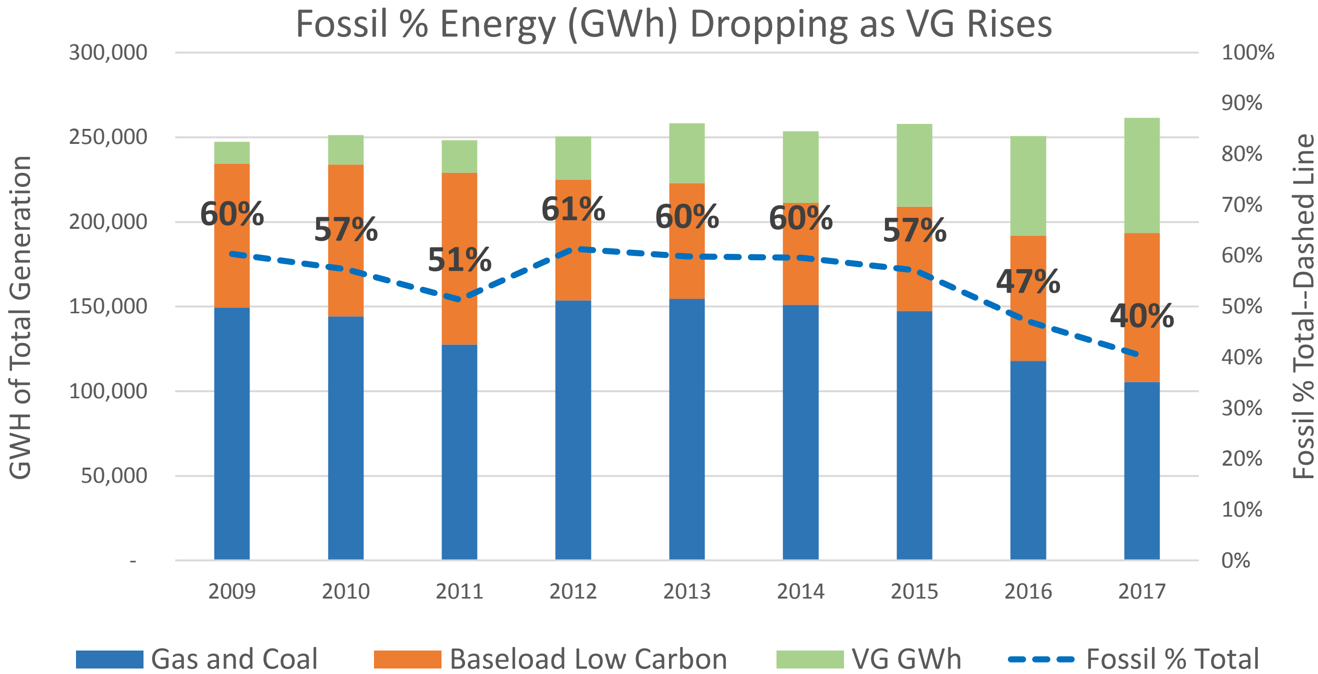
- California PUC concluded you need 8MW of wind to replace 1MW of “perfect capacity” gas backup. The chart is confusing because it shows draft and final results—focus on final.
- They concluded 2MW of PV to replace 1MW of gas backup—*but only during the daytime in the summer*, which seems like a poor comparison.

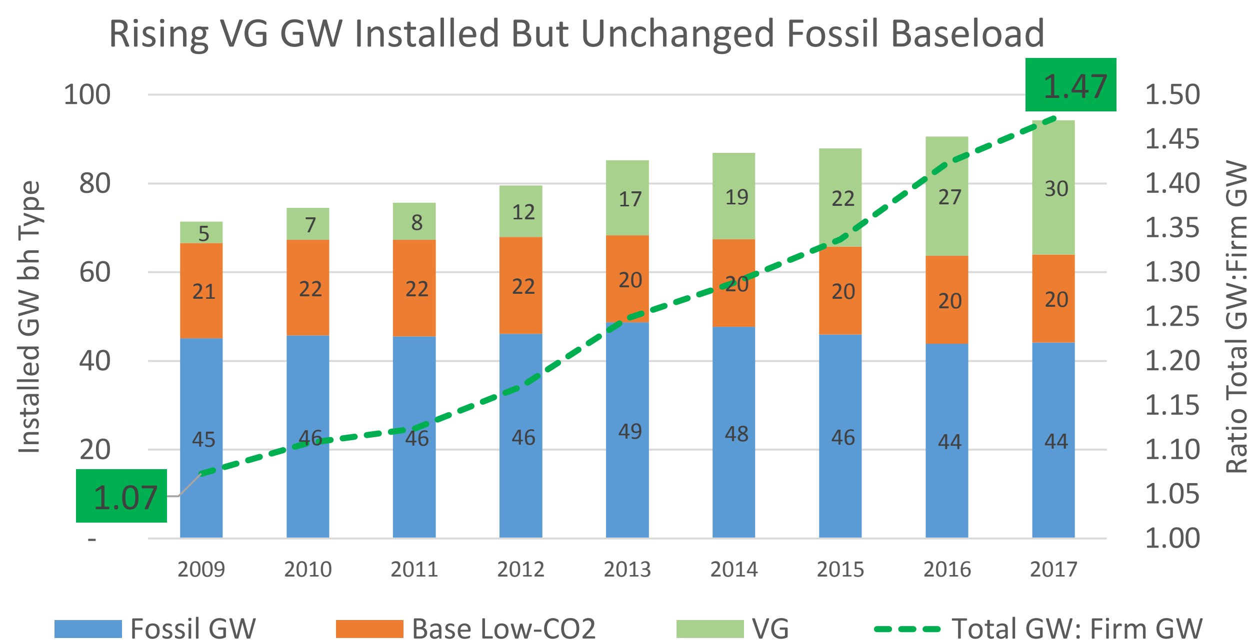
Figure 1 Wind/Solar Capacity Compared to "Perfect Capacity" Draft versus Final (MW)



Takes 6,492 MW of wind to get rid of 817 MW of gas: 8:1 ratio.

More VG, Running Fossil Less, But Fossil Units Remain





Source: California Energy Commission reports. See https://www.energy.ca.gov/almanac/electricity_data/

NETL's VG Penetration →Curtailment:

High RPS with High PV Hits a Wall at 45% RPS & 21% PV with >10% avg. curtailment & >50% marginal curtailment

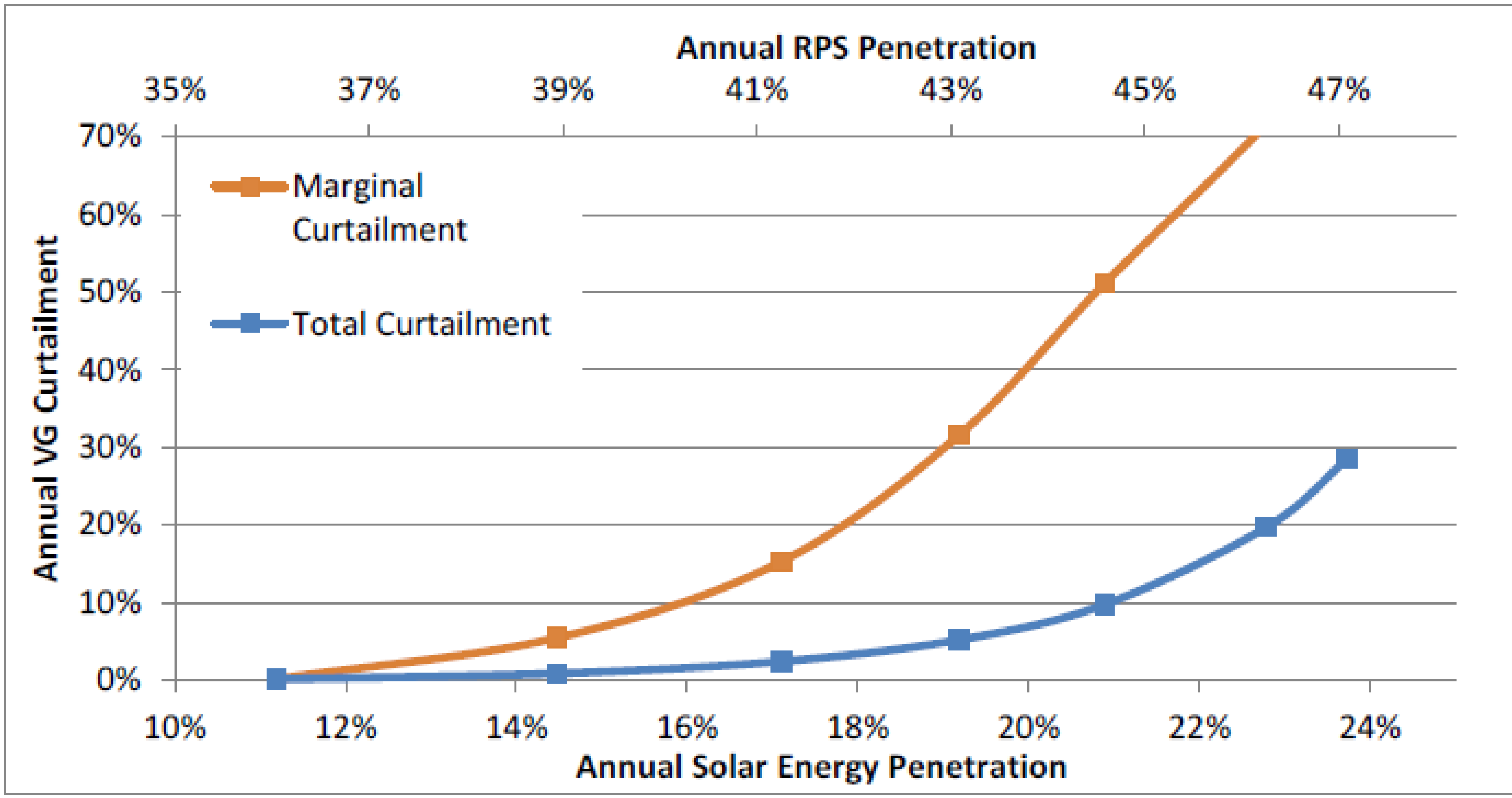
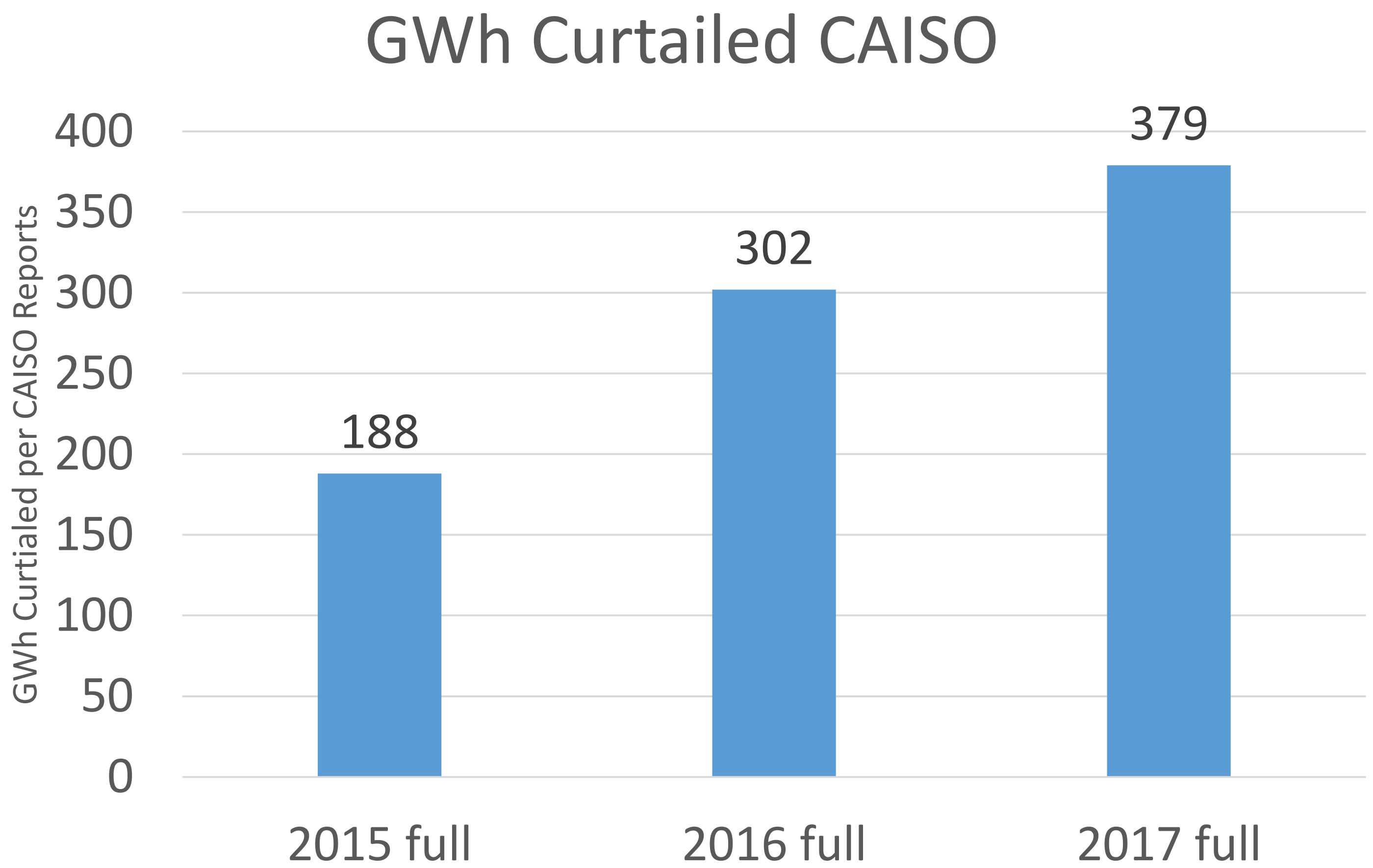


Figure 17. Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

Source: "Overgeneration from Solar Energy in California: A Field Guide to the Duck Curve", Paul Denholm et al, NREL, Technical Report NREL/TP-6A20-65023, November 2015.

Curtailment is Not a Myth



These are not alarming numbers per se. They simply indicate that there is a measurable increase in curtailment over time. Growth in curtailment appears to be slowing, with power surplus being exported to neighboring states at low prices in the new Energy Imbalance Market. Since power "exports" are not disaggregated by type of generation in public sources, it is hard to tell how much or when electric energy is being dumped instead of being switched off. Source: CAISO curtailment reports.

Short-term Storage Breaks-even @ ~50% Marginal Curtailment

1MW Solar Only @ 50% Curtailment	
Cap Cost	$1.3 million
Annual @ 10% CRF	$130,000
Annual O&M	$ 15,000
Total/yr	$145,000/yr
Production MWh @ 15% (30% x 50%)	1,314 MWh/yr
Cost per MWh	**$110**
less NGCC fuel credit	($20)
Net Cost per MWh	$90
÷ 0.4 ton CO2/MWh	**$226 per avoided ton**

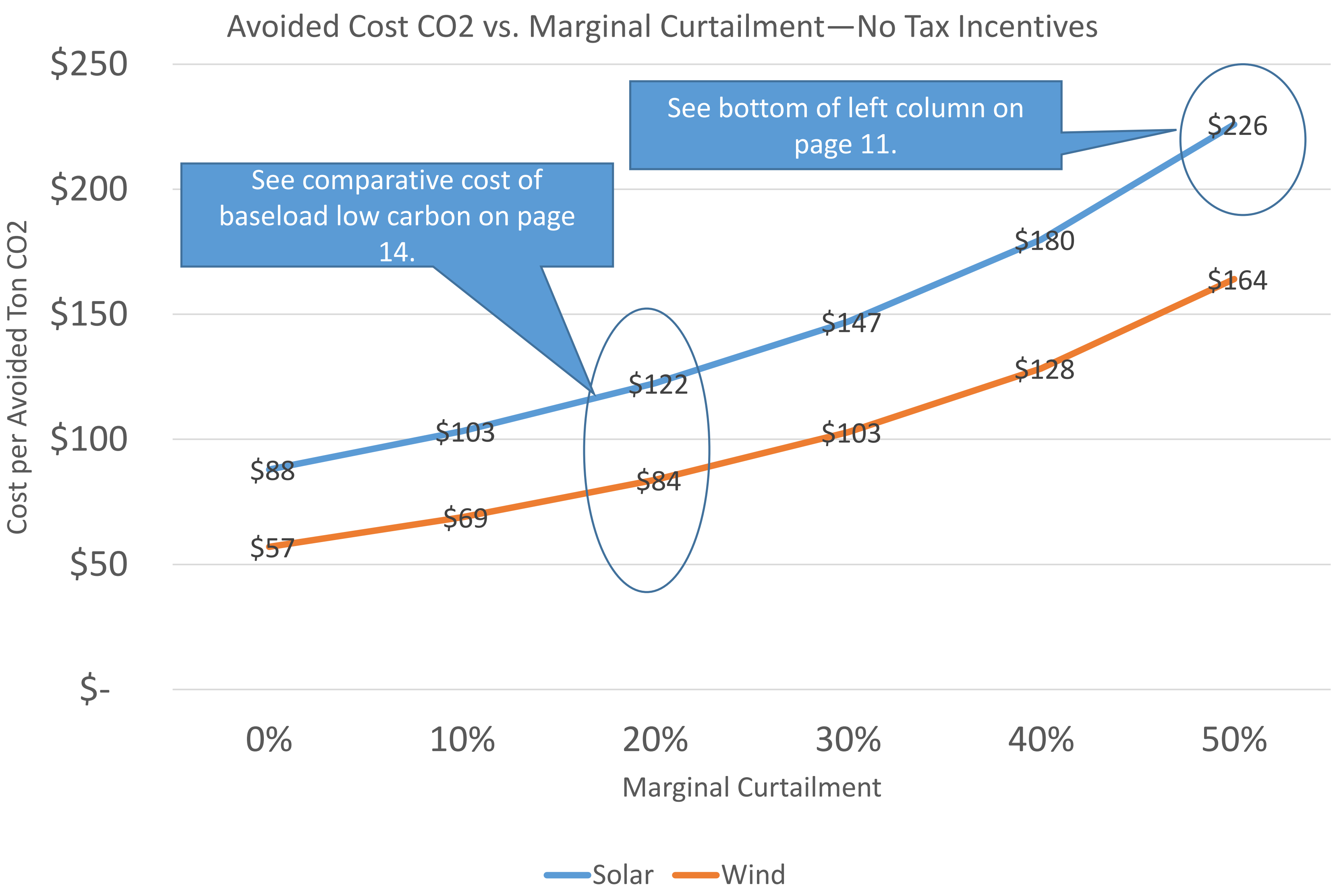
1MW Solar @ 50% + 4MWh Battery*	
Cap Cost	$0.8 million
Annual @ 15% CRF	$125,000
Annual O&M	$ 5,000
Total/yr +Solar	$130,000/yr + 145,000 $ 275,000/yr
Production MWh @ 30% (no curtailment)	2,628 MWh/yr
Cost per MWh	**$105**
less NGCC fuel credit	($20)
Net Cost per MWh	$85
÷ 0.4 ton CO2/MWh	**$213 per avoided ton**

*Many quotes on "solar plus storage" combine a lot of solar and tiny amounts of storage—they are quite confusing. Read footnotes next page.

Notes for Break evens on p. 11

- Cap cost for solar for Lazard V11 LCOE was $1.375 mm per MW, but reduced down to $1.3 mm/MW because old number.
- Solar O&M $15,000 per MW-yr, adjusted up from Lazard $12,000 because I think they are low on property tax and insurance.
- Battery pack number $207/kWh for cells in packs and racks (i.e., not raw cell cost, which is ~$100/kWh). Source was Utility Dive news letter quoting GTM (storage expert). Battery O&M from Lazard.
- Capital costs were 8% debt, 12% equity (Lazard) tax adjusted for depreciation and interest shield and using 20 year asset life for solar and 10 year asset life for Li-ion battery. All then converted to a Capital Recovery Factor.
- 30% is solid annual capacity factor for single axis polycrystalline in desert.
- Assumed no significant incremental charging losses because battery on-site with solar and is charged w/ D.C. direct from panels, bypassing inverters until discharged.
- NGCC $20 per MWh = 6800 MWh @ $2.60/mmBtu gas plus $2.50/MWh variable O&M. 0.4 s-tons CO2/MWh: 6800 MWh x 118 lbs CO2/mmBtu = 802 lbs/MWh = ~0.4 s-tons

Curtailment → Increases Cost of Avoided CO2

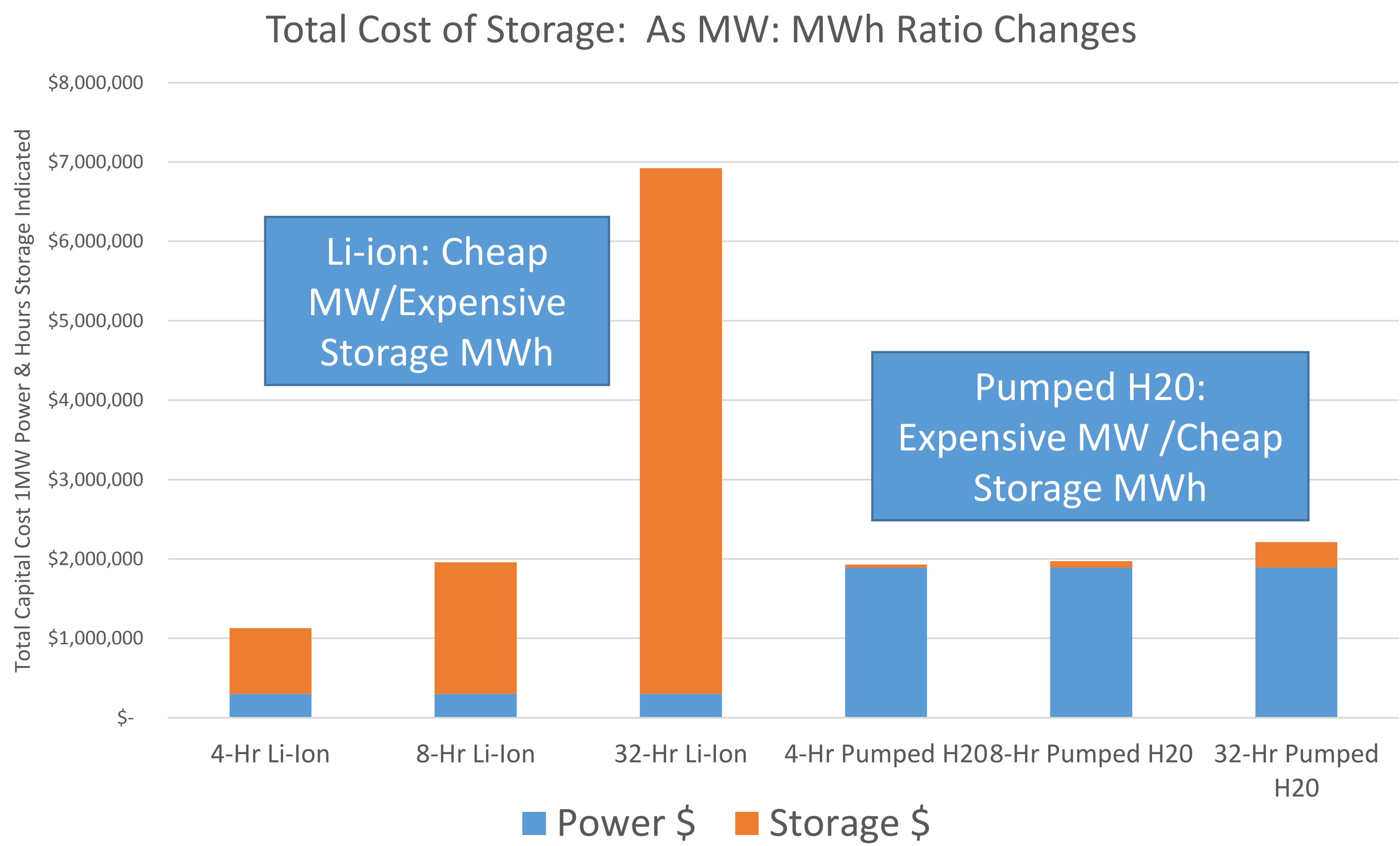


The Road Not Taken: Base-load Low Carbon Breaks Even with VG at Low Curtailment Levels

Baseload Renewables & Carbon Capture			
Technology	Cost per MWh	Gas Plant Capacity and Fuel Displaced/MWh*	Avoided CO2 Cost per s-ton**
Geothermal	$97	($50)	$118
Biomass	$85	($50)	$88
NGCC w/ CCS @ 85% NCF: saline	$67	($50)	$75
Nuclear***	$83	($50)	$82

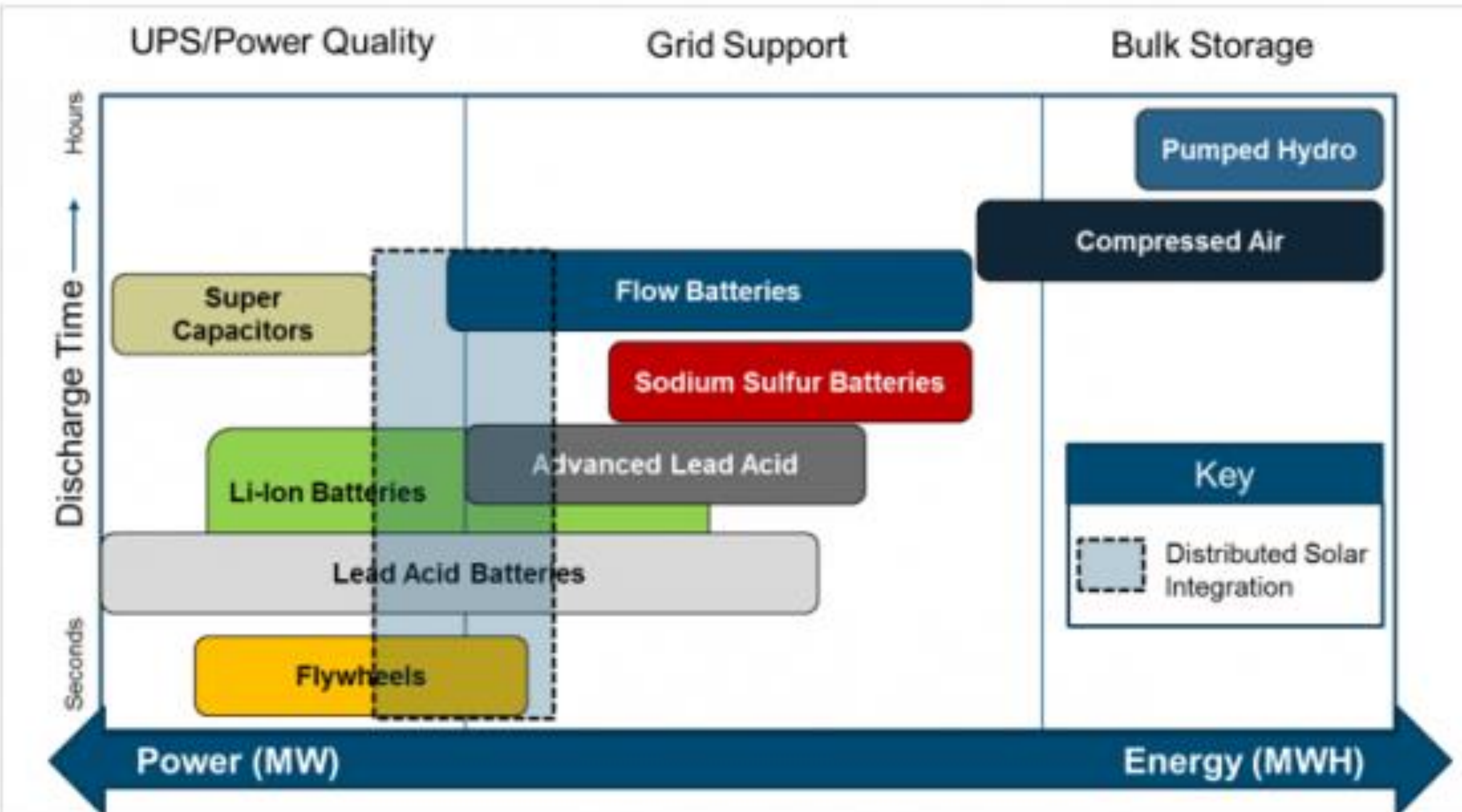
*Combined cycle gas plant using 50% capacity factor. All gas plants (CT and NGCC) in CA now are 25% annual NCF.
** (Cost per MWh minus Gas Plant displaced cost per MWh)/(tons CO2 per MWh displaced). Tons displaced are 0.4 tons for NGCC and 0.36 tons for NGCC w CCS. NGCC w CCS assumes 90% capture, 80% capacity factor, no tax incentives, $10/ton CO2 disposal cost—no CO2-EOR revenues, 10% CRF. ***Nuclear $5 million per MW @ 10% Capital Recovery Factor, 90% capacity factor, and $20 per MWh fuel & O&M.

What Storage You Should Buy Depends on How Many Hours You Want

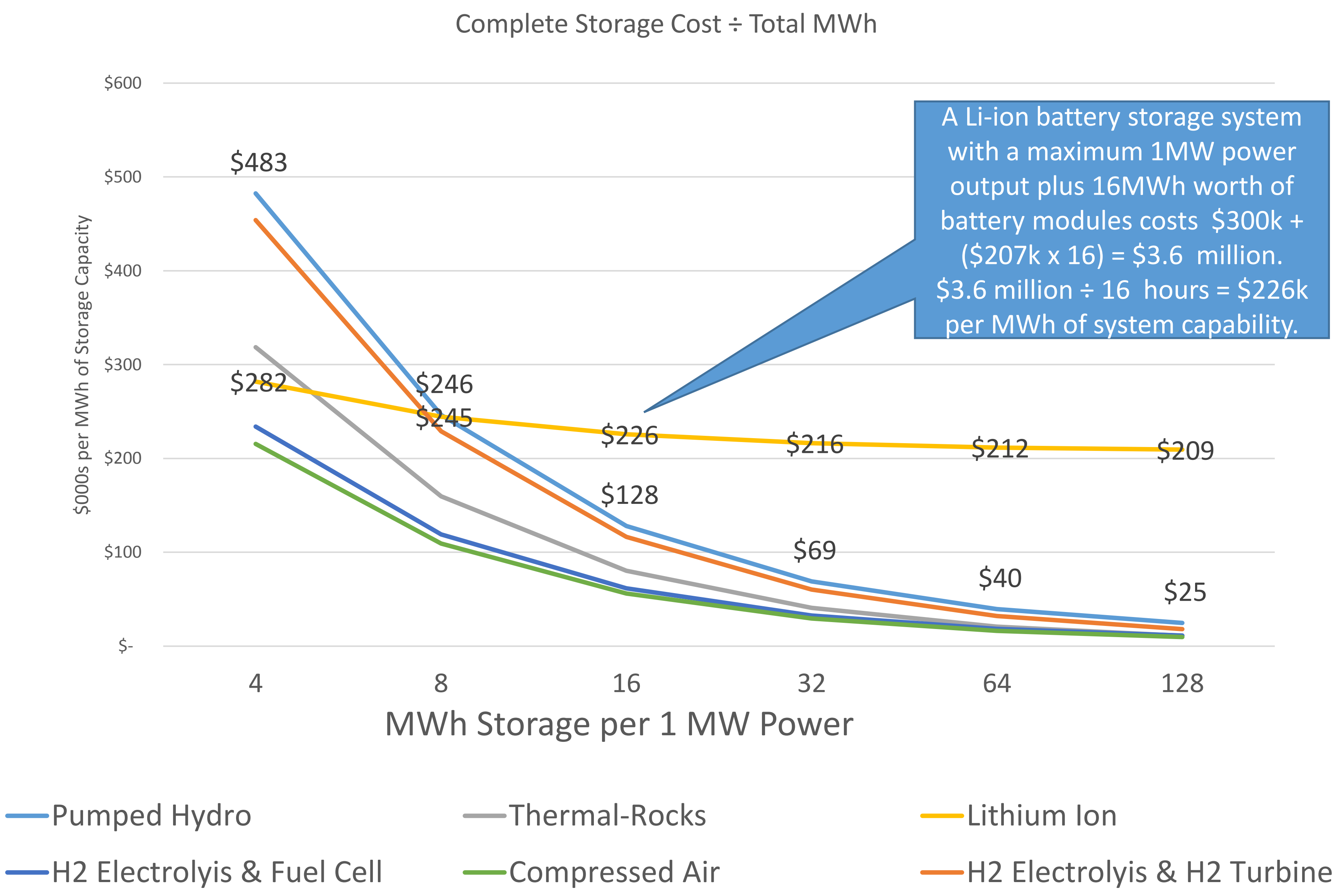


Data is very scattered on costs of Pumped Storage and Li-ion. For Li-ion I I used $300,000 per MW for power capex and $207,000 per MWh (combination of Lazard and GTM sources). For Pumped Storage I used $1.89 million per MW and $10,000.00 per MWh. Approximately 1 Acre-foot stored with 1,000 foot head, costing $10,000 gives, 1 MWh of electricity.

Storage can be optimized for power or energy: MW vs. MWh



Lots of Promising Options for Long-Term Storage



Concluding Thoughts

- *Marginal* curtailment, not average, drives storage break-evens vs. curtailment.
- Curtailment raises CO2 abatement cost even if LCOE "looks the same" if you ignore curtailment.
- It takes a lot of curtailment before it is worth it to build storage—maybe 50% marginal.
- Much sooner, at 10-20% curtailment, long before large storage investments are worthwhile, we should consider changing tactics to buying more base-load and dispatchable low-carbon resources.
  - Geothermal, biomass, improved large hydro, and fossil w/ CCS are likely all better than either curtailment or storage.
  - [Perhaps nuclear—cost uncertainty.]
- Storage over 8 hours demands other technologies than batteries.