NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Lessons Learned from Dispatch Modelling of High Renewable Penetration

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EIA Electric Capacity Expansion Modelling Workshop

Conclusions

- There are no inherent technical limits to how much variable renewable generation can be placed on the grid…..

- **But there are economic limits driven by variability of the wind and solar resource.**
- **But why?**

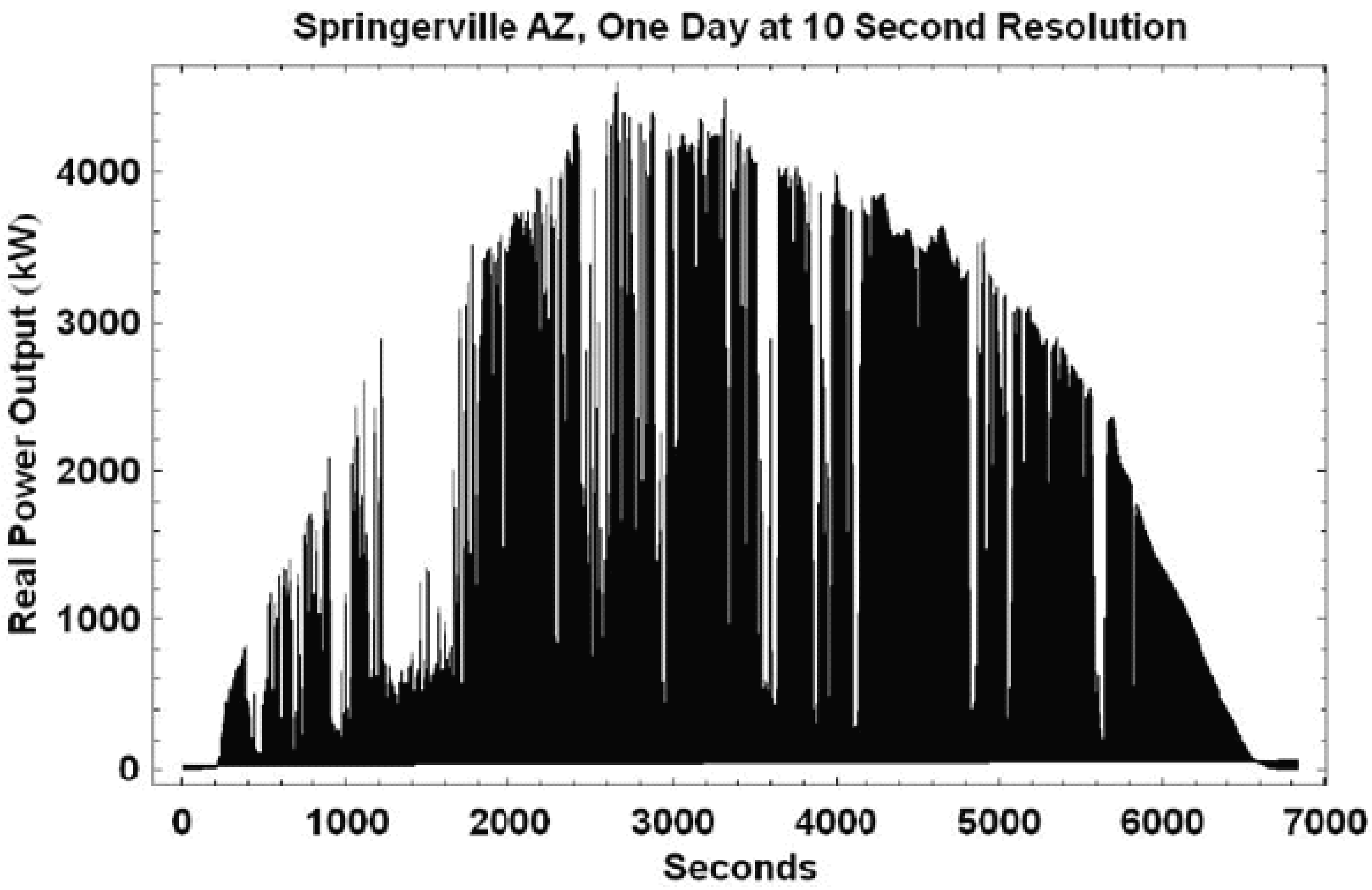
Three things I think know

1. **Ramp ramps don't seem to be a major constraint**
2. **Increased operating reserves don't seem to be a major problem**
3. **Supply/demand mismatch and minimum generation levels are the biggest problem**
   - **leads to curtailment and increased costs**

Variability and Uncertainty

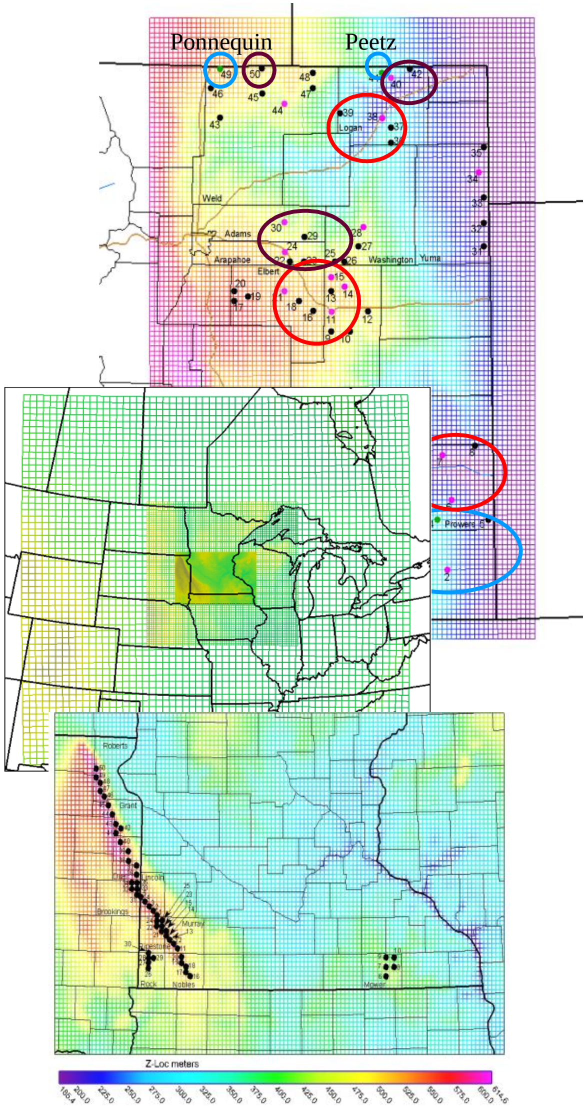
- **Hypothesis was that massive ramp rates and variability and uncertainty of the resource will lead to significant "integration costs"**
  - **Need extra generation capacity to deal with ramp rates?**
  - **Increased operating reserves?**
- **This is the major focus of many grid-integration studies of wind and solar**

This is Scary!



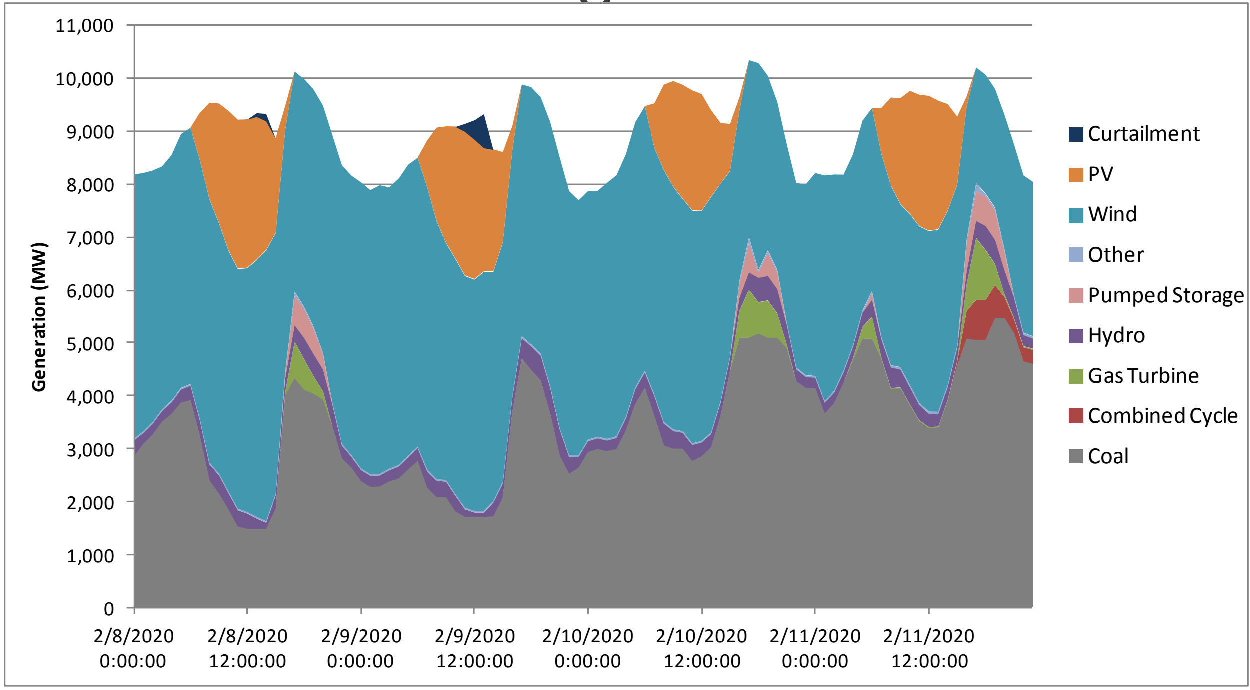
Integration Studies

- Simulate system with solar and wind compared to a proxy resource
  - Use unit commitment software includes existing generation mix, transmission system
  - Use lots of wind and solar simulations to consider spatial diversity
  - May involve substantial costs
- Evaluate impacts of forecast errors, resource variability, additional reserves, curtailment etc.



Simulation Outputs

- Did the grid work?
  - Did you drop load or violate reserve requirements?
- What was the impact of forecast error or variability on cycling costs and emissions?
- Did you actually use all the renewable generation?
  - How much curtailment?



Integration Cost

Wind Energy Penetration	1%	4%	7%	10%
Within-hour Regulating	$0.40	$0.41	$0.31	$0.37
Hour-ahead Uncertainty	$0.11	$1.88	$2.32	$2.65
Day-ahead Uncertainty	$0.39	$0.95	$0.93	$1.06

Costs of Wind Integration

Date	Study				Unit ...mitment ...Wh)	Other ($/MWh)	**Total Oper. Cost Impact ($/MWh)**
2003	Xcel-UWIG	[illegible]	0	[illegible]	[illegible]	Na	**1.85**
2003	WE Energies	[illegible]	1.02	0.15	[illegible]	Na	**2.92**
2004	Xcel-MND	[illegible]	0.23	na	[illegible]	Na	**4.6**
2005	PacifiCor	[illegible]	0	1.48	[illegible]	[illegible]	**4.64**
2006	Calif. (m	[illegible]	[illegible]	trace	tr	[illegible]	**0.45**
2006	Xcel-P	[illegible]	[illegible]	na	3.3	[illegible]	**4.97**
2006	MN-M	36	[illegible]	na	na	[illegible]	**4.41**
2007	Puget	12	[illegible]	[illegible]	na	[illegible]	**6.94**
2007	Arizona	15	[illegible]	[illegible]	1.	[illegible]	**4.08**
2007	Avista U	30	1.43	[illegible]	[illegible]	[illegible]	**8.84**
2007	Idaho Pow	20	na	[illegible]	[illegible]	a	**7.92**
2007	PacifiCorp-2	18	na	[illegible]	[illegible]	na	**5.1**
2008	Xcel-PSCo[e]	[illegible]	na	n	[illegible]	na	**8.56**

[a] Regulation costs represent 3-year a

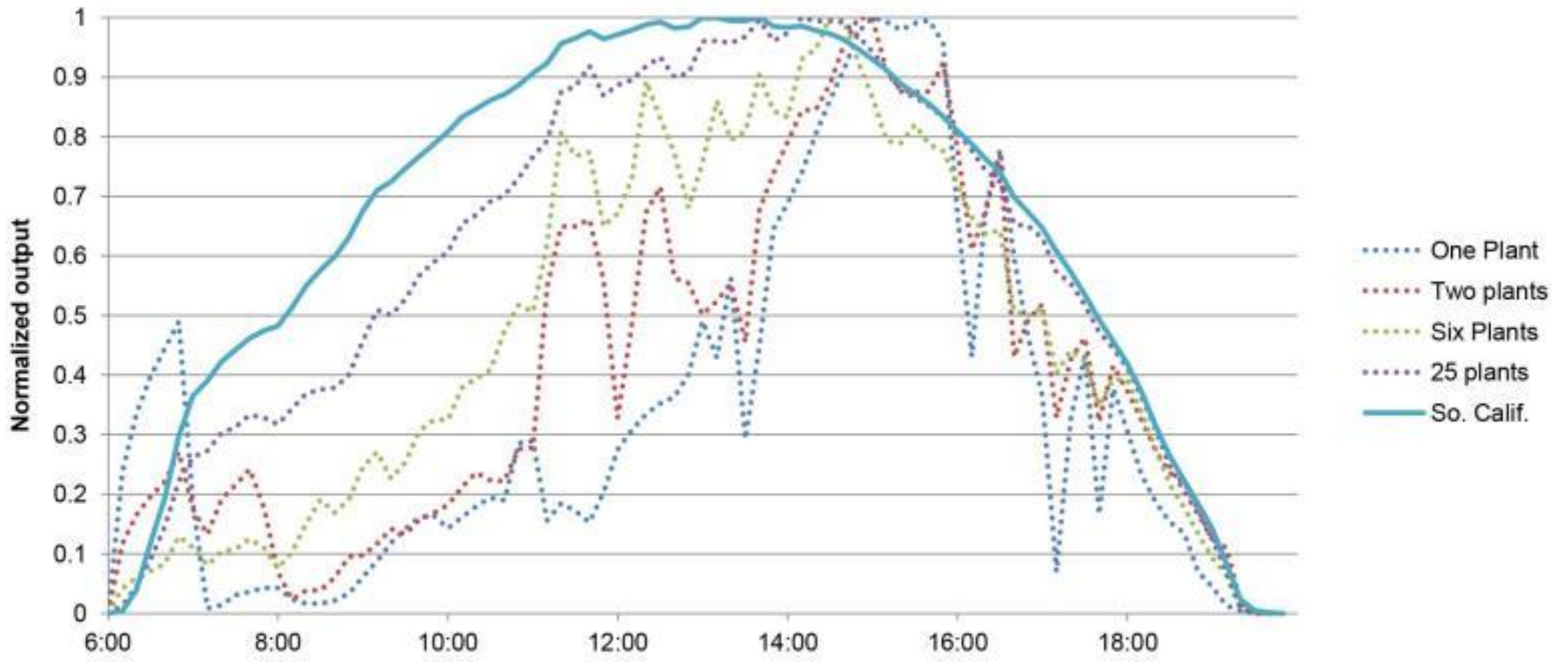
[b] The Xcel/PSCO study also examine the co ... ts and may increase costs of gas supply contracts.

[c] Highest over 3-year evaluation period. 30.7% capacity ... on

[d] Unit commitment includes cost of wind forecast error.

[e] This integration cost reflects a $10/MMBtu natural gas scenario. This cost is much higher than the integration cost calculated for Xcel-PSCo in 2006, in large measure due to the higher natural gas price: had the gas price from the 2006 study been used in the 2008 study, the integration cost would drop from $8.56/MWh to $5.13/MWh.

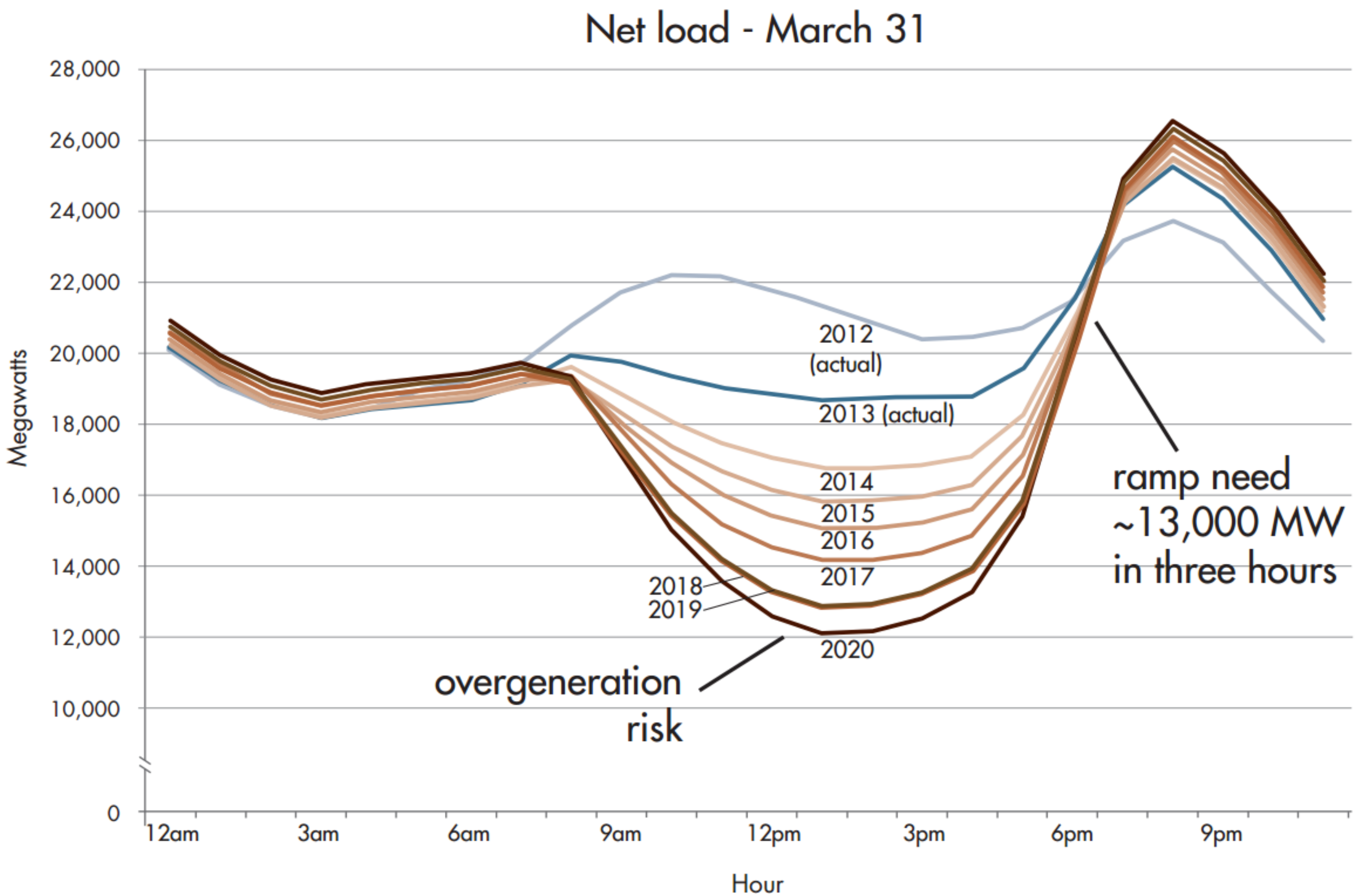
Spatial diversity appears to address very short-term variability



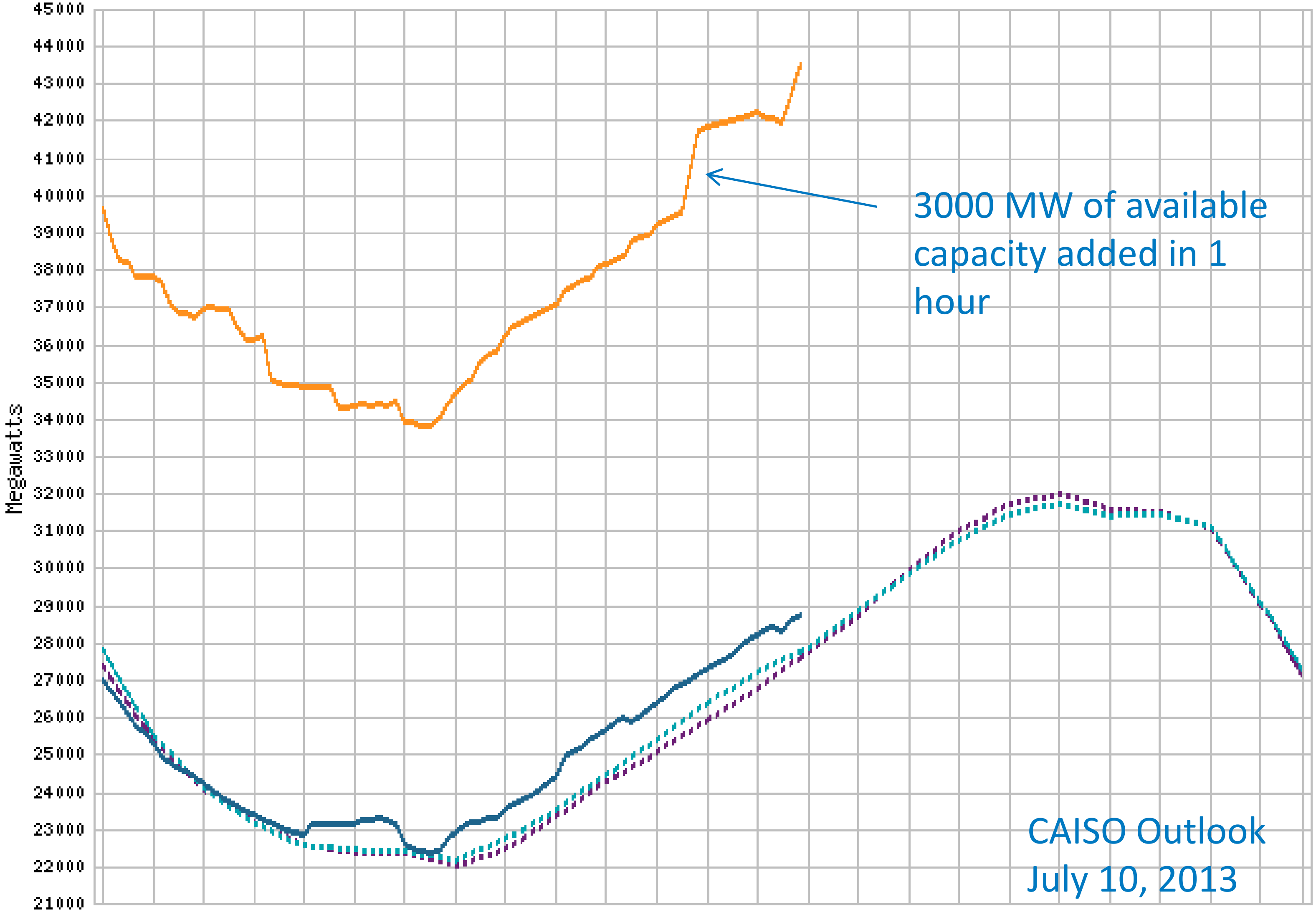
Lew et al. 2013

- For solar *in the bulk power system*, short term variability and instantaneous ramp rates are largely mitigated by spatial diversity

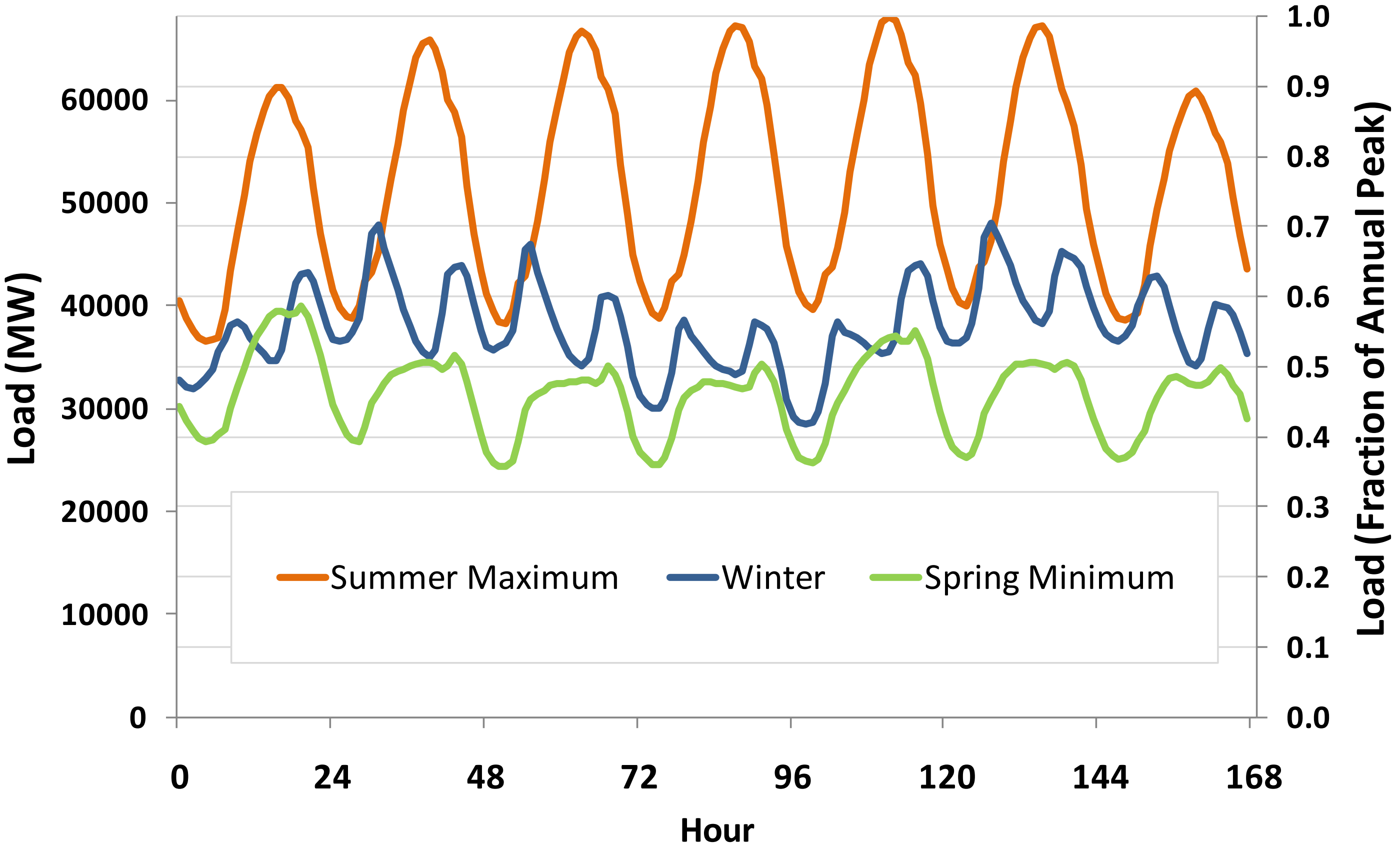
Obligatory Duck Chart



But systems routinely deal with large ramps



ERCOT already does this



Hourly electricity demand for three weeks in the ERCOT (Texas) Grid in 2005. Max ramp rate is over 5,000 MW per hour. Max three hour ramp rate was 12,609 MW.

Conclusions Regarding Ramping and Reserves

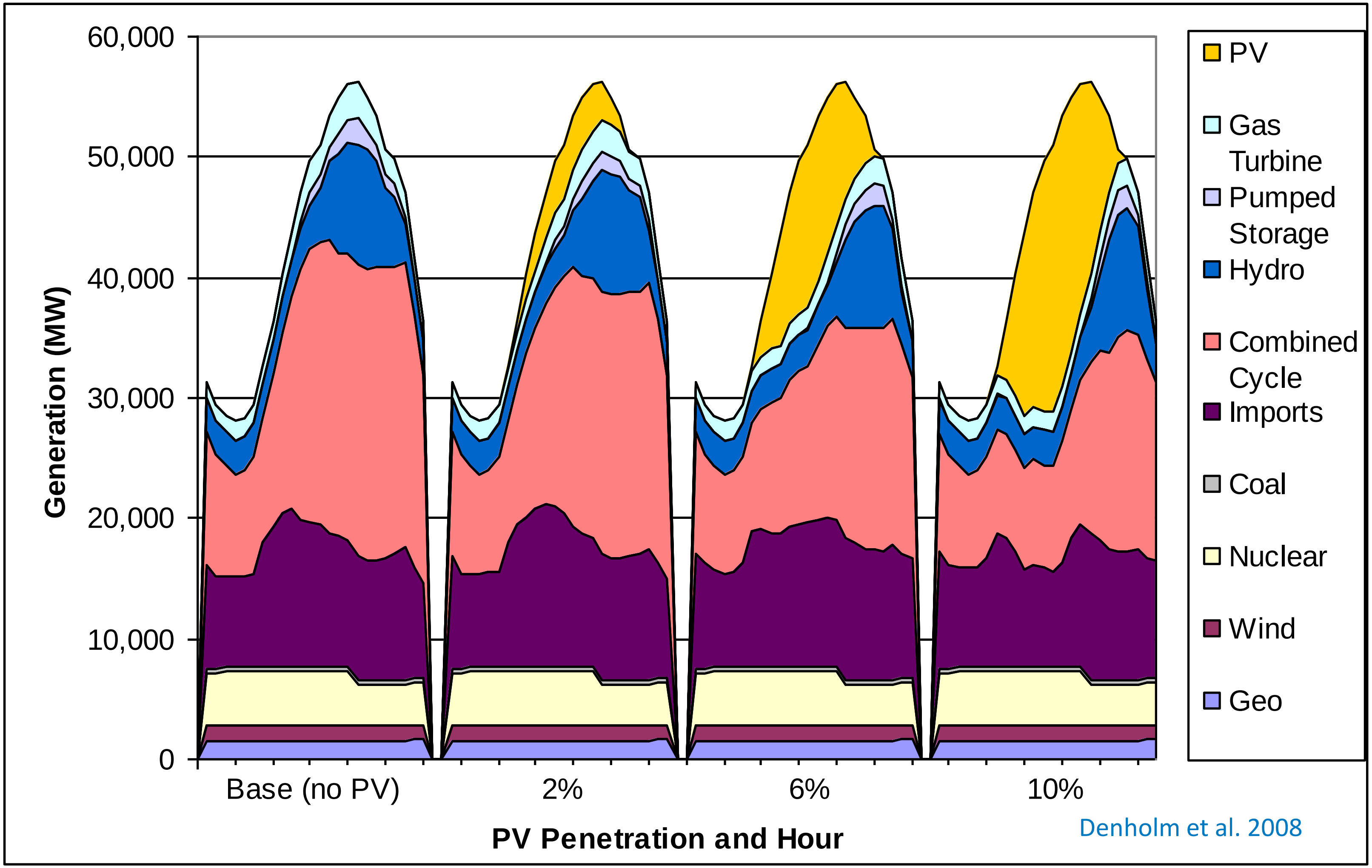
- Spatial diversity smoothes aggregated wind output reducing short-term fluctuations to hour time scales
- Variability can be met with long-duration flexibility reserves compared to high-cost regulation reserves
- Increased variability can be accommodates by existing generator flexibility and other “low-cost” flexibility such as increased balancing area cooperation (balancing wind generation and load over larger areas to “share” the increased variability
- Typically plenty of spare ramping capacity already in the system to meet peak summer demand

14

Economic limits to VG penetration due to ramp range

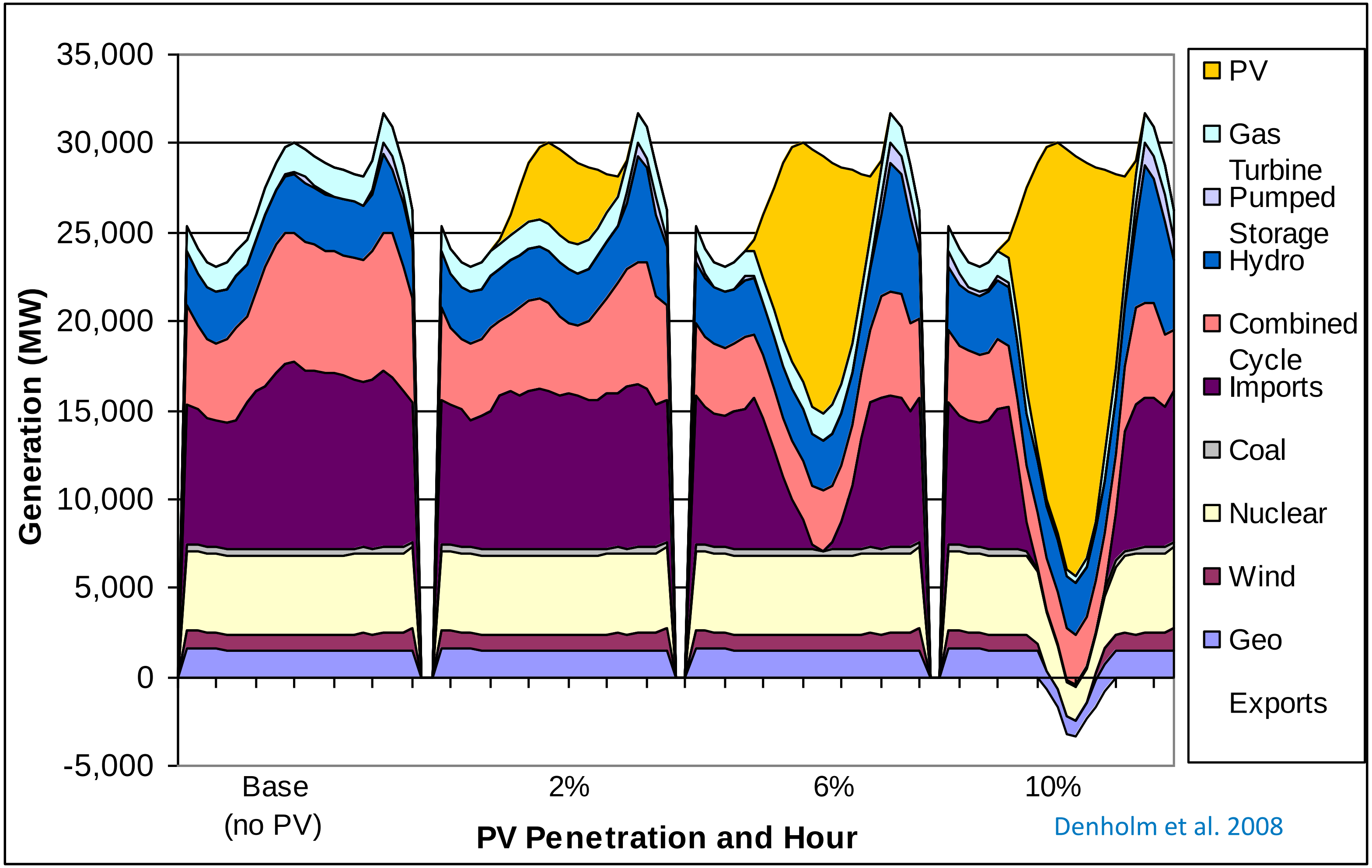
- At high penetration, economic limits will be due to curtailment
  - Limited coincidence of VG supply and normal demand
  - Minimum load constraints on thermal generators
  - Thermal generators kept online for operating reserves
  - Transmission constraints

Example Simulation - Solar PV in the Summer



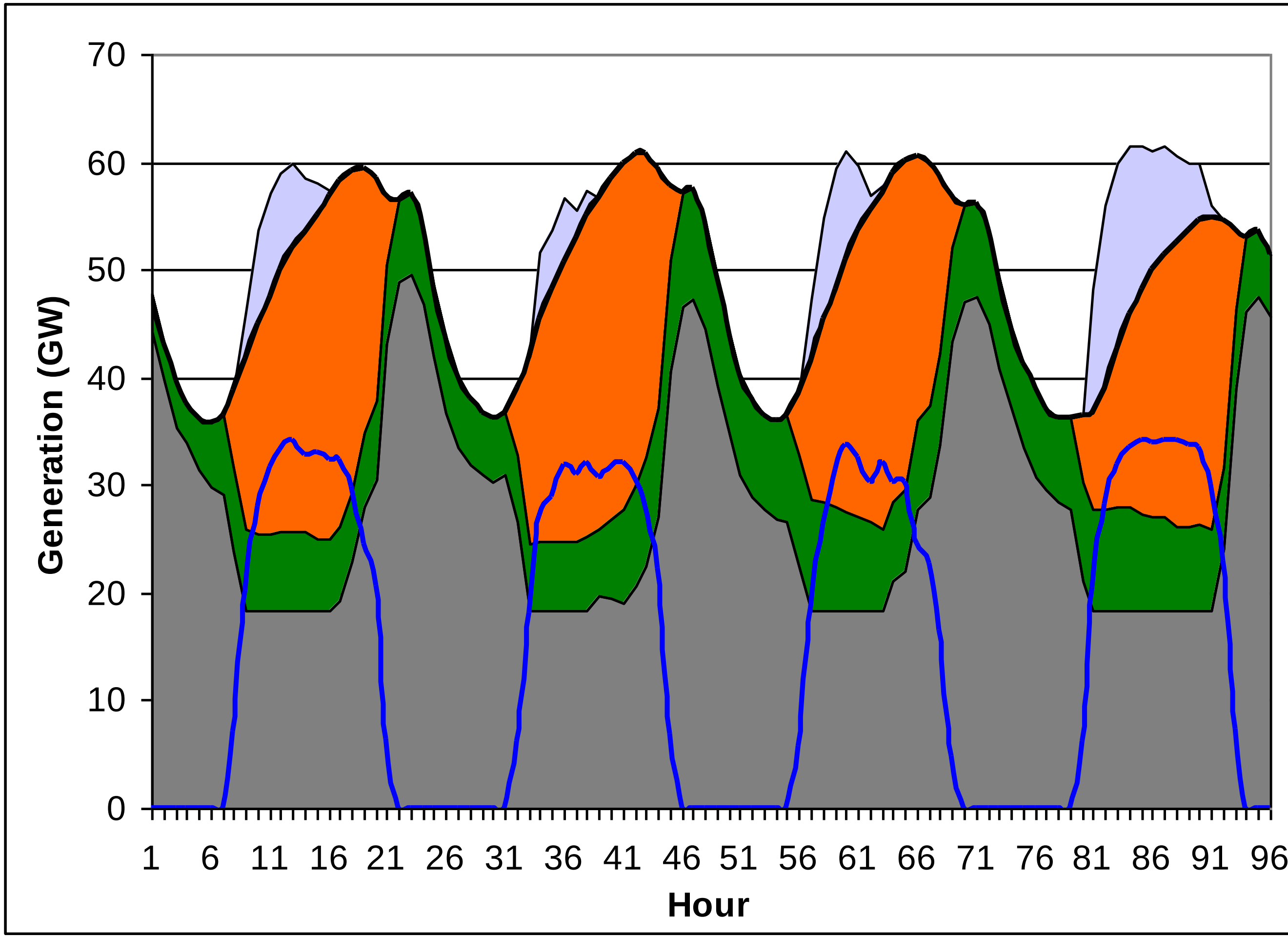
Simulated Dispatch in California for a Summer Day with PV Penetration from 0-10%

Solar PV in the Spring



Simulated Dispatch in California for a Spring Day with PV Penetration from 0-10%

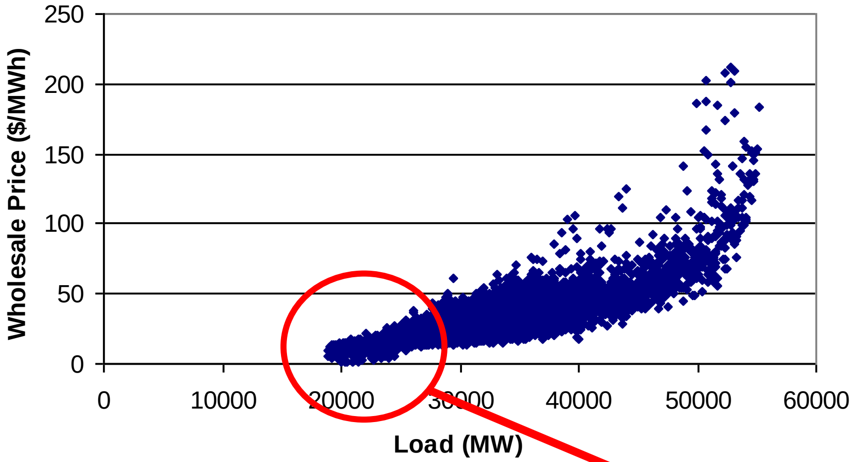
Extreme Case - Zero Value (Curtailed) PV



Denholm and Mehos. 2011

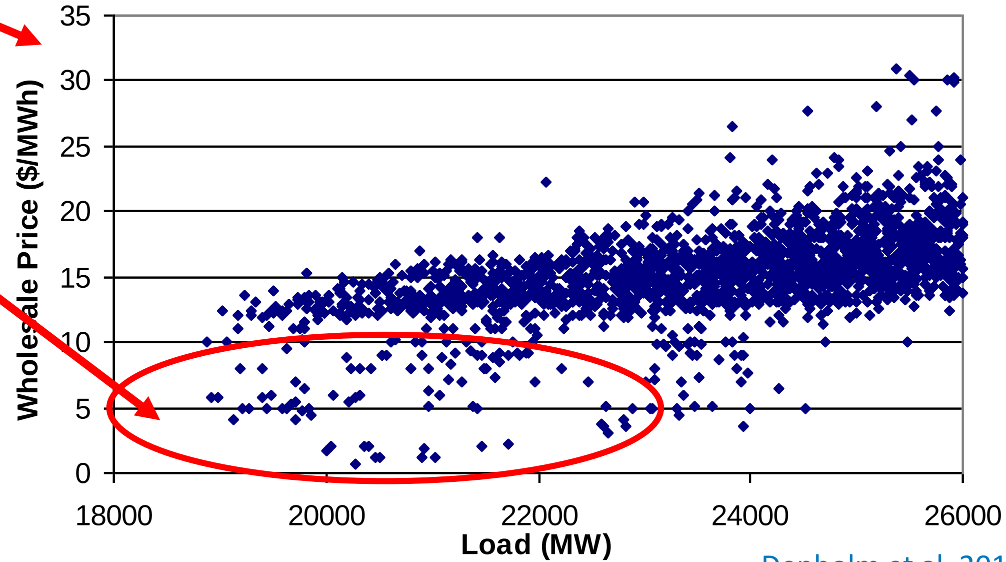
20% Contribution from PV

System Flexibility (Minimum Generation) Limits



Price/Load Relationship in PJM

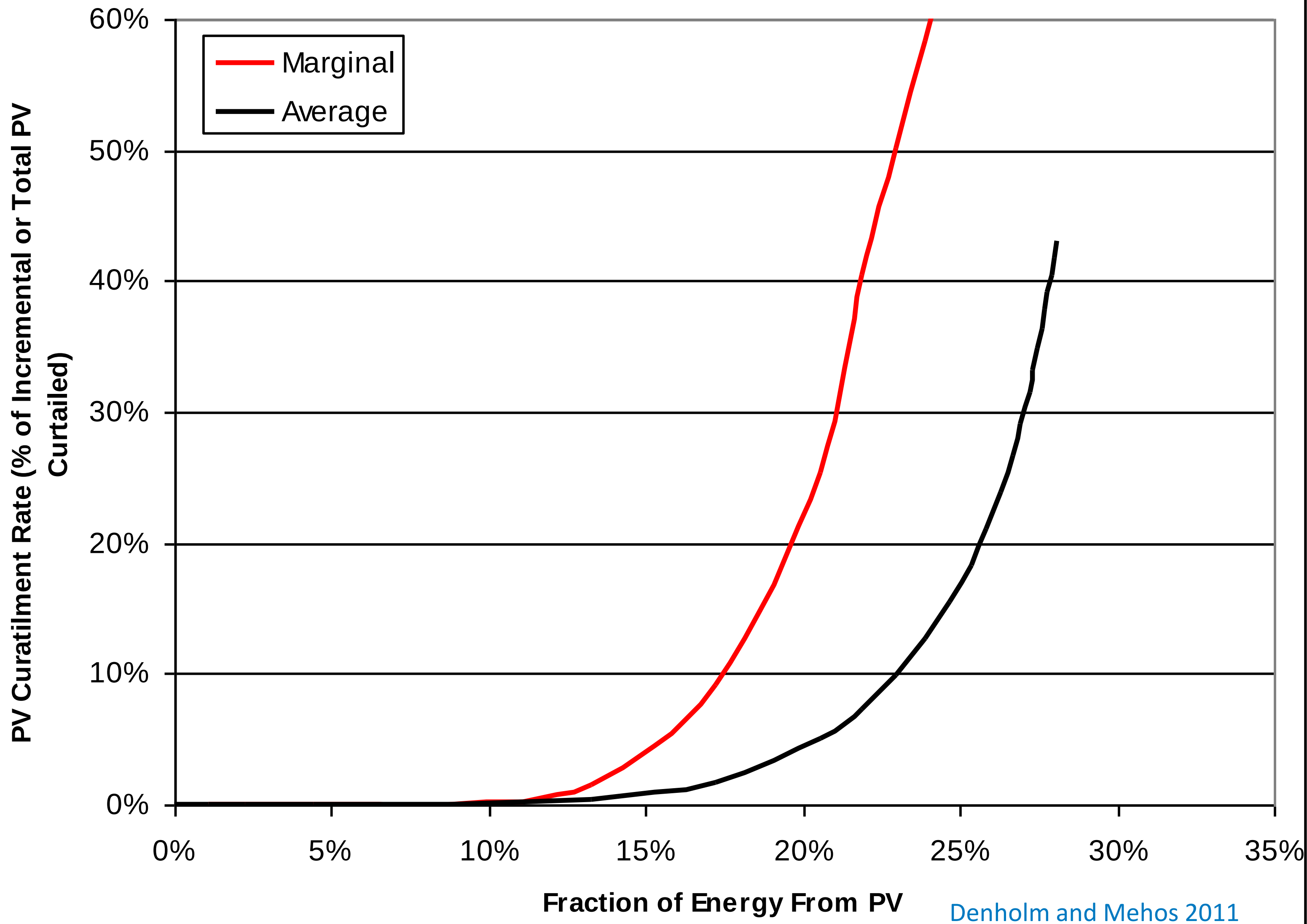
Below Cost Bids



Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind and solar may be curtailed under these conditions.

Denholm et al. 2010

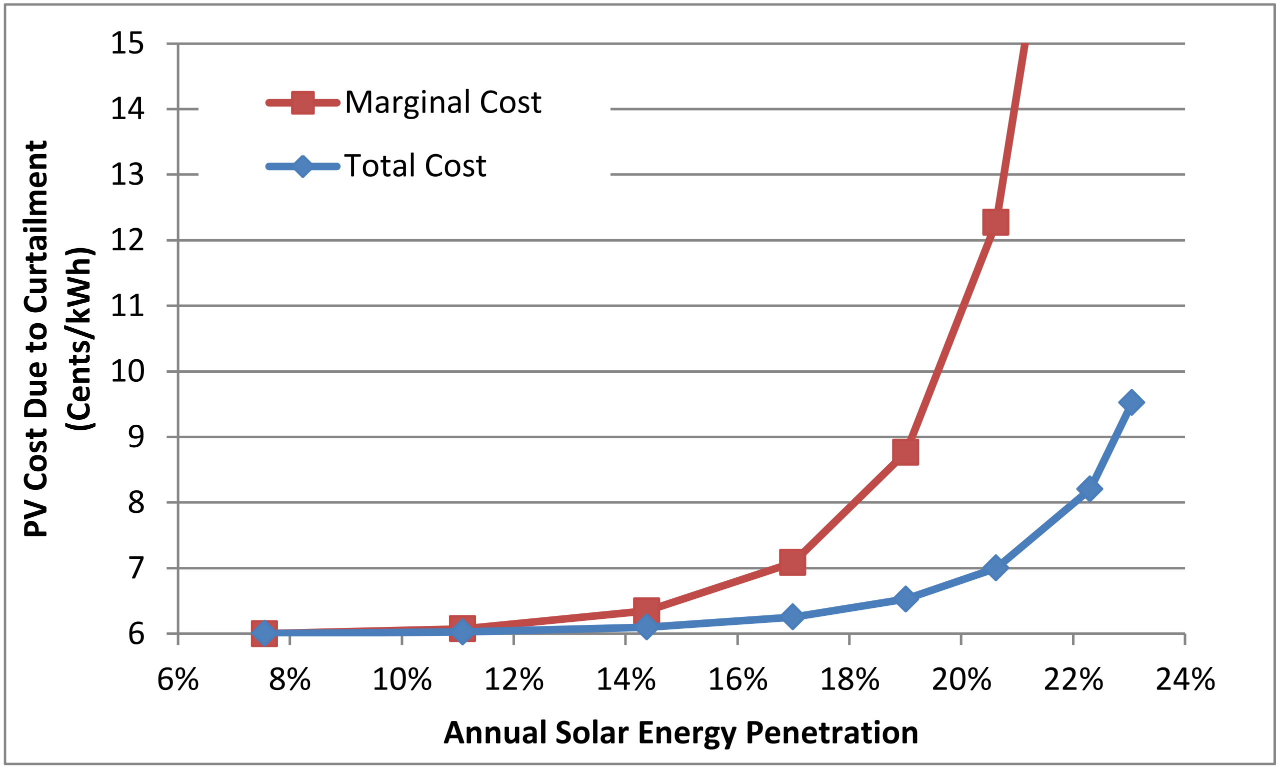
PV Curtailment



Denholm and Mehos 2011

Impact of VG curtailment on LCOE

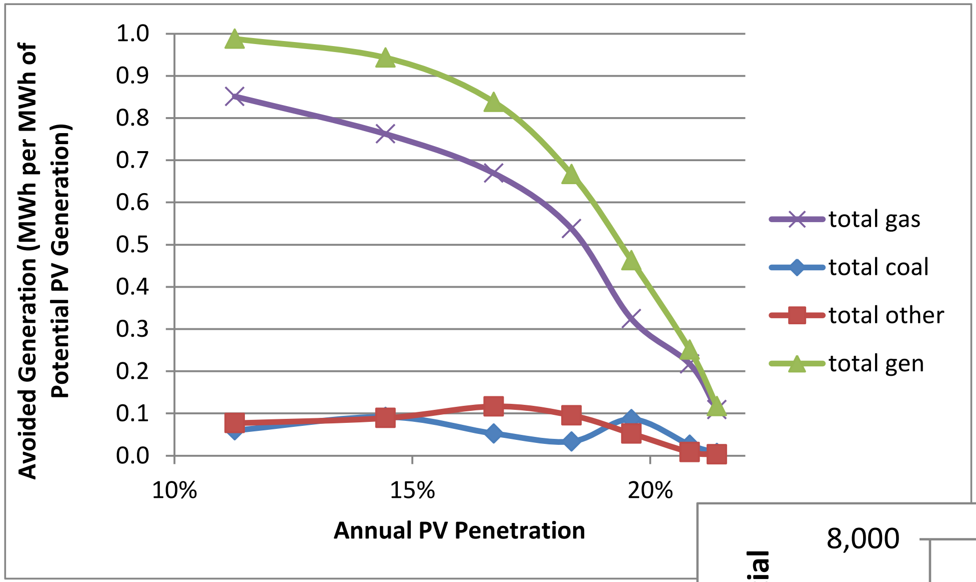
- Curtailed energy means less can be sold and incremental costs of additional PV rise dramatically

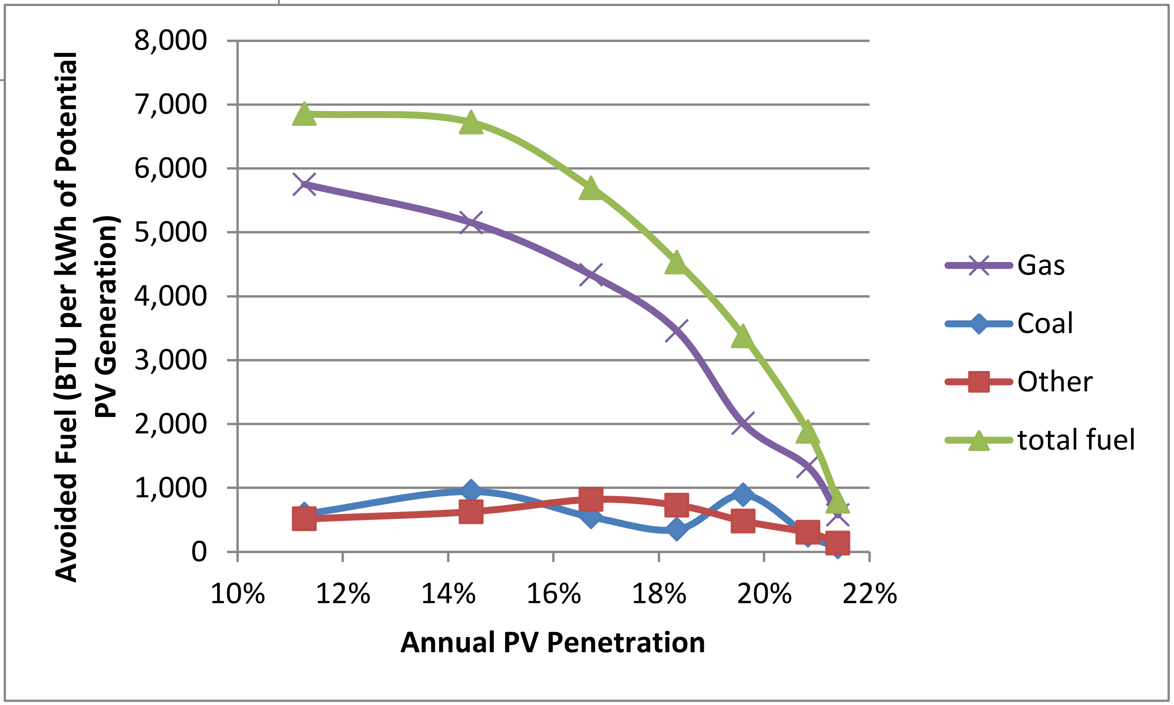


Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with limited grid flexibility

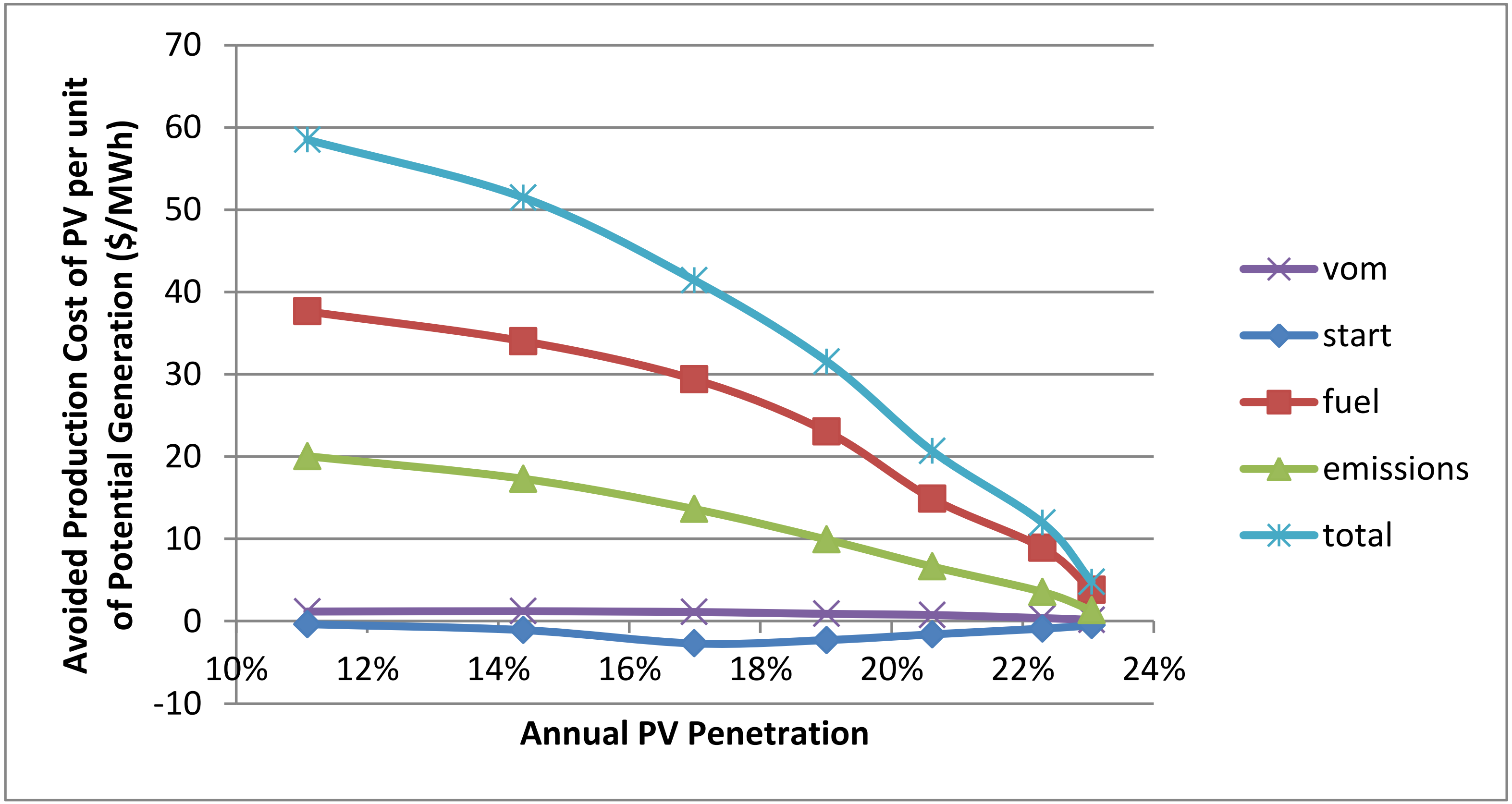
Denholm et al. 2016

Avoided Generation and Fuel



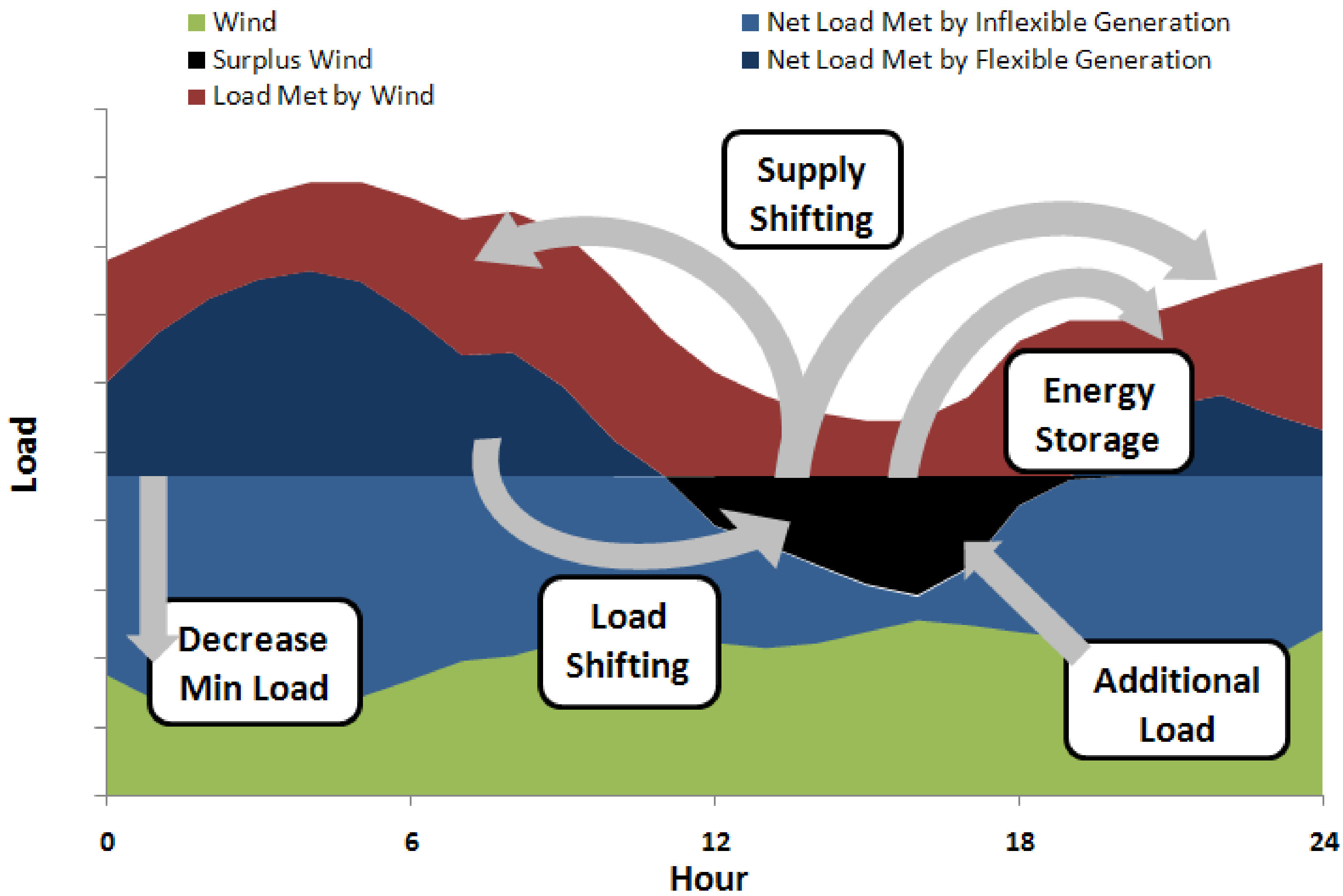


Avoided Generation Costs



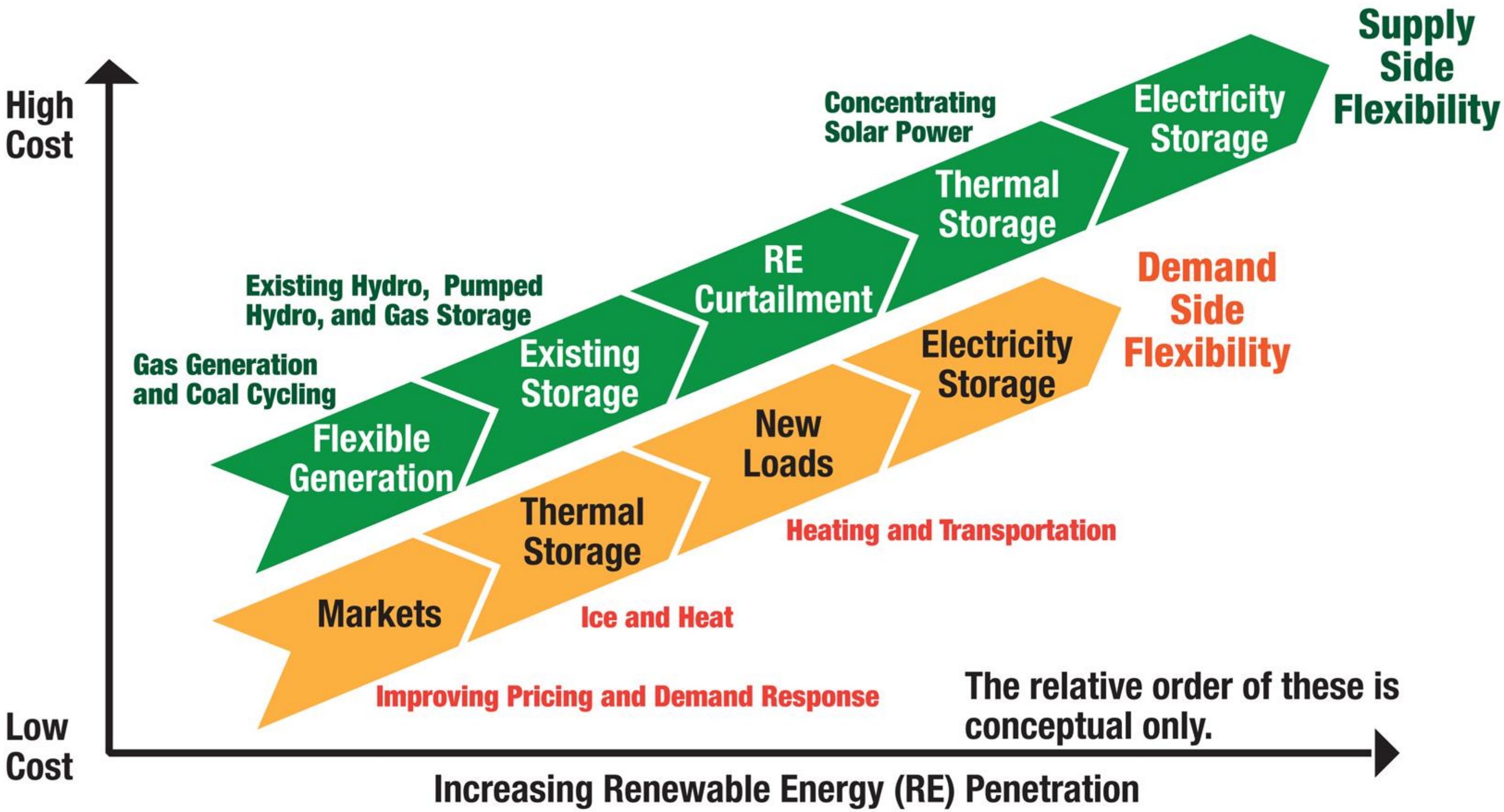
This is the avoided production (variable) costs of PV

Increasing PV Value and Avoiding Curtailment



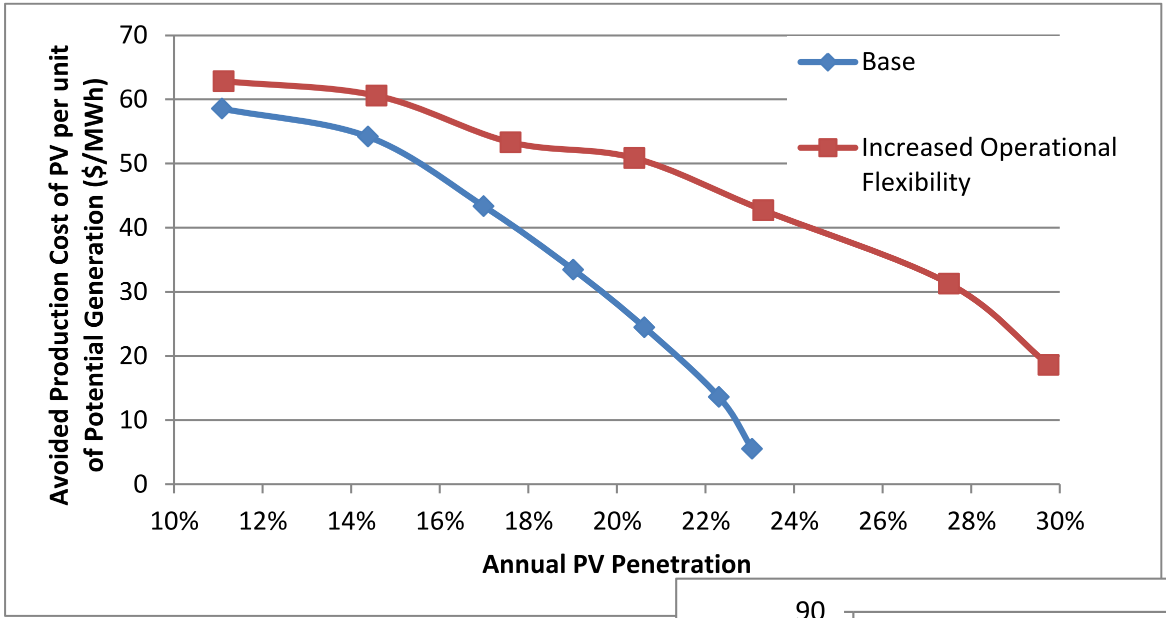
Denholm et al. 2010

Flexibility Supply Curve Concept



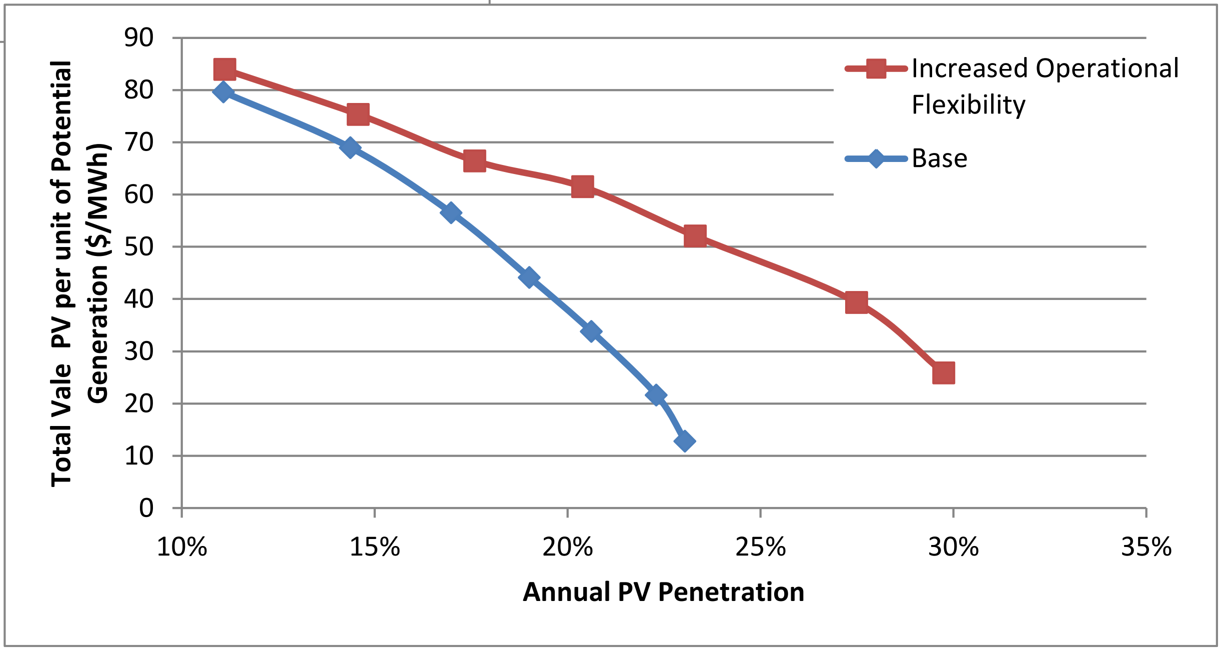
Denholm et al. 2010

Increased Flexibility Increases PV Value

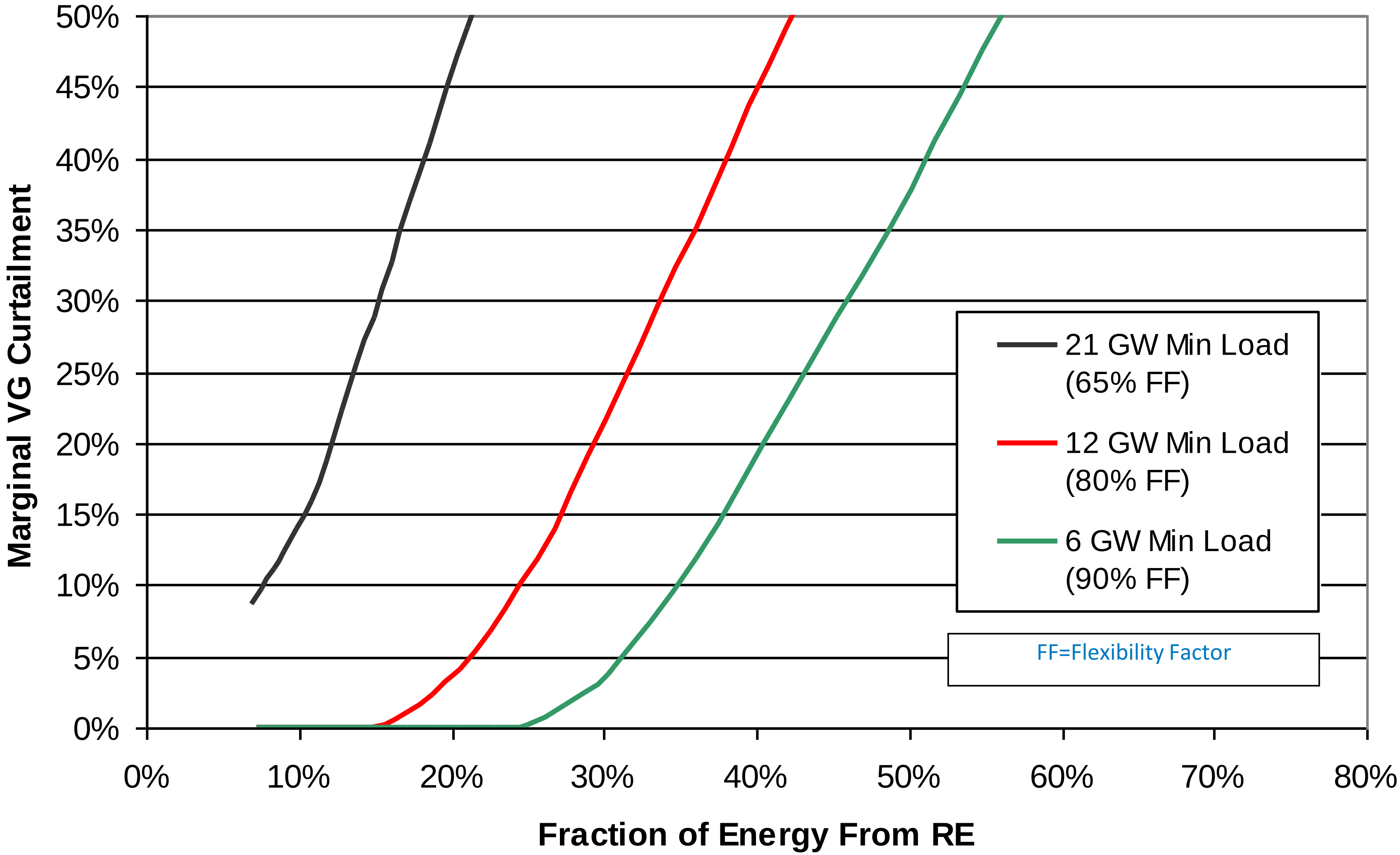


Operational value

Total value

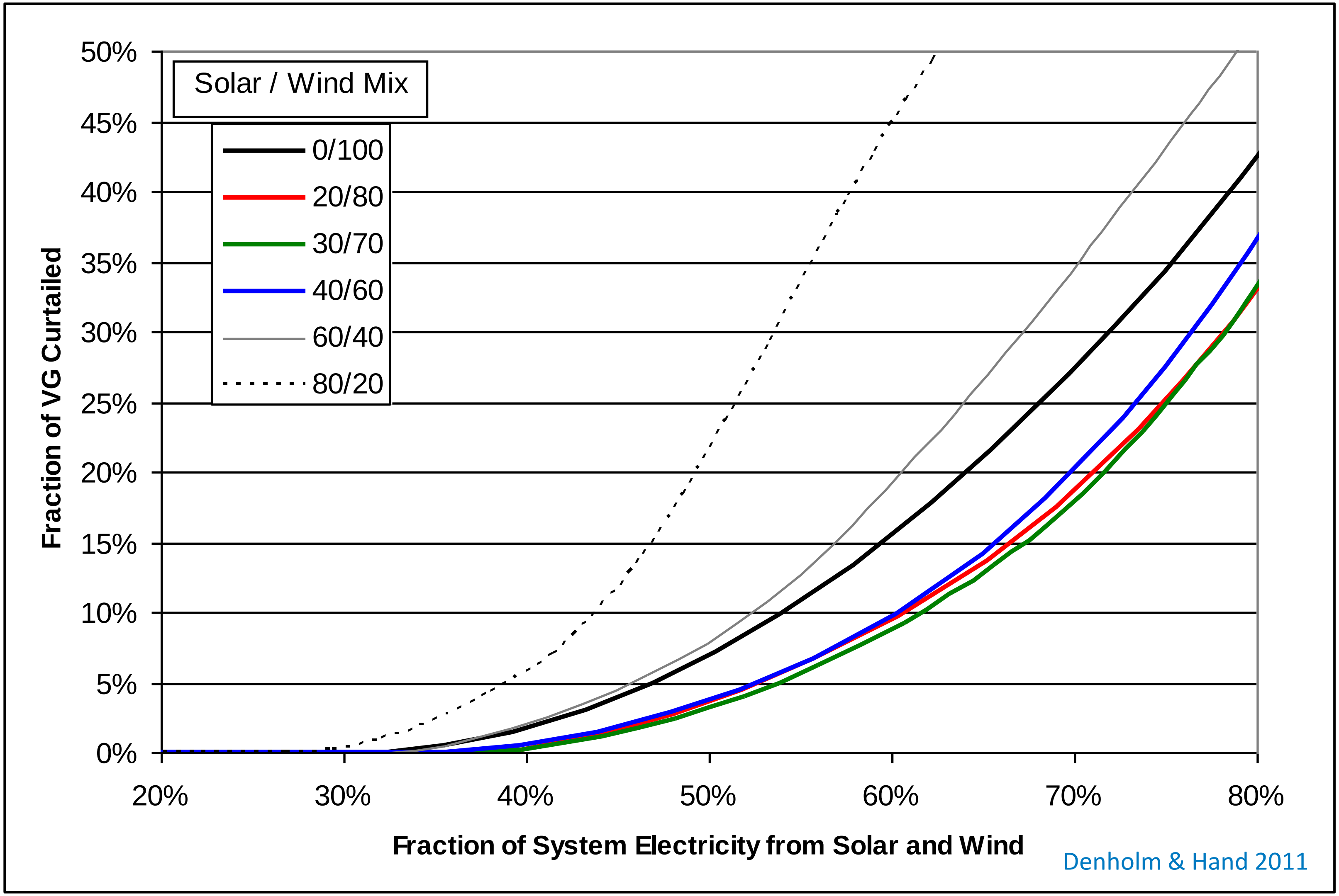


And Wind…



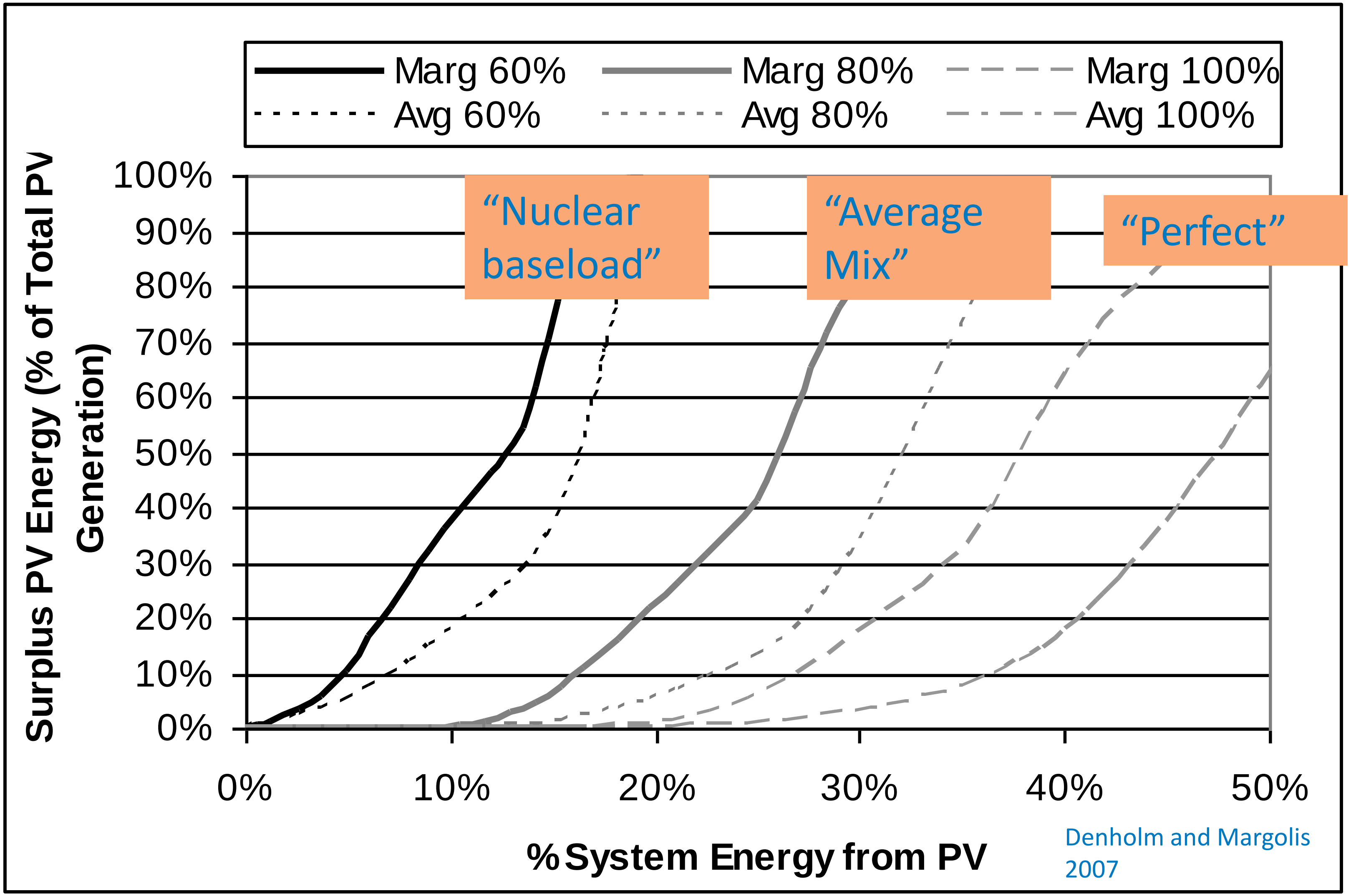
Denholm et al. 2010

Different RE Mixes Improves Supply/Demand Coincidence

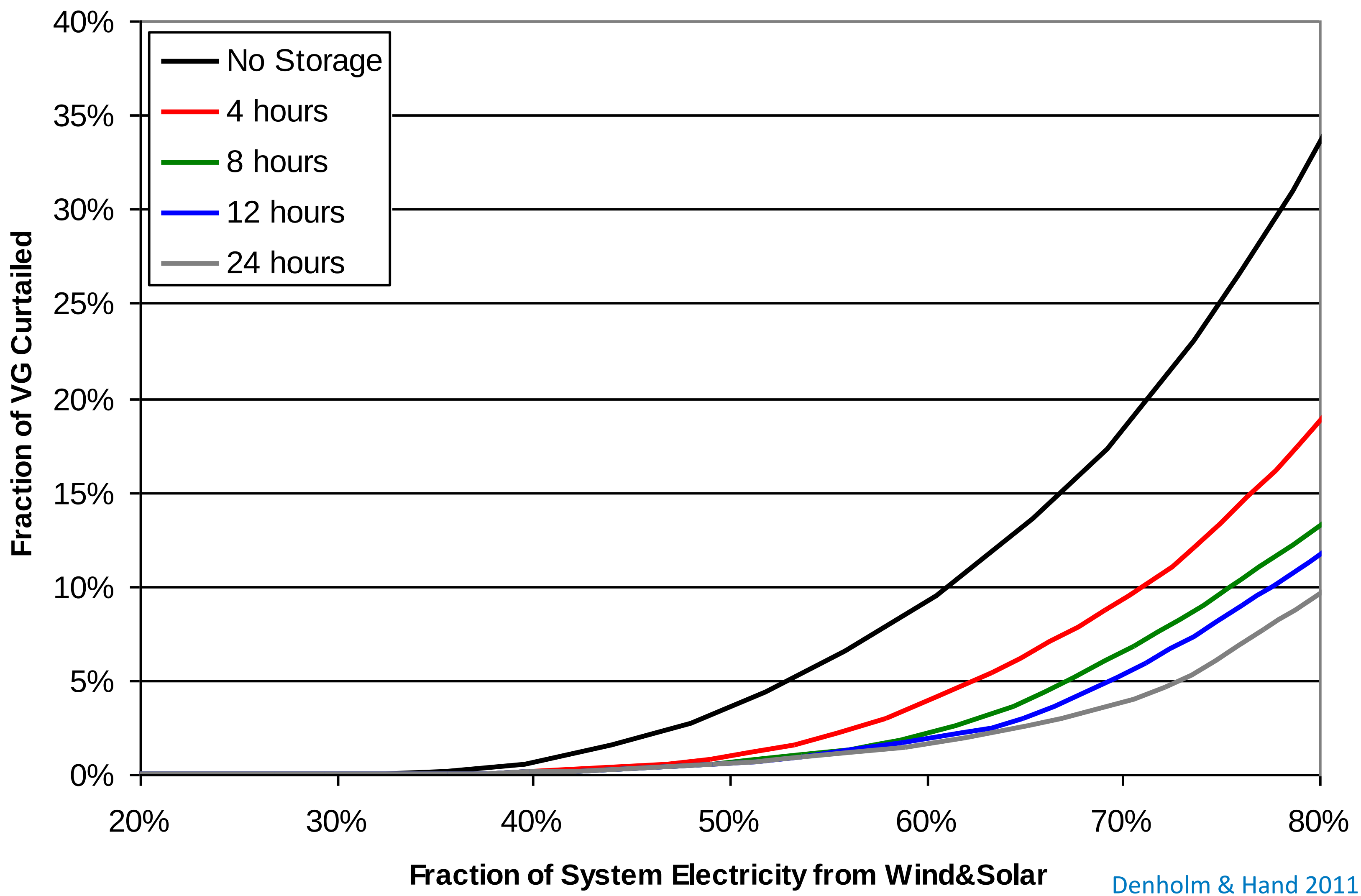


Denholm & Hand 2011

But there are limits with load shifting or storage..



Energy Storage Can Reduce VG Curtailment



Denholm & Hand 2011

Instead of Conclusions, My Opinions

- The scary problems of ramp rates, uncertainty and variability are on there way to being solved problems
- The limits to RE deployment are based on the economics of curtailment driven by system flexibility and supply demand coincidence
- Daily ramp range is the primary limit to economic VG deployment

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