Third Annual Trottier Symposium on
Sustainable Engineering, Energy and Design

The Trottier Institute for Sustainability in Engineering and Design (TISED) and the Institut de l'énergie Trottier (IET) present:

Renewables: What holds us back? What moves us ahead?

March 8 & 9, 2016

Montréal, Québec, Canada

#energyhorizon

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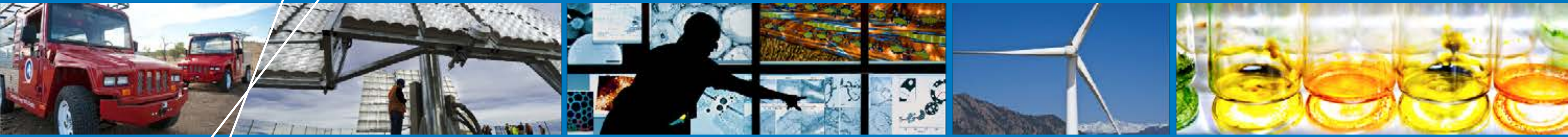
TISED Trottier Institute for Sustainability in Engineering and Design

IET INSTITUT DE L'ÉNERGIE TROTTIER

POLYTECHNIQUE MONTRÉAL

Do we really need storage to operate the renewable grid of the future?



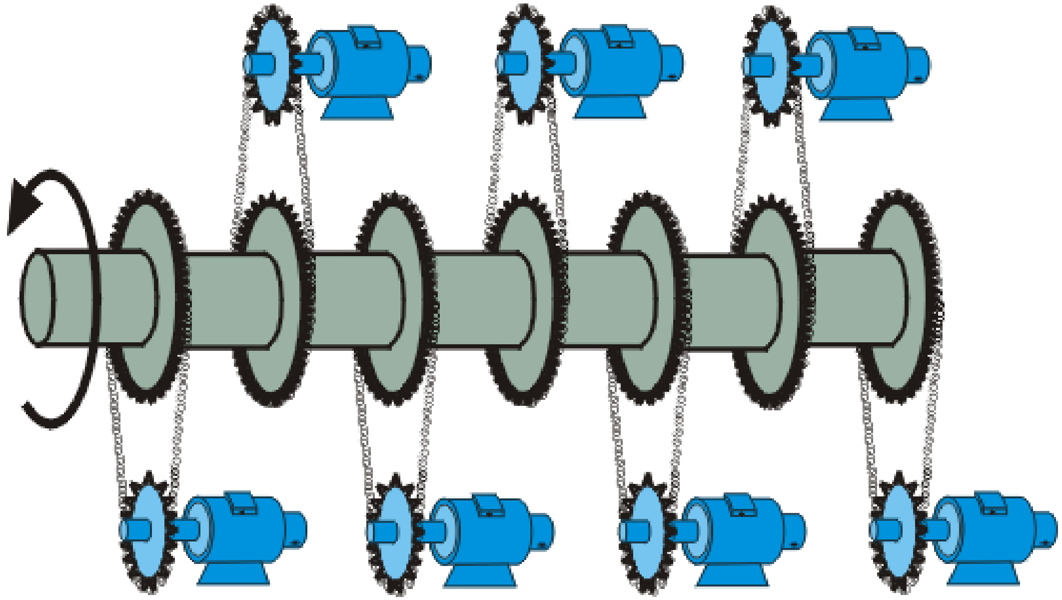
Paul Denholm

Third Annual Trottier Symposium in Sustainable Engineering, Energy and Design

March 8, 2016

What is the Electric Grid?

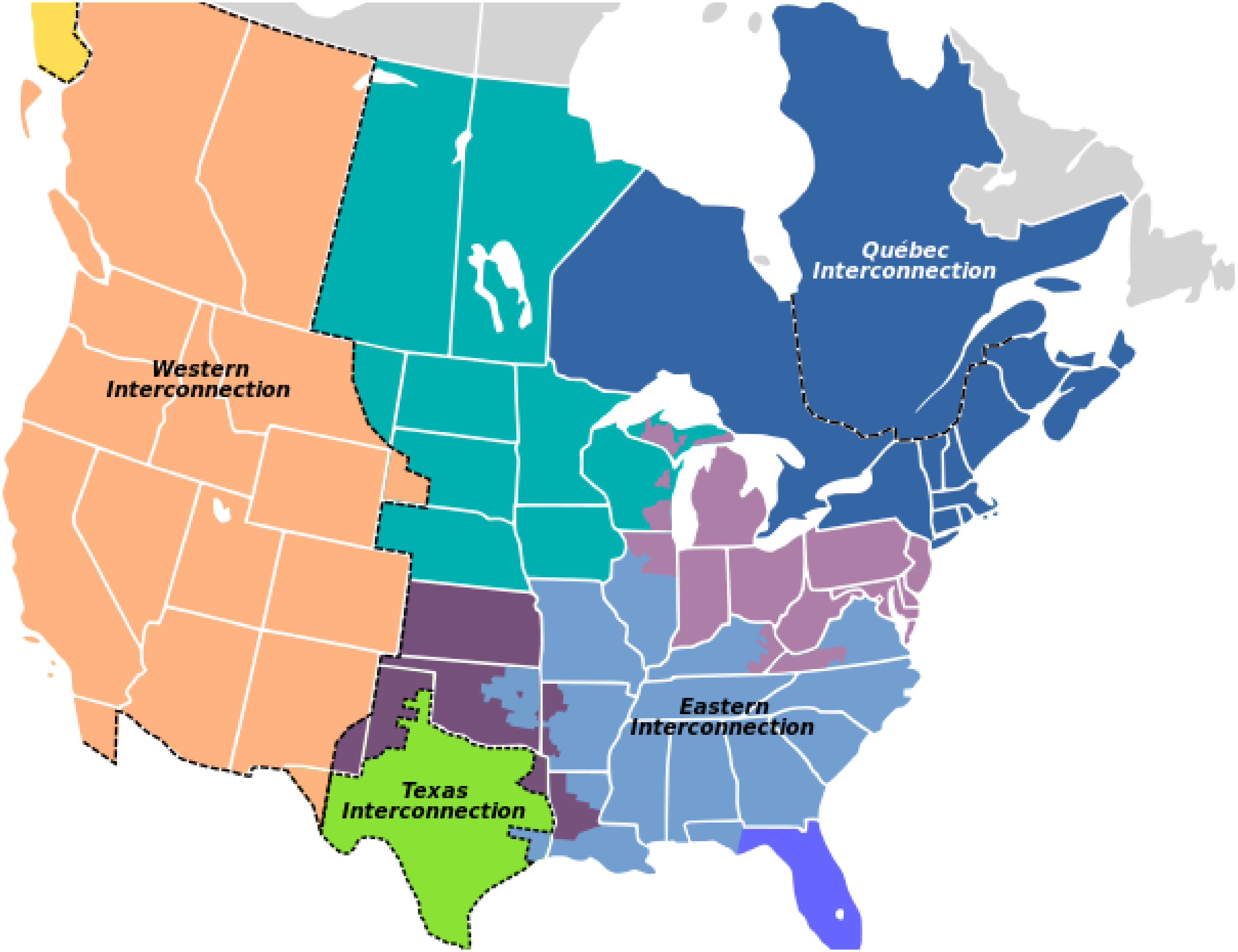
A very large rotating machine spinning at 60 Hz



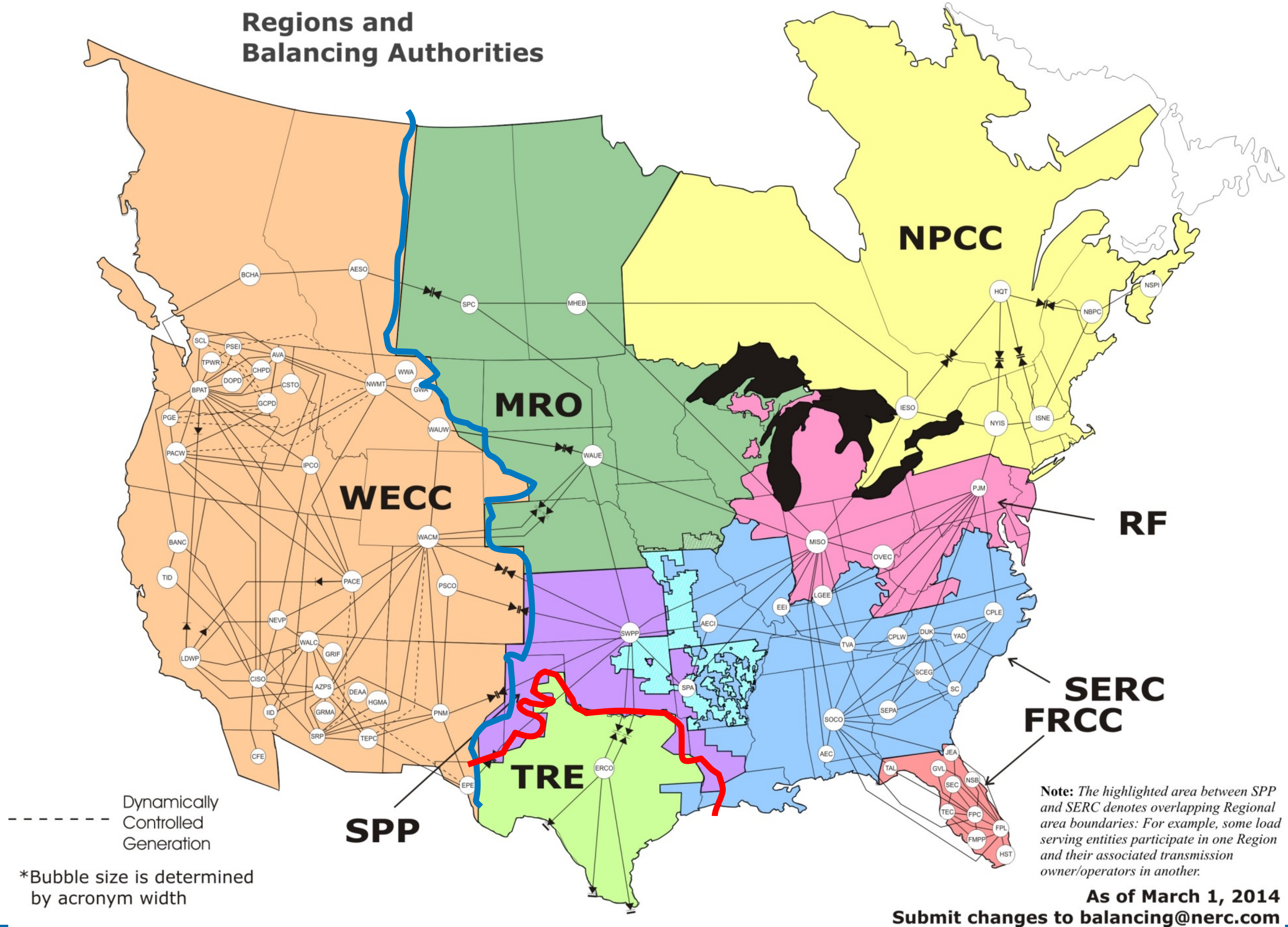
Source: Mullane & O'Malley

- **Features –**
  - Supply must always meet demand (sort of)
  - Large hourly and season variations in electricity demand
  - Operating reserves to maintain system stability and reliability

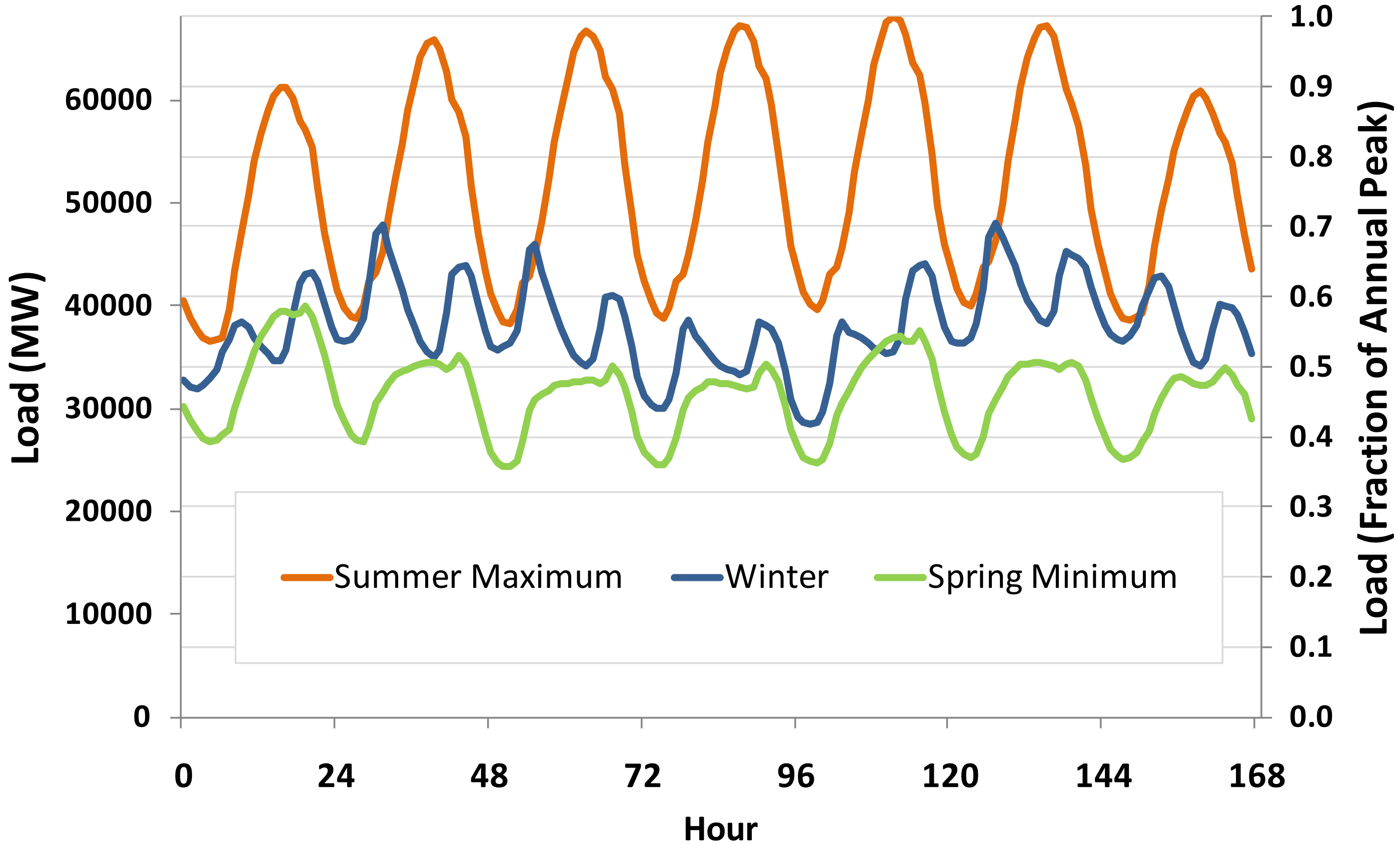
Four Independent North America Grids



And Many Balancing Areas

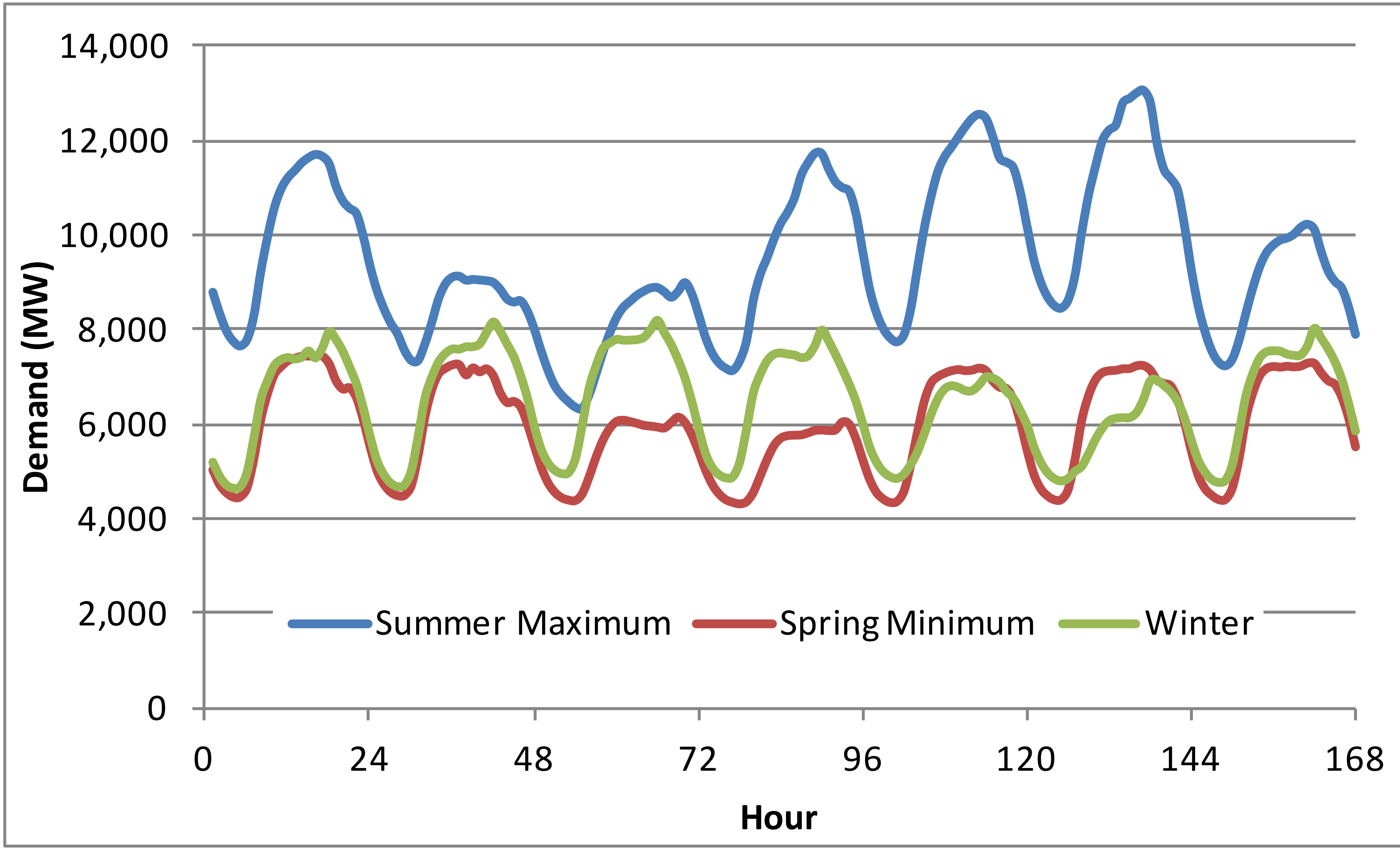


Each Balancing Area Must Constantly Balance Variation in Demand



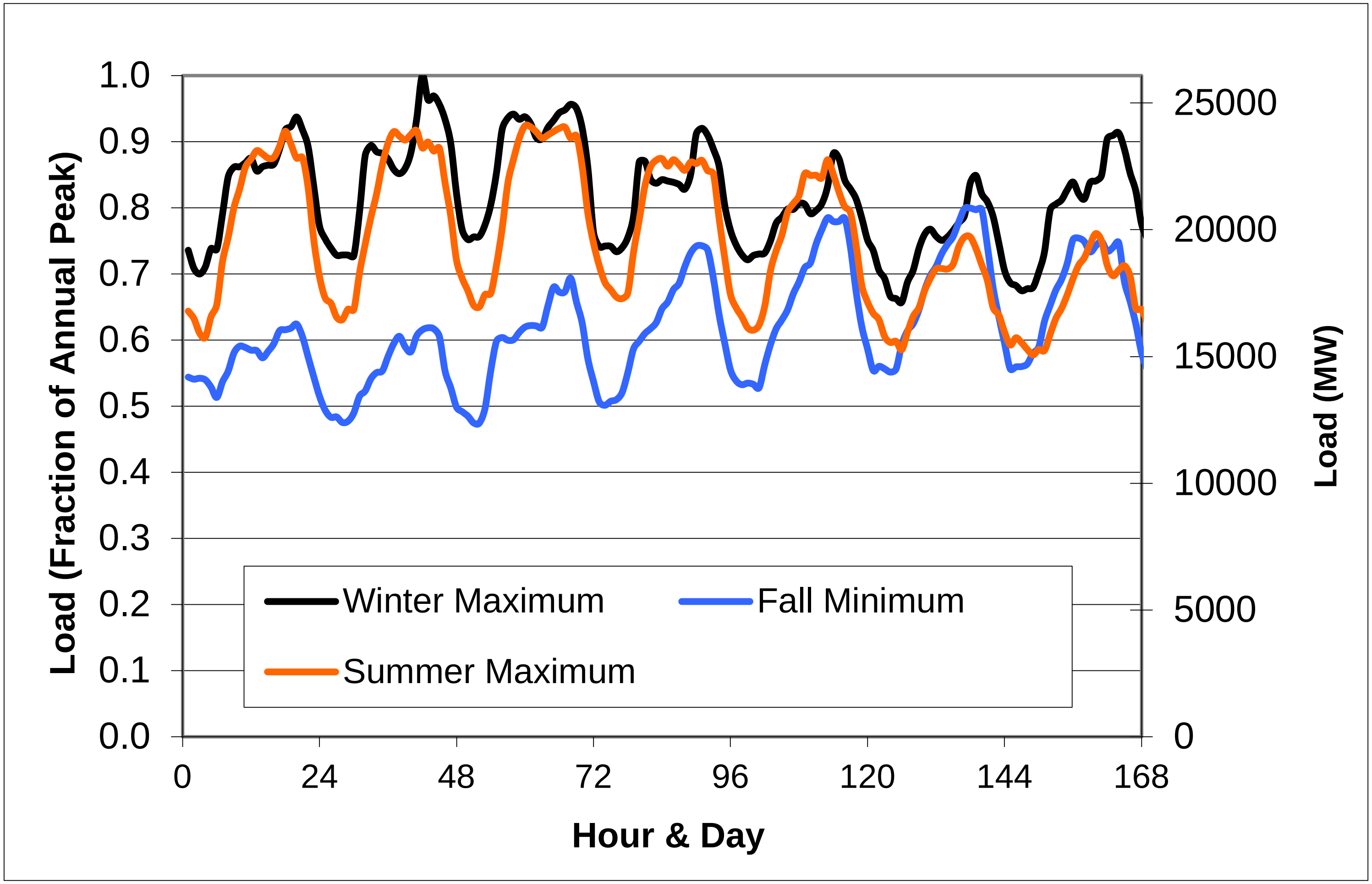
Hourly electricity demand for three weeks in the ERCOT (Texas) Grid in 2005

Demand Patterns Similar for Much of the U.S.



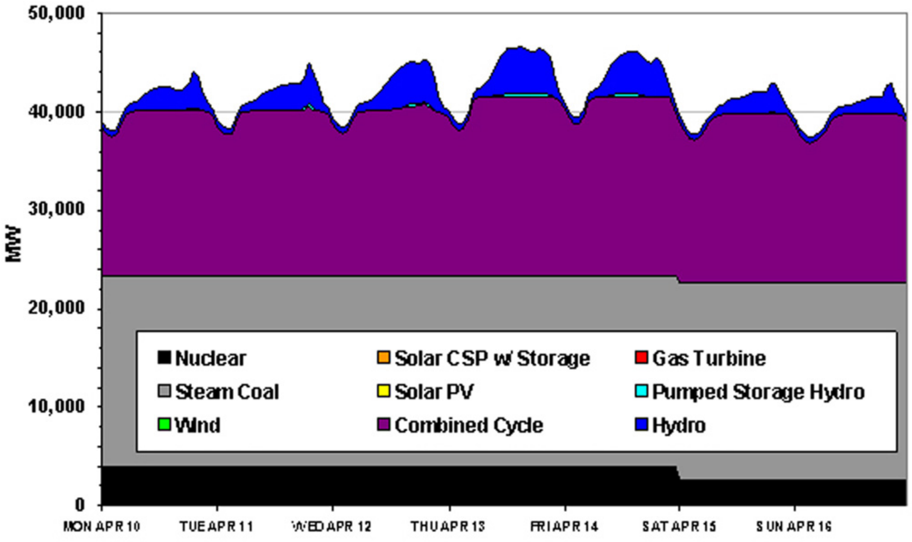
NYC (Con Ed) Demand in 2005

A Few Locations in North America are Winter Peaking

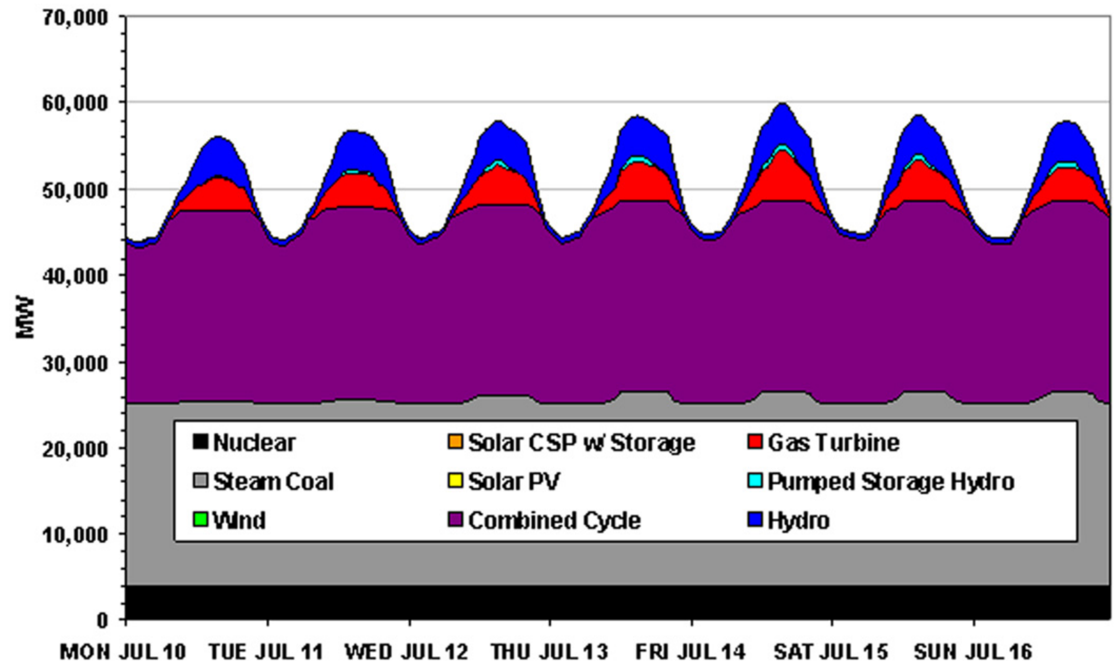


Ontario - 2015

Traditional System Operation



Variations in demand traditionally met by thermal and hydroelectric plants



GE Energy
2010 (WWSIS)

How Can We Possibly Make the Grid Work with Lots of VG?

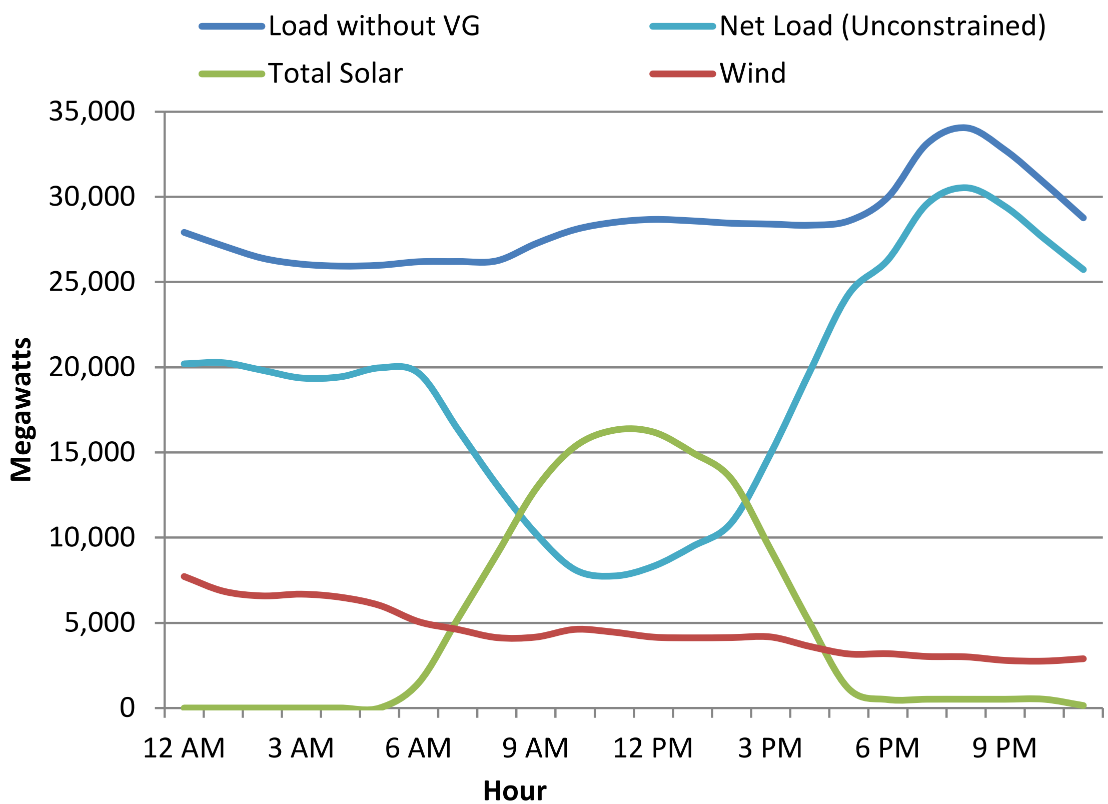
1. **Claim it isn't possible, or it is possible but lots of storage needed**

2. **Just build lots of renewables and see what happens**

3. **Perform actual science, math, engineering, and analysis**

Framework – Net Load

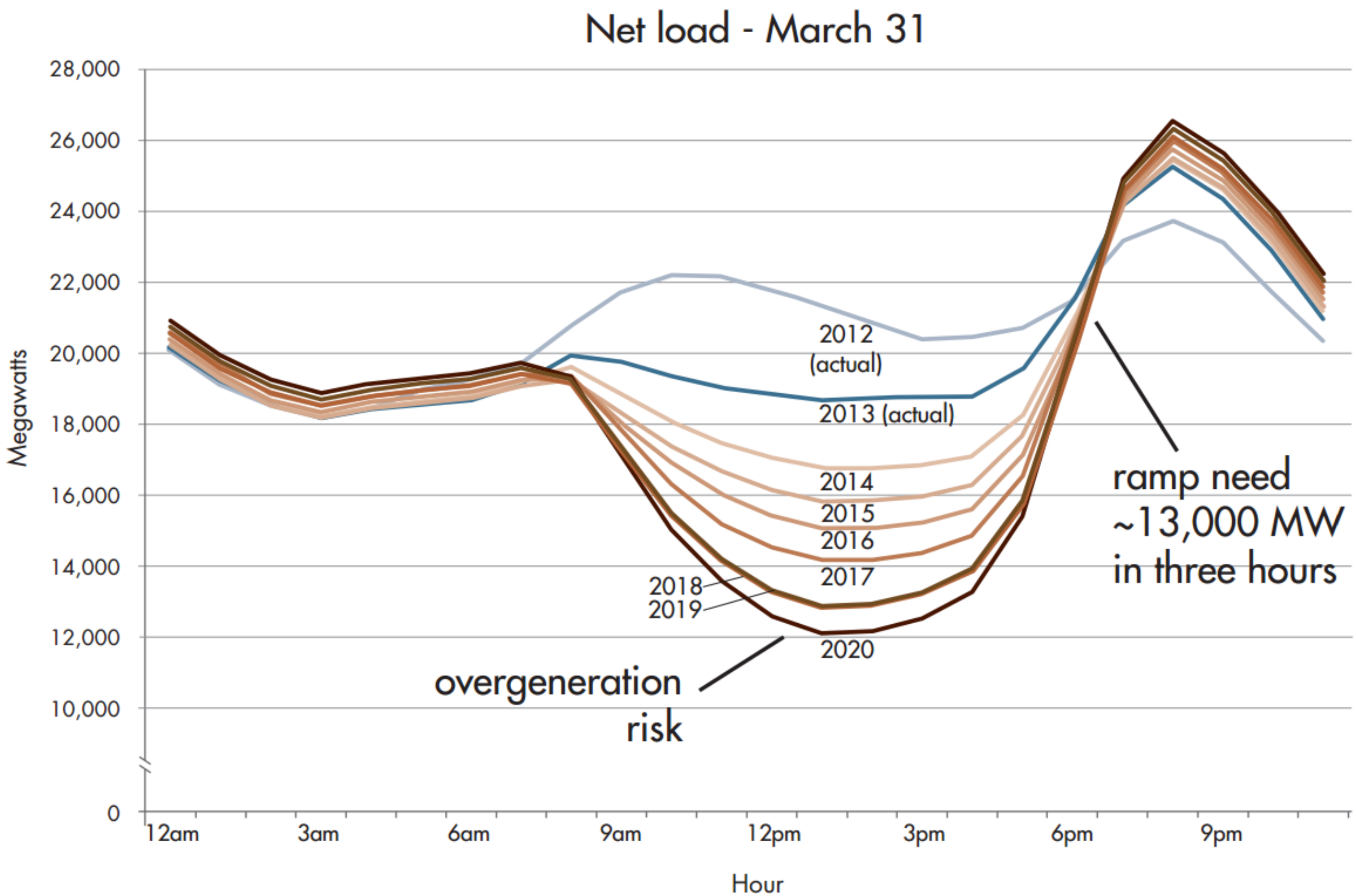
Net load- what's left over when you add wind and solar



Load, solar, and wind profiles for California on March 29 in a scenario with 11% annual wind and 11% annual solar assuming no curtailment

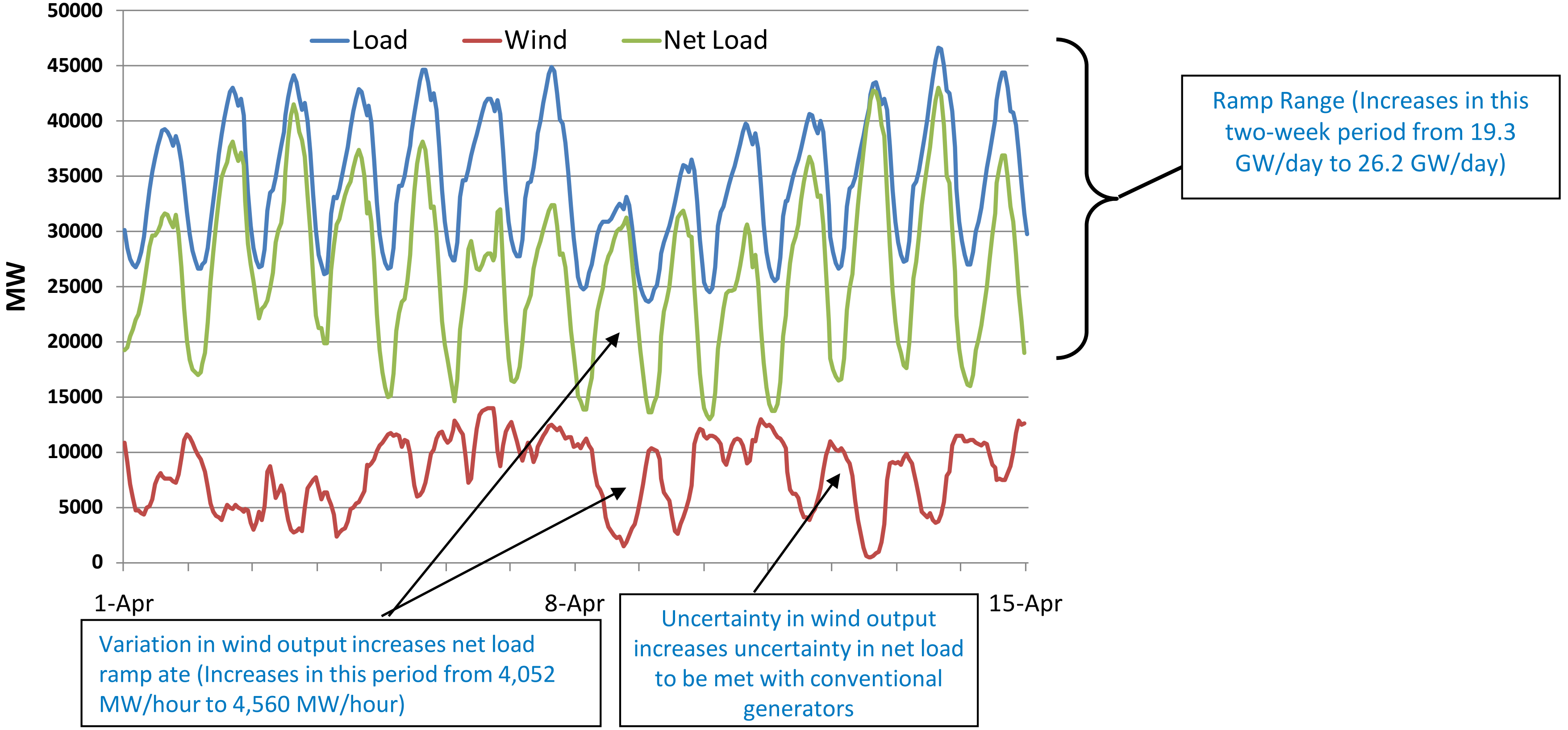
Denholm et al. 2016

The Most Famous Version



Source: CAISO 2013

Impacts of Renewables on the Grid



Four major impacts of variable generation (VG) on the grid:

1) Increased need for operating reserves
2) Increase in hourly ramp rate
3) Increase in uncertainty of net load
4) Increase in ramp range

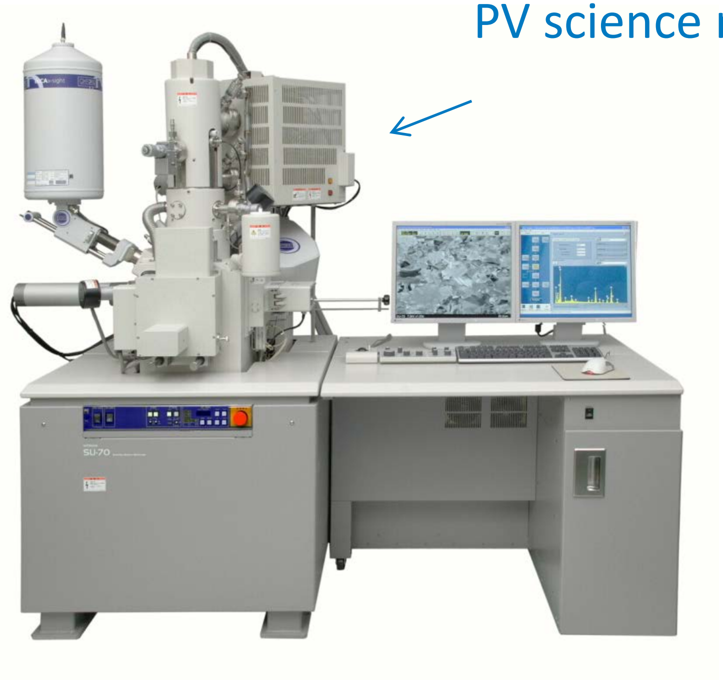
Quantifying the Impacts of Renewables on the Grid

- **How much fuel is actually saved?**
- **What is the actual economic value?**
- **Is “backup” needed? Doesn’t this add costs and emissions?**
- **How much renewables can even be used?**
- **If the wind blows more at night do you need to store some for use in the day?**
- ***Is storage needed?***

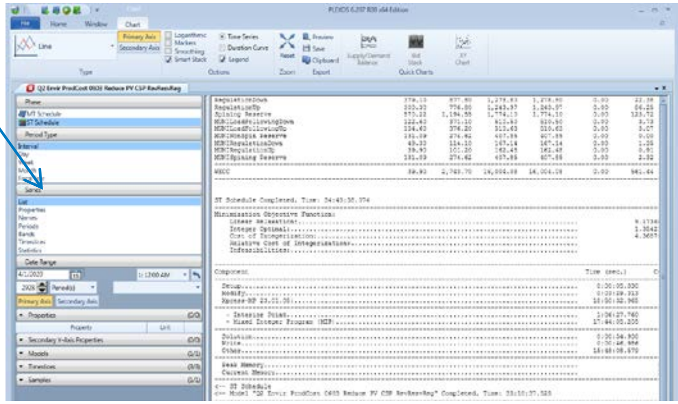
How We Do Grid Integration Science

- Software that simulates a large interconnected grid considering thousands of generators, and transmission

PV science machine



Grid integration science machine



Grid Simulation Requirements

- **Very expensive commercial software package that includes existing generation mix, transmission system**
  - ~10 Vendors/Software packages
  - Annual licenses routinely exceed $100k
  - Massive database
  - ~5 hours to >400 ***days*** per simulation
- **Names include**
  - "security constrained unit commitment and economic dispatch"
  - "production cost model"
  - "chronological dispatch model"

Steps to Performing a Realistic Analysis of Renewables on the Grid

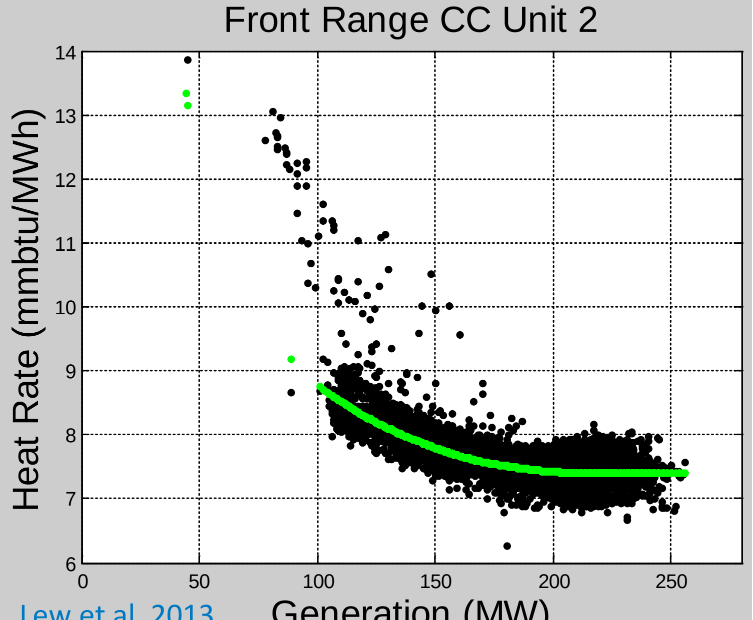
1. Acquire detailed solar and wind data

- Use lots of wind and solar simulations to consider spatial diversity
- Sub-hourly wind and solar data across large amounts of the U.S. didn’t exist before a few years ago

2. Calculate change in reserve requirements

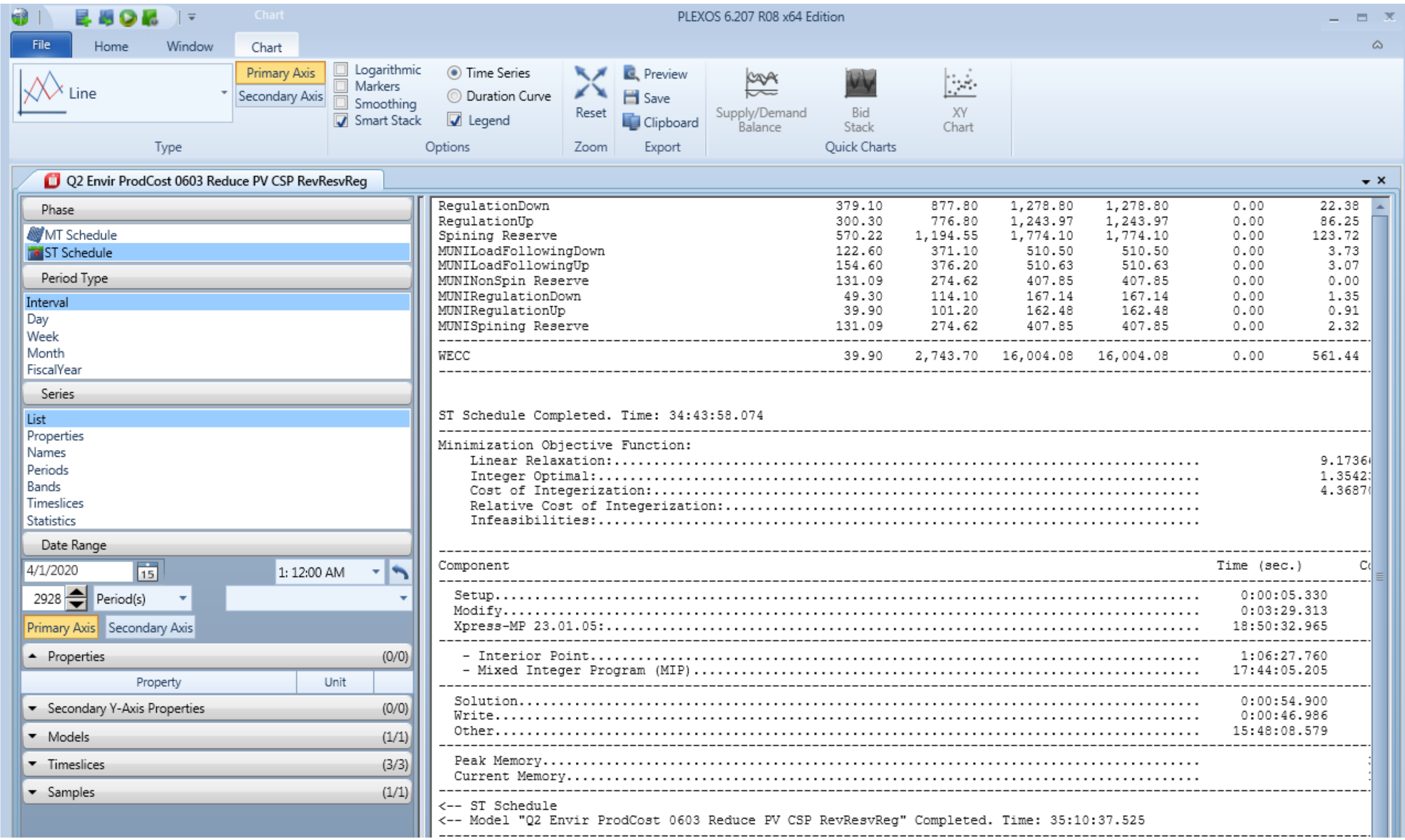
- Use standard industry methods for calculating changes in regulation reserve requirements based on variability
- Consider new methods of addressing longer term variability and uncertainty

3. Modify data sets to incorporate more realistic generator performance



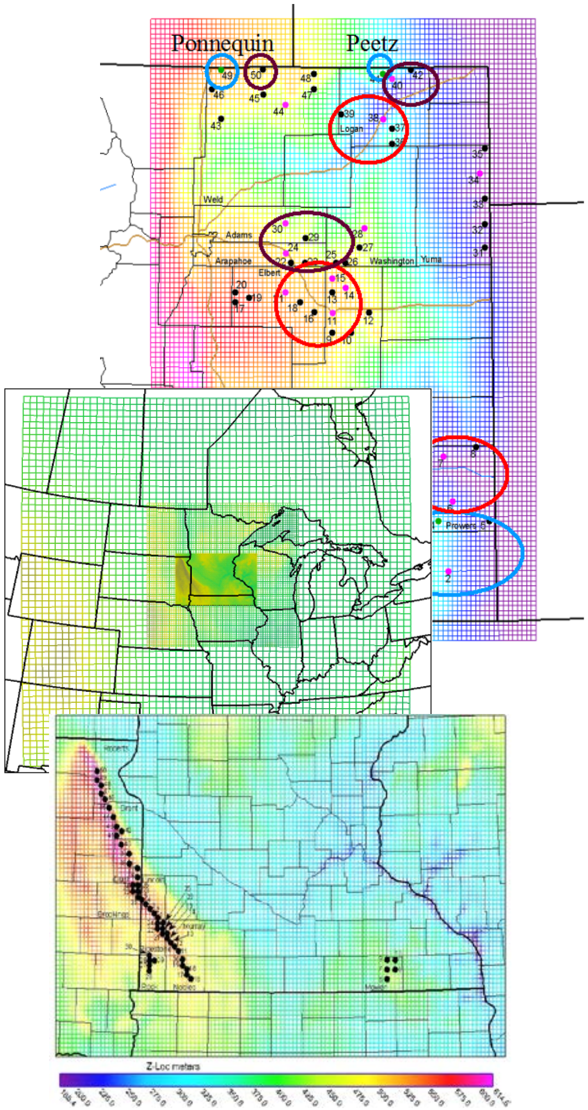
Lew et al. 2013

4. Hit go and wait…

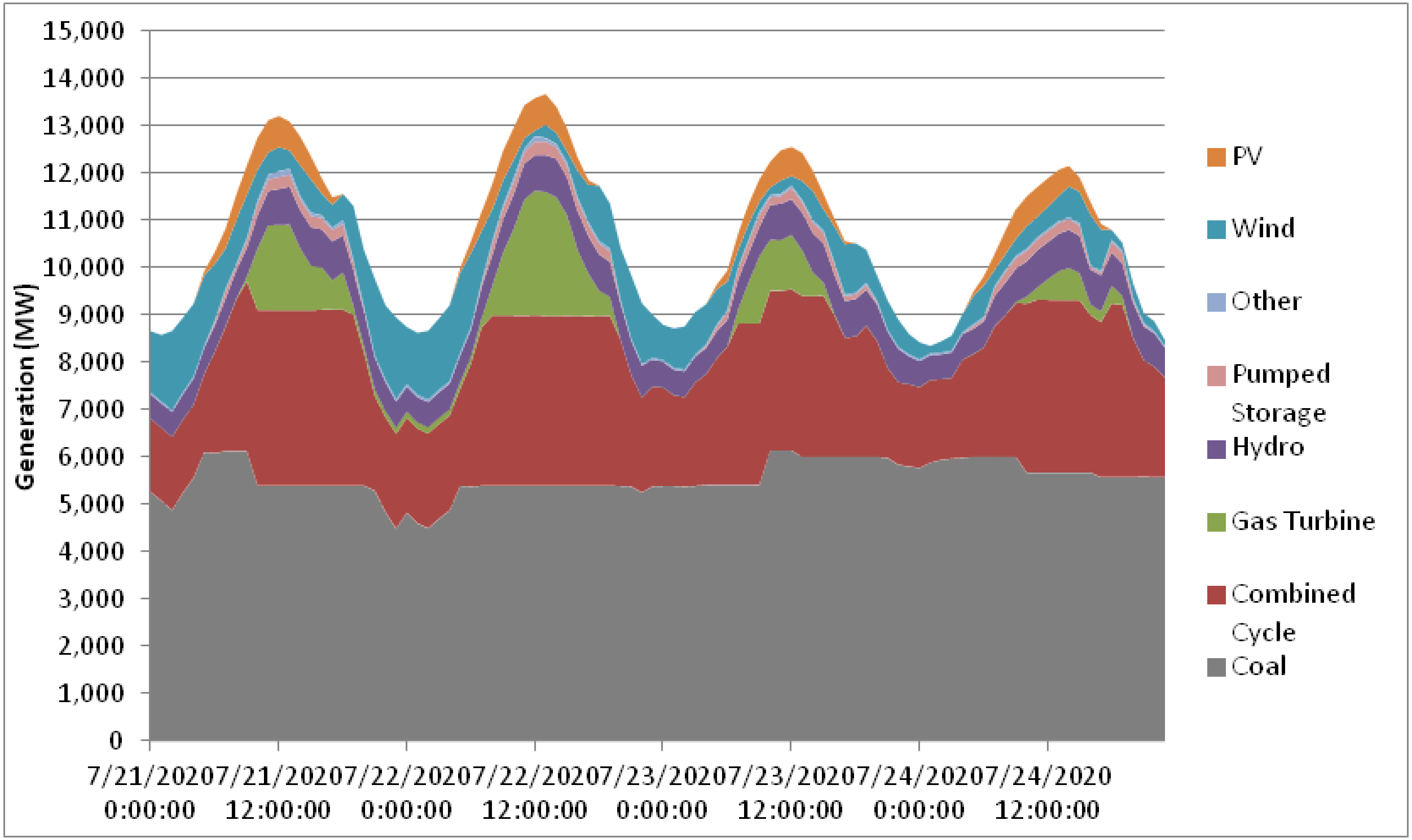
- 

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?**
  - o How much curtailment?
- **Did a bunch of bad things happen to indicate storage is needed?**

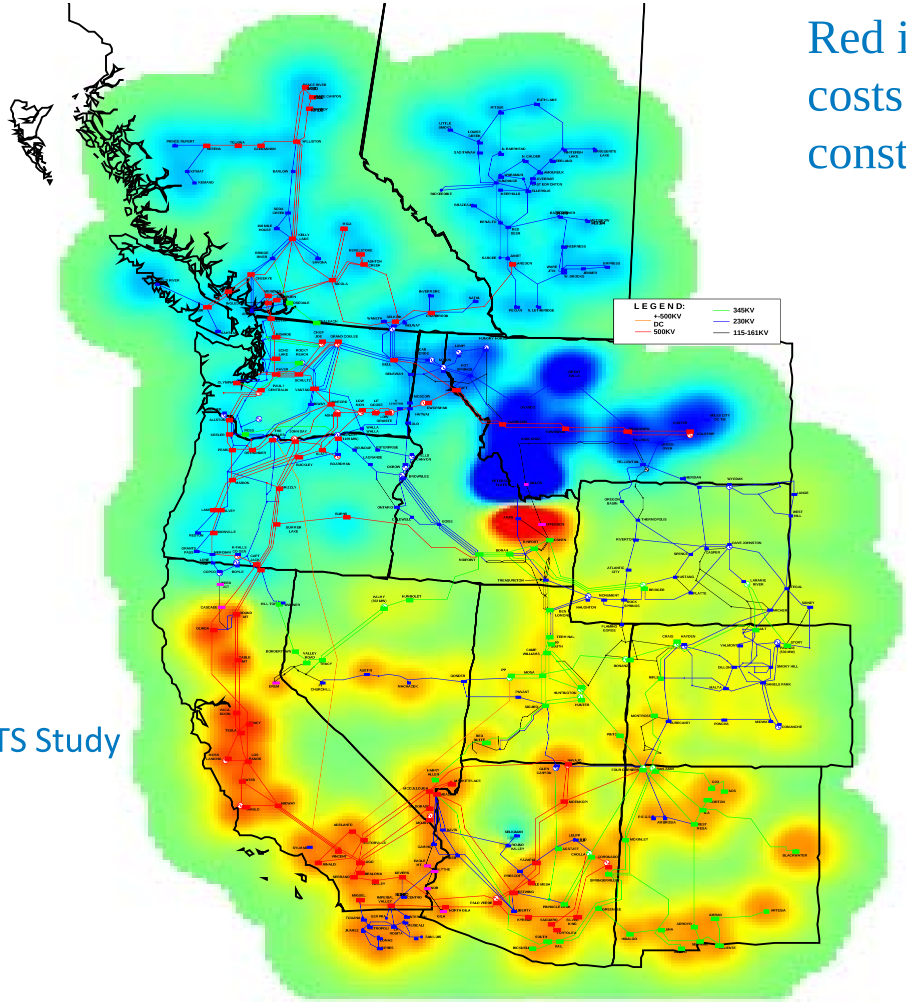


Example Dispatch in Colorado



Denholm et al. 2014

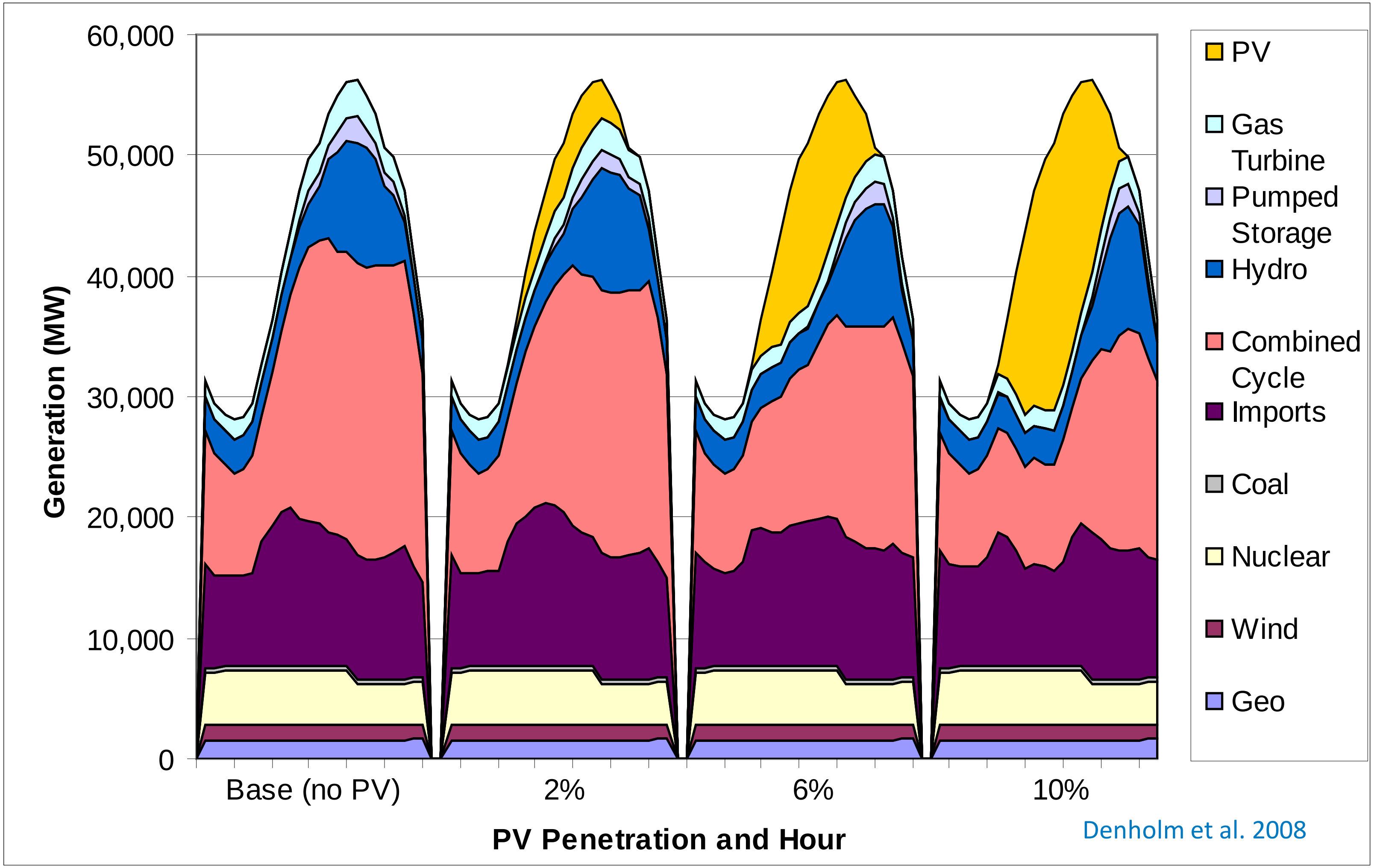
Power Flow and Transmission



Red indicates high costs and transmission constraints

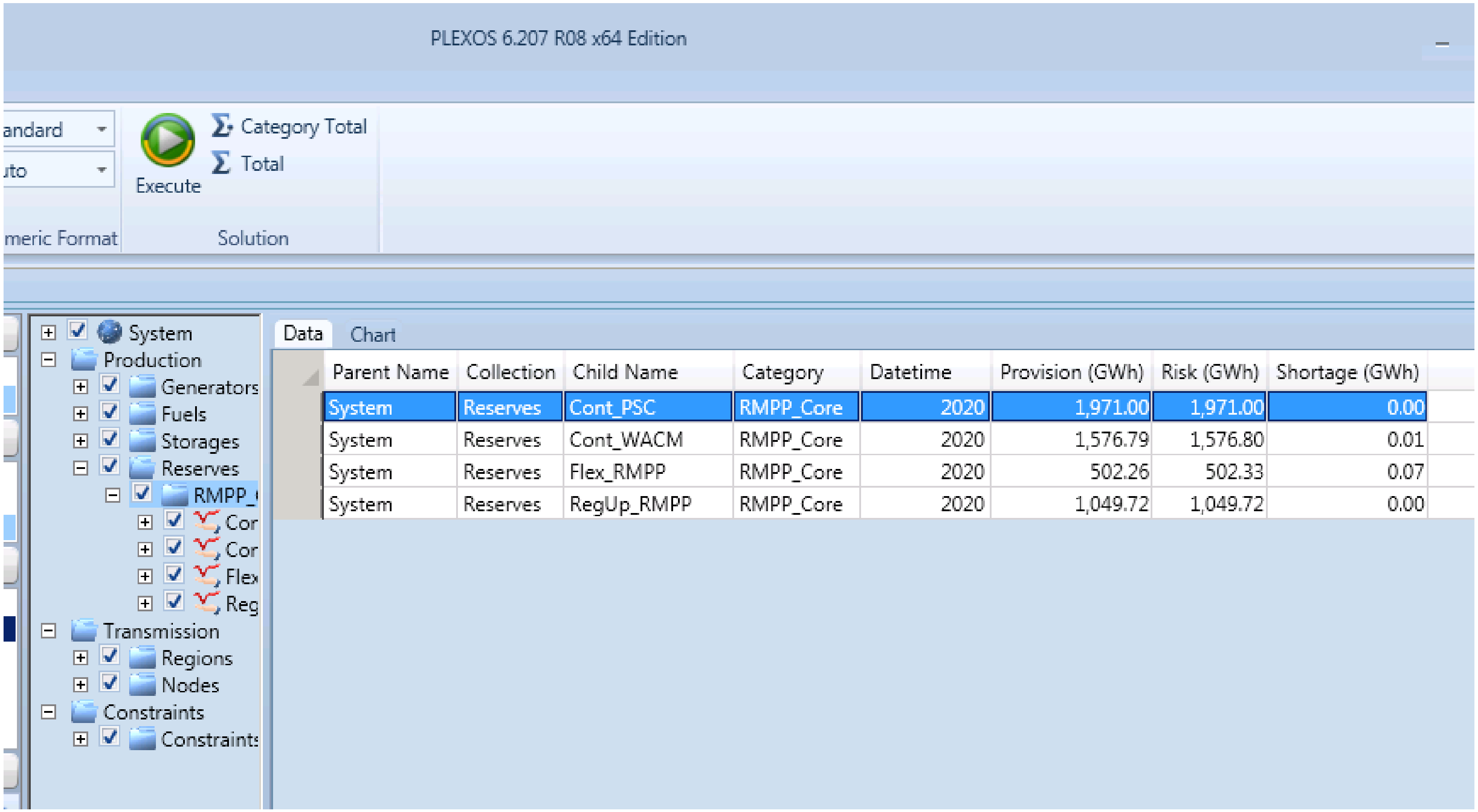
Source: RMATS Study

Example Simulation - Solar PV in the Summer



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

Reserve Violations can Indicate Loss of Reliability



First Generation of Wind Integration Studies

(<2010, up to about - 20% Penetration)

- **Focused on basic operability and "integration costs".**
- **Integration costs are modest (typically less than $5/MWh). Ongoing questions as to what this even means….**
- **Spatial diversity smooths aggregated wind output reducing short-term fluctuations to hour time scales**
- **Almost all the wind can be used (very little curtailment)**
- **Additional reserves have a modest impact on operational costs**

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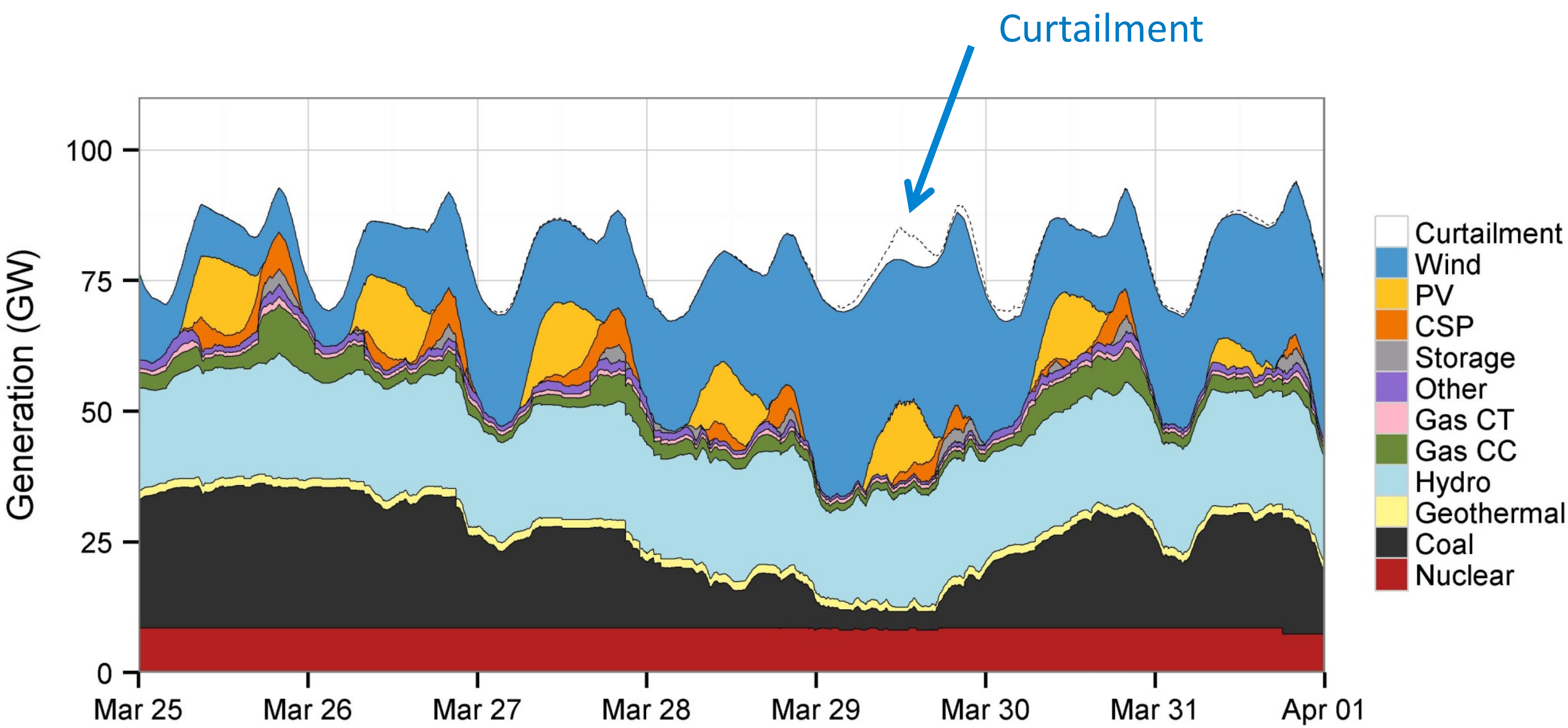
Second Generation

- **Higher penetration (up to 35% penetration of wind and solar)**
- **Examines impact of increased system flexibility**
- **General Conclusions**
  - Extensive co-operation will be needed
  - We may be nearing the flexibility limits of the grid as it exist today
  - High solar penetrations are more difficult than high wind
  - Curtailment may be the primary limitation for economic deployment of wind and solar

Limits to VG Penetration - Curtailment

- **There are no technical limits to how much VG can be put on the grid – only economic limits**
  - You can always find a piece of hardware to solve the problem (*including storage*….)
- **At high penetration, economic limits will likely be due to curtailment**

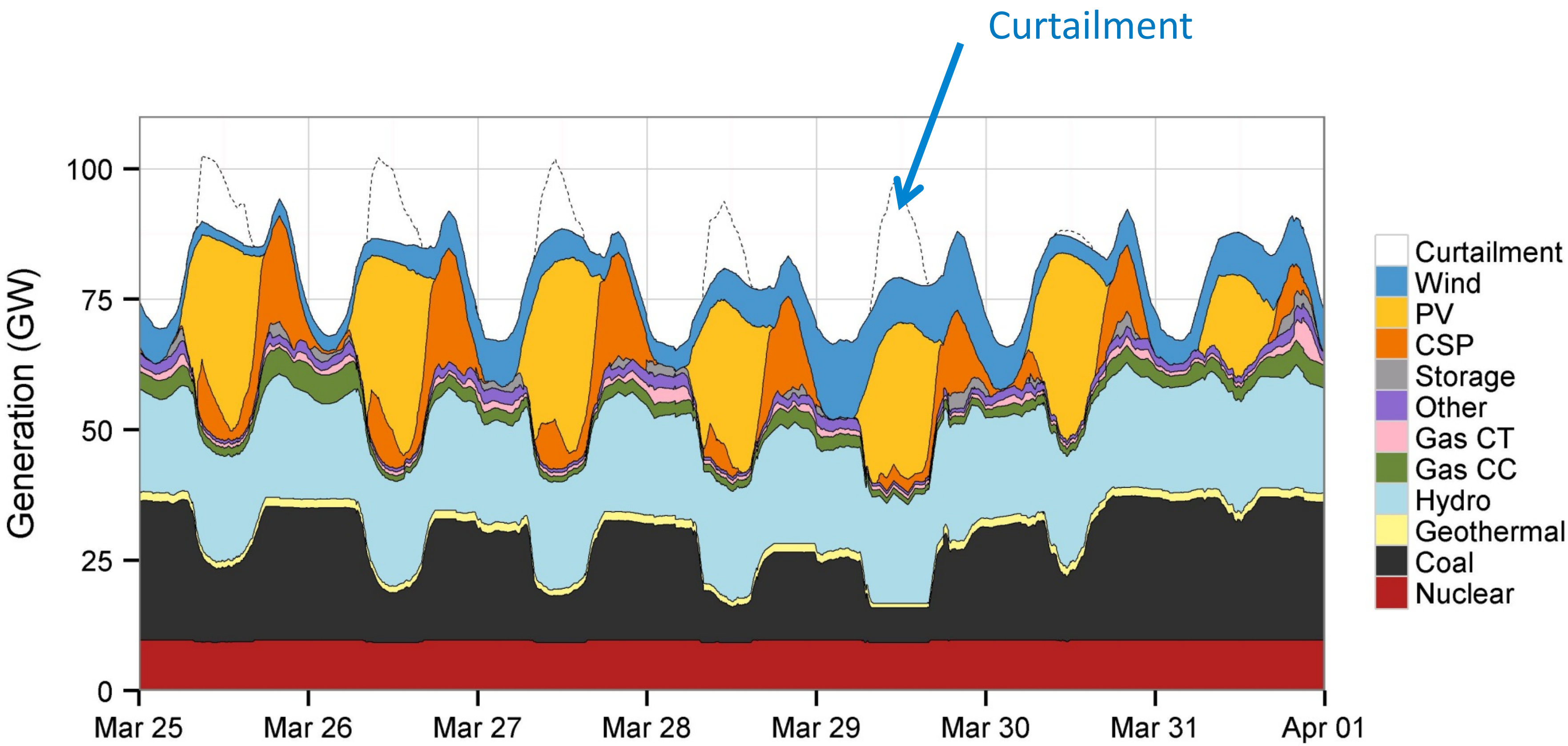
WWSIS II High Wind Case (8% solar, 25% wind)



http://www.nrel.gov/electricity/transmission/western_wind.html

Lew et al. 2013

WWSIS II High Wind Solar (25% solar, 8% wind)



Solar is 60% PV and 40% Concentrating Solar Power with 6 hours thermal storage

Lew et al. 2013

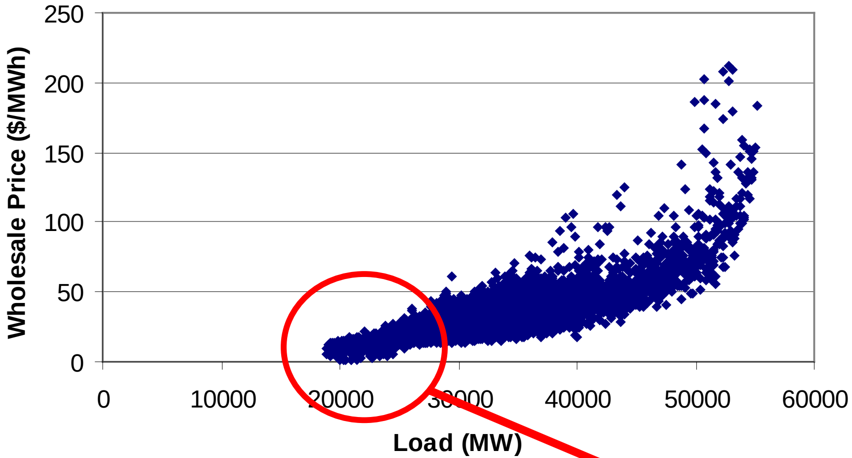
Sources of Curtailment

Too much supply, not enough demand, when considering:

- **Ramp constraints**
- **Transmission constraints**
- **Minimum output levels from hydro and thermal generators**
    - o This also includes the need to operate partially loaded capacity to maintain system reliability
- **Many of these challenges are *institutional* in addition to technical**

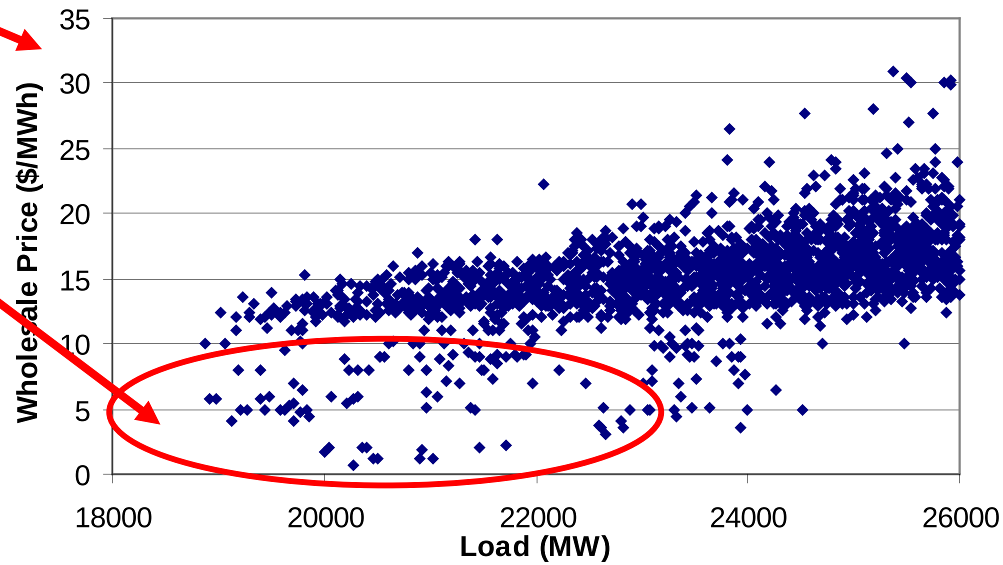
Current System Flexibility

Limited by Baseload Capacity



Price/Load Relationship in PJM

Below Cost Bids

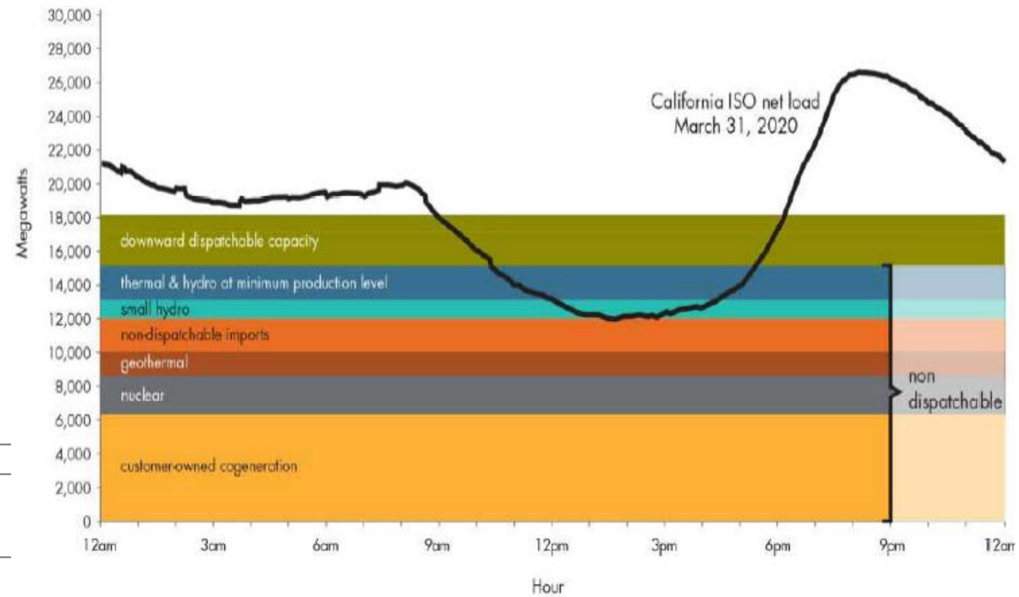


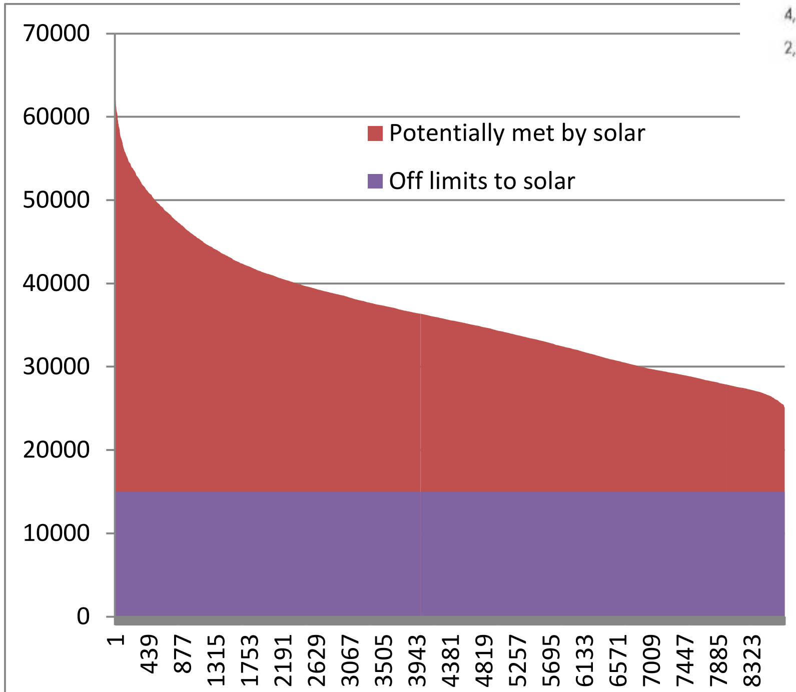
Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind and solar may be curtailed under these conditions.

30

Impacts of "Must-Run" Generation

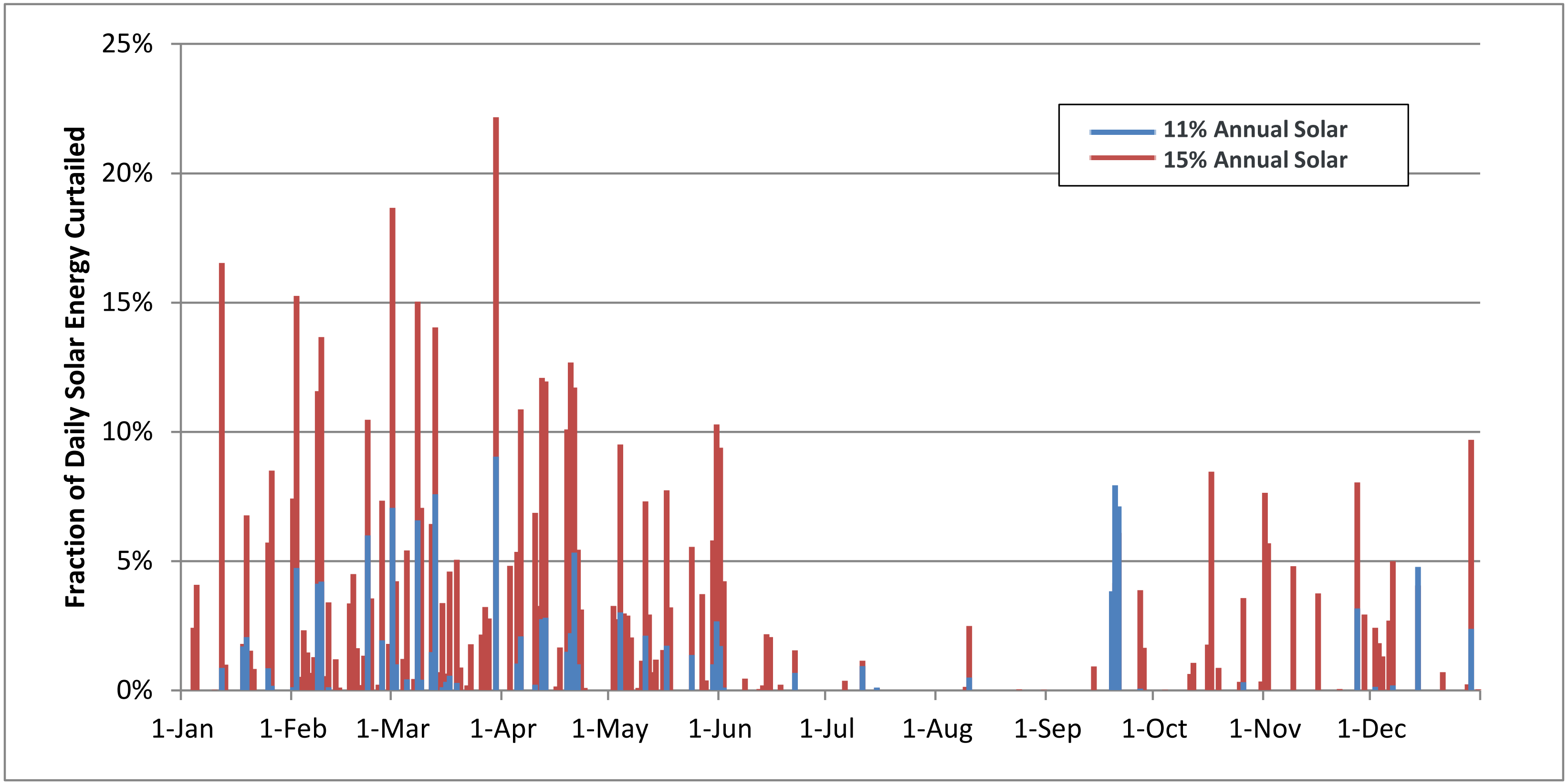
CAISO estimate of must run generation in current system





This translates into 41% of CAISO load "off limits" to wind and solar

Curtailment with Limited Flexibility



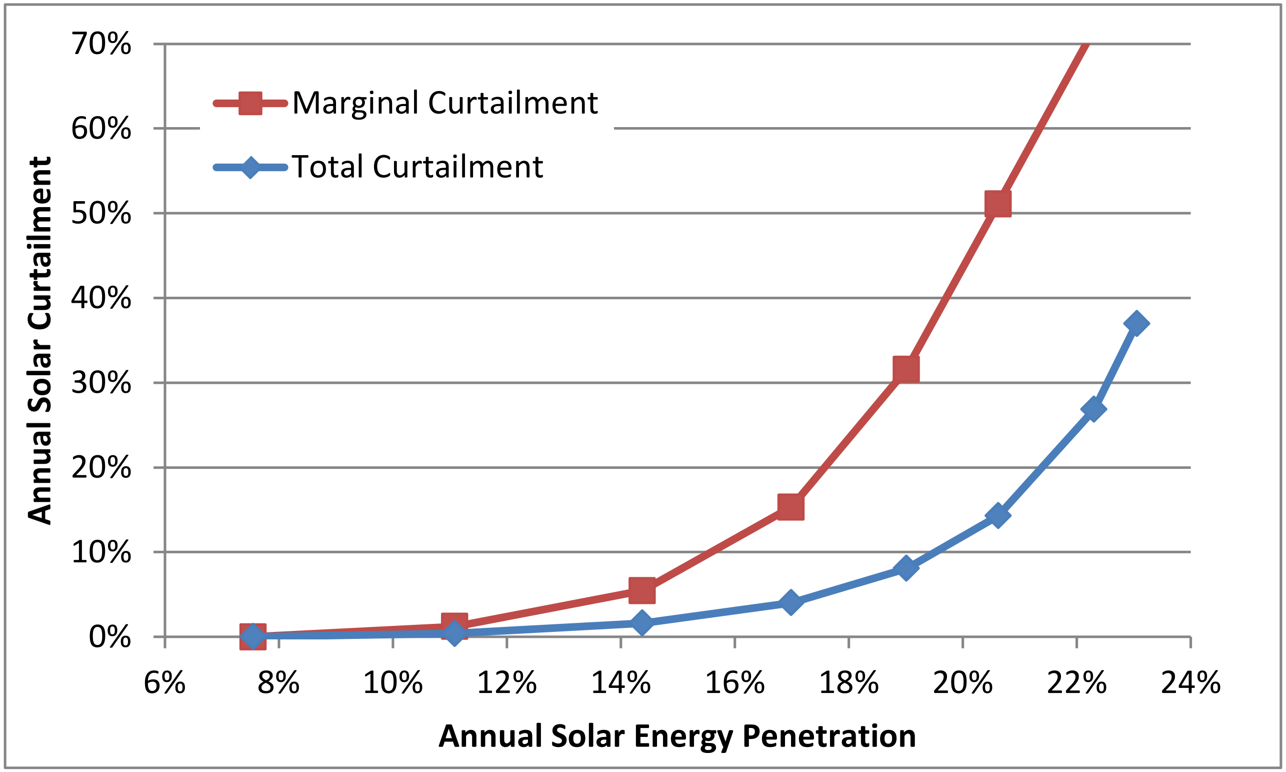
Used and curtailed VG in California on March 29 in a scenario with 11% annual wind and 11% annual solar

Denholm et al. 2016

Curtailment Increases Rapidly

Marginal curtailment = curtailment of all incremental VG moving from one penetration level to the next

Total curtailment = curtailment rate of all PV installed on the system at a certain penetration level



Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with limited grid flexibility

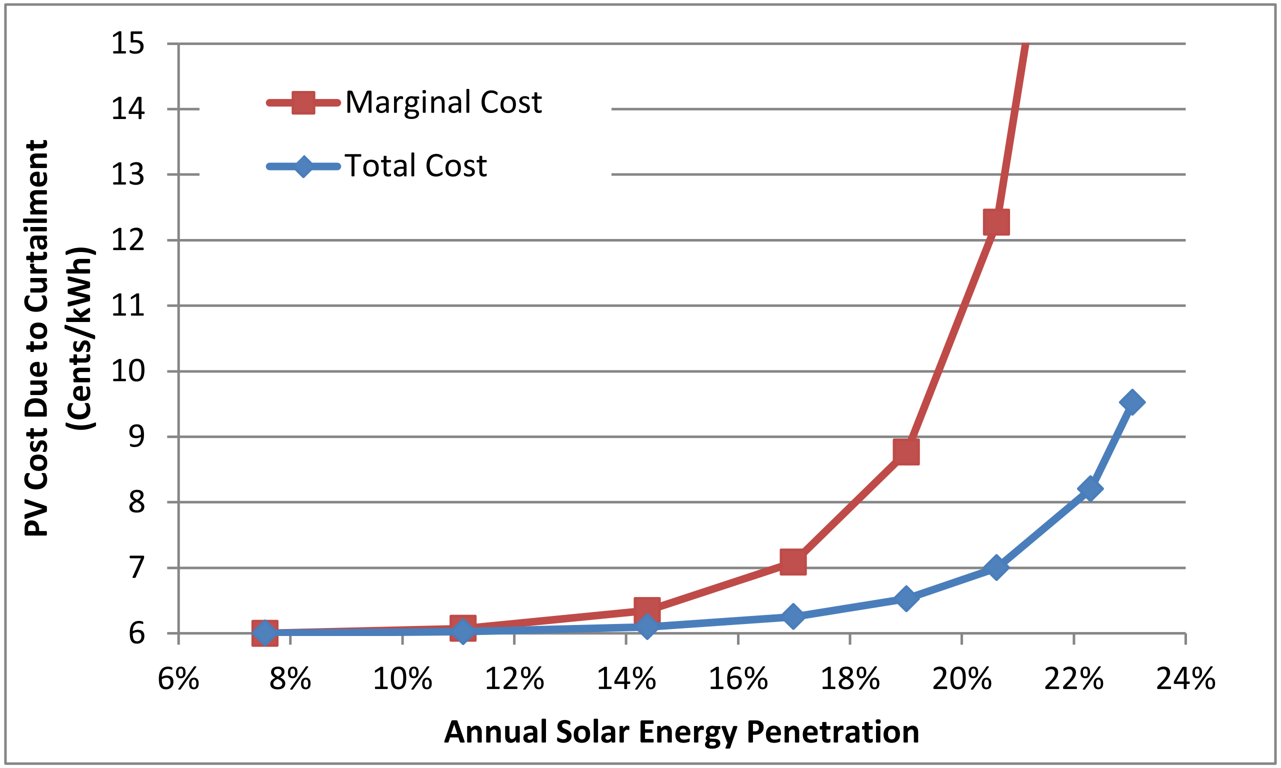
Denholm et al. 2016

Consequences of RE curtailment

- Technically easy to do (at least on utility-scale renewable energy generation)
- But reduces economic benefits measured by either increased cost of decreased benefit

Impact of VG curtailment on LCOE

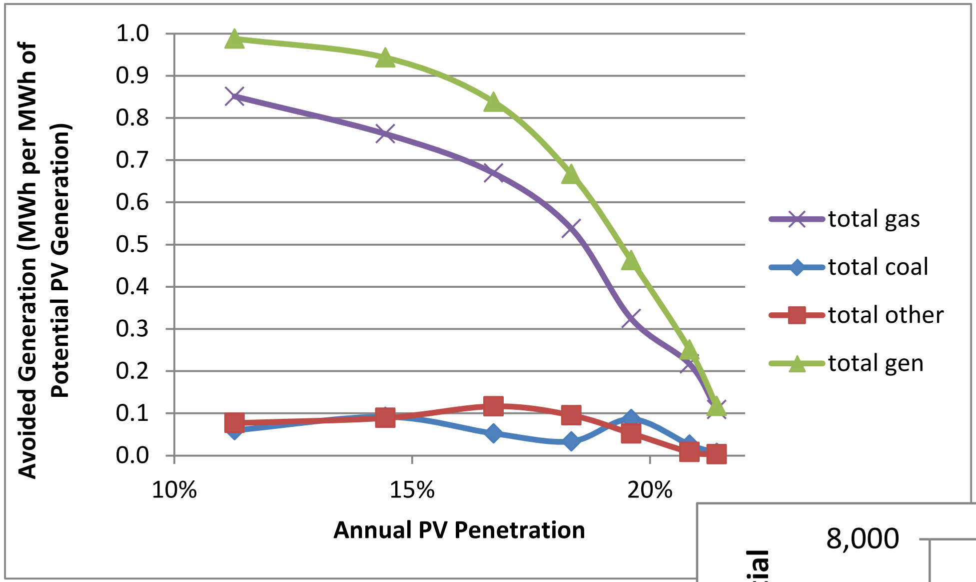
Curtailed energy means less can be sold and incremental costs of additional PV rise dramatically

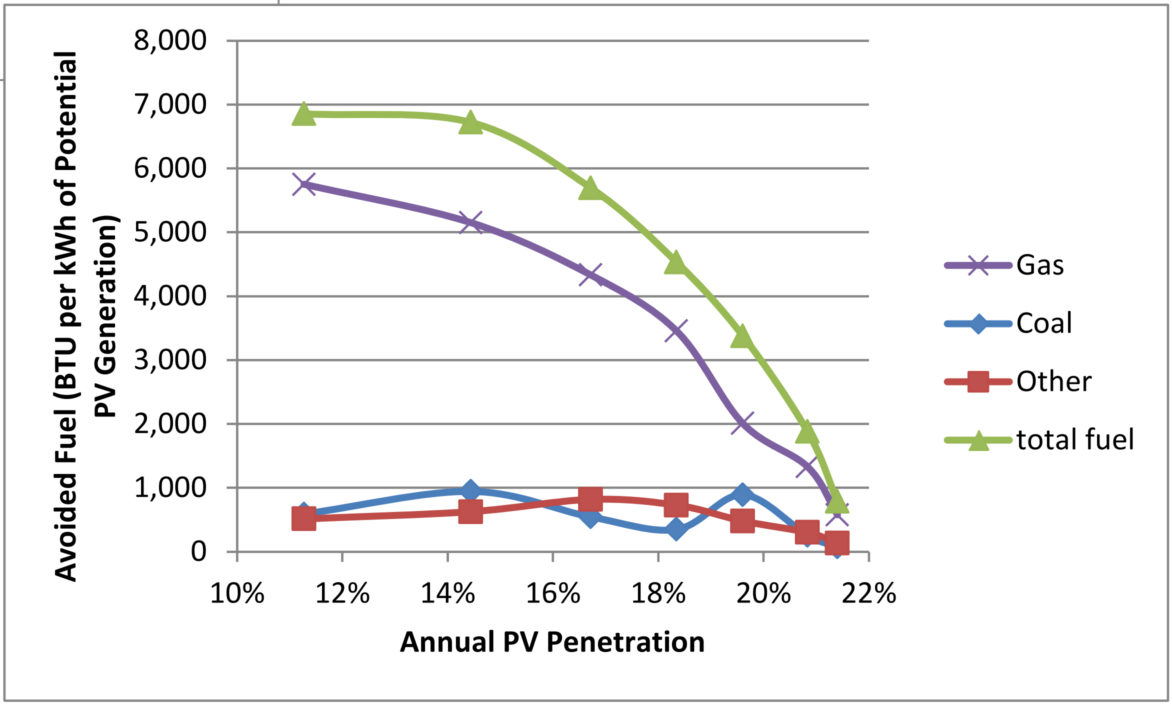


Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with limited grid flexibility

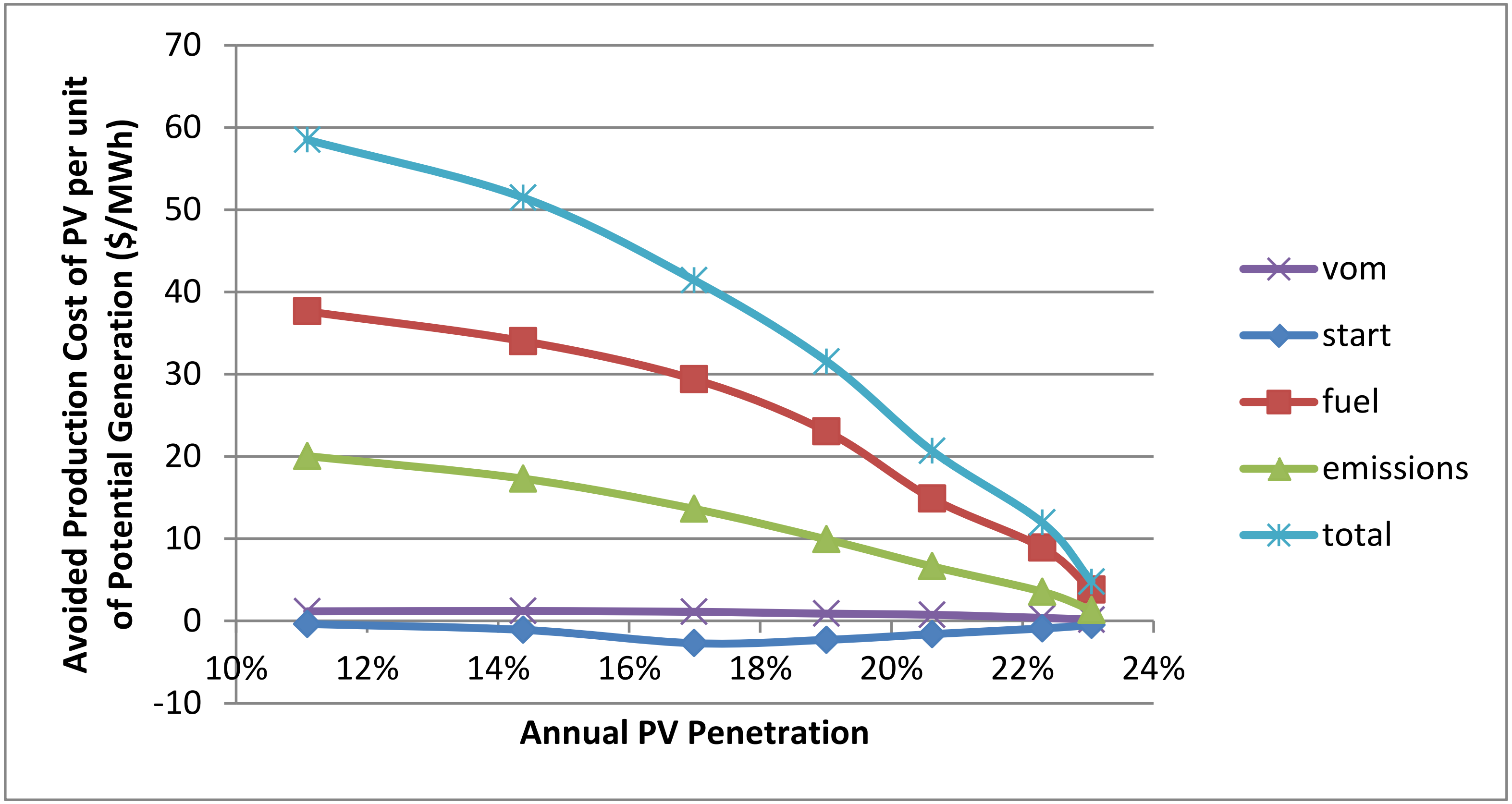
Denholm et al. 2016

Avoided Generation and Fuel





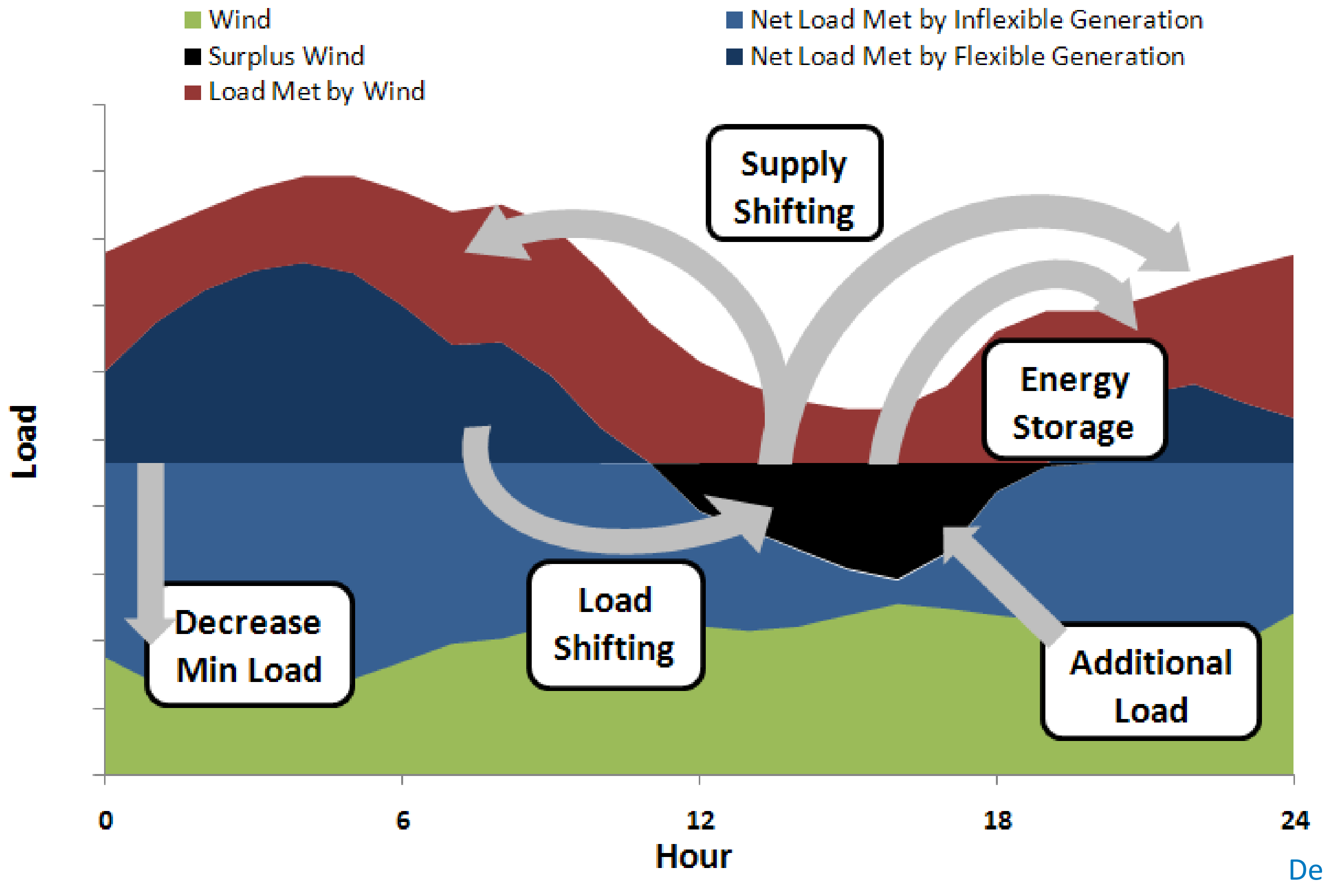
Avoided Generation Costs



This is the avoided production (variable) costs of PV

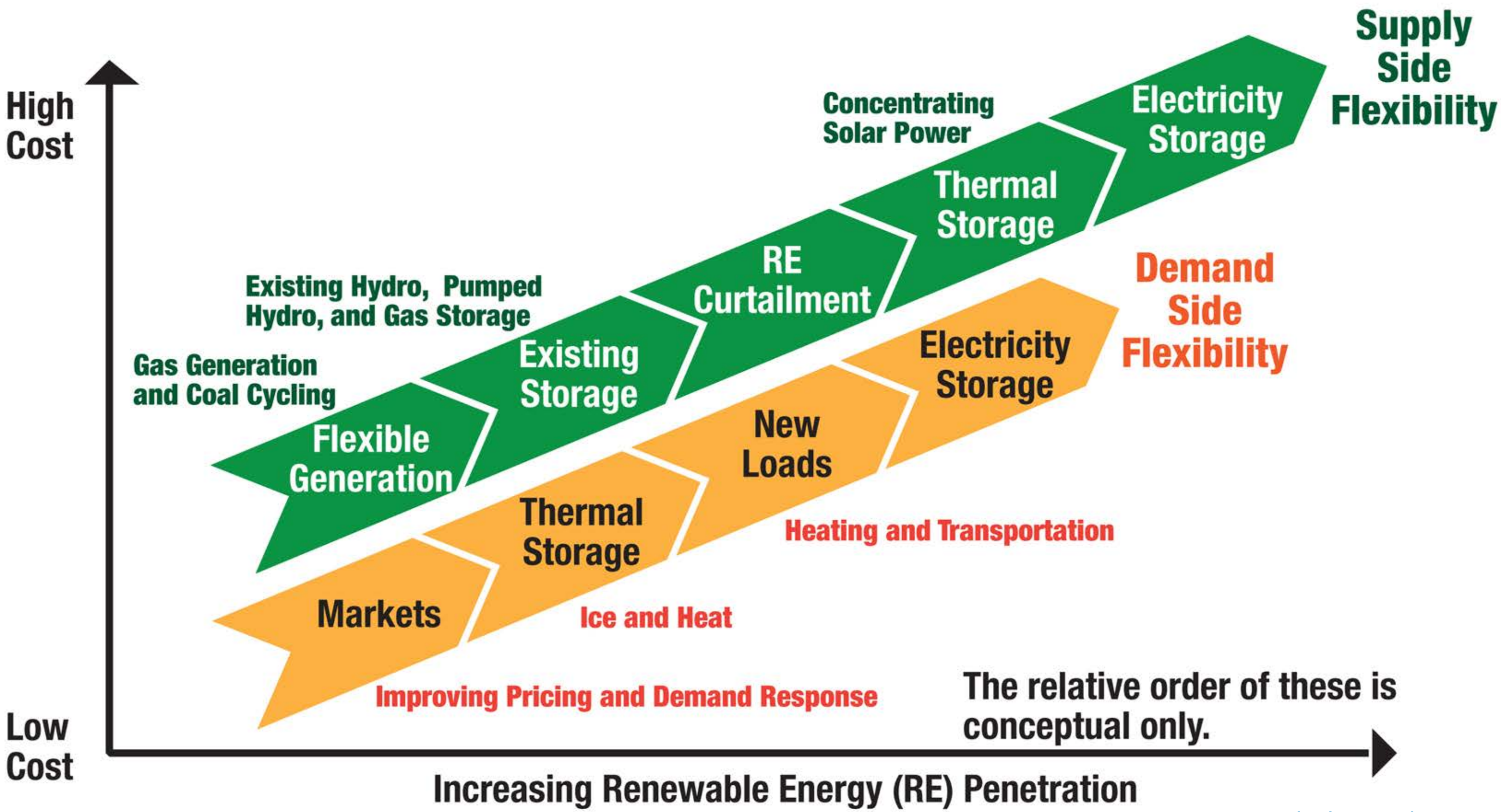
Increasing PV Value and Avoiding Curtailment

- **While storage provides an "obvious" answer to the problem of supply-demand coincidence, there are a number of options**



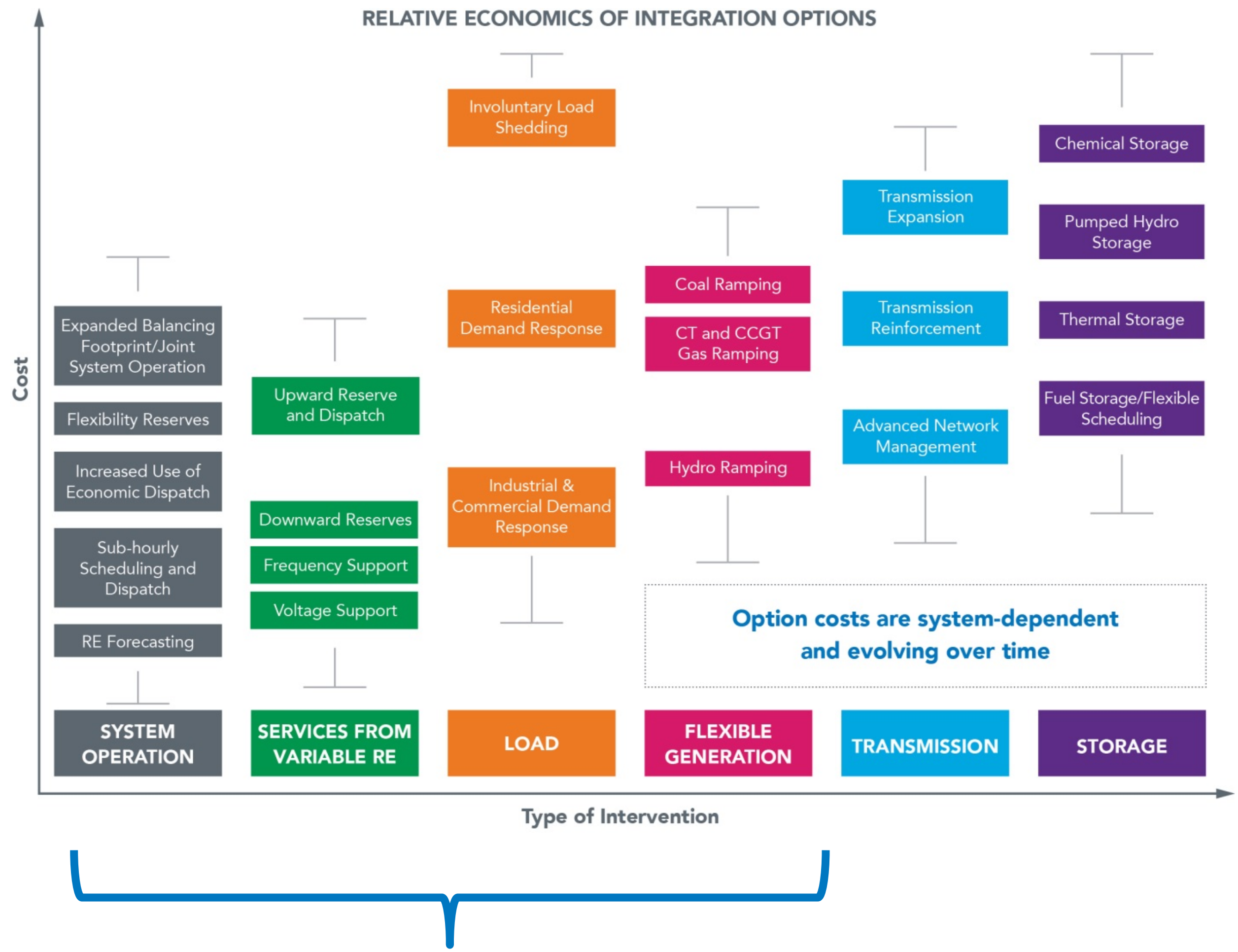
Denholm et al. 2010

Flexibility Supply Curve Concept



Denholm et al. 2010

Flexibility Supply Curve Concept



You probably do this first

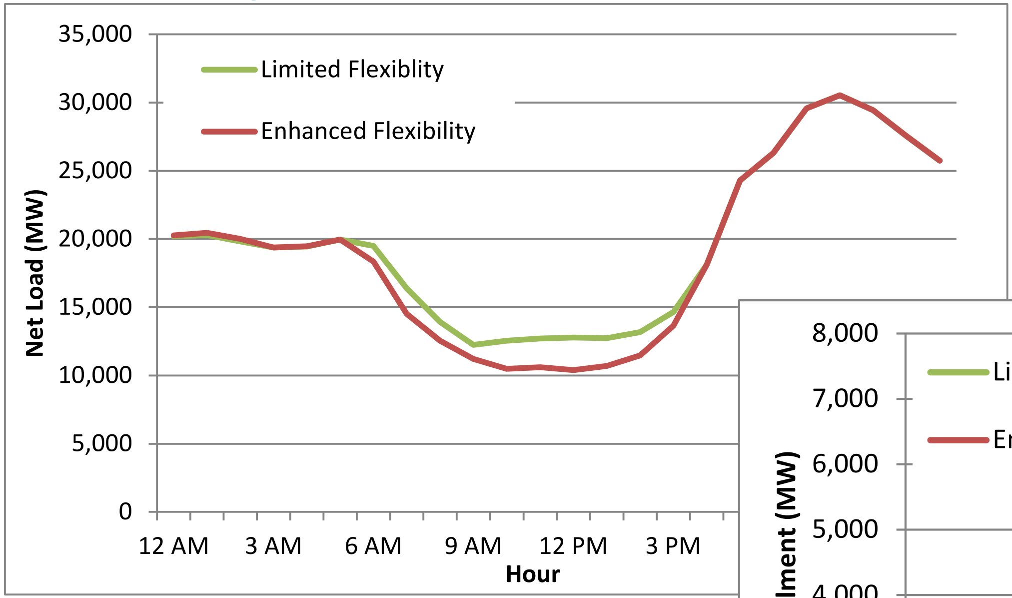
Cochran et al. 2015

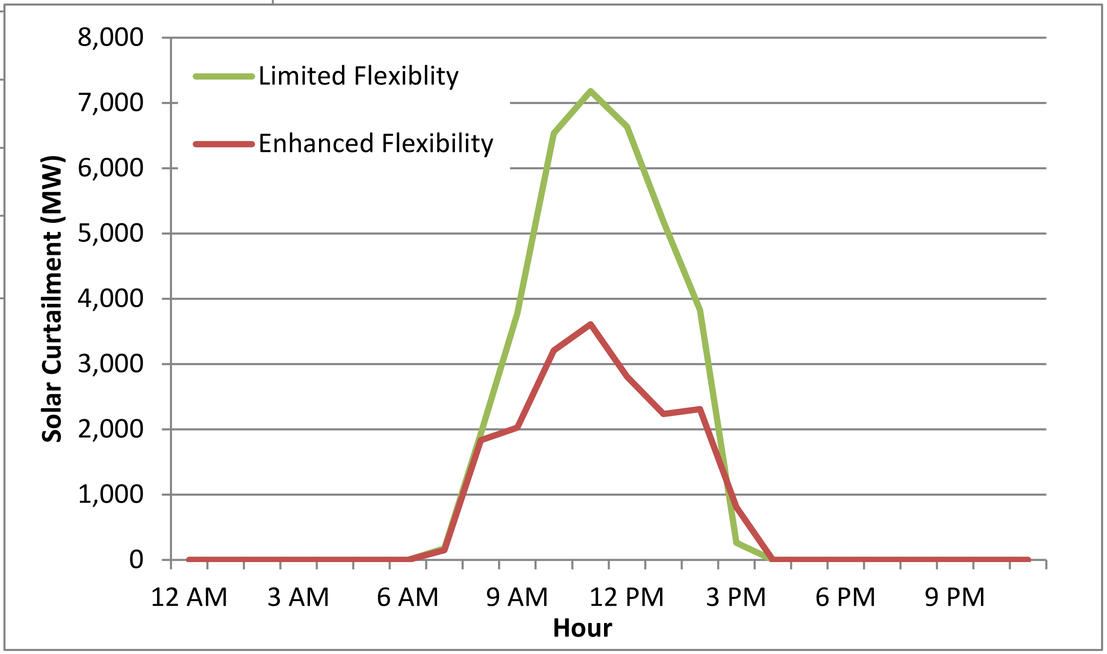
Mitigation Options

Type	Description
Generator flexibility	Ability of conventional generation to vary output over various time scales
Storage flexibility	Ability to store energy during periods of low demand and release that energy during periods of high demand
Geographic flexibility	Ability to use transmission to share energy and capacity across multiple regions
Load flexibility	Ability to vary electricity demand in response to grid conditions

Impact of Increased Flexibility

Dropping the minimum generation level increases the amount of load served by PV



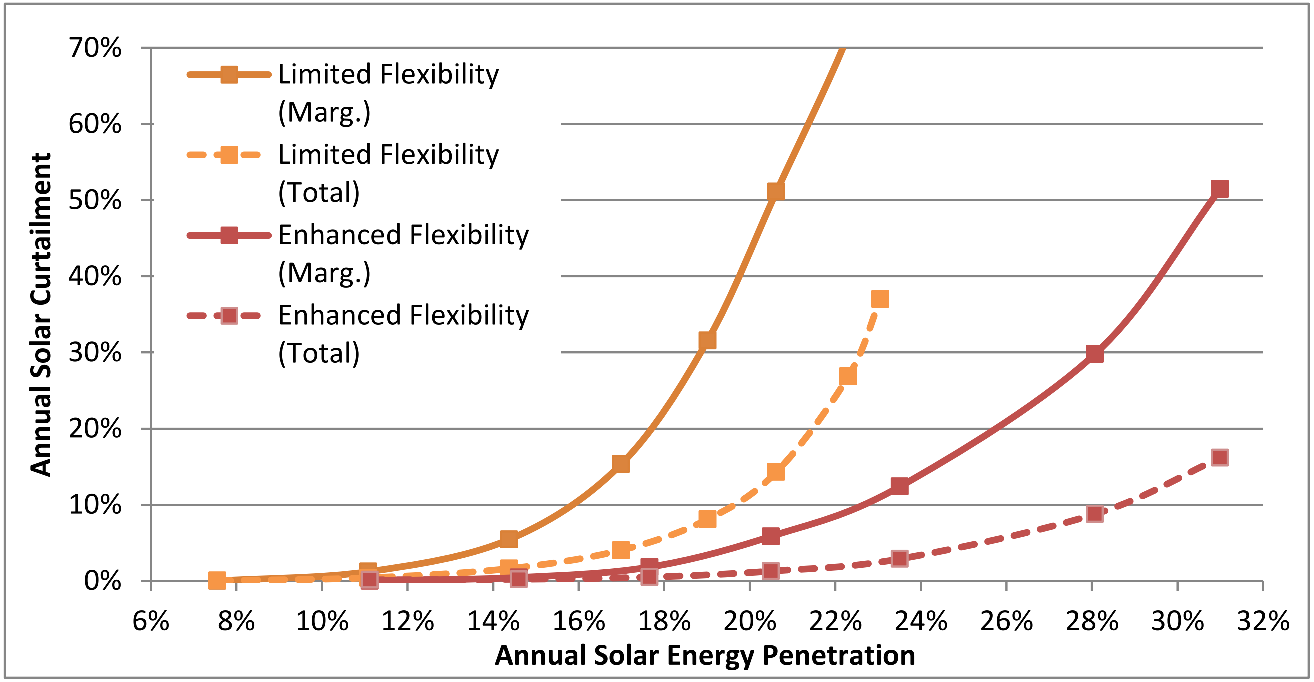


Net load on March 29 in a scenario with 15% annual solar increasing the grid flexibility

Denholm et al. 2016

Increased Flexibility = Increased Penetration

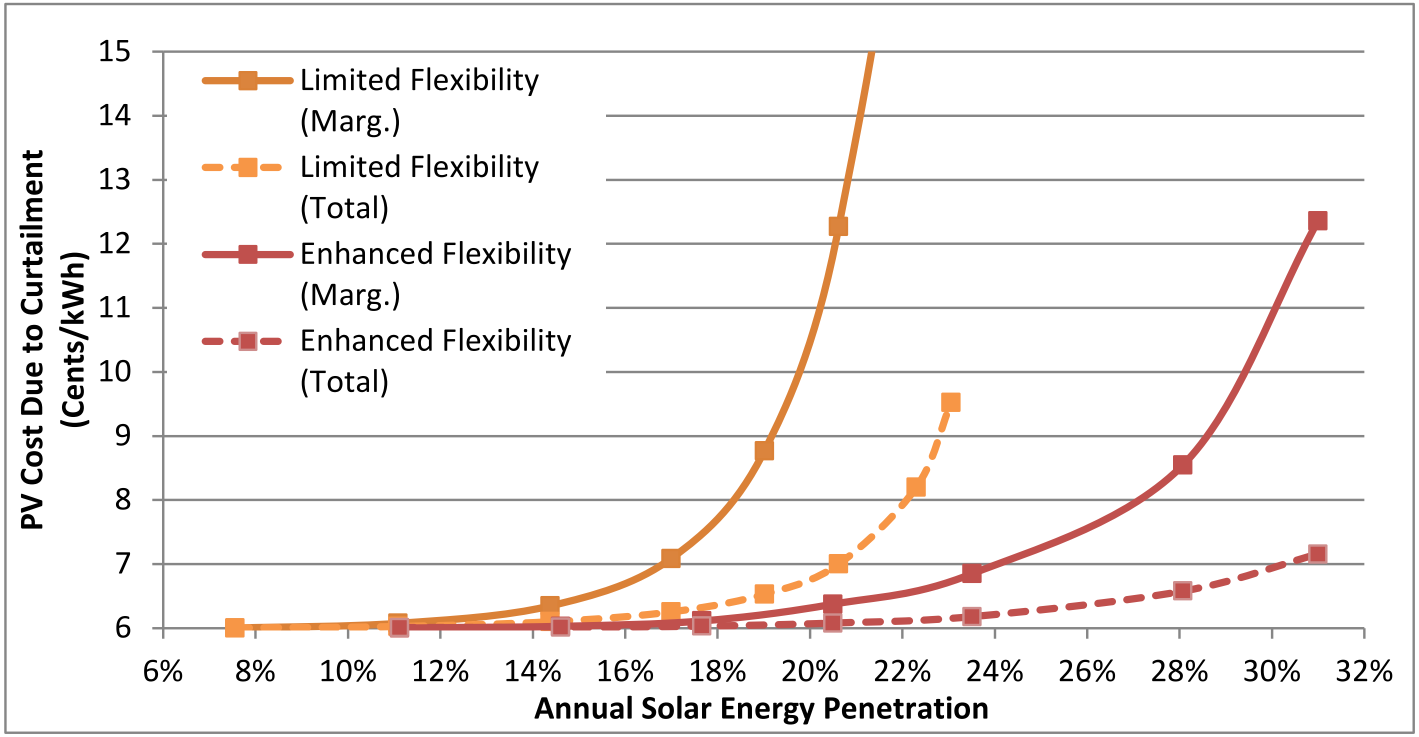
PV penetration of 25% with less than 20% marginal and 5% total curtailment



Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with enhanced grid flexibility

Denholm et al. 2016

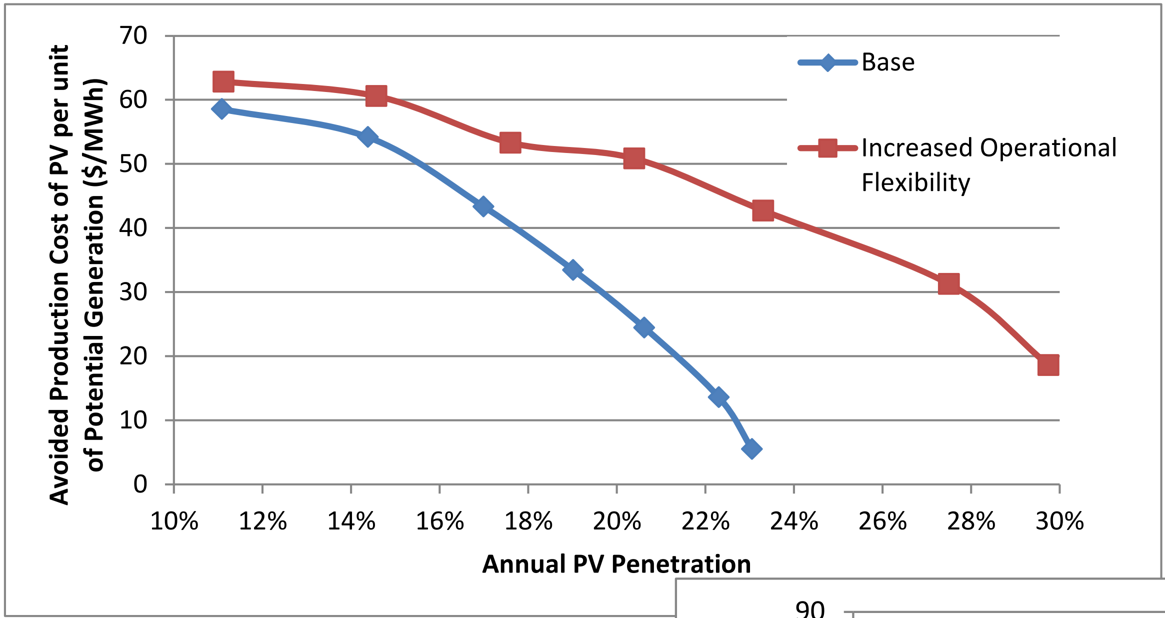
And More Competitive Costs



Marginal and average LCOE due to overgeneration under increasing penetration of PV in California with enhanced grid flexibility

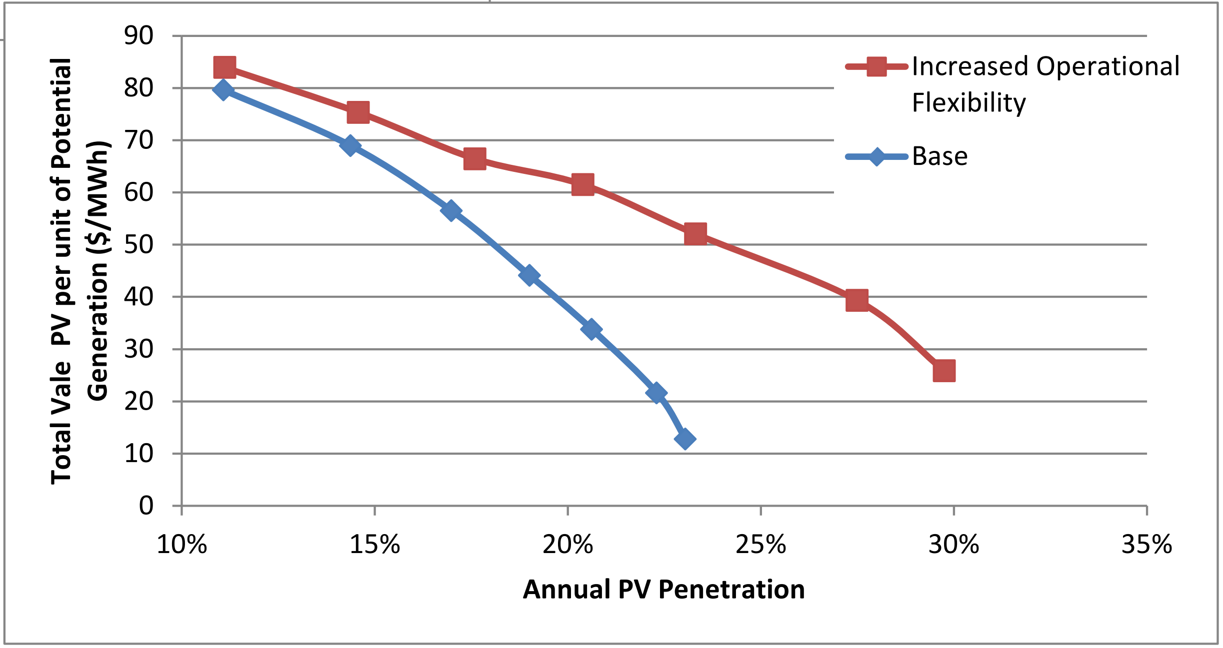
Denholm et al. 2016

Increased Flexibility Increases VG Value

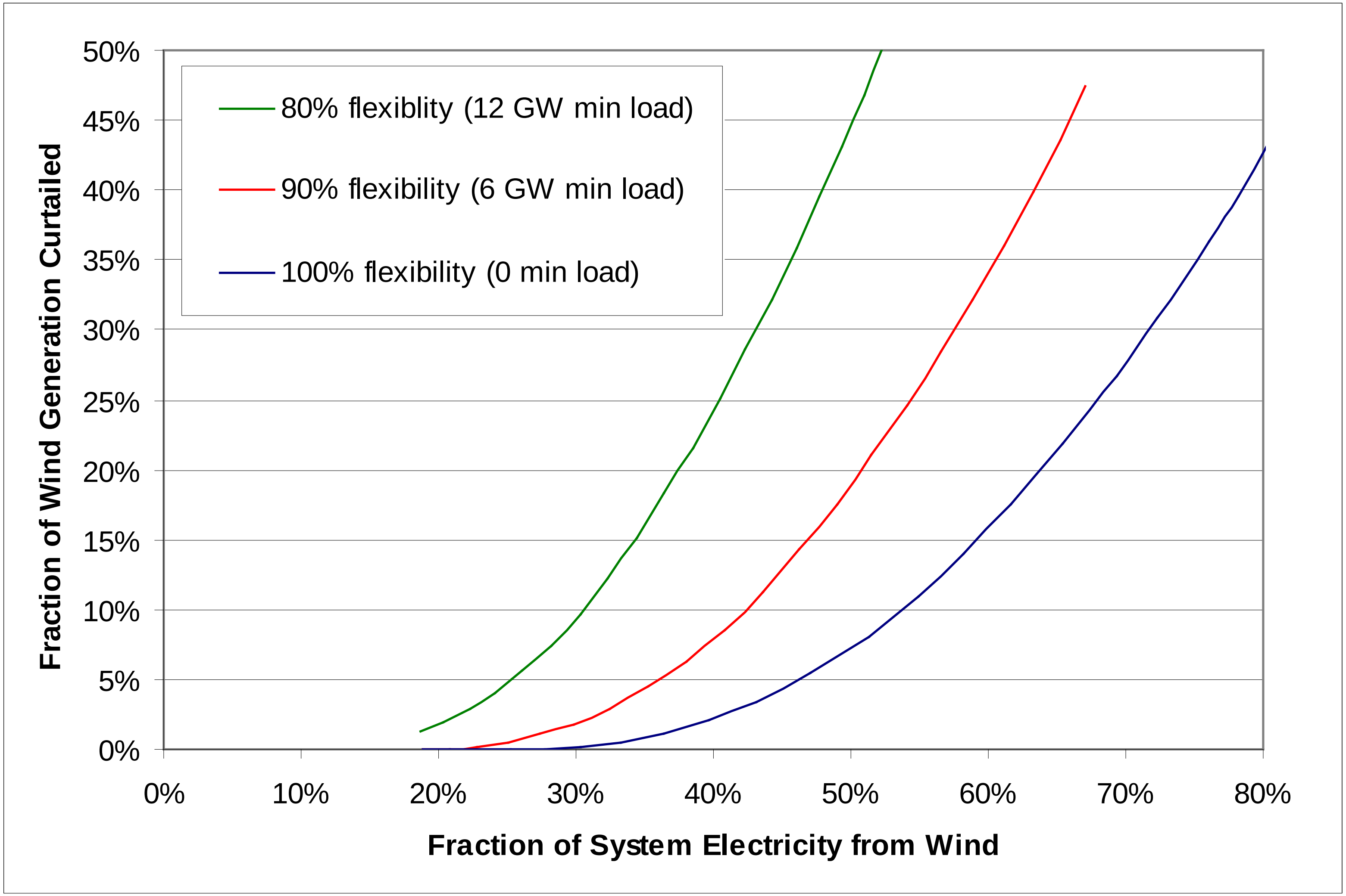


Operational value

Total value



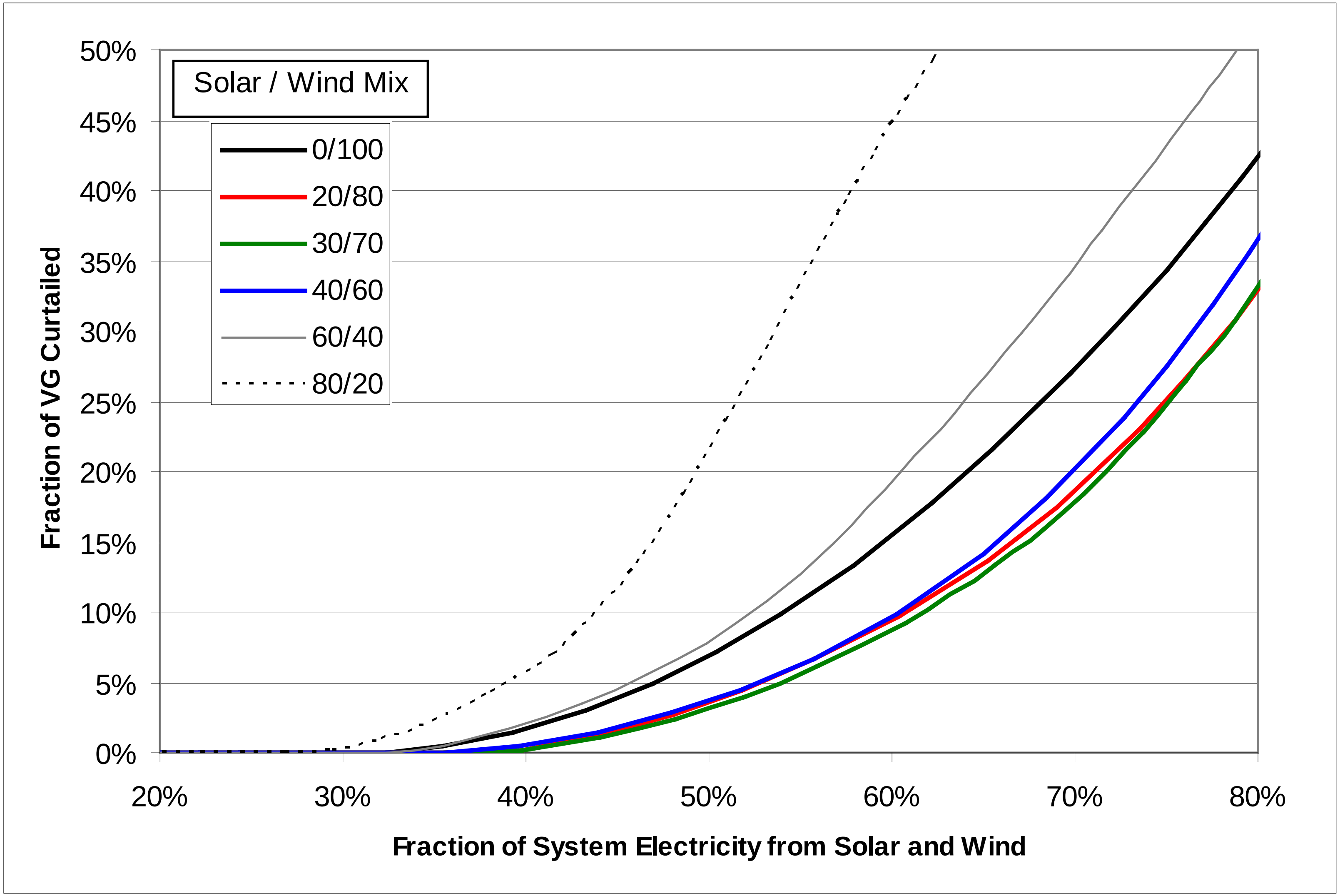
Curtailment as a Function of Flexibility



Average curtailment rate as a function of VG penetration for different flexibilities in ERCOT

Denholm and Hand 2011

Different RE Mixes Improves Supply/Demand Coincidence

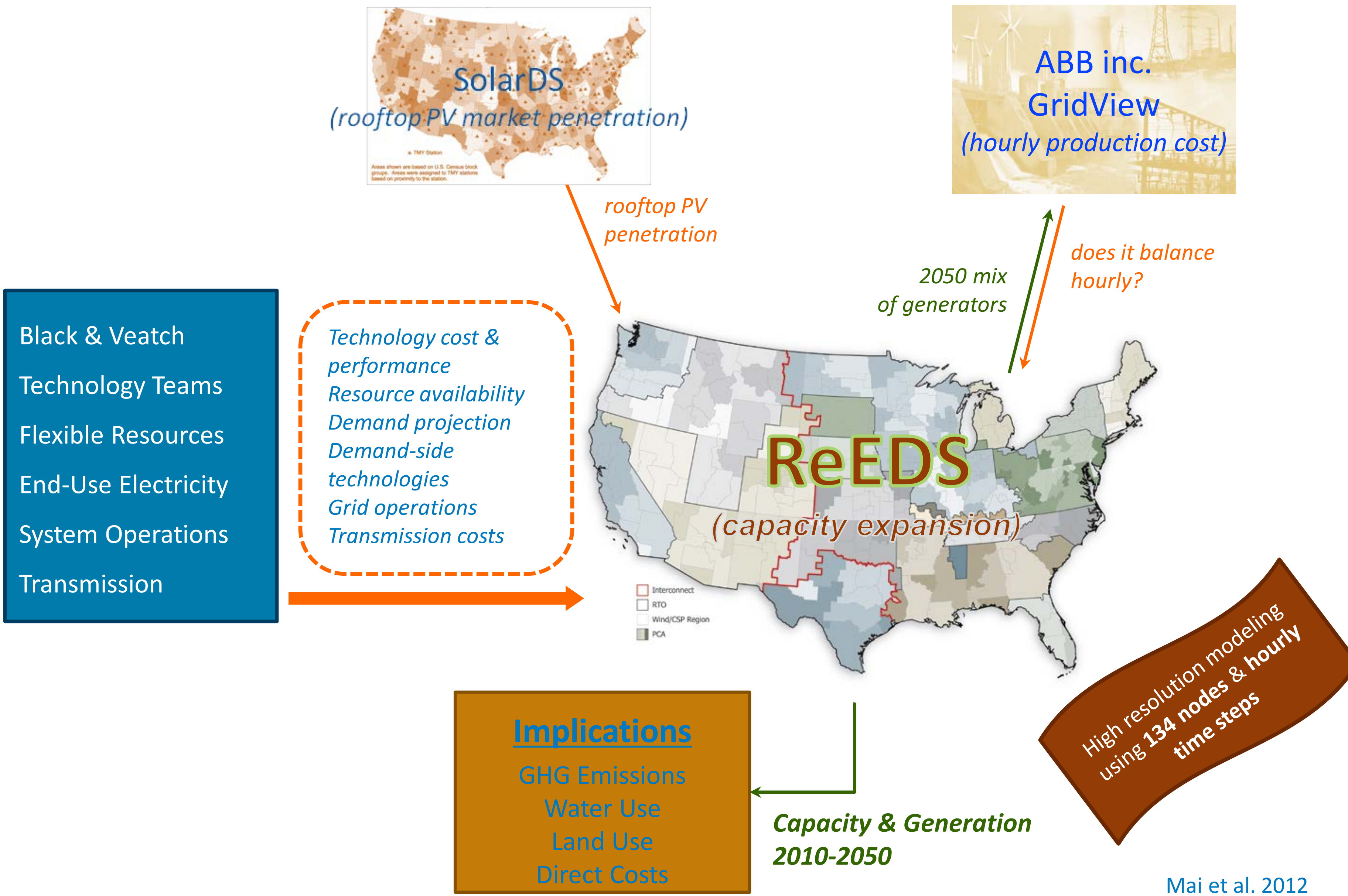


Denholm and Hand 2011

How High Can We Go?

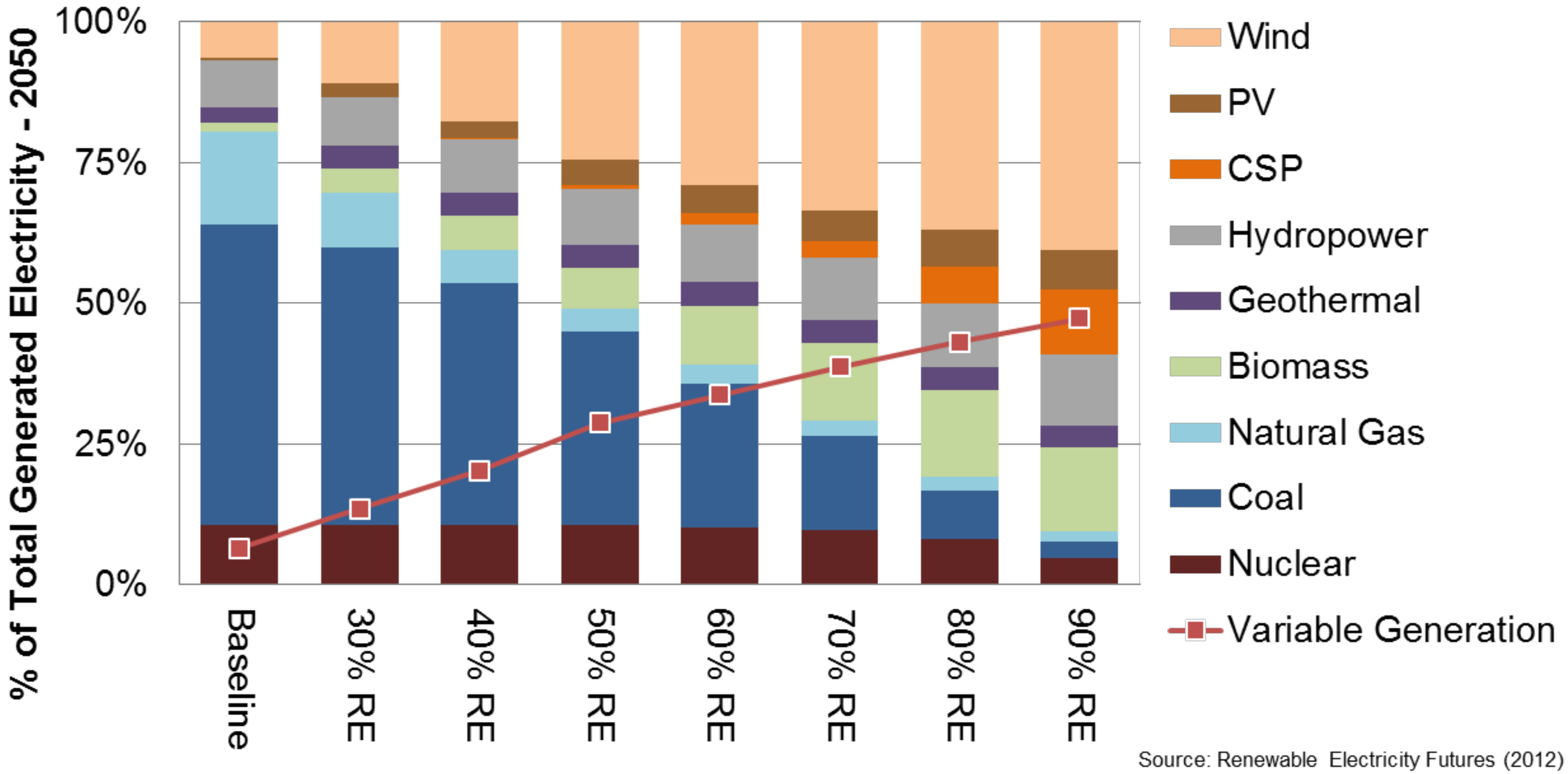
- Can renewables themselves largely de-carbonize the electric sector?
- Results from various studies indicate that beyond 35% VG, new sources of flexibility will be needed for economic deployment of renewables
- Need to perform scenario analysis to consider all options and mixes of renewable resources

Renewable Electricity Futures



Mai et al. 2012

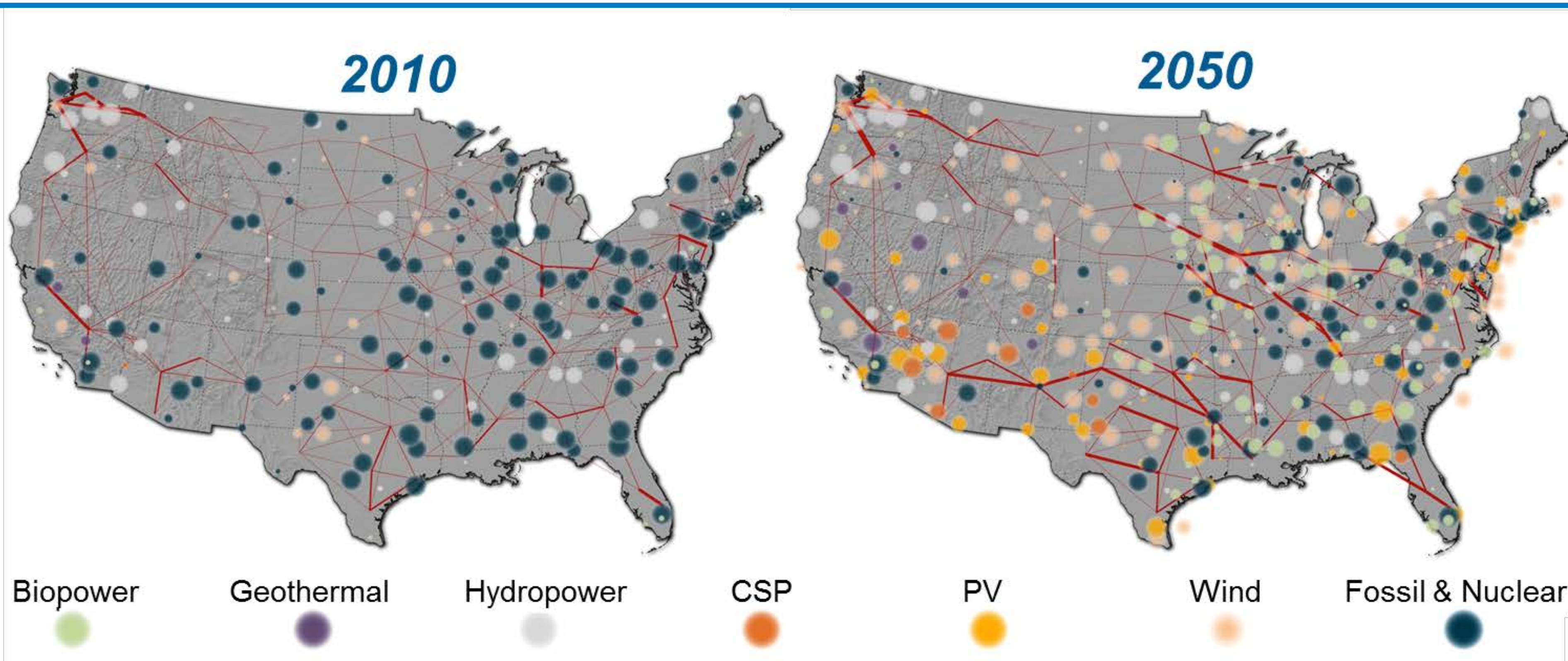
RE Resource Supply from 30% - 90% Electricity



Mai et al. 2012

Additional variability challenges system operations, but can be addressed through increased use of supply- and demand-side flexibility options and new transmission.

A Transformation of the U.S. Electricity System

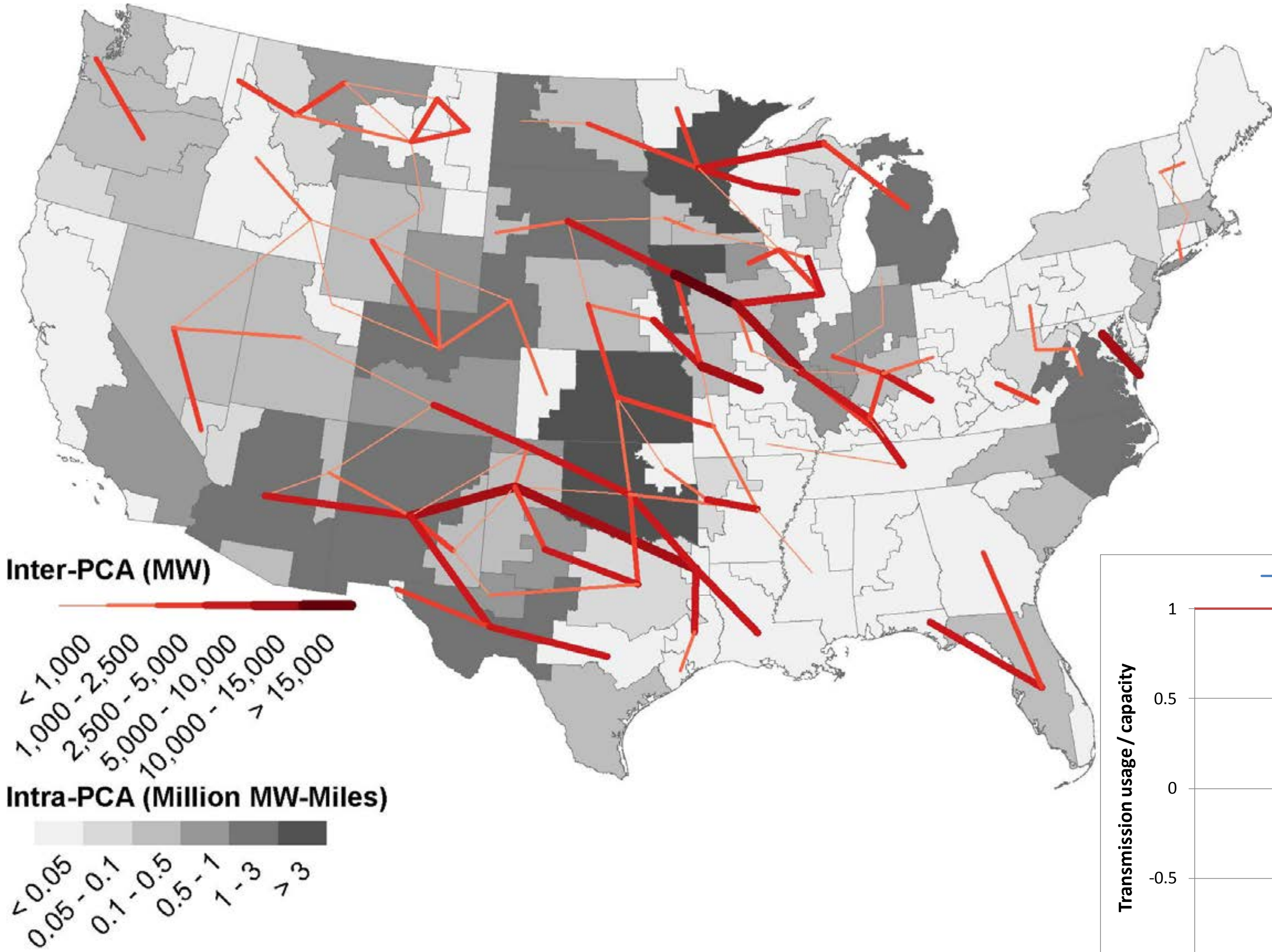


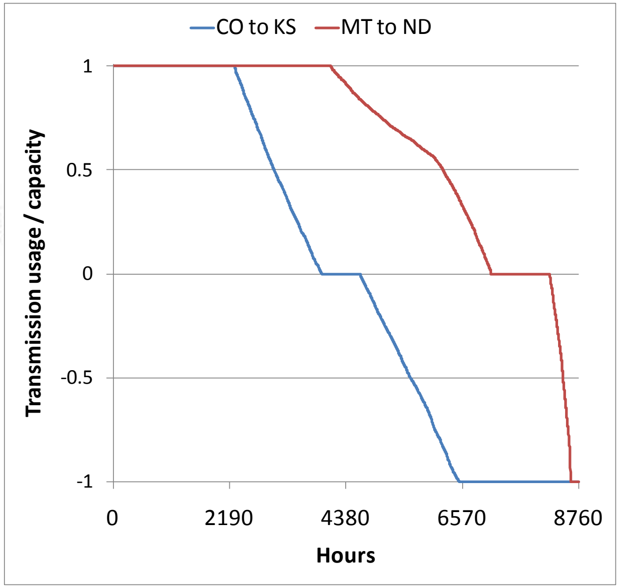
Source: Renewable Electricity Futures (2012)

Mai et al. 2012

RE generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050—while meeting electricity demand on an hourly basis in every region of the country.

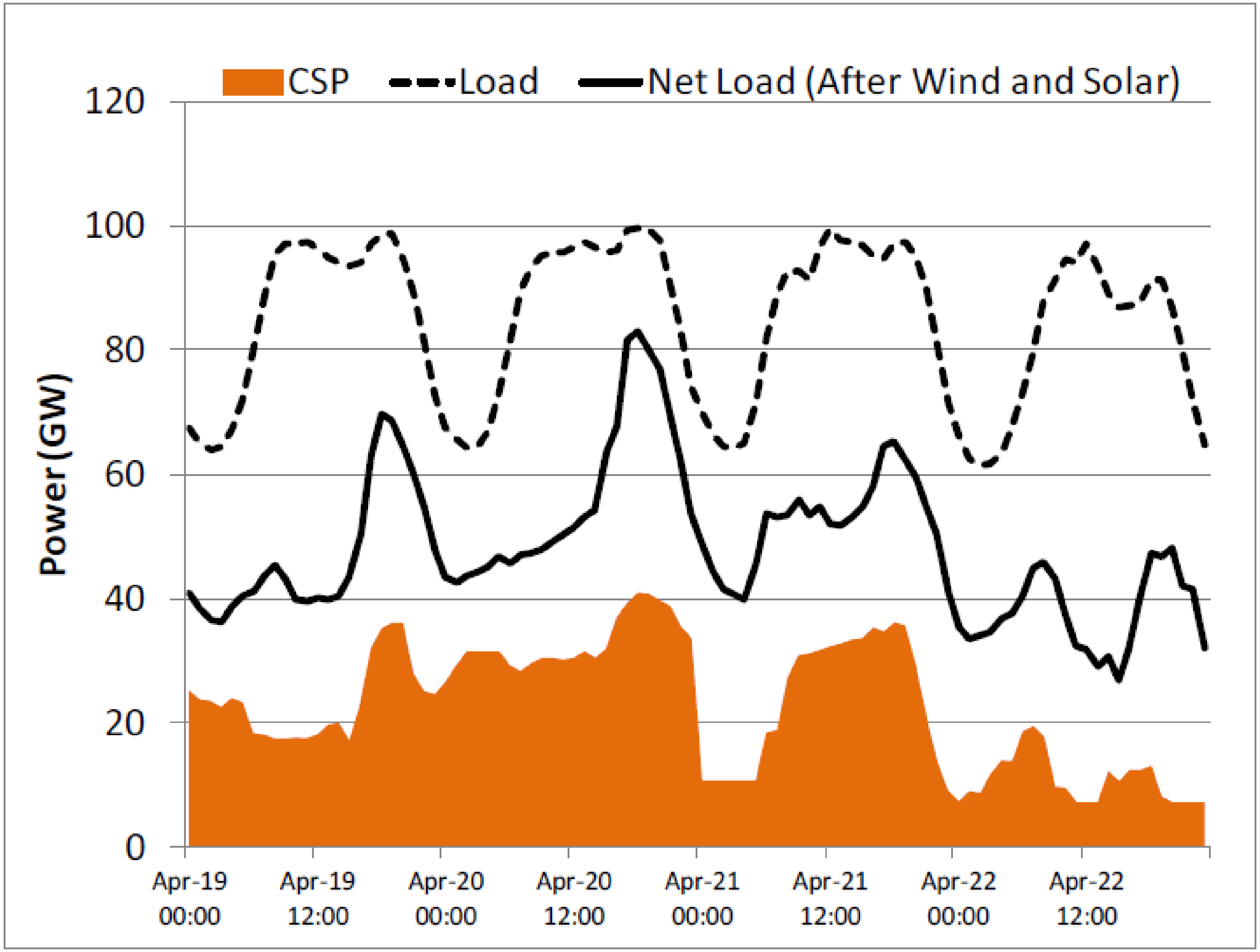
How? Build New Transmission…





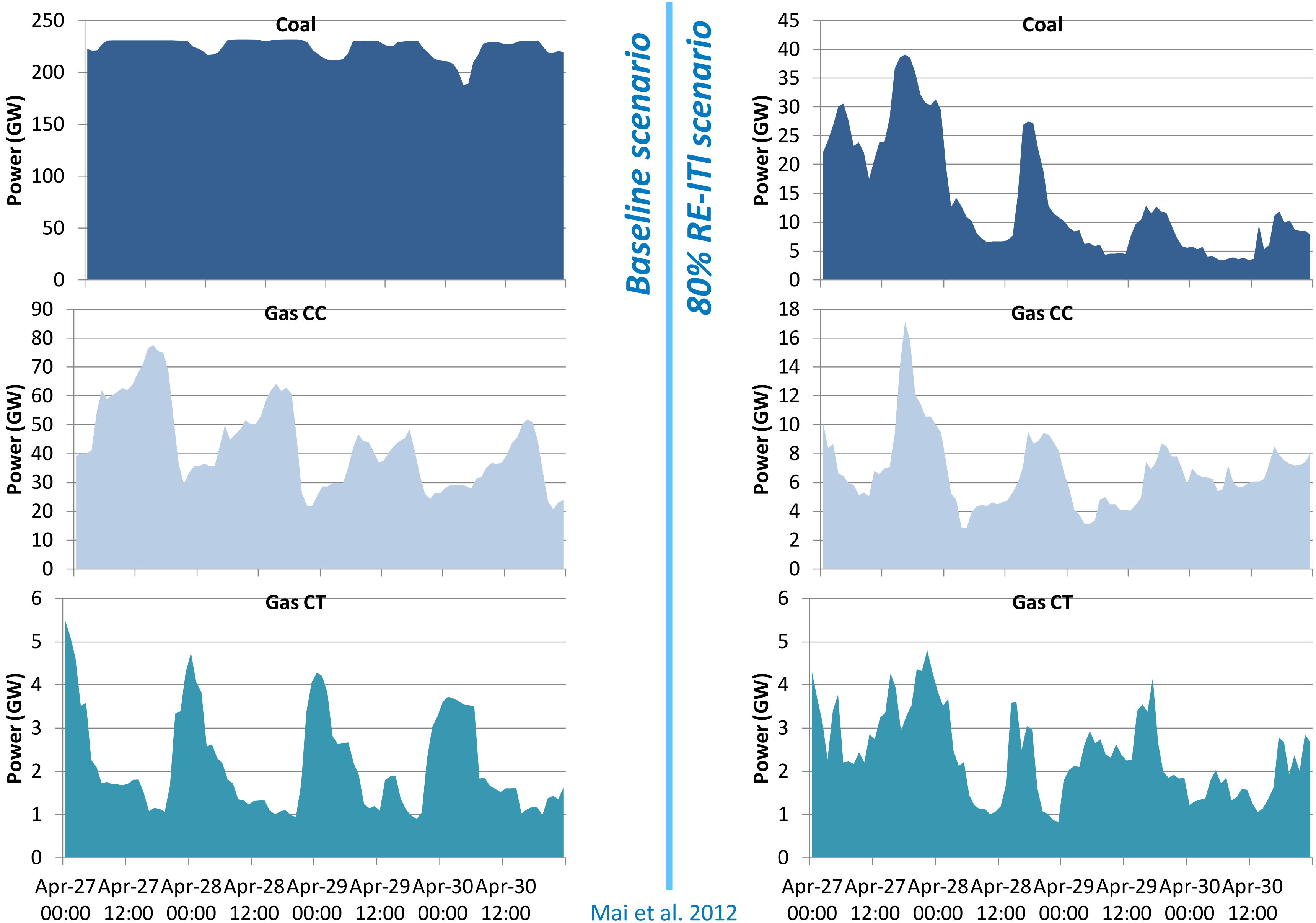
Mai et al. 2012

Deploy Dispatchable Renewables



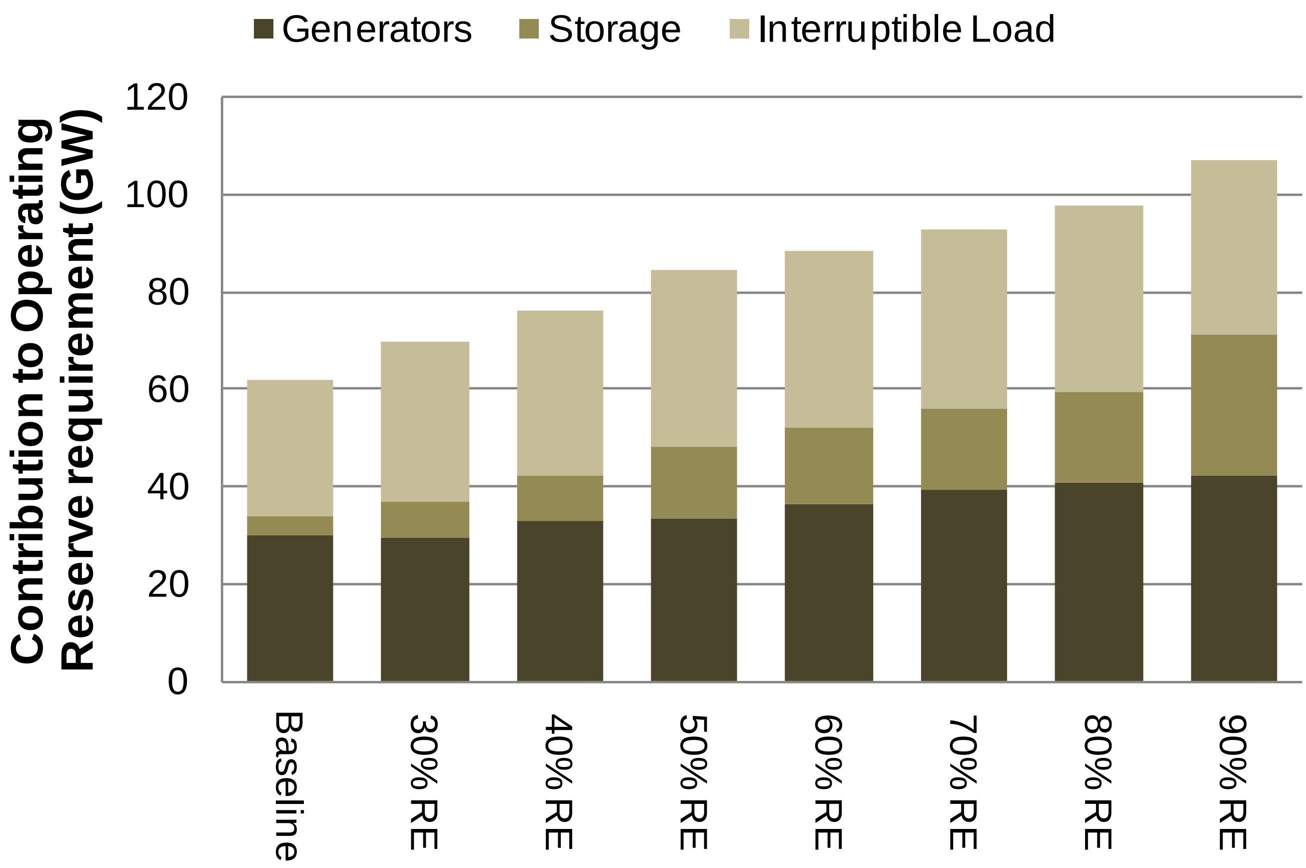
Source: Denholm et al (2012)

Design for cycling



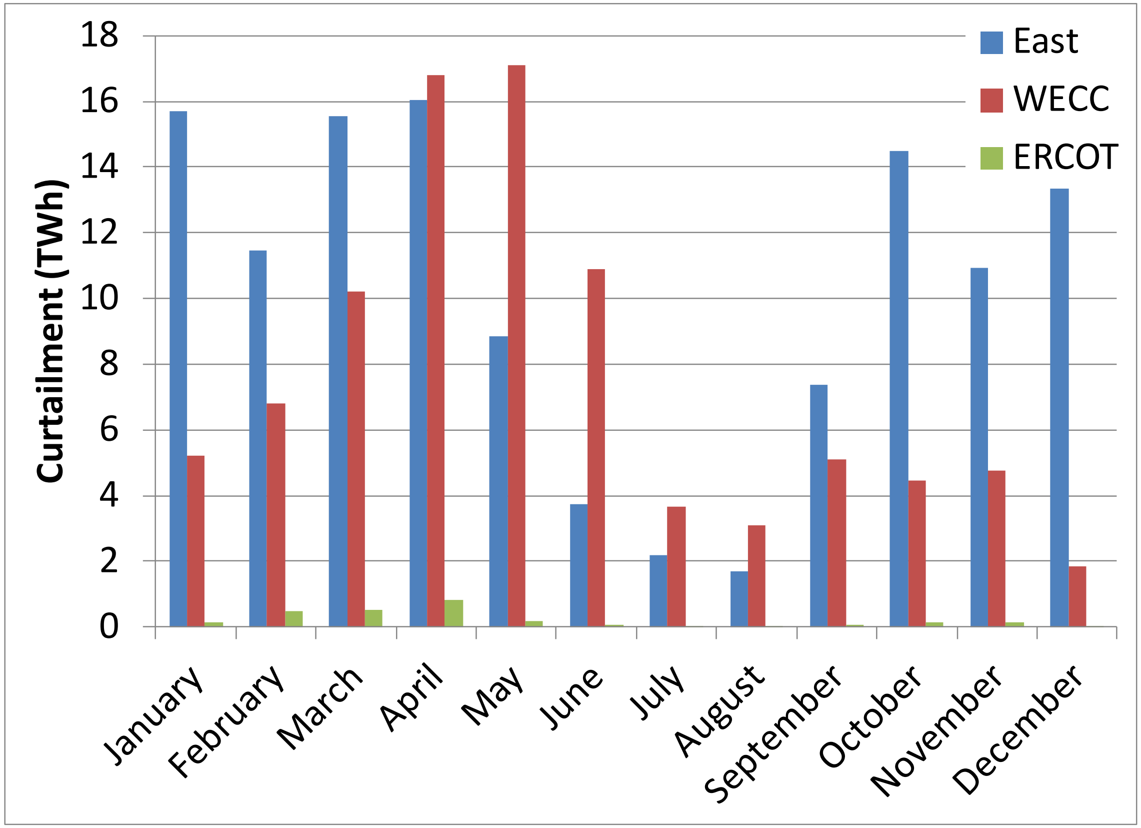
Mai et al. 2012

Harness Responsive Demand (smart grid?)



Mai et al. 2012

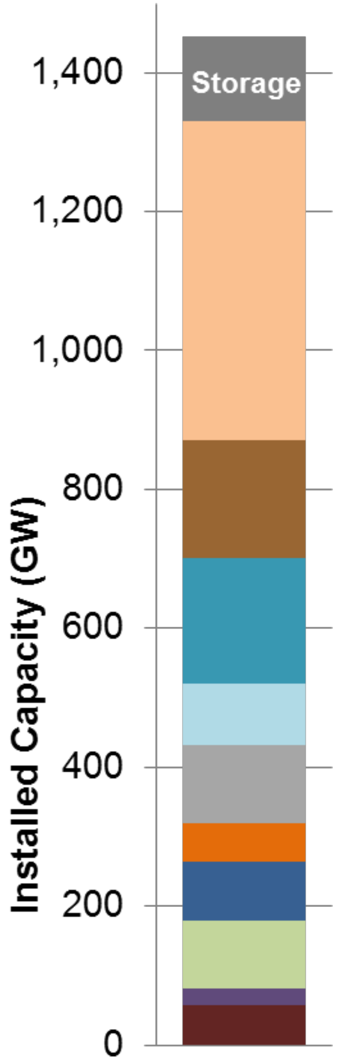
Accept inevitable curtailment in the spring.



- **8-10% of wind, solar, hydropower curtailed in 2050 under 80% RE scenarios**

Mai et al. 2012

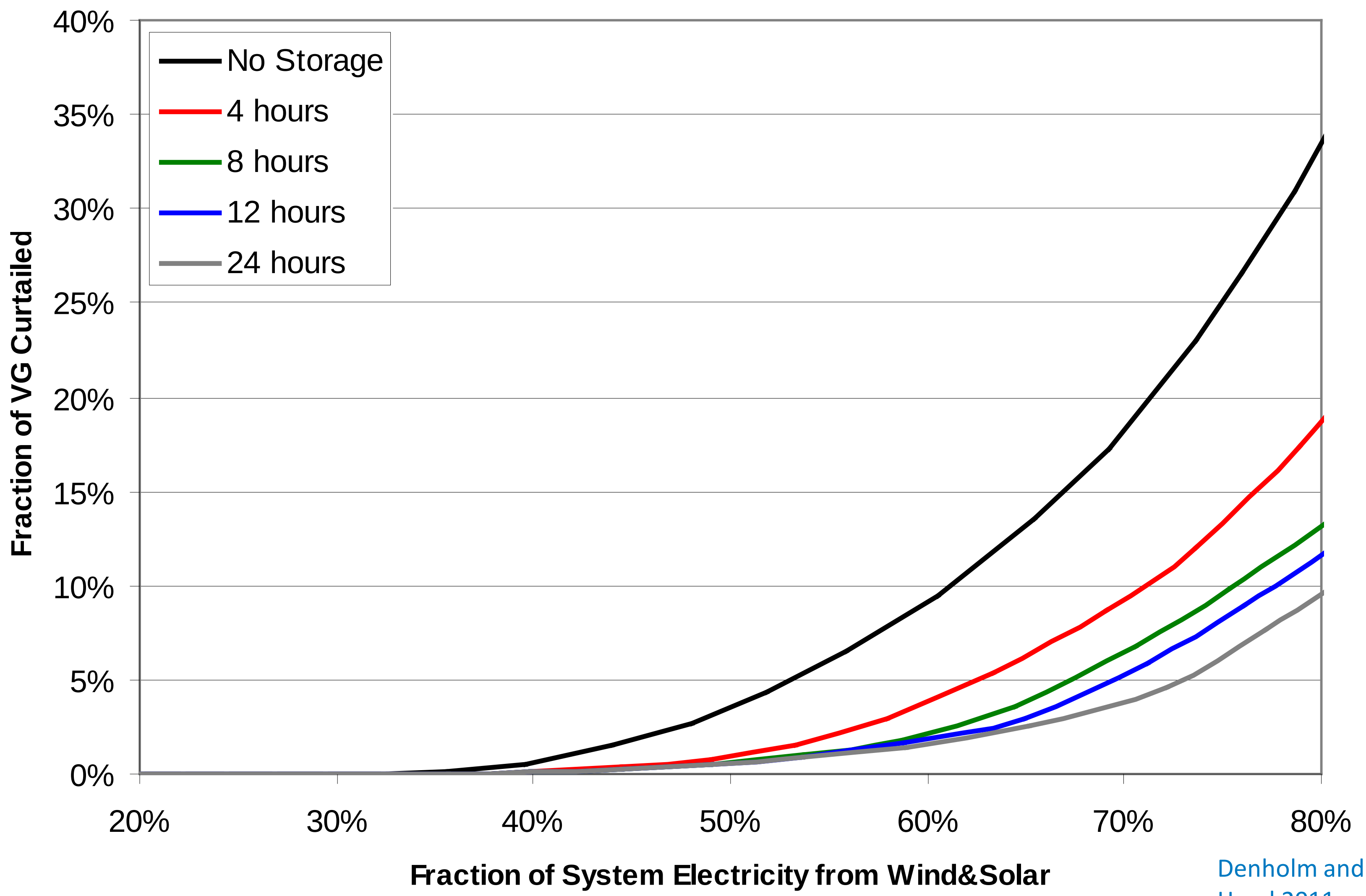
..And yes, develop new storage



Mai et al. 2012

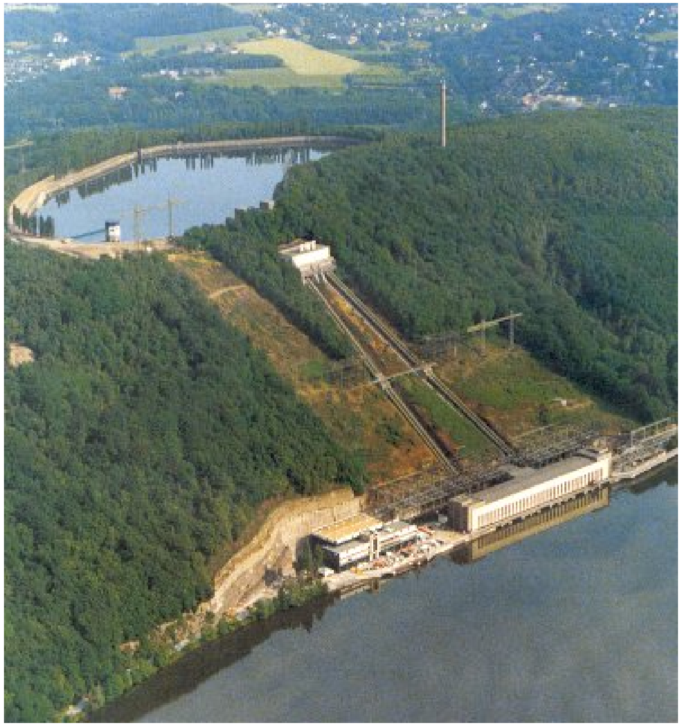
- RE Futures develops about 80 GW of new storage, in addition to the 20 GW of pumped storage existing in the U.S.
- Lower cost storage would be more competitive
- We don't understand the opportunities of a world with low cost energy storage

Energy Storage Can Reduce VG Curtailment

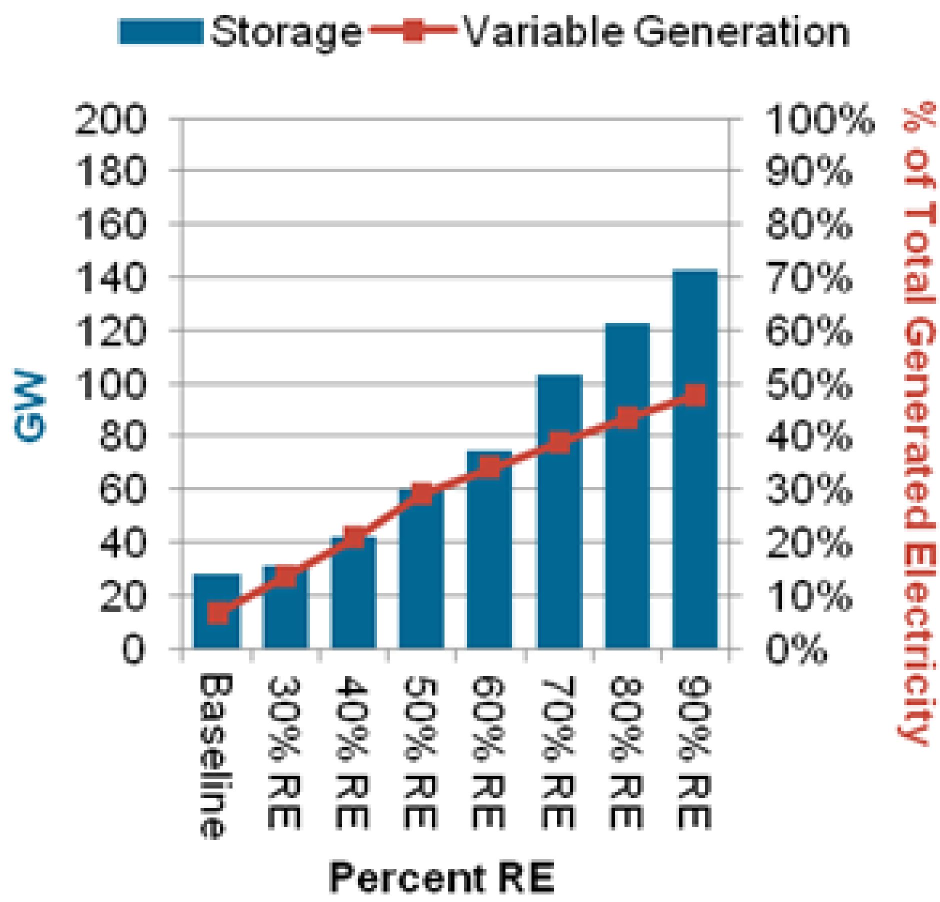


Denholm and Hand 2011

Cost Optimal Storage Deployment?



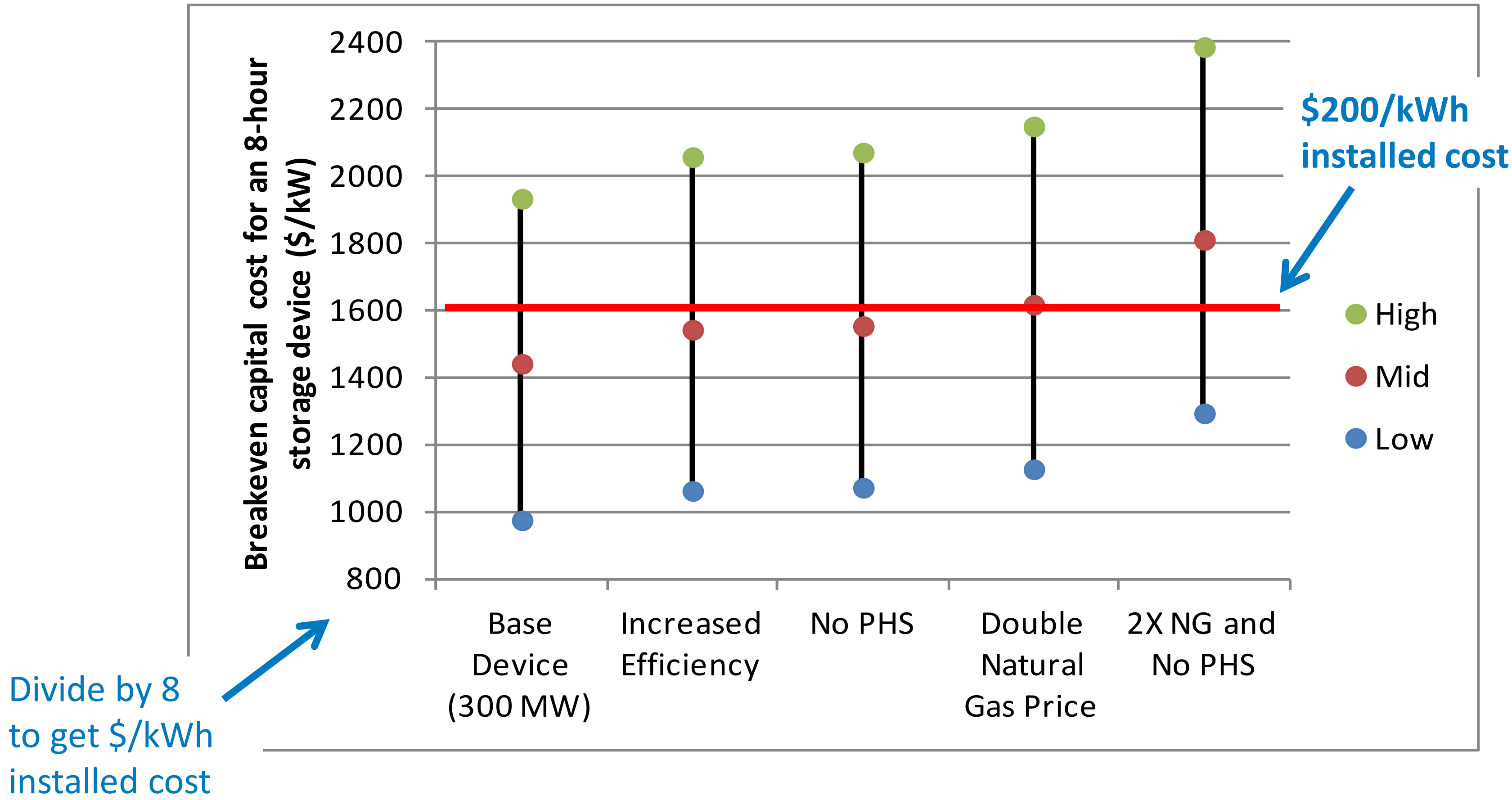
Now - Conventional
Pumped Hydro: ~ 20 GW



Future 80-140 GW
depending on REF scenario

Mai et al. 2012

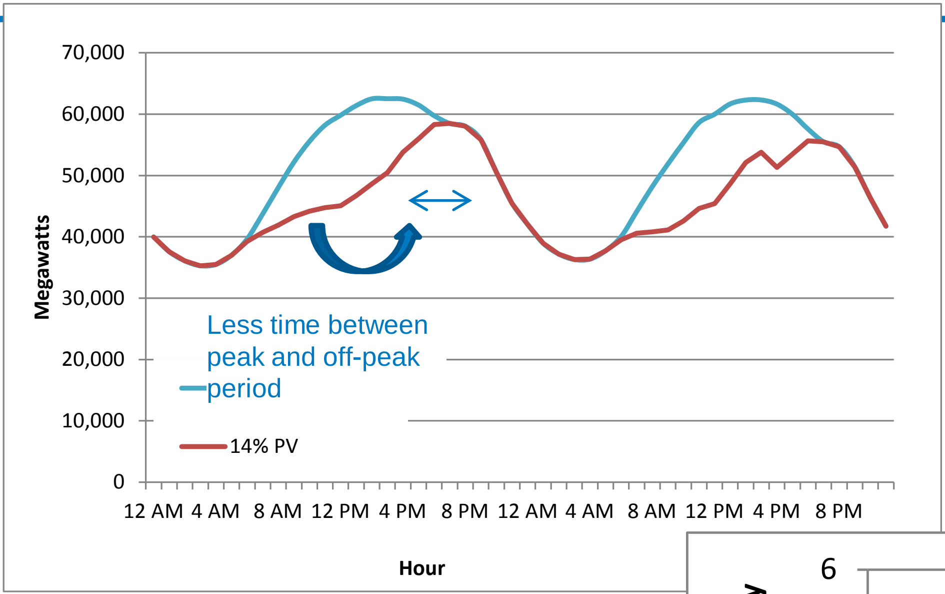
But we are just not there yet….

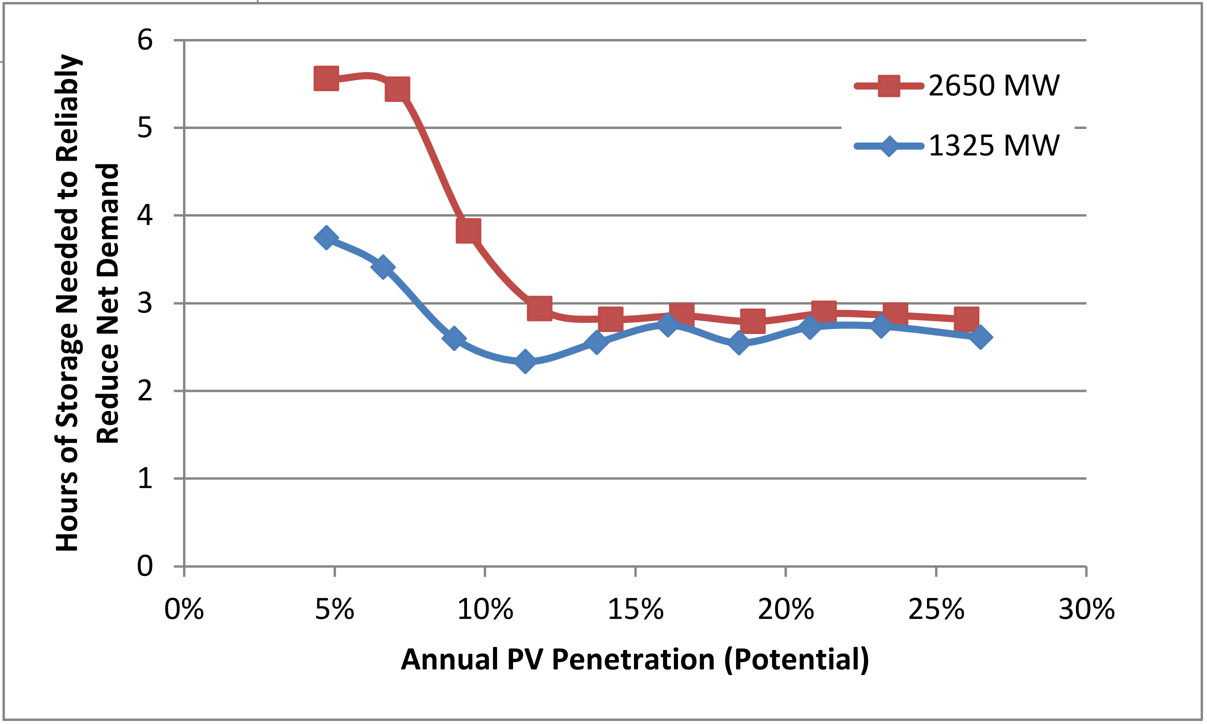


Value of bulk storage (sited on the transmission network) in today's system

Denholm et al. 2013

Storage/PV Synergy

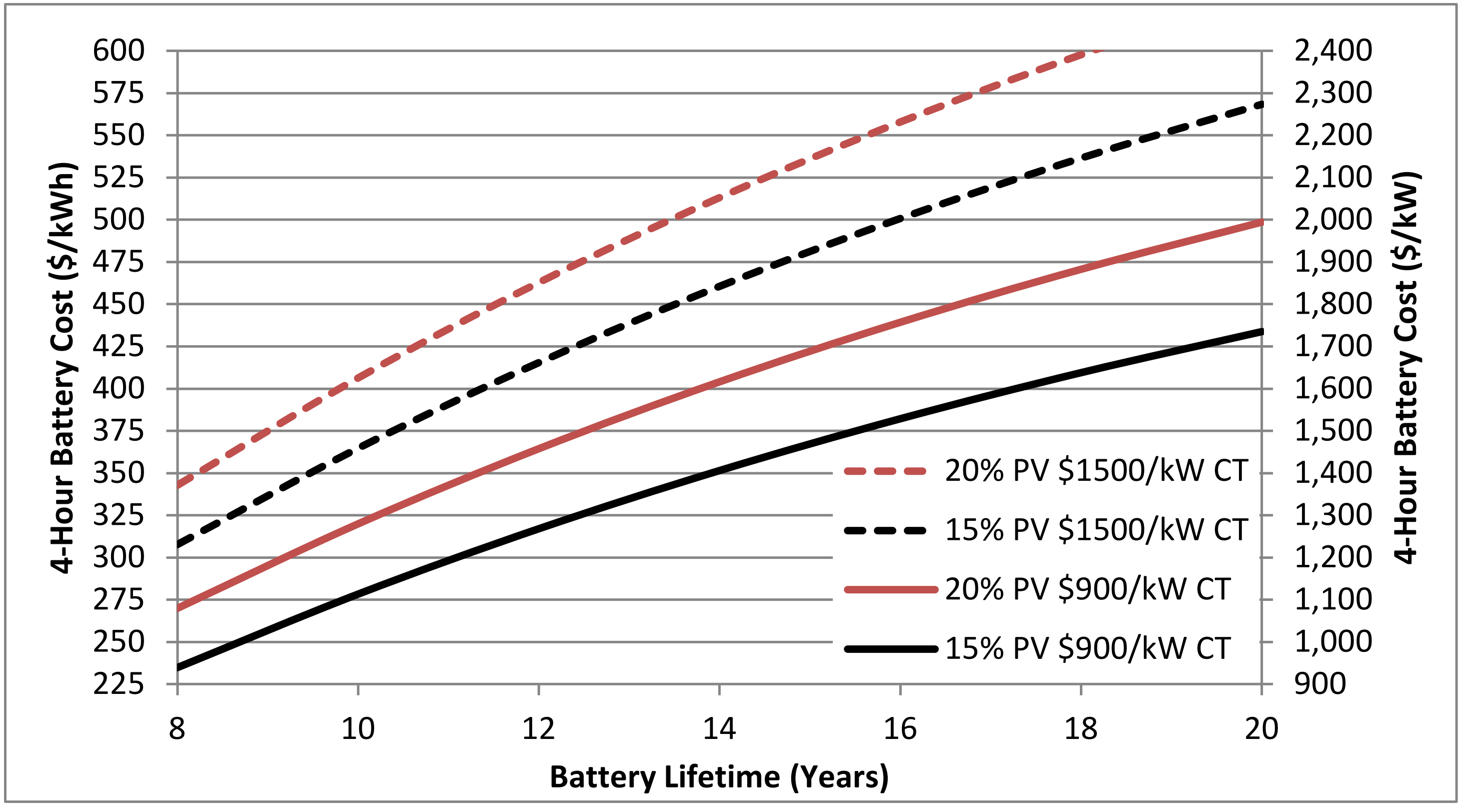




Narrower peak means less storage needed

Denholm et al. 2016

A Tipping Point for Storage?



The adoption of storage may be primarily driven by its ability to offset conventional capacity *aided by the increase in value associated with VG deployment*

Denholm et al. 2015

Conclusions: What I Think I Know About the Grid and Storage (<35%)

- **Numerous studies have demonstrated the feasibility of 35% RE**
- **New methods of grid operation are required**
  - Significantly increased cooperation across large areas
  - More ramping of thermal units
  - Storage is probably not the least-cost option for increased integration

What I Think I Know About the Grid and Storage (>35%)

- **Less explored territory**
- **Curtailment rates increase**
- **Any and all sources of grid flexibility will be needed**
  - Demand Response
  - Long distance transmission?
- **Value of storage increases**
- **At some point low cost sources of flexibility will be exhausted and storage will be an increasingly attractive means of utilizing wind and solar**
  - Non obvious sources of storage may be cost-competitive (Thermal storage in buildings, CSP with TES)
- **Storage adoption may be driven by its ability to replace conventional capacity**

Questions?

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