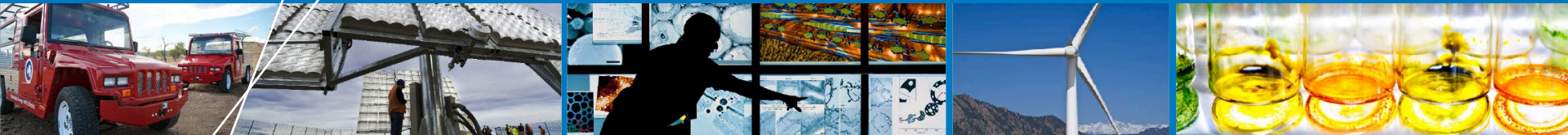


Do We Really Need Storage to Operate the Renewable Grid of the Future?



Paul Denholm

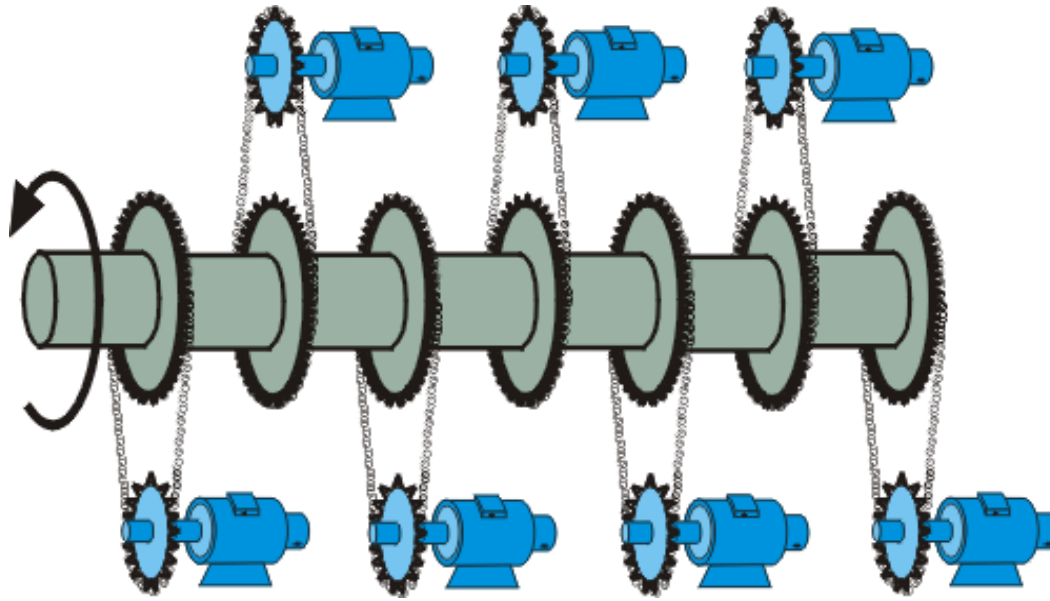
**Third Annual Trottier Symposium
on Sustainable Engineering,
Energy and Design**

Montreal, Canada

March 8, 2016

What is the Electric Grid?

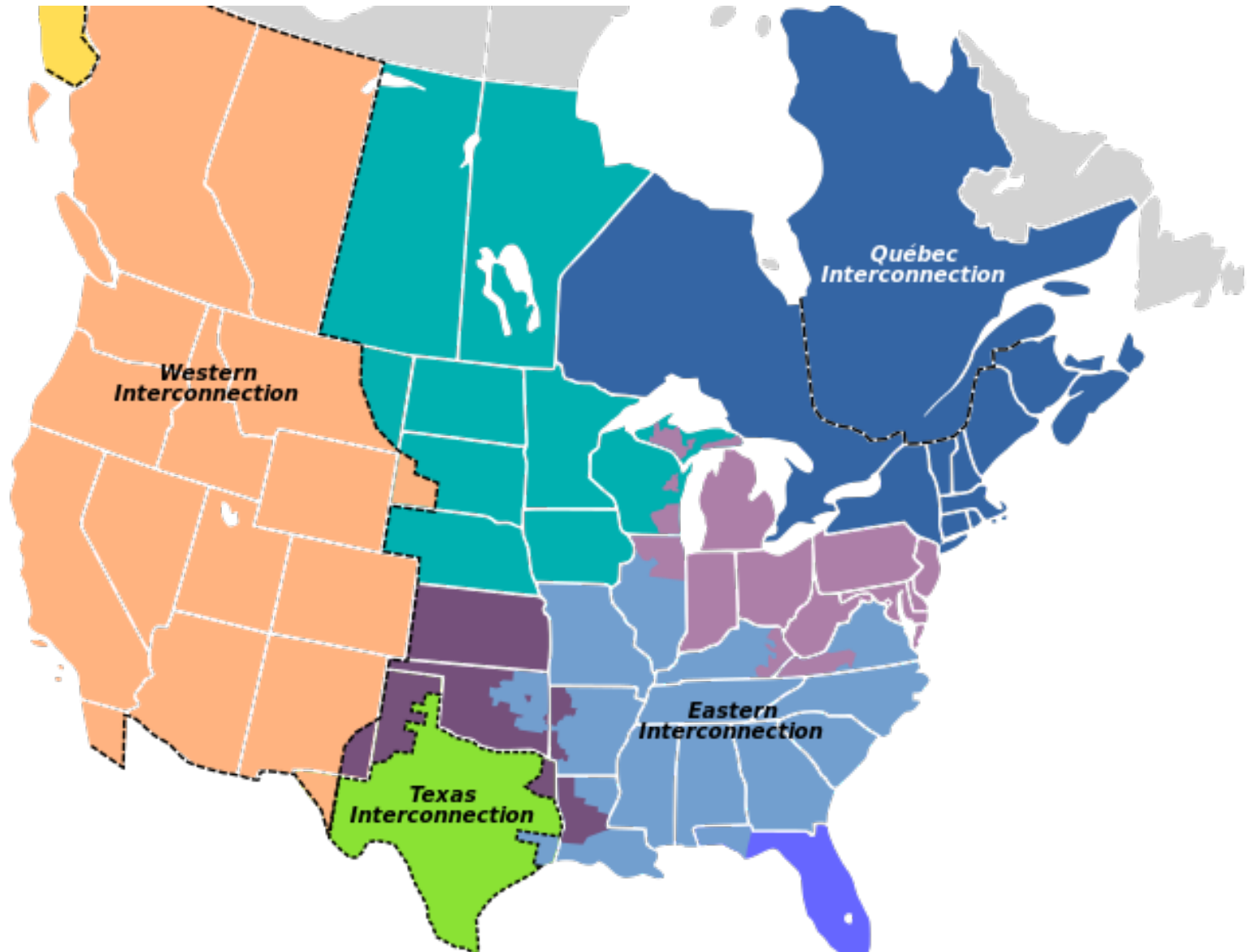
A very large rotating machine spinning at 60 Hz



Source:
Mullane &
O'Malley

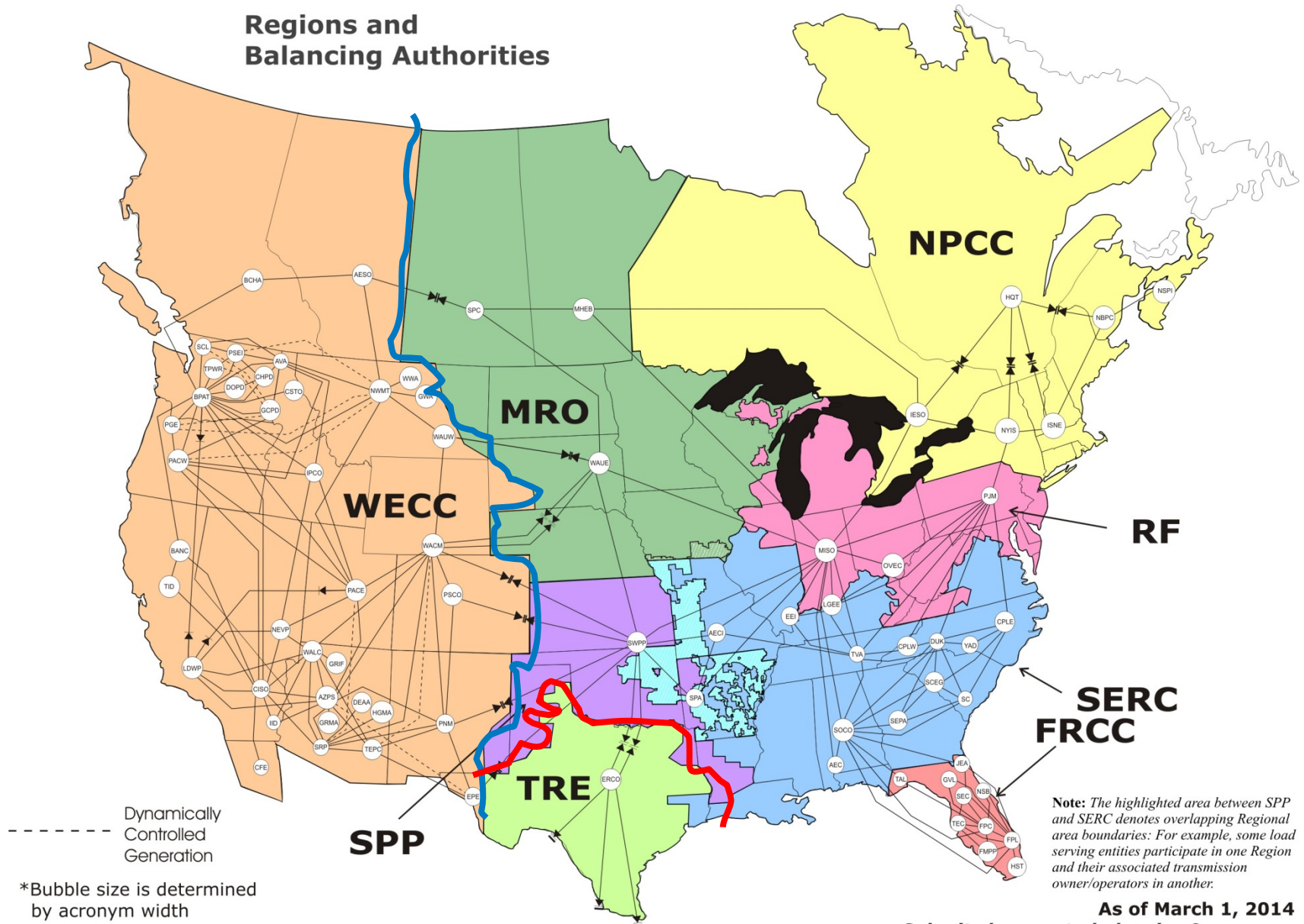
- **Features –**
 - Supply must always meet demand (sort of)
 - Large hourly and season variations in electricity demand
 - Operating reserves to maintain system stability and reliability

Four Independent North America Grids



And Many Balancing Areas

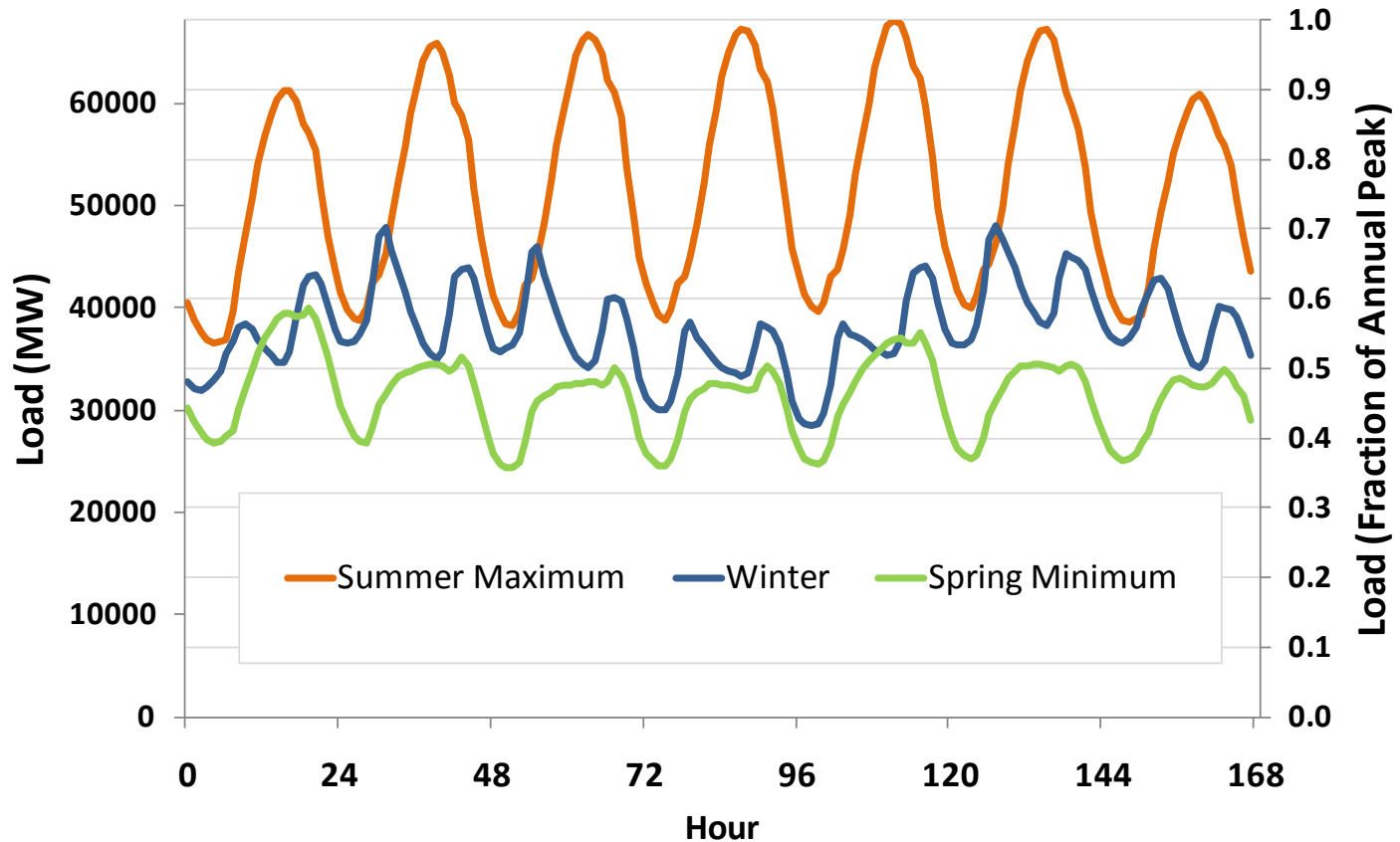
Regions and Balancing Authorities



As of March 1, 2014

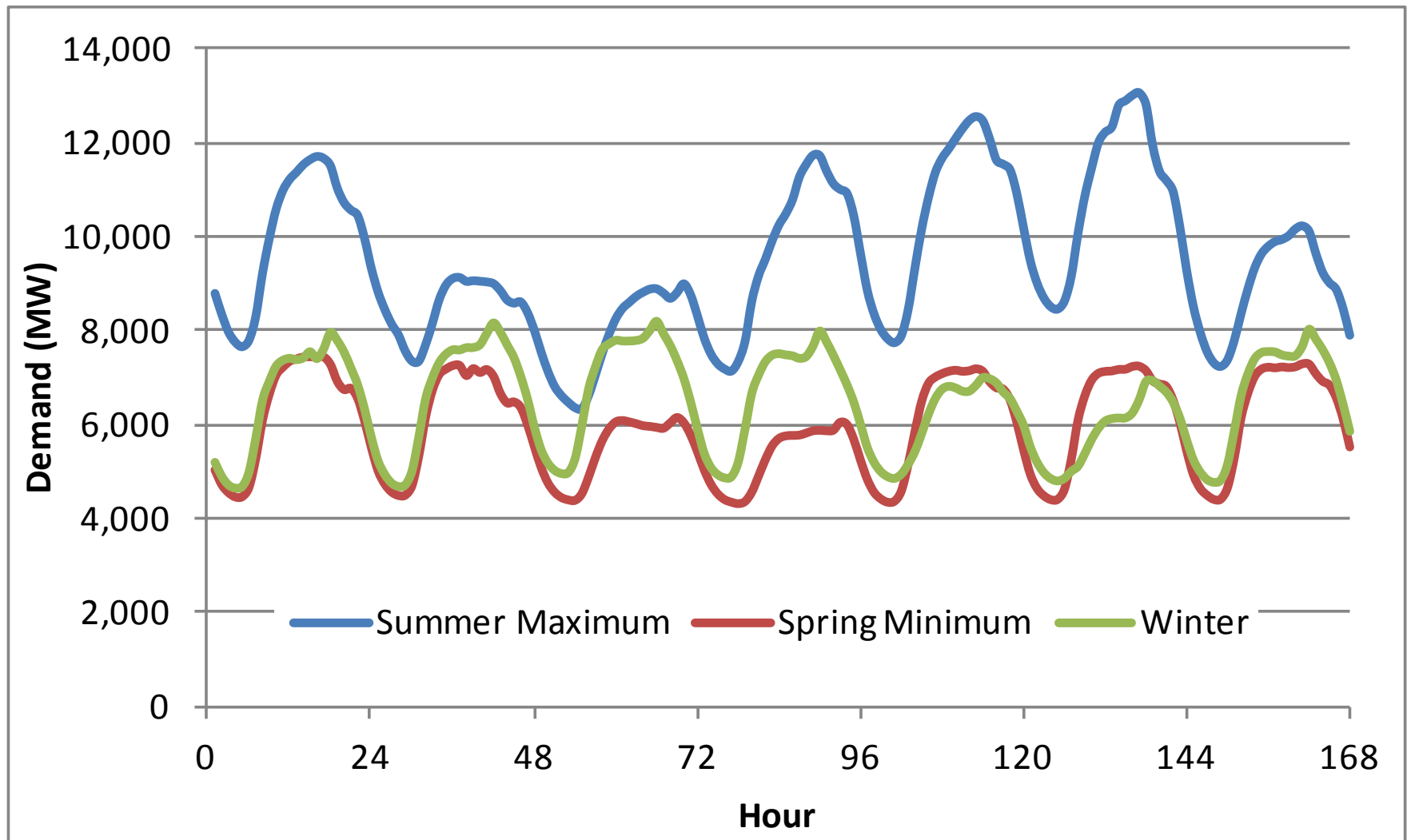
Submit changes to balancing@nerc.com

Each Balancing Area Must Constantly Balance Variation in Demand



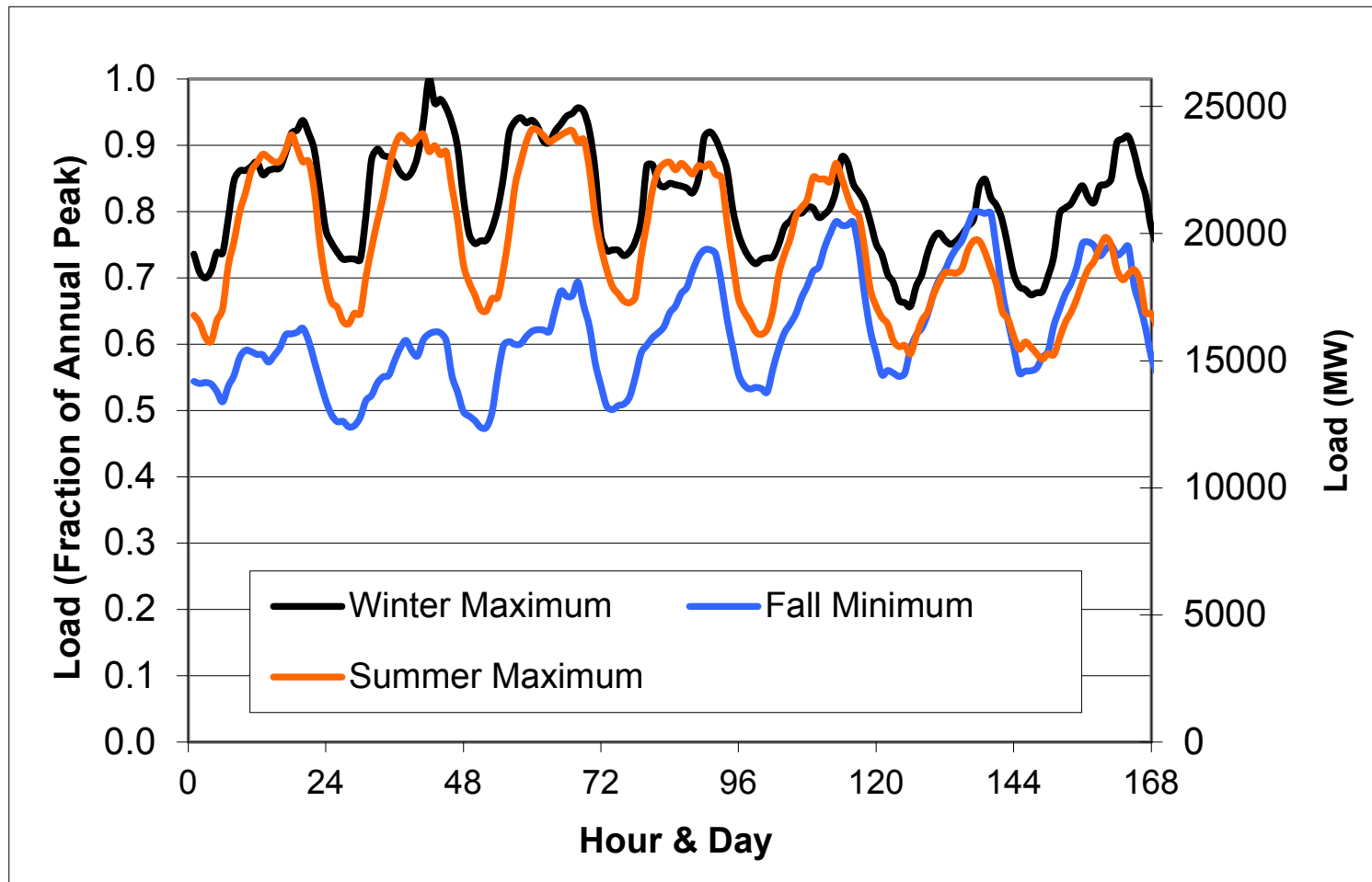
Hourly electricity demand for three weeks in the ERCOT (Texas) Grid in 2005

Demand Patterns Similar for Much of the U.S.



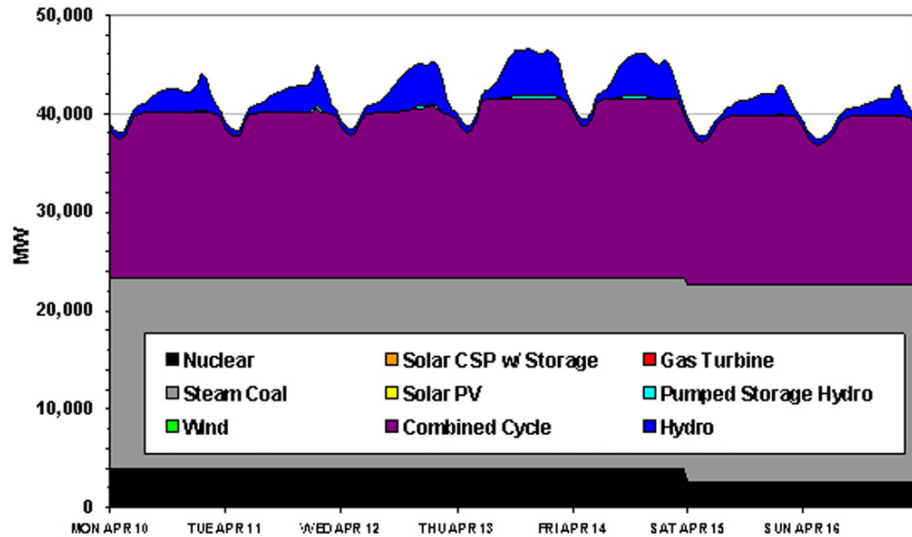
NYC (Con Ed) Demand in 2005

A Few Locations in North America are Winter Peaking

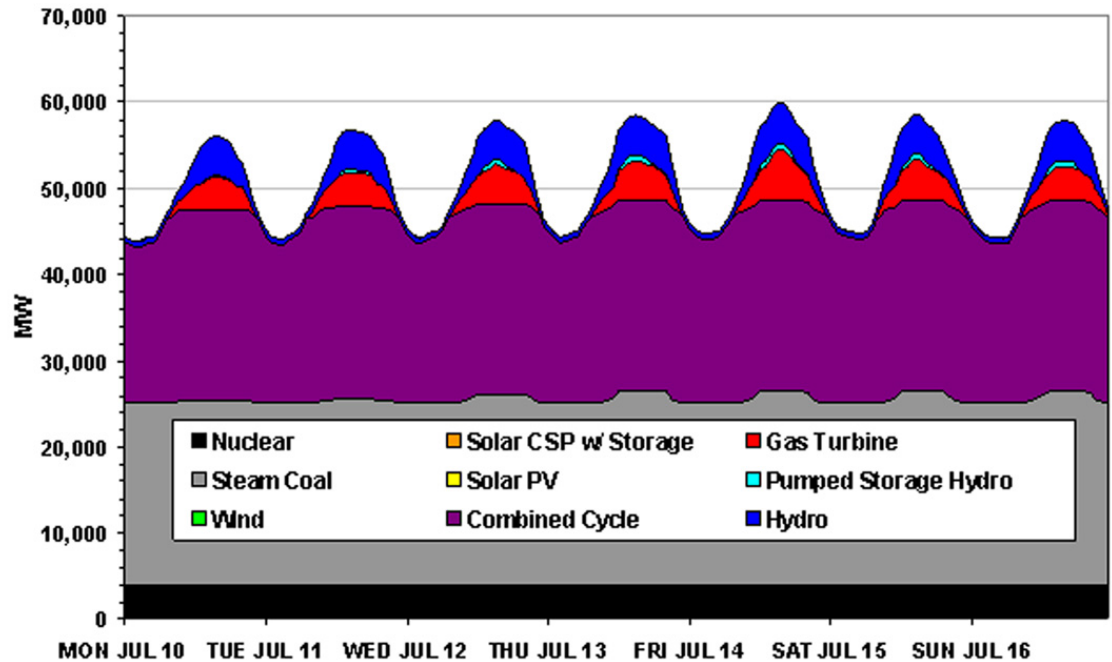


Ontario - 2015

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

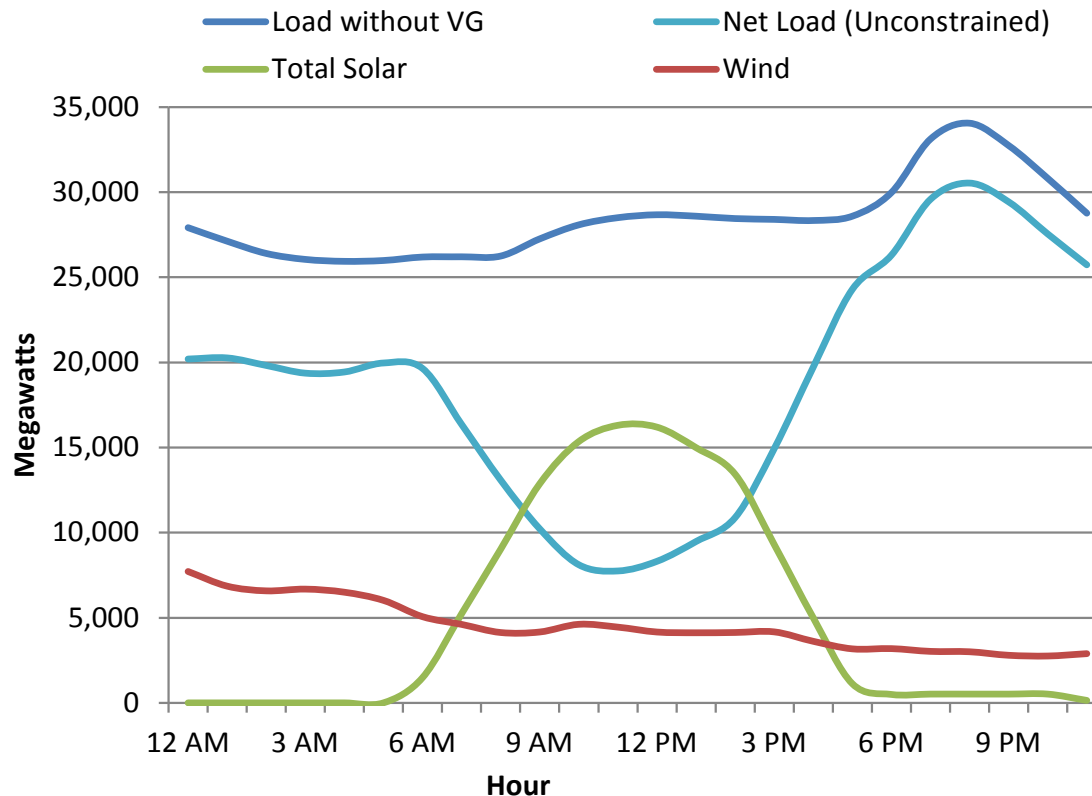


2. Just build lots of renewables and see what happens

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

Framework – Net Load

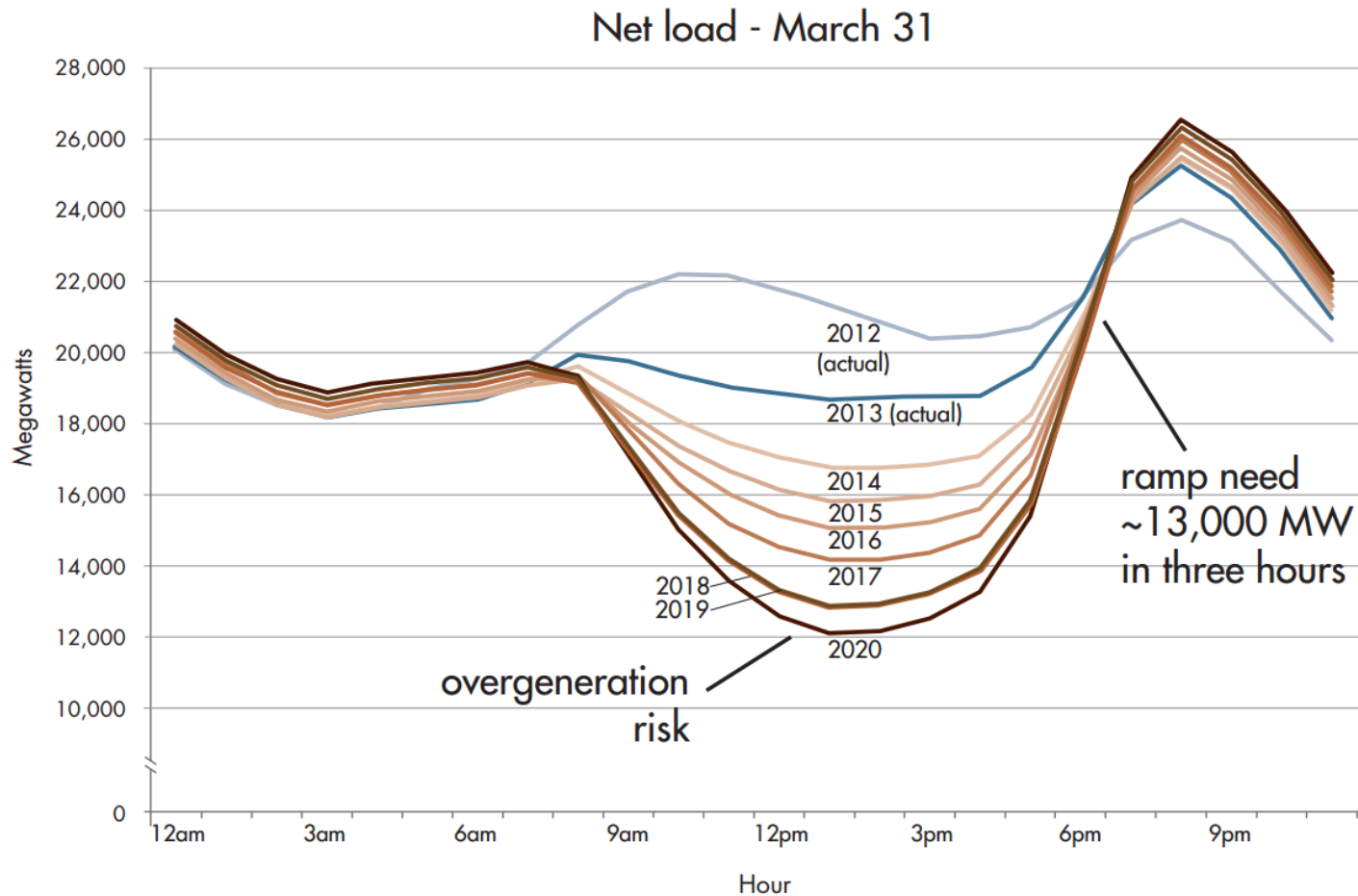
Net load- what's left over when you add wind and solar



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

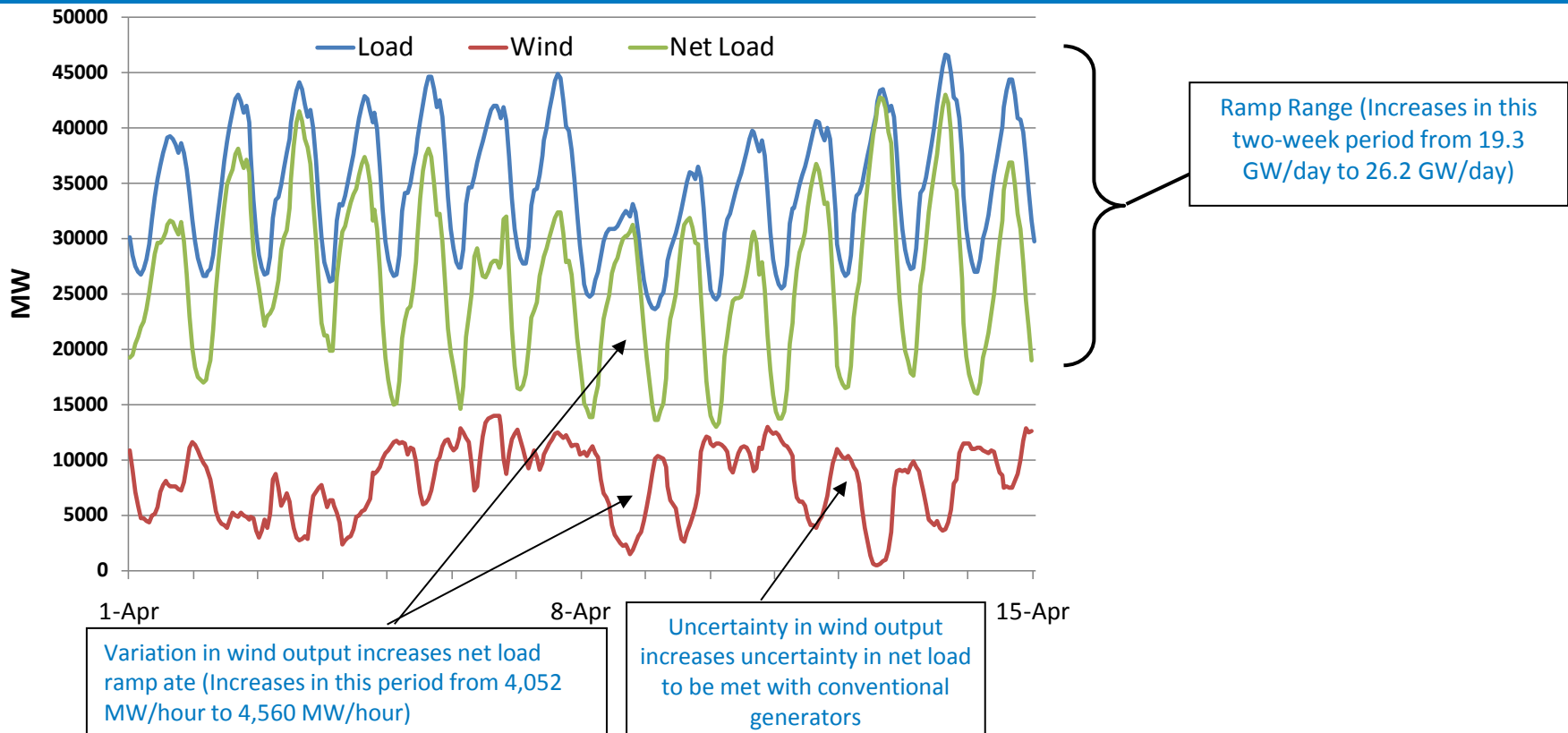
Denholm et al.
2016

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?*

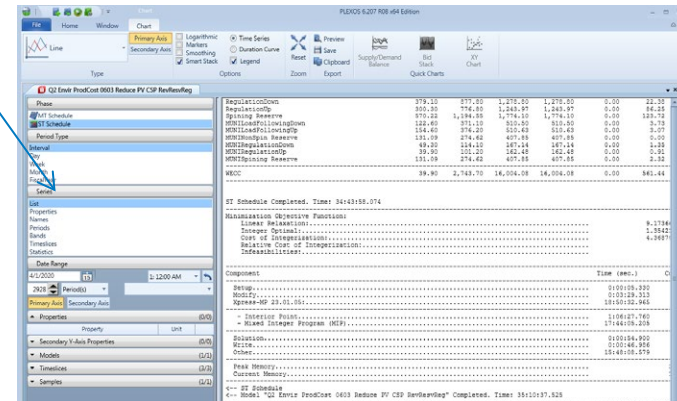
How We Do Grid Integration Science

- 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

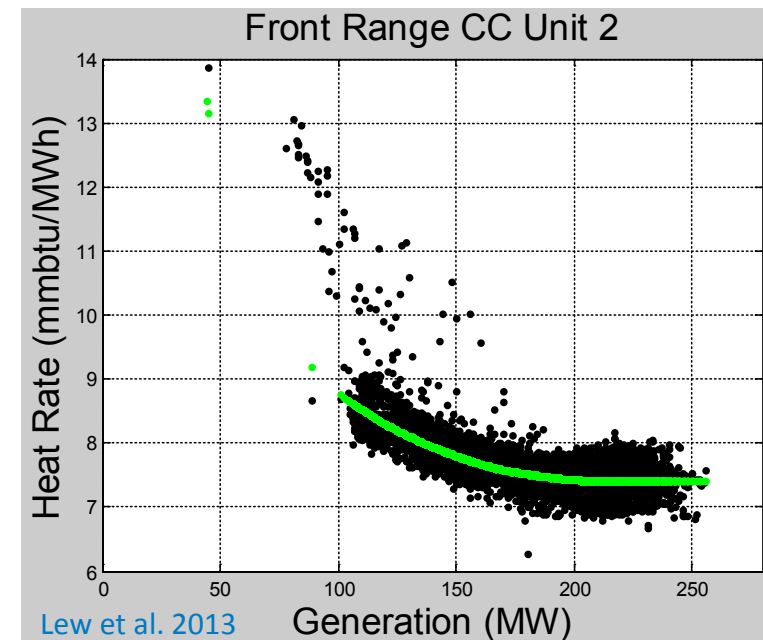
1. Acquire detailed solar and wind data

- 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



Steps to Performing a Realistic Analysis of Renewables on the Grid

4. Hit go and wait...

The screenshot shows the PLEXOS 6.207 R08 x64 Edition software interface. The main window displays a table of results for the 'Q2 Envir ProdCost 0603 Reduce PV CSP RevResvReg' model. The table lists various components and their associated costs. Below the table, there is a log window showing the completion of the 'ST Schedule' and the results of the 'Minimization Objective Function'.

Component	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
RegulationDown	379.10	877.80	1,278.80	1,278.80	0.00	22.38
RegulationUp	300.30	776.80	1,243.97	1,243.97	0.00	86.25
Spining Reserve	570.22	1,194.55	1,774.10	1,774.10	0.00	123.72
MUNILoadFollowingDown	122.60	371.10	510.50	510.50	0.00	3.73
MUNILoadFollowingUp	154.60	376.20	510.63	510.63	0.00	3.07
MUNINonSpin Reserve	131.09	274.62	407.85	407.85	0.00	0.00
MUNIRegulationDown	49.30	114.10	167.14	167.14	0.00	1.35
MUNIRegulationUp	39.90	101.20	162.48	162.48	0.00	0.91
MUNISpining Reserve	131.09	274.62	407.85	407.85	0.00	2.32
WECC	39.90	2,743.70	16,004.08	16,004.08	0.00	561.44

ST Schedule Completed. Time: 34:43:58.074

Minimization Objective Function:

Linear Relaxation:	9.17364
Integer Optimal:	1.3542
Cost of Integerization:	4.36871
Relative Cost of Integerization:	
Infeasibilities:	

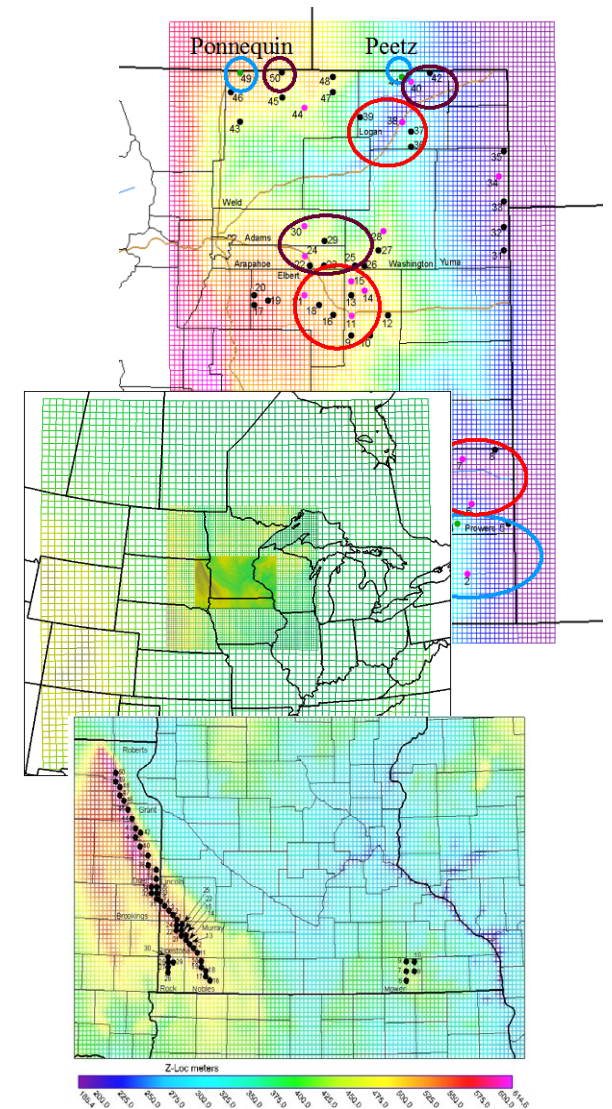
Component Time (sec.)

Setup	0:00:05.330
Modify	0:03:29.313
Xpress-MP 23.01.05:	18:50:32.965
- Interior Point	1:06:27.760
- Mixed Integer Program (MIP)	17:44:05.205
Solution	0:00:54.900
Write	0:00:46.986
Other	15:48:08.579
Peak Memory	
Current Memory	

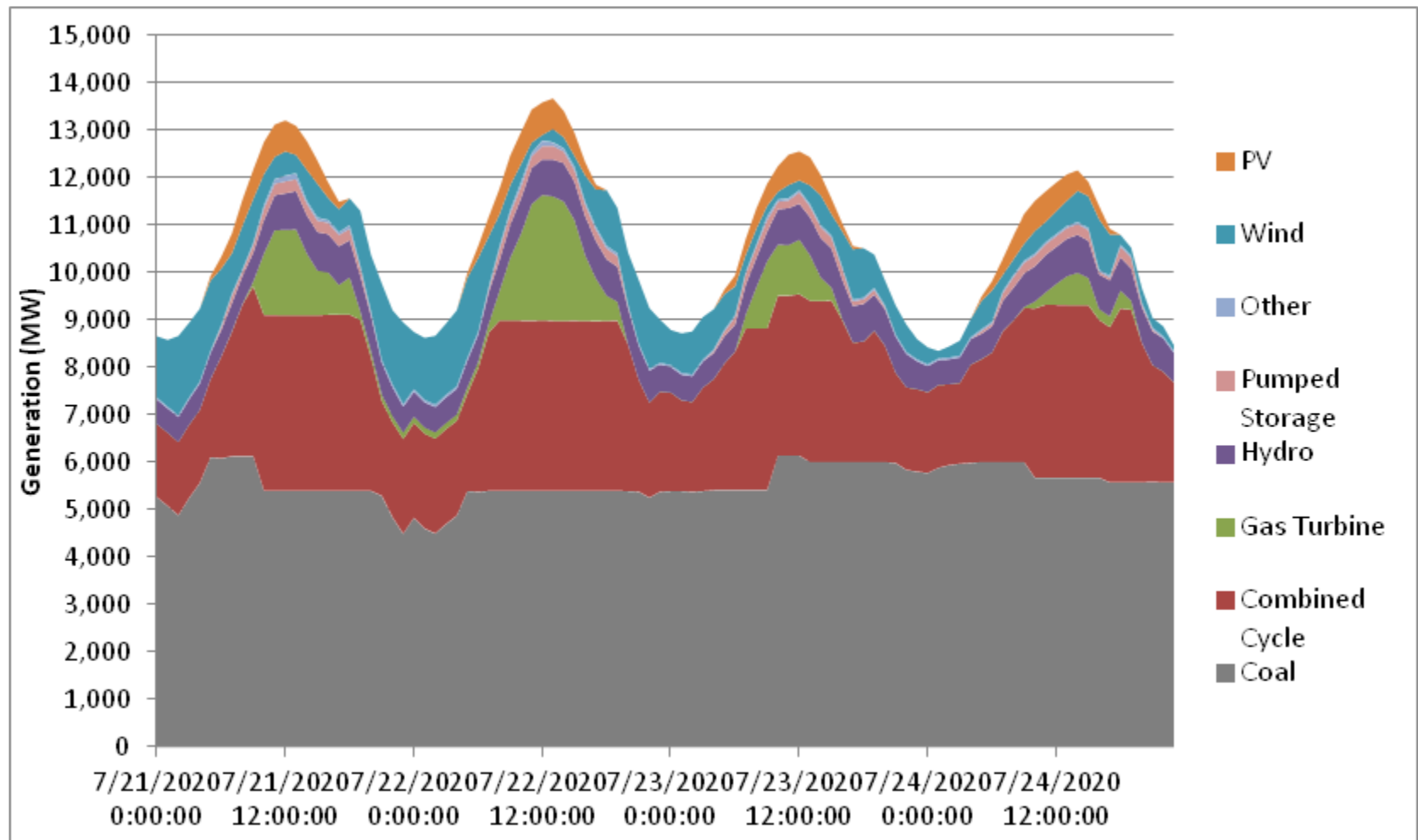
<<-- ST Schedule
<<-- Model "Q2 Envir ProdCost 0603 Reduce PV CSP RevResvReg" Completed. Time: 35:10:37.525

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?
- **Did a bunch of bad things happen to indicate storage is needed?**

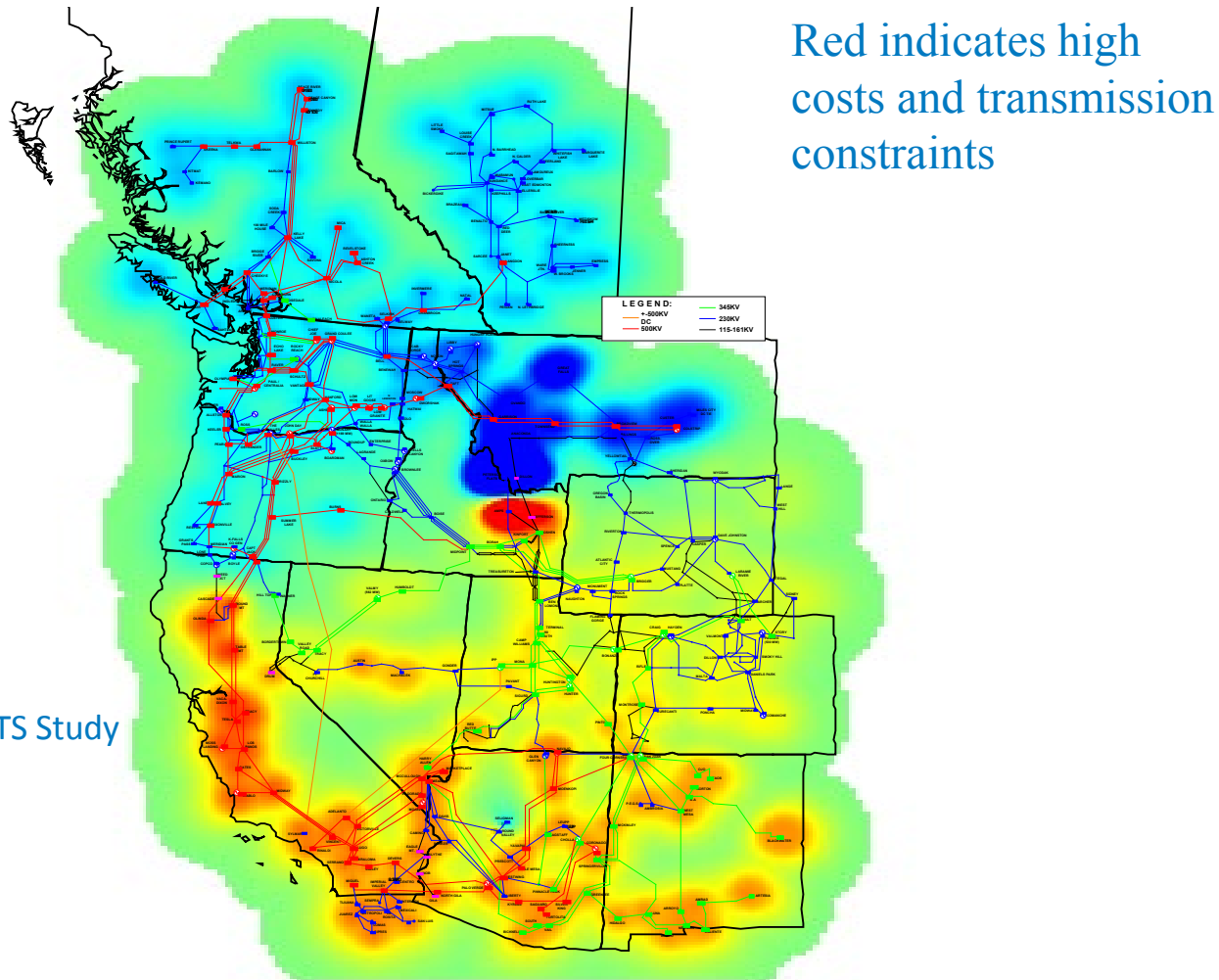


Example Dispatch in Colorado



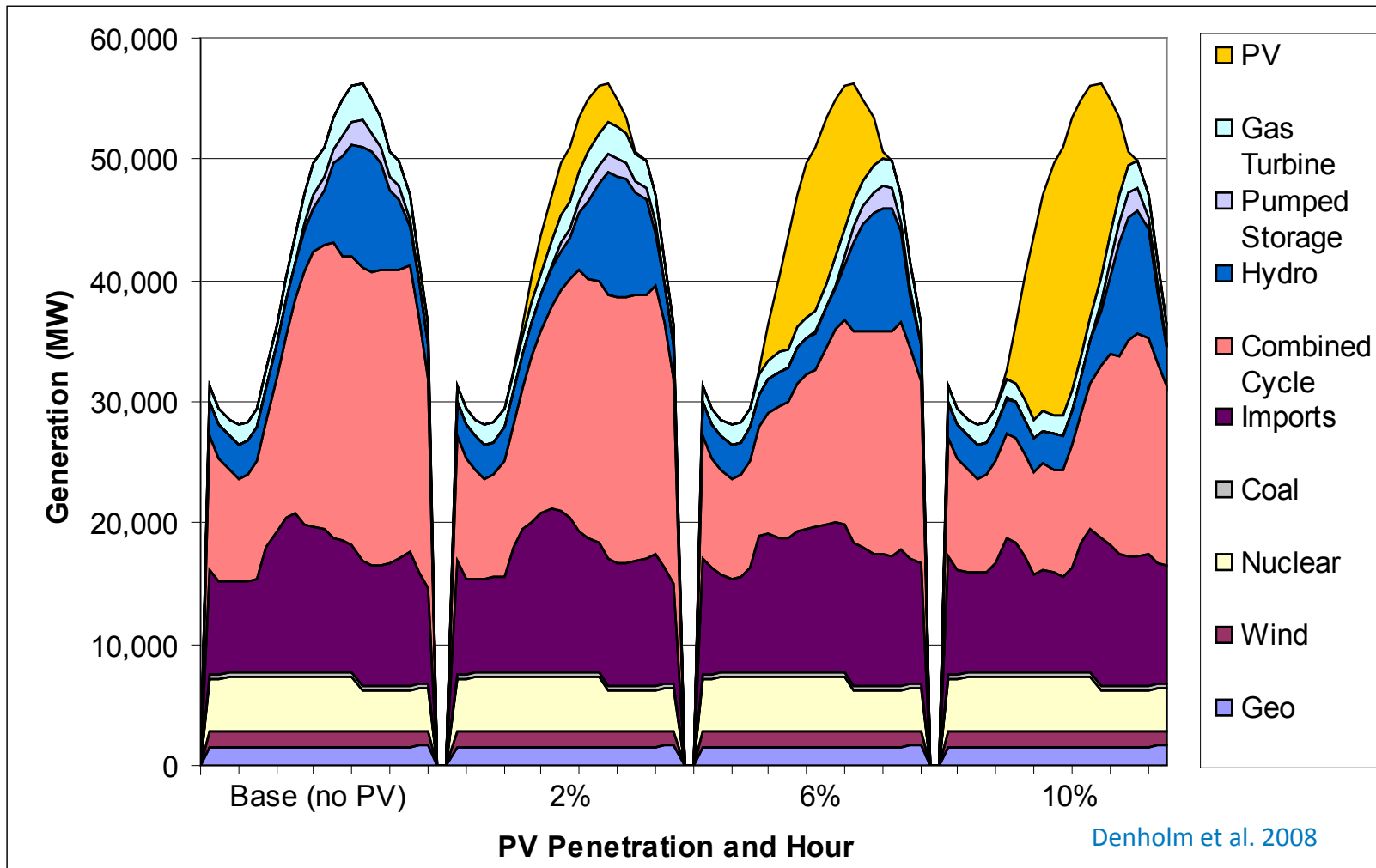
Denholm et al.
2014

Power Flow and Transmission



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

PLEXOS 6.207 R08 x64 Edition

Standard Category Total
Execute Total
Numeric Format Solution

System
Production
Generators
Fuels
Storages
Reserves
RMPP
Transmission
Regions
Nodes
Constraints

Parent Name	Collection	Child Name	Category	Datetime	Provision (GWh)	Risk (GWh)	Shortage (GWh)
System	Reserves	Cont_PSC	RMPP_Core	2020	1,971.00	1,971.00	0.00
System	Reserves	Cont_WACM	RMPP_Core	2020	1,576.79	1,576.80	0.01
System	Reserves	Flex_RMPP	RMPP_Core	2020	502.26	502.33	0.07
System	Reserves	RegUp_RMPP	RMPP_Core	2020	1,049.72	1,049.72	0.00

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

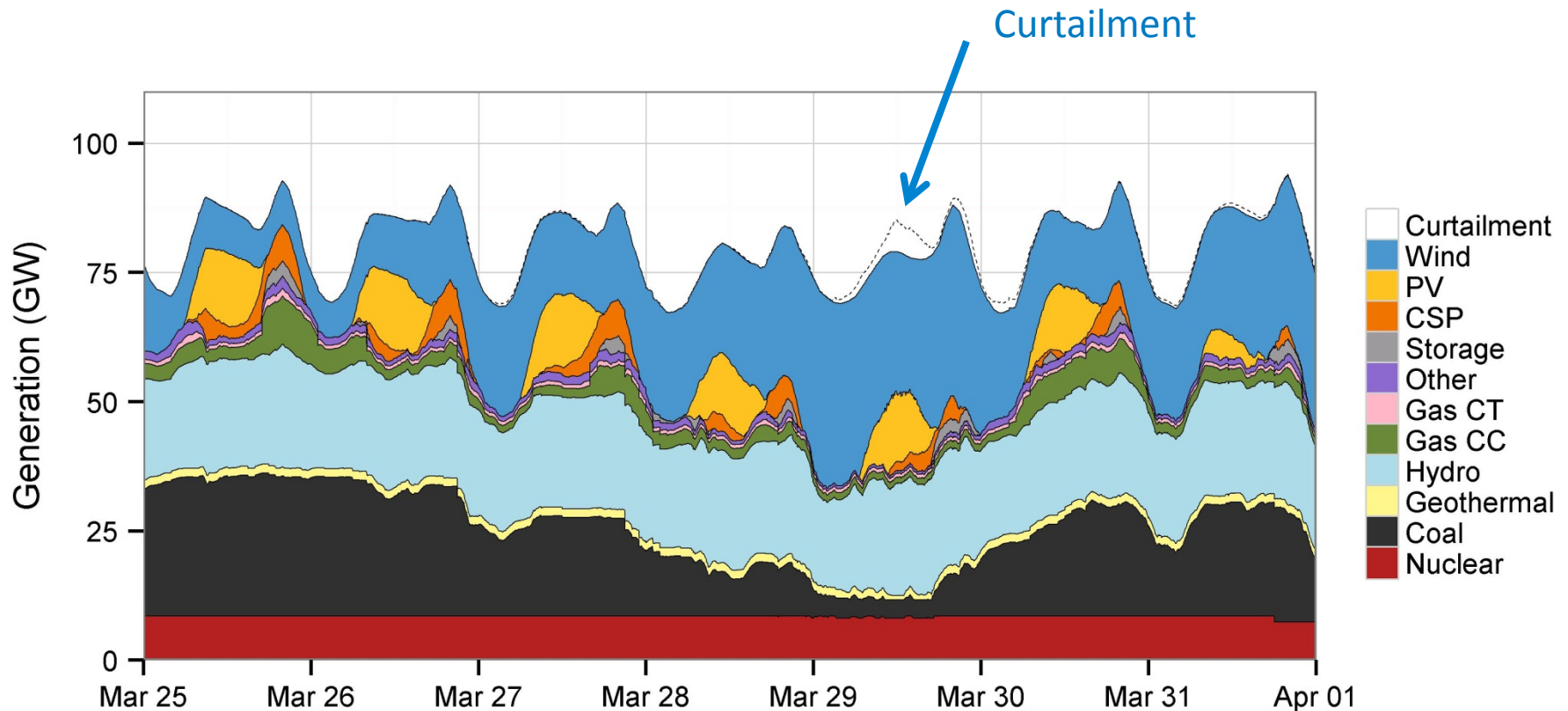
Second Generation

- **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**

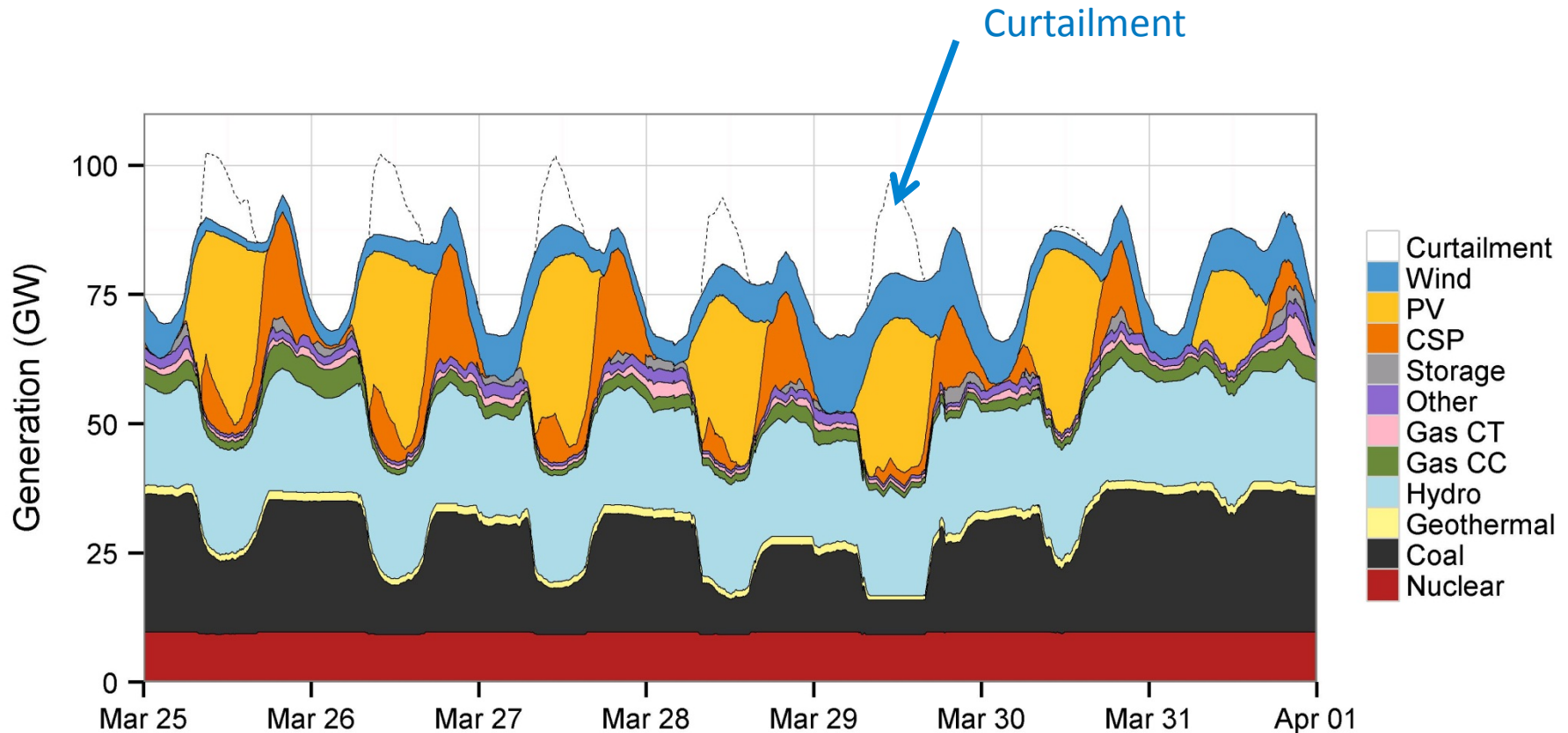
WWSIS II High Wind Case (8% solar, 25% wind)



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

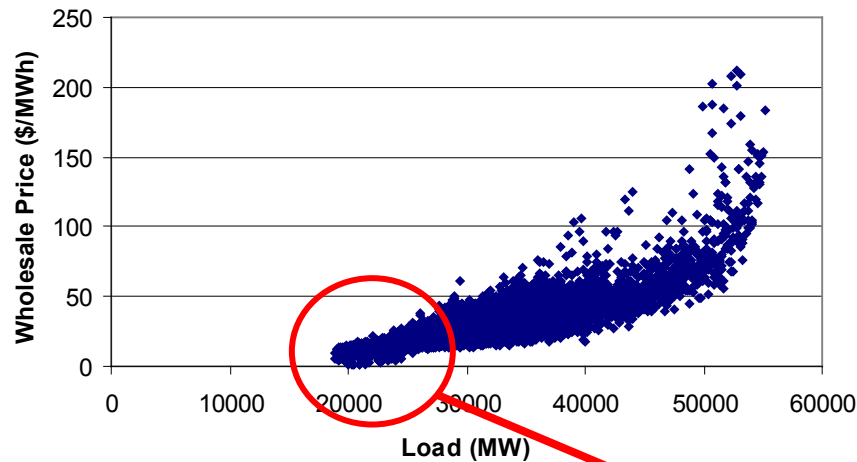
Sources of Curtailment

Too much supply, not enough demand, when considering:

- Ramp constraints
- Transmission constraints
- Minimum output levels from hydro and thermal generators
 - 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

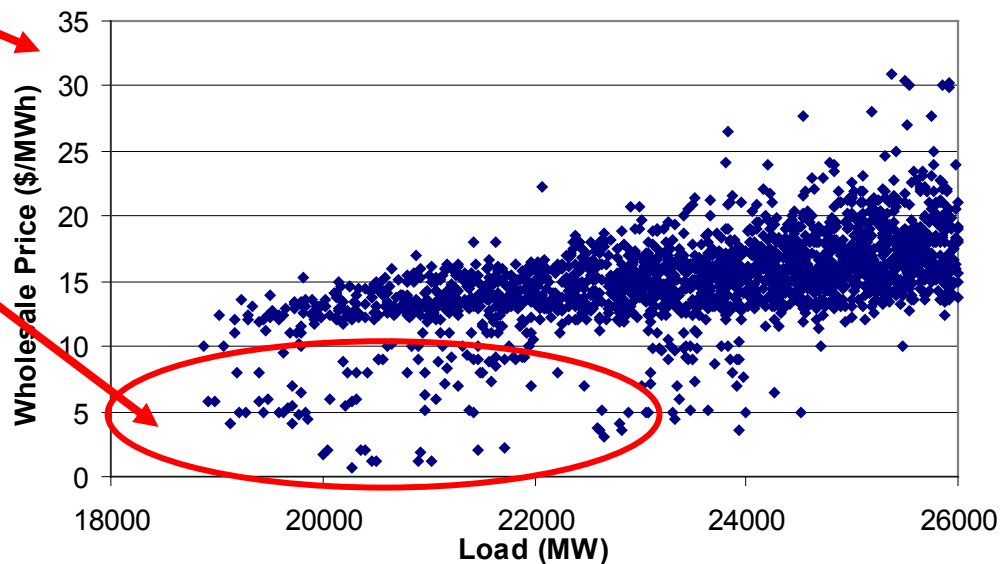


Price/Load Relationship in PJM

Below Cost Bids

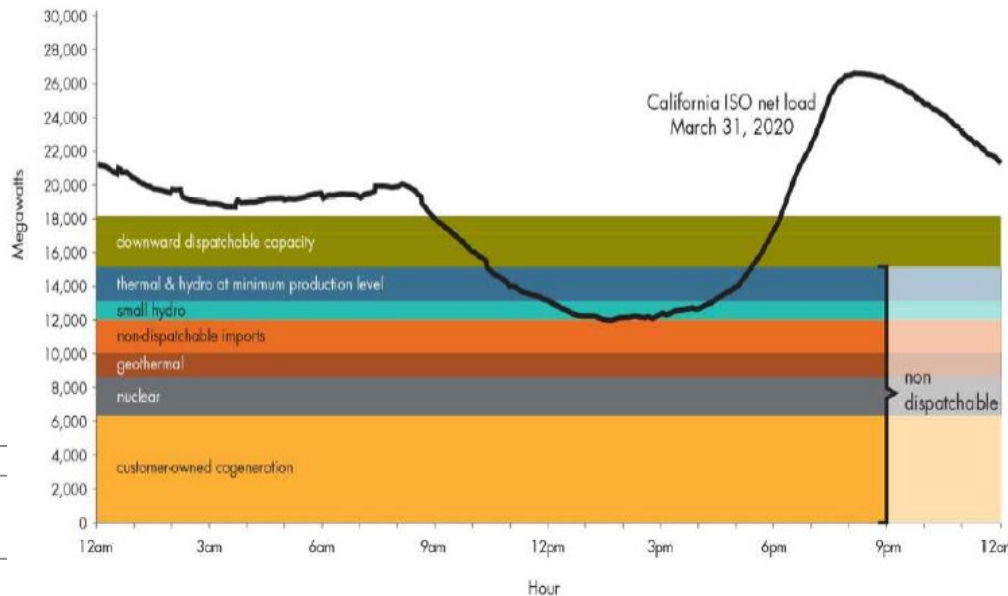
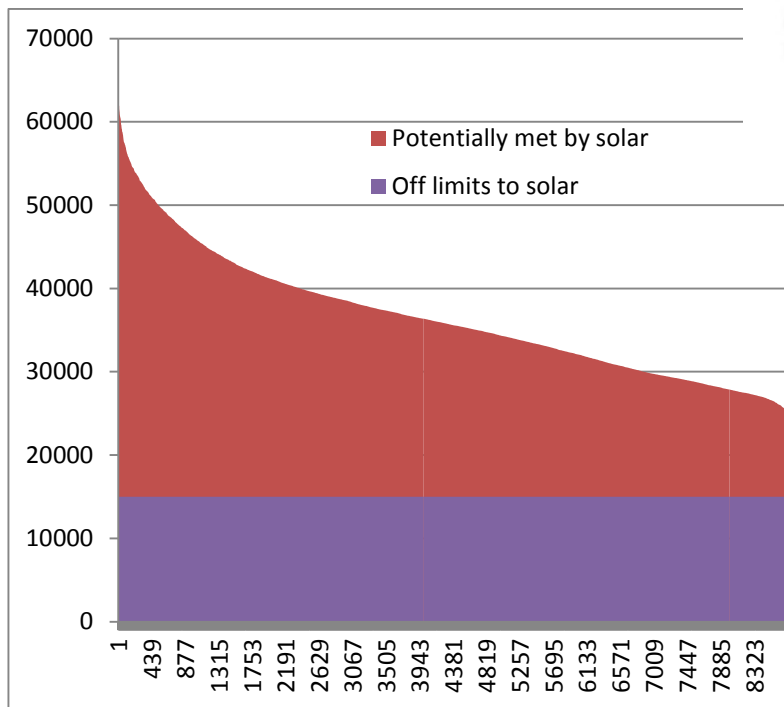
Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind and solar may be curtailed under these conditions.

29



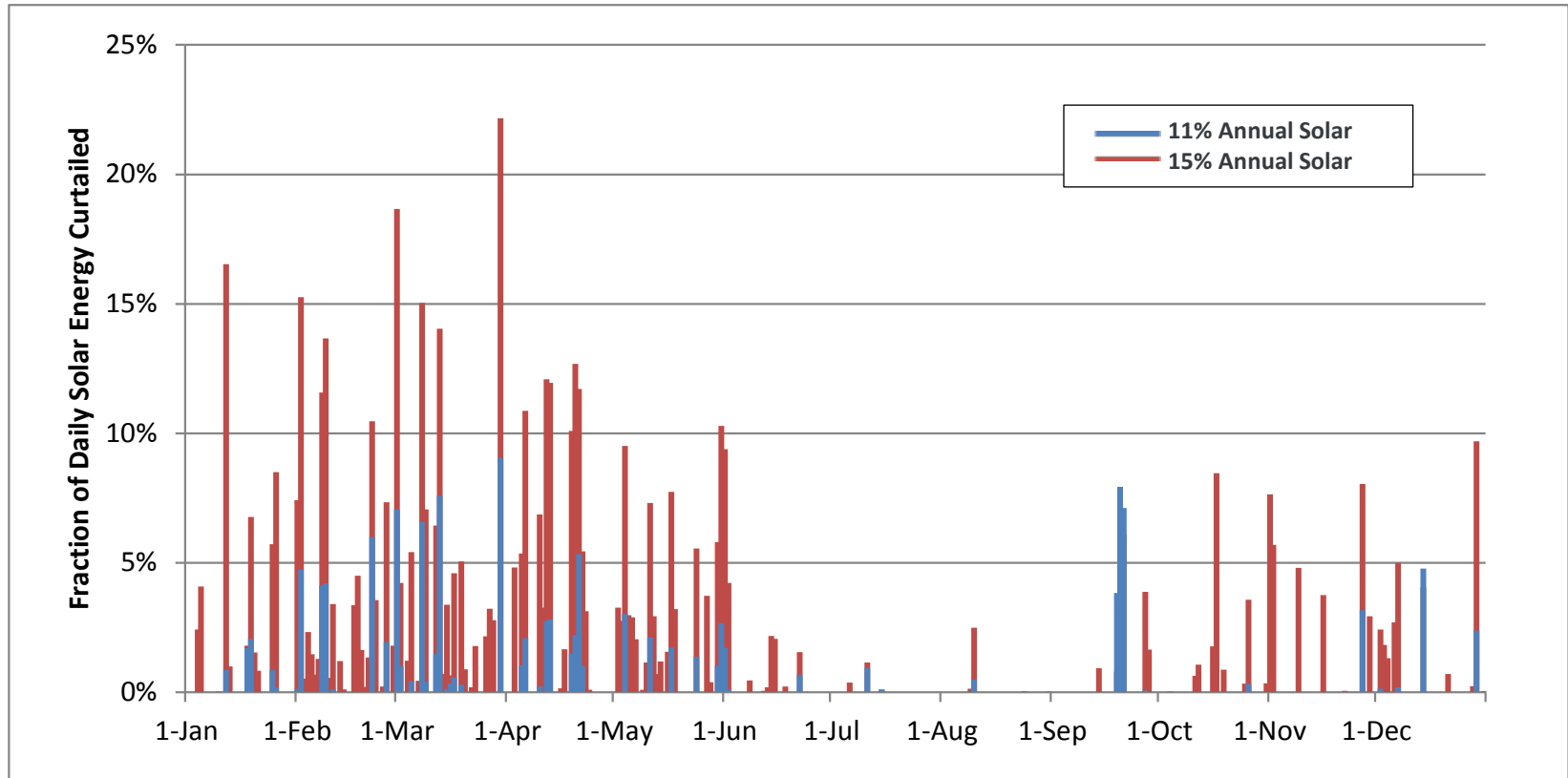
Impacts of “Must-Run” Generation

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



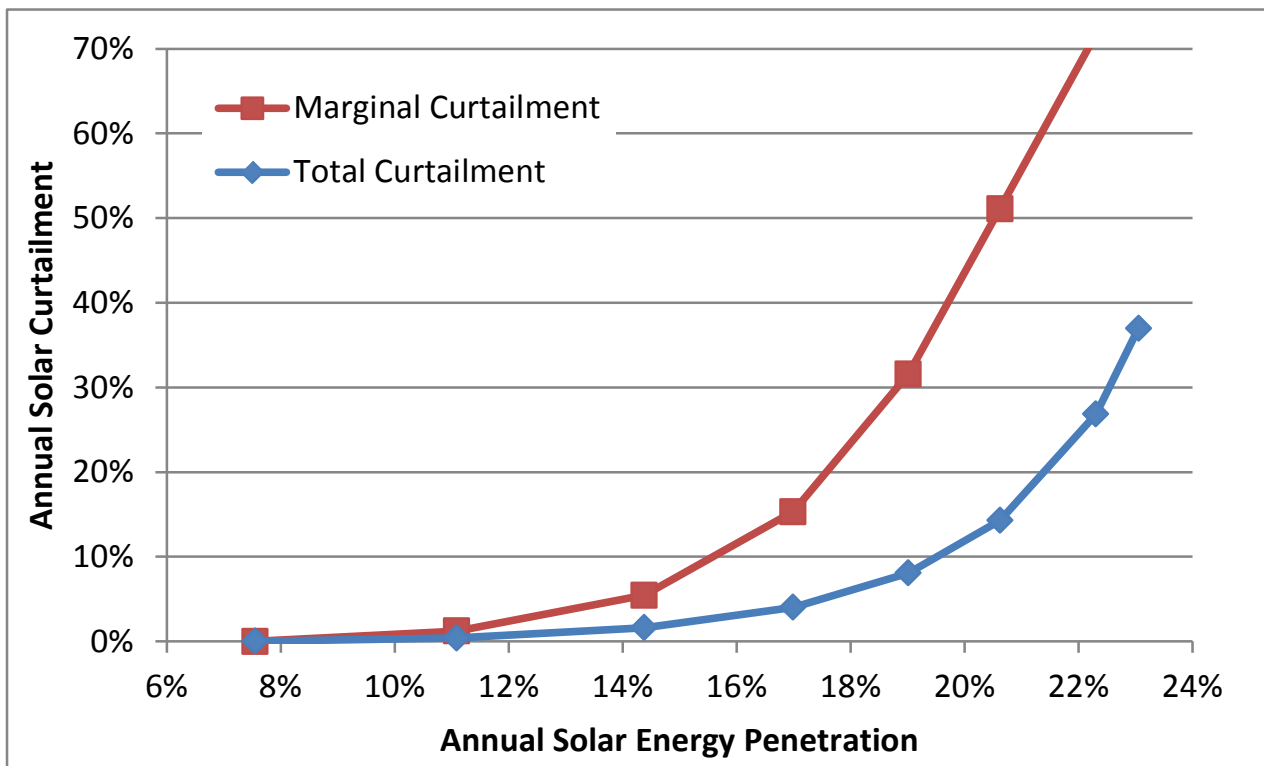
**Used and curtailed VG in California on March 29
in a scenario with 11% annual wind and 11% annual solar**

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

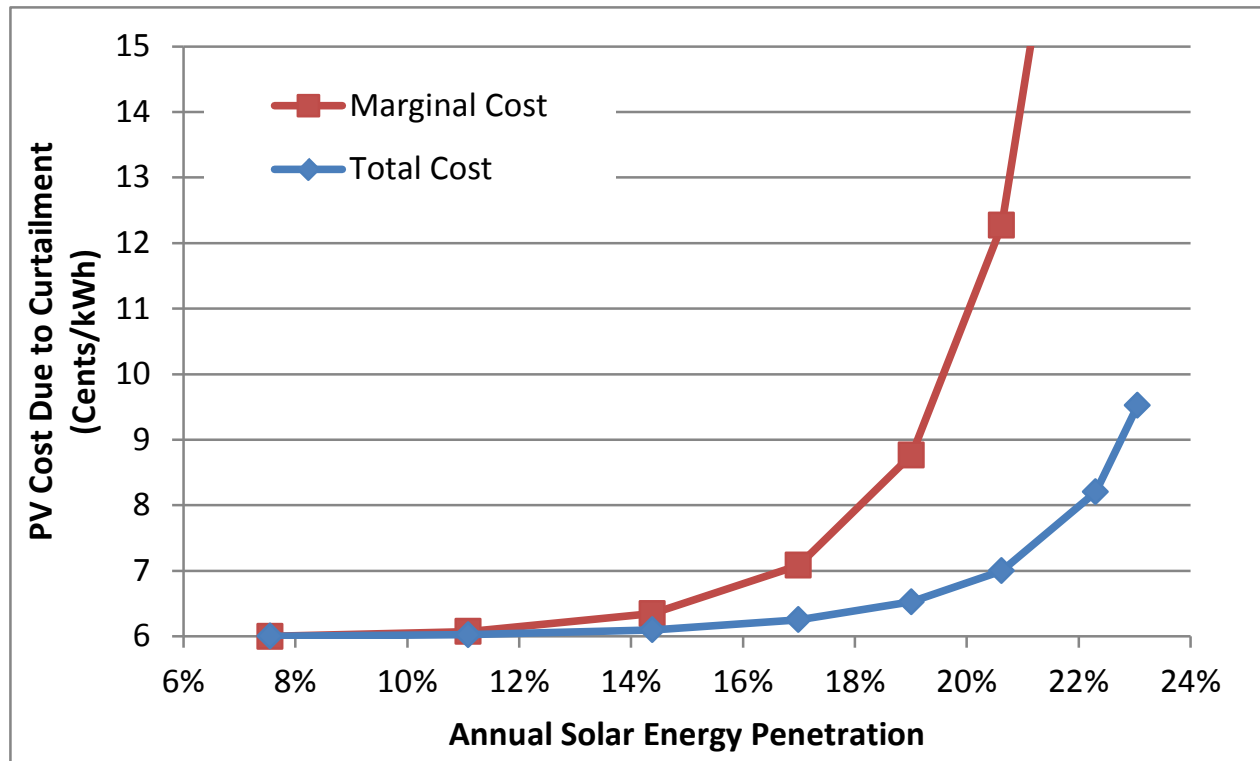
Denholm et al.
2016

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 or decreased benefit**

Impact of VG curtailment on LCOE

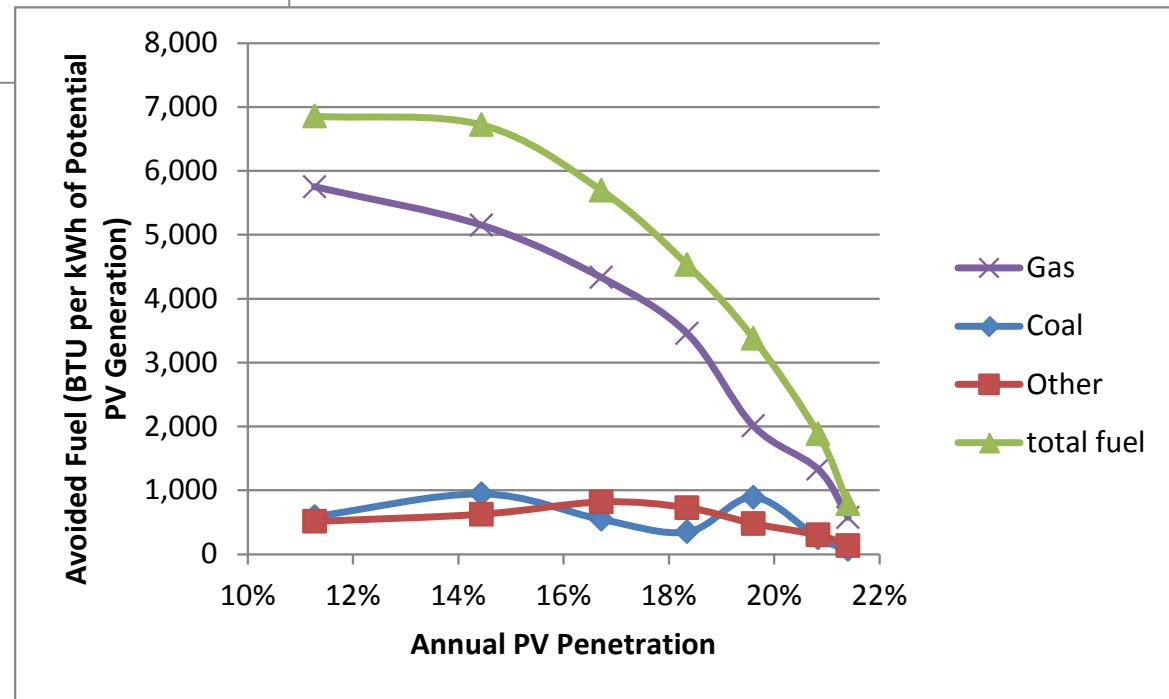
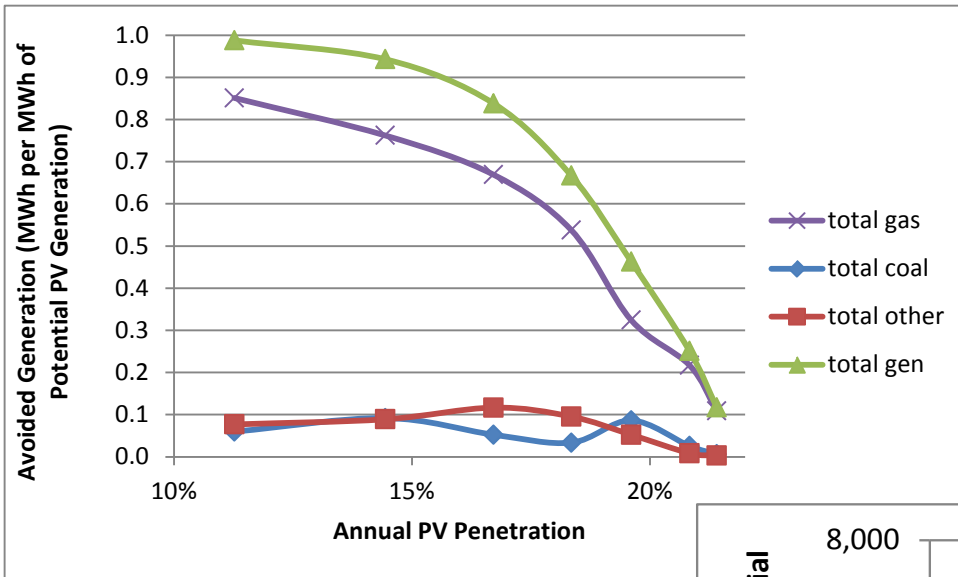
Curtailed energy means less can be sold and incremental costs of additional PV rise dramatically



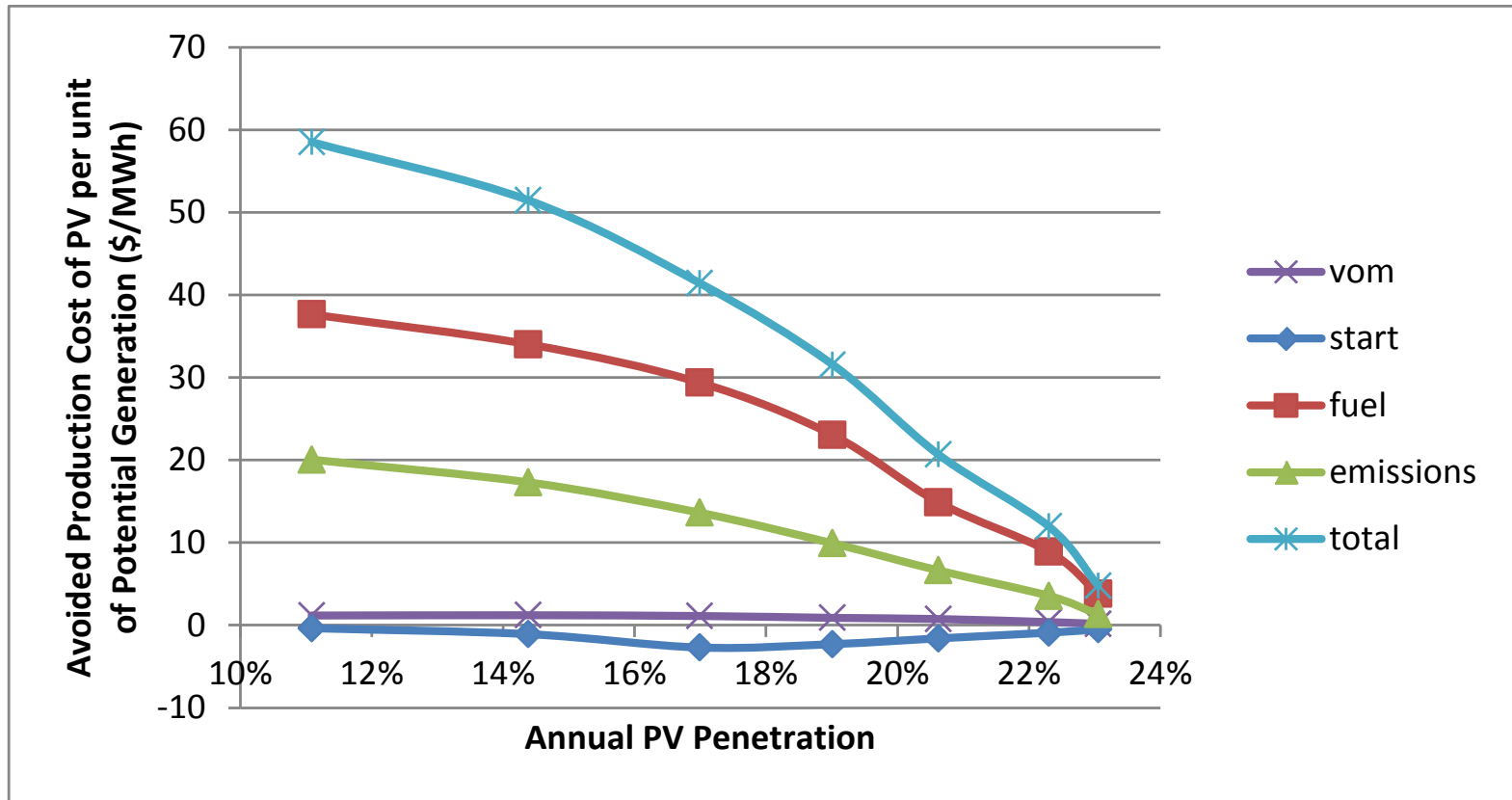
Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with limited grid flexibility

Denholm et al.
2016

Avoided Generation and Fuel



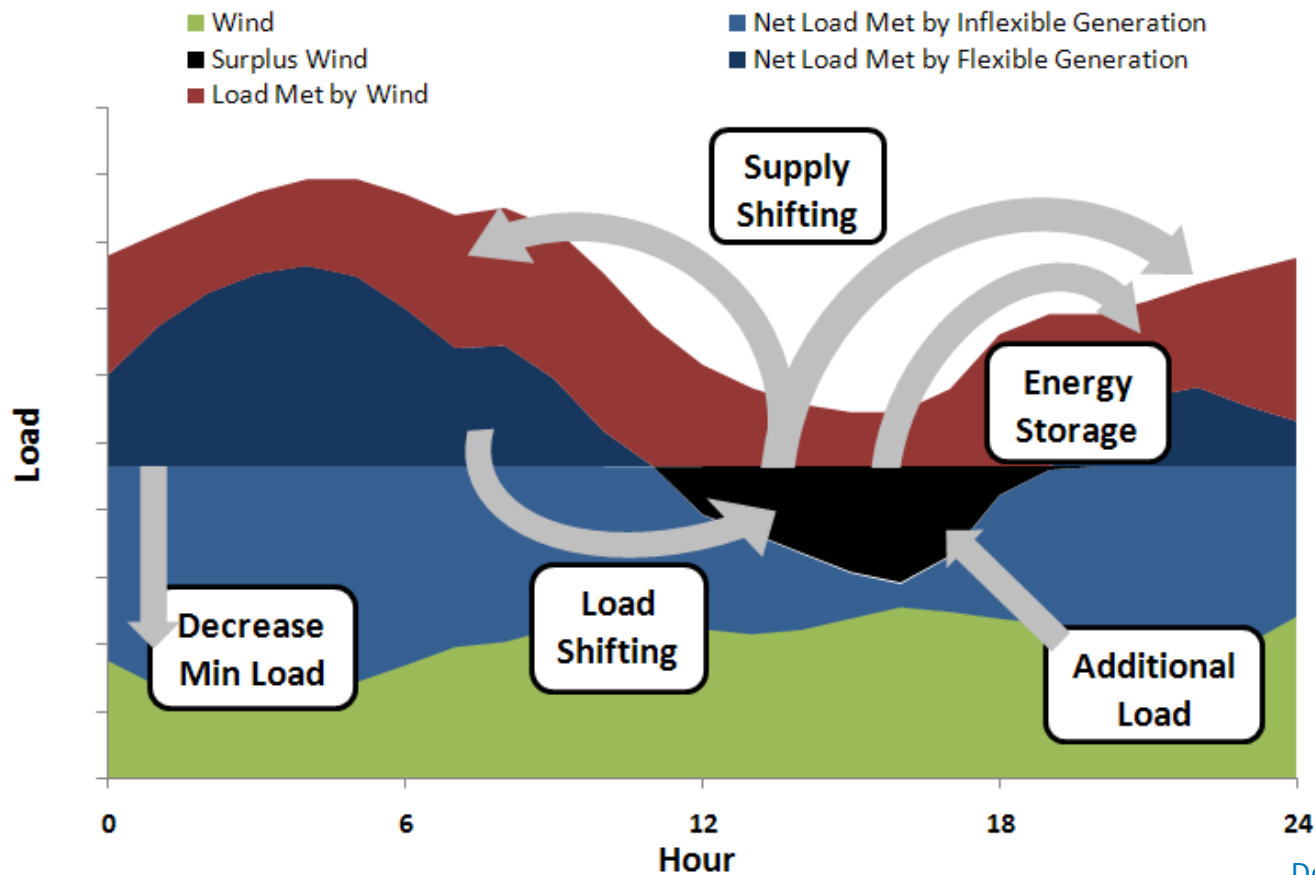
Avoided Generation Costs



This is the avoided production (variable) costs of PV

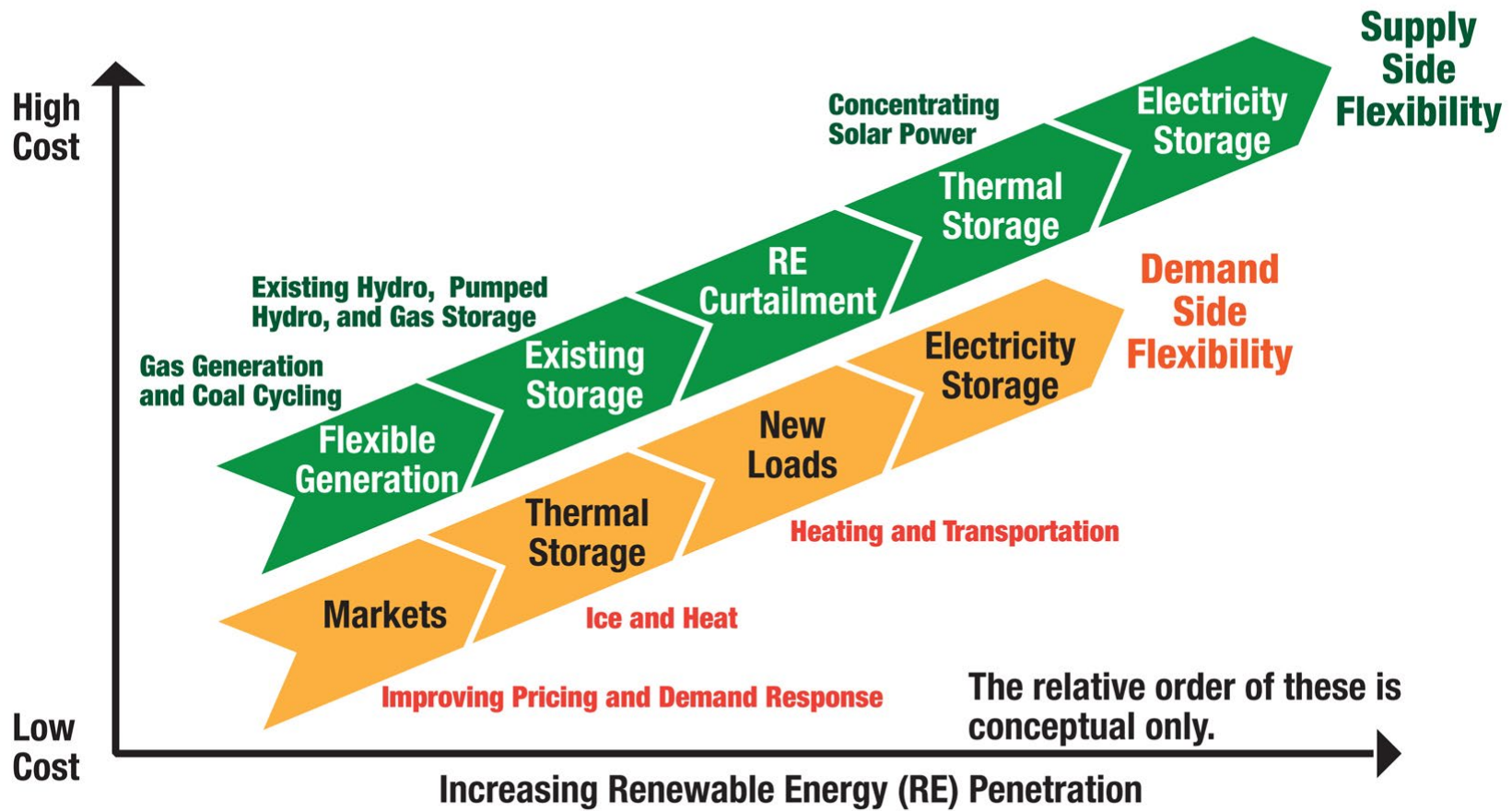
Increasing PV Value and Avoiding Curtailment

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



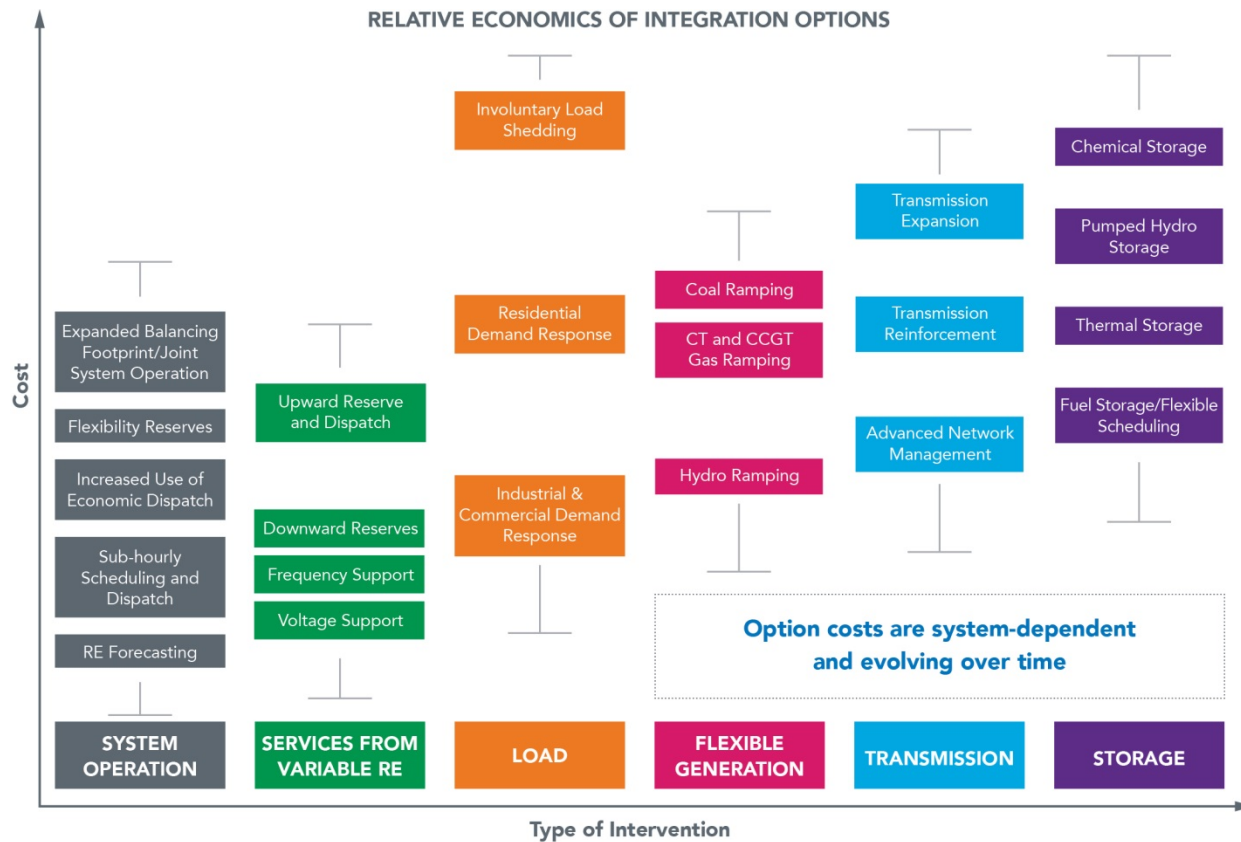
Denholm et al. 2010

Flexibility Supply Curve Concept



Denholm et al. 2010

Flexibility Supply Curve Concept



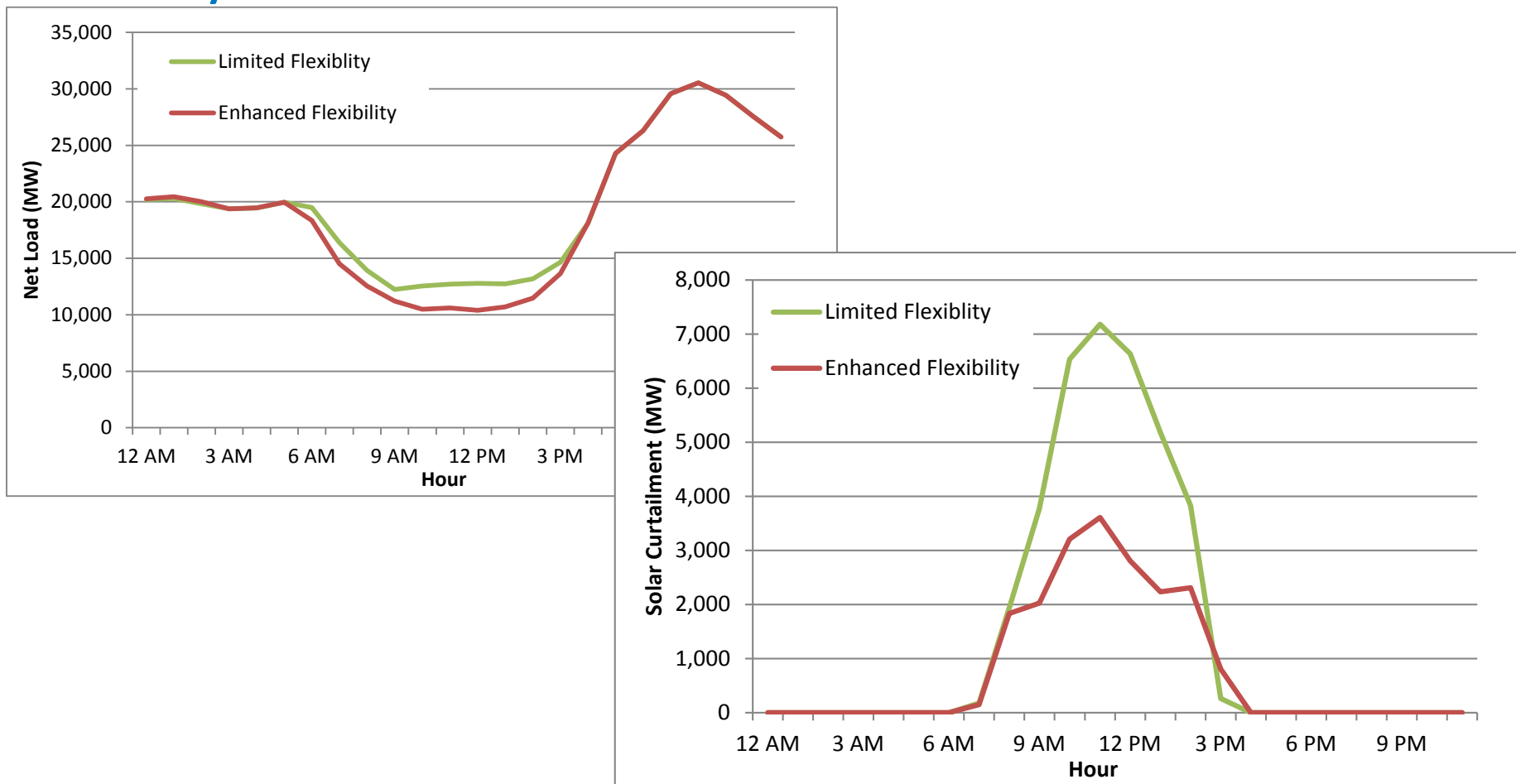
You probably do this first

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

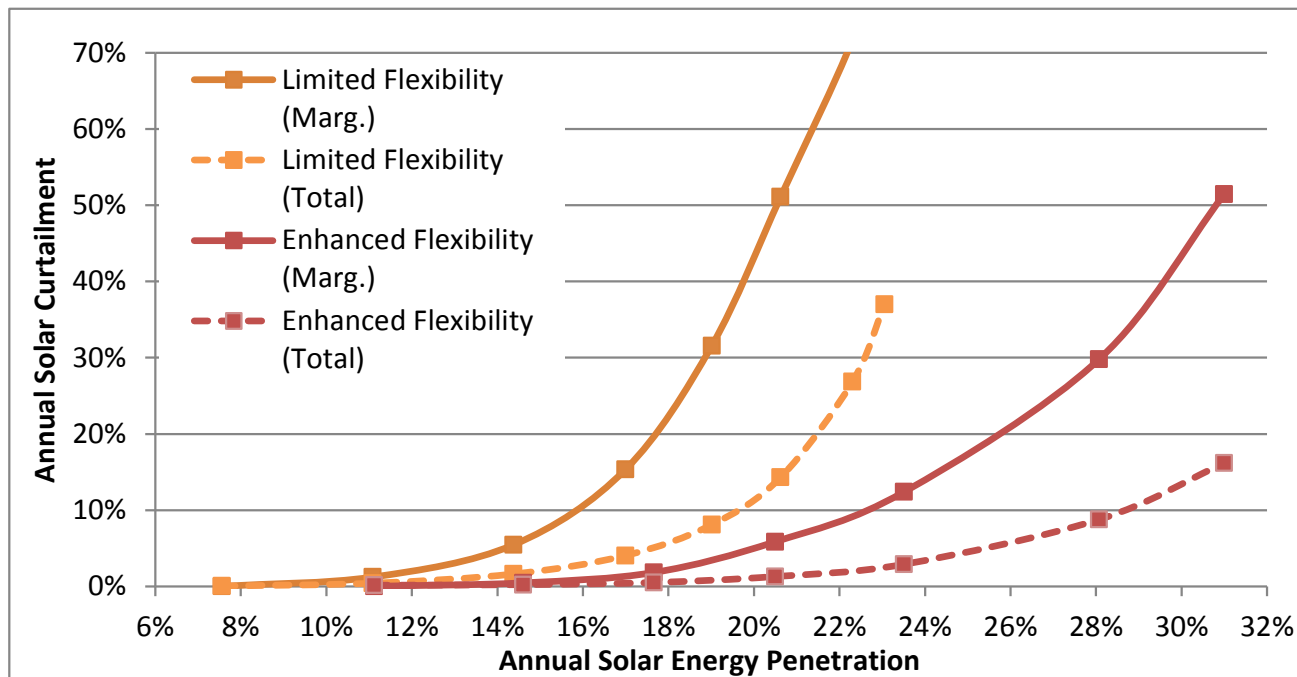


Net load on March 29 in a scenario with 15% annual solar increasing the grid flexibility

Denholm et al.
2016

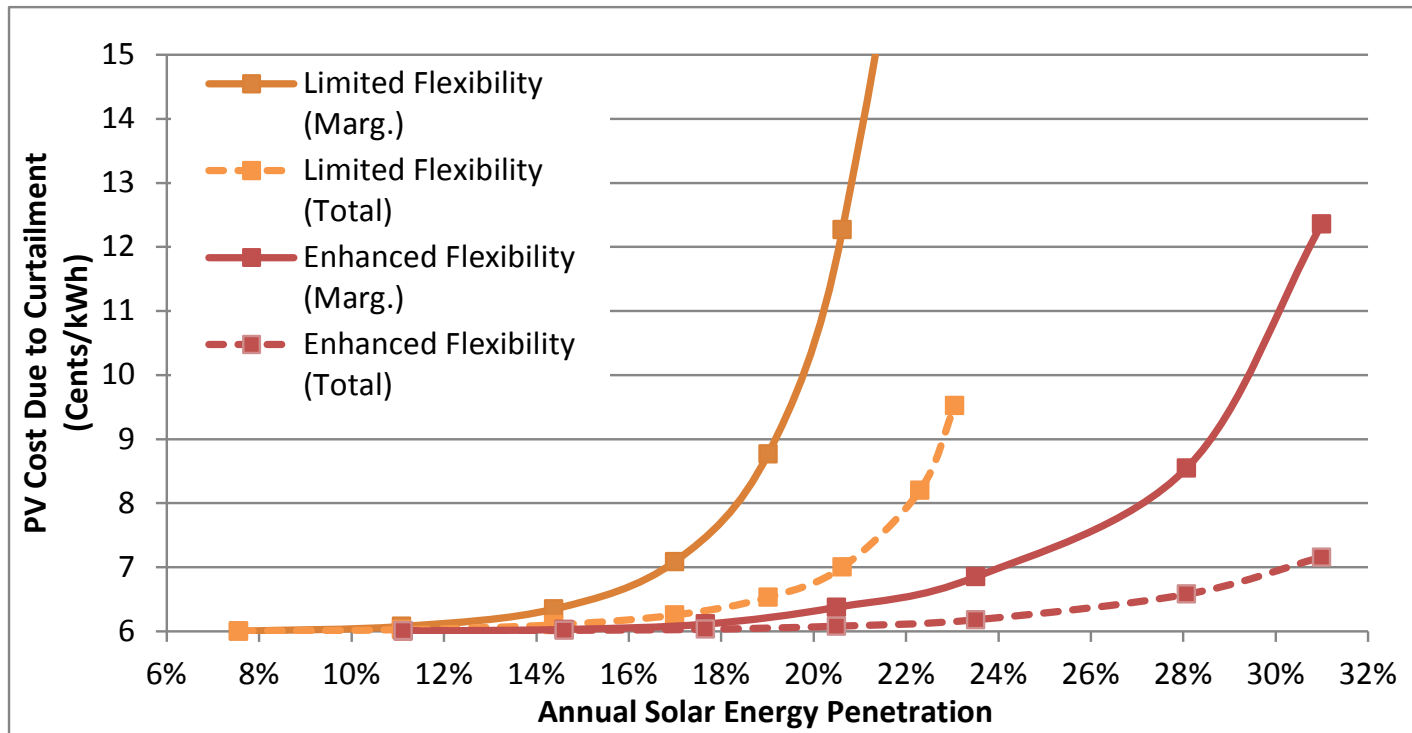
Increased Flexibility = Increased Penetration

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



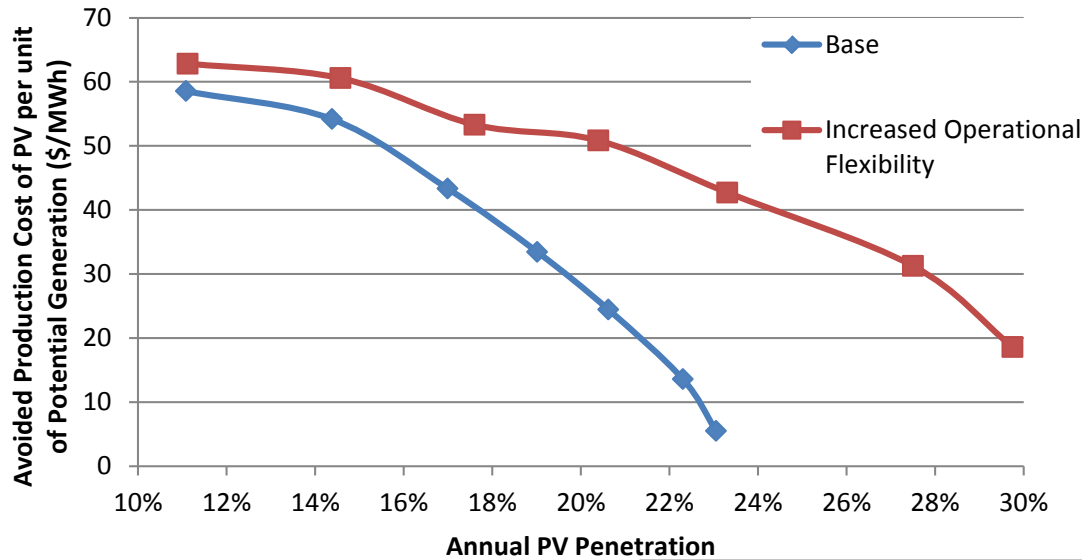
Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with enhanced grid flexibility

And More Competitive Costs

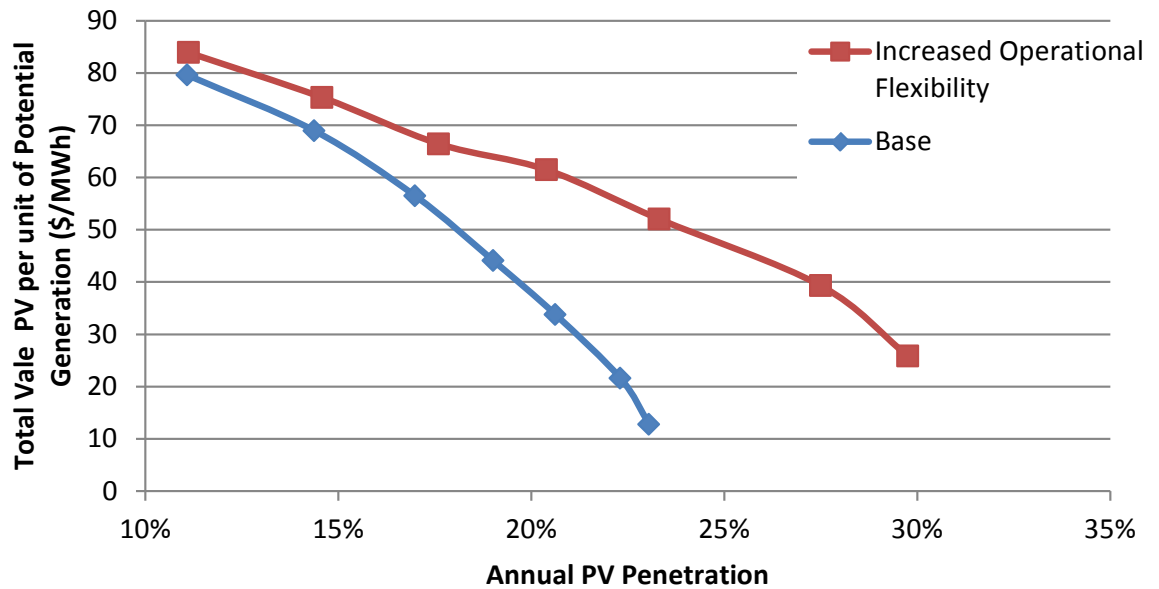


Marginal and average LCOE due to overgeneration under increasing penetration of PV in California with enhanced grid flexibility

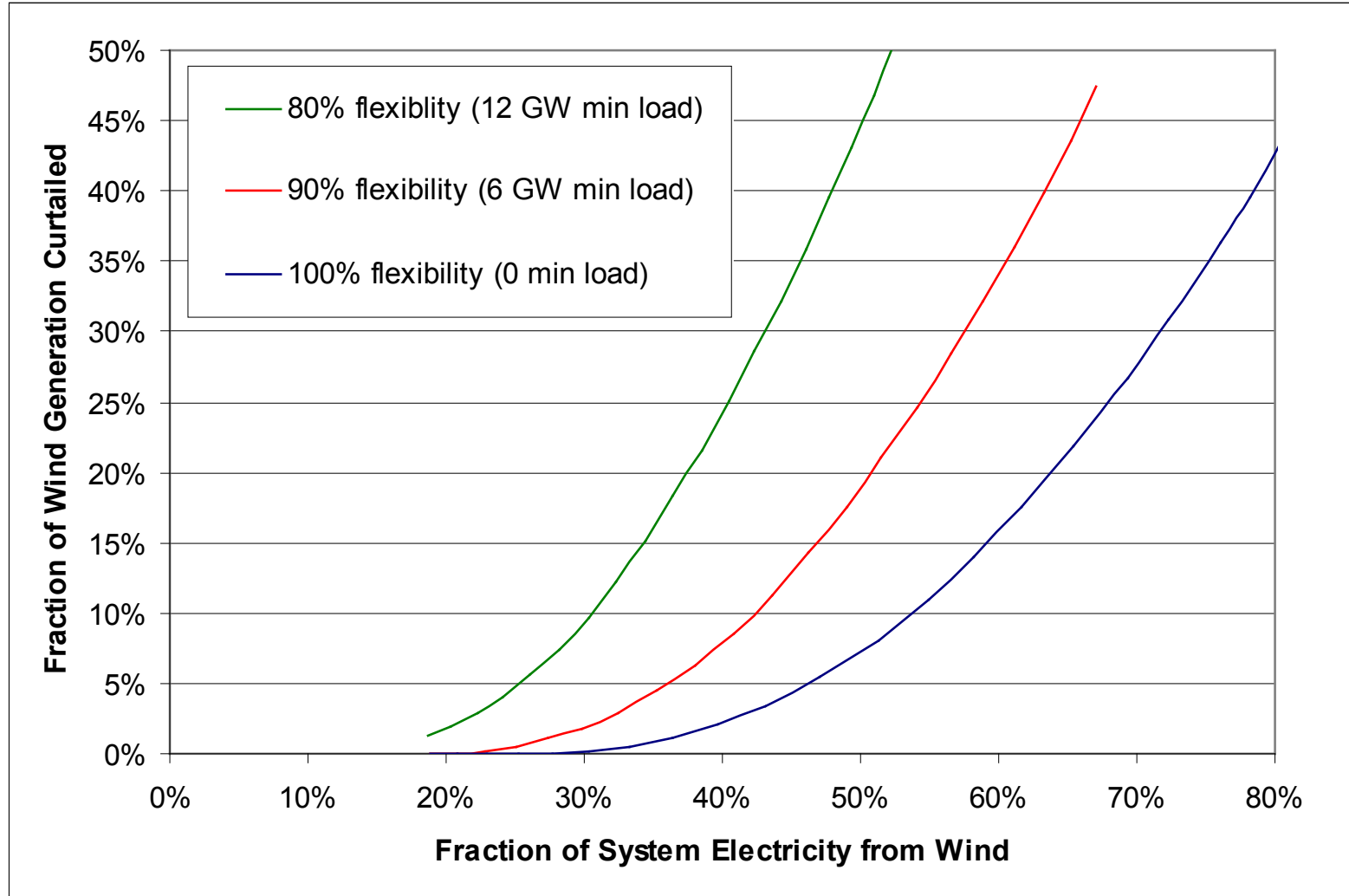
Increased Flexibility Increases VG Value



Total value



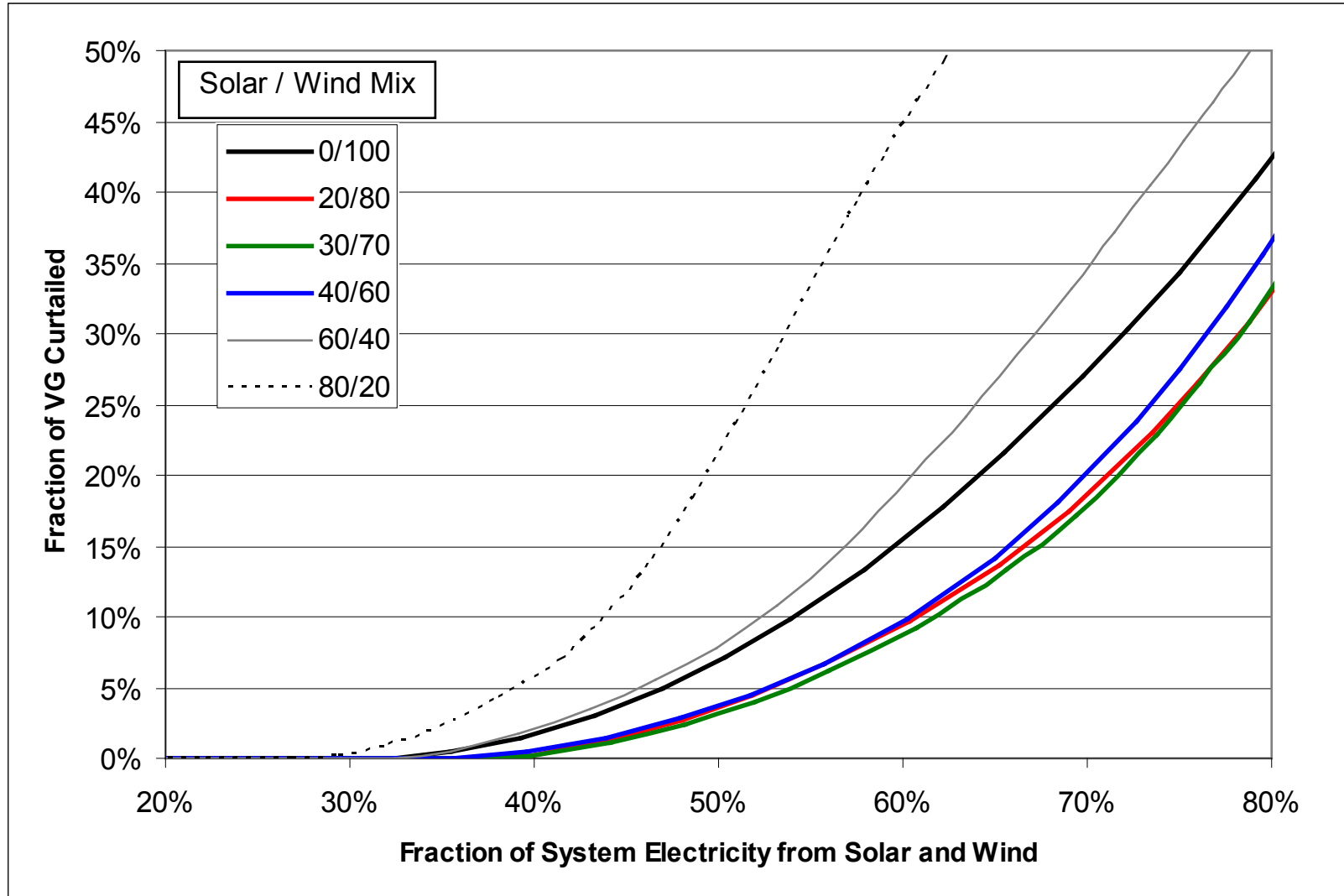
Curtailment as a Function of Flexibility



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

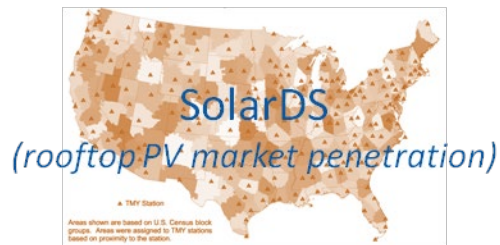


Denholm and Hand 2011

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



rooftop PV penetration

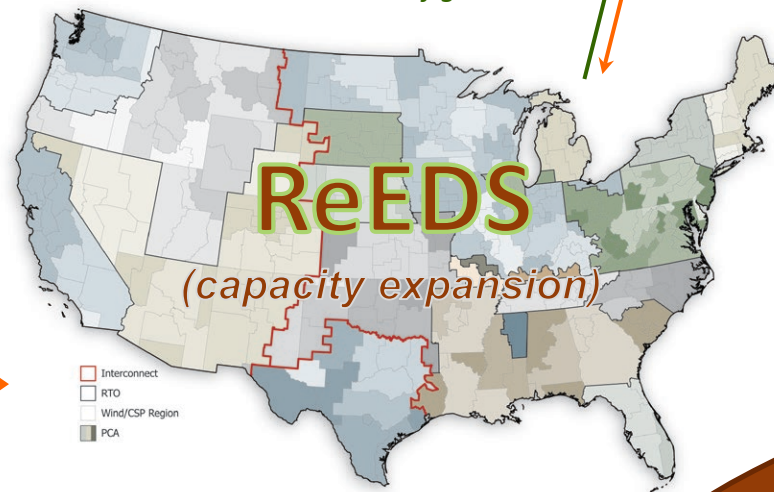


does it balance hourly?

2050 mix of generators

Black & Veatch
Technology Teams
Flexible Resources
End-Use Electricity
System Operations
Transmission

Technology cost & performance
Resource availability
Demand projection
Demand-side technologies
Grid operations
Transmission costs



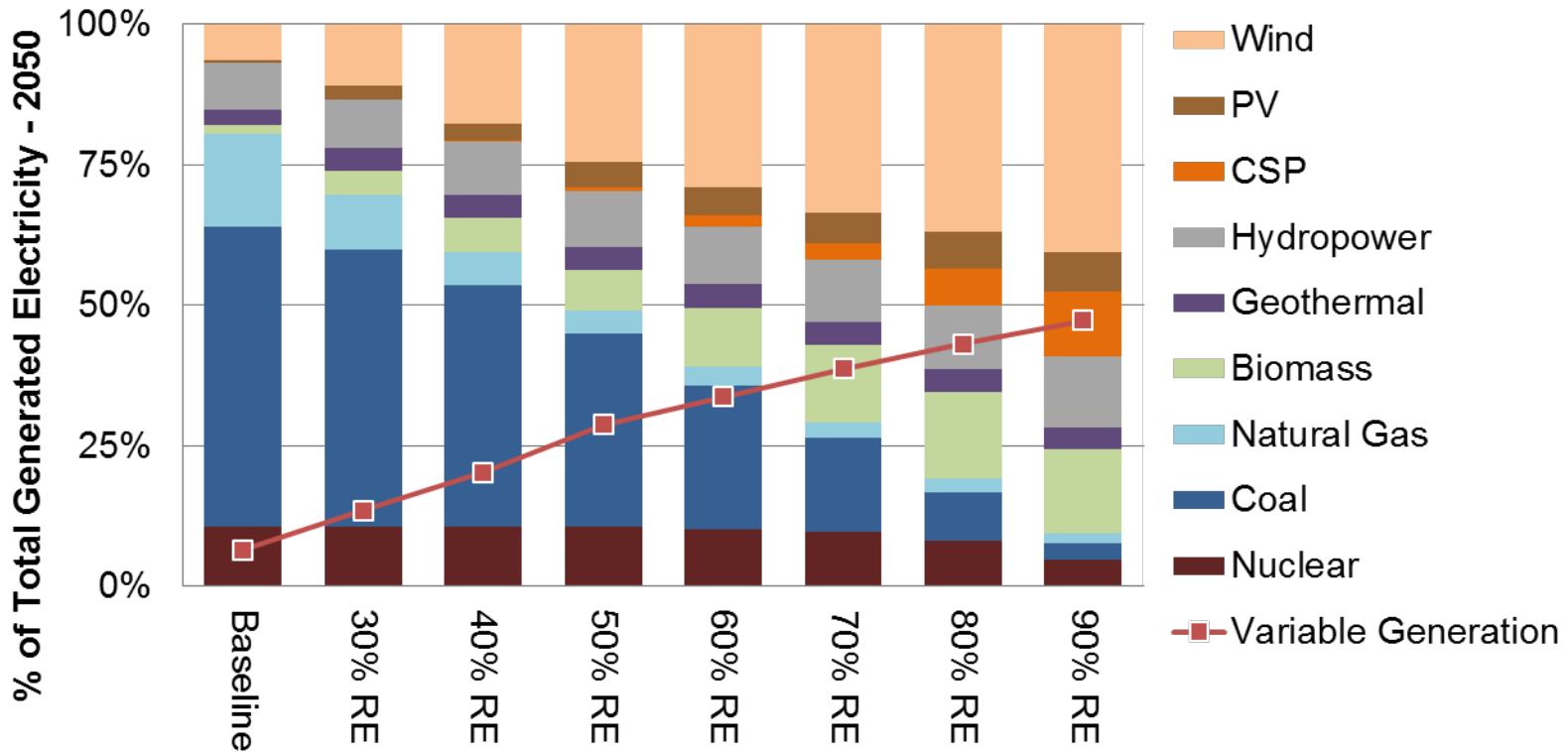
Capacity & Generation
2010-2050

High resolution modeling
using 134 nodes & hourly
time steps

Implications

GHG Emissions
Water Use
Land Use
Direct Costs

RE Resource Supply from 30% - 90% Electricity

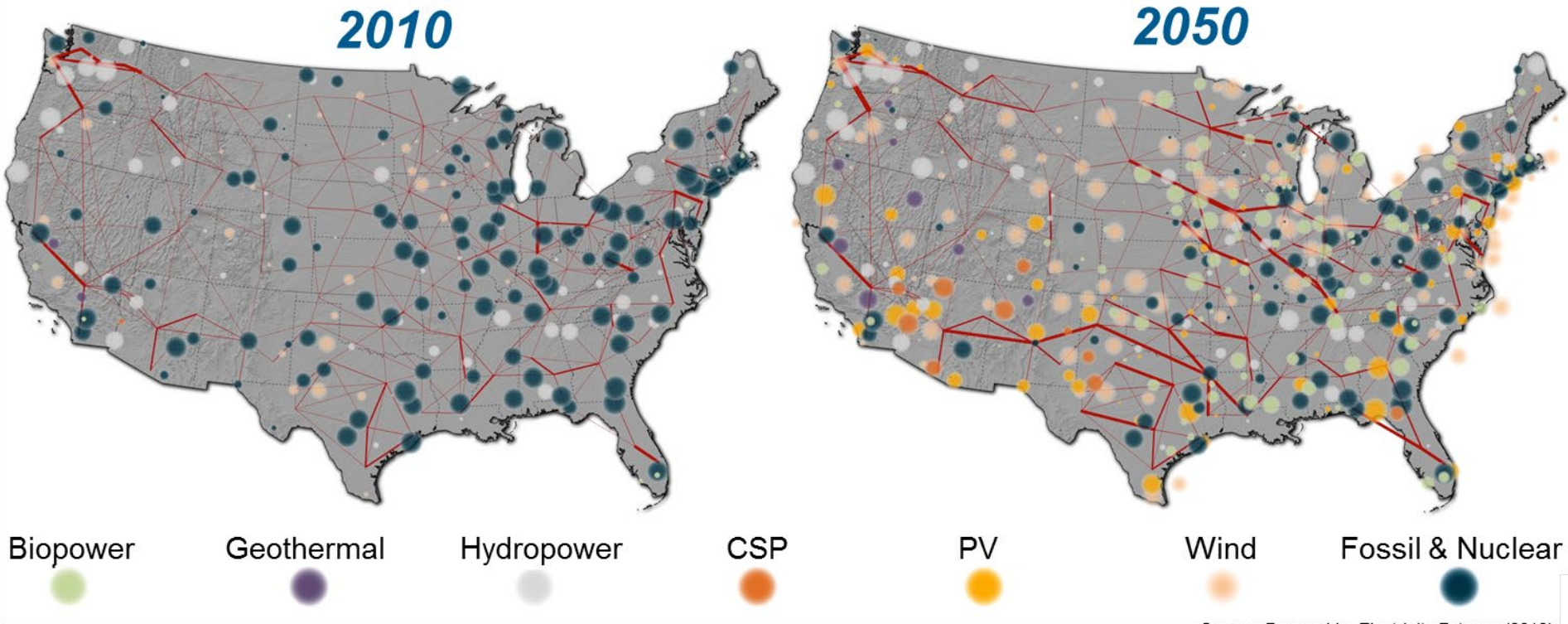


Source: Renewable Electricity Futures (2012)

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

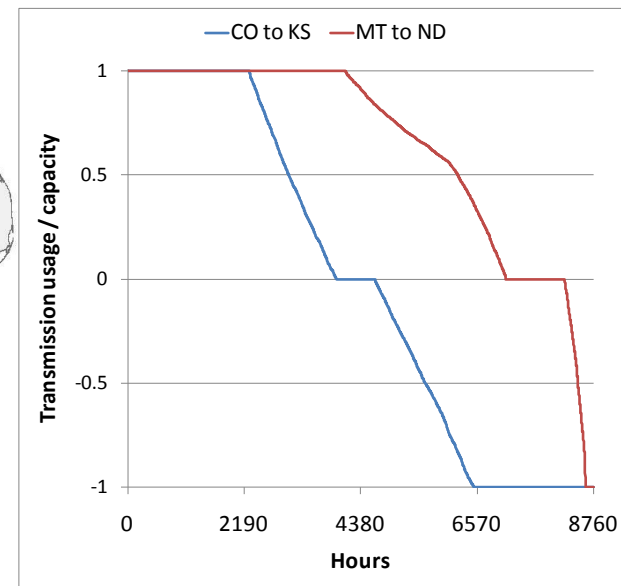
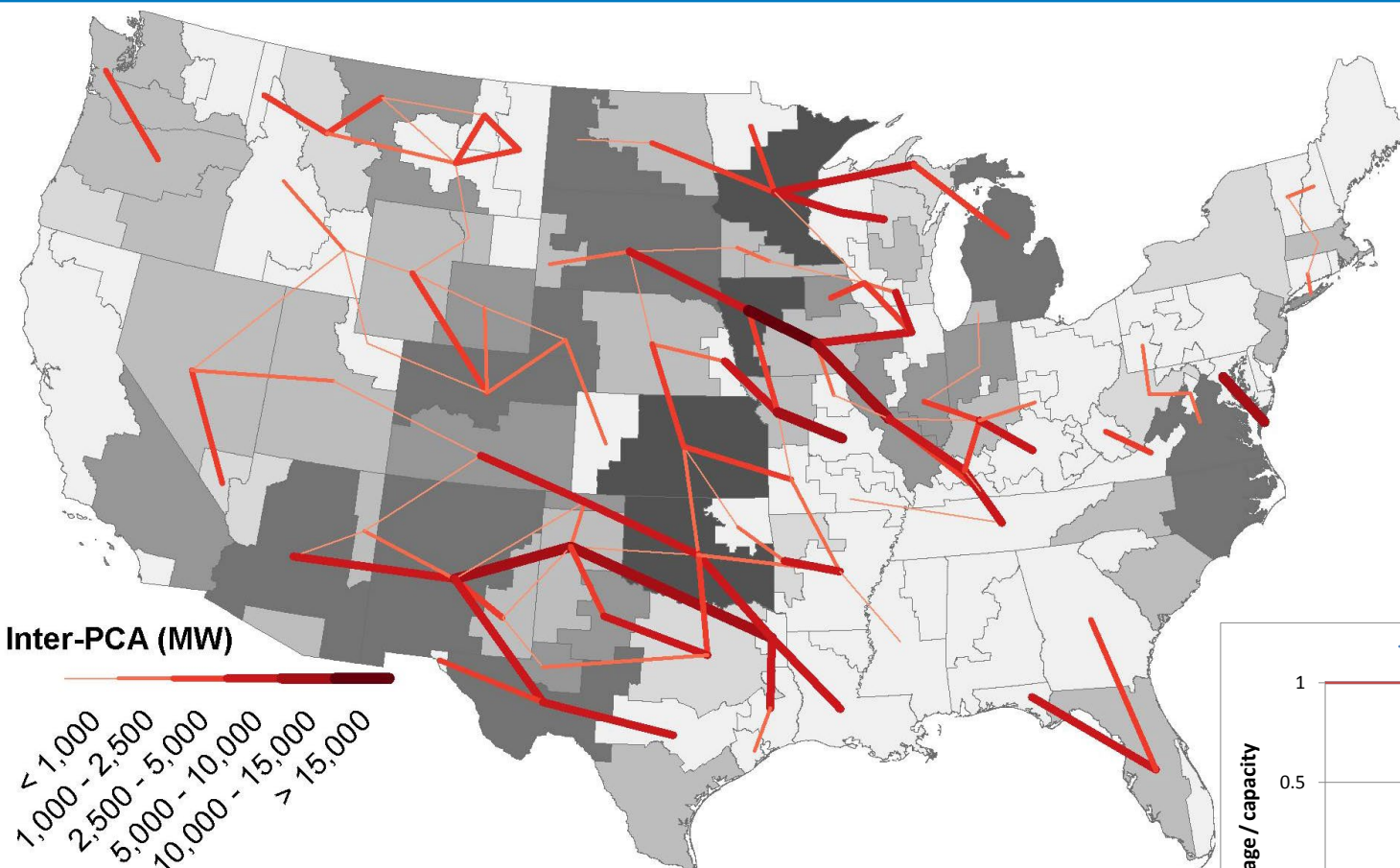


Source: Renewable Electricity Futures (2012)

Mai et al. 2012

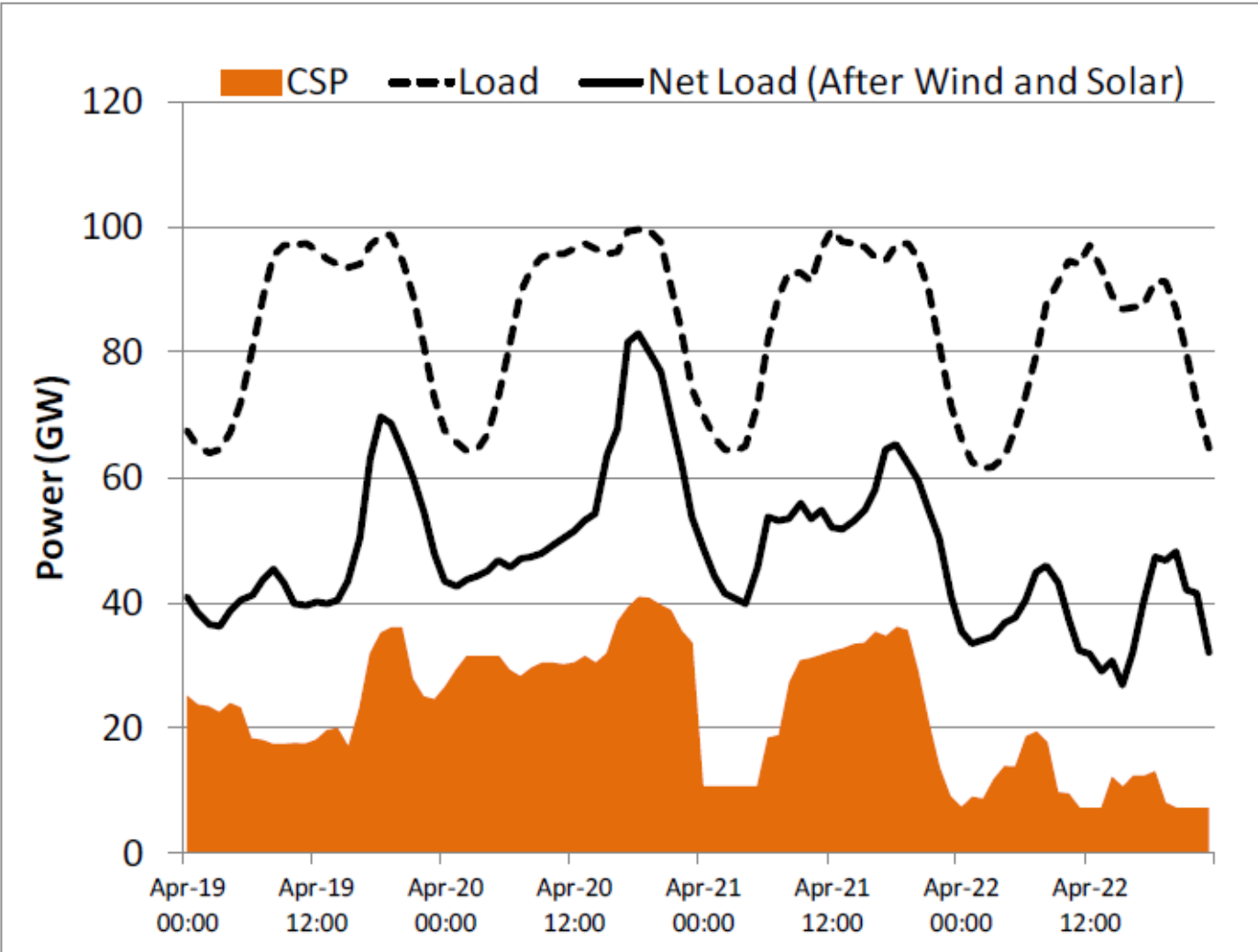
RE generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050—while meeting electricity demand on an hourly basis in every region of the country.

How? Build New Transmission...



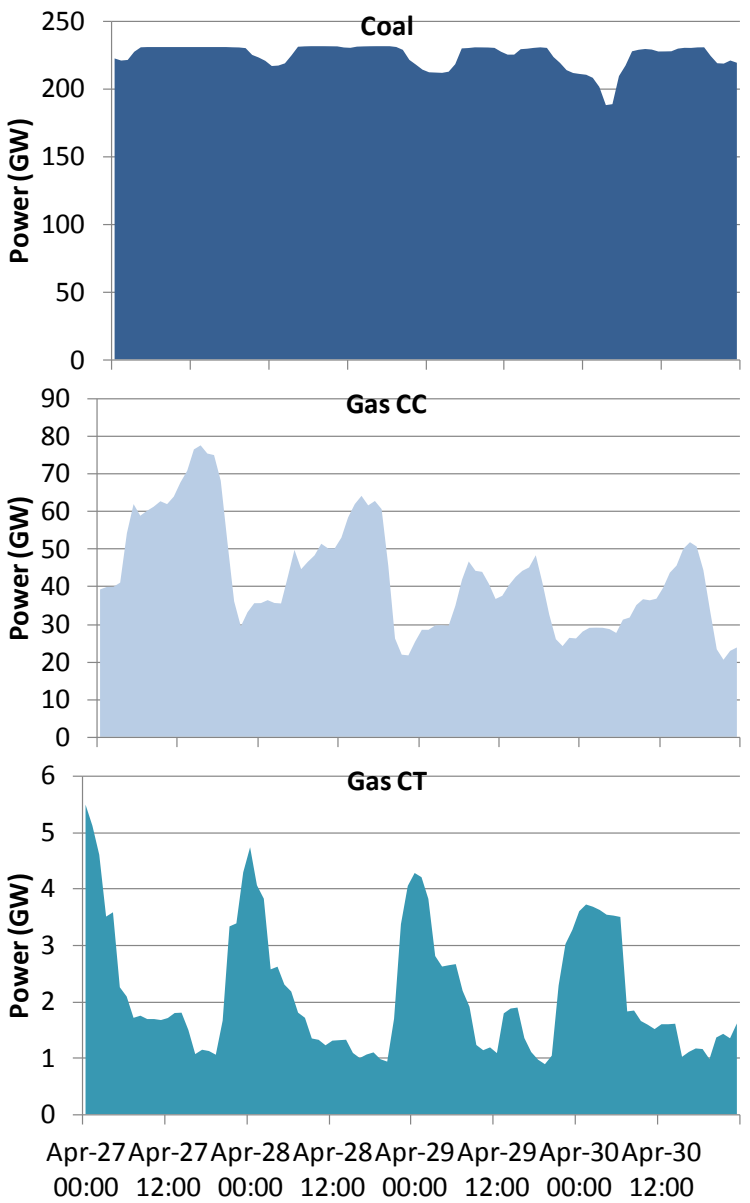
Mai et al. 2012

Deploy Dispatchable Renewables



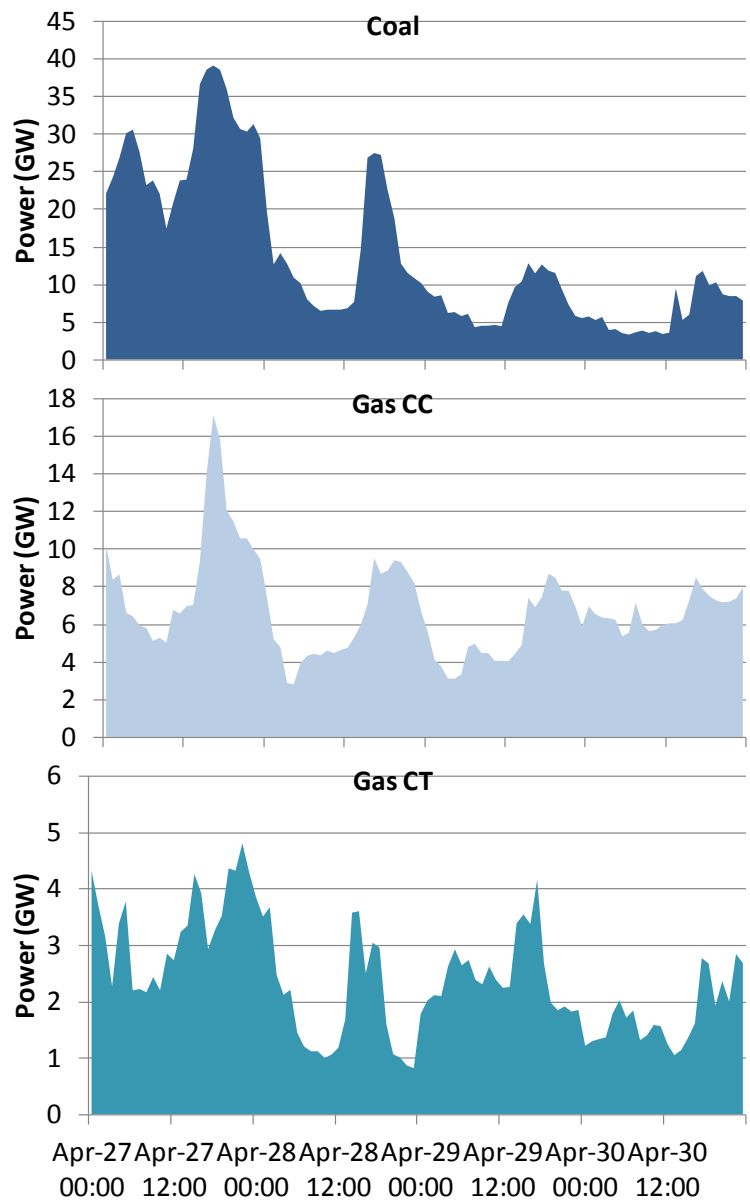
Source: Denholm et al (2012)

Design for cycling



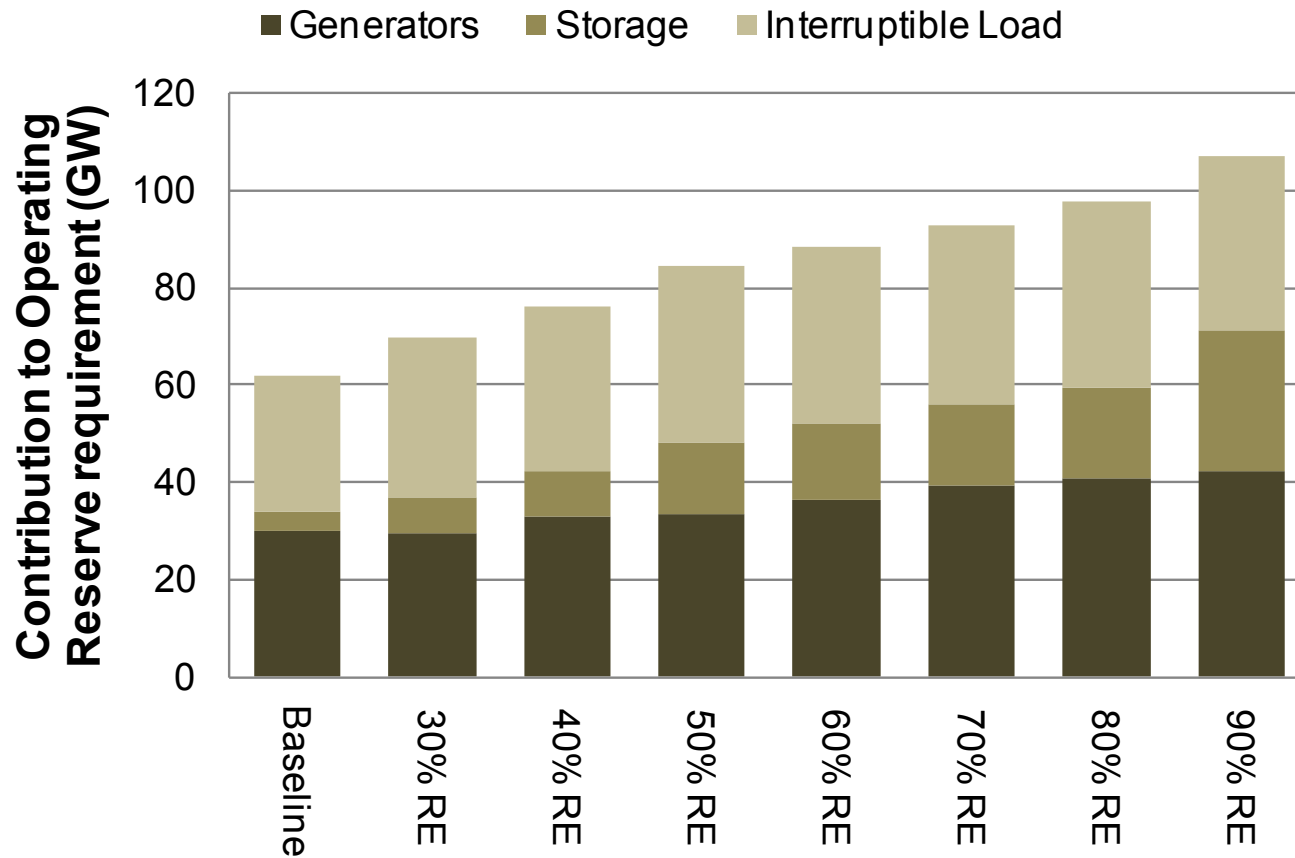
Baseline scenario

80% RE-ITI scenario

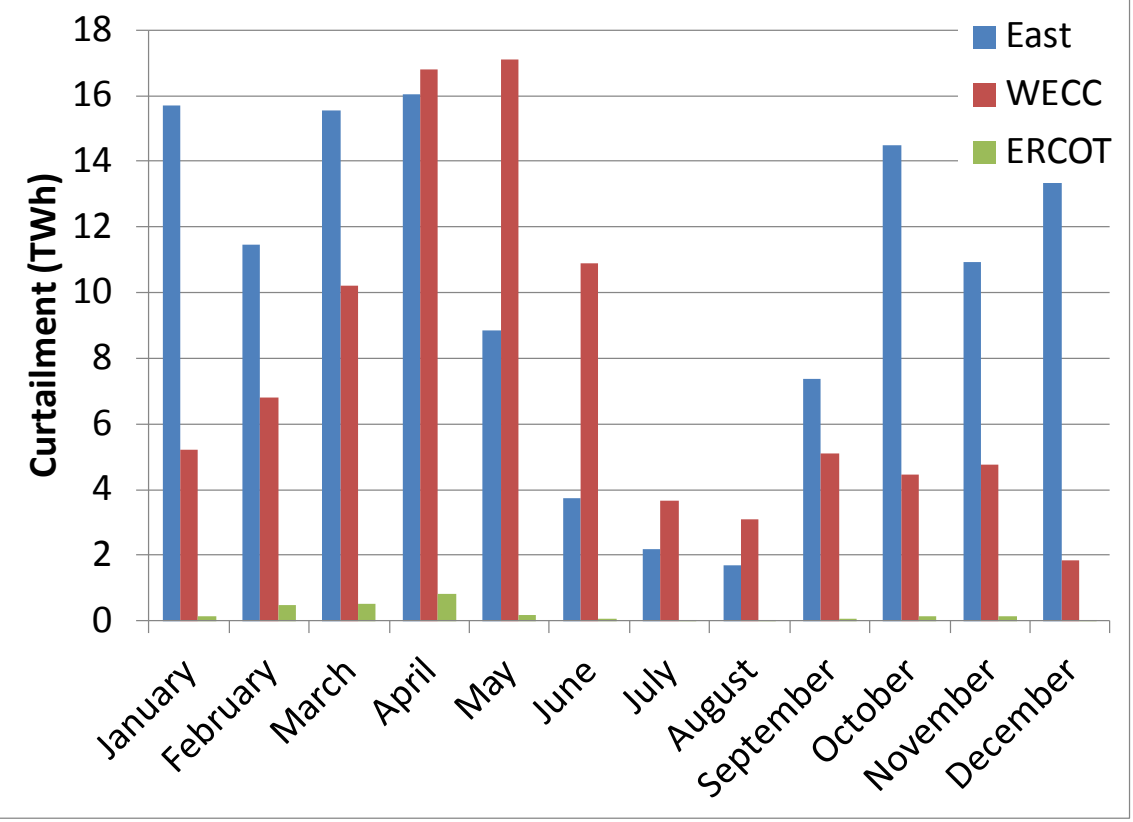


Mai et al. 2012

Harness Responsive Demand (smart grid?)

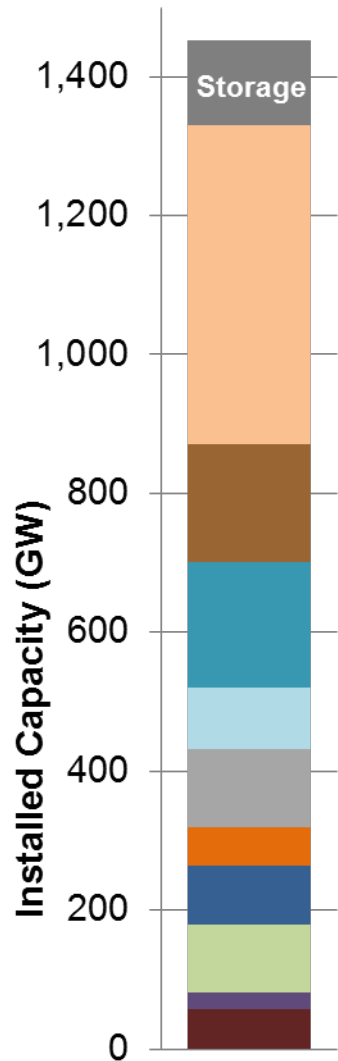


Accept inevitable curtailment in the spring.



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

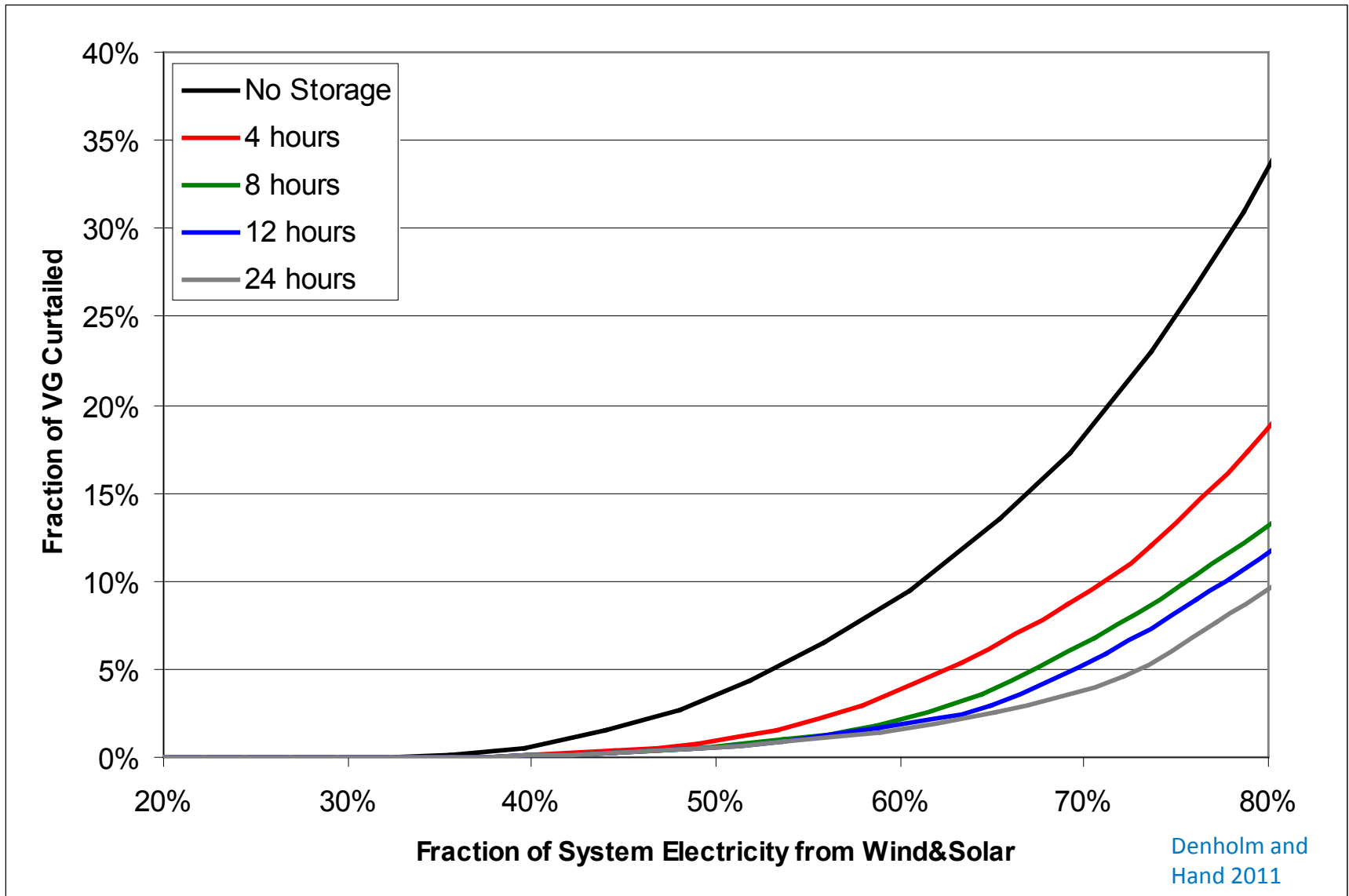
..And yes, develop new storage



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

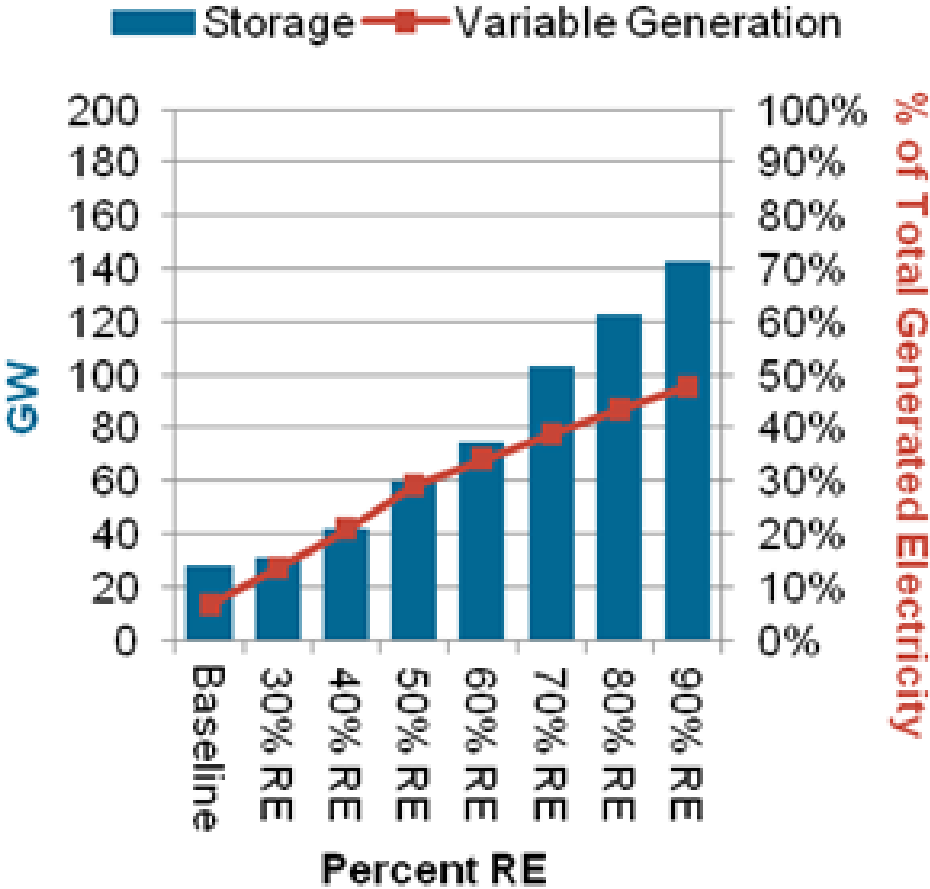
Energy Storage Can Reduce VG Curtailment



Cost Optimal Storage Deployment?

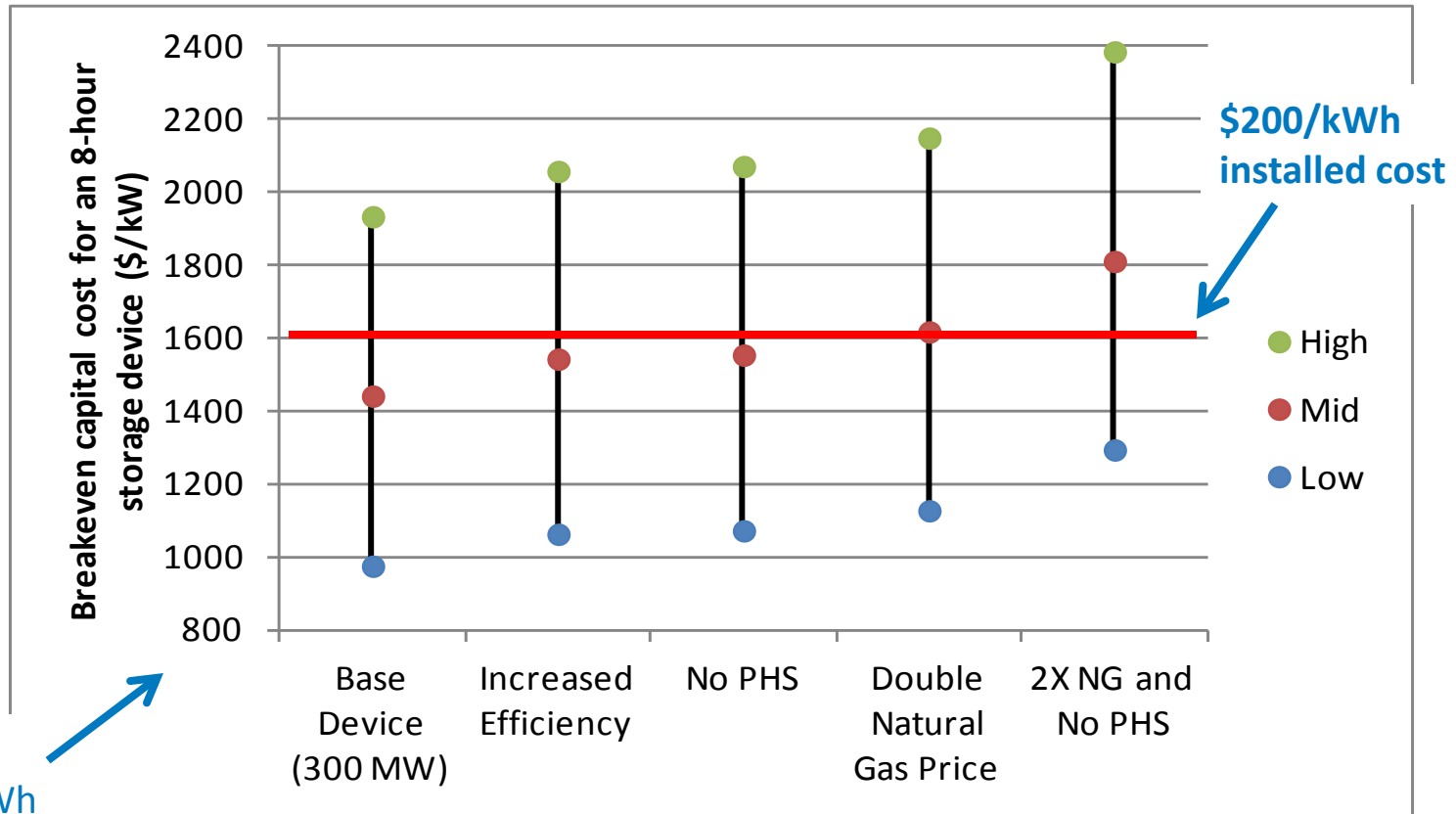


Now - Conventional
Pumped Hydro: ~ 20 GW



Future 80-140 GW
depending on REF scenario

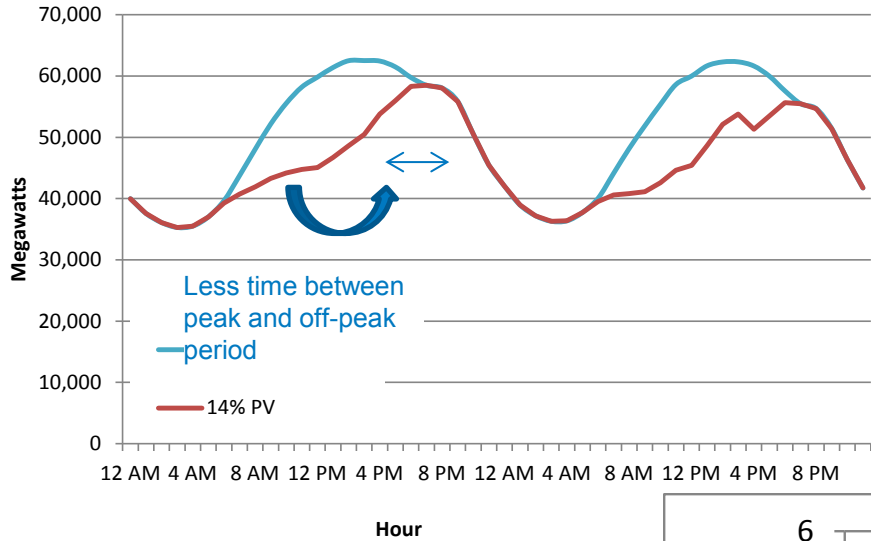
But we are just not there....



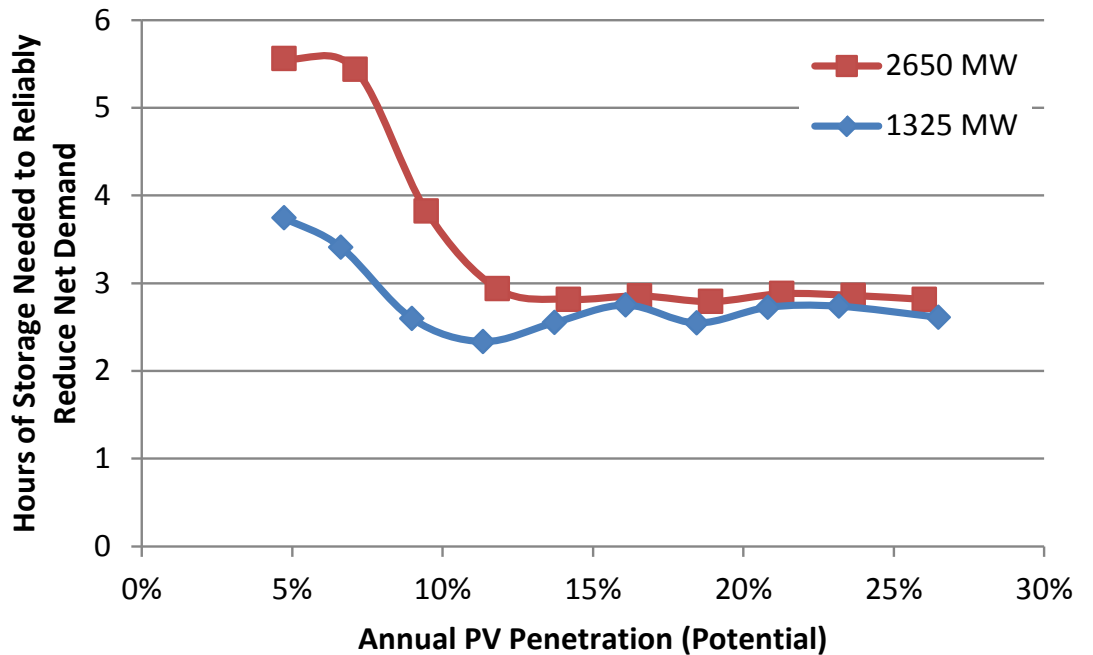
Divide by 8
to get \$/kWh
installed cost

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

Storage/PV Synergy

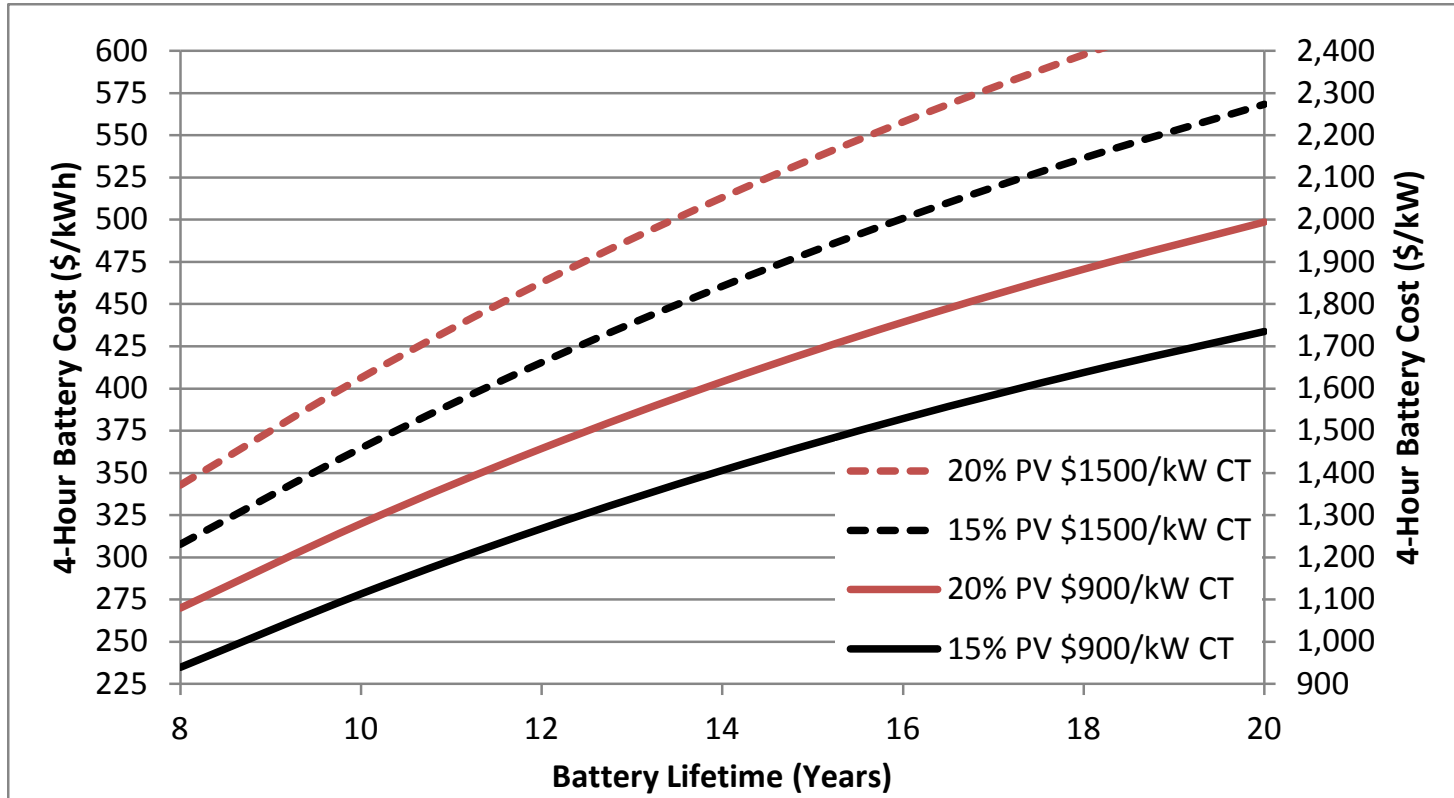


Narrower peak means less storage needed



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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

- **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**
- **Curtailement 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?

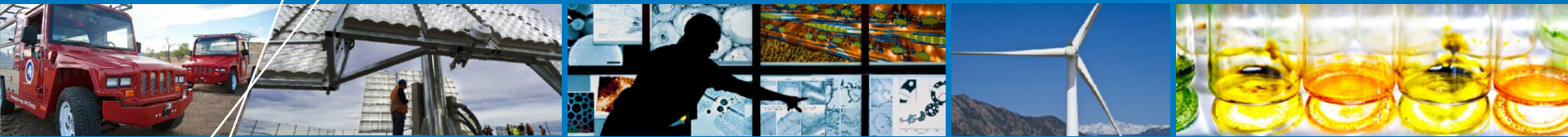
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