Retaining the Value of PV at High Penetration Workshop

Electric Power Research Institute, Washington DC
October 13, 2016

Sarah Kurtz: NREL
Michael Bolen: EPRI

PR-5J00-67467

Background

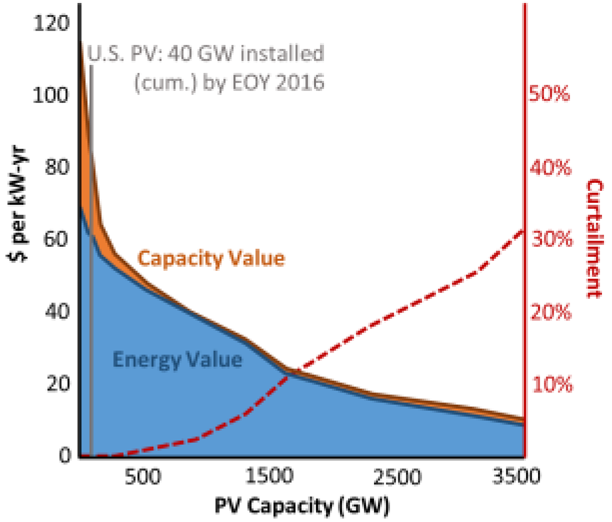
The “Retaining the Value of PV at High Penetration Workshop” was hosted by the Electric Power Research Institute (EPRI) in Washington DC, on October 13, 2016 with support from the National Renewable Energy Laboratory (NREL) and Arizona State University (ASU). It was organized by Michael Bolen of EPRI, Sarah Kurtz of NREL and Christiana Honsberg of ASU. The concept for the workshop grew partially from conversations of PV Horizons, a discussion group bringing together PV researchers from across the United States.

TABLE OF CONTENTS

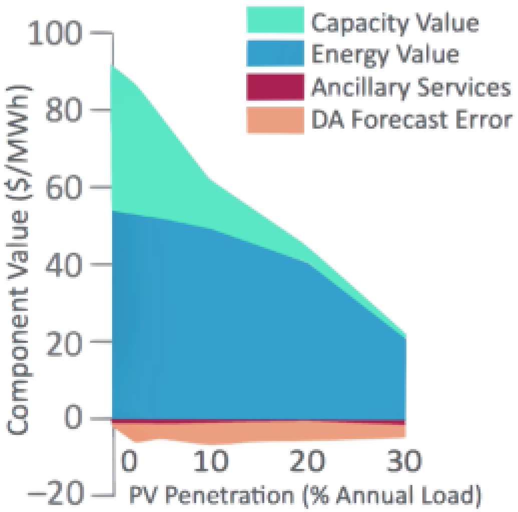
Strategies for retaining the value of PV at high penetration:

Motivation

- PV prices have dropped and are now attractive without incentives for peaking applications in some locations. Modeling suggests and, empirically, some regions demonstrate that as PV penetration increases its value decreases, predominantly due to a decrease in energy and capacity value. It is not apparent what technologies and price may be needed for PV to supply tens of percent of electricity in the most economically efficient manner. A 1-day workshop was co-sponsored by EPRI and NREL with support from ASU. A dozen presentations and discussions introduced how the interplay of various technologies impact the value of PV, identified technical challenges and gaps impeding implementation, and discussed future R&D needs and opportunities.



EPRI US-REGEN model showing declining PV value and increasing curtailment as PV deployments increase



California specific modeling demonstrating the factors leading to declining marginal value of PV

Key Workshop Questions

- To what extent can other technologies–such as storage, grid upgrades, or consumer behavior modifiers–enable economically efficient deployment as penetration levels increase?
- What key metrics or specifications should guide when to use each?
- What technical barriers might be limiting use of each?
- How do these strategies impact the design of future PV plants?

Key Workshop Takeaways

- Simulations of the grid in California suggest that the “Value” of PV to the grid may drop by about a factor of four as the penetration increases from 0 to 30%. However, studies in Arizona suggest that the match between the generation from PV and the peak load in the more consistently hot climate gives a different result (less change in value with penetration level). Based on the studies in California, the most useful knob to turn is to increase the flexibility of the grid. The next biggest knob is to adopt electrical vehicles and charge them during the day.
- Reaching high PV penetrations requires flexibility of existing (and future) generation assets, storage, grid infrastructure, and demand-side technologies. This is an important technical enabler for the future electricity system.
- Determining a correct, consistent metric upon which to measure the value of PV is critical for multiple reasons, such as benchmarking and comparing research amongst groups, gathering support to work towards a common “optimal” goal, and holistically assessing the cost-benefit of PV to the entire system including electrical, environmental, societal, and customers/operators.
- The cost, price, and value of distributed energy resources and necessary supporting infrastructure are dynamically changing. As such, strategies need to be equally dynamic and regularly revisited to assess optimum technology mix.

Key Workshop Takeaways (cont.)

- Generation dispatch modeling (at the country level) suggests that PV penetrations above 10% electricity are positively benefited by storage. Below ~10%, cheap storage (significantly cheaper than today's pricing) is a competitor to PV deployment.
- Transmission has been shown, from a technical perspective, capable of enabling tens of percent on PV penetration. From a PV value perspective, it is not immediately apparent if building additional transmission infrastructure has a positive or negative cost-benefit to the value of PV. The economics, permitting, and required balancing authority coordination are non-trivial difficulties associated with increased transmission build out. Modeling at EPRI and NREL suggests that increased transmission infrastructure has negligible impact to the declining marginal value of PV.
- Successful demand-response and/or load shifting technologies must strike a balance between customers' desire for convenience, comfort, and minimal cost. Negative impact to any of these 3 C's will likely impede technology adoption. LBL modeling suggests that real-time pricing increases the energy value of PV under high penetration scenarios.
- The PV plant itself has opportunity for increasing value by producing electricity when the system values it most (i.e., time of day matters), providing ancillary services to the grid, siting at preferred locations within transmission and distribution system, and, if storage is needed, finding ways to cost-effectively integrate it at the plant.

Background and Additional Material

- The electric grid is evolving technically and financially. From a technical perspective, there are changes to the way electricity is generated, delivered, and managed. Financial evolution is underway to business models and rates. Calculating the holistic "system" value requires assessment of these complex interplays. As such, singling out only PV deployment misses any potential coupling with other technologies being deployed, such as grid infrastructure (e.g., new or upgraded transmission and distribution networks), storage (e.g., thermal, standalone batteries, electric vehicles), and demand-side innovations (e.g., smart thermostats, demand response technologies).
- Each of these strategies were explored through invited talks (attached). Workshop attendees came from EPRI, utilities, U.S. national labs, U.S. federal government, trade associations, industry, and academia.

EPRI ELECTRIC POWER RESEARCH INSTITUTE NREL NATIONAL RENEWABLE ENERGY LABORATORY ASU ARIZONA STATE UNIVERSITY

Retaining the Value of PV at High Penetration

October 13, 2016
1325 G St. NW. STE 1080, Washington, DC 20005

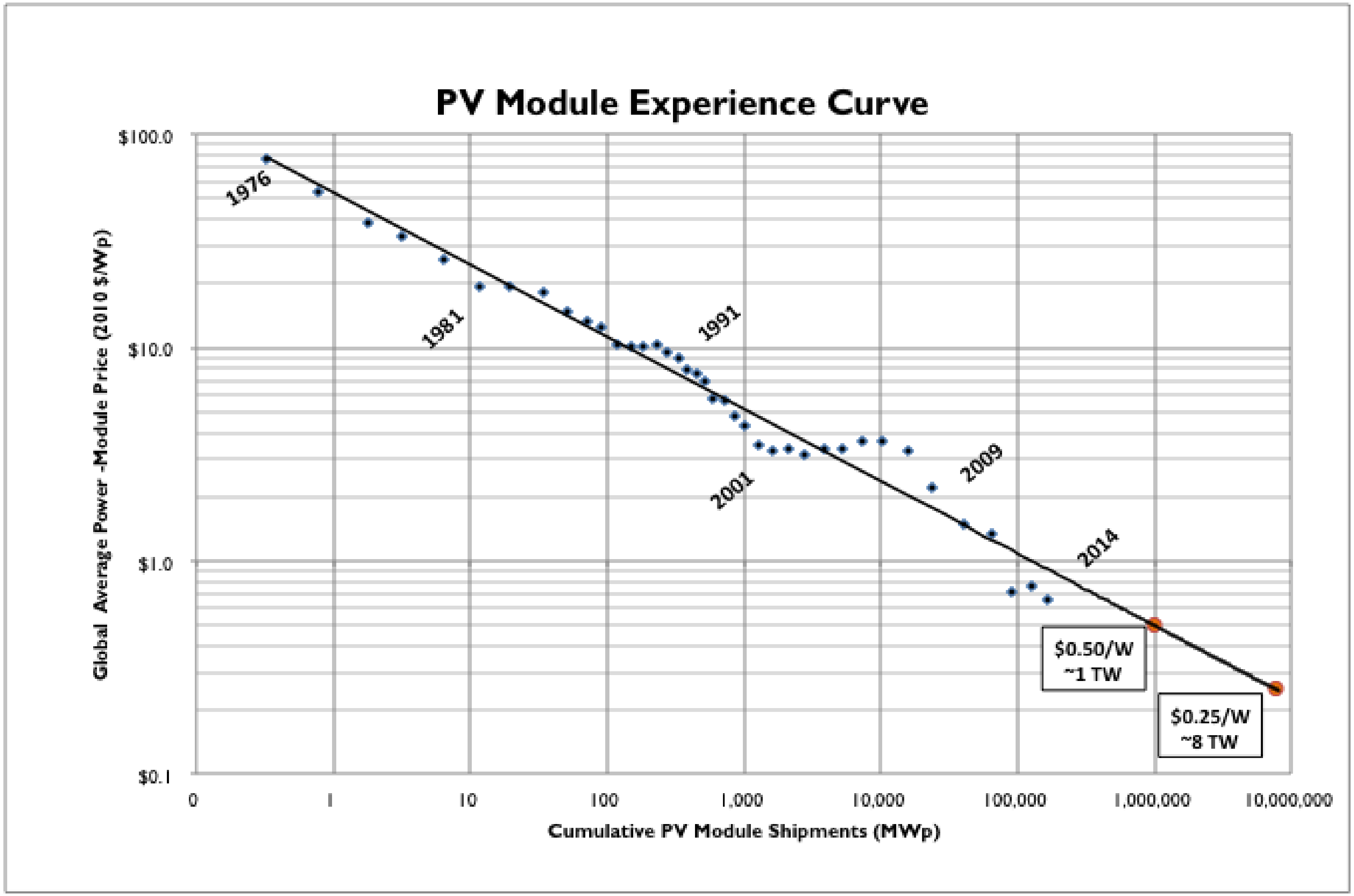
8:00a	*Registration and Breakfast*
MOTIVATION AND OVERVIEW	
8:30a	“Welcome and Introductory remarks” - **Sarah Kurtz**, NREL, and **Michael Bolen**, EPRI
9:00a	“Postcard from the future: Case studies of high PV penetration” – **Jan von Appen**, Fraunhofer IWES
9:30a	“Economic Value of PV Generation at High Penetration Levels” – **Geoffrey Blanford**, EPRI
10:00a	“Strategies for Retaining the Value of PV at High Penetration Levels” – **Robert Margolis**, NREL
10:30a	*Break*
RETAINING VALUE VIA…	
…STORAGE	
11:00a	“Value of PV in a Location with High Air Conditioning Loads” – **Christiana Honsberg**, ASU
11:30a	“Use of Storage (Batteries, Thermal, V2G) in UCSD’s Microgrid” – **David Weil**, Univ. of California San Diego (UCSD)
…THE GRID	
12:00p	“Use of Transmission to Extend Solar Electricity Past Sundown” – **Nate Blair**, NREL
12:30p	*Lunch*
1:30p	“Enabling cost-effective grid planning through PV adoption forecasting” – **Bernard Neenan**, EPRI
…CONSUMER BEHAVIOR	
2:00p	“Impact of Price-Responsive Demand on the Value of PV” – **Andrew Mills**, Lawrence Berkeley National Laboratory
2:30p	“Analyzing Technology Solutions toward Load Shaping” – **Marc Perez**, Clean Power Research
3:00p	*Break*
DISCUSSION & WRAP-UP	
3:30p	Key questions to discuss: - To what extent can each strategy enable high penetration? - What key metrics or specifications should guide when to use each? - What technical barriers might be limiting use of each? - How do these strategies impact the design of future PV plants?

Retaining the Value of PV at High Penetration - Motivation

Sarah Kurtz

October 13, 2016
Retaining the Value of PV at High Penetration Workshop
EPRI, Washington DC

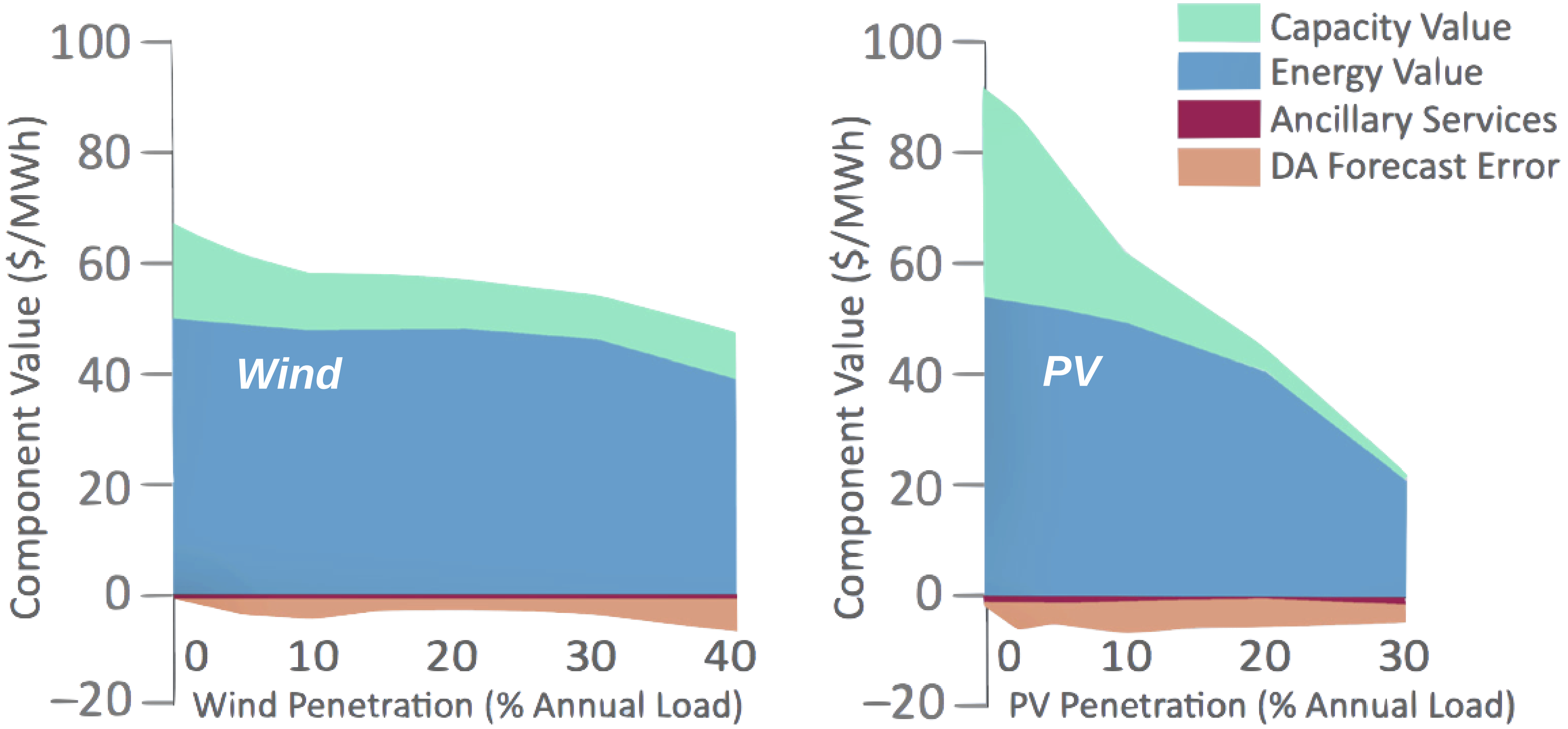
PV Prices are dropping – will they go low enough?



PV prices are low, but are they low enough to take us where we want to go?

PV Is a Poor Match to Electricity Load as Penetrations Increase, Reducing "Value"; Wind does better at high penetration

Value = ability to offset electric sector costs, considering Energy Value, Capacity Value, DA Forecast Error, Ancillary Services; Source: Mills and Wiser (2012); California focus

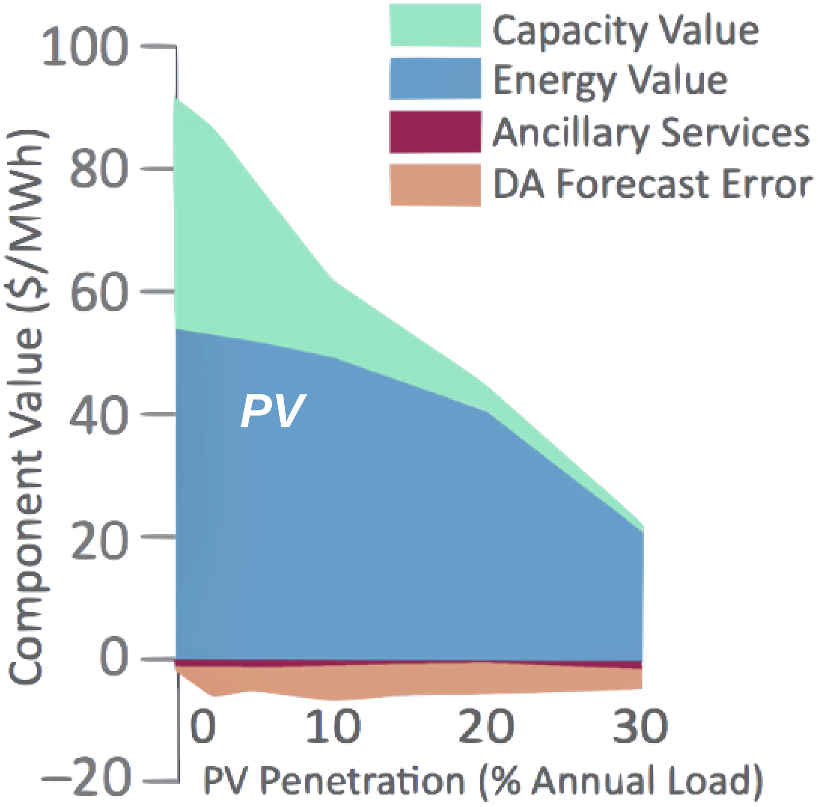


Slide courtesy of Ryan Wiser and Andrew Mills

PV Is a Poor Match to Electricity Load as Penetrations Increase, Reducing "Value"

Value = ability to offset electric sector costs, considering Energy Value, Capacity Value, DA Forecast Error, Ancillary Services; Source: Mills and Wiser (2012); California focus

PV prices are low enough for peaking applications today.
How much lower do prices need to go to enable PV to reach high penetration?
A factor of 4? Or more?



Slide courtesy of Ryan Wiser and Andrew Mills

WHAT IF?

- Today you’ll hear about strategies to enable solar electricity at higher penetrations – these studies use known strategies for making the grid more flexible

- *What if* we invested in technologies that reduced the cost of storage, transmission, load shifting, etc.

PV Is a Poor Match to Electricity Load as Penetrations Increase, Reducing "Value"; Wind does better at high penetration

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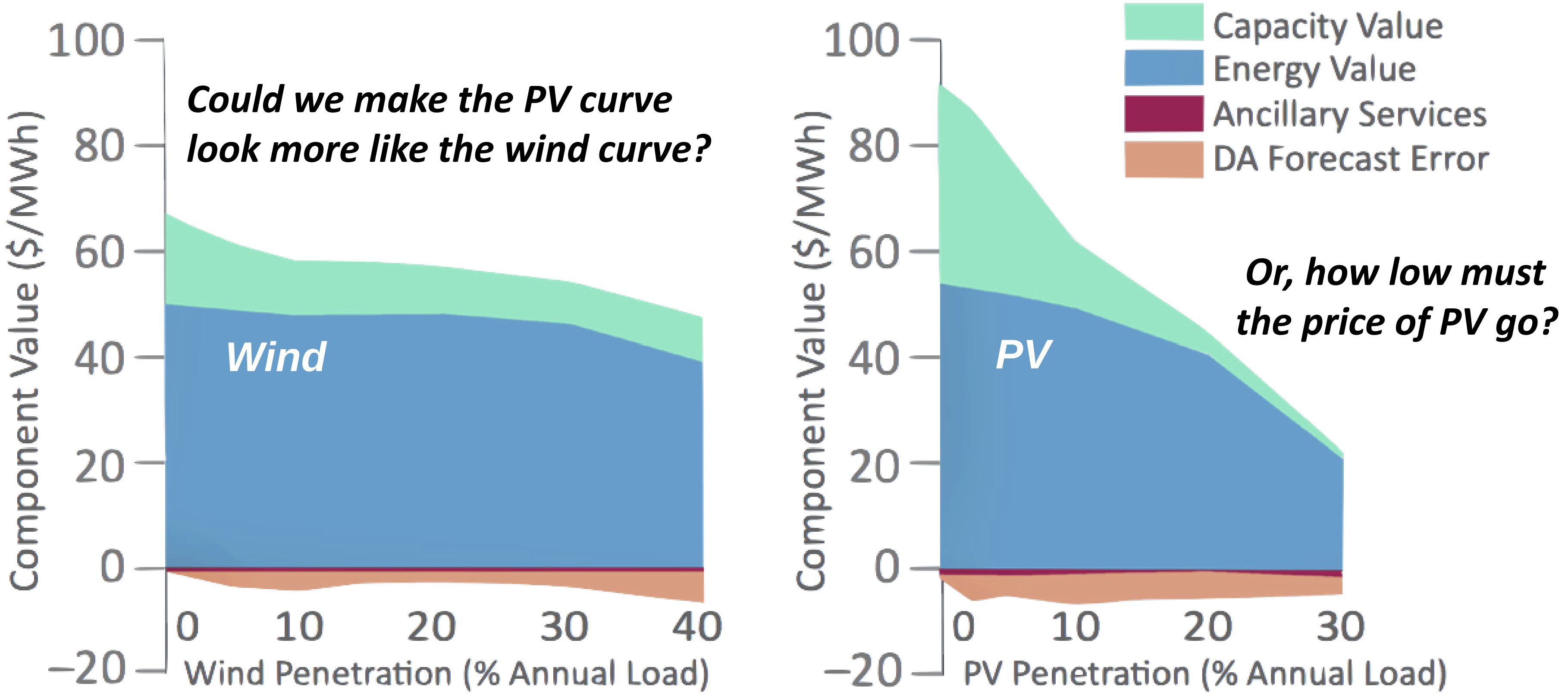


Could we make the PV curve look more like the wind curve?

Or, how low must the price of PV go?

Slide courtesy of Ryan Wiser and Andrew Mills

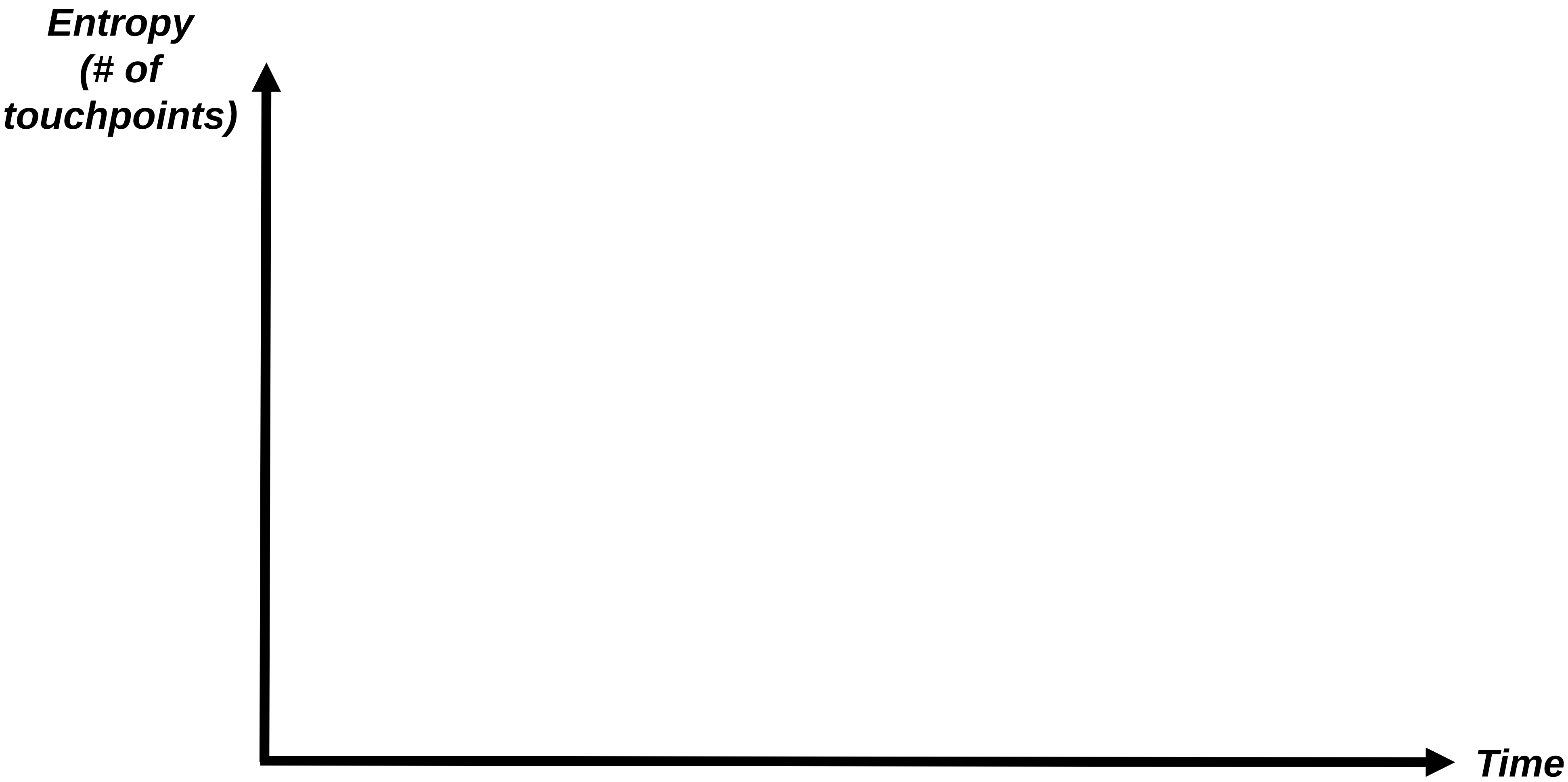
Retaining Value of PV Workshop

Michael Bolen

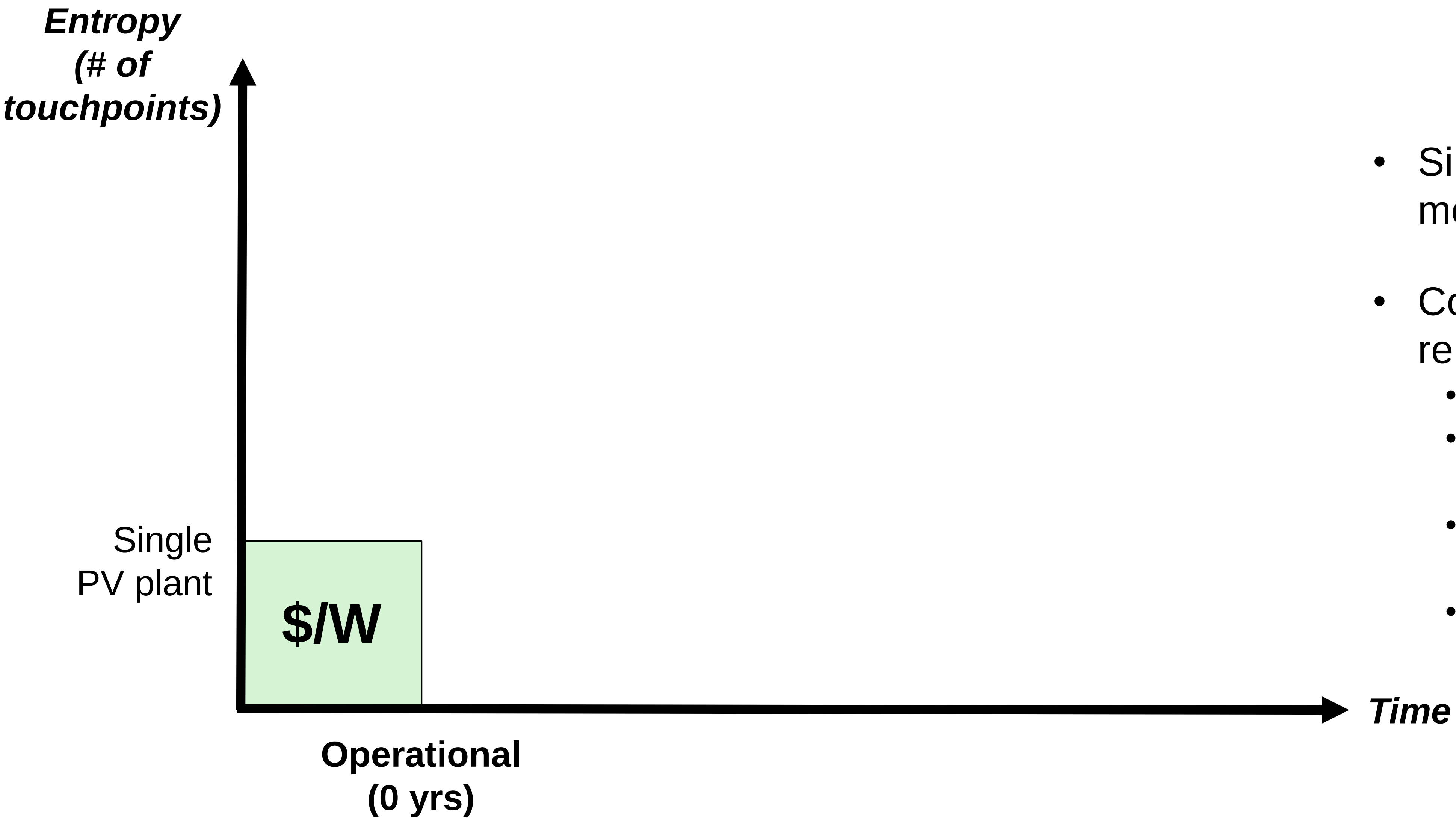
Sr. Technical Leader

mbolen@epri.com

Increasing complexity requires increased collaboration & coordination



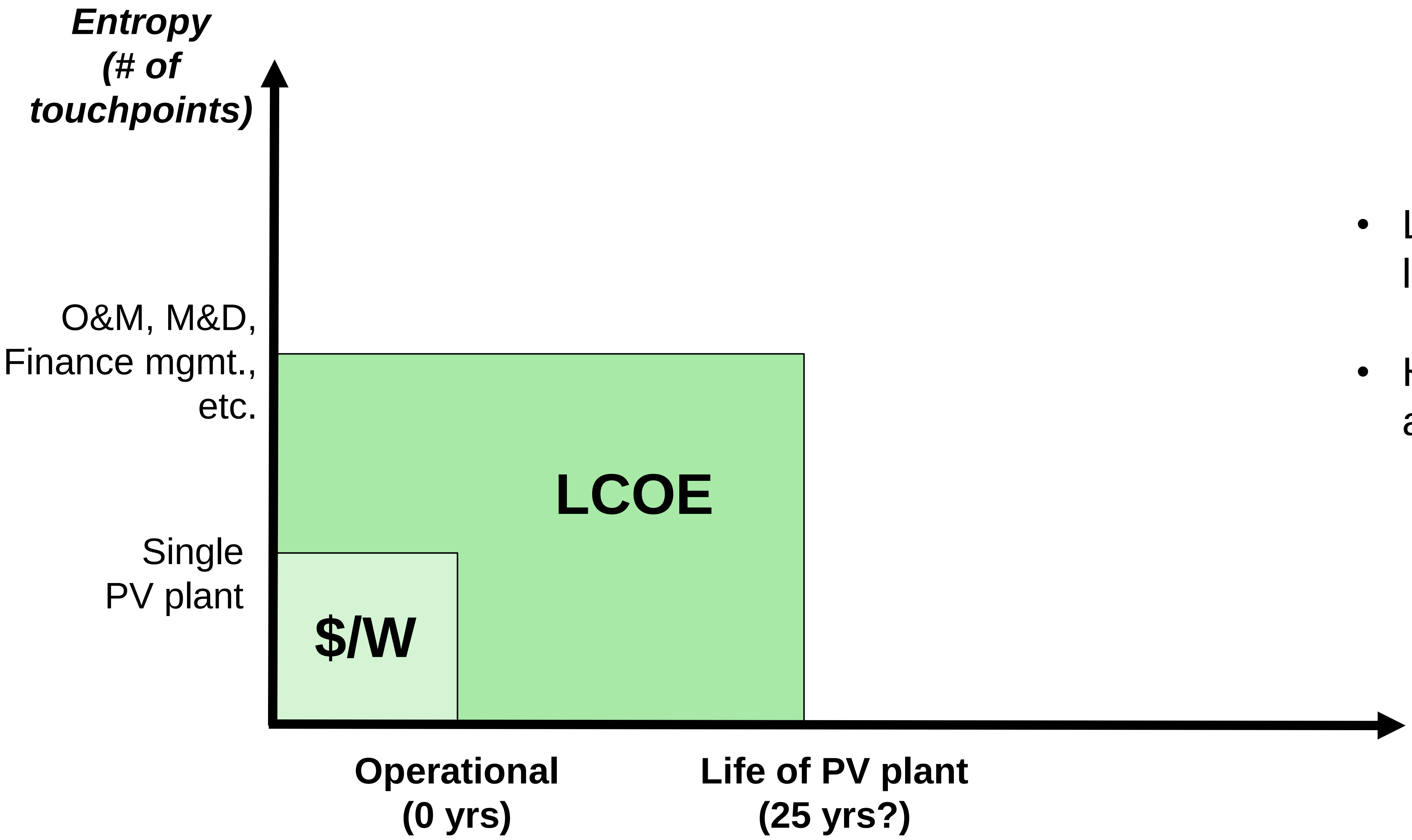
Increasing complexity requires increased collaboration & coordination



$/W

- Simple, but important metric!
- Considerations relevant to PV plant(s)
  - Cost for new build
  - Mid-life acquisition & due diligence
  - Type of hardware & technology to use
  - Monitoring & Instrumentation

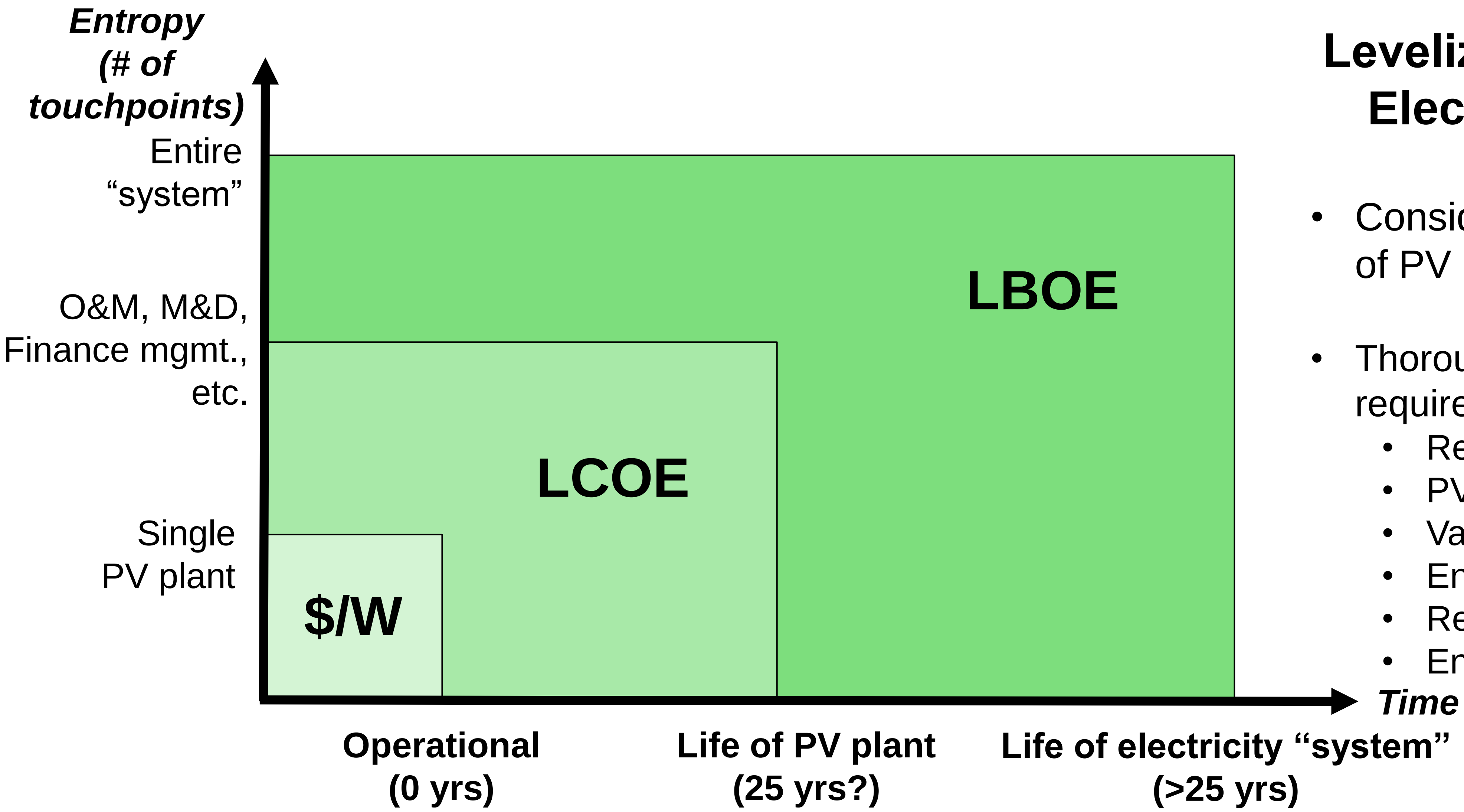
Increasing complexity requires increased collaboration & coordination



Levelized Cost of Electricity (LCOE)

- Lifetime costs divided by lifetime energy production
- Holistic consideration of all aspects of the PV plant
  - O&M
  - Reliability & Degradation
  - Energy production
  - Performance analysis & benchmarking
  - End-of-life & Disposal

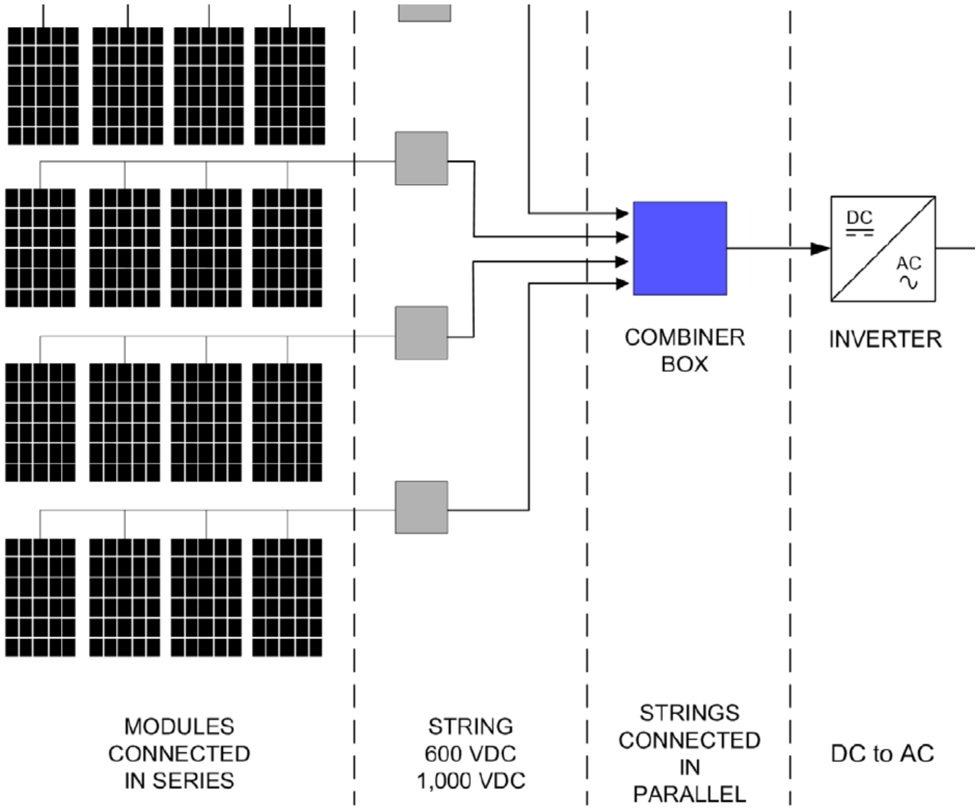
Increasing complexity requires increased collaboration & coordination

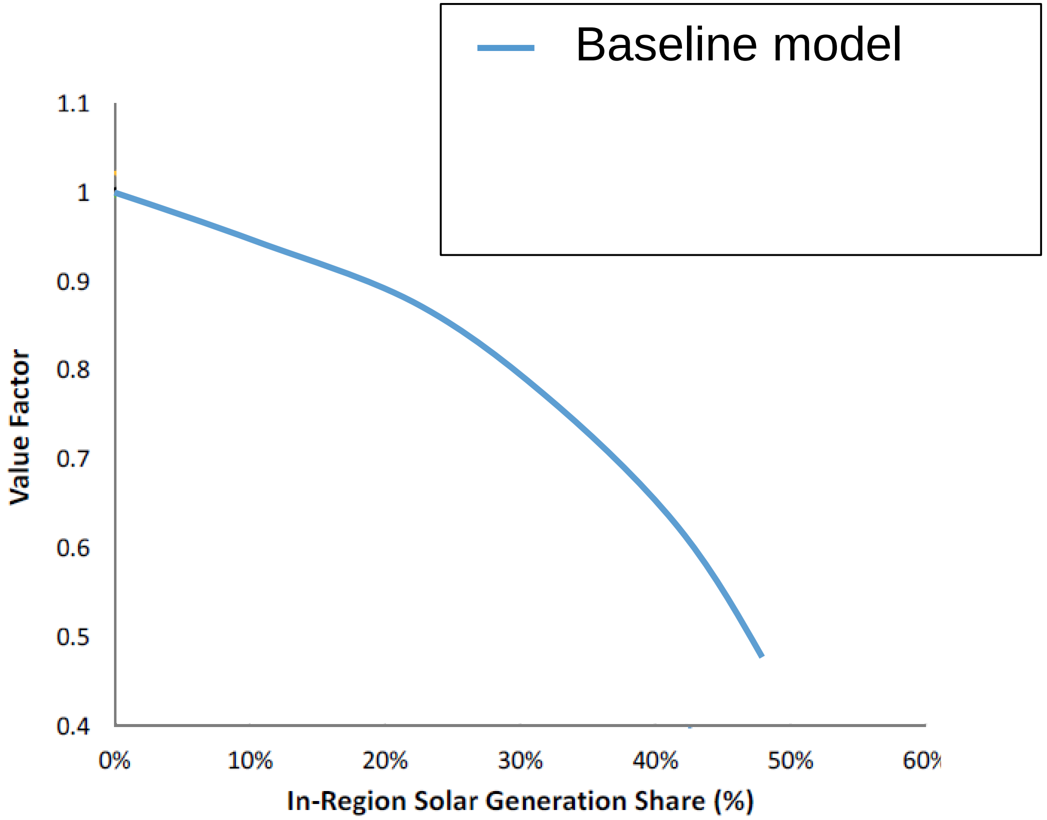


Levelized "Benefit" of Electricity (LBOE)

- Considers holistic impact of PV (e.g., value of solar)
- Thorough understanding requires broad collaboration
  - Resiliency / Microgrids
  - PV + Storage
  - Variability / T & D
  - Energy forecast / timing
  - Resource planning
  - Environmental impacts

Example: How can plant design benefit PV value?





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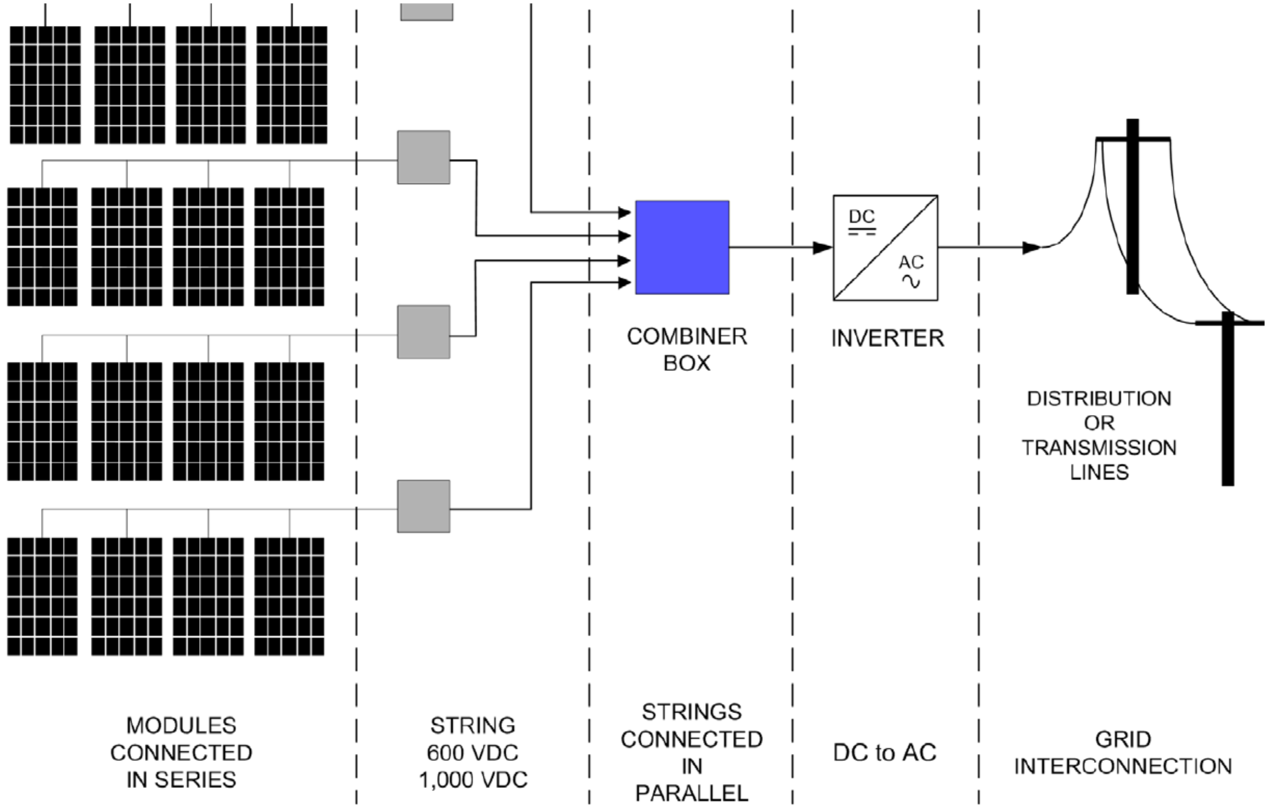

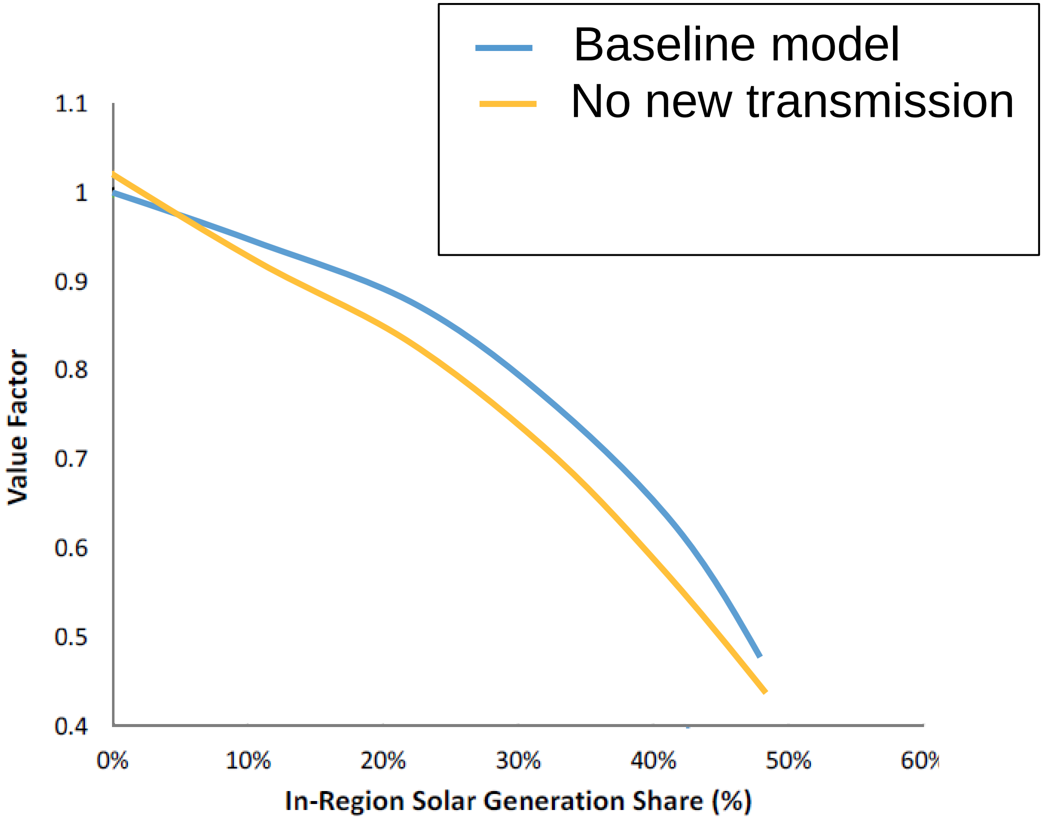

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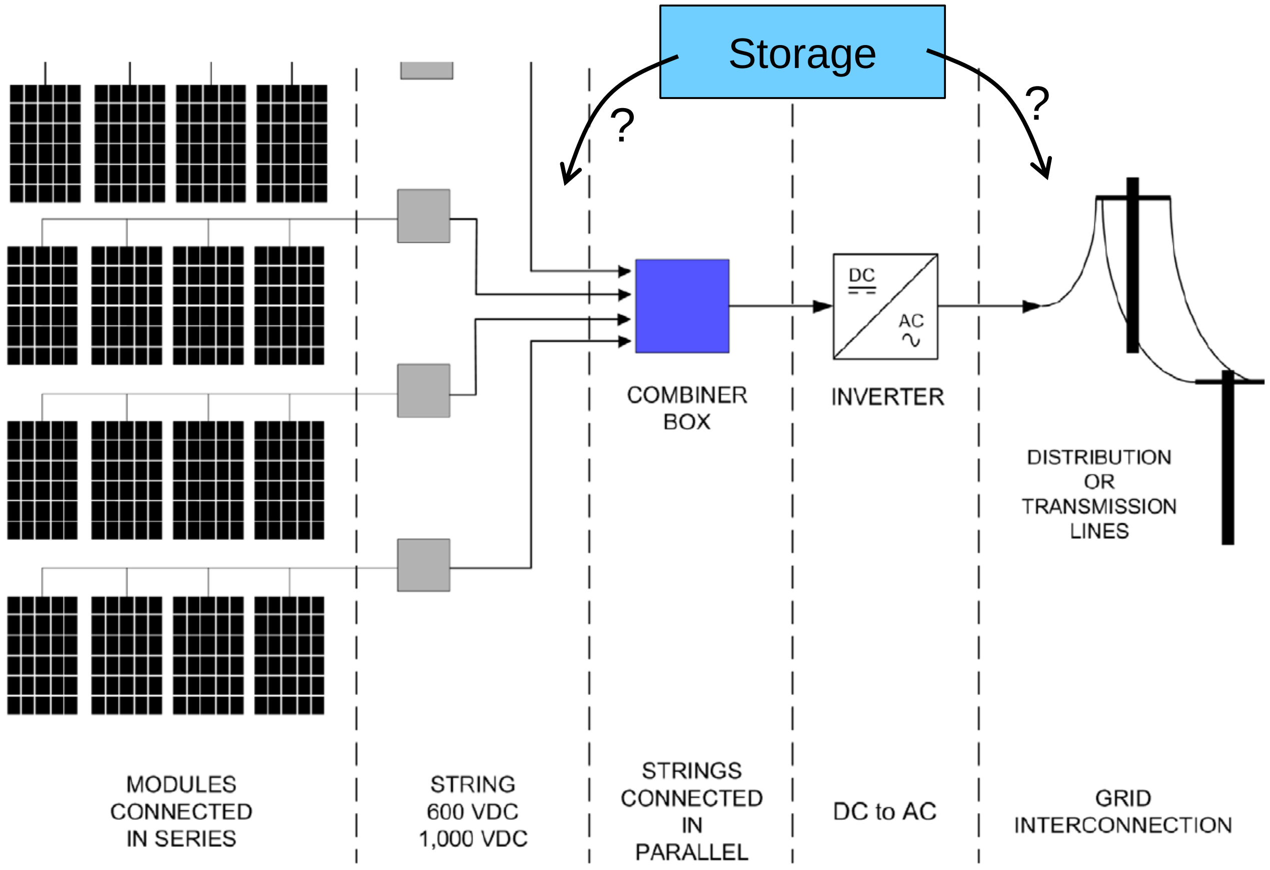

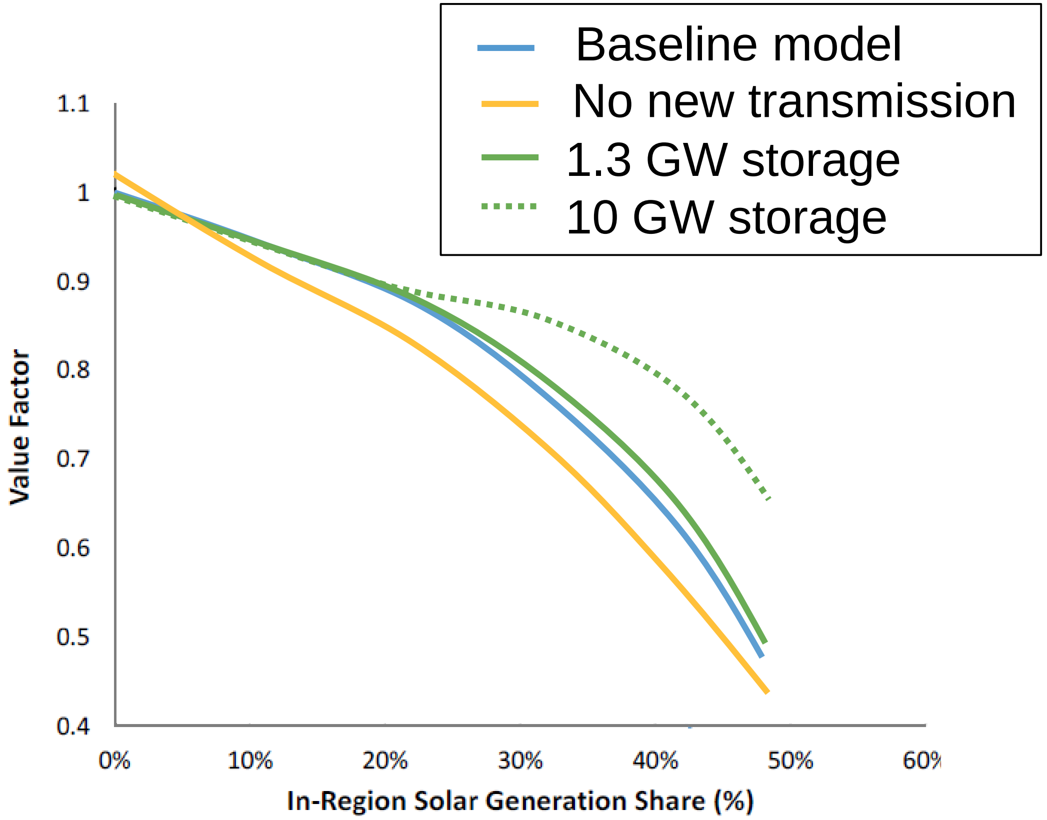

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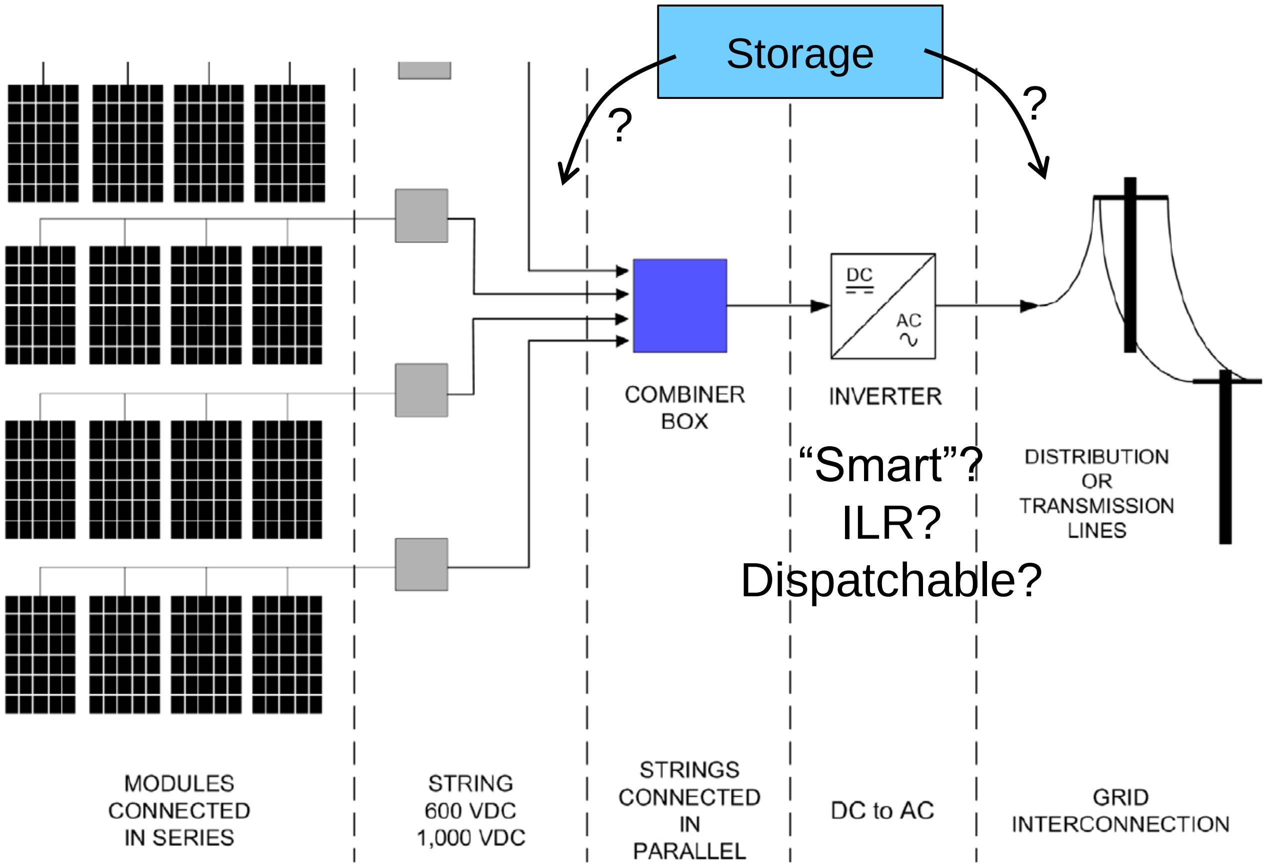
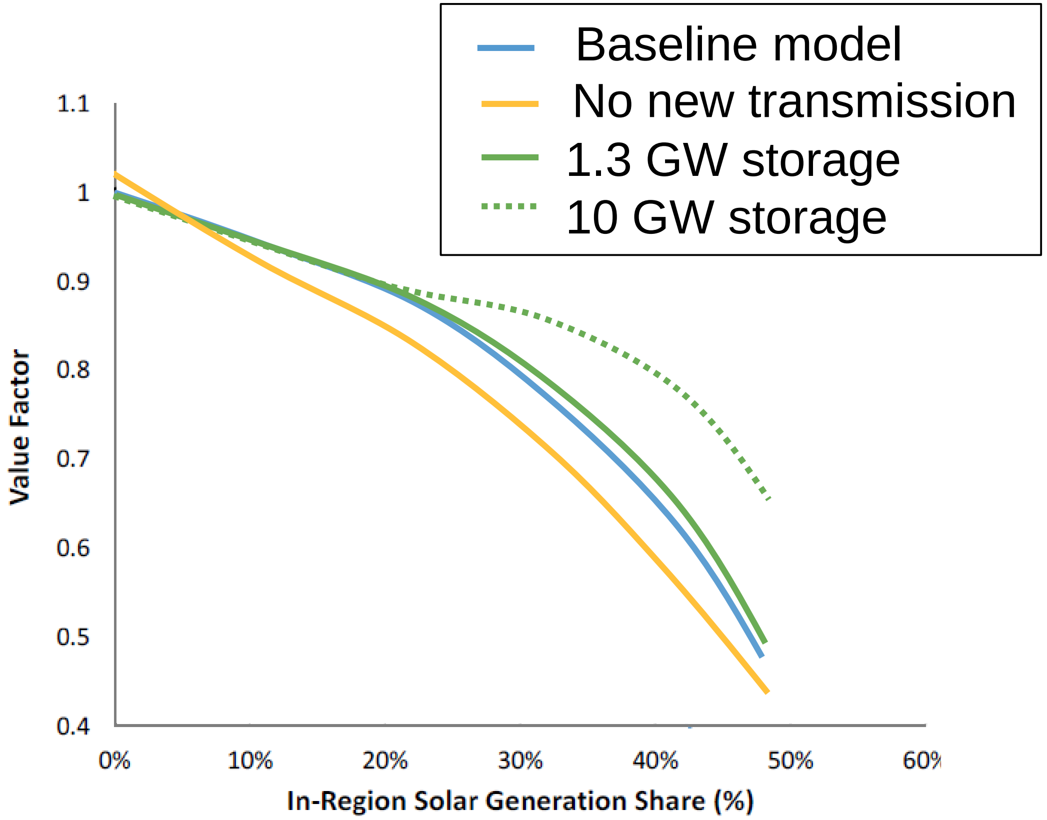


"Smart"?
ILR?
Dispatchable?

Orientation?
Tracking?
MLPE?

Voltage? Wiring?
Instrumentation?



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Workshop overview

- **Goal**
  - Confirm opportunities for retaining value
    - Storage, the “Grid”, Consumer Behavior
  - Discuss the technical challenges and gaps
  - Chart a roadmap for future R&D
  - Provide an alternative forum for focused discussion

- **Key Questions**
  - To what extent can current strategies enable high penetration?
  - What key metrics or specs should guide when to use each?
  - What technical barriers might be limiting each?
  - How do these strategies impact the design of PV plants?

  - *What are your questions…?*

Together…Shaping the Future of Electricity

Postcard from the future – Case studies of high PV penetration

Retaining Value of PV Workshop

10/13/2016, Washington, D.C.

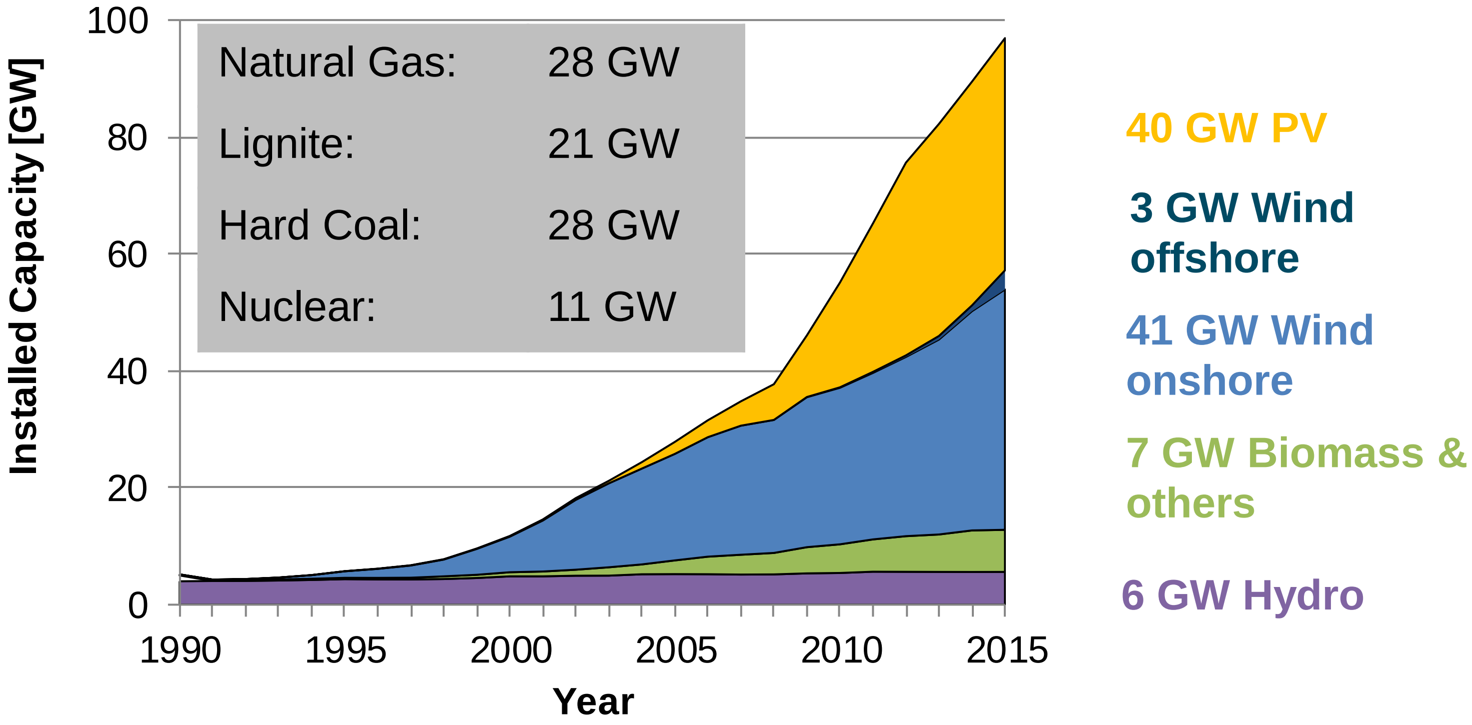
Jan von Appen (jan.vonappen@iwes.fraunhofer.de)

Fraunhofer Institute for Wind Energy and Energy Systems Technology IWES, Kassel, Germany

Status quo of the German Energy Transition – Installed RES capacity

The RES capacity reaches 100 GW in Germany in 2016 and already exceeds the max. vertical peak load by over 20 GW.

Growth of RES in Germany 1990 - 2015:*

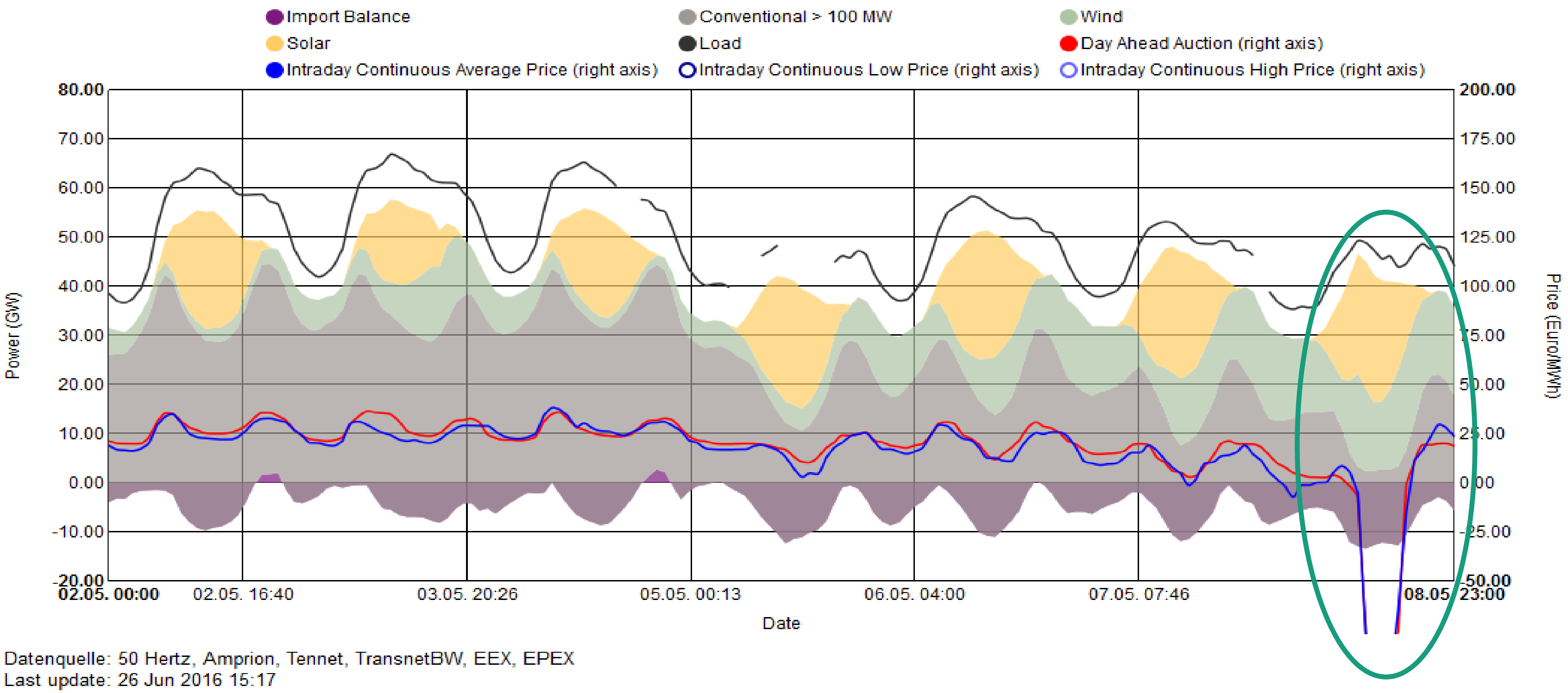


Natural Gas:	28 GW
Lignite:	21 GW
Hard Coal:	28 GW
Nuclear:	11 GW

*Source: BMWi, UBA (2016)

Increasing feed-in of renewable energy is changing the electricity markets and grid operation in Europe.

Electricity production and spot market prices in Germany (Week 18, 2016):*



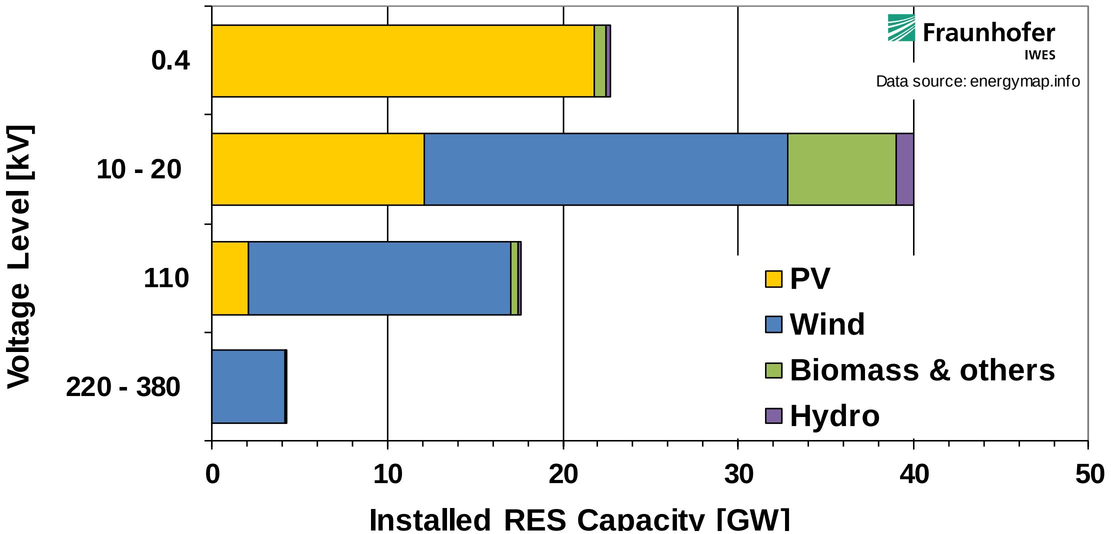
Datenquelle: 50 Hertz, Amprion, Tennet, TransnetBW, EEX, EPEX
Last update: 26 Jun 2016 15:17

*Source: Fraunhofer ISE: www.energy-charts.de

Status quo of the German Energy Transition – Grid transition (1)

Especially, the distribution system undergoes a huge transition right now.

Distribution of installed RES capacity over different voltage levels in Germany:*



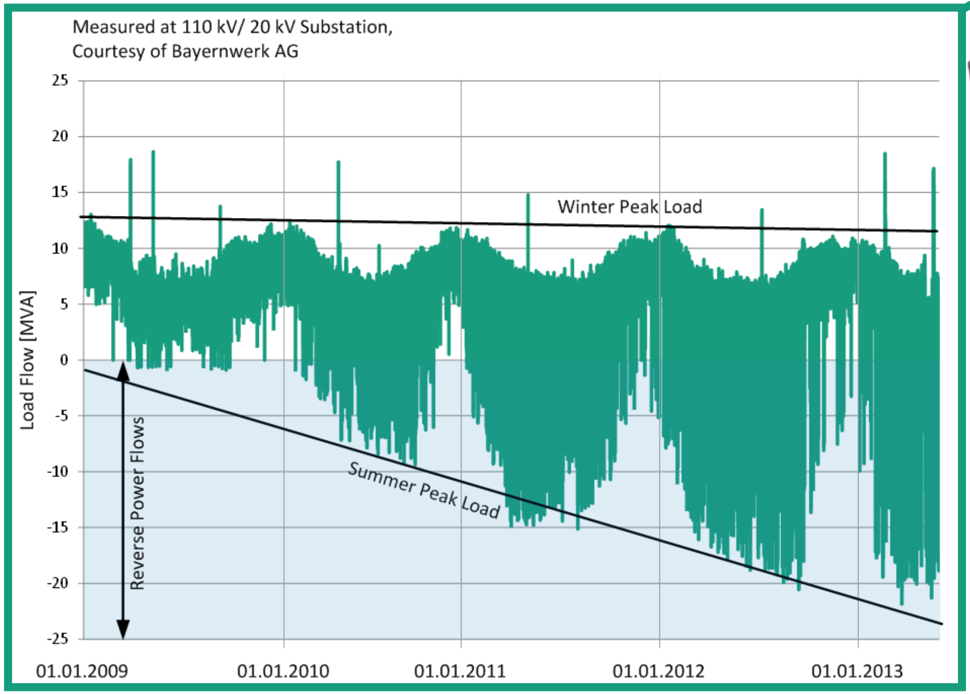
Increasing PV hosting capacity through optimal balance between grid reinforcement, investment in smart grid technologies and using smart inverter functionalities

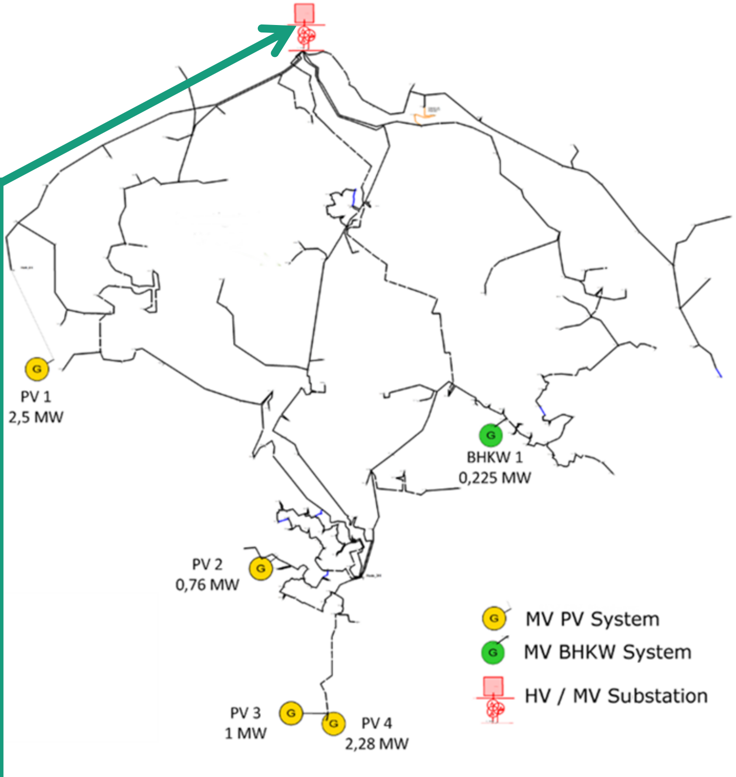
*Source: www.energymap.info

Status quo of the German Energy Transition – Grid transition (2)

More and more distribution grids are changing from consumption to supply grids.

German MV case study:*

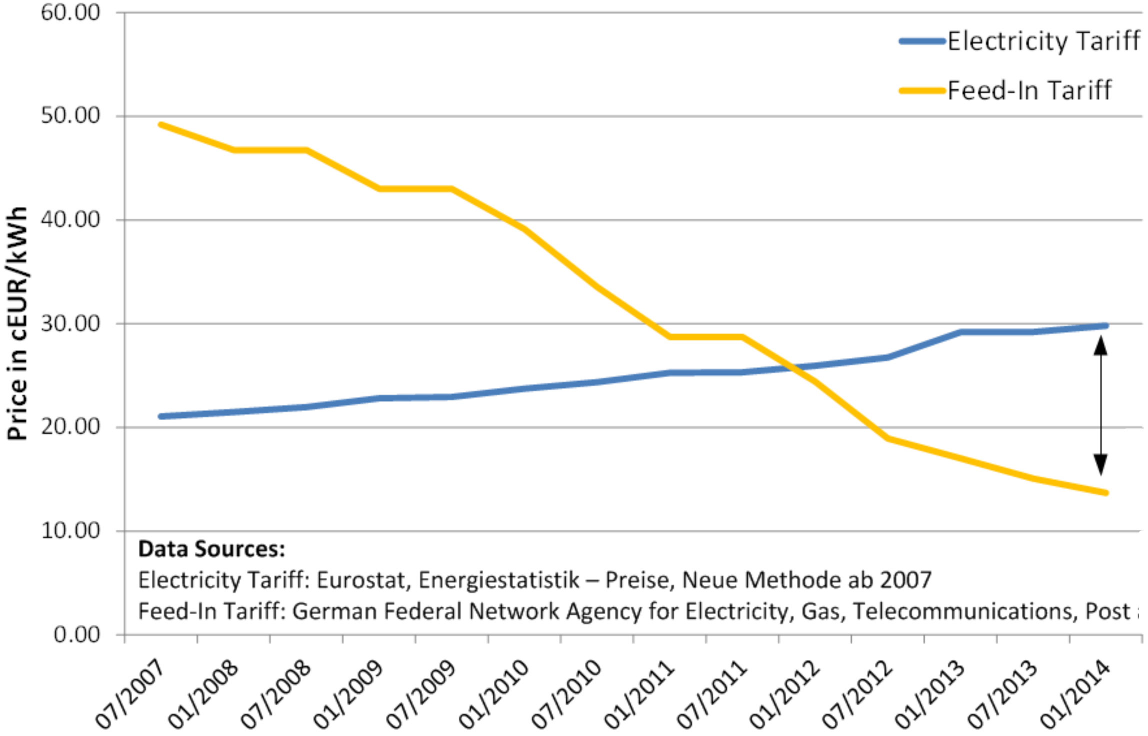




*Source: Bayernwerk AG

The spread between feed-in tariffs and household electricity costs provides a strong incentive for PV self-consumption.

Development of household electricity price and feed-in tariff for PV systems (< 10 kWp):



Data Sources:
Electricity Tariff: Eurostat, Energiestatistik – Preise, Neue Methode ab 2007
Feed-In Tariff: German Federal Network Agency for Electricity, Gas, Telecommunications, Post

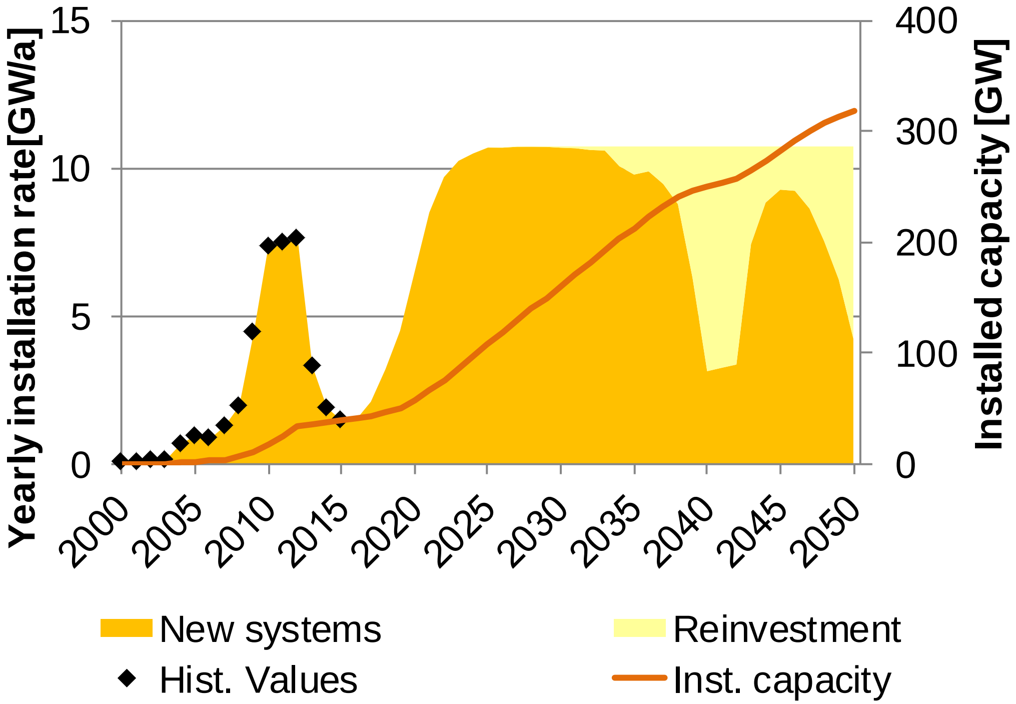
Business cases for PV systems in combination with battery storage systems or heat pumps emerge: 20,000 PV battery systems were installed 2015 in GER

Self-consumption incentive is also partially steaming from avoidance of grid fee and tax payment

Back to the future II – PV growth ahead

A higher electrification of the entire energy demand will allow to move to more ambitious climate goals.

PV development for 95% emission reduction scenario for Germany:*



*Source: IWES, Kasseler Symposium Report 2016

Necessary measures:

- Flexible power plants (biomass and power-to-gas)
- Reinforced smart grids
- Sector coupling through heat pumps, power-to-X and e-mobility

Back to the future II – PV system sizing for high PV penetration scenarios (1)

Lower spot market prices and self-consumption incentives change sizing and configuration possibilities of PV systems.

Reimbursement of PV grid feed-in:

- Roof-top PV systems will play a major role in future PV growth scenarios; however FIT and market value of PV grid feed-in drop
- Types of reimbursement: Reduced feed-in tariff (FIT), Market value, 0 ct./kwh
- ➢ What is the impact of the reimbursement system on PV system sizing in a self-consumption world?

Adaption of storage systems and sector coupling:

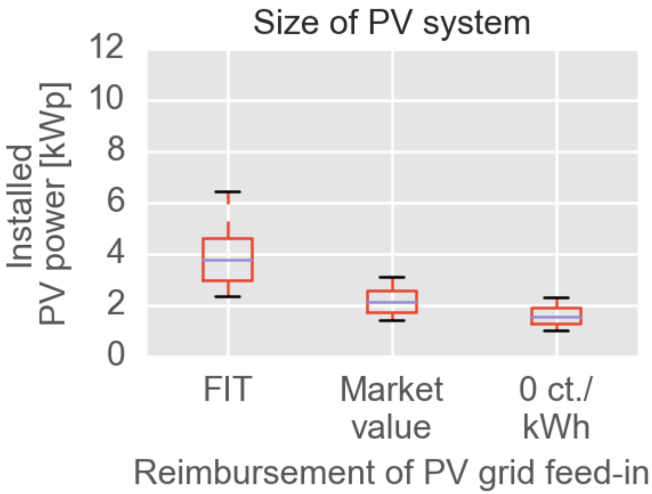
- Energy efficiency measures and self-consumption impact PV investments
- Sys. variation: PV + storage system (BSS) and PV + heat pump (HP), PV + BSS & HP
- ➢ How do such new system configurations impact the PV system size?

Case study approach:

- MILP formulation of investment and operation decisions for DER system
- Input data: 4 locations with 10 PV profiles, ~ 50 load profiles between 3.5 – 5.5 MWh

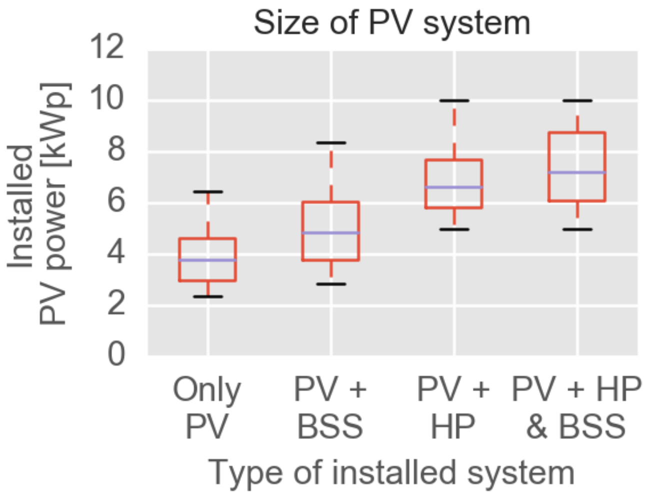
To capture the full PV potential, incentives have to be designed properly and sector coupling barriers have to be removed.

Impact of reimbursement of PV grid feed-in on PV system size:



- Rooftop PV system size might highly decrease or become financial unattractive in a post FIT world

Impact of BSS and heat pumps on PV system size:



- Sector coupling provides a bigger chance for PV systems than battery systems

Automated and probabilistic analyses of PV hosting capacity allow DSOs to focus on critical grids.

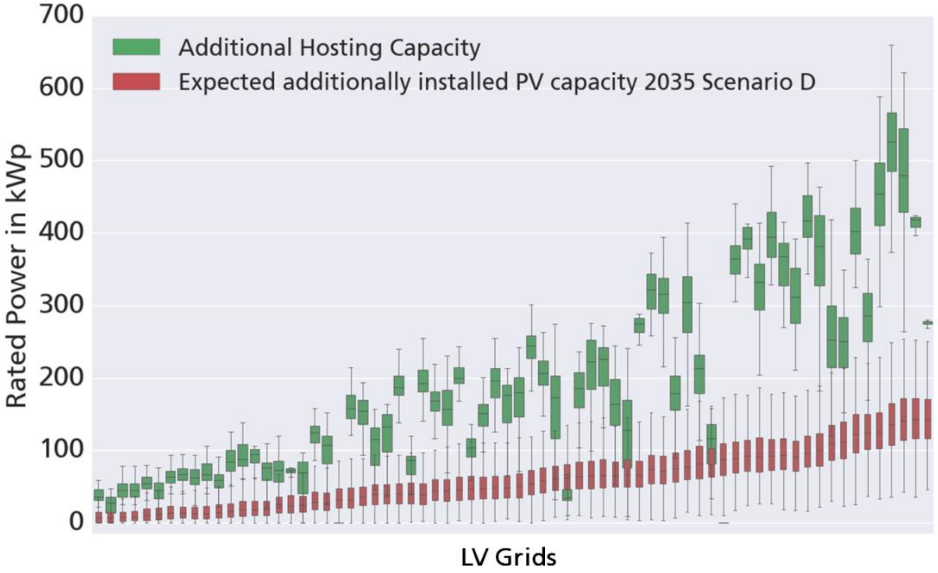
Grid planning for high PV penetration:

- Complexity of grid planning is increasing (PV growth, regulatory framework, BSS, HPs)
- New control options of inverters and new smart grid technologies

Analysis approach:

- Determination of PV hosting capacity using own simulation framework PANDAPOWER
- Monte-Carlos simulation of grid connection point for new PV sys.

PV hosting capacity for different LV grids of one DSO:*



➡ PV hosting capacity is only reached in a few LV grids

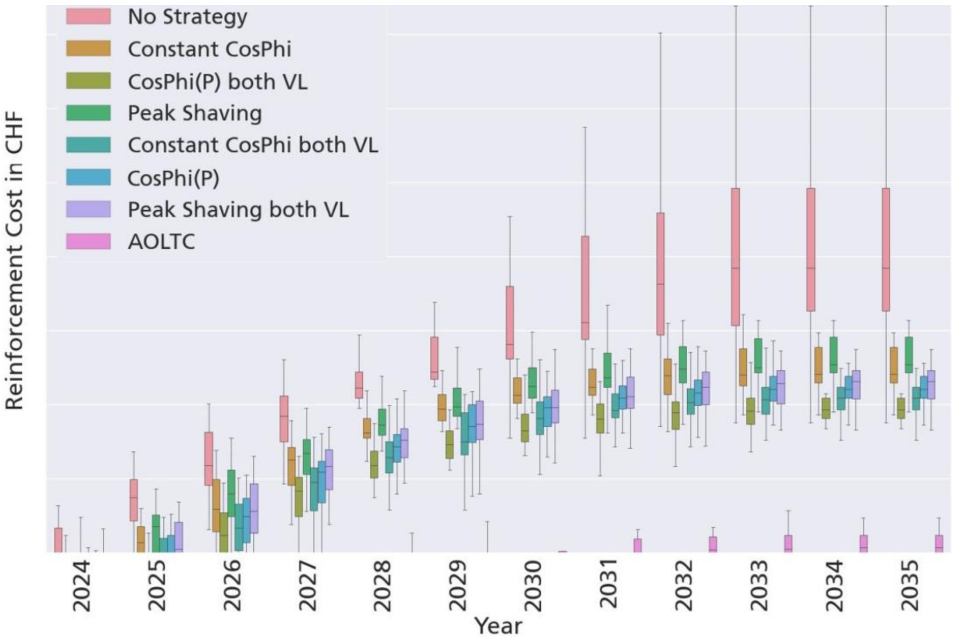
*Source: Scheidler, Thurner, Kraiczy, Braun (2016)

Lower PV grid integration cost can be achieved through combining local control approaches with new smart grid technology.

Optimization of grid reinforcement:

- Smart grid reinforcement through line replacement and grid reconfiguration
- Smart inverter functionalities:
  - Q-control: Constant CosPhi, CosPhi(P)
  - P-control: peak shaving
- Advanced OLTC transformer control (AOLTC)
- Case study for a MV grid

Evaluation of cost savings in grid reinforcement with control strategies:*



*Source: Scheidler, Thurner, Kraiczy, Braun (2016)

Conclusion and discuss questions

Business cases for PV systems

- Sector coupling increases the value of local PV generation and enables tapping into the full PV potential
- Battery provide a flexibility solution, but require an adaption of the tariff and pricing system to fully realize their market and grid integration potential

PV grid integration:

- Automated grid planning allows an accurate assessment of grid integration costs
- Combining smart grid technologies with inverter functionality highly decreases PV grid integration cost while allowing for a step-by-step increase of PV hosting capacity

Outlook:

- How do we address investor uncertainty in a post FIT-world?
- Is PV self-consumption really incentivizing grid defection?
- How do we bring down costs for PV systems with different generation profile (facades, etc.) to move more towards system-friendly PV generation?

Contact data:

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- Head of department Energy Management and Energy Efficiency
- Mail: jan.vonappen@iwes.fraunhofer.de

References and read suggestions

- J. von Appen, J. H. Braslavsky, J. K. Ward, and M. Braun, “Sizing and grid impact of PV battery systems,” in 2015 Symposium on Smart Electric Distribution Systems and Technologies (EDST), Sept 2015, pp. 612–619.
- A. Scheidler, L.Thurner, M. Kraiczy, M.Braun, “Automated Grid Planning for Distribution Grids with Increasing PV Penetration,” to be published at Solar Integration Workshop, Vienna, Nov. 2016.
- T. Stetz, J. von Appen, F. Niedermeyer, G. Scheibner, R. Sikora and M. Braun, "Twilight of the Grids: The Impact of Distributed Solar on Germany’s Energy Transition," in IEEE Power and Energy Magazine, vol. 13, no. 2, pp. 50-61, March-April 2015.
- J. von Appen and M. Braun, “Grid integration of market-oriented PV storage systems,” in Proceedings International ETG Congress 2015, Nov 2015, pp. 1–8

Economic Value of Solar PV at High Penetration Levels

(Decreasing Returns to Scale)

Geoffrey J. Blanford, Ph.D.
Technical Executive
Energy and Environmental Analysis, EPRI

EPRI Workshop, Washington, DC
October 13, 2016

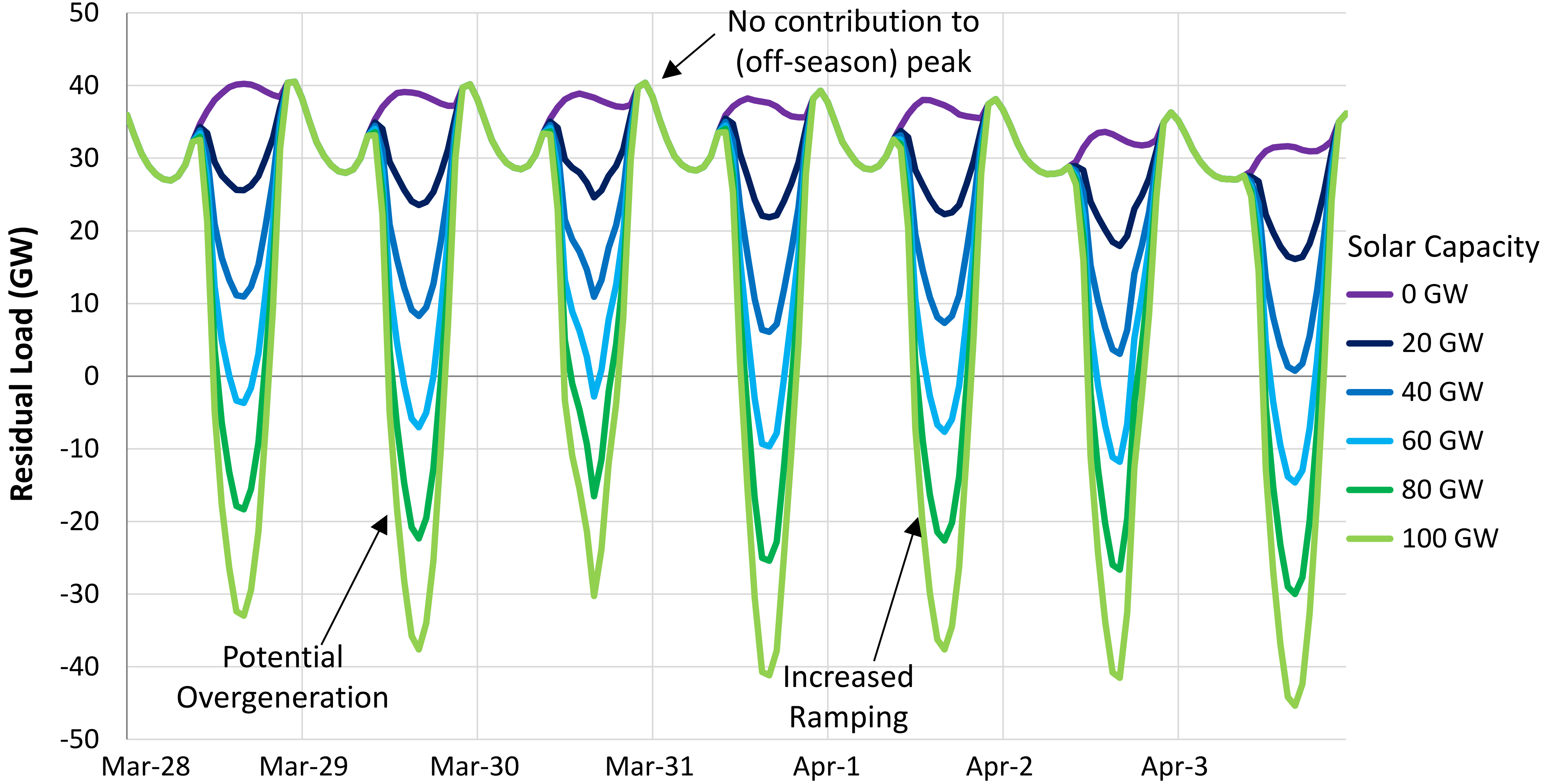
Key insights from economic modeling

- Renewable energy exhibits decreasing returns to scale, i.e. the ***value*** of solar (and wind) capacity ***declines*** as more is added
- Partially driven by resource supply curve (i.e. scarcity of good sites), but ***intermittent temporal profile*** is the main factor
- Storage, transmission, and demand response help “retain” value
- However: each of these has costs (and value unrelated to PV)

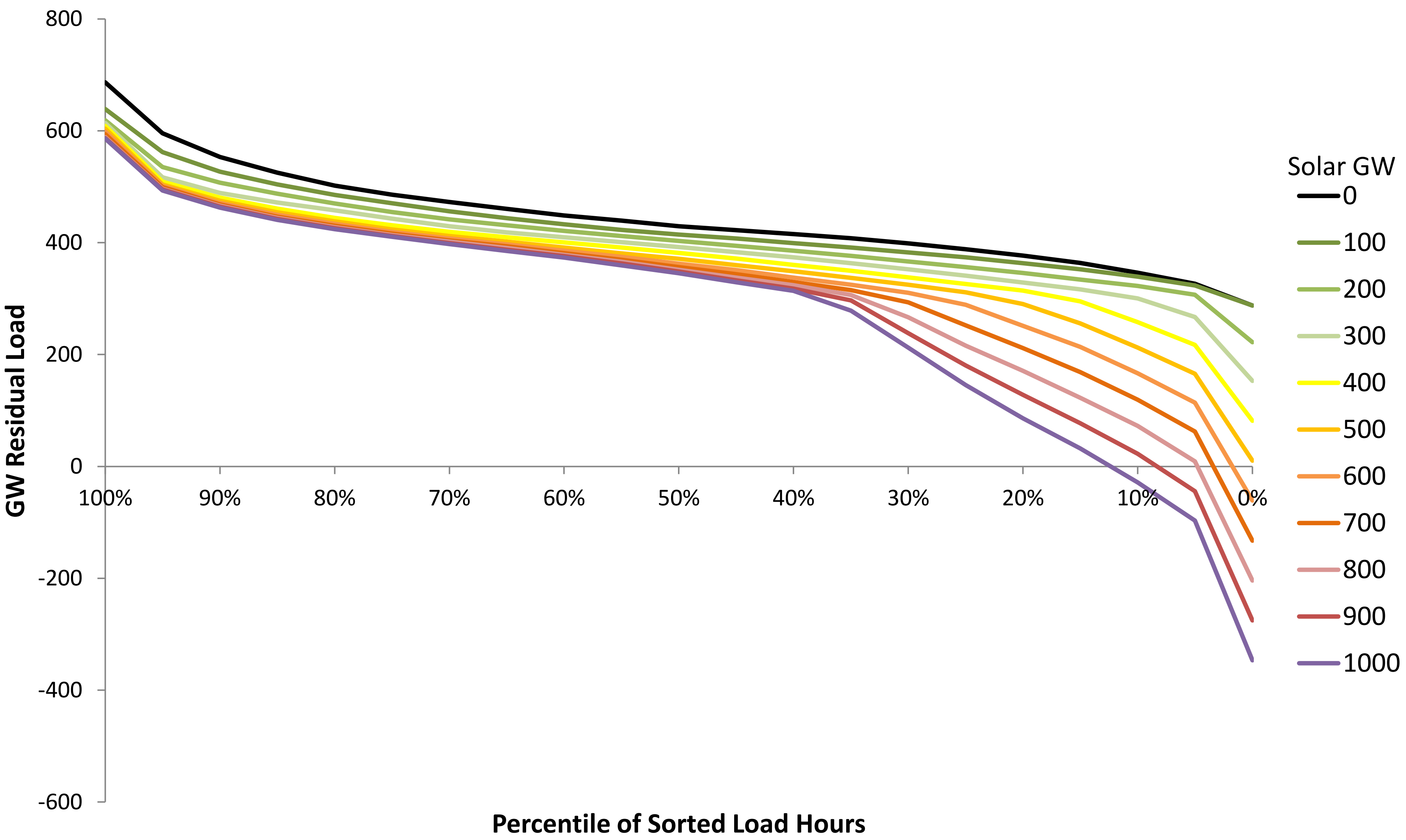
→Declining value of marginal solar investments is a fact of life

- Policy design or investment decisions based on “levelized” cost / value will miss this key feature of solar (and wind)

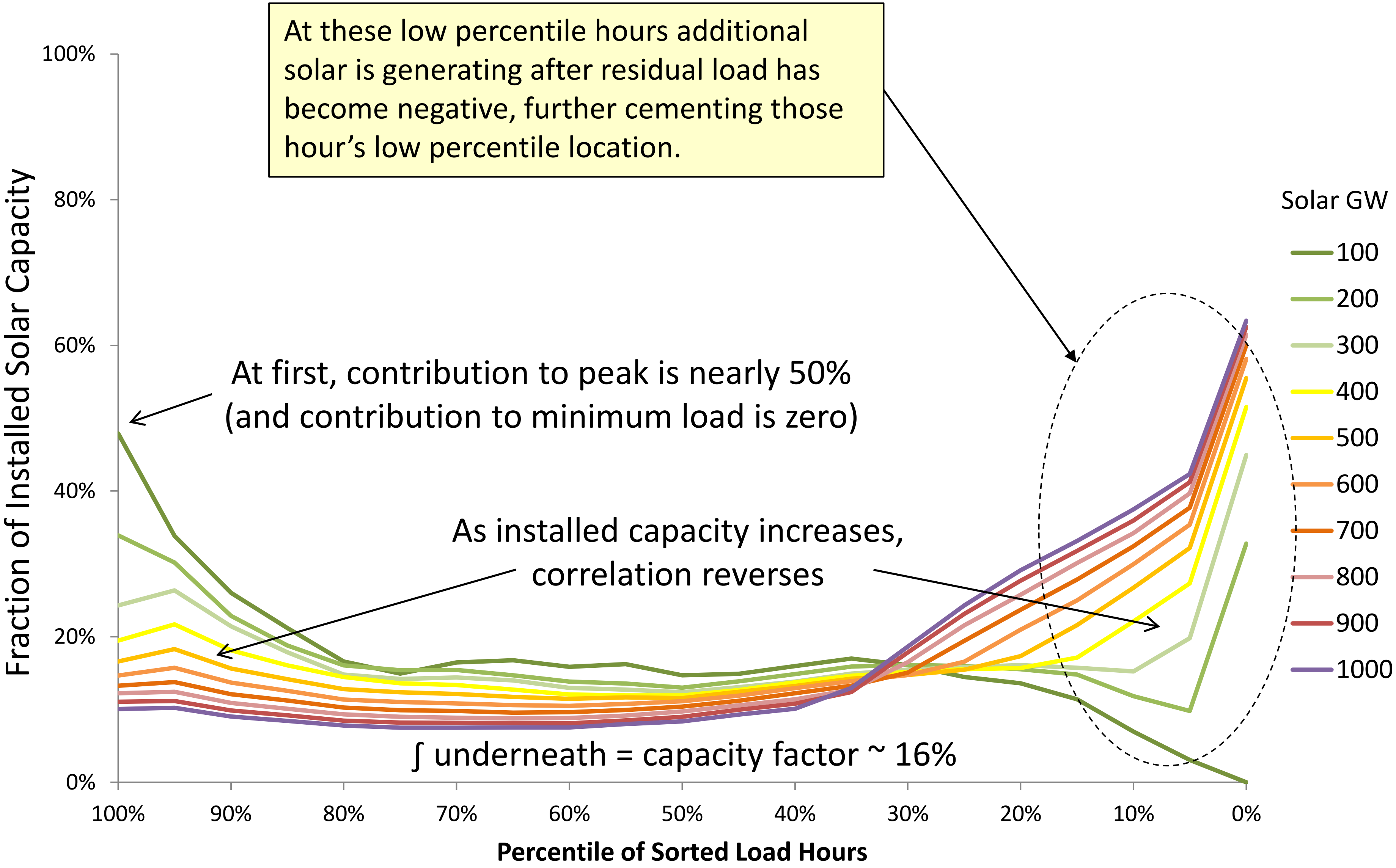
California residual load with solar generation



Residual Load Duration Curve shifts with increasing PV



- Begin with hourly data for load and solar PV output at regional level
- This illustration shows joint distribution between US total load and US total PV output
- Timing of contribution relative to load is the key factor driving capacity needs and economic value of PV investments



At these low percentile hours additional solar is generating after residual load has become negative, further cementing those hour’s low percentile location.

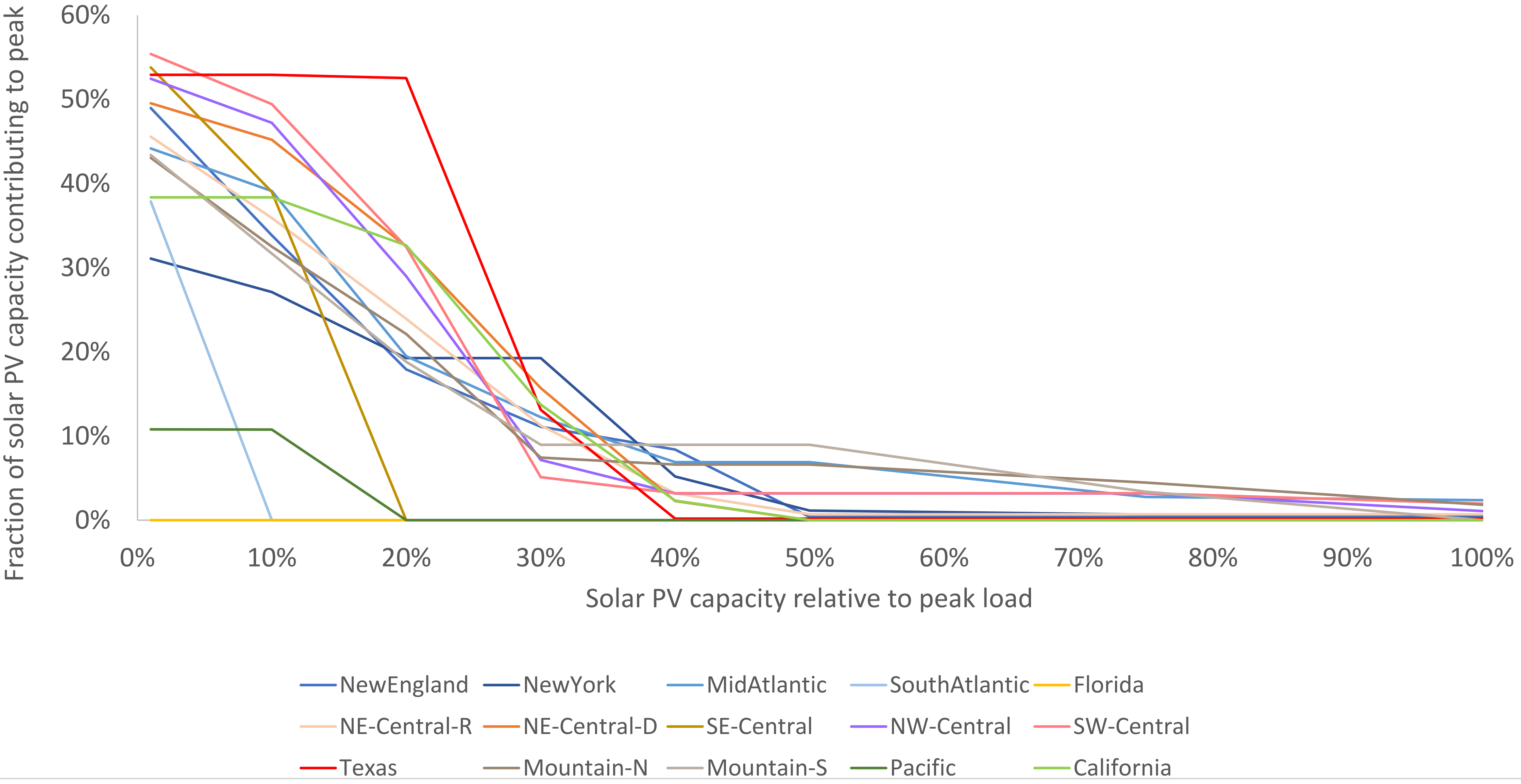
At first, contribution to peak is nearly 50% (and contribution to minimum load is zero)

As installed capacity increases, correlation reverses

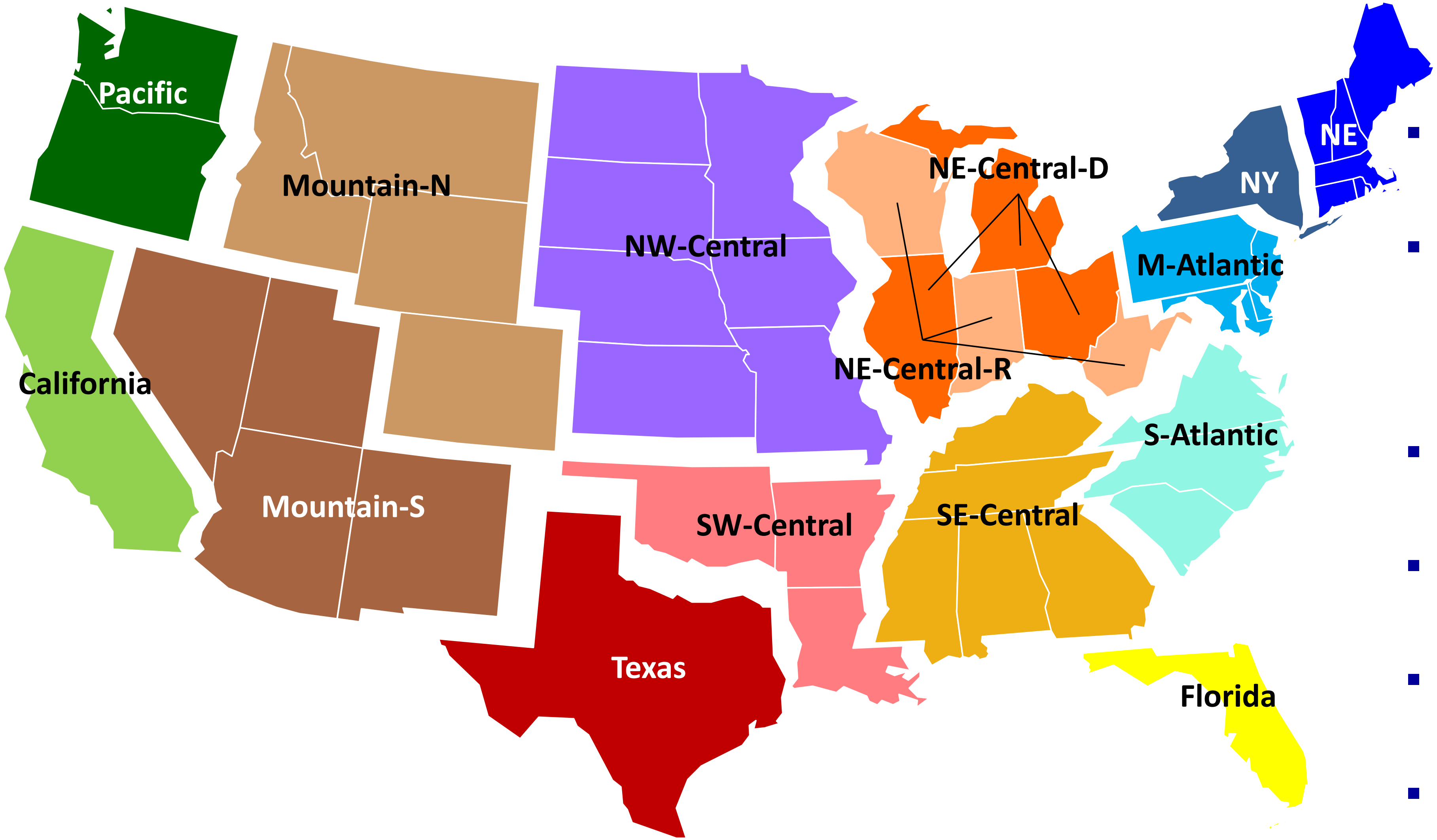
∫ underneath = capacity factor ~ 16%

- This illustration shows the contribution to residual load as a fraction of installed solar PV

Marginal Contribution to Peak of Solar PV



Modeling Solar PV Value in US-REGEN



- US electricity market model with regional detail
- Endogenous dispatch and investment (rental) of generation, transmission, and storage capacity
- In this analysis, hourly resolution in static mode (single year)
- All capacity is rented to simulate long-run equilibrium
- No unit commitment costs or constraints (in this version)
- Systematically vary the cost of solar PV to map out value curve

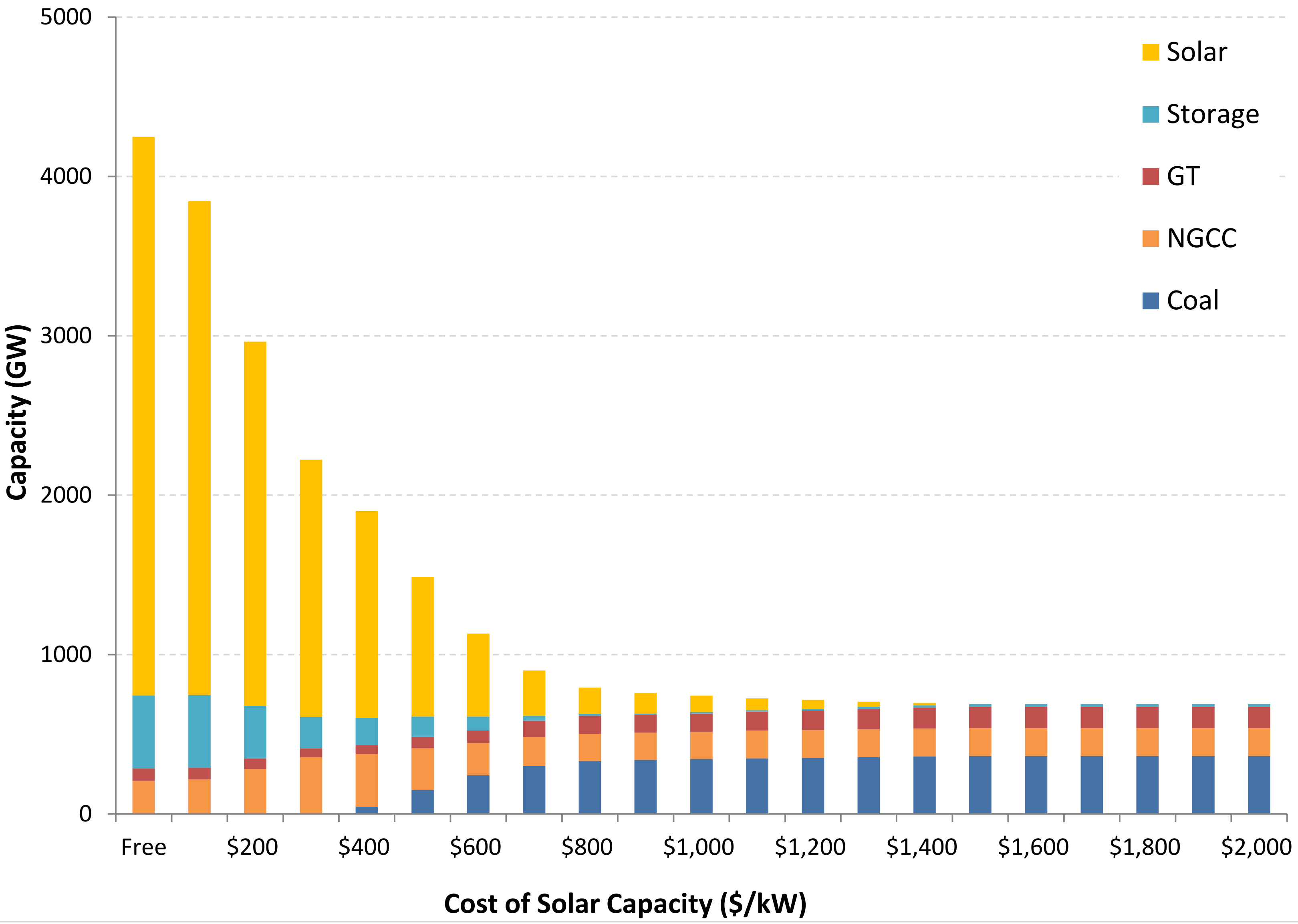
Technology Cost Assumptions

	Investment Cost ($/kW)	Lifetime (years)	Annualized @ 7% ($/kW-yr)	Fixed O&M ($/kW-yr)	Variable O&M ($/MWh)	Heat Rate (th.btu/ MWh)	Fuel price ($/mmbtu)
Nuclear	$6,000	70	$423	$80	$2	10,000	$0.5
Coal	$2,500	50	$181	$40	$3	10,000	$2
NGCC	$1,200	50	$87	$20	$3	7,000	$5
GT	$800	30	$64	$20	$4	11,000	$5

	Investment Cost ($/kW)	Hours of Storage	Charge Penalty	Storage Loss Rate
Pump Hydro	$1500	10	20%	---
Battery	$500	1	10%	10% / mo.

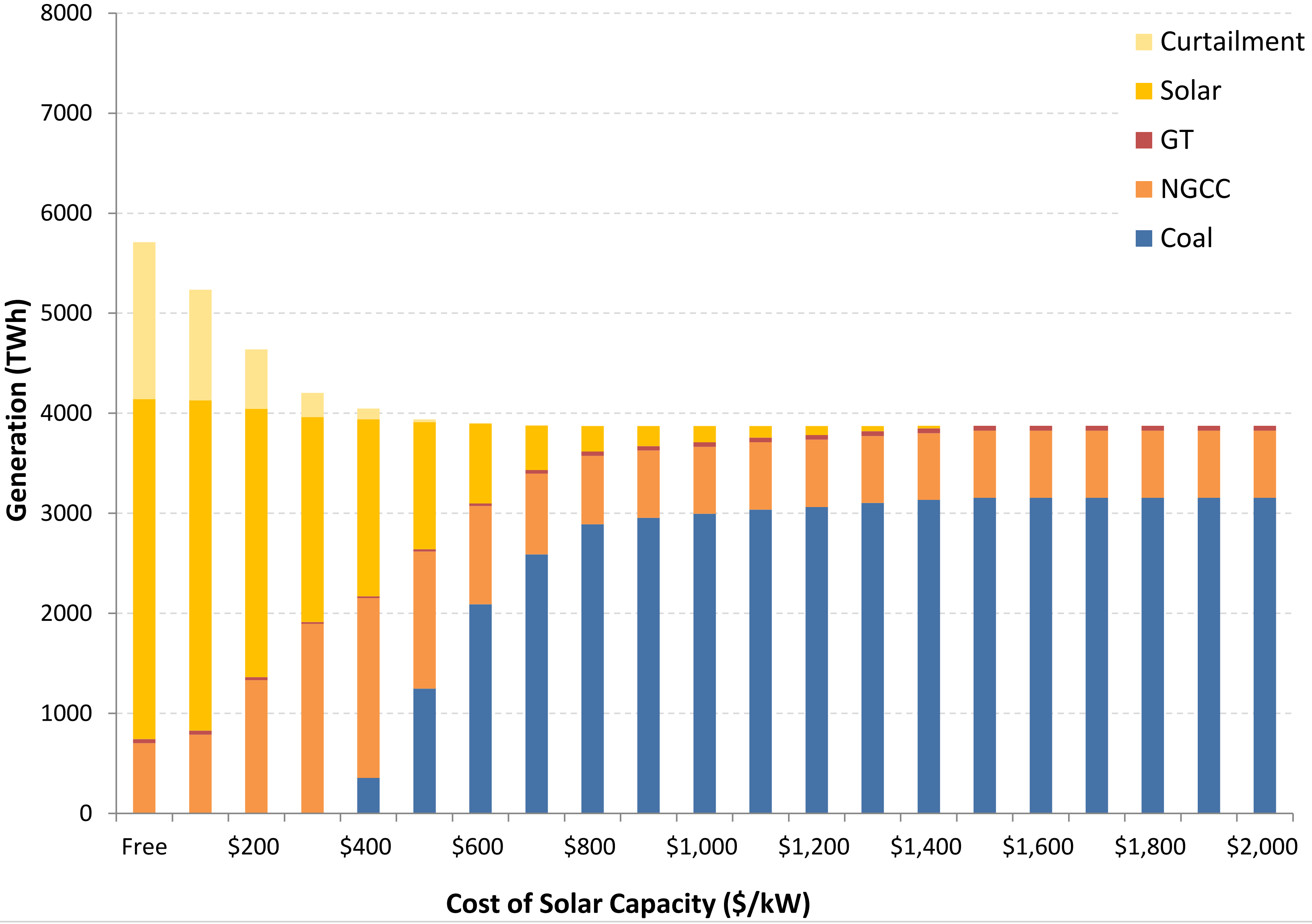
Transmission Capacity costs $3.85M per mile for a 6.4 GW line = $270/kW between CA and Mtn-S

US Capacity Mix as a function of Solar PV cost



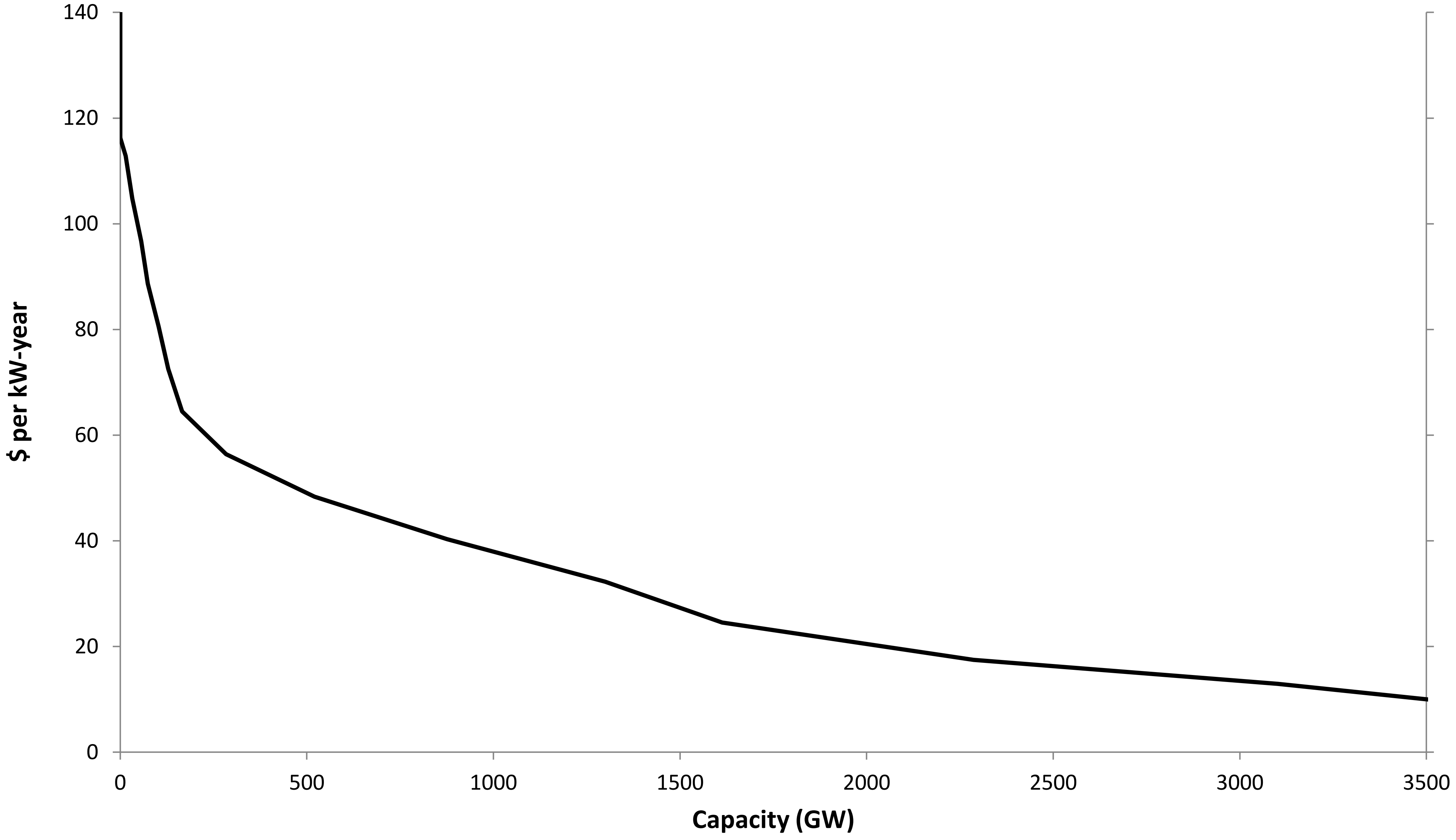
- When solar is “out of the money”, capacity mix of coal, NGCC, and GT reflects current baseline (stylized model omits existing hydro, nuclear)
- As costs decline, model depicts a series of snapshots showing “optimal” solar penetration
- Gradual increase in “optimal” capacity levels as costs decline indicates gradual decrease in marginal value
- Rest of the system (including transmission, not shown) adapts to solar penetration

US Generation Mix as a function of Solar PV cost

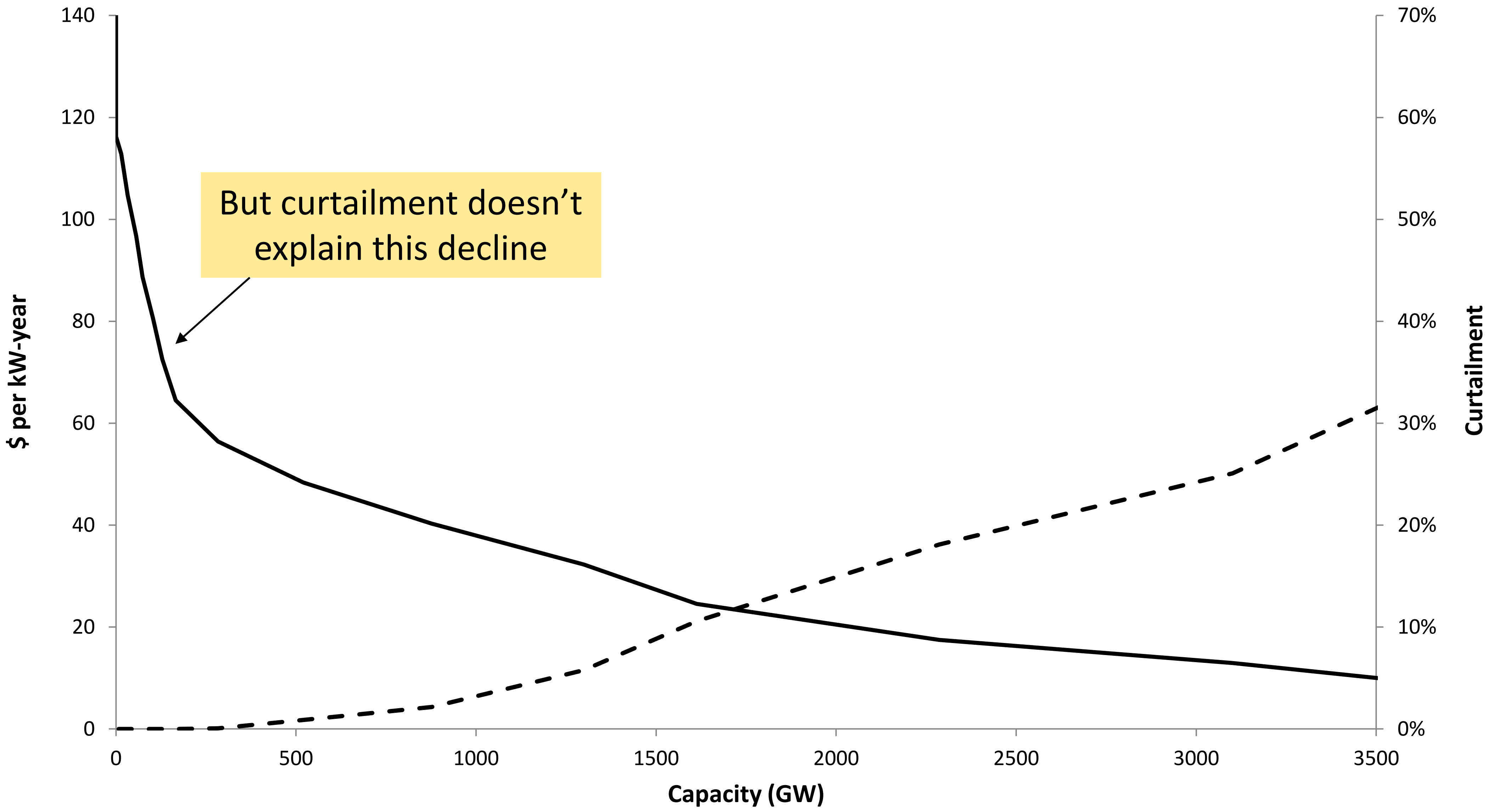


- Even with increasing storage, significant curtailment remains at high penetration levels
- Declining marginal value for storage → additional capacity additions to reduce curtailment are not worth it

Marginal Value of Solar PV

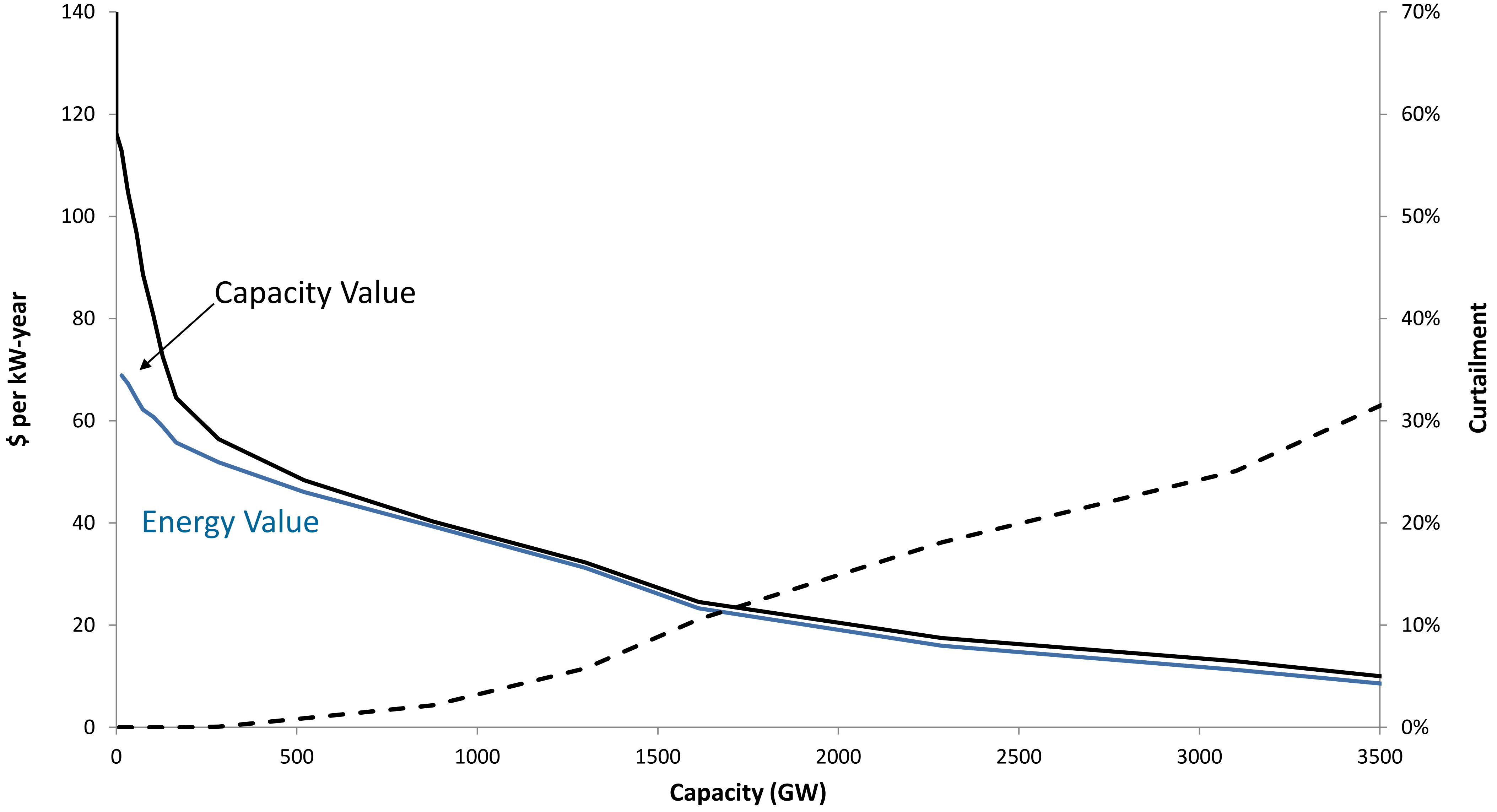


Curtailment increases with penetration

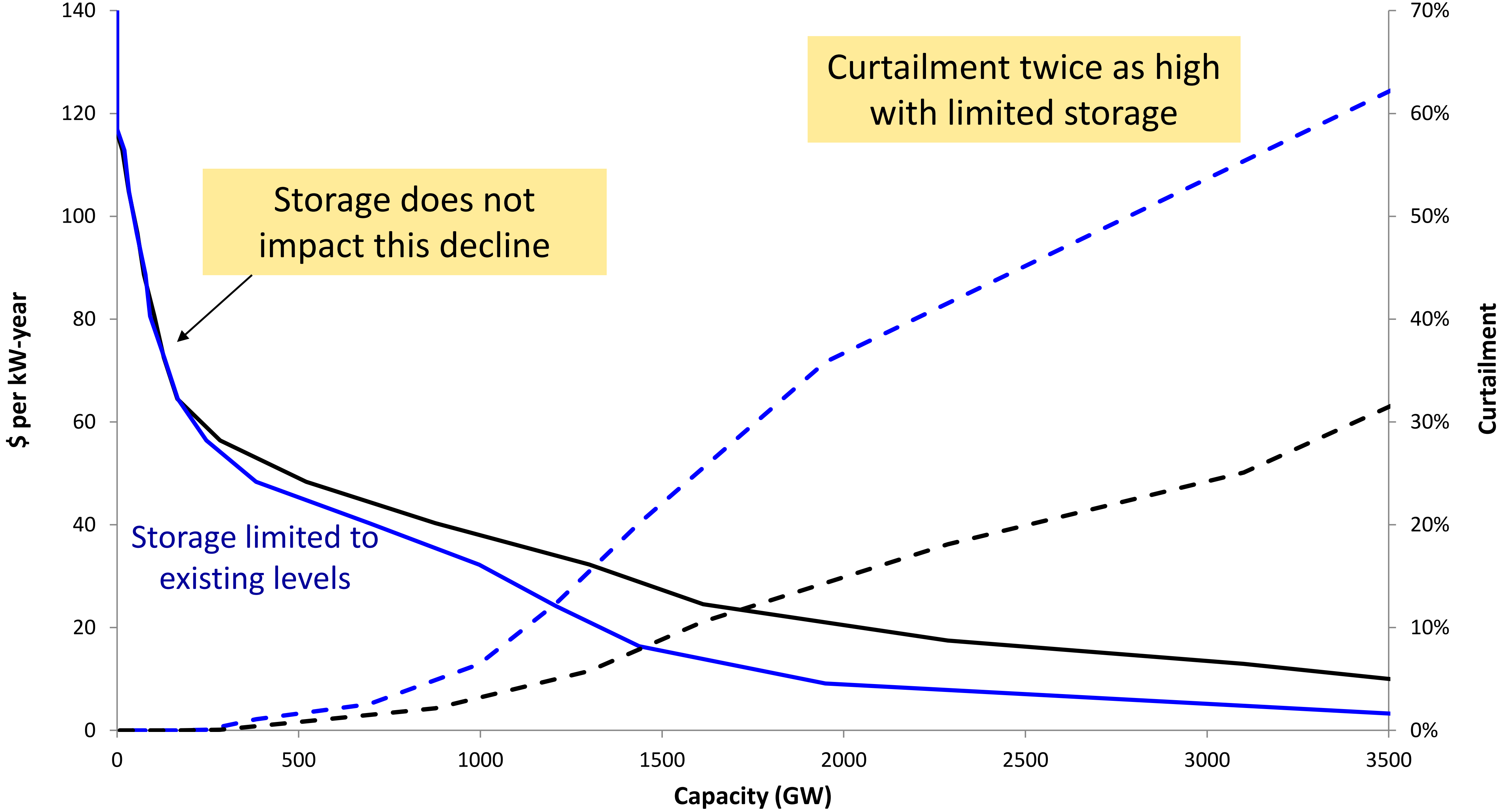


But curtailment doesn't explain this decline

Value of solar profile declines rapidly as peak shifts to night



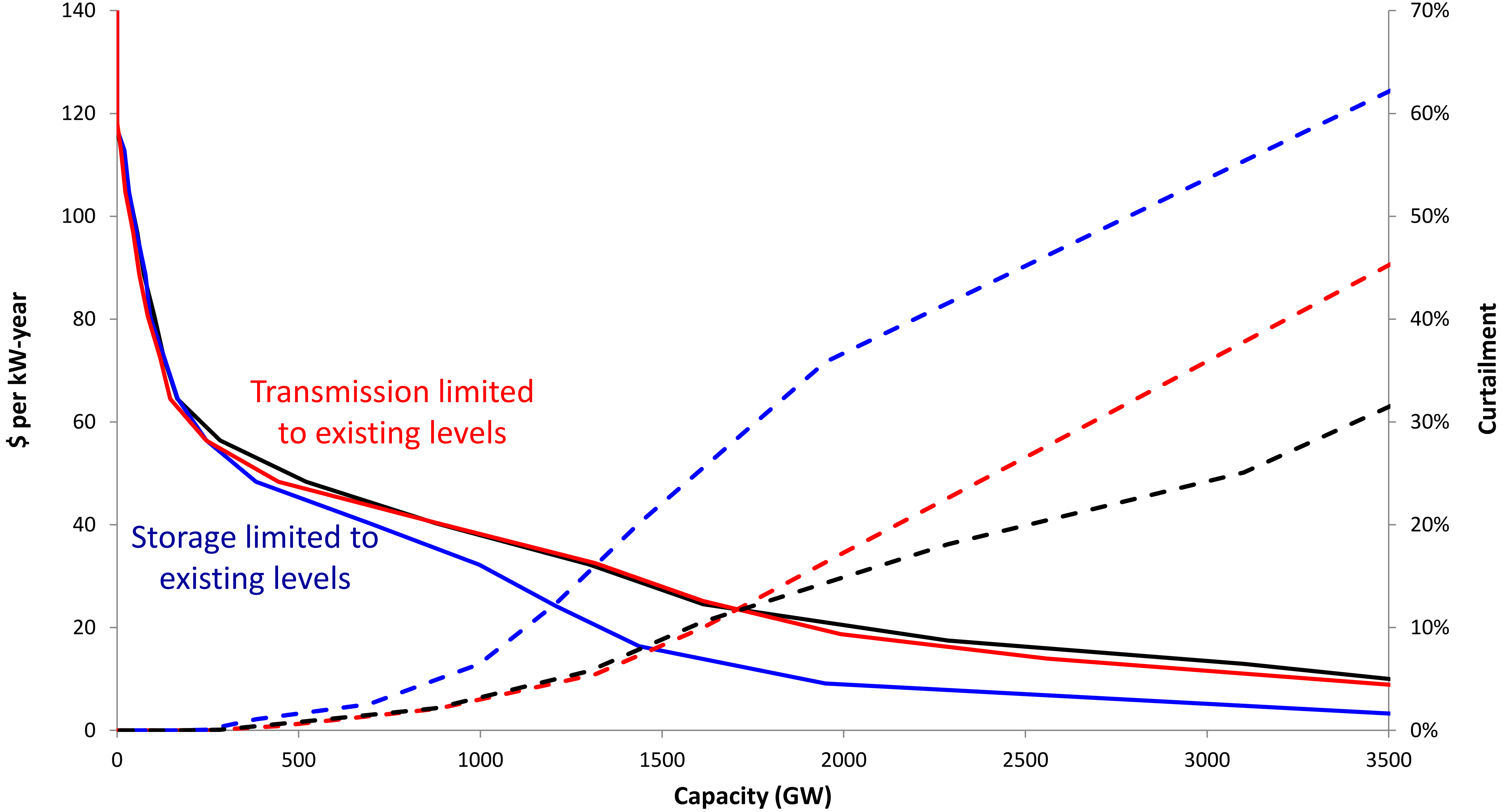
Value of solar is less if storage cannot be expanded



Storage does not impact this decline

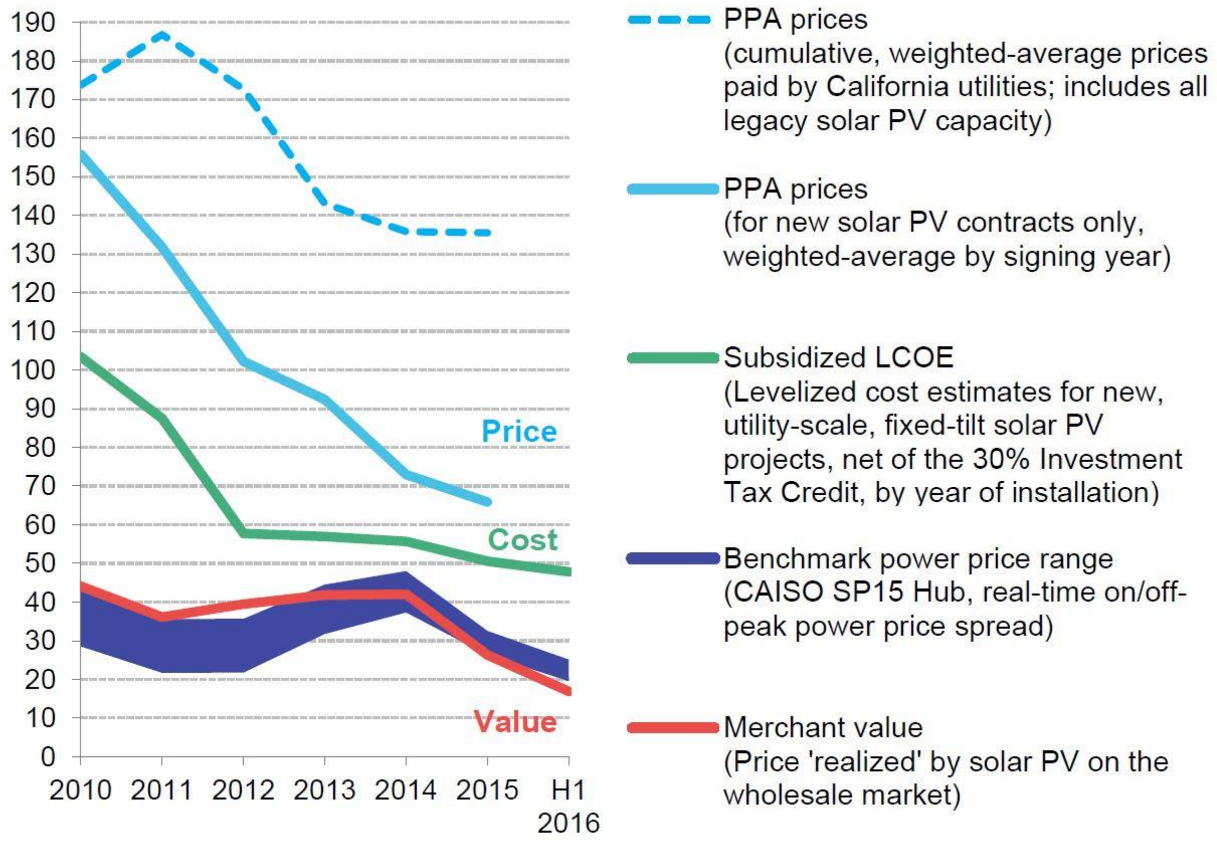
Curtailment twice as high with limited storage

Limiting transmission to existing levels has smaller effect



Declining value observed in CA market

Figure 1: Merchant value of California solar versus PPA prices and levelized costs ($/MWh – real 2015USD)



Source: Bloomberg New Energy Finance, Bloomberg Terminal functions ISO<GO> and CARNPV Index; *CAISO daily renewables watch, California Public Utilities Commission (CPUC), California Energy Commission (CEC), FERC, Federal Reserve* *Click here for underlying data*

Takeaway Messages

- Initial capacity value of solar profile is significant, but ***vanishes*** in most regions as installed solar capacity hits ~30% of peak load (~10% of energy) (region-dependent)
- After this threshold, value declines more slowly with increased penetration due to both ***quantity*** and ***quality***:
  - Quantity: fewer hours of production due to curtailment
  - Quality: lower value of solar production hours
- Storage can't overcome the first effect, but it can (partially) counteract the second; transmission has smaller effect
- Value of solar would be lower with unit commitment constraints

Together…Shaping the Future of Electricity

NATIONAL RENEWABLE ENERGY LABORATORY

Strategies for Retaining the Value of PV at High Penetration: Achieving 50% Solar in California

Robert Margolis and Paul Denholm
Presented at the EPRI-NREL-ASU workshop on
“Retaining the Value of PV at High Penetration”

Washington, DC – October 13, 2016

Outline

- Background on California's Current System
- Defining a Base Scenario
  - Low Storage, Low Flexibility
- Scenarios with Non-Storage Flexibility Options
  - Flexible Generation/Lower Minimum Generation Levels
  - Electricity Exports
  - Demand Response and Shiftable Load
  - Additional Load from Electric Vehicles (EVs)
- Scenarios with Storage
  - Low, Mid, and High Flexibility Cases
- Conclusions

Current (2014) California Generation Mix

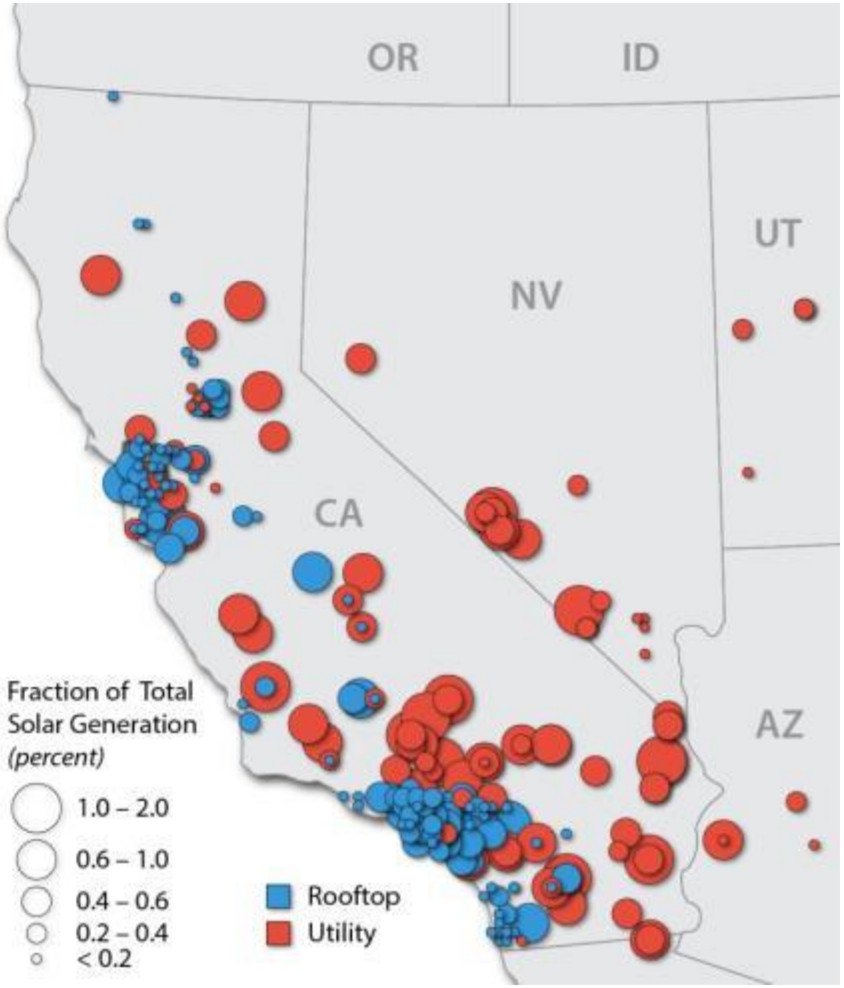
	California Annual Generation in 2014	
	(Gigawatt-hours) GWh	Percentage
Biomass	7,507	2.5%
Concentrating solar power (CSP)	1,619	0.5%
Fossil	151,037	50.0%
Geothermal	13,030	4.3%
Large hydro	16,350	5.4%
Nuclear	25,220	8.4%
PV (rooftop)	5,115	1.7%
PV (utility scale)	10,932	3.6%
Small hydro	2,787	0.9%
Wind	23,913	7.9%
Other (unspecified imports)	44,433	14.7%
Total	**301,943**	**100.0%**

Sources

- Rooftop PV: GTM Research and Solar Energy Industries Association. 2015. *U.S. Solar Market Insight Q2 2015*.
- Other technologies: California Energy Commission. 2014. California electricity statistics and data. http://energyalmanac.ca.gov/electricity/system_power/2014_total_system_power.html. Imports are included in the respective generator category as described in this source.

Creating a 2030 Scenario

- Add enough wind to meet 11% of annual demand.
- Add PV to meet up to 50% of annual demand.
  - 60%/40% mix of utility/rooftop PV
  - Utility-scale PV is 60% tracking, 40% fixed
- Use PV and wind profiles from NREL Low-Carbon Grid Study http://www.nrel.gov/docs/fy16osti/64884.pdf
- Use NREL's Renewable Energy Flexibility (REFlex) model - a reduced form dispatch model - to simulate high-PV scenarios in California.

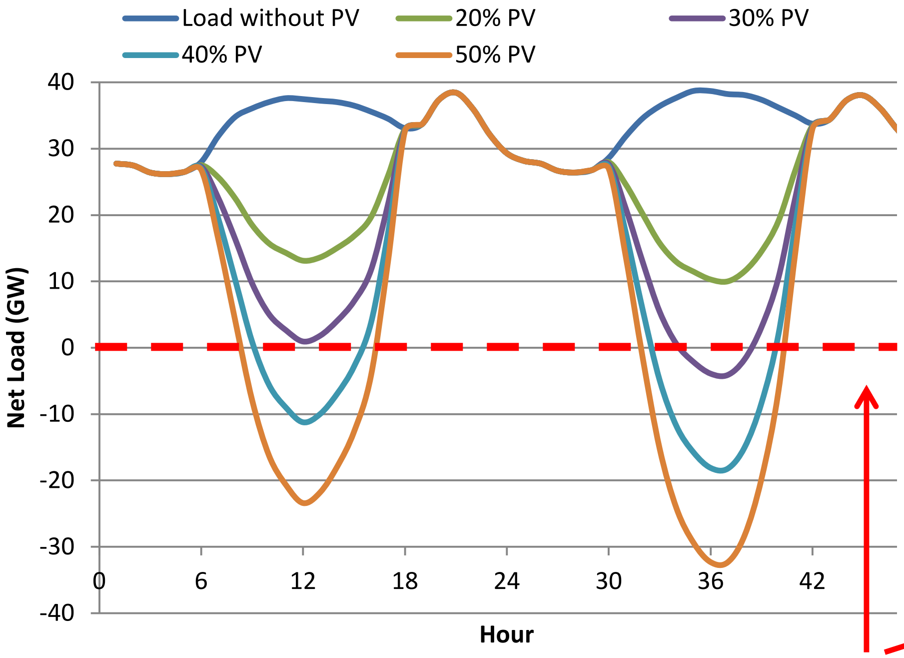


Locations of PV capacity

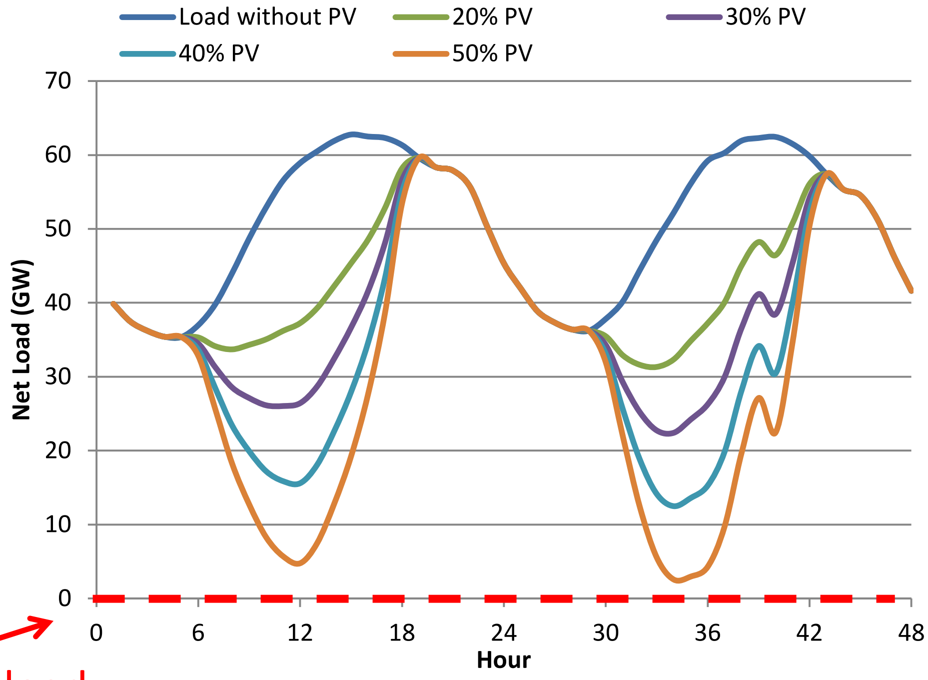
Why is 50% PV Challenging?

- Figures show load and theoretical net load profiles for California during two days in the spring and summer when PV provides up to 50% of annual electricity, assuming no PV curtailment is required.
- Extreme changes in net load are well beyond what can be accommodated in the current power system (net load < 0 for ~2,200 hours per year).
- In remainder of presentation, we explore how 50% PV could be achieved.

Spring (April 9–10)



Summer (July 27–28)



Zero net load

Base Scenario
(Low Flexibility, Low Storage)

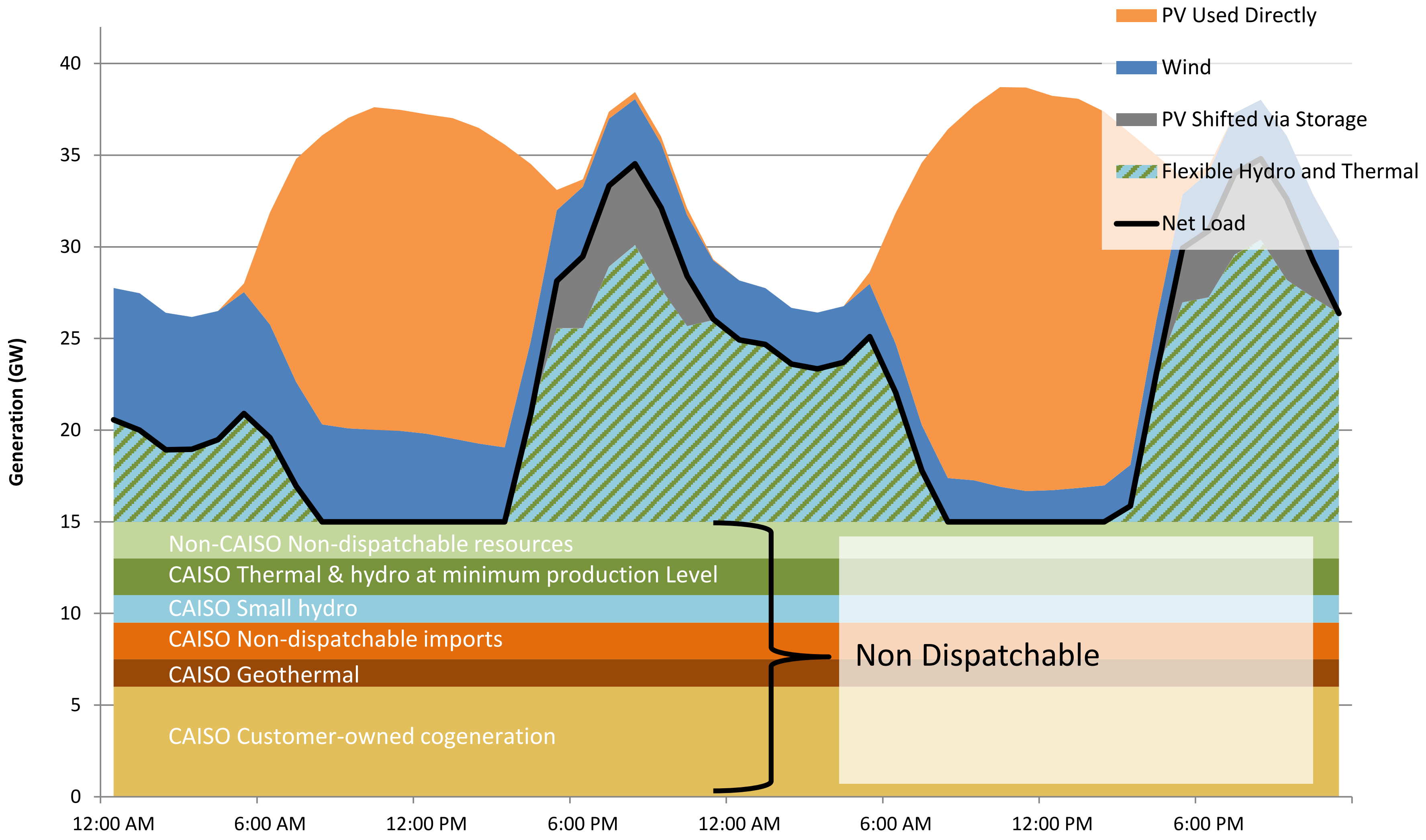
Base Scenario Characteristics

The base scenario assumes limited changes in grid operations between now and in 2030.

- 15-GW minimum generation level on hydro and thermal capacity
- Retirement of Diablo Canyon nuclear plant before 2030
- No new demand response
- No electric vehicles (EVs)
- No exports of solar generation to surrounding states
- No demand shifting
- 4.4 GW of storage (based on existing + mandated new storage in California)
- Load grows to 320 TWh, 64.7 GW peak demand

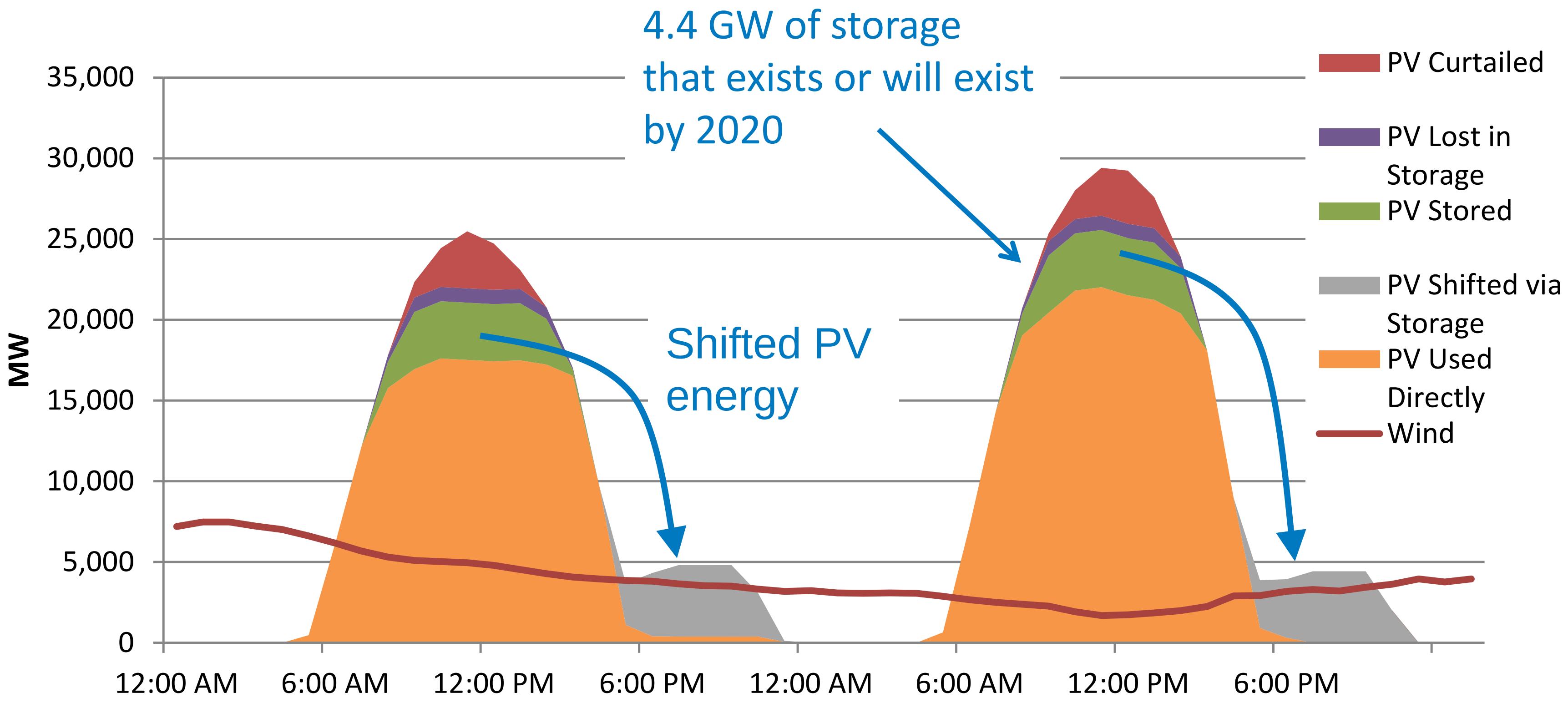
Base Scenario: System Dispatch at 20% PV, April 9–10

Midday wind and solar exceed what can be accommodated at 15-GW minimum generation, resulting in "overgeneration" and curtailment



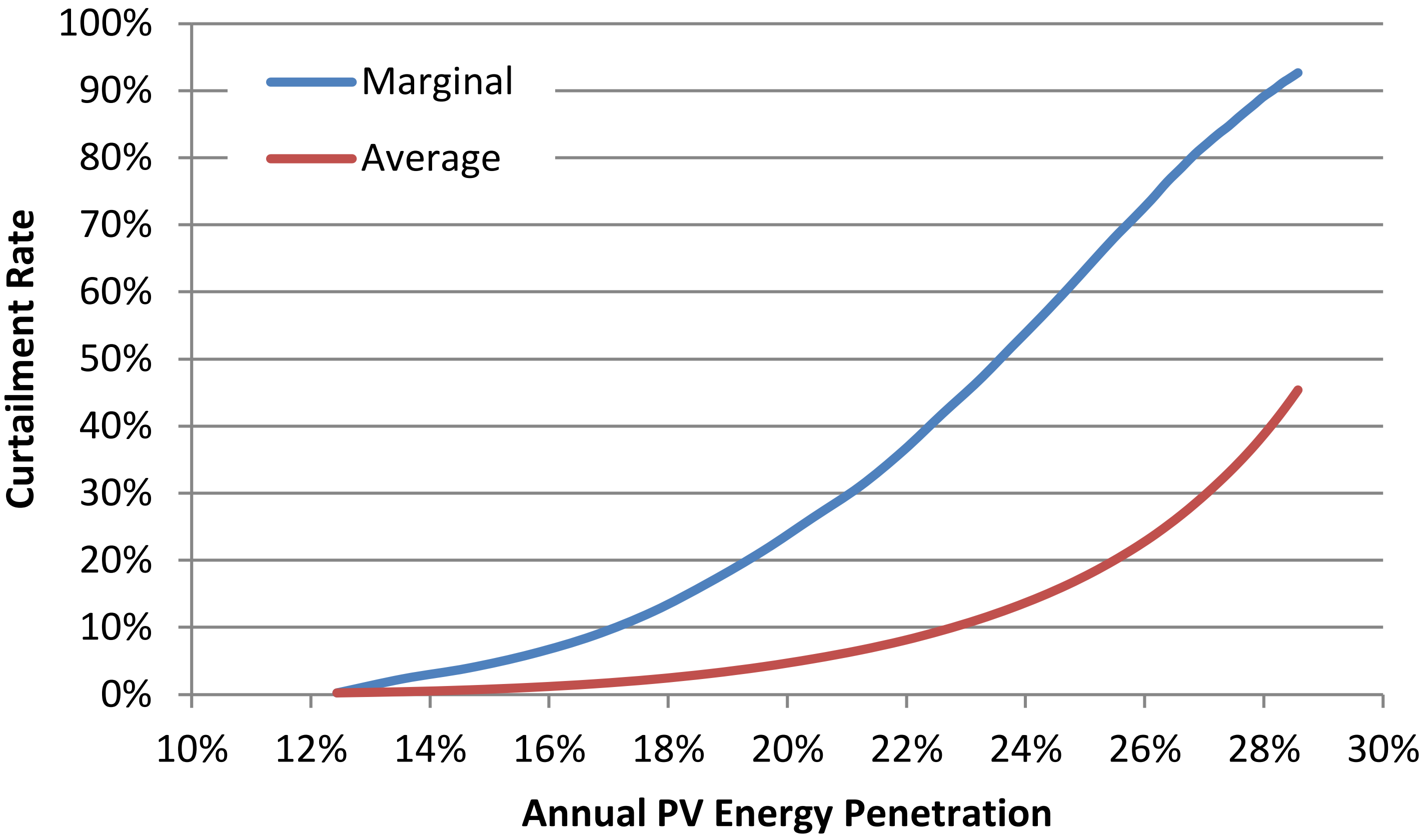
Base Scenario: PV Dispatch at 20% PV, April 9–10

- Existing and projected storage eliminates most curtailment.
- About 5% of potential PV is curtailed annually, including storage losses.



Base Scenario: Curtailment Rate at Various PV Levels

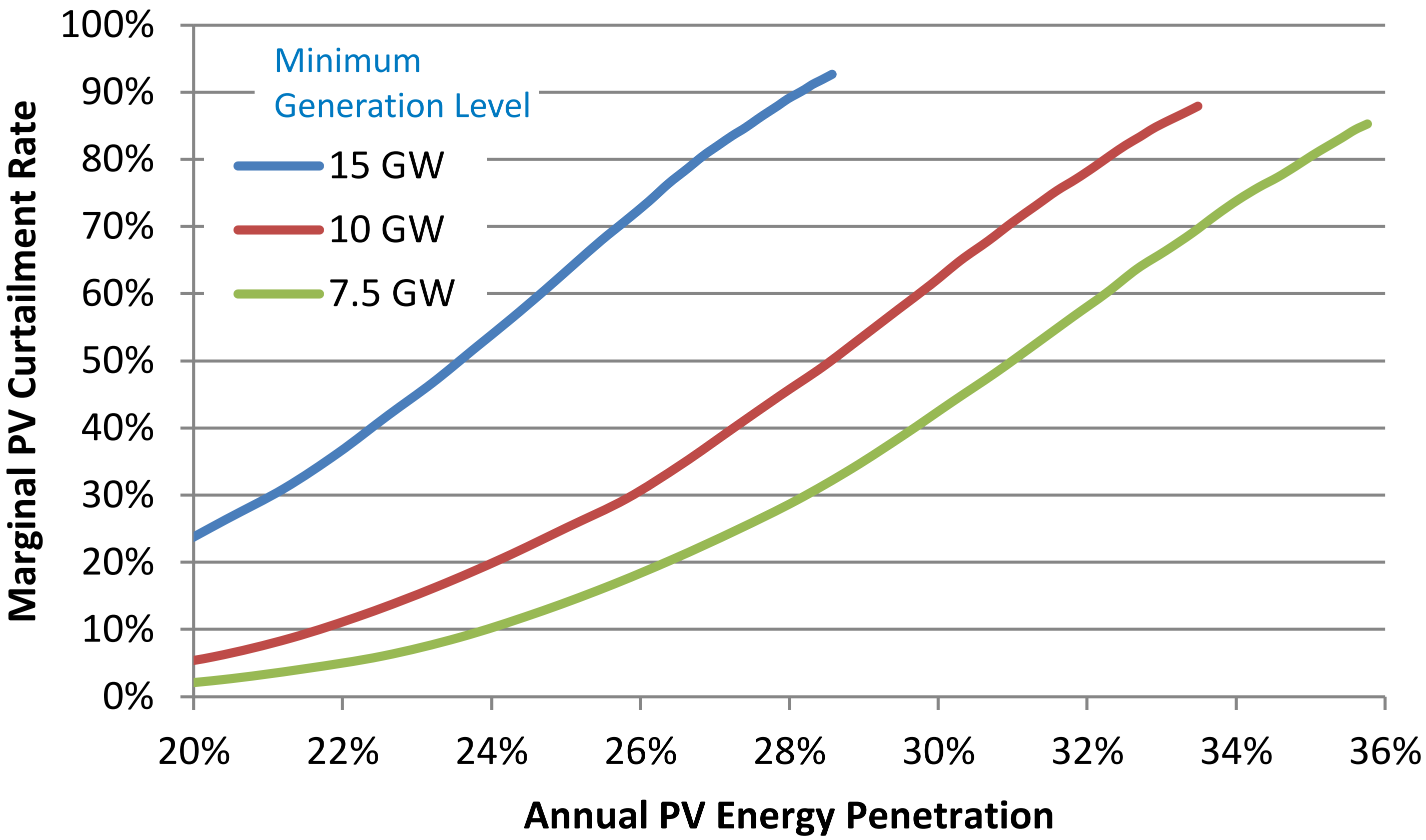
- Marginal curtailment rates can indicate the threshold at which PV becomes uncompetitive with alternative resources.
- Under the base scenario, PV's marginal curtailment rate increases rapidly once PV penetration rises above 20%.



Scenarios with Non-Storage Flexibility Options

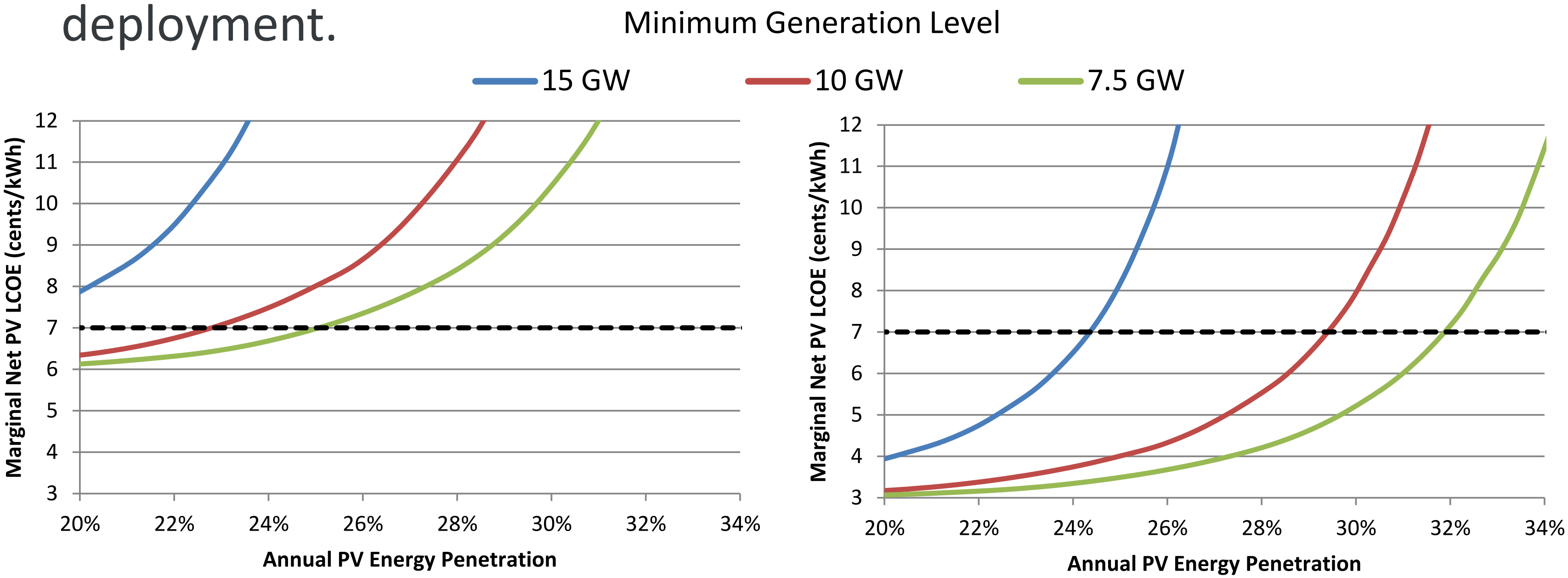
Flexible Generation: Curtailment Rate at Various PV Levels

- Base minimum-generation level is 15 GW.
- Both reduced minimum-generation scenarios (10 GW and 7.5 GW) substantially reduce marginal curtailment rates.



Flexible Generation: Net PV LCOE at Various PV Levels

- At the lowest minimum generation, PV with a base LCOE of 6 cents/kWh achieves a marginal net LCOE of 7 cents/kWh dashed line, which is comparable to variable costs of a future combined-cycle gas generator) at greater than 25% PV penetration.
- However, even with a base LCOE of 3 cents/kWh and high flexibility, the marginal net LCOE of PV increases rapidly beyond 35% PV penetration, so additional measures likely are needed to enable such deployment.

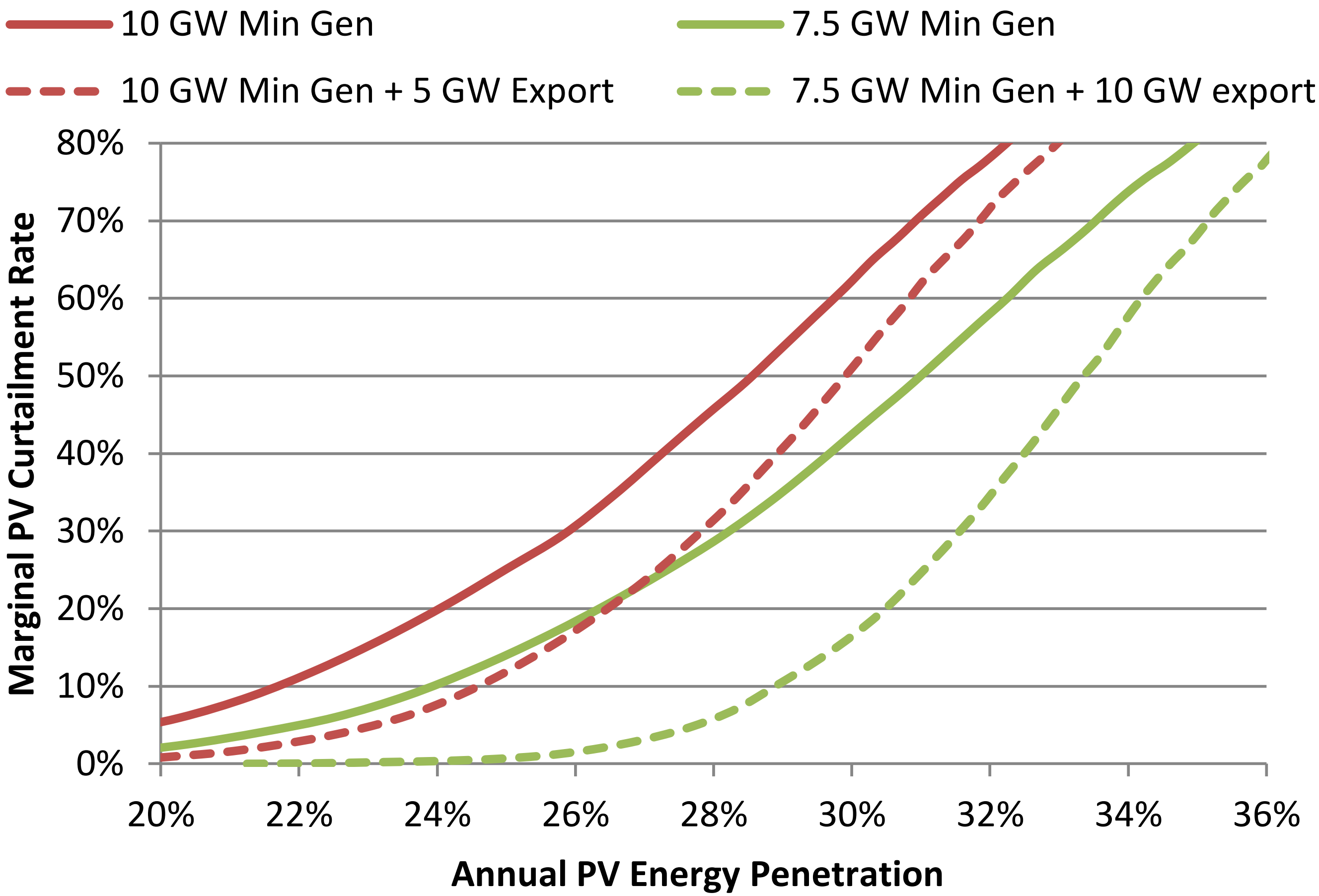


6 cents/kWh base PV LCOE

3 cents/kWh base PV LCOE

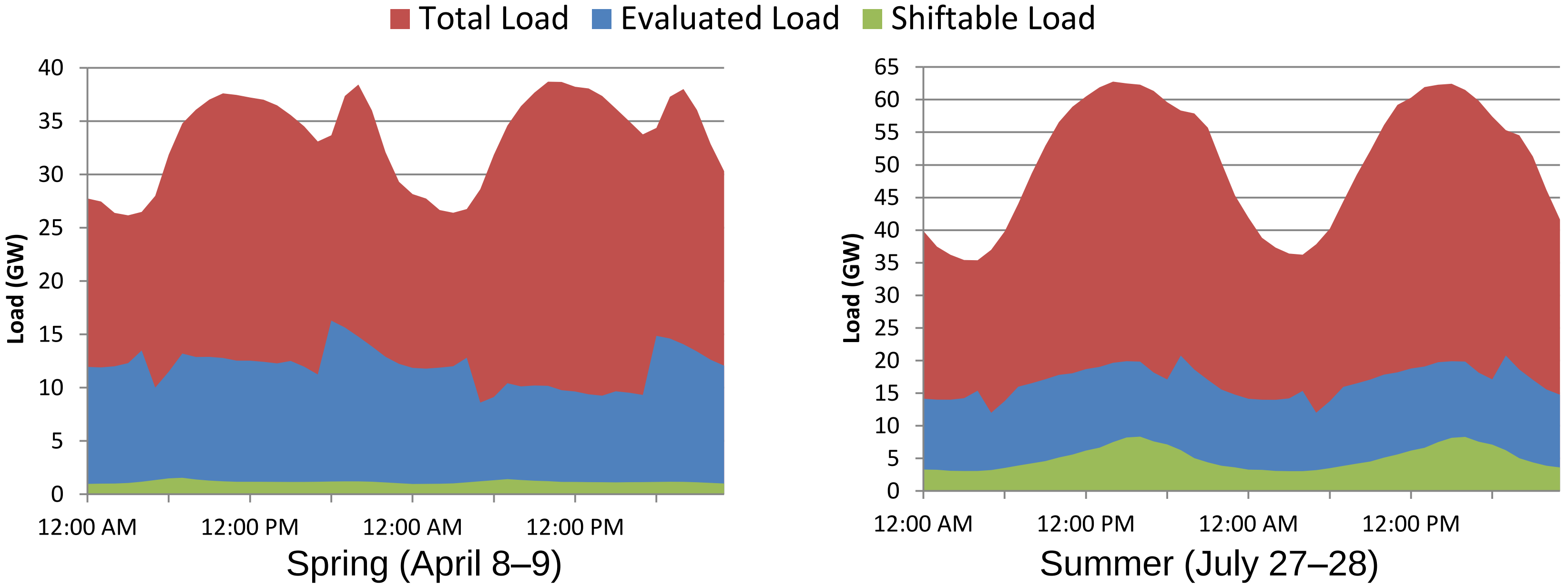
Increased Exports: Curtailment Rate at Various PV Levels

We assume exports from California to neighboring states do not count toward in-state generation. Thus, each gigawatt of export capacity is less effective at shifting the curtailment curves than each gigawatt of minimum generation reduction.



Demand Response Availability

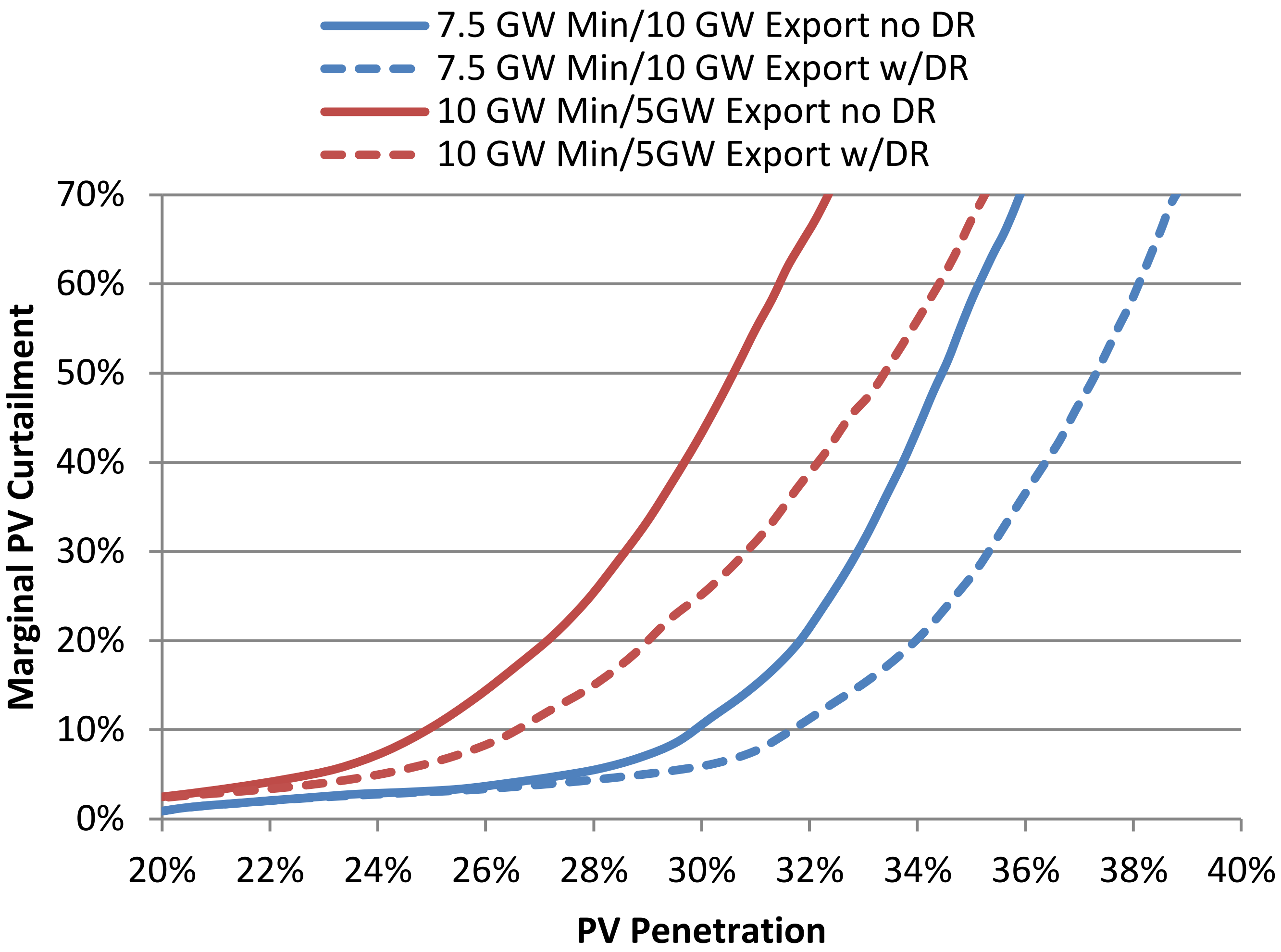
- The ability to shift load varies hourly, daily, and seasonally.
- We use demand-shifting assessments from the Lawrence Berkeley National Laboratory (LBNL) and the Oak Ridge National Laboratory (ORNL).
- Both assessments show relatively little ability to shift loads during the spring, when curtailment is highest.
- Only a fraction of existing loads is evaluated; future work could consider the full potential for load shifting and fuel switching.



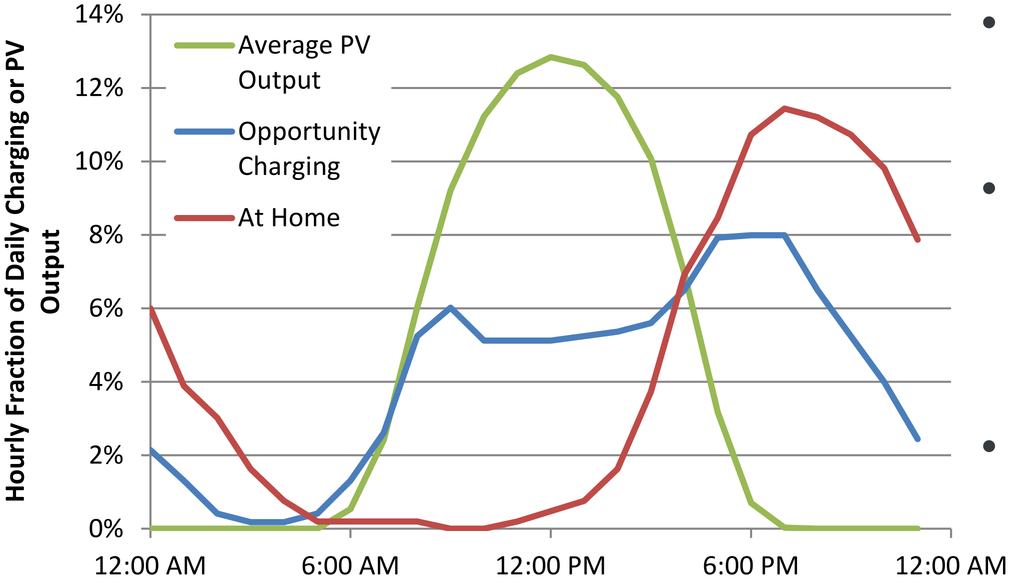
Load-reduction potential in the LBNL technical potential resource data set.

Demand Response: Curtailment Rate at Various PV Levels

Adding demand response shifts the curtailment curves by as much as about two percentage points.

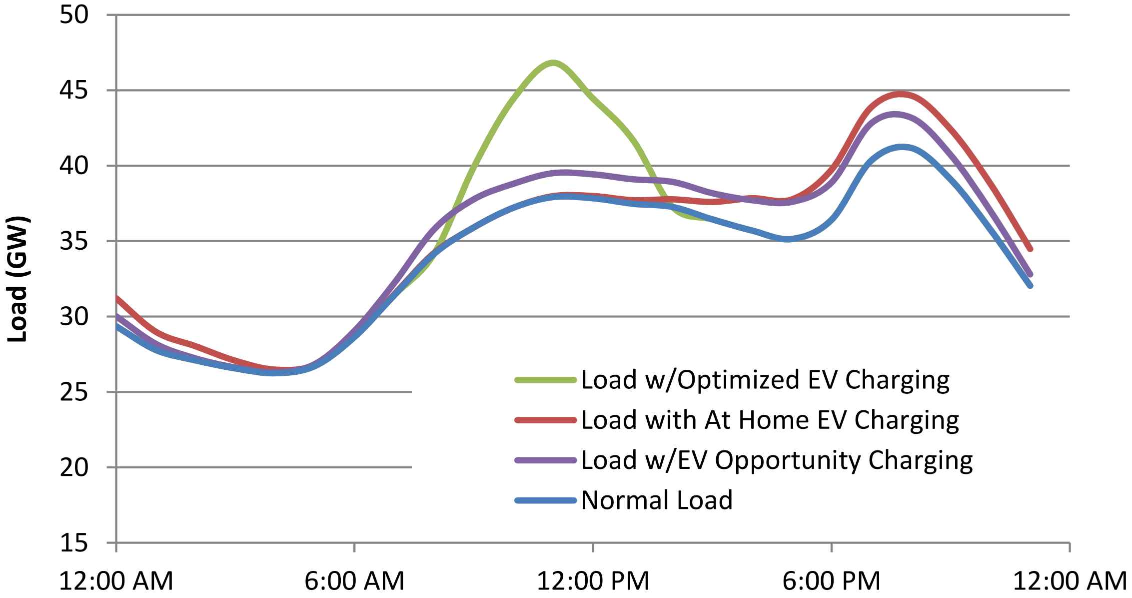


Electric Vehicles: Load Profiles Depend on Charging Pattern



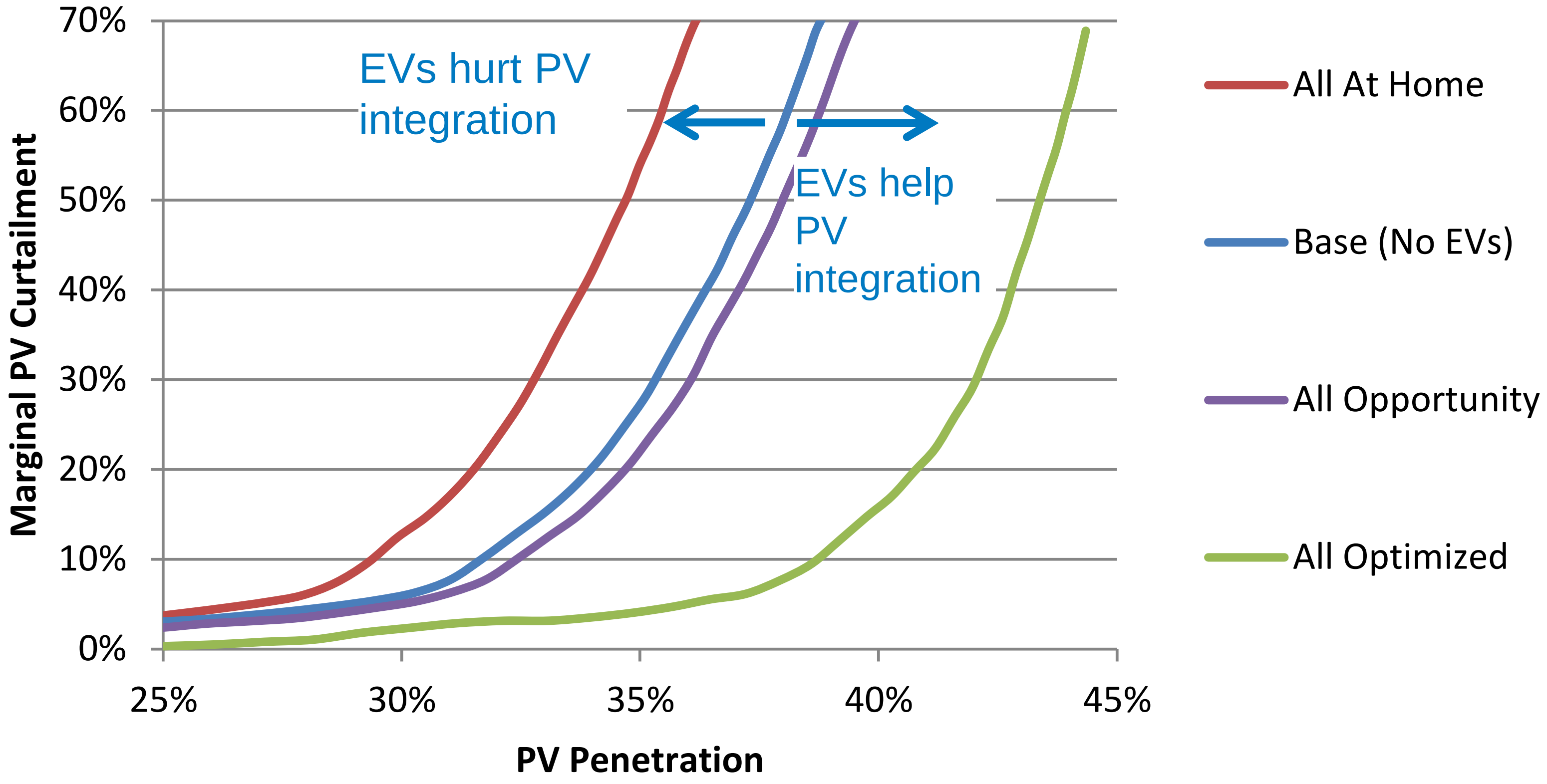
- We assume vehicles require 12.1 kWh/day (35.4 miles/day and 0.34 kWh/mile)
- Opportunity charging (blue line at left) is better for integrating PV, with about half of the demand occurring during periods of significant PV output (green line).
- But, peak charging demand occurs in early evening when PV output is declining rapidly.

- Optimization aligns EV charging load with high PV generation (green line at right) better than opportunity (purple line) or at-home (red line) charging.
- Scenario shown assumes 10% EV penetration on April 1.



Electric Vehicles: Impact of 25% EV Penetration on PV Curtailment

- We assume 6.4 million EVs (25% penetration), a 7.5-GW minimum-generation level, 10-GW export capacity, and full demand response availability.
- Optimized and opportunity charging help PV integration, whereas at-home charging hurts PV integration.



Energy Storage Scenarios

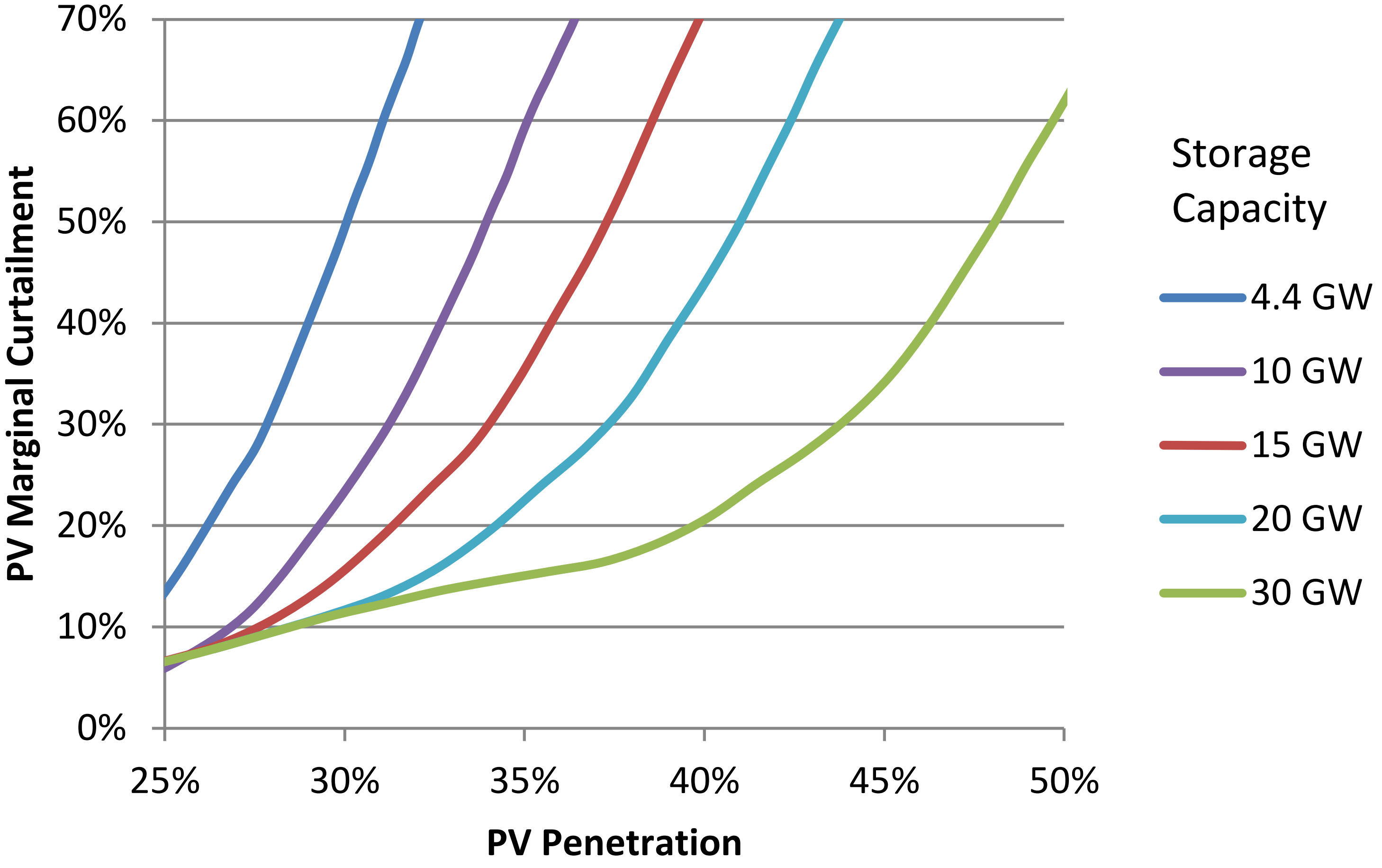
Energy Storage Scenarios Evaluated

	Low Flexibility	Mid Flexibility	High Flexibility
Minimum generation level (GW)	10	8.75	7.5
Export capacity (GW)	2.5	5	10
Demand response availability (GW peak/avg. daily GWh)[a]	0.4/2.2	2/10	4/21
EV penetration (% of California light-duty vehicles)	5%	15%	25%
EV charging profile (optimized-opportunity-at home)	33%-33%-33%	50%-25%-25%	75%-15%-10%

[a] These values represent the peak and average shiftable load during months of highest PV curtailment (March–May), with the high-flexibility scenario using the full LBNL technical potential, which assumes about 2% of the average daily demand is shiftable.

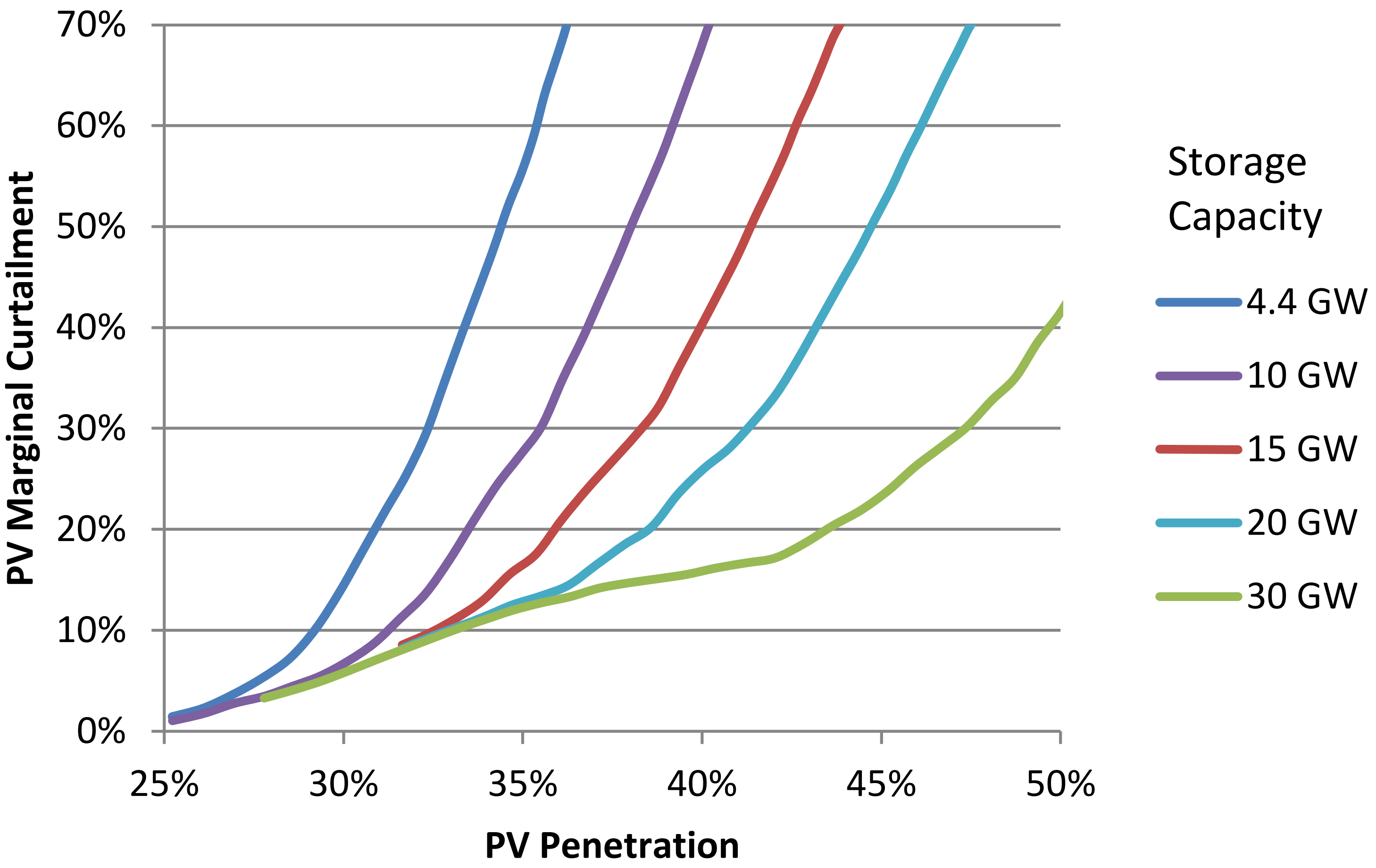
Low Flexibility: Curtailment Rate at Various PV Levels

Thirty (30) GW of storage and low flexibility result in marginal curtailment exceeding 60% at 50% PV.



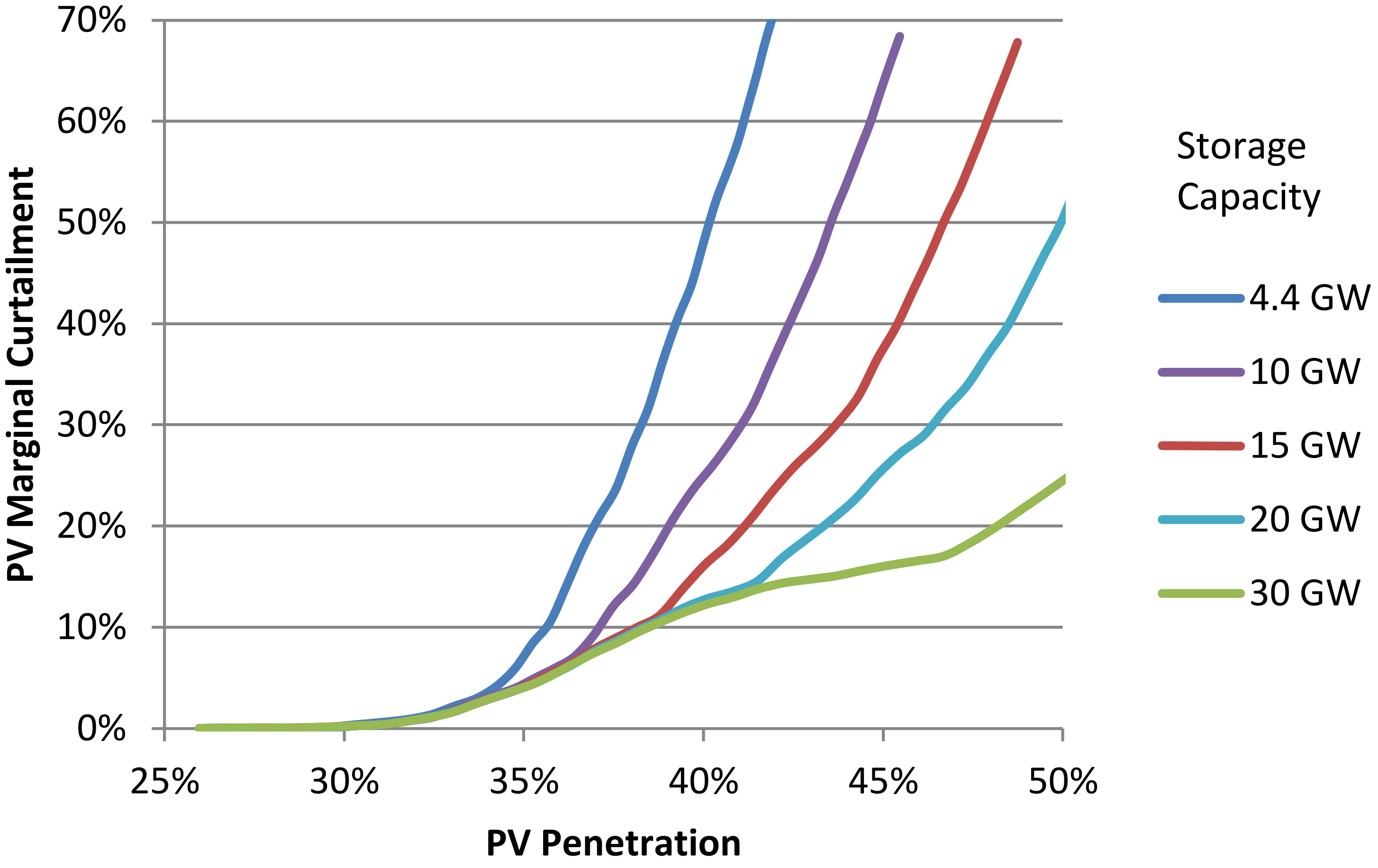
Mid Flexibility: Curtailment Rate at Various PV Levels

With 50% PV penetration and 30 GW of storage, the marginal curtailment rate drops to about 40%.



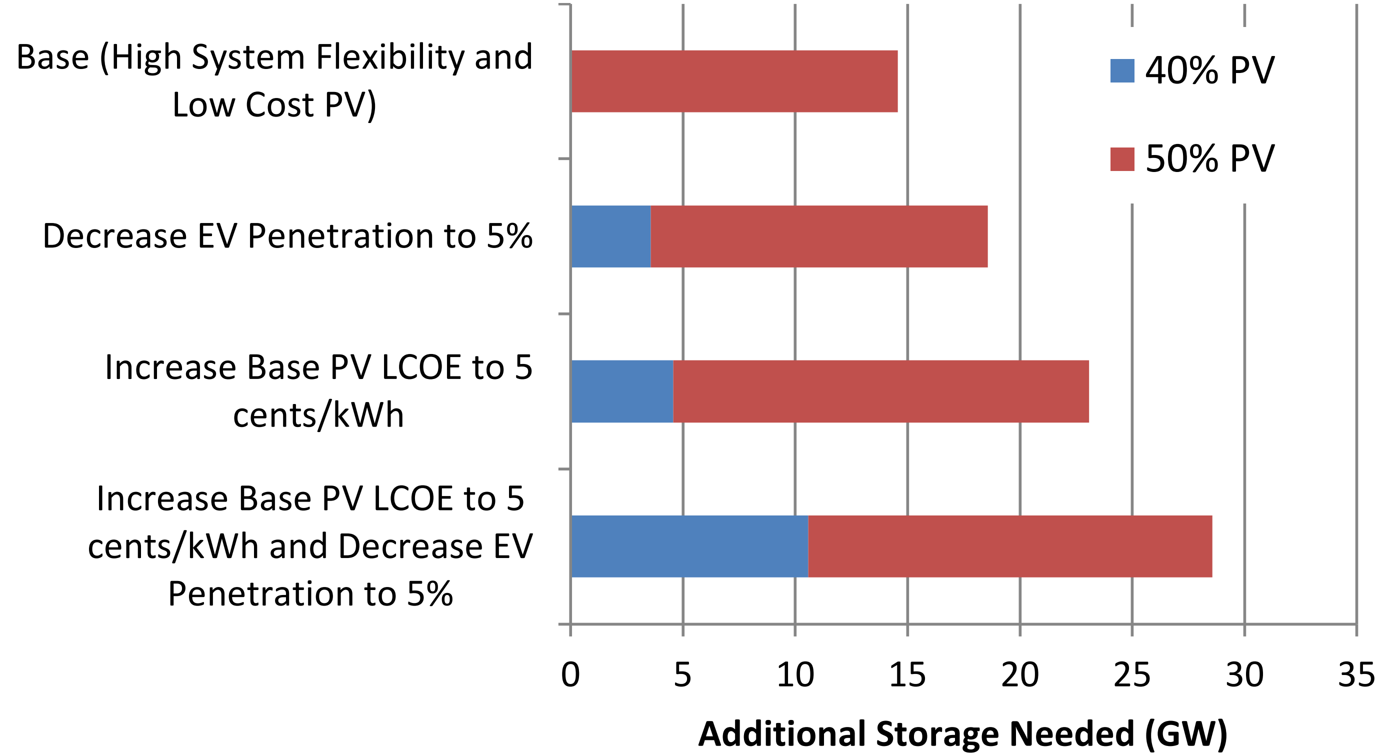
High Flexibility: Curtailment Rate at Various PV Levels

With 50% PV penetration and 30 GW of storage, the marginal curtailment rate approaches 20%.



High-Flexibility Scenario: Storage Sensitivity Analysis

- In the high-flexibility scenario with base PV cost of 3 cents/kWh, about 15 GW of additional energy storage are required to achieve 50% PV at a marginal net PV LCOE of 7 cents/kWh (top bar).
- Decreasing EV penetration, increasing the base PV cost, or doing both increases the additional storage requirements (other bars).
- Achieving only 40% PV penetration reduces the storage requirements substantially.



Conclusions

- **California would require at least 19 GW of total storage to support 50% PV at a marginal net PV LCOE comparable to projected variable costs of combined-cycle gas generators.**
  - This includes about 15 GW of new storage beyond the storage that already exists or is planned.
  - It would represent a substantial storage increase—in the entire United States, today's total installed storage capacity is only about 22 GW.
- **The 19 GW of storage requirement for 50% PV depends on very low-cost PV, high EV penetration, and other robust flexibility measures.**
  - Without these measures, total storage requirements can exceed 30 GW.
  - Storage requirements are much lower at 40% PV penetration.
  - Rapidly increasing storage requirements beyond 40% PV suggests the need to examine the feasibility of large-scale energy storage deployment and the optimal mix of low-carbon generation resources (e.g., with CSP, wind).
- **Declining storage costs could make large-scale storage competitive with deployment of new conventional peaking resources.**
  - California currently has about 22 GW of fossil-fueled peaking capacity, 14 GW of which is more than 25 years old.
  - Cost-competitive energy storage might be able to replace much of the retiring fossil-fueled peaking capacity.

Contact: robert.margolis@nrel.gov
Full report available at:
http://www.nrel.gov/docs/fy16osti/66595.pdf

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Method

Modeling High-PV Scenarios in California

- We use NREL's Renewable Energy Flexibility (REFlex) model to simulate high-PV scenarios in California.
    - REFlex is a reduced-form dispatch model that focuses on minimum-generation constraints.
    - It performs chronological dispatch of storage, demand response, and electric vehicle charging.

Net Levelized Cost of Energy (LCOE) is our primary Metric

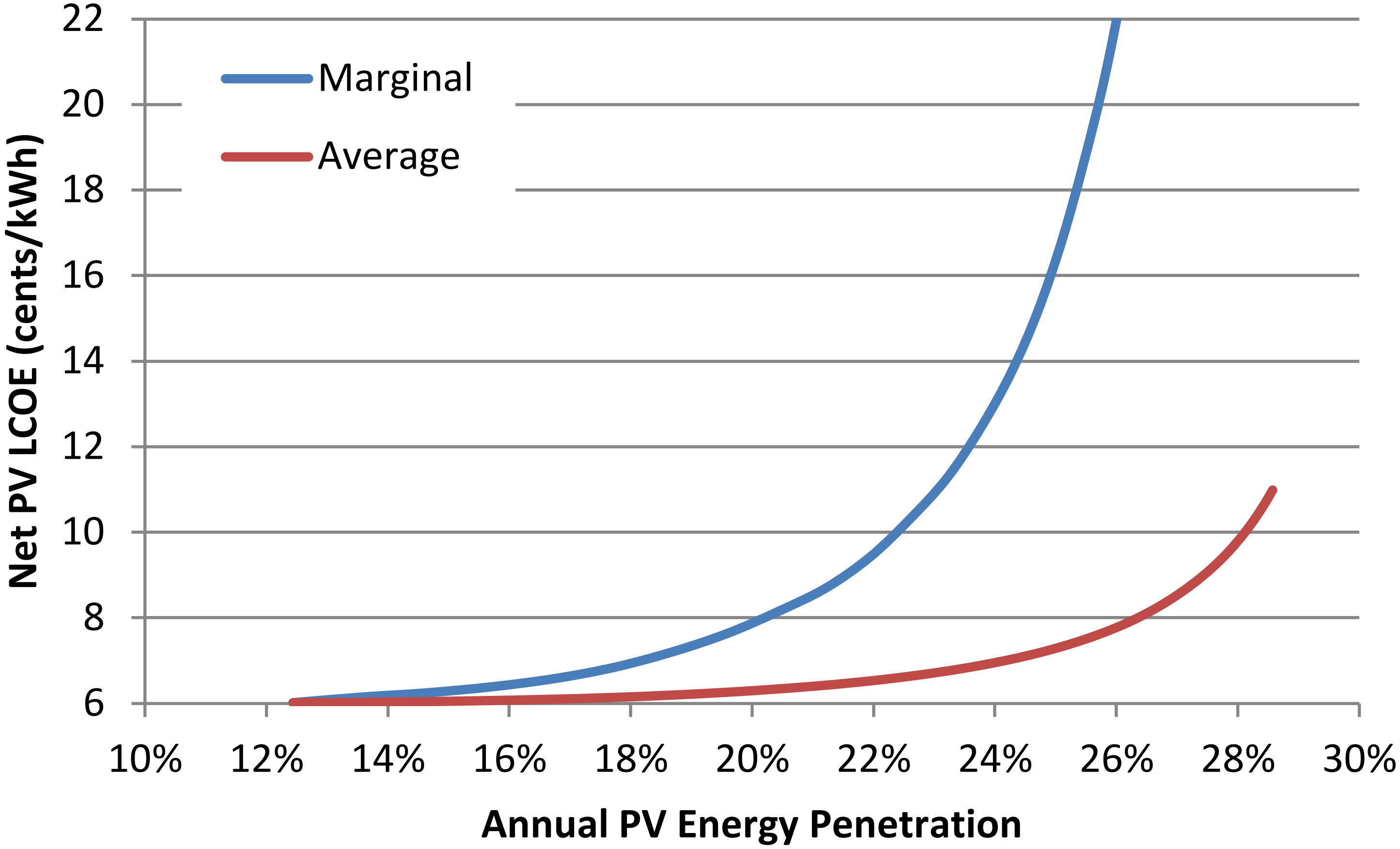
- Net LCOE is the cost of PV energy after considering curtailment and storage losses.
    - Net LCOE = base LCOE/(1 – curtailment rate)
    - Net LCOE does not include the cost of storage, which is largely recovered through providing resource adequacy capacity.
    - Our target net LCOE is the variable cost of a combined-cycle generator in 2030: 7 cents/kWh

Flexibility Options

- Flexible Generation/Lower Minimum Generation Levels
  - Changing long-term contracts with combined heat and power plants and other thermal generators
  - Learning the true costs of frequent thermal plant cycling
  - Incorporating improved forecasting
  - Using curtailed variable generation for reserves
- Electricity Exports
  - Expanding footprint of day-ahead and real-time exports
- Demand Response and Shiftable Load
  - Increasing the number of consumers using real-time pricing, time-of-use pricing, and/or utility-controlled loads
- Additional Load from Electric Vehicles (EVs)
  - Adding EVs to California's fleet and optimizing EV charging

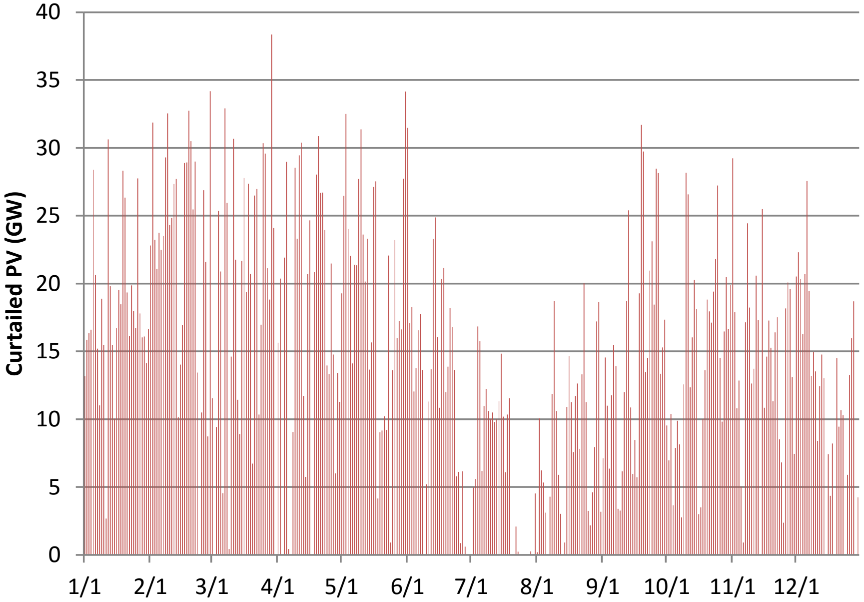
Base Scenario: Net PV LCOE at Various PV Levels

- We calculate net LCOE assuming a base PV LCOE of 6 cents/kWh.
- Reducing the base PV LCOE would help maintain cost competitiveness, but the shape of the marginal curve means even very low-cost PV would require additional grid flexibility to achieve penetrations beyond 25%.

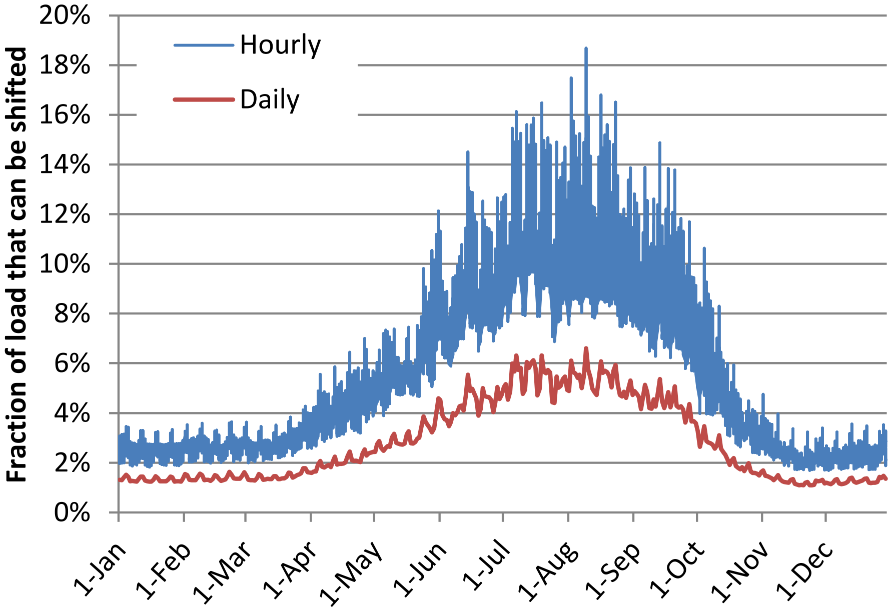


Demand Response: Load-Shifting Potential (LBNL and ORNL Data)

- Load shifting depends on the ability to reduce load during low solar output and increase load during high solar output.
- In a system with 50% PV, curtailments peak in the spring and are low in the summer, largely because this is the period of highest load (left figure).
- Yet load shifting availability peaks in the summer and is low during the spring, when only about 2% of demand is assumed to be shiftable (right figure).
- This mismatch of high-curtailment periods and shiftable-demand periods limits the curtailment-reduction potential of demand response.



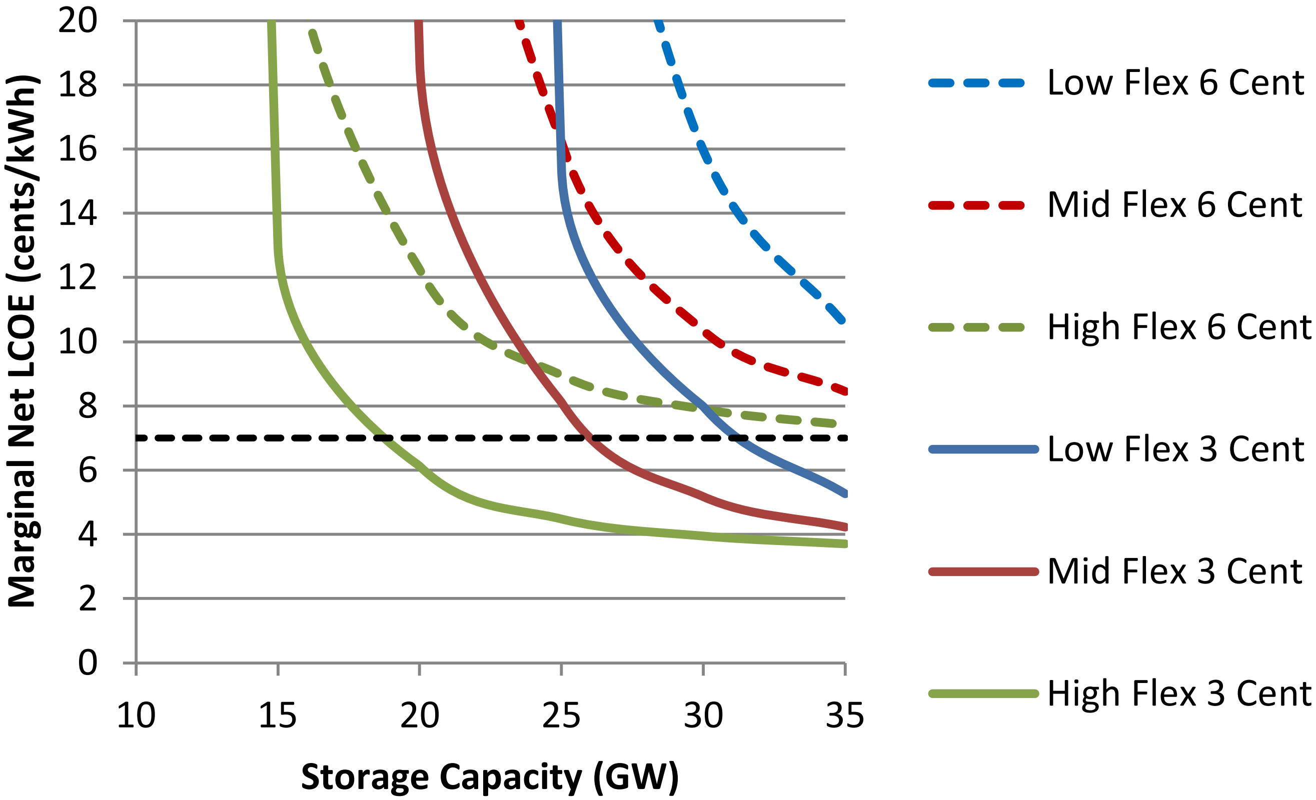
Hourly curtailment in a system with enough PV to achieve 50% PV with a 7.5-GW system minimum-generation level and a 5-GW export capacity



Fraction of total hourly and daily load that can be shifted using the LBNL and ORNL technical potential

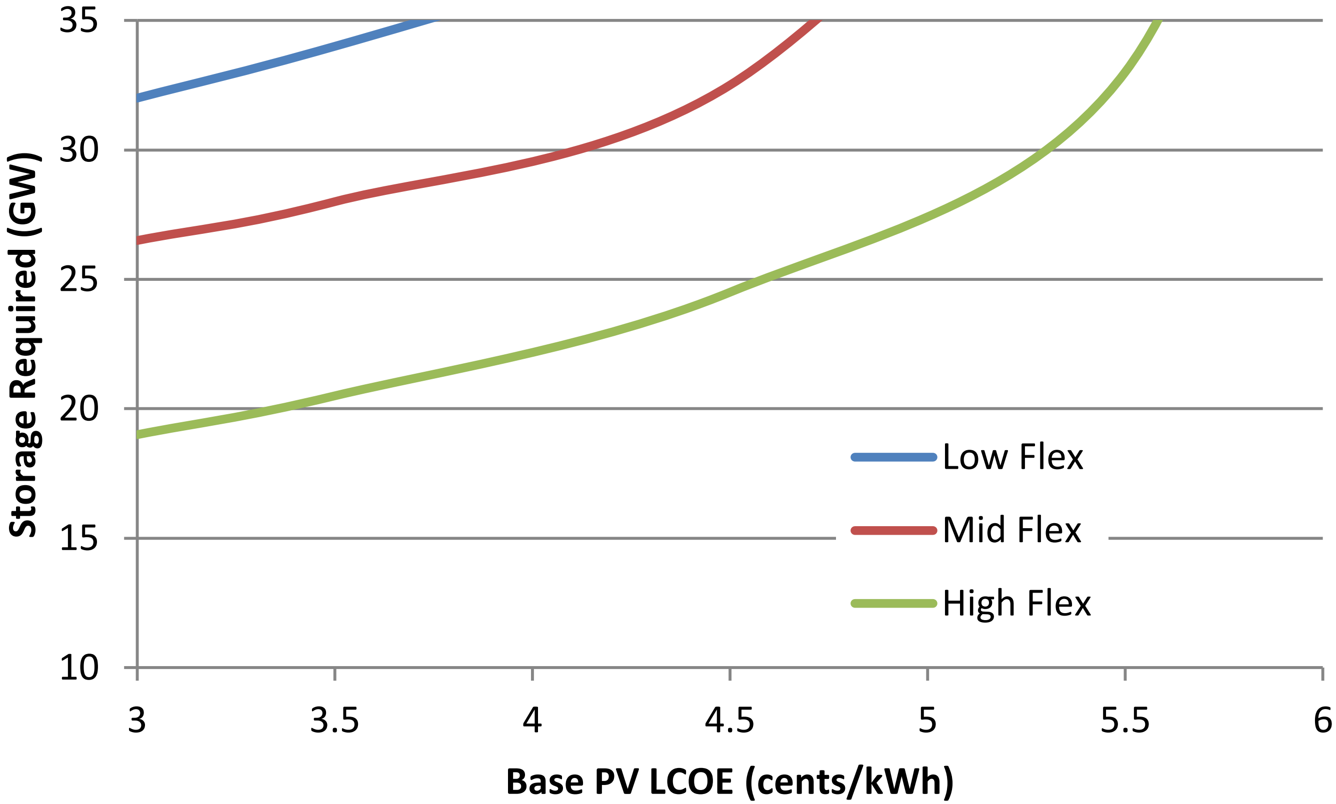
All Scenarios, Two Base PV Costs: Net LCOE at 50% PV

- Dashed marginal net LCOE target line (7 cents/kWh) approximates the variable cost of future combined-cycle gas turbines, including carbon costs.
- With lower-cost PV (3 cents/kWh) and high flexibility, achieving 50% PV with target net LCOE requires about 19 GW of storage.
- With lower-cost PV and less flexibility, reaching 50% PV could require 25–30 GW of storage.



All Scenarios: Storage Required to Achieve 50% PV

- Figure shows energy storage required to achieve a marginal net PV LCOE of 7 cents/kWh as a function of base PV LCOE at 50% PV penetration and three levels of grid flexibility.
- Both grid flexibility and low-cost PV appear critical to reducing storage requirements.



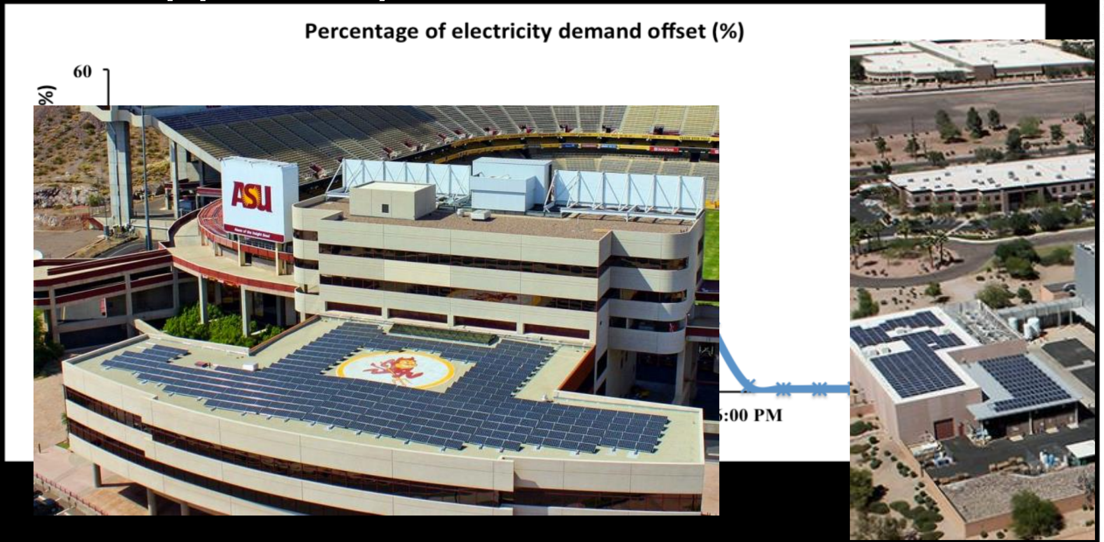
Value of PV in a Location with High Air Conditioning Loads

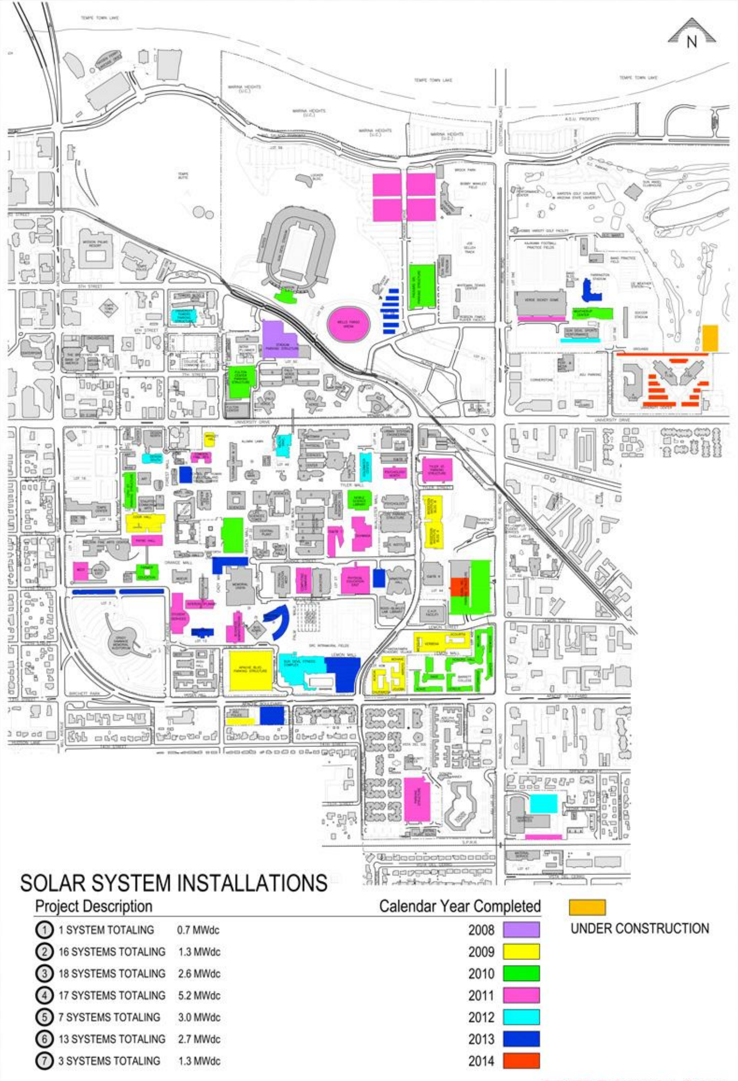
Christiana Honsberg

Arizona State University, Tempe, AZ
QESST Engineering Research Center, Director

sustainability at ASU

- ASU largest research university in US 85,000 students; 20,000 in engineering
- Carbon neutral by 2025
- Rapid installation of solar, in a urban area - reached 50% of total electricity supplied by PV





SOLAR SYSTEM INSTALLATIONS

Project Description		Calendar Year Completed	
① 1 SYSTEM TOTALING	0.7 MWdc	2008	🟪
② 16 SYSTEMS TOTALING	1.3 MWdc	2009	🟨
③ 18 SYSTEMS TOTALING	2.6 MWdc	2010	🟩
④ 17 SYSTEMS TOTALING	5.2 MWdc	2011	🟪
⑤ 7 SYSTEMS TOTALING	3.0 MWdc	2012	🟦
⑥ 13 SYSTEMS TOTALING	2.7 MWdc	2013	🟦
⑦ 3 SYSTEMS TOTALING	1.3 MWdc	2014	🟥

🟧 UNDER CONSTRUCTION

Publication Date: 08.07.2014
File Name: 2014_SOLAR_INSTL_MAP

ASU Arizona State University at the Tempe campus

asu campus metabolism

Campus Metabolism is an interactive web tool that displays real-time energy use on campus.

Total currently being tracked on Campus Metabolism:

New: Renewable Energy Data

Electricity	Heating	Cooling	Renewables
1993.1 kW	1.77 mmBtu / hr	1521.4 tons	590 kW

Total Usage by Percentage:

Renewables not included in total, they reduce usage

- Cooling 68%
- Electricity 25%
- Heating 7%

San Pablo Hall

Compare to other buildings   View campus map

Electricity	Heating	Cooling
108.4 kW	0 mmBtu / hr	20.7 tons

Sustainability on Campus

Congressional tour spotlights ASUs 'green'
Thu, 24 Sep 2009
ASUs commitment to sustainability education and innovation is attracting the interest of leaders across the nation.read more

- Congressional tour spotlights ASUs 'green' effor
- Cheetah preservation inspires sustainable initiat
- Professor wins 2009 Faculty Pioneer Award
- ASU praised for green efforts by national maga
- Pursuit of engineering Ph.D. aided by awards
- Engineering prof lauded as leading innovator
- Professor works toward safer nuclear options

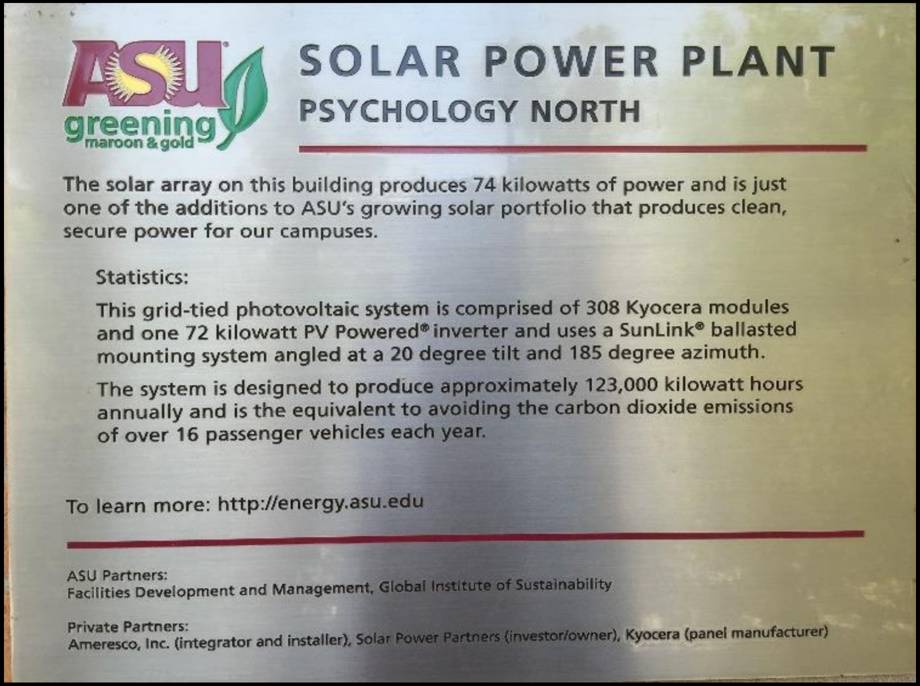
Factoid: The Campus Metabolism is a collaborative project between many departments across the University.

©2008 Arizona State University   Questions, comments, problems? Contact us at: CampusMetabolism@asu.edu   APS energy SERVICES

Thermal energy storage

- Air-conditioning
  - Chillers
    - Pumps
    - Cooling towers
  - Air handler
    - Filter
    - Fan
    - Coiling coil
- Thermal Energy Storag
  - Chilled water system
  - Very low losses

- 77 total solar systems
  - Condensed to 66 in the model
  - 22.5 MW_p – All campuses
  - 40,412,653 kWh in 2015
    - 71% produced on Tempe campus
    - 14% of energy consumed
  - Capacity factors between 20 and 25%
  - energy.asu.edu



greening maroon & gold

SOLAR POWER PLANT

PSYCHOLOGY NORTH

The solar array on this building produces 74 kilowatts of power and is just one of the additions to ASU's growing solar portfolio that produces clean, secure power for our campuses.

Statistics:

This grid-tied photovoltaic system is comprised of 308 Kyocera modules and one 72 kilowatt PV Powered® inverter and uses a SunLink® ballasted mounting system angled at a 20 degree tilt and 185 degree azimuth.

The system is designed to produce approximately 123,000 kilowatt hours annually and is the equivalent to avoiding the carbon dioxide emissions of over 16 passenger vehicles each year.

To learn more: http://energy.asu.edu

ASU Partners:
Facilities Development and Management, Global Institute of Sustainability

Private Partners:
Ameresco, Inc. (integrator and installer), Solar Power Partners (investor/owner), Kyocera (panel manufacturer)

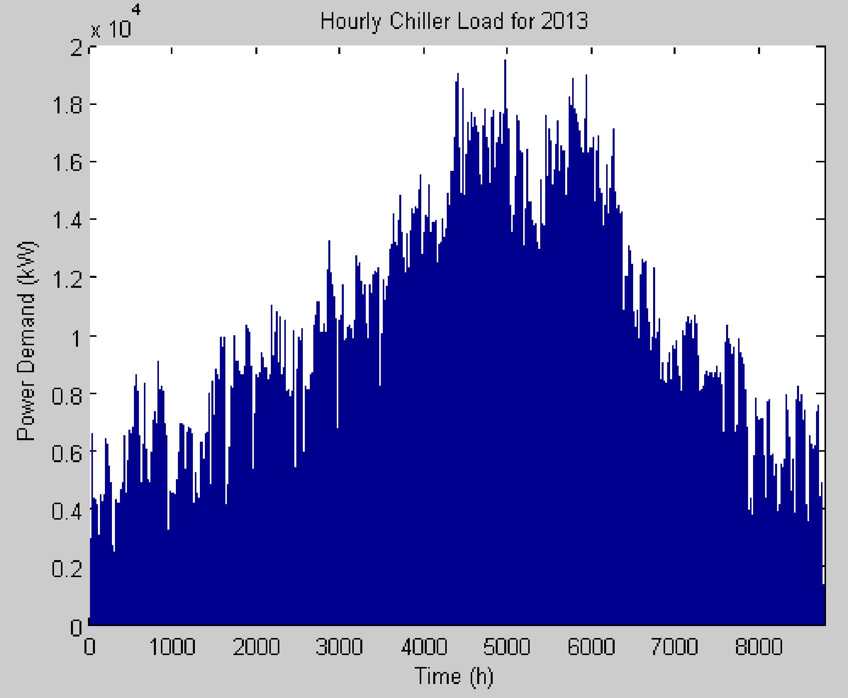
Thermal energy storage and PV

Presently, thermal energy storage charged at night

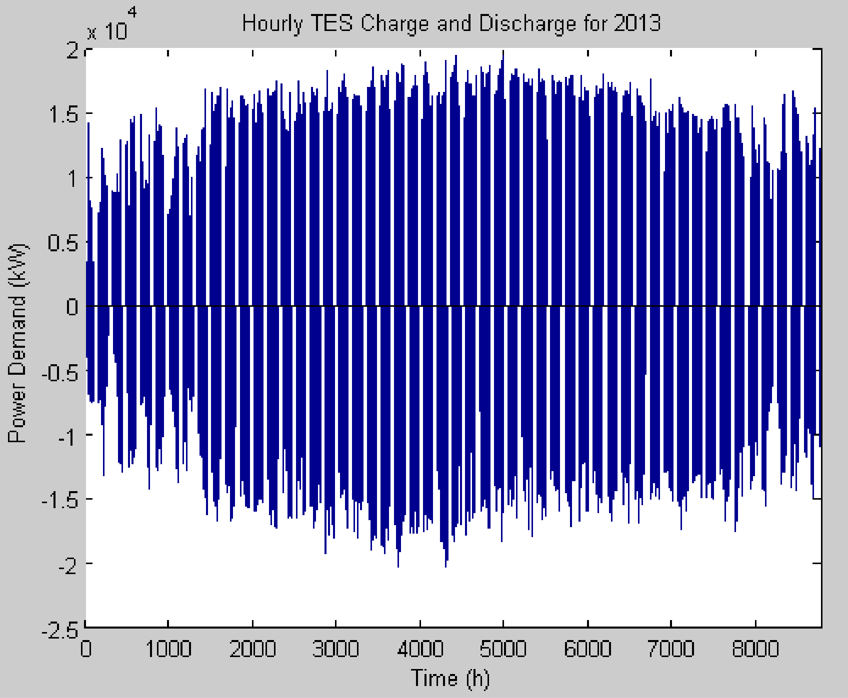
If PV is used to charge the thermal energy storage during the day, what is the maximum penetration with no supply of electricity to grid, no curtailment, no “dumped power”?

Model Details – Chillers

Hourly Chiller Load for 2013

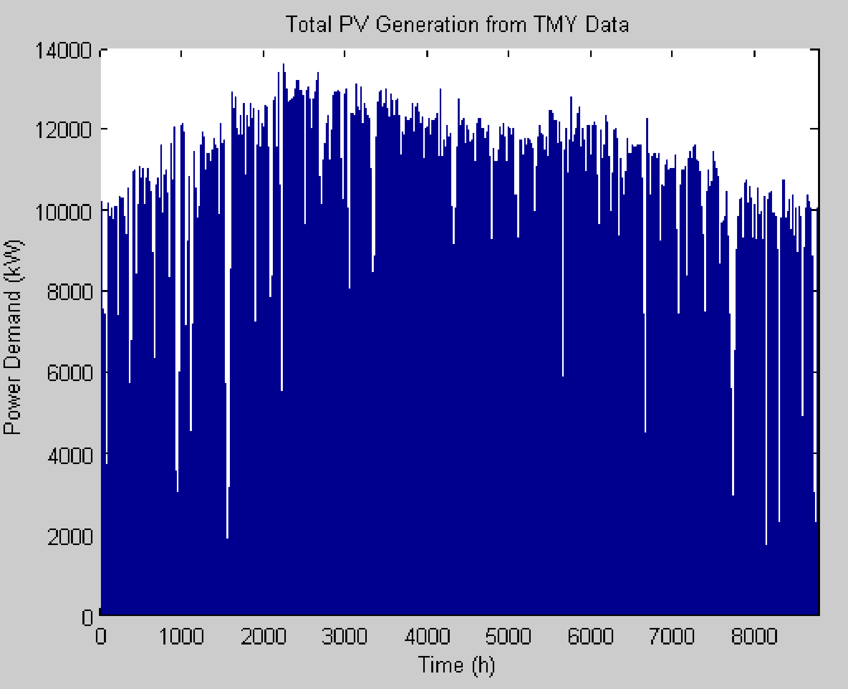


Hourly TES Charge and Discharge for 2013

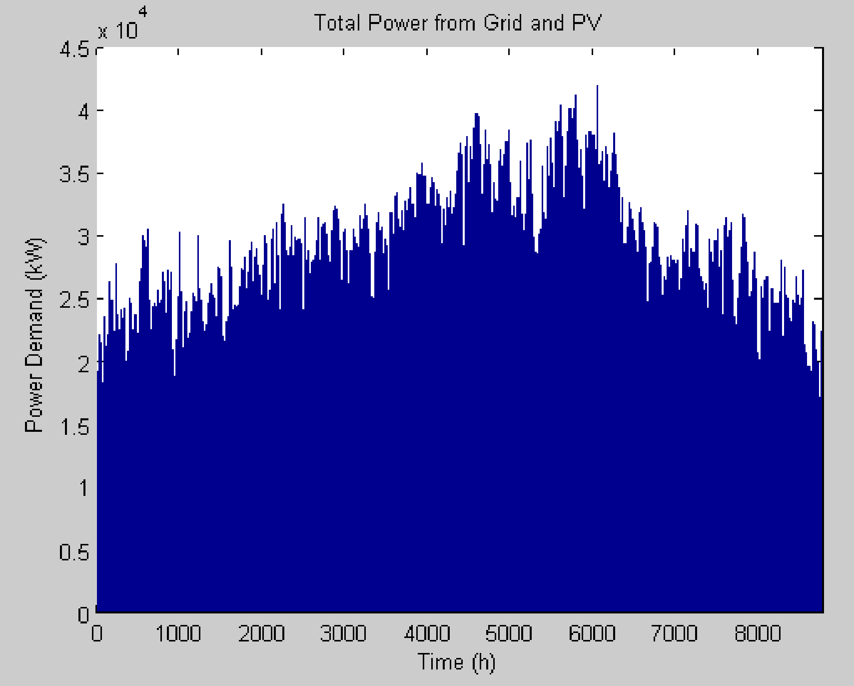


Generation and Load Profile

Total PV Generation from TMY Data

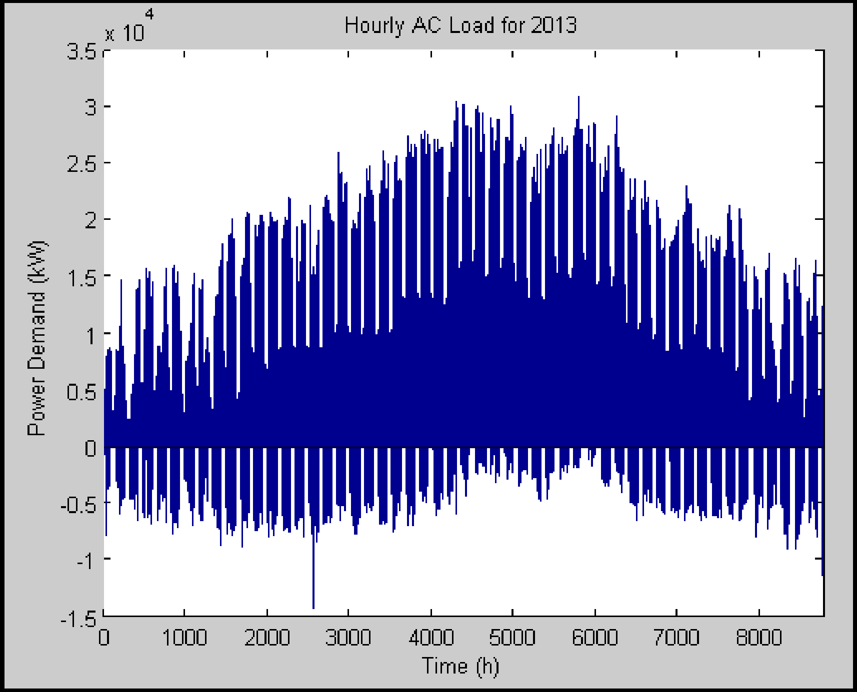


Total Power from Grid and PV

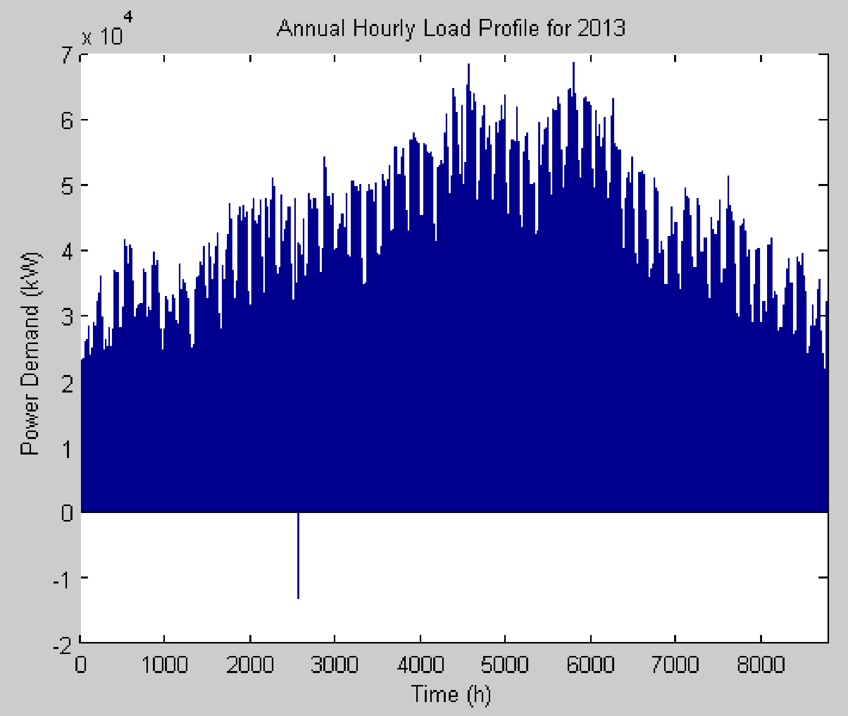


Generation and Load Profile

Hourly AC Load for 2013



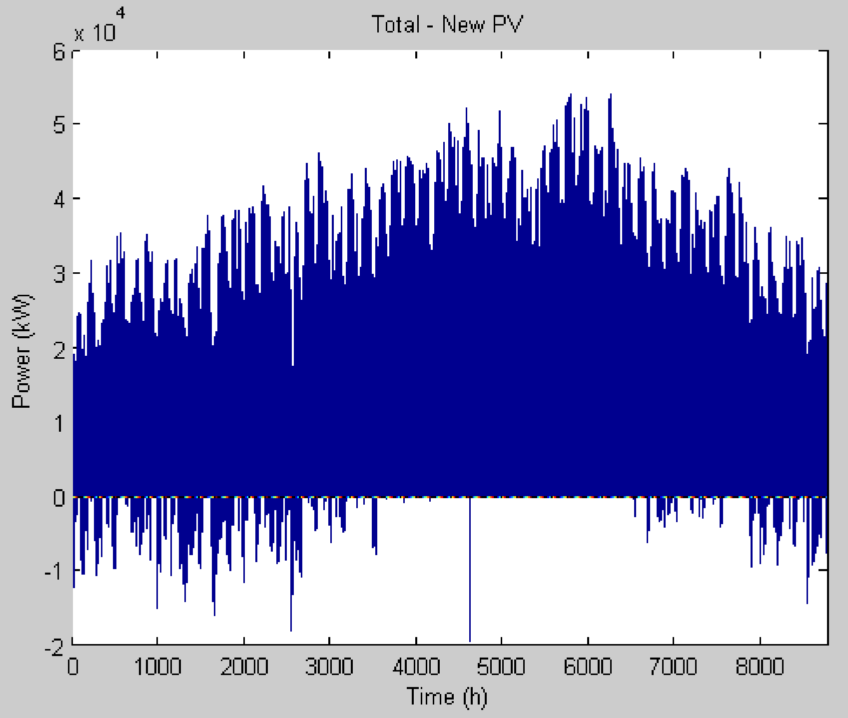
Total PV Generation from TMY Data



Results –Scaling Factor

- Total Load – PV*scaling factor = Excess Load
  - When Positive, need to discharge TES or use grid
  - When Negative, need to charge TES
  - maximum charge rate of TES
    - Avoids sending power back to the grid

Total Load – PV*3.460



- Max scaling factor = 3.460
- 98,831,000 kWh
- 48% of annual load

How location dependent?

- Air conditioning loads represent 27% of electrical load in Arizona
- Southeast also has high electricity loads, averaging near 3=20%
- Other states have electricity usage from water heating

Conclusion

- Existing TES allows increase of PV capacity without sending electricity back to the grid

- Increasing PV generation by a factor of 3.460 allows 48% of power to come from PV resources

- There is a seasonal effect
  - Oversupply occurs in the winter
  - Decreasing tilt angle to optimize for summer may allow a further increase in scaling factor

UC San Diego

Dave Weil, PE
Director, Campus CNP

UC San Diego
Sustainability

University Perspective

- University campuses are major energy consumers
- Campuses nationwide are going solar:
  - ➢ 333 campuses, 223 MWs of solar
    - ❖ Some already 100% renewable
  - ➢ Attracts students & faculty
  - ➢ Good community PR
  - ➢ Reduced energy costs
- More are realizing the value of solar integrated storage

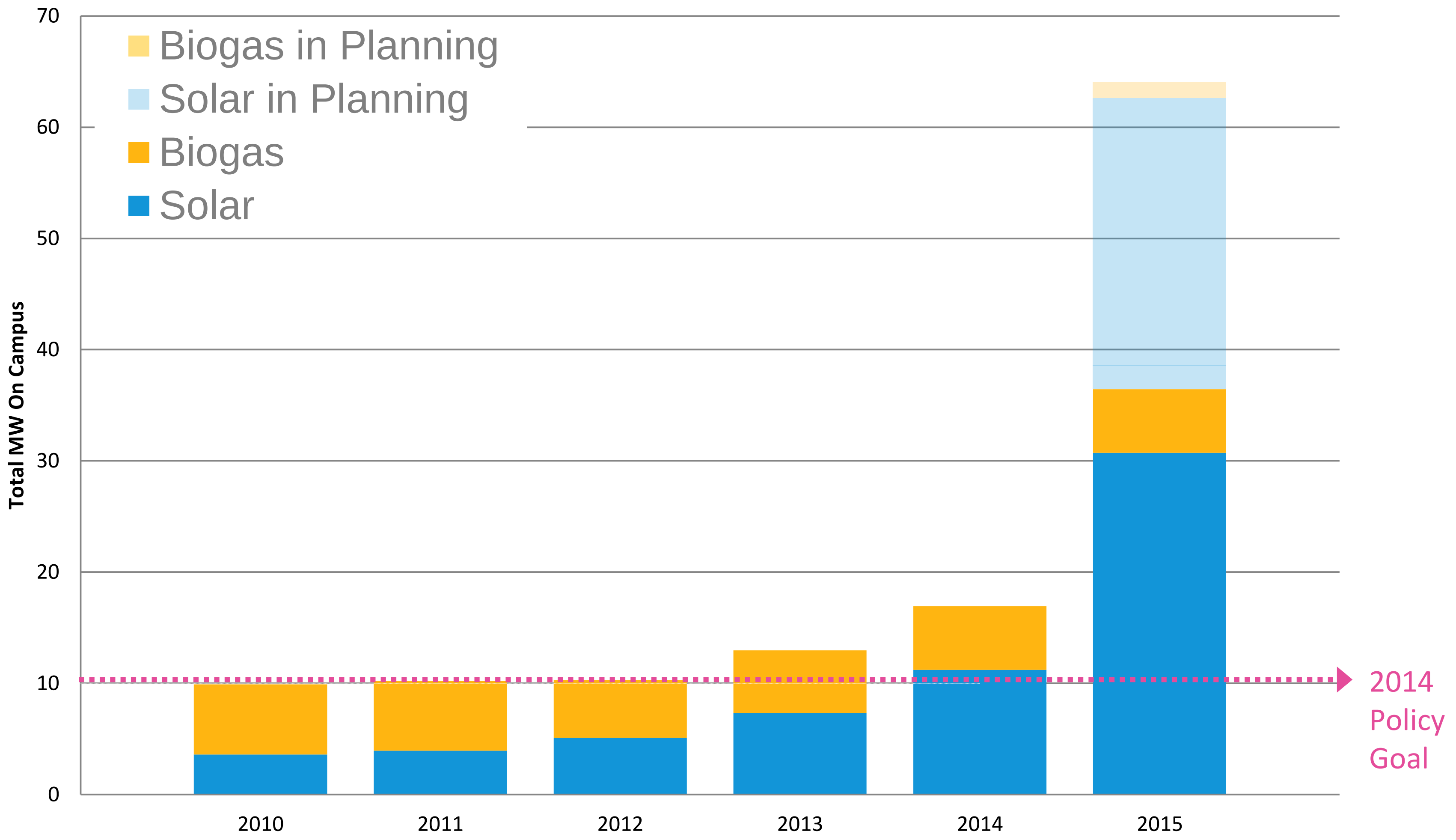
UC San Diego
Sustainability

UC Carbon Neutrality

- University of California will be carbon neutral by 2025
- The UC is developing scalable solutions to build a low-carbon future
- The actions of the University will:
  - Promote research, teaching, and public service
  - Be financially responsible
  - Provide tangible environmental benefits
  - Optimize existing & future campus infrastructure
  - Demonstrate the value of coordinated action

UC San Diego
Sustainability

Renewable Energy Progress



UC San Diego
Sustainability

Wholesale Power Program

Greener, less-expensive electricity provided by UC's "electricity company" managed by the Energy Services Governing Board.

The UC-funded 400-acre, 60-MW solar project in Five Points, CA is now on-line, supplying carbon neutral electricity to seven of our campuses

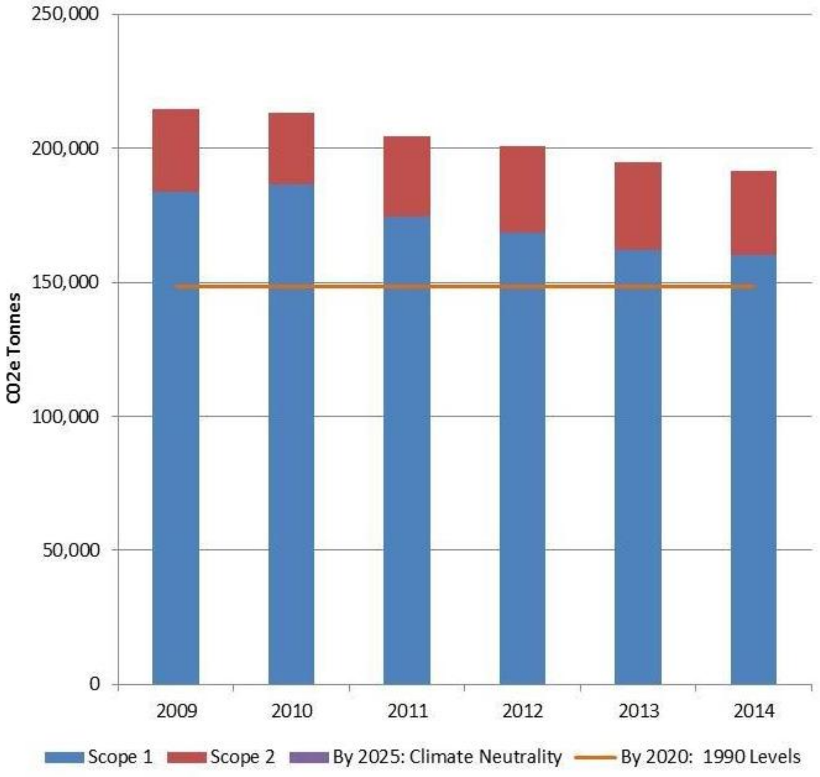
Another 20MWs is under construction

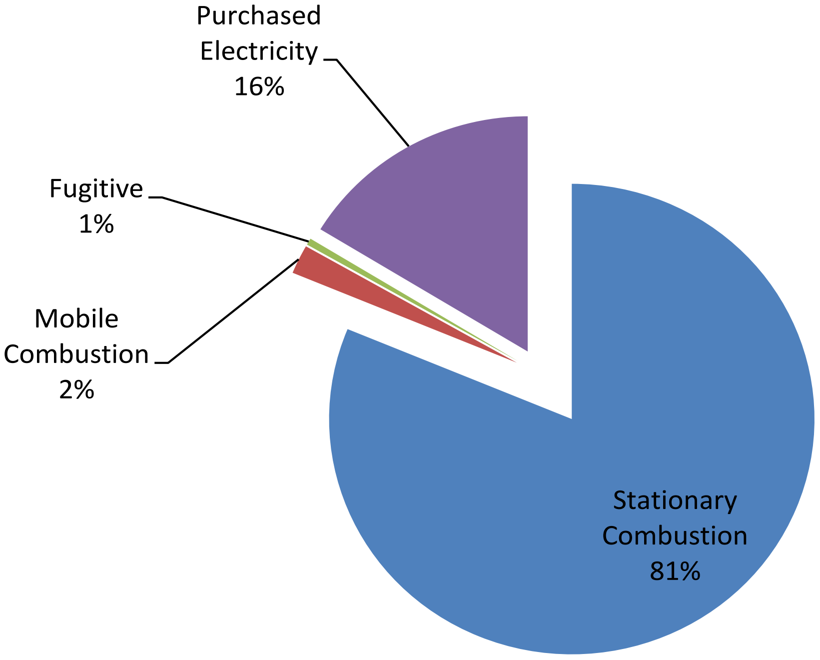
UCSD Campus Overview

- Daily population 50,000+
- 18 million MGSF, 800 Bldgs
  - Growing at $250M/yr
- 2 medical centers, 900 labs
  - 2x's the energy density
- Peak load 45 MWs
  - 3rd largest in region
- Generate 90% of campus energy
- Climate neutral by 2025

UC San Diego
Sustainability

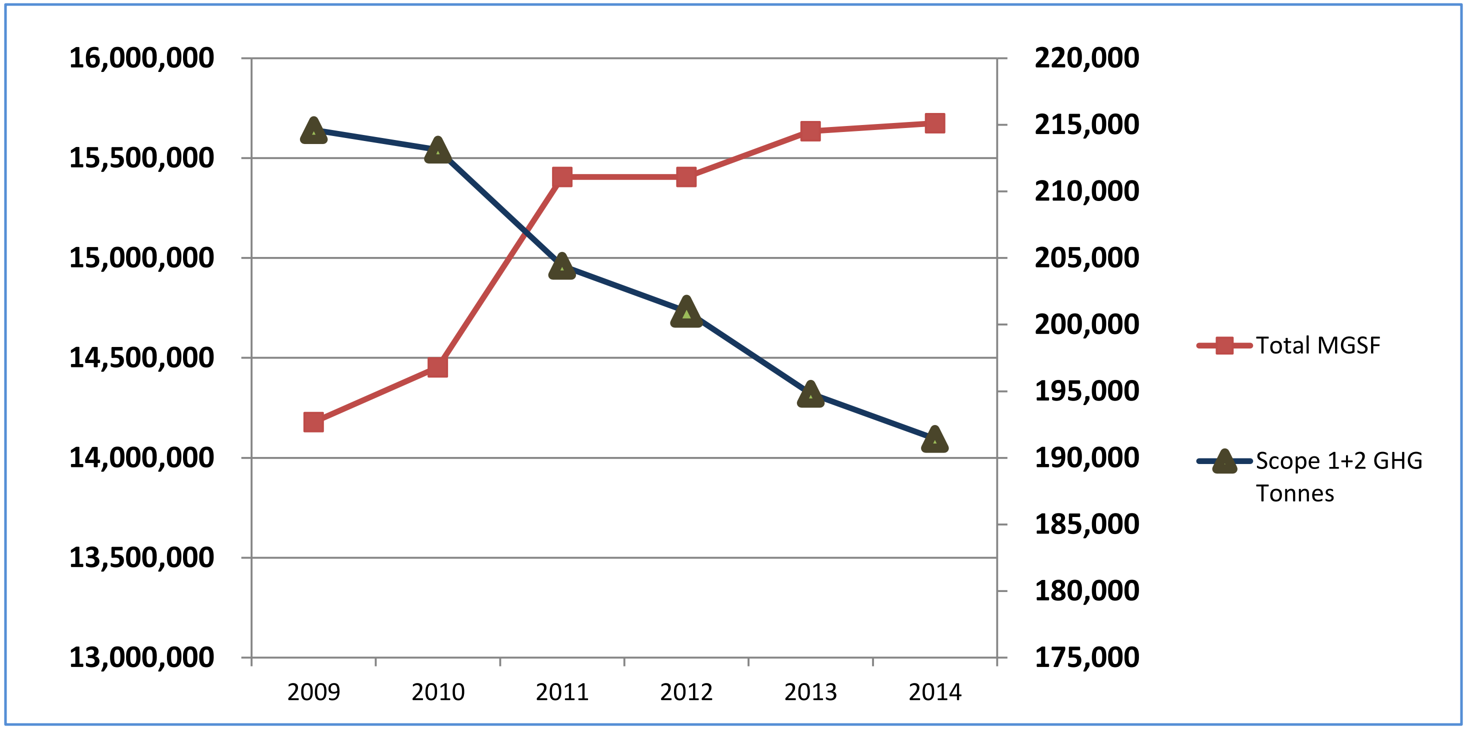
Current Emissions & Trends





Significant Campus Progress

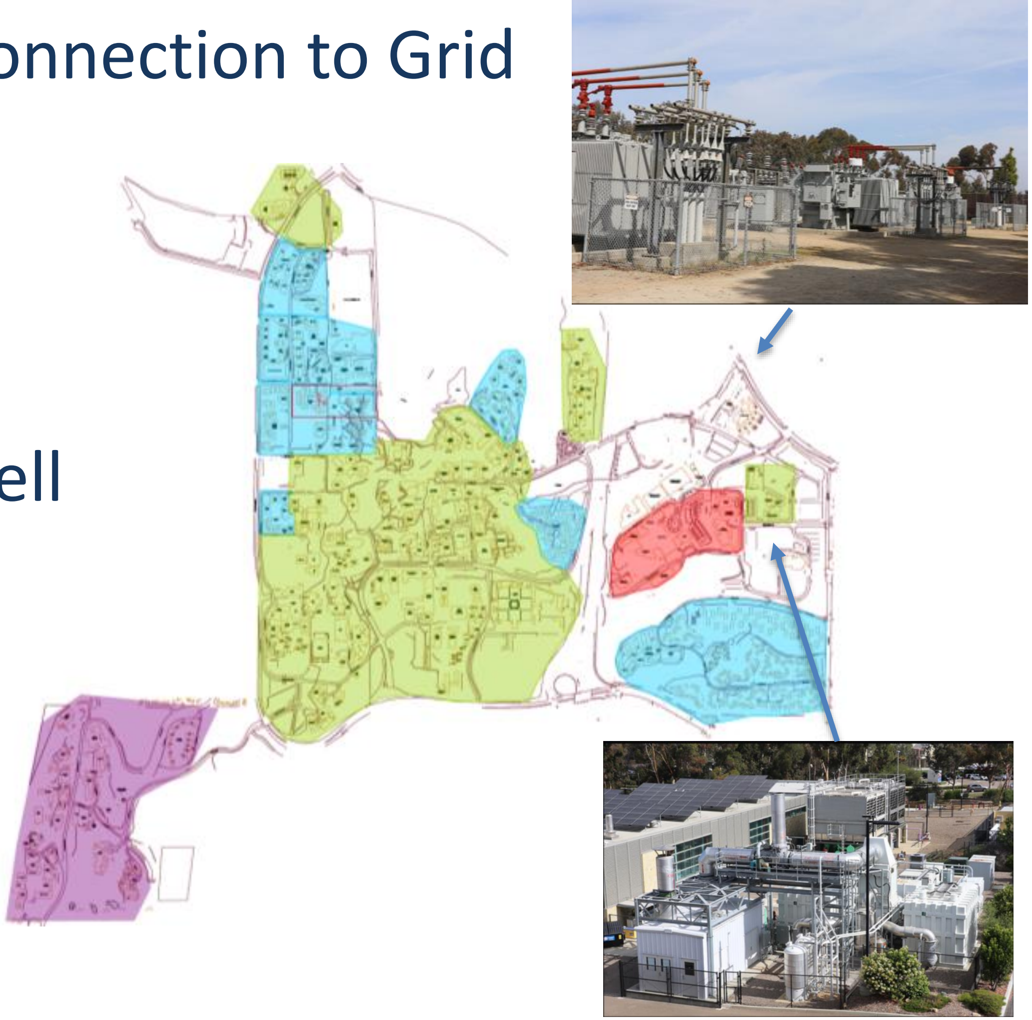
Greenhouse Gas Emissions vs. Campus Growth



UC San Diego
Sustainability

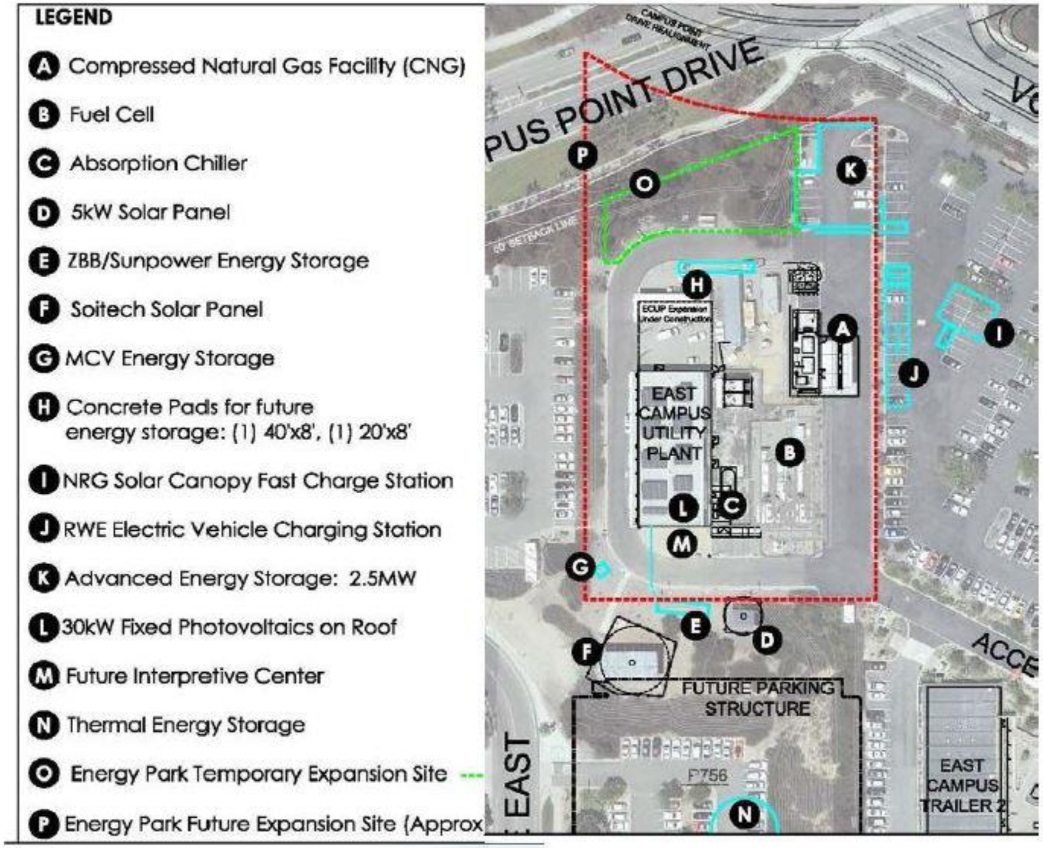
Campus Microgrid

- 69 KV single point of connection to Grid
- 45 MW Peak Load
- 12 KV distribution
- 30 MW Cogen plant
- 2.8 MW Bio-gas Fuel Cell
- Provides Campus
  - ➢ **Resiliency**
  - ➢ **Survivability**
  - ➢ **Redundancy**
  - ➢ **Safety**



UC San Diego
Sustainability

Energy Research Park



LEGEND

- A Compressed Natural Gas Facility (CNG)
- B Fuel Cell
- C Absorption Chiller
- D 5kW Solar Panel
- E ZBB/Sunpower Energy Storage
- F Soitech Solar Panel
- G MCV Energy Storage
- H Concrete Pads for future energy storage: (1) 40'x8', (1) 20'x8'
- I NRG Solar Canopy Fast Charge Station
- J RWE Electric Vehicle Charging Station
- K Advanced Energy Storage: 2.5MW
- L 30kW Fixed Photovoltaics on Roof
- M Future Interpretive Center
- N Thermal Energy Storage
- O Energy Park Temporary Expansion Site
- P Energy Park Future Expansion Site (Approx

UC San Diego
Sustainability

Solar Generation

- 3.1 MWs total on/off campus
  - 2.2 MWs on microgrid
  - 2.1 MWs campus owned
    - CREBs financing
  - 1 MW 3rd Party PPA
- Provides stable energy costs
- Potential for additional 9 MWs

UC San Diego
Sustainability

Energy Storage

- 2.5 MW / 5 MWh LI-ion Energy Storage
  - Demand reduction
  - Working to "green" energy supply
- 250 kW/ 500 KWh solar integrated energy storage
  - Coupled with Solar Forecasting
  - Smooths Intermittency

Energy Storage

- 108 kW /180 kWh BMW 2nd life battery demonstration site:
  - 330 kW building PV
  - Level 2 EV Charging
- 8 kW Sunverge Energy Storage with 60 kW PV system
- 28 kW Maxwell Ultra-Capacitor:
  - Coupled with Solar Forecasting
  - Smooths Intermittency

Energy Storage

Thermal Energy Storage

- 3.8 Mgal at Cogen Plant
  - ➢ Main campus loop
  - ➢ Demand Reduction

- 3.8 Mgal on East Campus
  - ➢ Demand reduction

San Vicenti Pumped Storage

- 500 MWs / 8 hours
- All renewable energy

EV Grid Integration

- Integrating EVs into microgrid
  - ➢ 57 EVs in campus fleet
  - ➢ Over 250 EV drivers on campus
    - ❖ EV leasing program
  - ➢ 50 L2 & 4 DC fast chargers
    - ❖ Plan to have 200+
  - ➢ 100 kWh solar integrated Fast Charger

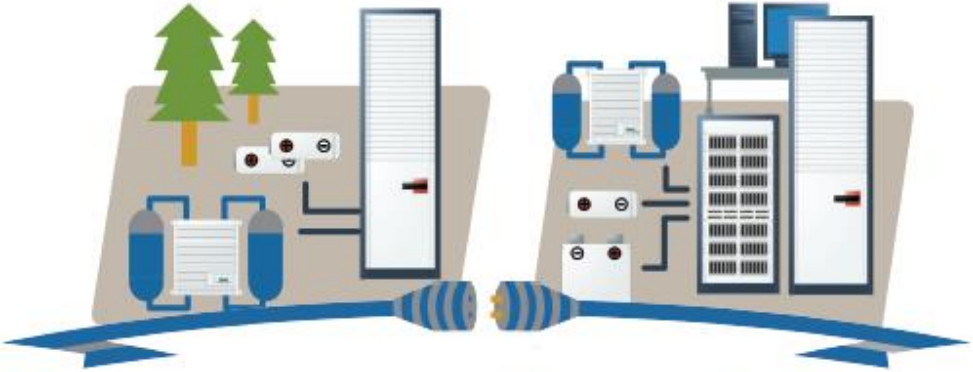
- EV Smart Charging (V2G)
  - ➢ ISO 15118
  - ➢ Solar integrated increases value of PV

UC San Diego
Sustainability

ECONOMIC MODELING, TESTING AND VALIDATOIN OF ADVANCED GRID STORAGE TECHNOLOGIES

UC San Diego
JACOB SCHOOL OF ENGINEERING
Center for Energy Research

UC San Diego is helping bridge the gap between battery R&D and the real world grid storage market, by validating grid storage echnologies, leveraging its experience in battery testing, economic modeling, and grid-connected validation to identify the market-ready energy storage solution for the future utility grid. -CHARGES project funded by ARPAe

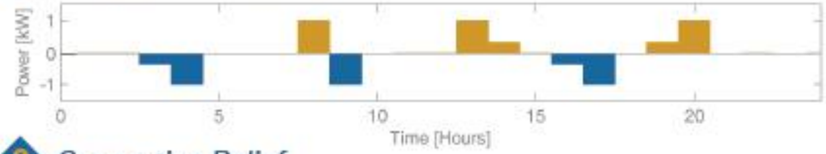


Lab testing *provides single cell or module validation using advanced battery testers, controlled testing enviouronment, and cloud enabled data aqcuisition*

Grid-connected testing *validates more commercially matual storage systems in a realistic setting*

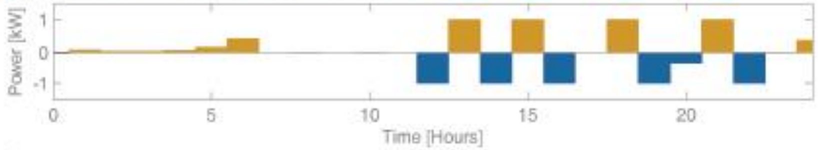
New storage technologies *of diverse chemistries, sizes, form factors and commercial maturities have been tested, with more to come!*

1 Energy Time Shifting



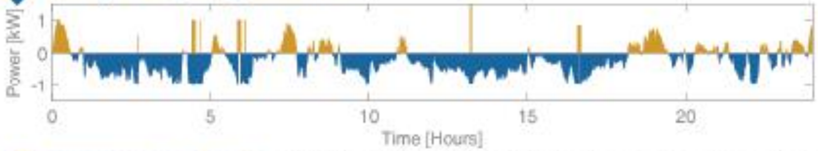
2 Congestion Relief

3 Demand Charge Management



4 Flexible Ramping

5 Frequency Regulation



Economic analysis *of 2 Years' California Independent System Operator (CAISO) data has been conducted to develop revenue models and testing protocols of five energy services*

Contact: stong@ucsd.edu
Contributor: William V. Torre, Shirley Meng, Graham Elliot,
Mike Verde, Dan Davies, Oytun Babacan, Antonio Tong

Future Challenges

- Improved methods for solar forecasting
- Implementation of smart inverter standards
- Integration of solar and energy storage to make PV a more dispatchable and firm resource

Thank You!

Dave Weil, PE
Director, Campus CNP

UC San Diego
Sustainability

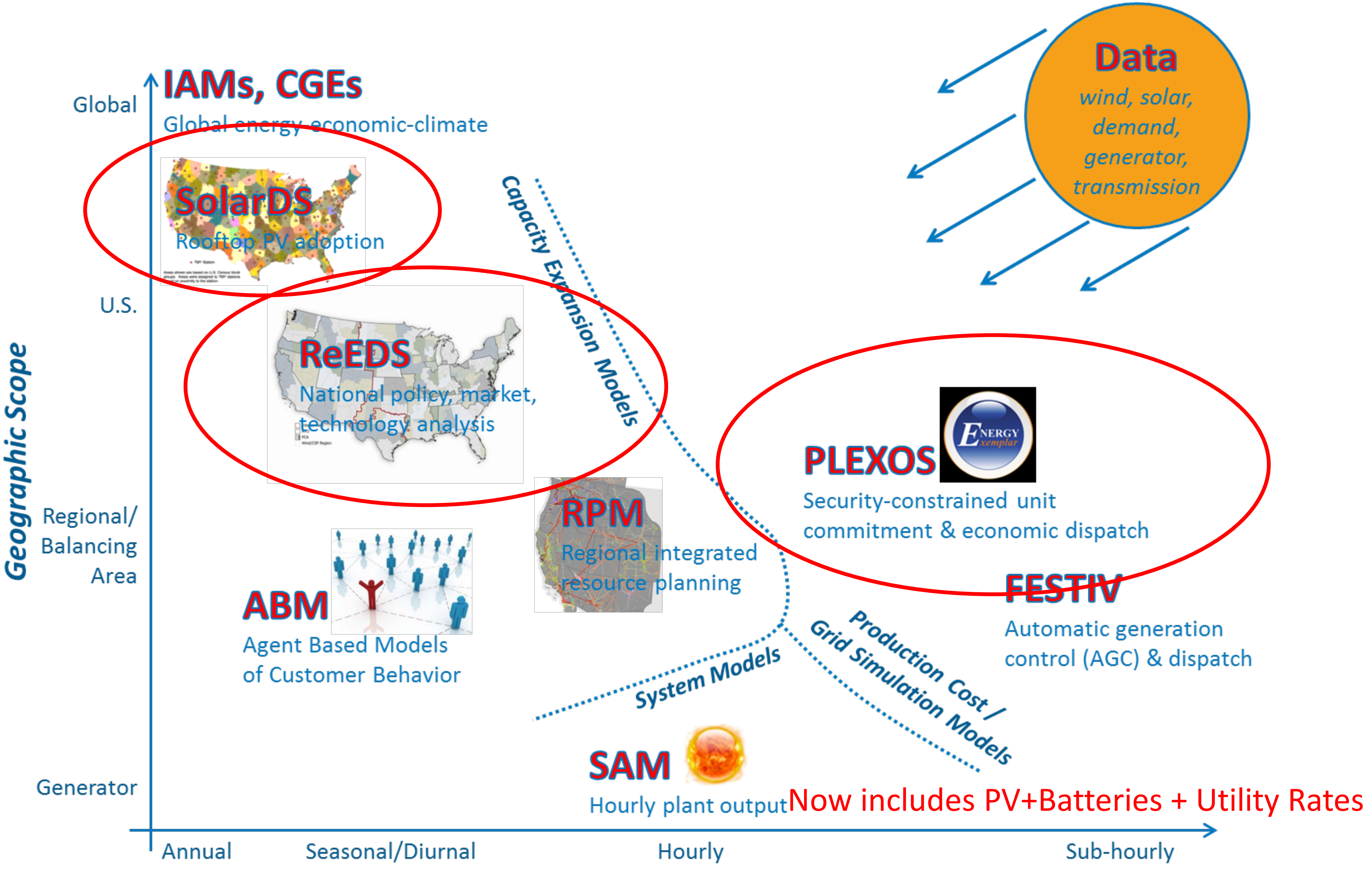
Transmission and other Grid Flexibility Options to Enable High Values of PV

Nate Blair

Input from Aaron Bloom and many other NREL staff

October 13, 2016

Basic Set of Tools and Models across Varying Scope and Temporal Resolution



Geographic Scope

Global

U.S.

Regional/ Balancing Area

Generator

Annual

Seasonal/Diurnal

Hourly

Sub-hourly

IAMs, CGEs
Global energy-economic-climate

SolarDS
Rooftop PV adoption

ReEDS
National policy, market, technology analysis

ABM
Agent Based Models of Customer Behavior

RPM
Regional integrated resource planning

PLEXOS
Security-constrained unit commitment & economic dispatch

FESTIV
Automatic generation control (AGC) & dispatch

SAM
Hourly plant output

Now includes PV+Batteries + Utility Rates

Capacity Expansion Models

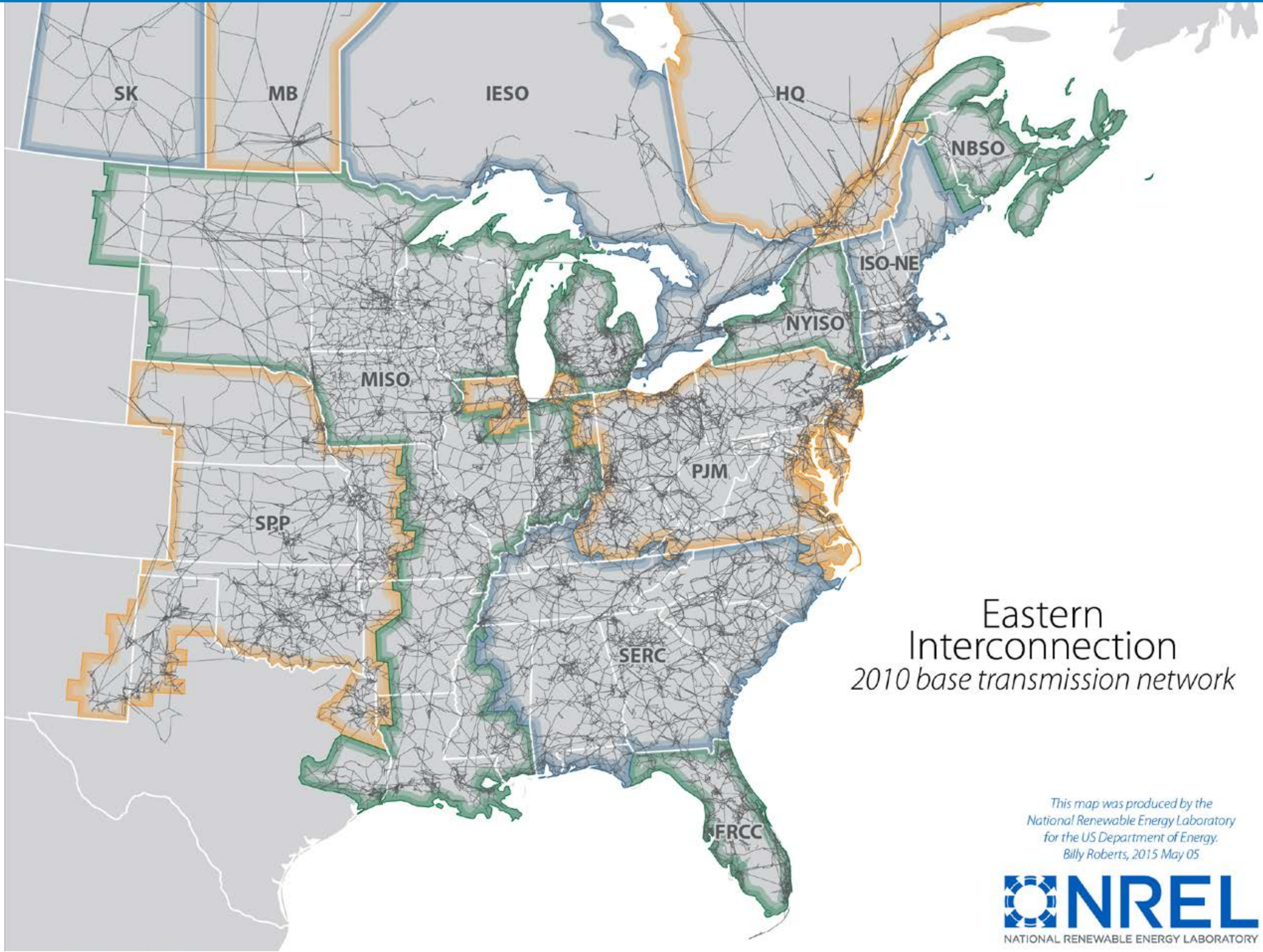
System Models

Production Cost / Grid Simulation Models

Data
wind, solar, demand, generator, transmission

Eastern Renewable Generation Integration Study

The Largest Coordinated Power System in the World



Eastern Interconnection

2010 base transmission network

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

NREL

NATIONAL RENEWABLE ENERGY LABORATORY

Reliably Designed for Traditional Fuel Sources

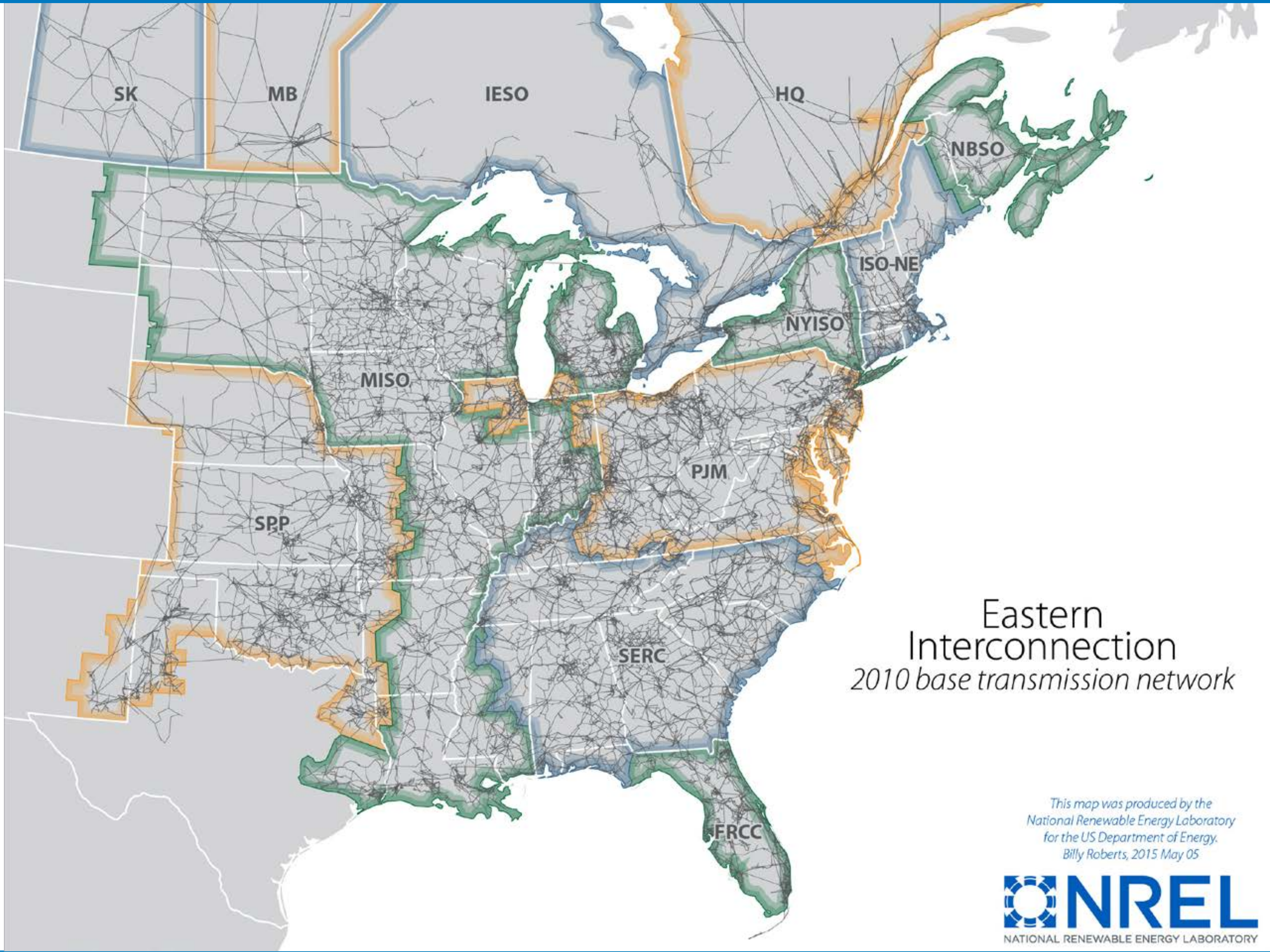
Combustion Turbine (Natural Gas)

Combined Cycle (Natural Gas)

Hydro

Nuclear

Coal

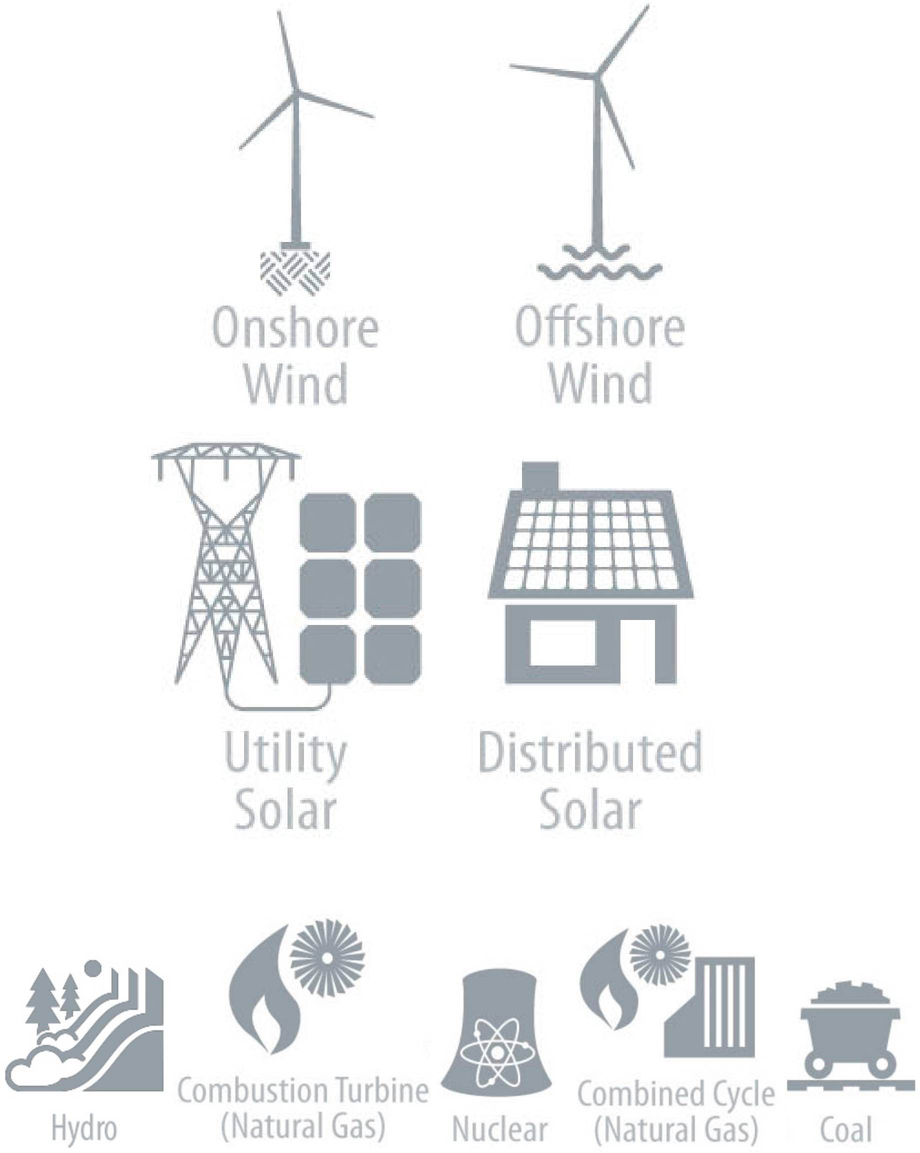


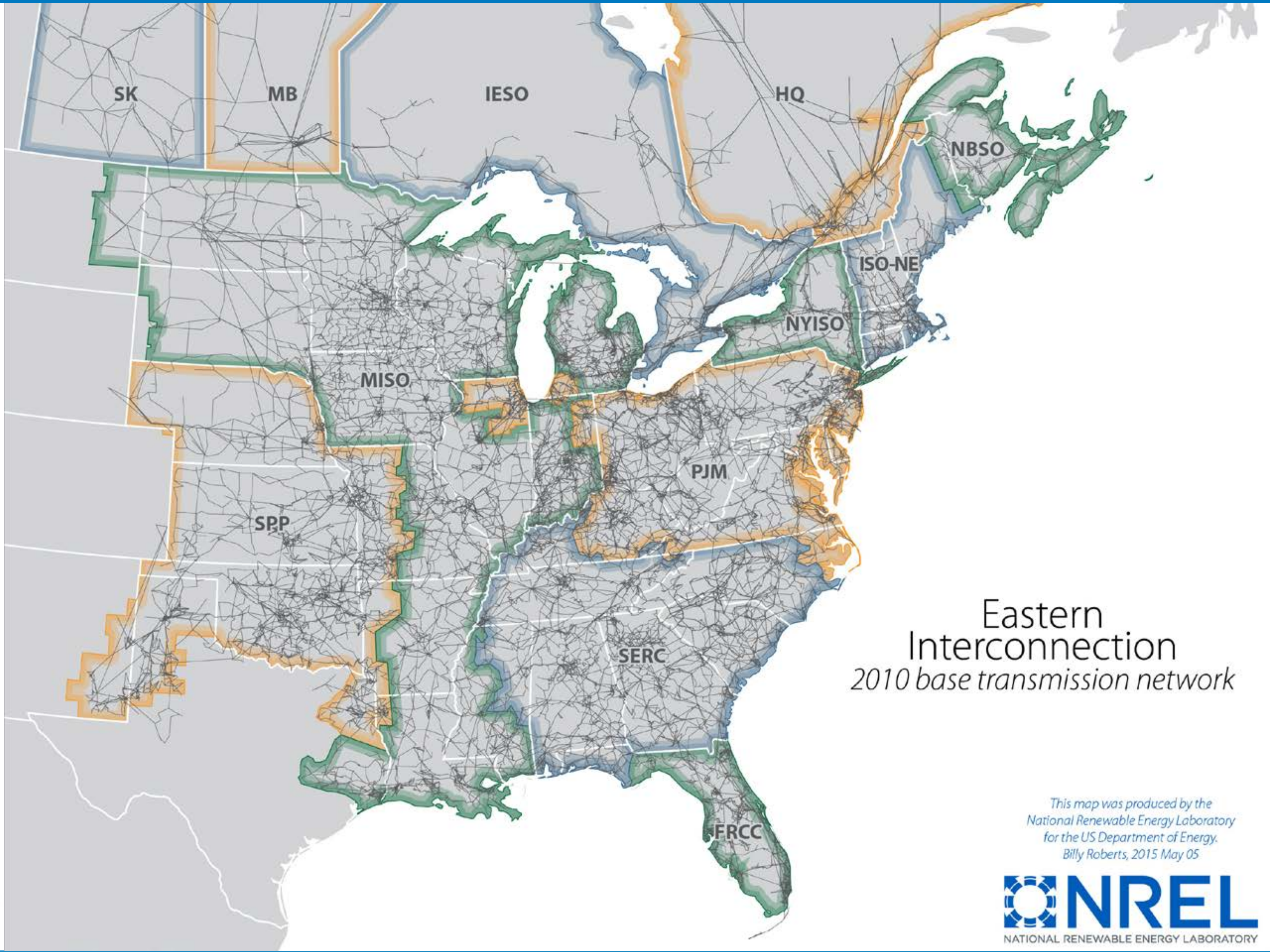
Eastern Interconnection
2010 base transmission network

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A System in Transition





Eastern Interconnection
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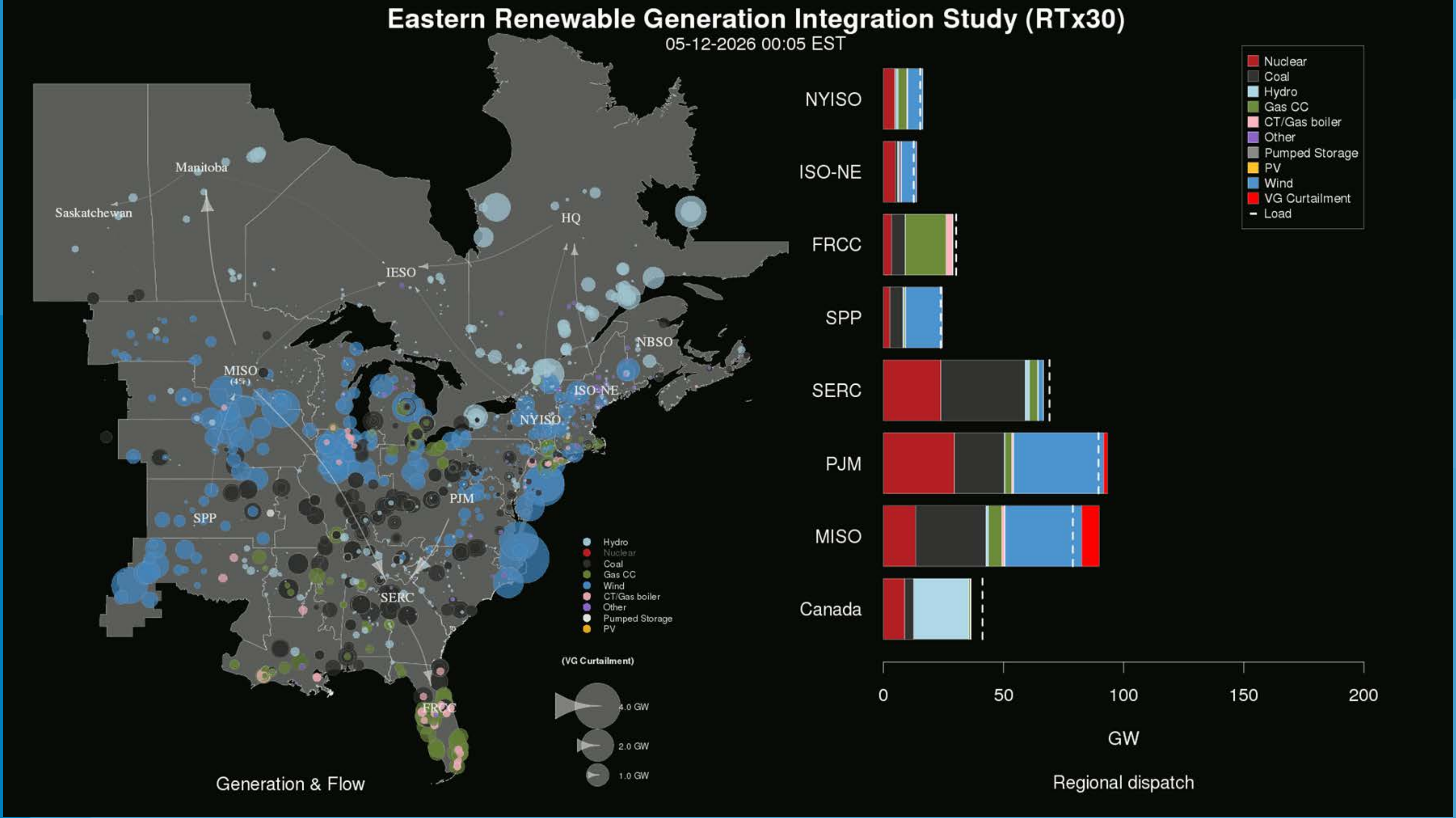
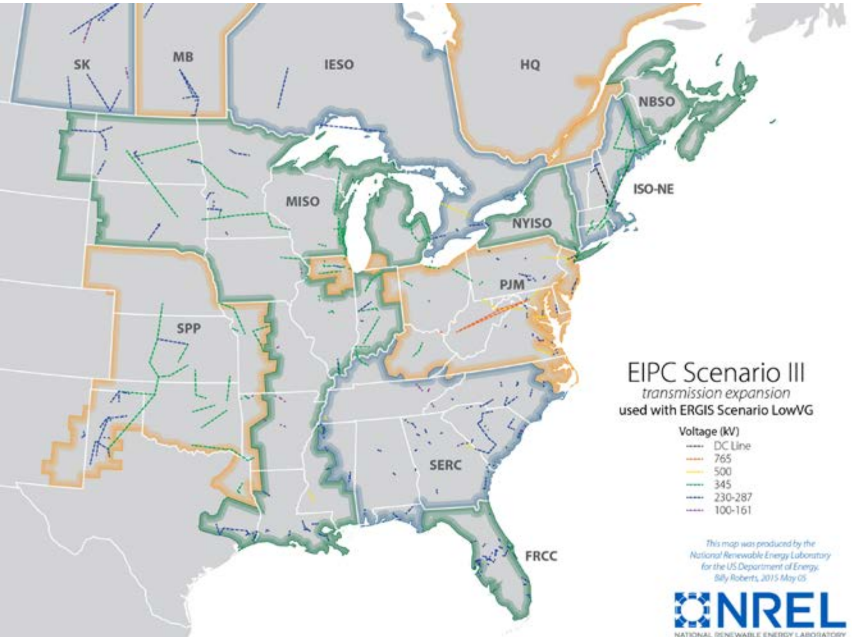


Click on this link to watch the animation of this graphic
https://www.youtube.com/watch?v=28-QU8AyISA&list=PLmIn8Hncs7bEl4P8z6-KCliwbYrwANv4p&index=21

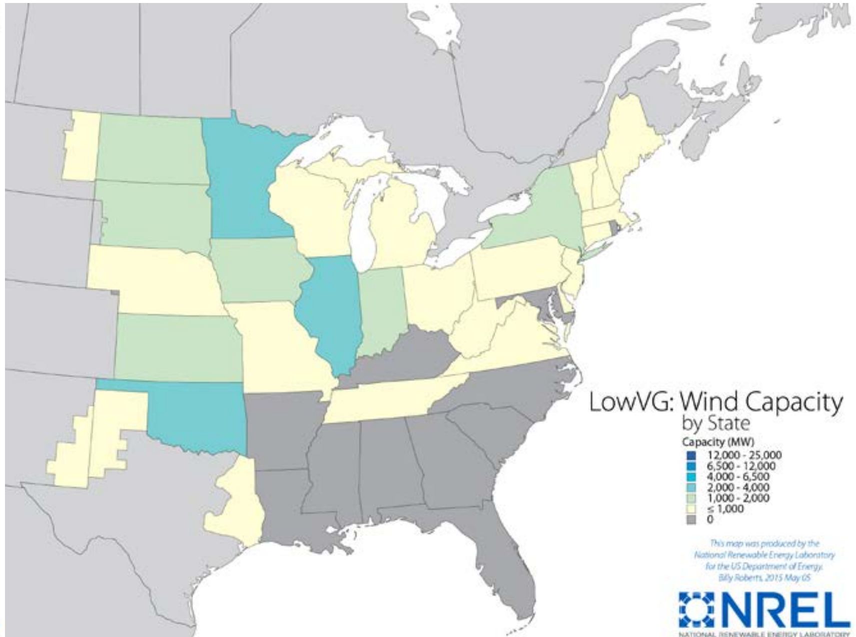
LowVG

- Base case
- Announced transmission upgrades
- Includes actual wind and solar on the grid in 2013
- 160 GW of announced retirements
- New natural gas is built to meet future system needs



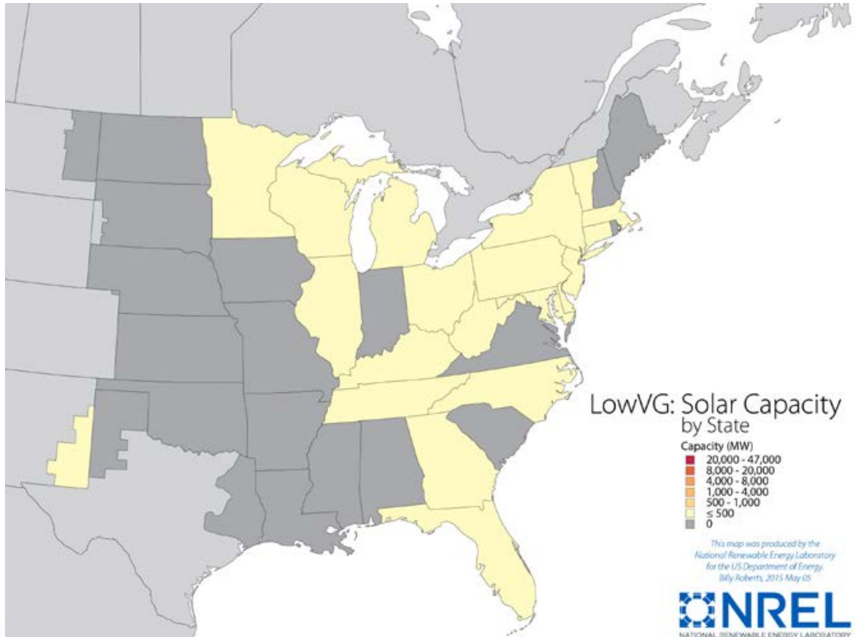
EIPC Scenario III
transmission expansion
used with ERGIS Scenario LowVG

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05



LowVG: Wind Capacity by State

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

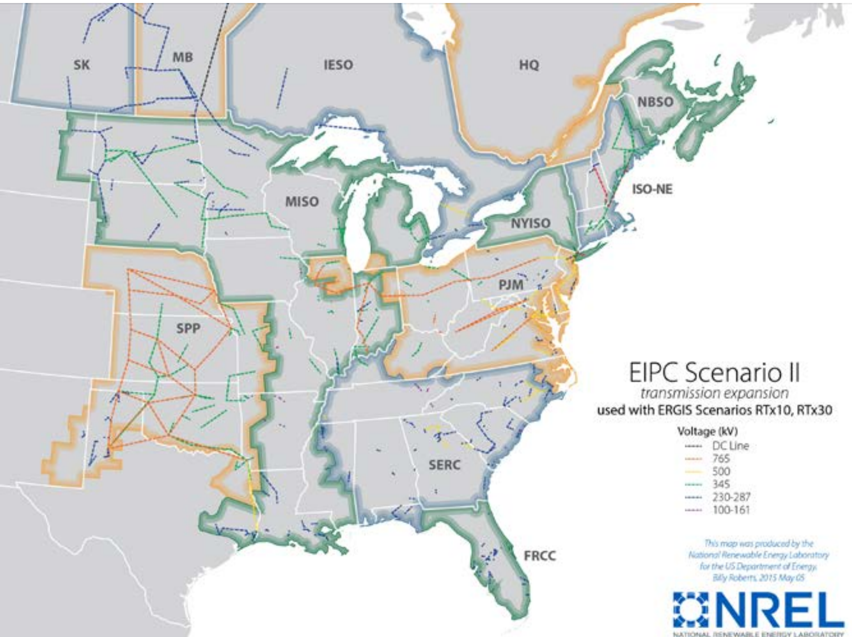


LowVG: Solar Capacity by State

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

RTx10

- Business as Usual Case
- Regional transmission upgrades
- Reflects currently effective State Renewable Portfolio Standards
- Identical thermal fleet to LowVG

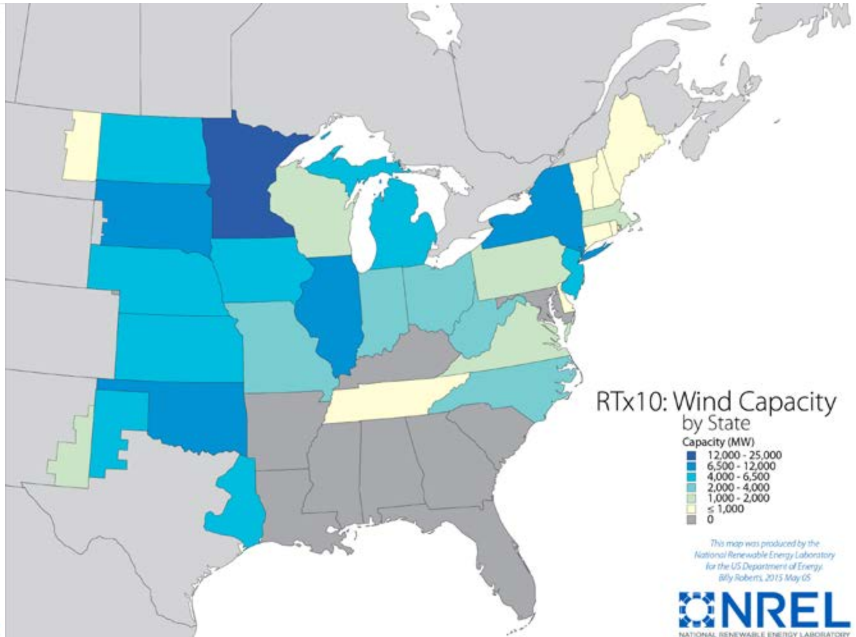


EIPC Scenario II

transmission expansion

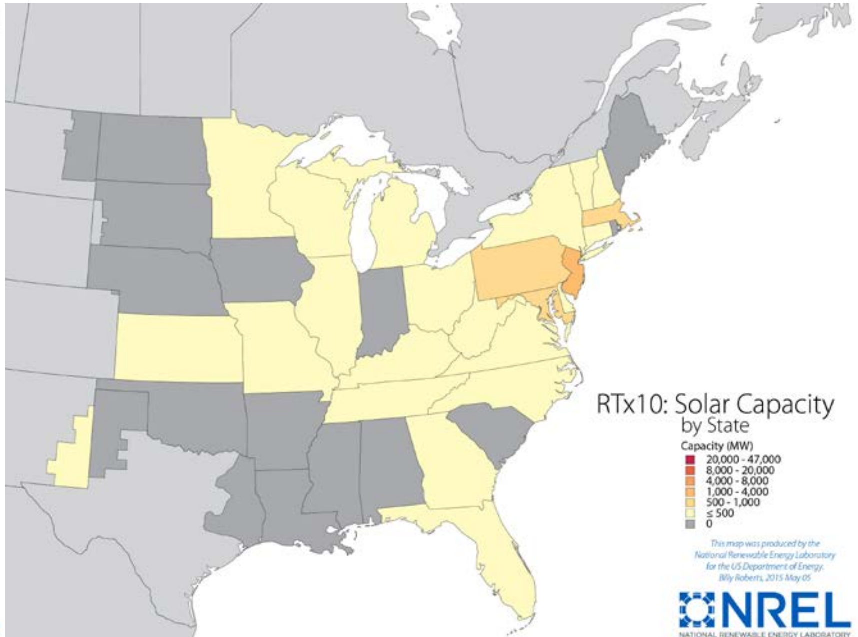
used with ERGIS Scenarios RTx10, RTx30

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05



RTx10: Wind Capacity by State

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

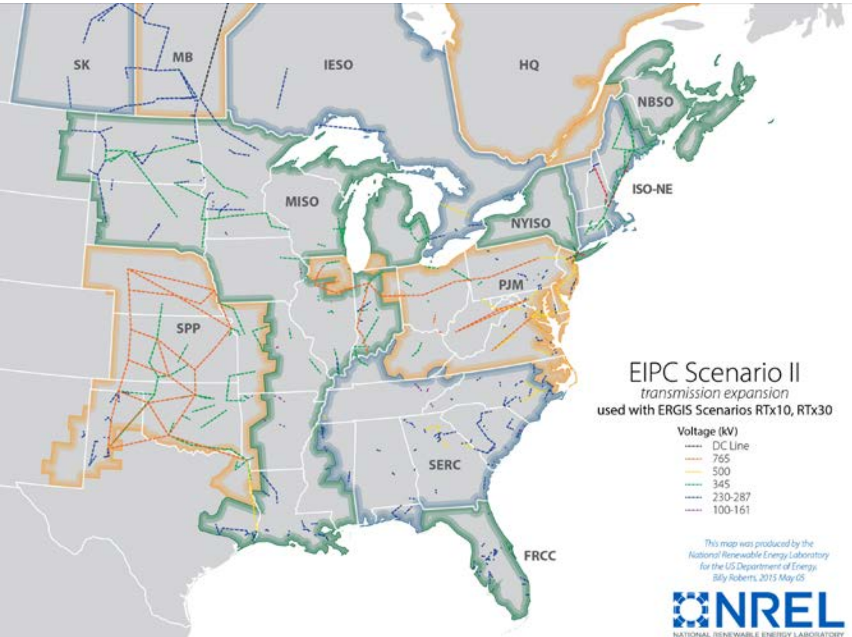


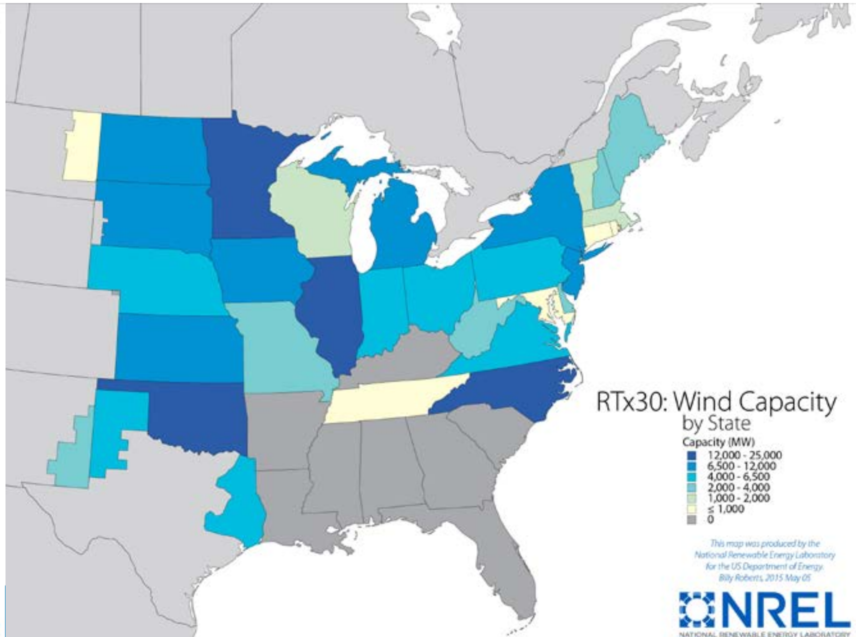
RTx10: Solar Capacity by State

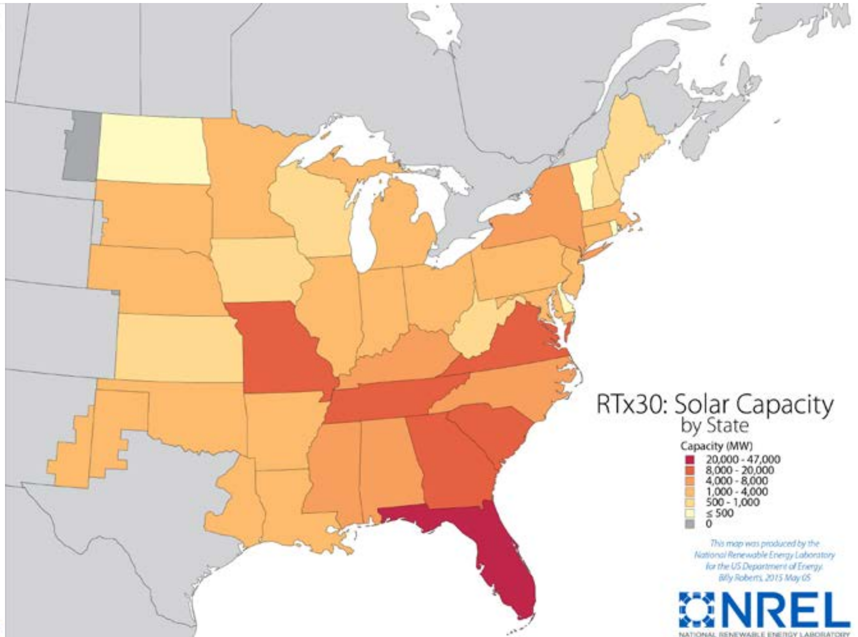
This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

RTx30

- 30% of all electricity demand is met by wind (20%) and solar (10%)
- Same transmission as the RTx10
- A future where large scale transmission is difficult and solar grows significantly
- Identical thermal fleet to LowVG

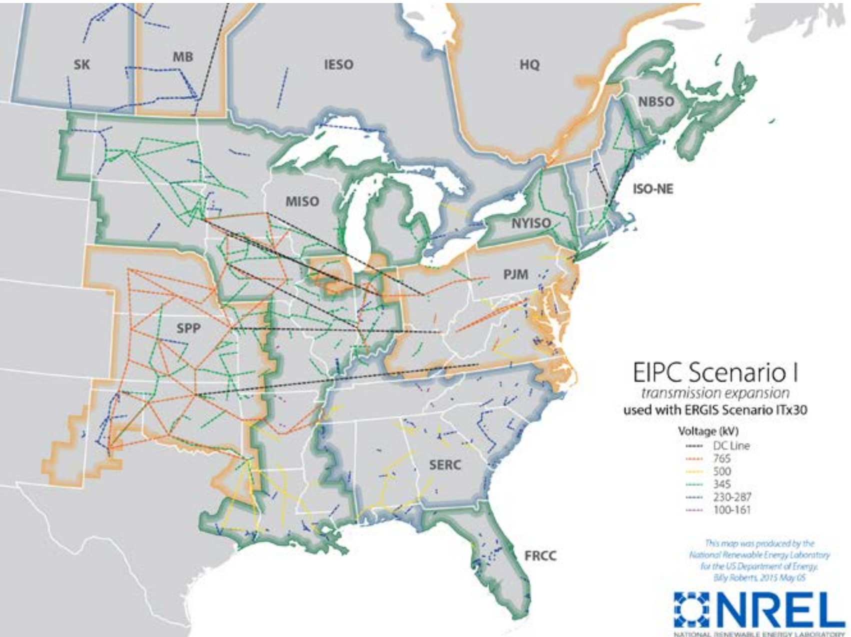




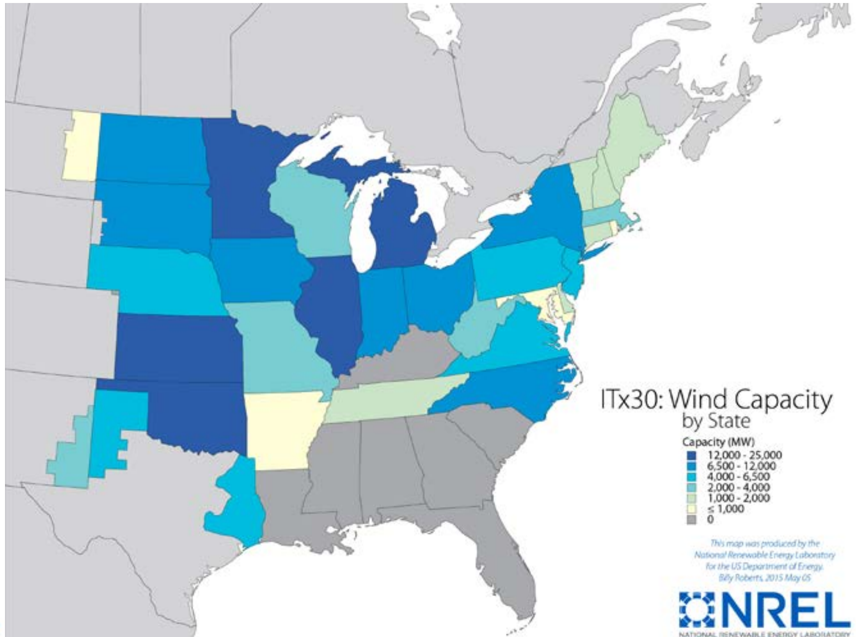


ITx30

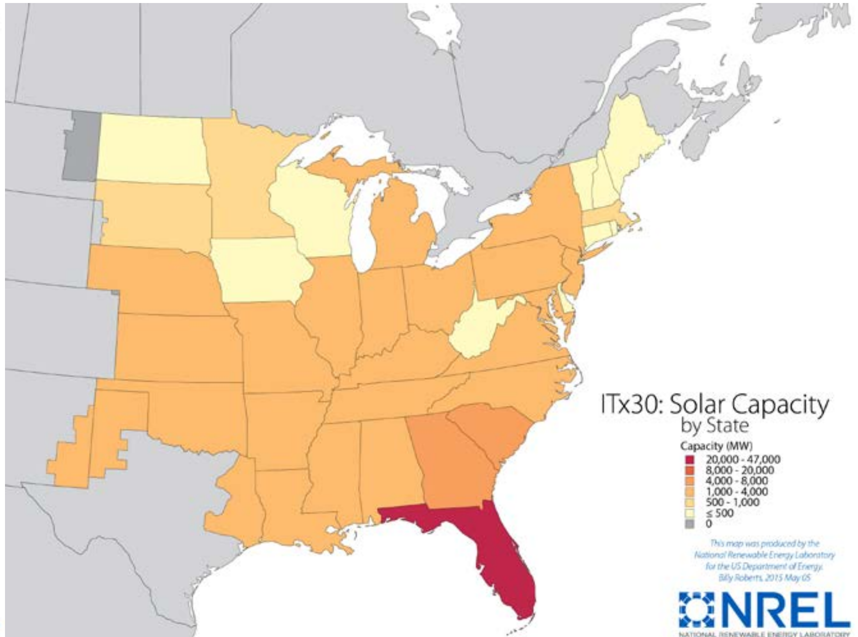
- 30% of all electricity demand is met by wind (25%) and solar (5%)
- Substantial inter-regional transmission expansion, including 8 HVDC lines
- The best wind and some solar everywhere
- Identical thermal fleet to LowVG


EIPC Scenario I
transmission expansion
used with ERGIS Scenario ITx30

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

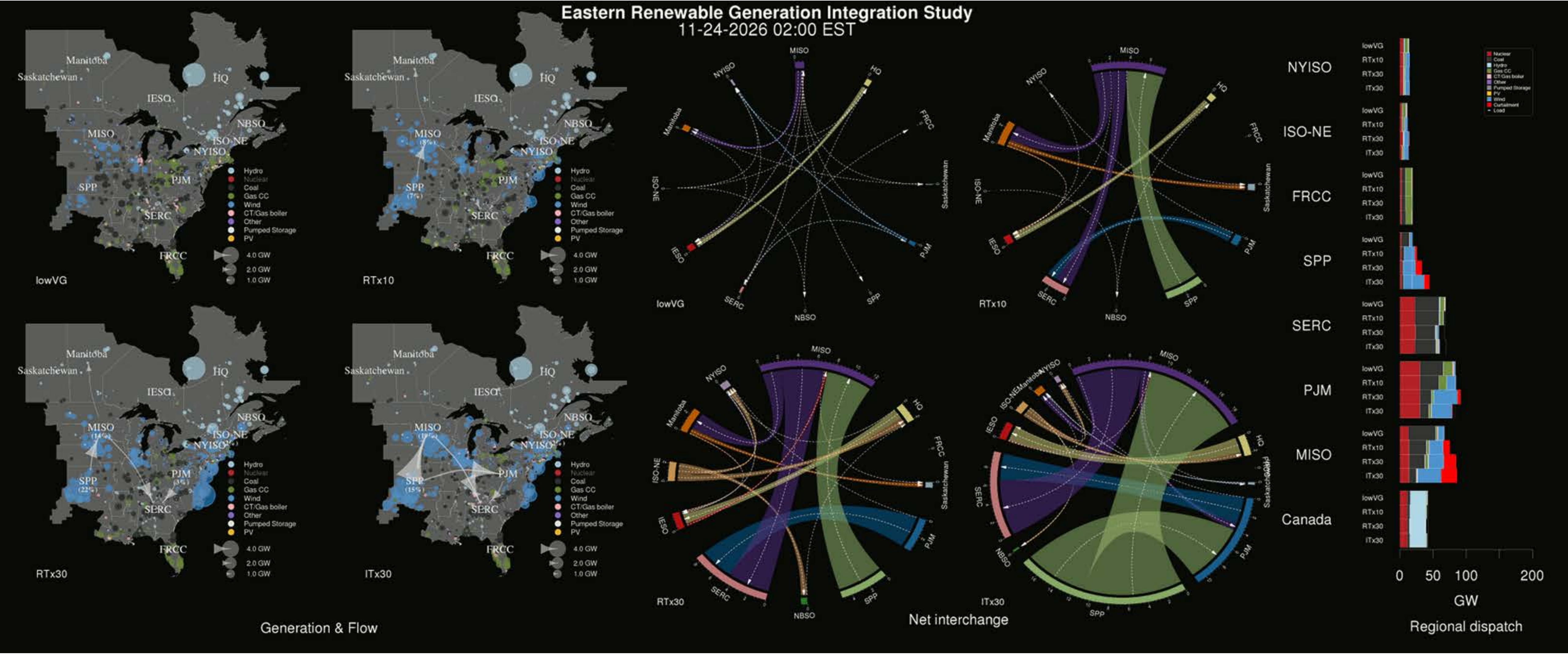

ITx30: Wind Capacity by State

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05


ITx30: Solar Capacity by State

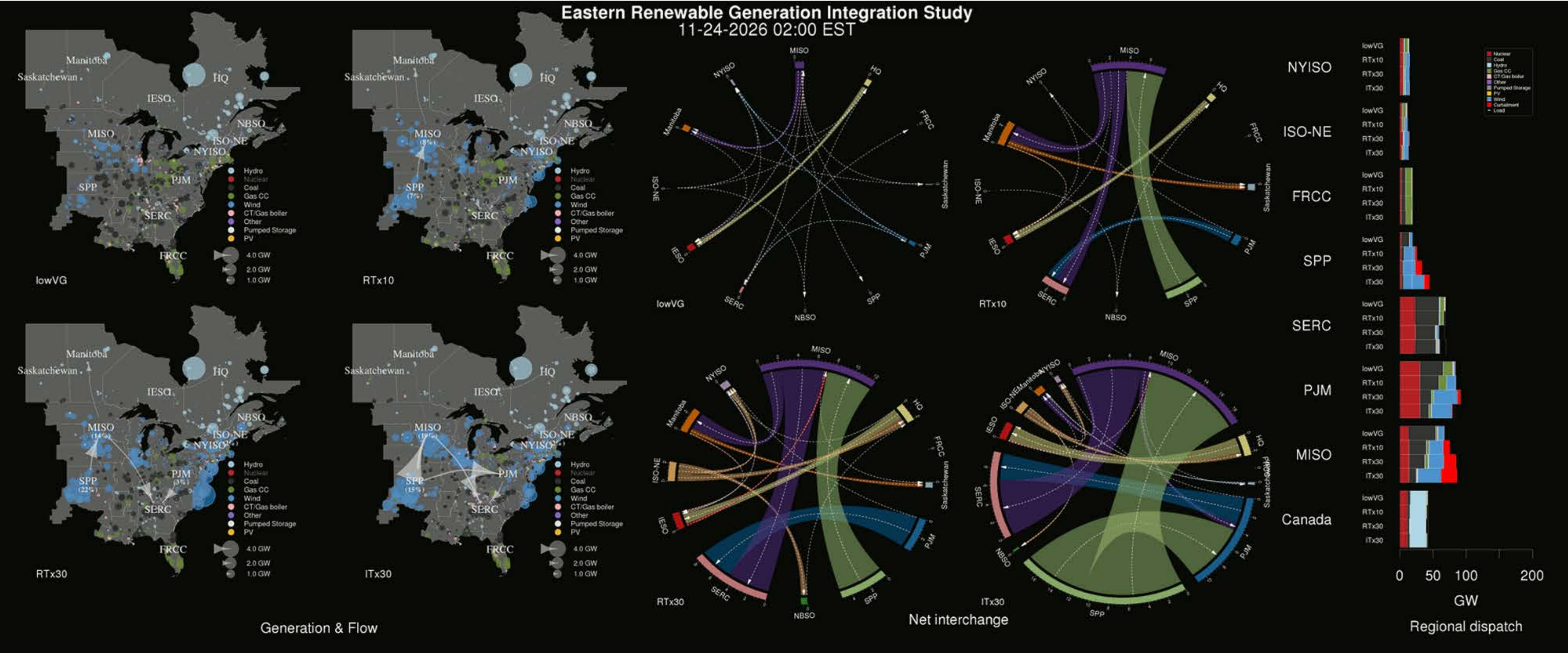
This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

Wind and Solar change how you operate traditional power plants



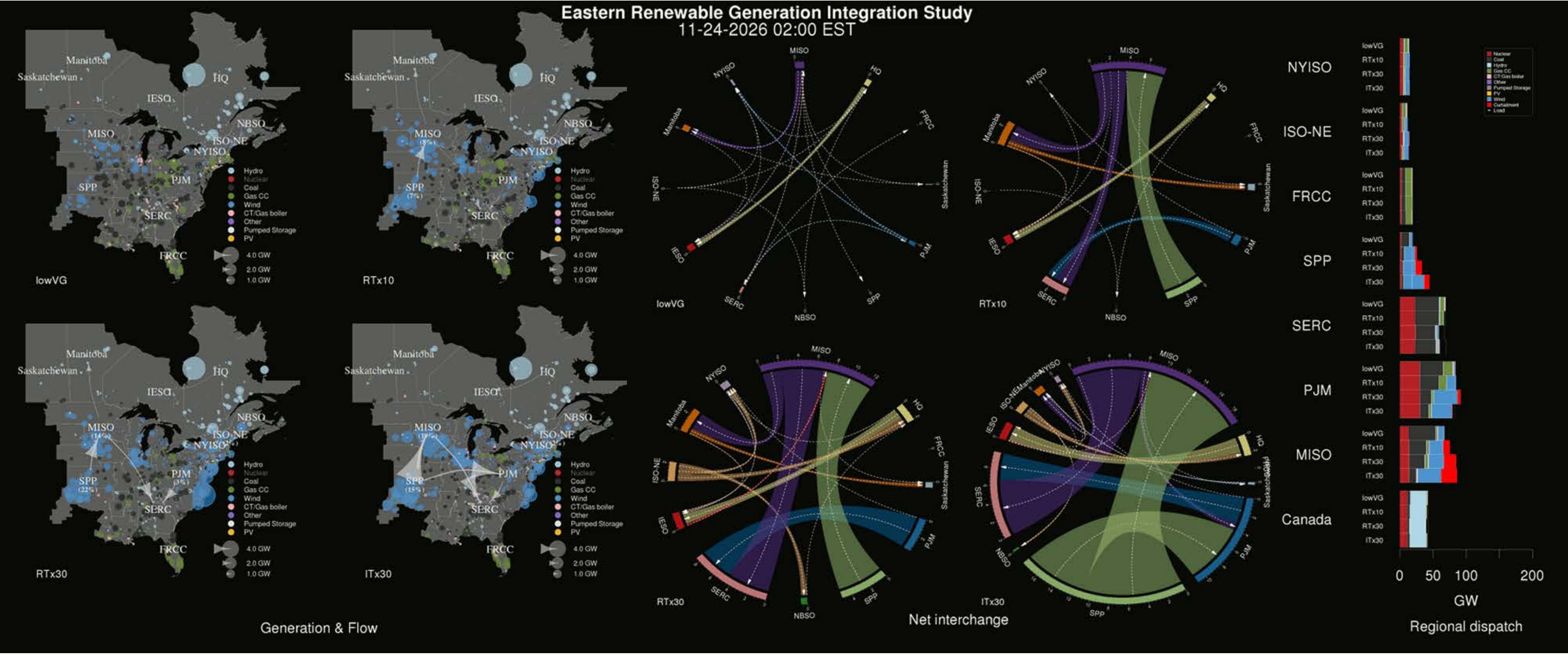
Note: Animation of above not currently available online

Sunrise and sunset complicate operations



Note: Animation of above not currently available online

High Penetration Wind and Solar cause bigger, faster swings in transmission flow



Note: Animation of above not currently available online

Transmission Impacts

- Three time zones in the Eastern Interconnect – allowing for shipping solar power significant distances
- Significantly broadens the daily solar production profile
- The trick is getting all of the balancing areas and markets coordinated enough to effectively ship the PV production across the country.

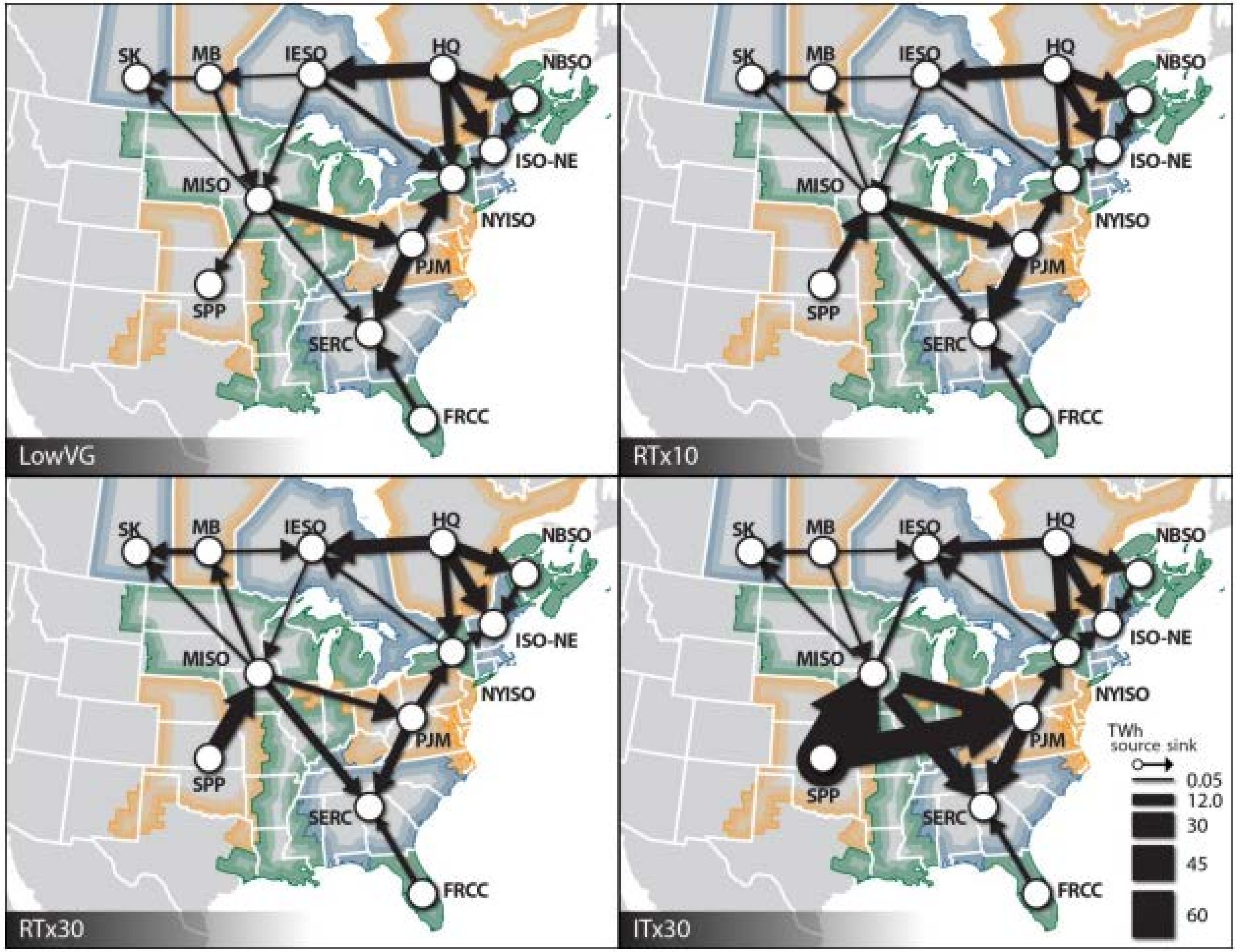
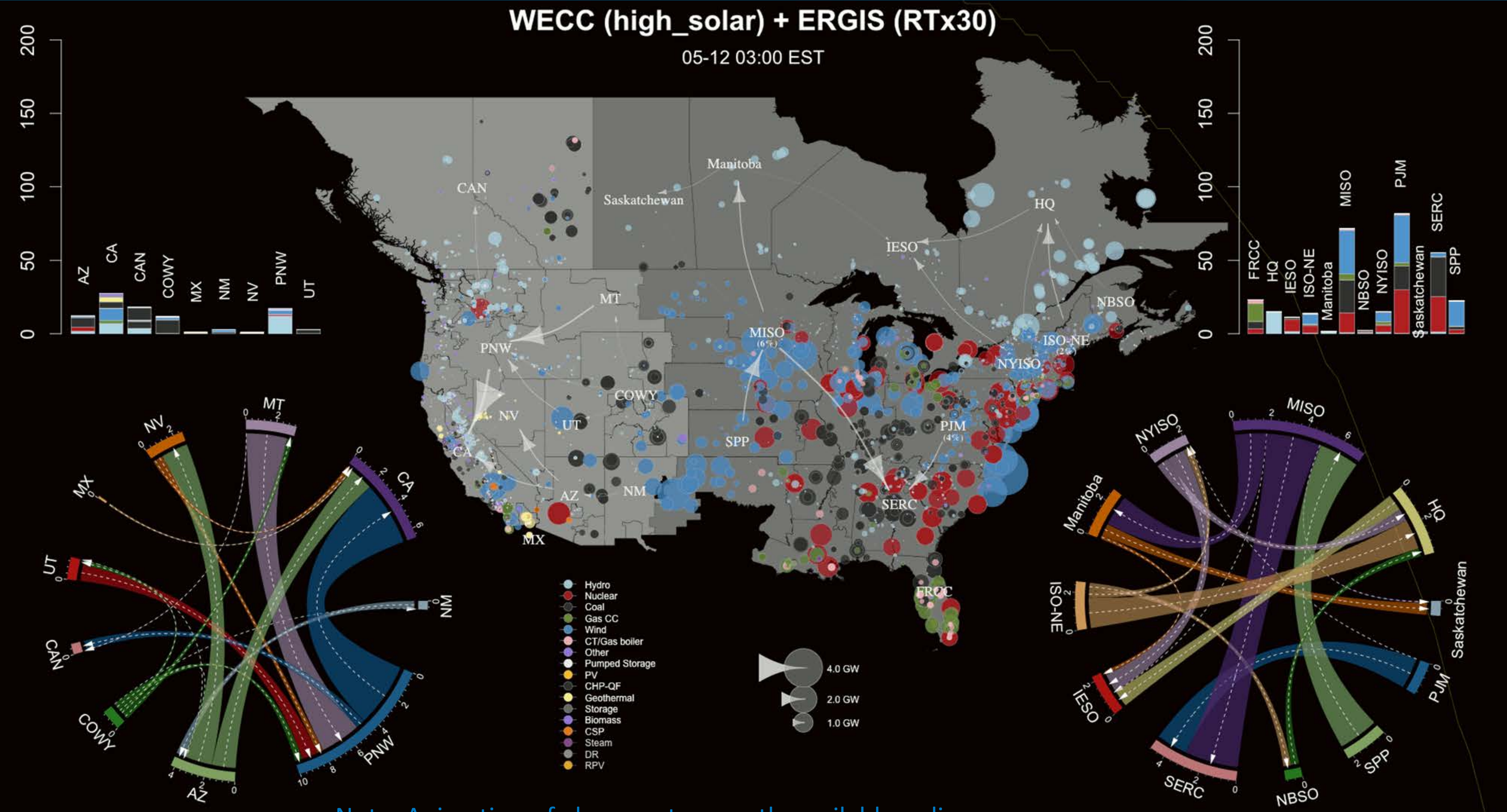


Figure 49. Total net interchange between regions

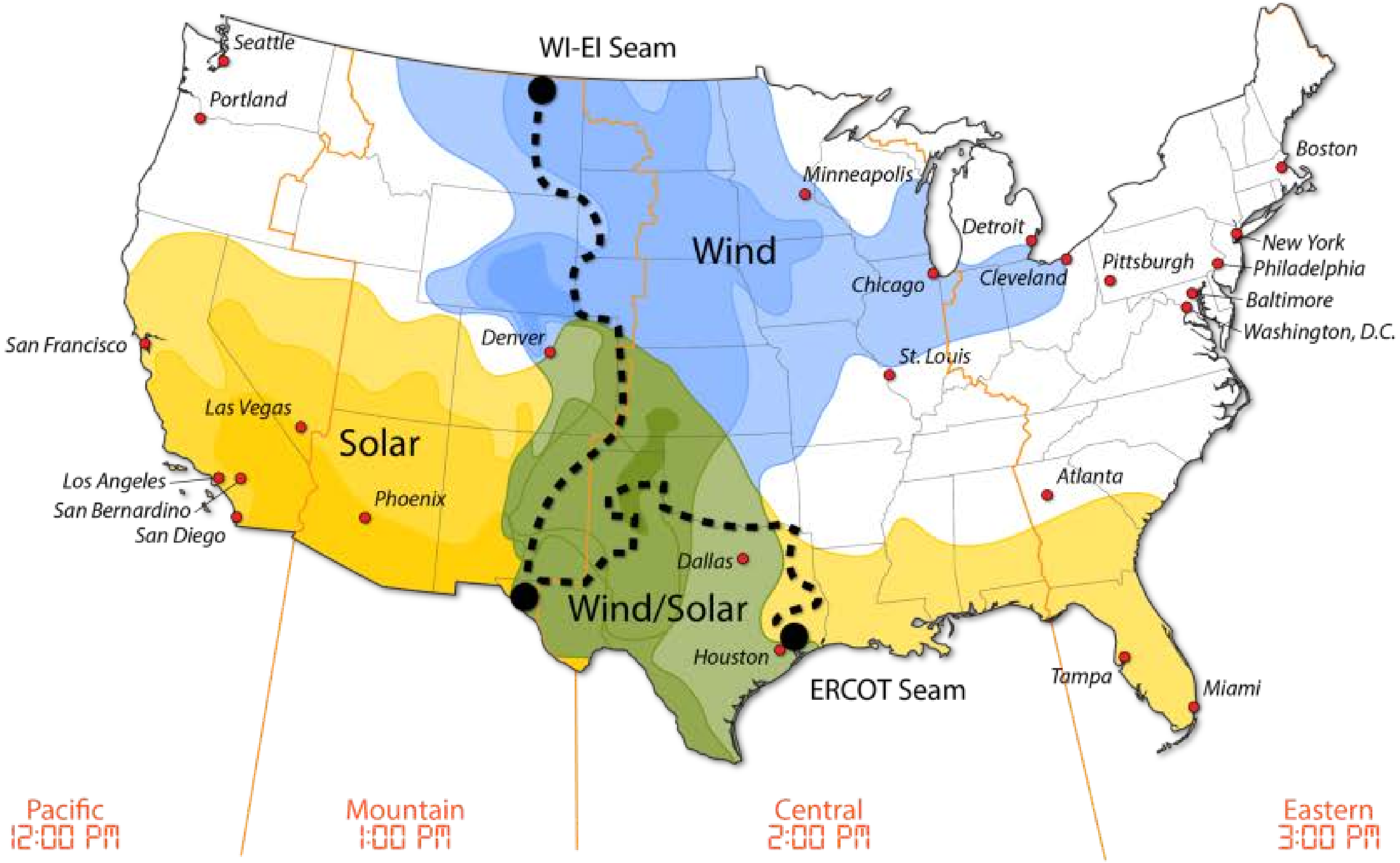
ERGIS Reports and Data available at:
http://www.nrel.gov/grid/ergis.html

What are we looking at now?



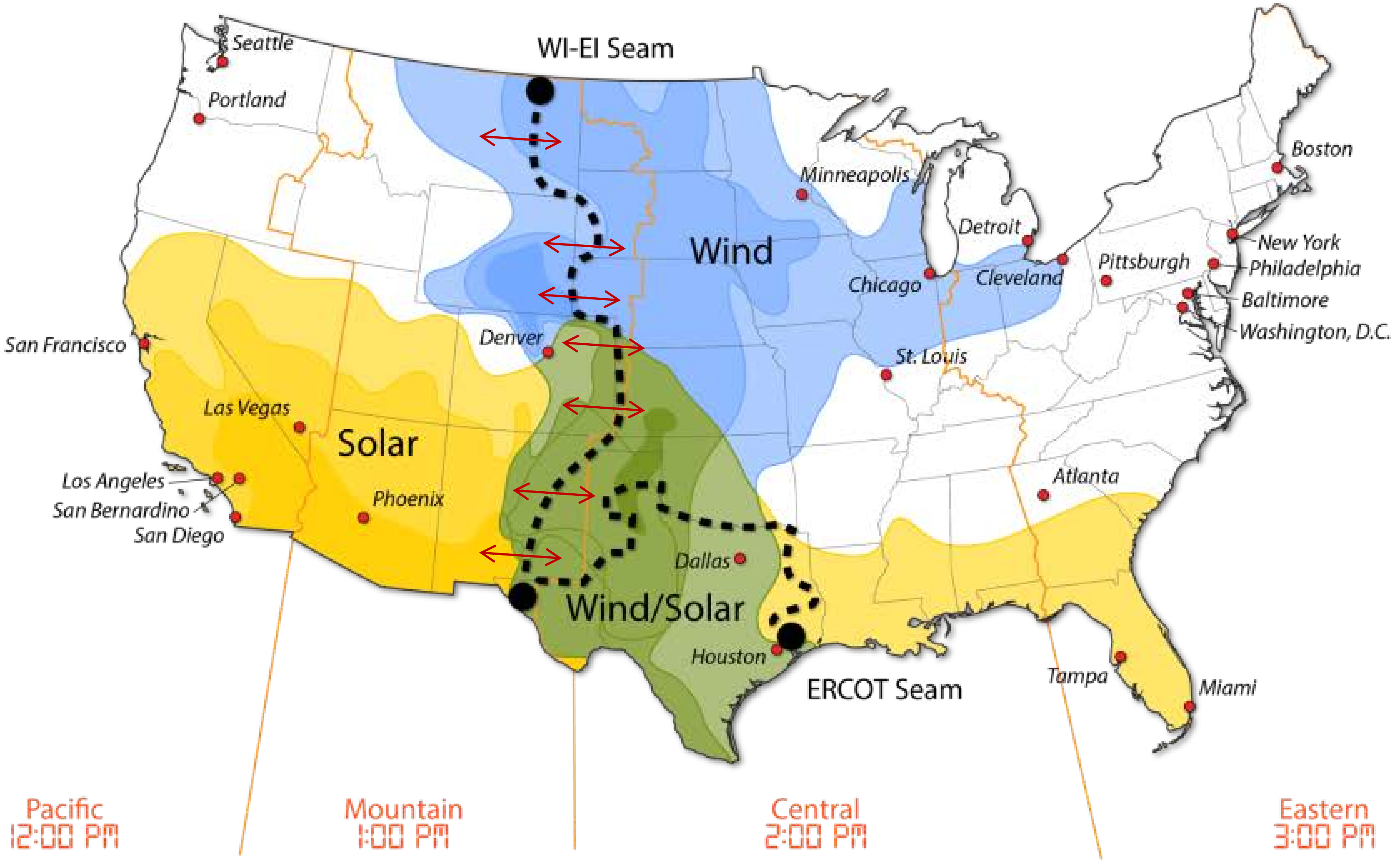
Note: Animation of above not currently available online

SEAMS Study

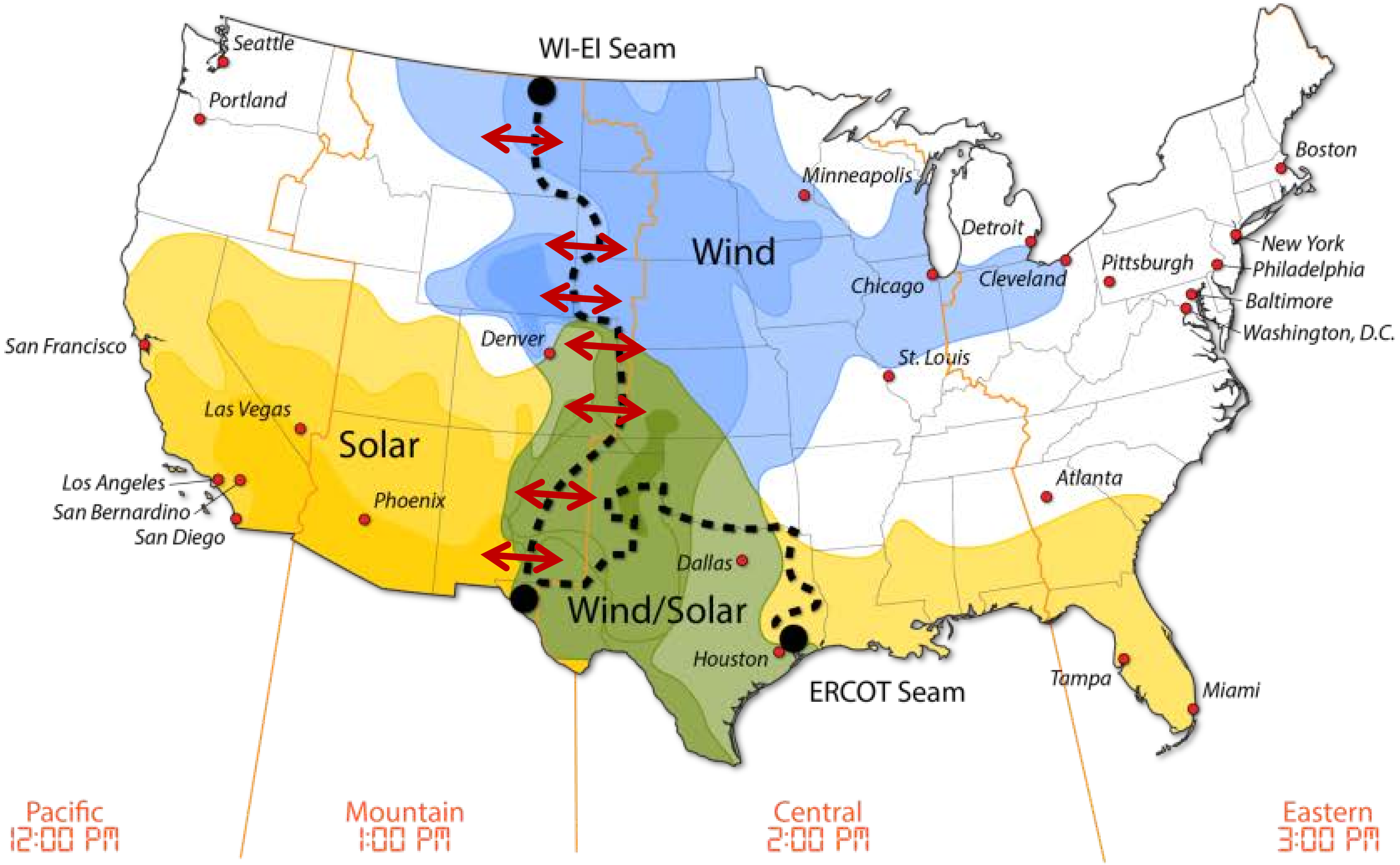


WI-EI Seam
Seattle
Portland
Boston
Minneapolis
Detroit
Wind
New York
Philadelphia
Pittsburgh
Chicago
Cleveland
Baltimore
Washington, D.C.
San Francisco
Denver
St. Louis
Las Vegas
Solar
Atlanta
Los Angeles
San Bernardino
San Diego
Phoenix
Dallas
Wind/Solar
Houston
ERCOT Seam
Tampa
Miami
Pacific
12:00 PM
Mountain
1:00 PM
Central
2:00 PM
Eastern
3:00 PM

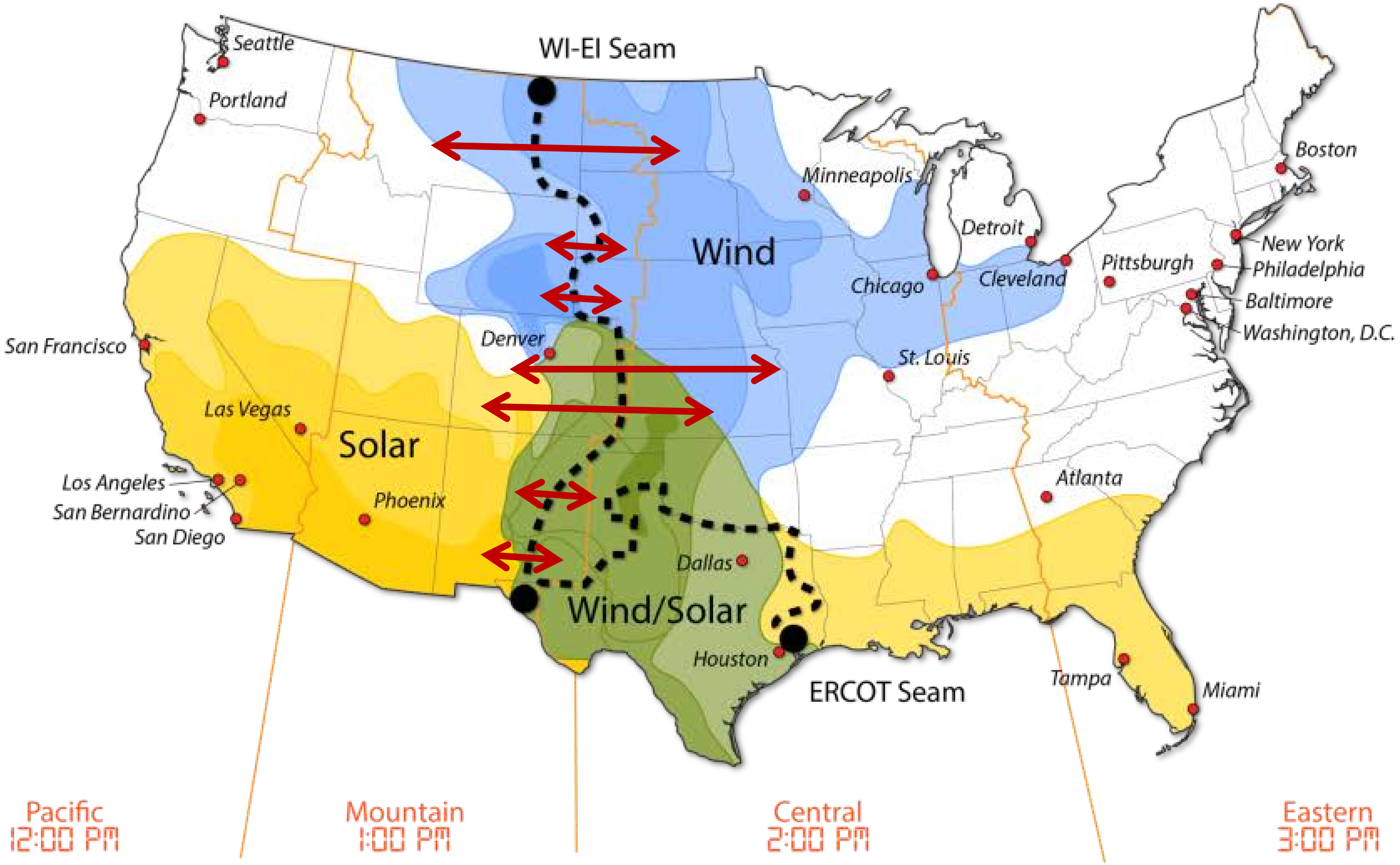
SEAMS Study Design 1--No Upgrades



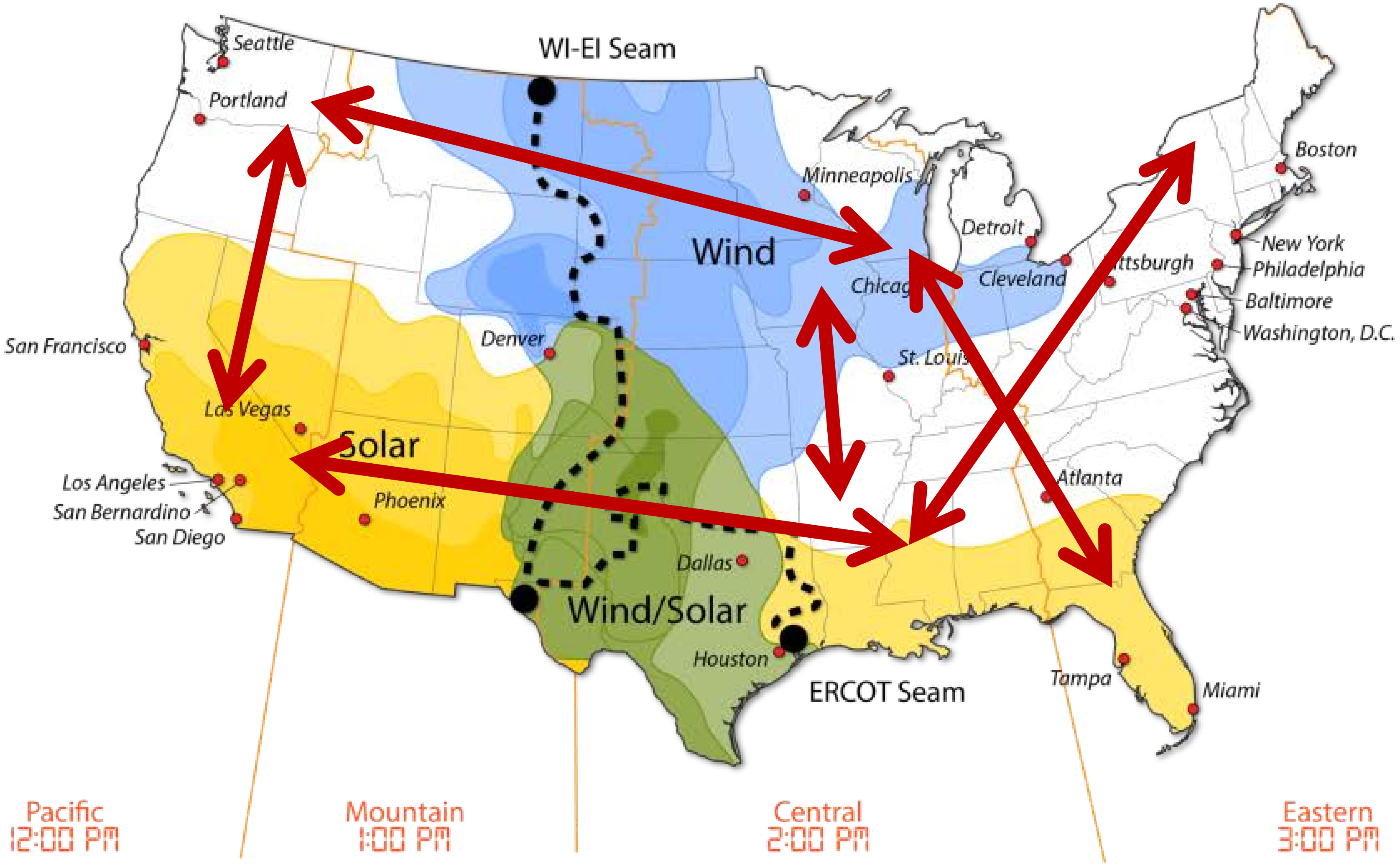
SEAMS Study Design 2a—Expand existing facilities



SEAMS Study Design 2b—Reconfigure size and/or location



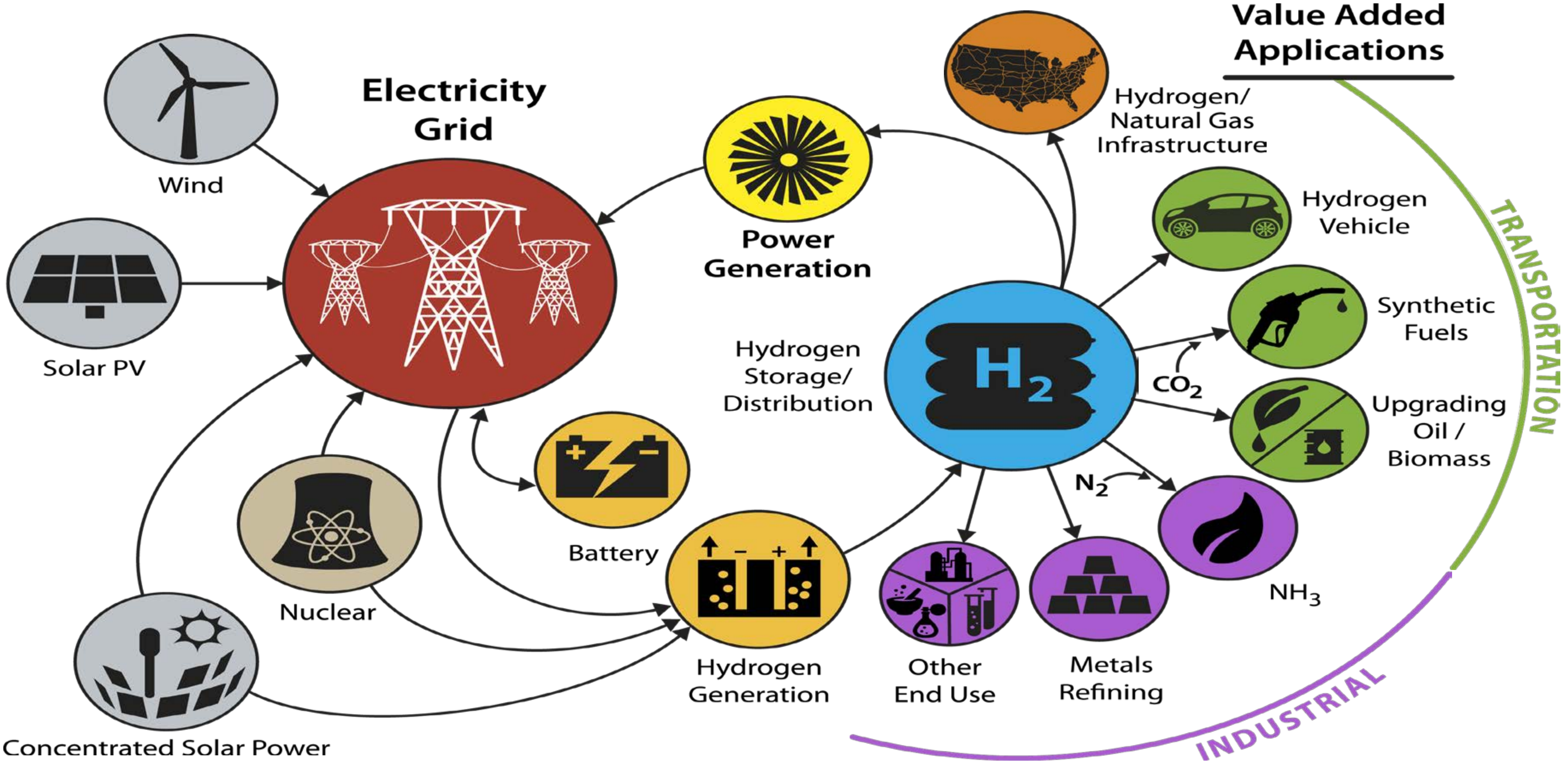
SEAMS Study Design 3—Macro grid overlay



North American Renewable Integration Study (NARIS)

- Partner with U.S. DOE, Natural Resources Canada and Mexico’s Secretaría de Energía (SENER)
- Study impacts of high penetrations of low-carbon and renewable electricity, and mitigating strategies
- Study interconnection of Canada, Mexico, and US power systems, from planning through operation and balancing at 5-minute resolution
- Understand potential benefits of cooperation
- Builds off the Interconnection Seams Study, Pan Canadian Wind Integration Study, and Mexico’s Renewable Integration Study

FOR DISCUSSION: USES OF CURTAILED PV : Conceptual H_2 at Scale Energy System*



*Illustrative example, not comprehensive

What we know and don't know about grid integration

1. Could the US operate the grid with high levels of VRE?
2. How could large amounts of distributed VRE impact the distribution and bulk power systems?
3. Can we control a grid with millions of control points that could result from large amounts of VRE and distributed energy resources (DER)?
4. What are the market and policy implications of high VRE generation?
5. What role could VRE play in decarbonization across the economy?

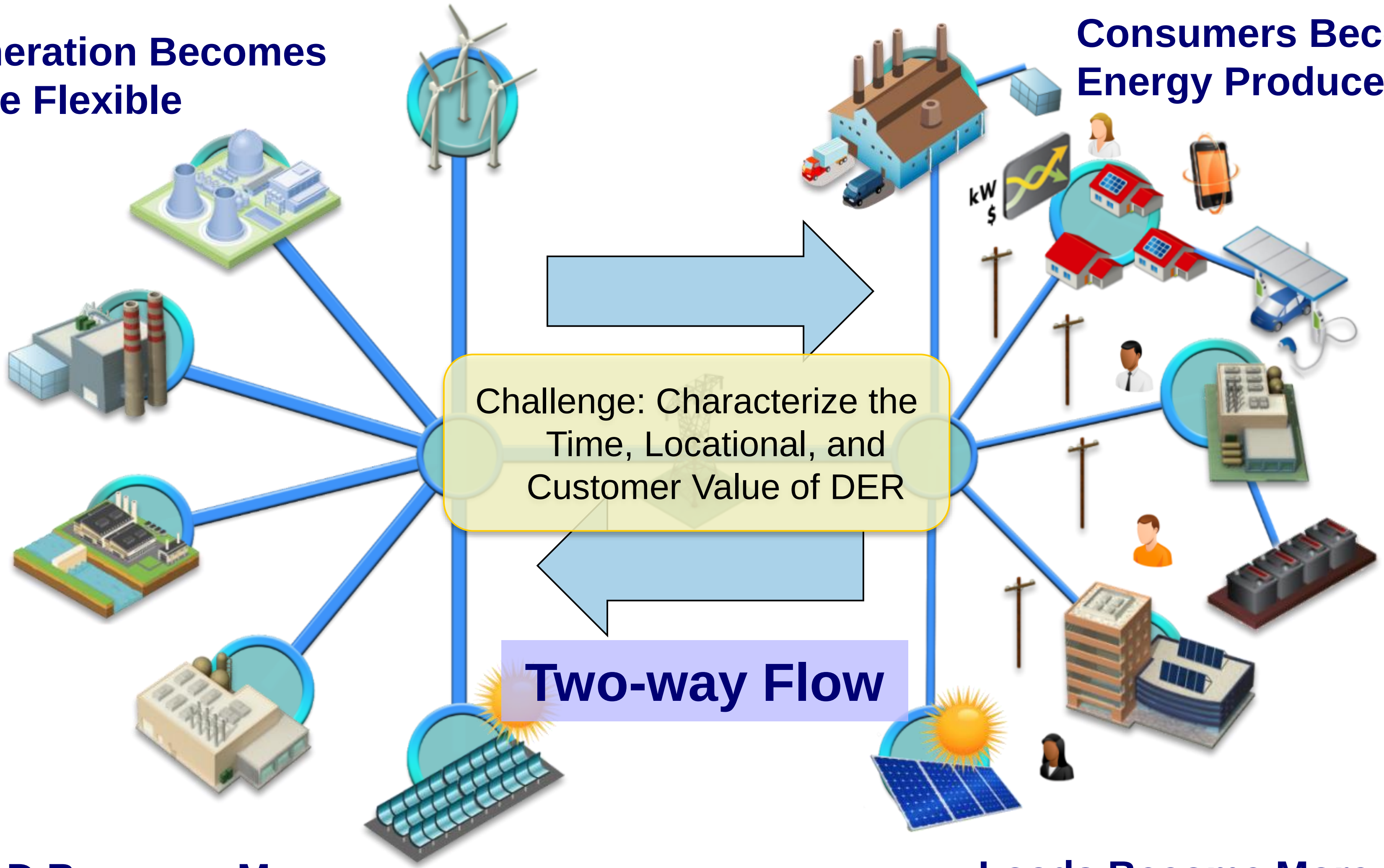
Time, Location, and Customer Value of DER

Workshop: Retaining the Value of PV at High Penetration

October 13, 2016, Washington DC

Bernie Neenan, EPRI

Evolving Power Delivery System



Generation Becomes More Flexible

Consumers Become Energy Producers

Challenge: Characterize the Time, Locational, and Customer Value of DER

Two-way Flow

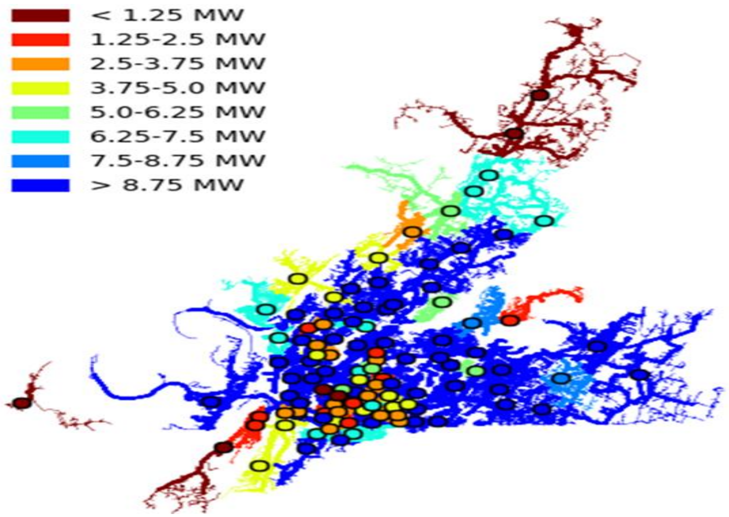
T & D Becomes More Controllable and Resilient

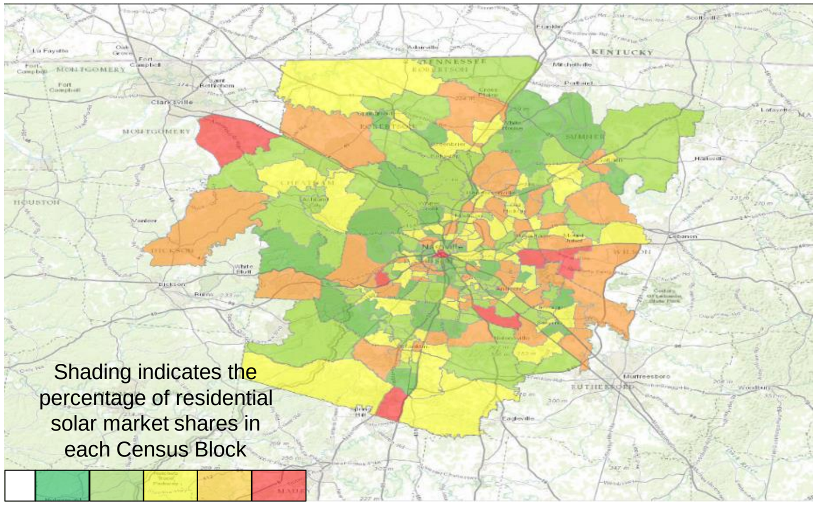
Loads Become More Interactive and Dynamic

Distribution System Readiness

Hosting Capacity

- Physical system capability
  - DER accommodation
  - DER integration
- Area and feeder level studies
- Power flow modeling

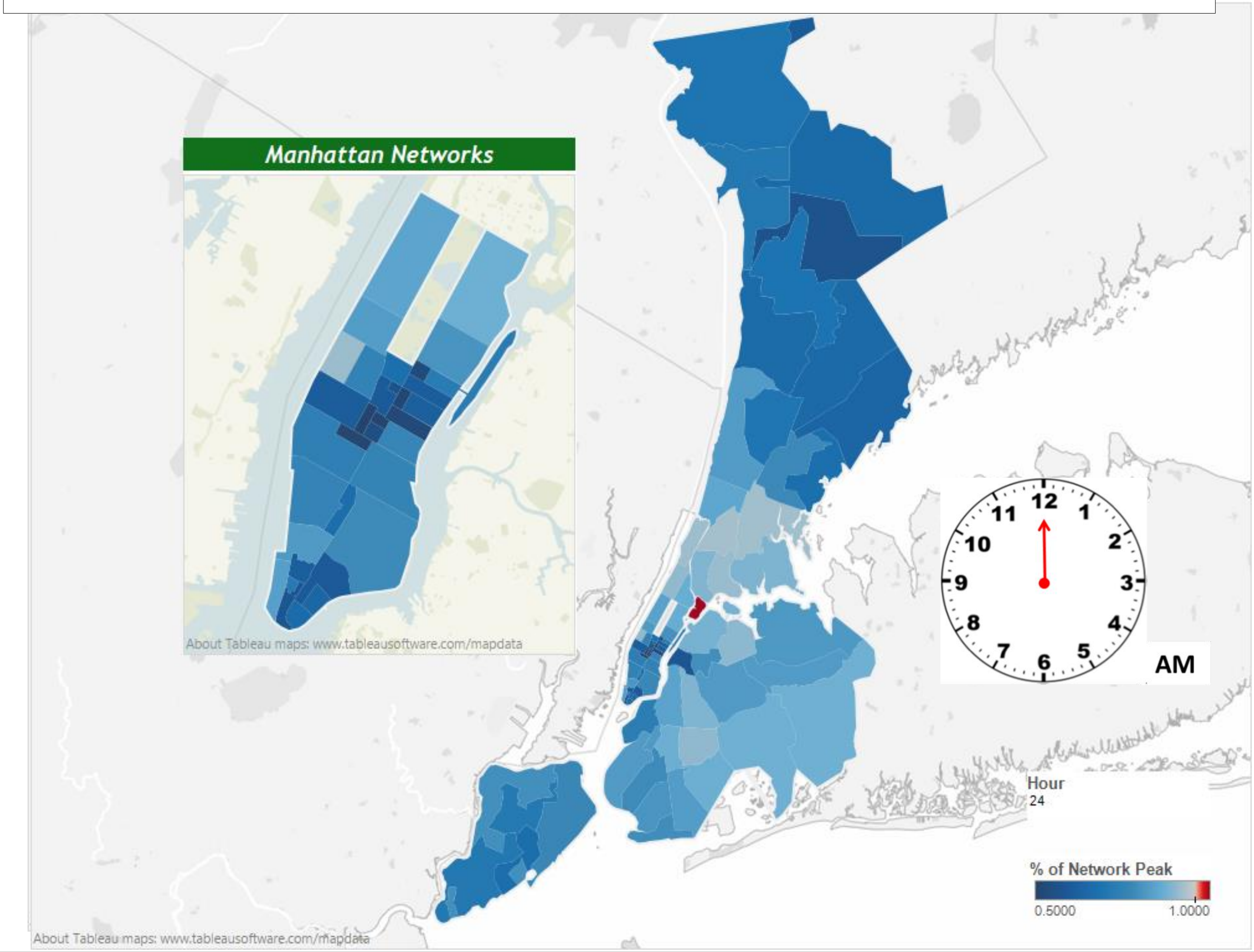



Shading indicates the percentage of residential solar market shares in each Census Block

Hosting Inclination

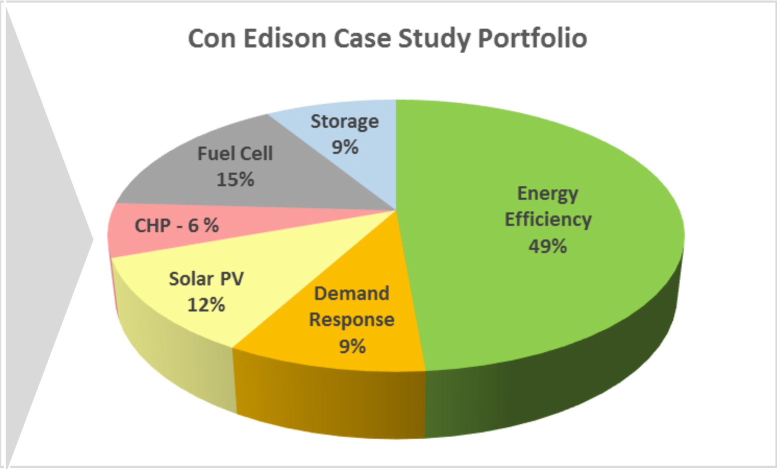
- Customer perspective
  - Premises potential
  - Customer inclination
- Map to area/feeders
- Preference/Adoption modeling

Time Value of DER



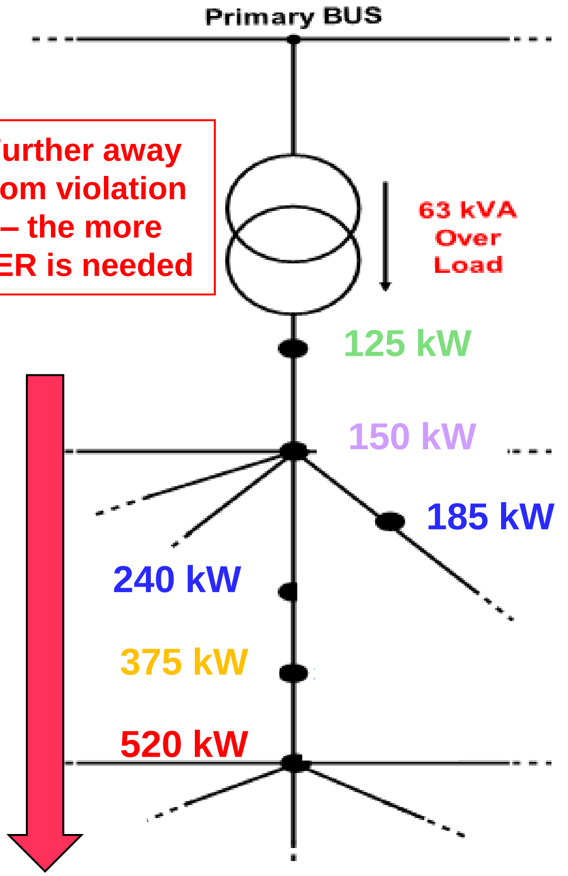
Time - It Takes a Portfolio of Technologies

Hour Ending	Peaking Risk Per Period	Estimated Solar Energy Production from a 1 MW installation (MW)	Estimated Energy Efficiency Relief from 1 MW Residential Lighting (MW)	Utility-side Battery Operations Assuming 1 MW Battery (MW)
01:00 AM	0.0%	0.00	0.38	-1.20
02:00 AM	0.0%	0.00	0.14	-1.20
03:00 AM	0.0%	0.00	0.12	-1.20
04:00 AM	0.0%	0.00	0.12	-1.20
05:00 AM	0.0%	0.00	0.12	-1.20
06:00 AM	0.0%	0.00	0.17	-1.20
07:00 AM	0.0%	0.02	0.32	-1.20
08:00 AM	0.0%	0.09	0.39	0.00
09:00 AM	0.0%	0.22	0.39	0.00
10:00 AM	0.0%	0.32	0.27	0.00
11:00 AM	0.0%	0.46	0.14	0.00
12:00 PM	0.0%	0.51	0.11	0.00
01:00 PM	6.5%	0.56	0.11	0.00
02:00 PM	8.1%	0.57	0.11	0.00
03:00 PM	8.8%	0.52	0.11	0.00
04:00 PM	9.0%	0.42	0.11	0.00
05:00 PM	8.8%	0.31	0.15	0.00
06:00 PM	9.2%	0.23	0.29	0.00
07:00 PM	9.8%	0.11	0.49	1.00
08:00 PM	8.4%	0.03	0.72	1.00
09:00 PM	9.1%	0.00	0.90	1.00
10:00 PM	12.7%	0.00	0.99	1.00
11:00 PM	7.6%	0.00	0.87	1.00
12:00 AM	1.9%	0.00	0.60	1.00



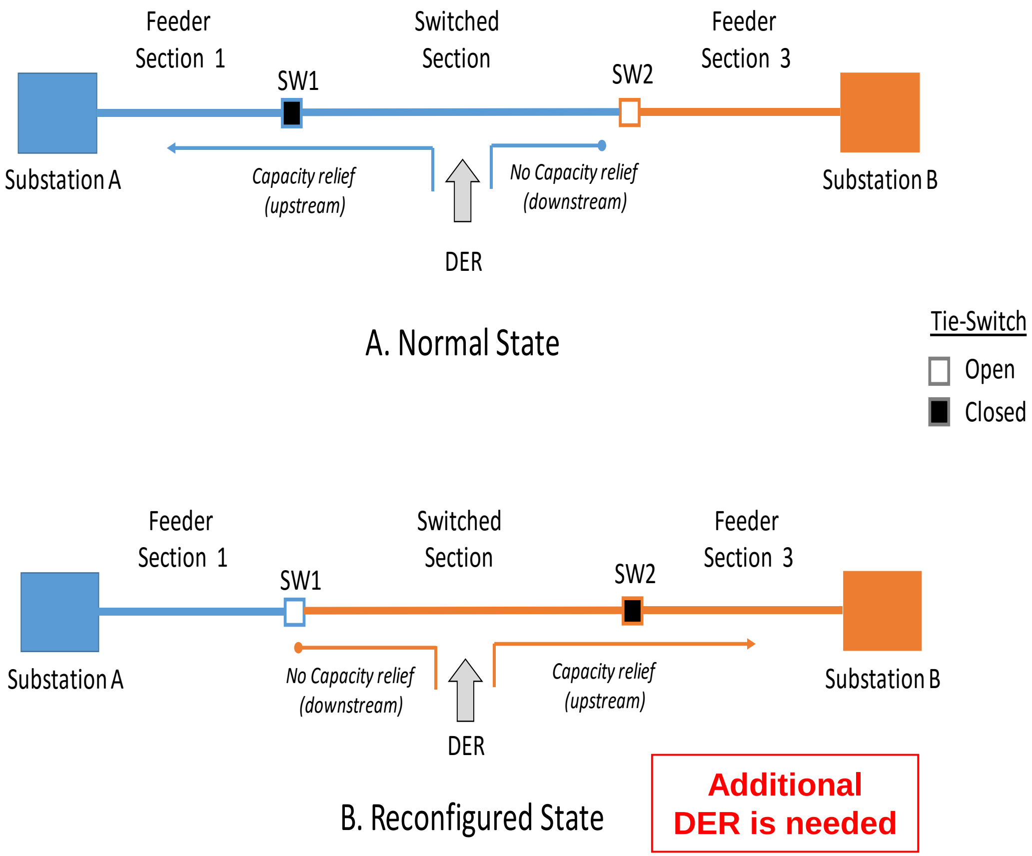
Illustrative Con Edison BQDM Example

Location, Location, Location



Further away from violation – the more DER is needed

Locational Sensitivity



Additional DER is needed

Network

Switchable Radial

Customer Value of DER – Discrete Choice Experiments

- Who adopts what DER technology, when and why?
- Quantify how individuals value attributes of a product/service by asking them choose amongst hypothetical alternatives
  - Attribute contribution to preferences
  - Demographics and other deep interactions can contribute to value
- Produces “choice models” to predict participation, and by whom
- Add market dynamics to estimate adoption

Stated preference: choices consumers say they would make if confronted with the purchase/choice decision

Revealed preference: derived from observed choices (market data, sales transactions) that consumers made

Residential Solar Market Share Model Development Flowchart

Survey

2016 Residential Solar Survey

- Establish attributes that drive preferences
- Sample from the attribute topology
- Design and test survey instrument
- Administer representative sample

- Estimate the choice model
  - Attribute influences
  - Deep interactions
  - Decision-making structures

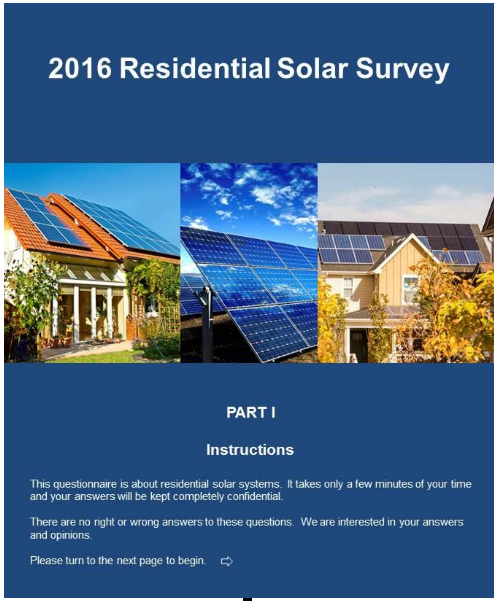
Choice Model

Residential Solar Preferences

DCE Residential Solar Survey Components

Administered to

- 5500 households
- May-July 2016
- In 8 markets
- Direct mail



2016 Residential Solar Survey

PART I

Instructions

This questionnaire is about residential solar systems. It takes only a few minutes of your time and your answers will be kept completely confidential.

There are no right or wrong answers to these questions. We are interested in your answers and opinions.

Please turn to the next page to begin. ⇨

Collected

- 45% overall response rate
- As high as 60%

Section A Household Characteristics and Electricity Use

Introduction to Residential Solar Alternatives

Section B Residential Solar Choices

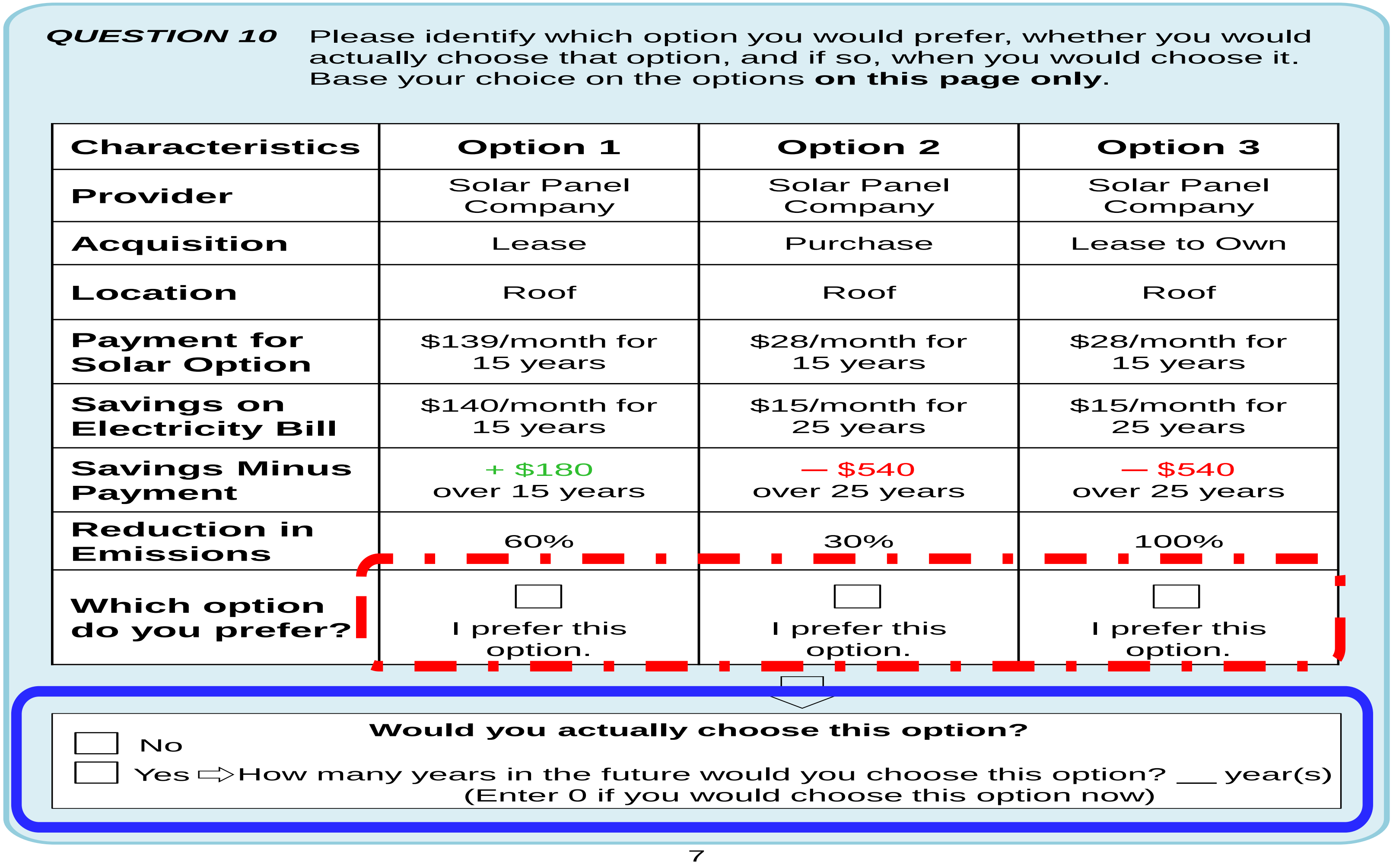
Sections C & D Additional Questions and Demographics

Developed and Tested Experimental Design of Attributes and Levels

Attributes	Levels	
Provider	Electric Utility, Solar Panel Company	
Acquisition	Purchase, Lease, Lease to Own, Community	
Location	Roof, Neighborhood, 5 miles from home, Another state	
Payment for Solar Option	$17/month - $417/month	1 year, 5 years, 15 years, 25 years
Savings on Electricity Bill	$15/month - $165/month	1 year, 5 years, 15 years, 25 years
Reduction in Emissions	10%, 30%, 60%,100%	

- Attributes NOT included as result of pretests:
  - Peer effects (Neighborhood penetration) – not relevant
  - Incentives / Discounts – payment and savings are better benefits measures
  - Size / physical appearance – did not influence preferences

Survey- Example Choice Situation



QUESTION 10 Please identify which option you would prefer, whether you would actually choose that option, and if so, when you would choose it. Base your choice on the options **on this page only**.

Characteristics	**Option 1**	**Option 2**	**Option 3**
Provider	Solar Panel Company	Solar Panel Company	Solar Panel Company
Acquisition	Lease	Purchase	Lease to Own
Location	Roof	Roof	Roof
Payment for Solar Option	$139/month for 15 years	$28/month for 15 years	$28/month for 15 years
Savings on Electricity Bill	$140/month for 15 years	$15/month for 25 years	$15/month for 25 years
Savings Minus Payment	+ $180 over 15 years	— $540 over 25 years	— $540 over 25 years
Reduction in Emissions	60%	30%	100%
Which option do you prefer?	☐ I prefer this option.	☐ I prefer this option.	☐ I prefer this option.

Would you actually choose this option?

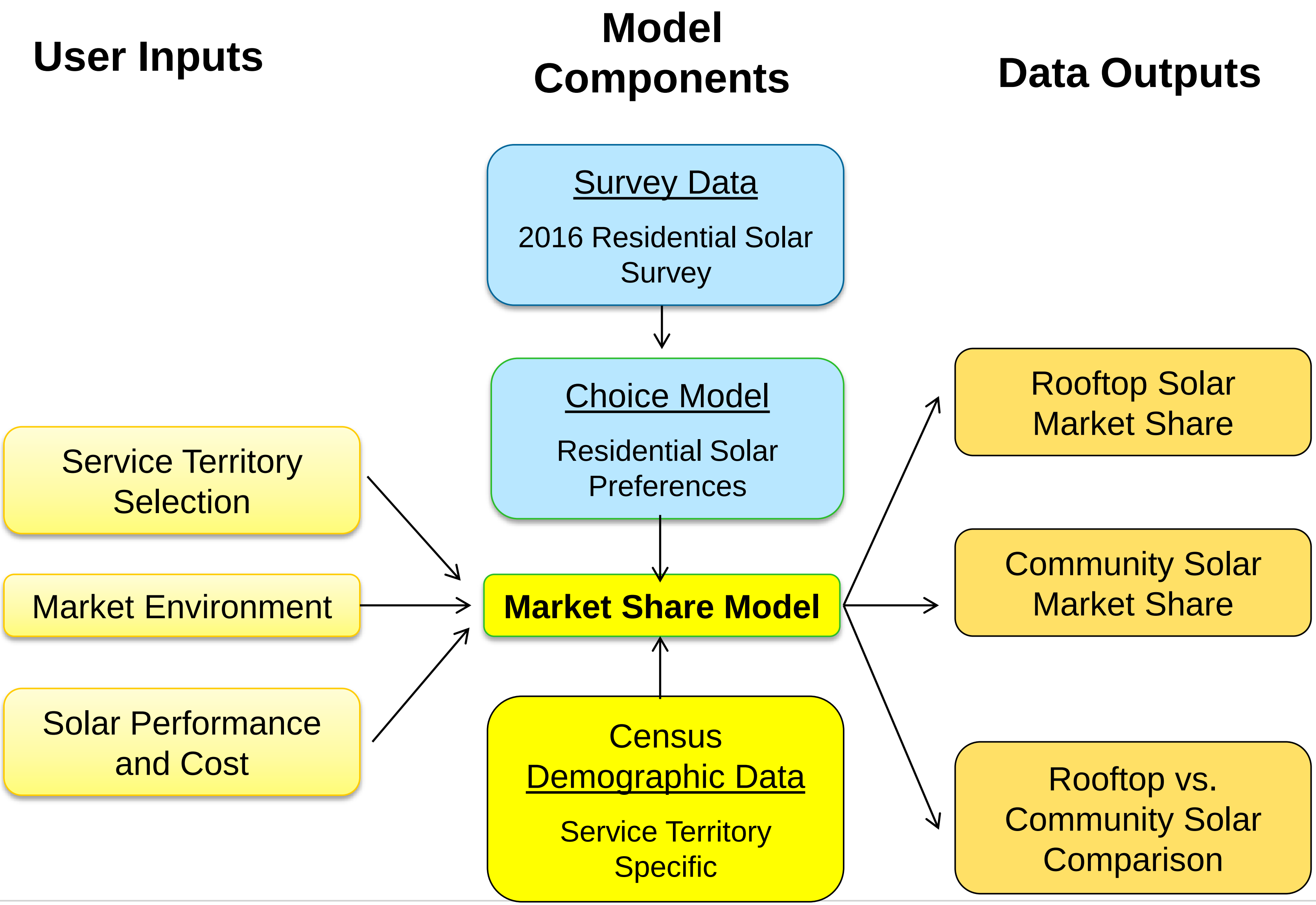
☐ No

☐ Yes ⇨ How many years in the future would you choose this option? ___ year(s)

(Enter 0 if you would choose this option now)

7

Residential Solar Market Share Model Development Flowchart



User Inputs

Model Components

Data Outputs

Survey Data

2016 Residential Solar Survey

Choice Model

Residential Solar Preferences

Service Territory Selection

Market Environment

Solar Performance and Cost

Market Share Model

Census Demographic Data

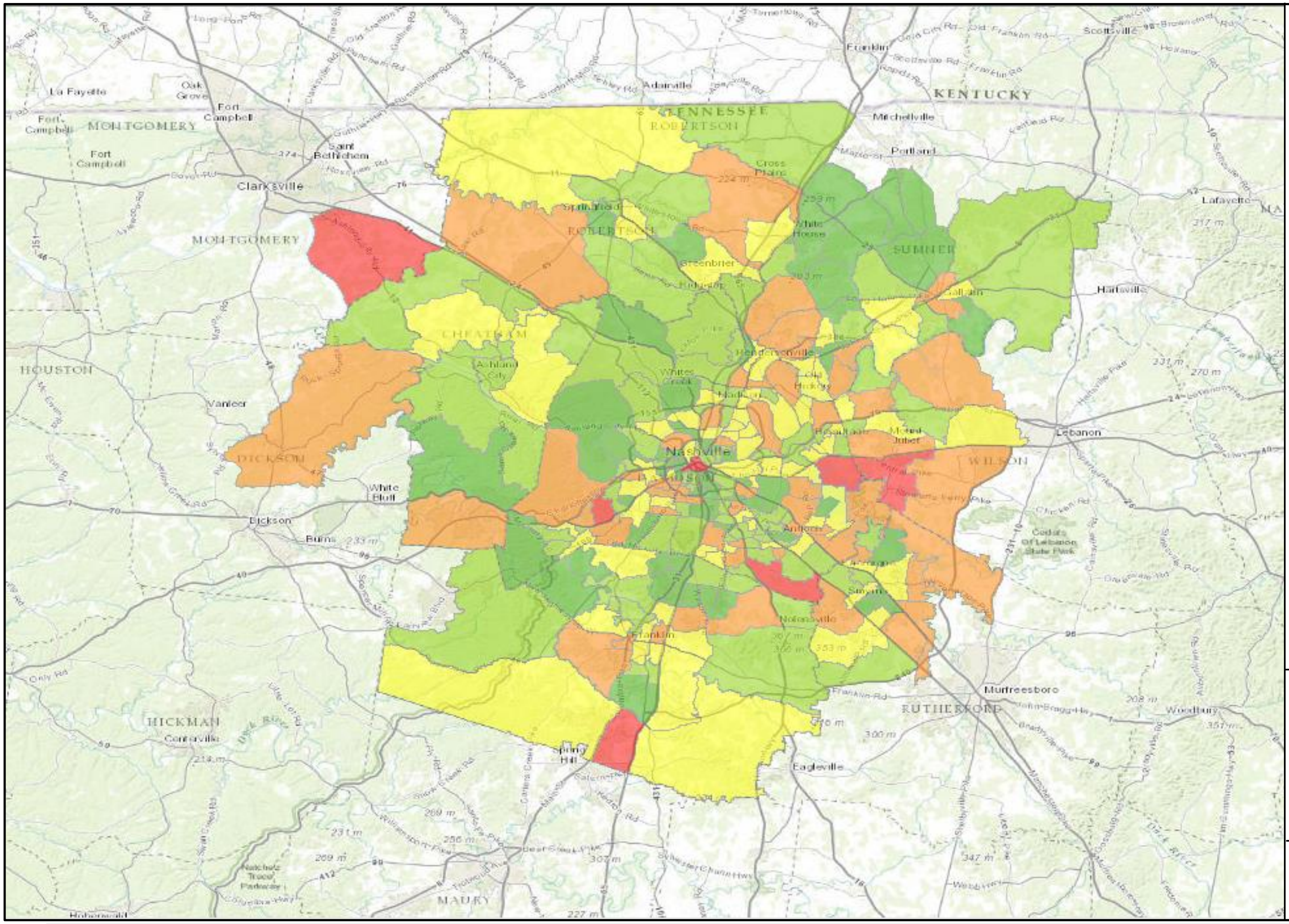
Service Territory Specific

Rooftop Solar Market Share

Community Solar Market Share

Rooftop vs. Community Solar Comparison

Results Can Be Mapped for Visualization



Legend

Shading indicates the percentage of residential solar market shares in each Census Block

⬜	🟩	🟩	🟨	🟧	🟥
<1%	1-2%	2-3%	3-4%	4-5%	>5%

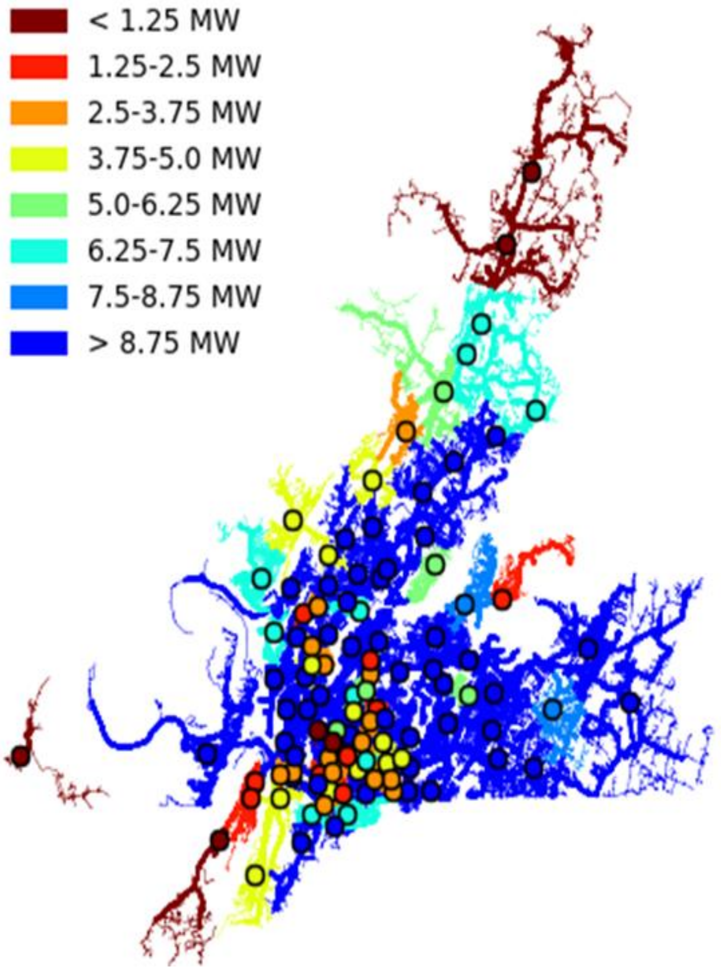
Nashville Residential Solar Market Shares

VERITAS
Economic Consulting

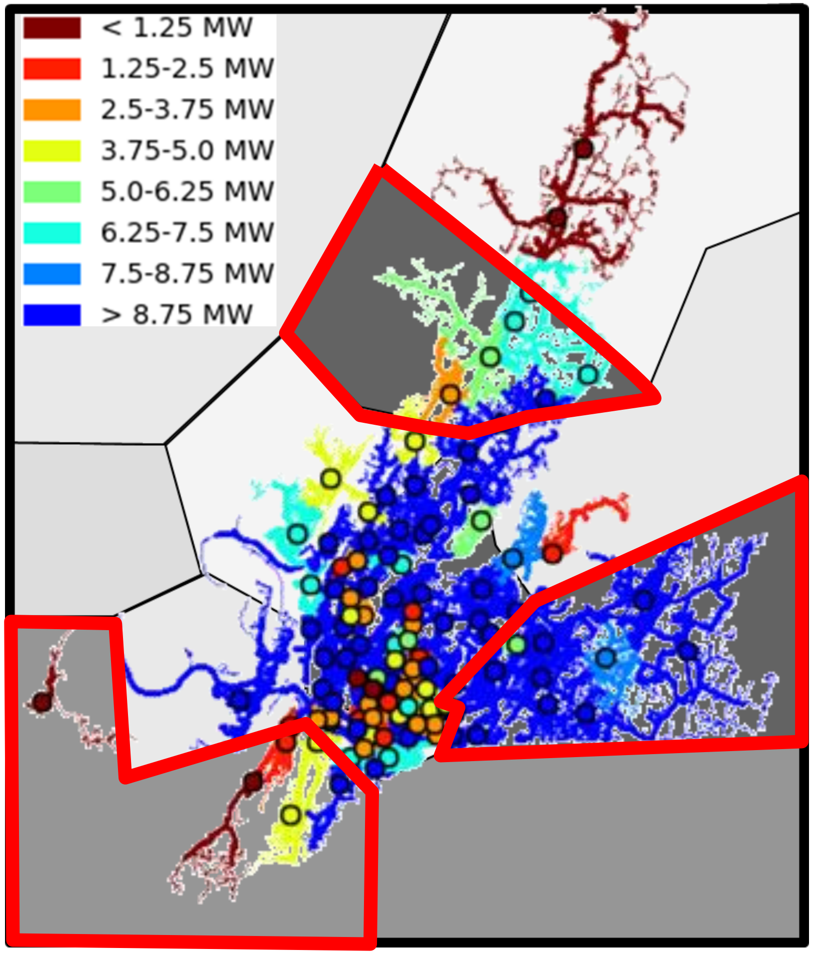
EPRI ELECTRIC POWER RESEARCH INSTITUTE

TLC Value of DER

DER Hosting Capacity



DER Hosting Inclination



Questions?

Thank You

Together…Shaping the Future of Electricity

Nadav Enbar	**Bernie Neenan**	**Steven Coley**
Principal Project Manager, EPRI	Technical Executive, EPRI	Sr. Project Engineer, EPRI
303.551.5208	865.218.8133	865.218.8082
nenbar@epri.com	bneenan@epri.com	scoley@epri.com

Impact of Price-Responsive Demand on the Value of PV

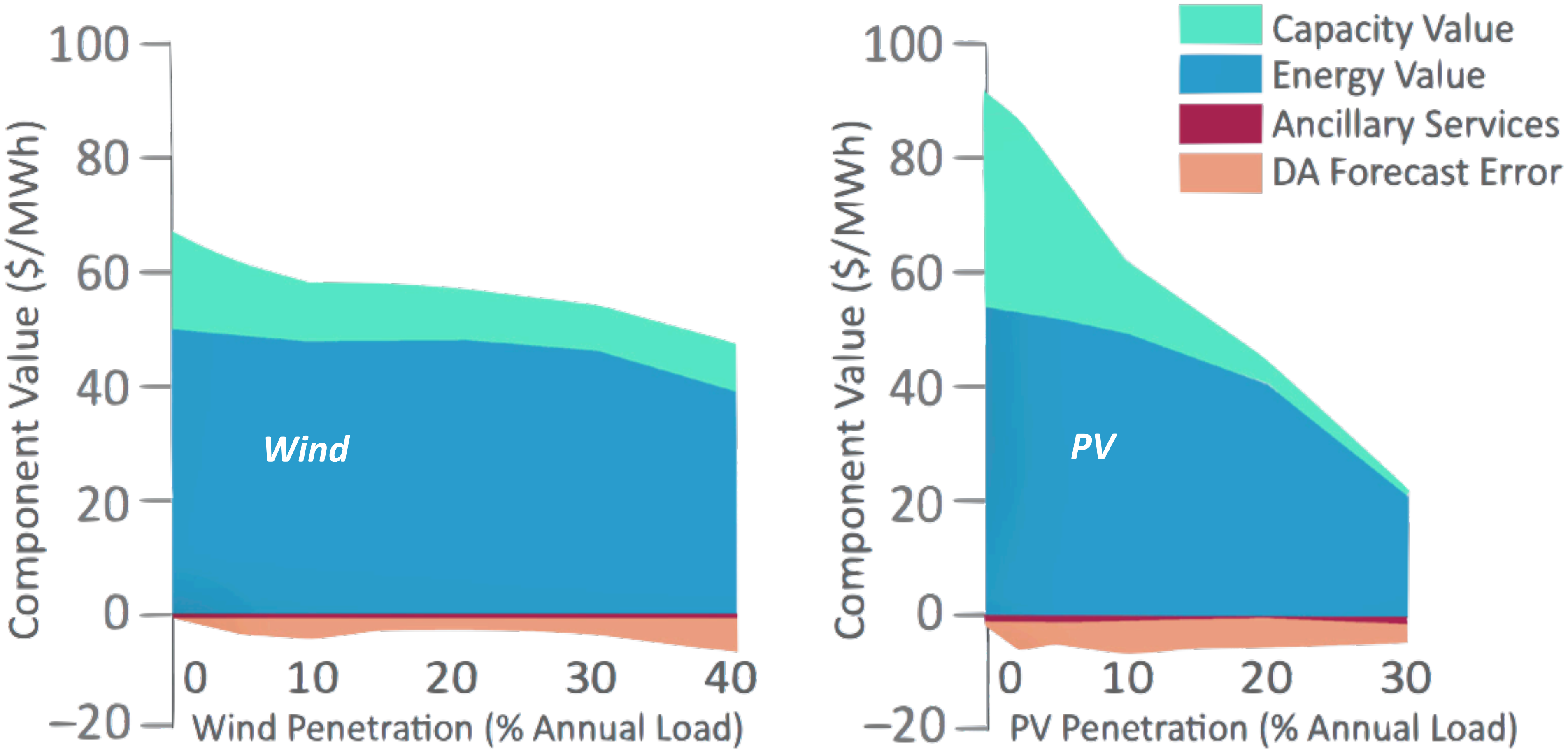
Andrew Mills

Lawrence Berkeley National Laboratory

Retaining the Value of PV at High Penetration

October 13, 2016

Decline in Economic Value Primarily Driven by Decreases in Capacity and Energy Value

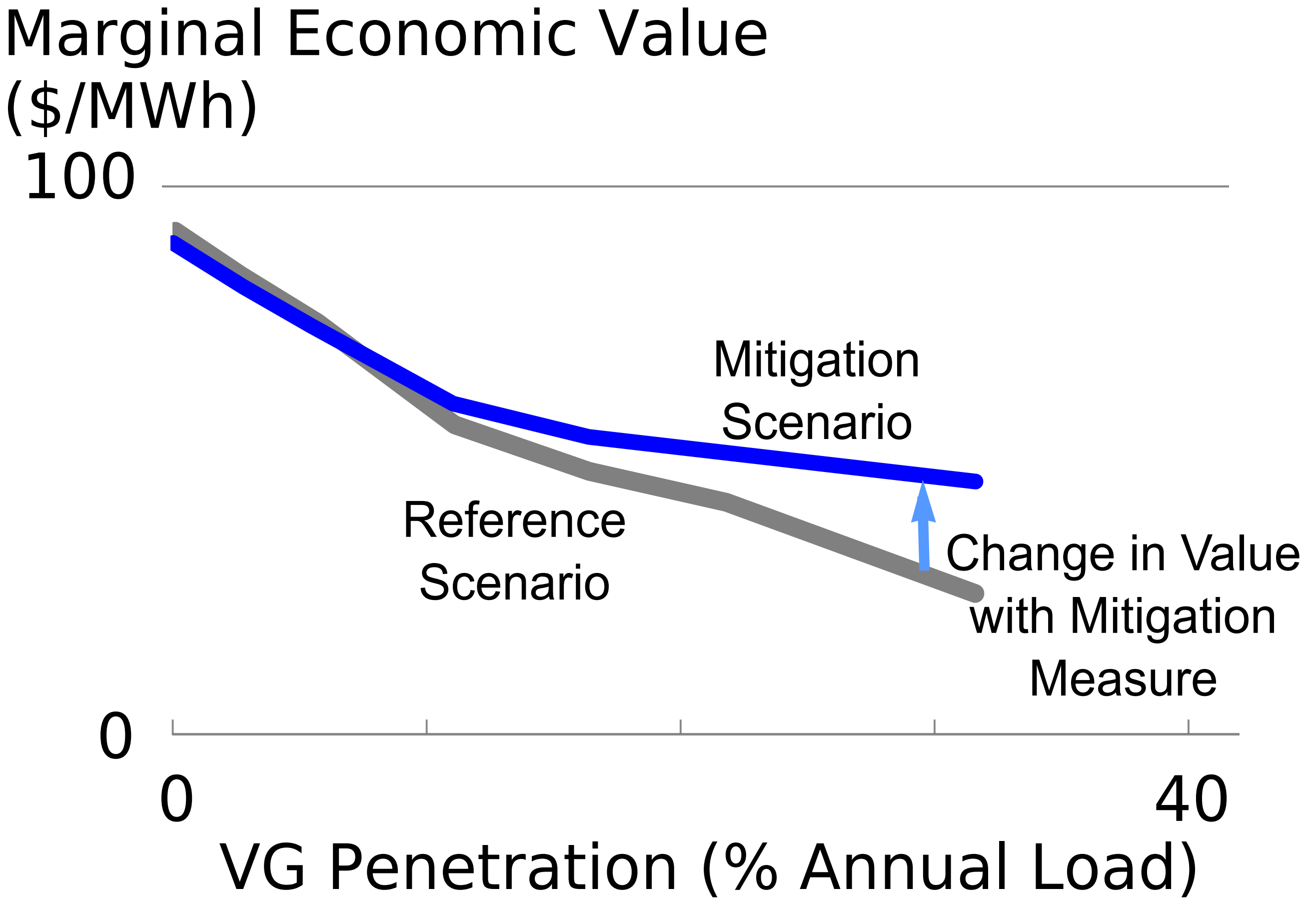


We examine causes in the decline in the marginal economic value. The primary factors are decreases in energy value (which fuels were displaced) and capacity value (how much conventional capacity was avoided).

Costs due to operational factors (day-ahead forecast errors and ancillary services) do not increase as much with penetration.

How Much Would the Value of VG Change if Mitigation Measures Were Implemented?

We use the same model and data to then estimate the degree to which different mitigation measures can stem the decline in the marginal economic value of variable generation.



The mitigation measures considered include:

- increased geographic diversity
- technological diversity
- more-flexible new conventional generation
- lower-cost bulk power storage
- price elastic demand subject to real-time pricing (RTP)

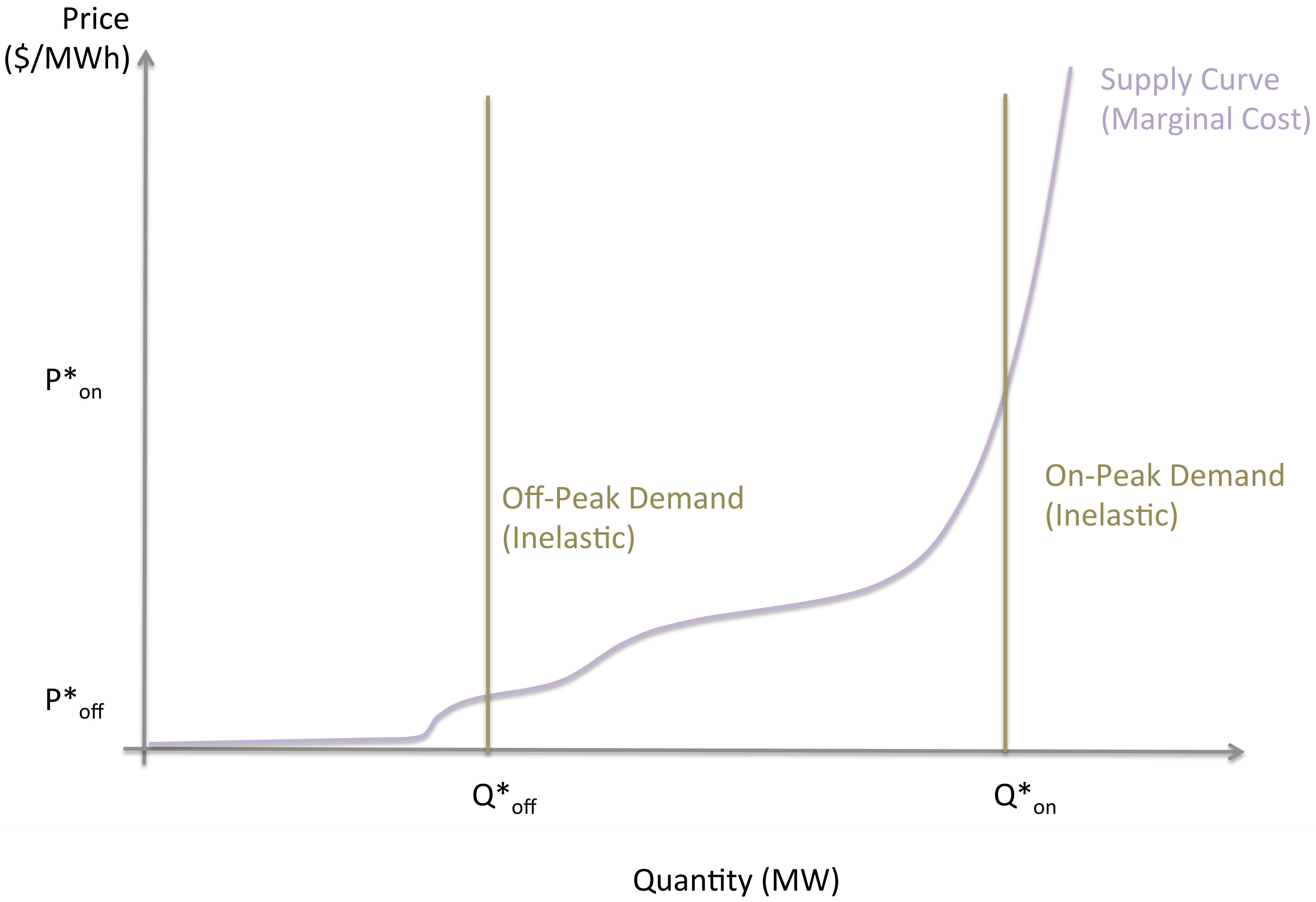
Overview of Results: Change in Value of VG with Implementation of Mitigation Measures

Mitigation Measure	Wind penetration		
($/MWh)	20%	30%	40%
Geographic Diversity	2.5	4.9	10.6
RTP	3.7	5.0	7.9
Low-cost Storage	-0.1	0.4	4.4
Quick-start CCGT	0.3	0.3	-0.6
10% PV	1.1	-1.1	-5.2
10% CSP₆	-0.2	-0.6	-4.4

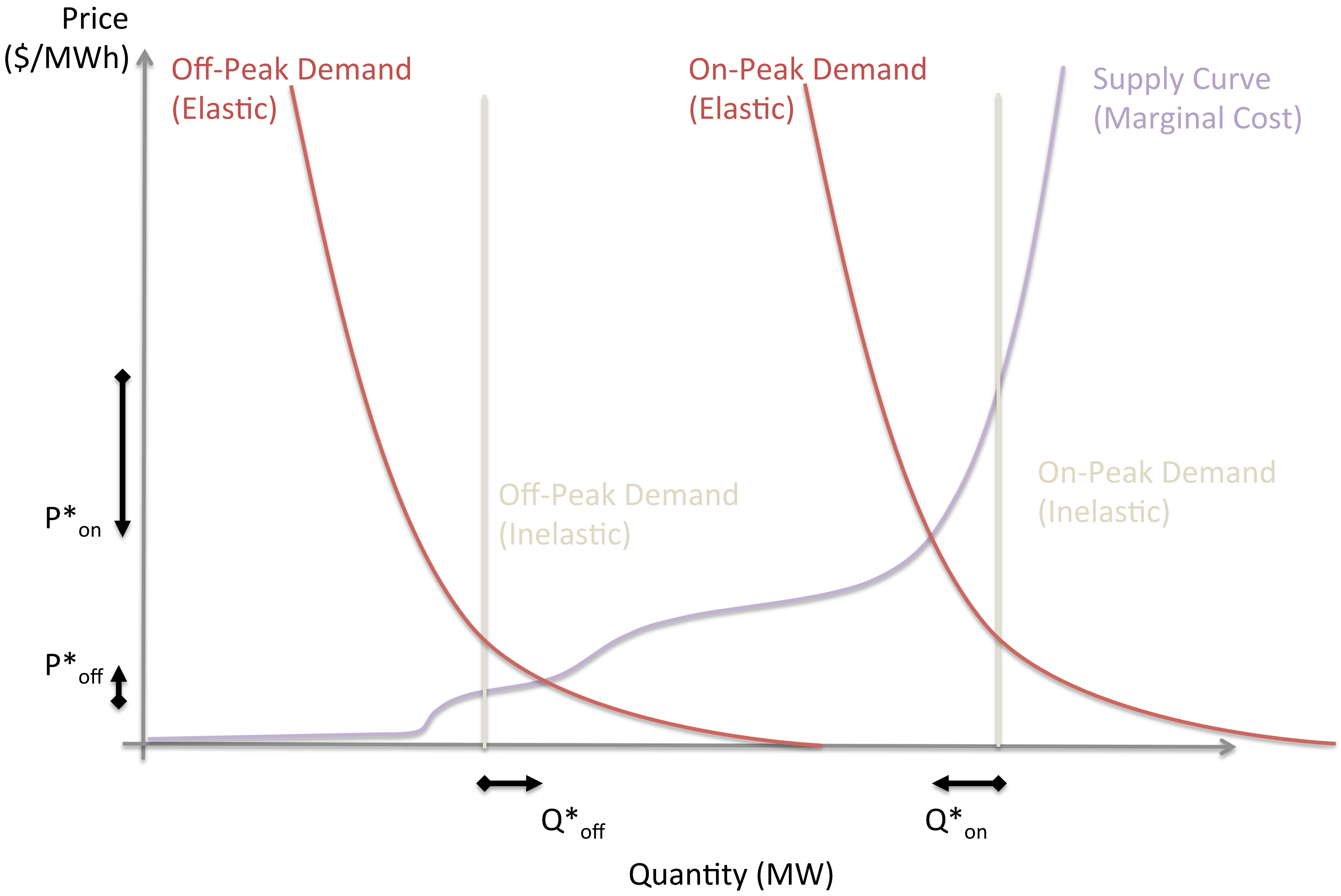
Mitigation Measure	PV penetration		
($/MWh)	10%	20%	30%
Low-cost Storage	3.3	8.4	19.7
RTP	10.4	7.5	7.4
Quick-start CCGT	-1.8	-1.0	-0.2
10% Wind	7.4	-1.1	-6.4

Tables show the change in the value of wind or PV with the implementation of the mitigation measure relative to the value in the Reference Scenario without the mitigation measure. Additional caveats and description of the results are available in the full report.

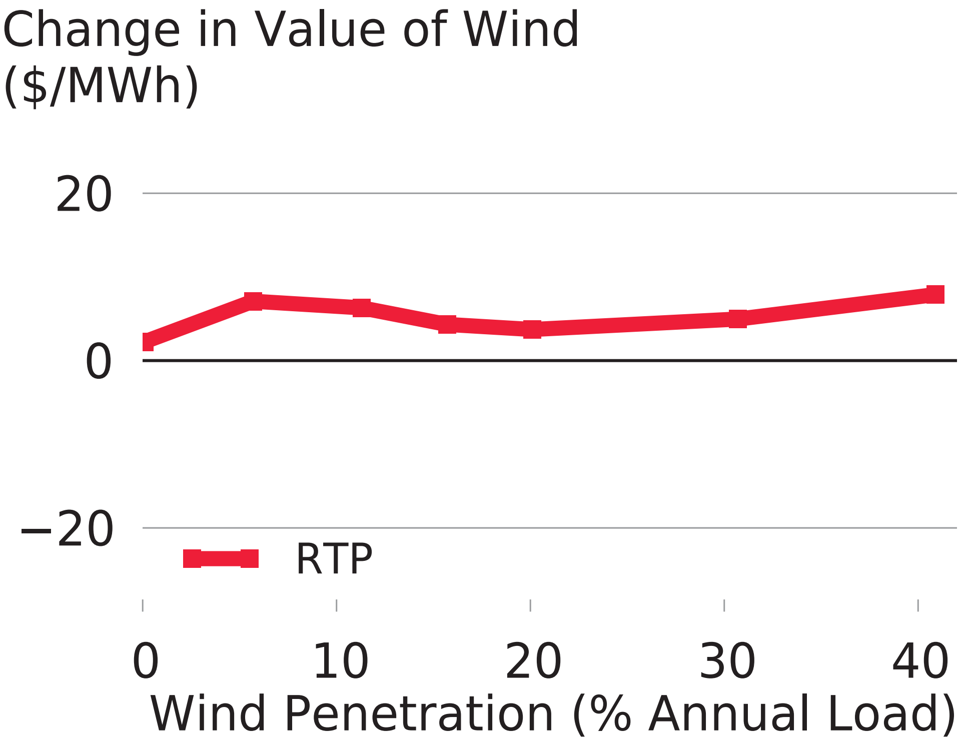
Real Time Pricing (RTP) Allows Demand to Be More Price Elastic



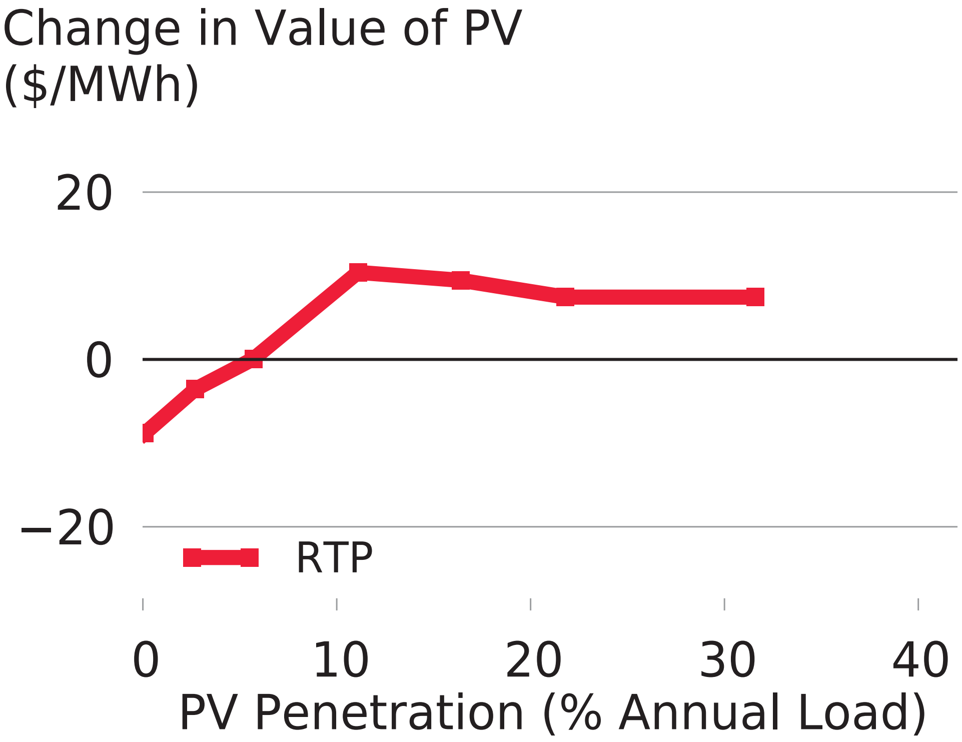
Real Time Pricing (RTP) Allows Demand to Be More Price Elastic



RTP Increases Value of VG By Allowing Demand to Change In Response to Availability of VG

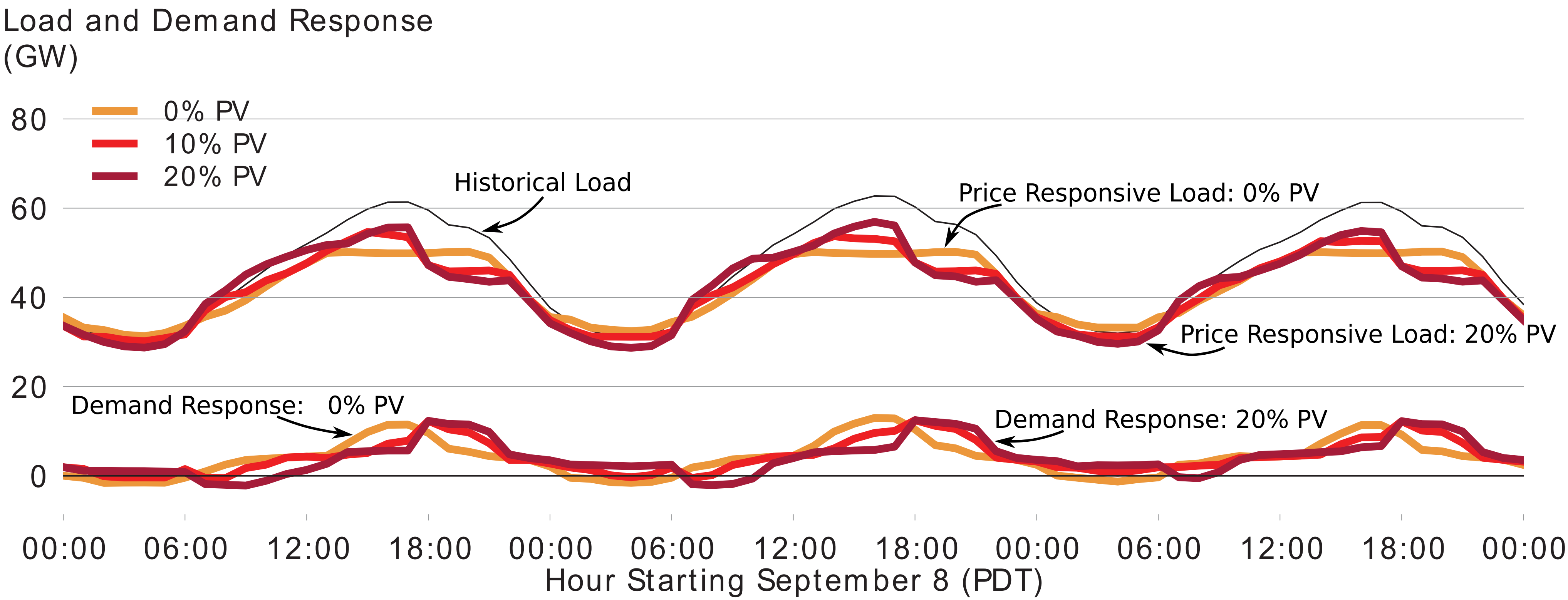


RTP leads to more frequent, but less severe, high prices which increases the capacity value of wind.
Energy value is increased since RTP increases demand during periods of high wind and decreases demand in periods of low wind.



At PV low penetration, RTP lowers demand in the summer afternoon and decreases the value of PV.
At high PV penetration, energy value of PV is increased as RTP shifts demand to times with PV generation.

Character of Demand Response Provided by RTP with High PV is Different than Without PV



RTP without PV leads to demand response that is greatest in the late afternoon and effectively levels the peak demand.

Increasing PV penetration shifts the demand response provided by RTP from late afternoon into early evening on peak load days.

Character of Demand Response Provided by RTP with High PV is Different than Without PV

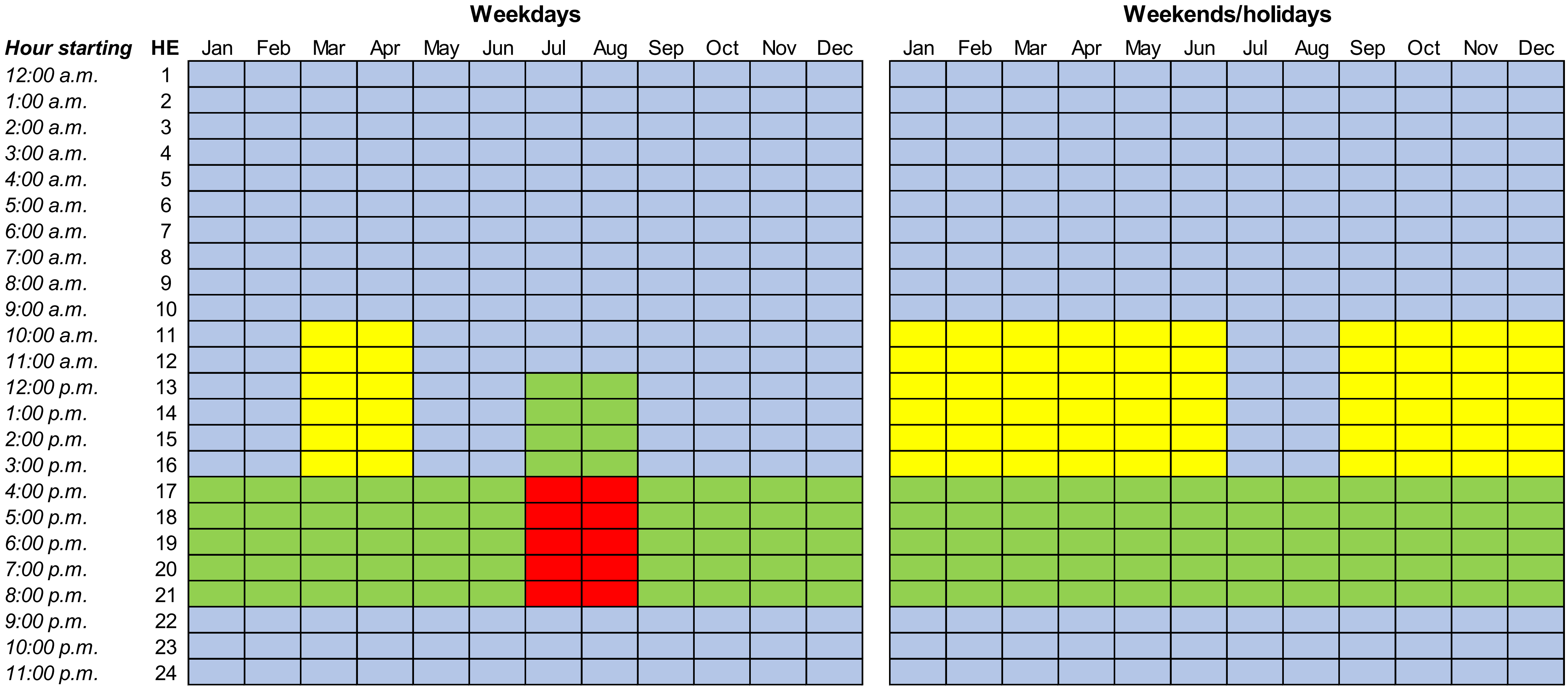
Correlation	VG Penetration						
	0%	5%	10%	15%	20%	30%	40%
Wind	-0.03	-0.17	-0.31	-0.39	-0.44	-0.54	-0.69
PV	0.27	0.09	-0.16	-0.42	-0.59	-0.79	N/A

RTP at low PV penetration has demand reductions when PV is generating (positive correlation between demand response and PV generation)

With high PV penetration, demand reductions increasingly occur when PV is not generating and demand increases when PV is generating.

Shifting Time-of-Use periods at the CAISO

CAISO proposed weekday and weekend/holiday TOU periods



		Weekdays												Weekends/holidays											
Hour starting	**HE**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12:00 a.m.	1	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
1:00 a.m.	2	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2:00 a.m.	3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
3:00 a.m.	4	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
4:00 a.m.	5	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
5:00 a.m.	6	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
6:00 a.m.	7	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
7:00 a.m.	8	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
8:00 a.m.	9	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
9:00 a.m.	10	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
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12:00 p.m.	13	🟦	🟦	🟨	🟨	🟦	🟦	🟩	🟩	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨
1:00 p.m.	14	🟦	🟦	🟨	🟨	🟦	🟦	🟩	🟩	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨
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3:00 p.m.	16	🟦	🟦	🟨	🟨	🟦	🟦	🟩	🟩	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨
4:00 p.m.	17	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
5:00 p.m.	18	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
6:00 p.m.	19	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
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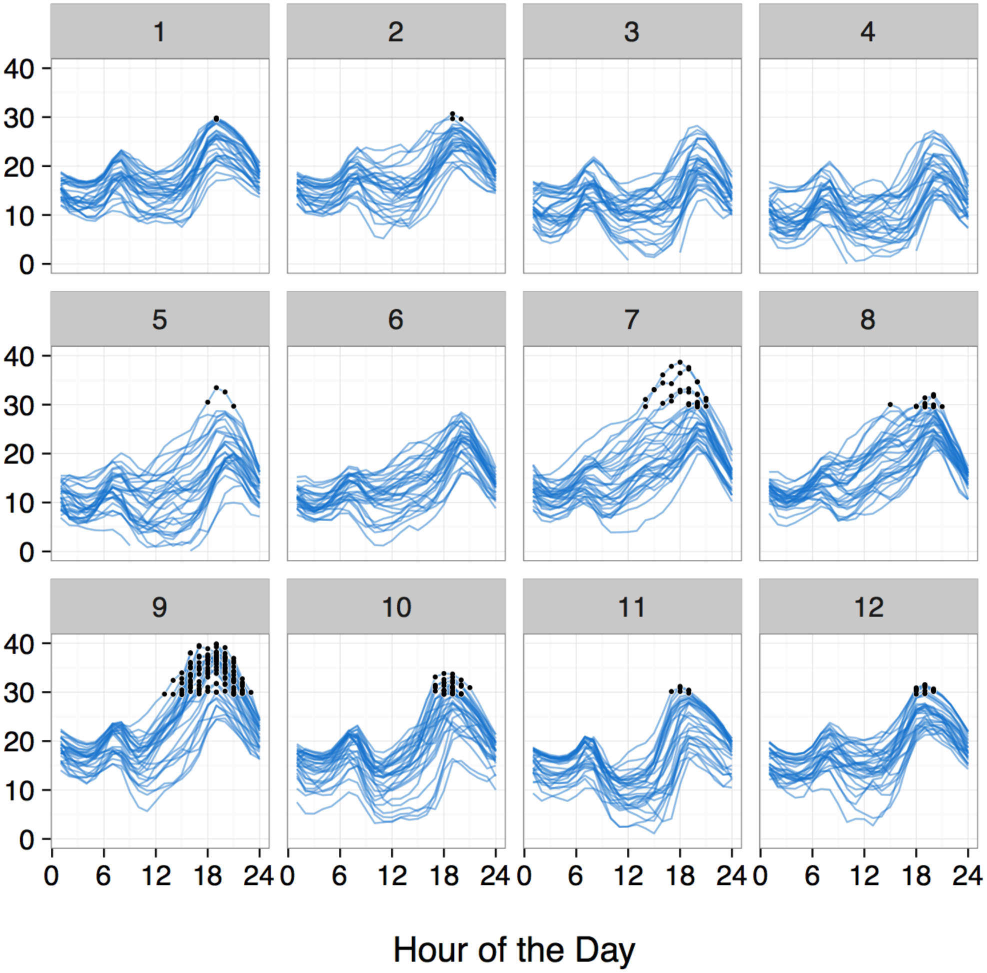
11:00 p.m.	24	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟥 Super peak 🟩 Peak 🟨 Super off-peak 🟦 Off-peak

Periods were simplified to provide a CAISO system-wide uniform approach and limit variation in peak and off-peak periods.

Source: CAISO (2016)

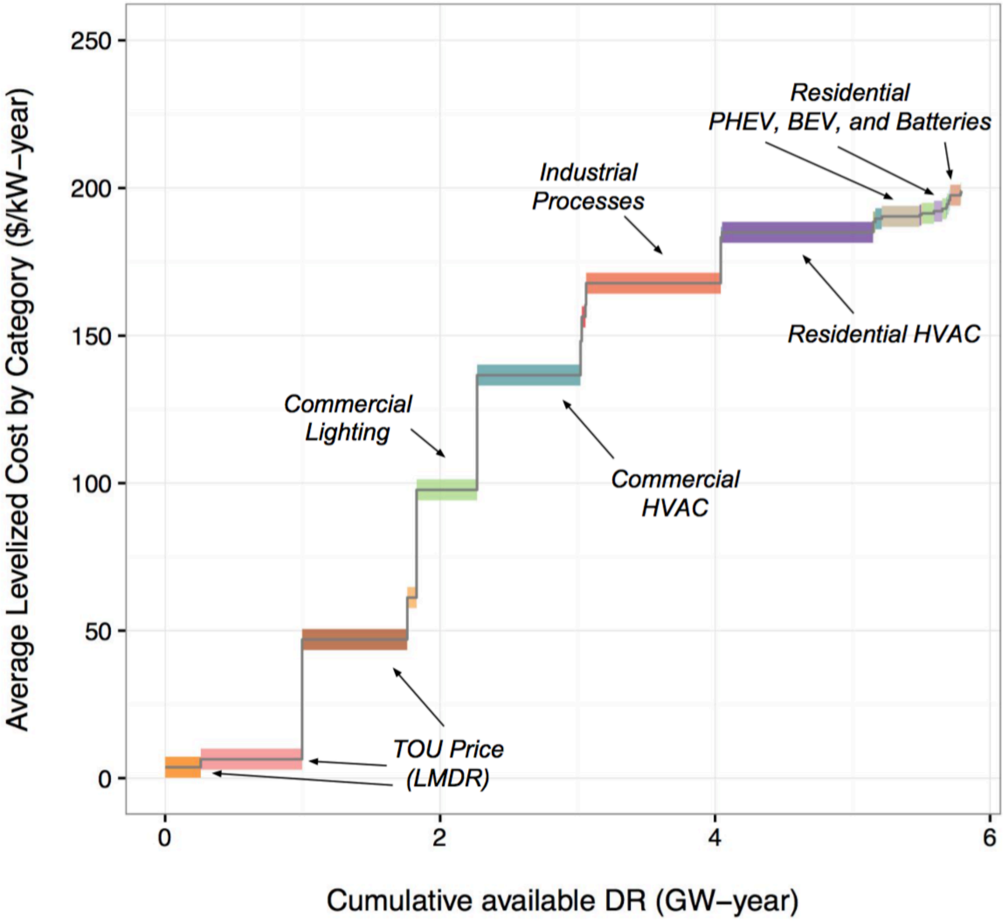
2016 California Demand Response Potential Study



2025 Daily Net Load Profile

By Month | CEC Medium Growth Building Stock | 1in2 weather

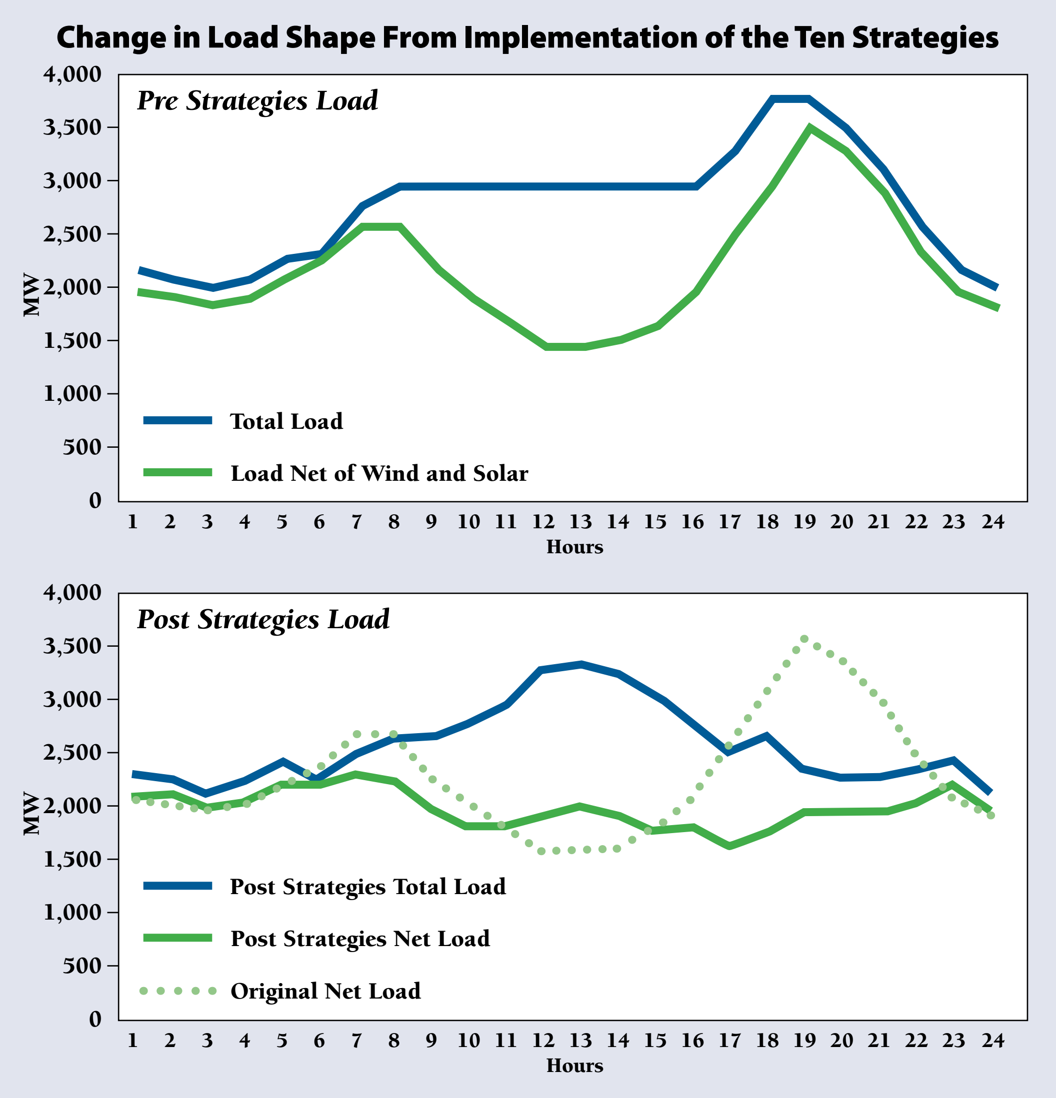
Source: Alstone et al. (2016)



- DR potential based on traditional demand reduction, but focused on the peak **net load** hours for 2025

Teaching the Duck to Fly: Regulatory Assistance Project

Figure 5



- Target energy efficiency to hours when load ramps up sharply
- Manage water and wastewater pumping loads
- Control electric water heaters to reduce peak and increase load at strategic hours
- Convert commercial air-conditioning to ice storage or chilled water storage

Source: Lazar (2016)

Advanced Demand Response: 50% RPS with Large Solar in California

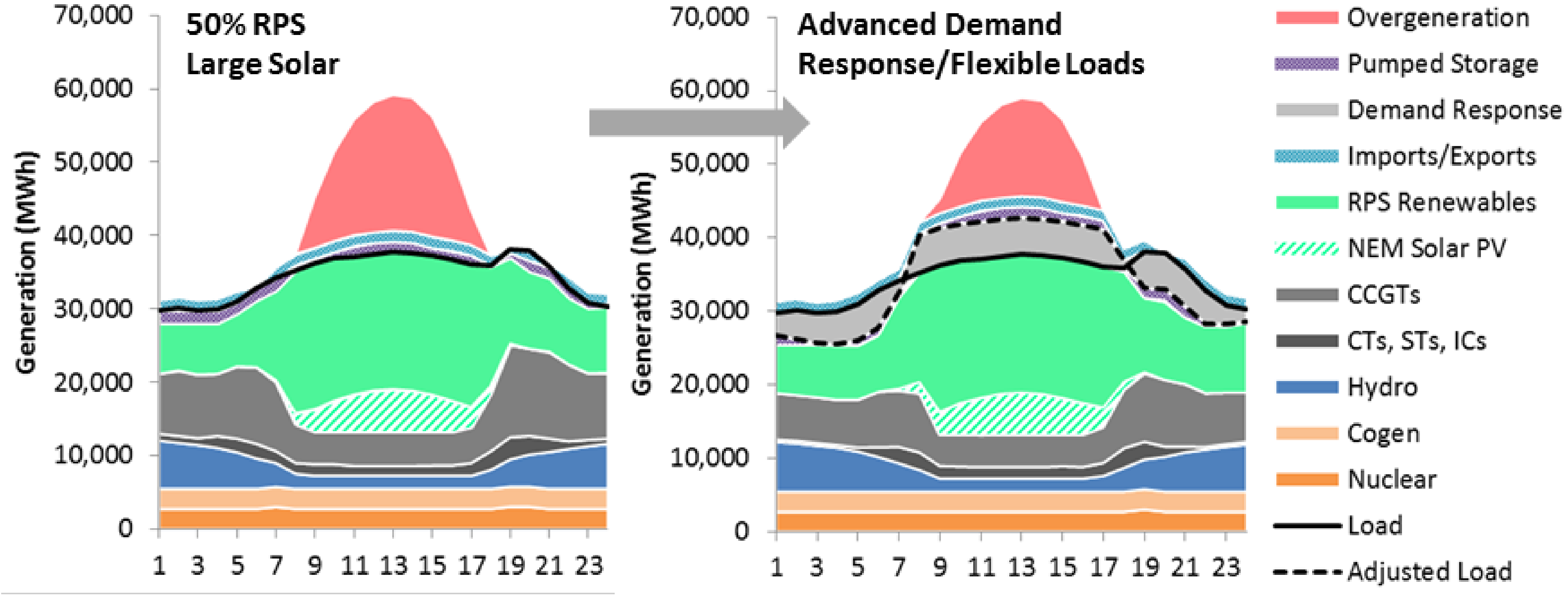


Figure 28. Generation mix on an April day for the 50% RPS Large Solar Scenario without and with the Advanced Demand Response solution

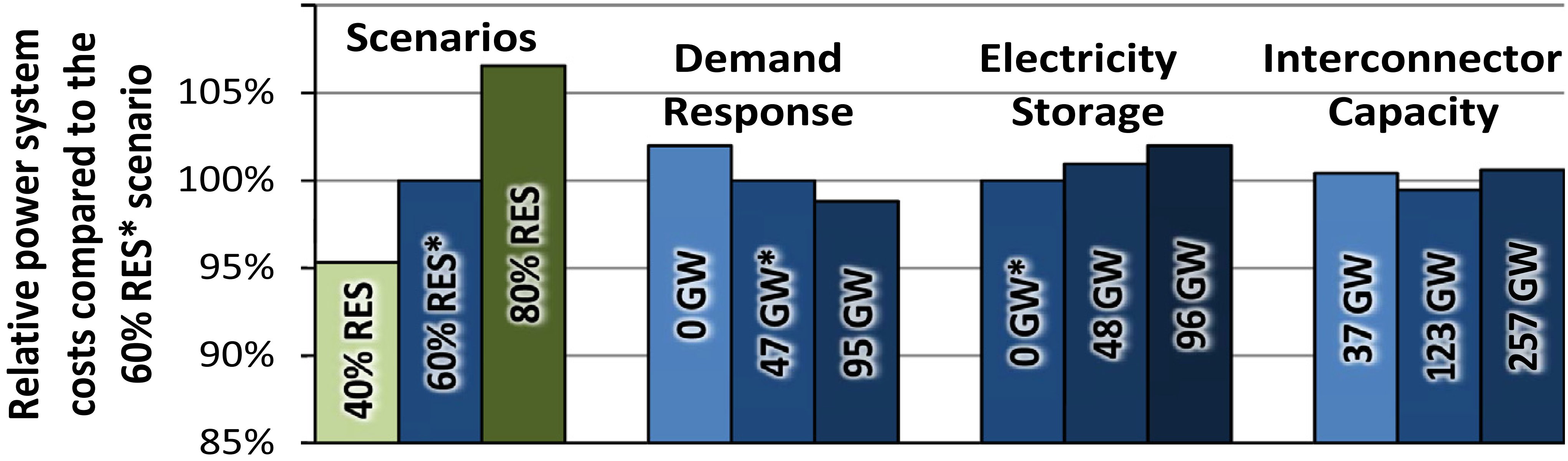
Source: E3 (2014)

- Advanced demand response programs provide downward flexibility by absorbing energy during times of surplus
- 5,000 MW of adv. DR lowers RE curtailment from 9% to 4%, lowering costs of high solar portfolio by $5-12/MWh
- Assumed to be from shifting deferrable loads (e.g., EV charging, pre-cooling)

Western Europe: Integrating Intermittent Renewables in a Low-Carbon System

Source: Brower et al. (2016)

Effect of flexibility options on total power system costs



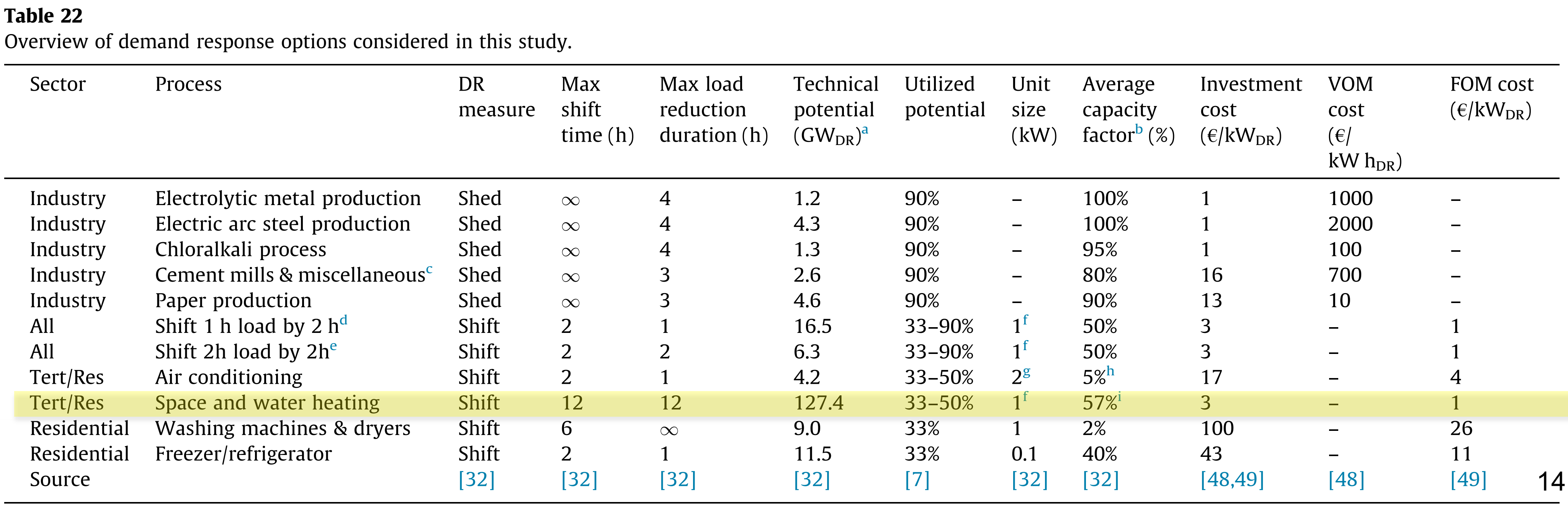


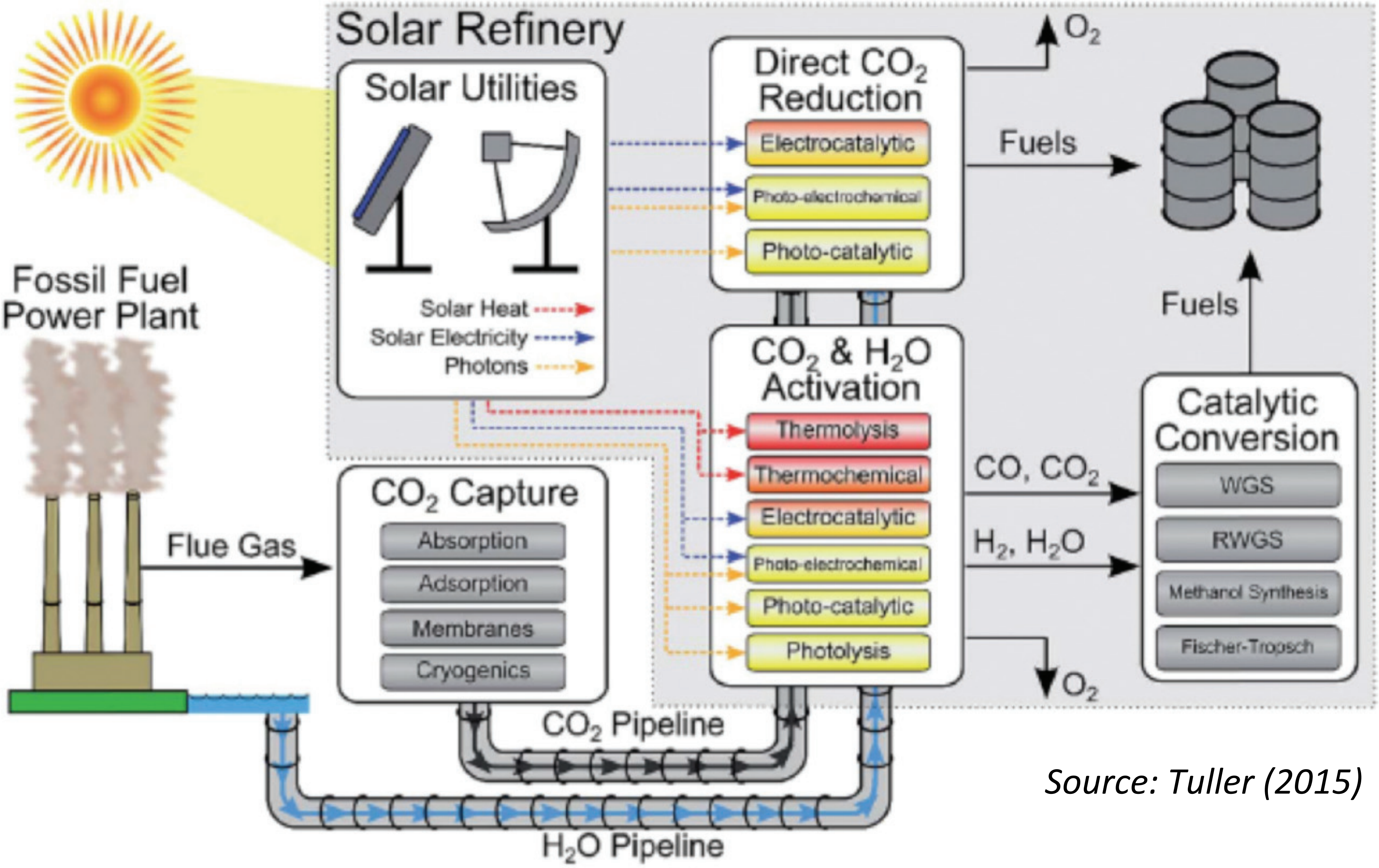
Table 22

Overview of demand response options considered in this study.

Sector	Process	DR measure	Max shift time (h)	Max load reduction duration (h)	Technical potential ($\mathrm{GW_{DR}}$)[a]	Utilized potential	Unit size (kW)	Average capacity factor[b] (%)	Investment cost (€/$\mathrm{kW_{DR}}$)	VOM cost (€/kW $\mathrm{h_{DR}}$)	FOM cost (€/$\mathrm{kW_{DR}}$)
Industry	Electrolytic metal production	Shed	∞	4	1.2	90%	–	100%	1	1000	–
Industry	Electric arc steel production	Shed	∞	4	4.3	90%	–	100%	1	2000	–
Industry	Chloralkali process	Shed	∞	4	1.3	90%	–	95%	1	100	–
Industry	Cement mills & miscellaneous[c]	Shed	∞	3	2.6	90%	–	80%	16	700	–
Industry	Paper production	Shed	∞	3	4.6	90%	–	90%	13	10	–
All	Shift 1 h load by 2 h[d]	Shift	2	1	16.5	33–90%	1[f]	50%	3	–	1
All	Shift 2h load by 2h[e]	Shift	2	2	6.3	33–90%	1[f]	50%	3	–	1
Tert/Res	Air conditioning	Shift	2	1	4.2	33–50%	2[g]	5%[h]	17	–	4
Tert/Res	Space and water heating	Shift	12	12	127.4	33–50%	1[f]	57%[i]	3	–	1
Residential	Washing machines & dryers	Shift	6	∞	9.0	33%	1	2%	100	–	26
Residential	Freezer/refrigerator	Shift	2	1	11.5	33%	0.1	40%	43	–	11
Source		[32]	[32]	[32]	[32]	[7]	[32]	[32]	[48,49]	[48]	[49]

Accessing the Transportation Market: EV Charging and Solar Fuels

Figure 1 Schematic of a Solar Refinery[1]



Source: Tuller (2015)

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Analyzing Technology Solutions Through Load Shaping

The Potential of Solar + Homes

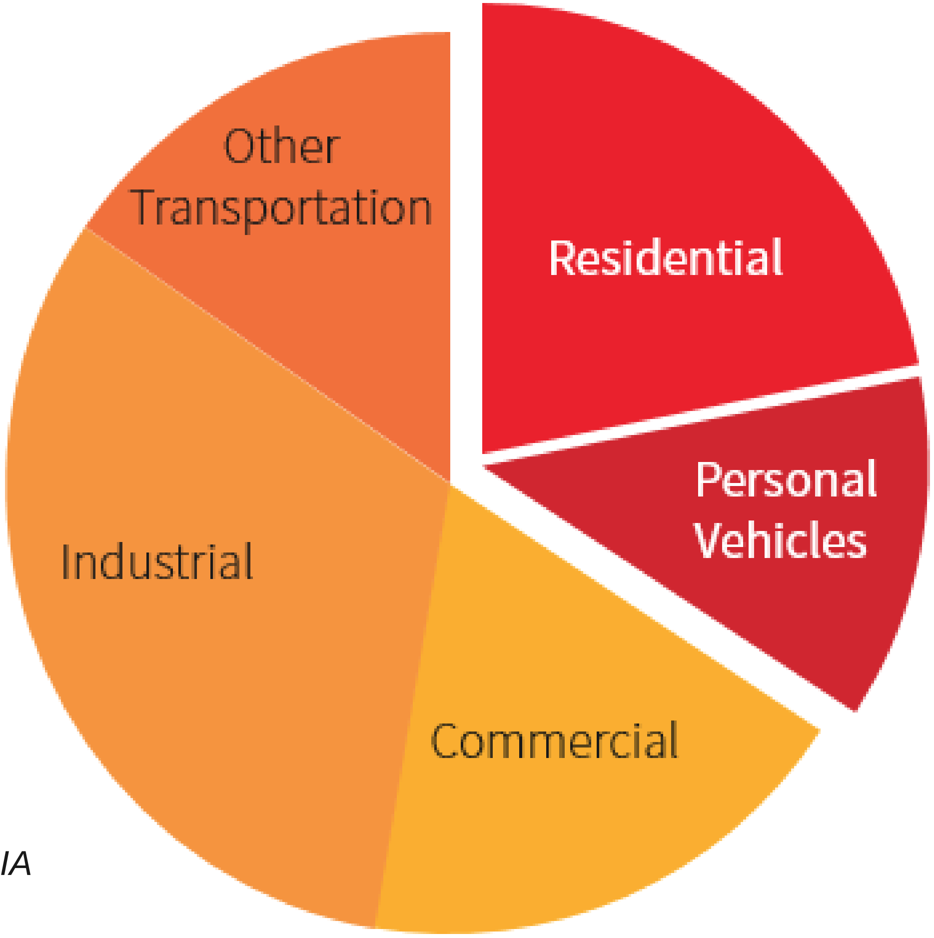
EPRI | Oct 13th 2016

Retaining the Value of PV at High Penetration

Marc Perez, Clean Power Research

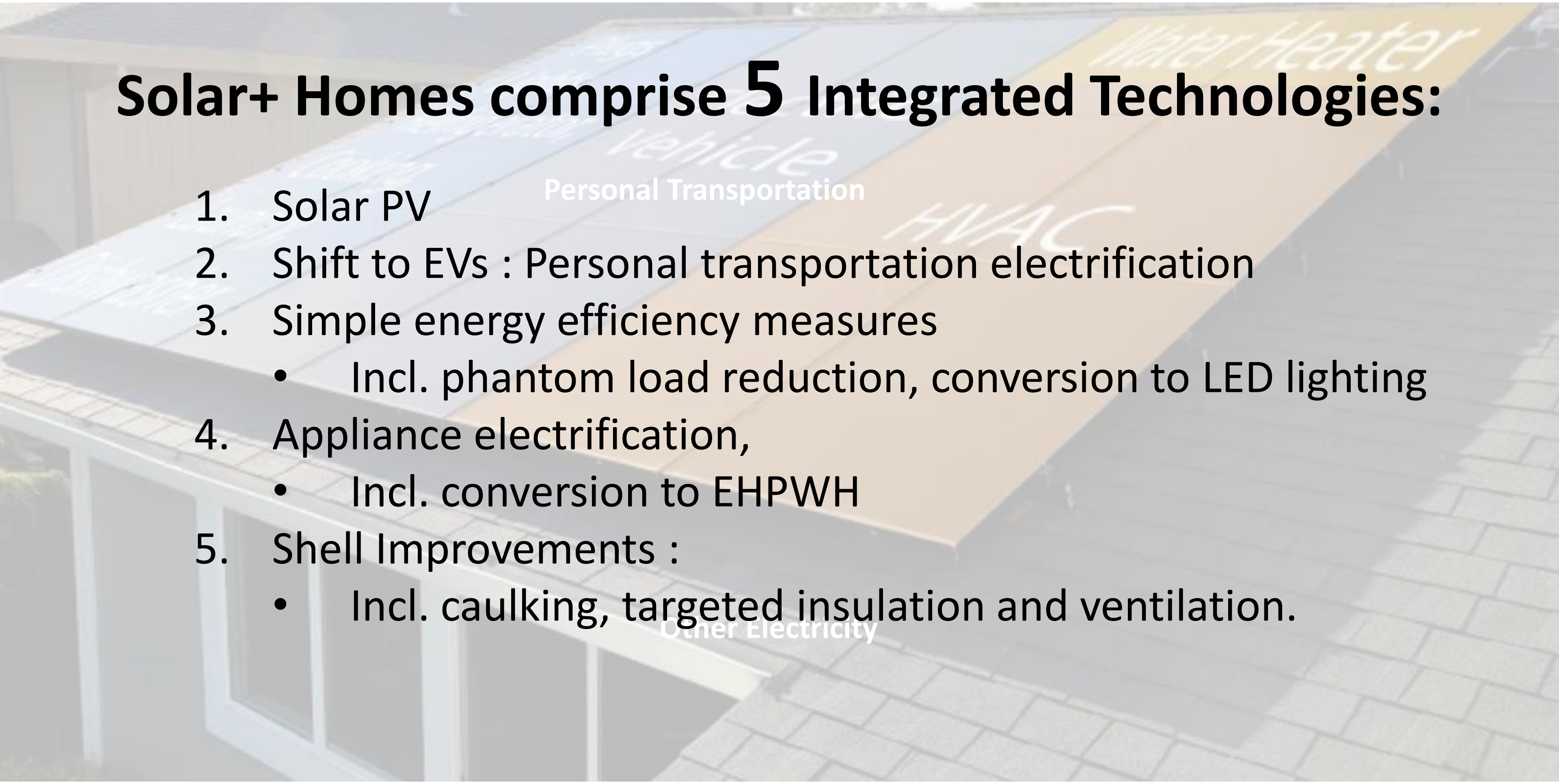
Residential Sector Provides Opportunity

Homes & Personal Vehicles Consume ~1/3 of US Energy



Source: EIA

Enter the Solar+ Home: A ZNE Concept

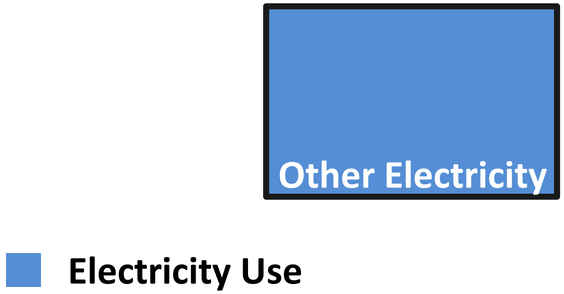


Solar+ Homes comprise 5 Integrated Technologies:

1. Solar PV
2. Shift to EVs : Personal transportation electrification
3. Simple energy efficiency measures
    - Incl. phantom load reduction, conversion to LED lighting
4. Appliance electrification,
    - Incl. conversion to EHPWH
5. Shell Improvements :
    - Incl. caulking, targeted insulation and ventilation.

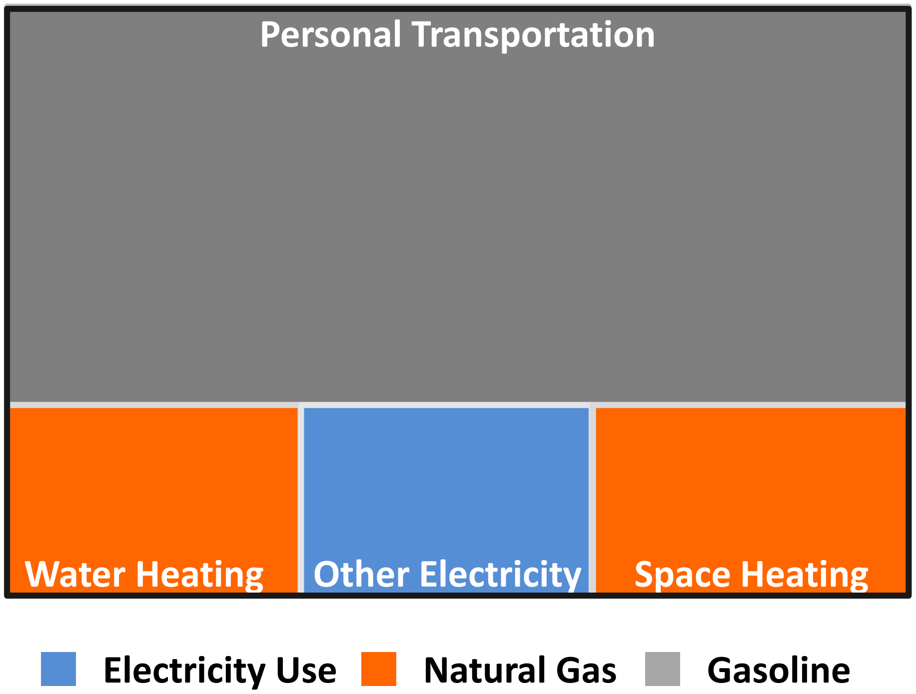
Focus is Usually Only on Electricity

~5 kW of PV would offset 6,500 kWh of consumption per year

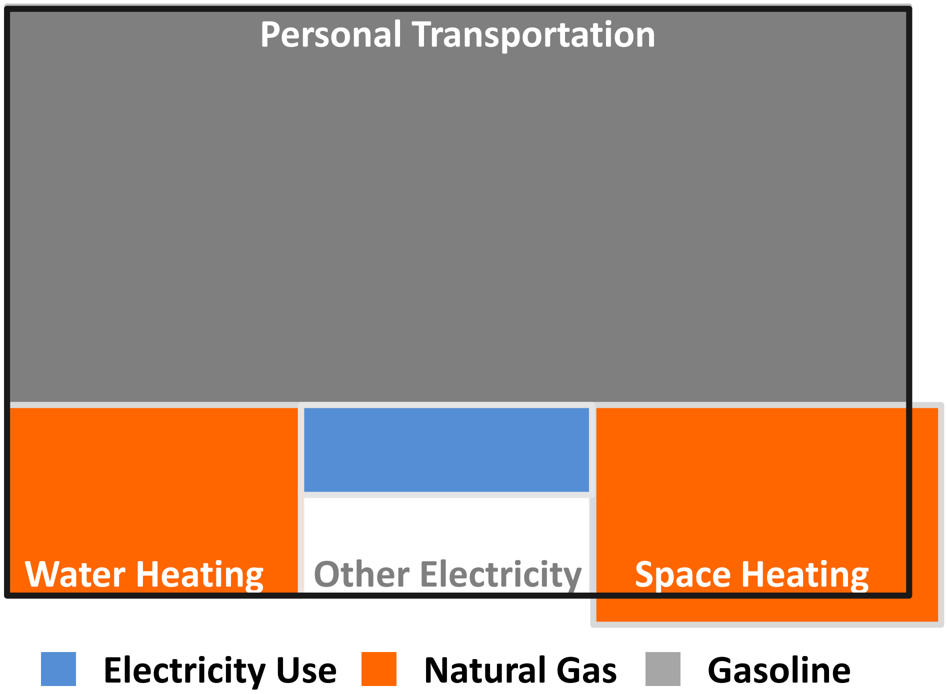


Need to Take Holistic View

Total site energy consumption is 10x electric consumption (62,000 kWh)

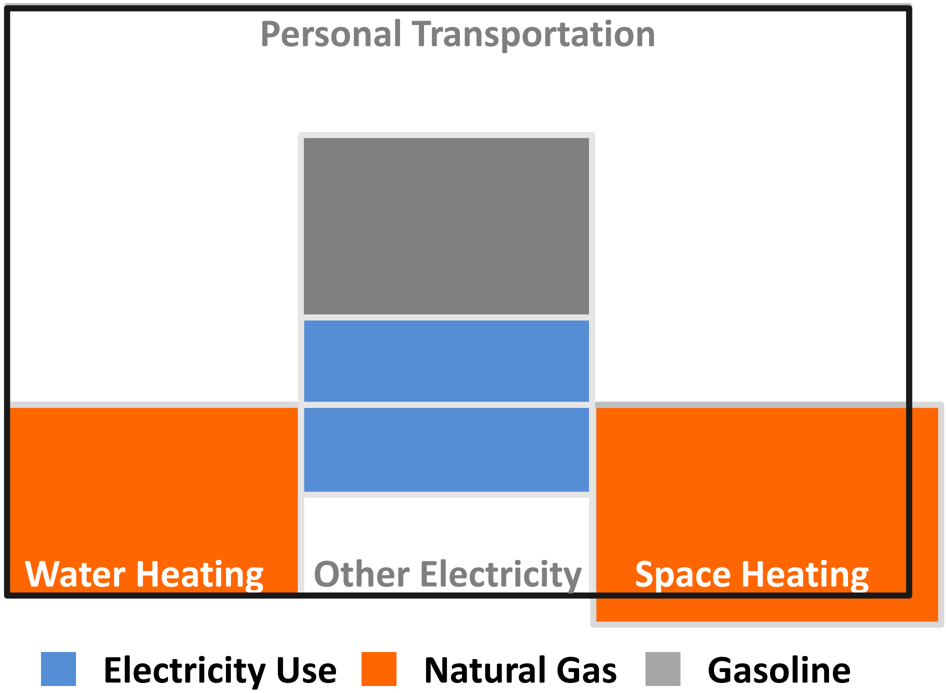


Implement Basic Electrical Energy Efficiency

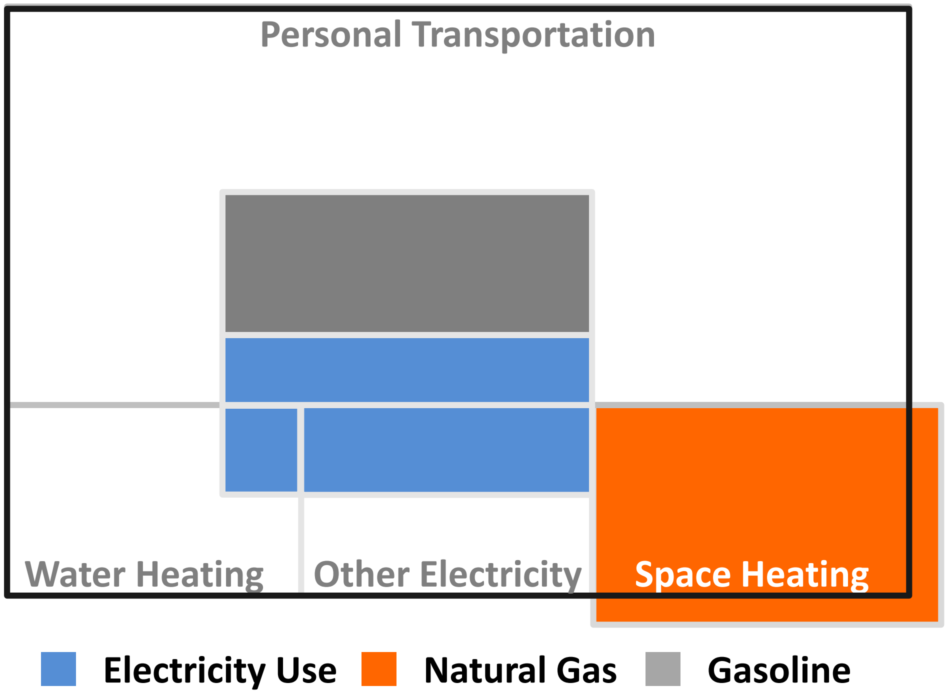


Include interacting effects

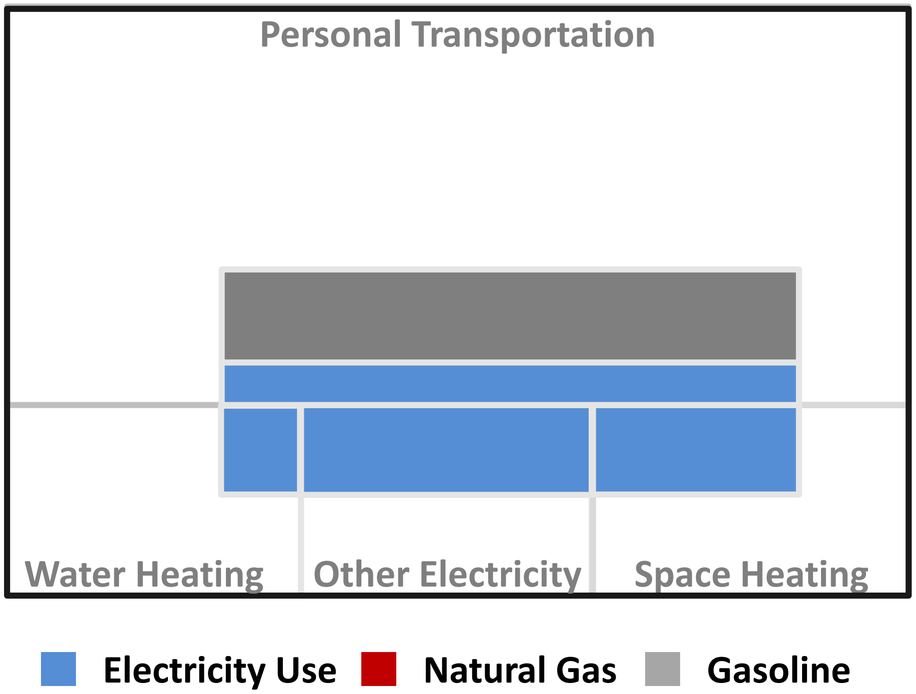
Switch to Efficient Transportation (EV & Hybrid)



Switch to Heat Pump Water Heater

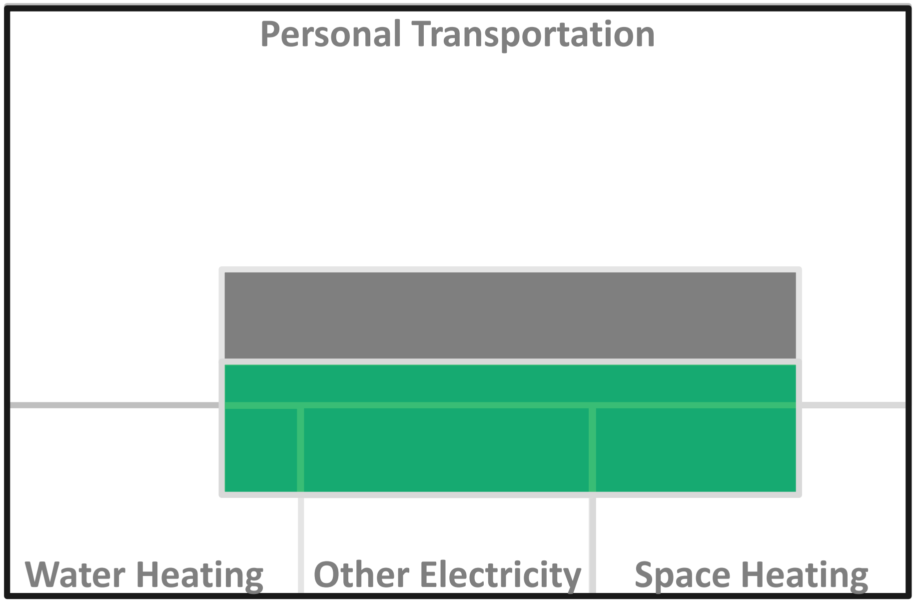


Improve Building Shell & Switch to Electric Heating



Offset Consumption with PV

6 kW of PV will offset all electricity consumption*

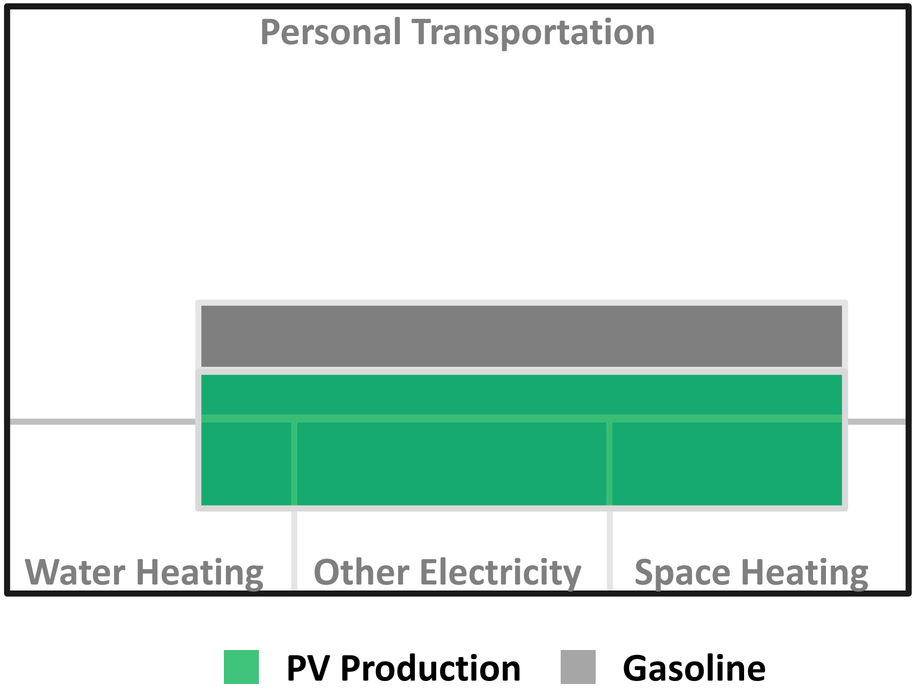


🟩 **PV Production** ⬜ **Gasoline**

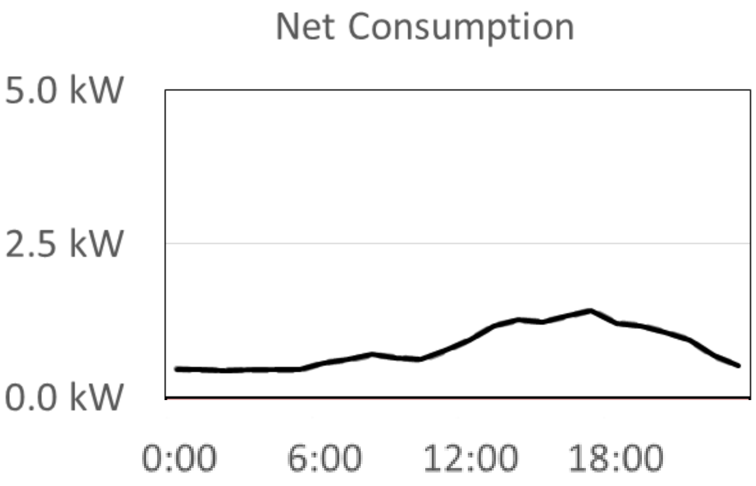
* About 200 gallons of gas remain

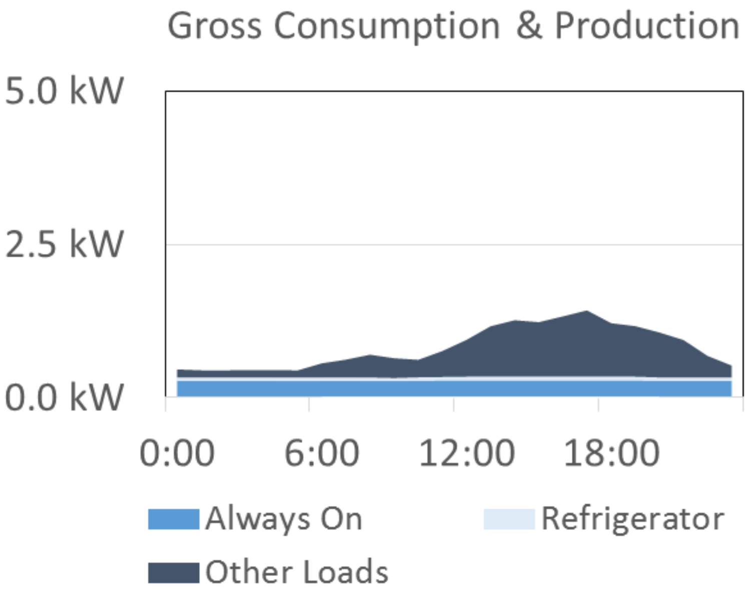
Repeat on Basis of Carbon Dioxide Emissions

16 tons reduced to 2 tons per year

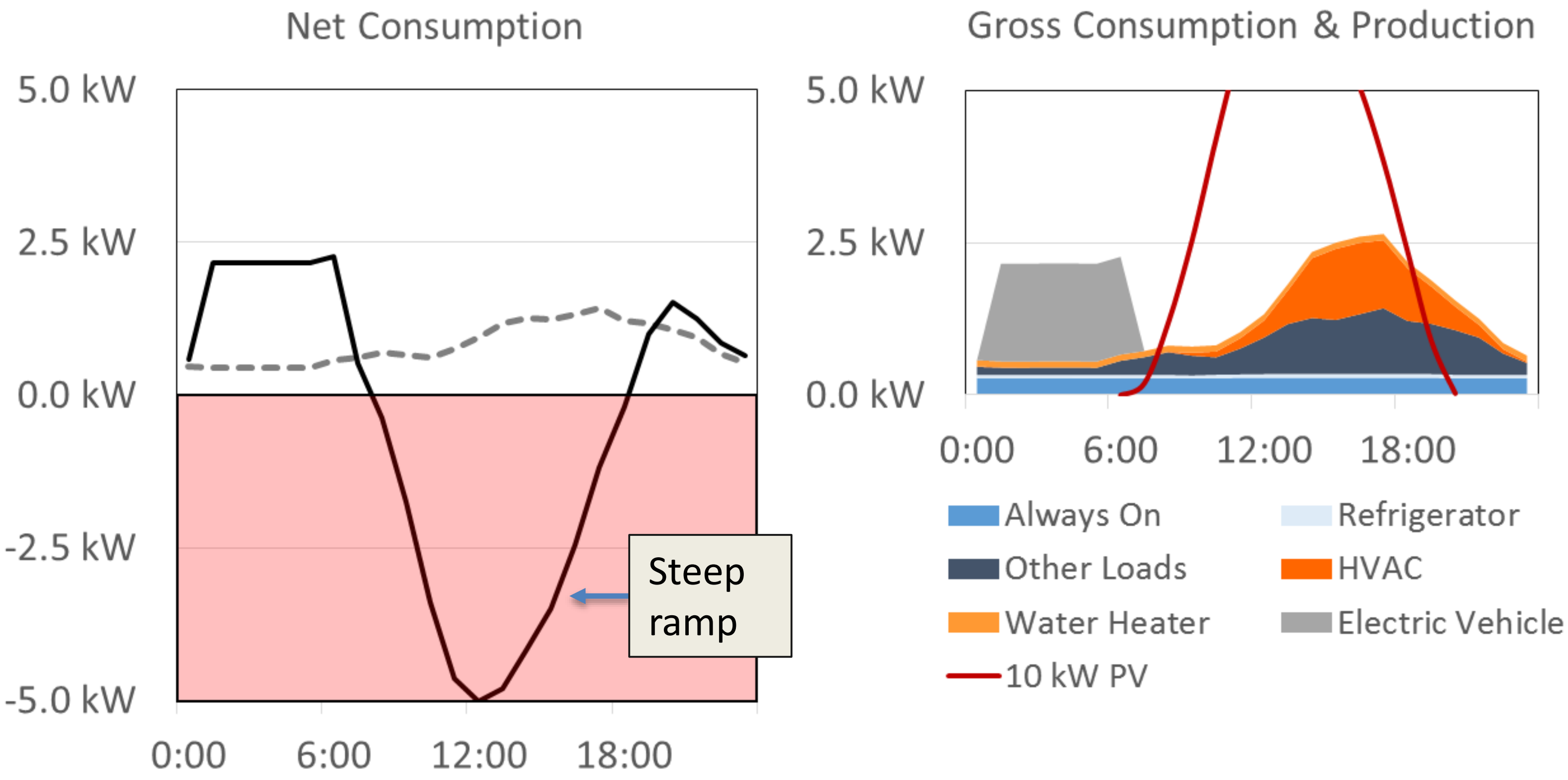


Existing Consumption (Average Summer Day)


Net Consumption

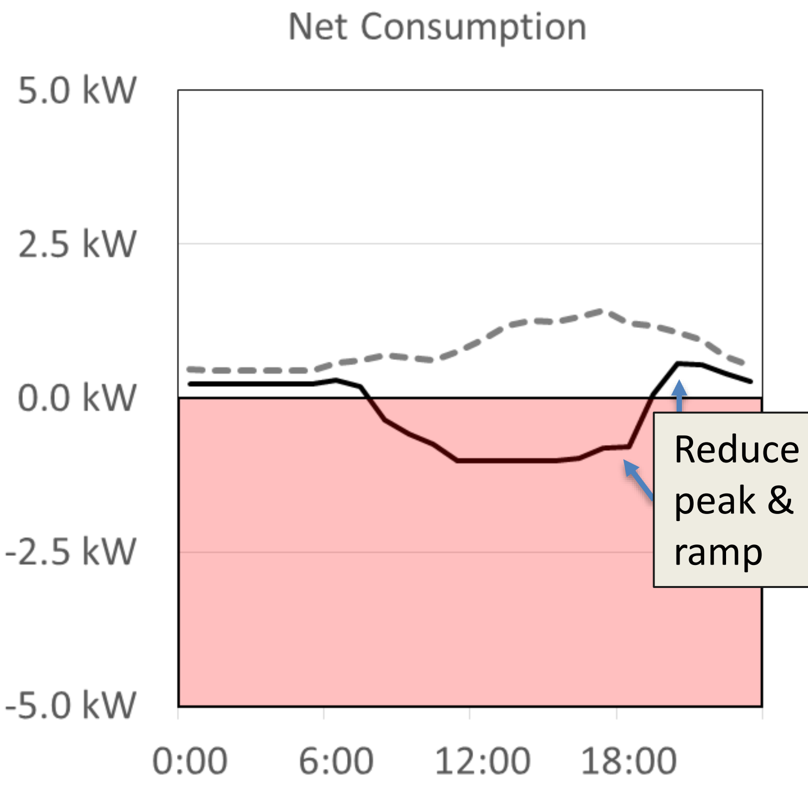

Gross Consumption & Production

Traditional Solar Home w/ Fuel Switching and w/o Control

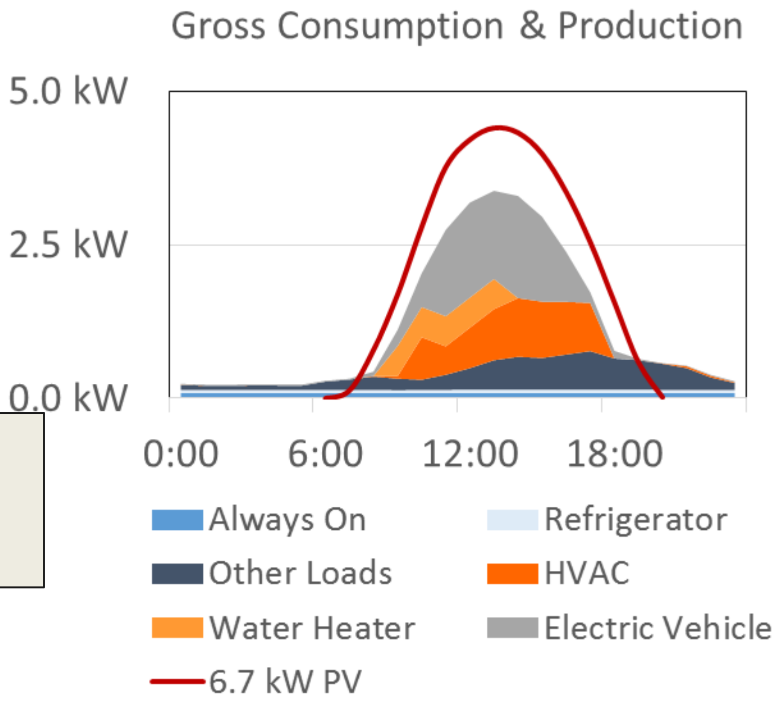


Steep ramp

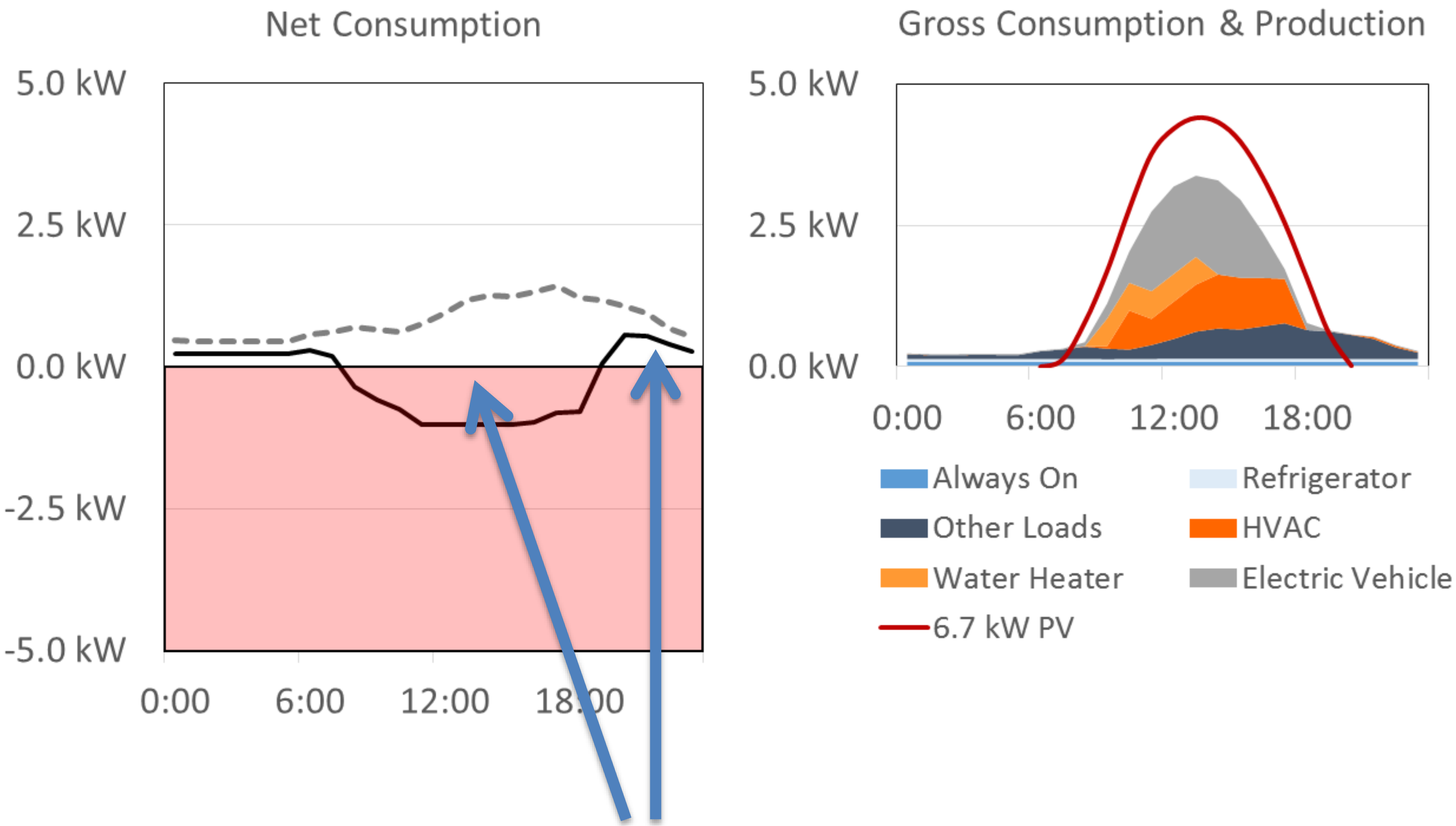
Solar+ Home w/ Fuel Switching, Efficiency, and Control



Reduce peak & ramp



Solar+ Homes demonstrate that load-shifting is certainly possible **but…**



This imbalance essentially treats the grid like a storage device!

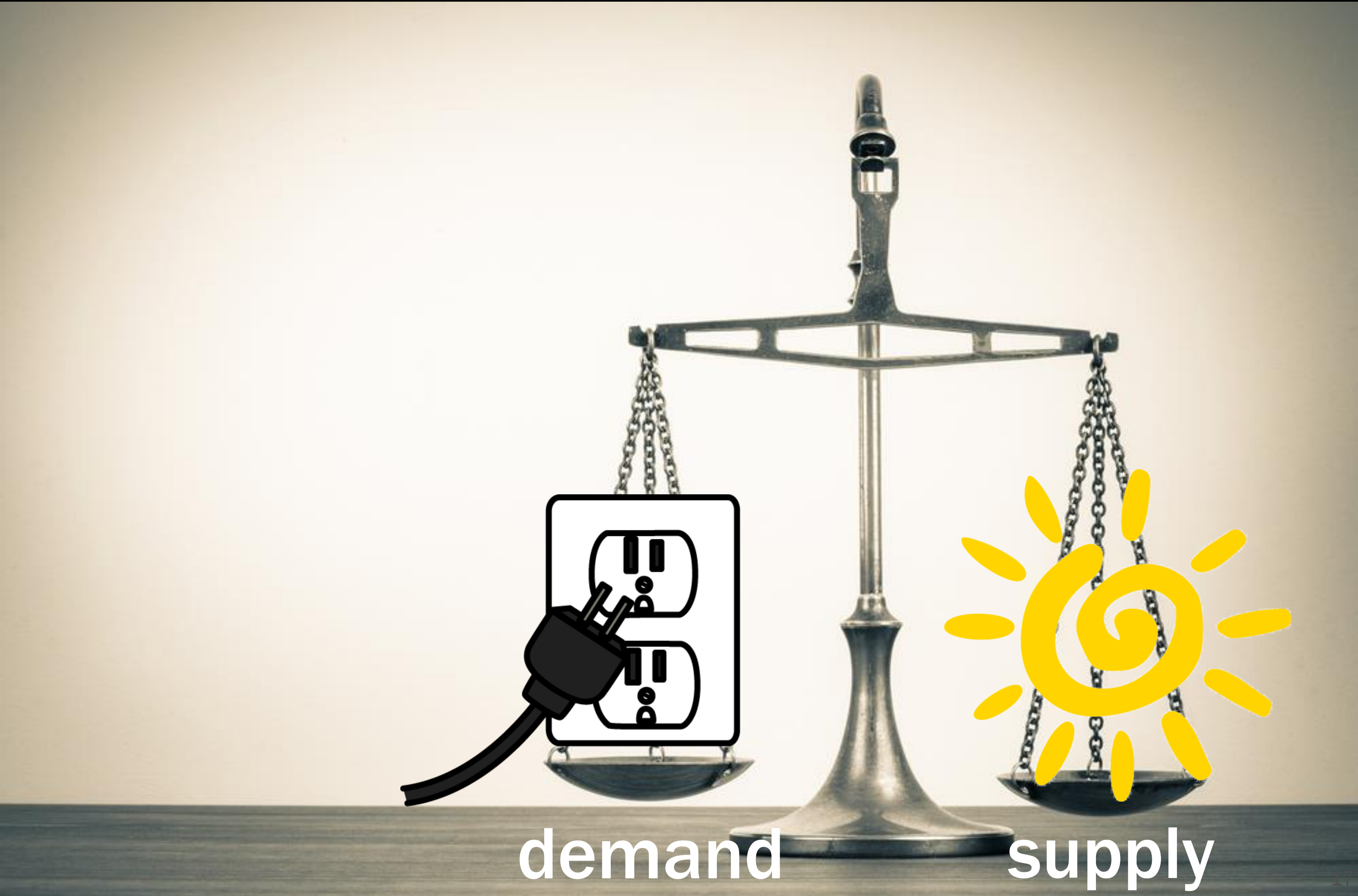
Clearly, there is an imbalance left to be addressed.

Demand-Side Management in Context:

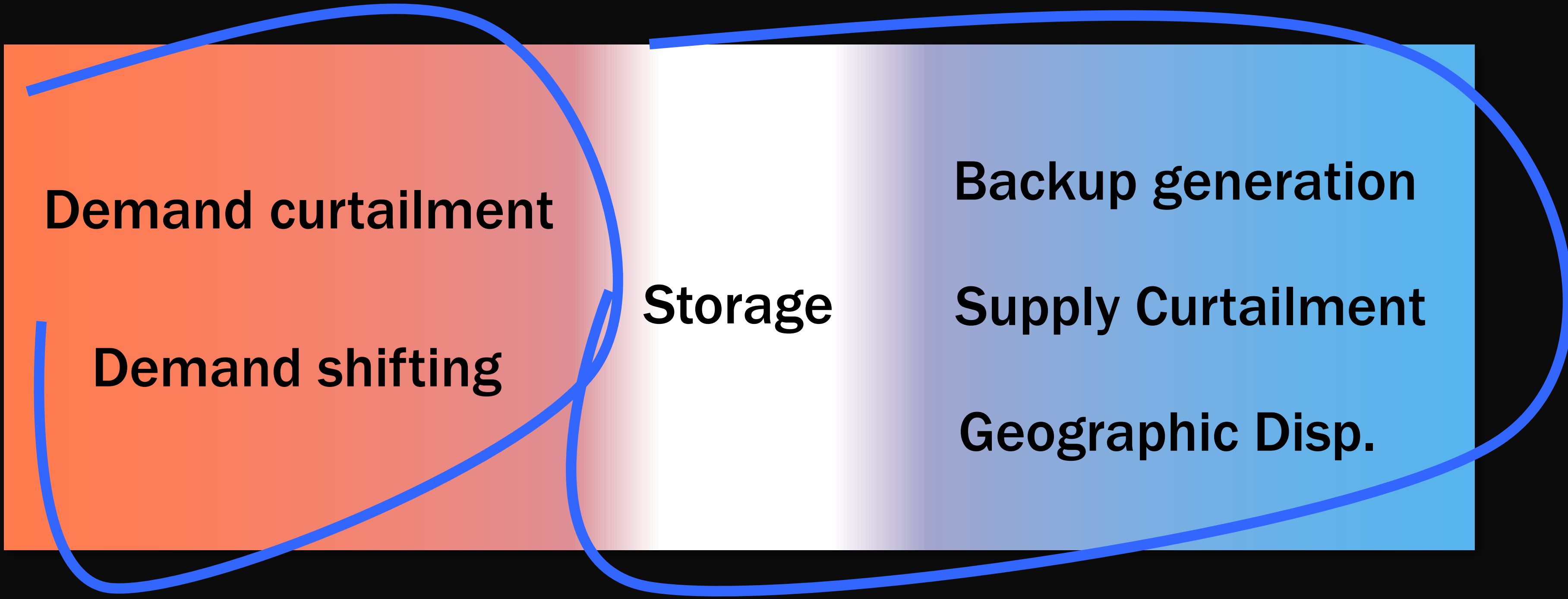
Achieving high penetration PV at minimal cost: An optimization of supply-side approaches for meeting guaranteed production targets.

EPRI | Oct 13th 2016
Retaining the Value of PV at High Penetration
Marc Perez, Clean Power Research

How Do We Achieve High-Penetration?



A spectrum of approaches for balancing supply and demand



Demand curtailment

Demand shifting

Storage

Backup generation

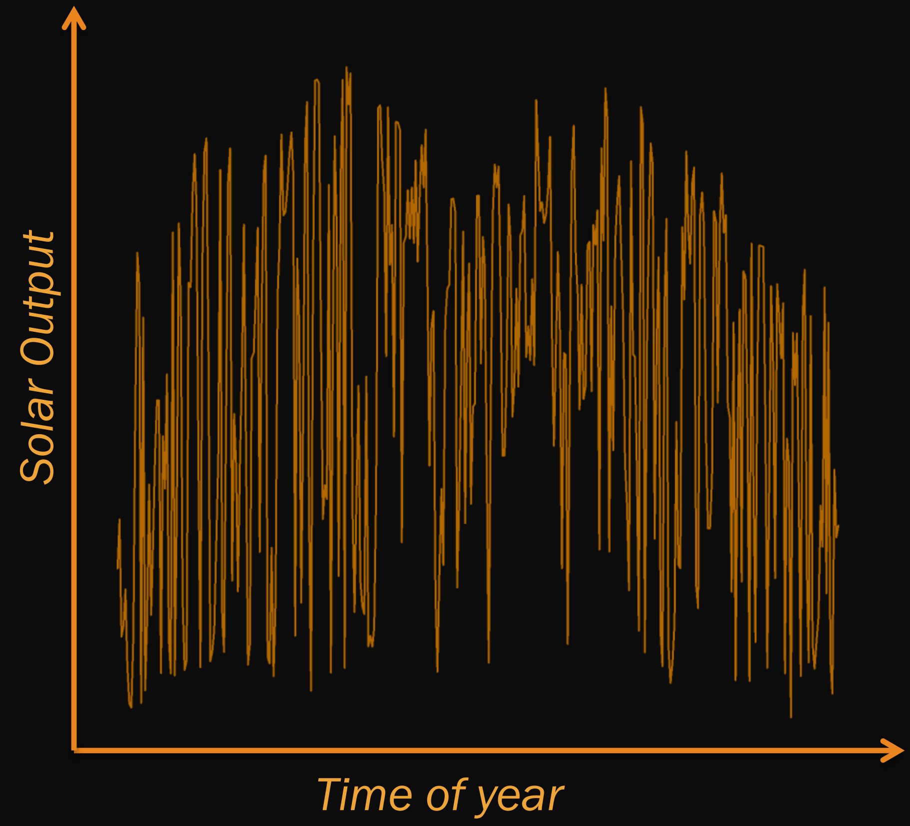
Supply Curtailment

Geographic Disp.

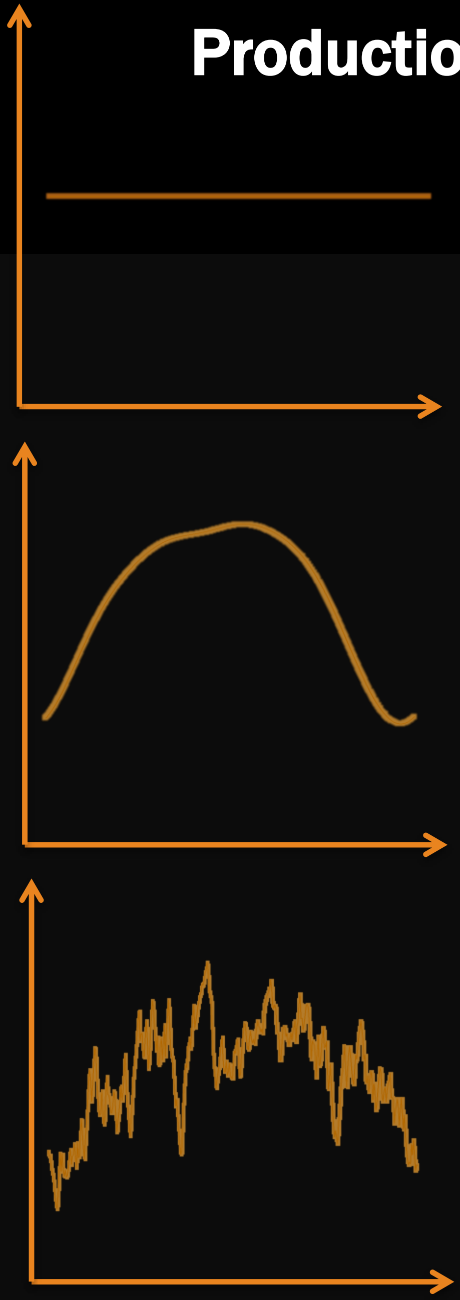
Demand-side

Supply-side

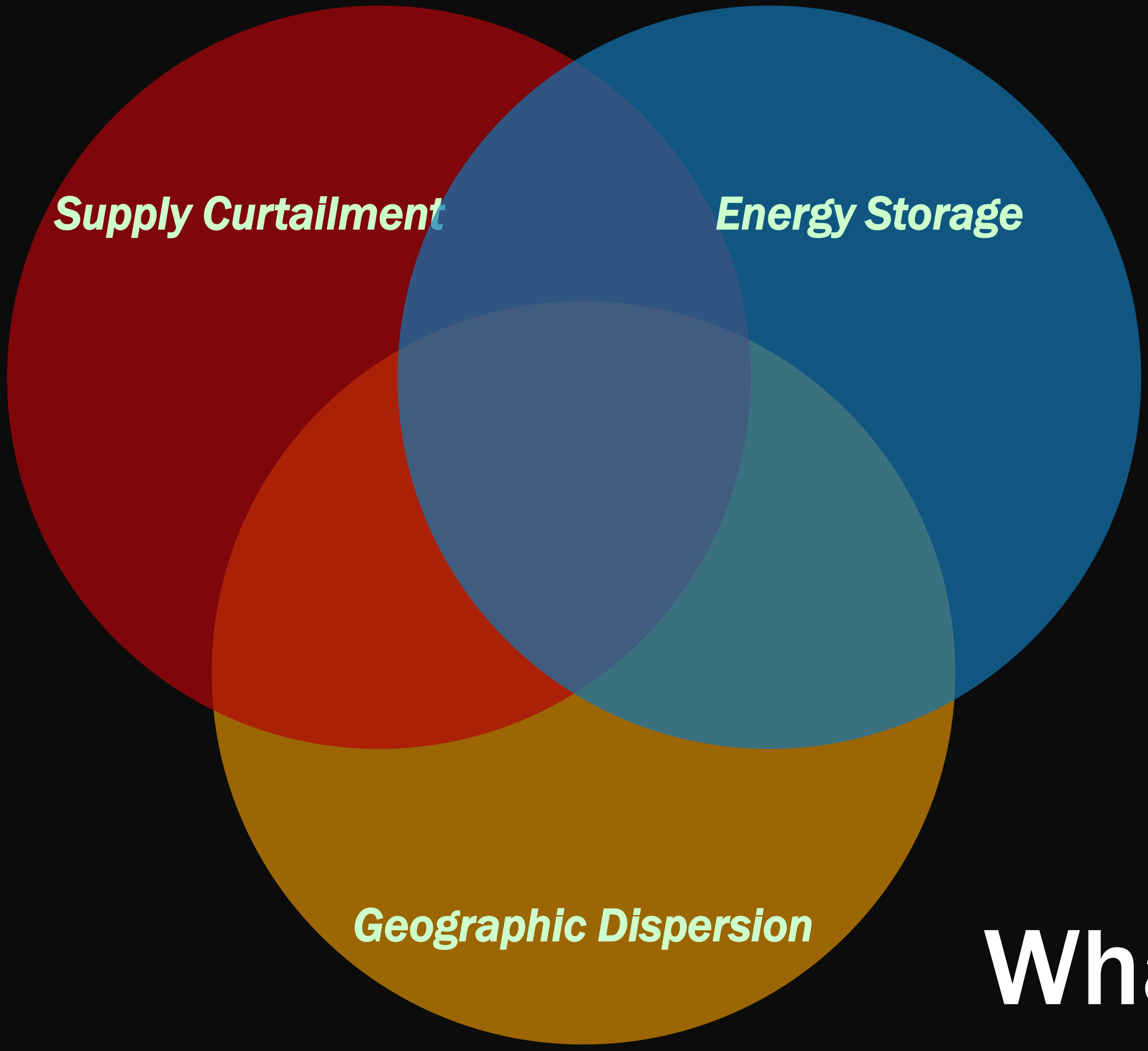
what does it take?



Guaranteed Production



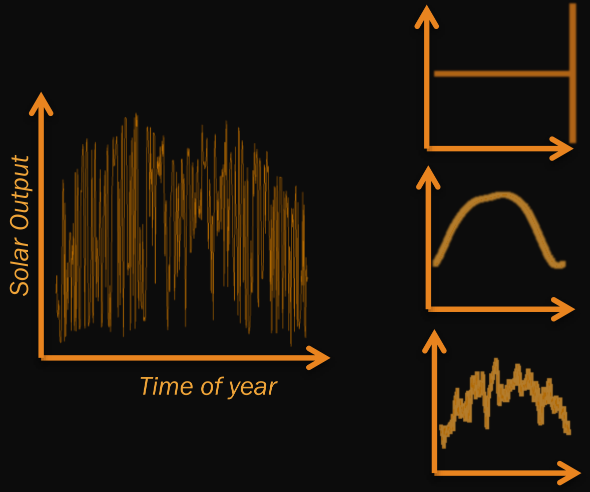
3 Supply-Side Solutions



Supply Curtailment

Energy Storage

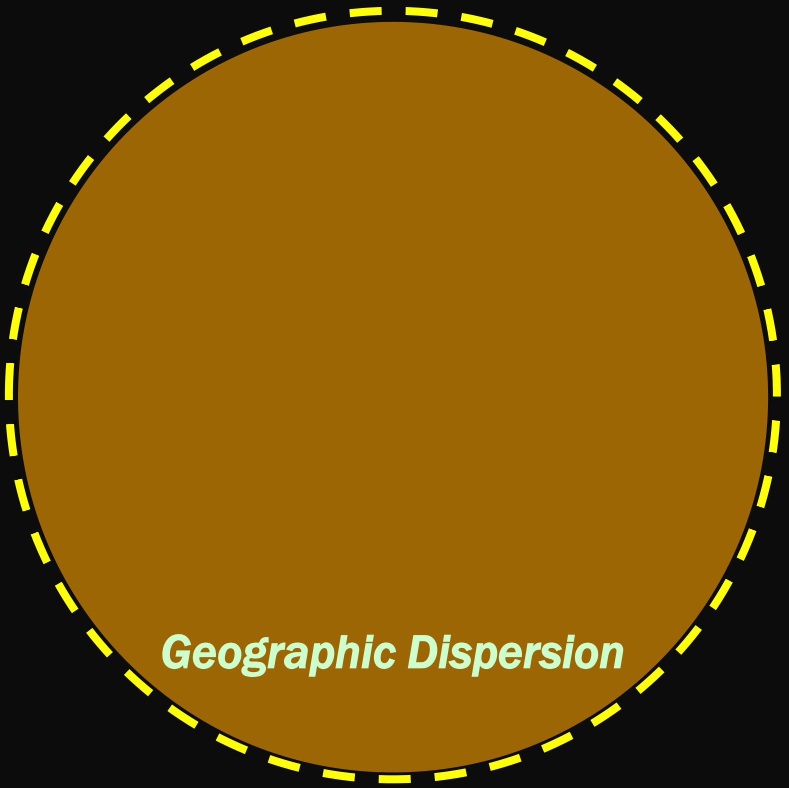
Geographic Dispersion

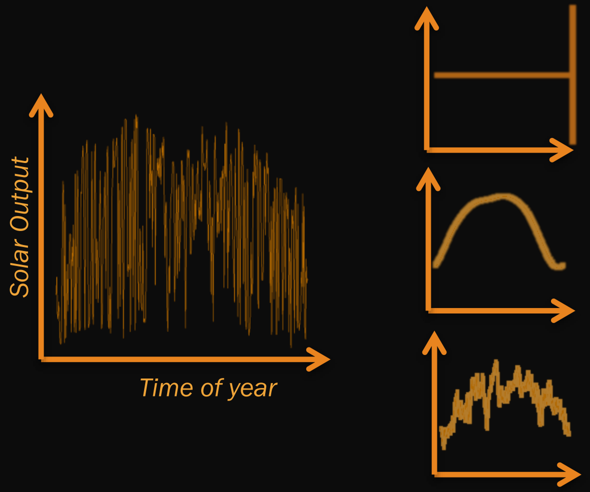


What do we need?

Solution 1.

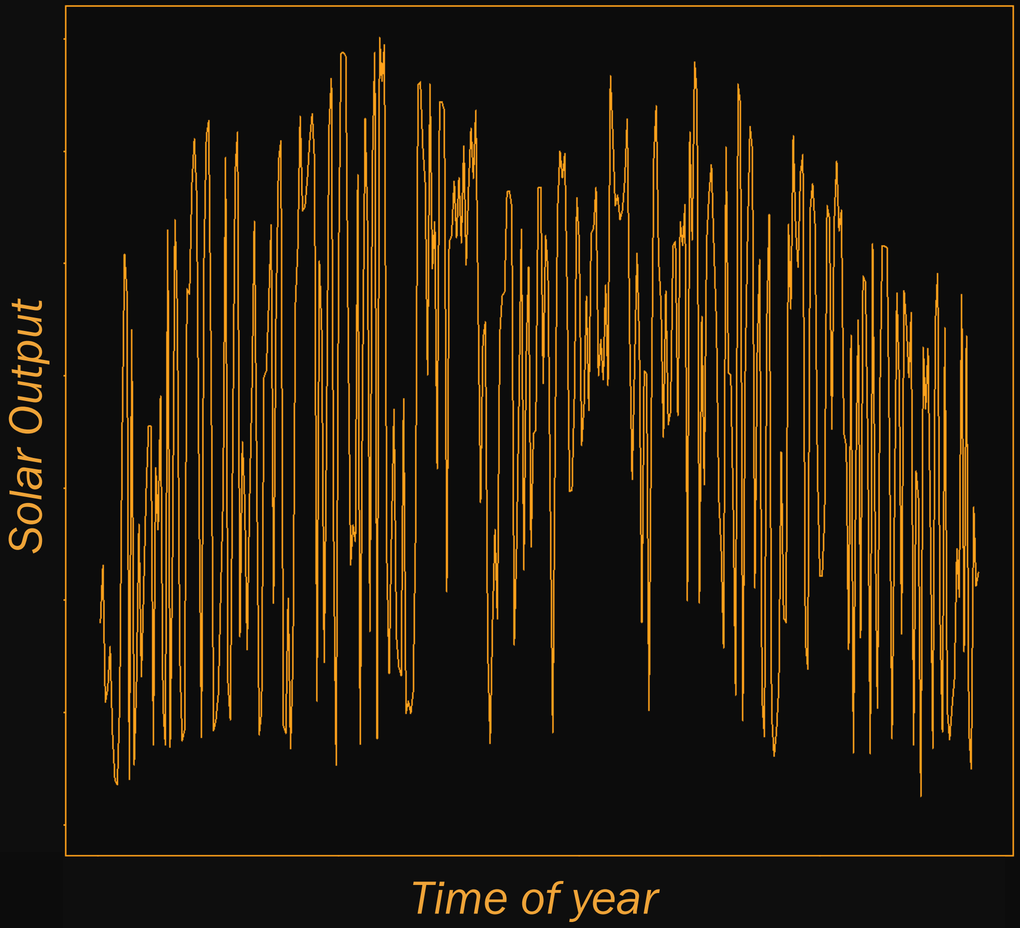
Geographic dispersion



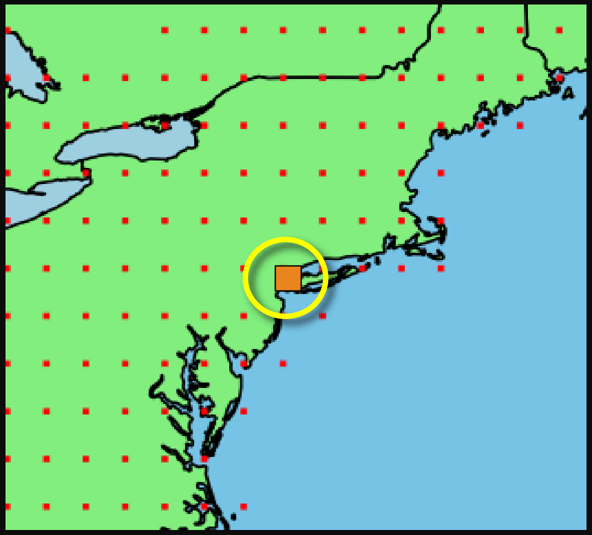


Solution 1.

Geographic dispersion

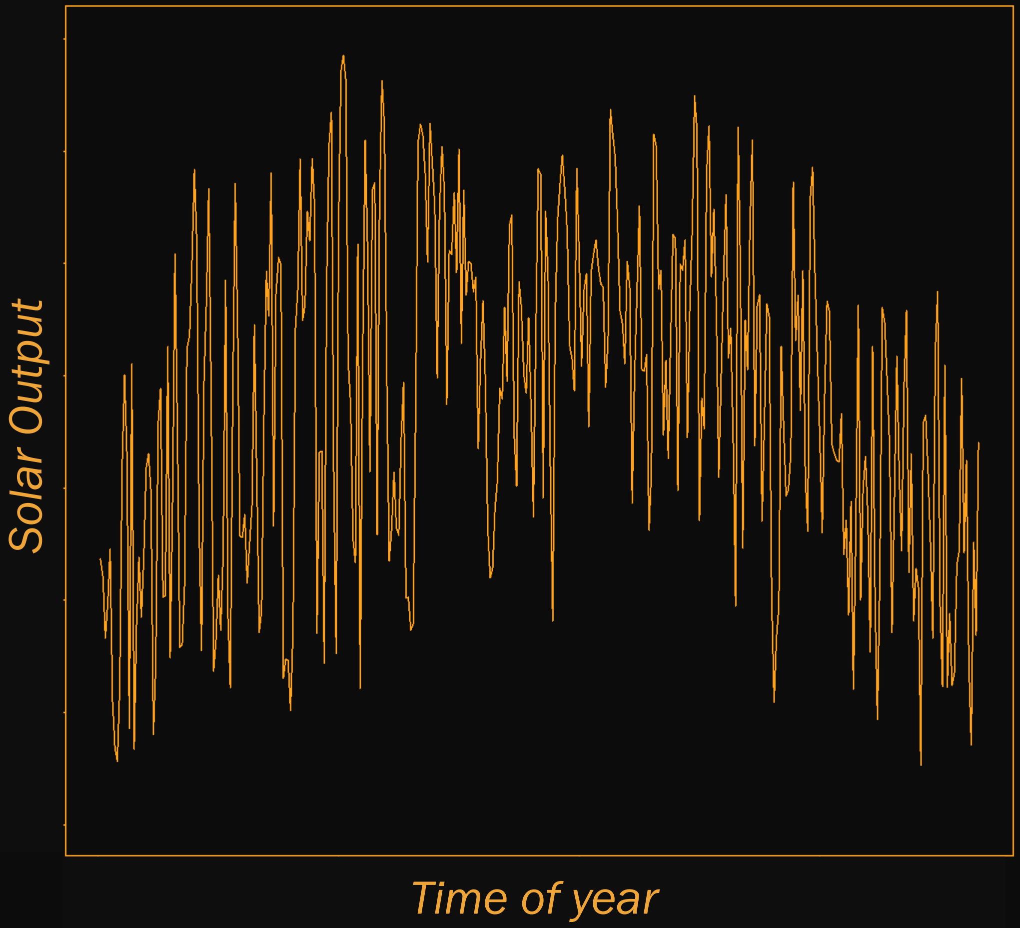


0 km

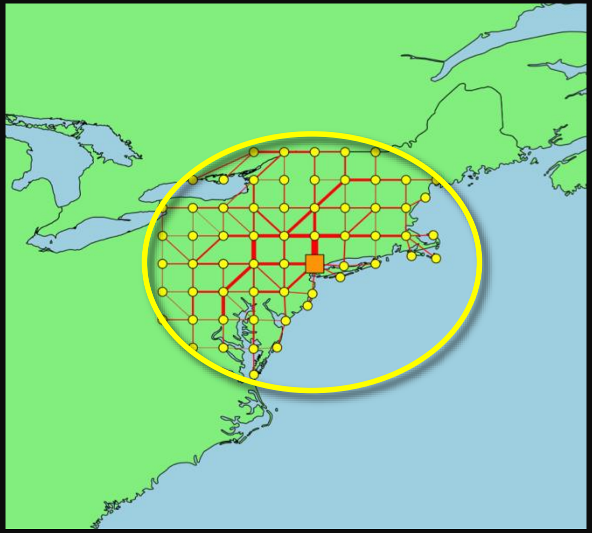


Solution 1.

Geographic dispersion

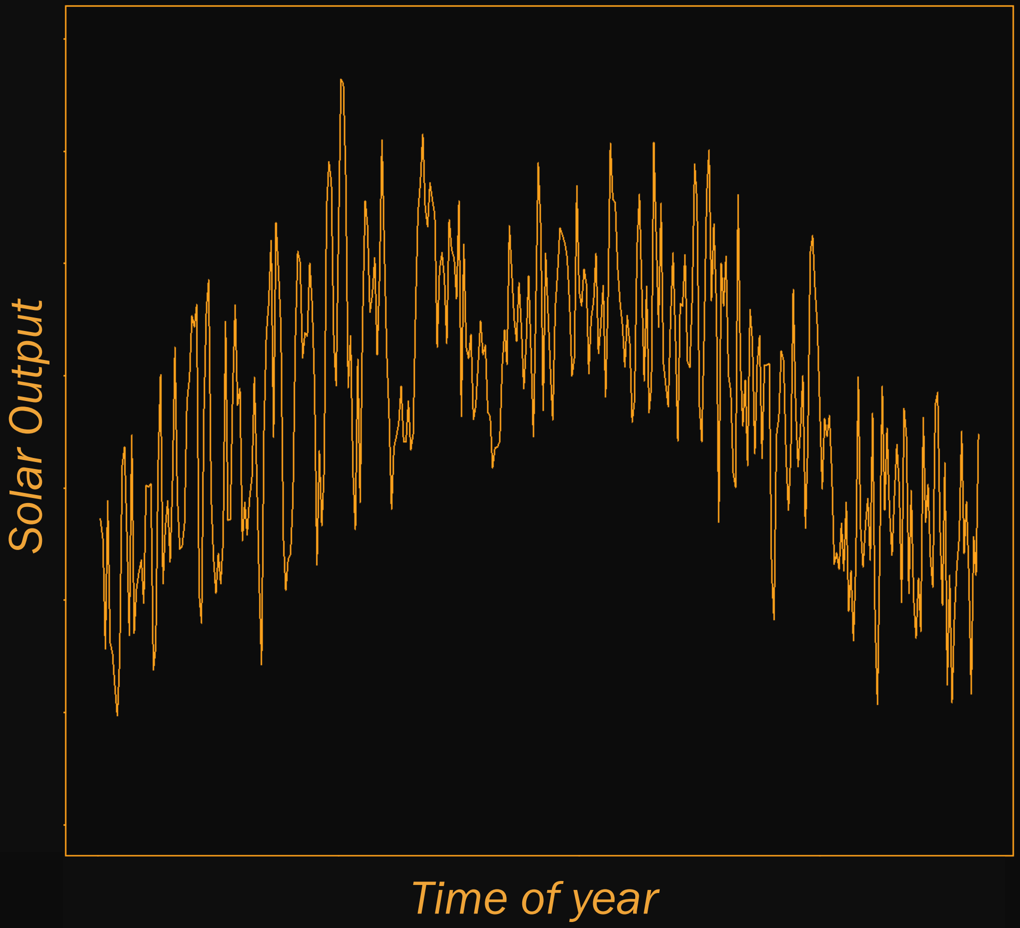


500 km

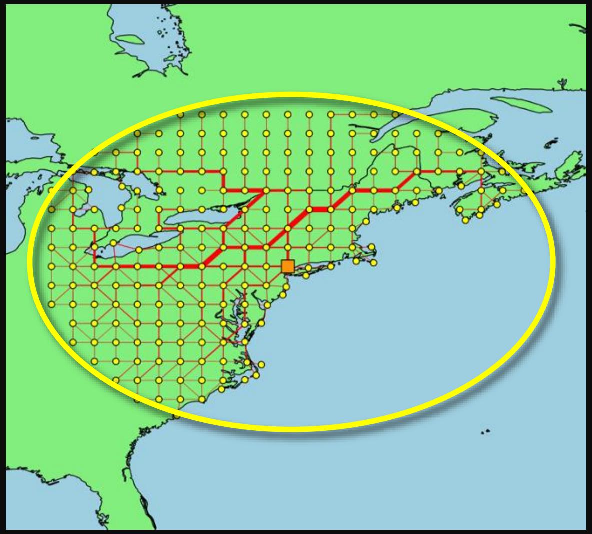


Solution 1.

Geographic dispersion

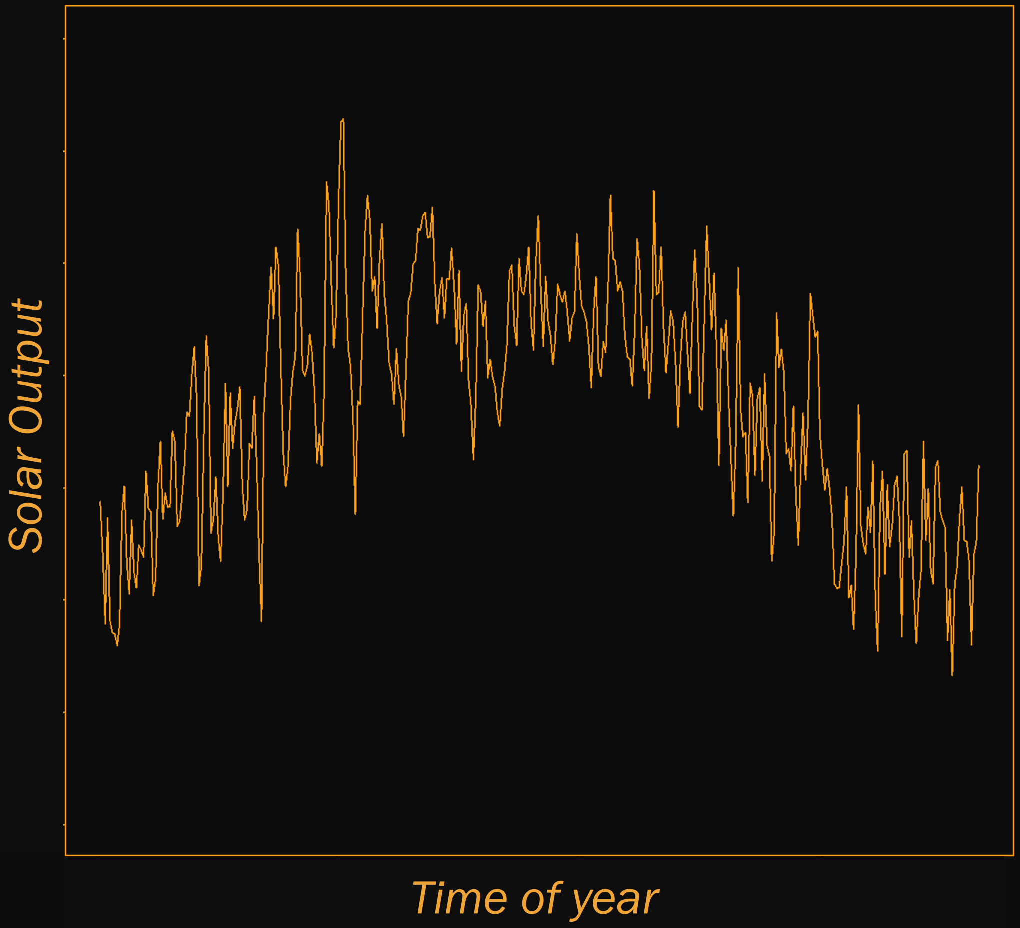


1000 km

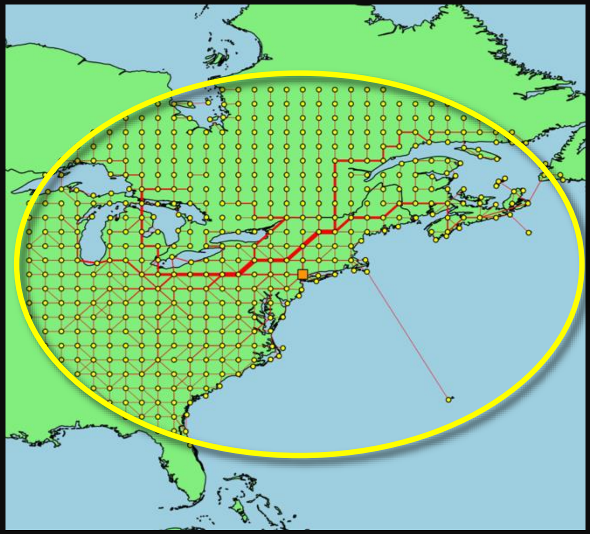


Solution 1.

Geographic dispersion

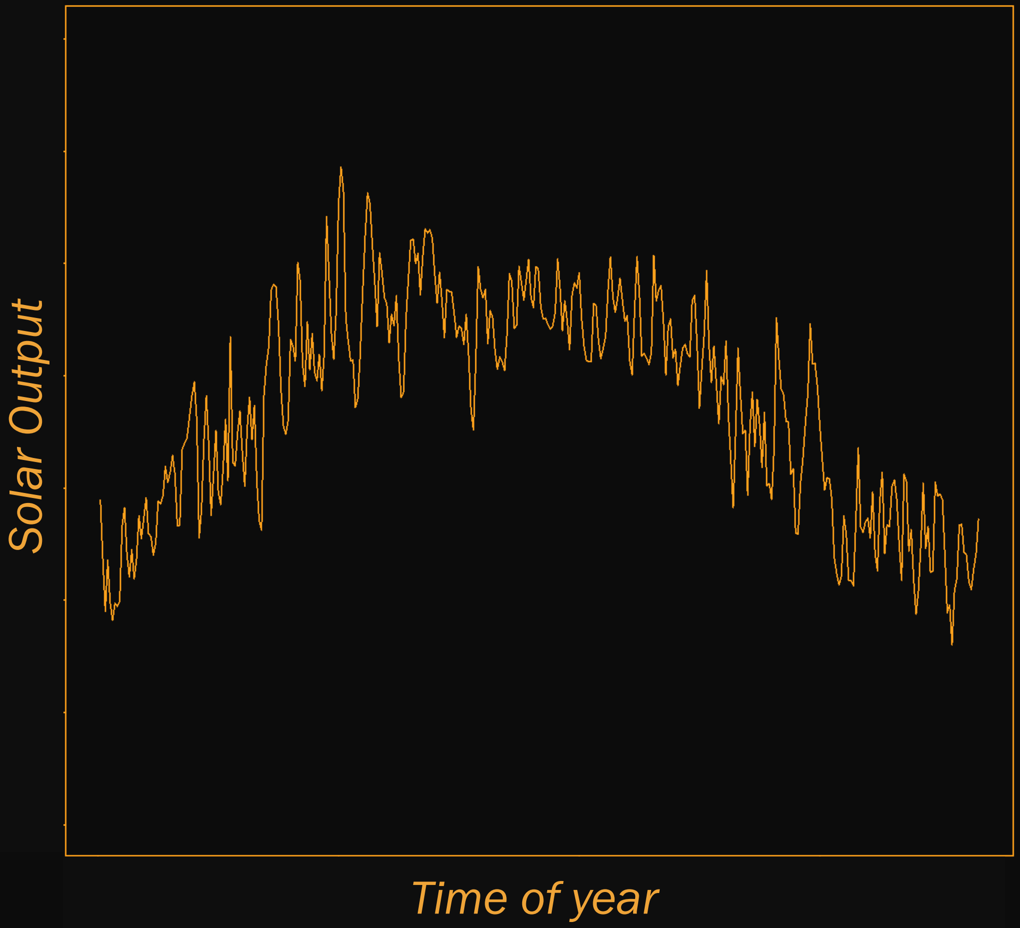


1500 km

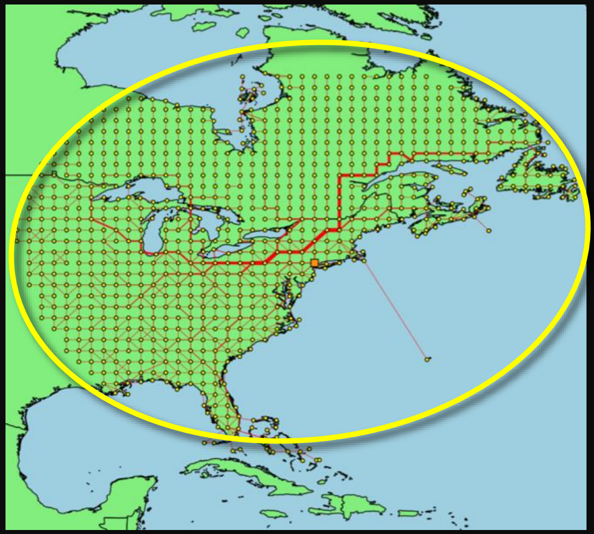


Solution 1.

Geographic dispersion

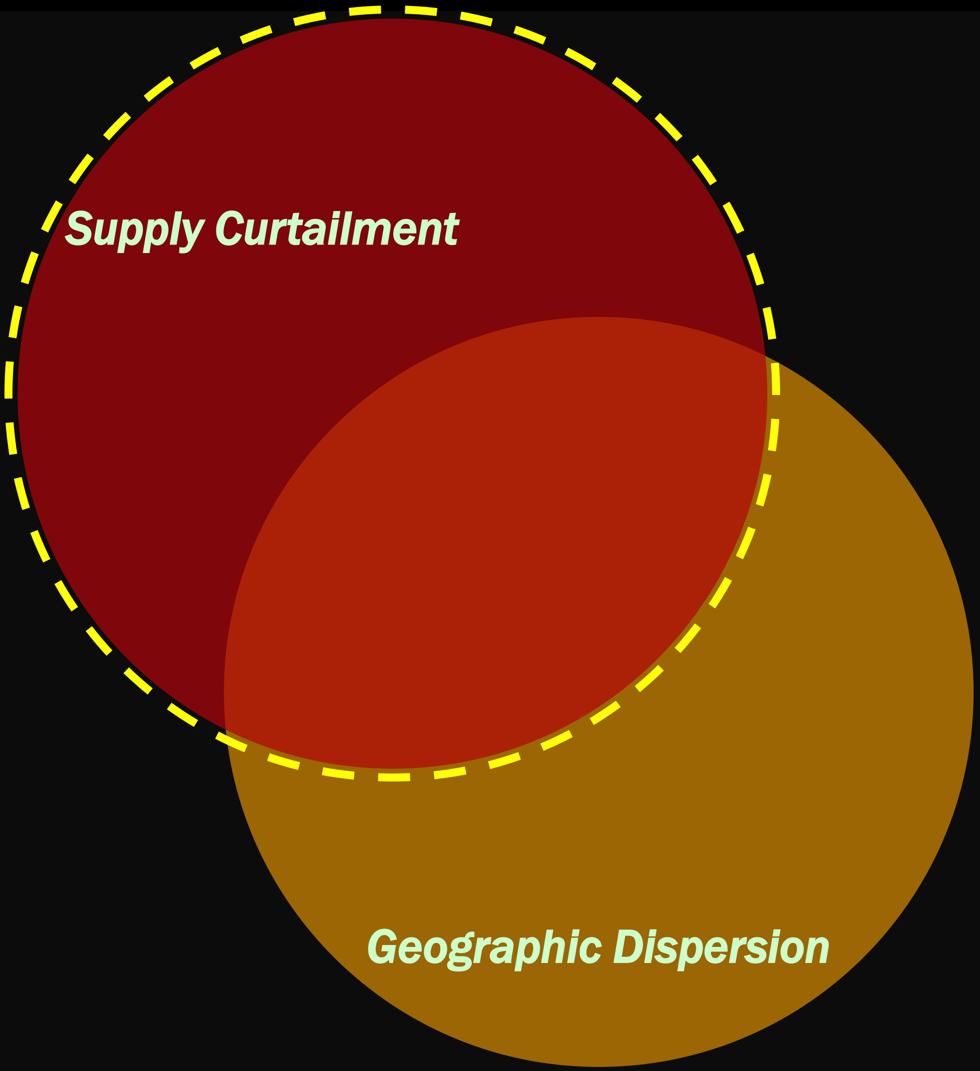


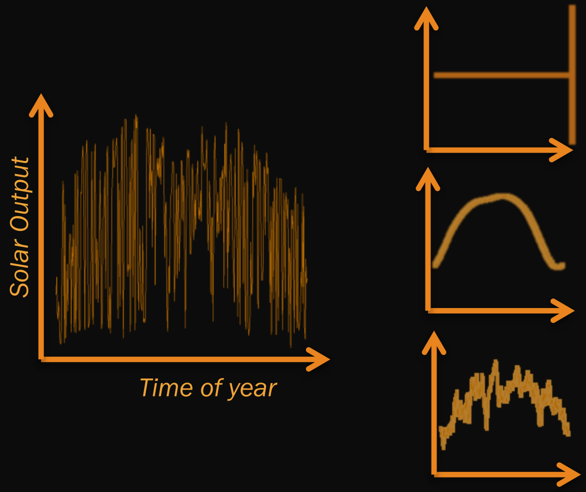
2000 km



Solution 2.

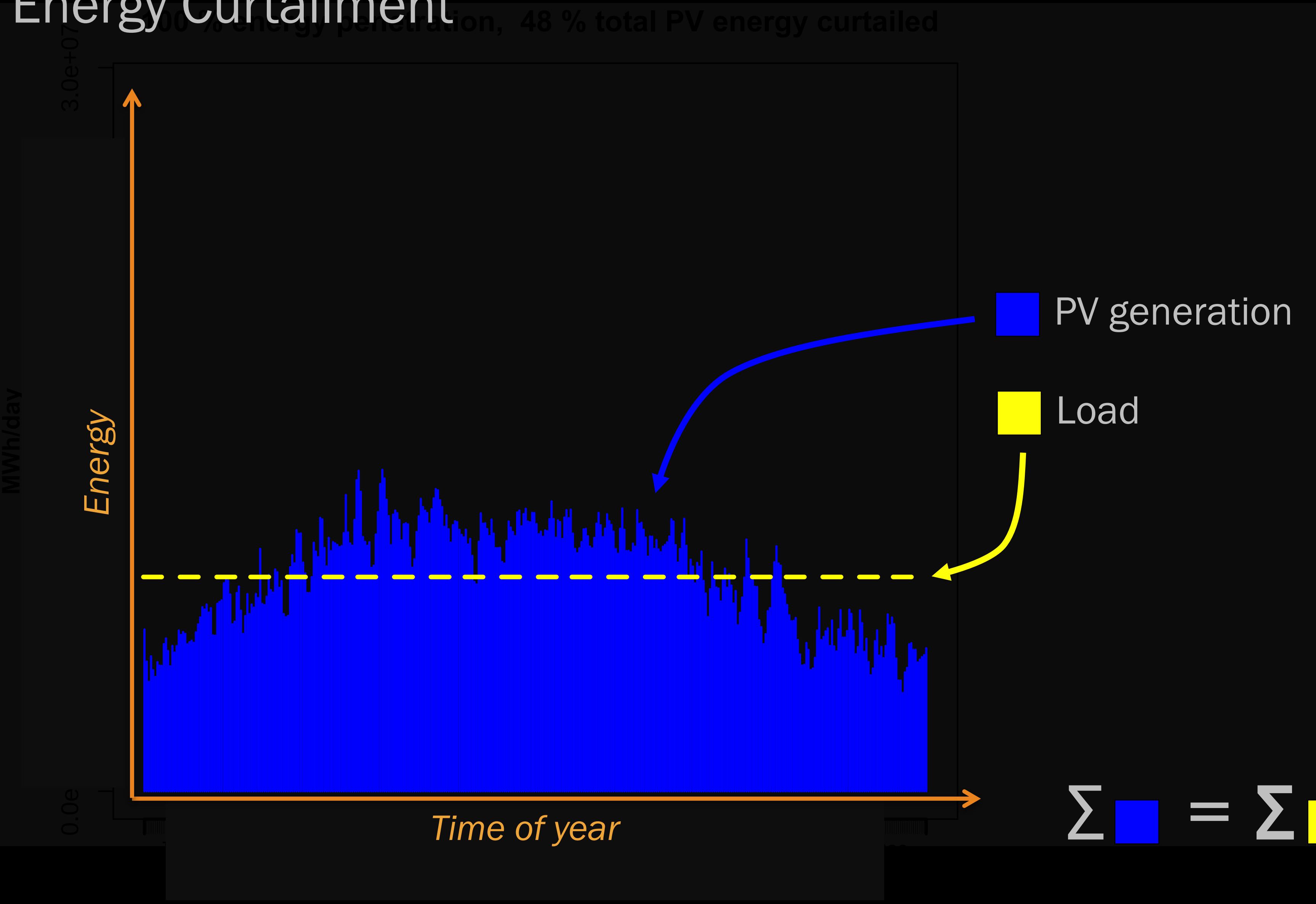
Energy Curtailment





Solution 2.

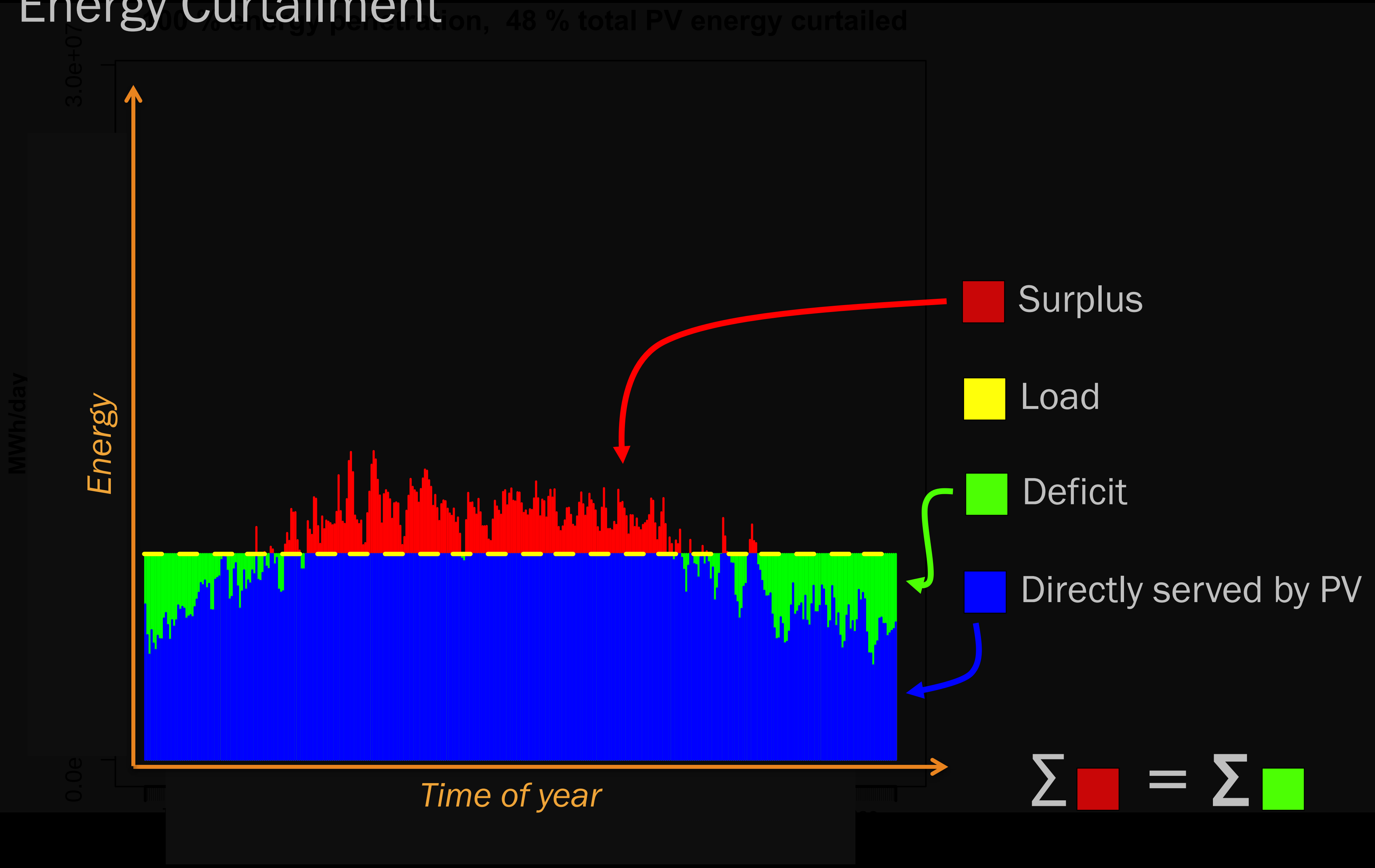
Energy Curtailment



$\sum$ 🟦 = $\sum$ 🟨

Solution 2.

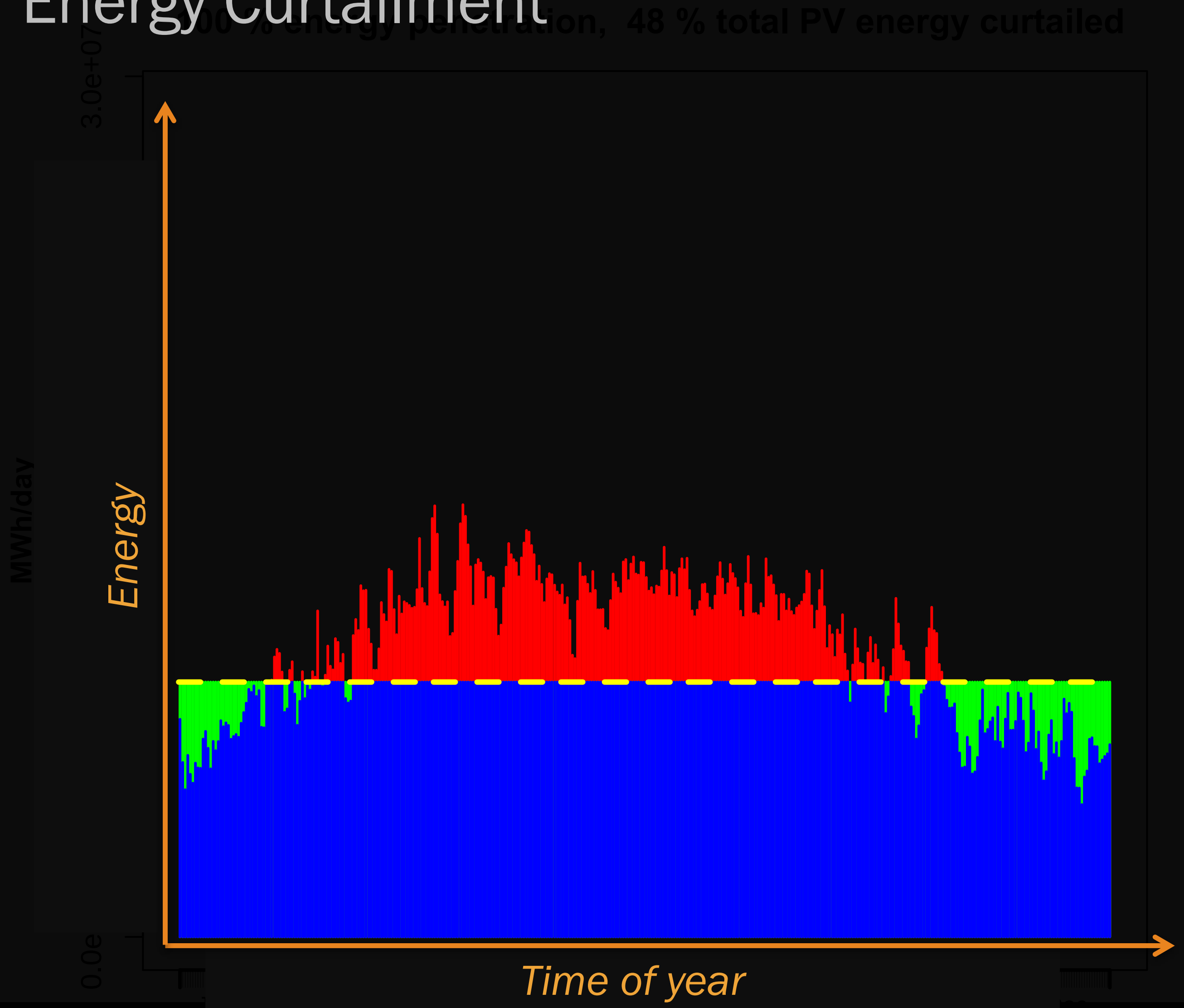
Energy Curtailment



Σ 🟥 = Σ 🟩

Solution 2.

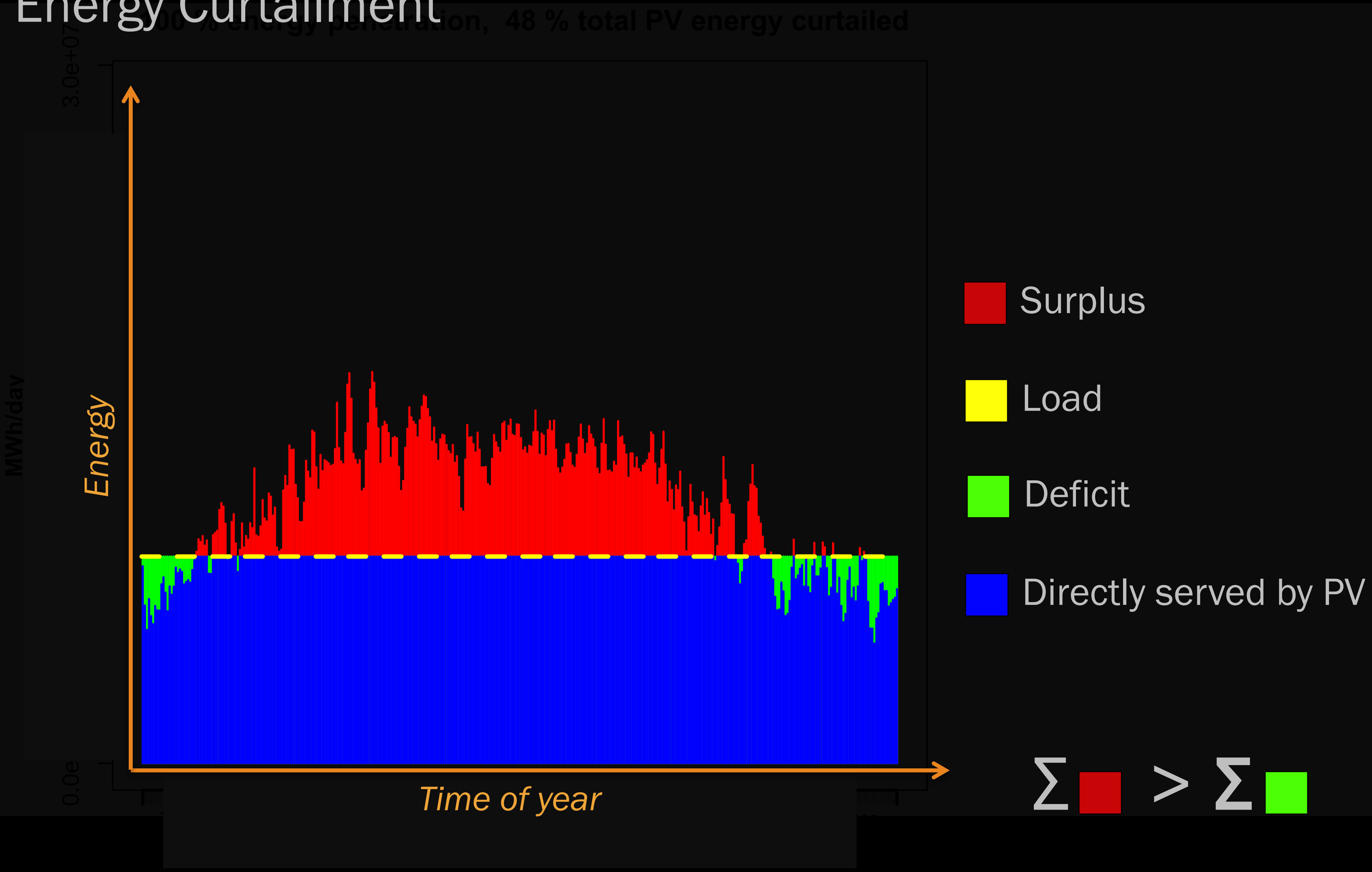
Energy Curtailment



$\sum$ 🟥 $>$ $\sum$ 🟩

Solution 2.

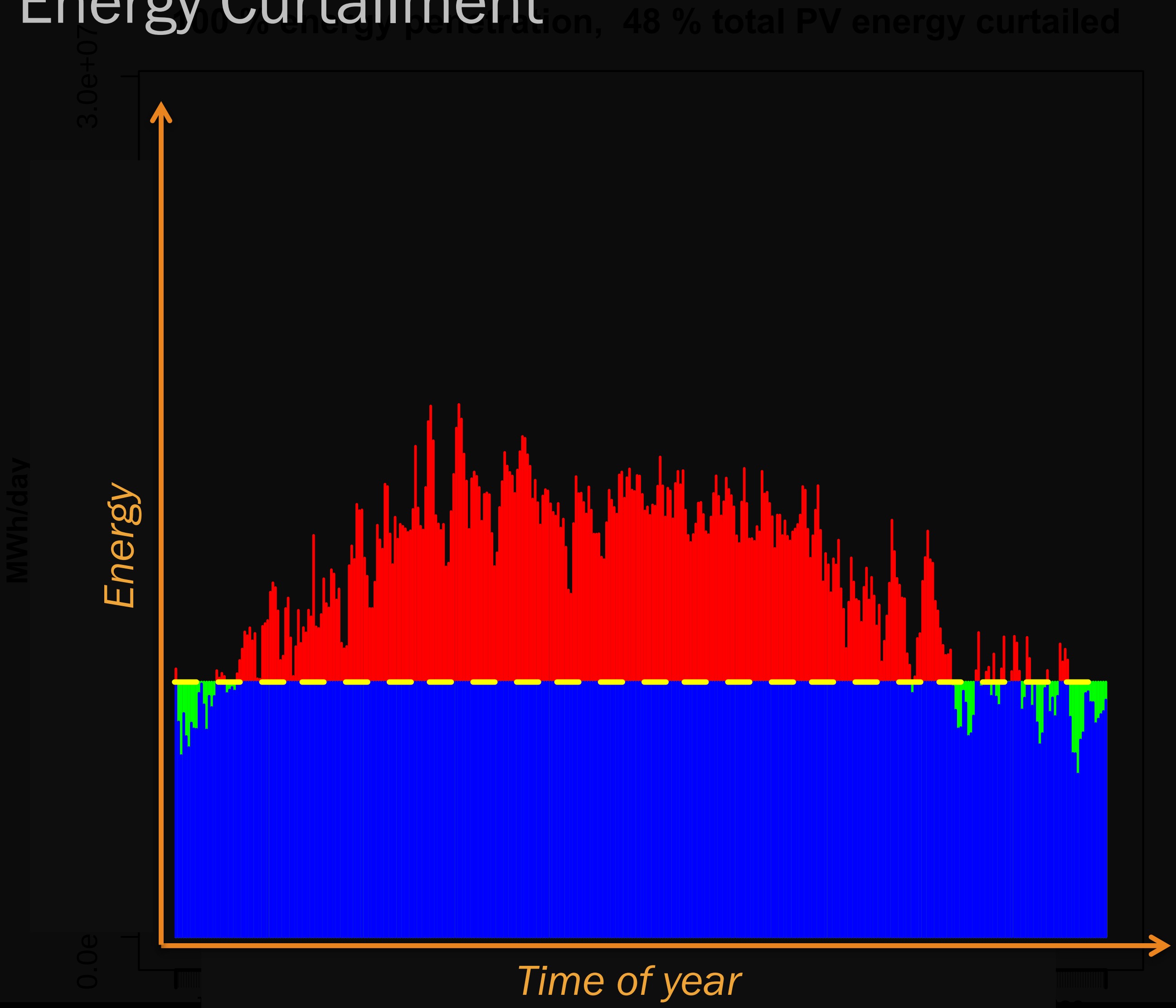
Energy Curtailment



$\sum$ 🟥 > $\sum$ 🟩

Solution 2.

Energy Curtailment



🟥 Surplus

🟨 Load

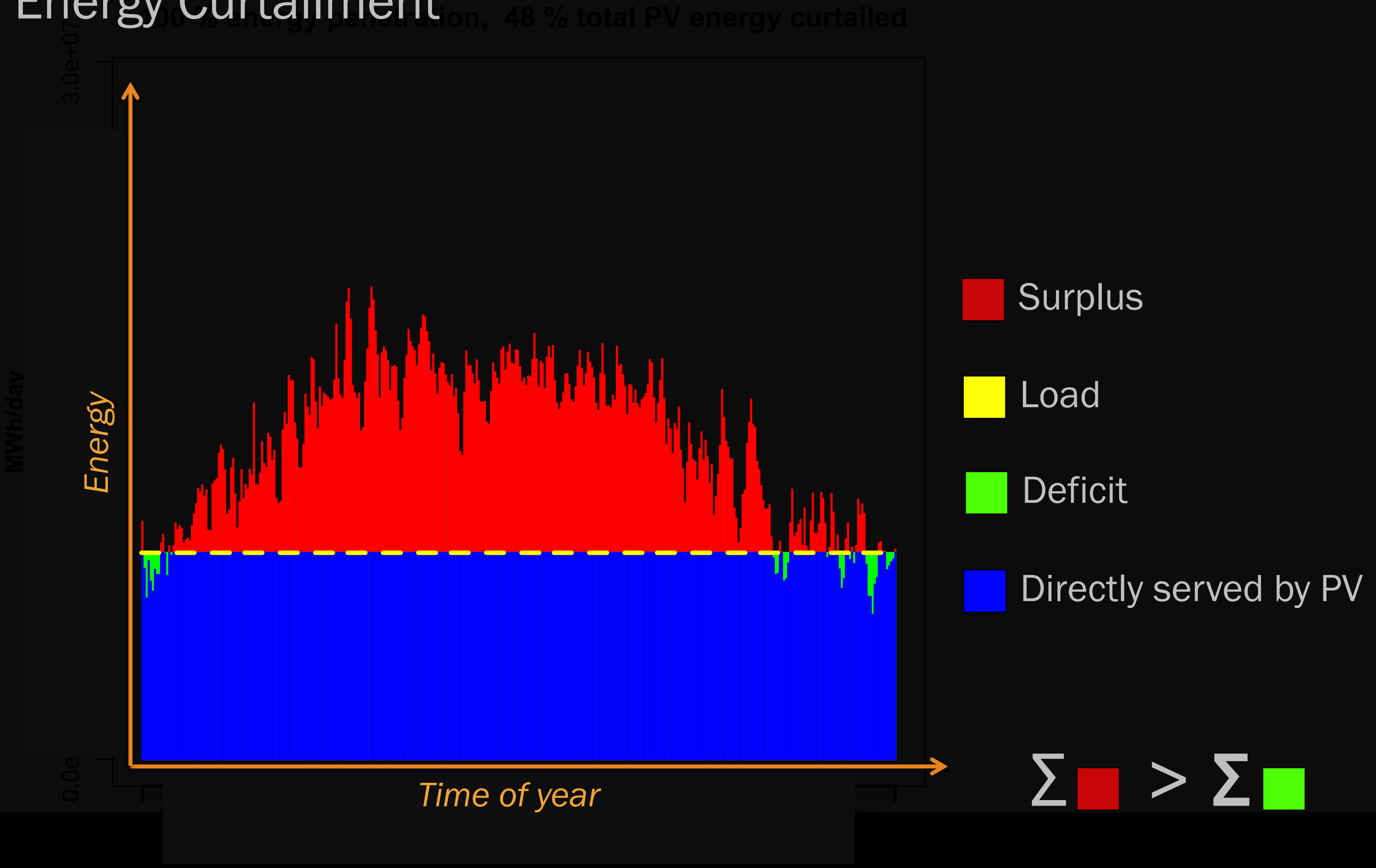
🟩 Deficit

🟦 Directly served by PV

$\sum$ 🟥 > $\sum$ 🟩

Solution 2.

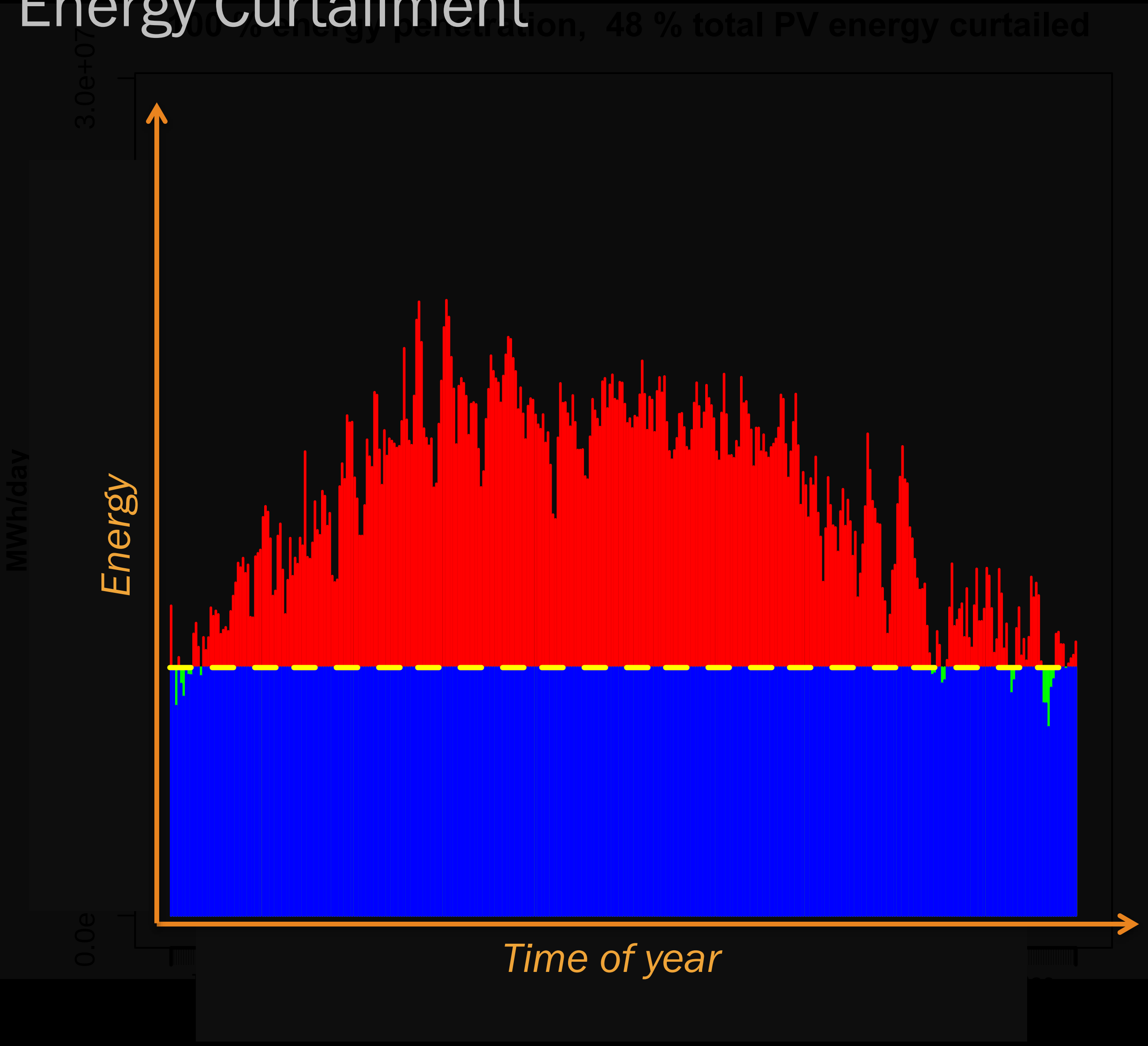
Energy Curtailment



Σ🟥 > Σ🟩

Solution 2.

Energy Curtailment



🟥 Surplus

🟨 Load

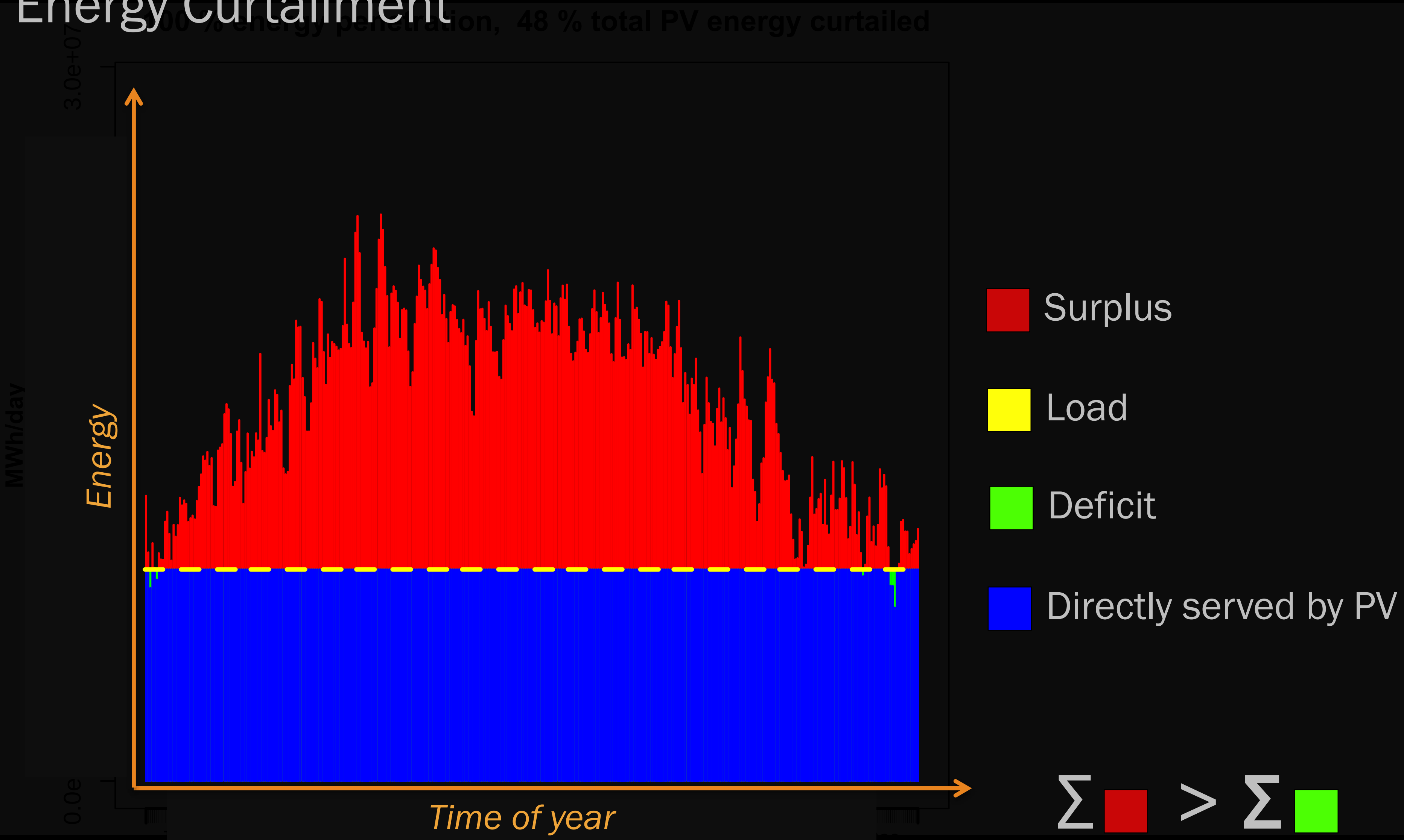
🟩 Deficit

🟦 Directly served by PV

$\sum$ 🟥 > $\sum$ 🟩

Solution 2.

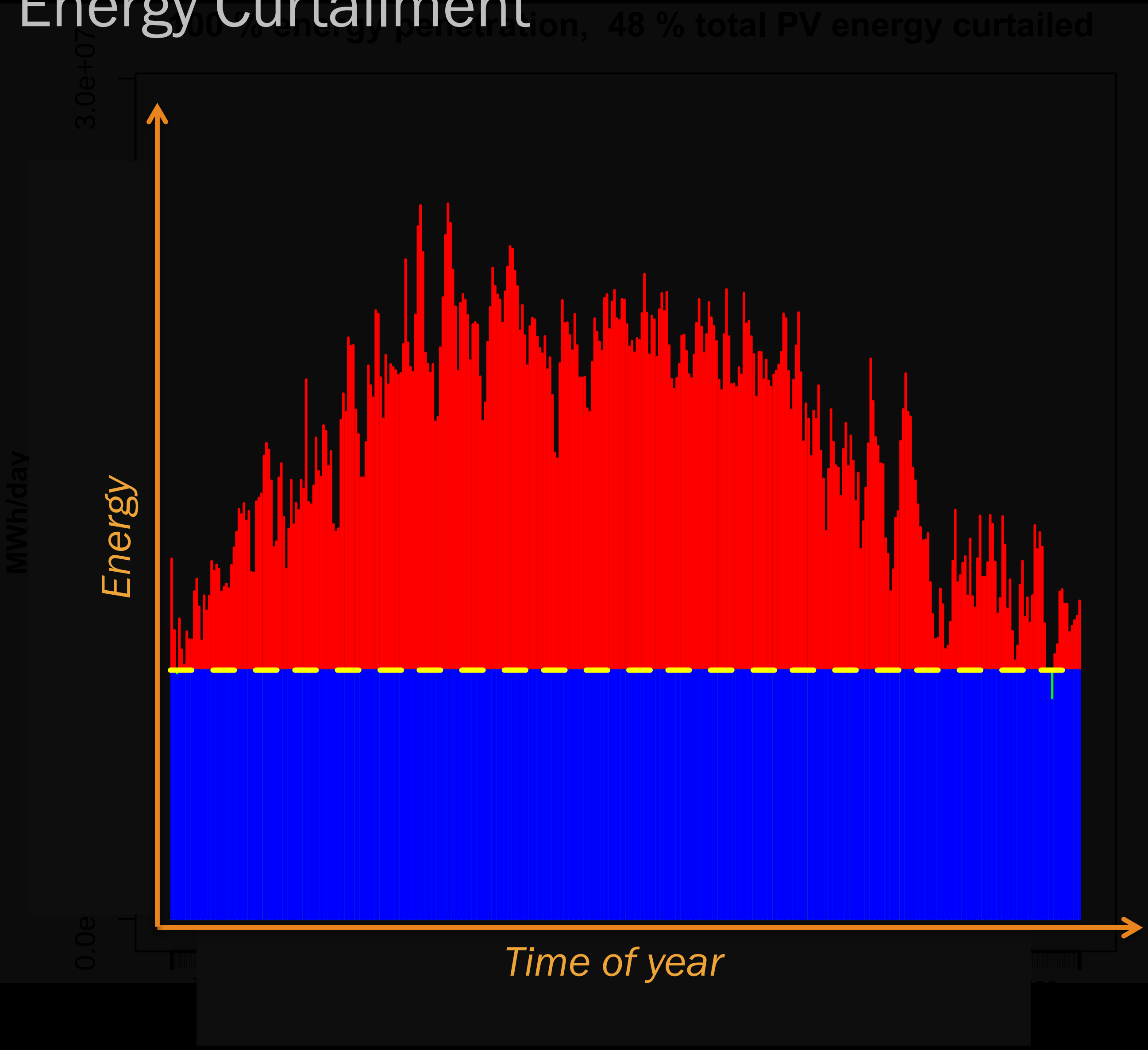
Energy Curtailment



$\sum$ 🟥 > $\sum$ 🟩

Solution 2.

Energy Curtailment



🟥 Surplus

🟨 Load

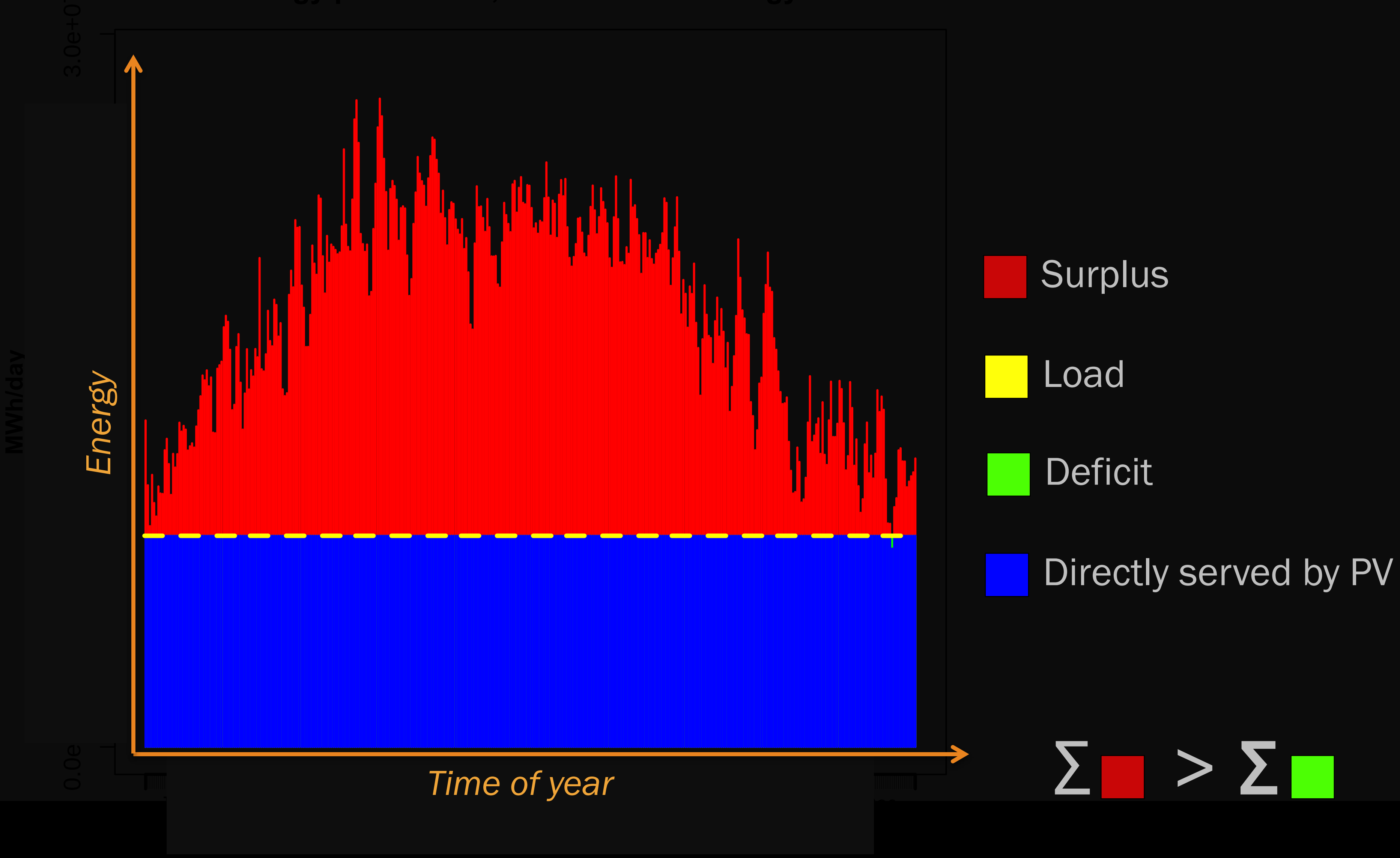
🟩 Deficit

🟦 Directly served by PV

Σ 🟥 > Σ 🟩

Solution 2.

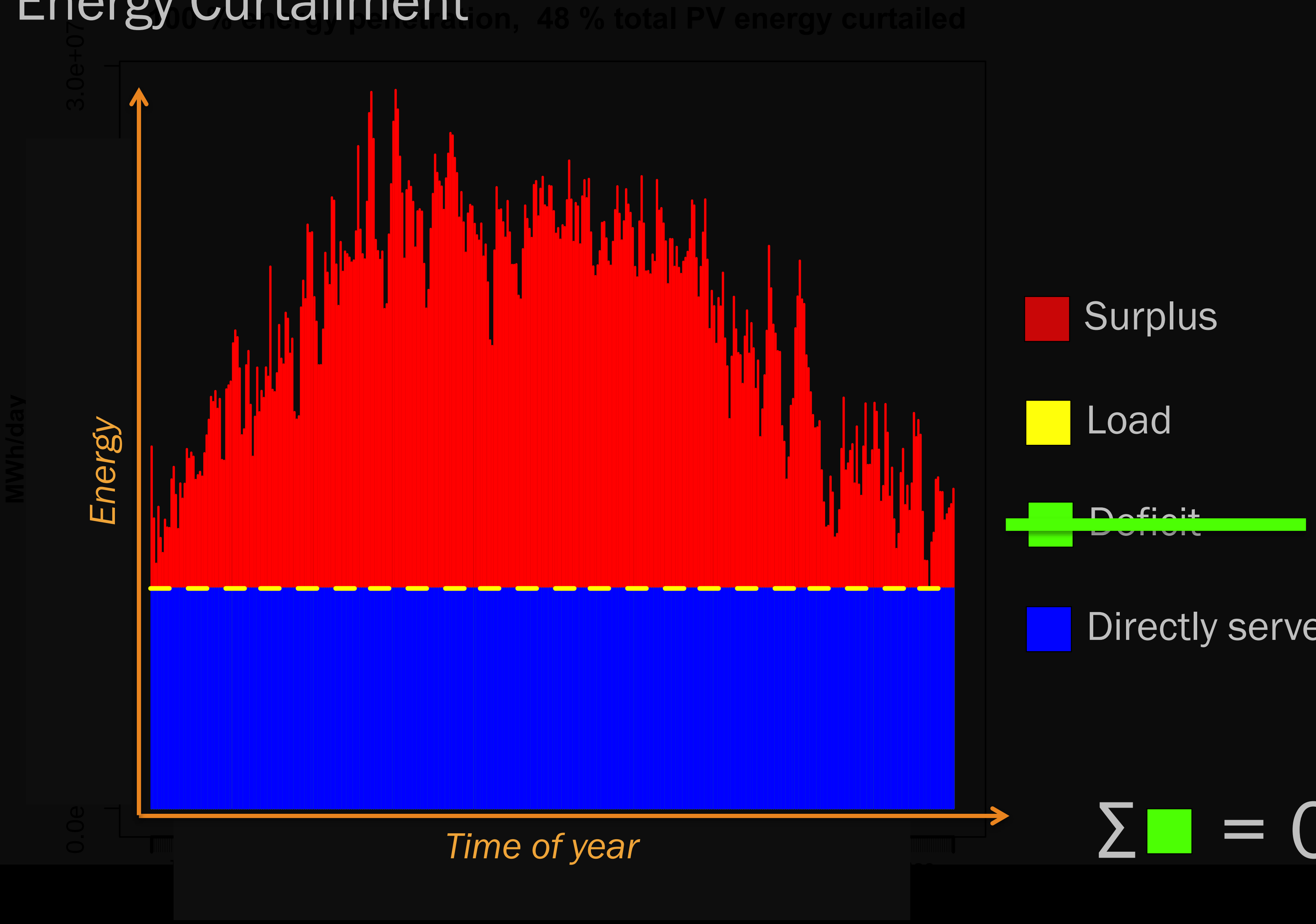
Energy Curtailment



$\sum$ 🟥 > $\sum$ 🟩

Solution 2.

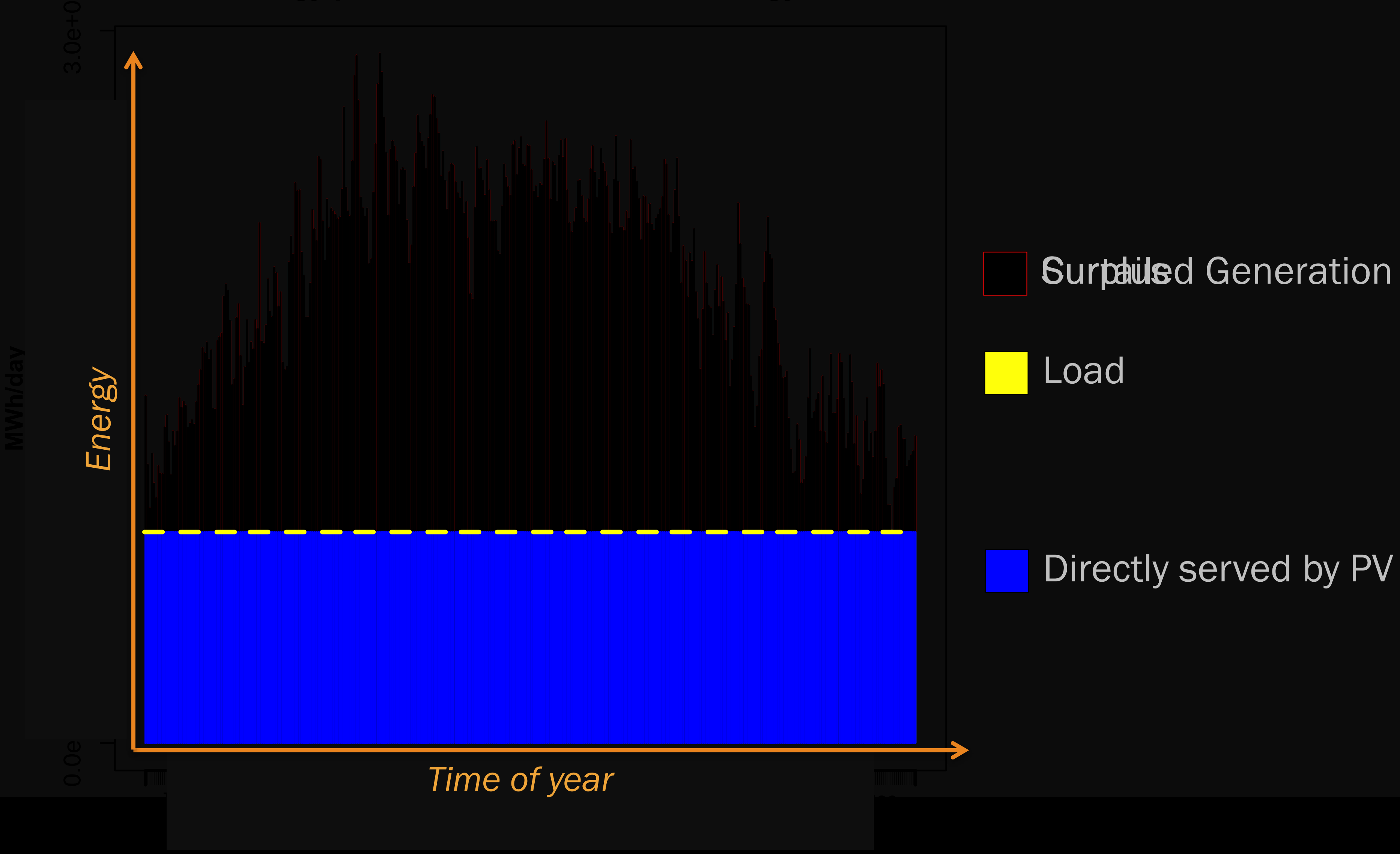
Energy Curtailment



Σ🟩 = 0

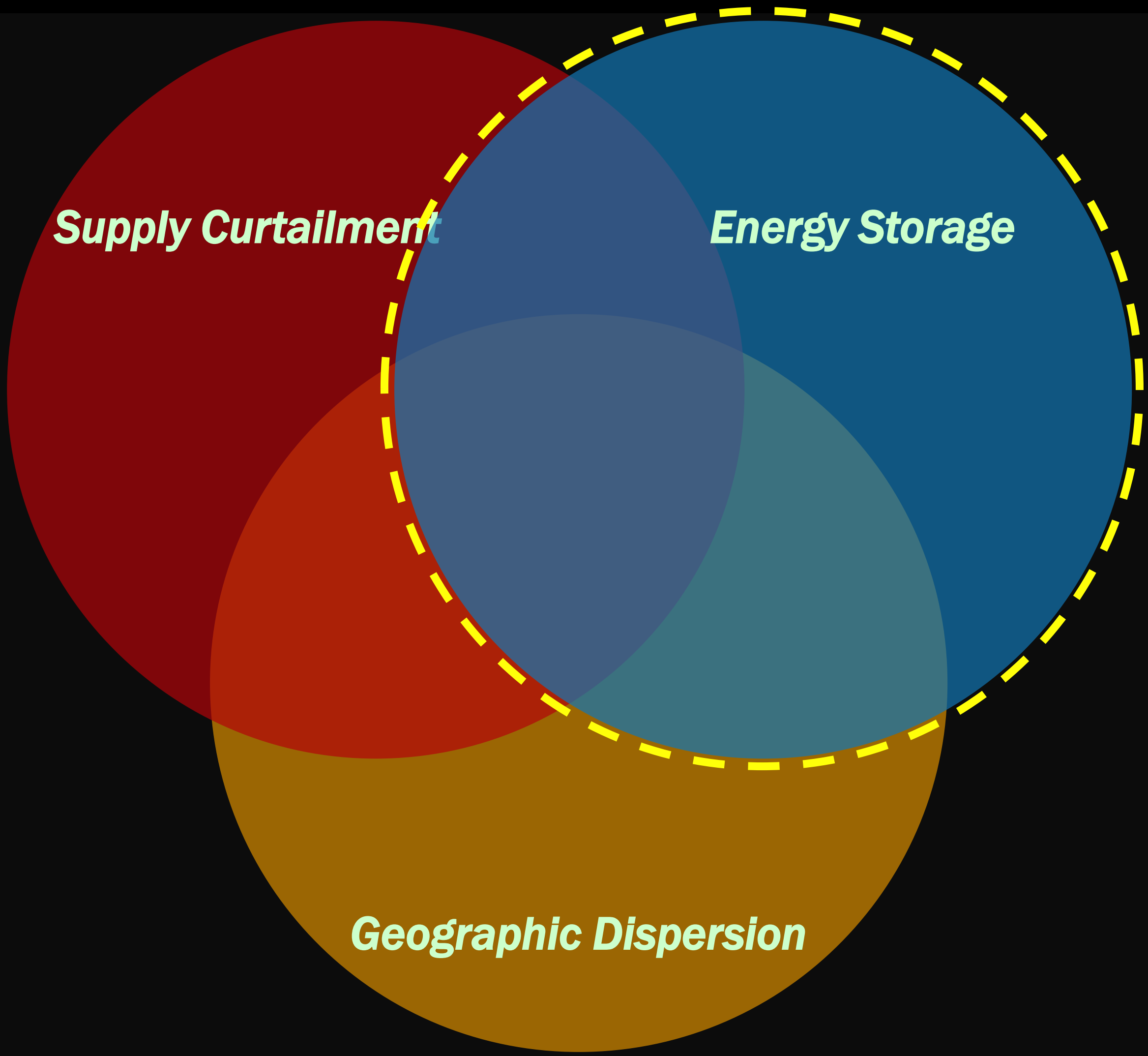
Solution 2.

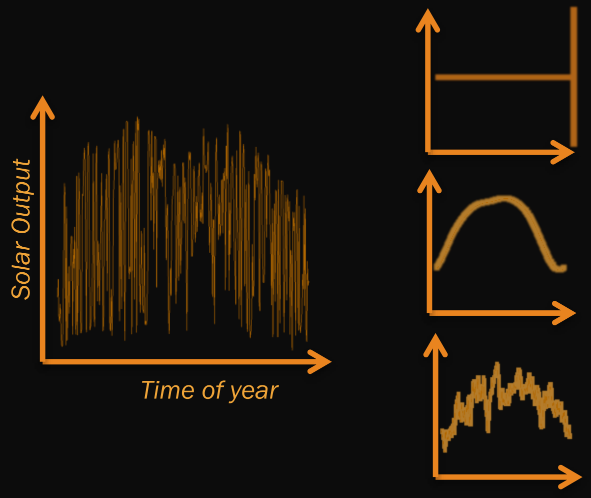
Energy Curtailment



Solution 3.

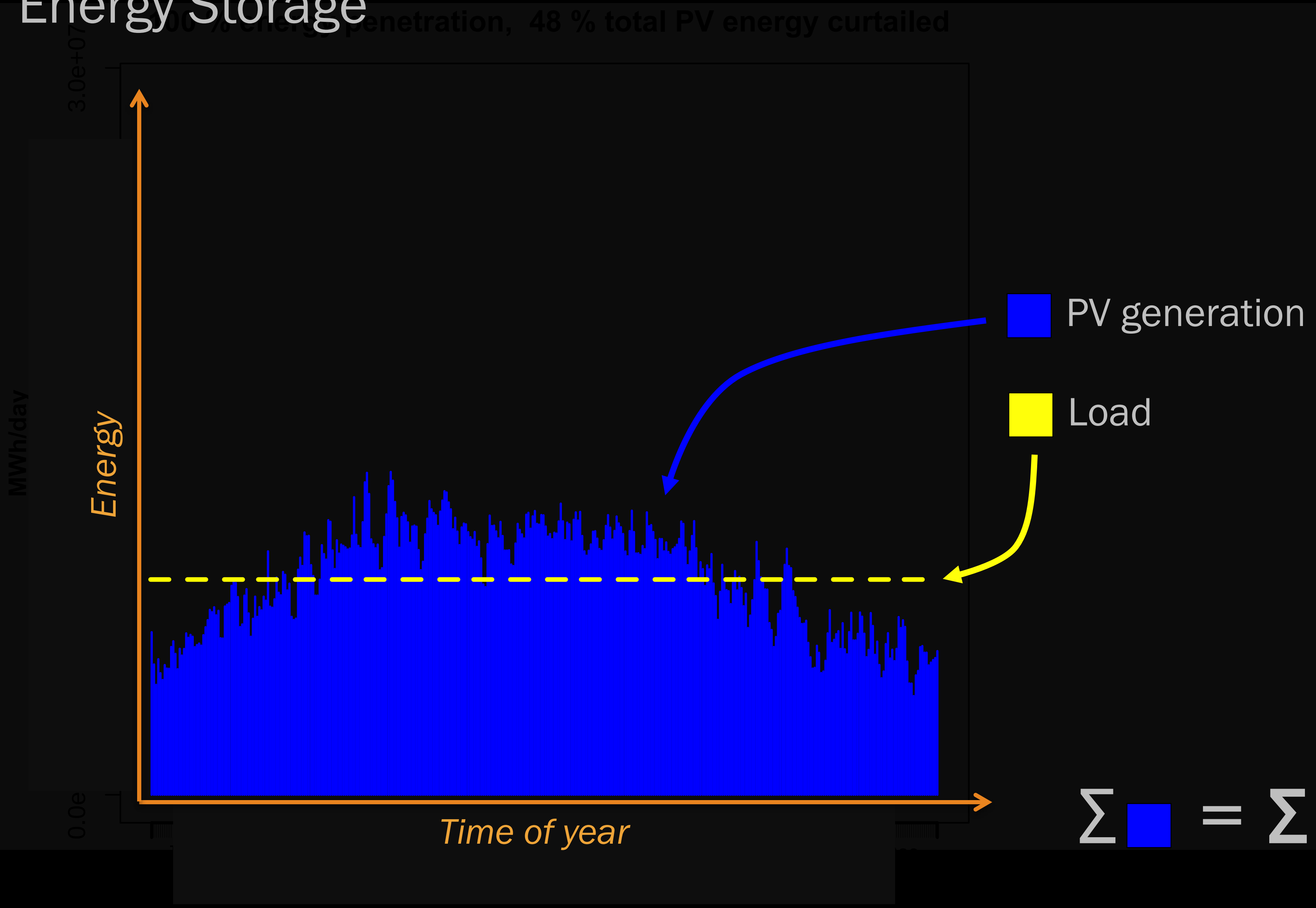
Energy Storage





Solution 3.

Energy Storage



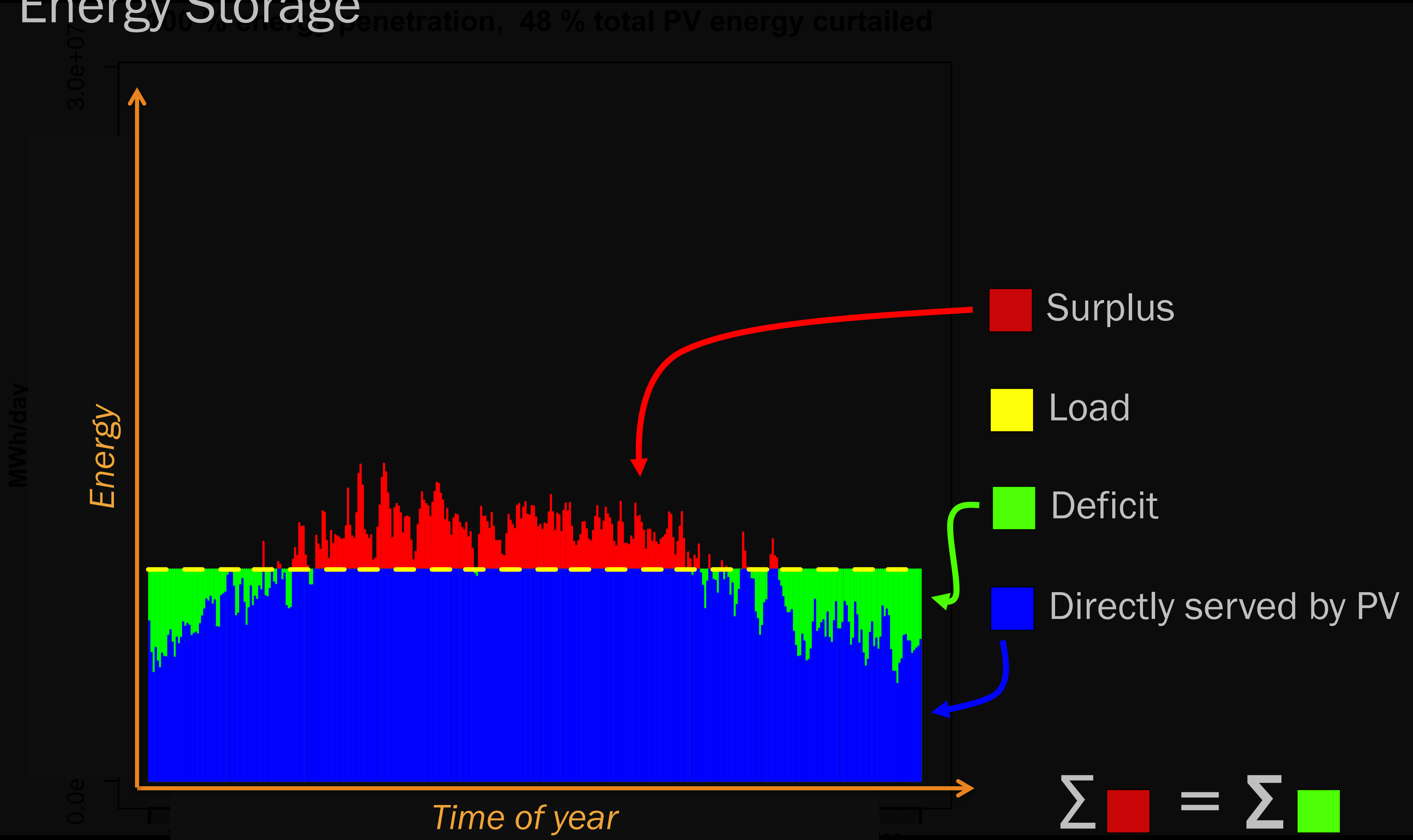
🟦 PV generation

🟨 Load

Σ🟦 = Σ🟨

Solution 3.

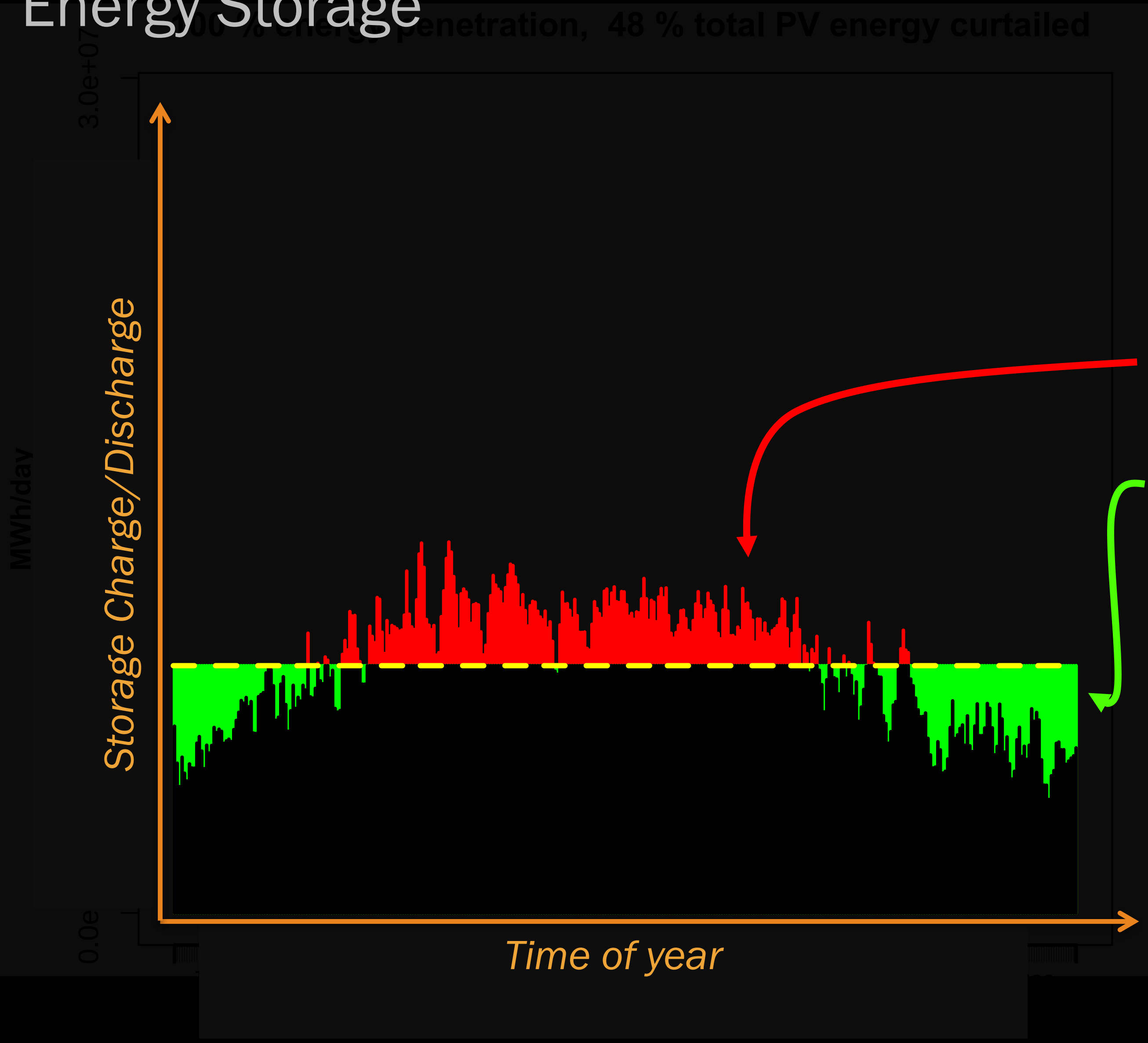
Energy Storage



Σ 🟥 = Σ 🟩

Solution 3.

Energy Storage

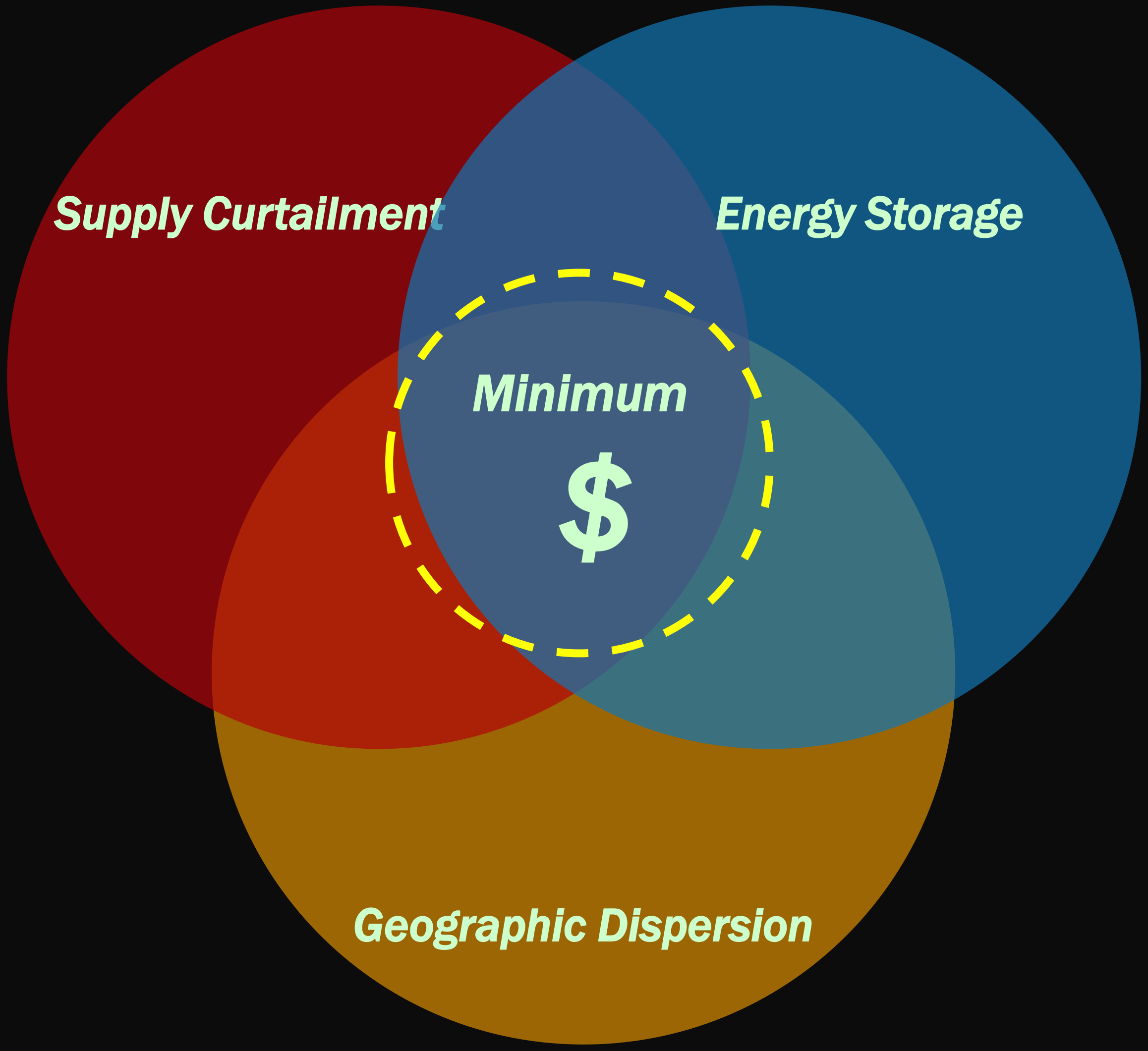


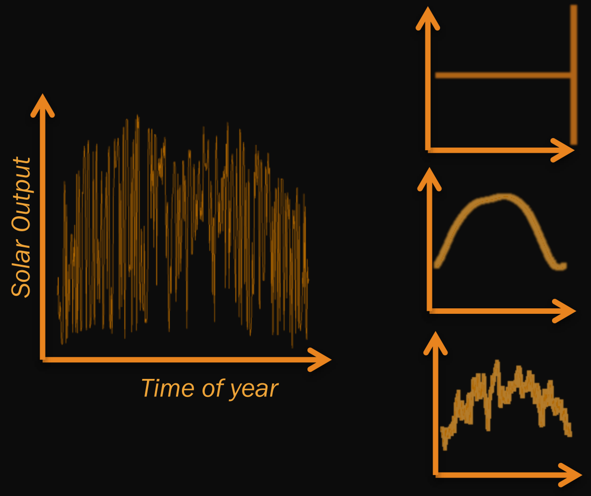
🟥 Storage Charging

🟩 Storage Discharging

3 Supply-Side Solutions

To the intermittency barrier

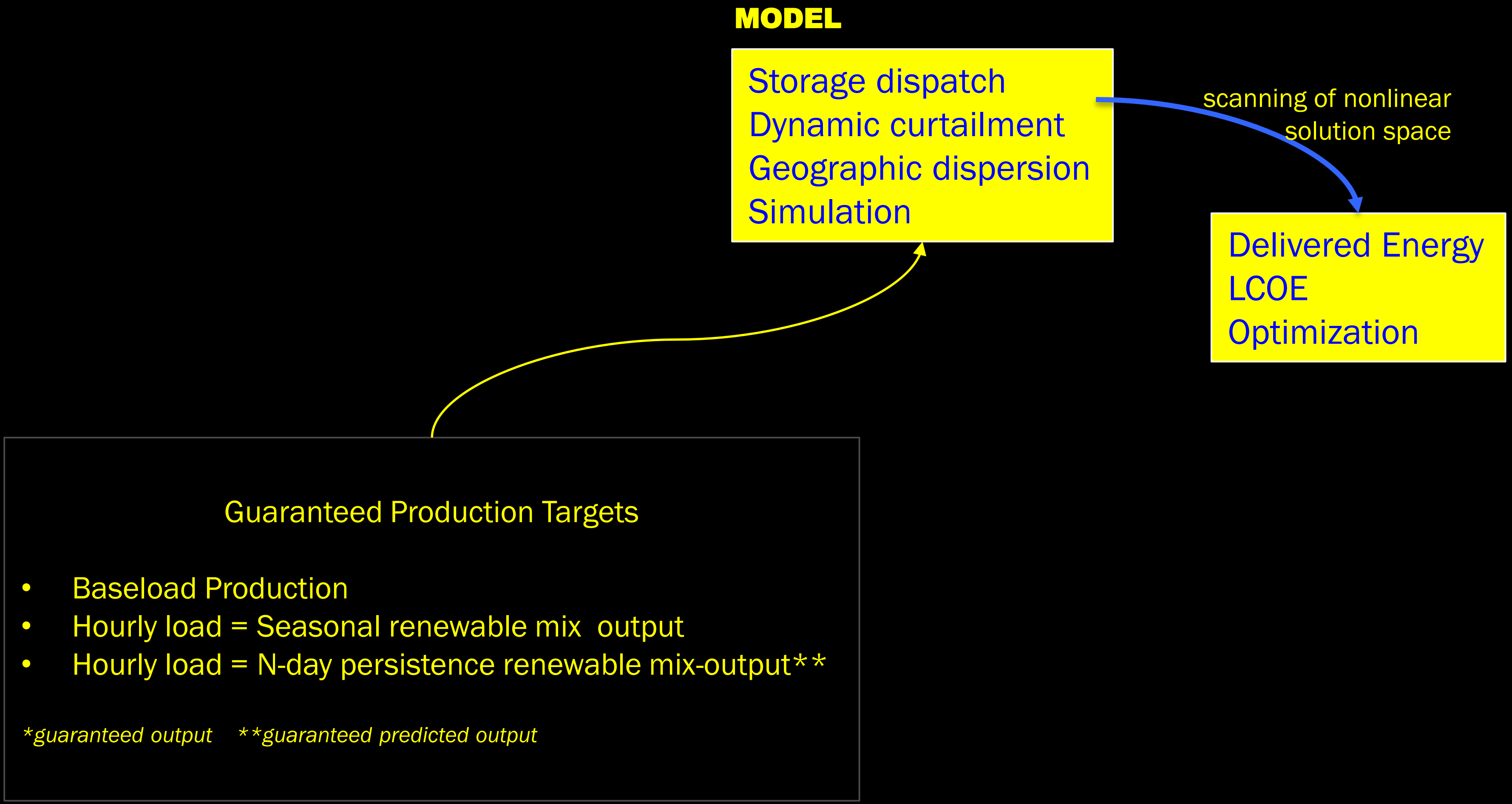




Optimization Model

Minimum

$



MODEL

Storage dispatch
Dynamic curtailment
Geographic dispersion
Simulation

scanning of nonlinear
solution space

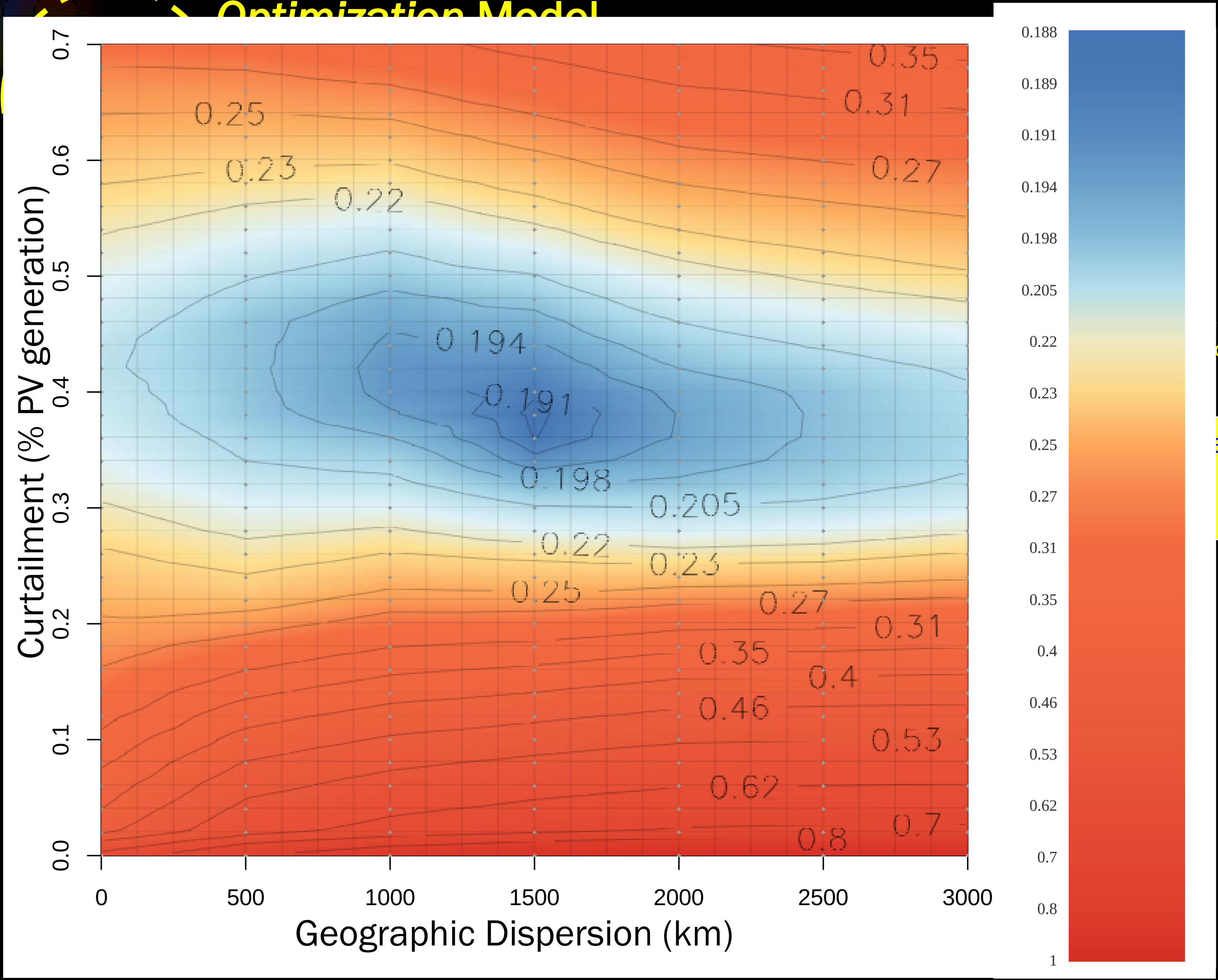
Delivered Energy
LCOE
Optimization

Guaranteed Production Targets

- Baseload Production
- Hourly load = Seasonal renewable mix output
- Hourly load = N-day persistence renewable mix-output**

**guaranteed output* ***guaranteed predicted output*

Optimization Model



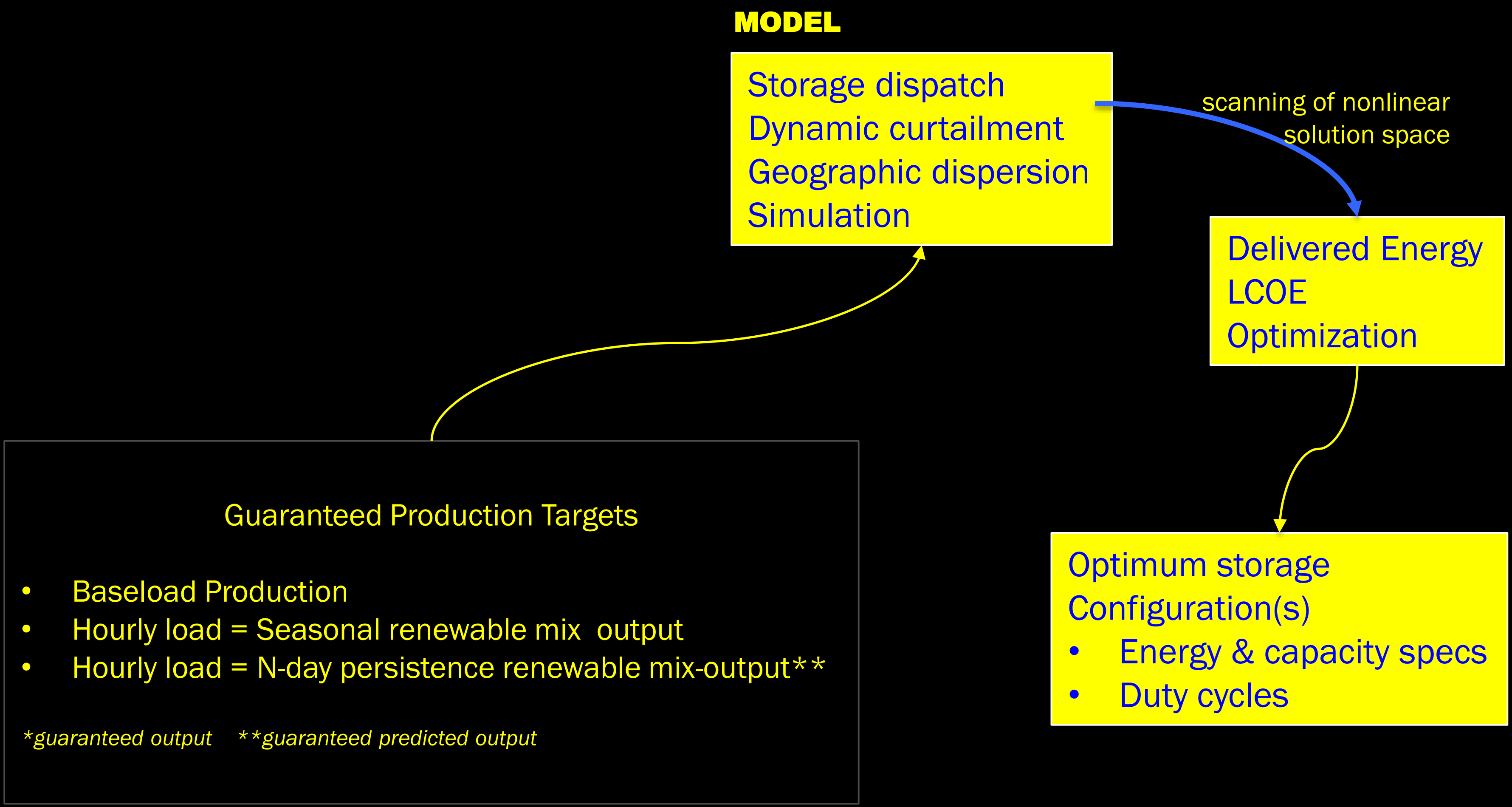
ar
ce

ergy

Optimization Model

Minimum

$



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Storage dispatch
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solution space

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LCOE
Optimization

Optimum storage
Configuration(s)
- Energy & capacity specs
- Duty cycles

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**guaranteed output* ****guaranteed predicted output*

Optimization Model

Minimum

$

MODEL

Hourly data
2008-2013

Gridded irradiances data
10 km

Local Met data

PV simulations

Storage dispatch
Dynamic curtailment
Geographic dispersion
Simulation

scanning of nonlinear
solution space

Delivered Energy
LCOE
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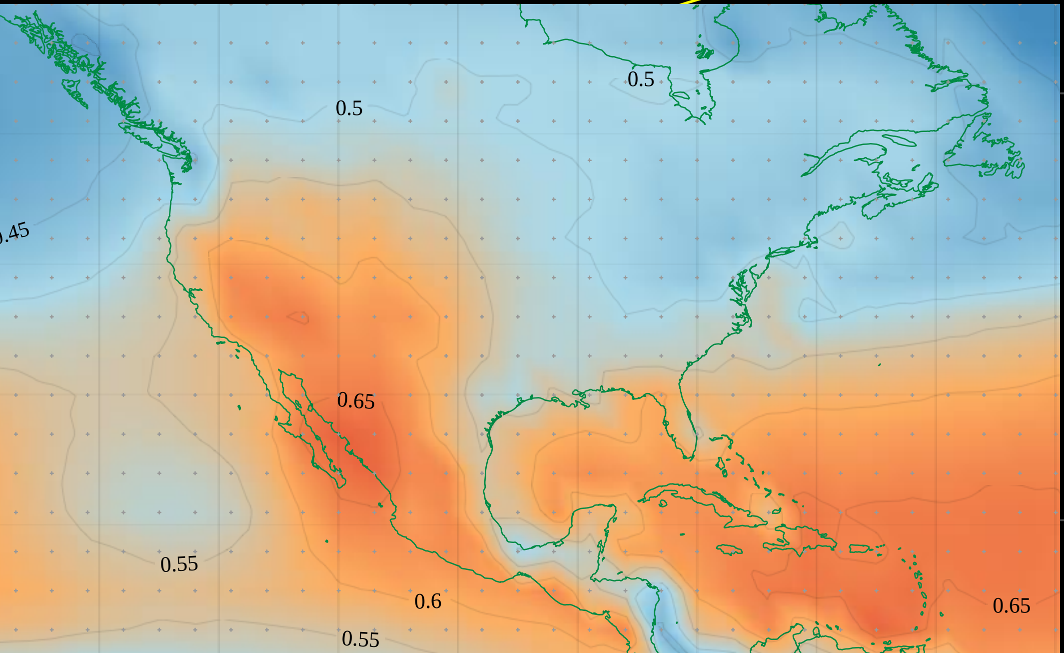
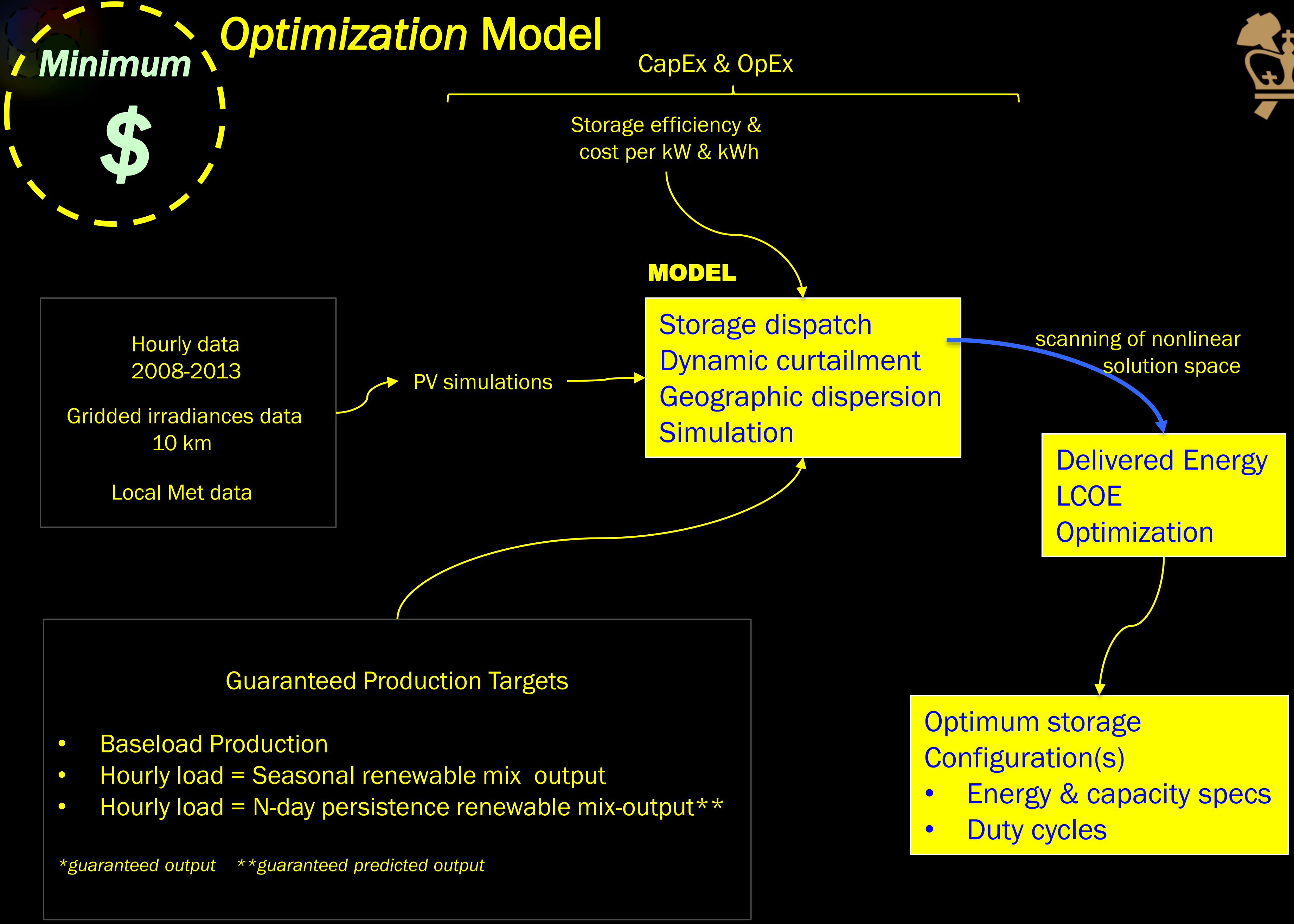
Optimum storage
Configuration(s)
- Energy & capacity specs
- Duty cycles



Optimization Model



Minimum

$

CapEx & OpEx

Storage efficiency &
cost per kW & kWh

MODEL

Storage dispatch
Dynamic curtailment
Geographic dispersion
Simulation

Hourly data
2008-2013

Gridded irradiances data
10 km

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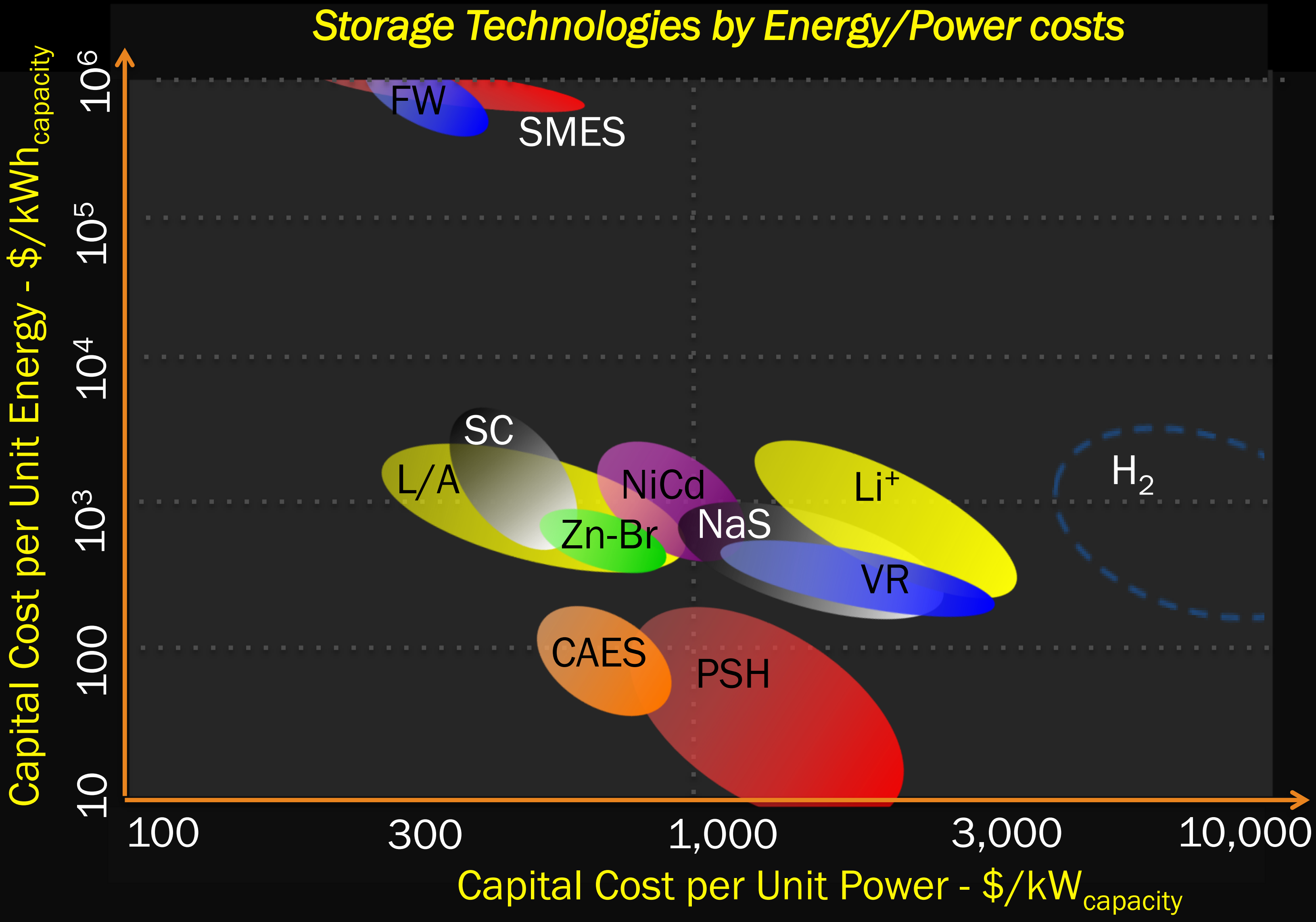
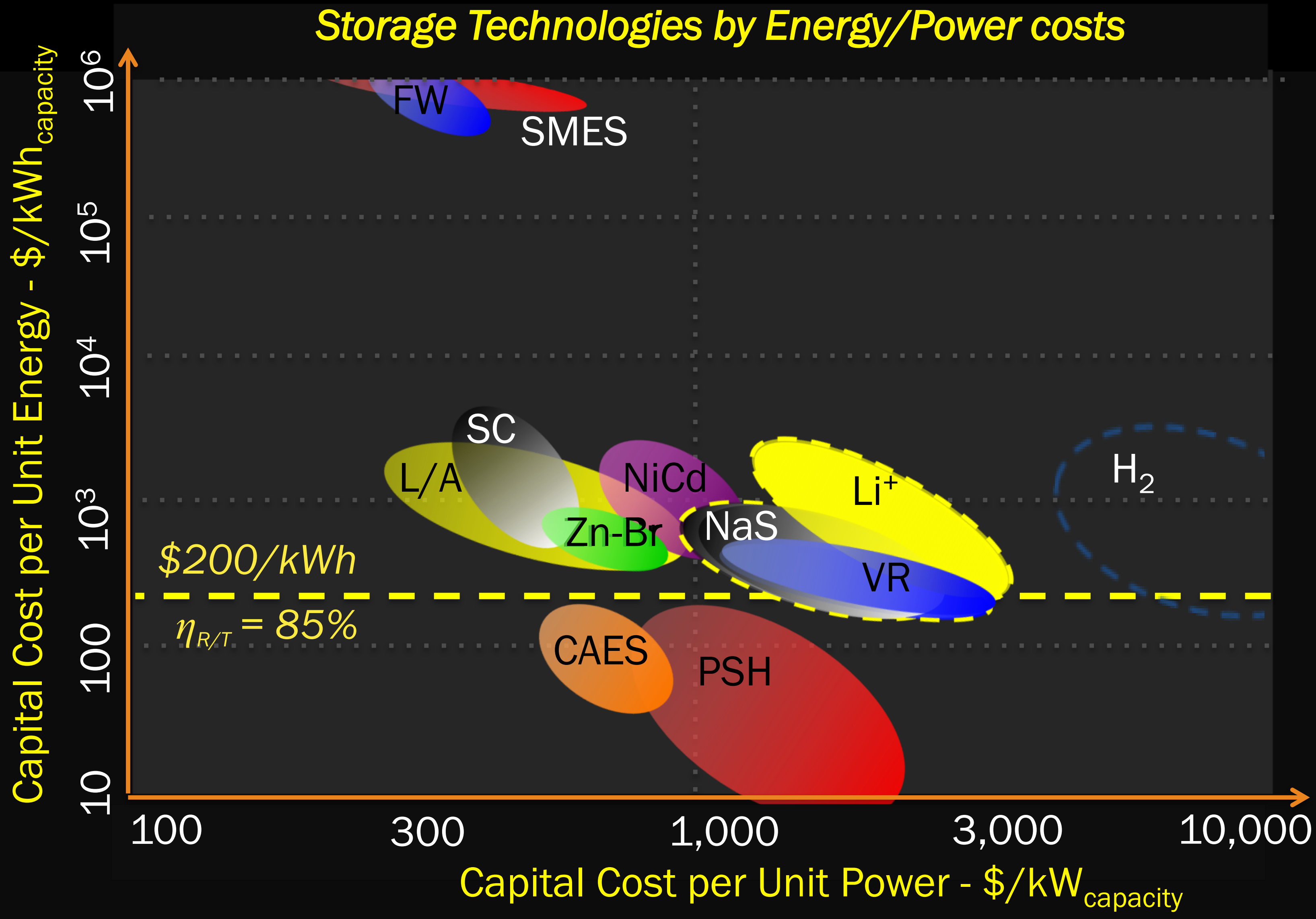
**guaranteed output* ***guaranteed predicted output*

Optimum storage
Configuration(s)
- Energy & capacity specs
- Duty cycles

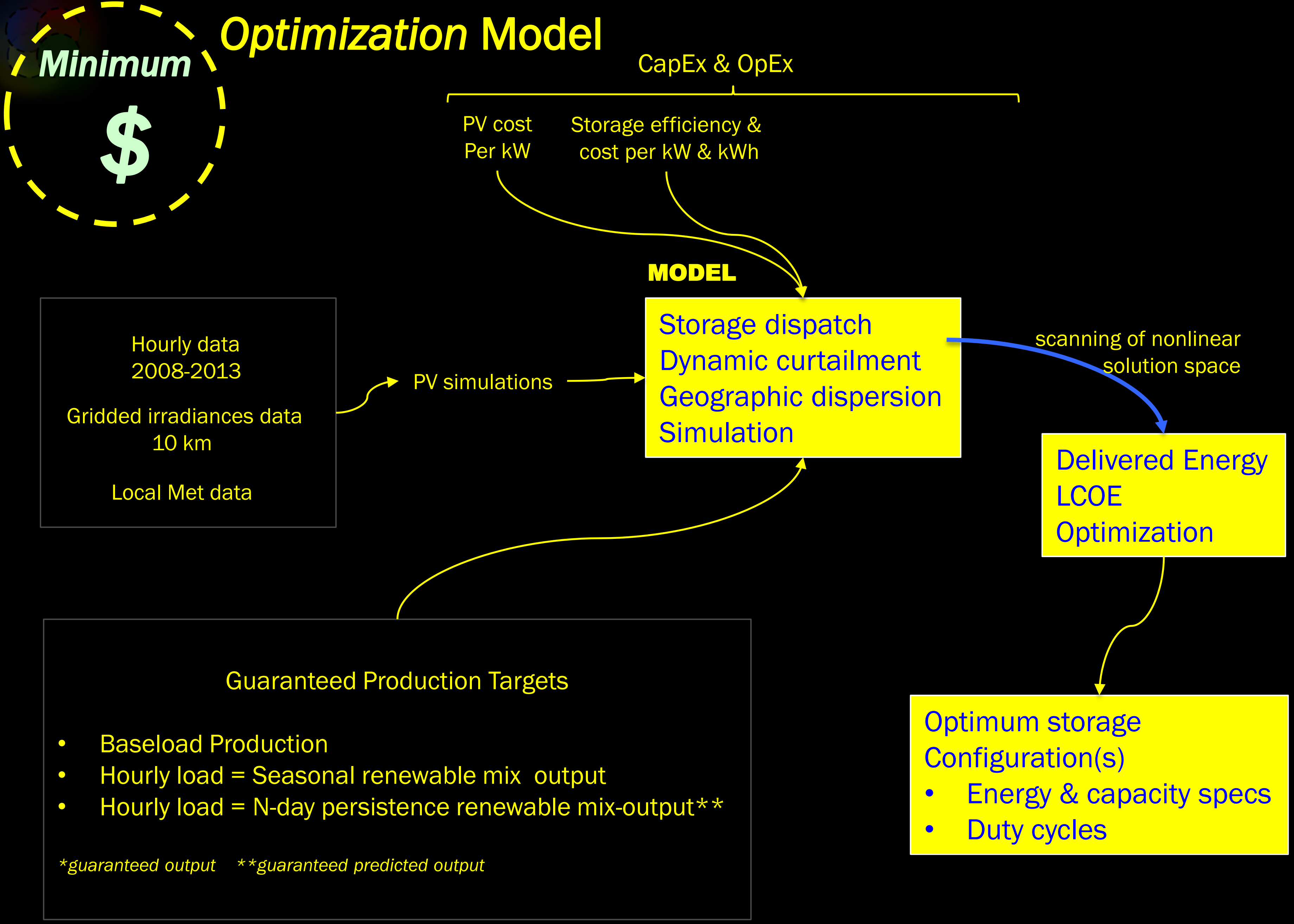
Storage Costs



Storage Costs



Optimization Model



Minimum

$

CapEx & OpEx

PV cost
Per kW

Storage efficiency &
cost per kW & kWh

MODEL

Storage dispatch
Dynamic curtailment
Geographic dispersion
Simulation

Hourly data
2008-2013

Gridded irradiances data
10 km

Local Met data

PV simulations

scanning of nonlinear
solution space

Delivered Energy
LCOE
Optimization

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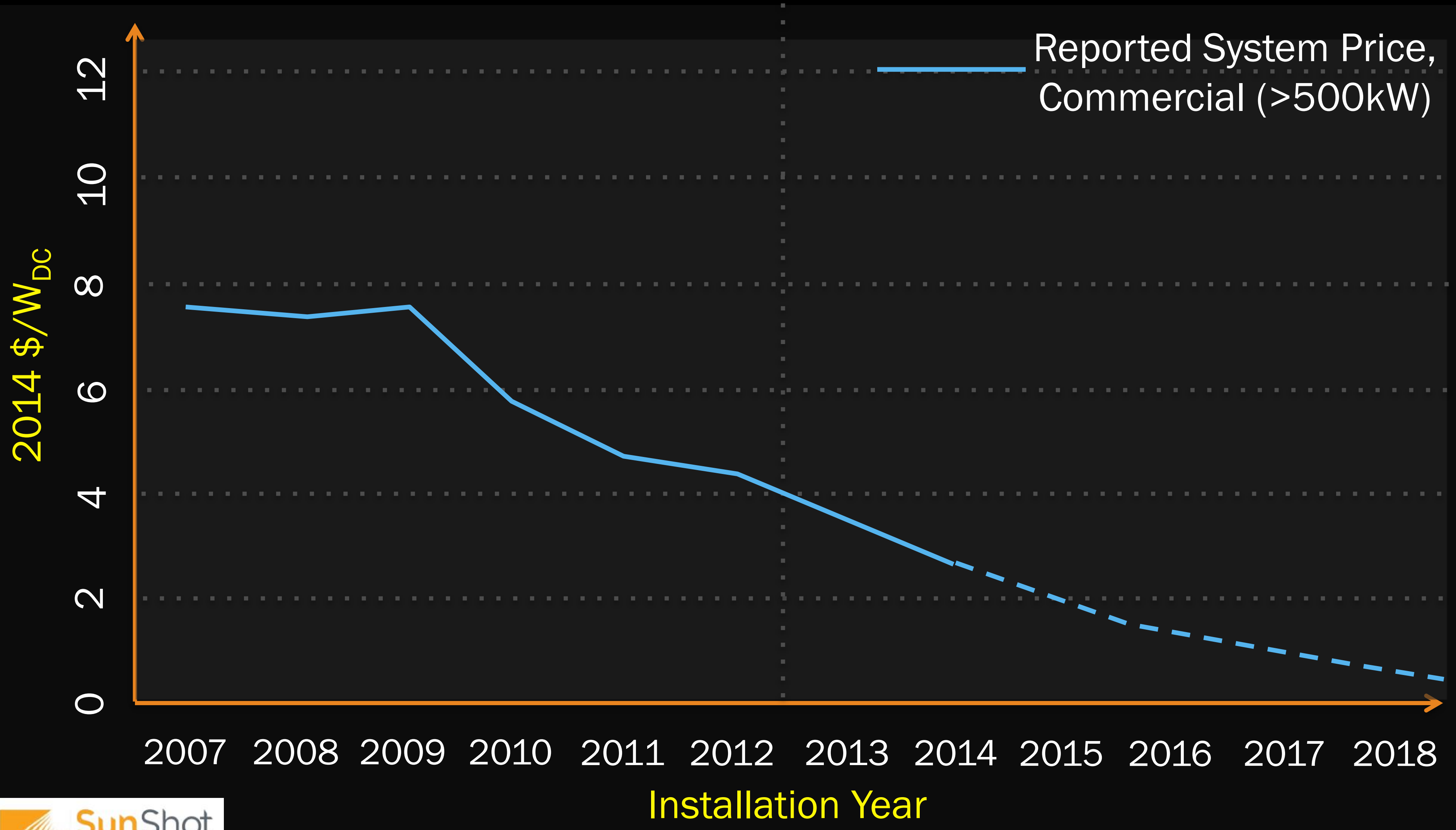
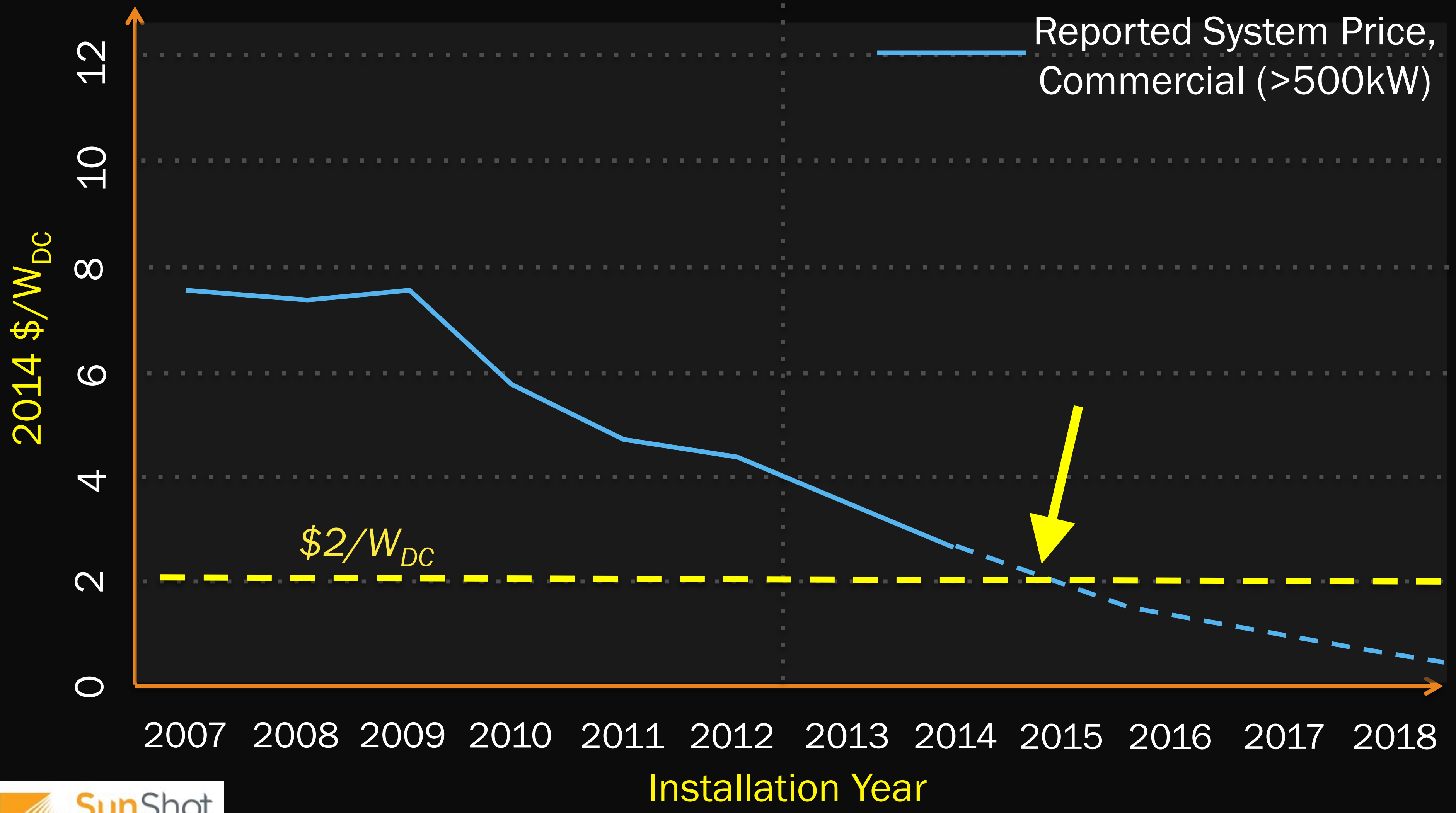
Optimum storage
Configuration(s)
- Energy & capacity specs
- Duty cycles

PV Costs

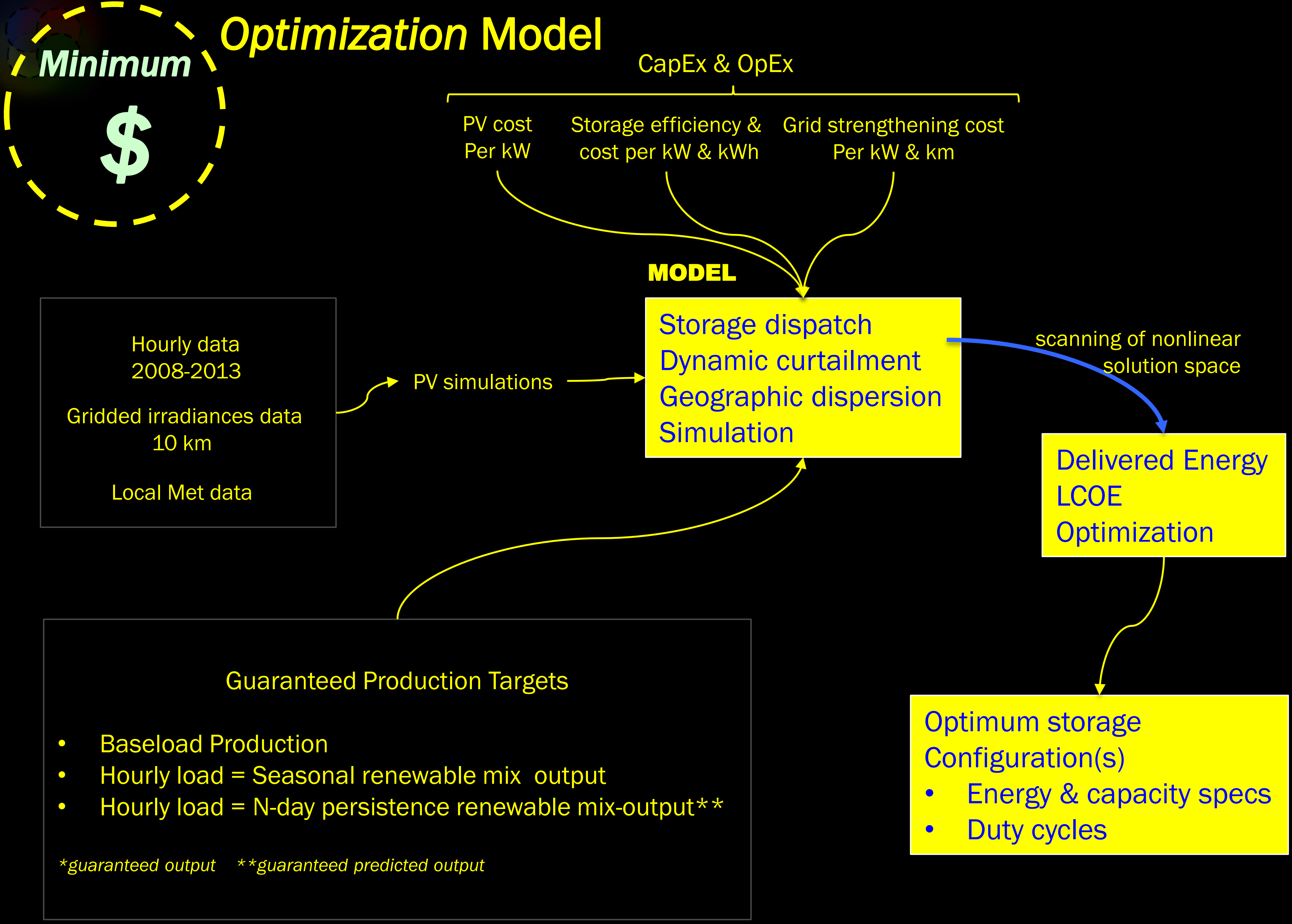


Reported System Price, Commercial (>500kW)
2014 $/W_DC
0
2
4
6
8
10
12
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Installation Year

PV Costs


Reported System Price, Commercial (>500kW)
2014 $/W_DC
0
2
4
6
8
10
12
$2/W_DC
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Installation Year

Optimization Model



Minimum

$

CapEx & OpEx

PV cost
Per kW

Storage efficiency &
cost per kW & kWh

Grid strengthening cost
Per kW & km

MODEL

Storage dispatch
Dynamic curtailment
Geographic dispersion
Simulation

Hourly data
2008-2013

Gridded irradiances data
10 km

Local Met data

PV simulations

scanning of nonlinear
solution space

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Optimum storage
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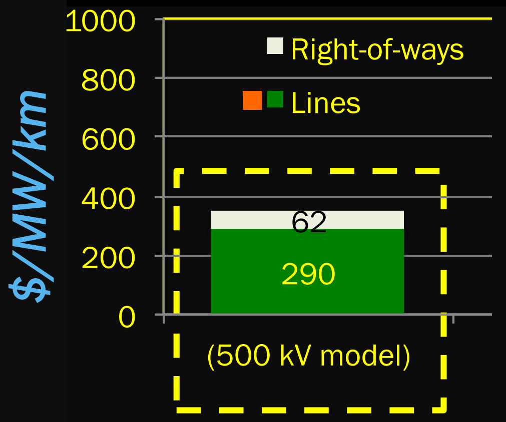
**guaranteed output* ***guaranteed predicted output*

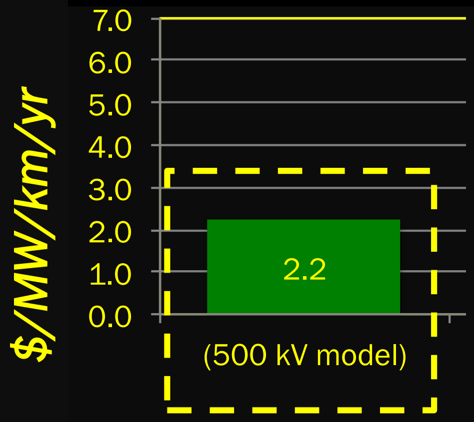
Transmission Costs

HVDC

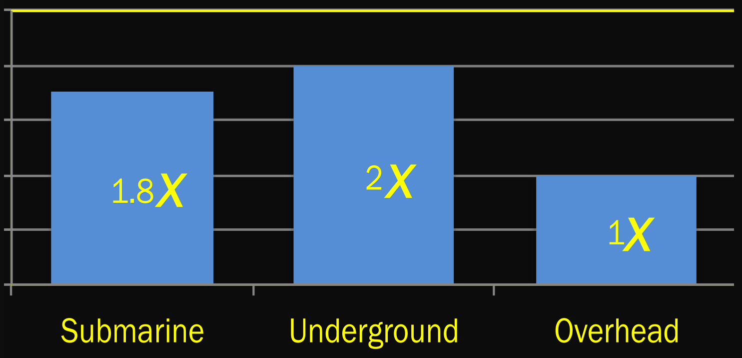
Line & Right-of-way CapEx



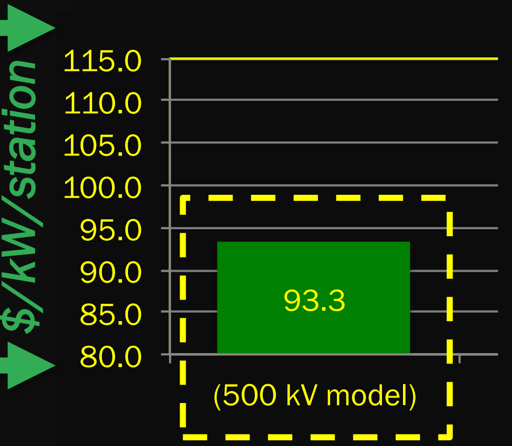
Line OpEx



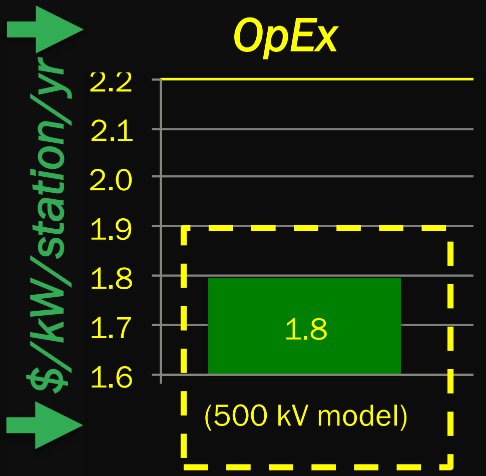
Terrain cost margin



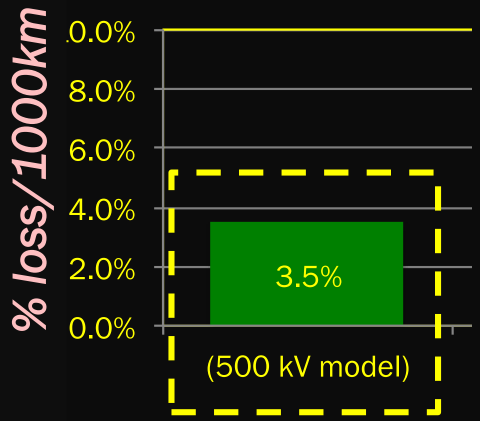
Converter Station CapEx



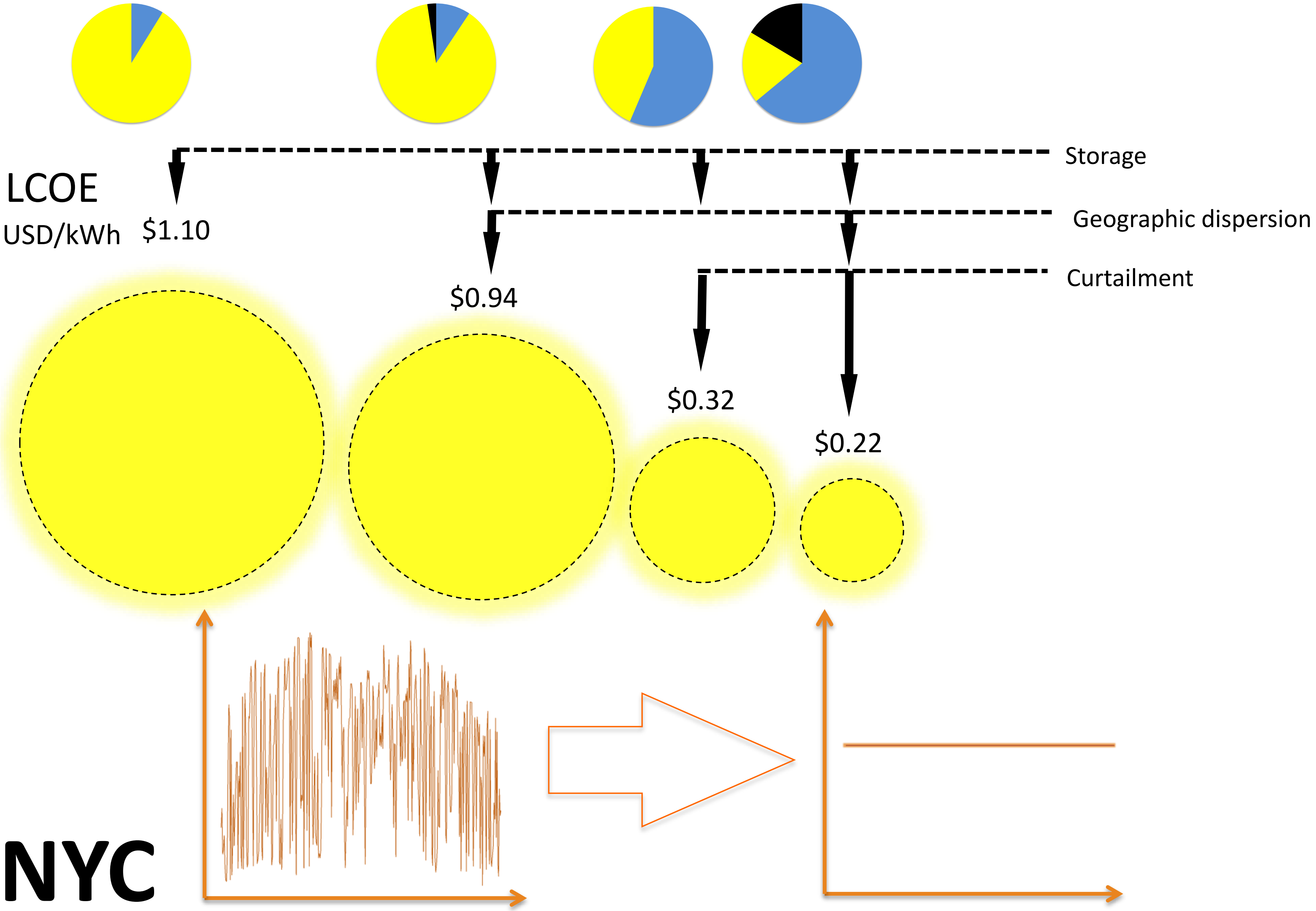
Converter Station OpEx



I^2R Line losses @ peak line loading



Bahrman, M. (2006) HVDC Transmission. IEEE PSCE. Atlanta, November 1, 20 nd ABB HVDC Development Topics



Storage

Geographic dispersion

Curtailment

LCOE

USD/kWh

$1.10

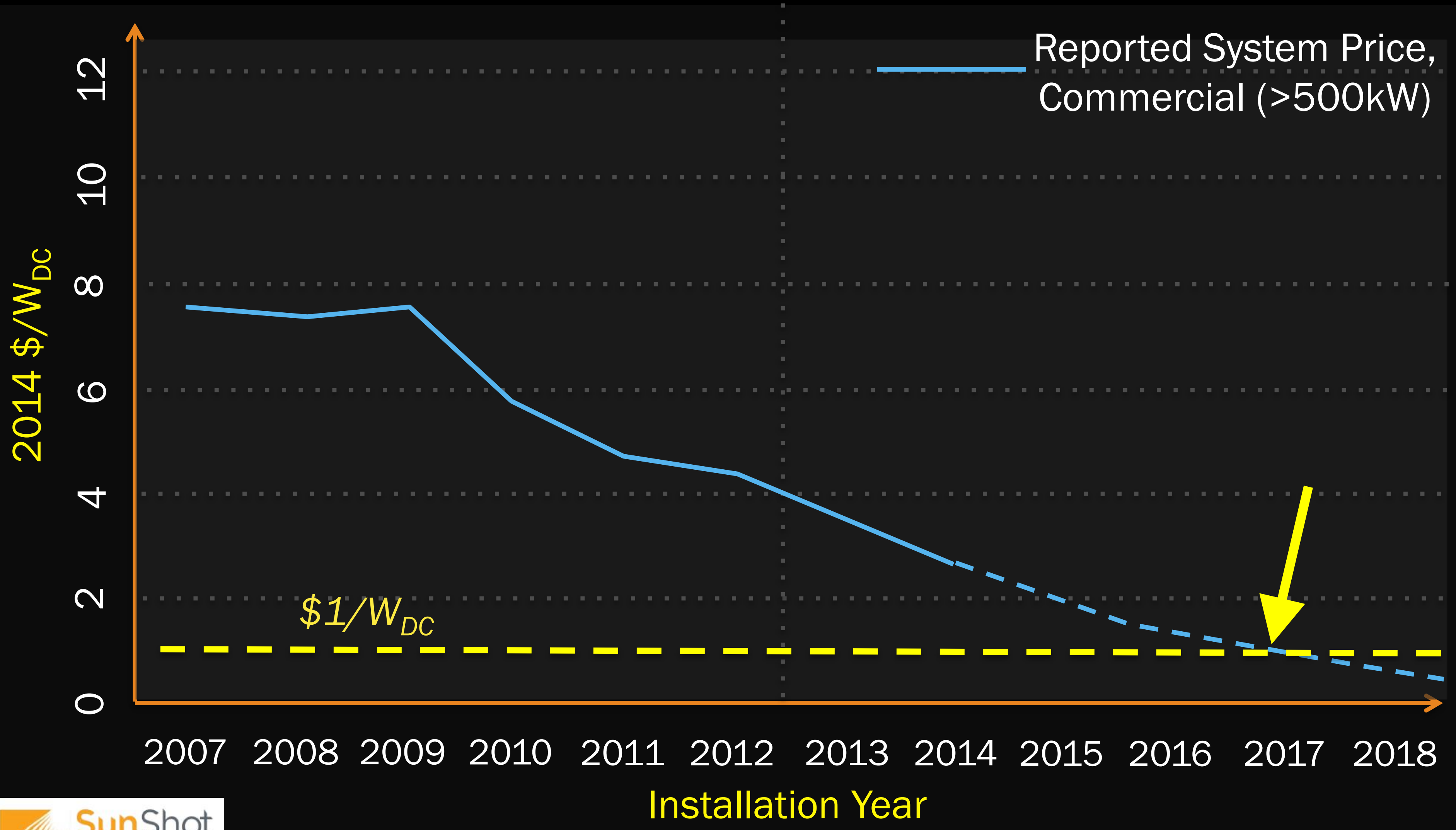
$0.94

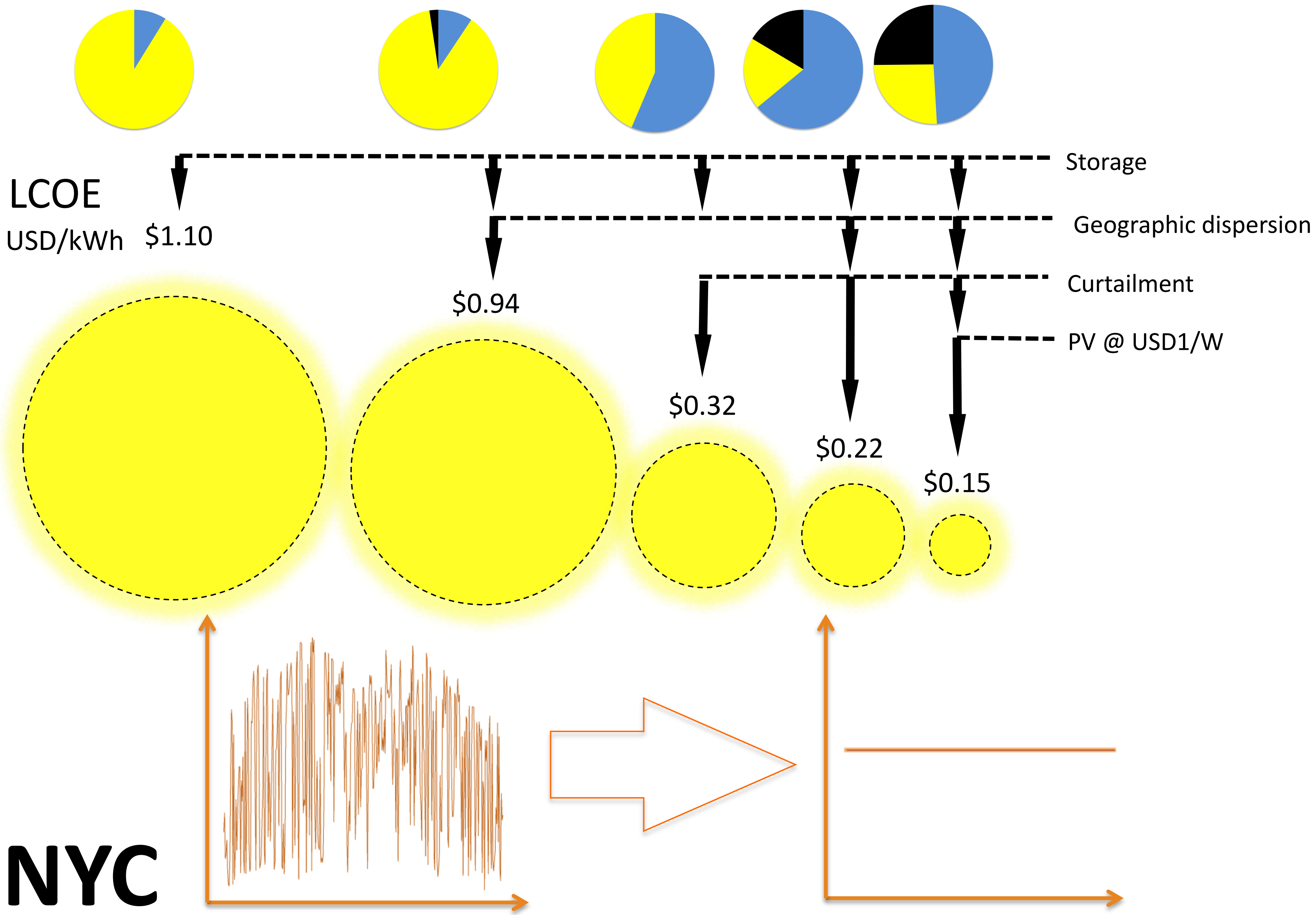
$0.32

$0.22

NYC

PV Costs


Reported System Price, Commercial (>500kW)
$1/W_{DC}$
2014 $/W_{DC}$
0
2
4
6
8
10
12
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Installation Year



LCOE

USD/kWh

$1.10

$0.94

$0.32

$0.22

$0.15

Storage

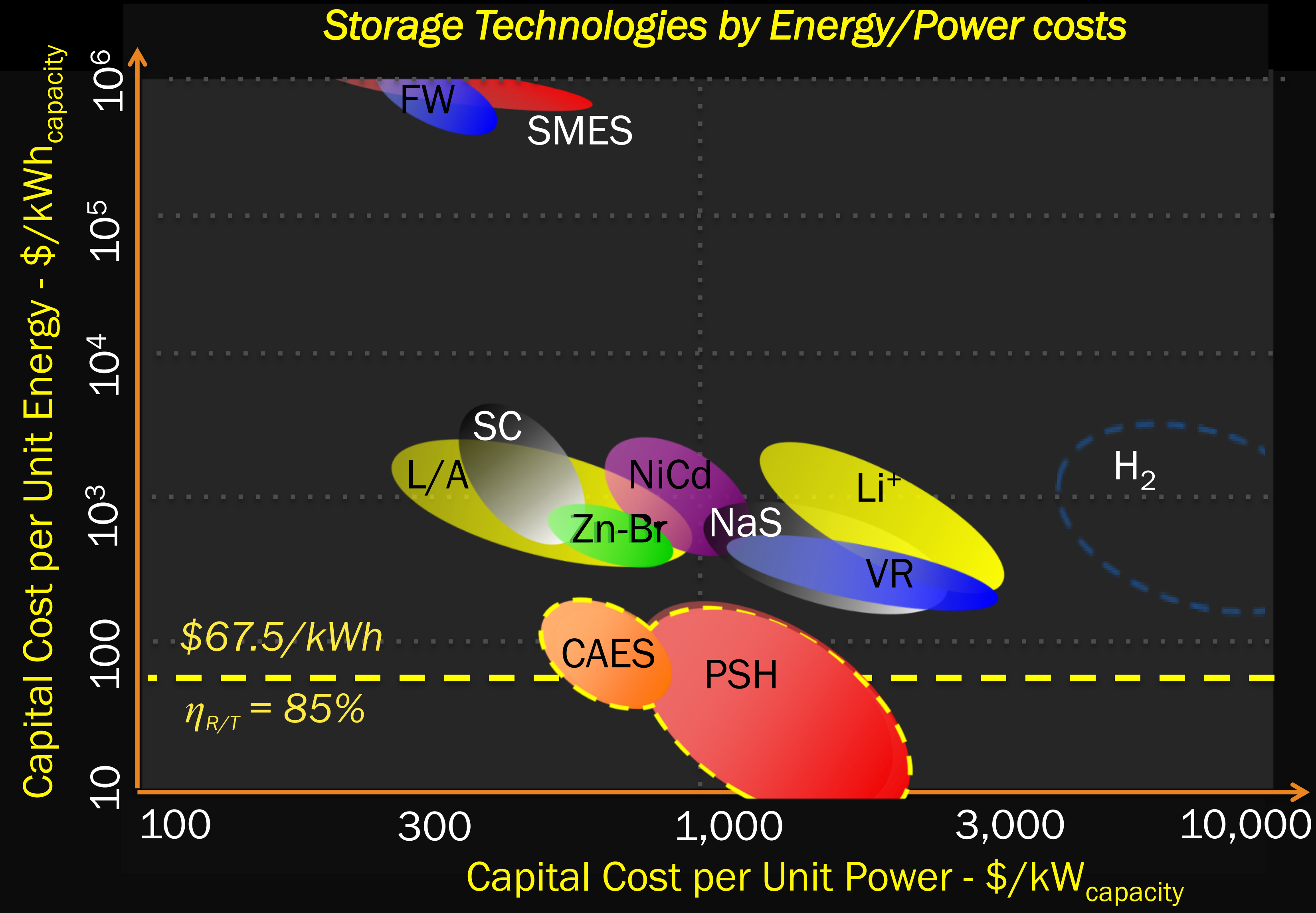
Geographic dispersion

Curtailment

PV @ USD1/W

NYC

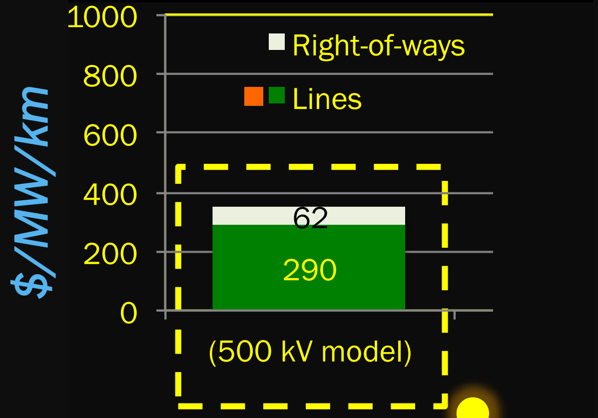
Storage Costs



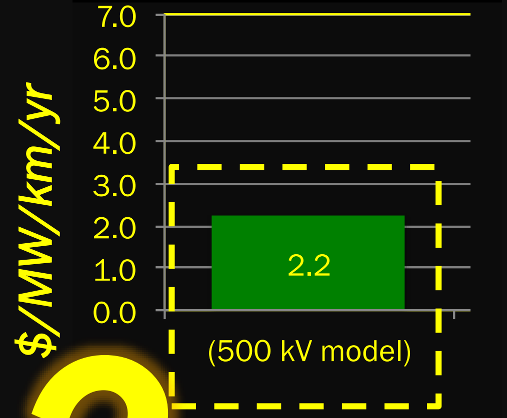
Transmission Costs

HVDC

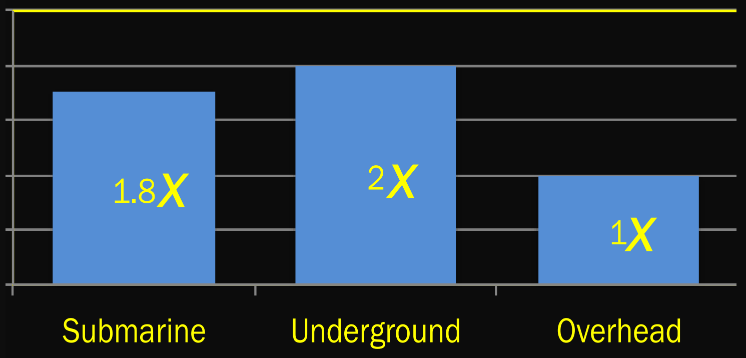
Line & Right-of-way CapEx



Line OpEx

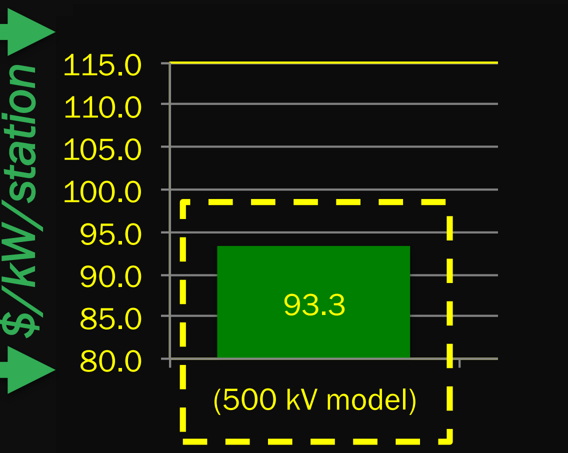


Terrain cost margin

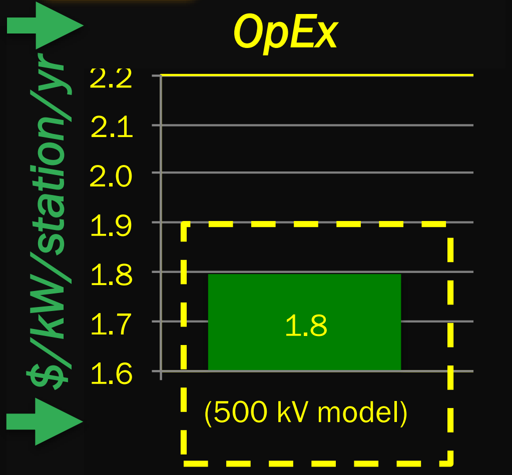


÷2

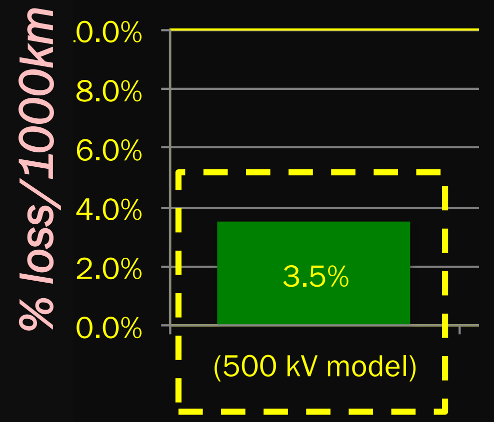
Converter Station CapEx



verter Station OpEx

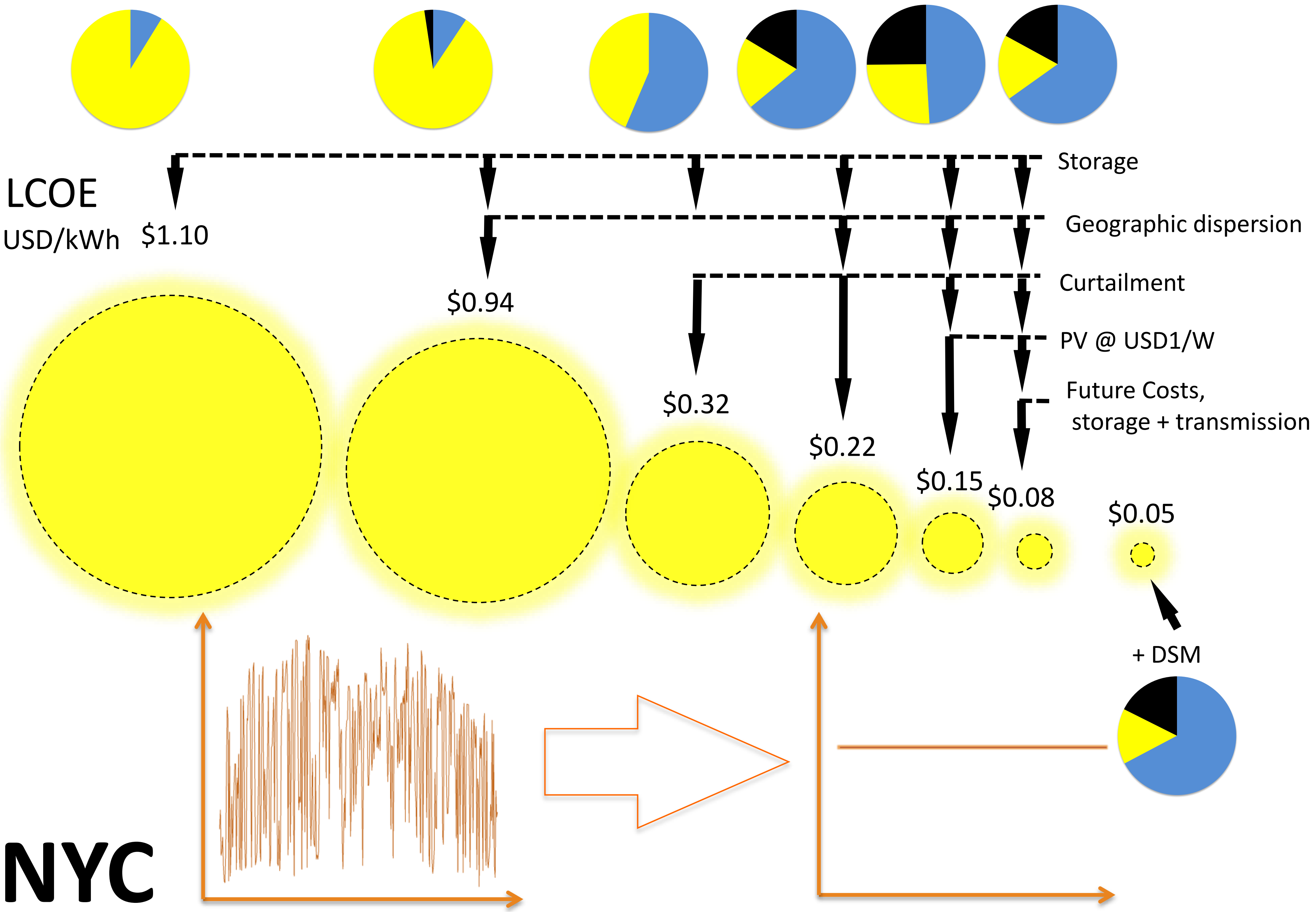


I^2R Line losses @ peak line loading



Bahrman, M. (2006) HVDC Transmission. IEEE PSCE. Atlanta, November 1, 20 nd ABB HVDC Development Topics

Guaranteed Baseload Power with PV



LCOE

USD/kWh

$1.10

$0.94

$0.32

$0.22

$0.15

$0.08

$0.05

Storage

Geographic dispersion

Curtailment

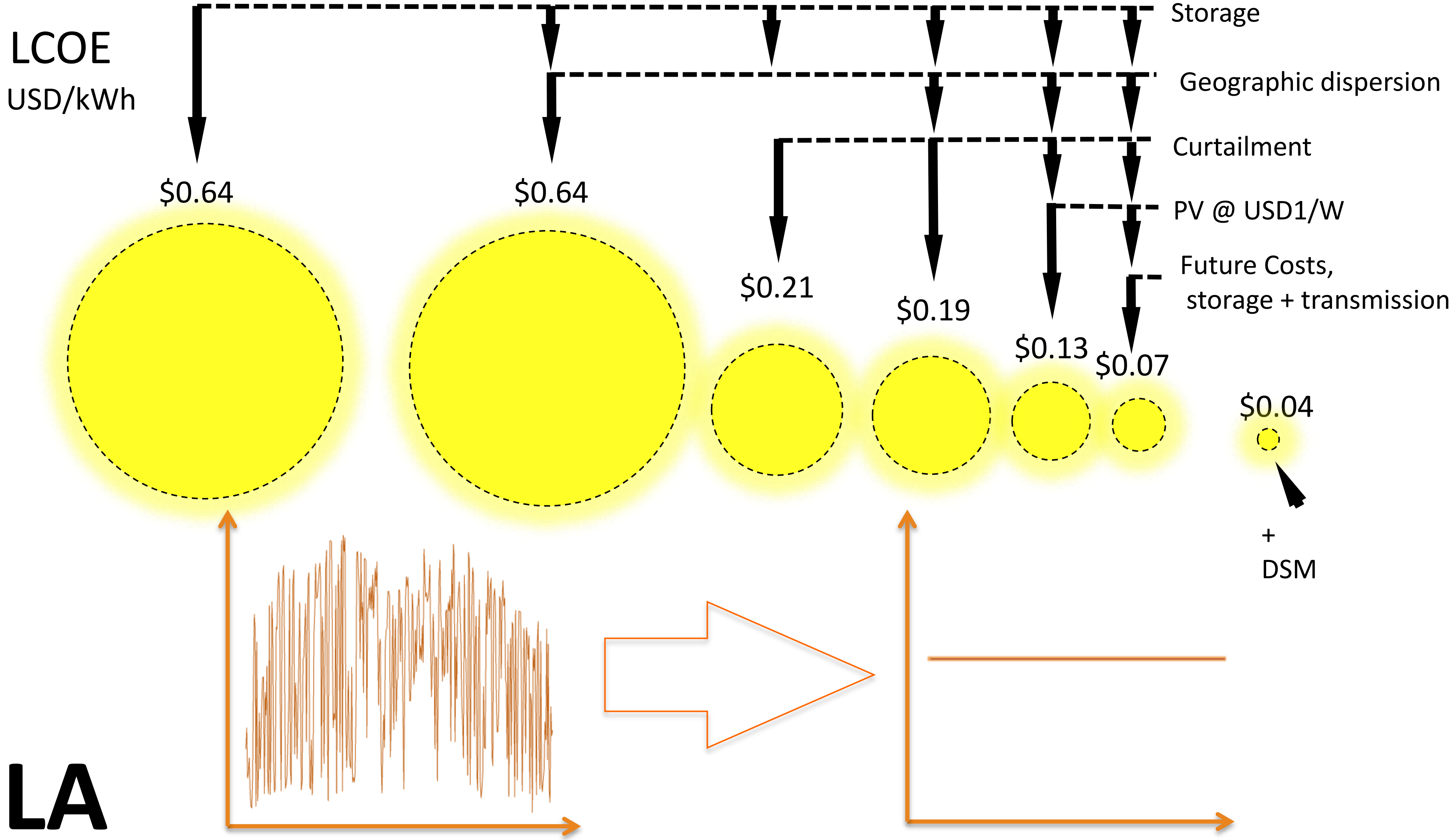
PV @ USD1/W

Future Costs,
storage + transmission

+ DSM

NYC

Guaranteed Baseload Power with PV



LCOE

USD/kWh

Storage

Geographic dispersion

Curtailment

PV @ USD1/W

Future Costs,
storage + transmission

$0.64

$0.64

$0.21

$0.19

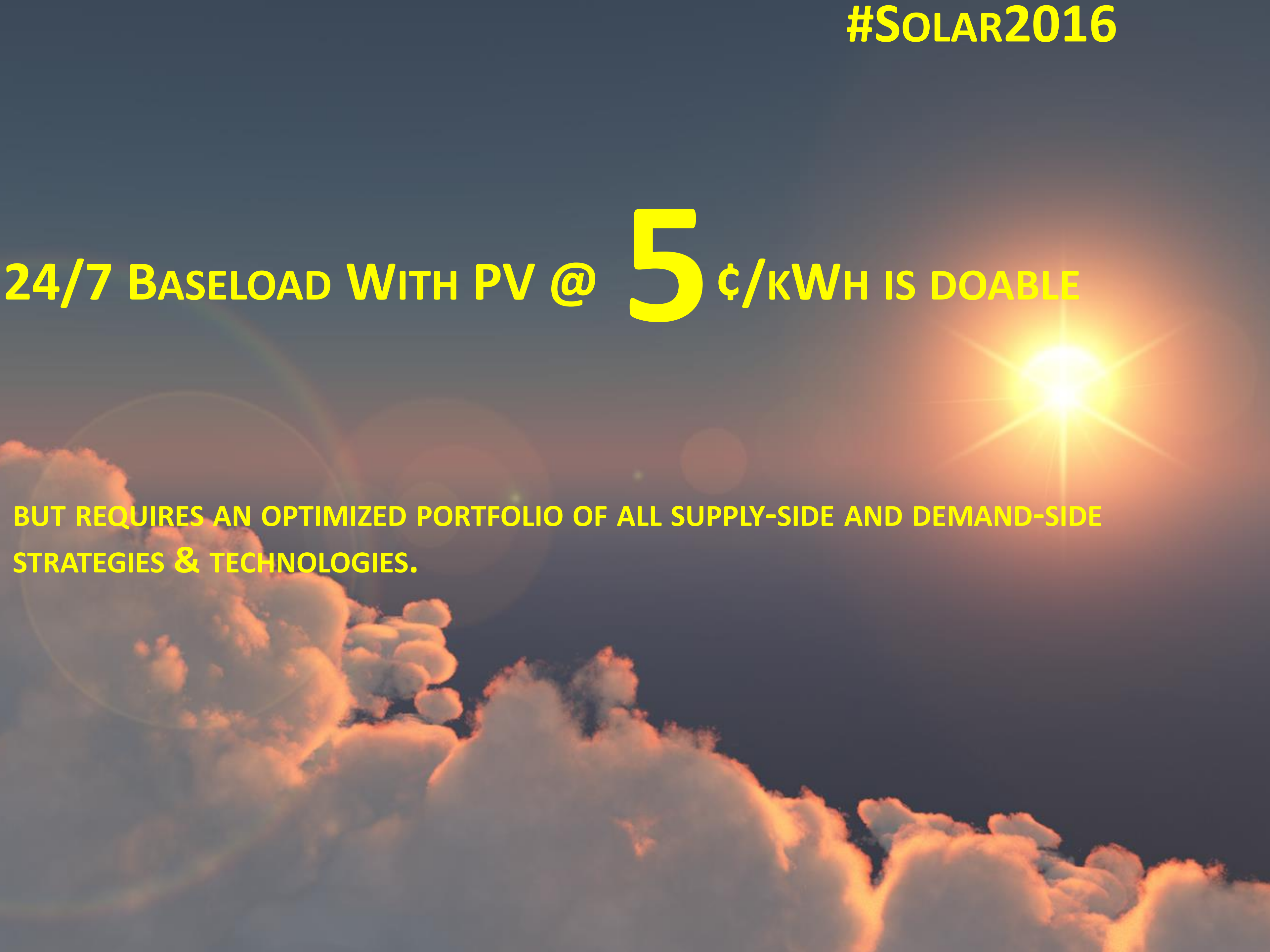
$0.13

$0.07

$0.04

+
DSM

LA



24/7 Baseload With PV @ 5 ¢/kWh is doable

but requires an optimized portfolio of all supply-side and demand-side strategies & technologies.

ELECTRICAL GENERATION & DISPATCH

New curtailment, storage + backup dispatch algorithm

20 % total PV energy curtailed

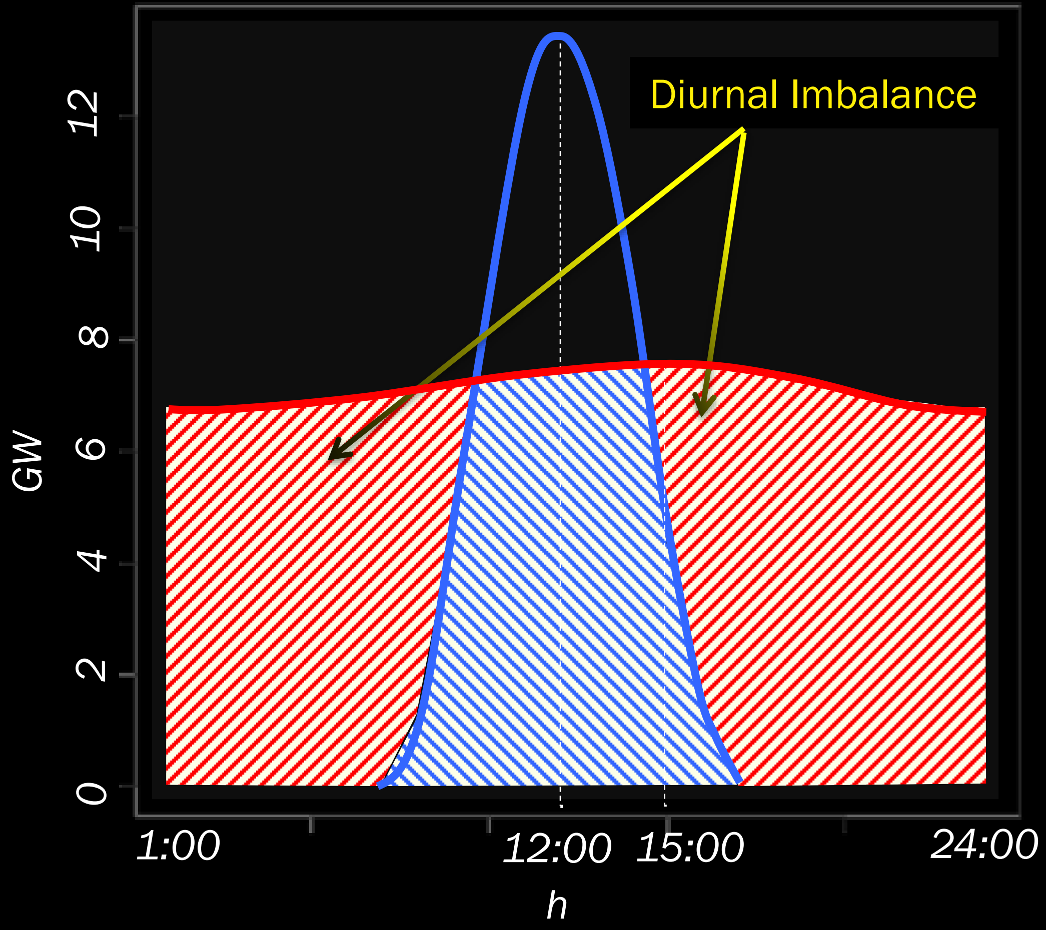
PV simulation, *smart* curtailment + storage optimization

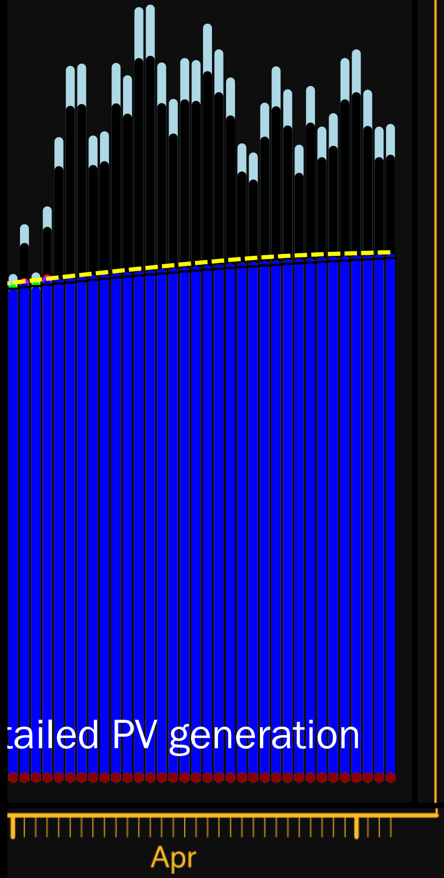
Generation + storage dispatch

LCOE & LEC calcs

Solar Data
Tech & Cost
ost & Layout
distribution

Meeting Seasonal Load Target, 20%curtailment





MODEL ::

Load
≡
Load Target

Storage Inefficiency 🔴
Transmission Losses ●