Future Power Markets Forum

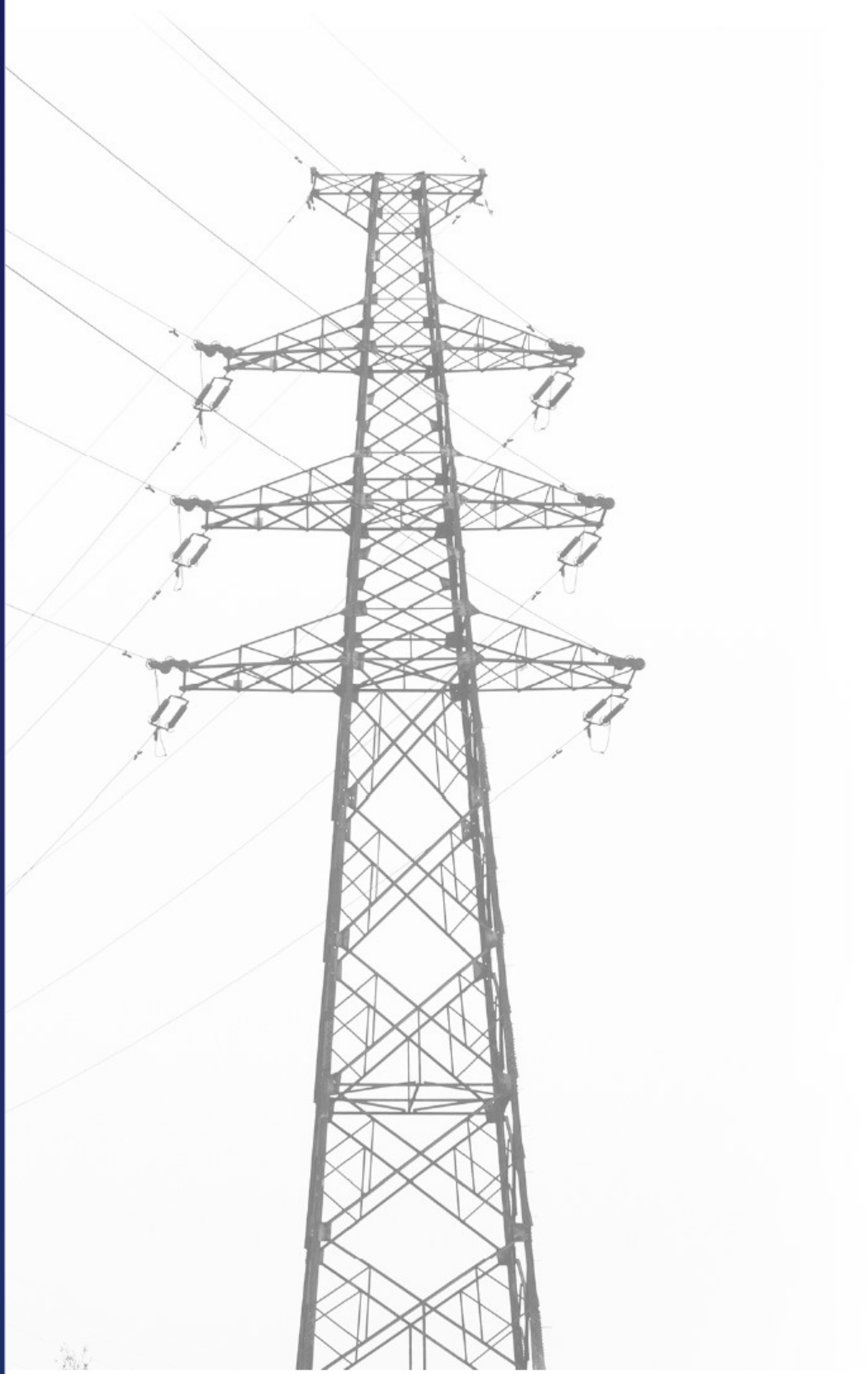
Reliable, Efficient and Low-Carbon Resource Portfolios

A PROJECT OF

Johns Hopkins Environmental Health & Engineering

Columbia | SIPA Center on Global Energy Policy

About Future Power Markets Forum



Future Power Markets Forum investigates proposals for market designs that maintain system efficiency and reliability with a high penetration of variable generation.

Future Power Markets Forum began in May 2020 as a joint project of the Columbia University SIPA Center for Global Energy Policy and Johns Hopkins University Whiting School of Engineering.

The Future Power Markets Forum website hosts materials on proposals for electricity market structure and design and a research library of relevant papers.

Forum contributors, representing a balanced group of the sector's practitioners, researchers and regulators, offer commentary on the issues and proposals.

Topic 1: Resource Portfolios

Mr. Arne Olson

E3 - Energy and Environmental Economics

Energy+Environmental Economics

Decarbonizing the Power System: Summary of Lessons Learned

Columbia University – Johns Hopkins University
Future Power Markets Forum Session 1

June 2, 2020

Remote Webinar

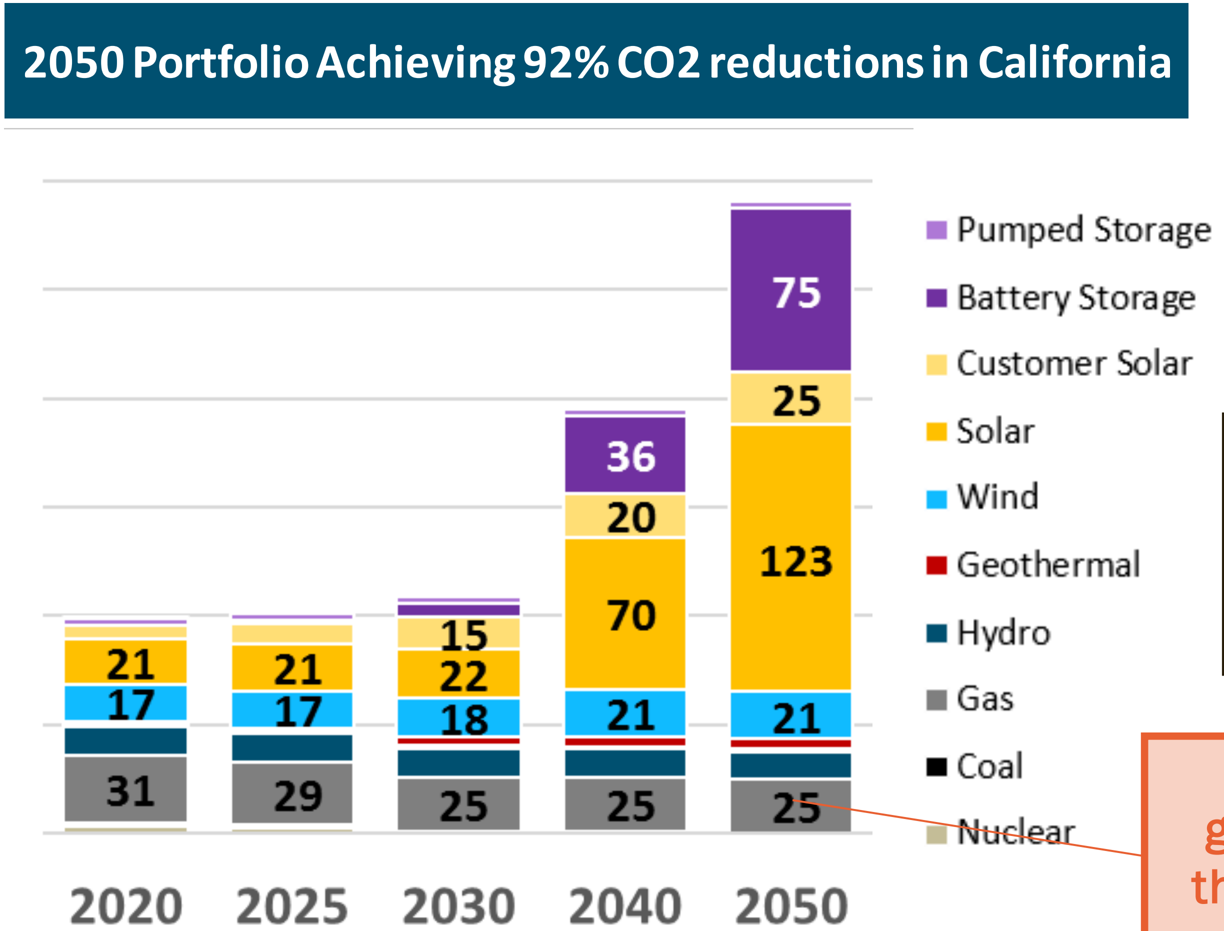
Arne Olson, Senior Partner

Key Commonalities Across E3 Studies

1) **Sensible near-term strategy for carbon reduction is to develop a least-cost combination of energy efficiency, renewables and natural gas generation**
2) **Achieving zero carbon emissions requires a form of clean firm generation capacity**
   - Candidate resources are fossil generation with CCS, nuclear, very long duration storage, zero-carbon gas, hydrogen
3) **"Flexibility" is critical for reliable operations but is not a significant driver of portfolio configuration**
   - Inverter-based resources can provide most essential grid services
4) **Clean generation technologies are very capital-intensive**
   - A stable, long-term price signal is required to provide the returns necessary to induce investment

Some Key Sponsors of E3's Clean Energy Work

California can achieve 90%+ reductions with 150 GW of solar and 75 GW of storage



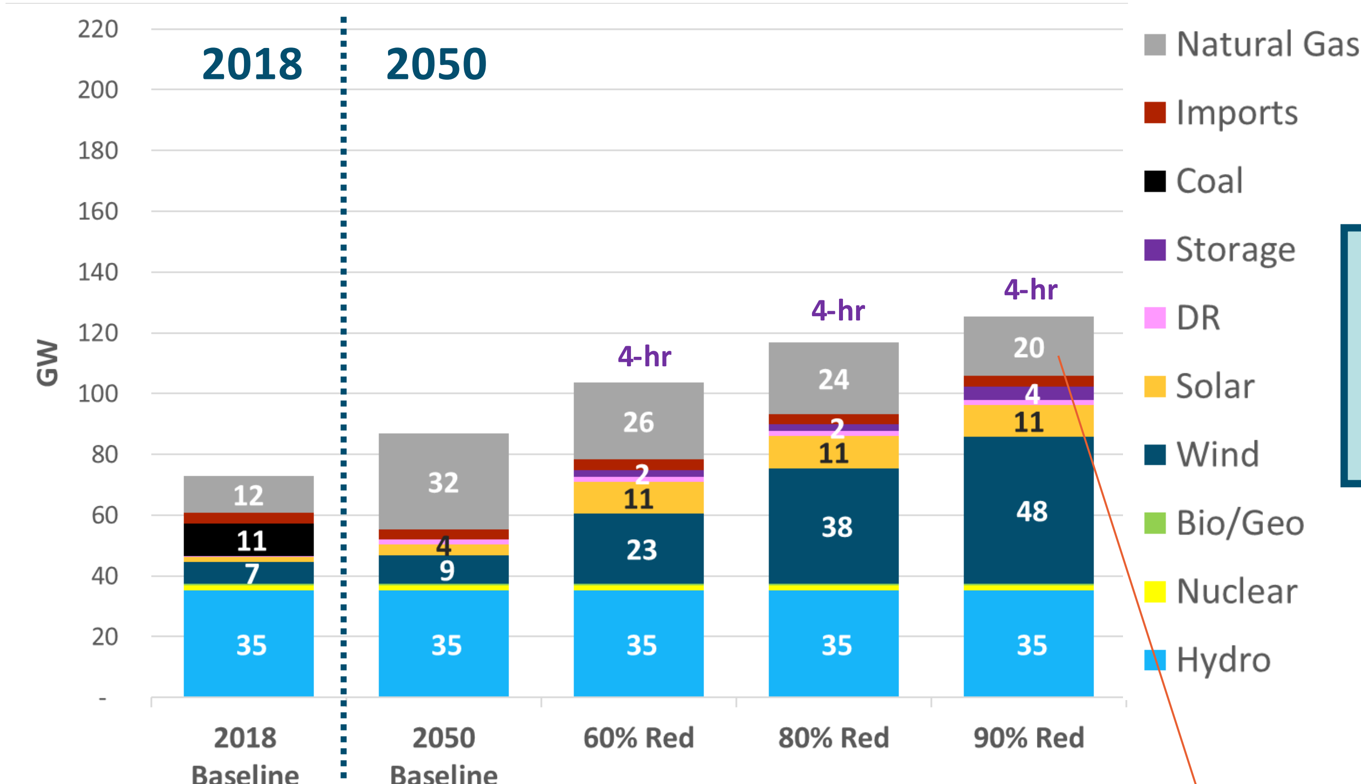
Achieves "100% Renewables" on a net basis (complies with SB 100)

Land area equivalent to 2% of California devoted to solar and wind production

25 GW of gas generation retained through 2050 (<10% capacity factor)

Source: E3, Long-Run Resource Adequacy under Deep Decarbonization in California: *https://www.ethree.com/wp-content/uploads/2019/06/E3_Long_Run_Resource_Adequacy_CA_Deep-Decarbonization_Final.pdf*

Pacific Northwest 90% reduction case selects wind and solar but little storage



Achieves "108% Renewables" on a net basis

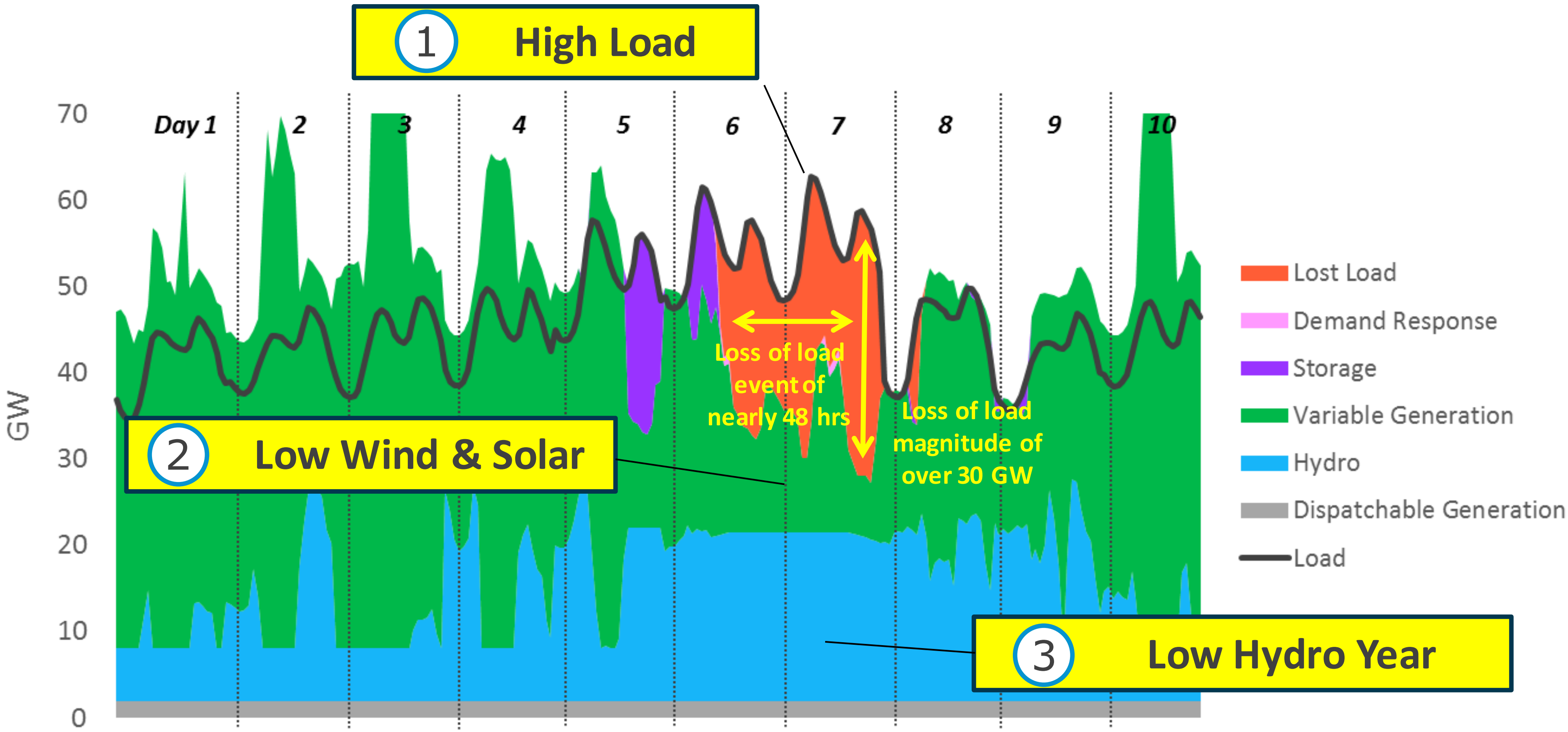
	2018 Baseline	2050 Baseline	60% Red	80% Red	90% Red
% GHG Reduction from 1990	16%	60%	80%	90%	
Clean Energy Share (%)	63%	86%	100%	108%	
Gas Capacity Factor (%)	46%	27%	16%	9%	
Additional Cost ($/MWh)	Base	$0 - $7	$3 - $14	$5 - $18	

Requires 8-12 GW of *new* gas for resource adequacy

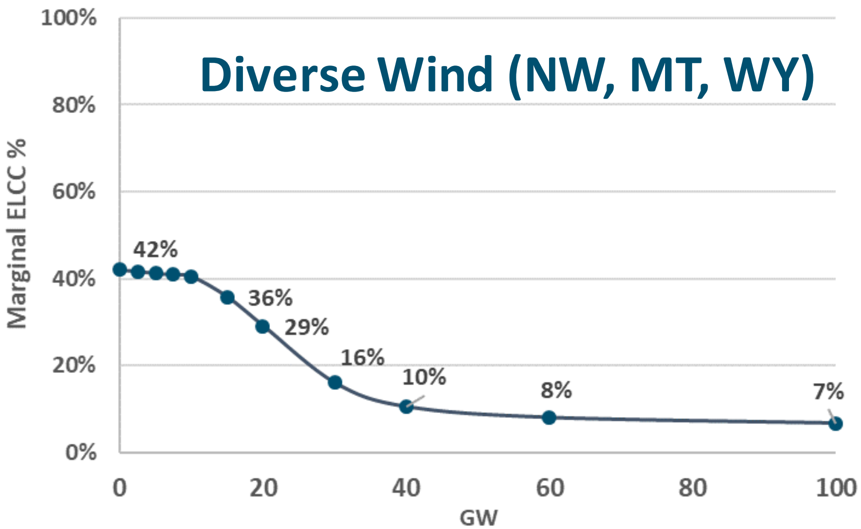
Source: E3, Resource Adequacy in the Pacific Northwest:
https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf

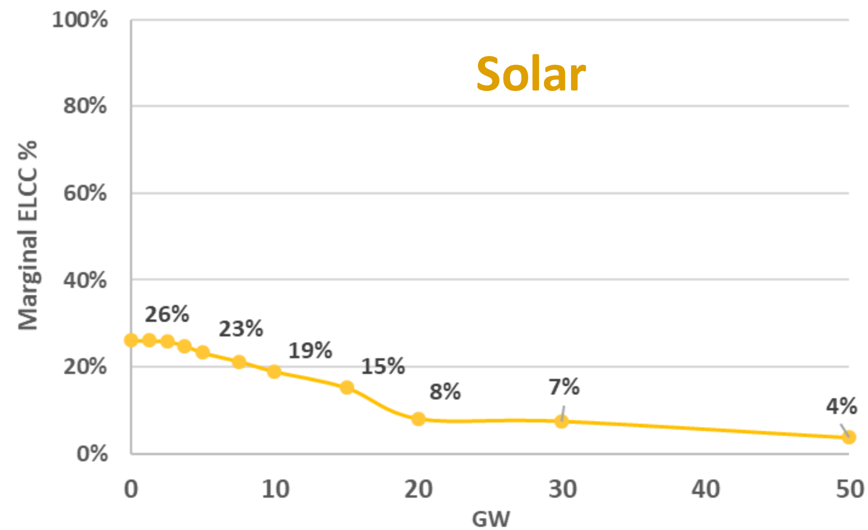
Firm generation is needed even on a system that is massively overbuilt with renewables

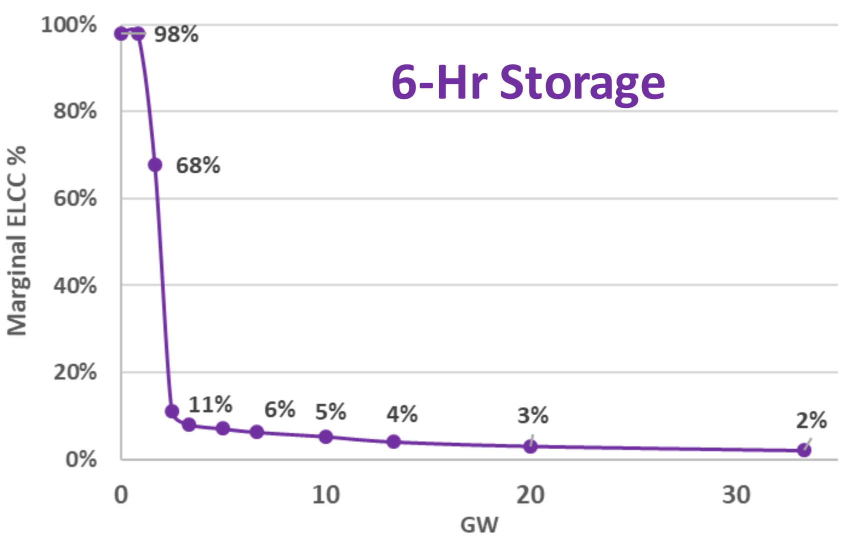
- The most challenging conditions in a deeply-decarbonized Pacific Northwest grid is when a multi-day cold snap occurs during a low-water year

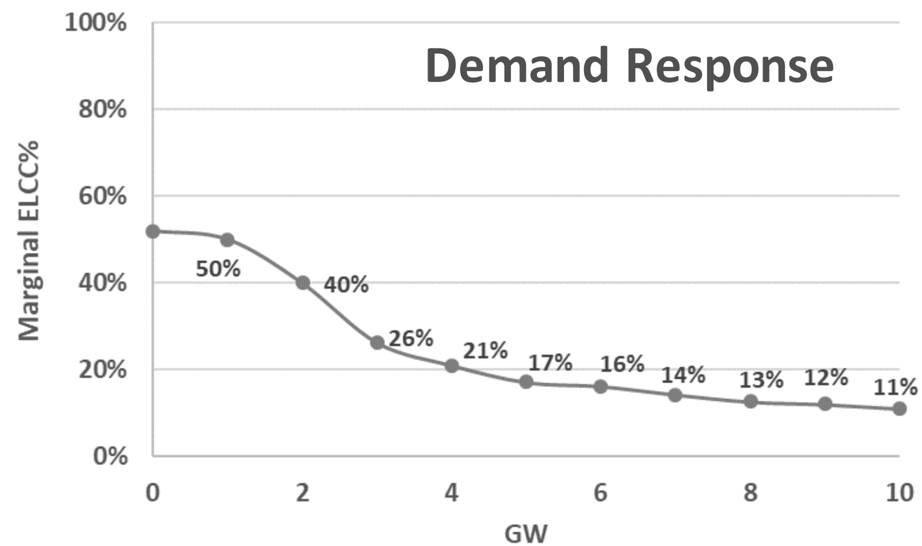


Wind, solar and storage all exhibit diminishing ELCC values as more capacity is added

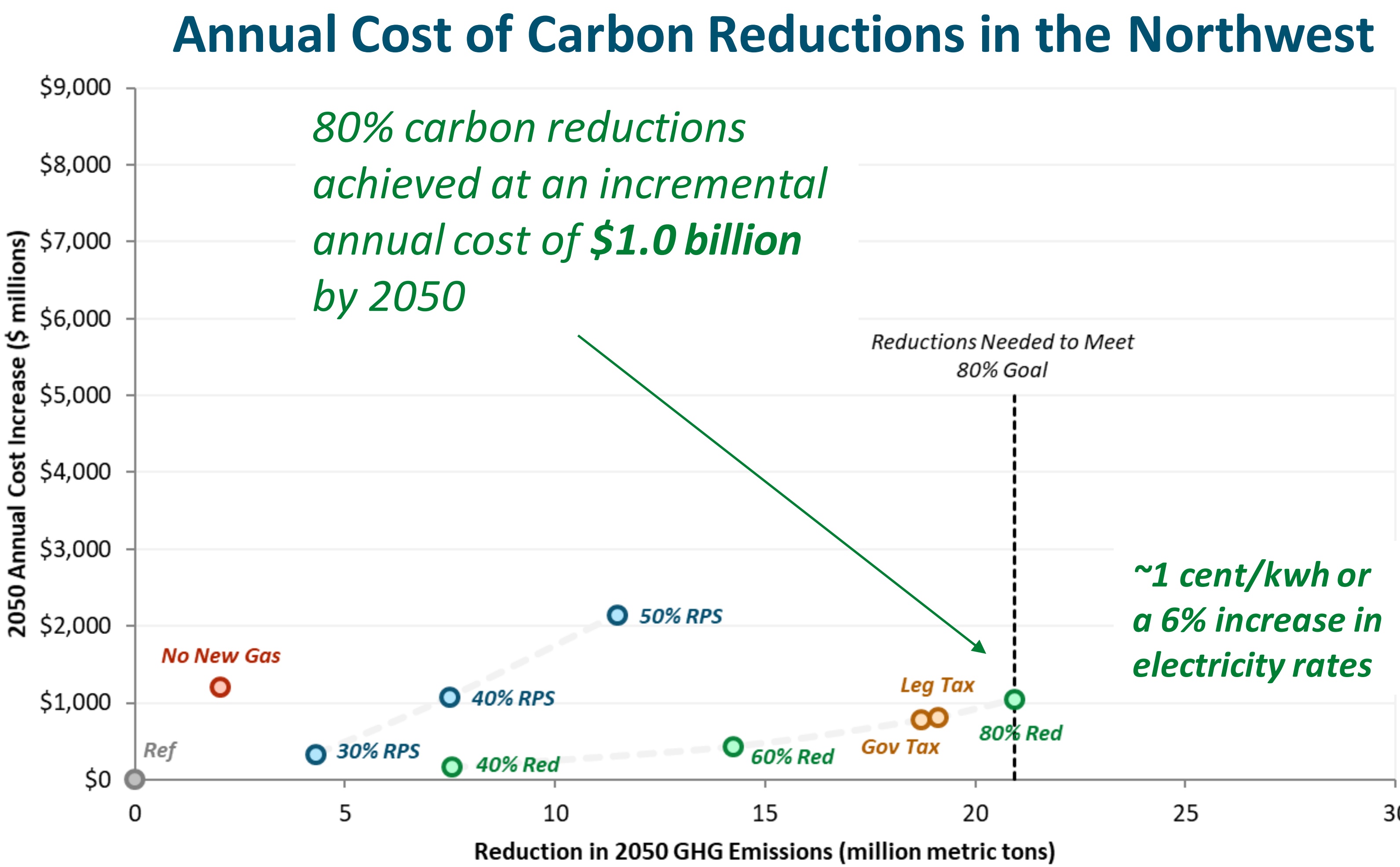








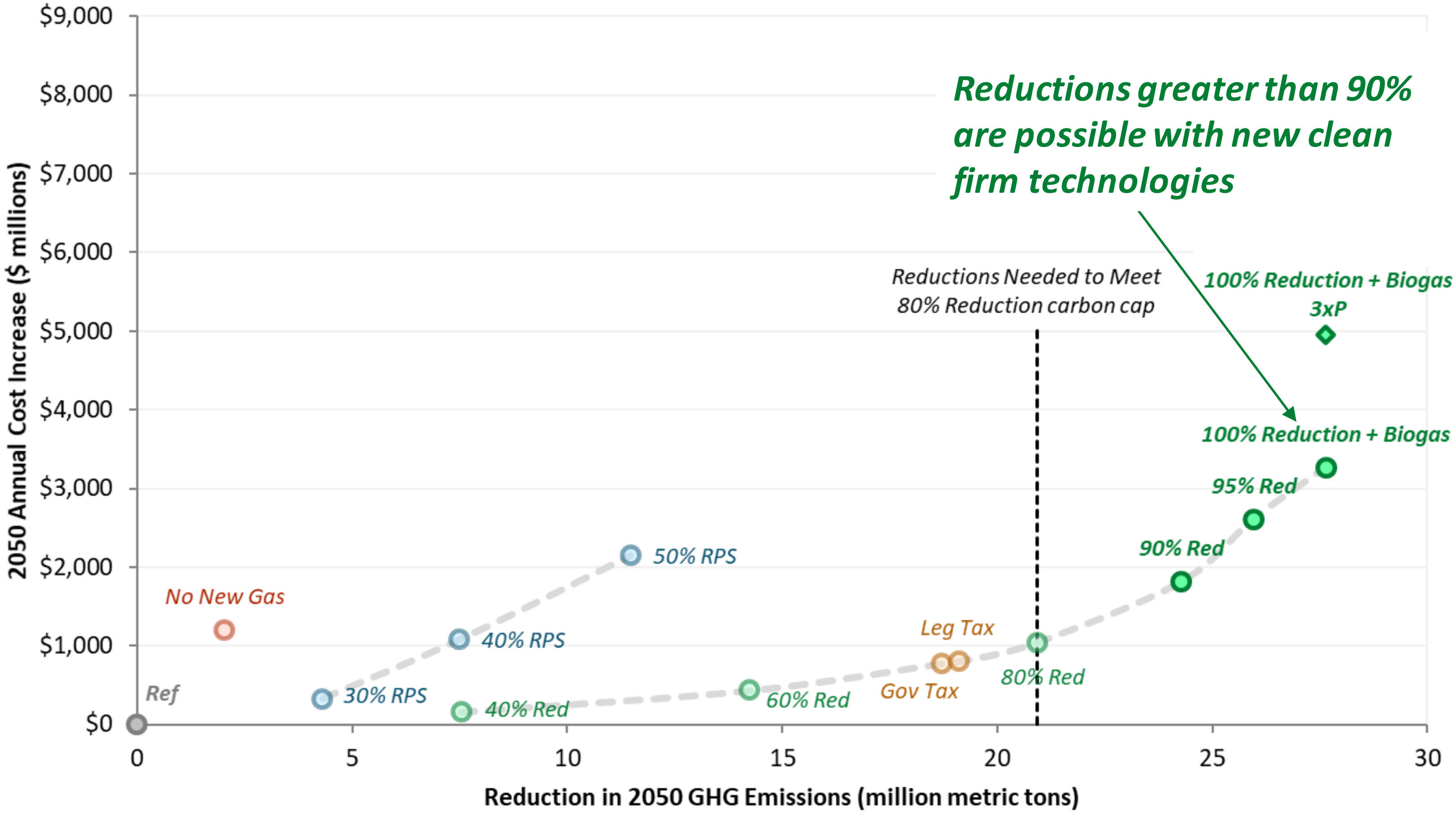
80% carbon reductions can be achieved at a reasonable cost in most markets



Source: E3, Pacific Northwest Low-Carbon Scenario Analysis: https://www.ethree.com/wp-content/uploads/2018/01/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf

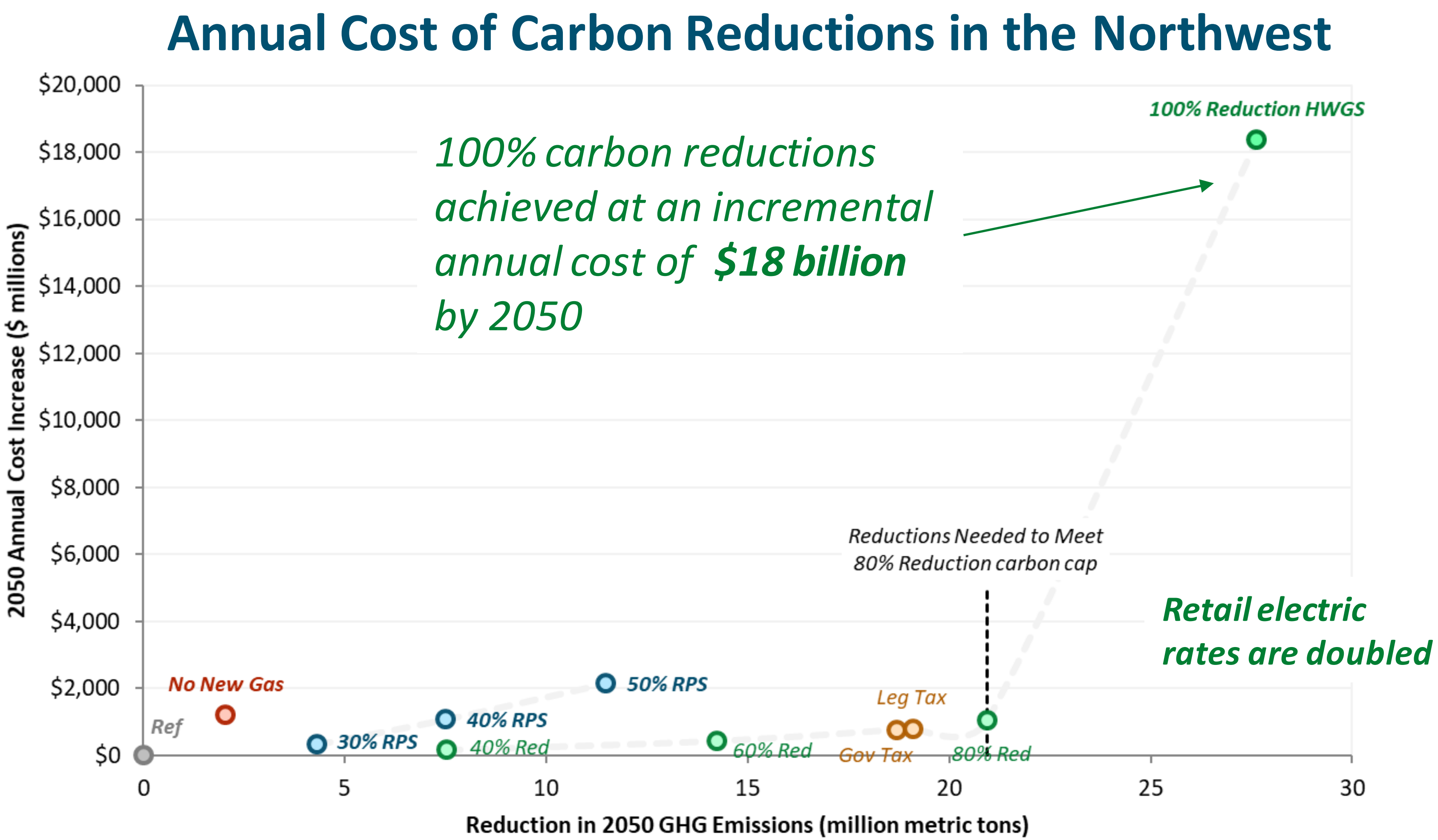
Clean firm generation options enable additional reductions

Annual Cost of Carbon Reductions in the Northwest



Source: E3, Pacific Northwest Low-Carbon Scenario Analysis: https://www.ethree.com/wp-content/uploads/2018/01/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf

100% carbon reductions is cost-prohibitive with only wind, solar and batteries

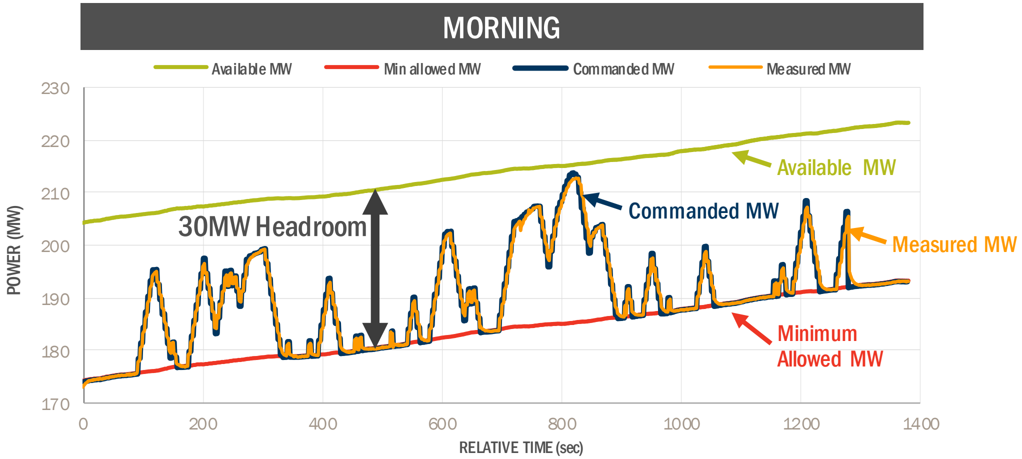


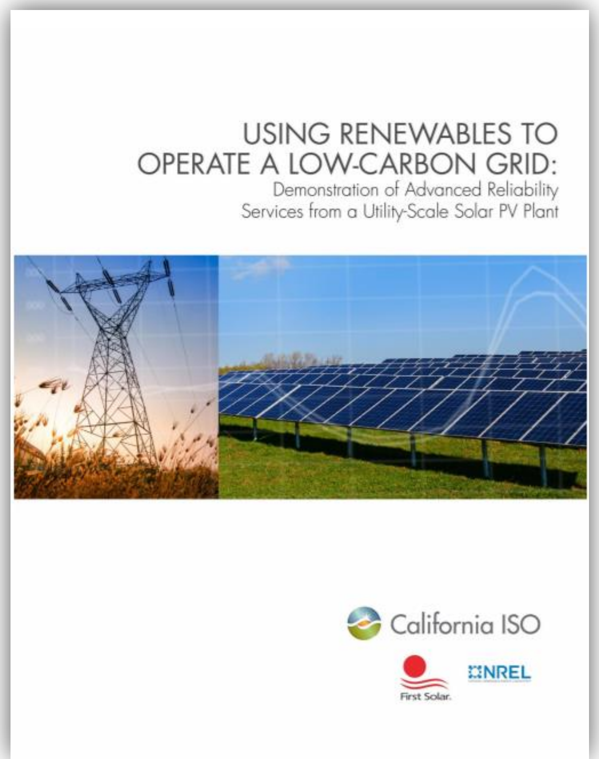
Source: E3, Pacific Northwest Low-Carbon Scenario Analysis: https://www.ethree.com/wp-content/uploads/2018/01/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf

First Solar/NREL/CAISO demonstration of using solar for essential grid services

Inverter-based resources such as utility-scale solar can provide NERC essential reliability services with greater precision than comparable conventional alternatives

- Example: regulation service / following AGC signal

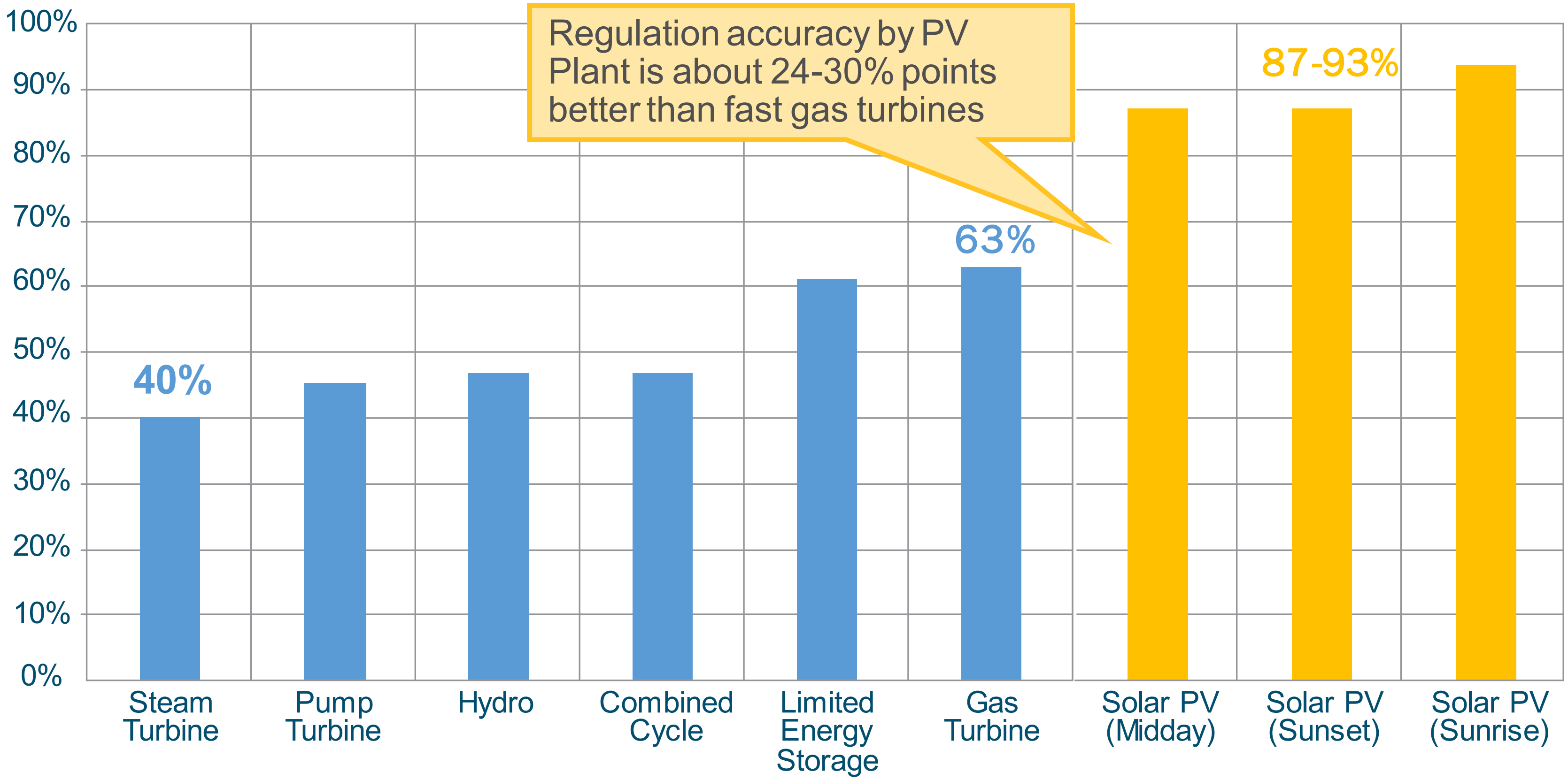




2017 NARUC Award Winner
Utility Industry Innovative Pilots or Demonstration Projects

http://www.caiso.com/Documents/TestsShowRenewablePlantsCanBalanceLow-CarbonGrid.pdf

PV Plants Outperform Conventional Resources in Frequency Regulation



California ISO

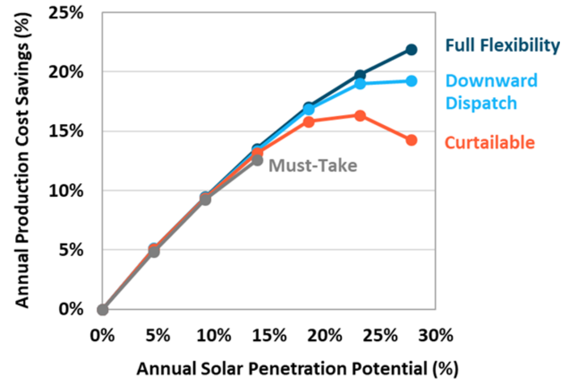
Blue bars taken from the ISO's informational submittal to FERC on the performance of resources providing regulation services between January 1, 2015 and March 31, 2016

http://www.caiso.com/Documents/TestsShowRenewablePlantsCanBalanceLow-CarbonGrid.pdf

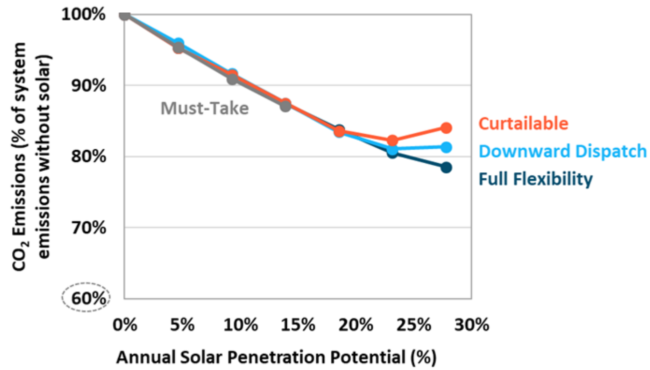
E3/First Solar/TECO study demonstrates the value of flexible solar power plants

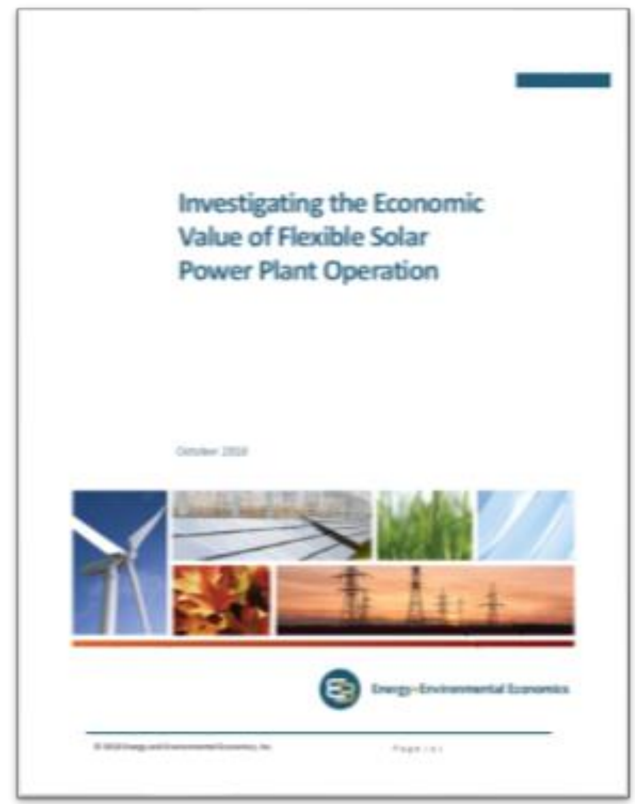
- Detailed study of operations under high solar penetration (up to 28% of annual energy supply)
- Dispatchable solar is key to retaining value of solar at penetrations in excess of 20%

Production Cost Savings



Emissions



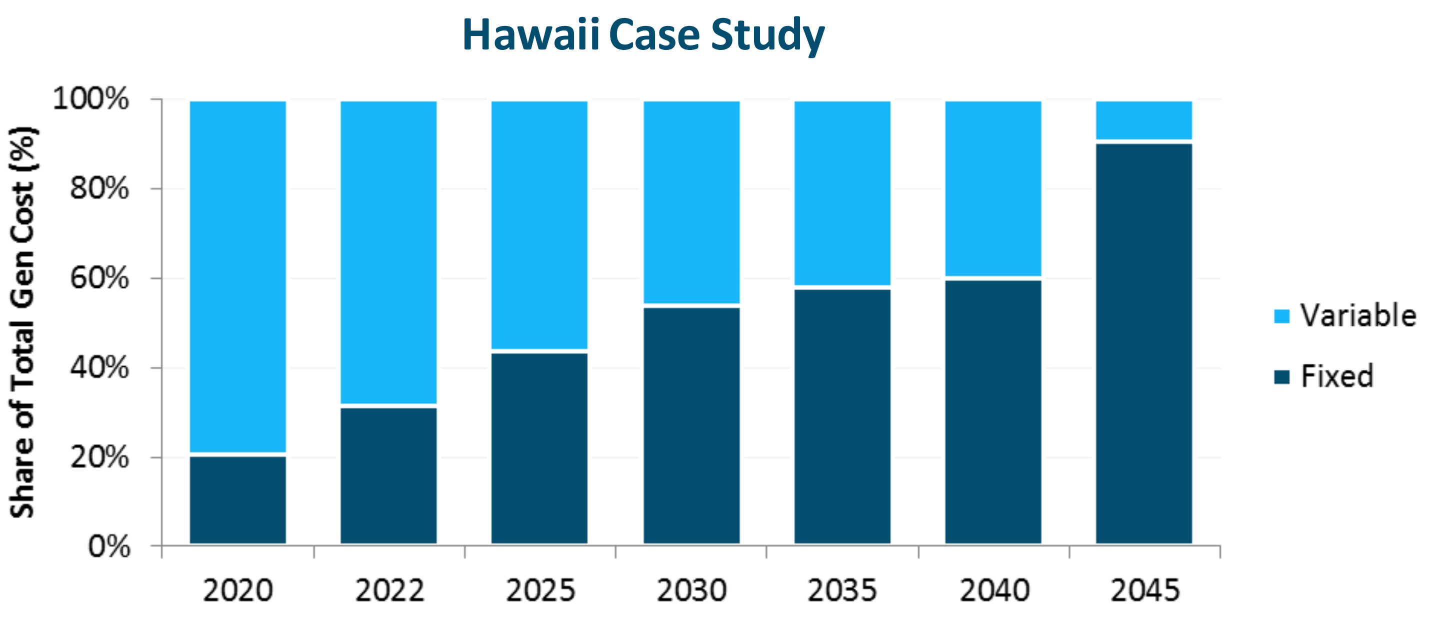


2018 Top Innovators
Public Utilities Fortnightly

Source: E3, Investigating the Economic Value of Flexible Solar Power Plant Operation. https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

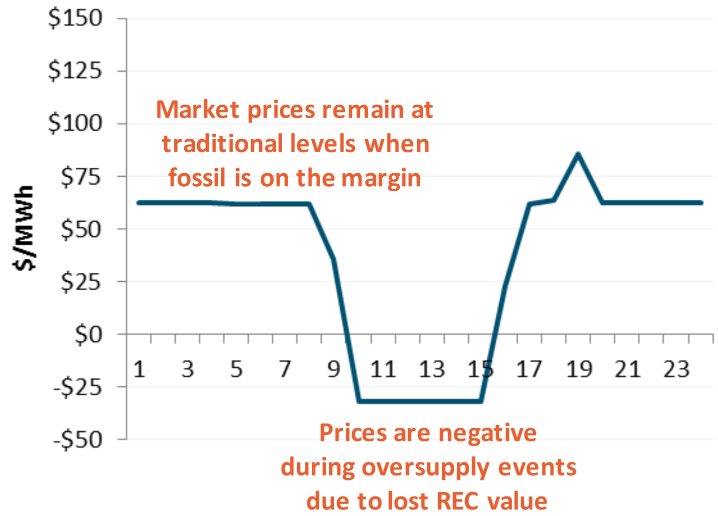
Efficient allocation of capital is the key to achieving decarbonization at a reasonable cost

- Power system is transitioning from one with significant fuel costs to one that is consists almost entirely of capital investments
- New market mechanisms for clean energy attributes may be needed to facilitate the long-term financial commitments required for highly capital-intensive investments

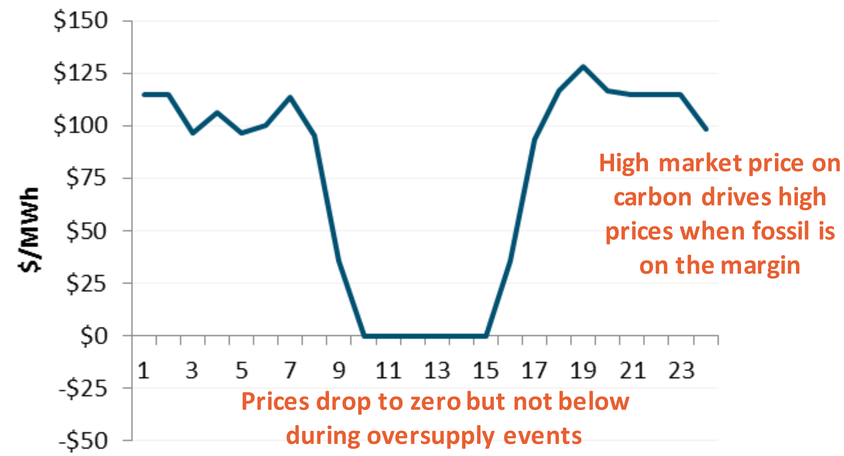


The policy mechanism for clean energy attributes can affect market performance

Daily Energy Price Profile under High RPS – California



Daily Energy Price Profile under low GHG Cap – California



+ Clean energy “attribute” markets (RECs, ZECs) have many hours with negative pricing
+ Challenge is to design a market mechanism that is stable until broader GHG regulation is in place

Key Findings

1) Sensible near-term strategy for carbon reduction is to develop a least-cost combination of energy efficiency, renewables and natural gas generation
2) Achieving zero carbon emissions requires at least one form of clean firm generation capacity
3) "Flexibility" is critical for reliable operations but is not a significant driver of portfolio configuration
4) Clean generation technologies are very capital-intensive, requiring stable, long-term price signal

Thank you!

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Topic 1: Resource Portfolios

Dr. Jesse D. Jenkins

Princeton University

Decarbonizing Electricity

The Critical Role of Firm Low-Carbon Resources

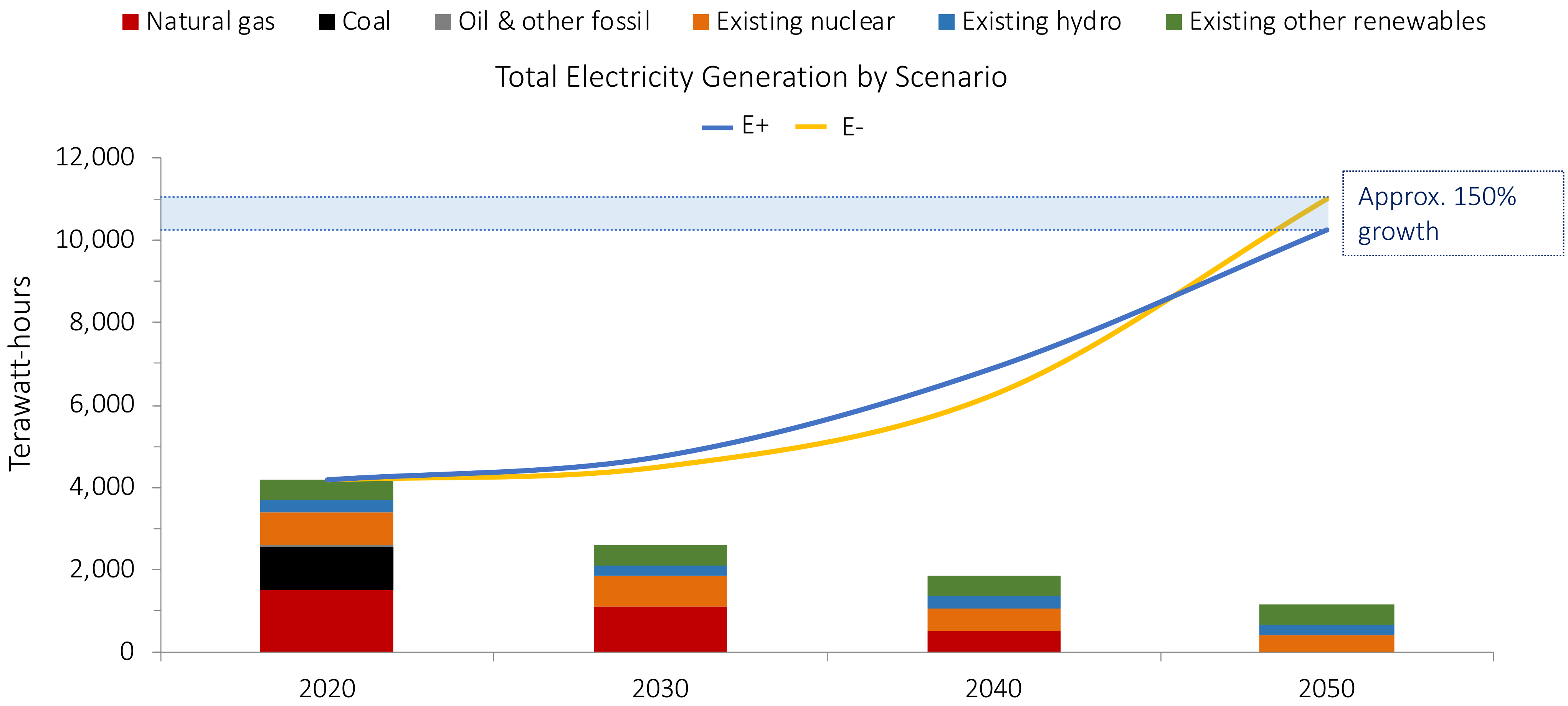
Jesse D. Jenkins, PhD

Assistant Professor | Princeton University

Dept. of Mechanical & Aerospace Engineering | Andlinger Center for Energy & Environment

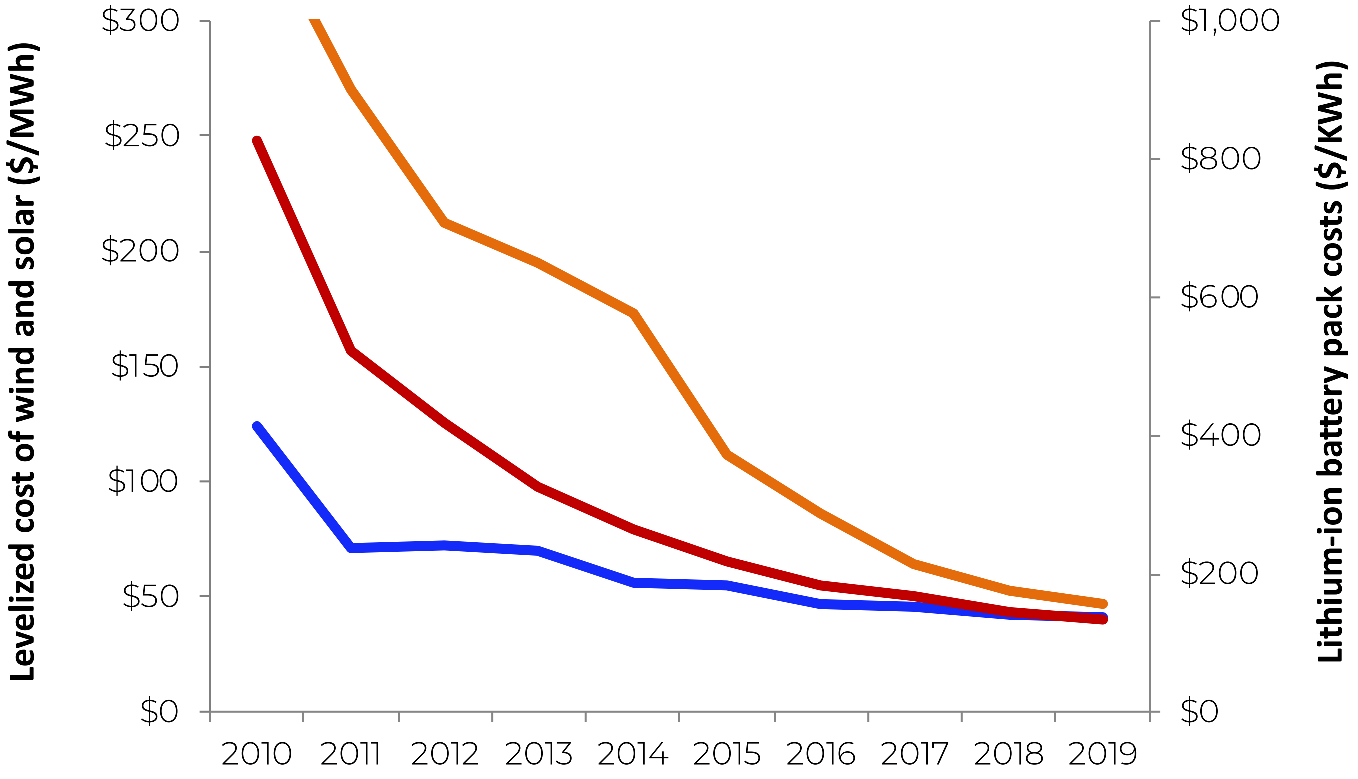
JHU-Columbia Future Energy Markets Forum | June 2, 2020

CLEAN ELECTRICITY: THE LINCHPIN



Data source: Preliminary results, Princeton University and Evolved Energy Research, *Net Zero America study*. Net zero greenhouse gas emissions by 2050 scenarios.

THE GOOD NEWS: WIND, SOLAR, BATTERY COSTS PLUMMET



Total cost declines
(2010-2019)

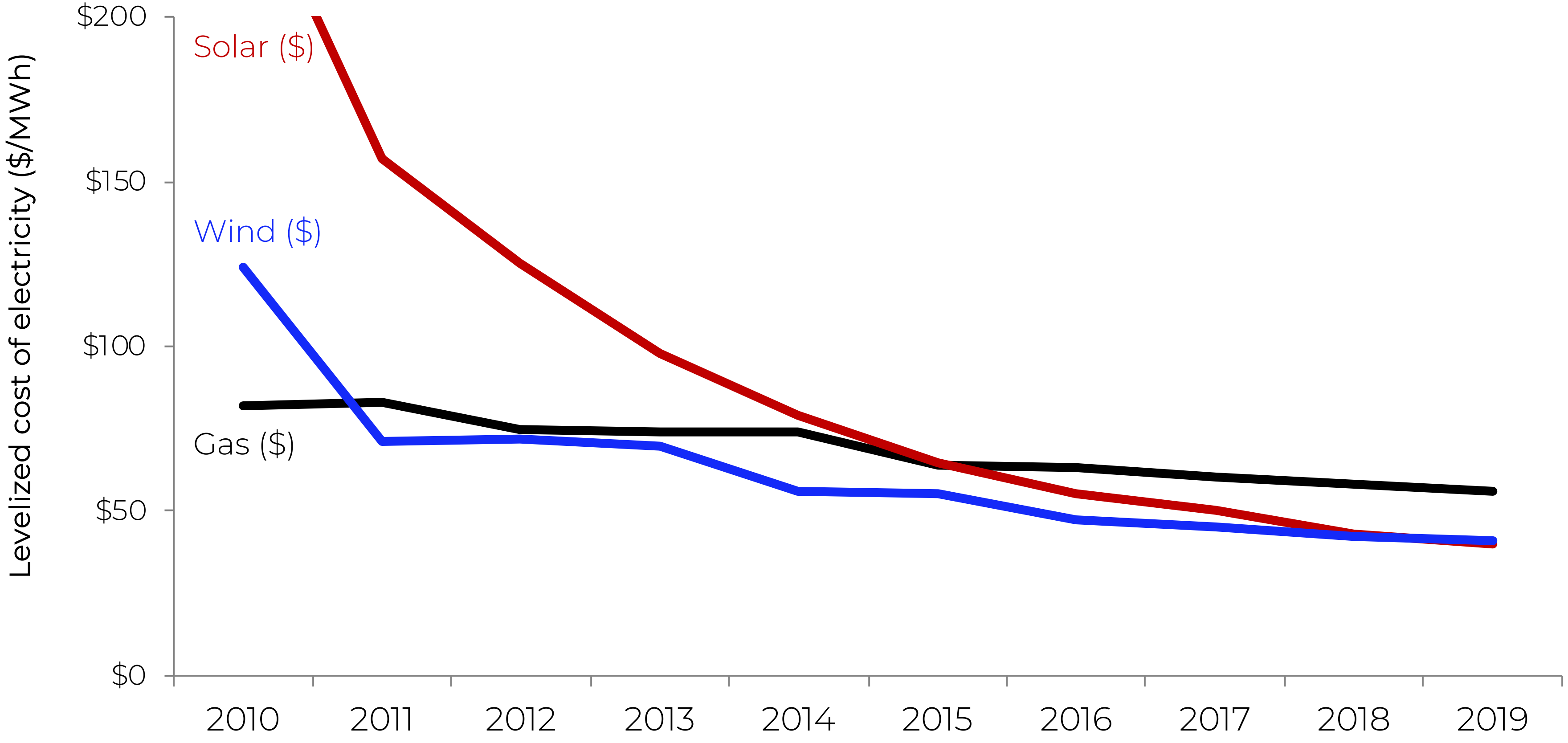
Solar $/MWh -84%

Li-ion packs $/KWh -87%

Wind $/MWh -67%

Data Sources: Wind & solar costs from Lazard (2019), Lazard's Levelized Cost of Energy Analysis – Version 13.0.
Battery pack costs from Bloomberg New Energy Finance (2019), Battery Price Survey.

A race to beat fossil fuels on cost…



Data Sources: Costs from Lazard (2019), Lazard's Levelized Cost of Energy Analysis – Version 13.0

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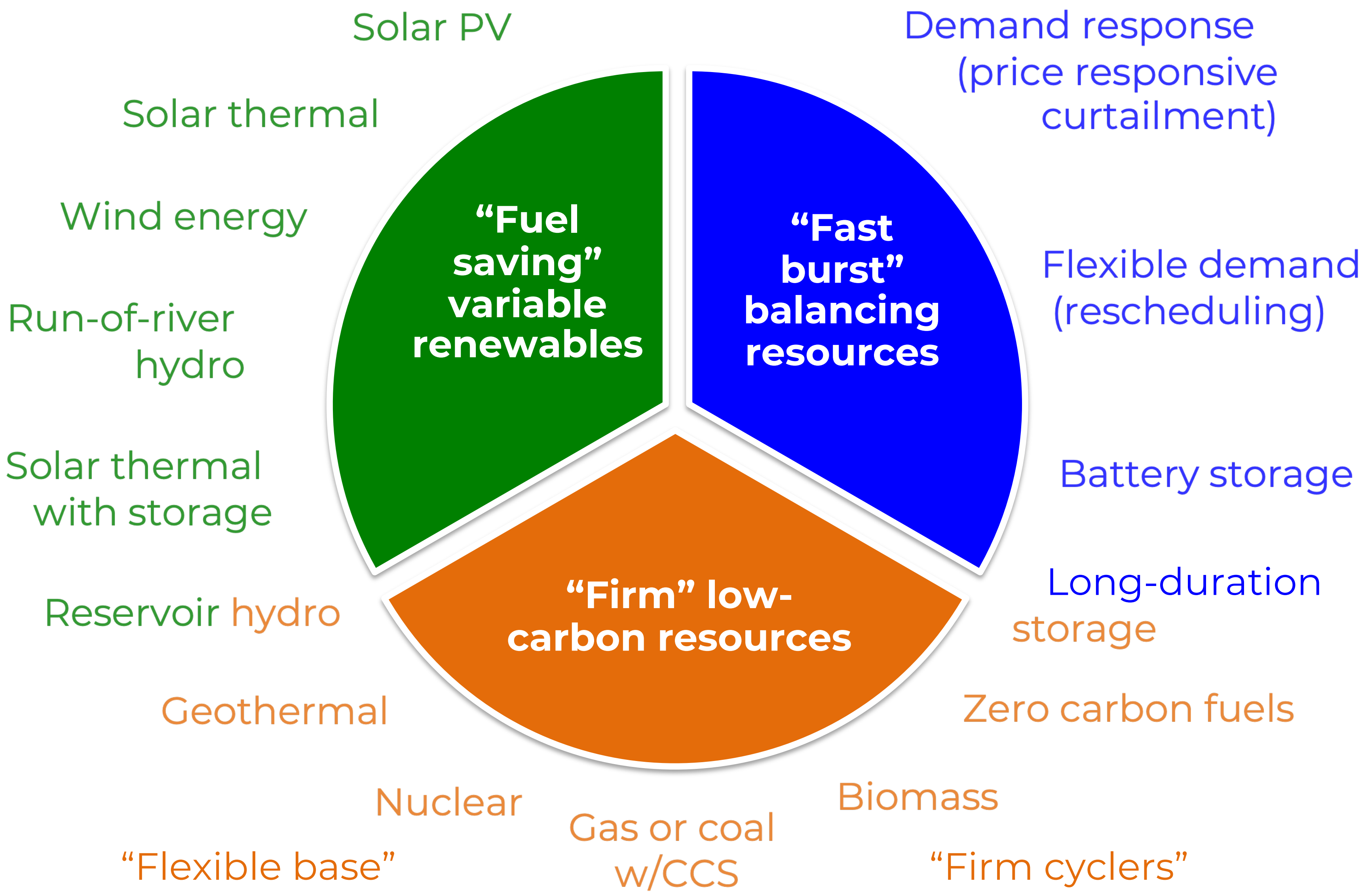
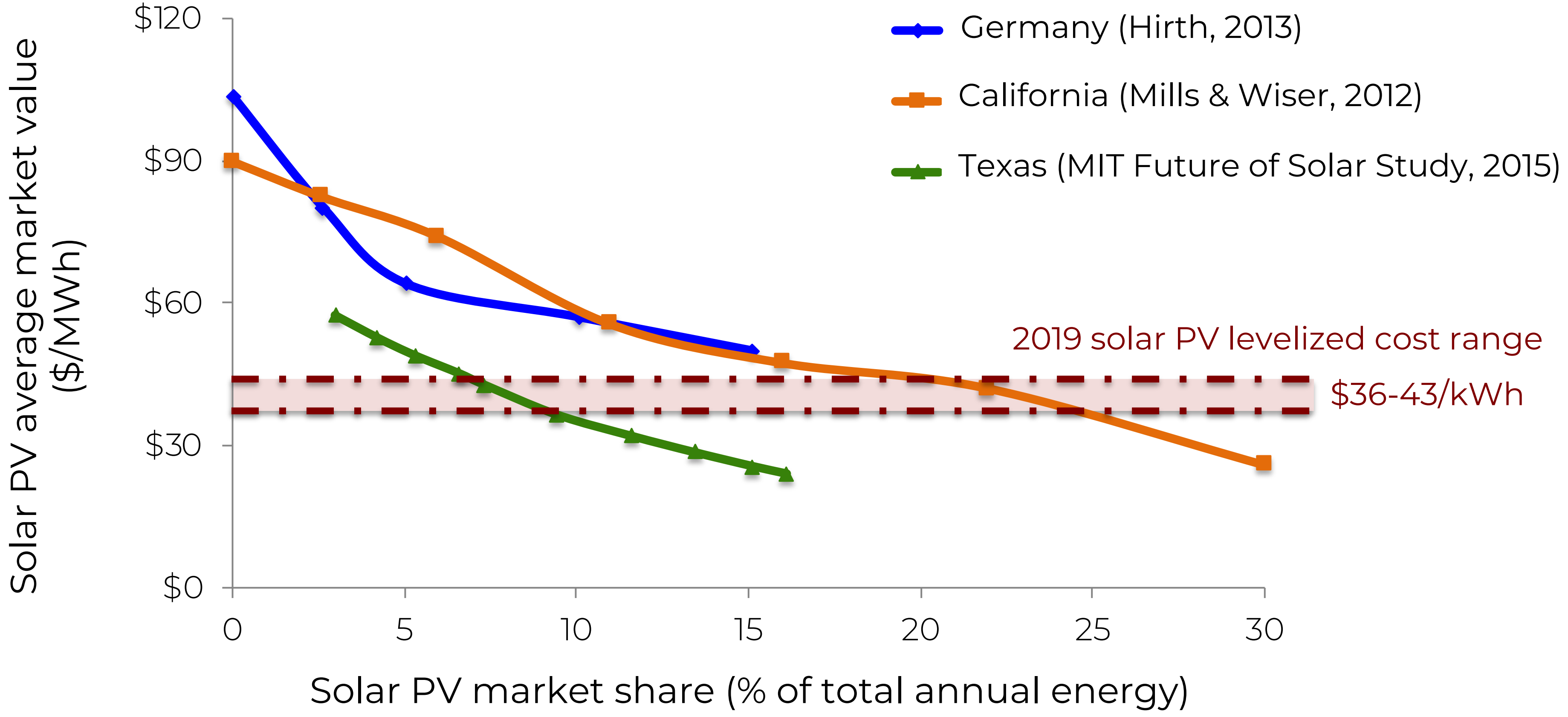

Solar PV
Solar thermal
Wind energy
Run-of-river hydro
Solar thermal with storage
Reservoir hydro
Geothermal
Nuclear
"Flexible base"
Gas or coal w/CCS
Biomass
"Firm cyclers"
Zero carbon fuels
Long-duration storage
Battery storage
Flexible demand (rescheduling)
Demand response (price responsive curtailment)
"Fuel saving" variable renewables
"Fast burst" balancing resources
"Firm" low-carbon resources

Win the Race Between Declining Cost & Value

A RACE AGAINST DECLINING VALUE (SOLAR PV)



Data Source: Sivaram & Kann (2016), Solar needs a more ambitious cost target, *Nature Energy* Vol. 1 (April 2016).
Solar cost estimate for 2018 from Lazard (2018) op. cit. above.

WIND/SOLAR VALUE DECLINE: KEY MECHANISMS

1. Declining "fuel-saving" value (energy substitution)

2. Decreasing "capacity value" (capacity substitution)

3. Increasing "over-generation" (energy that must be stored or wasted when supply exceeds demand)

Additional factors (aka "integration costs"):
Increasing flexibility, ramping and reserve requirements; thermal plant cycling costs; transmission network costs

WIND/SOLAR VALUE DECLINE: MITIGATION MECHANISMS

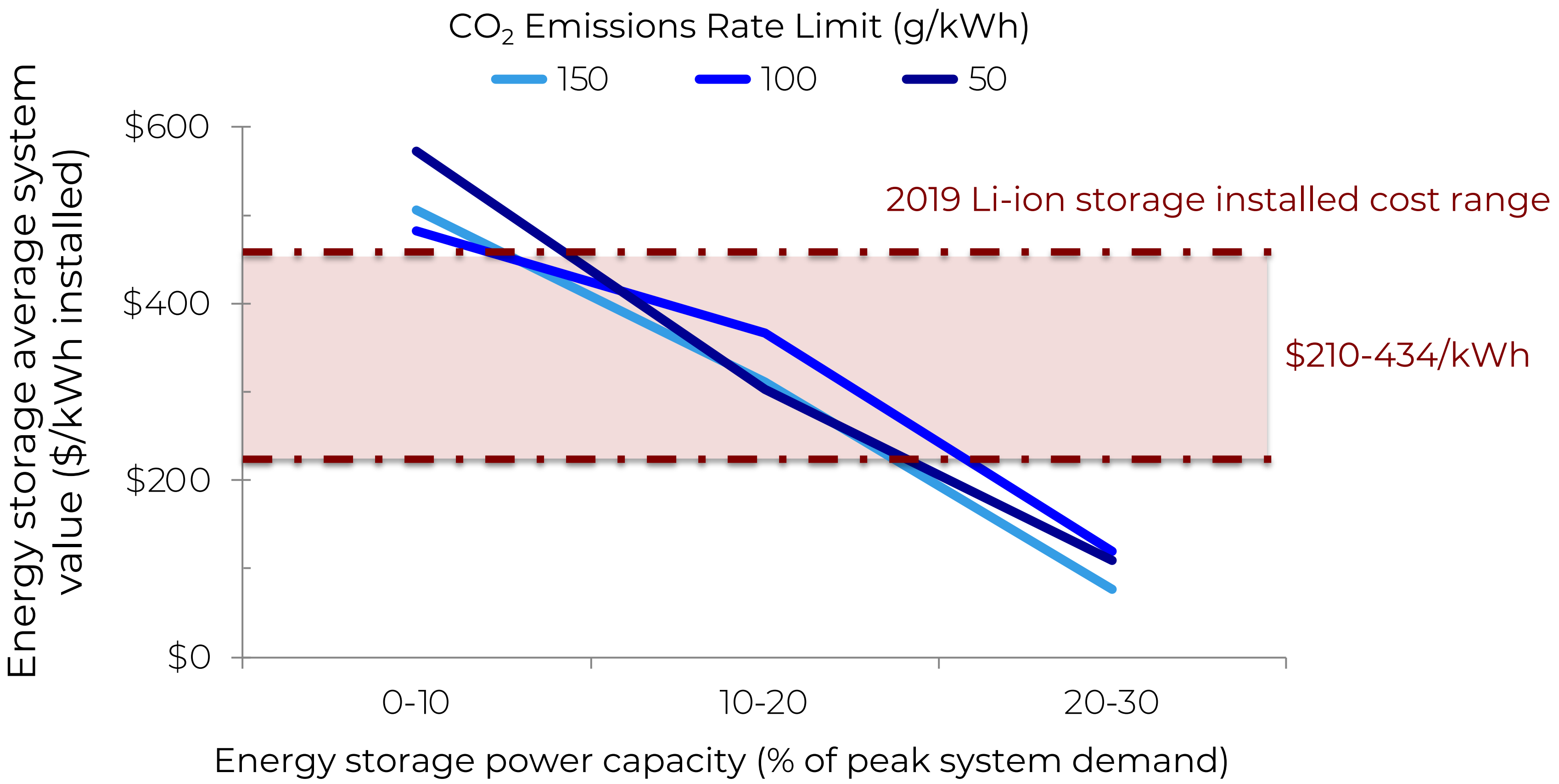
1. Energy storage

2. Demand shifting

3. Demand ‘sinks’

All help push back, but not stop decline in marginal value of wind and solar.

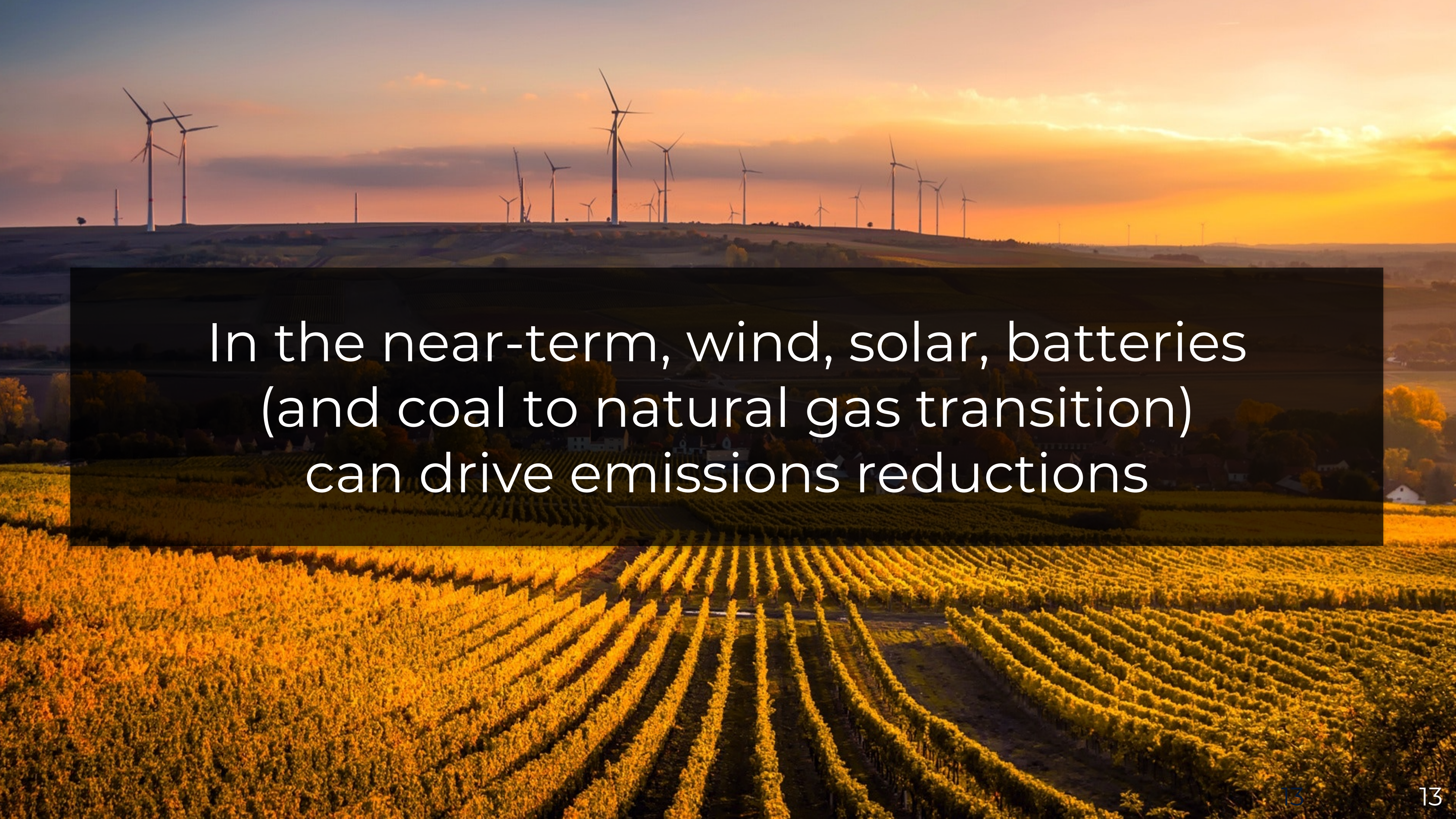
A RACE AGAINST DECLINING VALUE (ENERGY STORAGE)



Graphic is author's own created with data from: de Sisternes, Jenkins & Botterud (2016), "The value of energy storage in decarbonizing the electricity sector," *Applied Energy* 175: 368-379. Assumes Li-ion storage system with 2 hours storage duration and 10 year asset life. Estimated 2019 Li-ion storage cost per kWh from Lazard (2019), Lazard's Levelized Cost of Storage Analysis – Version 5.0 for 100 MW / 200 MWh system.

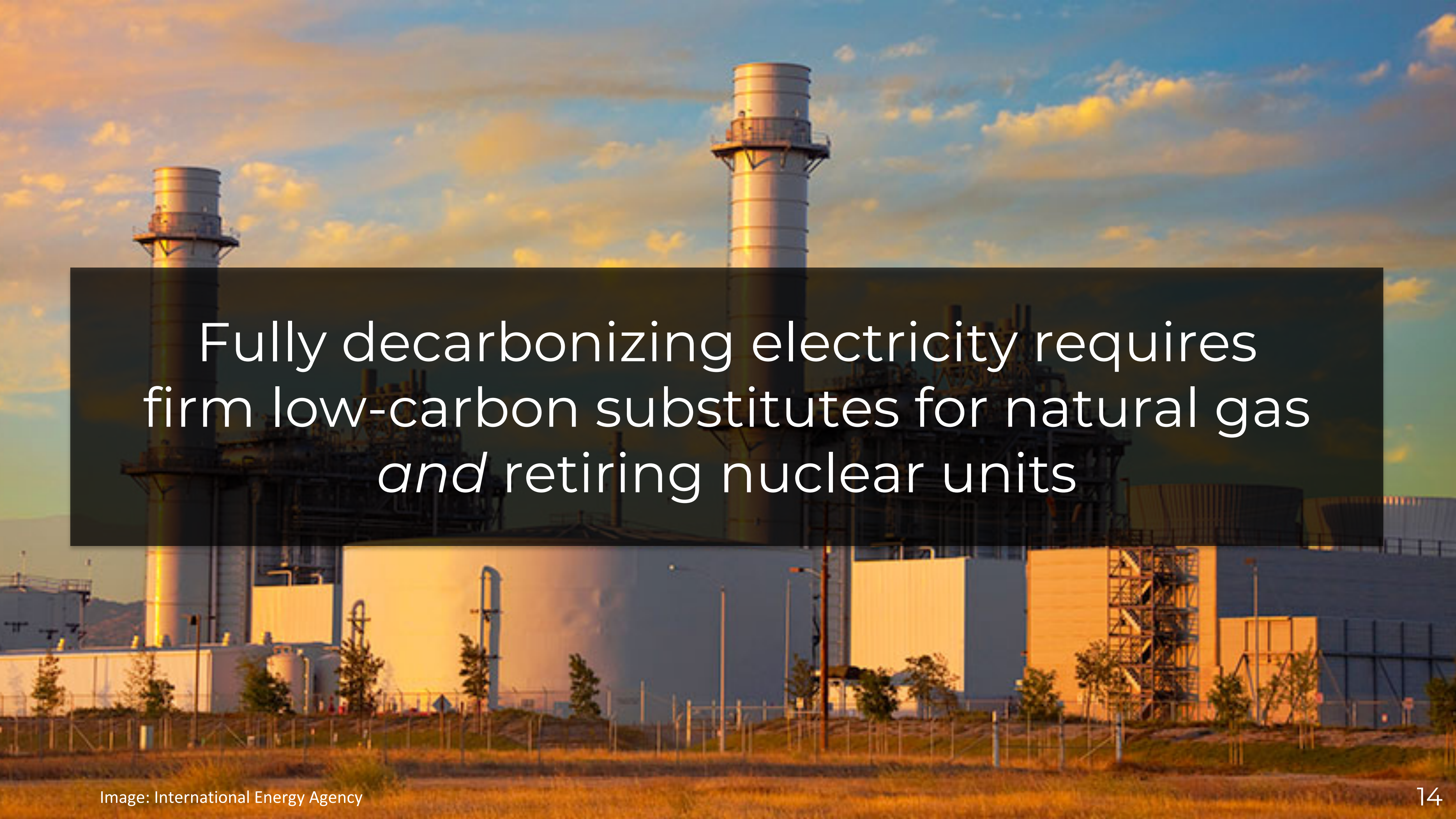
STORAGE VALUE DECLINE: KEY MECHANISMS

1. “Niche” markets fill quickly for regulation & reserves
2. Increasing energy storage (longer duration) needed to maintain capacity substitution value
3. Reduced energy arbitrage (buy-sell) spread
4. Declining utilization rate



In the near-term, wind, solar, batteries (and coal to natural gas transition) can drive emissions reductions

13



Fully decarbonizing electricity requires firm low-carbon substitutes for natural gas *and* retiring nuclear units

Image: International Energy Agency

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The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation

Nestor A. Sepulveda [4] • Jesse D. Jenkins • Fernando J. de Sisternes • Richard K. Lester •

Show footnotes

Published: September 06, 2018 • DOI: https://doi.org/10.1016/j.joule.2018.08.006

https://www.cell.com/joule/fulltext/S2542-4351(18)30386-6

PlumX Metrics

Highlights

Summary

Graphical Abstract

Keywords

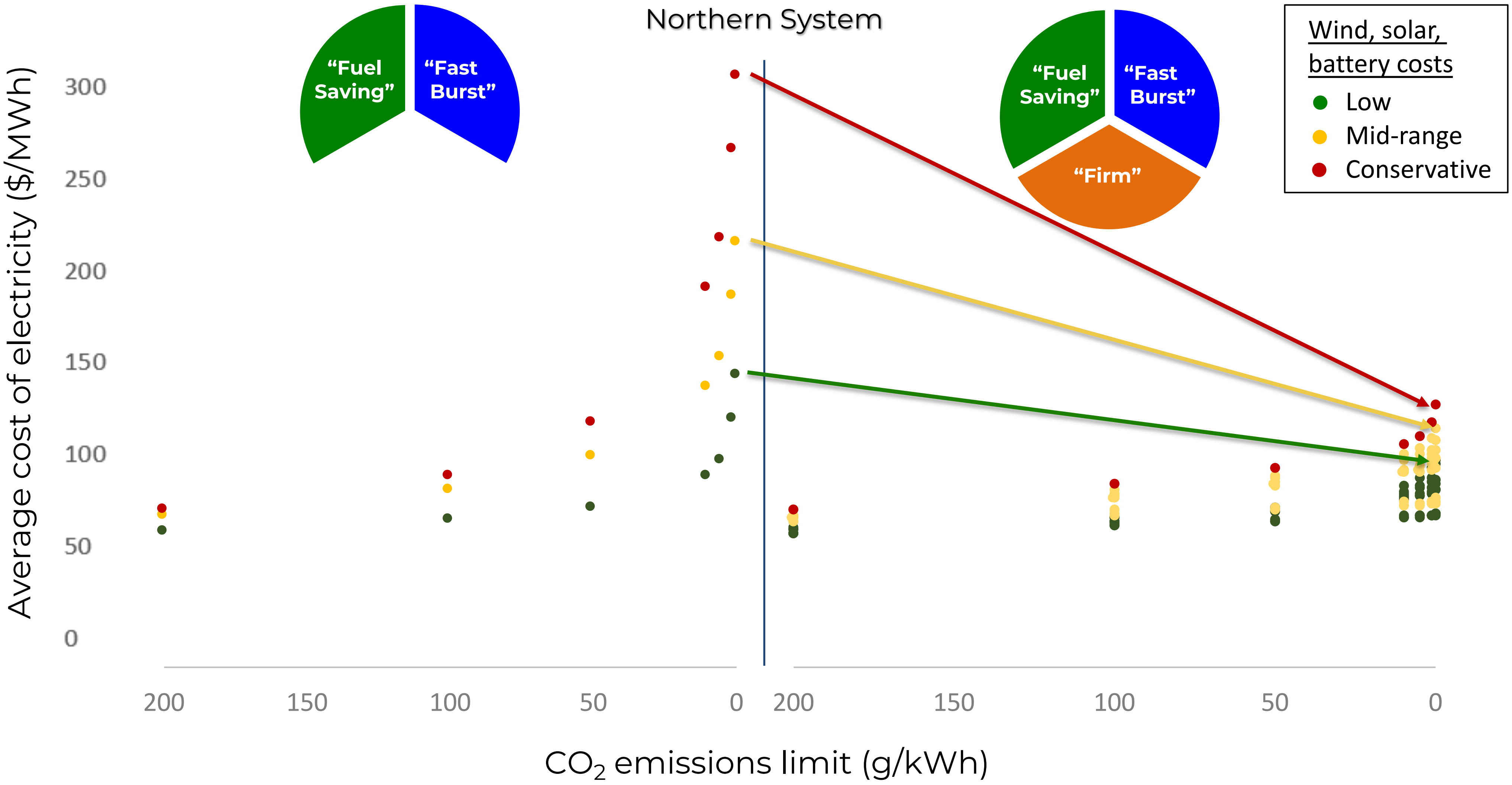
References

Article Info

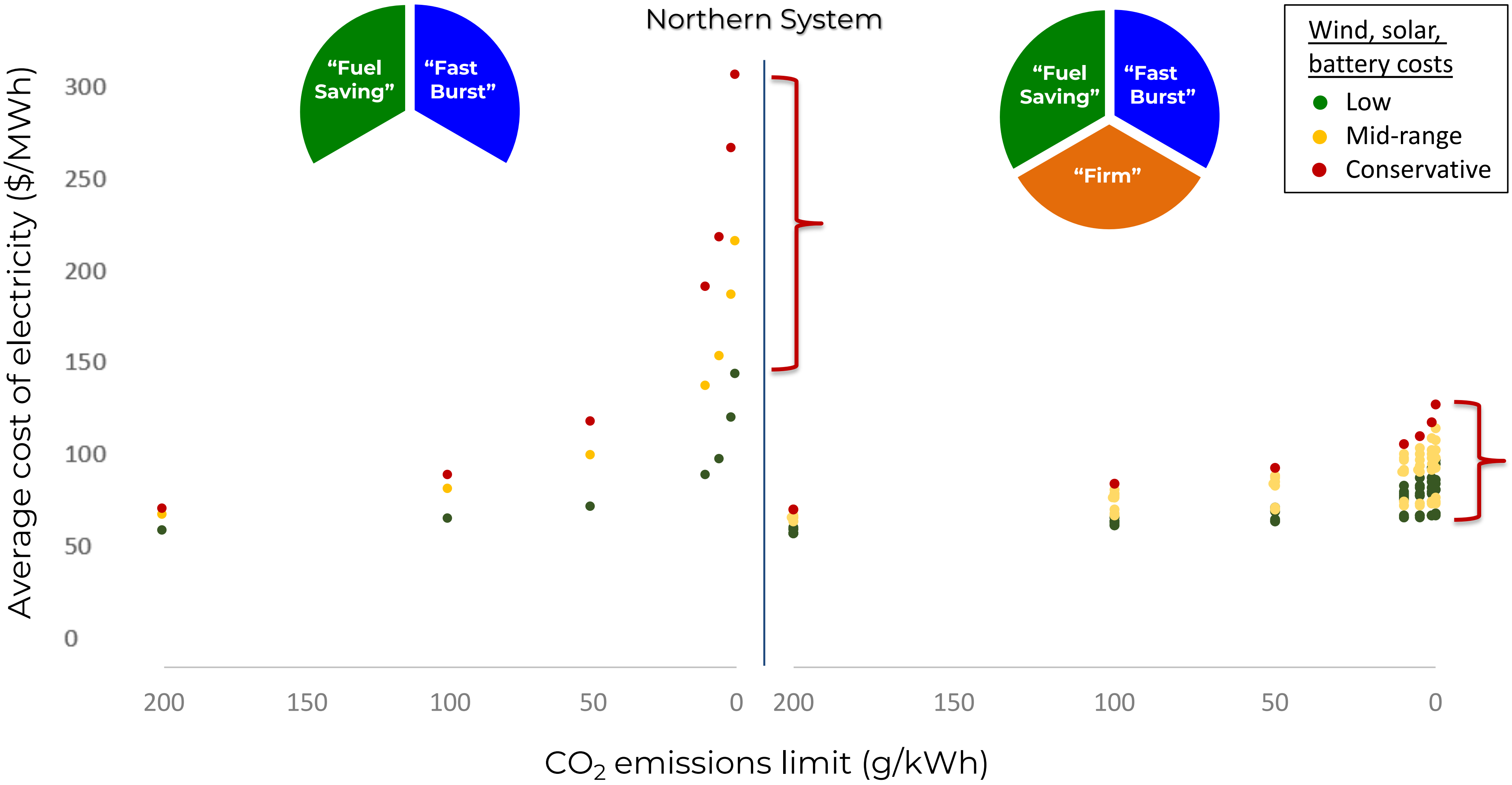
Highlights

- Firm low-carbon resources consistently lower decarbonized electricity system costs
- Availability of firm low-carbon resources reduces costs 10%–62% in zero-CO_2 cases
- Without these resources, electricity costs rise rapidly as CO_2 limits near zero

Recommend *Joule* to Your Librarian



Data source: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11).



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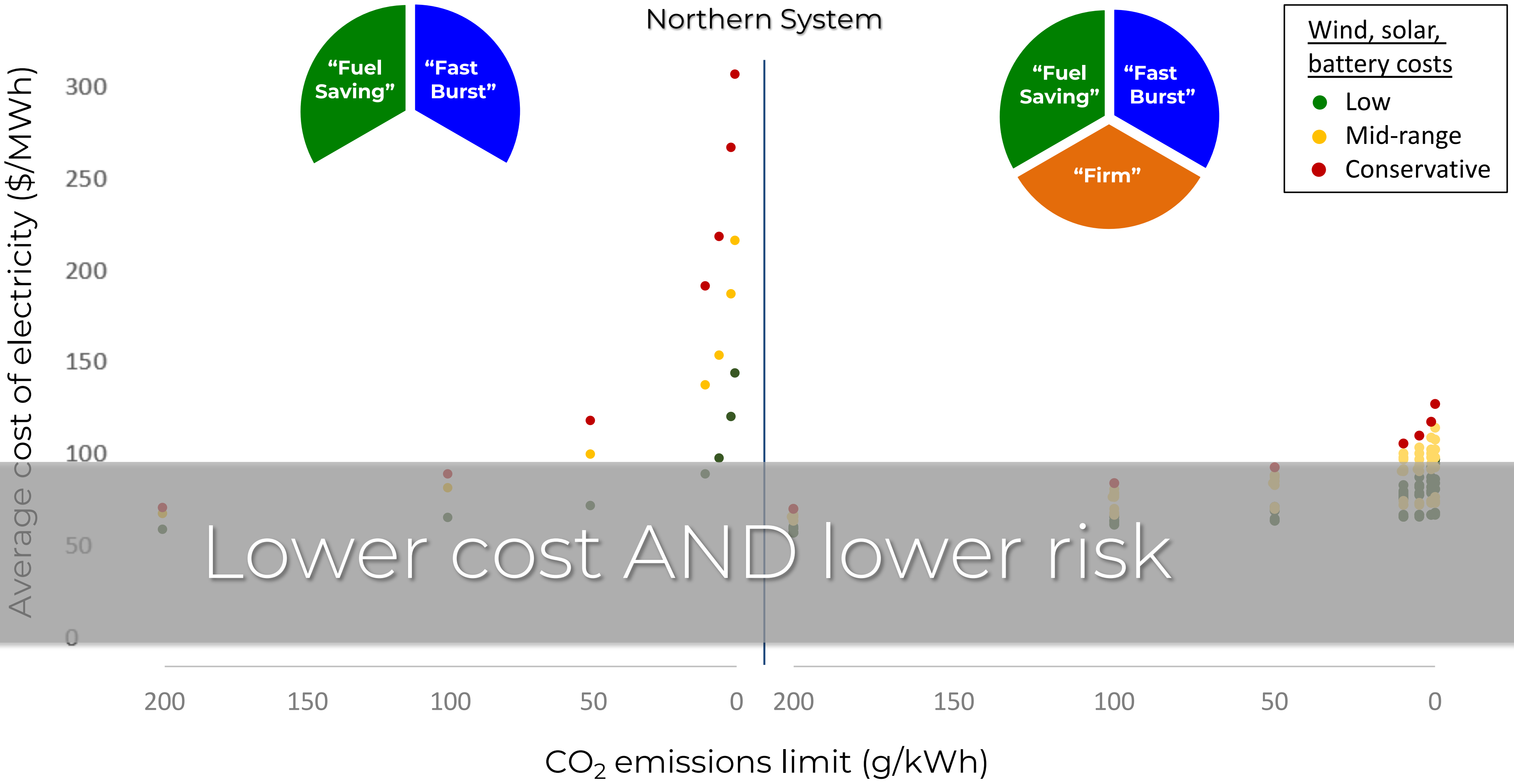
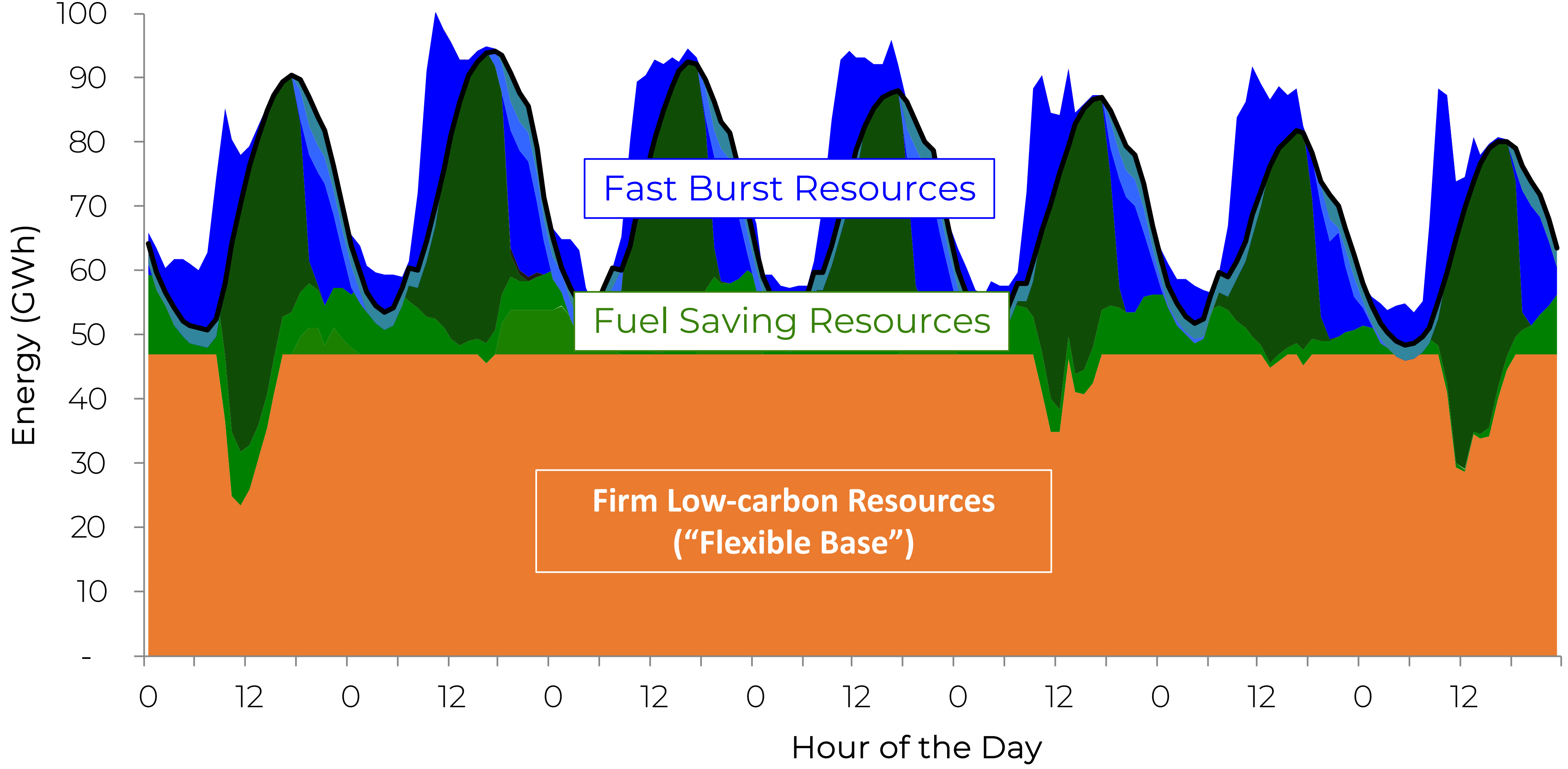


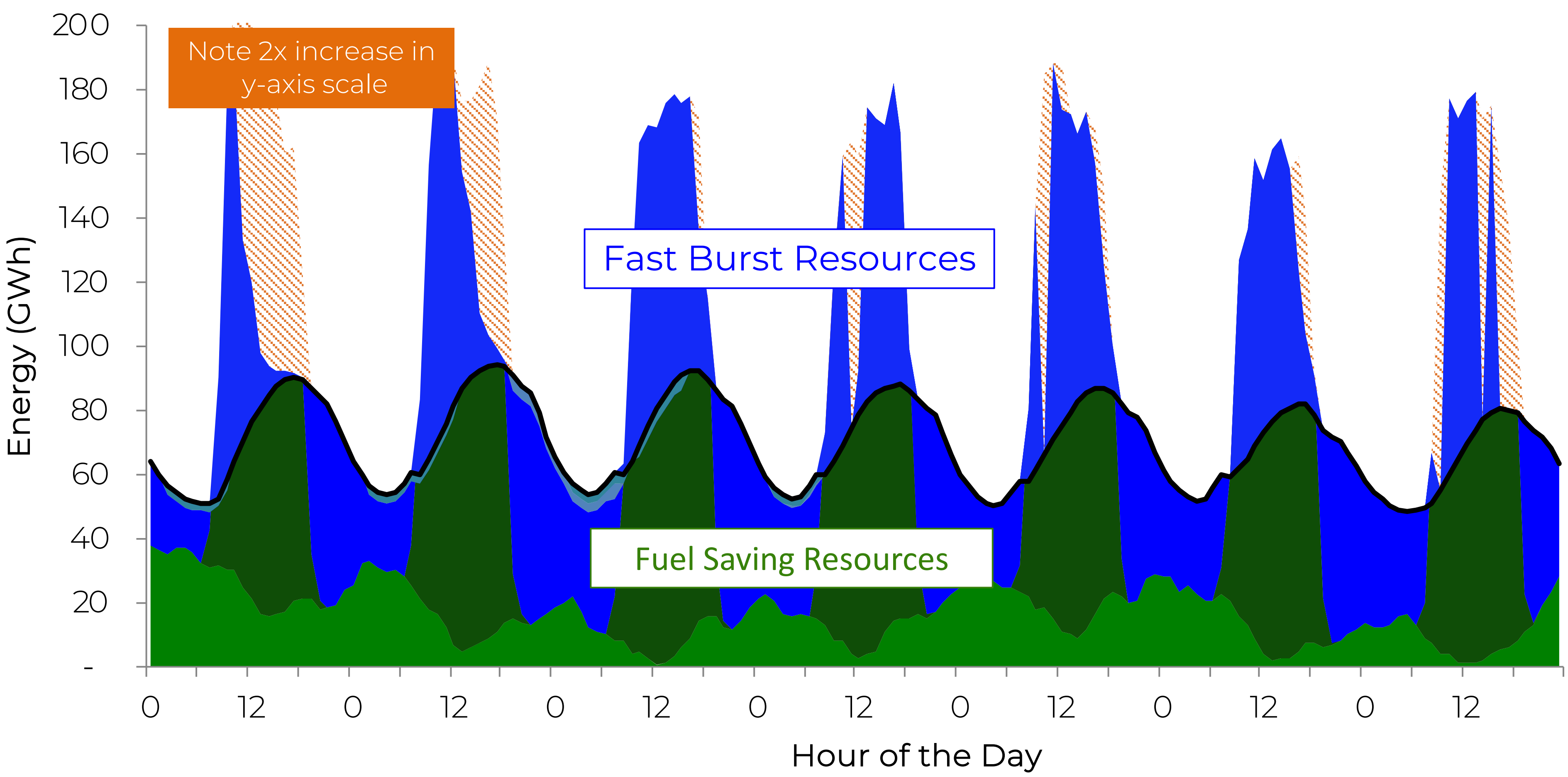
Lower cost AND lower risk

Data source: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11).

One Possible Balanced Portfolio

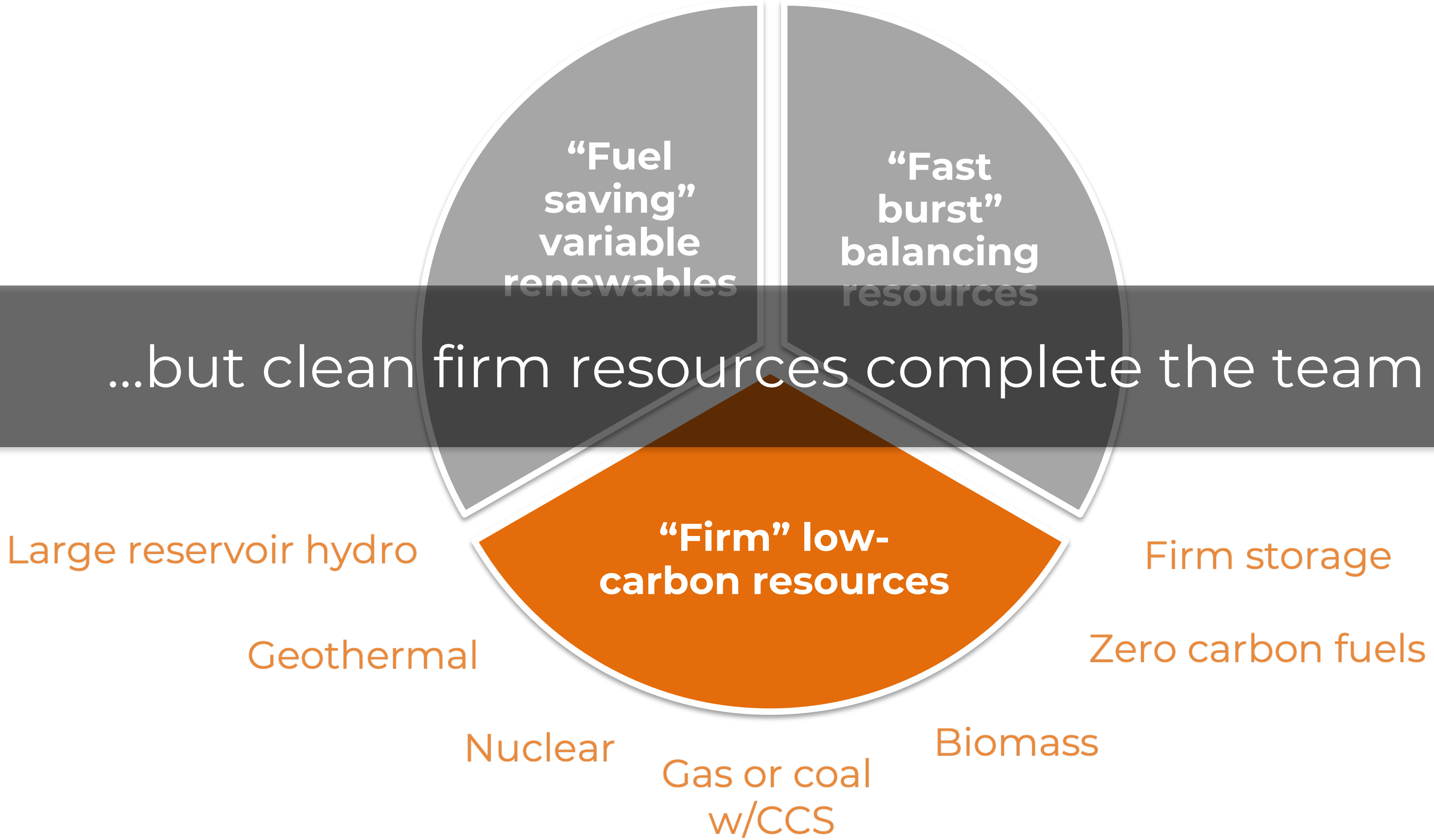


Without Firm Low-Carbon Resources



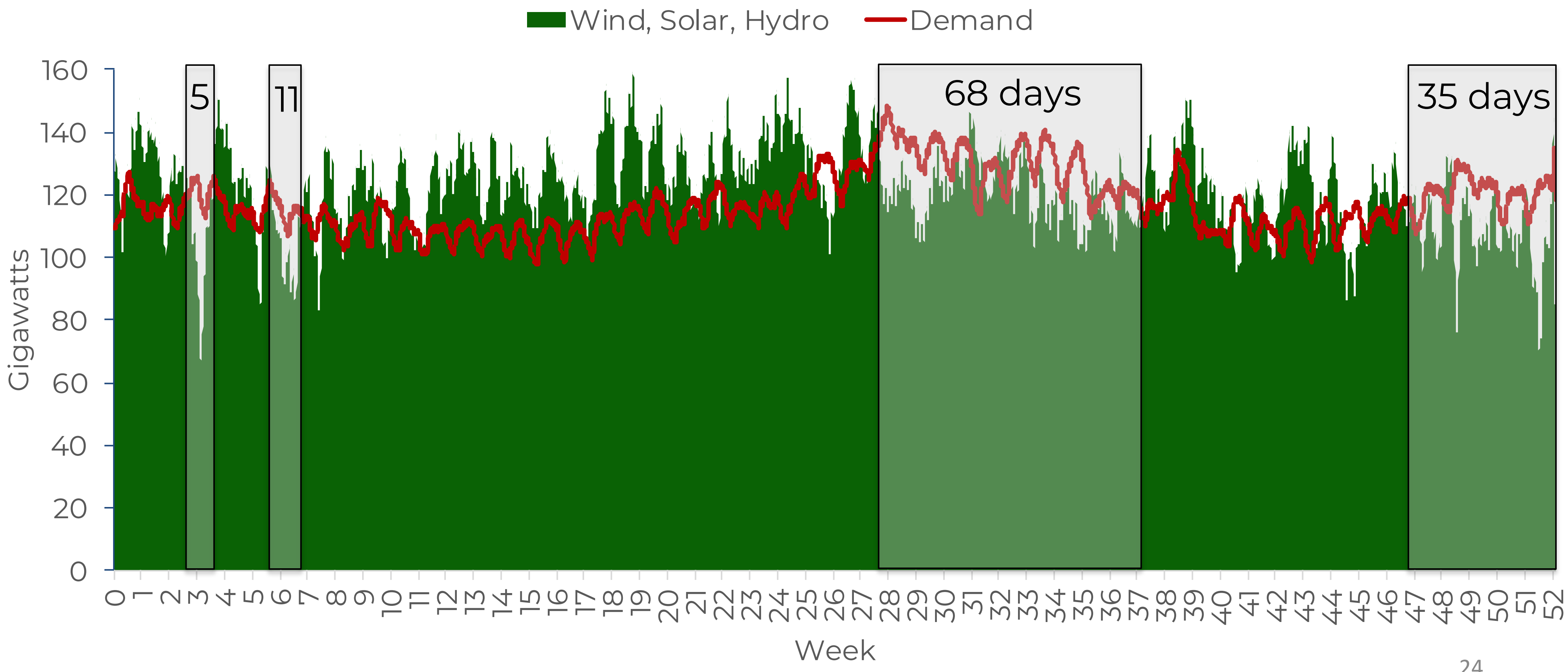

PRINCETON
2
Solar, wind & batteries will be stars…

…but clean firm resources complete the team



What about storage?

The *Dunkelflaute* ("Dark Doldrums")
Western Interconnection, Renewables + Storage Only
(24 hour rolling average power)

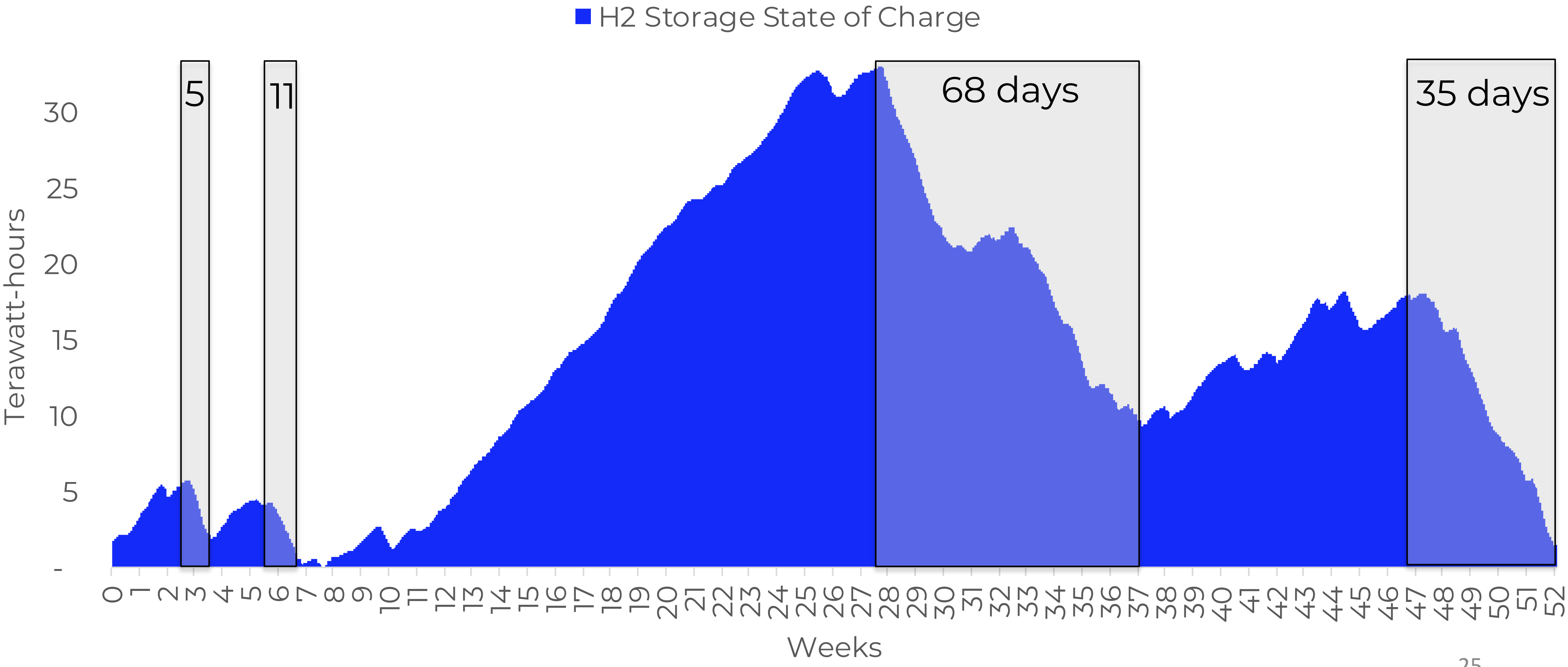


Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

Long Duration Storage Needed for Renewables + Storage Only

Western Interconnection, 0 CO_2 emissions limit

(24 hour rolling average power)



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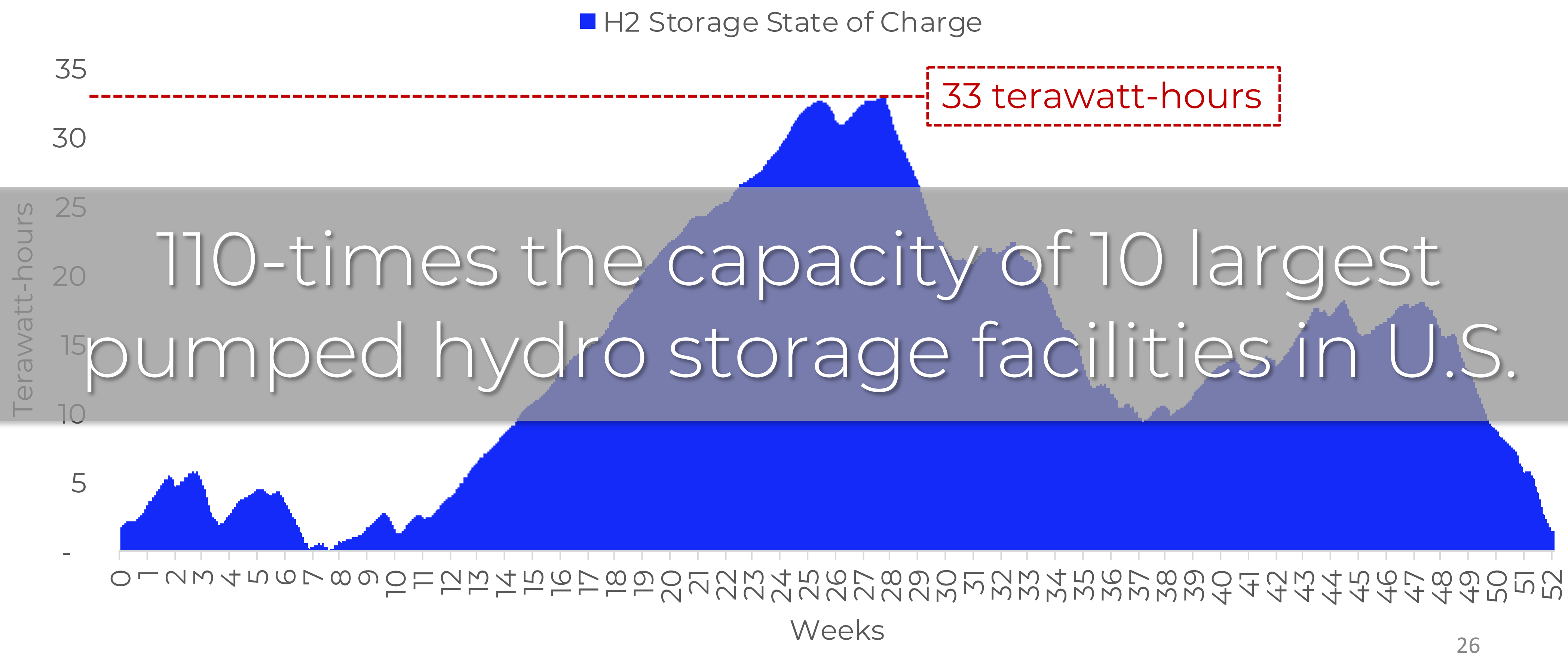
Long Duration Storage Needed

Western Interconnection, Renewables + Storage Only

(24 hour rolling average power)



110-times the capacity of 10 largest pumped hydro storage facilities in U.S.

Data source for pumped hydro facilities: DOE Global Energy Storage Database https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/. Sum of energy capacity for 10 largest PHES facilities in database by energy capacity, including: San Luis (William R. Gianelli); Racoon Mountain; Bath County; Bad Creek; John W. Keyes III; Blaenheim-Gilboa; Lundington; Castaic; Northfield Mountain; and Fairfield. Total capacity of these facilities is 0.3 TWh.

A very different kind of storage...

ENERGY STORAGE

Long Duration Breakthrough? Form Energy's First Project Tries Pushing Storage to 150 Hours

Minnesota utility Great River Energy will use new storage technology from the Bill Gates-backed startup to replace coal power with dispatchable wind.

JULIAN SPECTOR | MAY 07, 2020

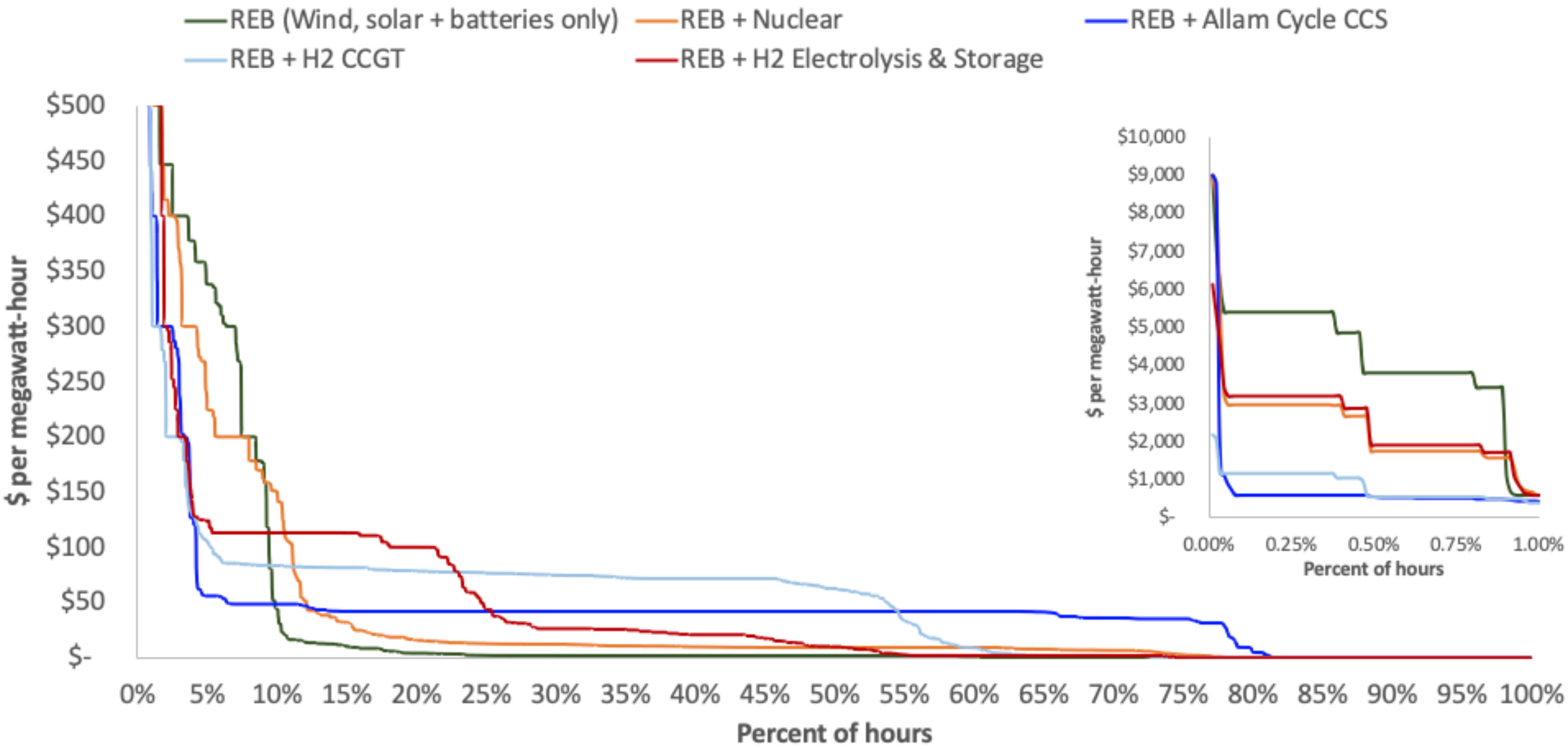
ENERGY STORAGE

Utah Aims to Shatter Records With 1,000MW Energy Storage Plant

The one-of-a-kind facility would combine compressed air storage in salt caverns with hydrogen storage, large flow batteries and solid-oxide fuel cells.

JULIAN SPECTOR | MAY 30, 2019

PRICES IN A ZERO CARBON SYSTEMS (CA + WECC EXAMPLES)



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICES IN A ZERO CARBON SYSTEMS (CA + WECC EXAMPLES)

	REB	REB+H2 Electrol.	REB+Nuclear	REB+H2 CCGT	REB+Allam
Average	**$ 70.3**	**$ 64.4**	**$ 63.3**	**$ 58.5**	**$ 56.1**
p1	$ 600.0	$ 636.4	$ 734.1	$ 455.0	$ 446.4
p5	$ 338.1	$ 124.0	$ 243.0	$ 106.4	$ 56.0
p25	$ 2.1	$ 44.7	$ 12.7	$ 76.5	$ 42.0
p50	$ 1.9	$ 10.0	$ 9.3	$ 62.8	$ 42.0
p75	$ -	$ 0.1	$ 2.8	$ -	$ 35.2
p95	$ -	$ -	$ -	$ -	$ -
% hours <= $0	**40%**	**22%**	**23%**	**26%**	**19%**

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

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RESOURCES

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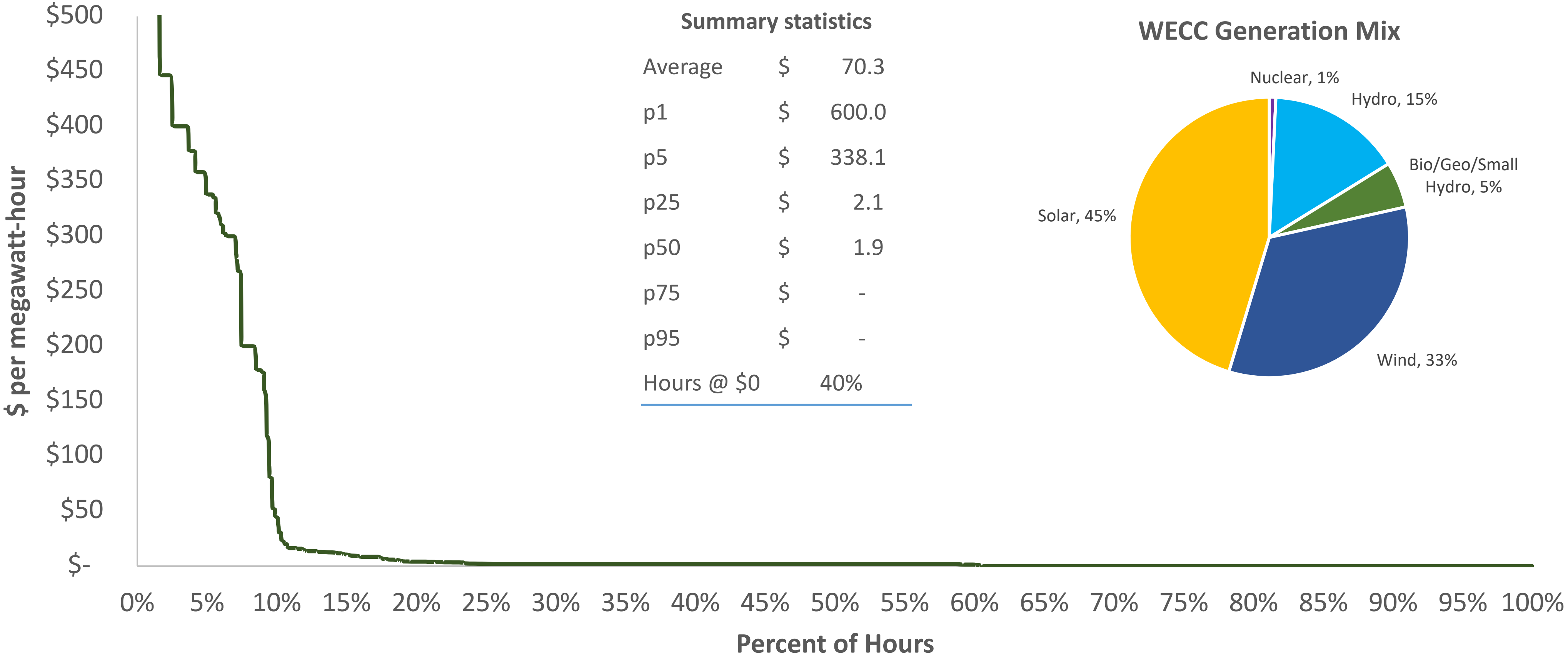
- Princeton Bradford Seminar, "Getting to Zero: Can America transition to a net-zero emissions energy systems?" February 10, 2020. Watch: https://www.youtube.com/watch?v=Liv1iuF_CDo

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries Only



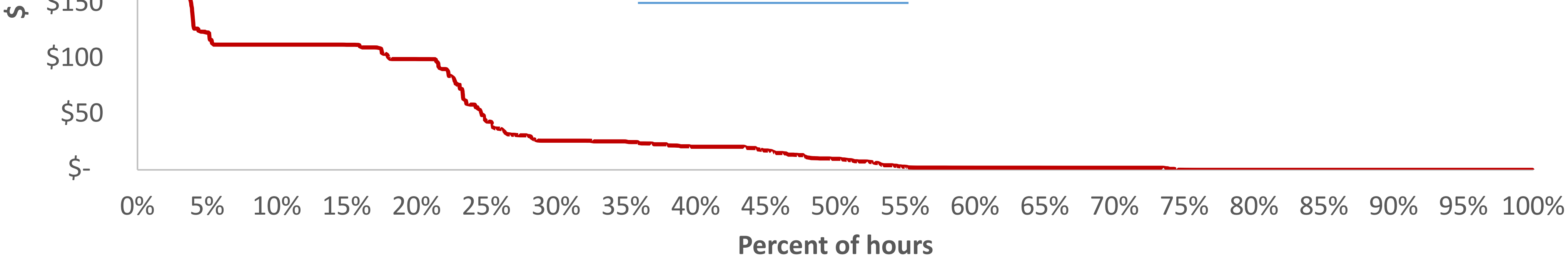
Summary statistics

Average	$	70.3
p1	$	600.0
p5	$	338.1
p25	$	2.1
p50	$	1.9
p75	$	-
p95	$	-
Hours @ $0	40%	

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

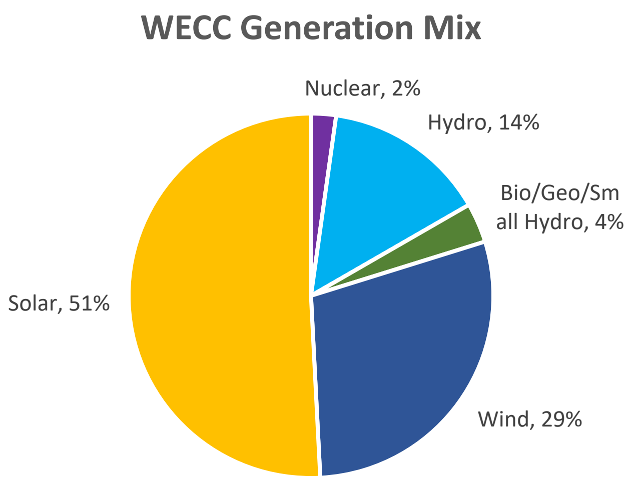
PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + H2 Electrolysis w/Storage



Summary statistics

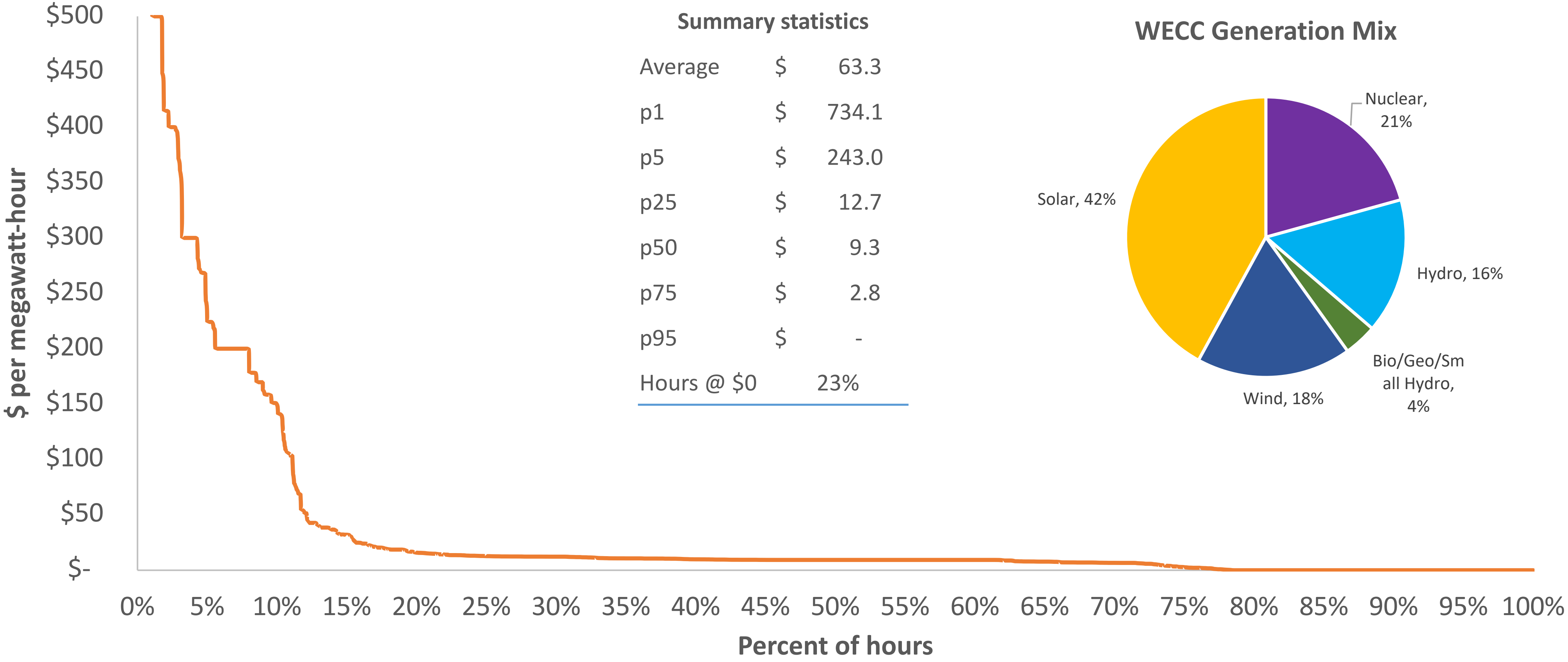
Average	$	64.4
p1	$	636.4
p5	$	124.0
p25	$	44.7
p50	$	10.0
p75	$	0.1
p95	$	-
Hours @ $0	22%	



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Nuclear



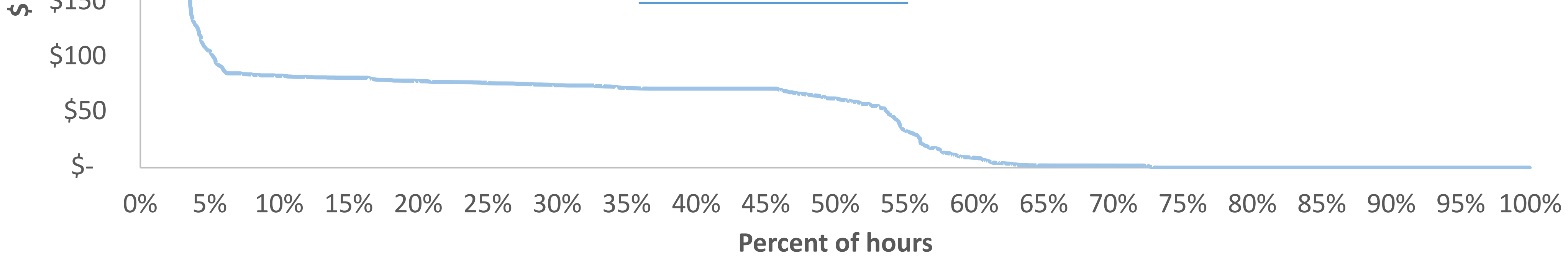
Summary statistics

Average	$	63.3
p1	$	734.1
p5	$	243.0
p25	$	12.7
p50	$	9.3
p75	$	2.8
p95	$	-
Hours @ $0	23%	

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

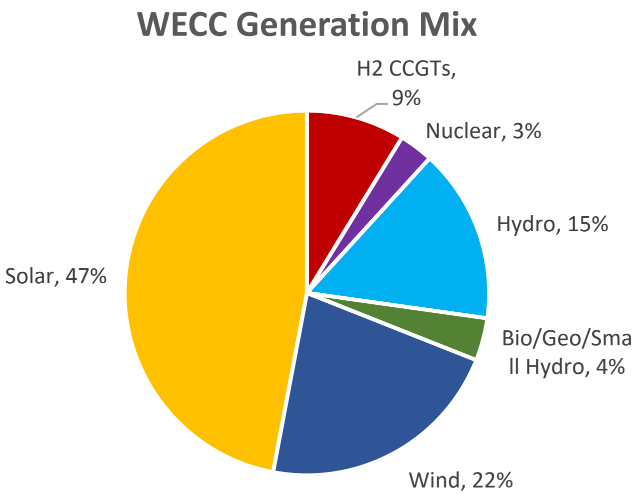
PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Hydrogen CCGTs



Summary statistics

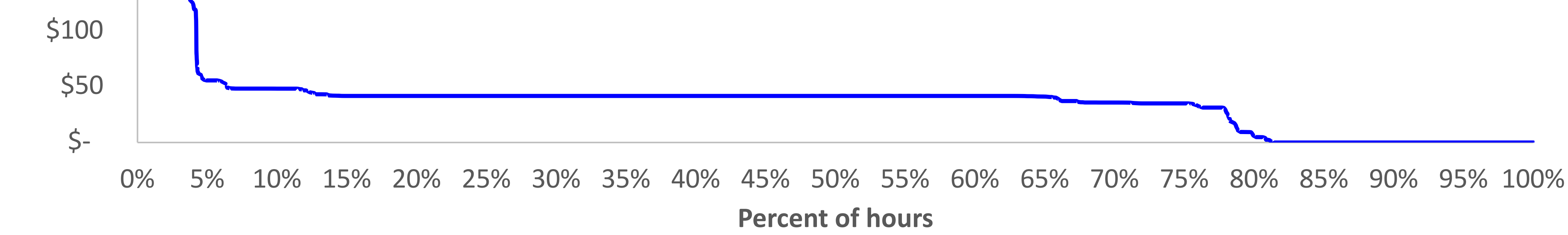
Average	$	58.5
p1	$	455.0
p5	$	106.4
p25	$	76.5
p50	$	62.8
p75	$	-
p95	$	-
Hours @ $0	26%	



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

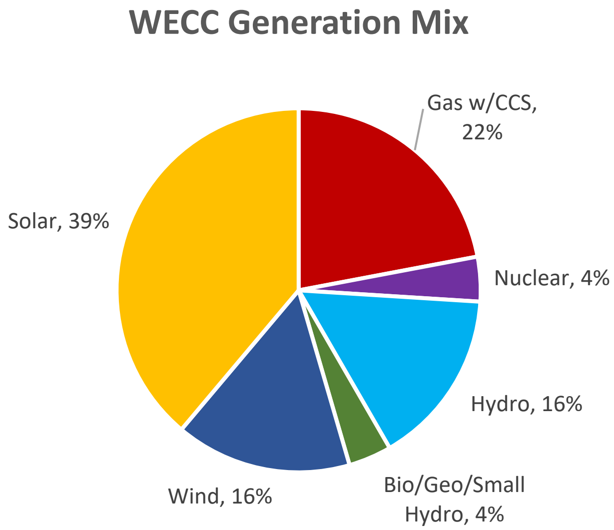
PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Allam Cycle Natural Gas w/CCS



Summary statistics

Average	$	56.1
p1	$	446.4
p5	$	56.0
p25	$	42.0
p50	$	42.0
p75	$	35.2
p95	$	-
Hours @ $0	19%	



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

Topic 1: Resource Portfolios

Dr. Christopher Clack

Vibrant Clean Energy

Reliable, Efficient & Low-Carbon Resource Portfolios:
Insights from WIS:dom® Modeling

Prepared By:

Vibrant Clean Energy, LLC

Dr Christopher T M Clack

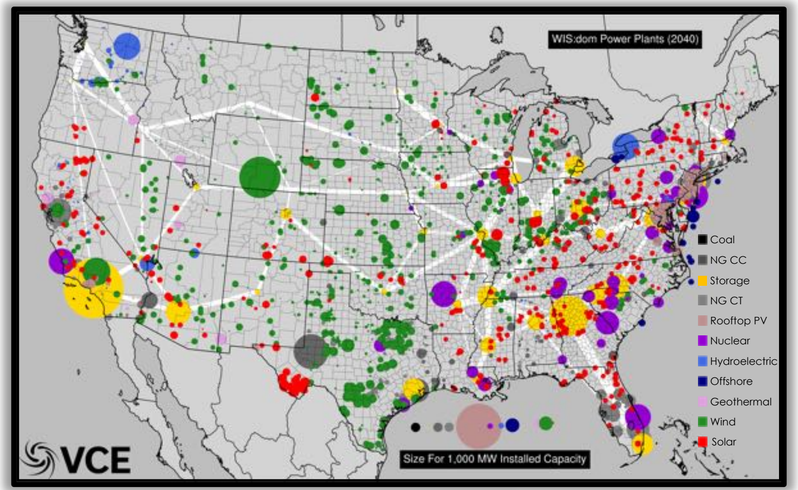
Prepared For:

Future Power Markets Forum

Online

June 2nd, 2020

Vibrant Clean Energy

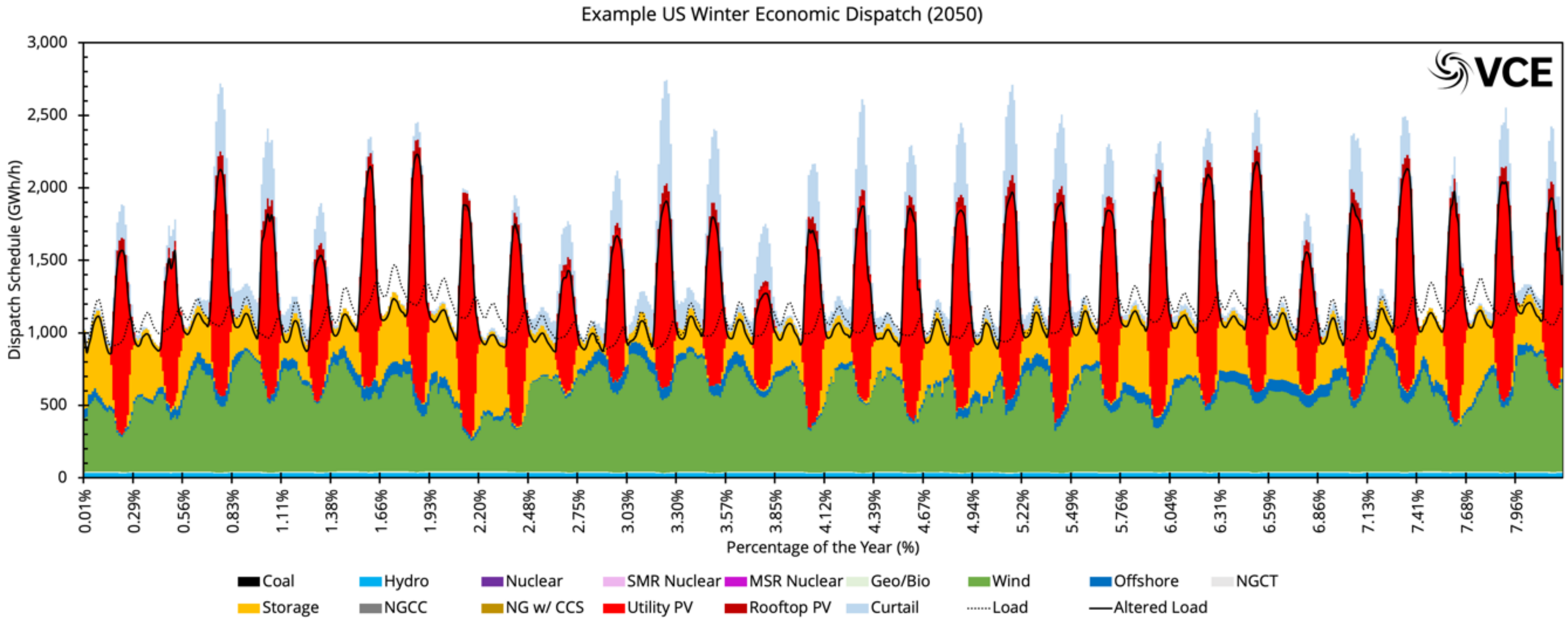


Purpose of Vibrant Clean Energy, LLC:

- ***Reduce the cost of electricity*** & help evolve economies to near zero emissions;
- ***Co-optimize*** transmission, generation, storage, & distributed resources;
- Increase the understanding of ***how Variable Generation impacts & alters the electricity grid*** and model it more accurately;
- ***Agnostically determine the least-cost portfolio*** of generation that will remove emissions from the economy;
- Model the ***electrification*** of industry, heating & transportation;
- License WIS:dom® optimization model and/or perform studies using the model;
- Assist clients ***unlock and understand the potential*** of high VRE scenarios, as well as zero emission pathways.

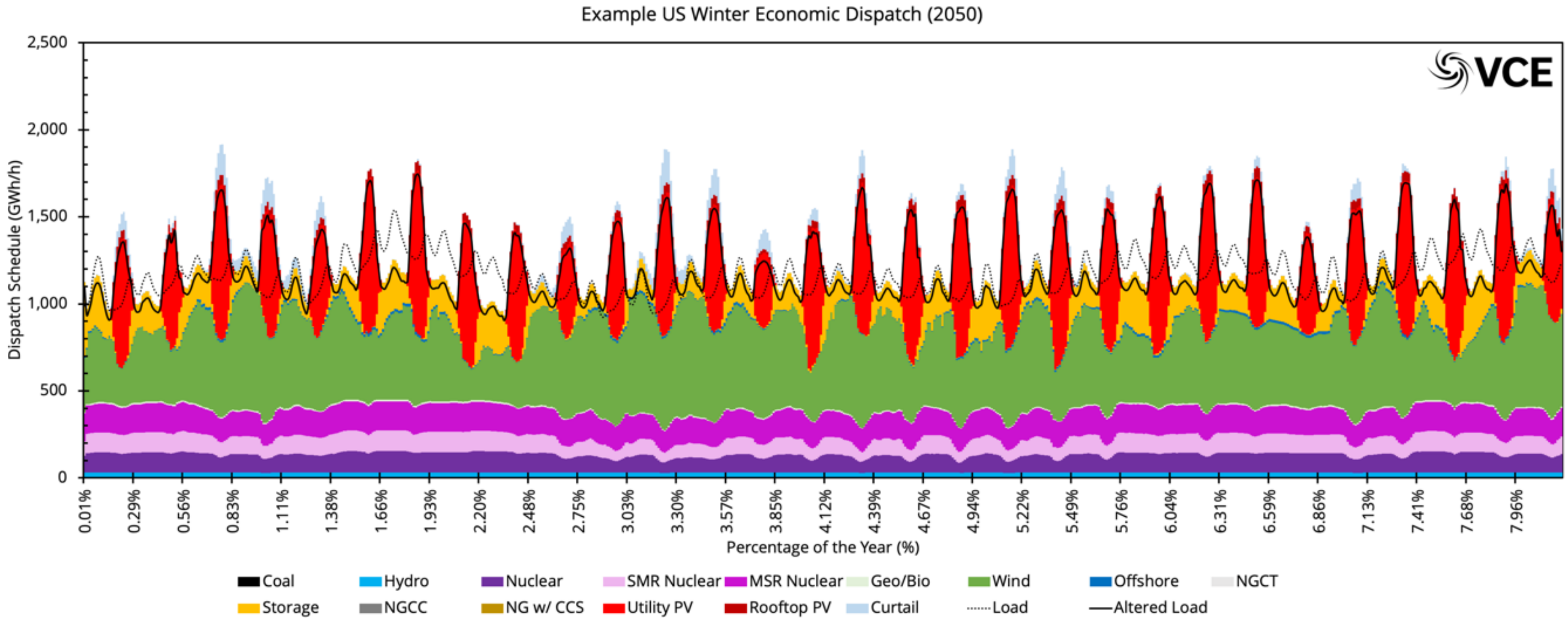
Technologies Do Work Together (Clean Energy)

With limited generation technologies, the system will need more flexibility from other assets



Technologies Do Work Together (Clean Energy)

Even with all generation technology types, the system still relies on them all to provide flexibility



info@vibrantcleanenergy.com

VCE
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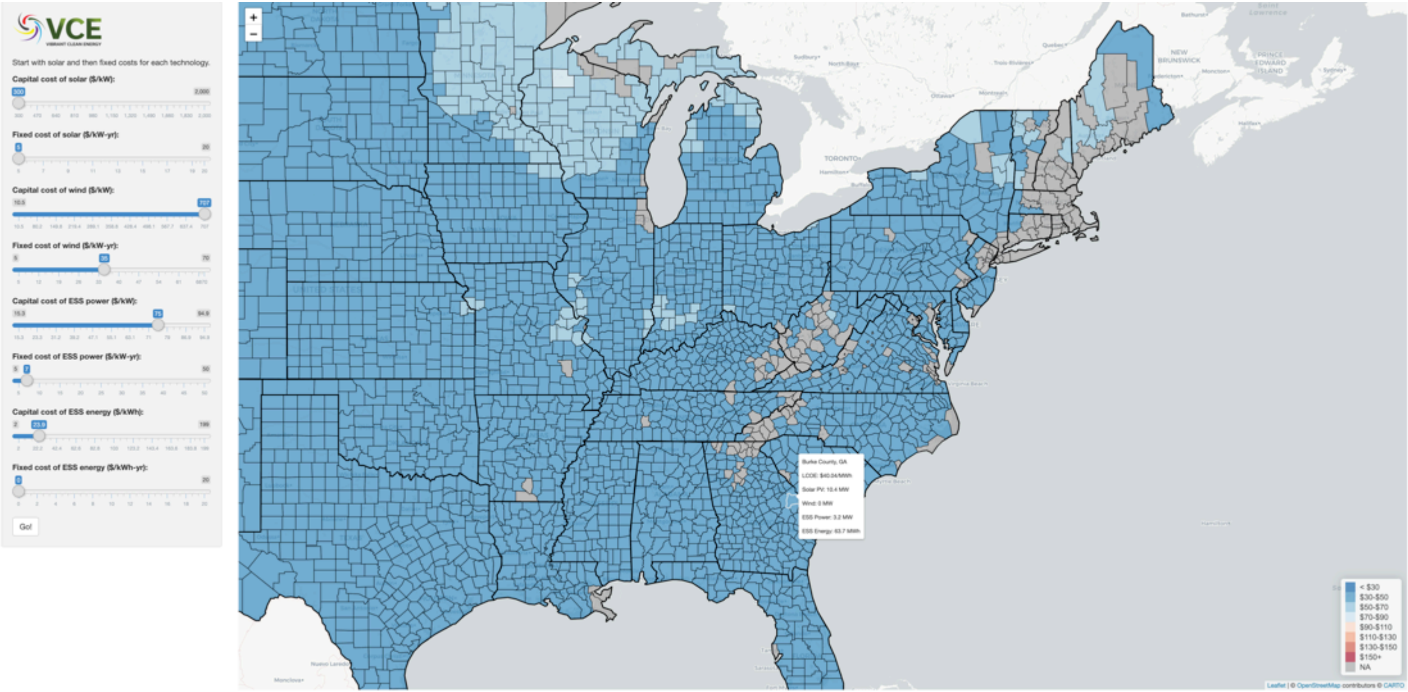
Local VREs Can Work Together to Provide Energy & Capacity

Combining wind, solar and storage (and possible synthetic fuels) allows for cheap, clean electricity & flexibility to ensure reliability



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VIBRANT CLEAN ENERGY

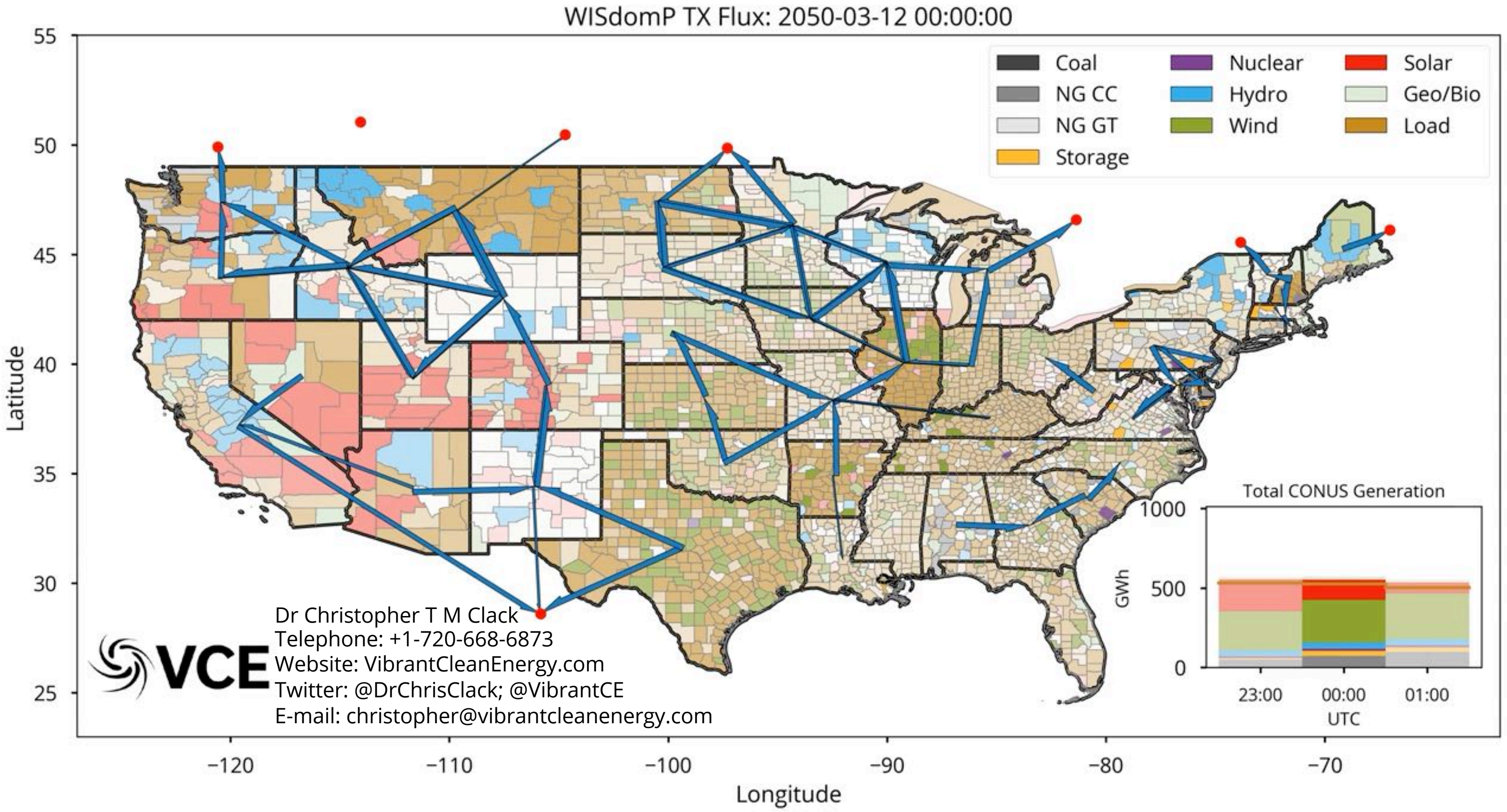
There are Only Two Key Portfolio Components

Low-marginal Cost Electricity Production Resources (kWh)

- *Wind*
- *Solar*
- *Geothermal*
- *Nuclear*
- *Hydroelectric*

Flexibility Resources (kWh → kW → kWh)

- *Transmission*
- *Hybrid Resources (wind+solar+storage)*
- *Storage (electricity+heat)*
- *Electrification*
- *Direct Air Capture*
- *Demand-side management*
- *Dispatchable Generation (SMR, EGS, H_2 CC, NGCC+CCS)*
- *Synthetic Fuel/Chemical Production (H_2, CH_4, NH_3)*
- *Peaking Generation (H_2 CT)*



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Thank You!

Topic 1: Resource Portfolios

Mr. Ric O'Connell

GridLab

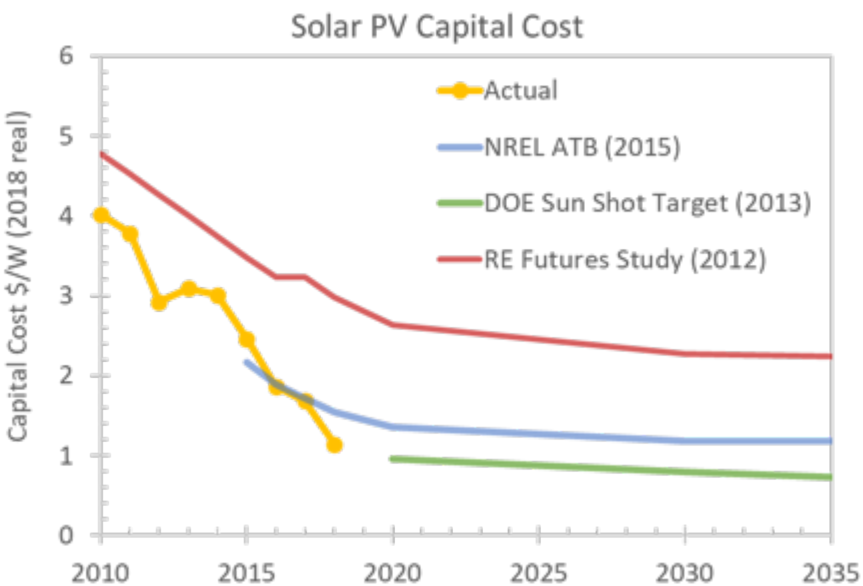

2035 Report
Plummeting Solar, Wind, and
Battery Costs Can Accelerate
Our Clean Energy Future
GridLAB
GOLDMAN SCHOOL
OF
PUBLIC POLICY
UNIVERSITY OF CALIFORNIA BERKELEY

Why 90% clean by 2035?

- We know getting to 100% Carbon Free is difficult.
- How far can we get in the near term to decarbonize the power sector using the technologies available?
- Recent cost declines have happened much faster than anyone anticipated, how does that drive future power systems?
- What are the cost impacts of a 90% Clean system?
- Project team from UC Berkeley
  - ReEDS for Capacity Expansion
  - PLEXOS for system operability in 2035, 7 weather years
  - NREL Annual Technology Baseline 2019 for costs

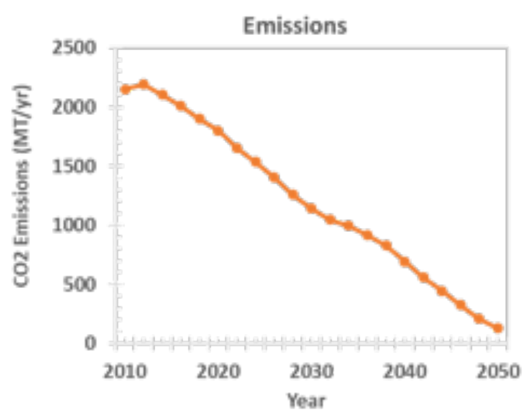
Dramatic cost declines have arrived sooner than anticipated

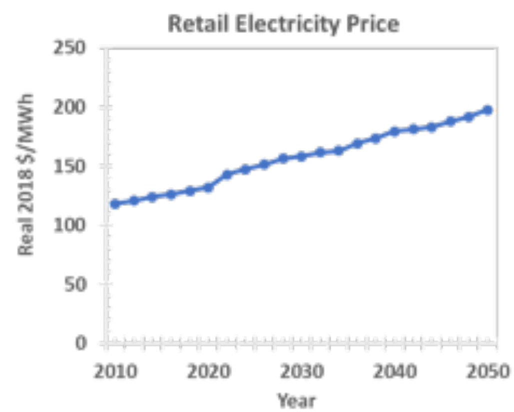
2017-18 actual costs are lower than 2030-35 projected costs



Most previous studies show that power sector decarbonization is possible by 2050, but prices will go up substantially

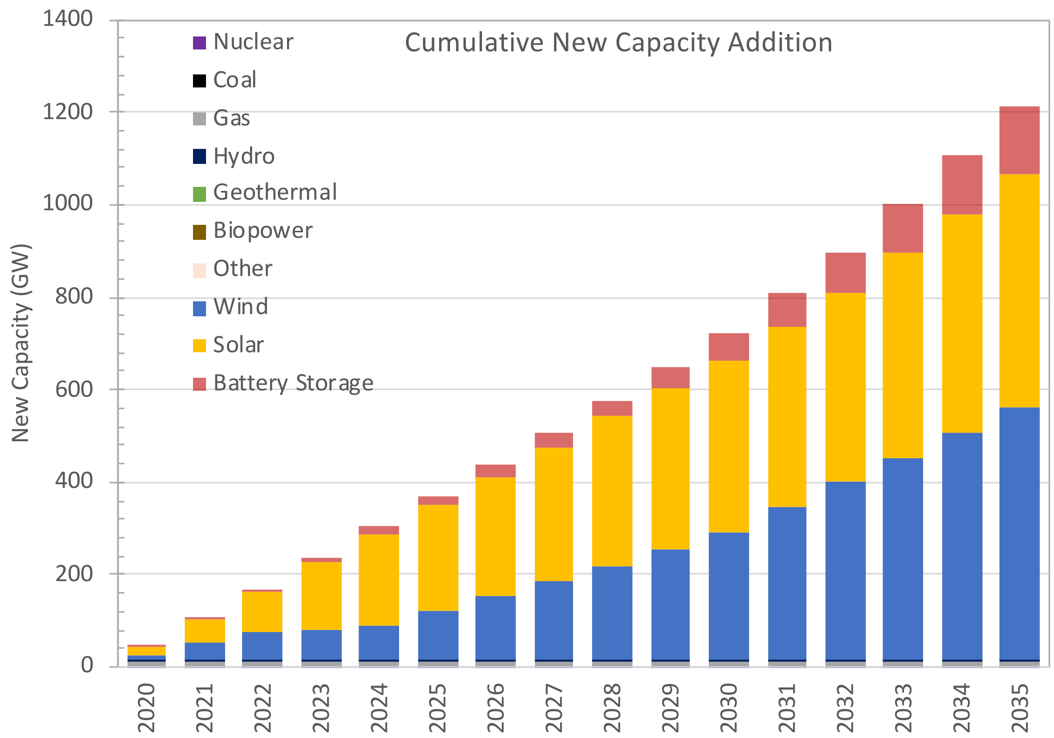
e.g. NREL RE Futures Study (2012-14) found that for RE penetration of 90% by 2050, retail prices may increase by ~42-67% relative to 2010





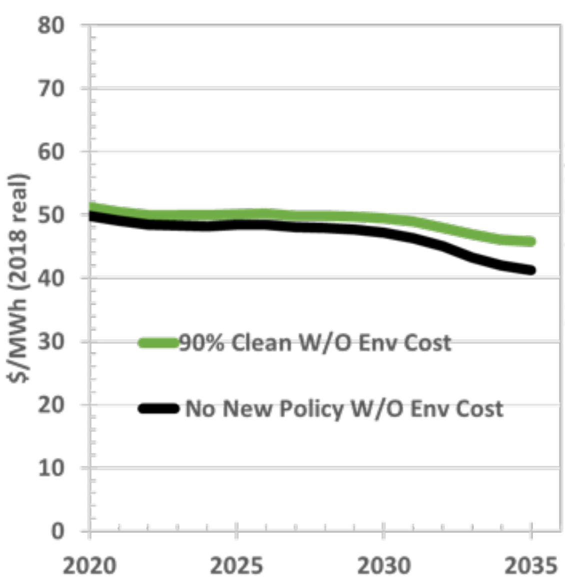
Charts show results for 90% RE ITI case
Total clean ~94%

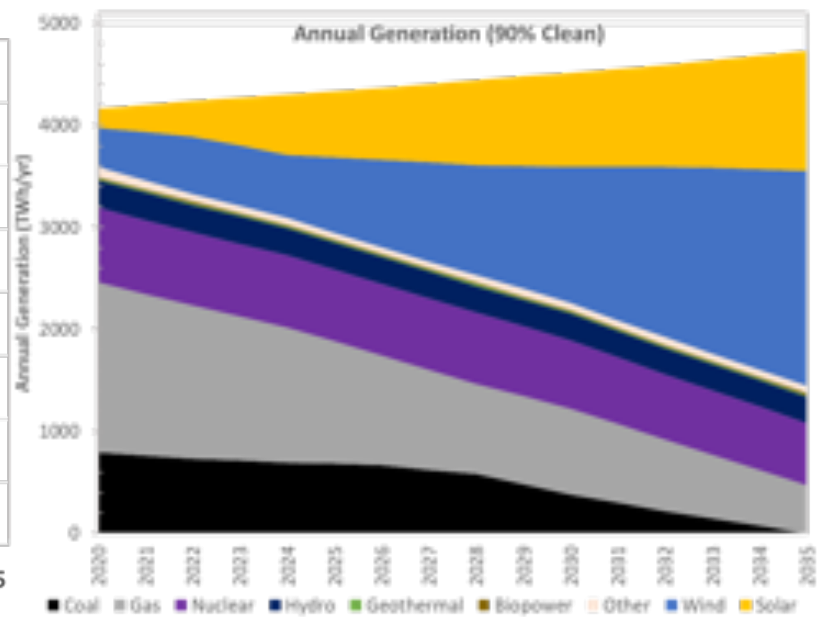
A 90% Clean by 2035 System.



- System on an Energy Basis in 2035:
  - 70% VRE (Wind/Solar)
  - 20% Firm Low Carbon (Nuclear, hydro)
  - 10% Gas
- Capacity Basis:
  - VRE: 1,200 GW
  - Firm Low Carbon: 200 GW
  - 400 GW Gas
  - Storage: 150 GW (10% Peak)
  - No Coal

Electricity Costs from the 90% Clean Grid Are Lower than Today's Costs



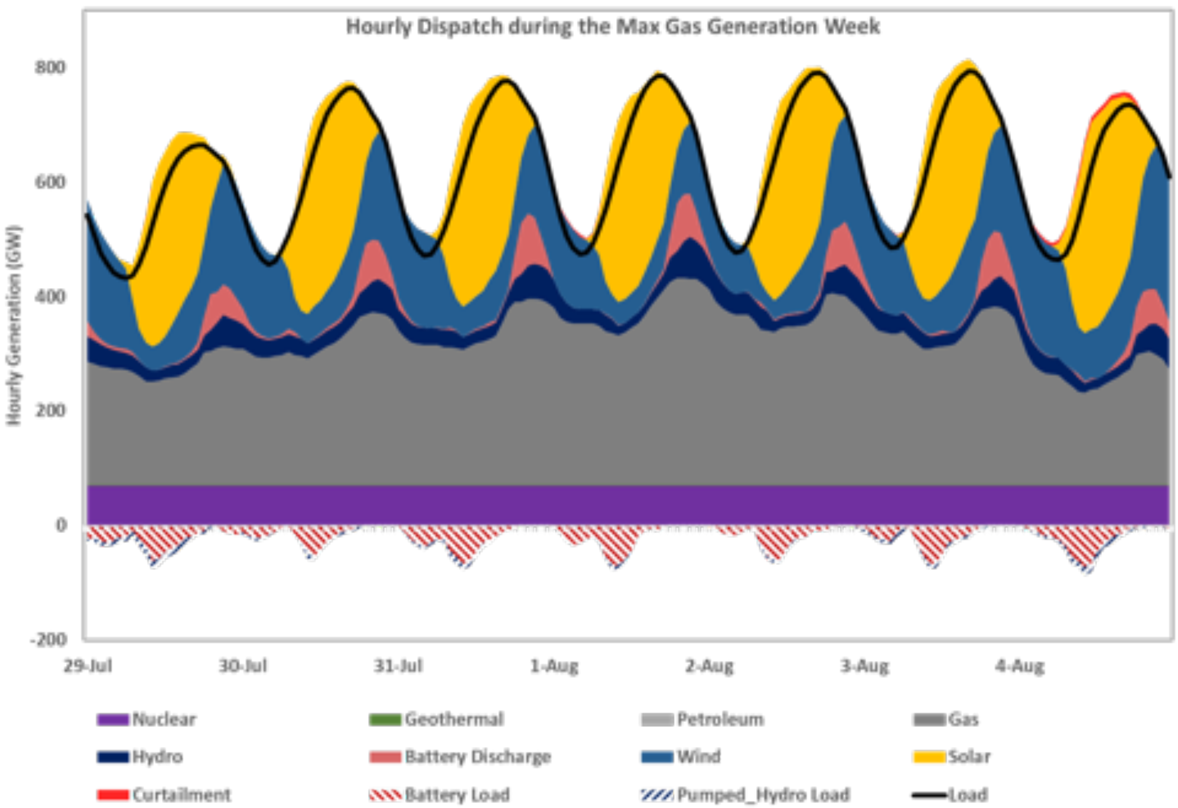


How do we get low costs?

1. Ubiquitous Low Cost RE
2. Existing gas along with low cost battery storage provide capacity
3. Existing low carbon (Nuclear, hydro, bio/geo) provide energy/capacity.
4. 2035 target year gives enough time for most undepreciated fossil assets to fully recover their fixed costs

Supporting Slides

90% Clean Grid Is Dependable without Coal or New Gas



Time in EST

The chart shows dispatch during the highest gas generation period (Jul 29 – Aug 4, 2035) in the 90% clean case

~360 GW of already built natural gas assets are dispatched to meet demand on August 1, while RE generation drops significantly.

Even when wind and solar generation drops to low levels, existing hydropower, nuclear power, and natural gas capacity, as well as new battery storage, are found to be sufficient to maintain system operations.

Future Power Markets Forum

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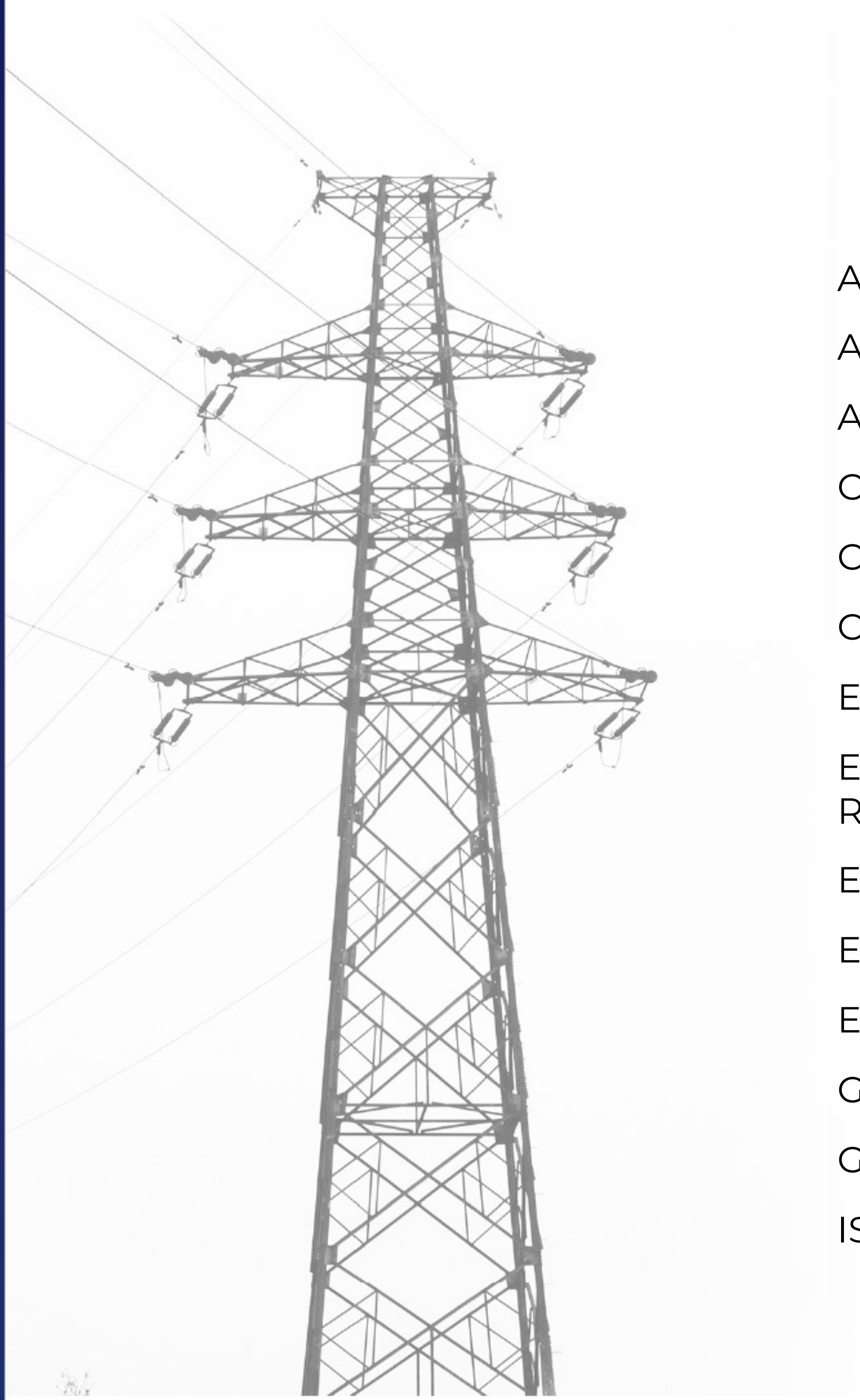

Thank You

Advanced Energy Economy

American Public Power Association

American Wind Energy Association

Calpine

ClearPath

Clearway Energy

Electric Power Supply Association

Electricity Consumers Resource Council

Enel Foundation

Energy Foundation

Exelon

Google

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ISO New England

Microsoft

Midcontinent Independent System Operator

National Hydropower Association

New York Independent System Operator

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National Hydropower Association

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Renewable Energy Buyers Alliance

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Tenaska

Vistra

Connect

Website powermarkets.org

Contact team@powermarkets.org