GETTING TO ZERO: DECARBONIZING ELECTRIC POWER

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- Previously:

  Ph.D. Engineering Systems, MIT (2018)

  S.M. Technology & Policy, MIT (2014)

  Director of Energy & Climate Policy, Breakthrough Institute (2008-2012)

  Research & Policy Associate, Renewable Northwest (2006-2008)

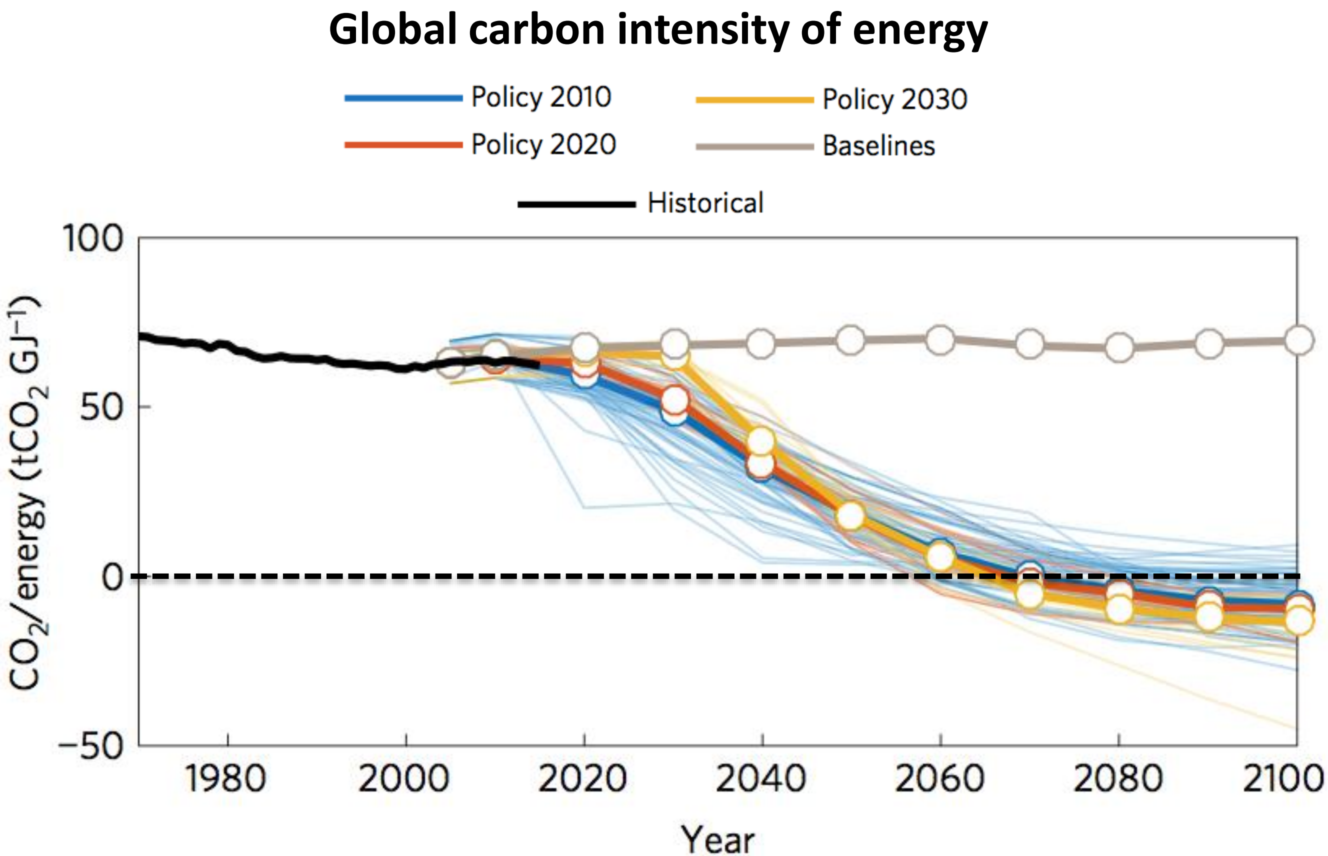
  B.S. Computer & Information Science, University of Oregon (2006)

Research objective:
to improve regulation, policy, and practice in the rapidly evolving electricity sector.

Resources

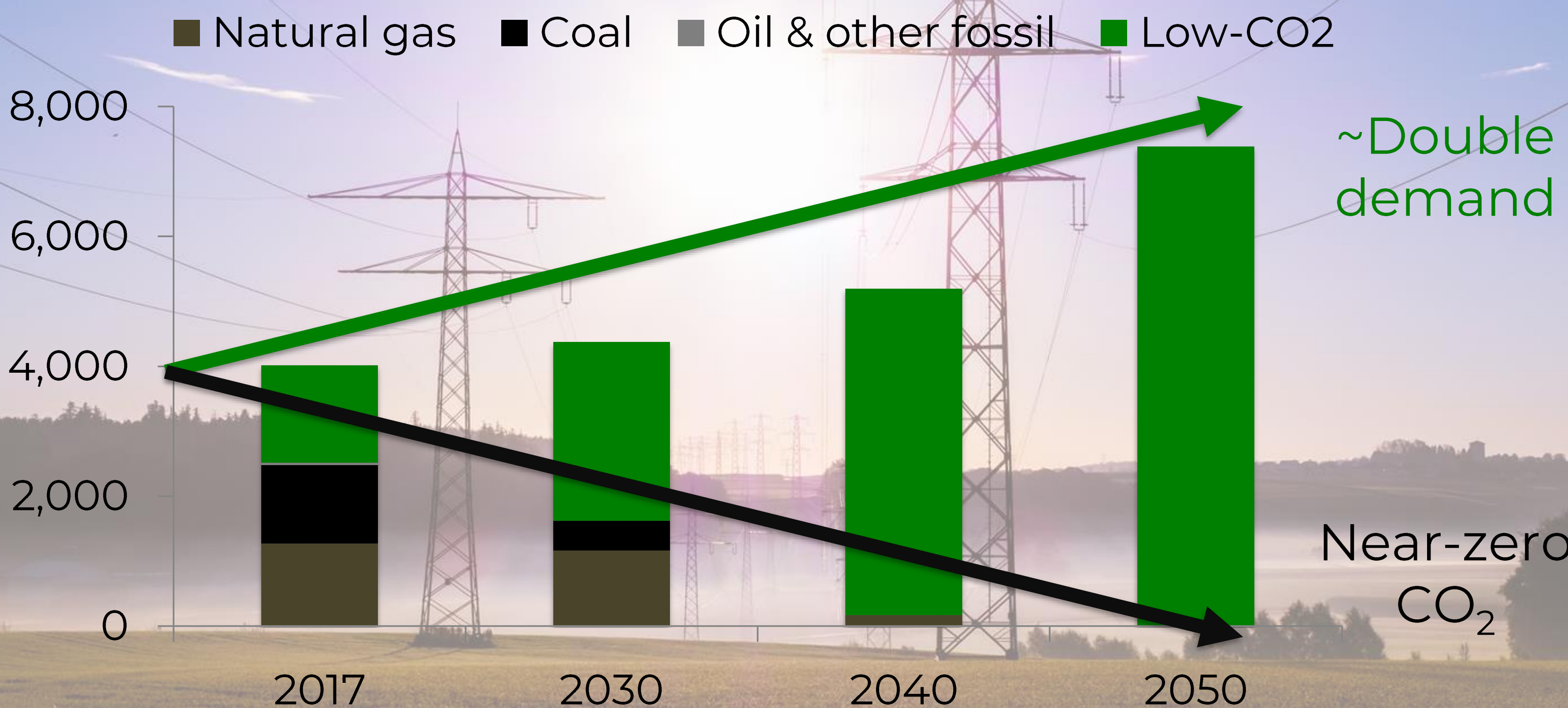
- Jenkins et al. (under review), “Getting to zero: insights from recent literature on the electricity decarbonization challenge,” *Joule* (under review). Download: http://bit.ly/DecarbReviewManuscript
- Sepulveda, Jenkins et al. (2018), “The role of firm low-carbon resources in deep decarbonization of power generation,” *Joule* (in press, online Sept 6). Download: http://bit.ly/FirmLowCarbon
- de Sisternes, Jenkins & Botterud (2016), “The value of energy storage in decarbonizing the electricity sector,” *Applied Energy* 175. Download: http://bit.ly/ValueOfStorage
- Loftus et al. (2014), “A critical review of global decarbonization scenarios: what do they tell us about feasibility?” *WIREs: Climate Change* 6(1). Download: http://bit.ly/GlobalDecarbReview
- The Energy Initiative @ MIT podcast, “Firm low-carbon energy resources: Pathways for reducing CO2 emissions in electricity,” August 30, 2018. Listen: http://bit.ly/MITEnergyPodcast

Getting to Zero



Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," *Nature Climate Change* 7: 118-122

Electricity: the Linchpin



Data source: PNNL "Reference +80%" scenario in GGCAM USA Analysis of U.S. Electric Power Sector Transitions May 2017 performed for the United States Mid-Century Strategy for Deep Decarbonization

THE DENVER POST

Xcel Energy receives shockingly low bids for Colorado electricity from renewable sources

January 17, 2018

Forbes

Renewable energy will be consistently cheaper than fossil fuels by 2020, report claims

January 13, 2018

SCIENTIFIC AMERICAN

The Price of Solar Is Declining to Unprecedented Lows

Despite already low costs, the installed price of solar fell by 5 to 12 percent in 2015

By Robert Fares on August 27, 2016

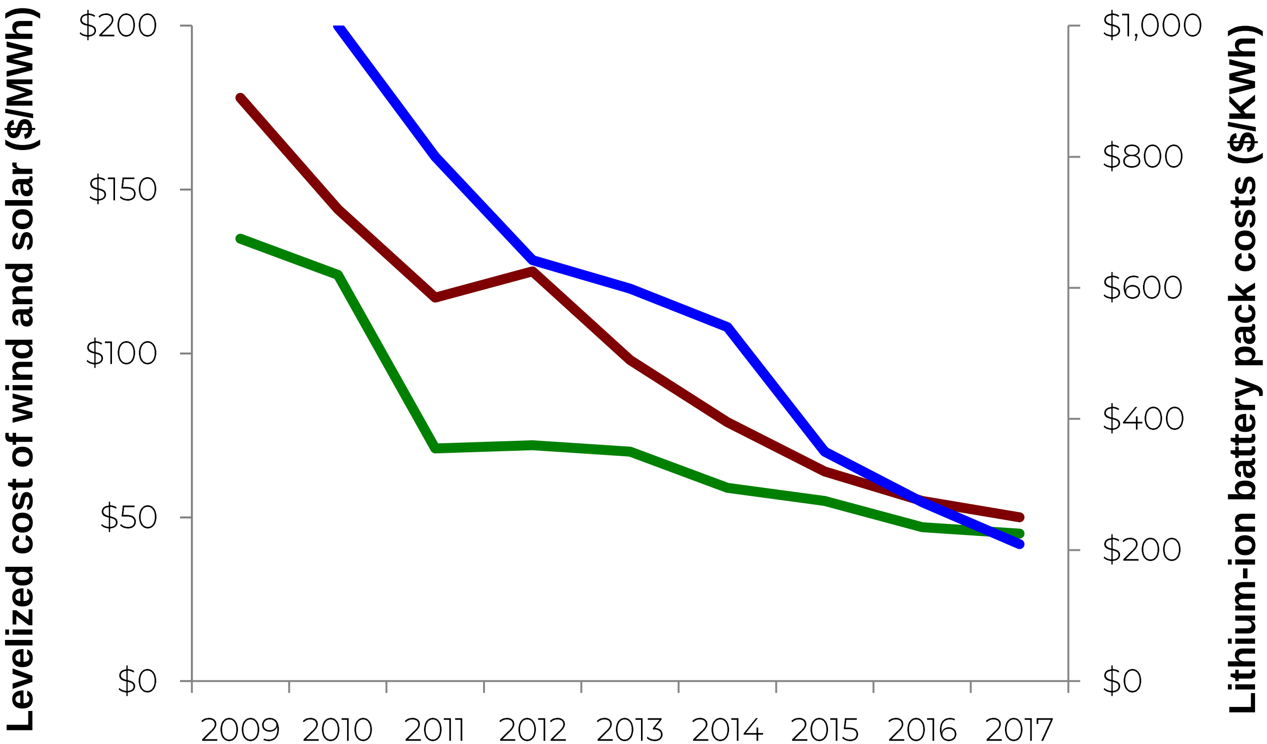
August 27, 2016

MIT Technology Review

Grid Batteries Are Poised to Become Cheaper Than Natural-Gas Plants in Minnesota

July 12, 2017

Wind, Solar & Battery Costs Plummet



Total cost declines

Solar $/MWh -72%

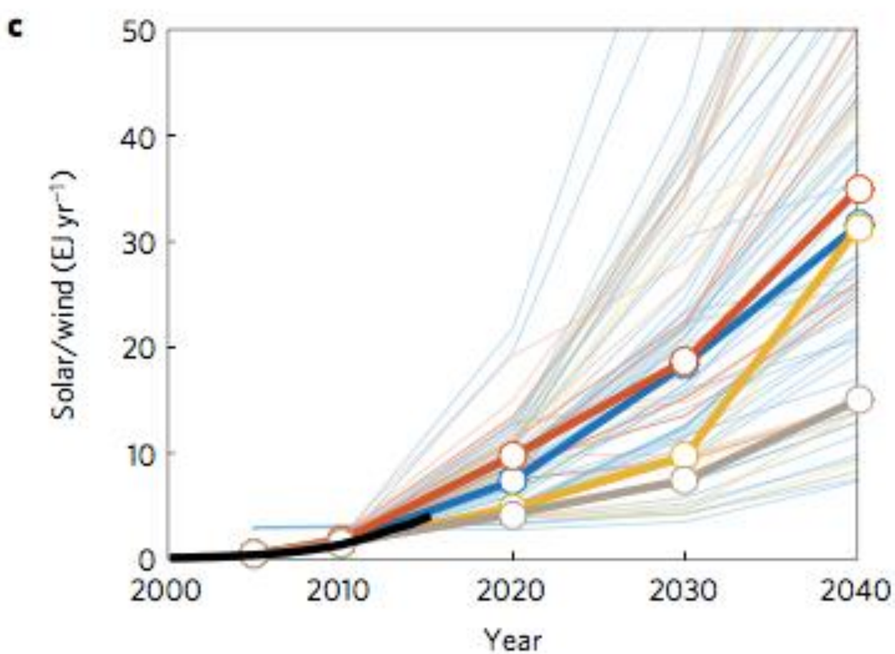
Wind $/MWh -67%

Li-ion packs $/KWh -79%

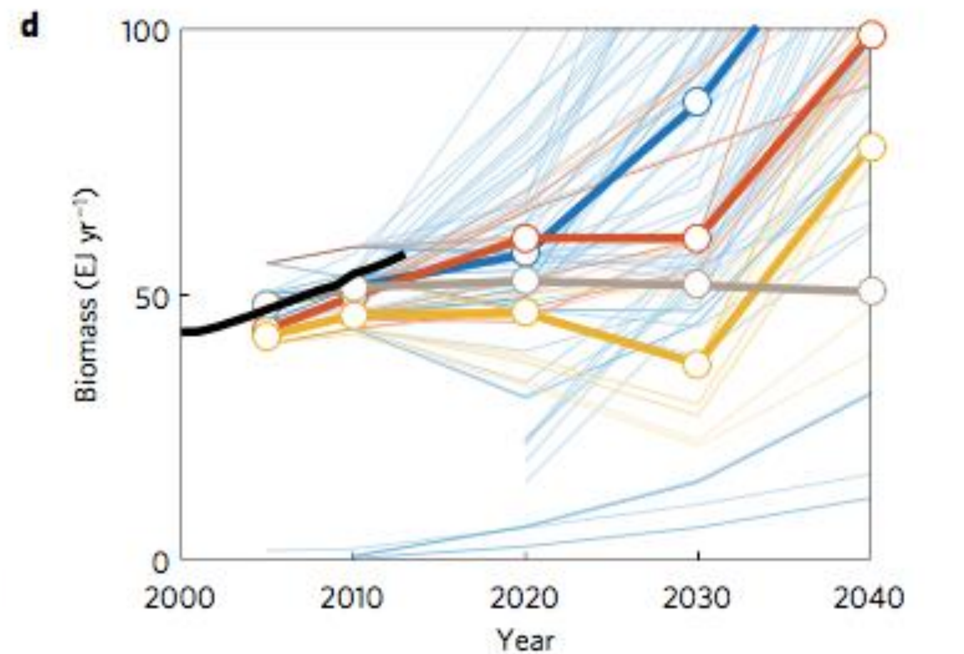
Data Source: Wind and solar levelized costs from Lazard. Battery pack costs from Bloomberg New Energy Finance

Renewables are Keeping Pace…

Wind & solar energy



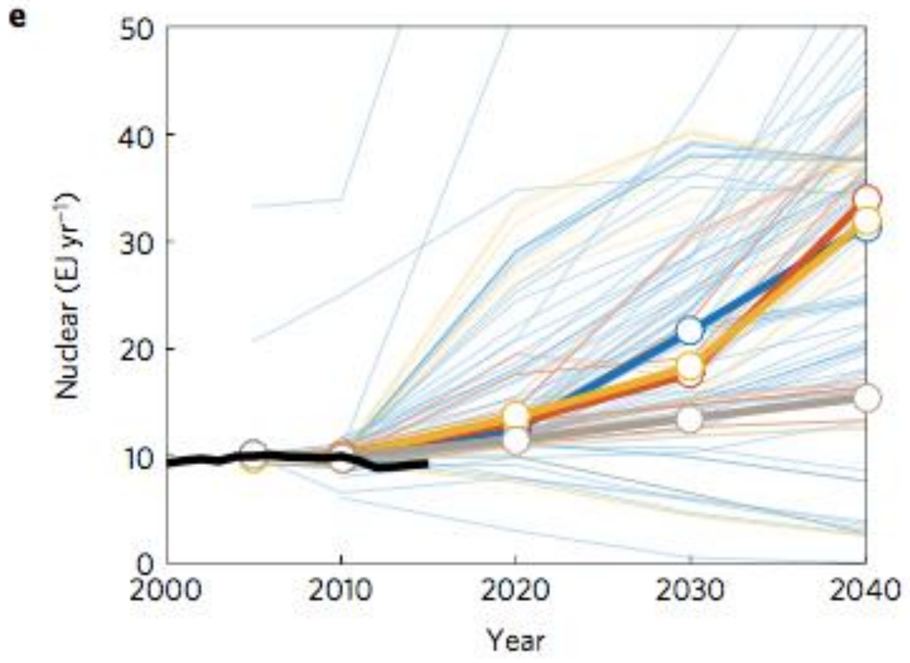
Biomass



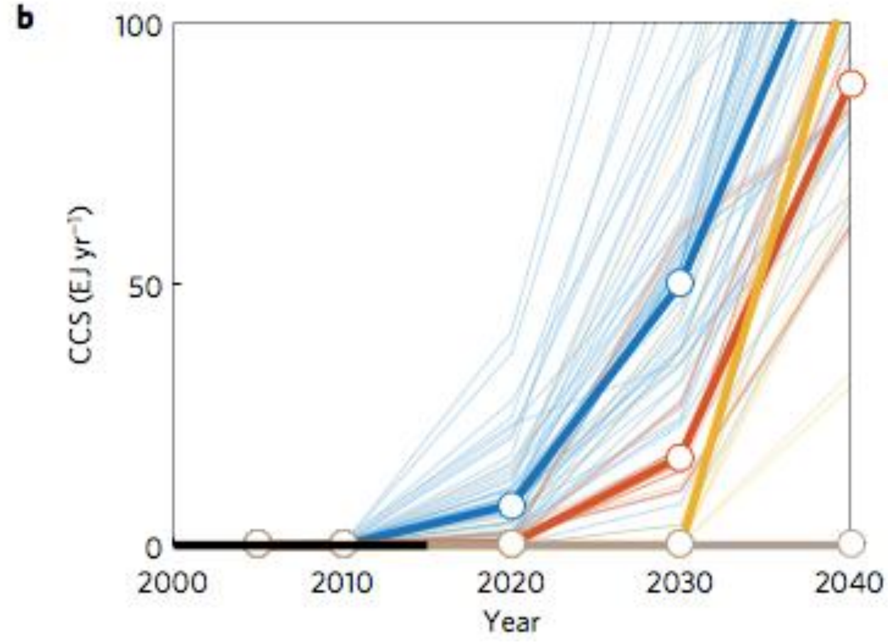
Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," *Nature Climate Change* 7: 118-122

…but Nuclear and CCS are Falling Behind

Nuclear energy



Carbon capture & storage



Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," *Nature Climate Change* 7: 118-122

The Post and Courier
Winner of the Pulitzer Prize

Santee Cooper, SCE&G pull plug on roughly $25 billion nuclear plants in South Carolina

July 31, 2017

The New York Times

Westinghouse Files for Bankruptcy, in Blow to Nuclear Power

March 29, 2017

greentechmedia:

Carbon Capture Suffers a Huge Setback as Kemper Plant Suspends Work

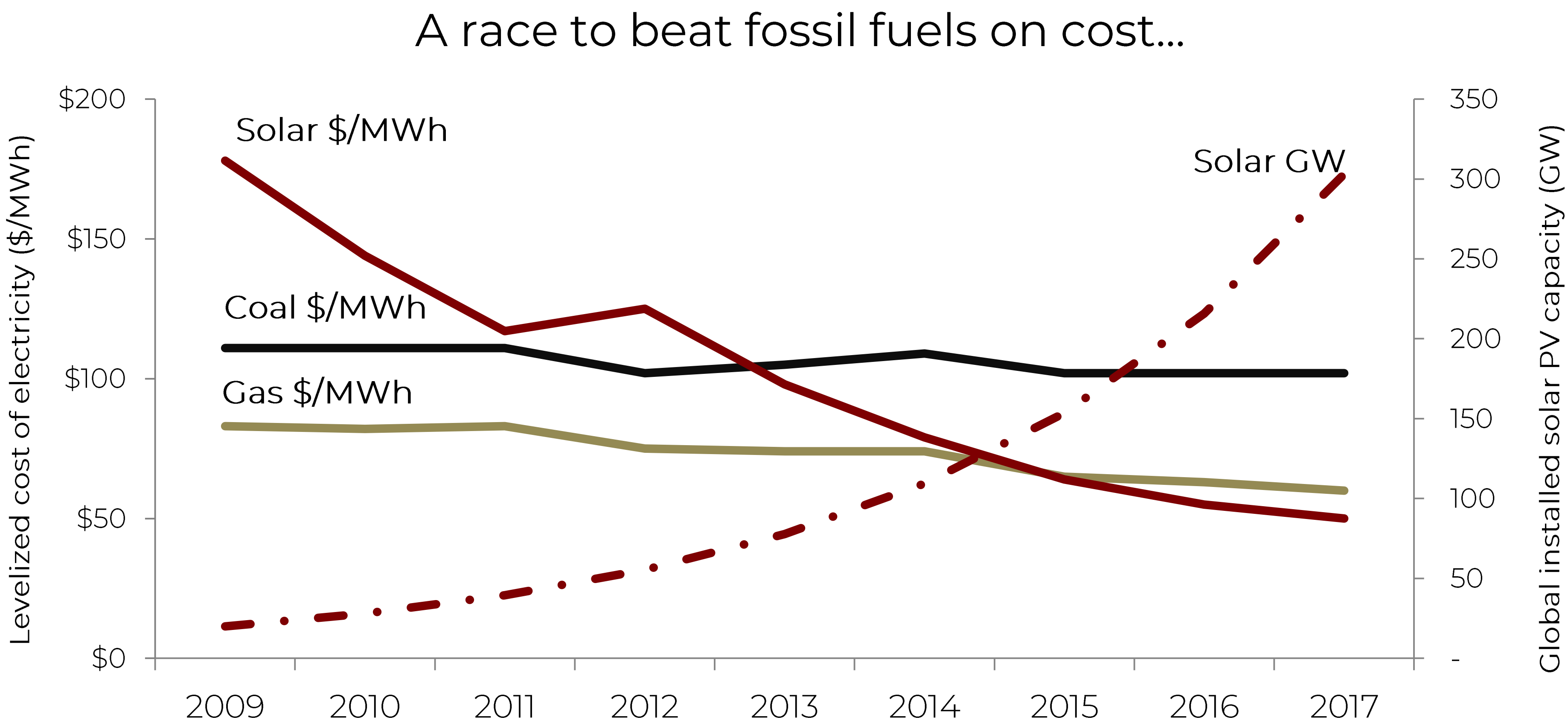
June 29, 2017

GO 100% RENEWABLE ENERGY

Do We Go All In?

Image Source: go100percent.org

The Mental Model

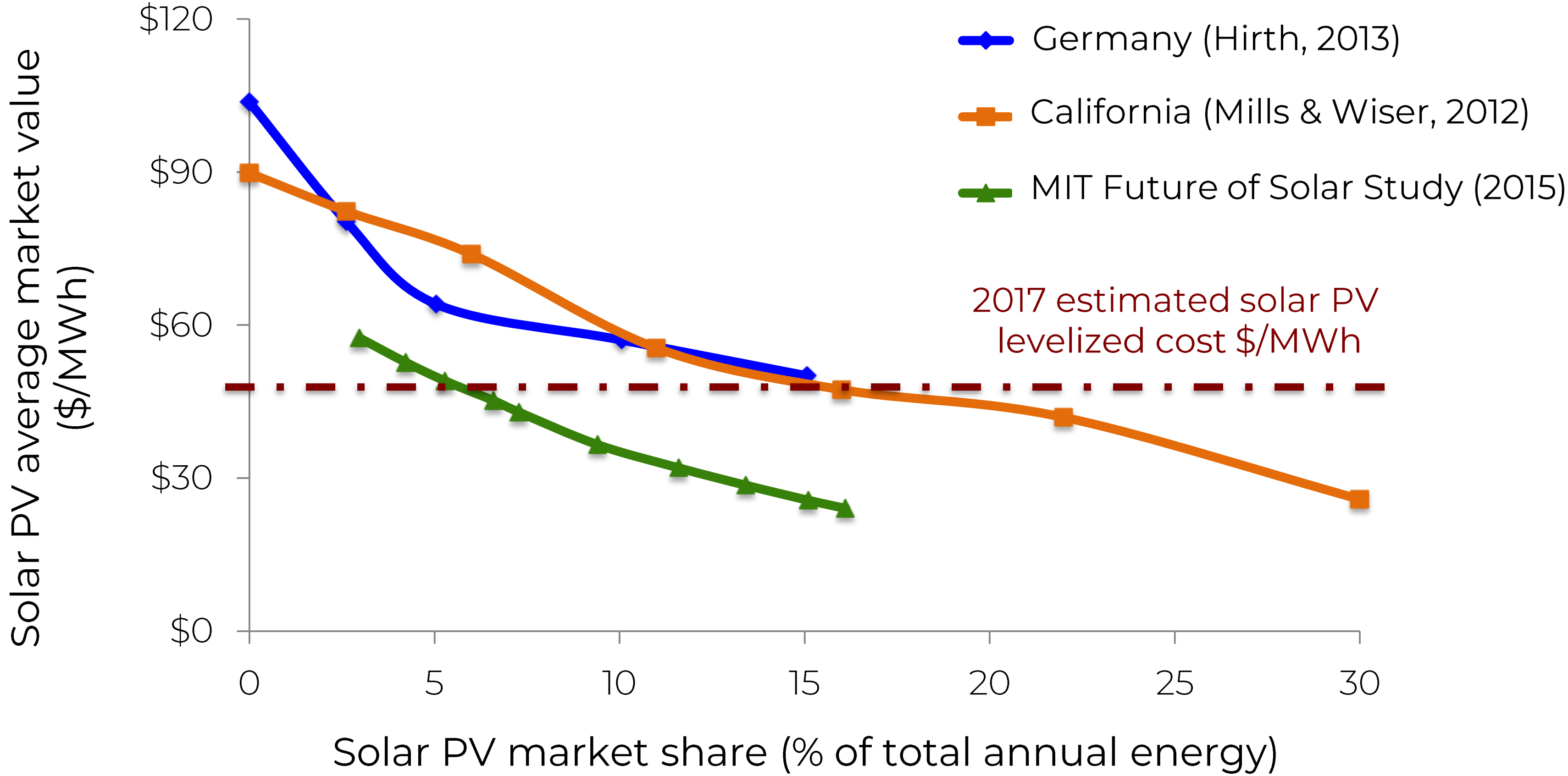


Data Source: Lazard (2017), Levelized Cost of Energy 2017, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/.

A Flawed Model

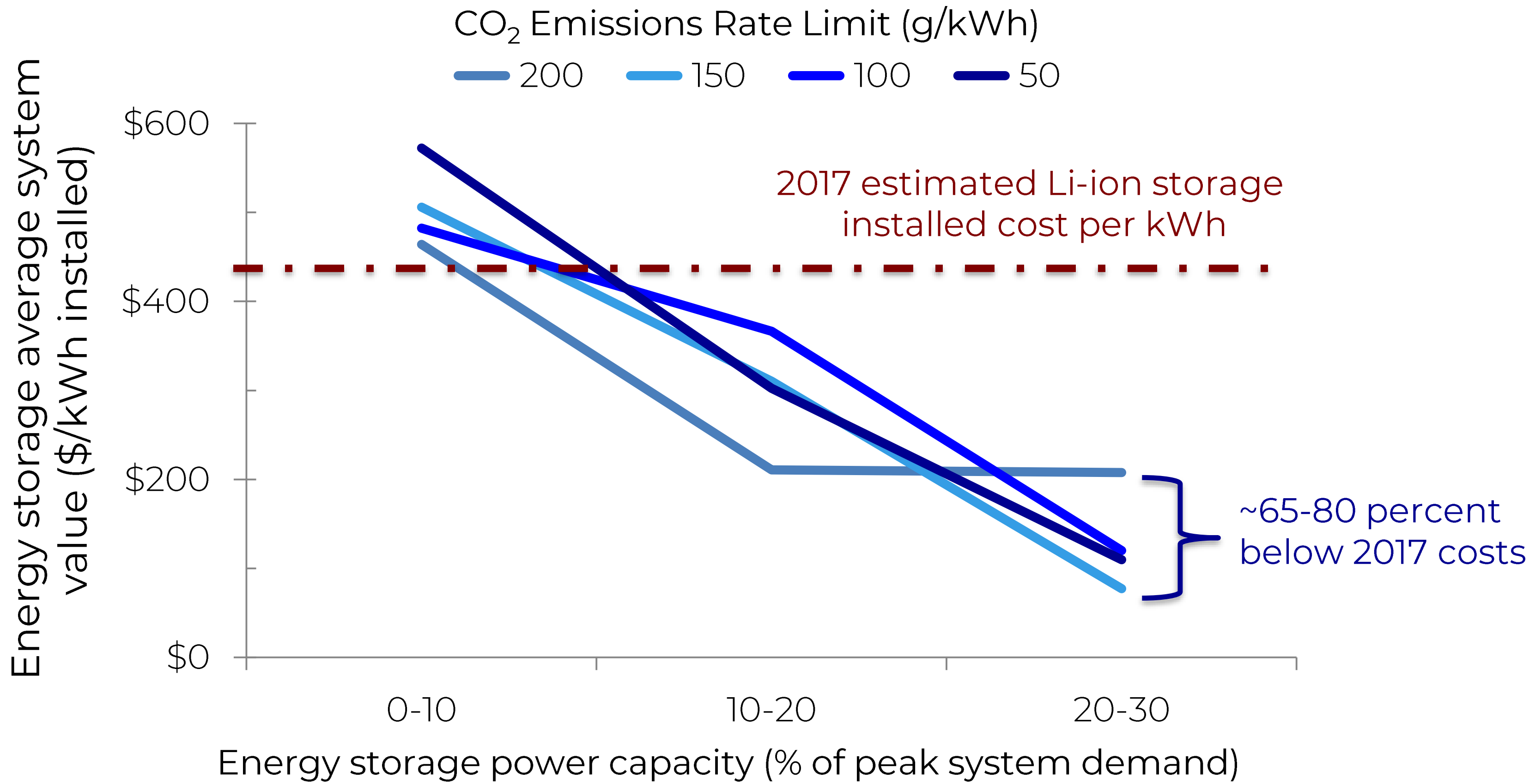
?

A Race Against Declining Value



Data Source: Sivaram & Kann (2016), Solar needs a more ambitious cost target, *Nature Energy* Vol. 1 (April 2016).

A Race Against Declining Value



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.

Declining Value: Three Key Mechanisms

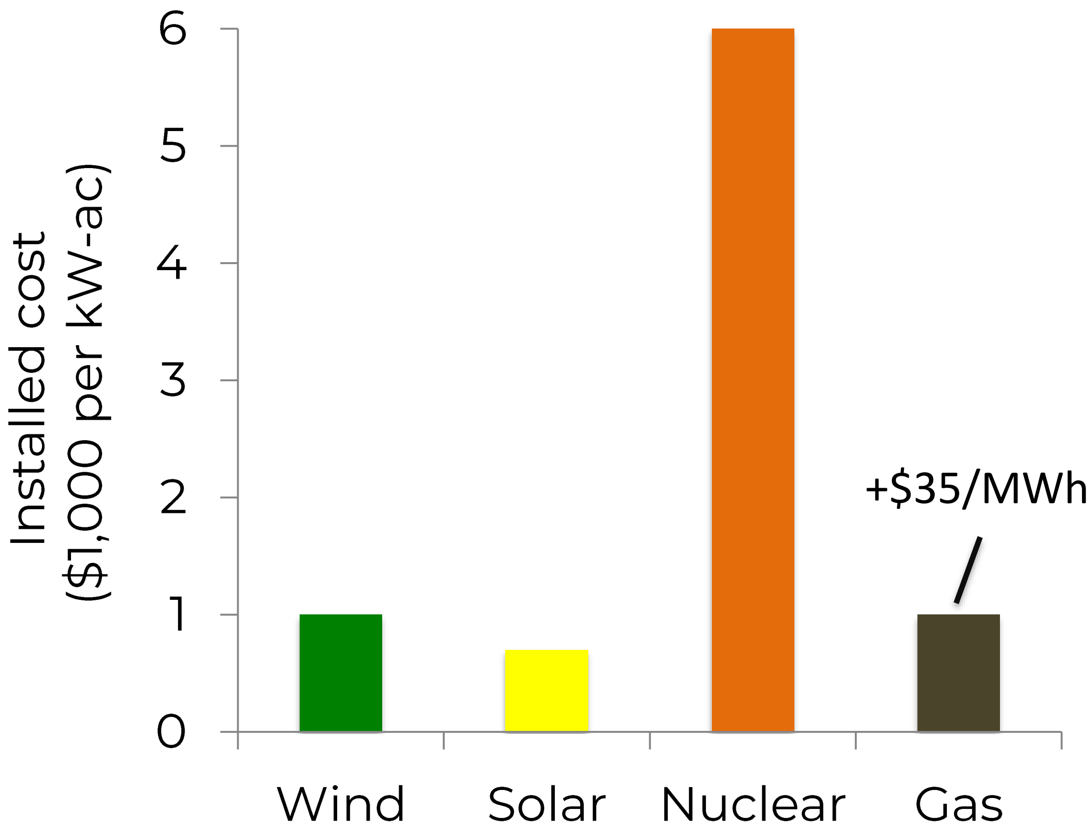
1. Declining "fuel-saving" value (energy substitution)

2. Decreasing "capacity value" (capacity substitution)

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

Additional factors: Increasing flexibility, ramping and reserve requirements, thermal plant cycling costs, transmission network costs

An Illustrative Example



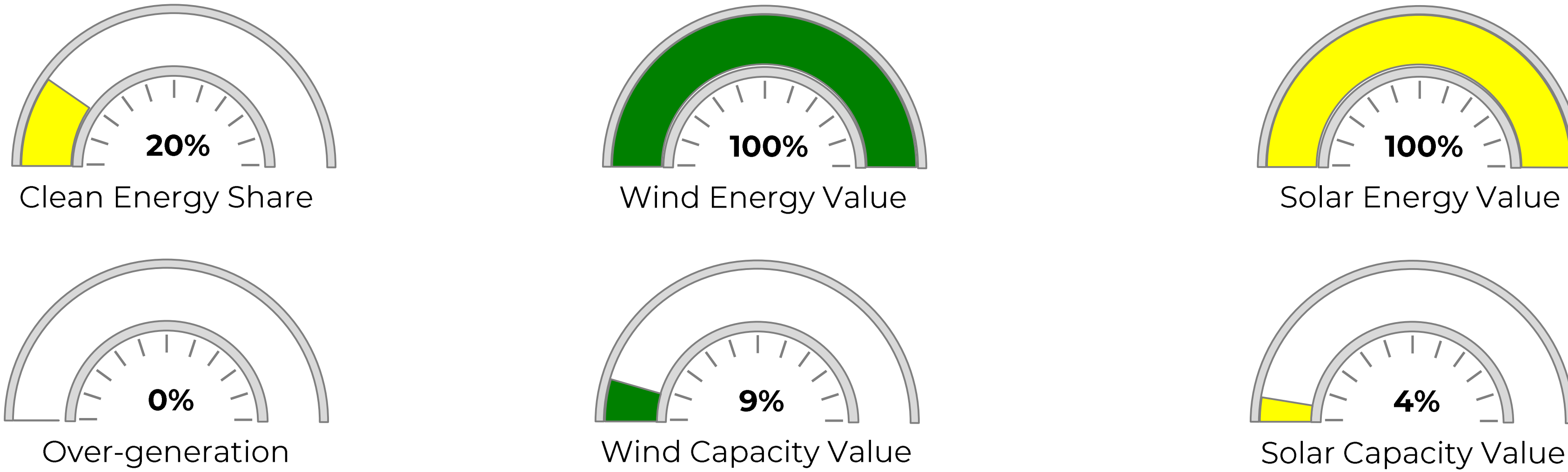
Peak demand: 34 GW

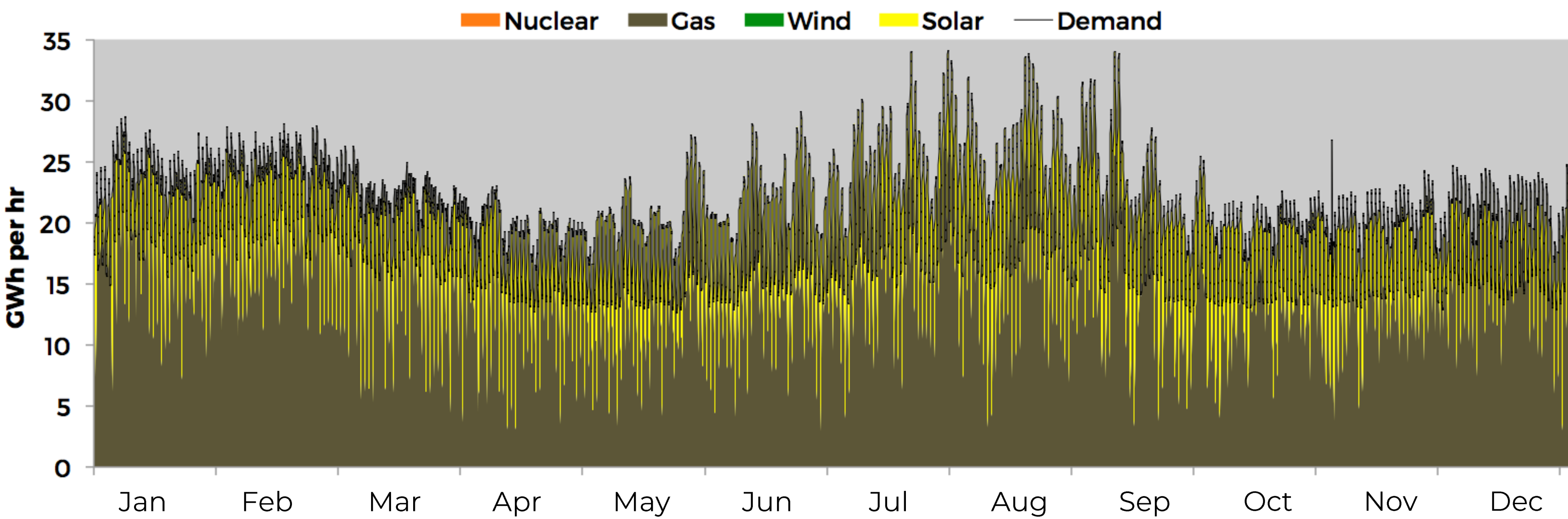
Capacity factors

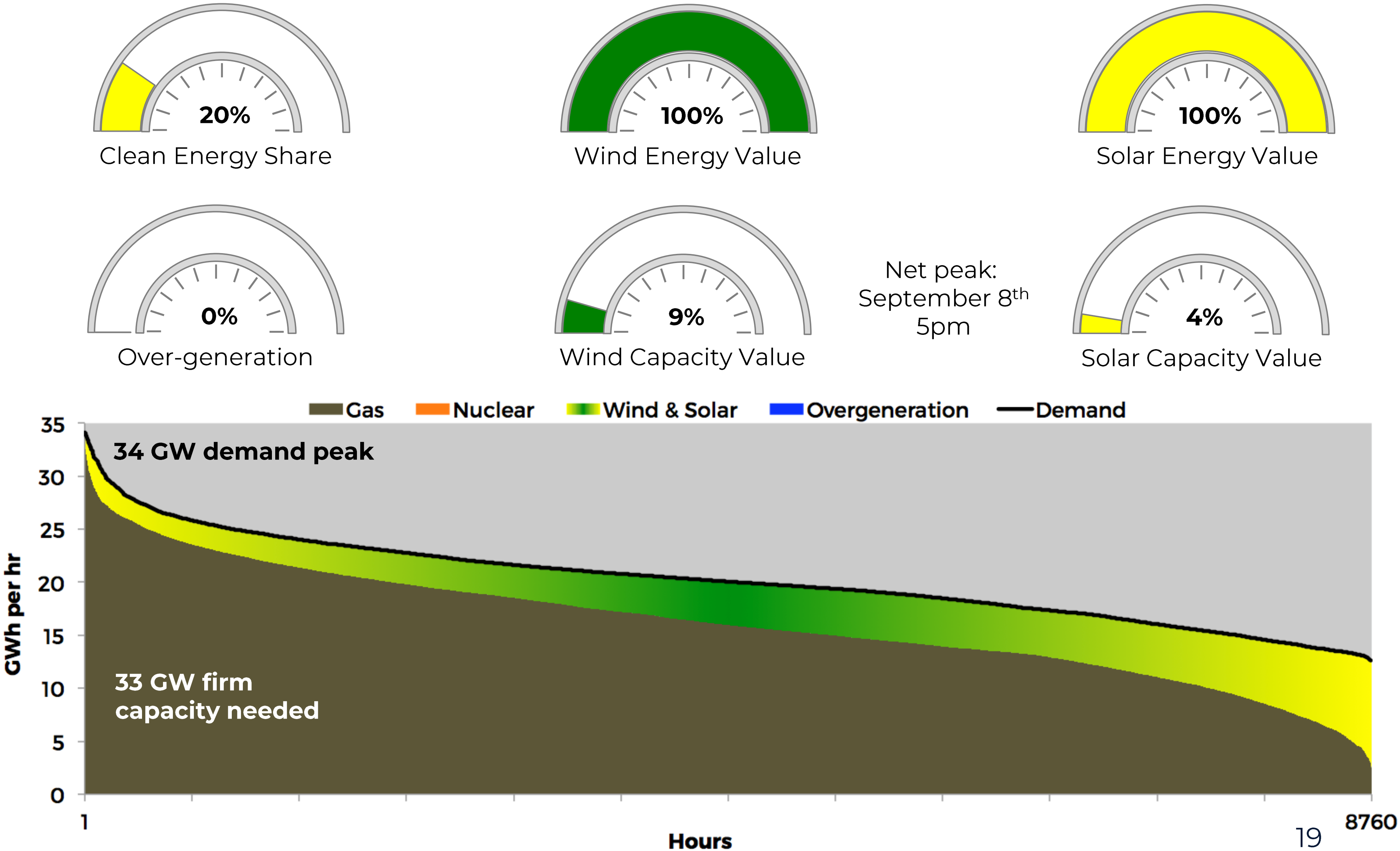
Wind: 28%

Solar: 24% (ac)

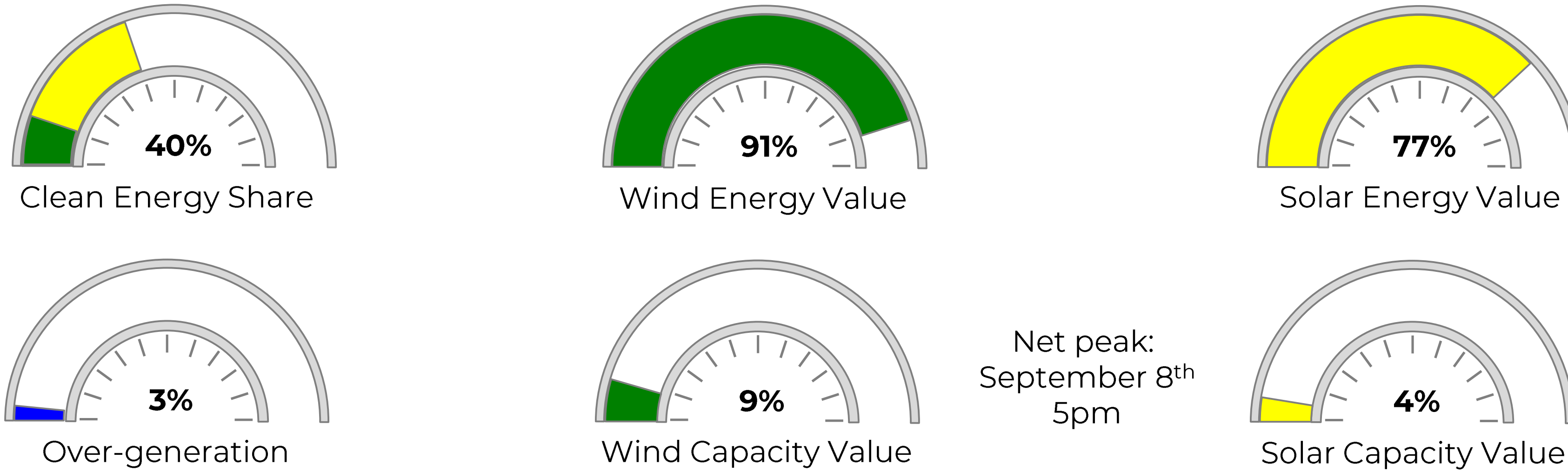
No storage in this example

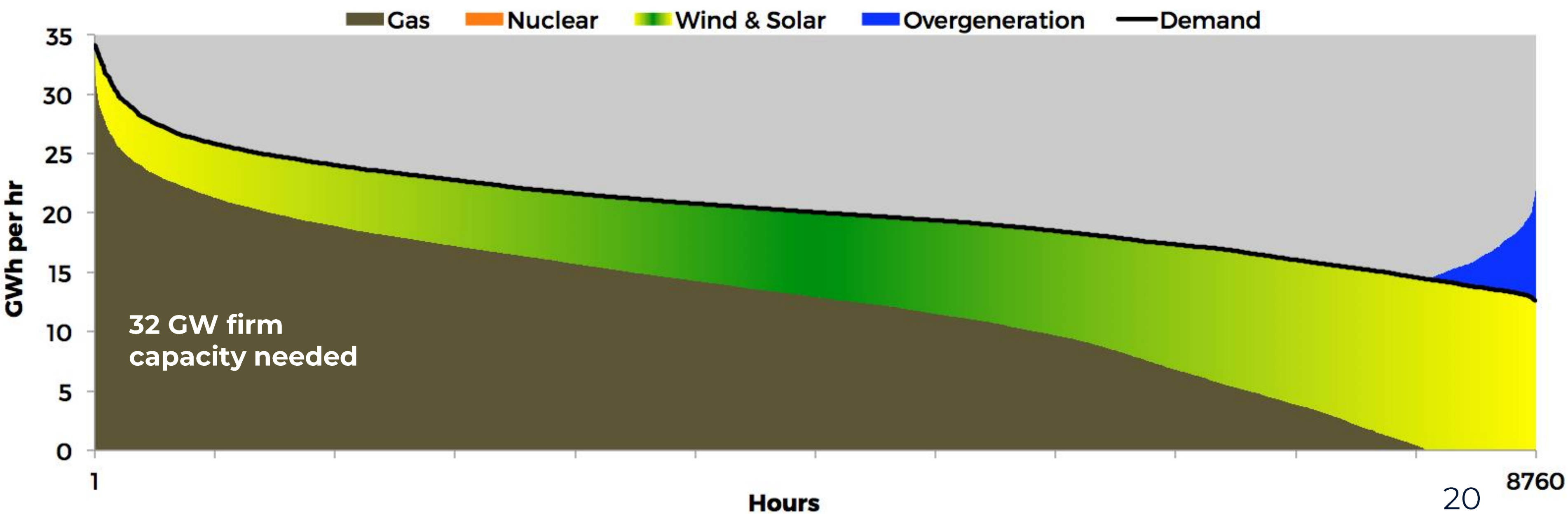

20%
Clean Energy Share
100%
Wind Energy Value
100%
Solar Energy Value
0%
Over-generation
9%
Wind Capacity Value
4%
Solar Capacity Value

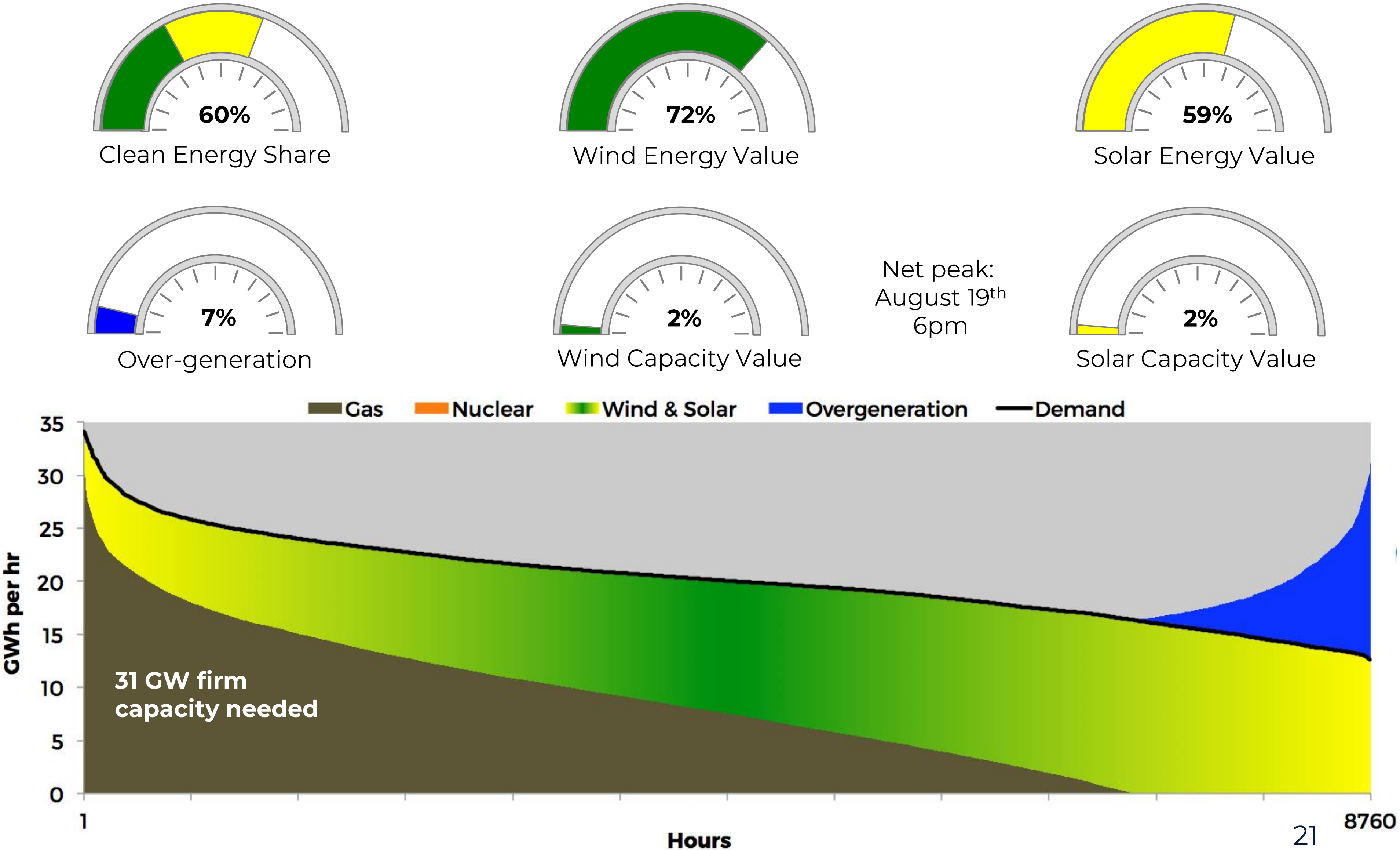

Nuclear
Gas
Wind
Solar
Demand
GWh per hr
0
5
10
15
20
25
30
35
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

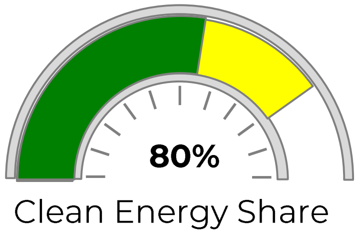


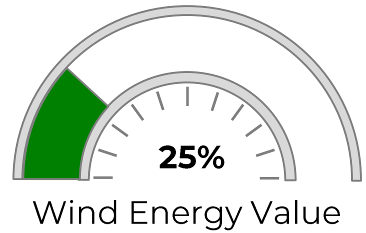
20%
Clean Energy Share
100%
Wind Energy Value
100%
Solar Energy Value
0%
Over-generation
9%
Wind Capacity Value
Net peak:
September 8th
5pm
4%
Solar Capacity Value
Gas
Nuclear
Wind & Solar
Overgeneration
Demand
34 GW demand peak
33 GW firm
capacity needed
GWh per hr
35
30
25
20
15
10
5
0
1
8760
Hours

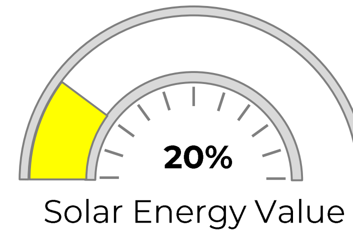

40%
Clean Energy Share
91%
Wind Energy Value
77%
Solar Energy Value
3%
Over-generation
9%
Wind Capacity Value
Net peak:
September 8th
5pm
4%
Solar Capacity Value

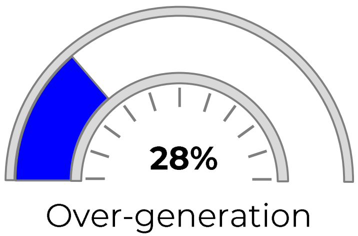

Gas
Nuclear
Wind & Solar
Overgeneration
Demand
GWh per hr
35
30
25
20
15
10
5
0
1
8760
Hours
32 GW firm
capacity needed

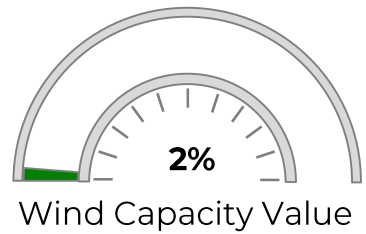

60%
Clean Energy Share
72%
Wind Energy Value
59%
Solar Energy Value
7%
Over-generation
2%
Wind Capacity Value
Net peak:
August 19th
6pm
2%
Solar Capacity Value
Gas
Nuclear
Wind & Solar
Overgeneration
Demand
35
30
25
20
15
10
5
0
GWh per hr
31 GW firm
capacity needed
1
8760
Hours



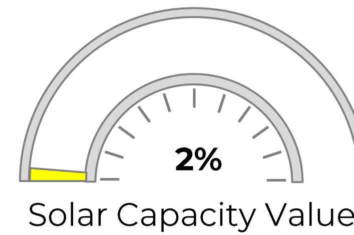


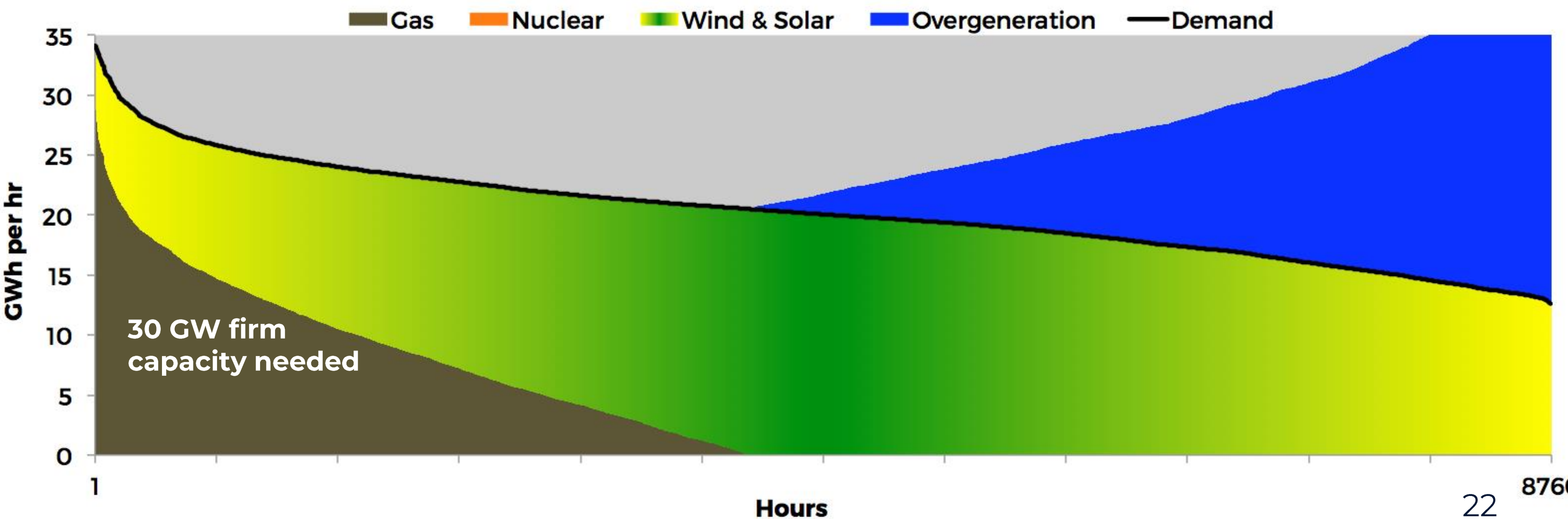


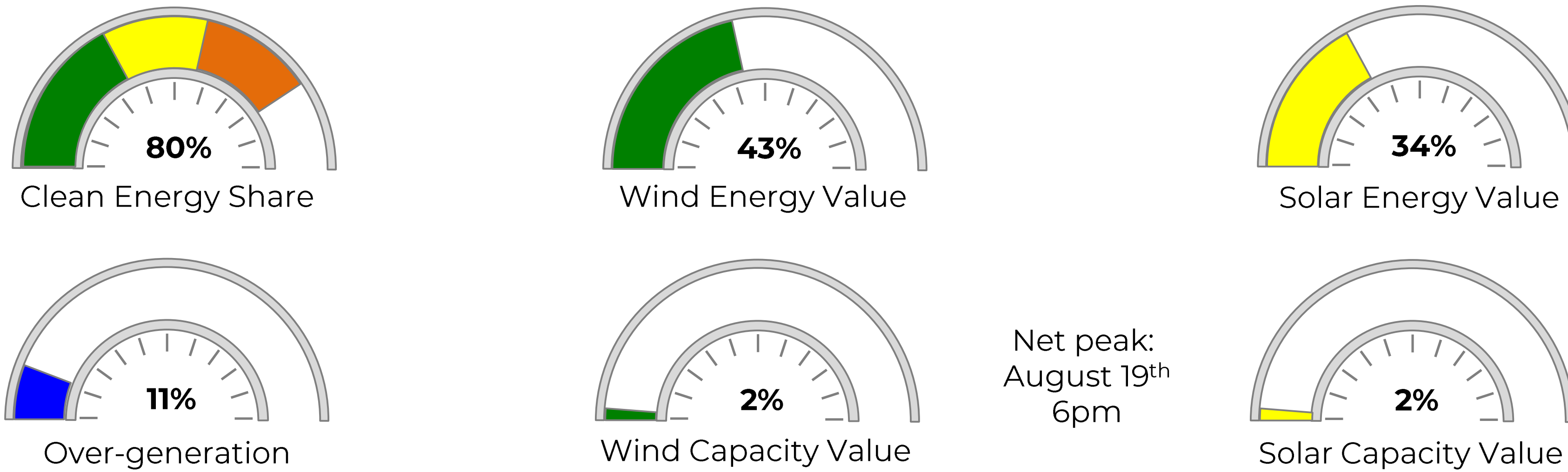




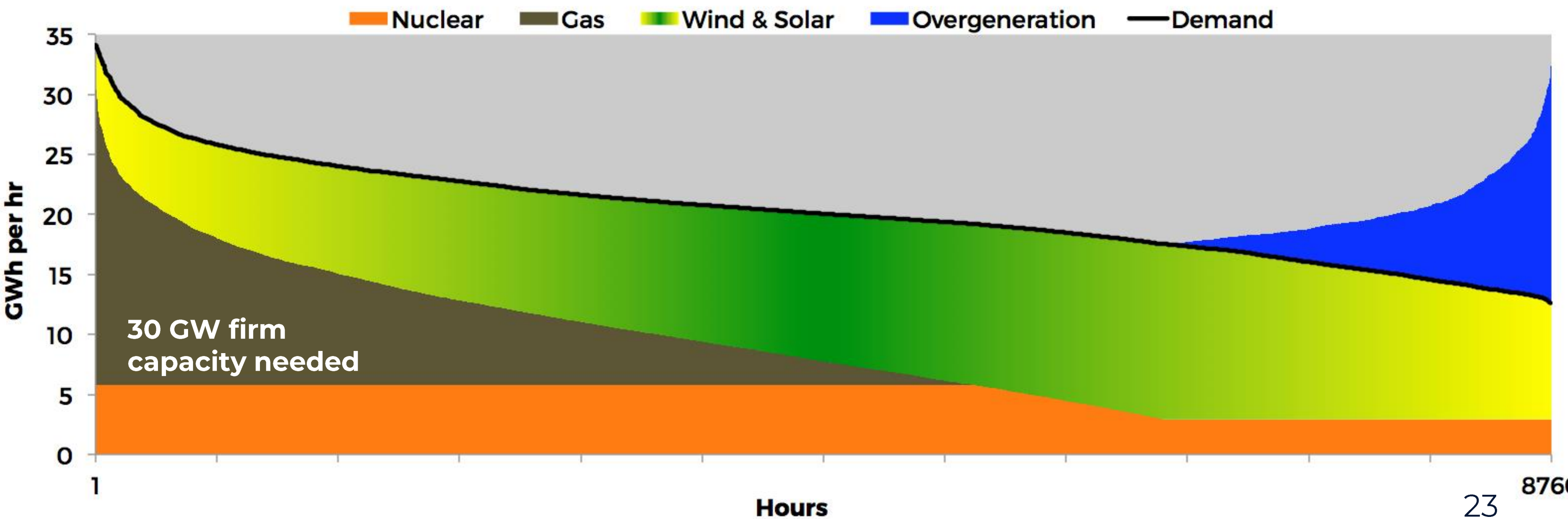
Net peak:
August 19th
6pm

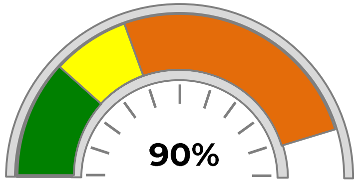




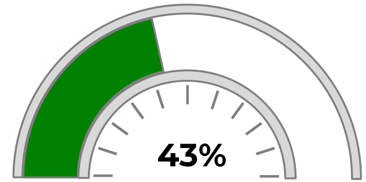


Net peak:
August 19th
6pm

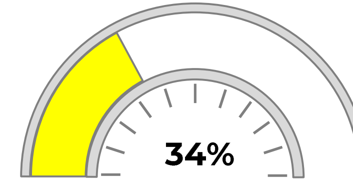




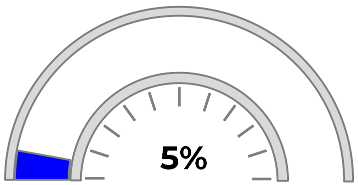
Clean Energy Share



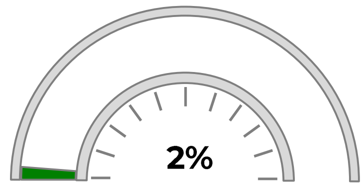
Wind Energy Value



Solar Energy Value

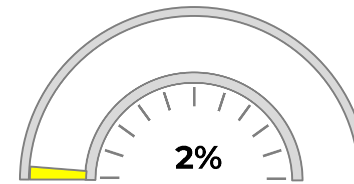


Over-generation

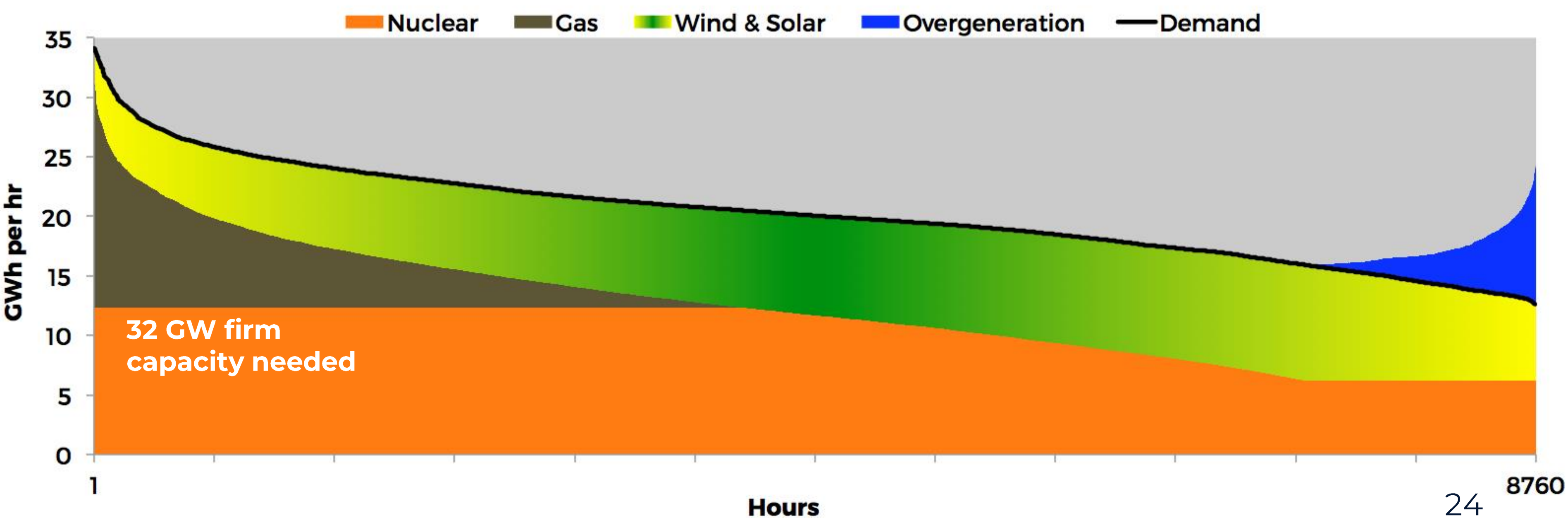


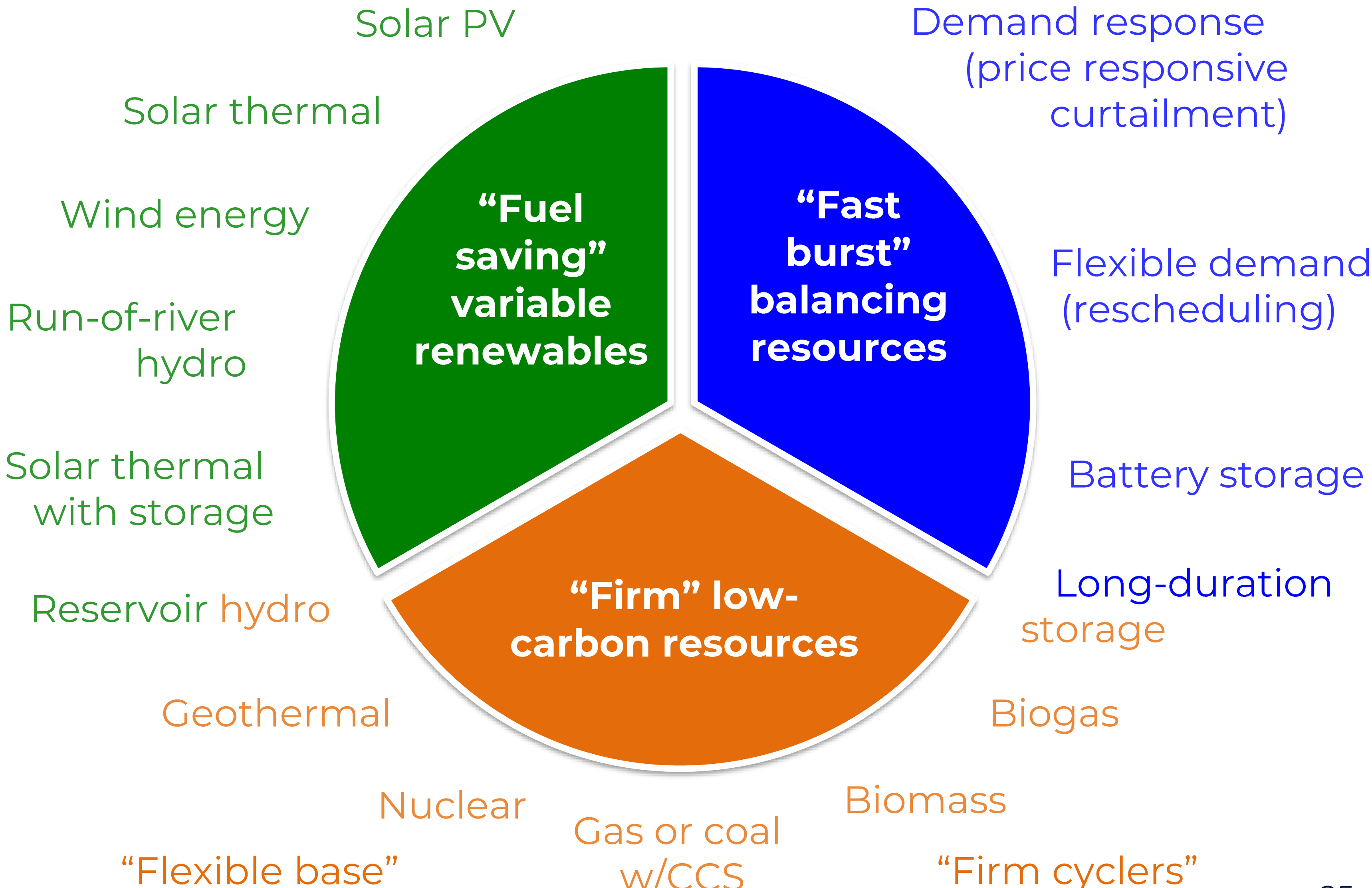
Wind Capacity Value

Net peak:
August 19th
6pm



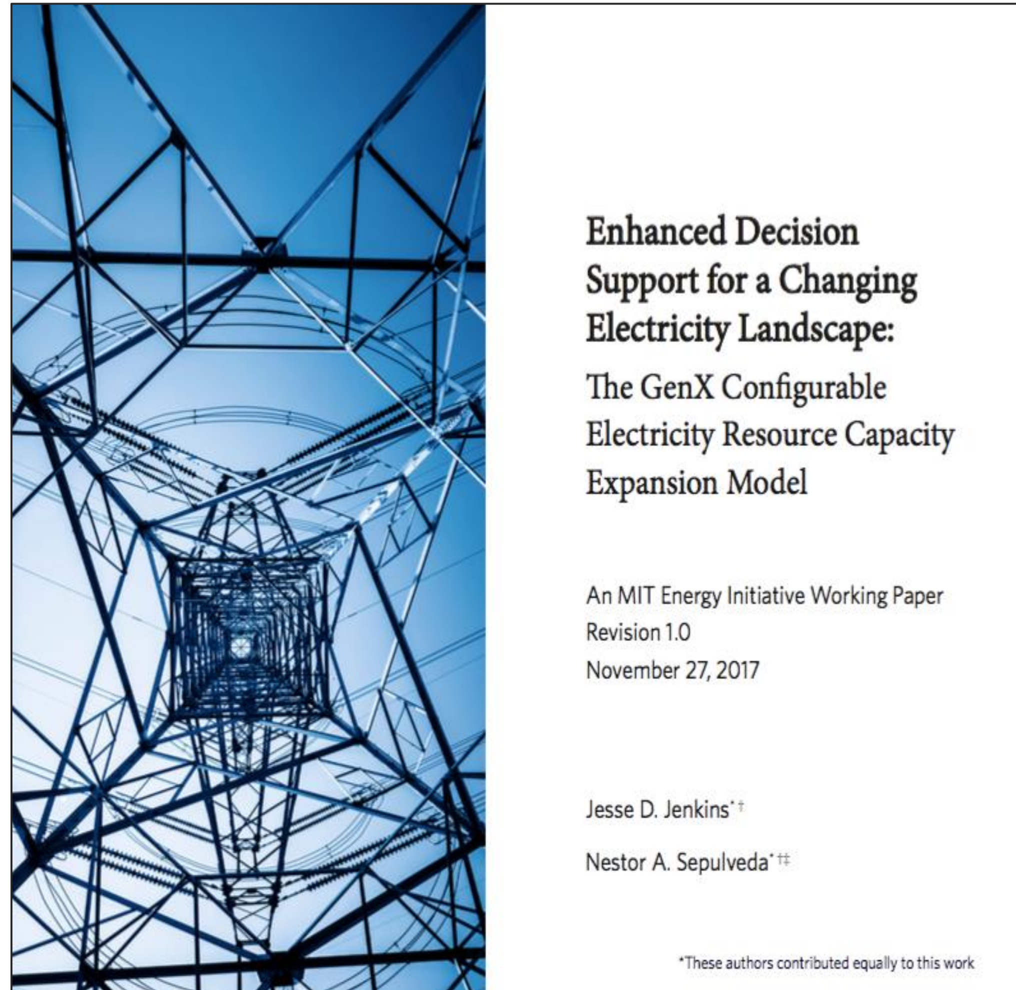
Solar Capacity Value




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

The GenX Model

- Highly configurable
- Detailed operating constraints (unit commitment, etc.)
- Hourly resolution
- Transmission losses & reinforcements
- Distribution losses, reinforcements & "non-wires" alternatives
- Distributed energy resources & flexible demand



Enhanced Decision Support for a Changing Electricity Landscape:

The GenX Configurable Electricity Resource Capacity Expansion Model

An MIT Energy Initiative Working Paper
Revision 1.0
November 27, 2017

Jesse D. Jenkins[*†]

Nestor A. Sepulveda[*‡]

[*]These authors contributed equally to this work

GENX OBJECTIVE FUNCTION

$$\min \Bigg\{ \sum_{z \in \mathcal{Z}} \sum_{v \in \mathcal{VL}} \sum_{y \in \mathcal{G}} \Big((CINV_{y,z,v} \times U_{y,z,v} \times \Omega_{y,z,v}) + (CFOM_{y,z,v} \times U_{y,z,v} \times (CAP^0_{y,z,v} + \Omega_{y,z,v} - \Delta_{y,z,v})) \Big)$$

1. Investment & Fixed O&M

$$+ \sum_{z \in \mathcal{Z}} \sum_{v \in \mathcal{VL}} \sum_{y \in \mathcal{G}} \sum_{t \in \mathcal{T}} \Big(((CVOM_{y,z,v} + CFUEL_{y,z,v}) \times \Theta_{y,t,z,v}) + (CVOM_{y,z,v} \times \Pi_{y,t,z,v}) \Big)$$

2. Variable O&M & Fuel

$$+ \sum_{z \in \mathcal{Z}} \sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}} \Big(CNSE_s \times \Lambda_{s,t,z} \Big)$$

3. Price-responsive Demand Curtailment and Involuntary Non-served Energy

$$+ \sum_{z \in \mathcal{Z}} \sum_{y \in \mathcal{G}} \sum_{t \in \mathcal{T}} \Big(CSTART_{y,z} \times \chi_{y,t,z} \Big)$$

4. Thermal unit start-up costs

$$+ \sum_{t \in \mathcal{T}} \Big(CRSV(\rho_t^{+,unmet} + \rho_t^{-,unmet}) \Big)$$

5. Unmet reserves penalty

$$+ \sum_{l \in \mathcal{L}} \Big(CTCAP_l \times \gamma_l \Big)$$

6. Transmission capacity expansion

$$+ \sum_{z \in \mathcal{V}} \Big(CDCAP_z^{lv} \times (\lambda_z^W + \lambda_z^I) \times (1 - S_z^{mv}) + (CDCAP_z^{mv} \times (\lambda_z^W + \lambda_z^I) \times S_z^{mv} \Big)$$

7. Distribution network expansion

$$- \sum_{z \in \mathcal{V}} \sum_{v \in \{LV,MV\}} \sum_{y \in \mathcal{G}} \Big(RDER_{y,z,v} \times (CAP^0_{y,z,v} + \Omega_{y,z,v} - \Delta_{y,z,v})) \Big) \Bigg\}$$

8. Additional exogenous DER revenue/value

ARTICLE | ONLINE NOW

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

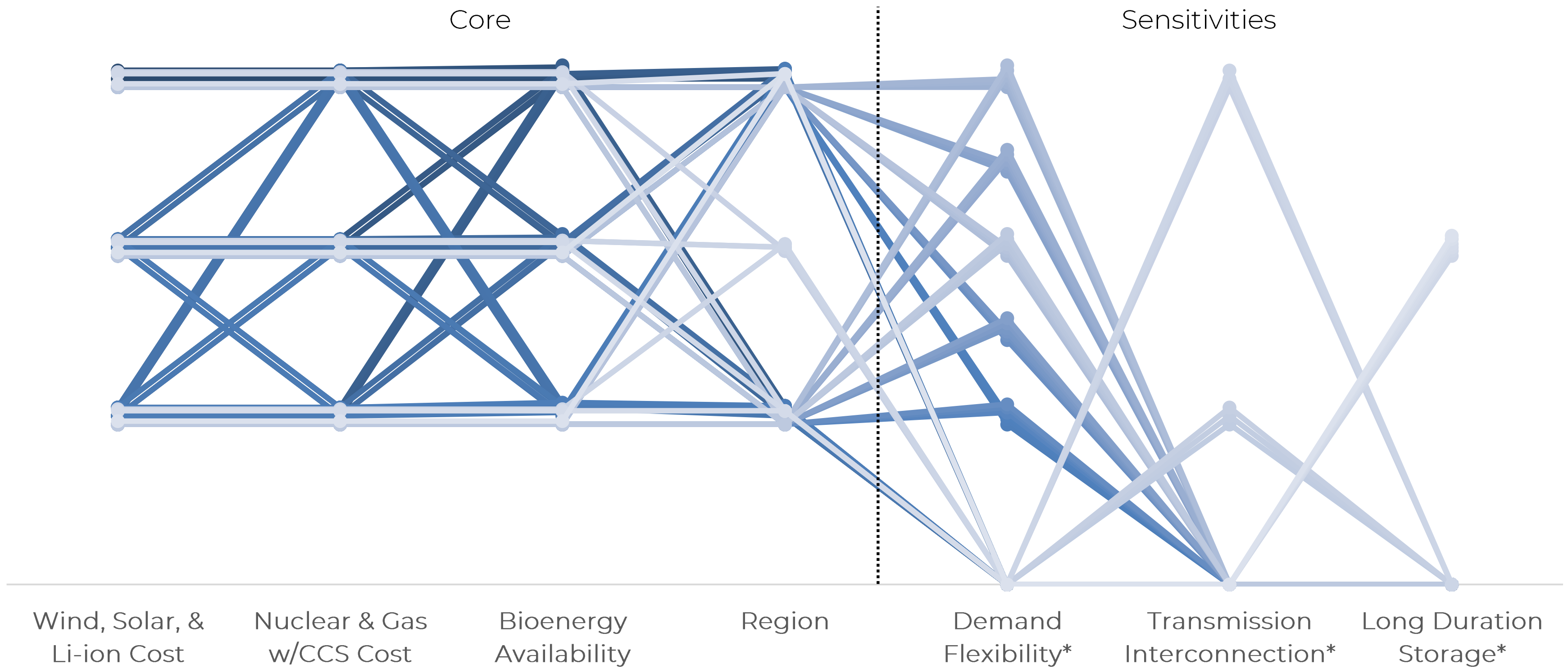
Highlights

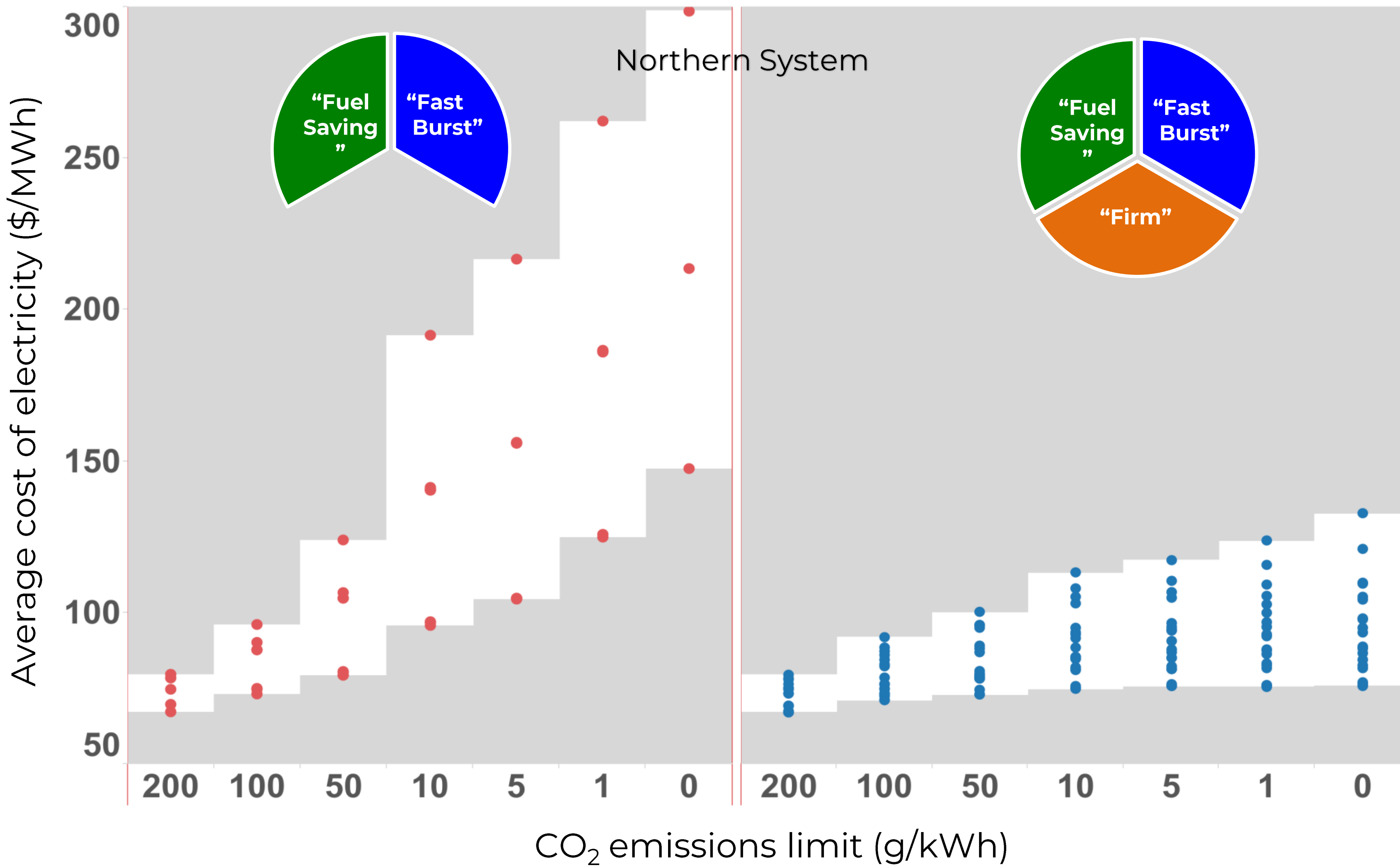
- Firm low-carbon resources consistently lower decarbonized electricity system costs
- Availability of firm low-carbon resources reduces costs 10%–62% in zero-CO_2 cases
- Without these resources, electricity costs rise rapidly as CO_2 limits near zero
- Batteries and demand flexibility do not substitute for firm low-carbon resources

Experimental Design

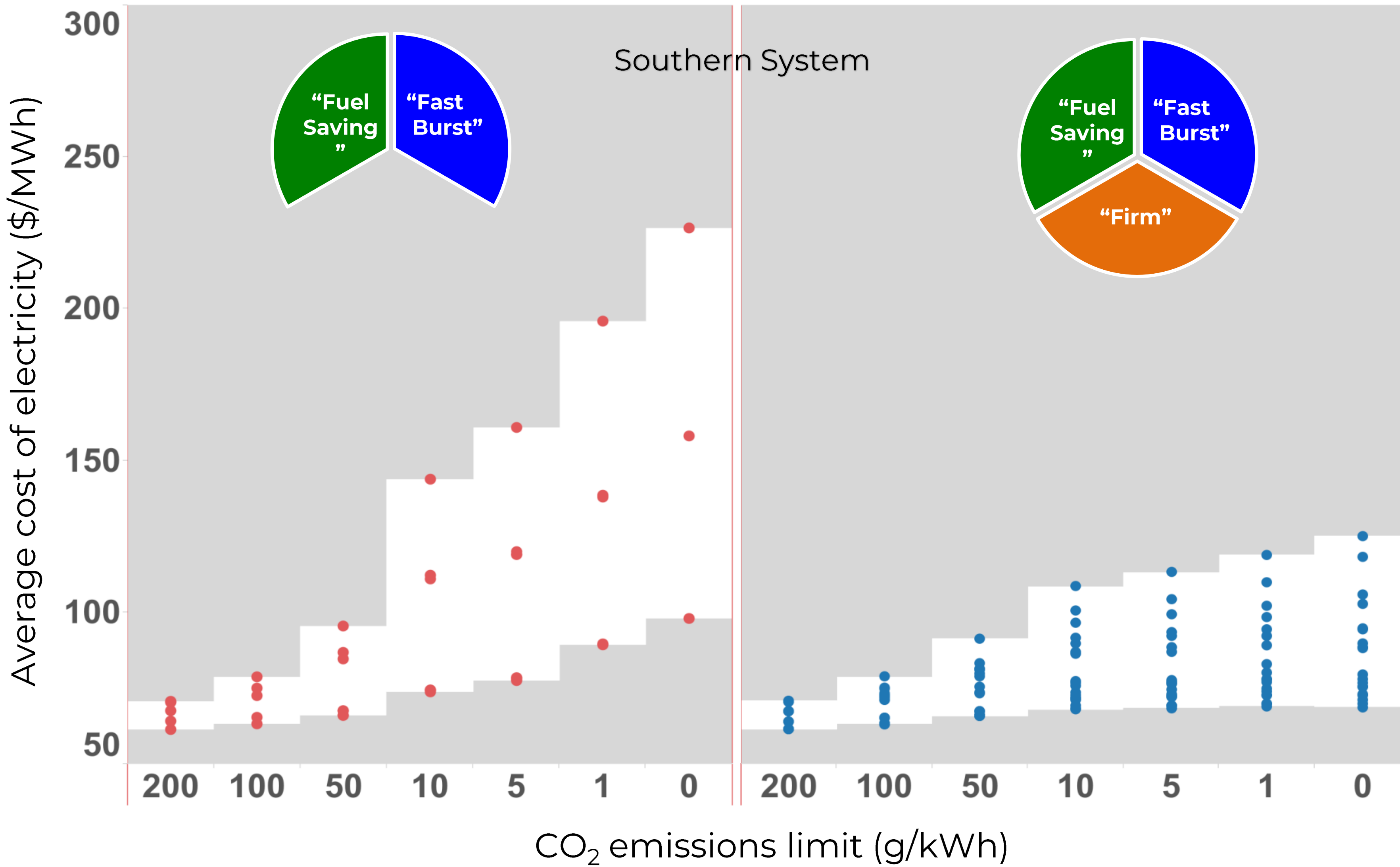
Core: 19 technology scenarios; 2 distinct regions; 7 emissionss limits; with & without firm resources

Plus: demand flexibility, transmission interconnection and long duration storage sensitivities





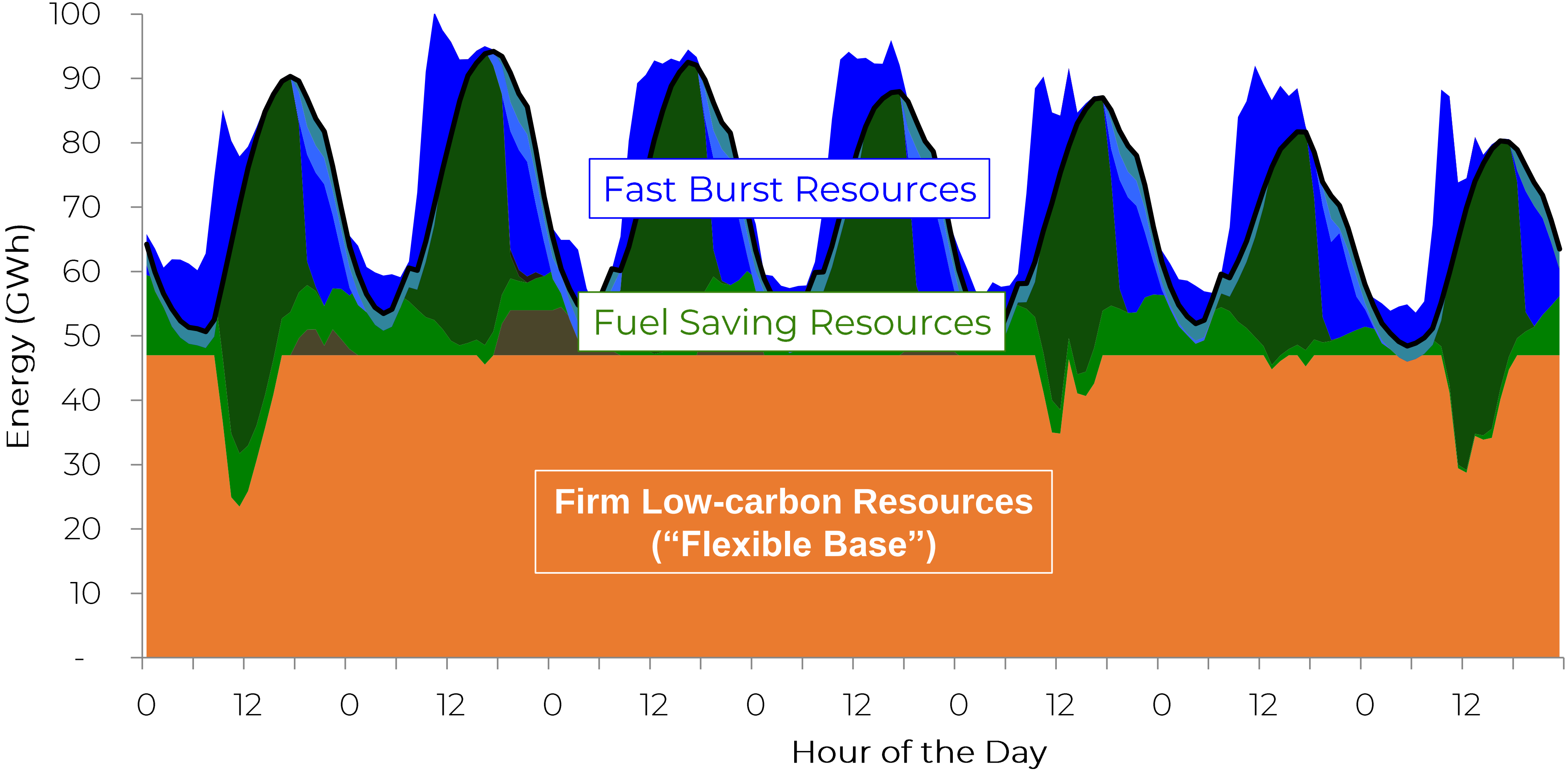
Data source: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* (in press).



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* (in press).

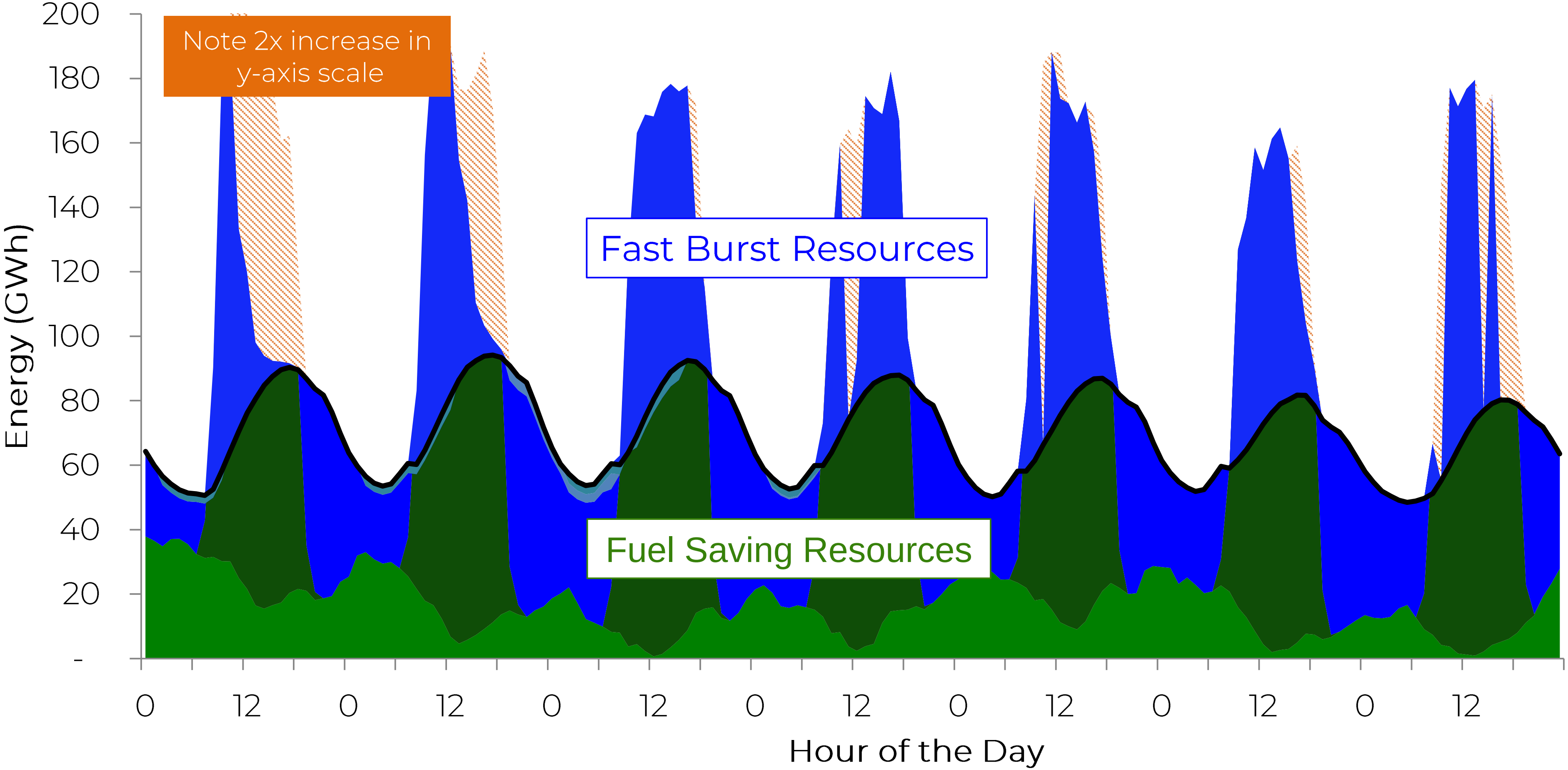
One Possible Balanced Portfolio

1 g/kWh CO_2 emissions limit (99.9% decline)



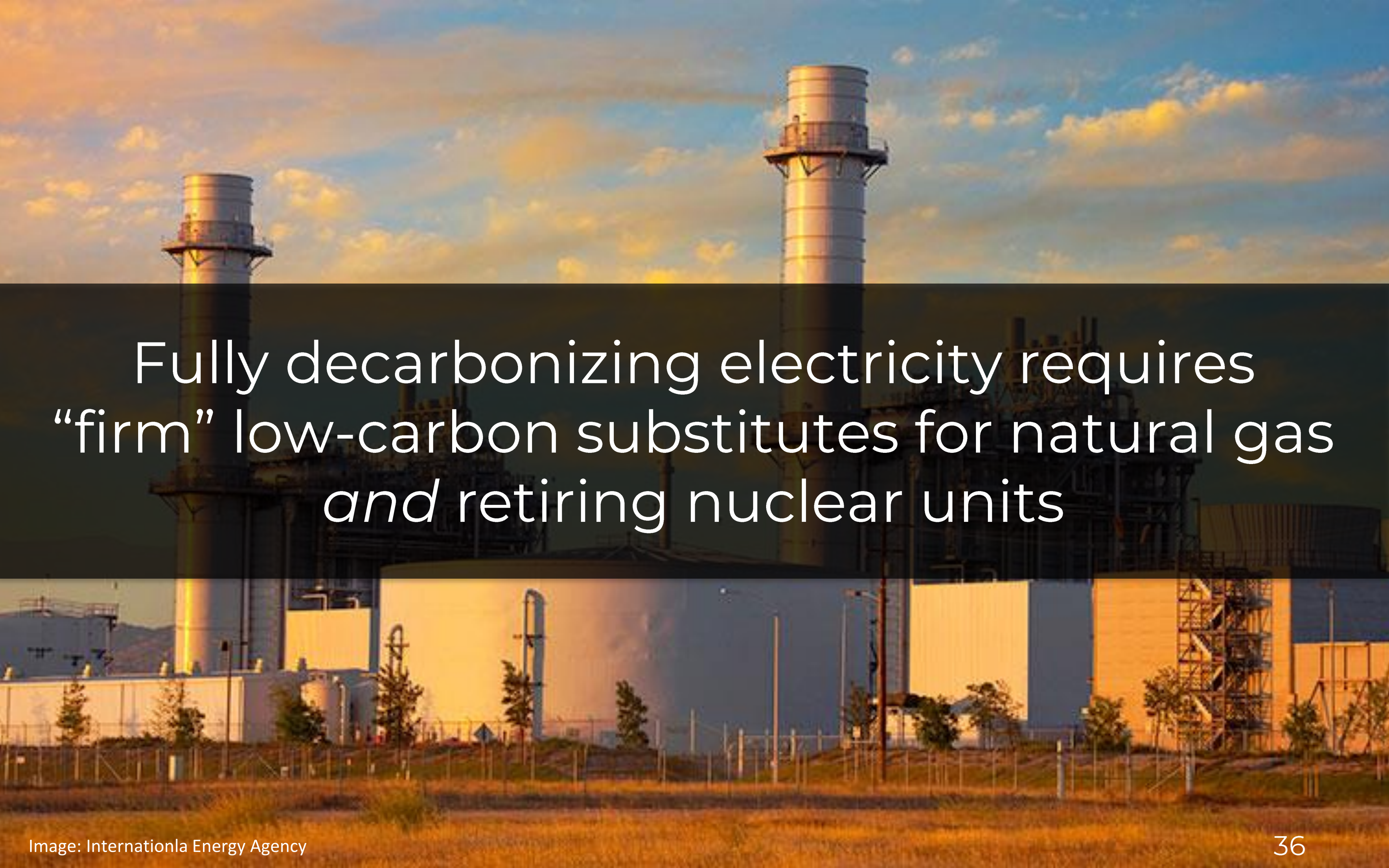
Without Firm Low-Carbon Resources

1 g/kWh CO_2 emissions limit (99.9% decline)




FLORIDA
15
GEORGETOWN
3
GEORGETOWN
5
Wilson
NCAA

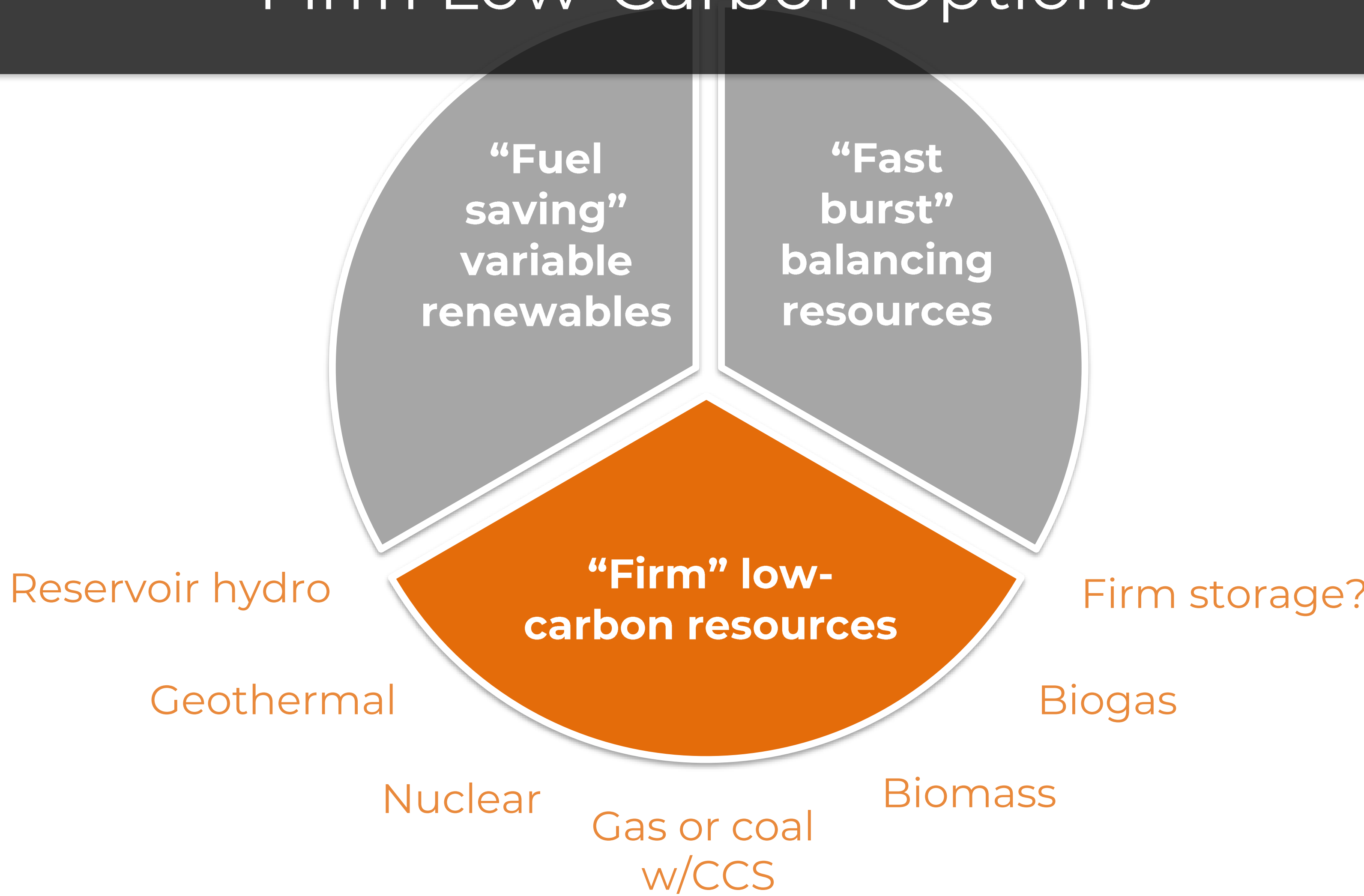
In the near-term, wind, solar, batteries and natural gas can drive emissions reductions.

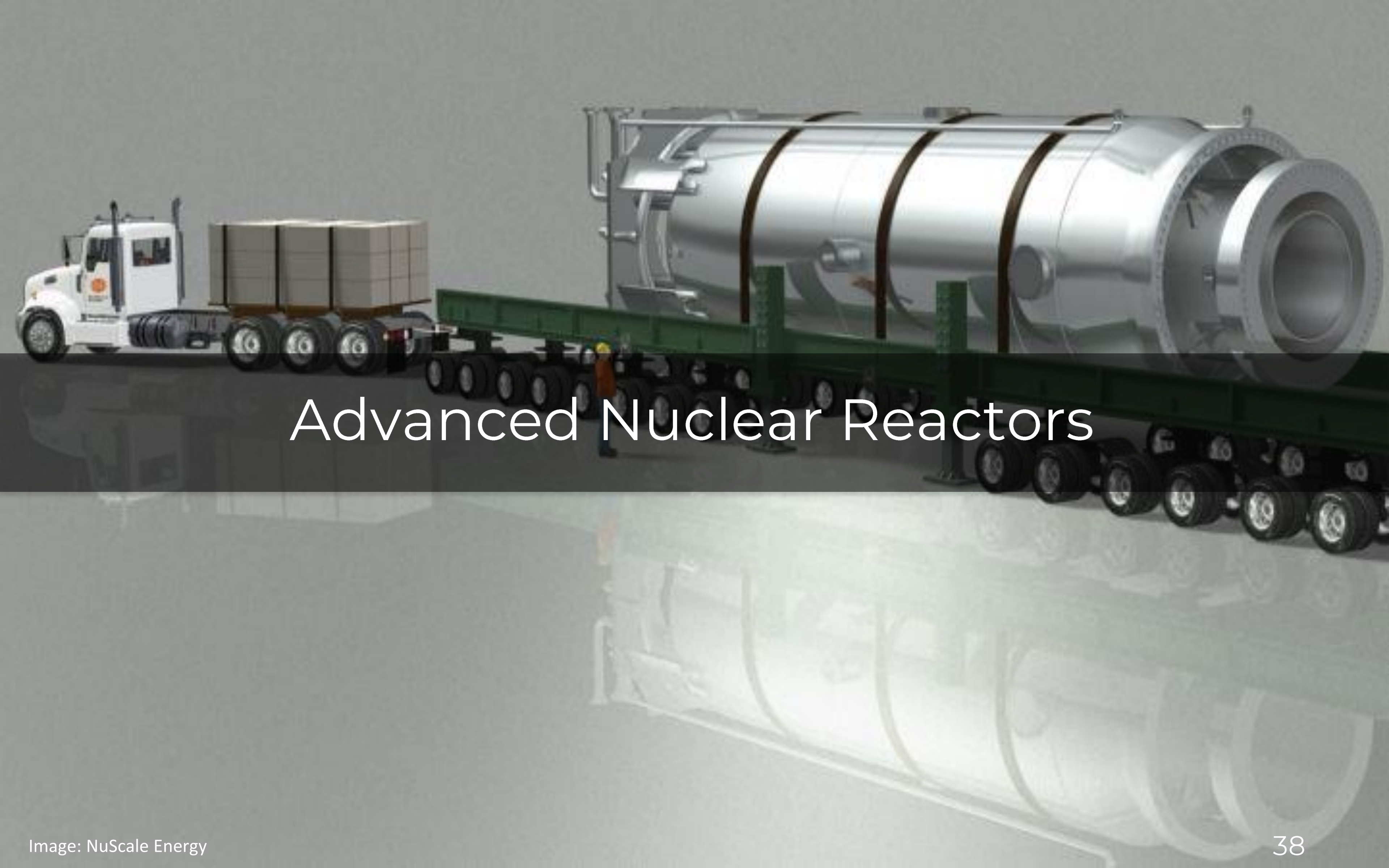


Fully decarbonizing electricity requires “firm” low-carbon substitutes for natural gas *and* retiring nuclear units

Image: Internationla Energy Agency

Firm Low-Carbon Options





Advanced Nuclear Reactors

Image: NuScale Energy

Engineered Geothermal Energy Systems

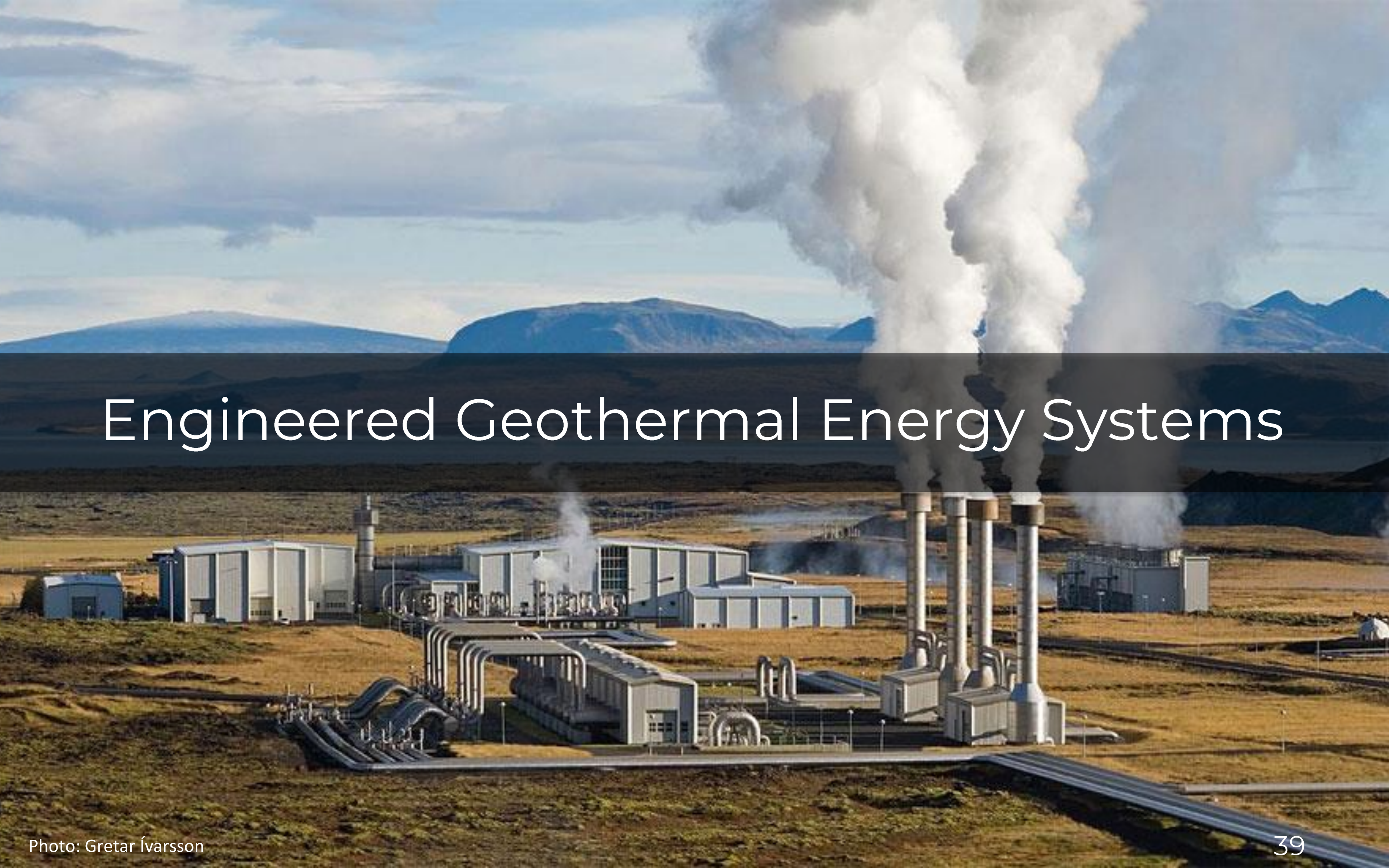
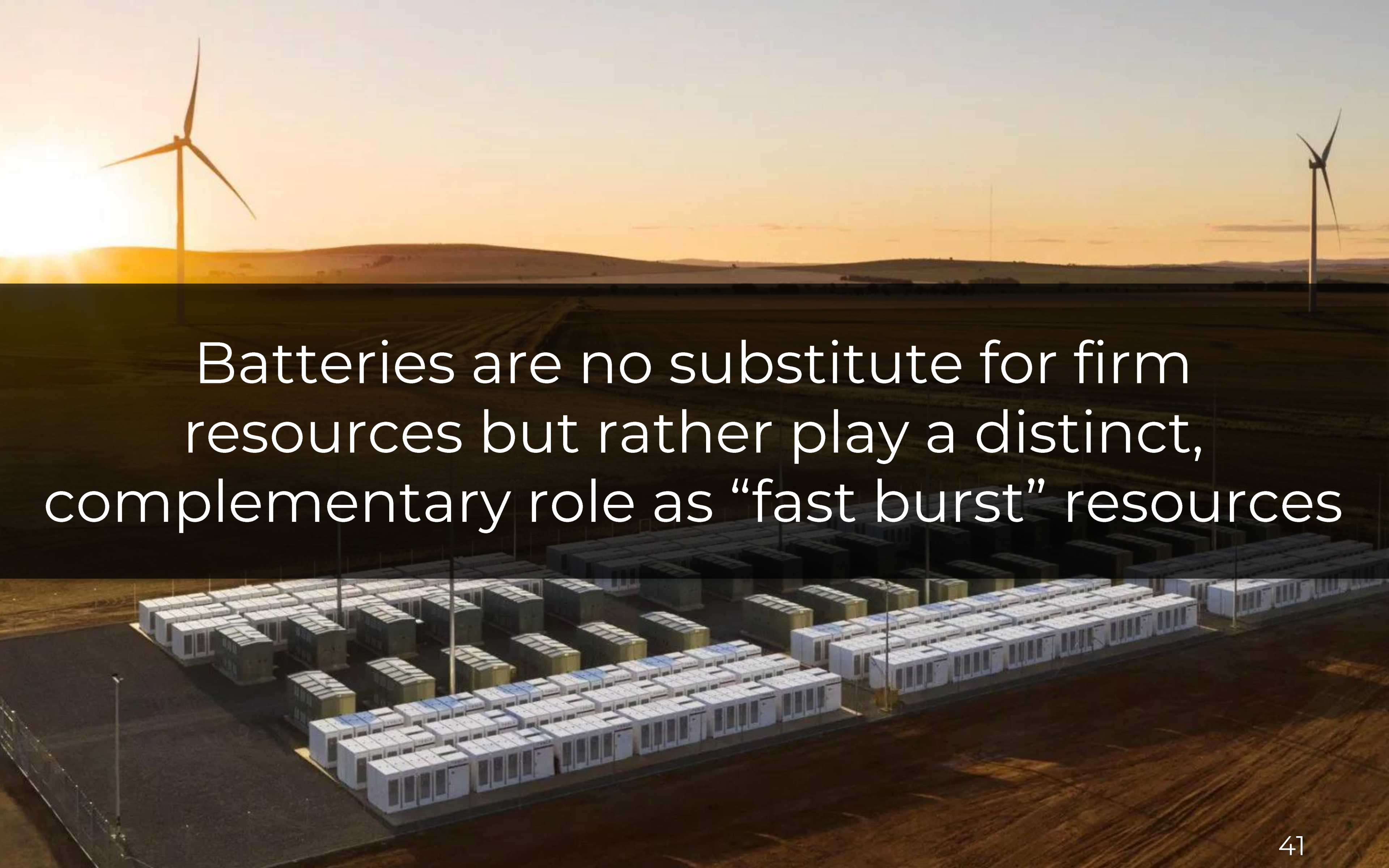


Photo: Gretar Ívarsson

Carbon Capture and Storage

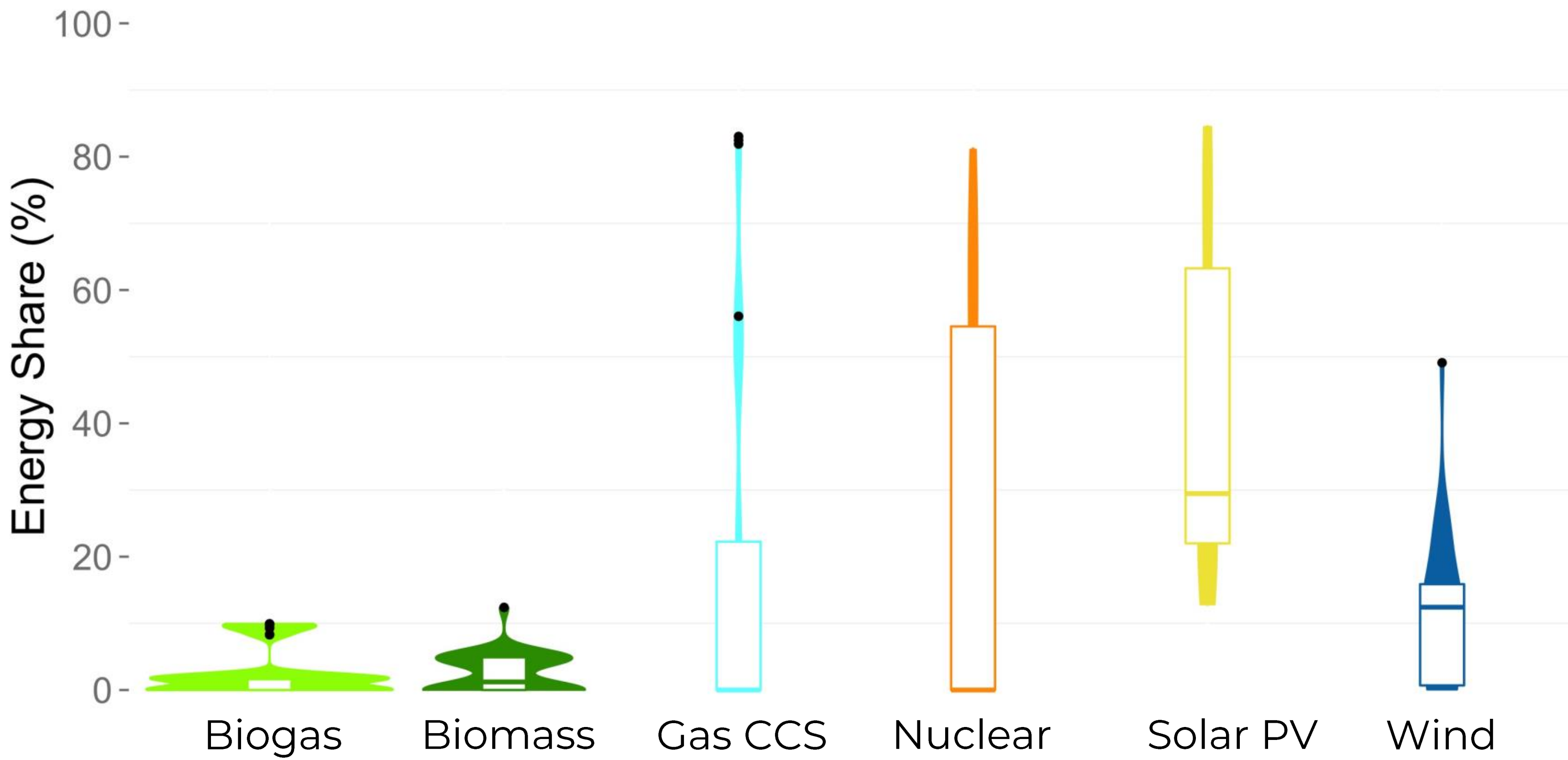
Photo: NET Power



Batteries are no substitute for firm resources but rather play a distinct, complementary role as “fast burst” resources

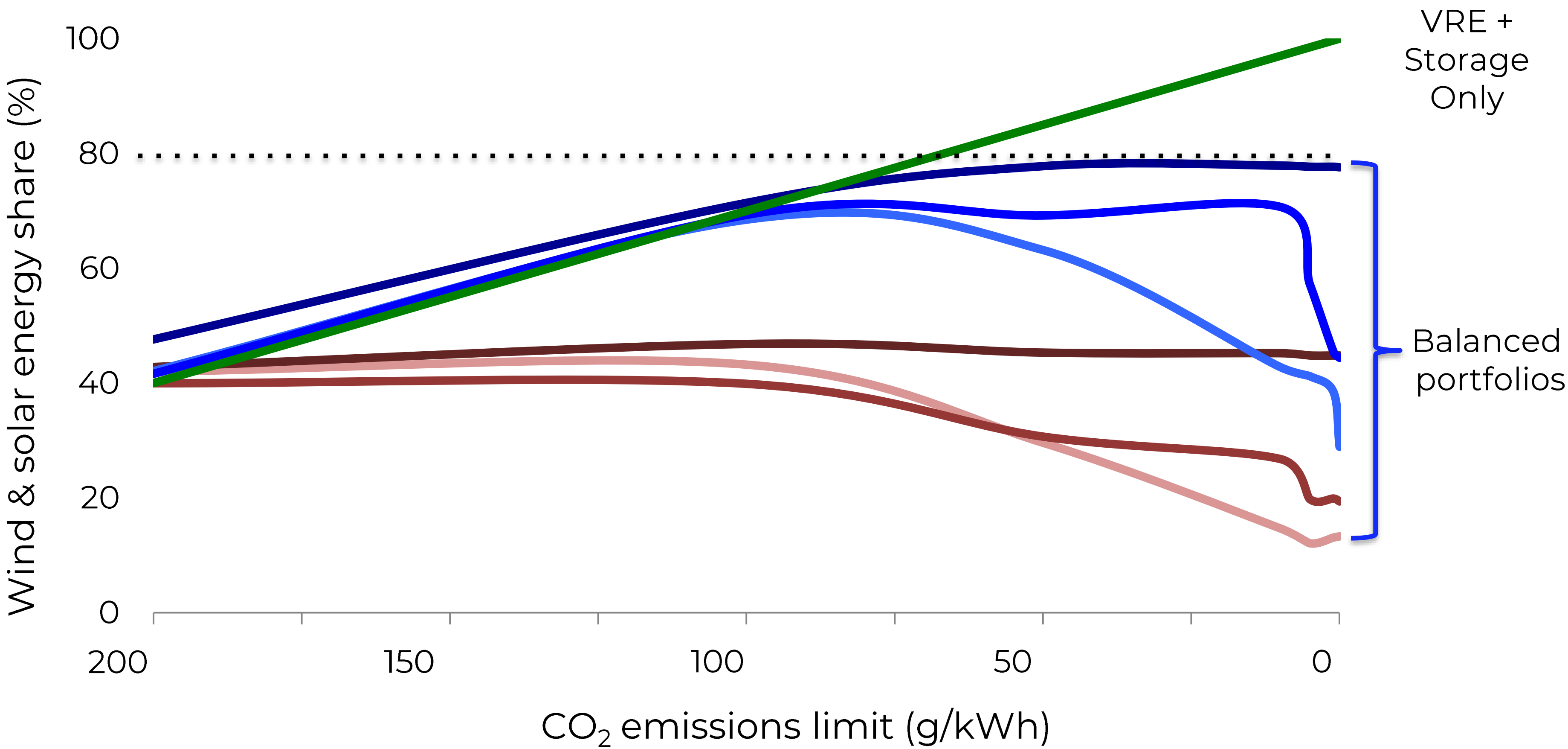
Can ultra-cheap, long-duration storage act as a true substitute for firm generation?

Substantial Uncertainty Remains



Data source: Sepulveda, N., Jenkins, J.D., et al. (forthcoming), "The role of flexible base resources in deep decarbonization of electric power systems," (revise & resubmit at *Joule*)

Not a Straight Line to Zero Carbon



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* (in press).

We Need Strategies Robust to Risk

continent-scale transmission

AND

highly flexible demand / efficiency gains

AND

very low-cost wind, solar, and batteries

AND

order-of-magnitude cheaper "firm" storage

affordable nuclear

OR

affordable CCS

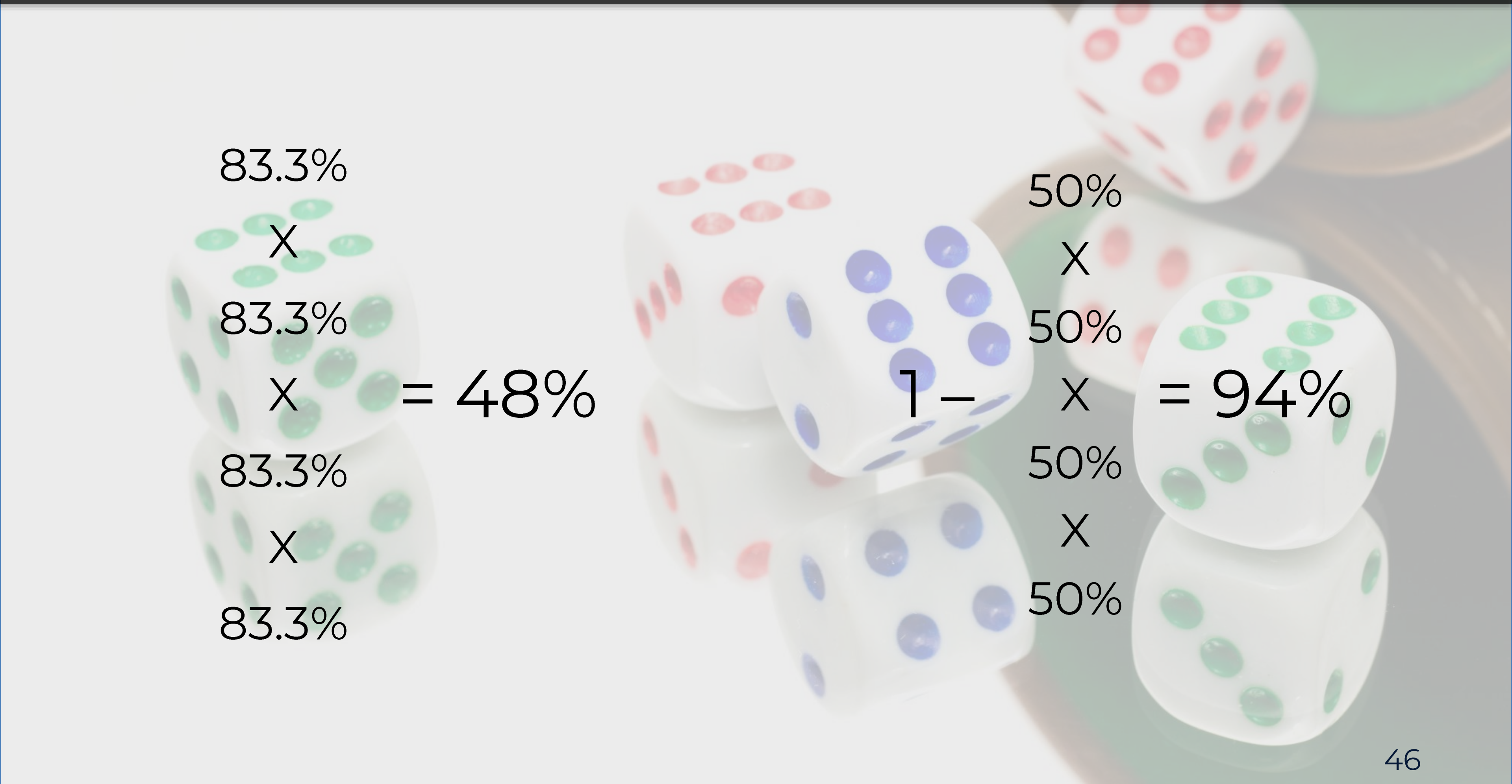
OR

sustainable biomass

OR

engineered geothermal

We Need Strategies Robust to Risk



83.3% X 83.3% X 83.3% X 83.3% = 48%

1 – 50% X 50% X 50% X 50% = 94%

We Need Strategies Robust to Risk

$$1 - \left(50\% \times 50\% \times 50\% \times 50\% \times (1-48\%) \right) = 97\%$$

Deep Decarbonization / Uncertainty

- Full combinatorial analysis of much broader range of uncertainties:
  - Technology costs; changes in electricity demand profiles (electrification, demand growth, efficiency); weather; policy timing
- Large combinatorial “end-points” analysis to map uncertainty space
- Narrower “pathways” analysis to identify inflection points/decision points and possible dead-ends

Deep Decarbonization / Uncertainty

1. Expert elicitation workshop to define “uncertainty space”
2. Using parallel supercomputing cluster perform full combinatorial analysis spanning 10s or 100s of thousands of discrete cases
3. Data analysis techniques to generate actionable insights for managing deep uncertainty

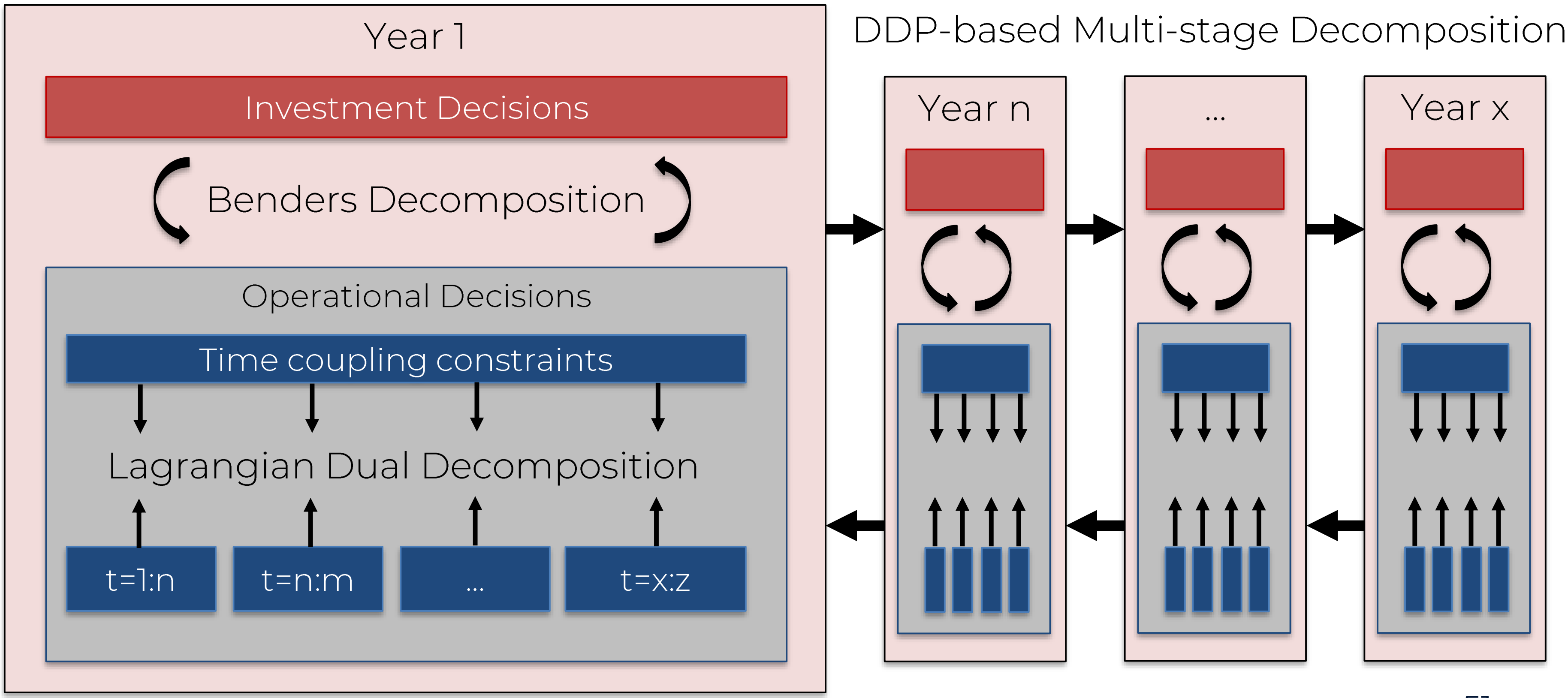
Deep Decarbonization Uncertainty

Insights:

- **Stable regions** – clustering sets of parameter values that result in similar outcomes
- **Knife edge changes** – small changes in parameter values resulting in large changes in optimal portfolio
- **Regret** – metric for each portfolio’s n-dimensional Euclidian distance from the “optimal” portfolio for each realization of uncertainty
- **Robustness** – metric for each resource describing robustness to parametric uncertainty
- **Optionality** – identifying substitute resources can expand option space (“more Ors; less Ands”)

New Computational Methods

Multi-level decomposition of electricity panning problem



Questions? jesse_jenkins@hks.harvard.edu