PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

Fusion, clean firm resources and the path to 100% carbon-free electricity

Jesse D. Jenkins

June 1, 2026 – PPPL Introduction to Plasma and Fusion Course

Research to improve decision-making and accelerate rapid, affordable, and effective transitions to net-zero carbon energy systems

PRINCETON UNIVERSITY

andlinger center for energy+the environment

Mechanical and Aerospace Engineering

Research areas

PRINCETON UNIVERSITY
ZERO LAB
Zero-carbon Energy Systems Research and Optimization Laboratory

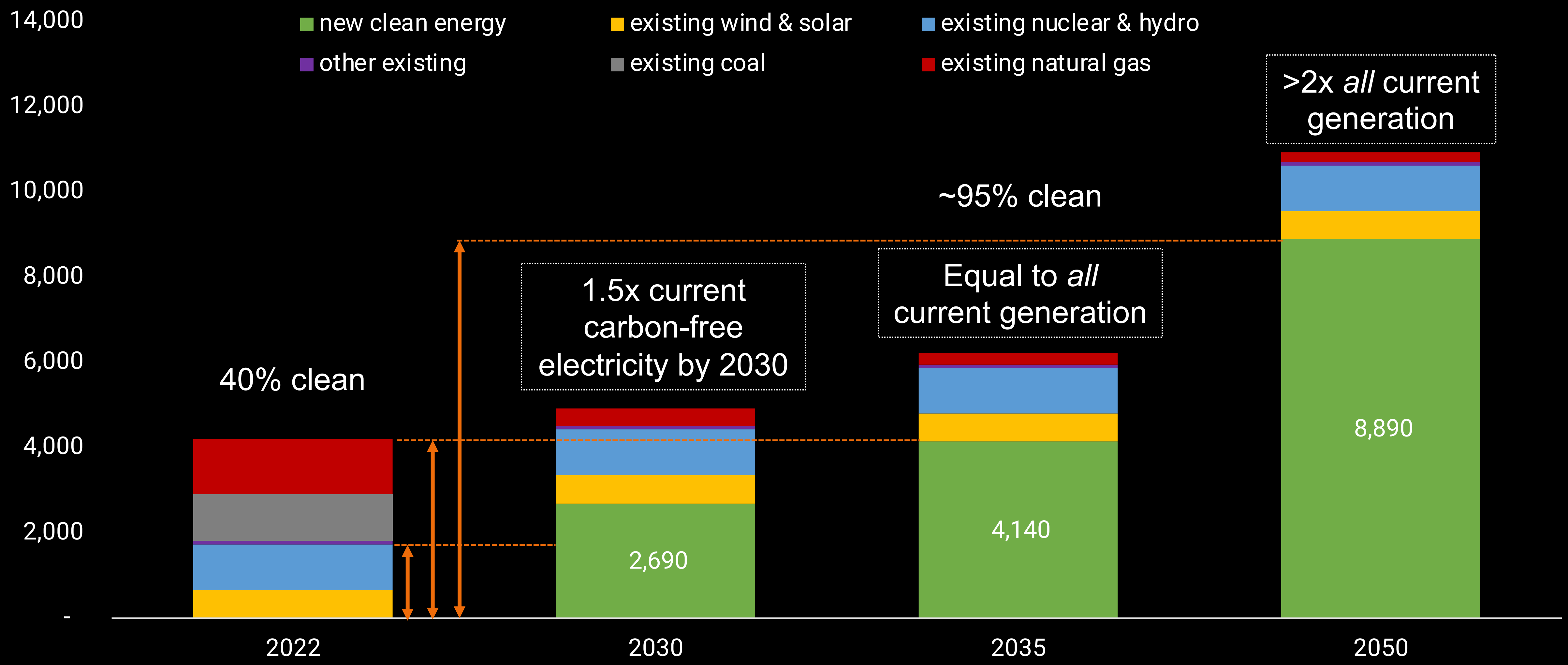
1. Improve macro-energy systems models & methods

2. Evaluate & optimize low-carbon technologies

3. Guide net-zero energy systems transitions

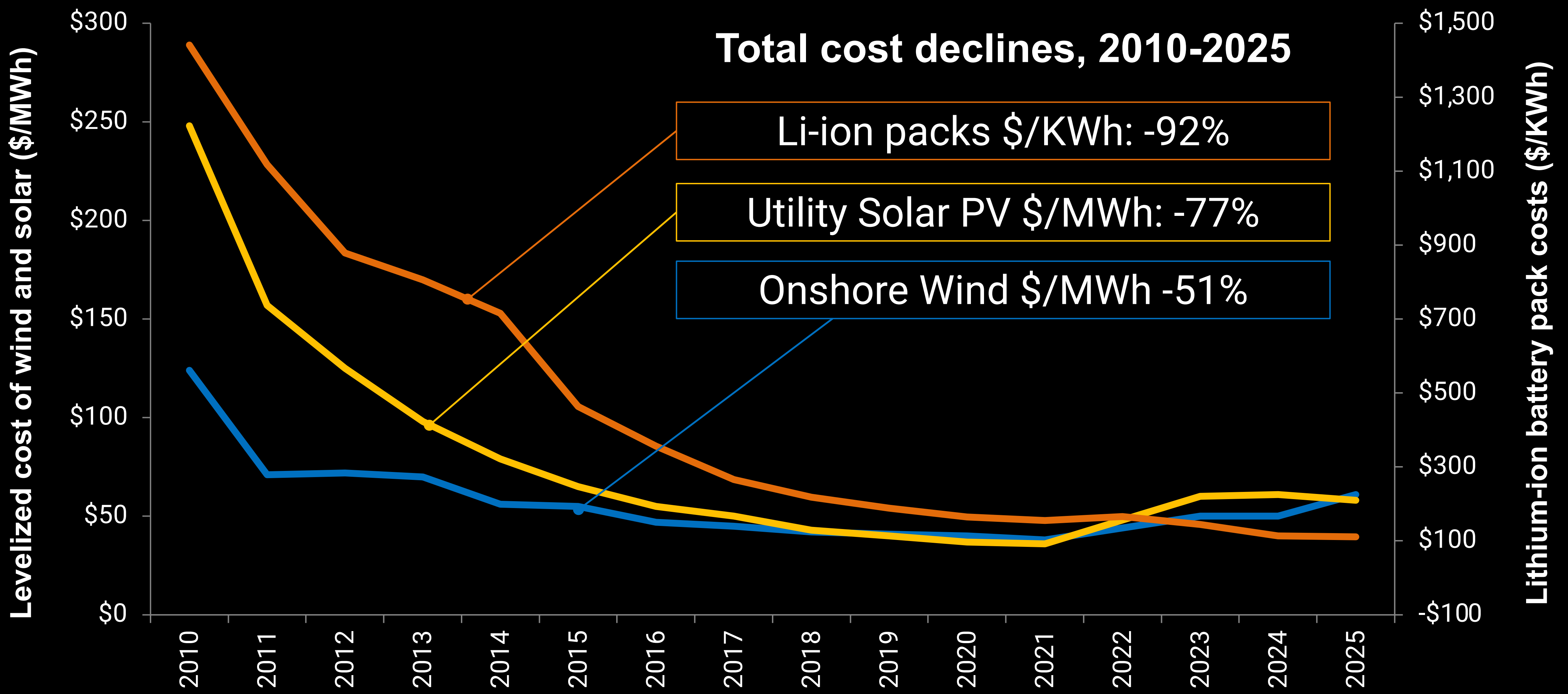
Clean electricity: the linchpin for decarbonization

Total annual U.S. electricity generation by resource
Billion kilowatt-hours (or terawatt-hours)



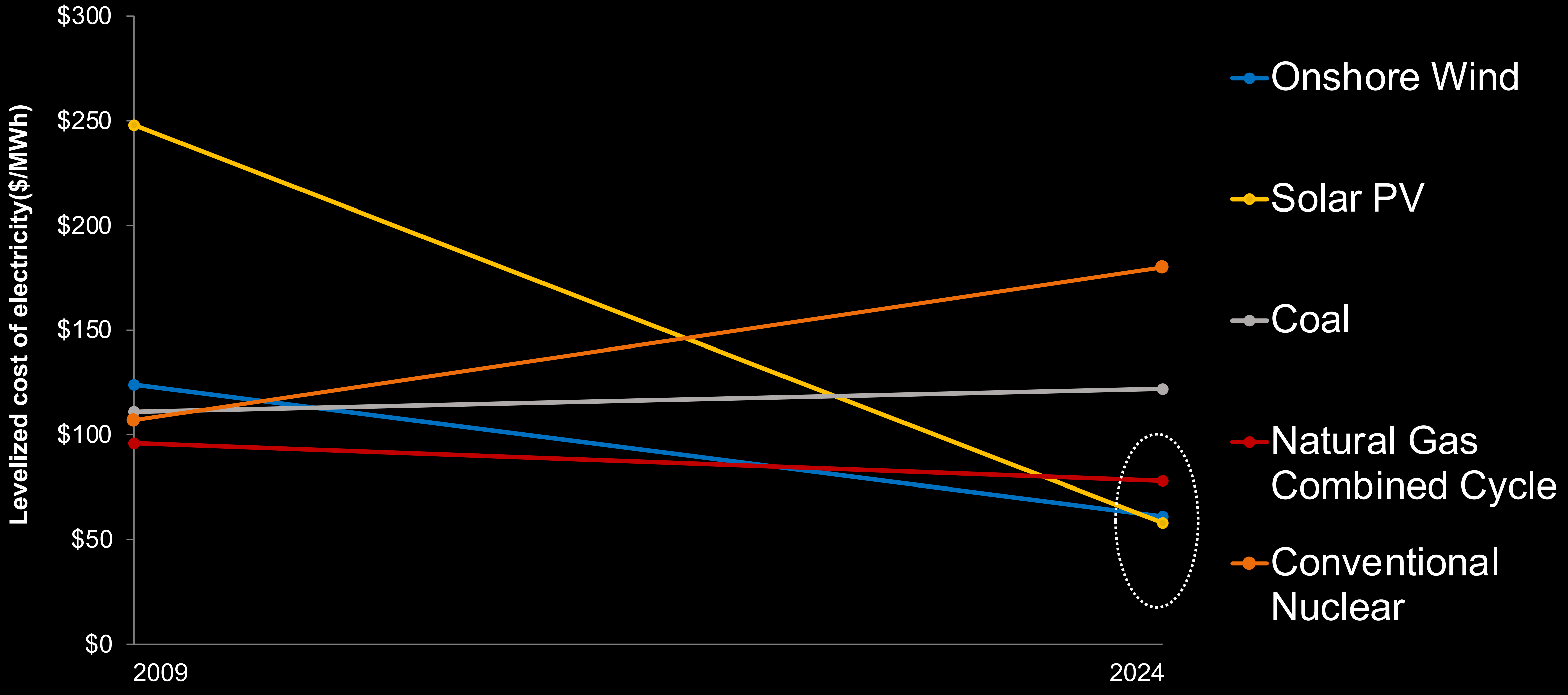
Data source: REPEAT Project (July, 2023), Net-Zero Pathway

Wind, solar, and battery costs have plummeted...



Data Sources: Wind & solar costs from Lazard (2023), 2023 Levelized Cost of Energy+.
Battery pack costs from Bloomberg New Energy Finance (2023), Battery Price Survey.

...and are now the cheapest sources of electricity



Data Source: Wind & solar costs from Lazard (2021), Lazard's Levelized Cost of Energy Analysis – Version 15.0.

So we’re done, right?

“It can be more expensive to add cheap solar than to add expensive geothermal”

(or fusion)

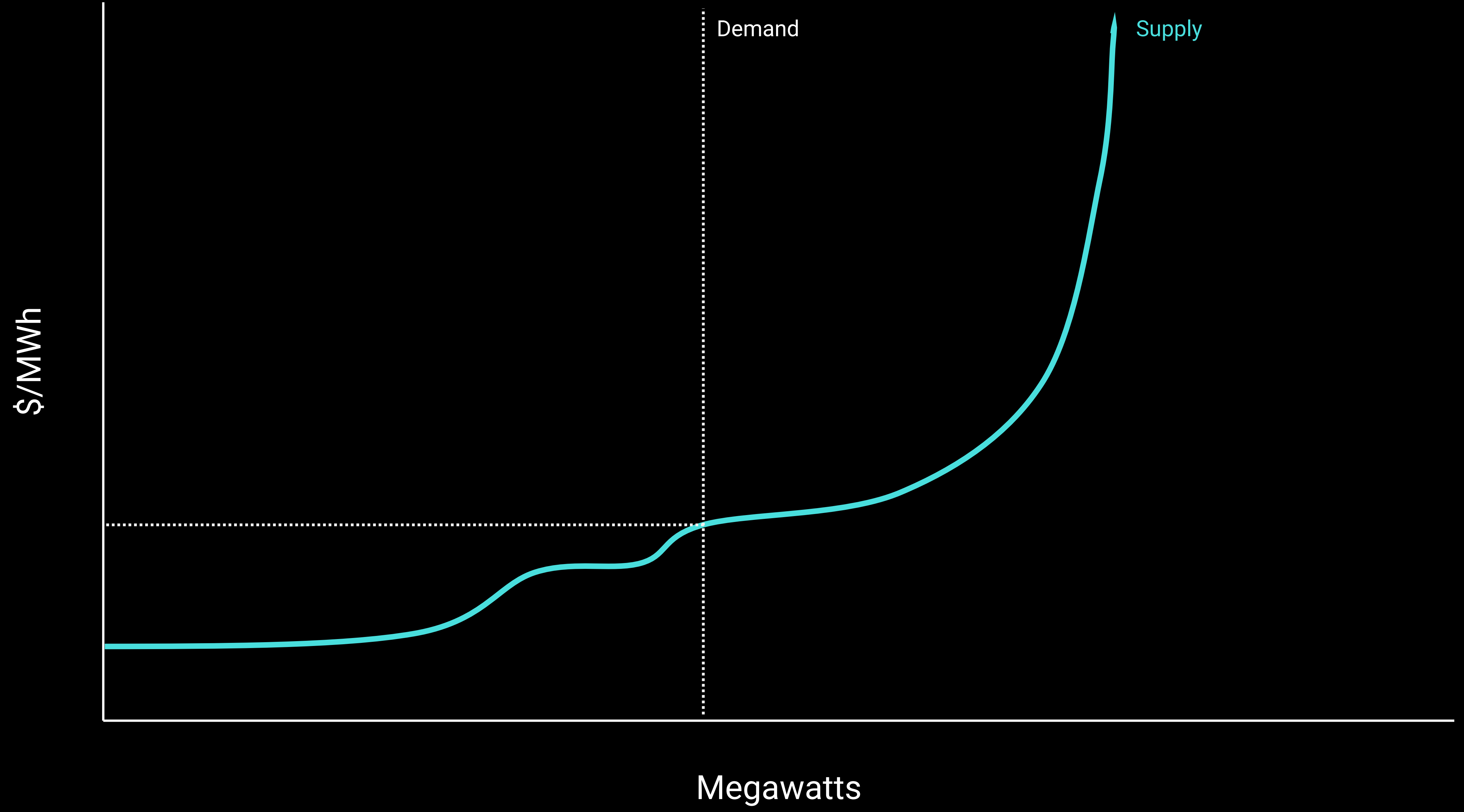
-David Olsen,

Member of CAISO Board of Governors,
former President & CEO of Patagonia (2020)

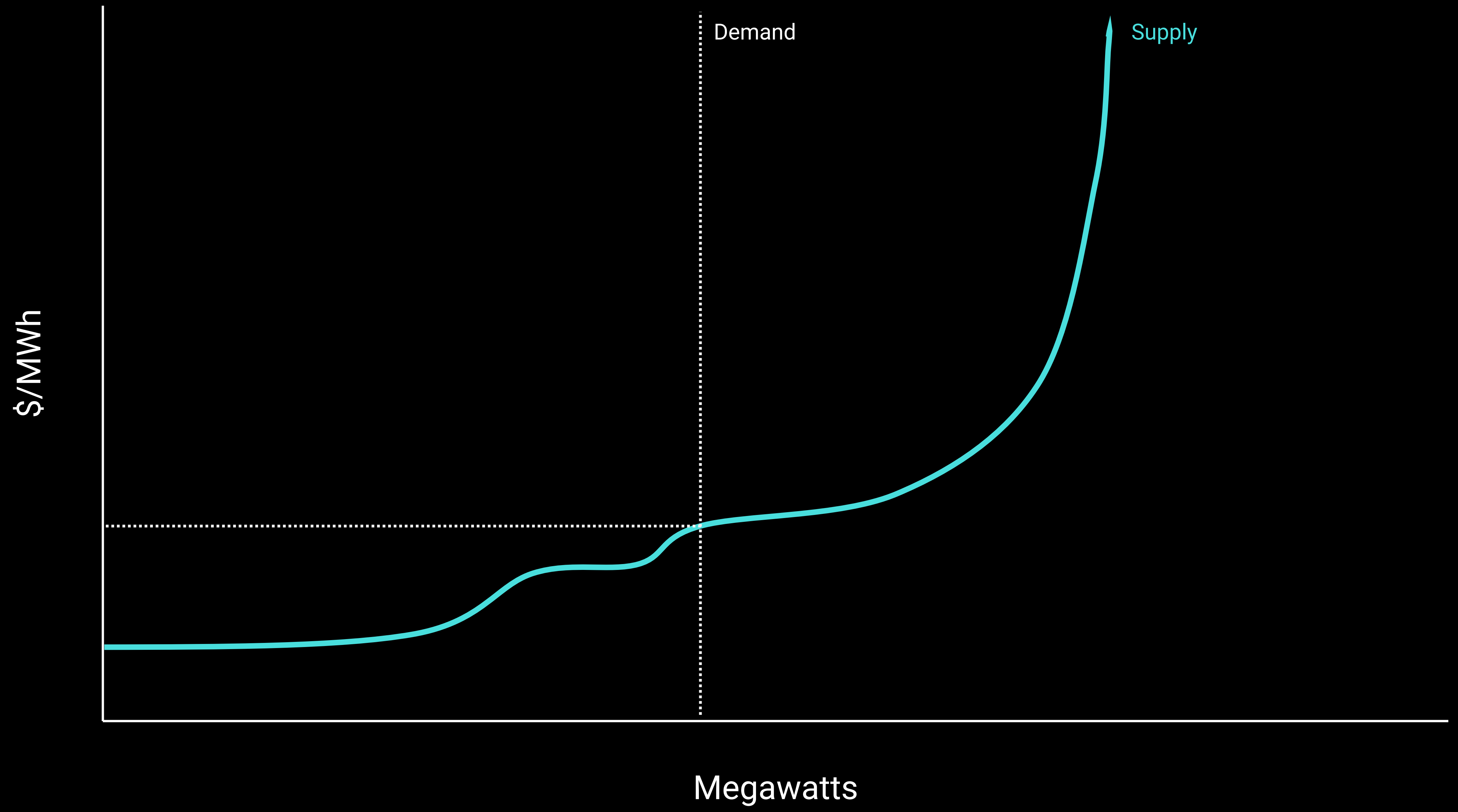
https://www.utilitydive.com/news/geothermals-surprise-cheap-renewables-could-keep-states-from-achieving-cl/569807/

?

Electricity markets 101



What happens when we add renewables?



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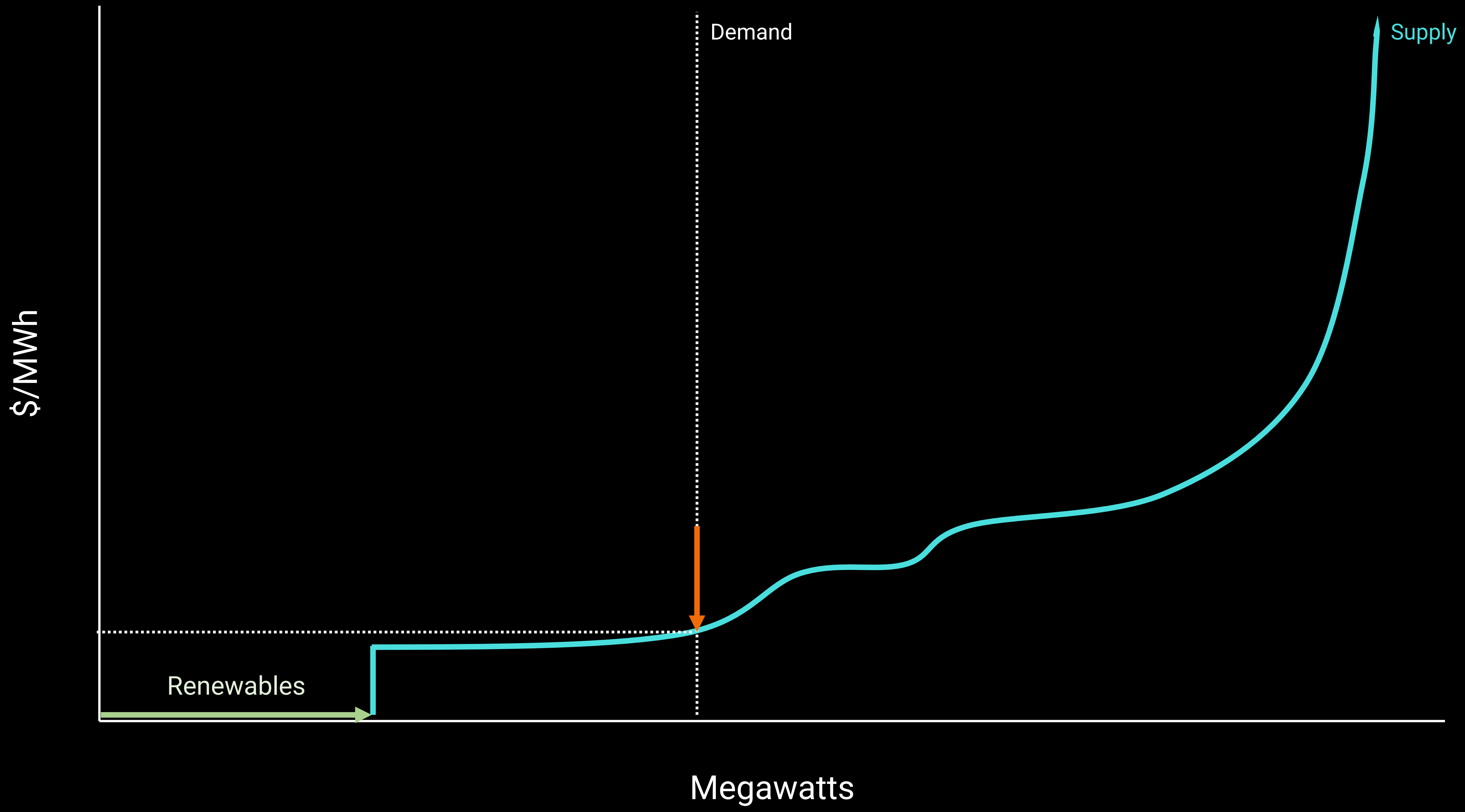
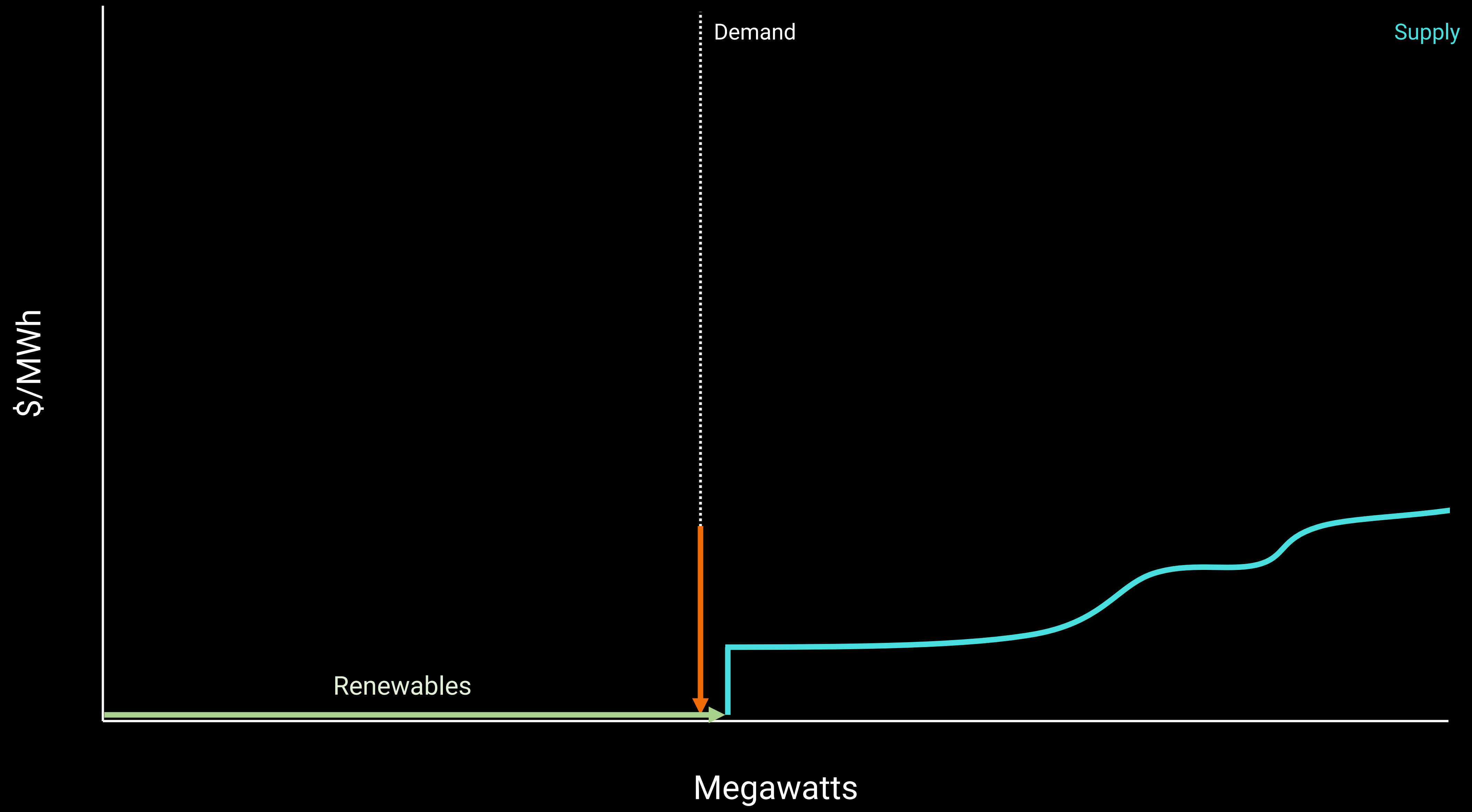
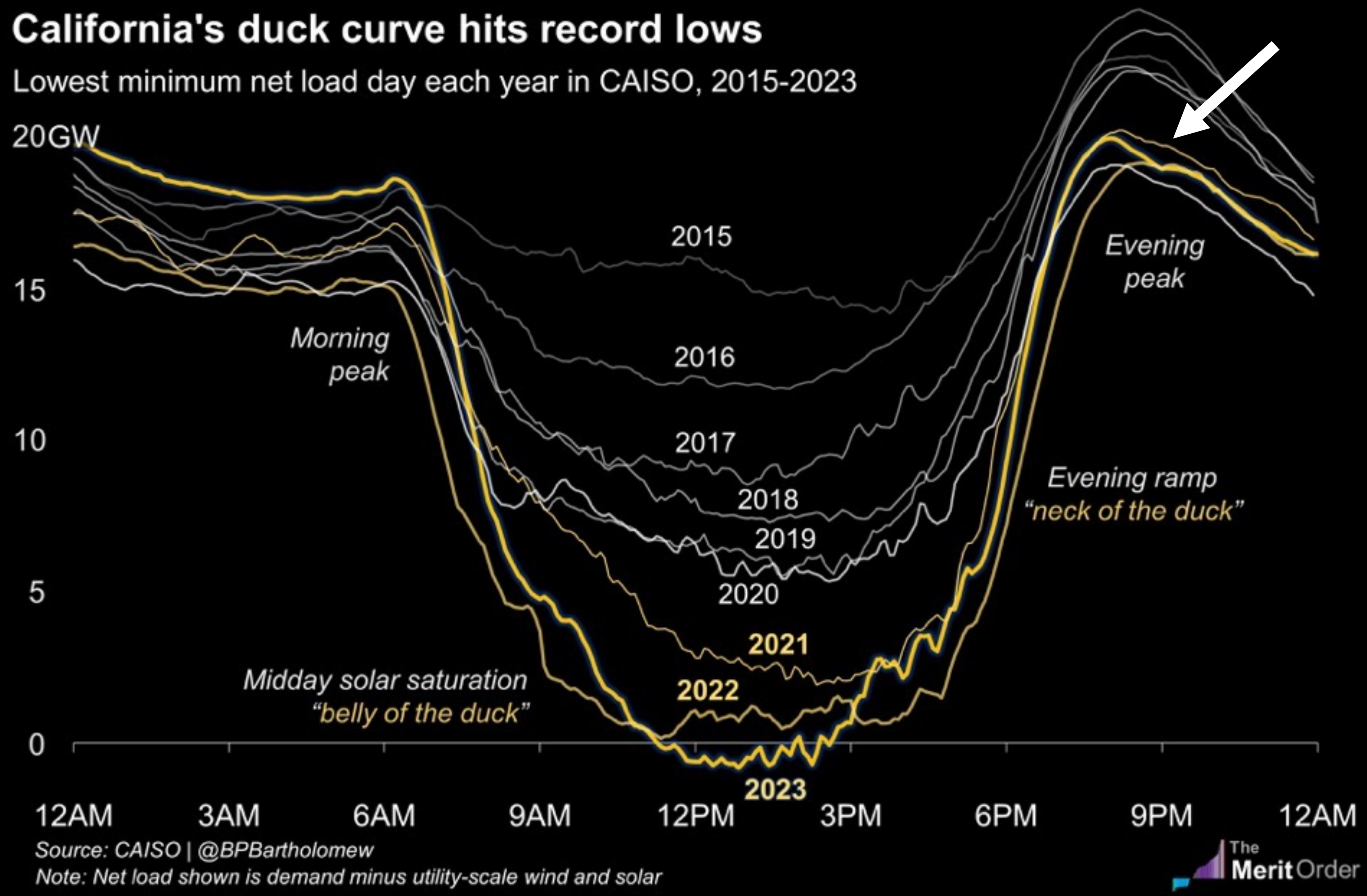


More wind & solar: declining energy value



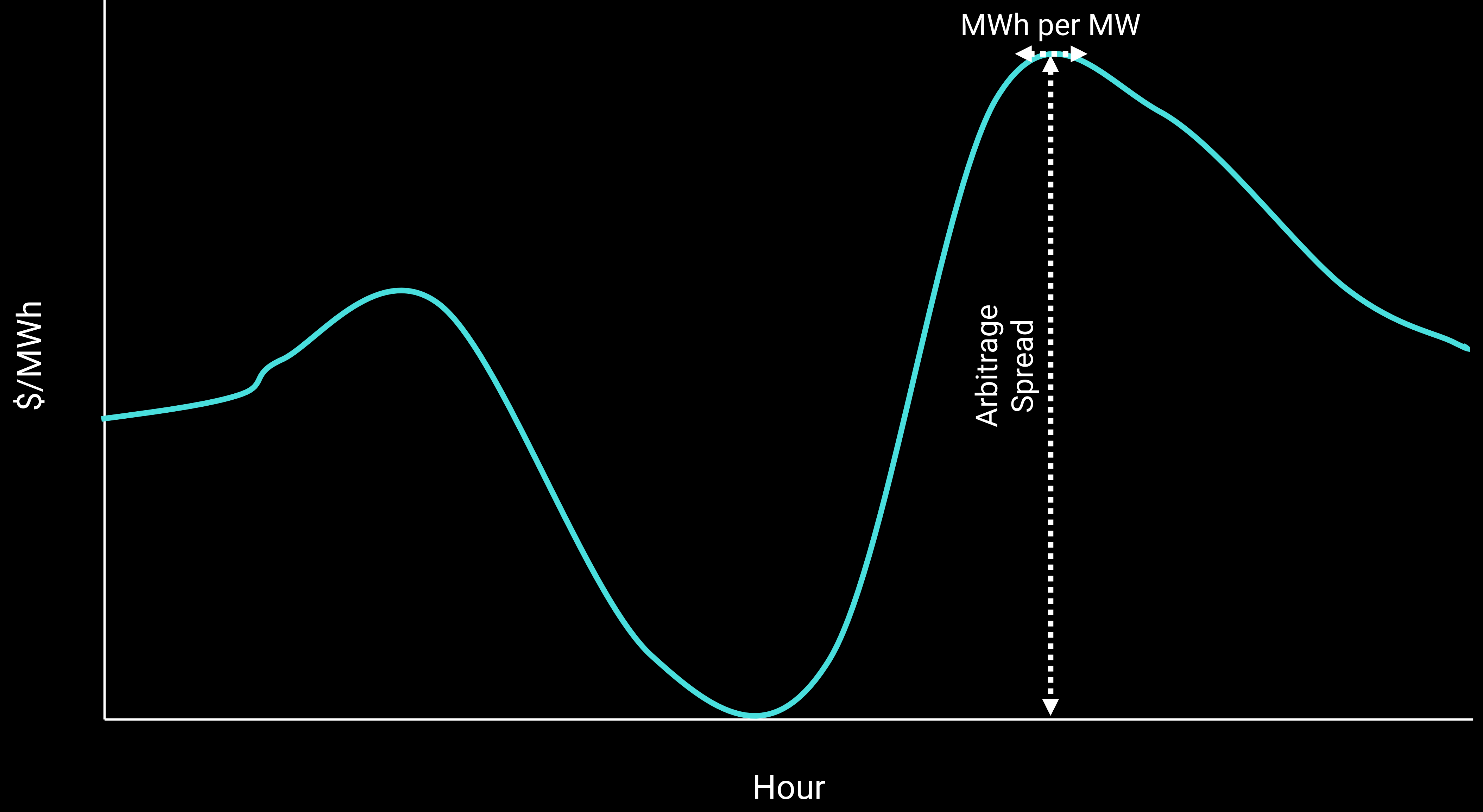
Wind & solar: declining capacity substitution value



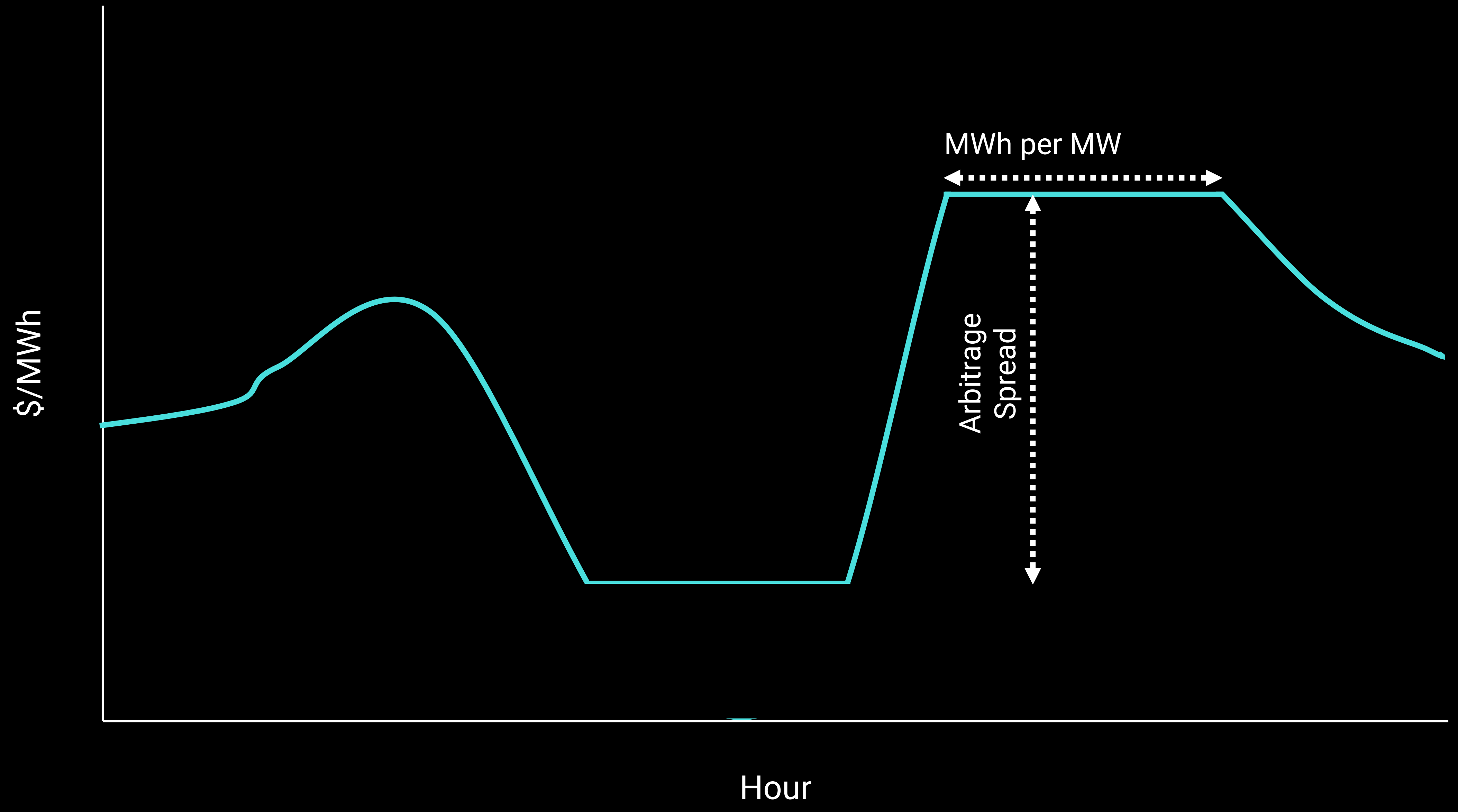
A Race Between Declining Cost & Value

What about energy storage?

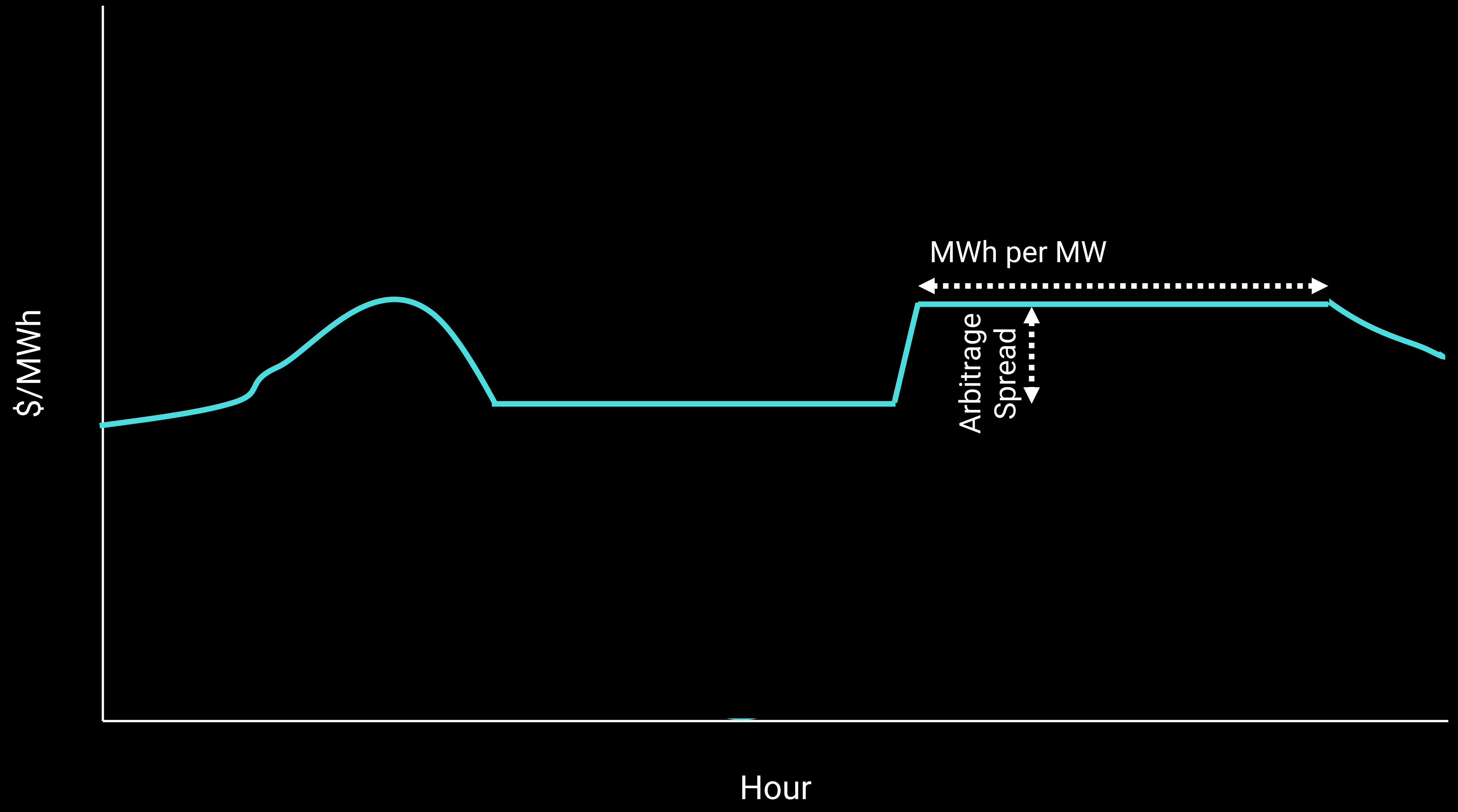
Storage: buy low, sell high!



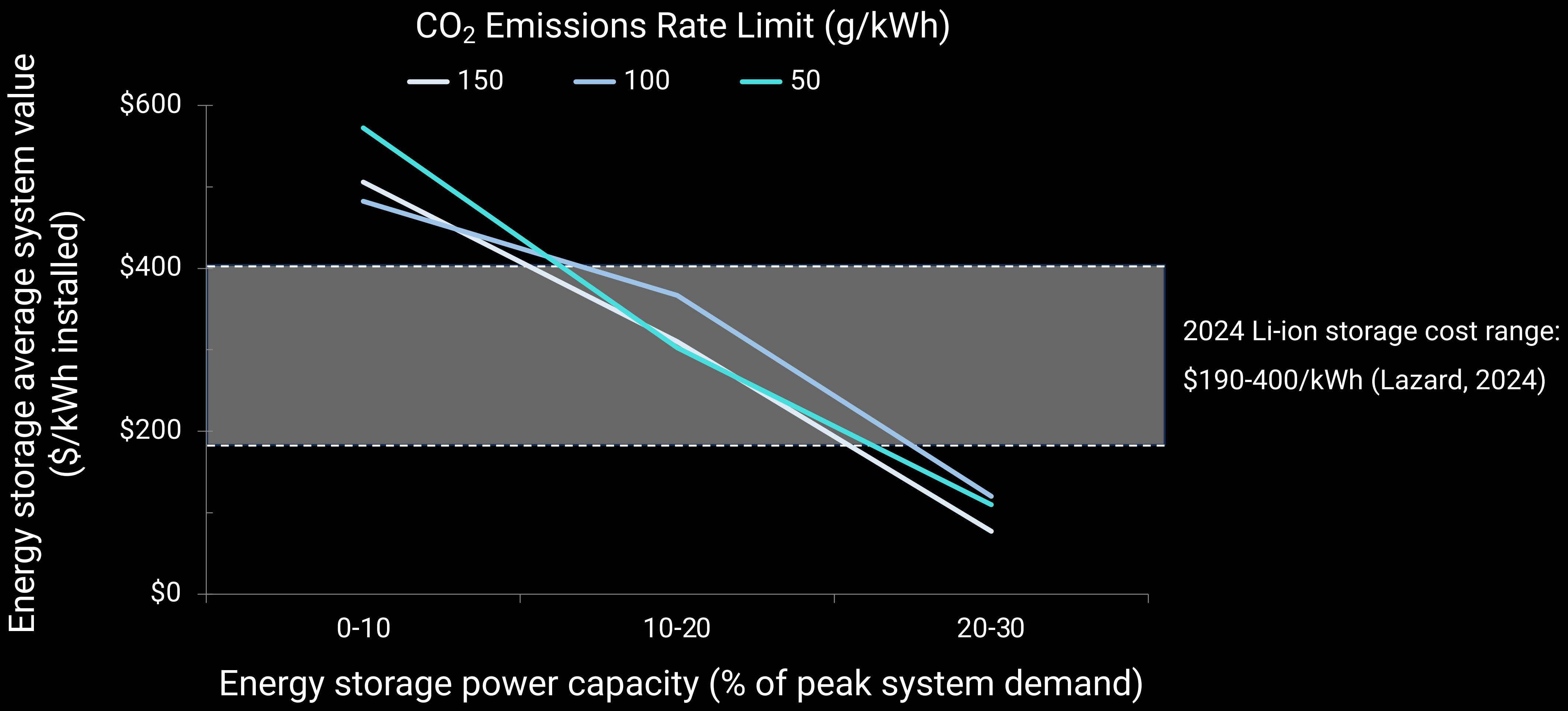
More storage: reduced arbitrage, longer durations



More storage: reduced arbitrage, longer durations



A race between declining cost and declining value

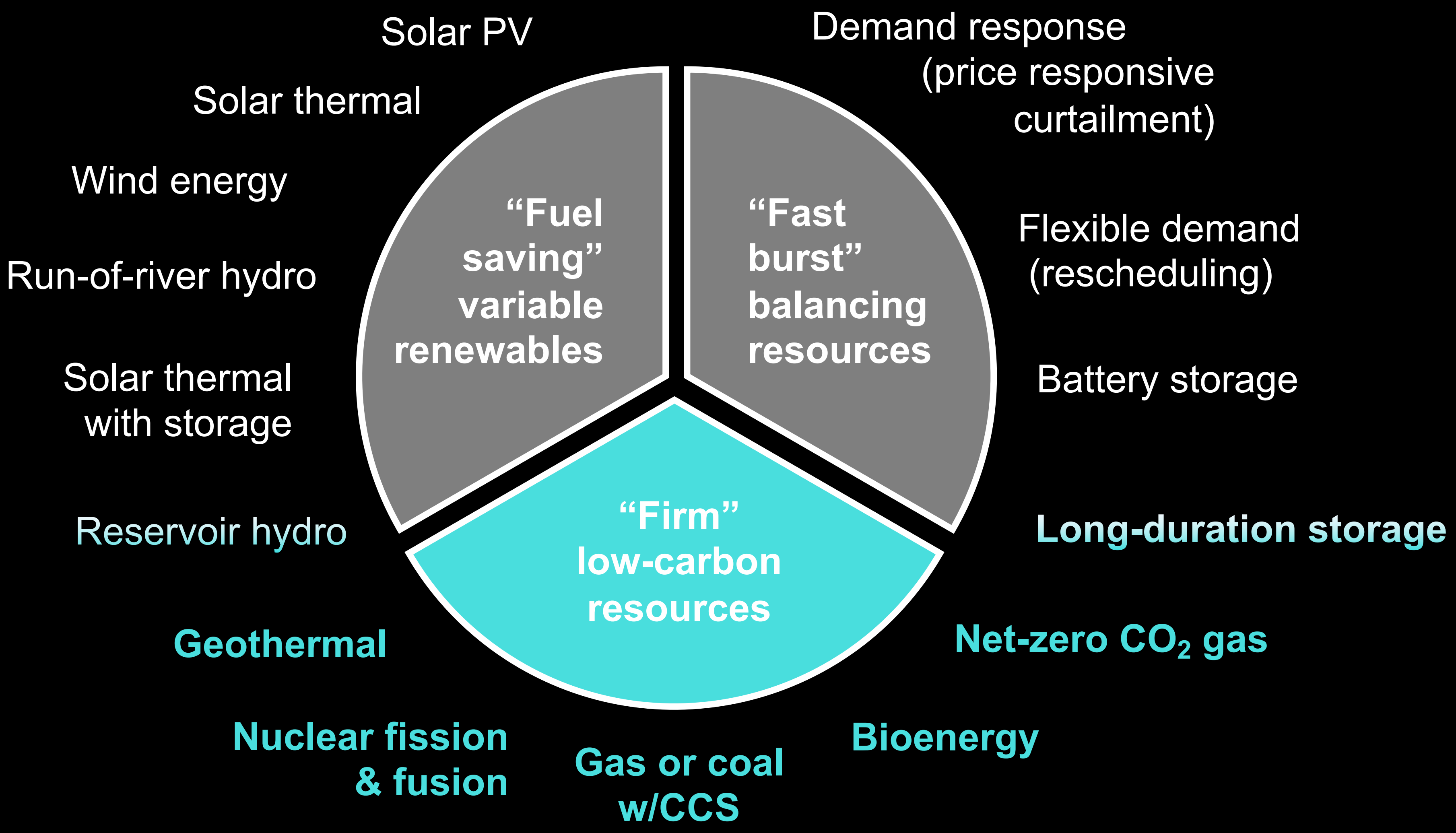


Results from de Sisternes, Jenkins & Botterud (2016), "The value of energy storage in decarbonizing the electricity sector," *Applied Energy* 175: 368-379. https://doi.org/10.1016/j.apenergy.2016.05.014

See also: Mallapragada, Sepulveda & Jenkins (2020), "Long-run system value of battery energy storage in future grids with increasing wind and solar generation," Applied Energy 275(1). https://doi.org/10.1016/j.apenergy.2020.115390

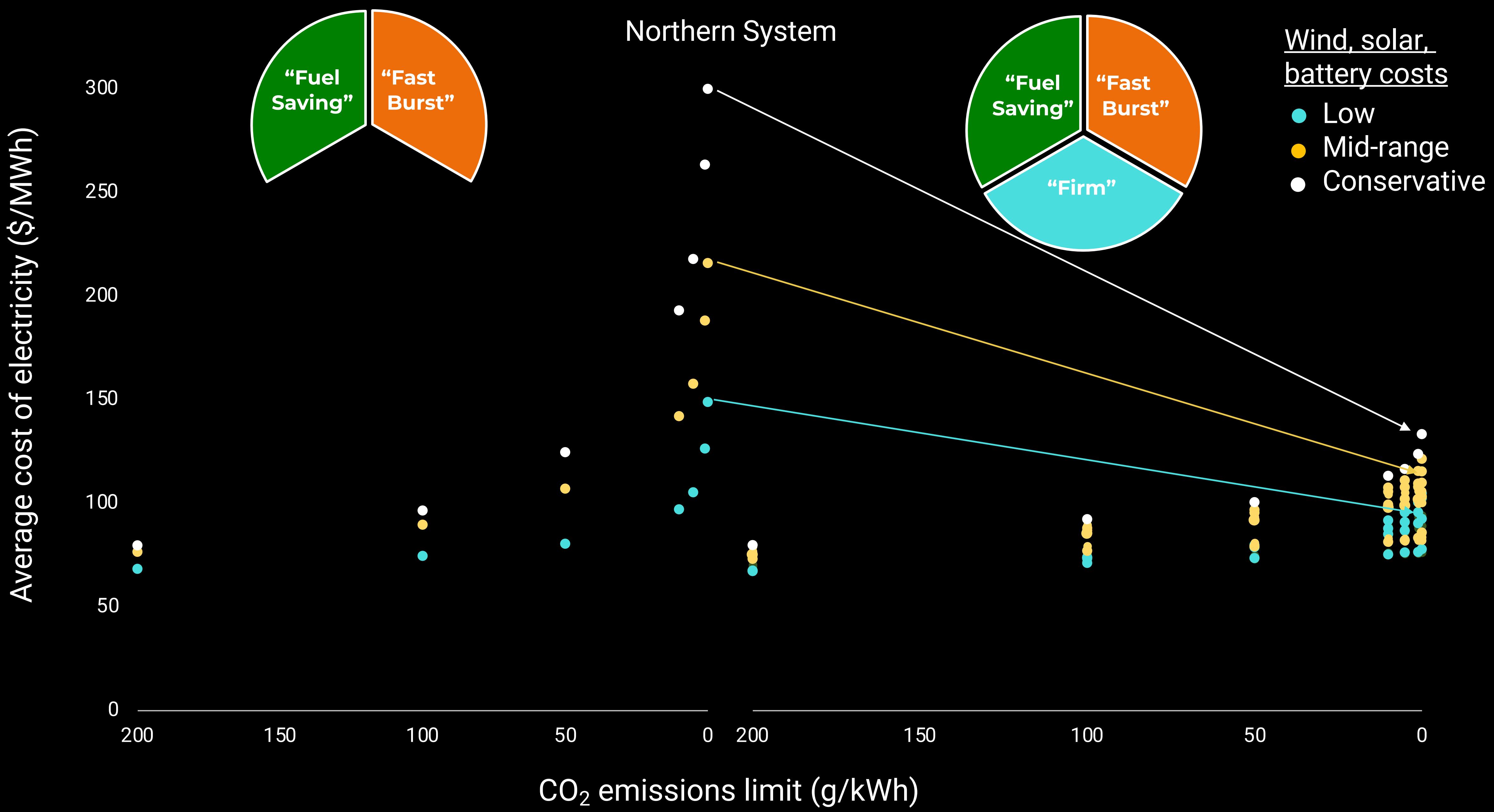
A balanced diet is key

A balanced clean electricity diet



Originally published in: Sepulveda, Jenkins et al. (2018), "The role of firm low-carbon electricity resources in deep decarbonization of power generation, *Joule* 2(11). https://doi.org/10.1016/j.joule.2018.08.006

See also: Baik et al. (2021), "What is different about different net-zero carbon electricity systems," *Energy & Climate Change* 2: https://doi.org/10.1016/j.egycc.2021.100046



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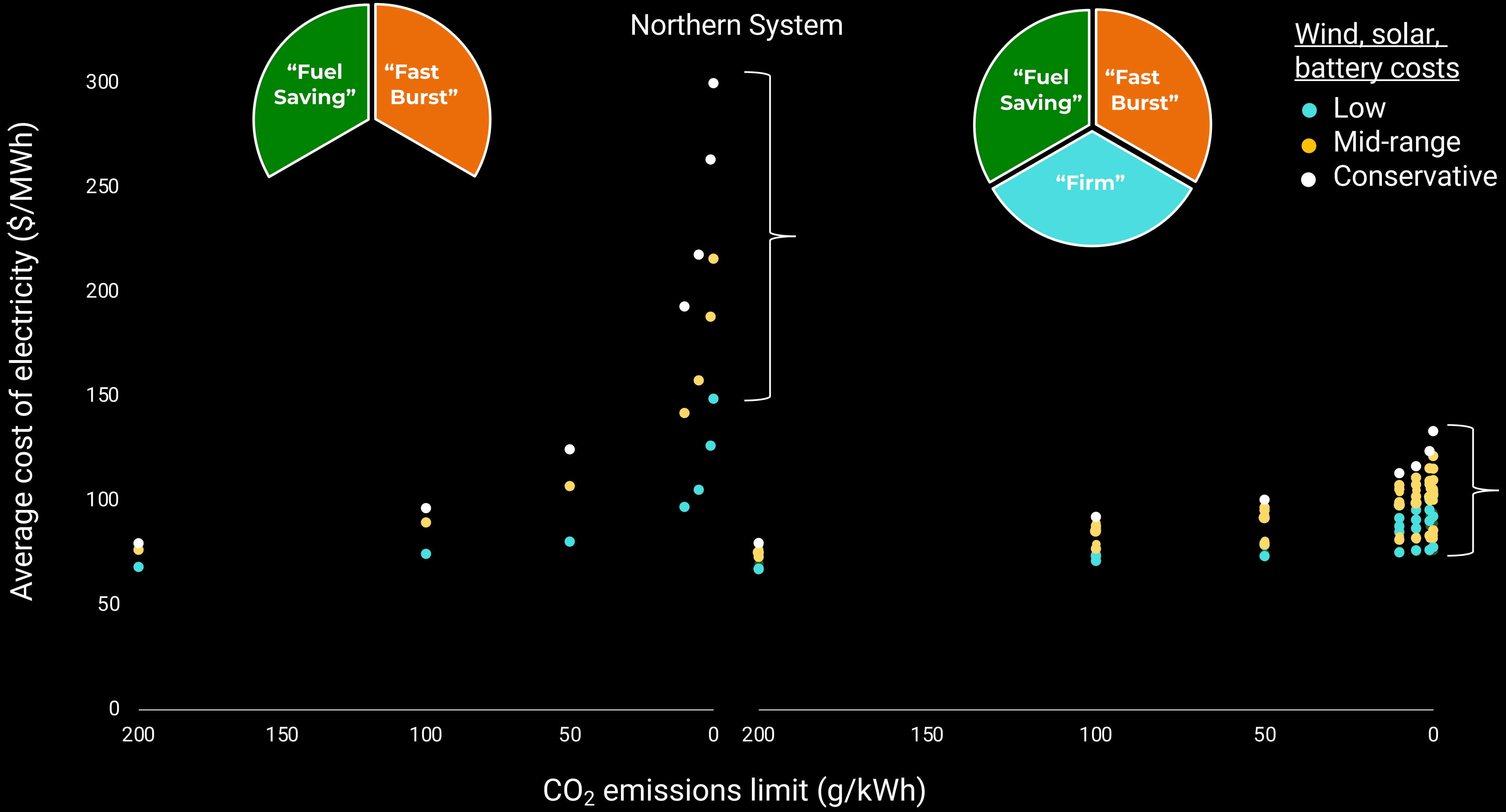
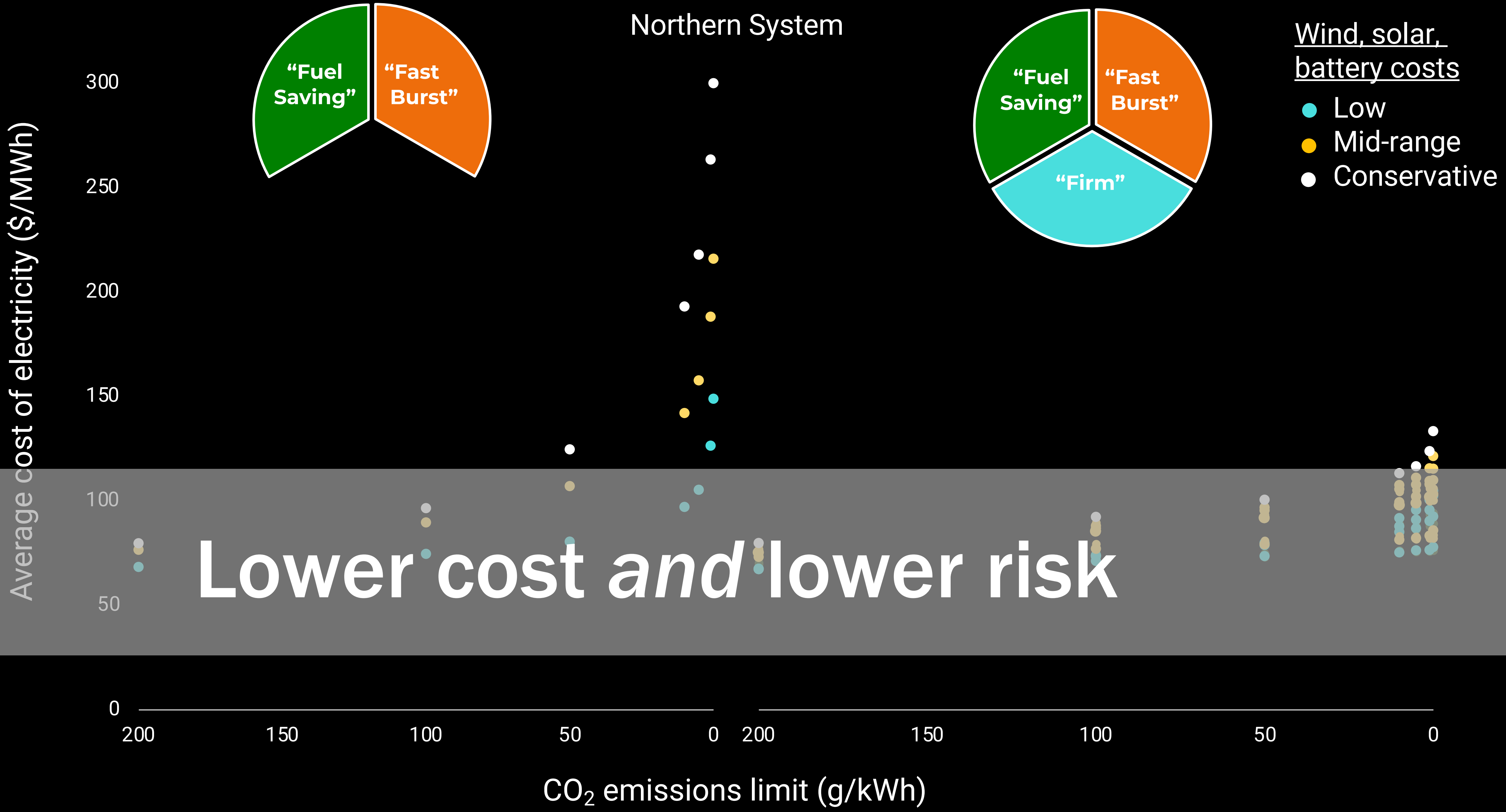
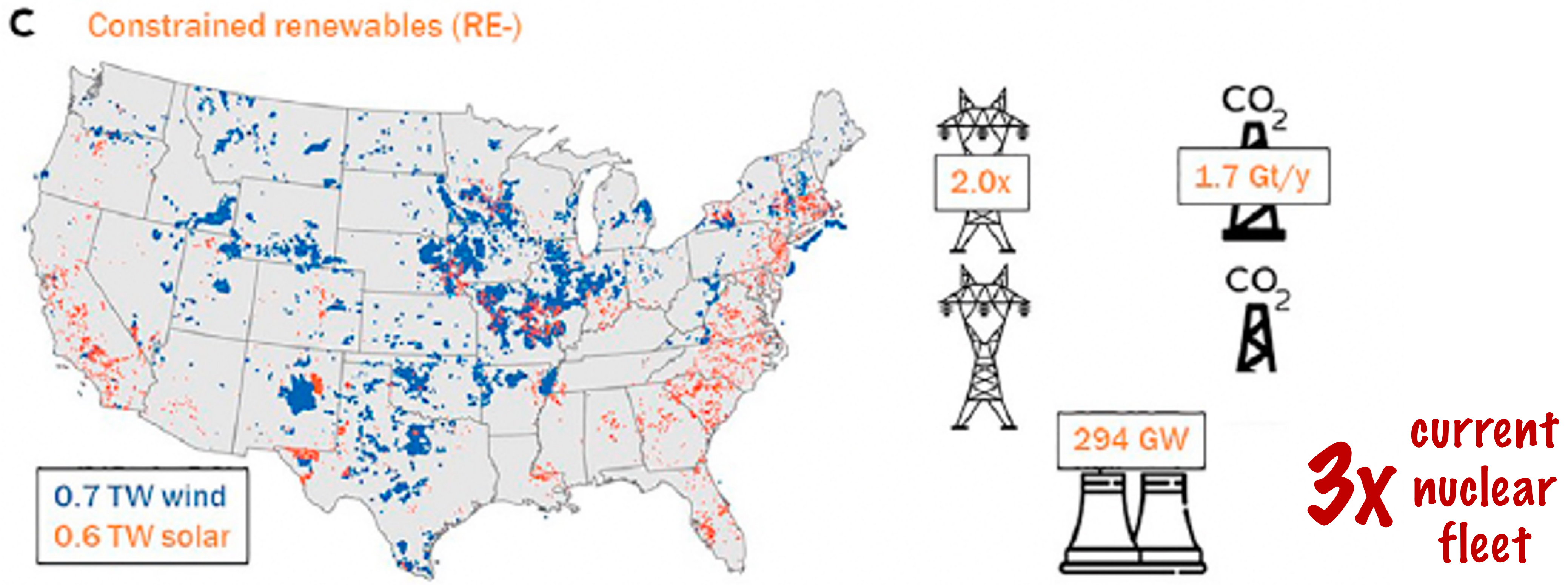


Results from: Sepulveda, Jenkins, et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11). https://doi.org/10.1016/j.joule.2018.08.006



Results from: Sepulveda, Jenkins, et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11). https://doi.org/10.1016/j.joule.2018.08.006

Power density offers advantages



Defining and exploring a new asset class

Evaluating the 'design space' for long-duration energy storage

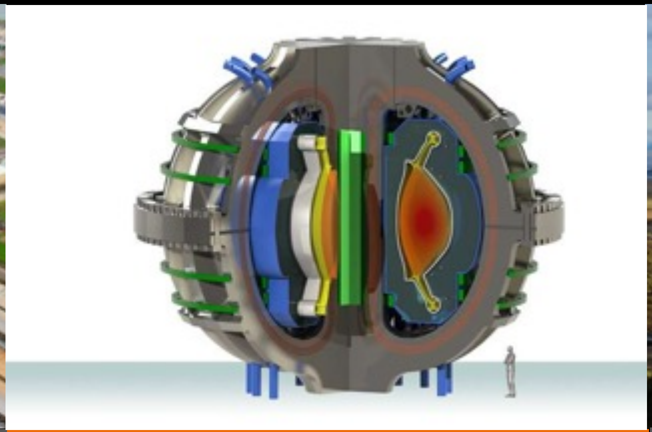
Sepulveda, Jenkins et al. (2021)
Nature Energy 6(5)

Jenkins & Sepulveda (2021)
Joule 5(9)

Evaluating and optimizing natural gas plants with CCS for operating flexibility: ARPA-E FLECCS

Cheng et al. (2022)
I.J. Greenhouse Gas Control 118

Cheng et al. (2025)
arXiv working paper



Cost targets for commercial fusion power plants

with Egemen Kolemen

Schwartz et al. (2023)
Joule 7(4)

Schwartz et al. (2026)
Journal of Fusion Energy 45(1)

Evaluation of enhanced geothermal systems with in-reservoir energy storage

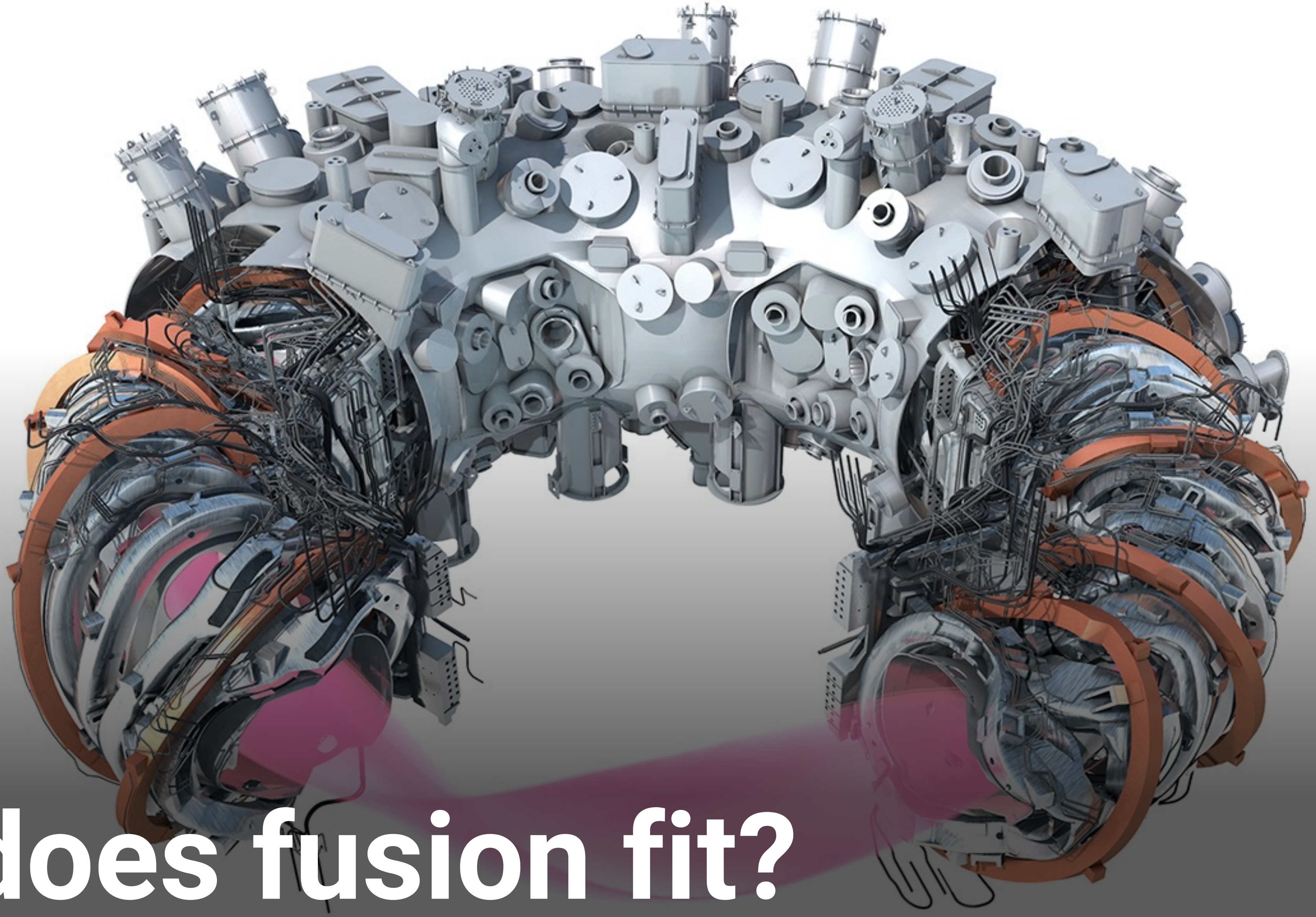
Ricks et al. (2022)
Applied Energy 313

Ricks et al. (2024)
Nature Energy

DOE (2024) *Commercial Liftoff*

Ricks & Jenkins (2025), *Joule* 9(7)

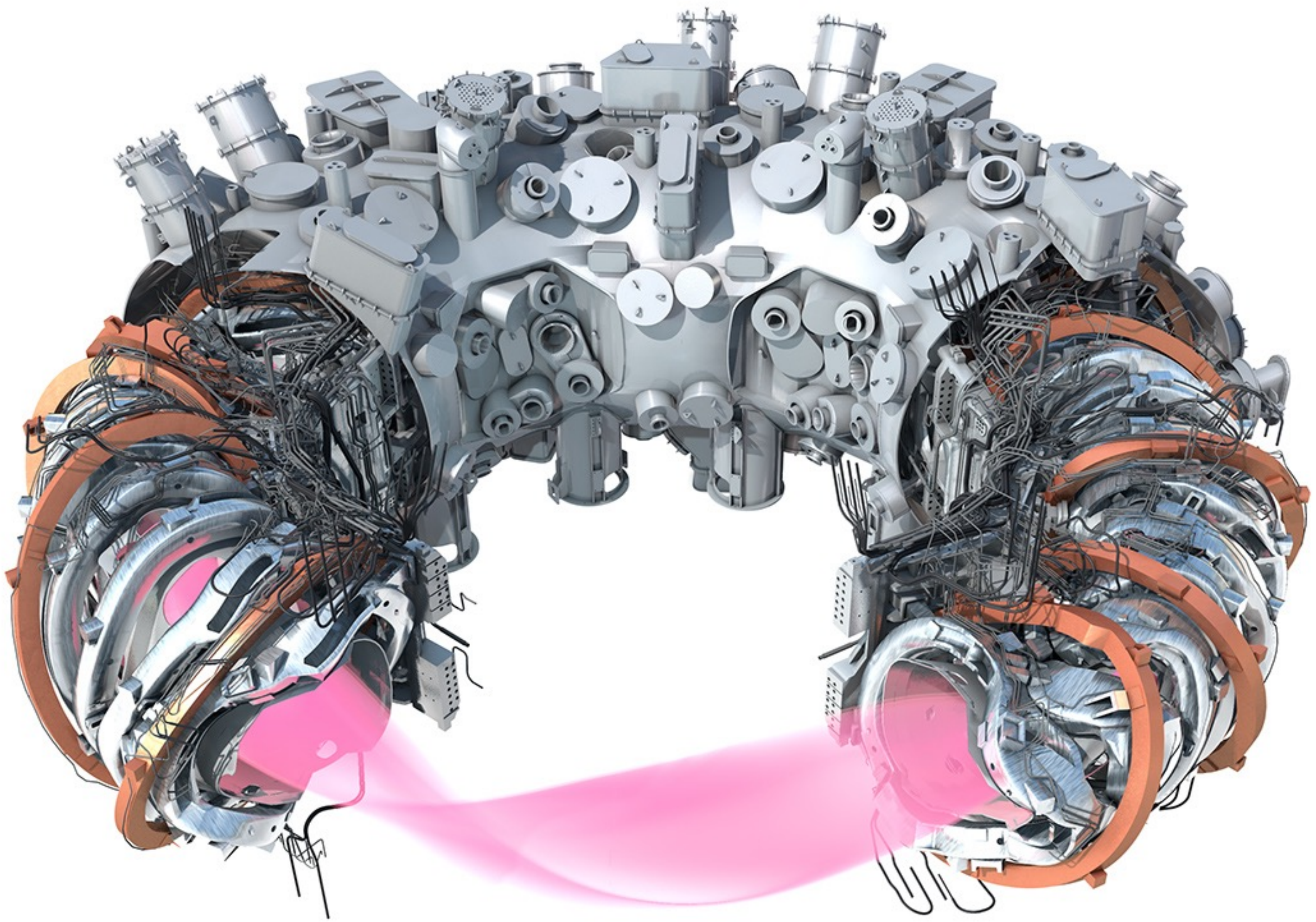
U.S. DEPARTMENT OF ENERGY · arpa·e Advanced Research Projects Agency • ENERGY · FERVO ENERGY · PPPL · Google · GE · Breakthrough Energy · CLEAR PATH



Where does fusion fit?

Producing "unlimited" clean energy doesn't cut it!

Unlimited *affordable* clean energy is required



The competition: from science fiction to reality

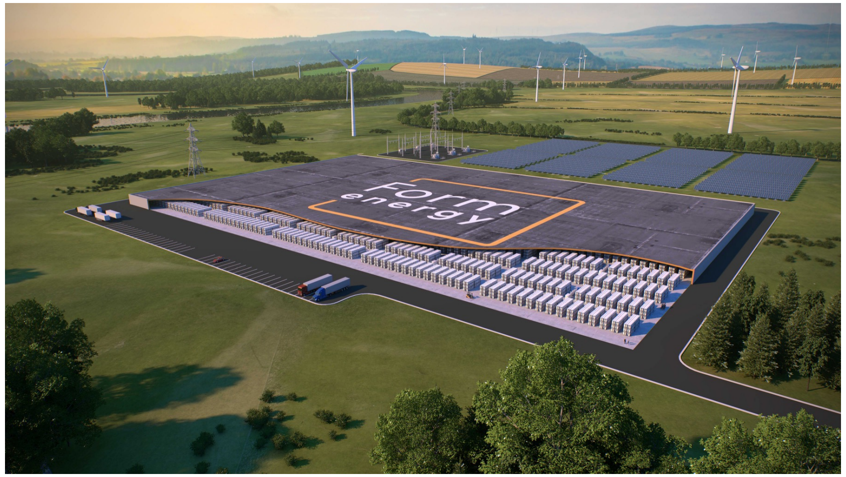
Gas with carbon capture

100% hydrogen turbines

Small modular nuclear reactors

Advanced geothermal (enhanced & closed loop)

Low-cost, long-duration energy storage



Fusion must compete on cost

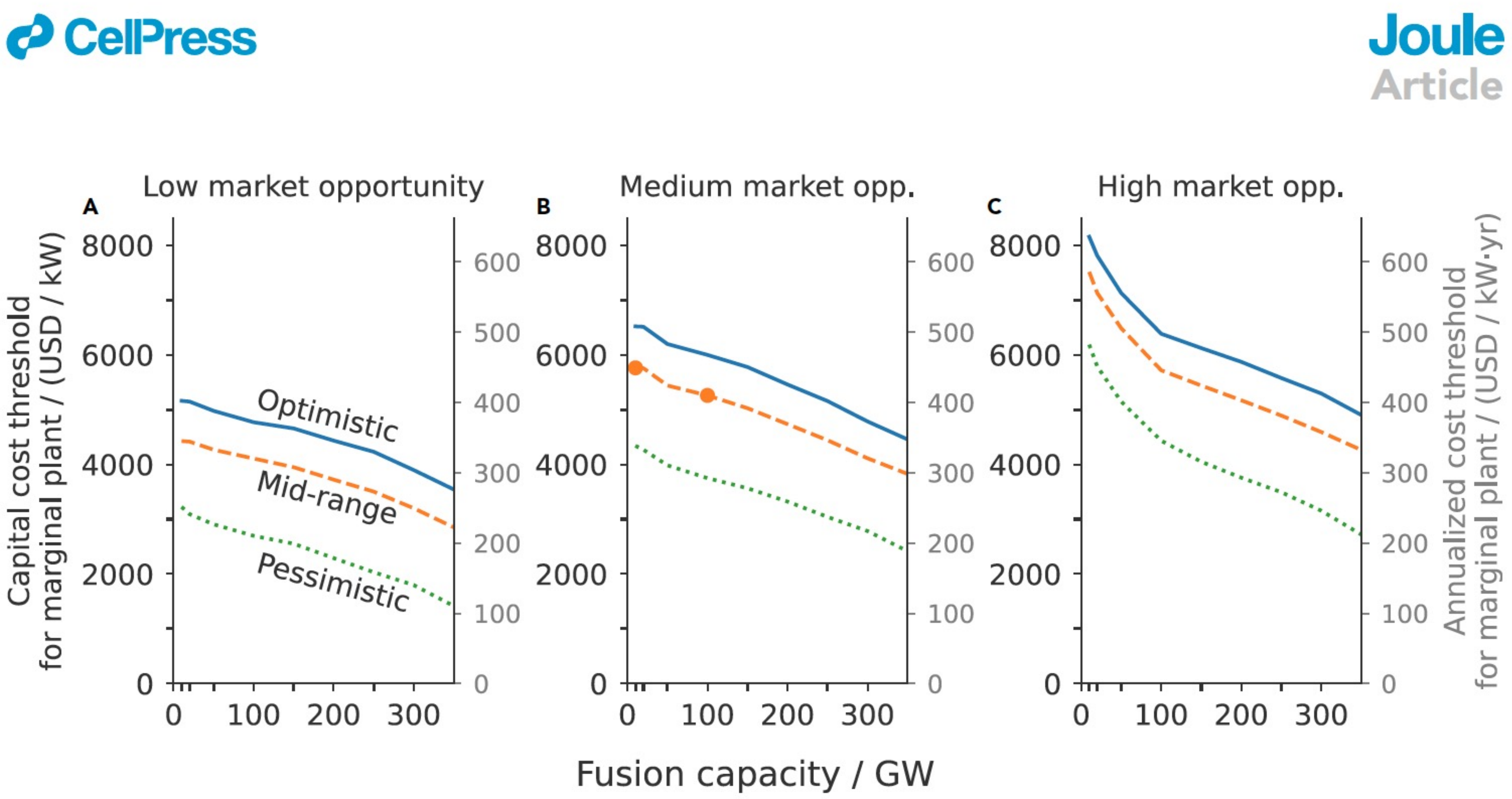


Figure 2. Cost thresholds for a marginal unit of fusion capacity as a function of the total installed fusion capacity

The cost threshold for a marginal unit of fusion capacity corresponds to the maximum breakeven capital cost for the final fusion plant built to reach a specified total installed capacity. Results are presented for three reference reactors without integrated thermal storage and in the three market opportunity scenarios. Annualized costs are 7.8% of the capital cost per year: see Note S2 for details. The two bold points on the mid-range core, medium market opportunity scenario curve highlight how a decrease in capital cost of $500/kW can increase the capacity penetration from 10 to 100 GW. See Figure S9 for cost thresholds in additional scenarios.

See:
Schwartz et al. (2023)
Joule 7(4)

Cost targets depend on competing resources, variable costs of fusion plant

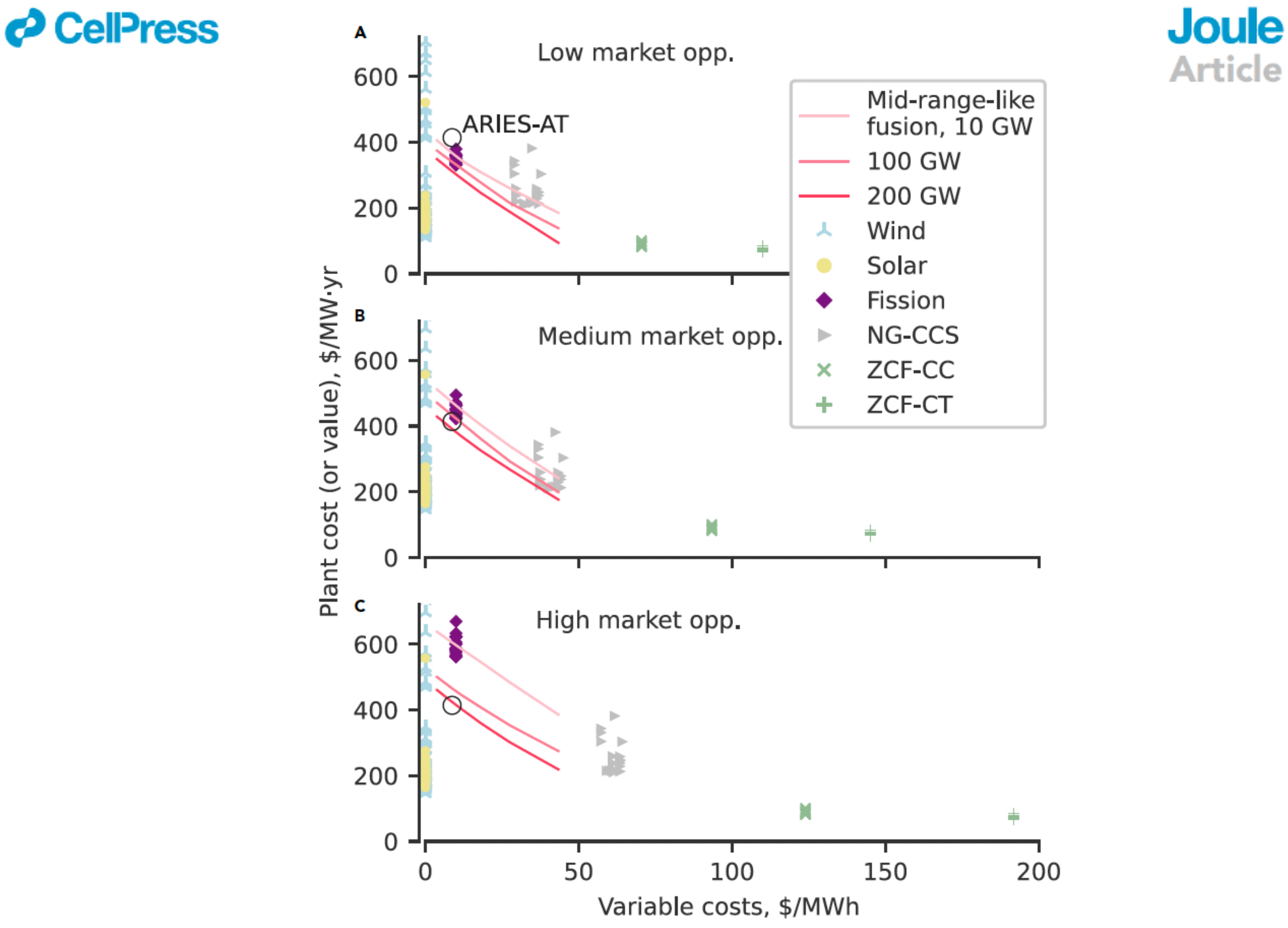


Figure 4. The value of fusion compared with the costs of competitor resources

See:
Schwartz et al. (2023)
Joule 7(4)

Will fusion be baseload? Not necessarily

CellPress

Joule
Article

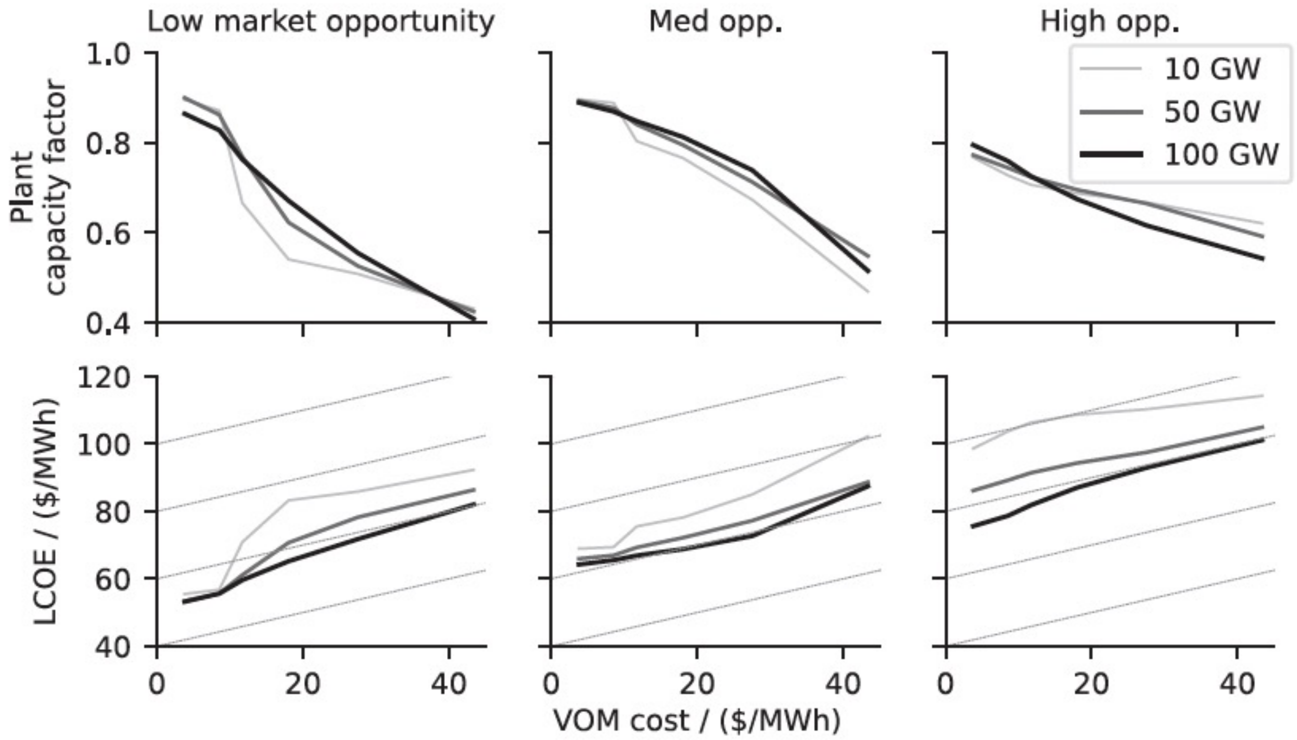
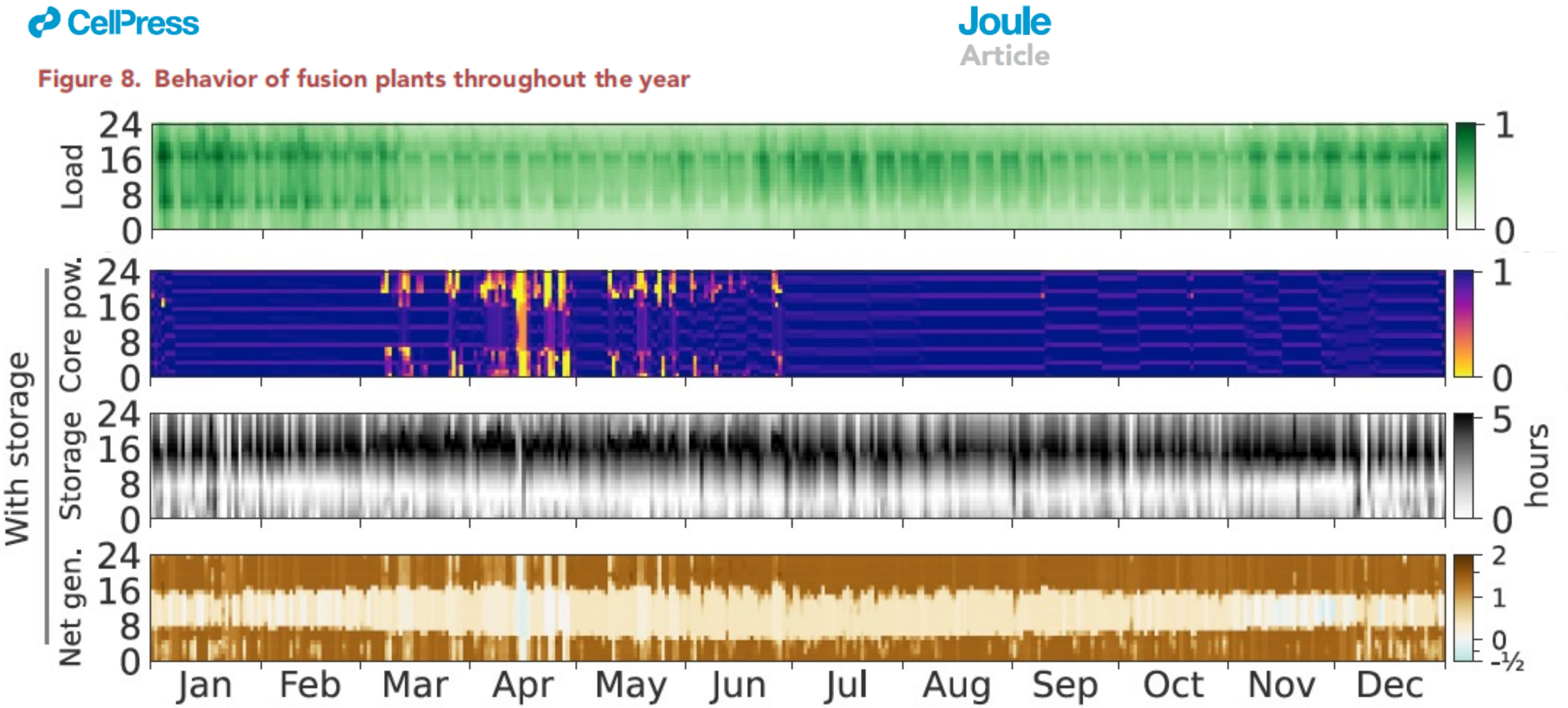


Figure 7. Fusion plant capacity factors and LCOE
Top row: capacity factors for mid-range-like plants with varying VOM costs in the three market opportunity scenarios, for three levels of capacity penetration, and without a TSS. Bottom row: computed "cost of electricity" metrics for the same plants, taking into account their capacity factor. Dashed lines with a slope of 0.5 guide the eye.

See:
Schwartz et al. (2023)
Joule 7(4)

Should fusion integrate thermal storage?



See: Schwartz et al. (2023) *Joule* 7(4)

Where do we really need fusion?

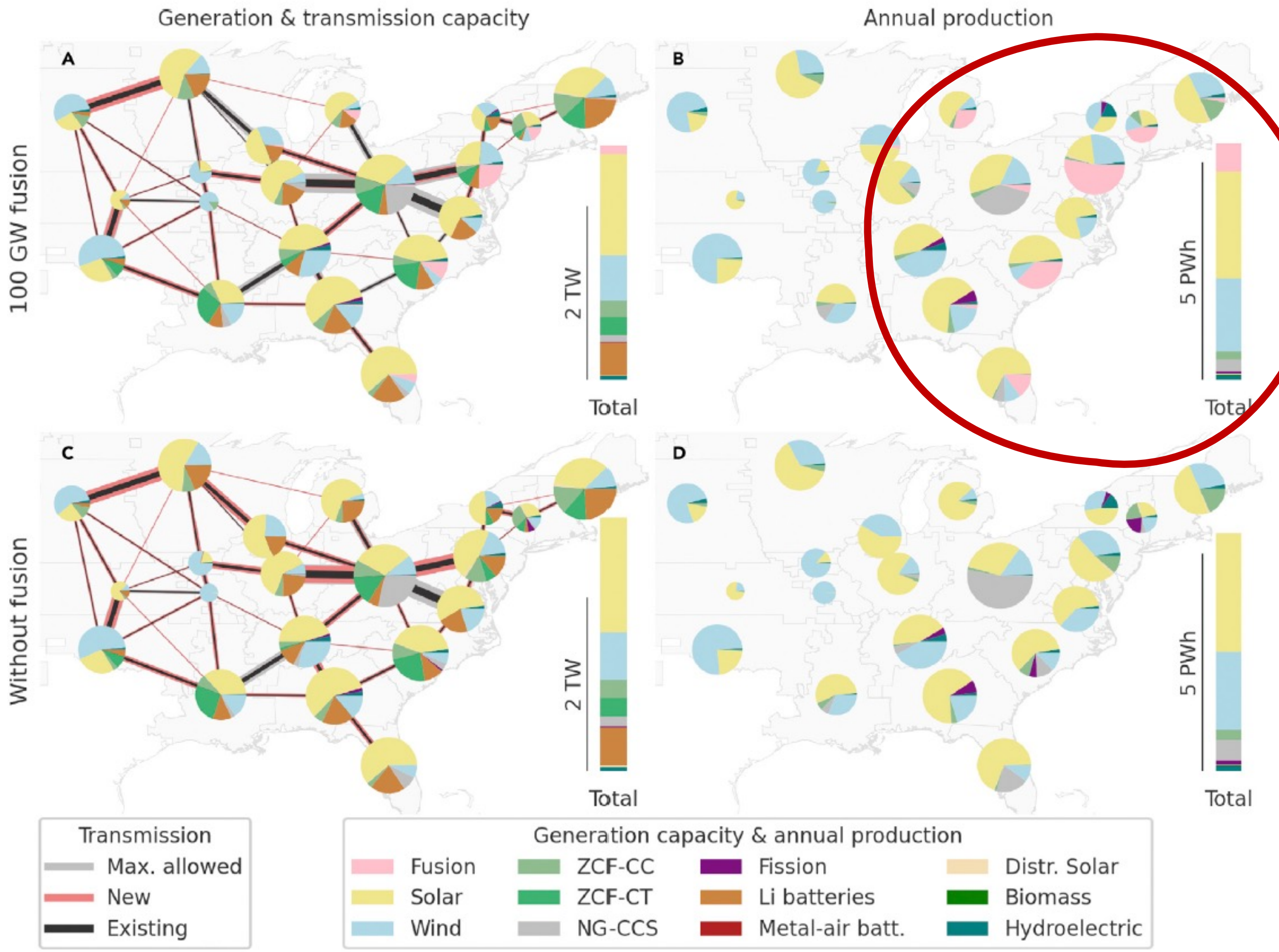


Figure 10. Map of electricity resource deployment and production

Generation capacity, transmission capacity, and annual production of each resource type in the high market opportunity scenario, for cases with 100 GW of mid-range fusion reactors (top) and without fusion (bottom). Fusion capacity is mostly along the eastern seaboard, where it is built (A versus C) instead of solar, wind, NG-CCS, and batteries and (B versus D) displaces a portion of their electricity production. The quantity of new transmission built (A versus C) is significantly smaller with the addition of fusion as a firm resource. See also Figures S35–S38 for maps of fusion deployment in other scenarios.

Joule
Article

See:
Schwartz et al. (2023)
Joule 7(4)

Rethinking maintenance strategies

Journal of Fusion Energy (2026) 45:15
https://doi.org/10.1007/s10894-026-00551-5

RESEARCH

Valuing Maintenance Strategies for Fusion Plants as Part of a Future Electricity Grid

Jacob A. Schwartz[1,4] · Wilson Ricks[2,3] · Egemen Kolemen[2,3] · Jesse D. Jenkins[2,3]

Received: 2 July 2025 / Accepted: 19 January 2026

Abstract
Scheduled maintenance is likely to be lengthy and therefore consequential for the economics of fusion power plants. The maintenance strategy that maximizes the economic value of a plant depends on internal factors such as the cost and durability of the replaceable components, the frequency and duration of the maintenance blocks, and the external factors of the electricity system in which the plant operates. This paper examines the value of fusion power plants with various maintenance properties in a decarbonized United States Eastern Interconnection circa 2050. Seasonal variations in electricity supply and demand mean that certain times of year, particularly spring to early summer, are best for scheduled maintenance. Seasonality has two important consequences. First, the value of a plant can be 15% higher than what one would naively expect if value were directly proportional to its availability. Second, in some cases, replacing fractions of a component in shorter maintenance blocks spread over multiple years is better than replacing it all at once during a longer outage, even through the overall availability of the plant is lower in the former scenario.

Keywords Power plant · Maintenance · Seasonality · Electricity market · Economics

See: Schwartz et al. (2026)
Journal of Fusion Energy

"…replacing fractions of a component in shorter maintenance blocks spread over multiple years is better than replacing it all at once during a longer outage, even though the overall availability of the plant is lower in the former scenario."

The electricity decarbonization playbook:

1. **Build wind & solar at record pace**
2. **Expand the grid & storage**
3. **Retire coal**
4. **Preserve existing nuclear**
5. **Maintain natural gas capacity (on net)**

These steps can deliver 80-90% cut in CO_2 emissions by 2035 with bulk electricity supply costs comparable to or lower than today's

Just two more steps to 100% clean electricity

1. Build wind & solar at record pace
2. Expand the grid & storage
3. Retire coal
4. Preserve existing nuclear
5. Maintain natural gas capacity (on net)
6. **Demonstrate clean firm resources in mid-to-late 2020s**
7. **Transition to clean firm resources in 2030s and 2040s**

8. Fusion goes here?

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Bibliography: see https://zero.lab.princeton.edu/publications/

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