Clean Electricity and the Road to Net-Zero

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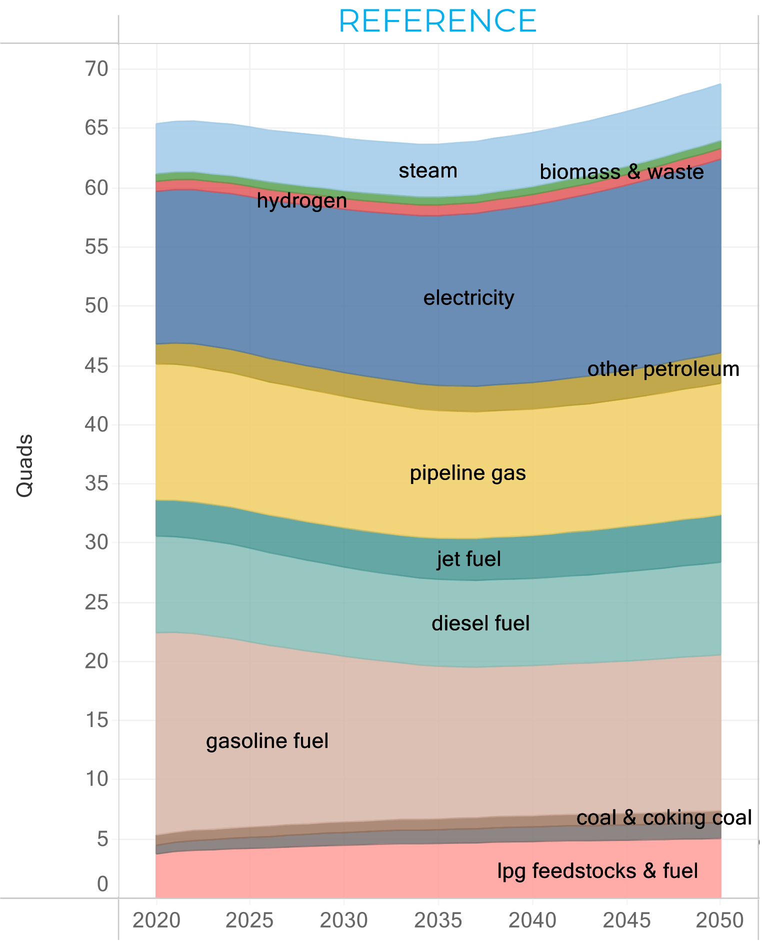
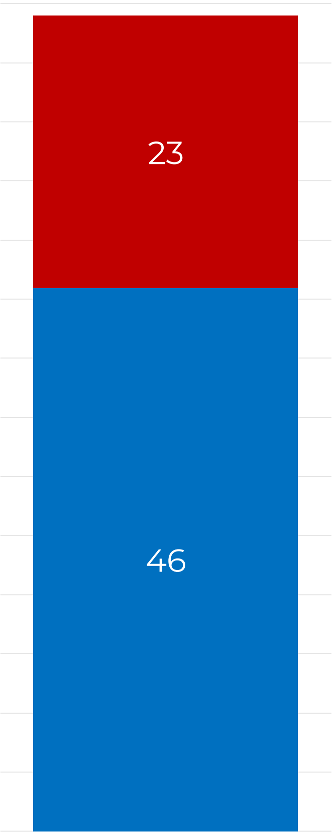
NET-ZERO AMERICA:

Potential Pathways, Infrastructure, and Impacts

https://netzeroamerica.princeton.edu/

Sizing up the challenge





~23 quads of non-hydrocarbon final energy demands could be satisfied with **zero carbon electricity** (1/3 of total)

~46 quads demand for hydrocarbons (2/3 of total), **too large** to meet with biofuels or offset with negative emissions or land use changes.

The Net Zero Strategy

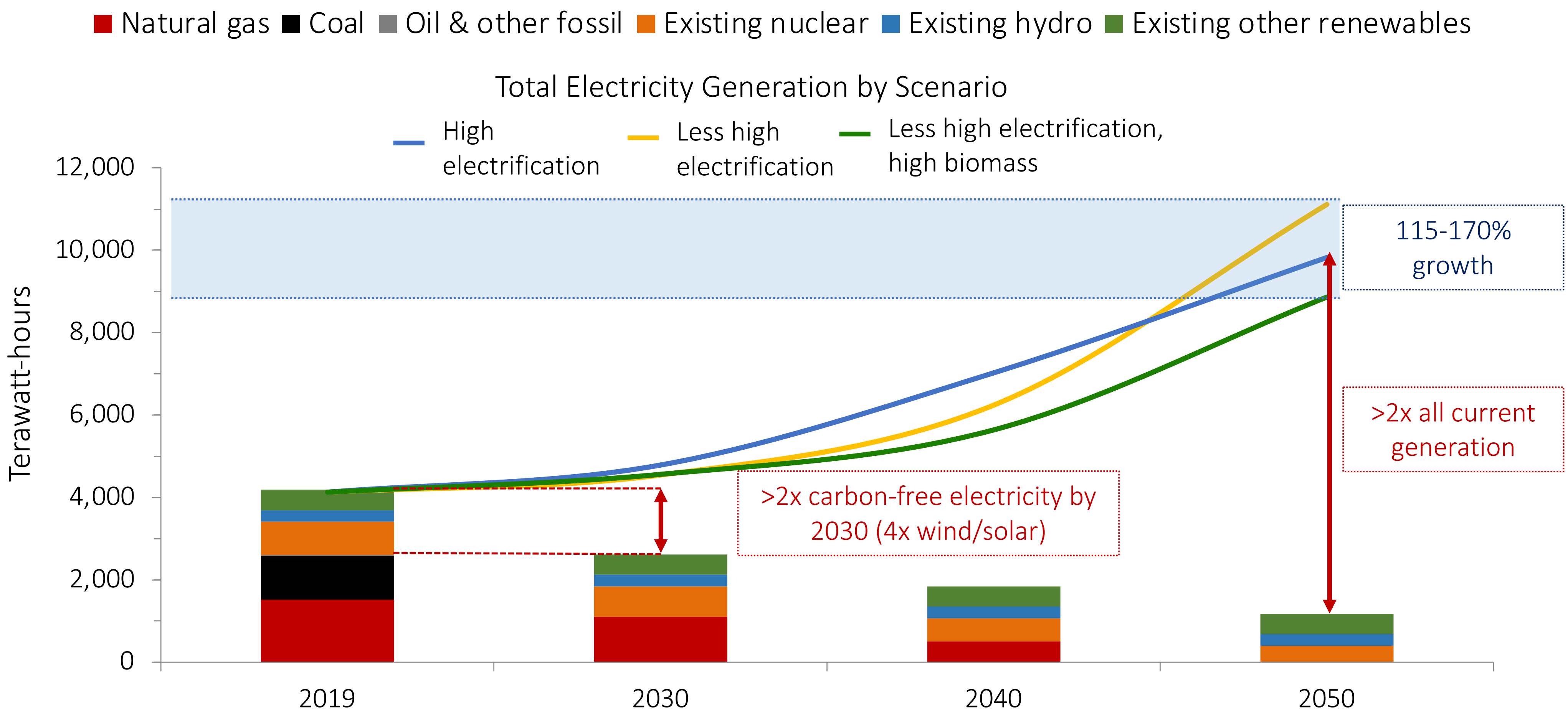
1. Clean electricity

2. Efficiency & electrification

3. Net-zero fuels

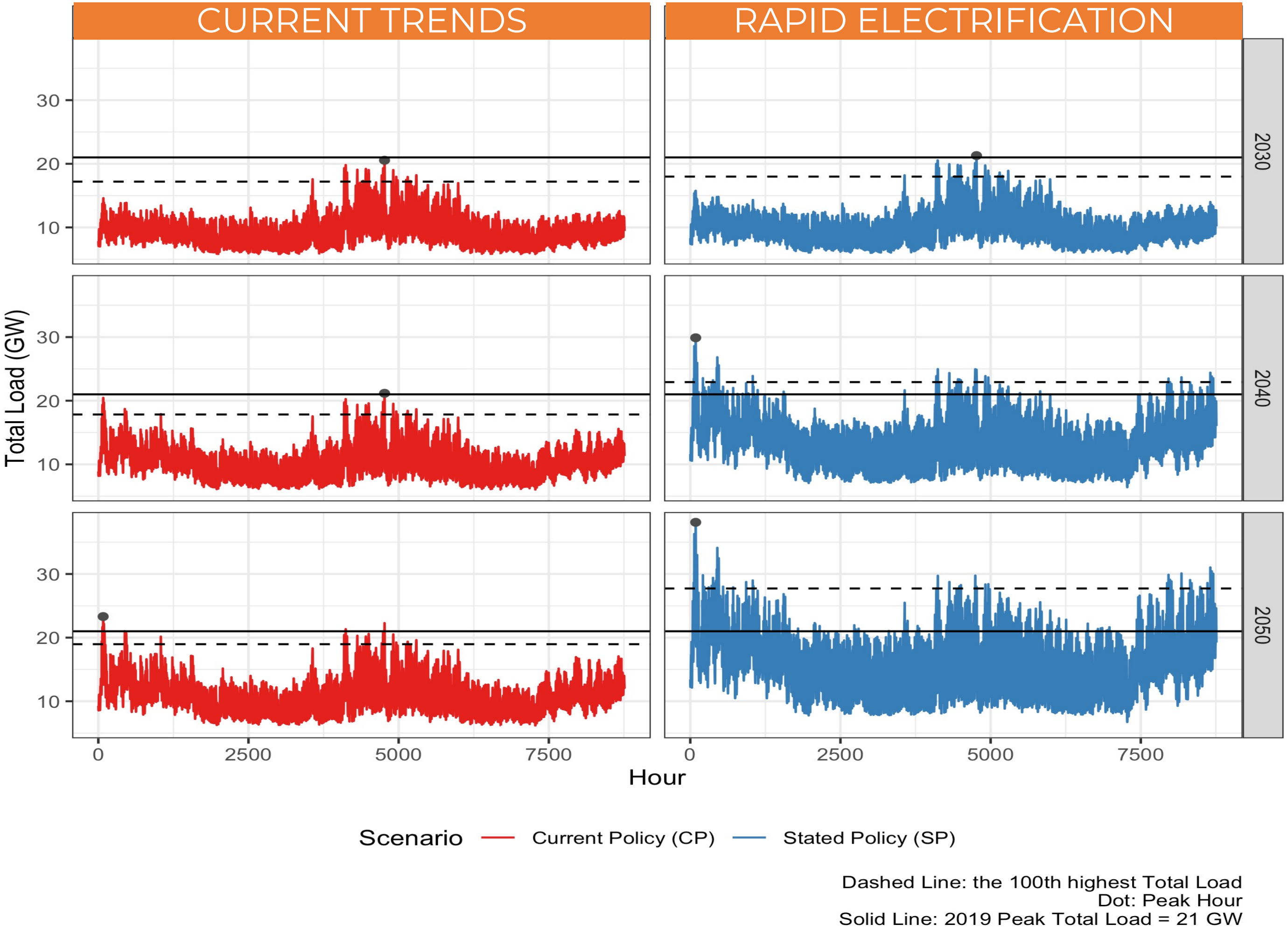
4. Carbon capture and sequestration

CLEAN ELECTRICITY: THE LINCHPIN FOR A NET-ZERO ECONOMY



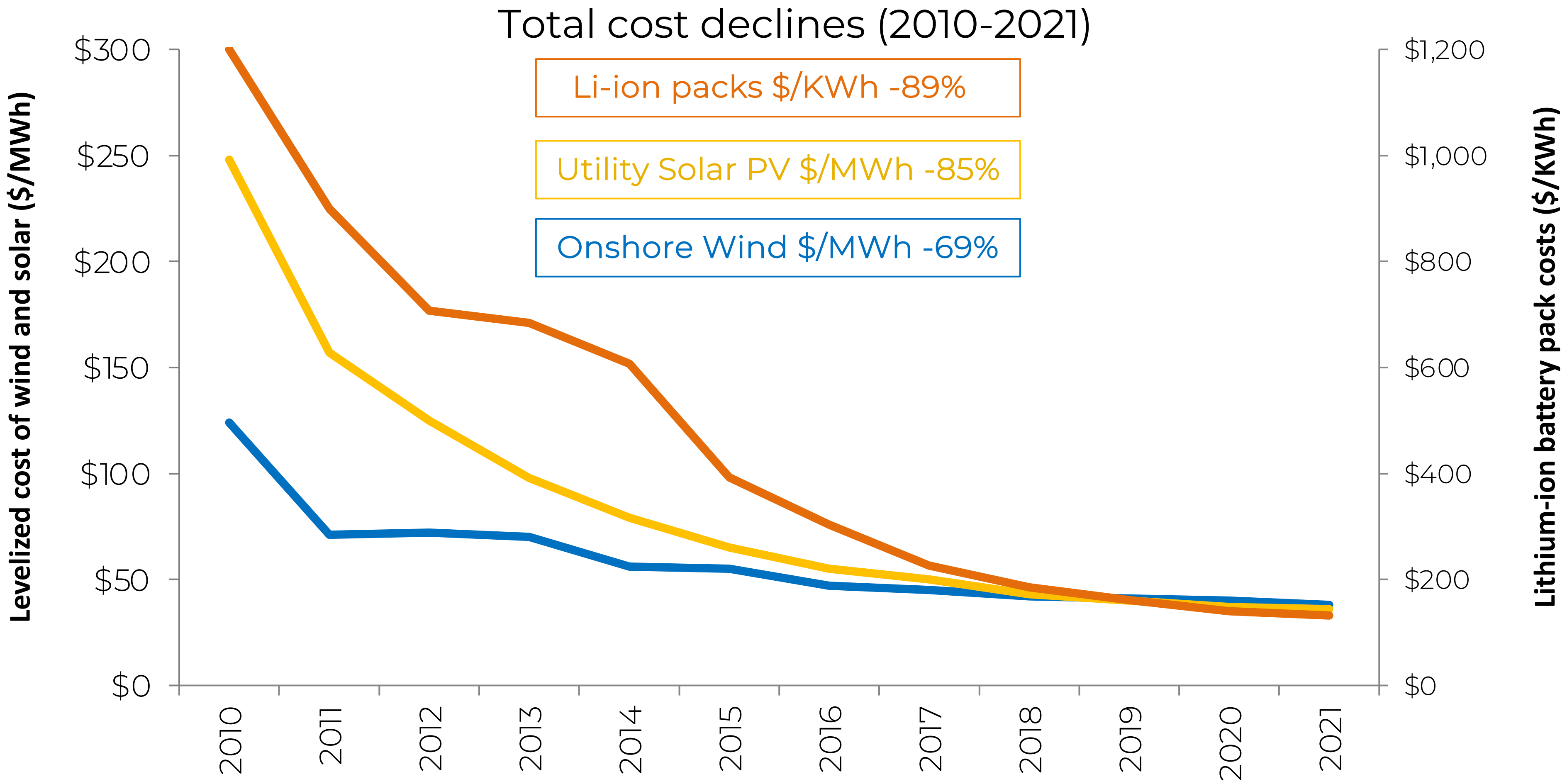
Data source: Larson et al. (2020), *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, interim report, Princeton University, Princeton, NJ, December 15, 2020.

ELECTRIFICATION CHANGES PATTERNS OF DEMAND SIGNIFICANTLY



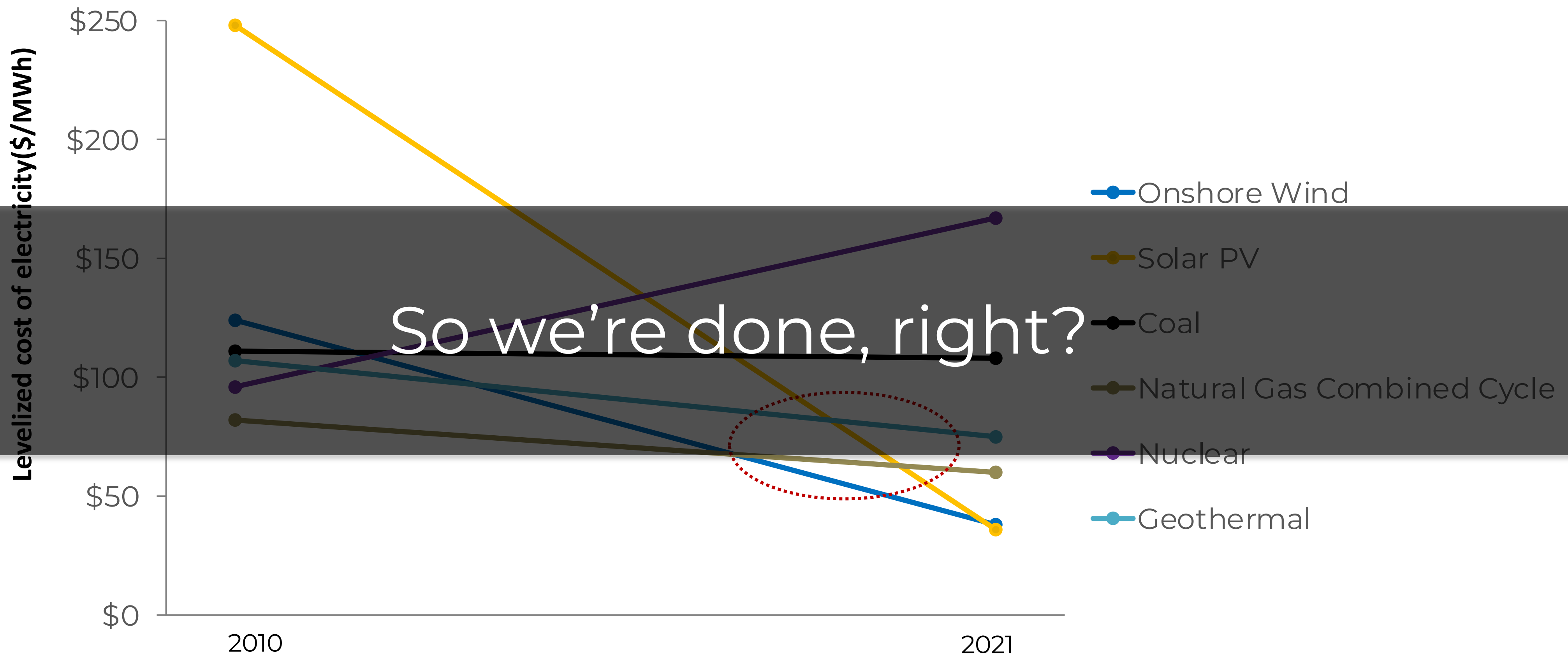
Data source: Xu et al. (2022), "New Jersey's Pathway to 100% Carbon-Free Electricity," Princeton University, Princeton, NJ, March 2022. https://zenodo.org/record/6386823#.Yrmo7BPMI-Q

THE GOOD NEWS: WIND, SOLAR, BATTERY COSTS PLUMMET…



Data Sources: Wind & solar costs from Lazard (2021), Lazard's Levelized Cost of Energy Analysis – Version 15.0.
Battery pack costs from Bloomberg New Energy Finance (2021), Battery Price Survey.

…AND ARE NOW CHEAPER THAN NEW FOSSIL GENERATION

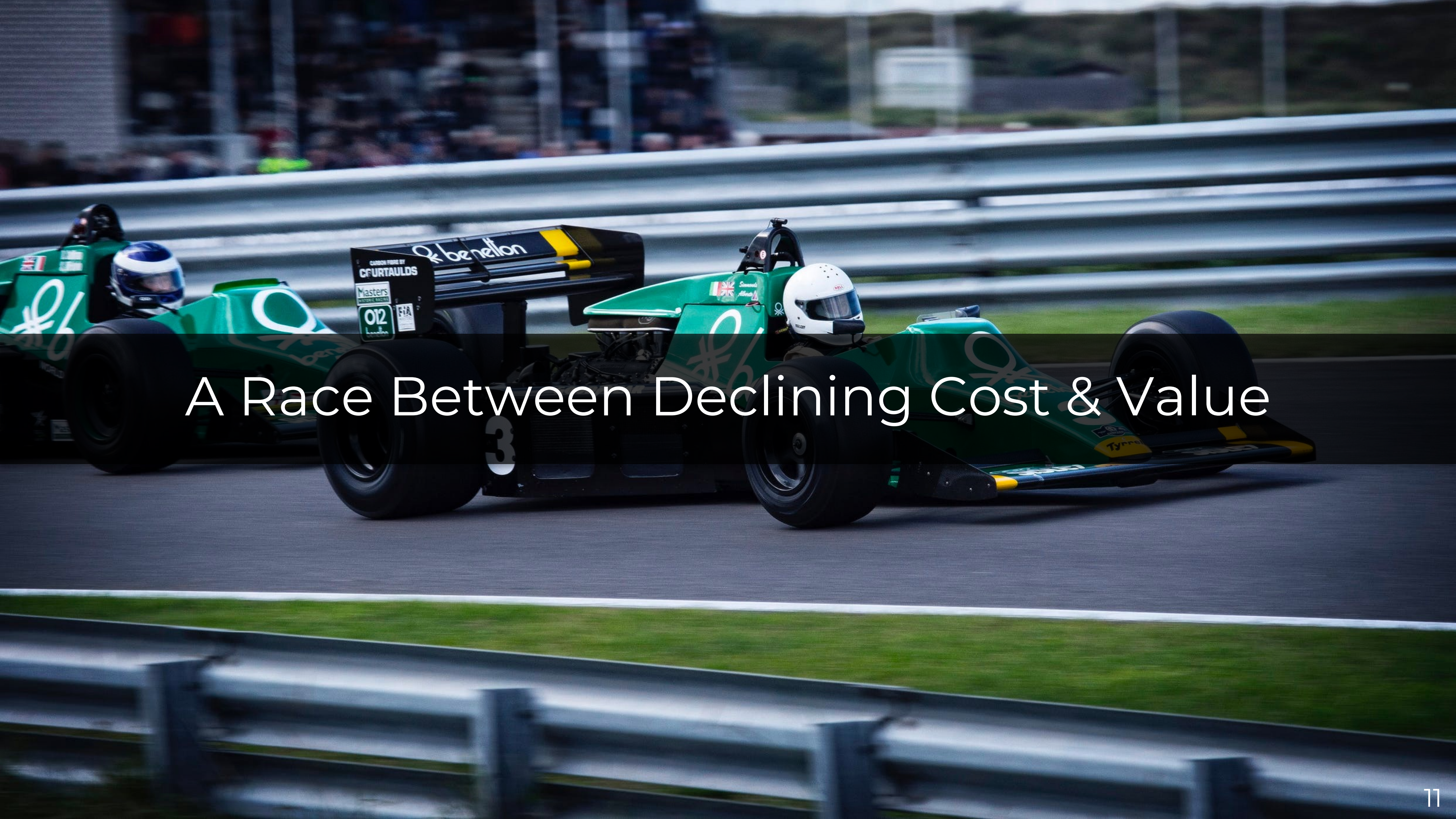


So we’re done, right?

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

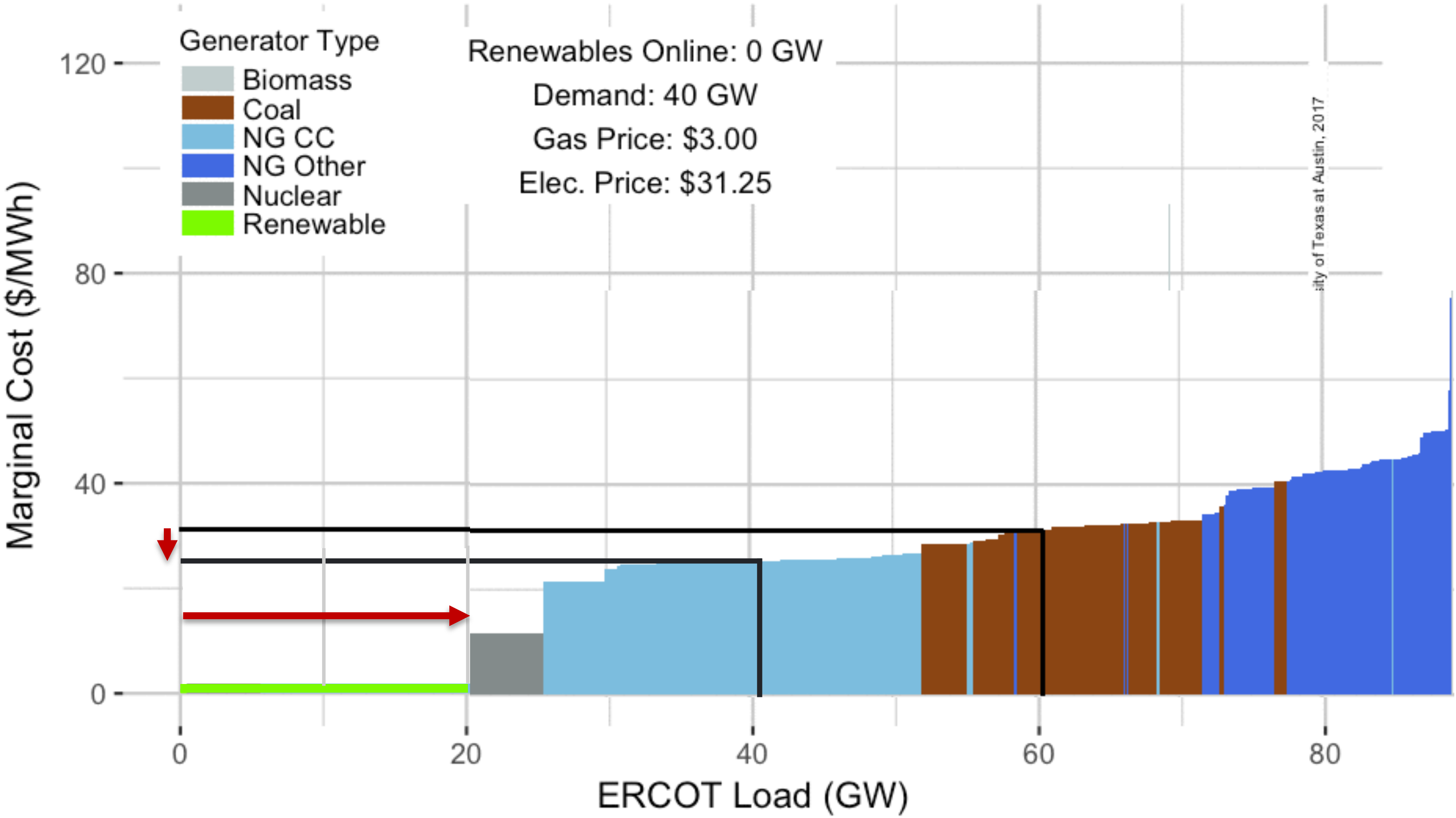
?

A balanced diet is key



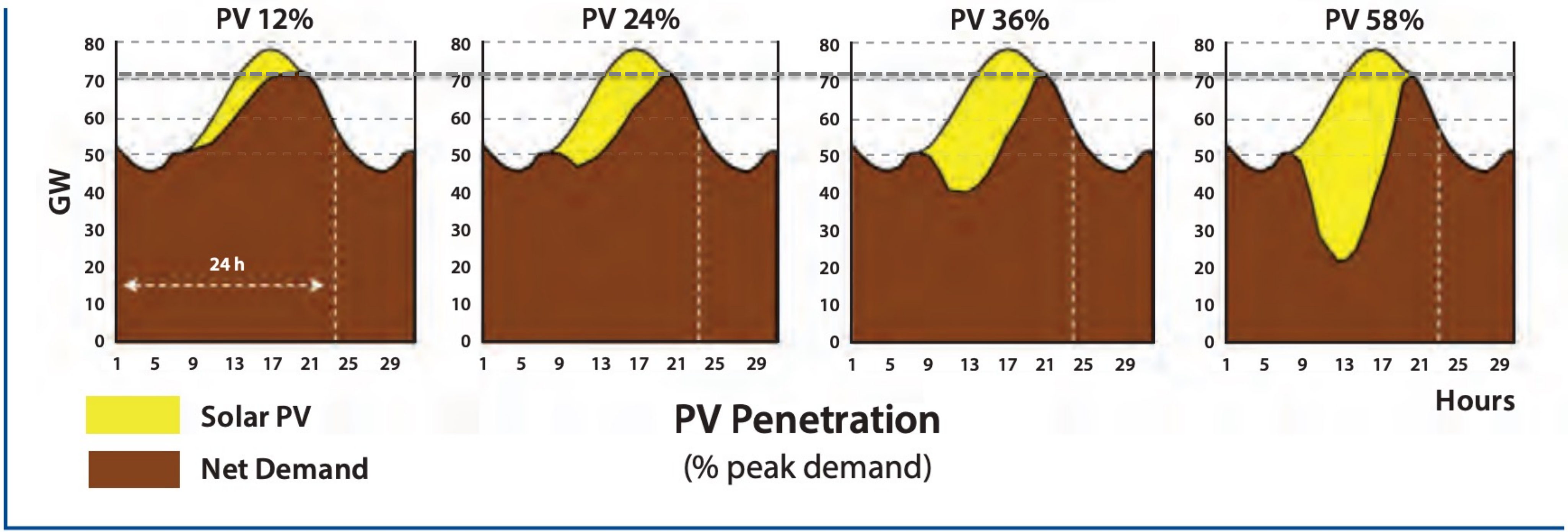
A Race Between Declining Cost & Value

KEY MECHANISMS: DECLINING “FUEL SAVING” VALUE (ENERGY VALUE)



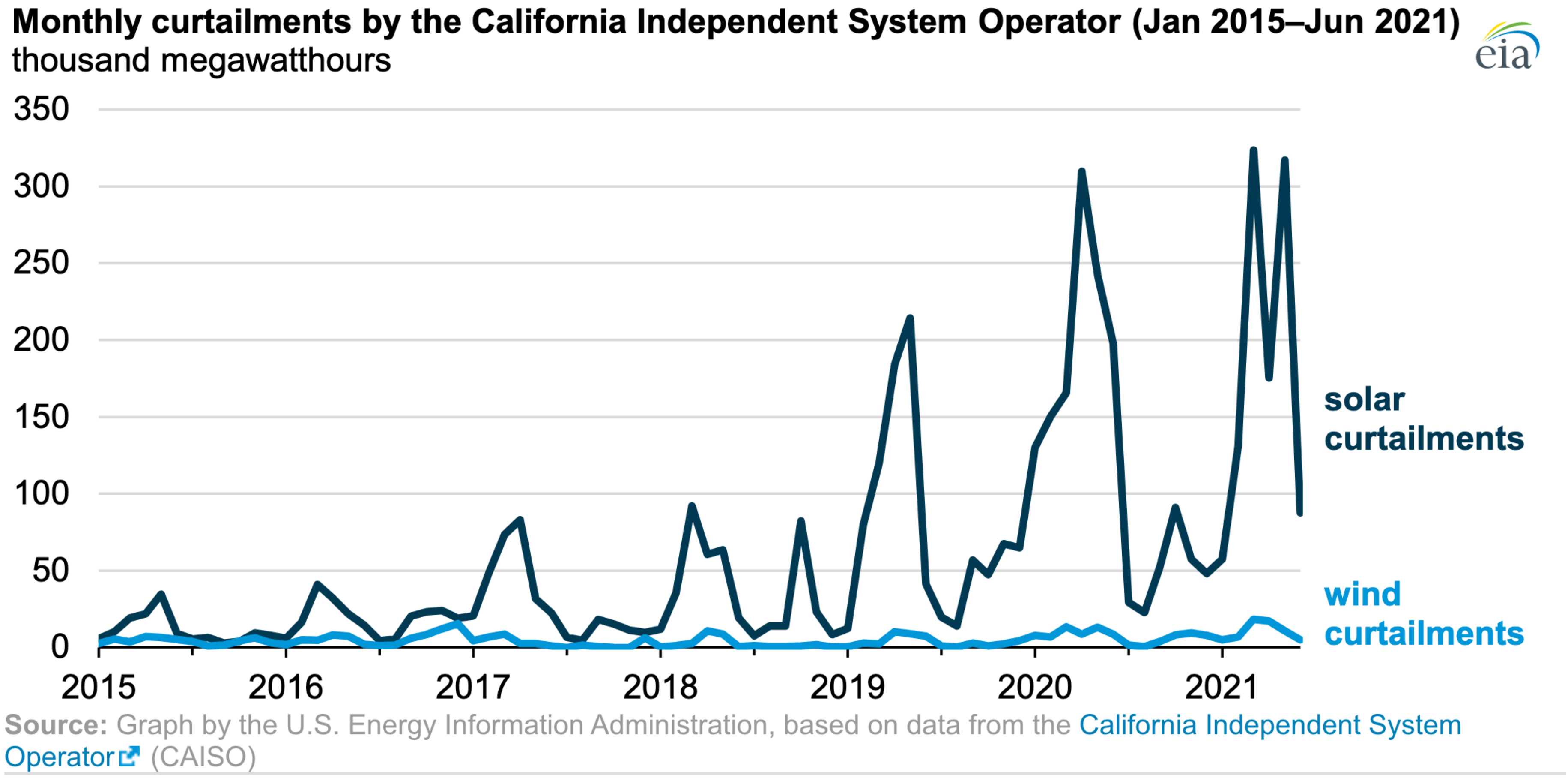
Source: J. Rhodes et al. 2017, “Are solar and wind really killing coal, nuclear and grid reliability?”
https://theconversation.com/are-solar-and-wind-really-killing-coal-nuclear-and-grid-reliability-76741

Figure 8.1 ERCOT Net Load for a Typical Summer Day at Different Levels of Solar PV Penetration



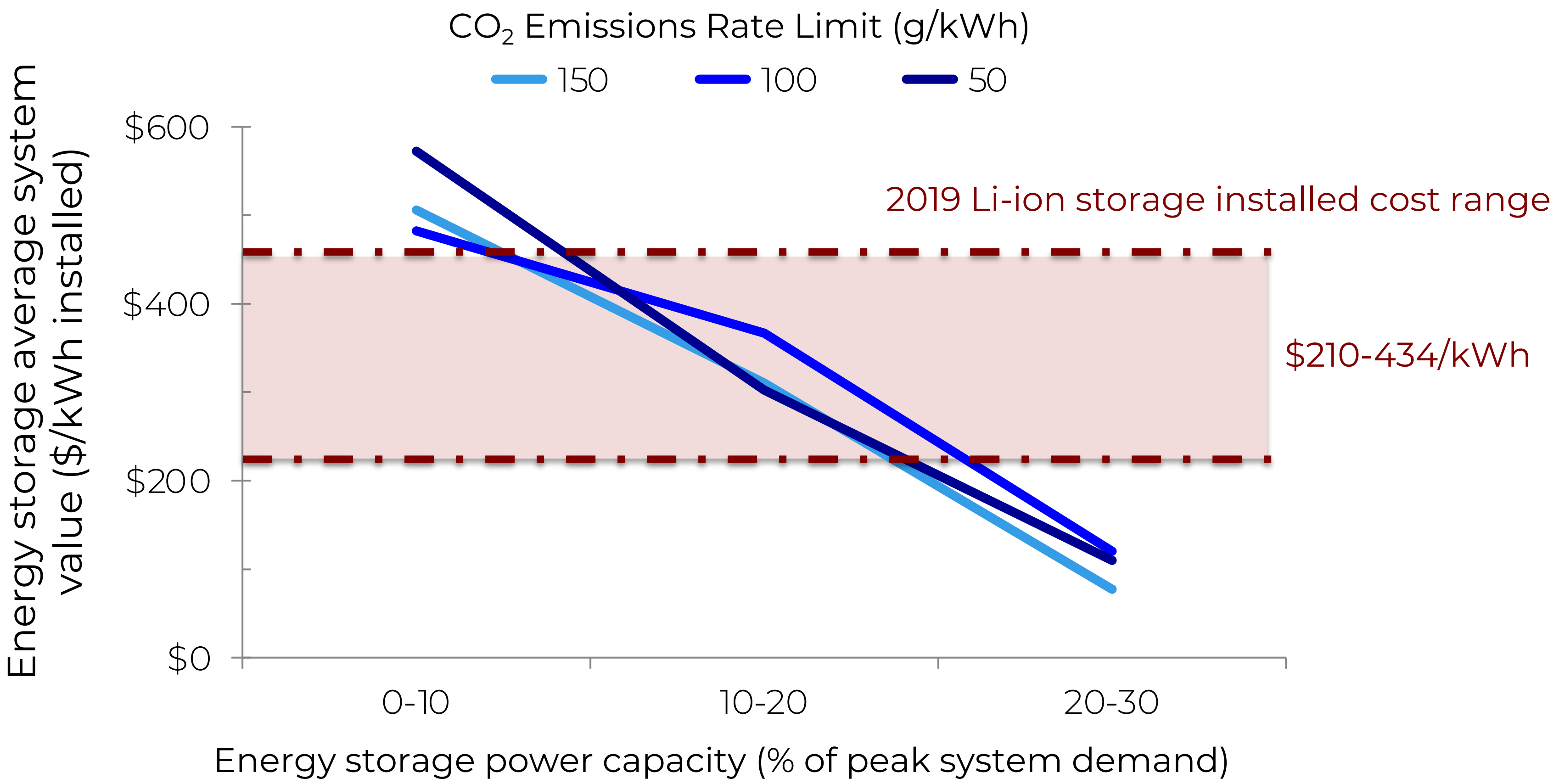
Source: Schmalensee et al. 2015, *The Future of Solar Energy*, Massachusetts Institute of Technology, https://energy.mit.edu/research/future-solar-energy/

WIND/SOLAR VALUE DECLINE: OVERGENERATION



Source: U.S. EIA, 2021, "California's curtailments of solar electricity generation continue to increase," *Today in Energy*, August 24, 2021, https://www.eia.gov/todayinenergy/detail.php?id=49276

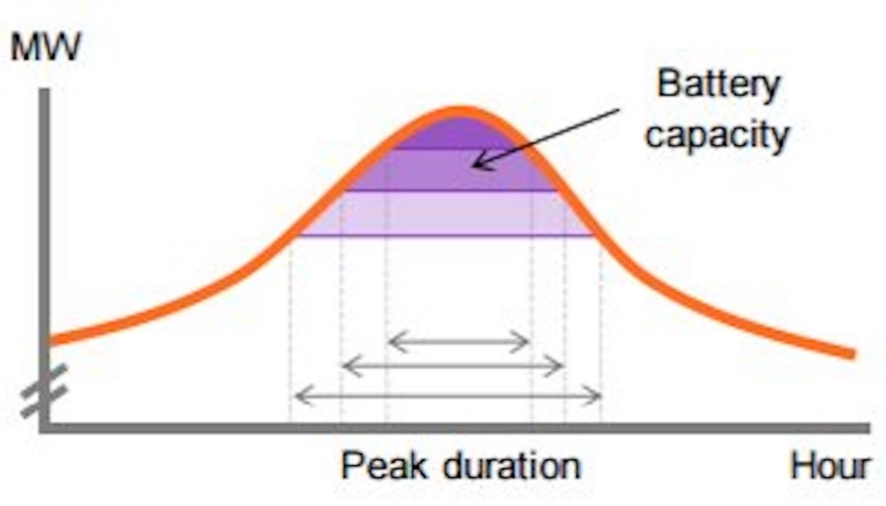
A RACE AGAINST DECLINING VALUE: ENERGY STORAGE



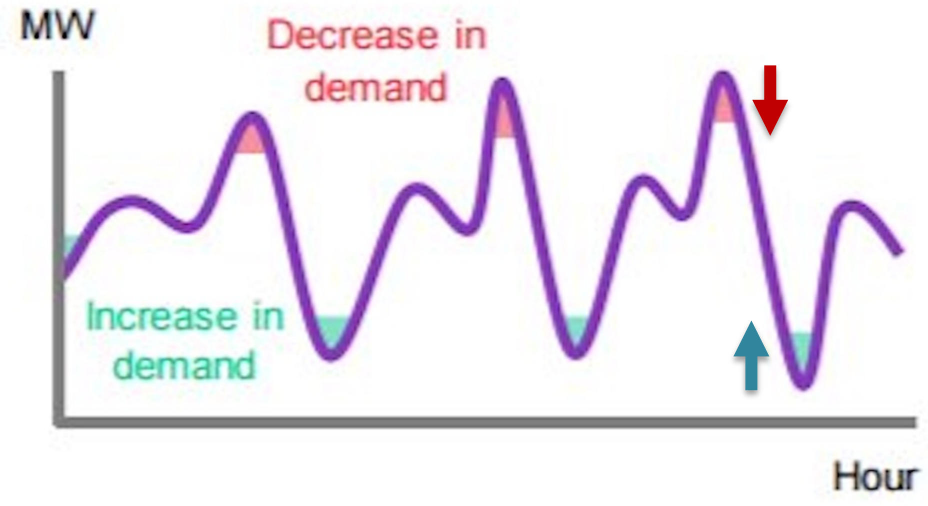
Graphic is author's own created with data from: de Sisternes, Jenkins & Botterud (2016), "The value of energy storage in decarbonizing the electricity sector," *Applied Energy* 175: 368-379. Assumes Li-ion storage system with 2 hours storage duration and 10 year asset life. Estimated 2019 Li-ion storage 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. Increasing energy storage (longer duration) needed to maintain capacity substitution value



2. Reduced energy arbitrage (buy-sell) spread

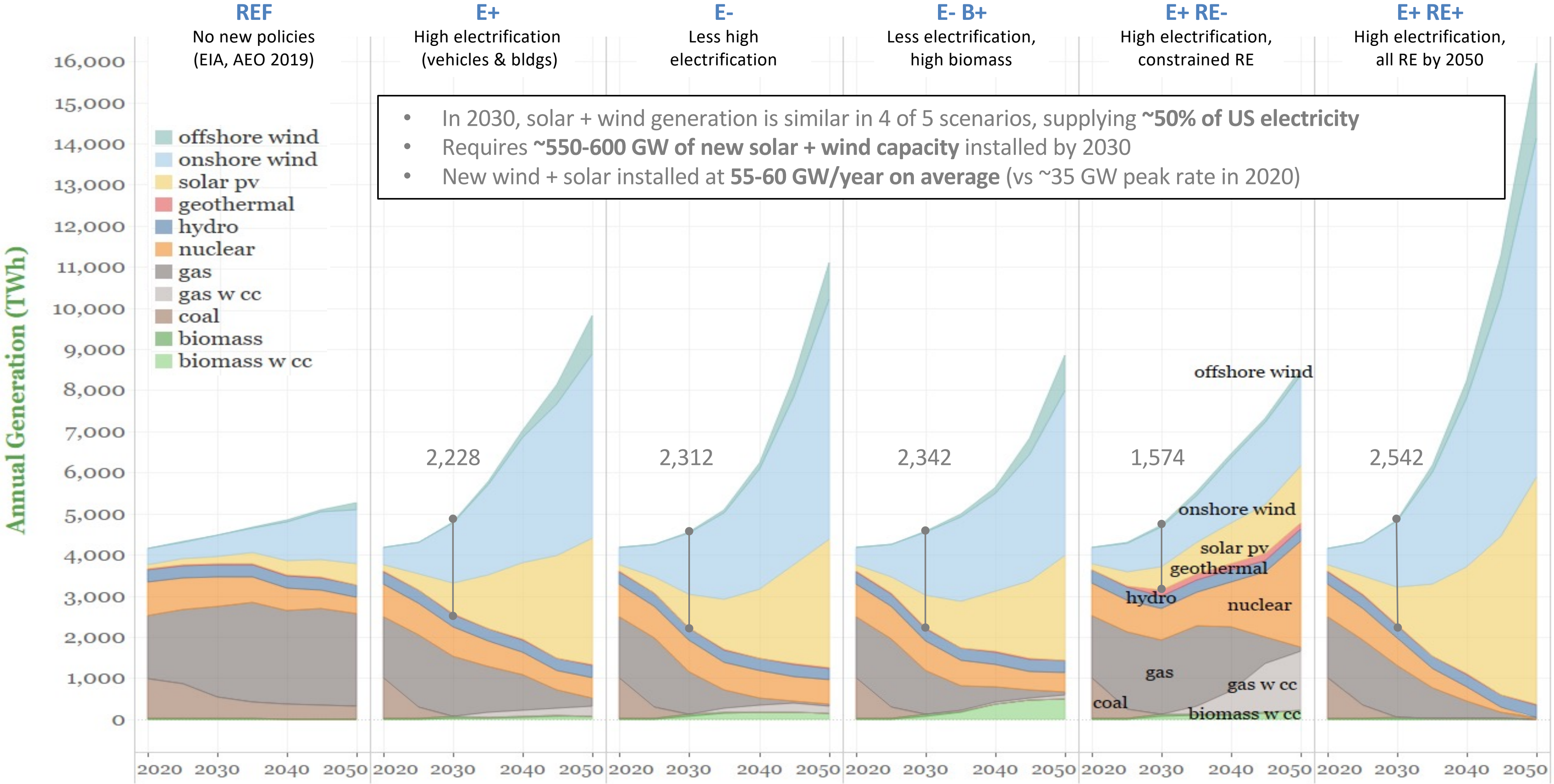


Source: Bloomberg New Energy Finance (2017) https://twitter.com/vsiv/status/875433676351340544/photo/1

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).

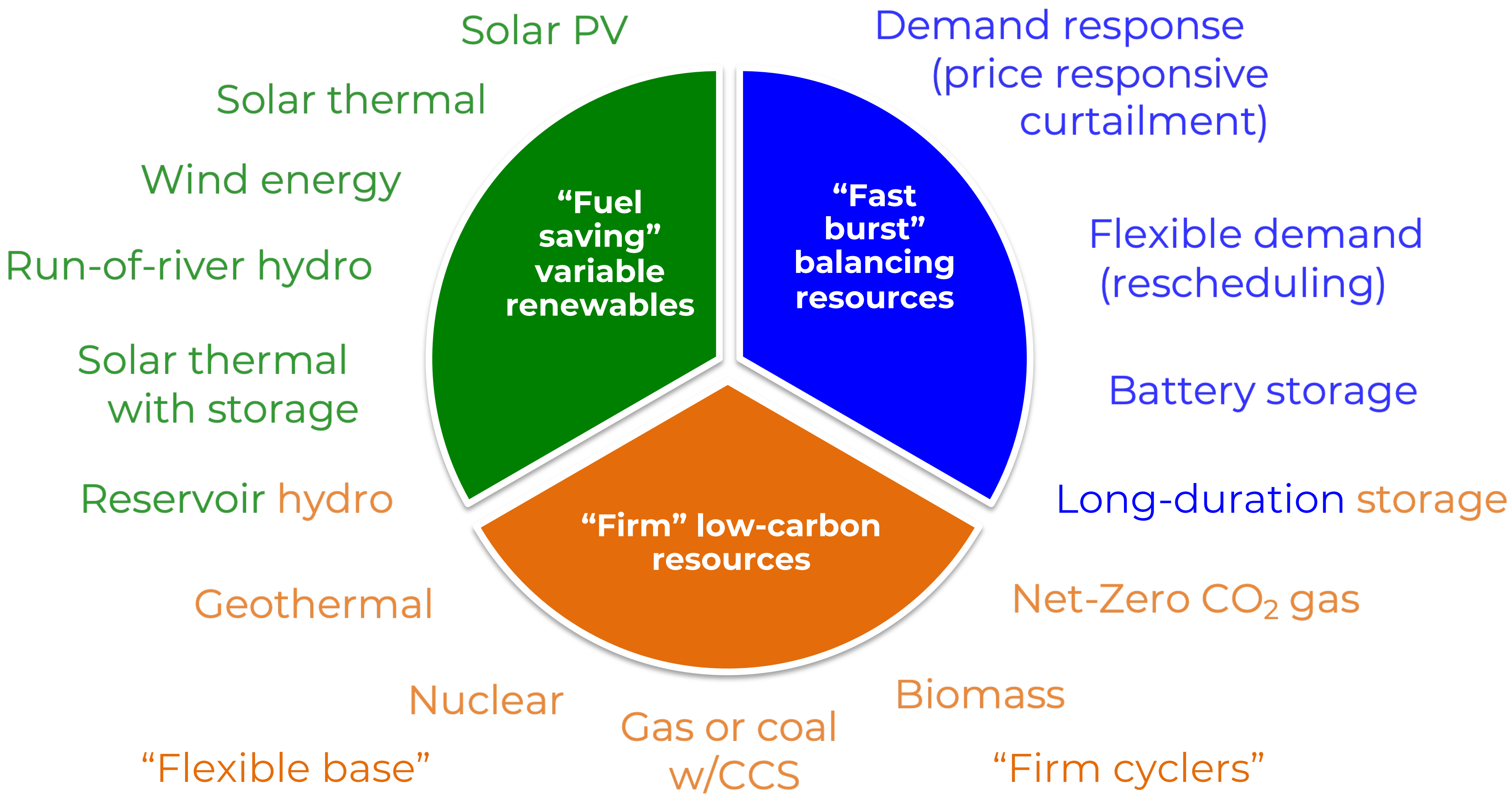
SOLAR AND WIND (AND BATTERIES) WILL BE STARS…

- In 2030, solar + wind generation is similar in 4 of 5 scenarios, supplying **~50% of US electricity**
- Requires **~550-600 GW of new solar + wind capacity** installed by 2030
- New wind + solar installed at **55-60 GW/year on average** (vs ~35 GW peak rate in 2020)

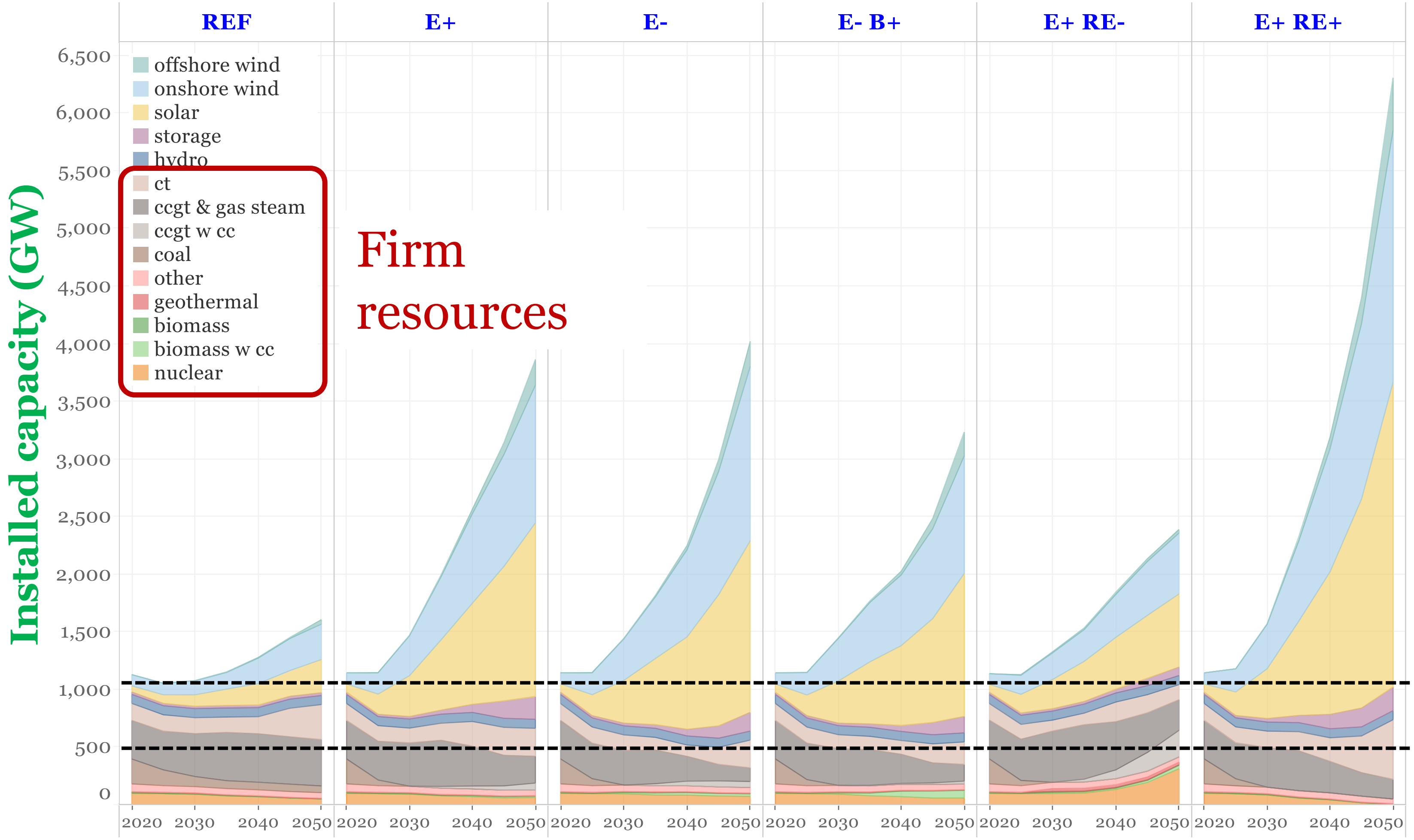


Solar, wind & batteries will be stars...

…BUT WE NEED TO COMPLETE THE TEAM



CLEAN FIRM RESOURCES ARE CRITICAL



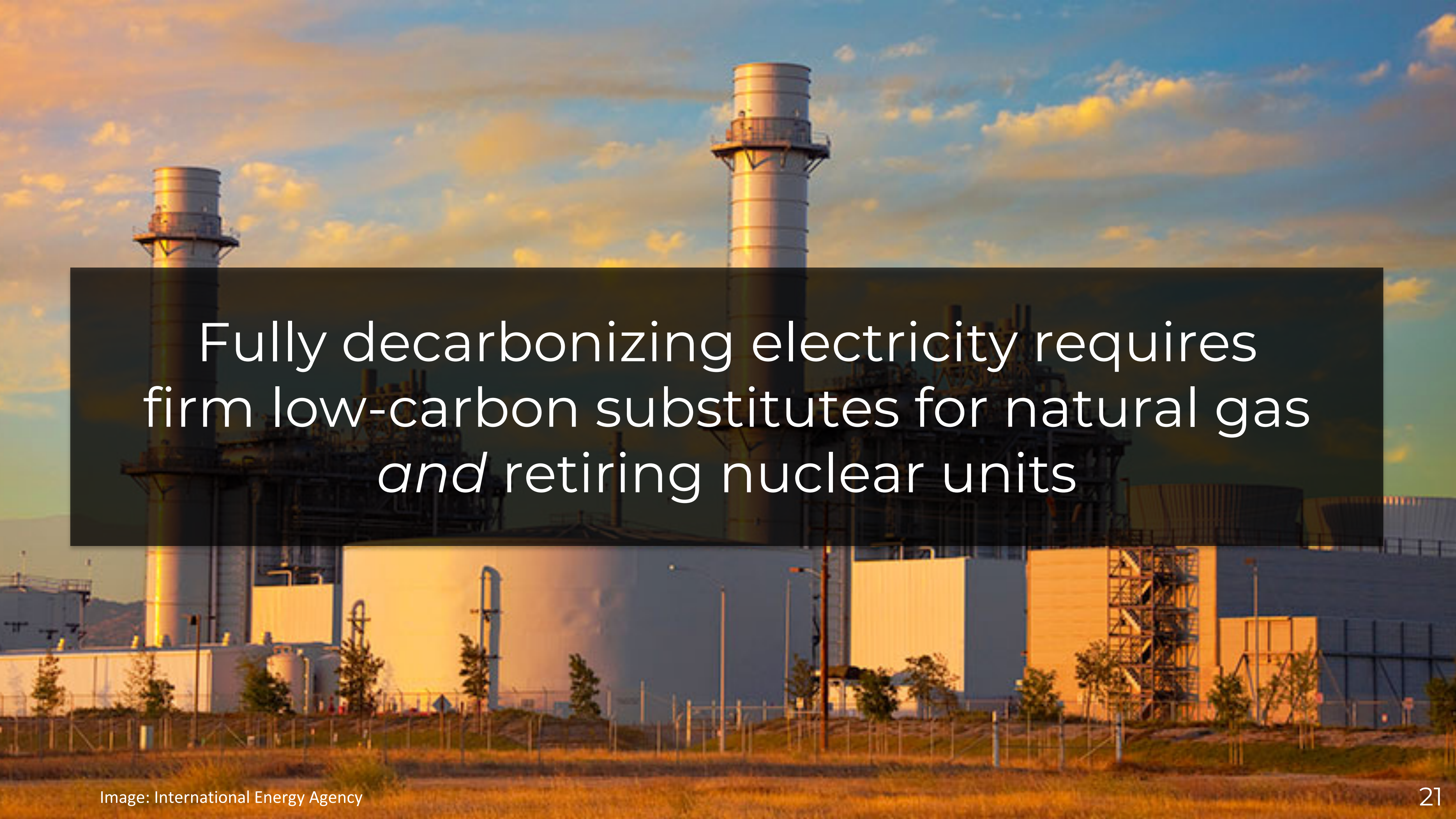
Note:

To reduce the carbon intensity of CCGT and CT generation, H_2 is blended as an increasing fraction of fuel to these units, up to an exogenously specified cap of 60% (HHV basis).

In sensitivities with 100% H_2 firing allowed, the model prefers 100% blend which modestly reduces total energy system costs.

Firm capacity (across all years)

~500-1000 GW

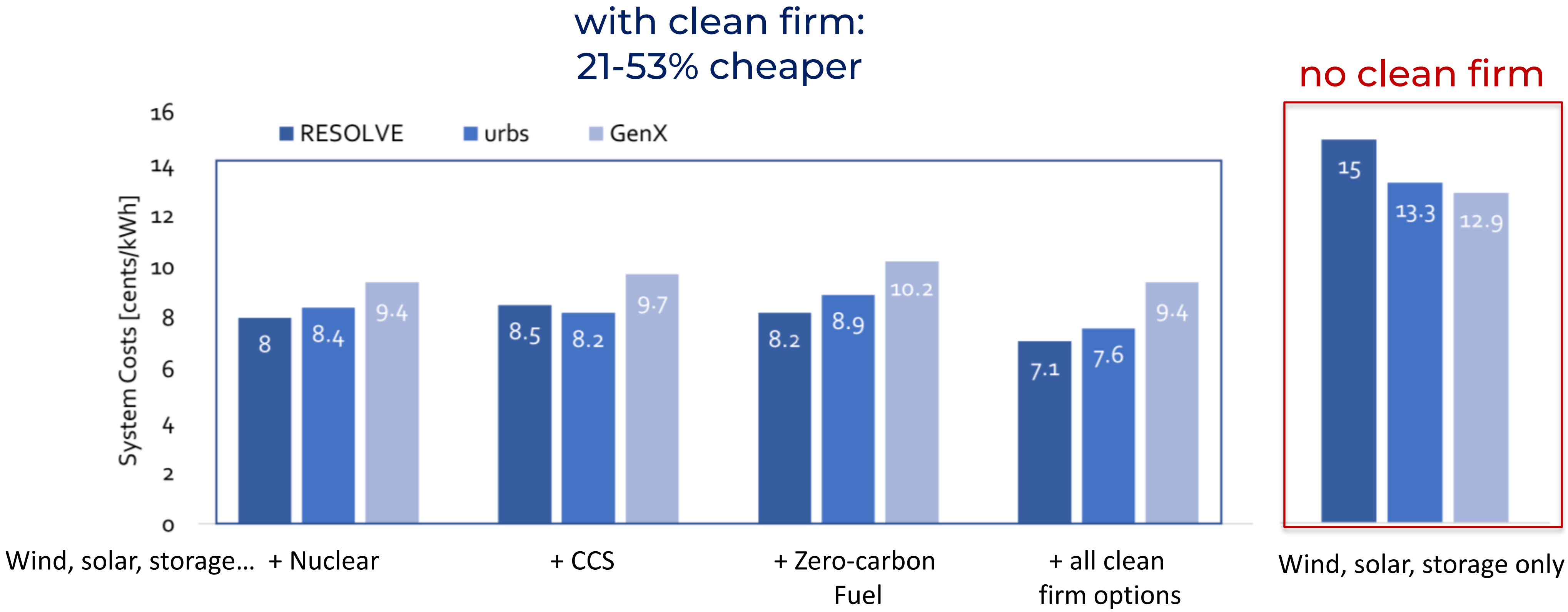


Fully decarbonizing electricity requires firm low-carbon substitutes for natural gas *and* retiring nuclear units

Image: International Energy Agency

SEVERAL CLEAN FIRM OPTIONS, ALL WORK TO GET THE JOB DONE

Modeled 100% carbon-free electricity system costs for California



Source: Baik et al. (2021), "What's different about different net-zero carbon electricity systems?" *Energy & Climate Change,* https://www.sciencedirect.com/science/article/pii/S2666278721000234

MULTIPLE CLEAN FIRM RESOURCES CAN CO-EXIST

"Firm Cyclers"

H_2 or biogas turbines or
Gas turbines + negative emissions offsets

Intermediate

Natural gas w/CCS
Allam cycle

"Flexible Base"

Nuclear
Geothermal
Fusion?

⟷

Firm Cyclers:

- Low fixed cost
- High variable/fuel cost
- Offline majority of time
- Many start-ups

Flexible Base:

- High fixed cost
- Low variable/fuel cost
- Online majority of time
- Fewer start-ups
- Integrated storage or co-products can add value

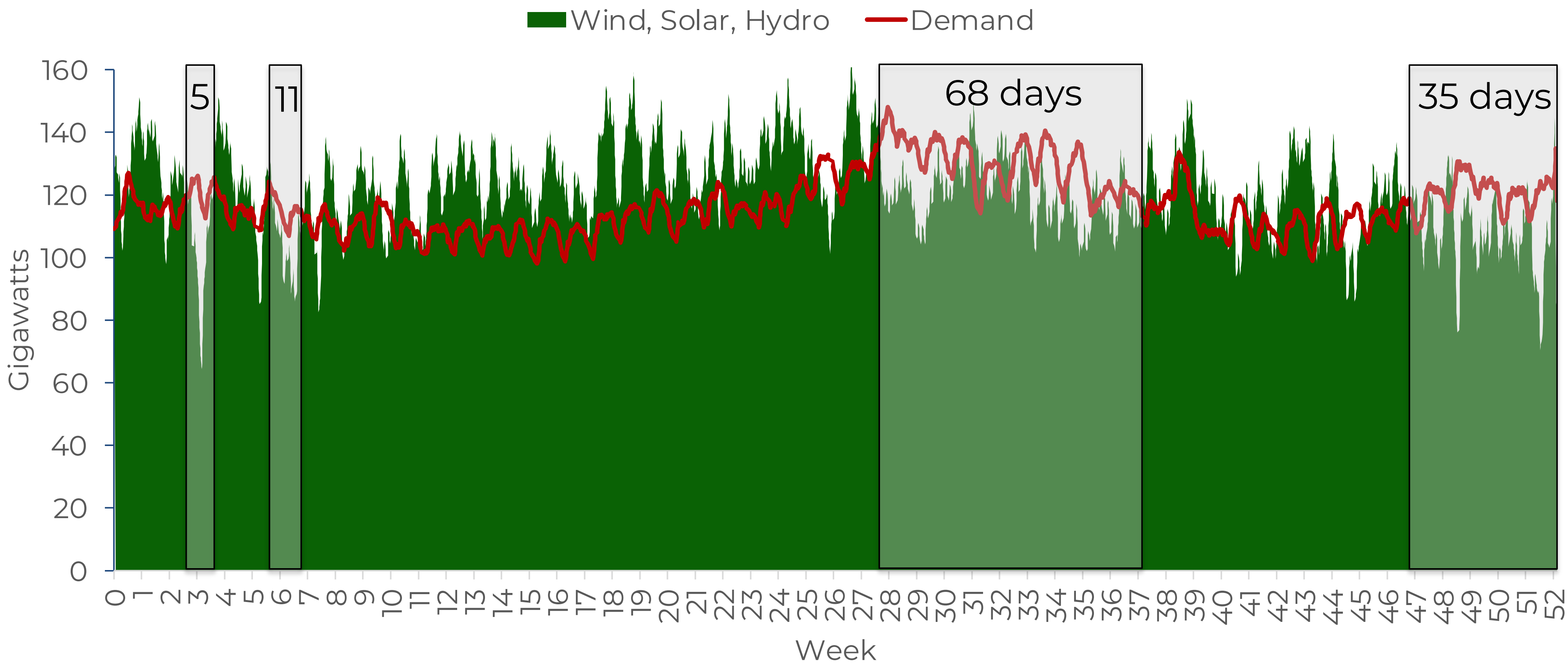
See also: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11).

What about long-duration storage?

The *Dunkelflaute* ("Dark Doldrums")

Western Interconnection, Renewables + Storage Only

(24 hour rolling average power)

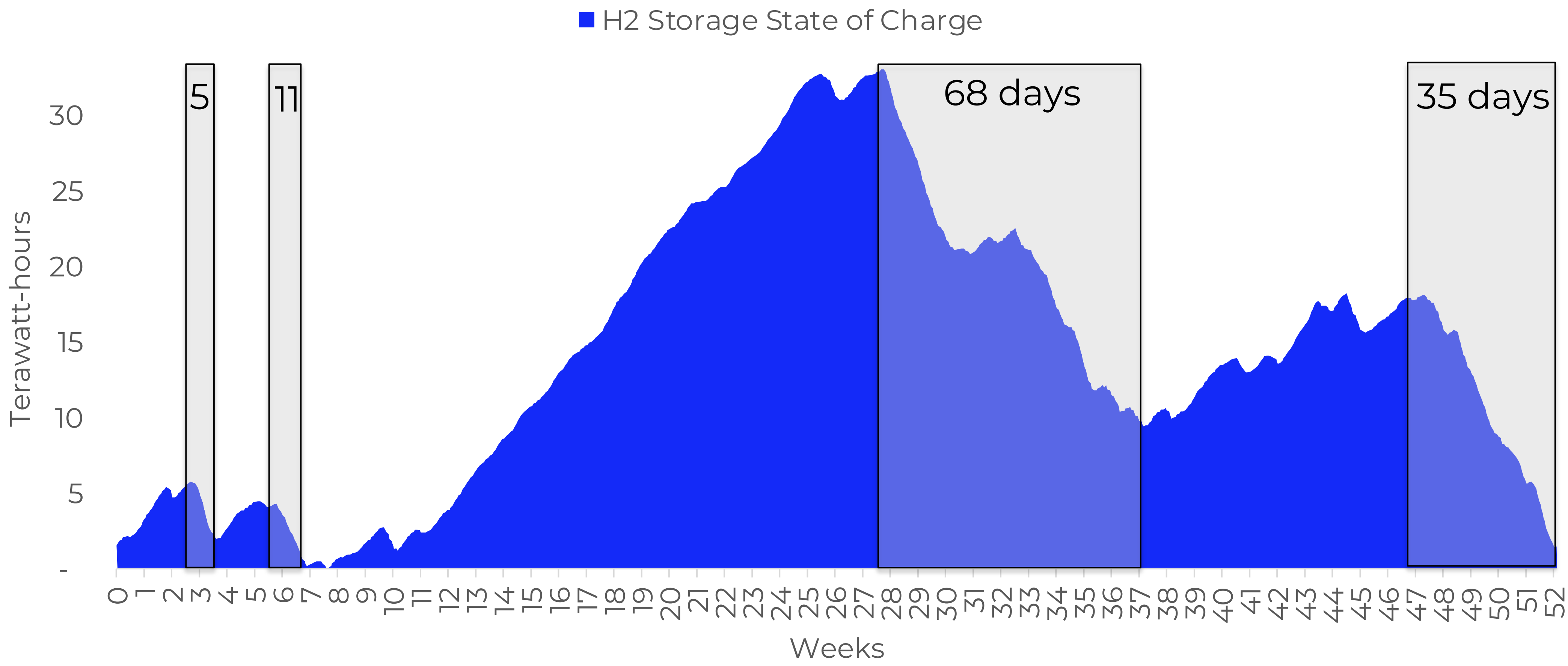


Data source: Unpublished results, Jesse D. Jenkins, GenX model, Western Interconnection.

Long Duration Storage Needed for Renewables + Storage Only

Western Interconnection, 0 CO_2 emissions limit

(24 hour rolling average power)

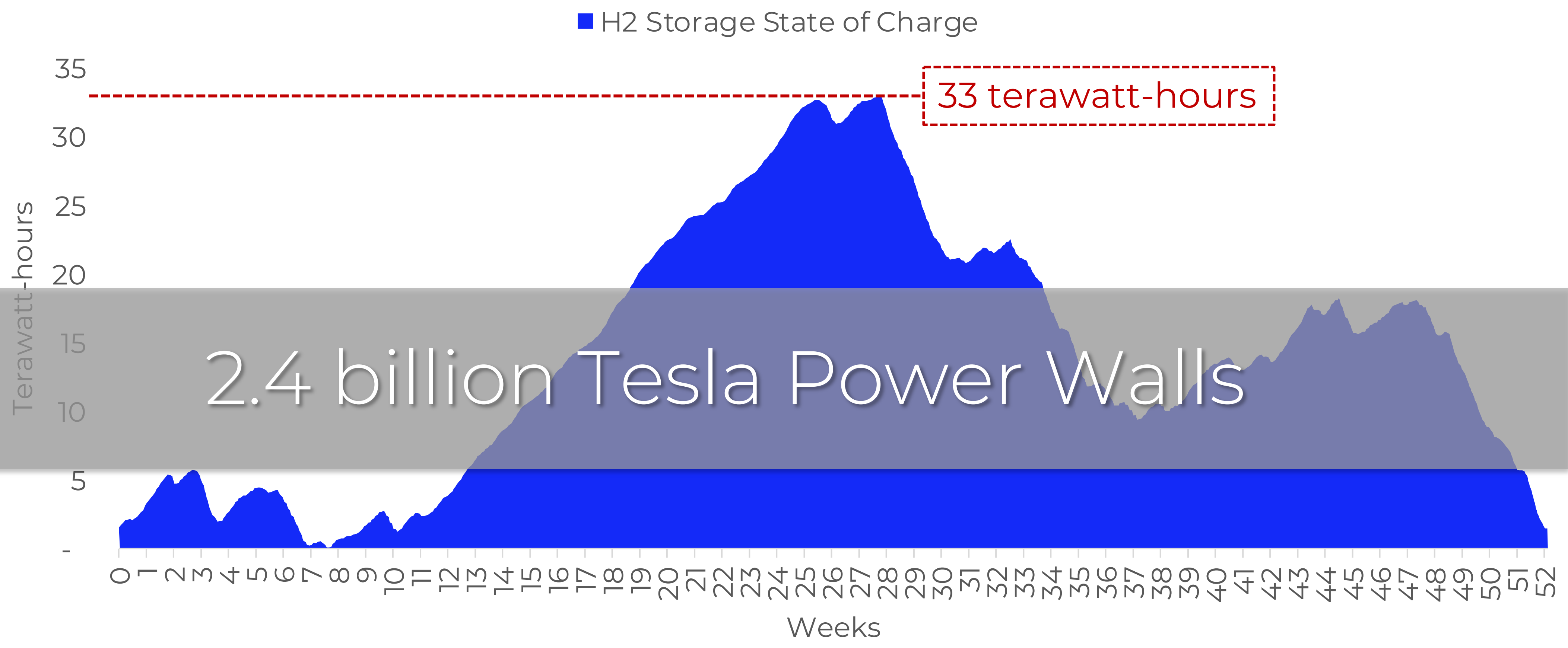


Data source: Unpublished results, Jesse D. Jenkins, GenX model, Western Interconnection.

Long Duration Storage Needed

Western Interconnection, Renewables + Storage Only

(24 hour rolling average power)



Data source: Unpublished results, Jesse D. Jenkins, GenX model, Western Interconnection.

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

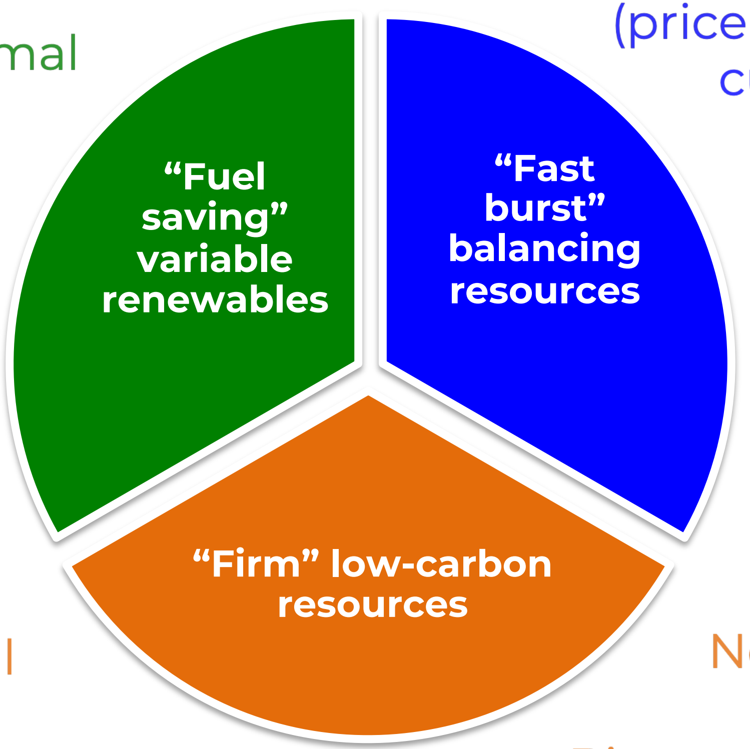
ENERGY STORAGE

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

The winning team



Solar PV

Solar thermal

Wind energy

Run-of-river hydro

Solar thermal with storage

Reservoir hydro

Demand response (price responsive curtailment)

Flexible demand (rescheduling)

Battery storage

Long-duration storage

Geothermal

Net-Zero CO_2 gas

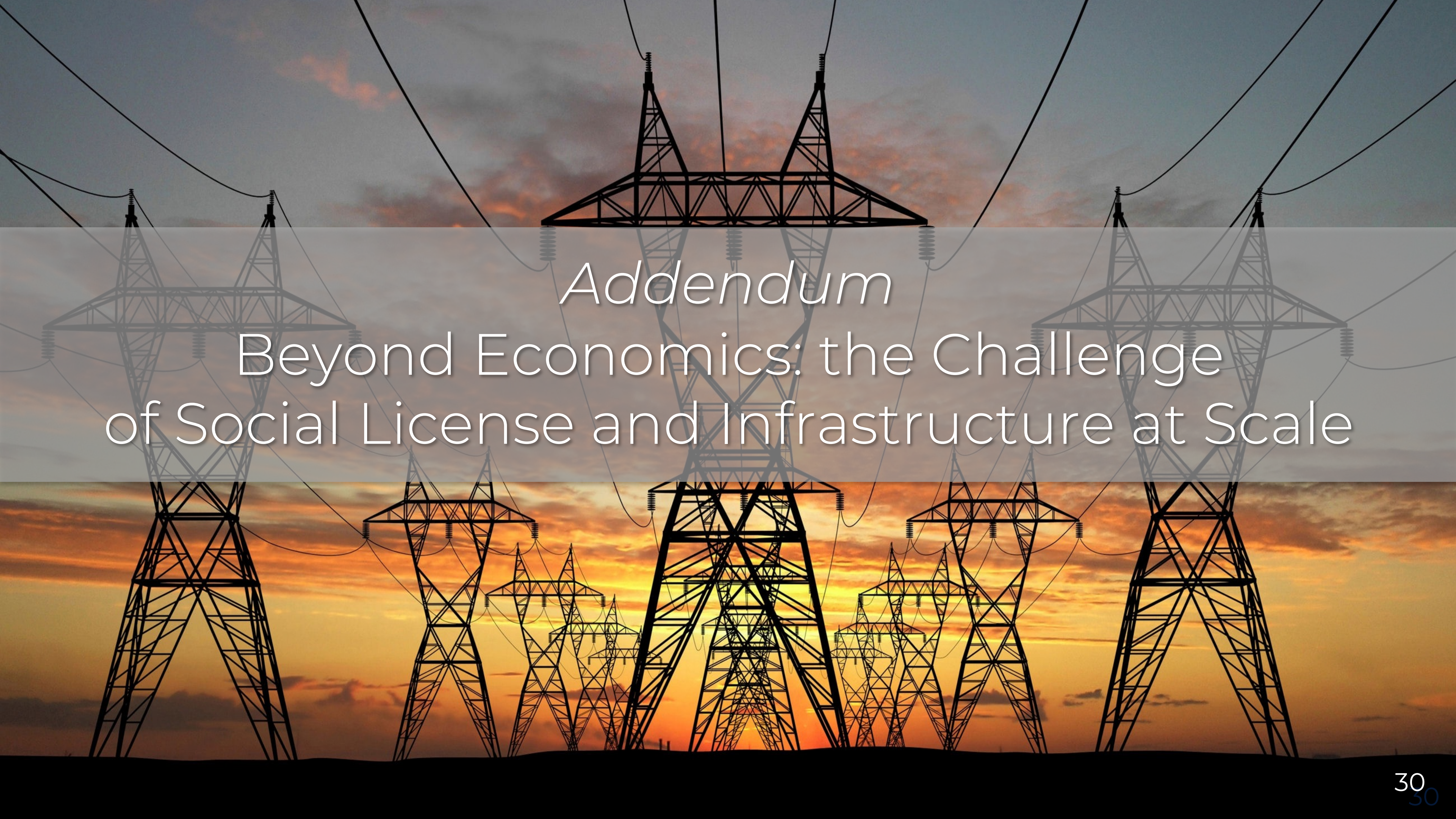
Nuclear

Gas or coal w/CCS

Biomass

"Flexible base"

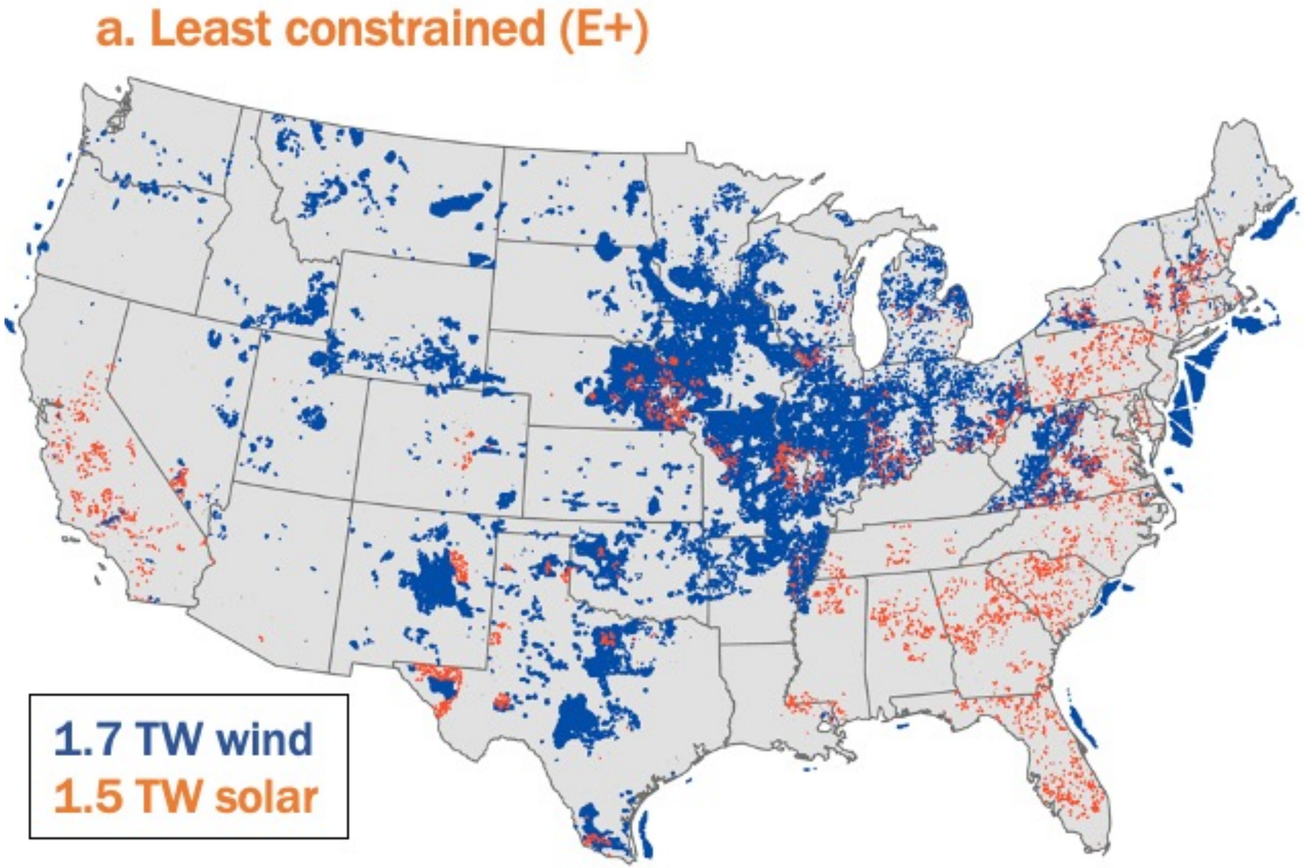
"Firm cyclers"

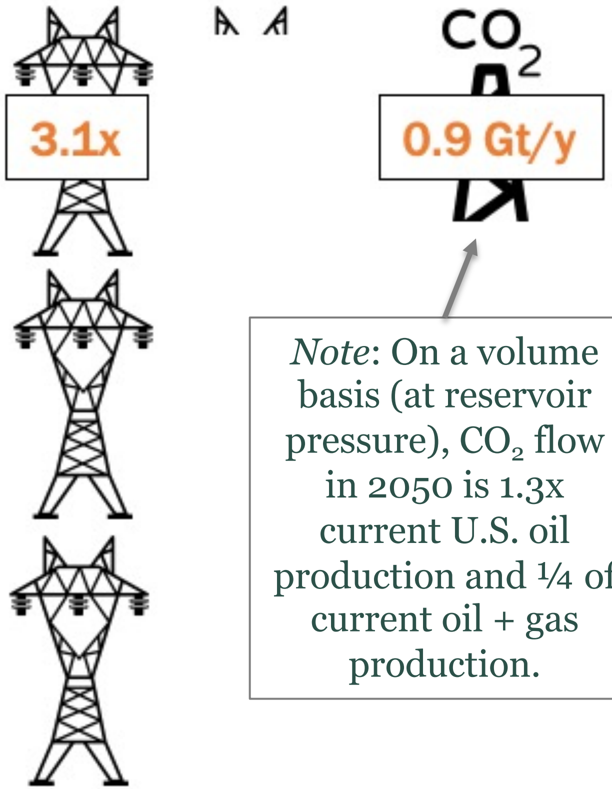


Addendum

Beyond Economics: the Challenge of Social License and Infrastructure at Scale

NO ROAD TO NET-ZERO WITHOUT INFRASTRUCTURE BUILD-OUT

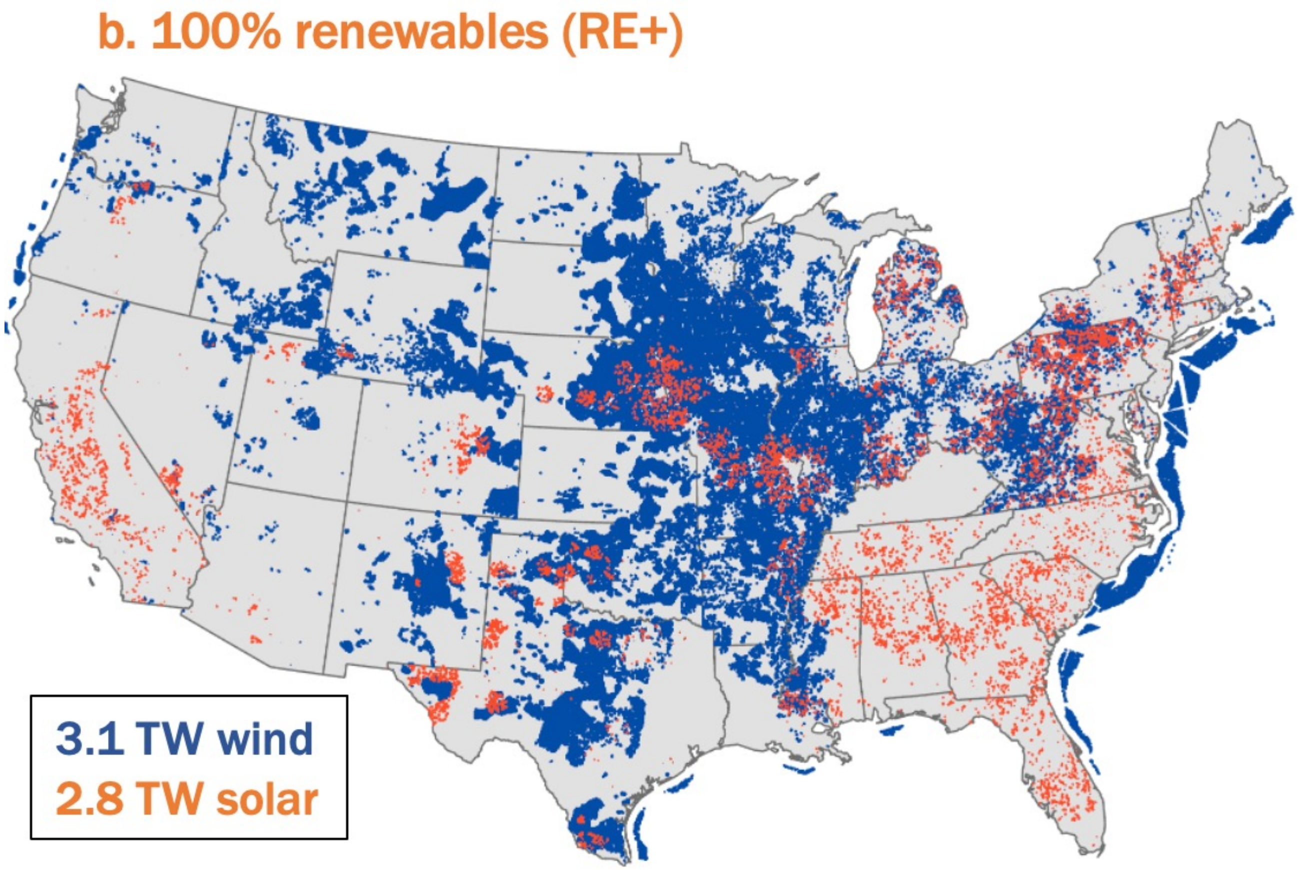


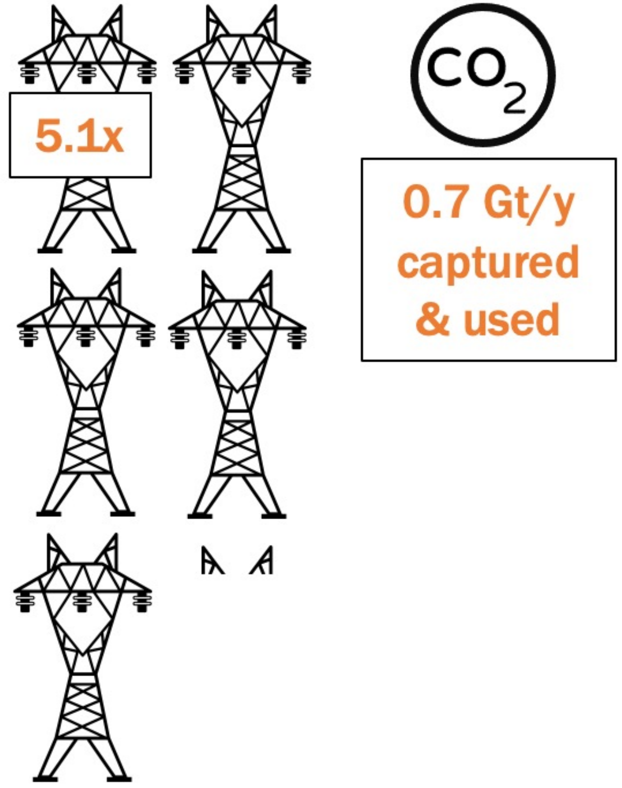


Note: On a volume basis (at reservoir pressure), CO_2 flow in 2050 is 1.3x current U.S. oil production and ¼ of current oil + gas production.

Source: Jenkins et al. (2021), "Mission Net-Zero: The nation-building path to a prosperous, net-zero emissions economy," *Joule,* 5(11)
https://www.cell.com/joule/fulltext/S2542-4351(21)00493-1

NO ROAD TO NET-ZERO WITHOUT INFRASTRUCTURE BUILD-OUT

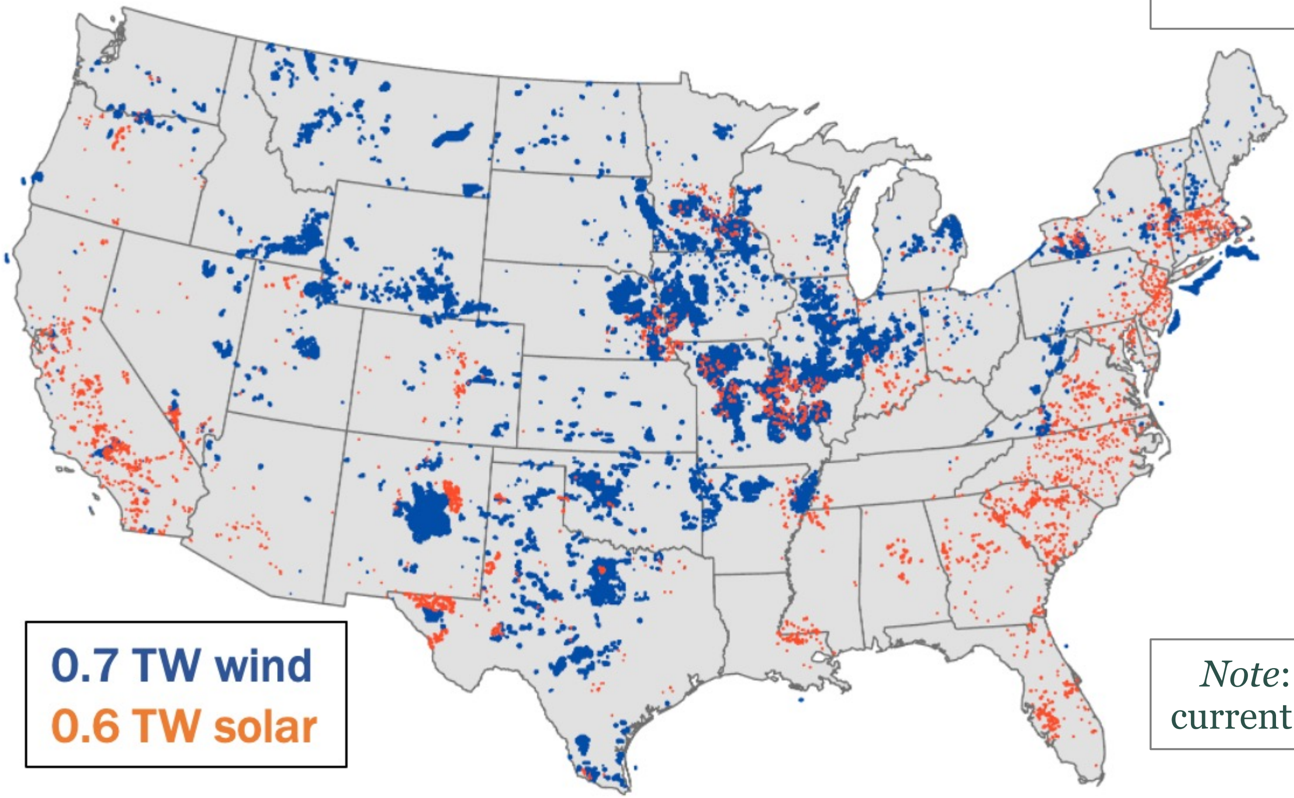




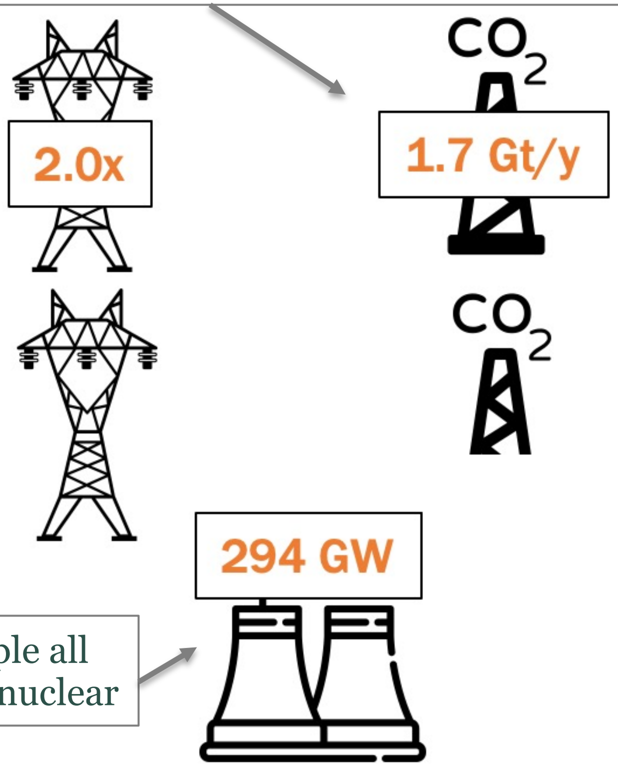
Source: Jenkins et al. (2021), “Mission Net-Zero: The nation-building path to a prosperous, net-zero emissions economy,” *Joule,* 5(11)
https://www.cell.com/joule/fulltext/S2542-4351(21)00493-1

NO ROAD TO NET-ZERO WITHOUT INFRASTRUCTURE BUILD-OUT

c. Constrained renewables (RE-)



Note: On a volume basis CO_2 flow in 2050 is 2.5*x* current U.S. oil production and nearly ½ of current oil + gas production.



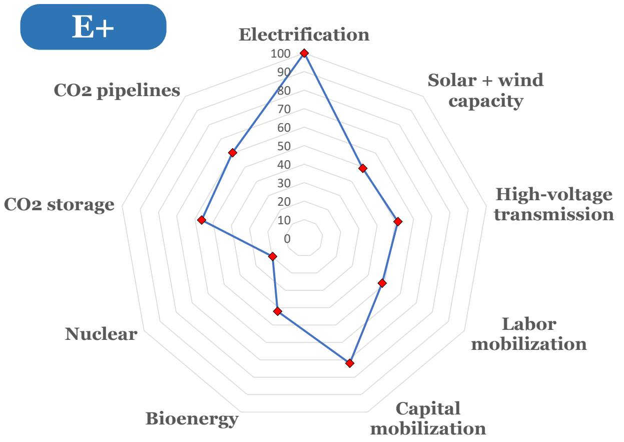
Note: ~Triple all current U.S. nuclear

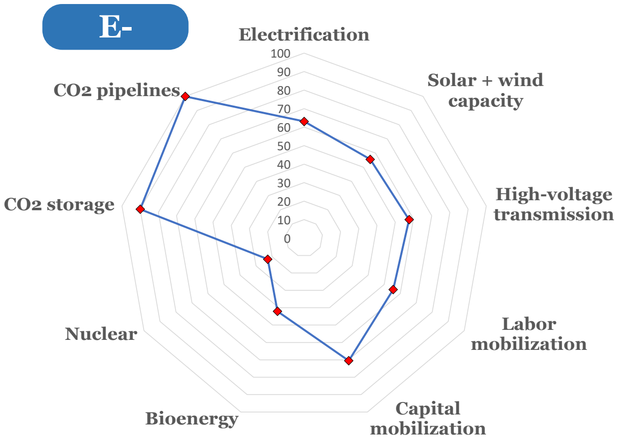
Source: Jenkins et al. (2021), "Mission Net-Zero: The nation-building path to a prosperous, net-zero emissions economy," *Joule,* 5(11)
https://www.cell.com/joule/fulltext/S2542-4351(21)00493-1

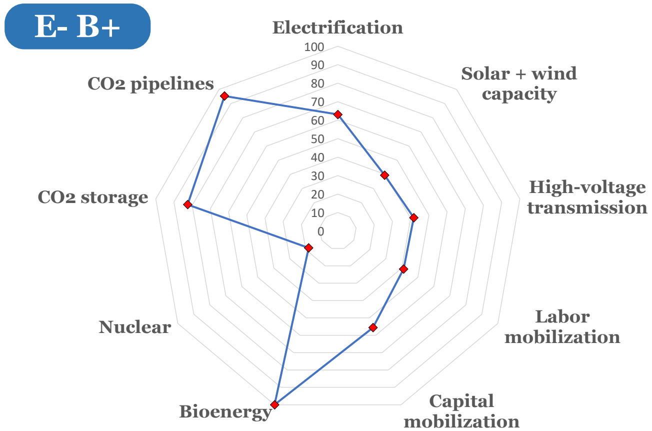
TRADE-OFFS VARY ACROSS PATHWAYS, CHALLENGES IN ALL

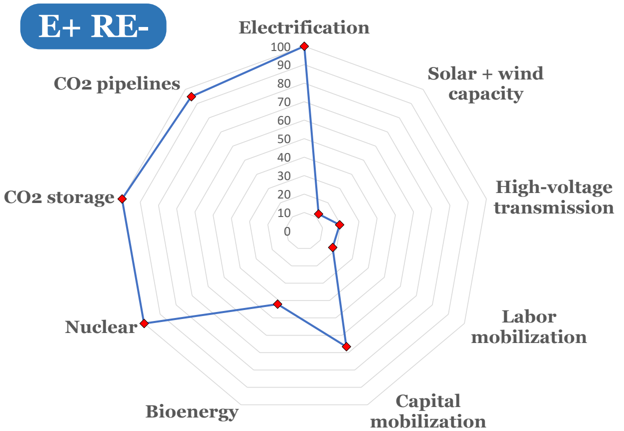
Level of Challenge (ordinal ranking)	
0	Lowest
100	Highest

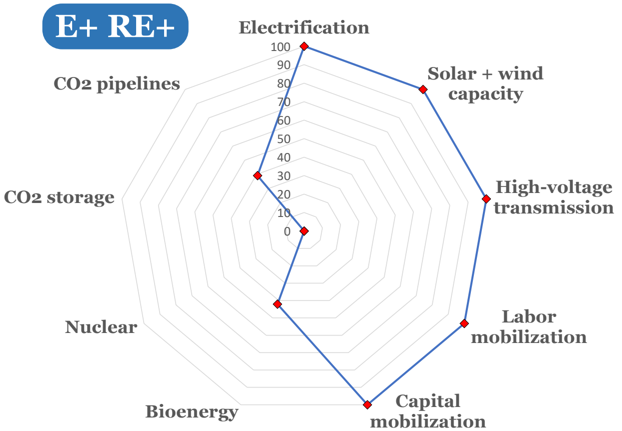
Challenge	Comparative metric
Electrification	% LDV stock that is EV in 2050
Solar + wind capacity	Capacity in 2050 vs. REF
High-voltage transmission	Cumulative capital invested by 2050
Labor mobilization	Energy workers, 2040s average
Capital mobilization	Cumulative capital vs. REF
Bioenergy	Bioenergy use in 2050 vs. REF.
Nuclear	Operating capacity in 2050
CO_2 storage	Tonnes CO_2 injected in 2050
CO_2 pipelines	Tonnes CO_2 captured in 2050











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RESOURCES

- Larson et al. (2022), *Net-Zero America: Potential Pathways, Infrastructure, and Impacts,* Princeton University https://netzeroamerica.princeton.edu/the-report
- Jenkins & Sepulveda (2021), "Long duration energy storage: a blueprint for research and innovation," *Joule*, 5(9): 2241-2246 https://bit.ly/LDES_Joule
- Sepulveda, Jenkins, et al. (2021), "The design space for long duration energy storage in decarbonized power systems," *Nature Energy,* https://rdcu.be/chG2k
- Baik et al. (2021), "What's different about different net-zero electricity systems," *Energy & Climate Change*, https://www.sciencedirect.com/science/article/pii/S2666278721000234
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- de Sisternes, Jenkins & Botterud (2016), "The value of energy storage in decarbonizing the electricity sector," *Applied Energy* 175. https://bit.ly/ValueOfEnergyStorage