Taking stock of energy transition research

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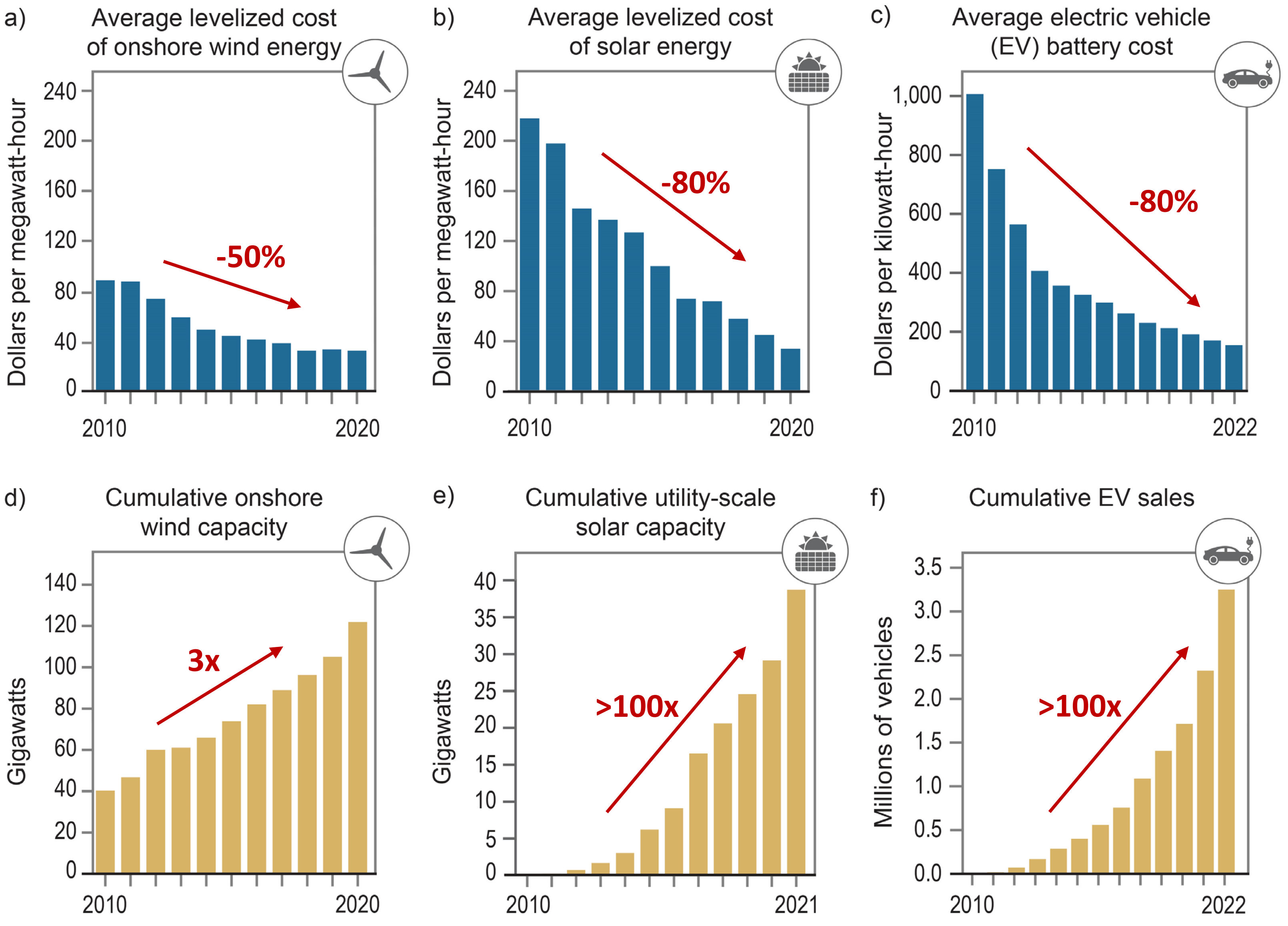
September 12, 2024

NASEM Workshop on
Macroeconomic Implications of
Decarbonization Policies and Actions

The cost-effective core technologies



Fifth National Climate Assessment, Mitigation chapter (Nov 2023)

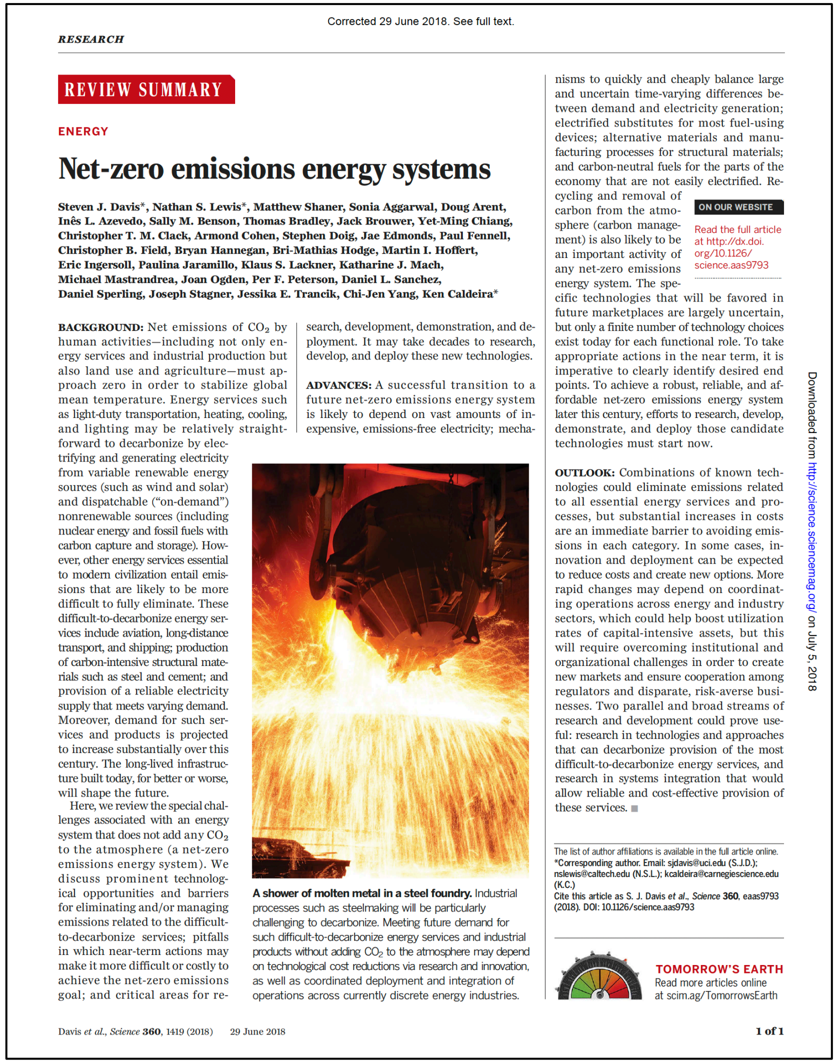
Deploying those core techs will keep us busy, but there's plenty more still to be figured out…

Two main research frontiers for energy systems analysis:

1. Cost-related, drilling down on difficult emissions sources

2. Non-cost considerations

Cost-related: what energy emissions will be the most difficult to avoid—and why?



Corrected 29 June 2018. See full text.

RESEARCH

REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*

BACKGROUND: Net emissions of CO_2 by human activities—including not only energy services and industrial production but also land use and agriculture—must approach zero in order to stabilize global mean temperature. Energy services such as light-duty transportation, heating, cooling, and lighting may be relatively straightforward to decarbonize by electrifying and generating electricity from variable renewable energy sources (such as wind and solar) and dispatchable ("on-demand") nonrenewable sources (including nuclear energy and fossil fuels with carbon capture and storage). However, other energy services essential to modern civilization entail emissions that are likely to be more difficult to fully eliminate. These difficult-to-decarbonize energy services include aviation, long-distance transport, and shipping; production of carbon-intensive structural materials such as steel and cement; and provision of a reliable electricity supply that meets varying demand. Moreover, demand for such services and products is projected to increase substantially over this century. The long-lived infrastructure built today, for better or worse, will shape the future.

Here, we review the special challenges associated with an energy system that does not add any CO_2 to the atmosphere (a net-zero emissions energy system). We discuss prominent technological opportunities and barriers for eliminating and/or managing emissions related to the difficult-to-decarbonize services; pitfalls in which near-term actions may make it more difficult or costly to achieve the net-zero emissions goal; and critical areas for research, development, demonstration, and deployment. It may take decades to research, develop, and deploy these new technologies.

ADVANCES: A successful transition to a future net-zero emissions energy system is likely to depend on vast amounts of inexpensive, emissions-free electricity; mechanisms to quickly and cheaply balance large and uncertain time-varying differences between demand and electricity generation; electrified substitutes for most fuel-using devices; alternative materials and manufacturing processes for structural materials; and carbon-neutral fuels for the parts of the economy that are not easily electrified. Recycling and removal of carbon from the atmosphere (carbon management) is also likely to be an important activity of any net-zero emissions energy system. The specific technologies that will be favored in future marketplaces are largely uncertain, but only a finite number of technology choices exist today for each functional role. To take appropriate actions in the near term, it is imperative to clearly identify desired end points. To achieve a robust, reliable, and affordable net-zero emissions energy system later this century, efforts to research, develop, demonstrate, and deploy those candidate technologies must start now.

OUTLOOK: Combinations of known technologies could eliminate emissions related to all essential energy services and processes, but substantial increases in costs are an immediate barrier to avoiding emissions in each category. In some cases, innovation and deployment can be expected to reduce costs and create new options. More rapid changes may depend on coordinating operations across energy and industry sectors, which could help boost utilization rates of capital-intensive assets, but this will require overcoming institutional and organizational challenges in order to create new markets and ensure cooperation among regulators and disparate, risk-averse businesses. Two parallel and broad streams of research and development could prove useful: research in technologies and approaches that can decarbonize provision of the most difficult-to-decarbonize energy services, and research in systems integration that would allow reliable and cost-effective provision of these services. ■

A shower of molten metal in a steel foundry. Industrial processes such as steelmaking will be particularly challenging to decarbonize. Meeting future demand for such difficult-to-decarbonize energy services and industrial products without adding CO_2 to the atmosphere may depend on technological cost reductions via research and innovation, as well as coordinated deployment and integration of operations across currently discrete energy industries.

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aas9793

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Cite this article as S. J. Davis *et al.*, *Science* **360**, eaas9793 (2018). DOI: 10.1126/science.aas9793

TOMORROW'S EARTH
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Davis *et al.*, *Science* **360**, 1419 (2018) 29 June 2018 1 of 1

Davis et al., *Science*, 2018

Highly-reliable electricity

Aviation and long-distance transport

Structural materials

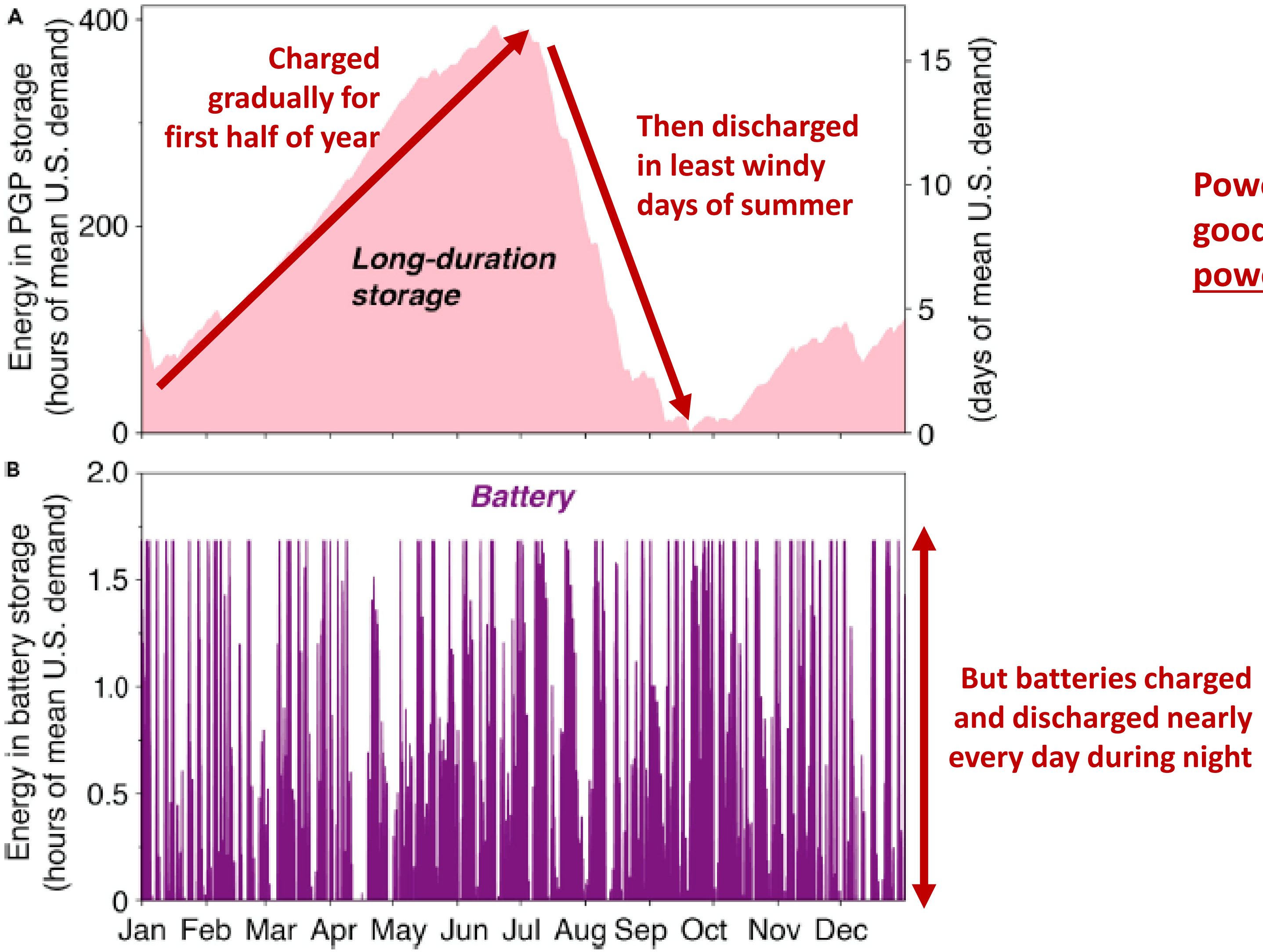
Solar and wind are cheap, but their variability is like a hot potato.
Who can most afford to make it reliable?

When and where is it cheapest to build firm generators?

Or pay people/industry to reduce their demand?

Or build lots of storage?

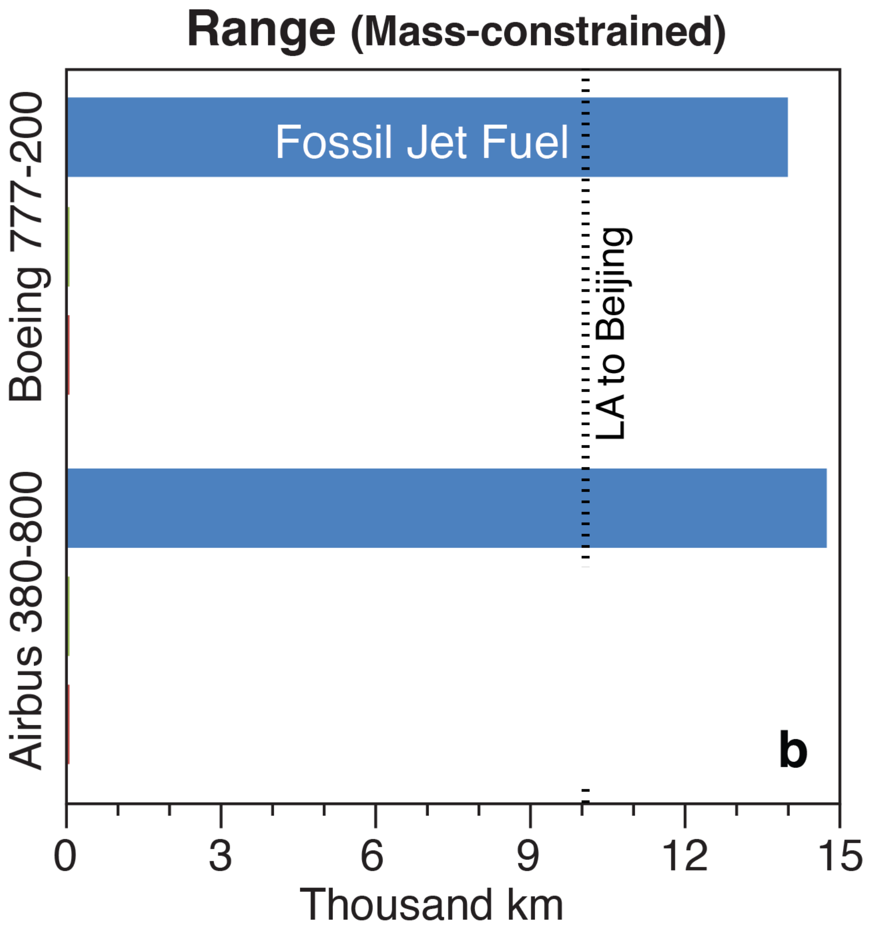
Specialized techno-economic characteristics of long-duration energy storage

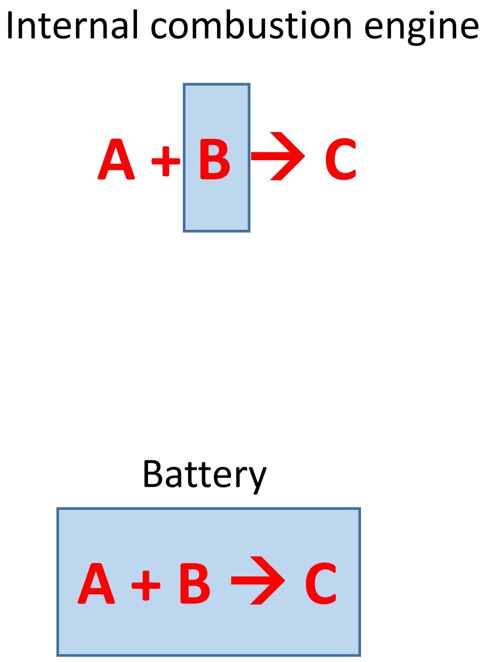


Power-to-gas-to-power (hydrogen) good fit for LDES because costs are power capacity dominated.

Dowling et al., *Joule,* 2020

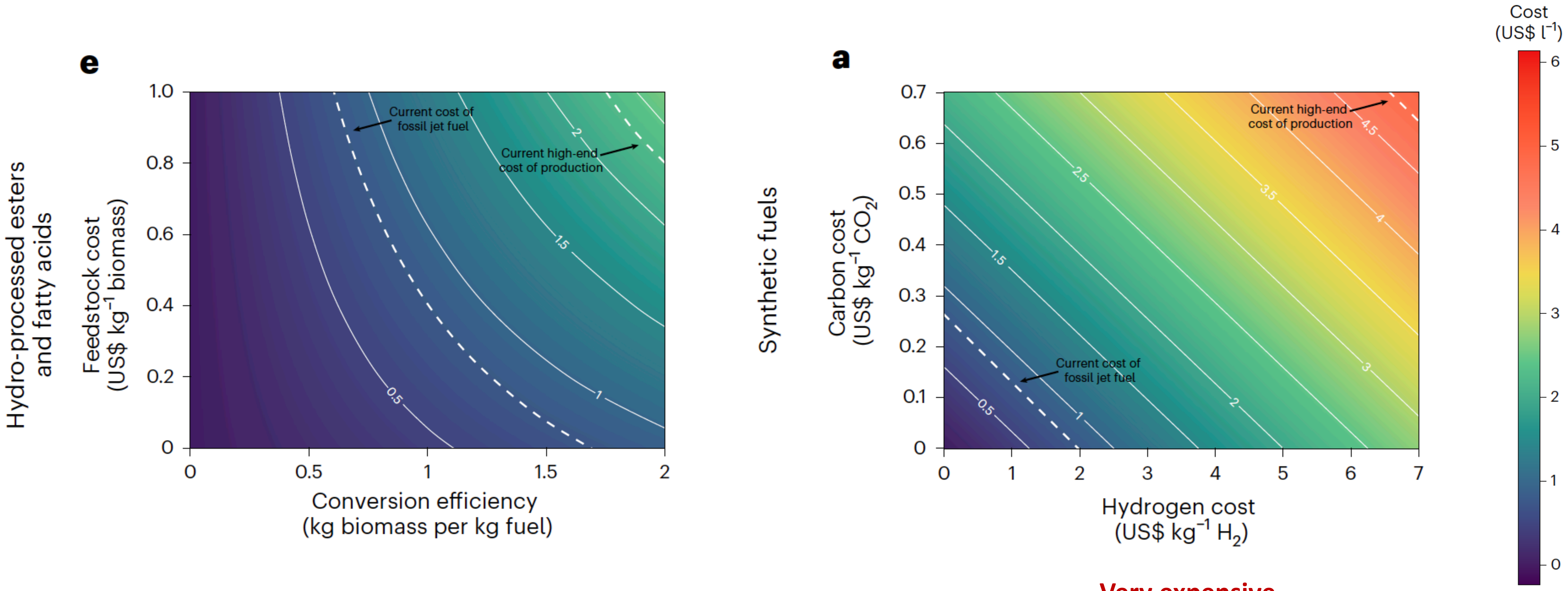
Aviation and long-distance transport need energy-dense liquid fuels





Bergero et al., *Nature Sustainabilty*, 2023

Sustainable Aviation Fuel (SAF) options are either pricey or supply-constrained

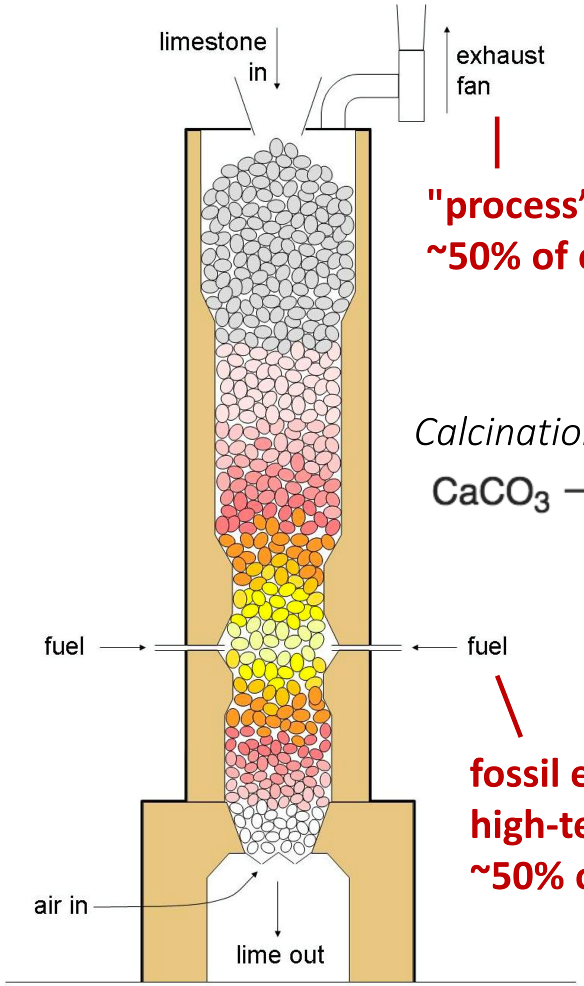


Supply-constrained and environmentally-problematic

Very expensive
75% cost decreases in both to be cost-competitive with fossil jet fuel

Bergero et al., *Nature Sustainabilty*, 2023

Cement accounts for ~8% of global CO_2 emissions (~2.6 Gt)



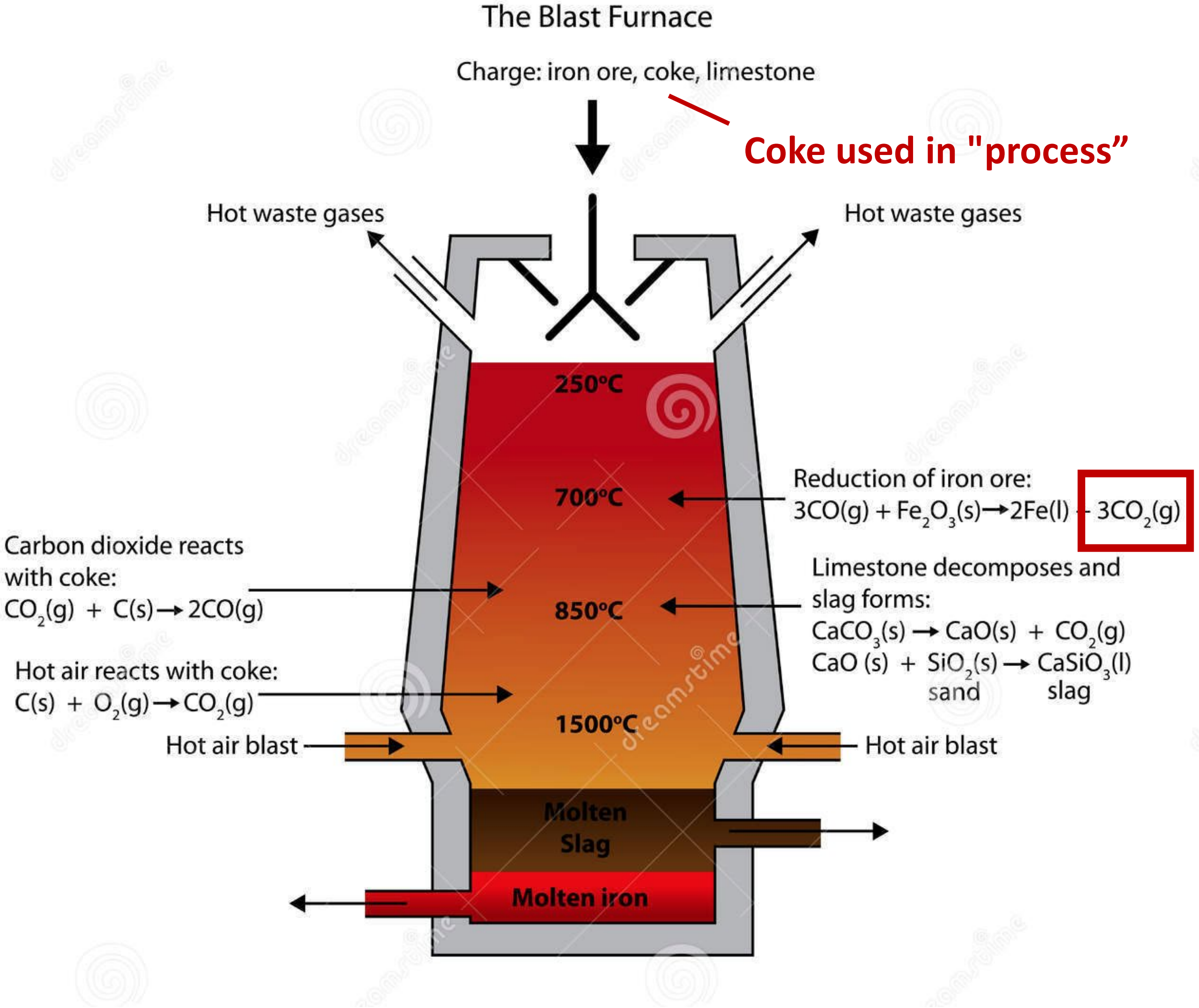
"process" = ~50% of emissions

Calcination:

$CaCO_3 \rightarrow CaO + CO_2(g)$

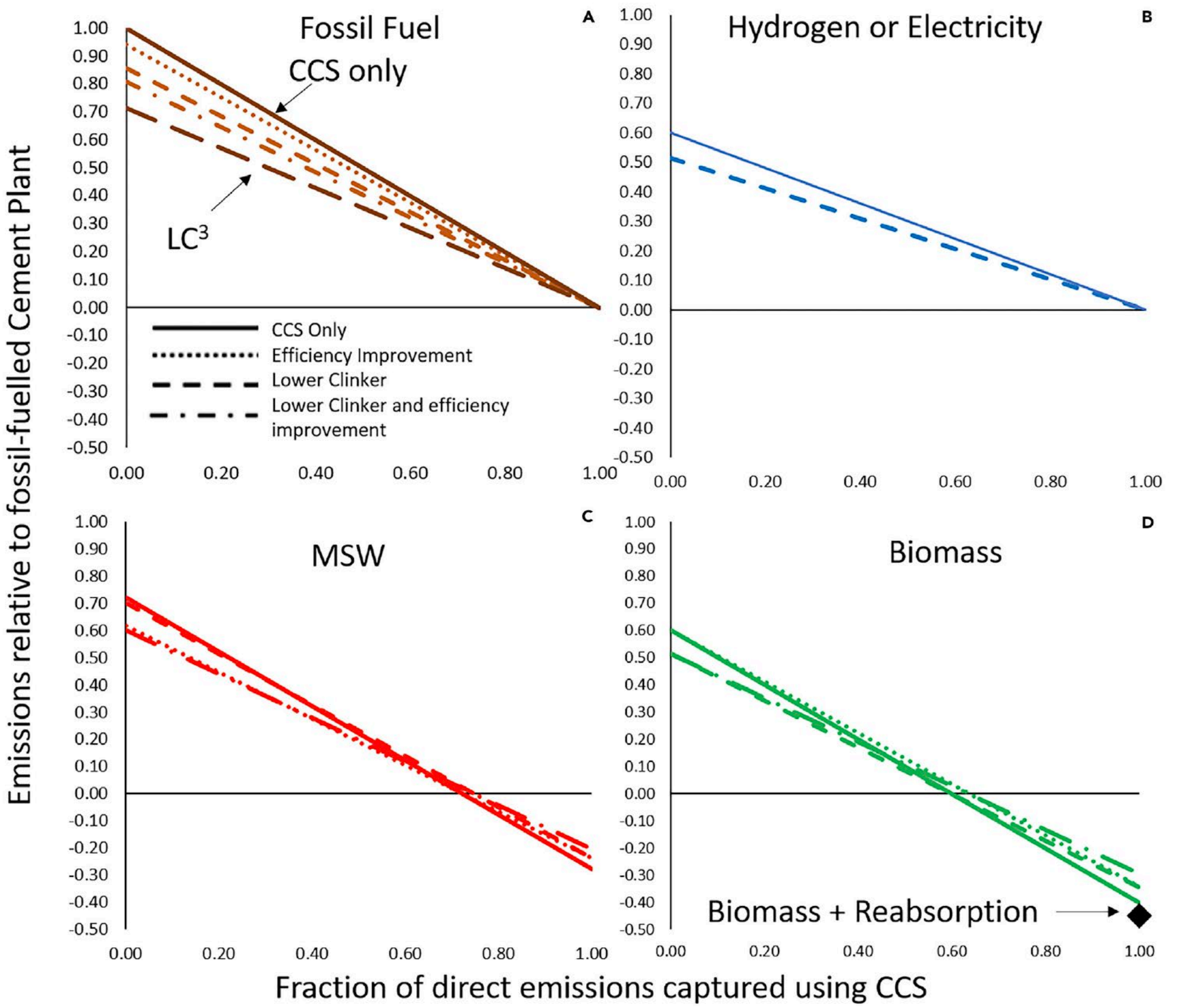
fossil energy for high-temp heat = ~50% of emissions

Steel accounts for ~6% of global CO_2 emissions (~2.0 Gt)



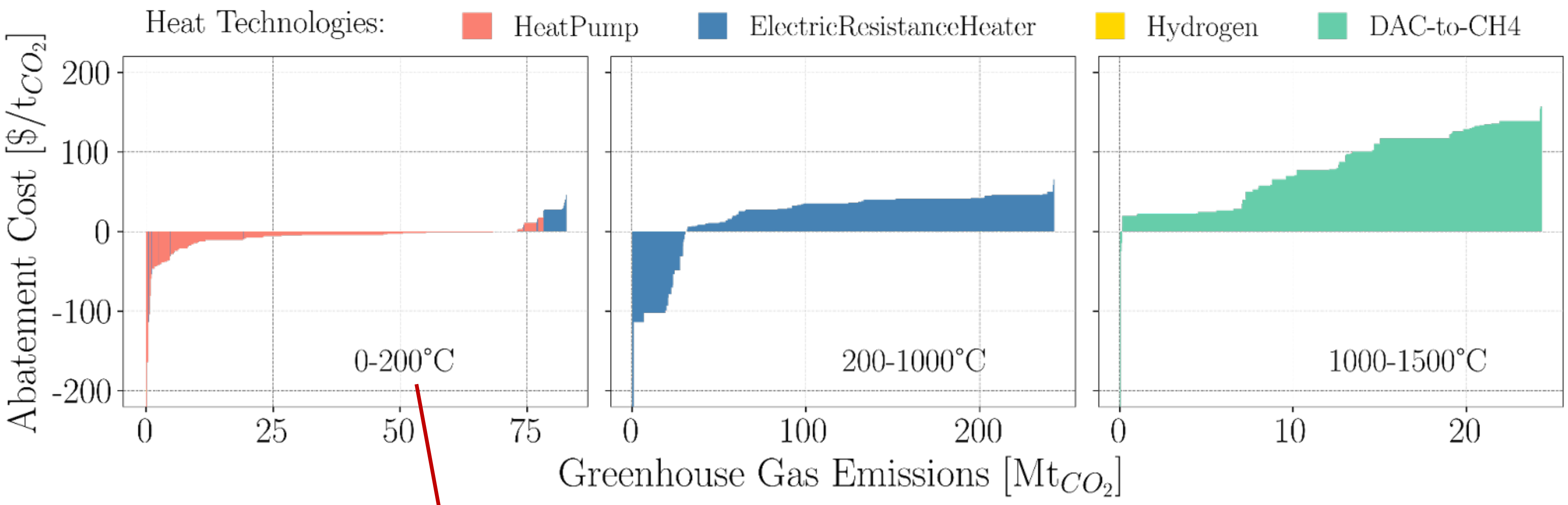
Coke used in "process"

Assessing potential reductions in cement emissions by fuel switching and using CCS



Fennell et al., *Joule,* 2021

And approaches to decarbonizing industrial heating

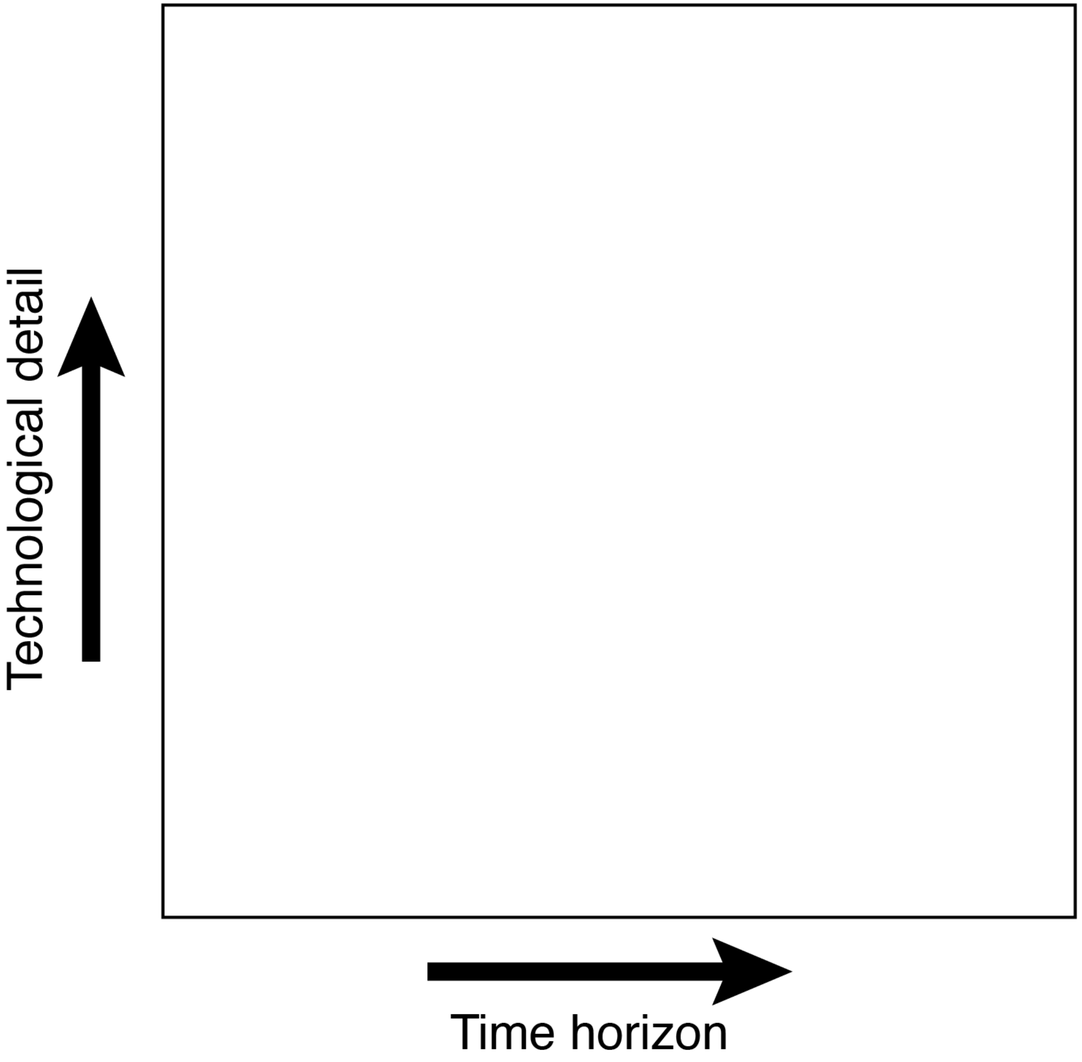


Most sensitive to temperatures required

Dowling, Saad, et al., *in prep*

Evolution of energy system models

Decisions need specificity

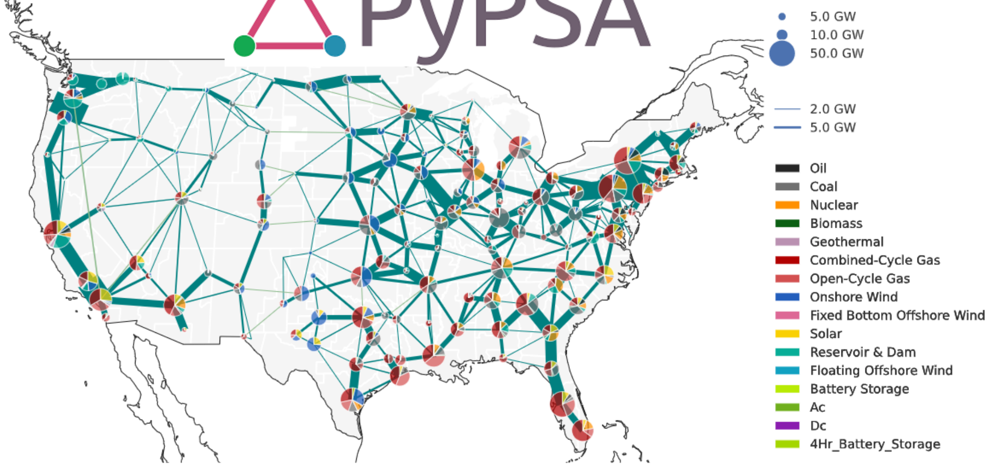


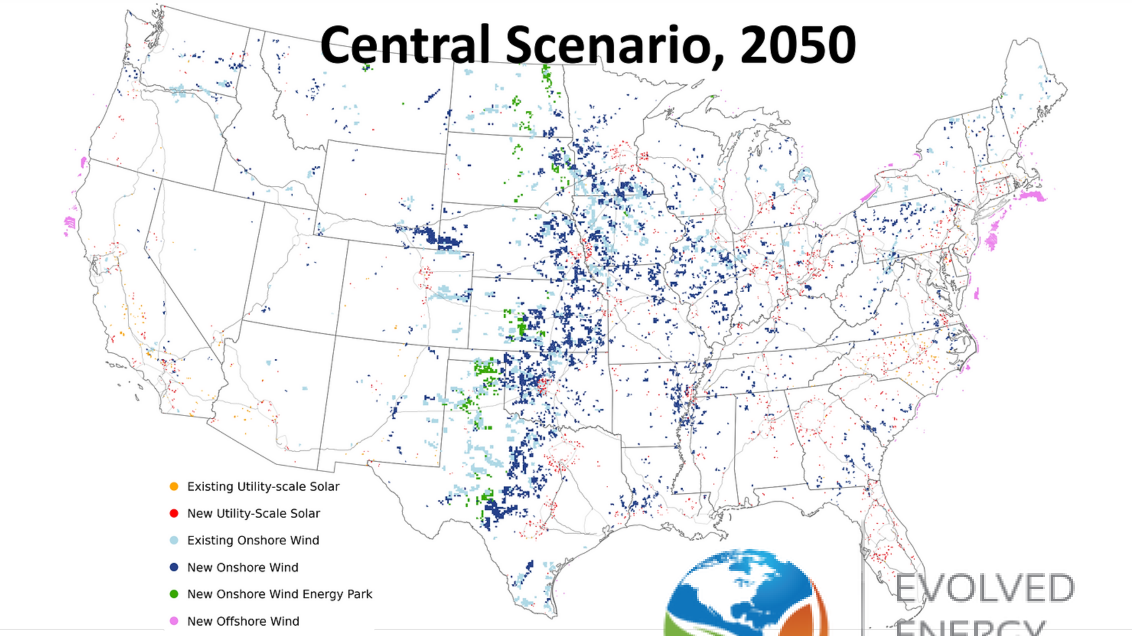
Need to anticipate trade-offs, feedbacks, and synergies

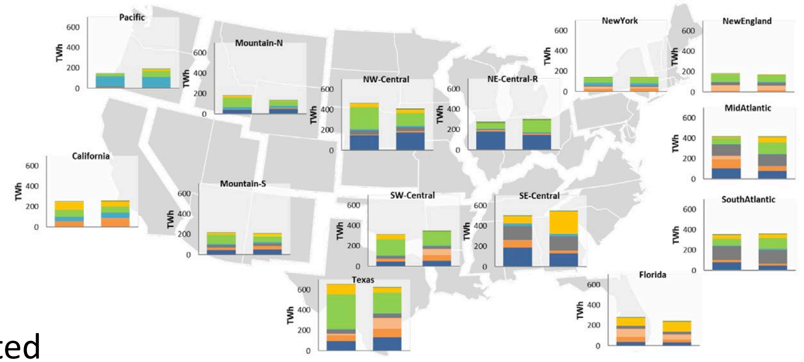
Benefits manifest over long-term

Davis, unpublished

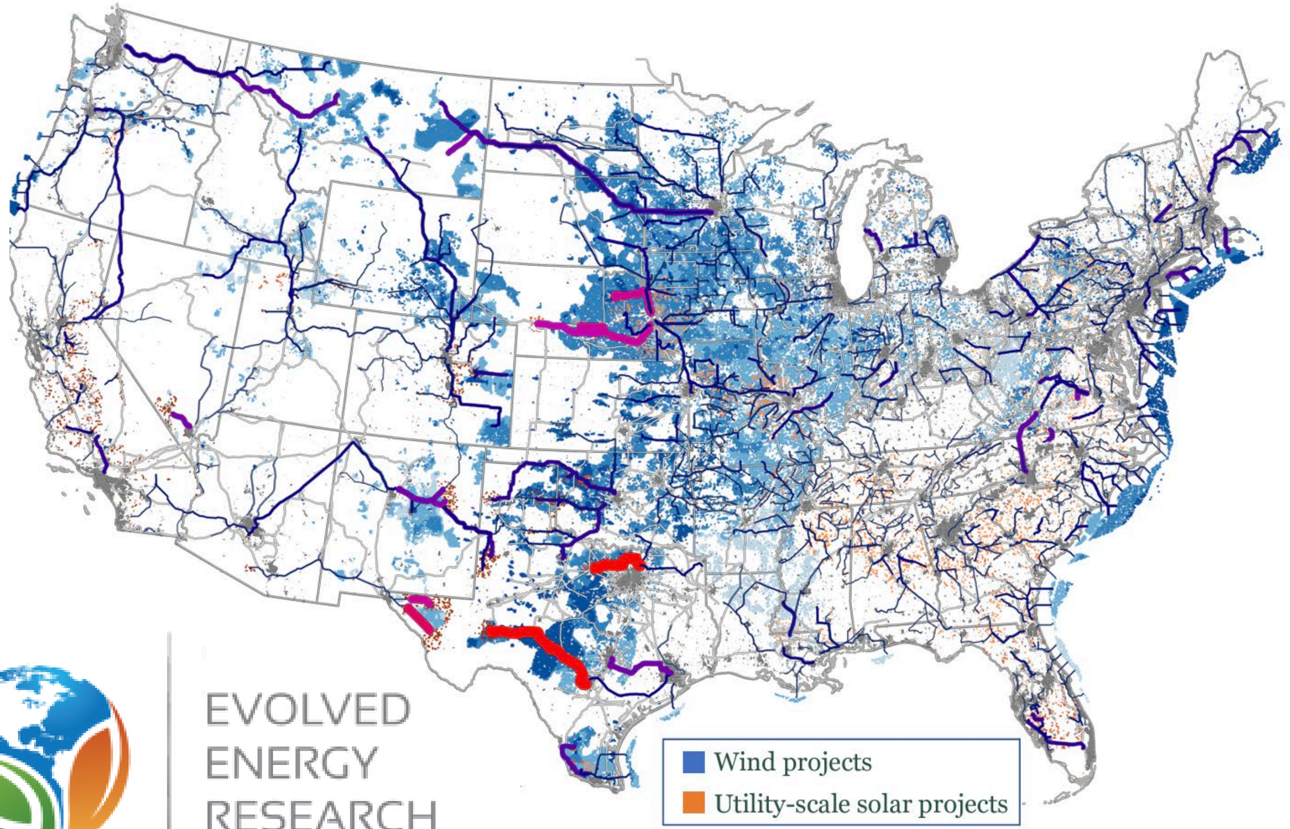
State-of-the-science (cost-optimizing) energy system models







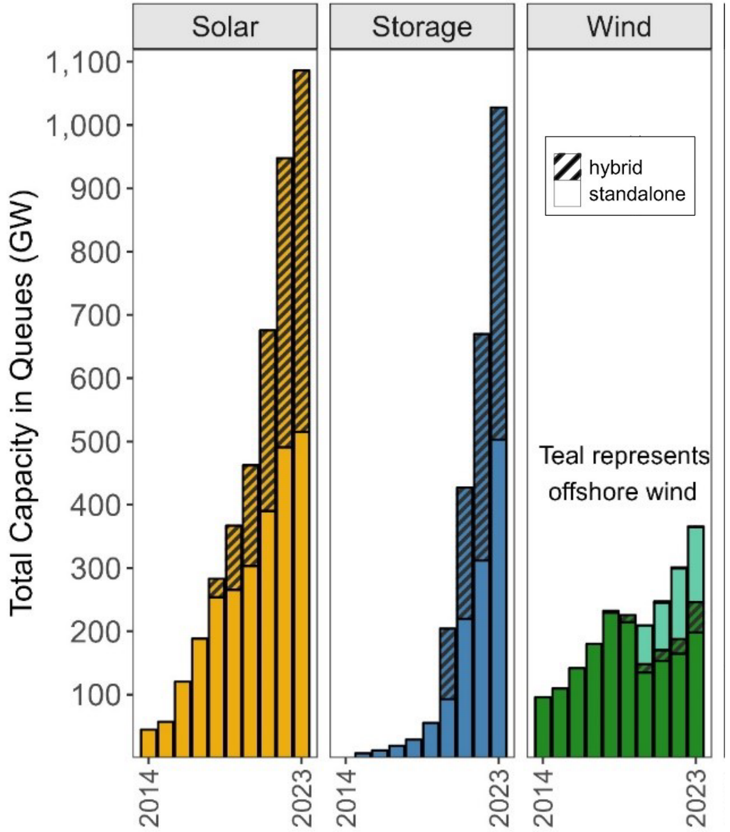
Not strictly cost-related: often neglected but critical factors



EVOLVED ENERGY RESEARCH

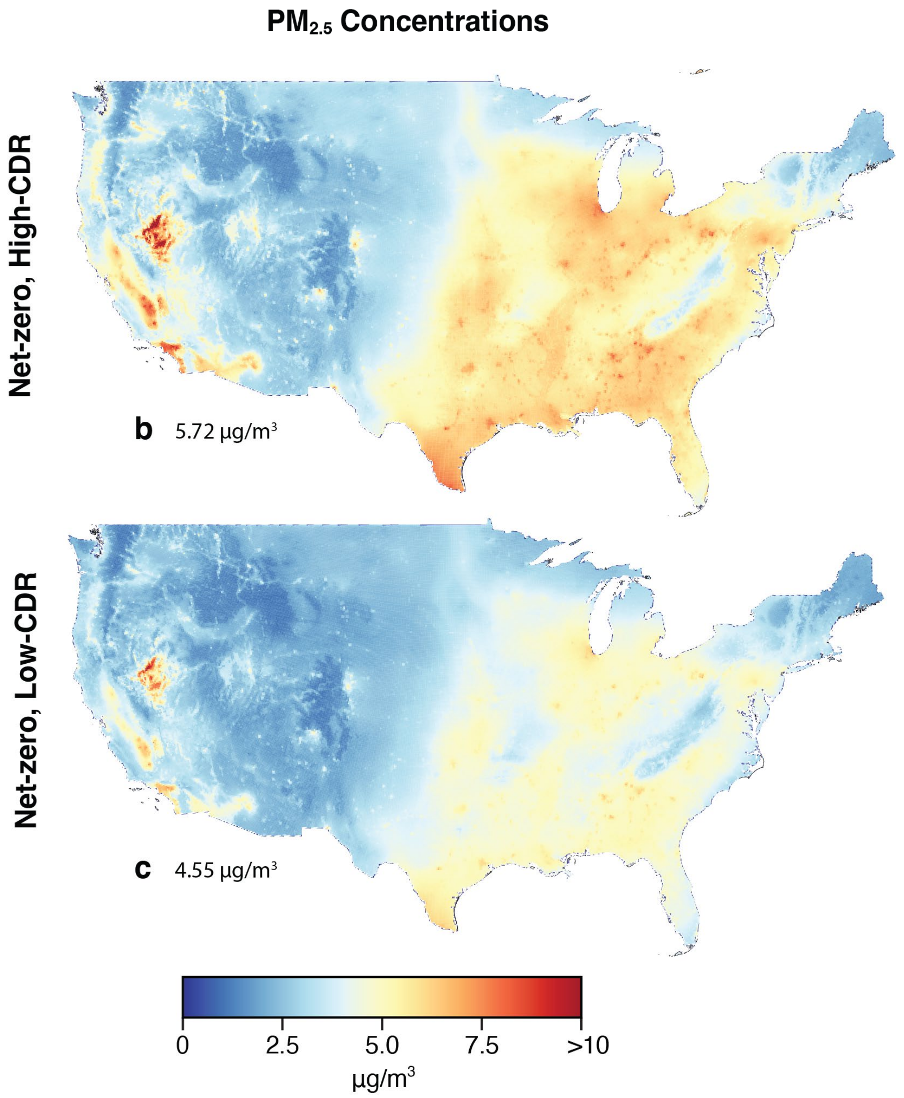
PRINCETON UNIVERSITY
NET-ZERO AMERICA
POTENTIAL PATHWAYS, INFRASTRUCTURE, AND IMPACTS

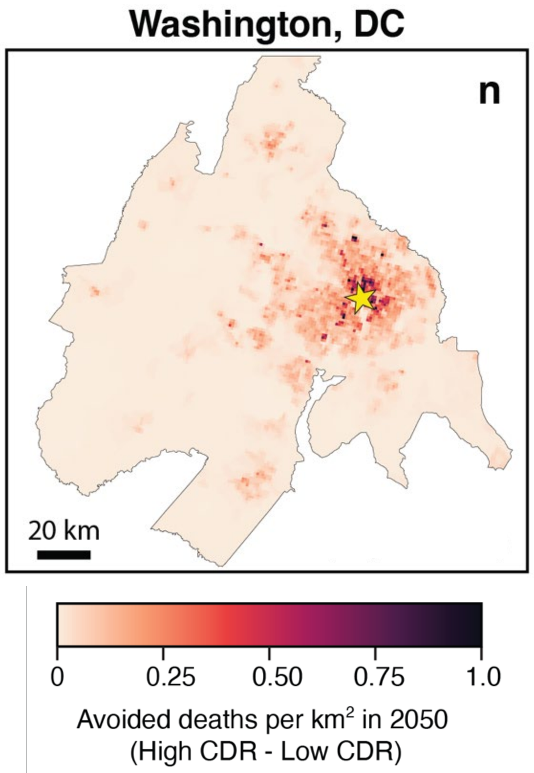
Vast land areas developed in net-zero scenarios raise many social, environmental, and economic questions that we've only begun to consider and assess.

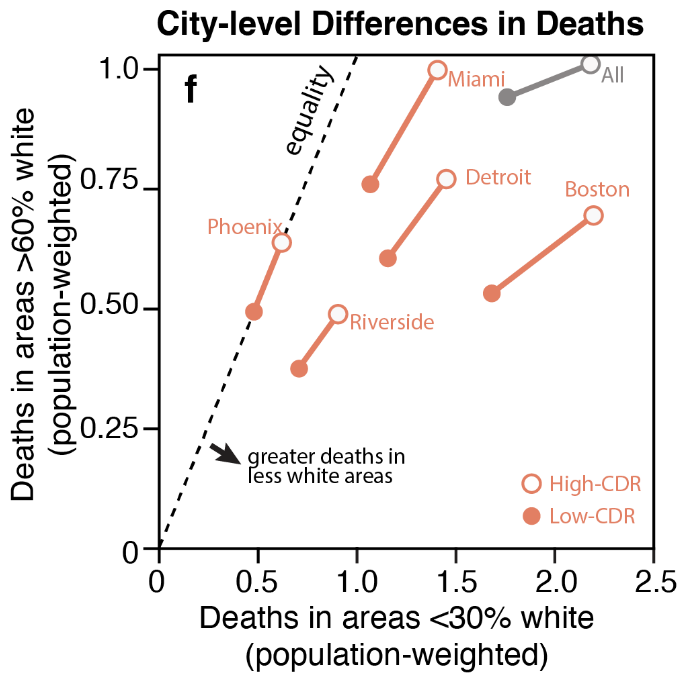


LBNL, 2024

The distribution of benefits will differ substantially depending on details of the net-zero pathway

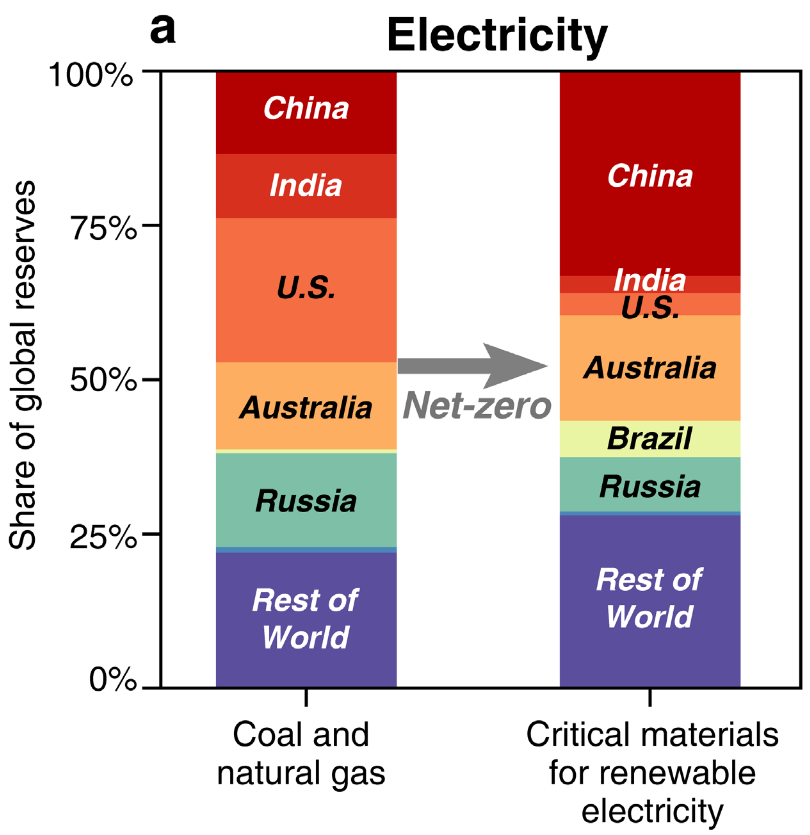


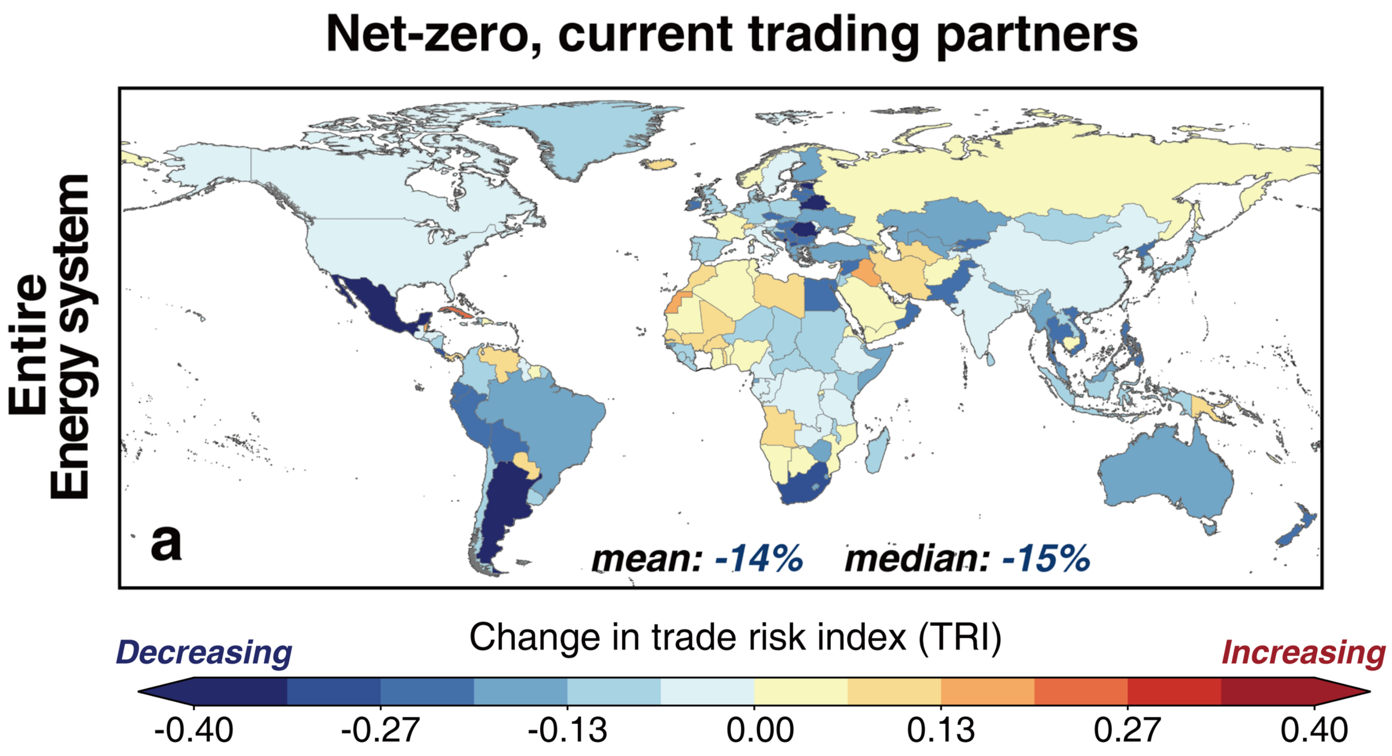




Bergero et al., *in prep*

Renewables-related materials are distributed very differently worldwide than fossil energy resources





Cheng et al., *in review*

Take-aways

Solar, wind, and electrification are core, cost-effective strategies, but two main research frontiers

1. Cost-related, ever more detail on the difficult stuff

- **Targeted innovation:** What tech costs and performance characteristics that net-zero *system costs* most sensitive to?
- **Policy-related:** How do different levels and types of policy intervention change the outlook for specific techs and system costs?

2. Non-cost considerations, e.g.

- **Land and water**: How will different natural resource constraints affect desired pathways?
- **Political economy**: Lock-in, regulatory capture, national security and international trade
- **Social license**: Jobs, environmental justice, NIMBYism, perceptions of safety
- **Co-benefits/trade-offs**: air quality, resilience to extreme events, conservation,

Thank you.

Much of the analysis I presented was led by postdocs **Jackie Dowling** and **Jing Cheng** and graduate students **Candelaria Bergero** and **Dimitri Saad** in collaboration with many others, including Ken Caldeira, Paul Fennell, Nate Lewis, and Dan Tong.

Decarbonization

National Academies, 12 September 2024

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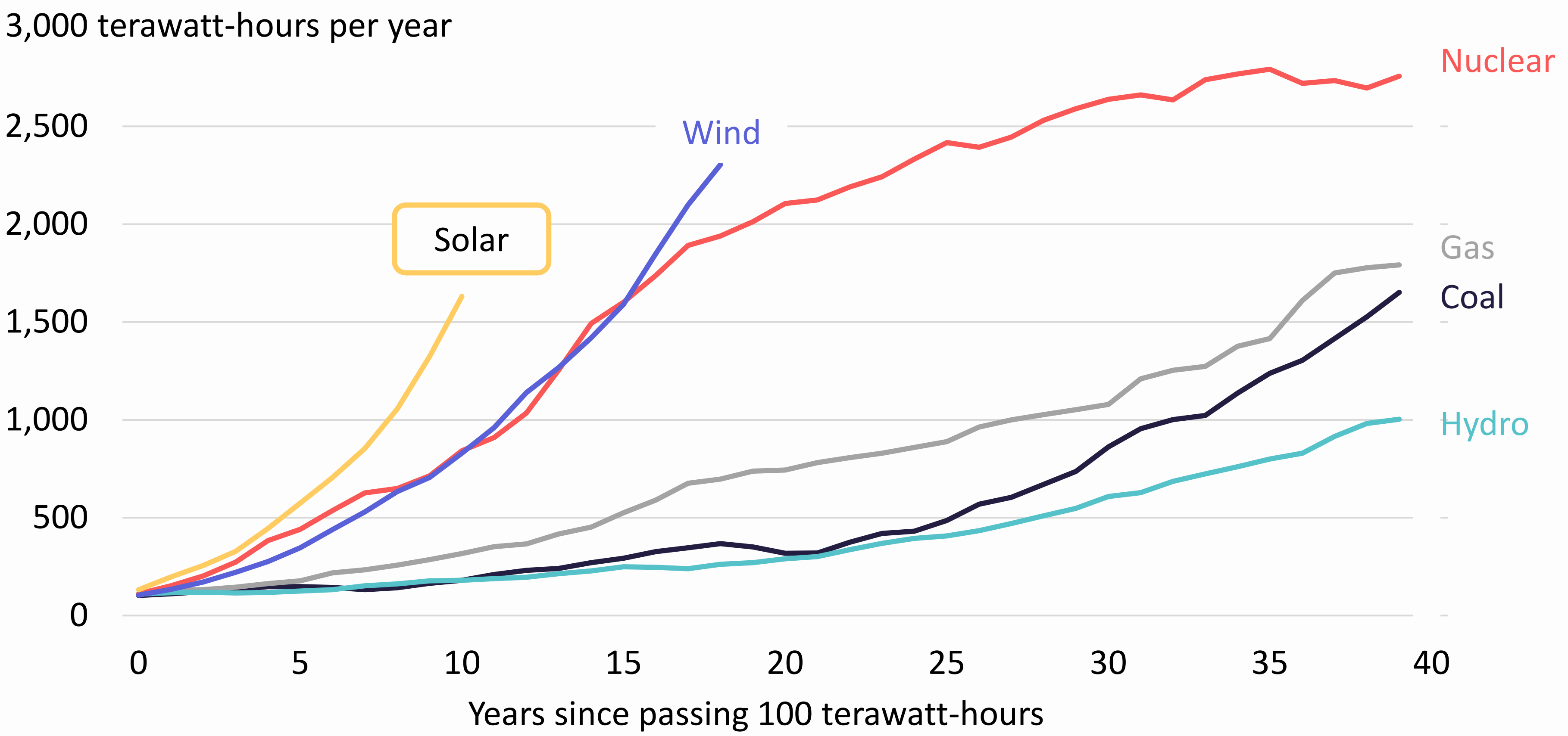
The fastest electrons in history

Wind and solar are growing faster than any other generation source in absolute terms

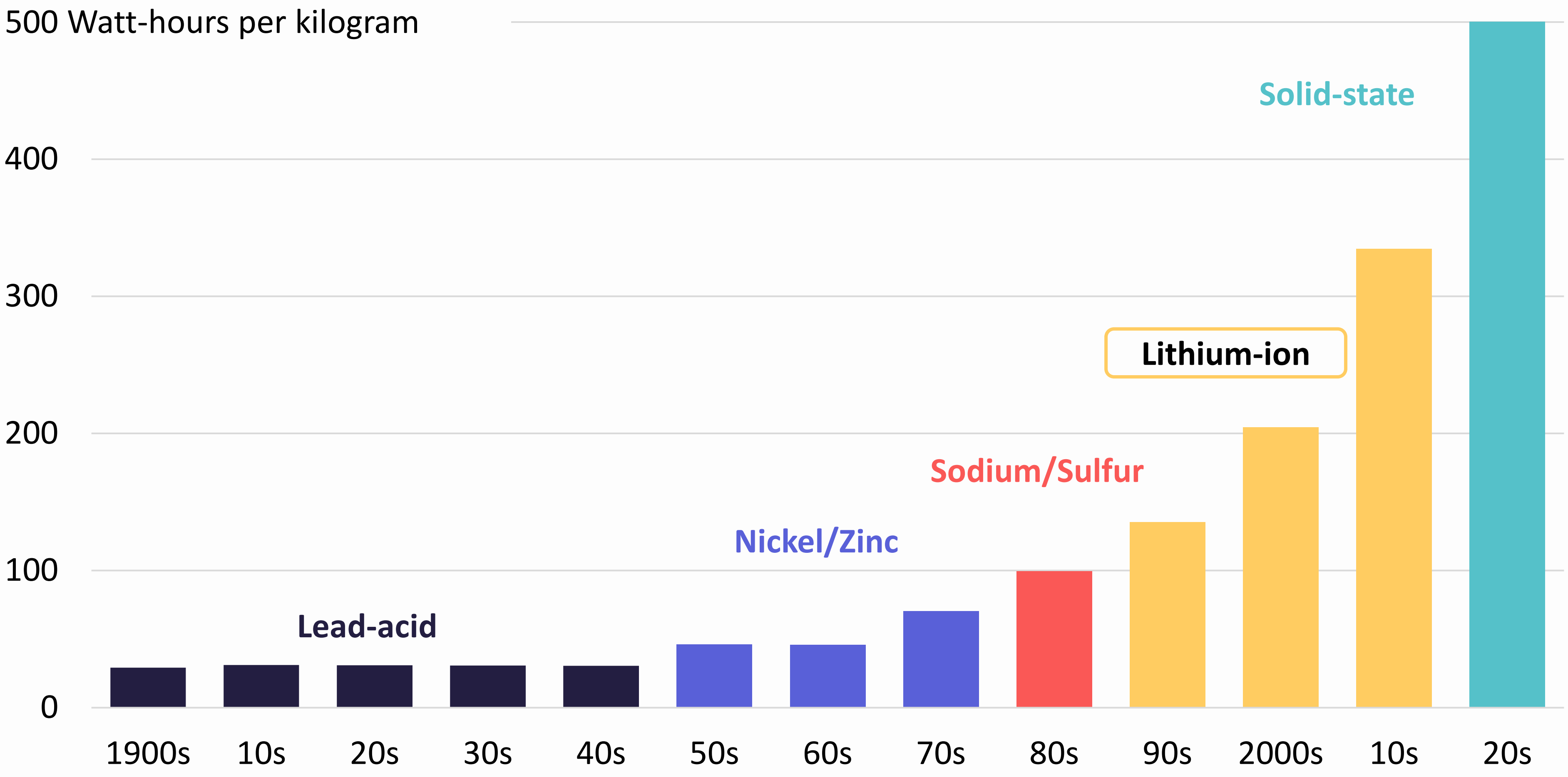
Source:
Ember Climate

Annual generation after exceeding 100 terawatt-hours in a year



A century of gains

Battery energy density has improved 10-fold since the 1920s, and five-fold since the 1980s

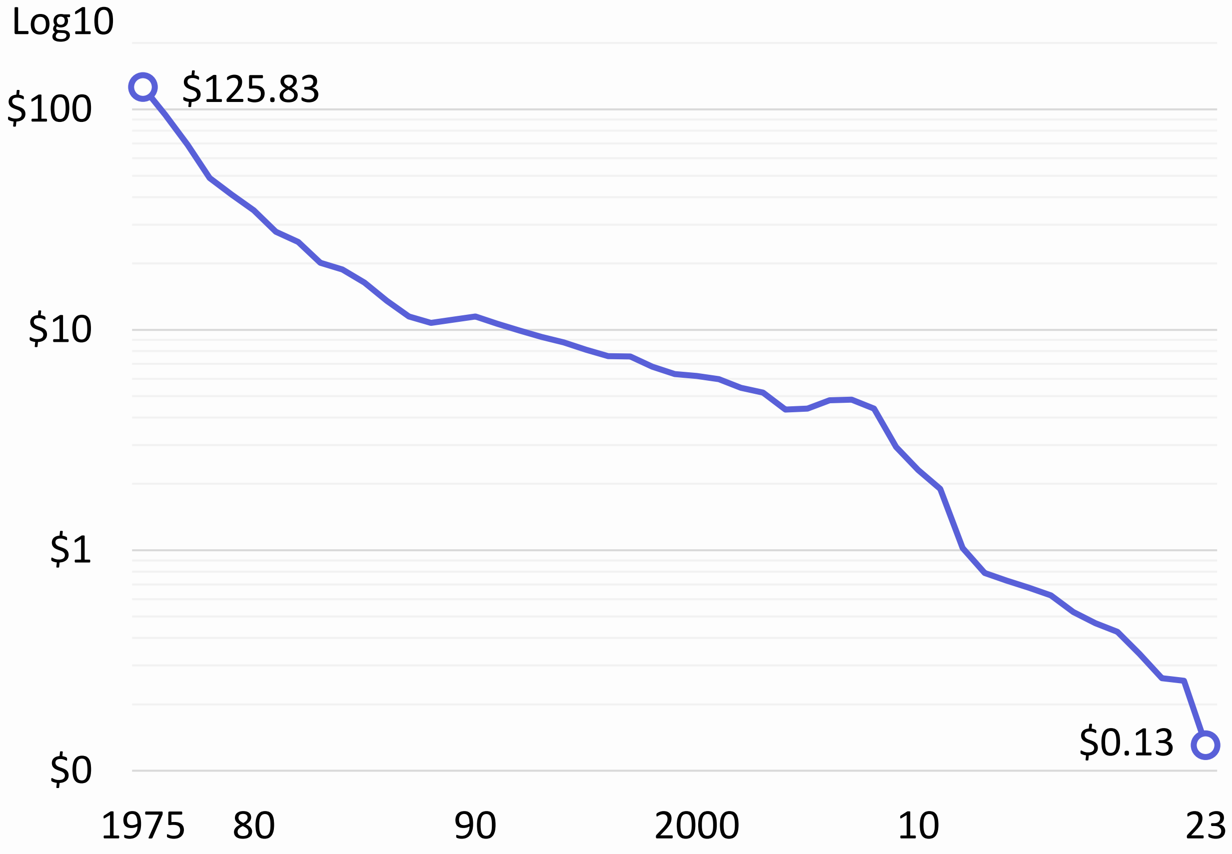


Source:
RMI,
Zu and Li (2011) for 1900s-2000s,
BloombergNEF (2023) for 2010s and 2020s

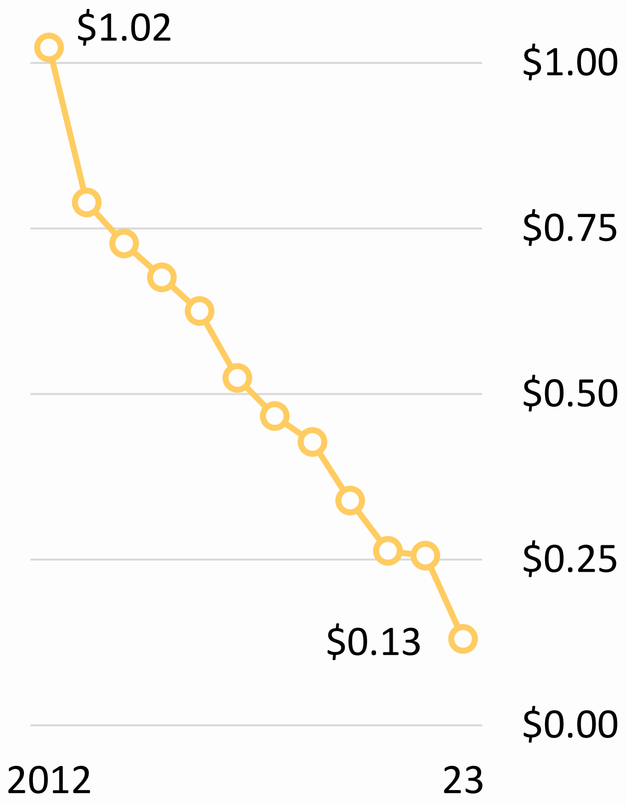
PV module prices gapped down 50%

PV module prices dropped 50% in 2023, and are down by more than 99% since 1975

PV module price per Watt, 1975 – 2023



2012 – 2023



Source:
IRENA (2023), Nemet (2009), Farmer and Lafond (2016) with major processing by Our World in Data, IEA (2023)

Note:
Real $ 2022

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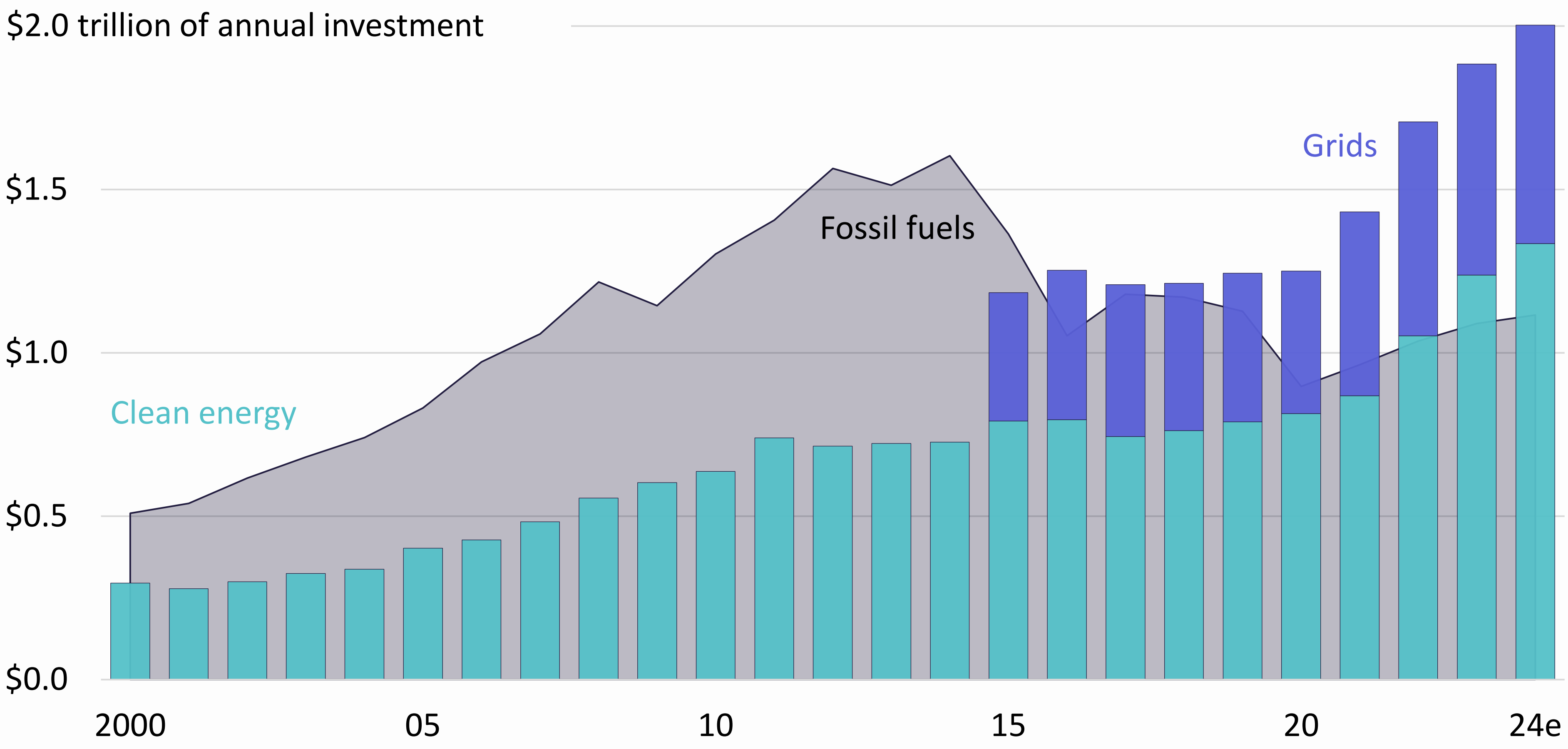
Fuels, clean energy, and grids

Investment in clean energy and grids is now greater than fossil fuel investment was in the 2010s



Source:
IEA

Note:
USD,
2023 MER

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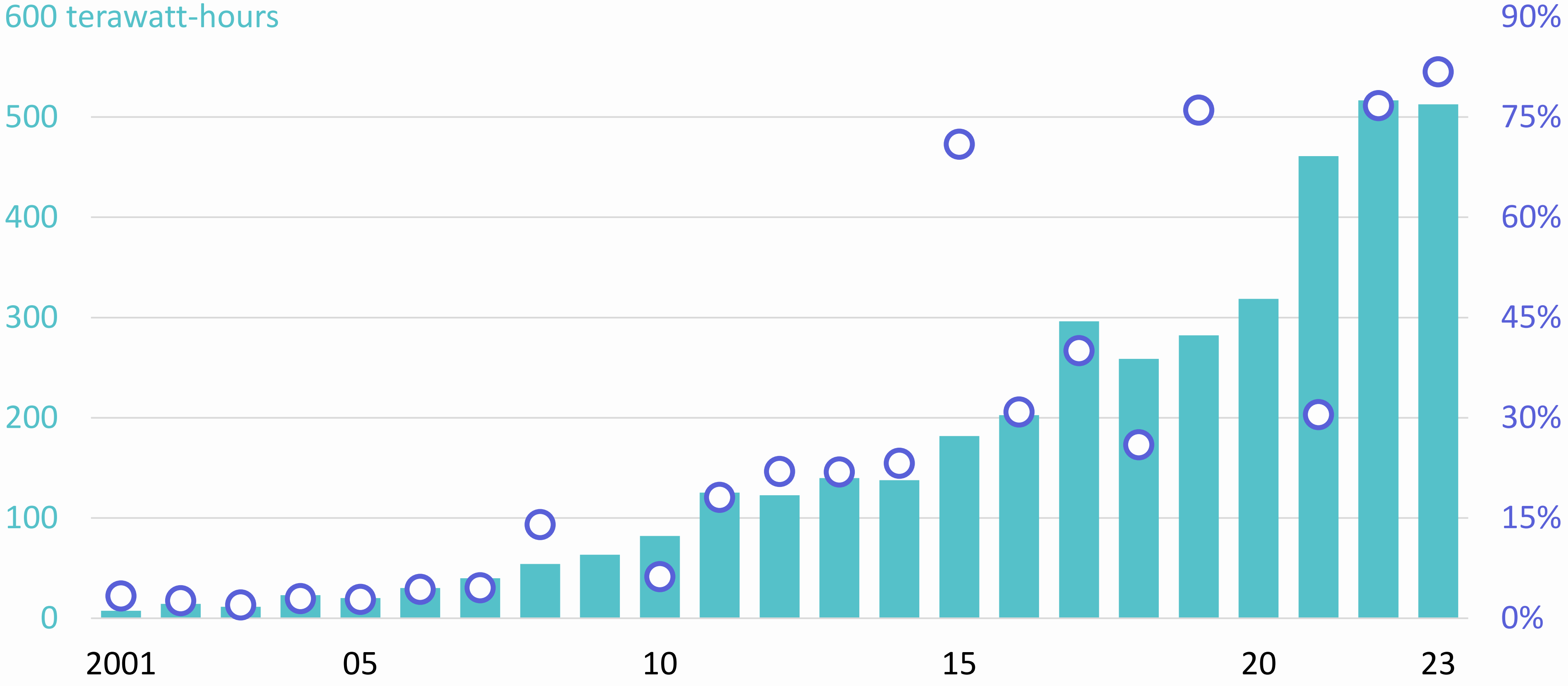
Supplying demand

Wind and solar are close to meeting all incremental electricity demand



Source: Ember

Note: omits percentage data in years when total demand declined (2009 and 2020)

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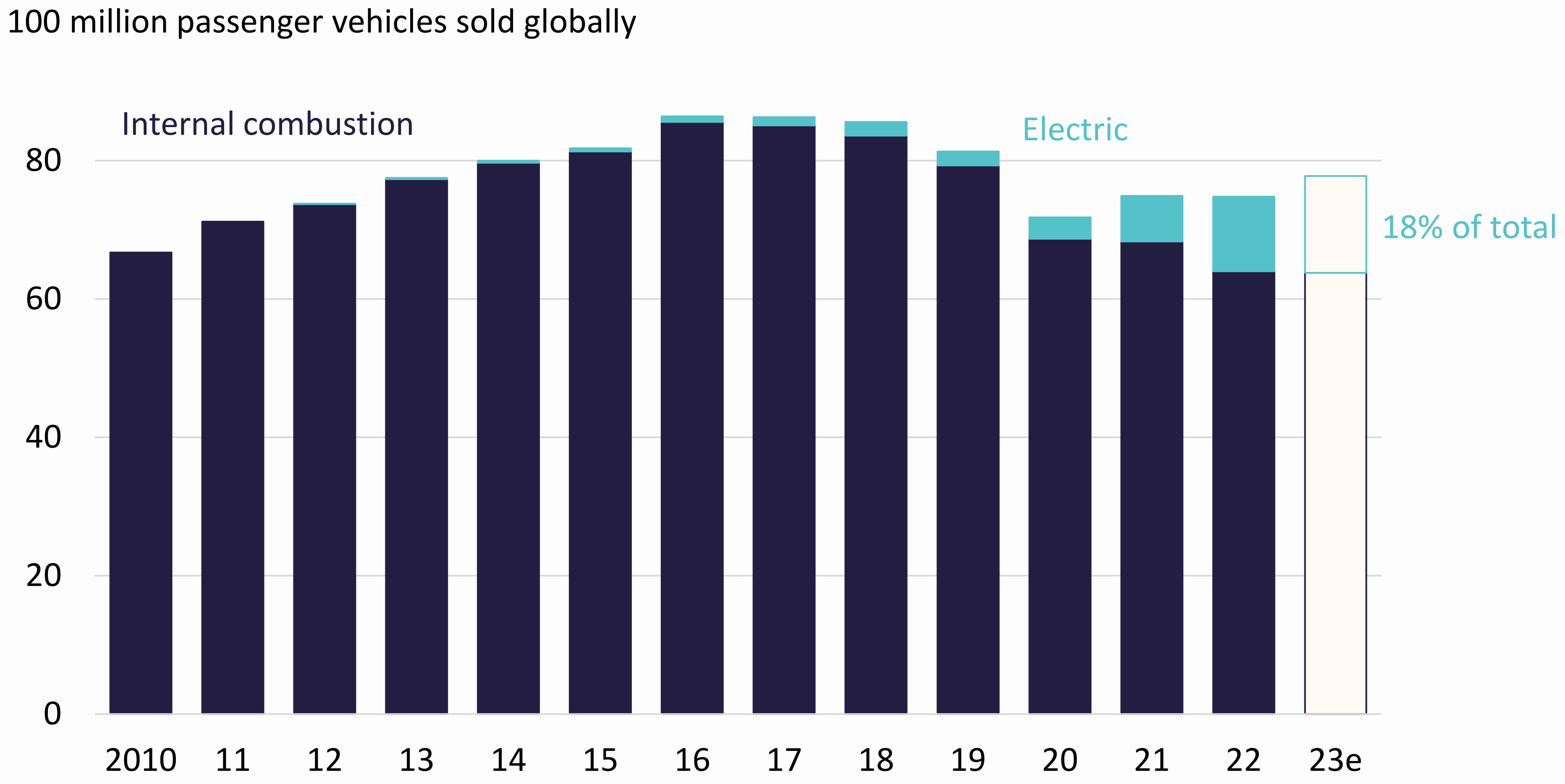
Growth engines, and fading motors

Electric vehicles were the only growth in global auto sales for the seventh year in a row

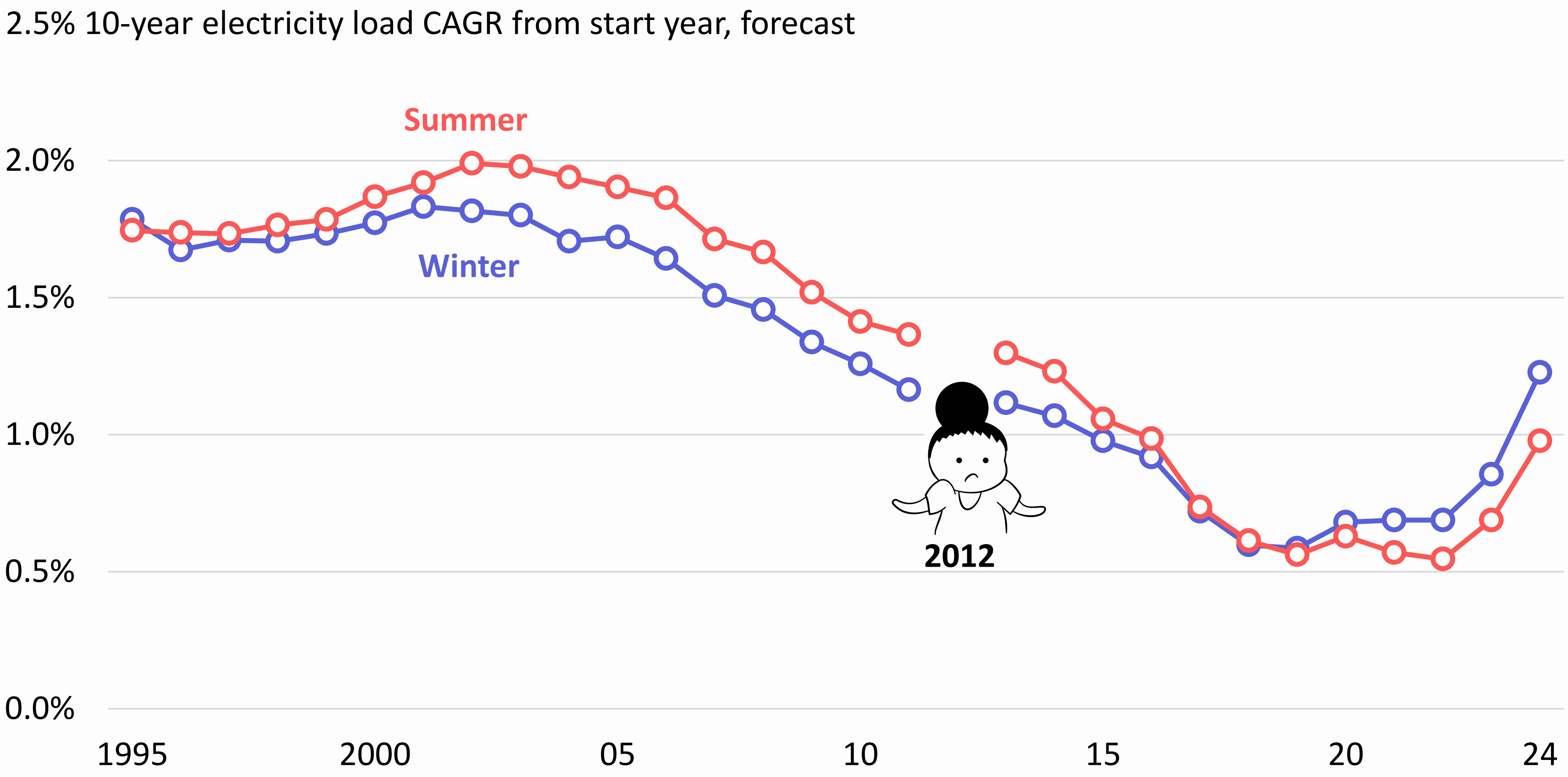


Source:
IEA

Note:
2023 is estimated

Bending the curve

Official forecasts point to power load growth – but still below what NERC expected 20 years ago



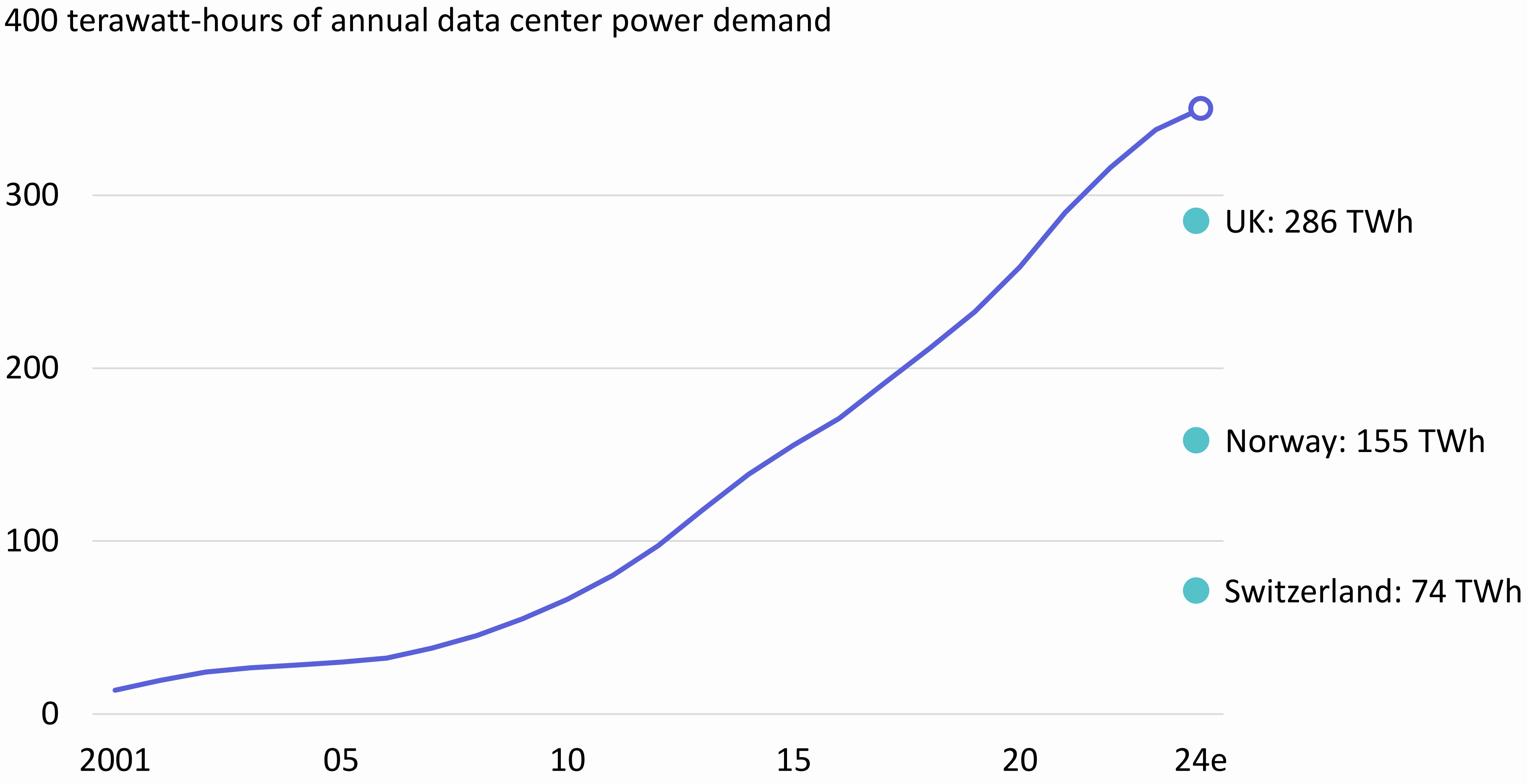
Source:
NERC

Note:
No data provided for 2012-22 forecast

Consuming data

Data center power consumption is country-sized already

Source: Bloomberg, BloombergNEF, DC Byte

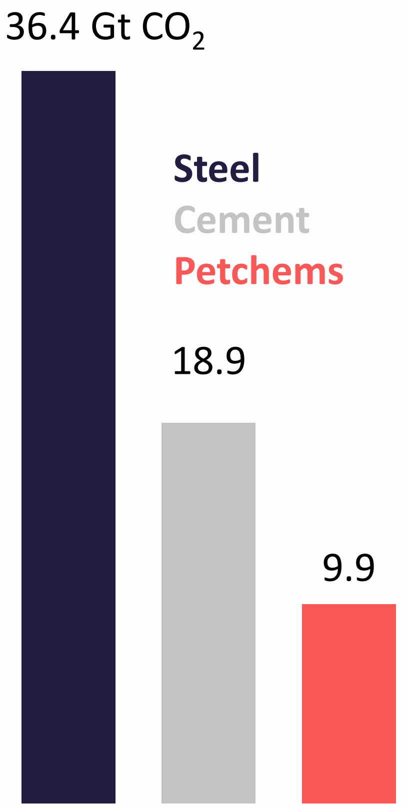


Varying processes, varying strategies

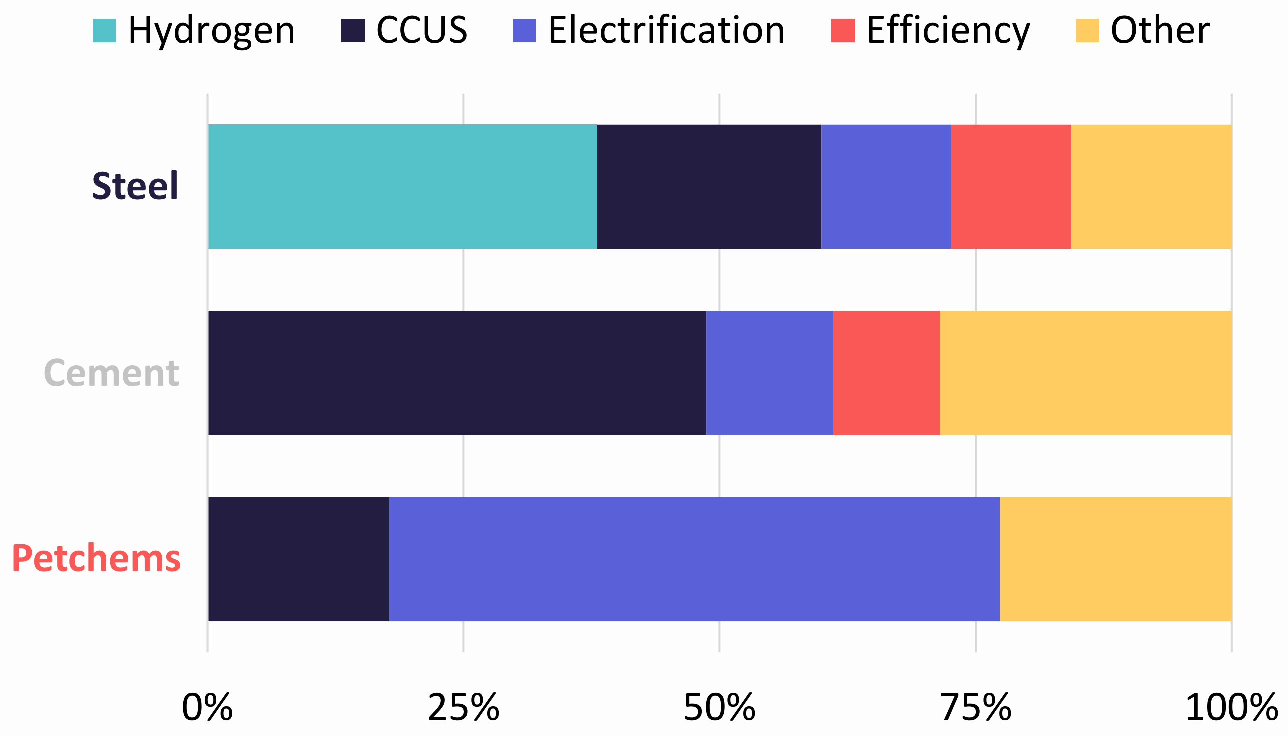
Hard-to-abate sectors have pledged 65 gigatons of abatement by 2050, with differing tech

Source: BloombergNEF New Energy Outlook 2022

Cumulative emissions abatement pledges

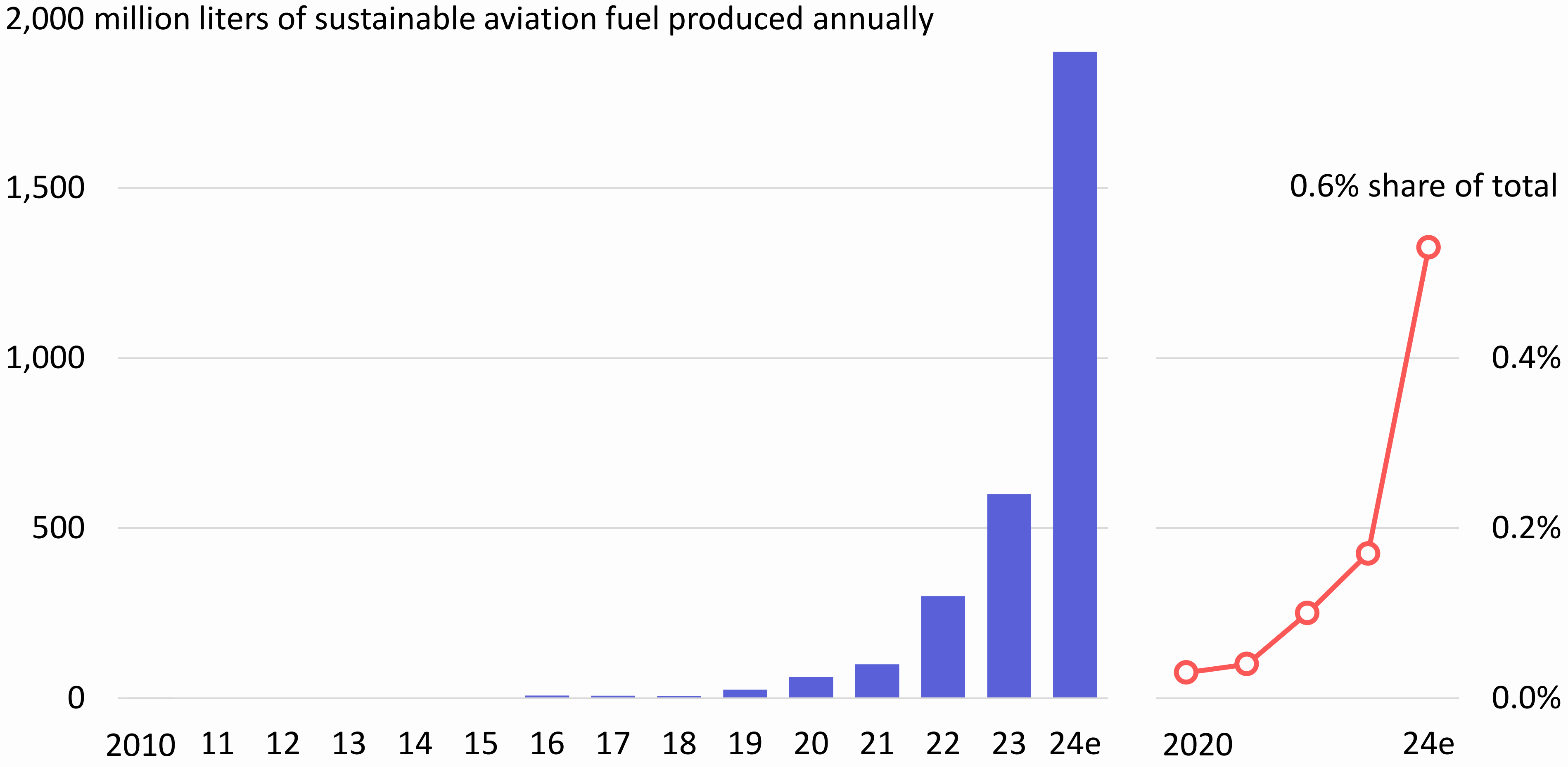


By emissions abatement technology, share of total abatement



Sustainable volumes

Sustainable aviation fuel volume is increasing markedly, but from a tiny base

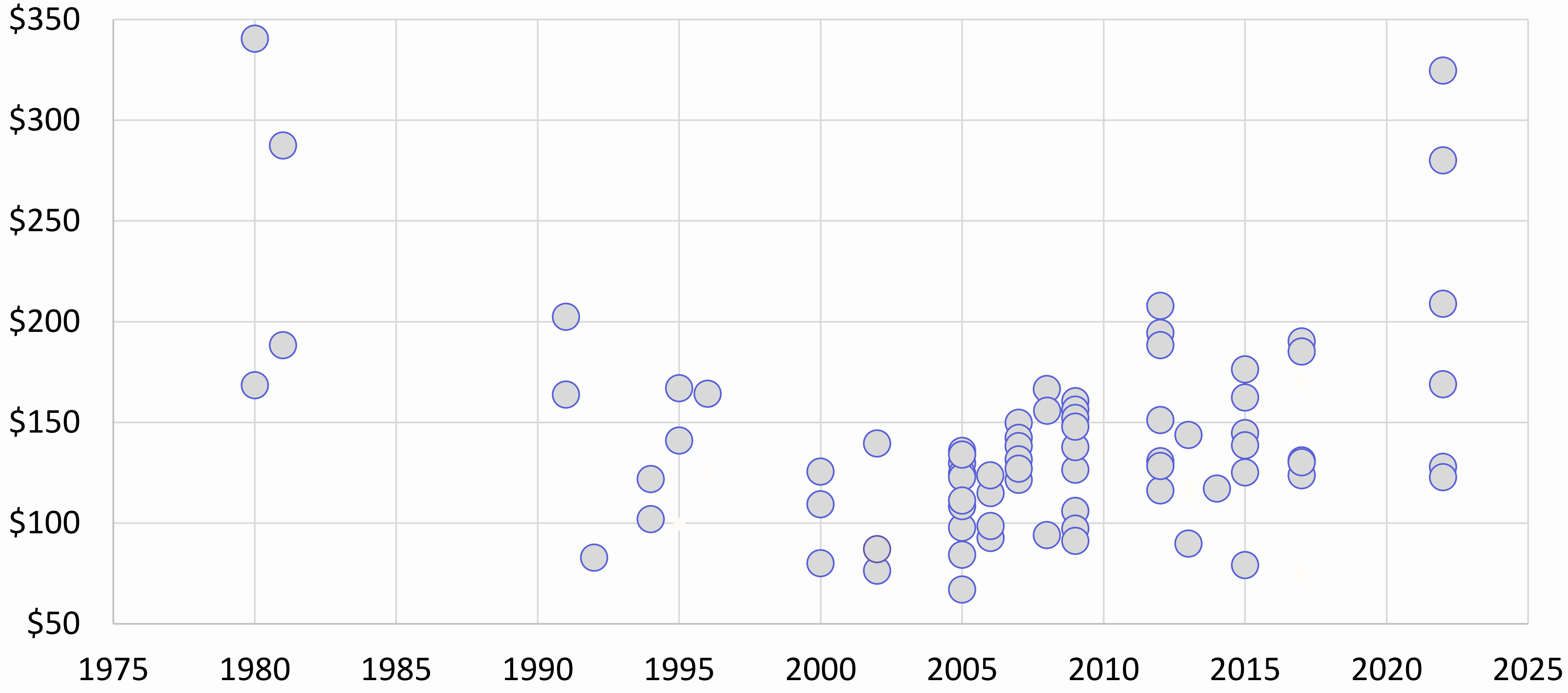


Source:
ICAO, IATA

CCS costs are not improving

And in fact, have only risen in academic studies since the 2000s

Techno-economic estimates of power-plus-CCS ($2022 per megawatt-hour)

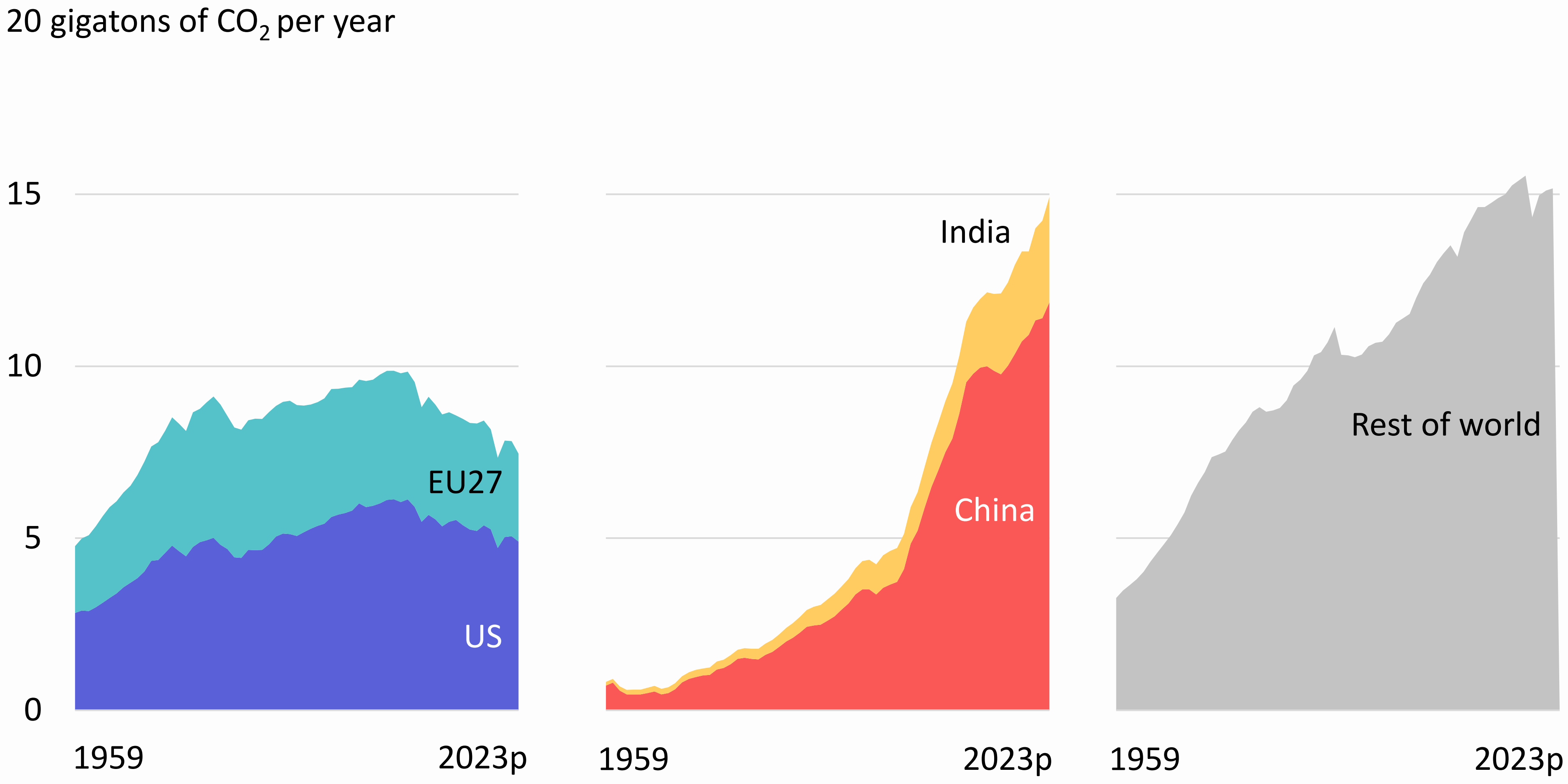


Source: Bacilieri, Black, Way (2023)

Note: includes power generation costs for coal (post-combustion), Coal (integrated combustion combined cycle), Coal (oxy-combustion), and gas with CCS

Three blocs, two paths

US and EU emissions have declined this century; emissions elsewhere have not



Source:
Friedlingstein et al. (2023), Global Carbon Budget 2023

Note:
2023 is preliminary

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