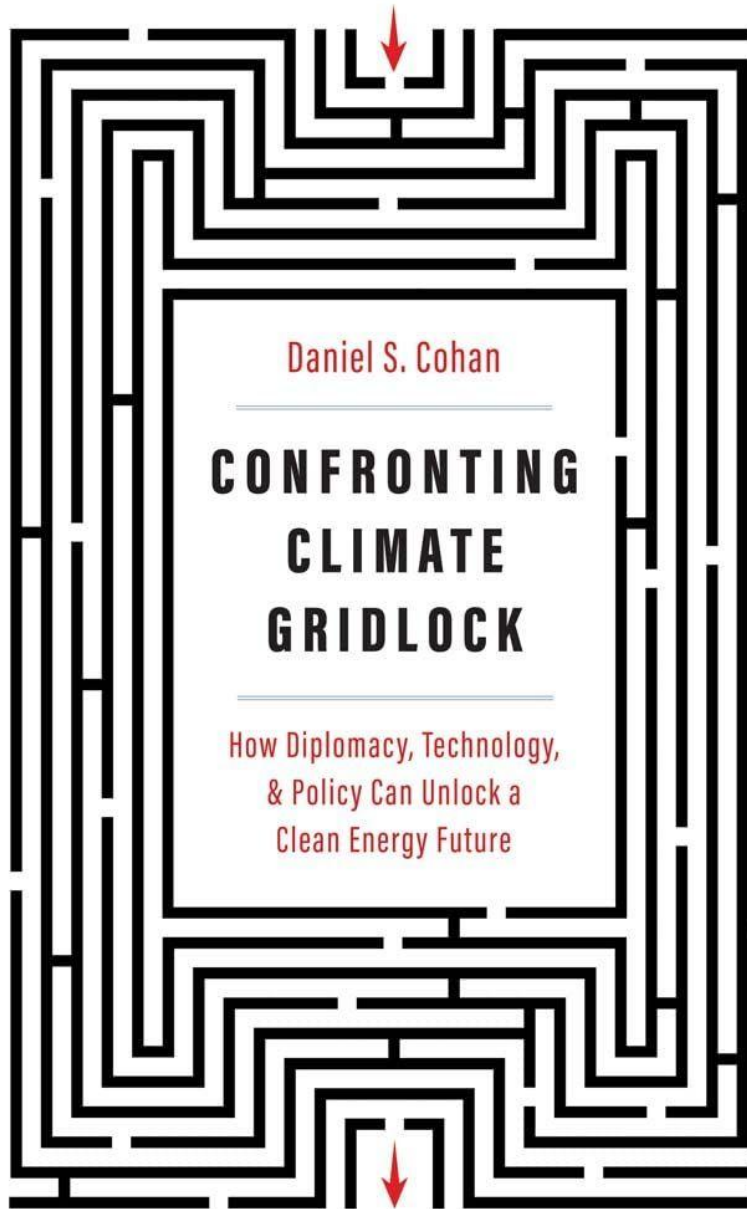


Confronting Climate Gridlock



Daniel Cohan
March 2022



About the speaker

- Associate Professor of Civil and Environmental Engineering at Rice
 - At Rice since 2006
 - A&WMA member
- National Science Foundation CAREER award
- 50+ peer-reviewed publications, 70+ op-eds
- Website: cohan.rice.edu



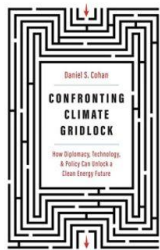
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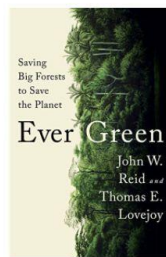
New Releases in Environmental Policy

#1



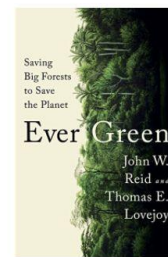
Confronting Climate Gridlock: How Diplomacy, Technology, and Policy Can Unlock a Clean Ener...
> Daniel S Cohan
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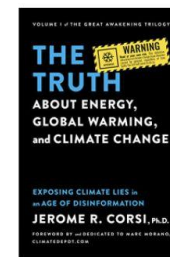
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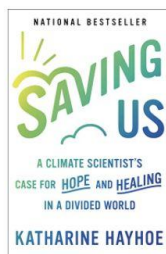
Ever Green: Saving Big Forests to Save the Planet
John W. Reid
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The Truth about Energy, Global Warming, and Climate Change: Exposing Climate Lies in an Age...
Jerome R. Corsi Ph.D.
Hardcover
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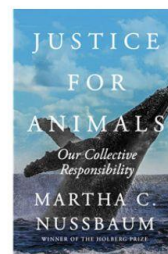
Saving Us: A Climate Scientist's Case for Hope an...
> Katharine Hayhoe
★★★★☆ 229
Paperback
\$18.99

#6



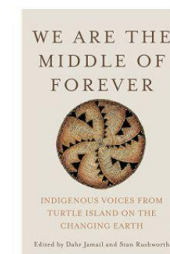
Saving Animals, Saving Ourselves: Why Animals...
> Jeff Sebo
★★★★☆ 1
Kindle Edition
\$17.99

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Justice for Animals: Our Collective Responsibility
> Martha C. Nussbaum
Hardcover
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#8



We Are the Middle of Forever: Indigenous Voices from Turtle Island on the Changing Earth
> Dahr Jamail
Hardcover
\$28.99

Three keys to confronting gridlock: Diplomacy, Technology, and Policy

Foreword by Michael E. Webber ix

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seven Going Negative 126

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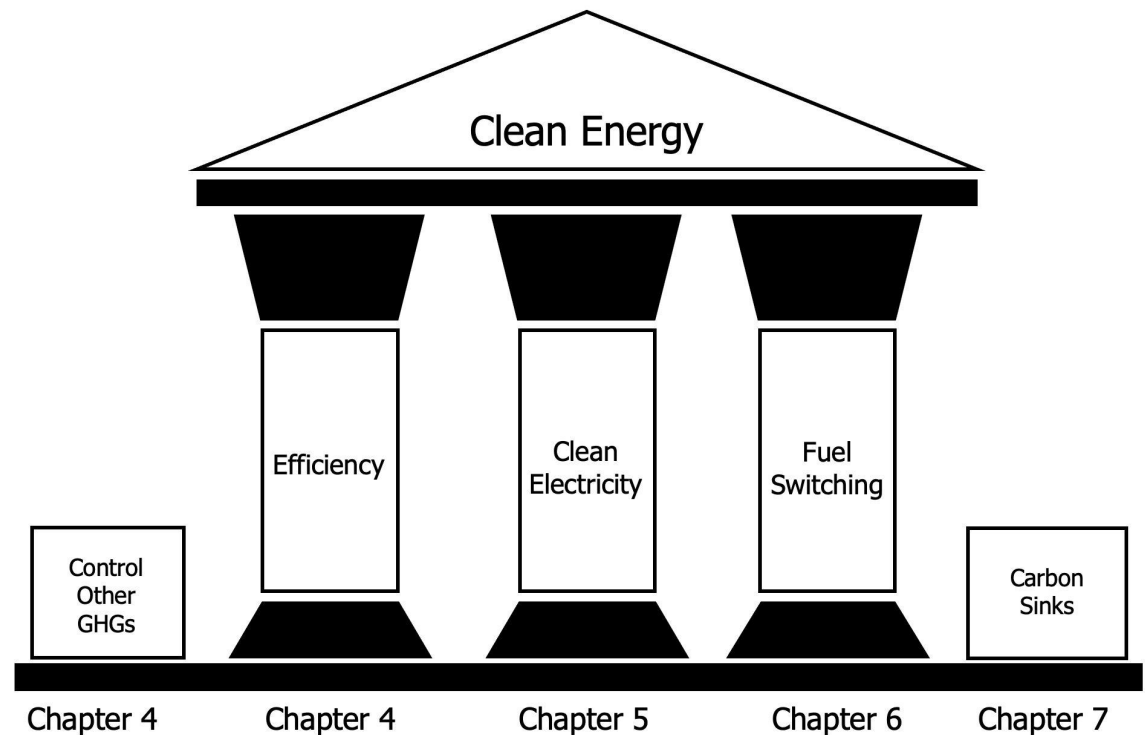
Index 225

I'll focus on the technology chapters today

Diplomacy

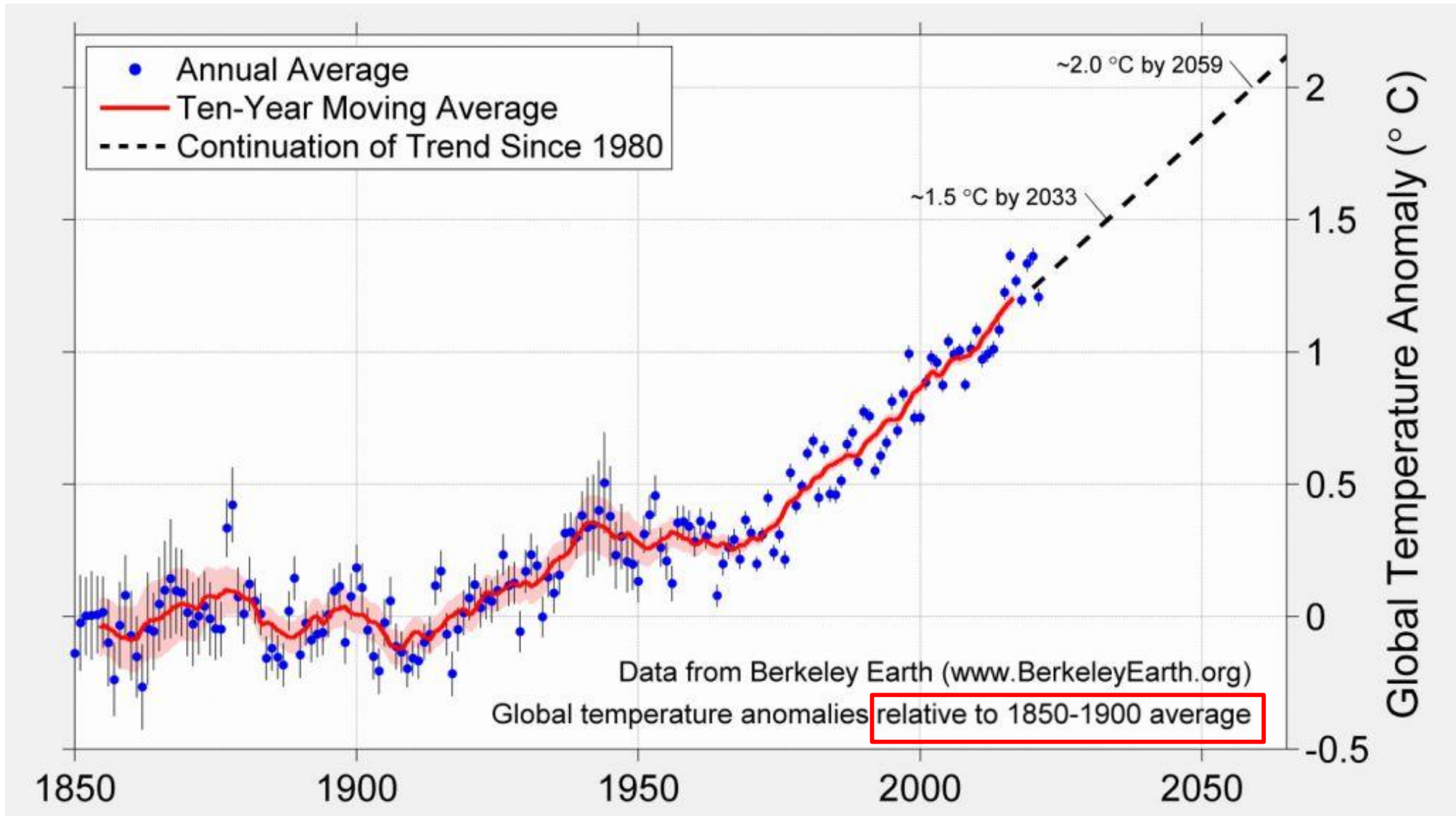
Technology

Policy



Book draws from >100 interviews with diplomats, scholars, innovators, etc.

Temperatures are nearing Paris Agreement limits



Worst-case scenarios avoided, but not on track for 1.5-2°C

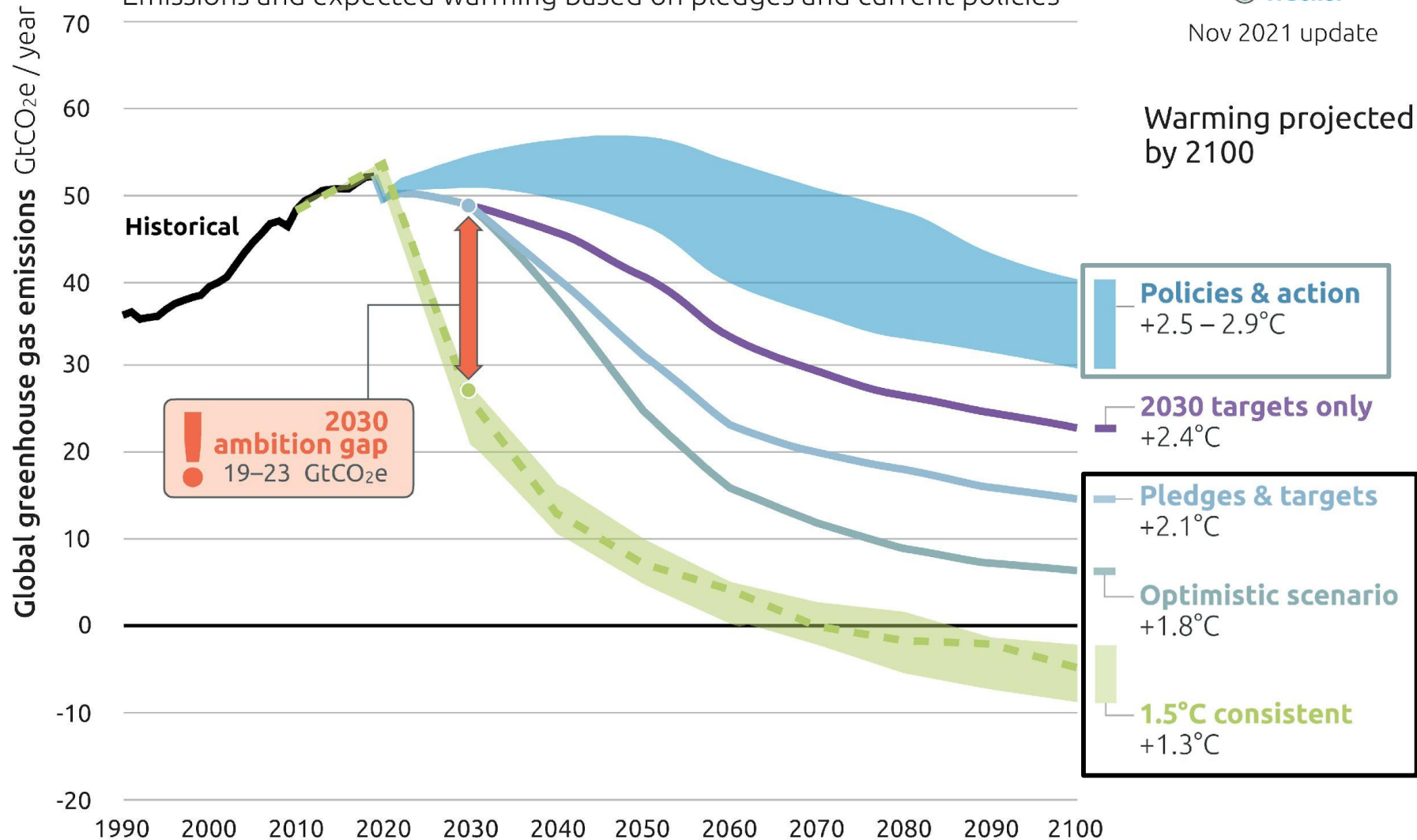
2100 WARMING PROJECTIONS

Emissions and expected warming based on pledges and current policies



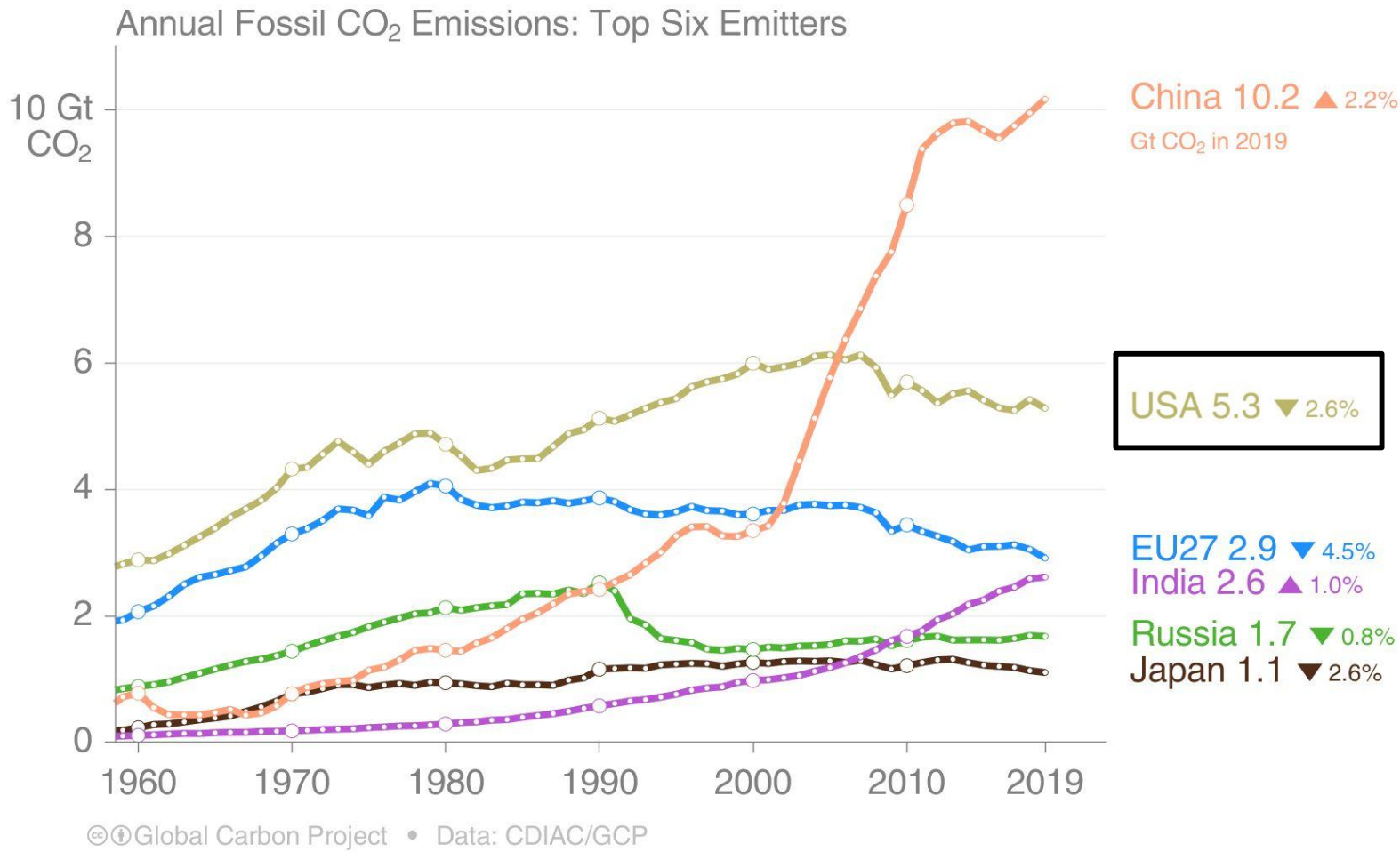
Nov 2021 update

Warming projected by 2100



U.S. Role in Emissions

The top six emitters in 2019 covered 65% of global emissions
 China 28%, United States 15%, EU27 8%, India 7%, Russia 5%, and Japan 3%



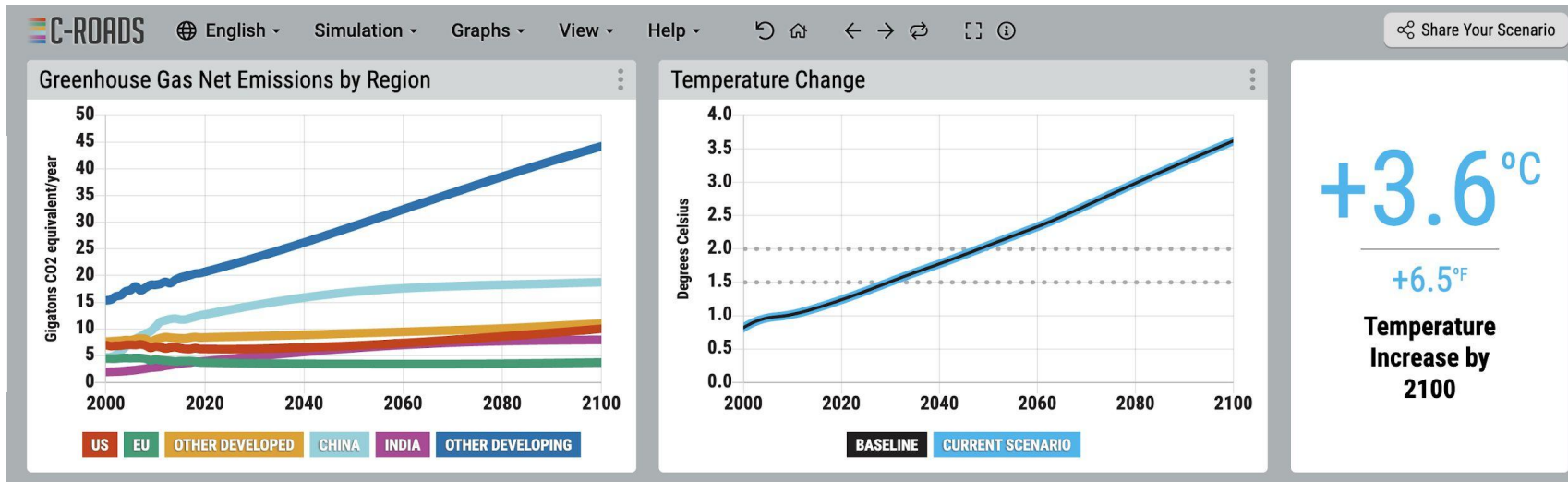
Second-largest emitter now, but <15% and falling

Bunker fuels, used for international transport, are 3.5% of global emissions.

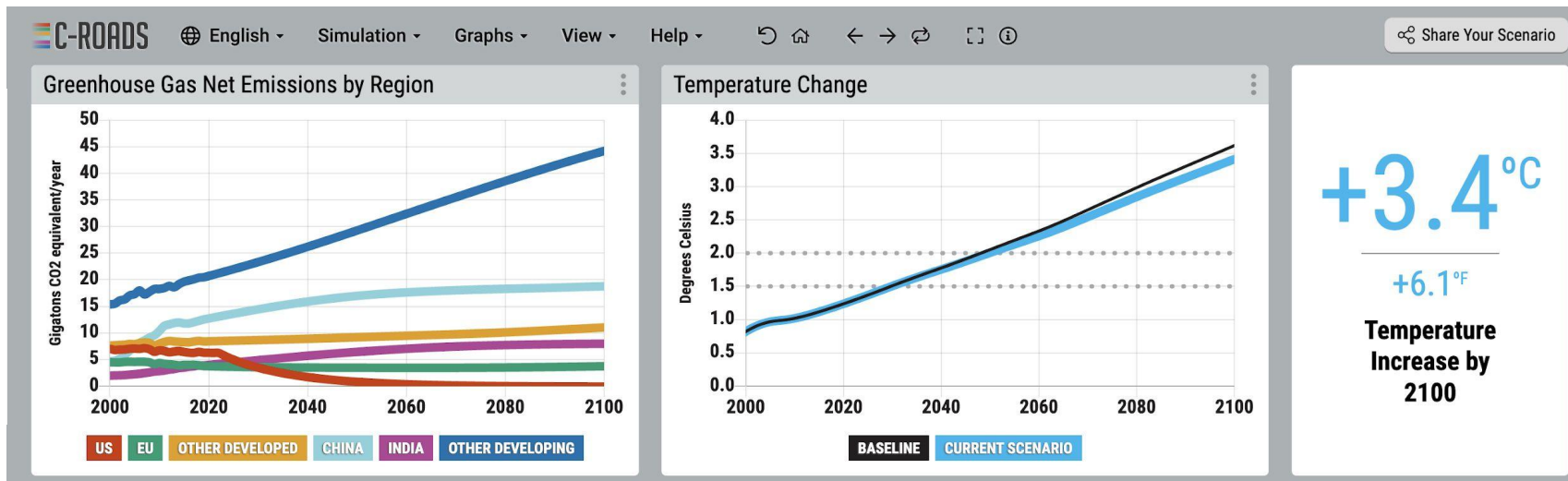
Source: [CDIAC](#); [Peters et al 2019](#); [Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Net-zero in U.S. isn't enough

C-ROADS
Base case



C-ROADS
with U.S.
nearing
net-zero



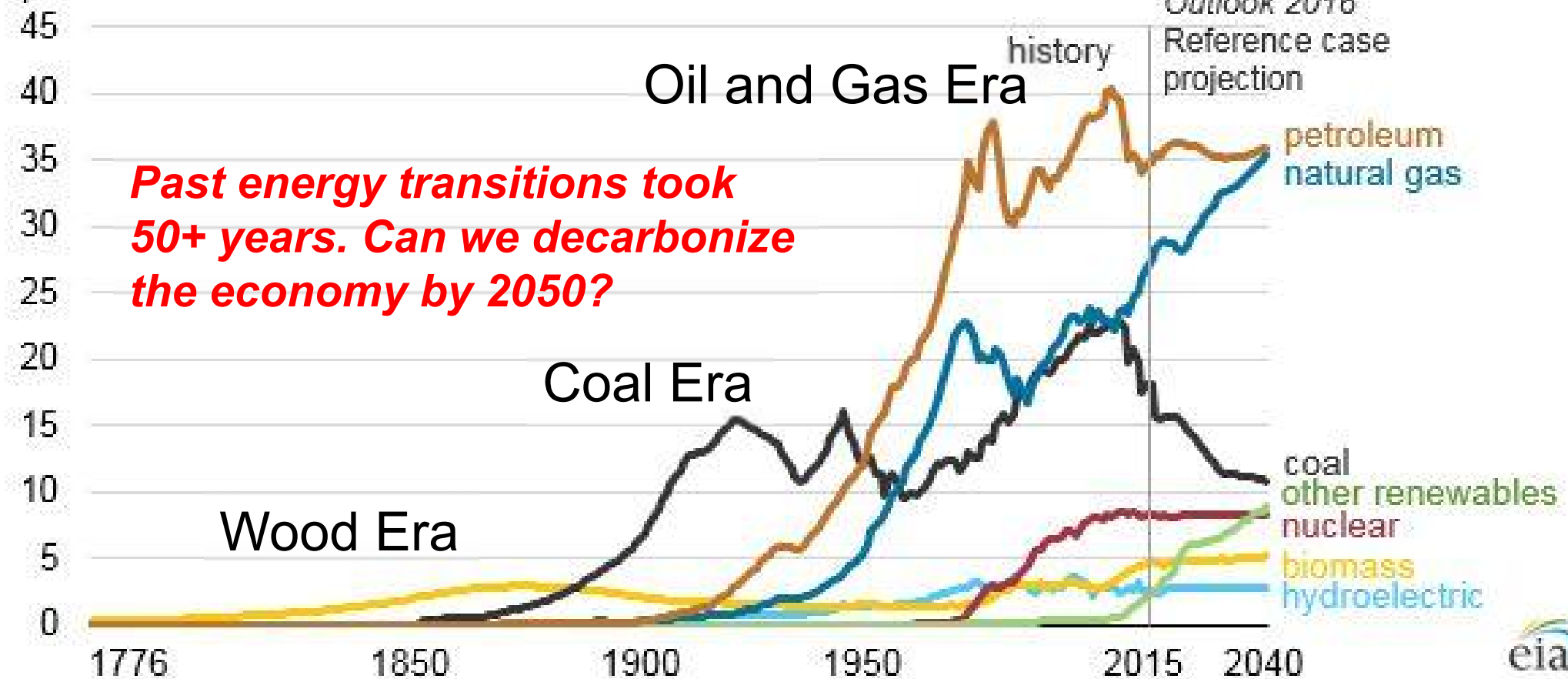
*Need to decarbonize energy affordably, reliably, and fast,
in ways that make it achievable globally*

Still, U.S. is crucial

- Most emissions historically and per-capita
- Largest economy and consumer market
- Leads in technology development
- Leading driver and barrier to diplomacy
- Need to make clean energy cheap here so it can be deployed elsewhere
 - Learning by doing drives down cost and improves performance

Energy transitions historically have been slow

Energy consumption in the United States (1776-2040)
quadrillion Btu

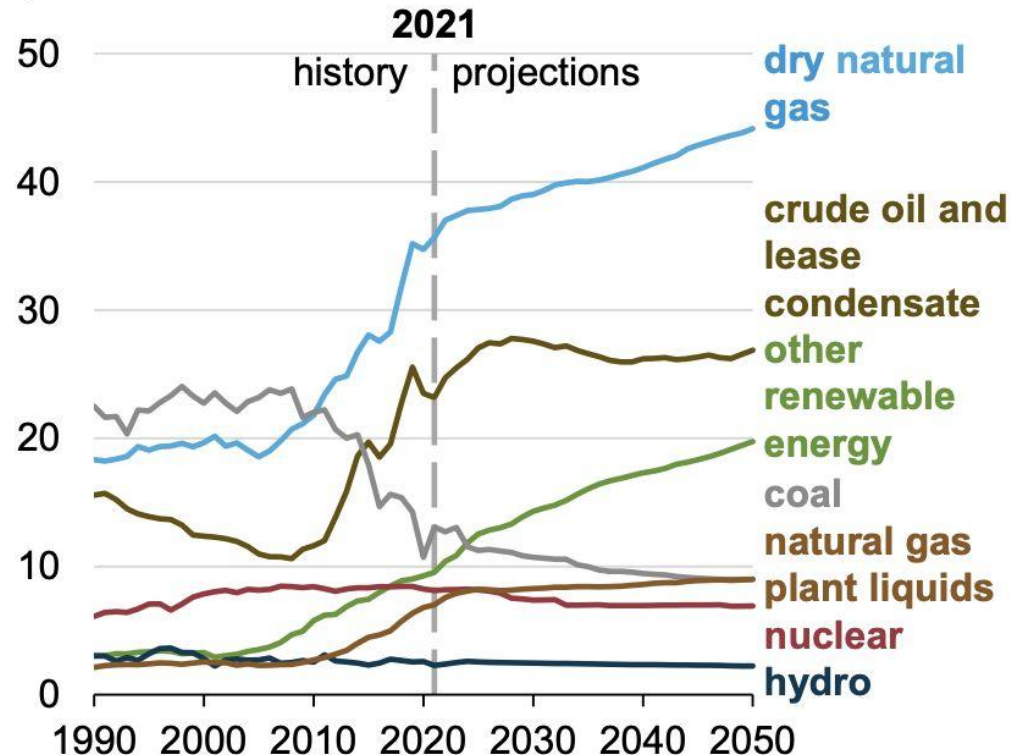


Baseline projections expect fossil fuels to remain dominant

Energy production by source

AEO2022 Reference case

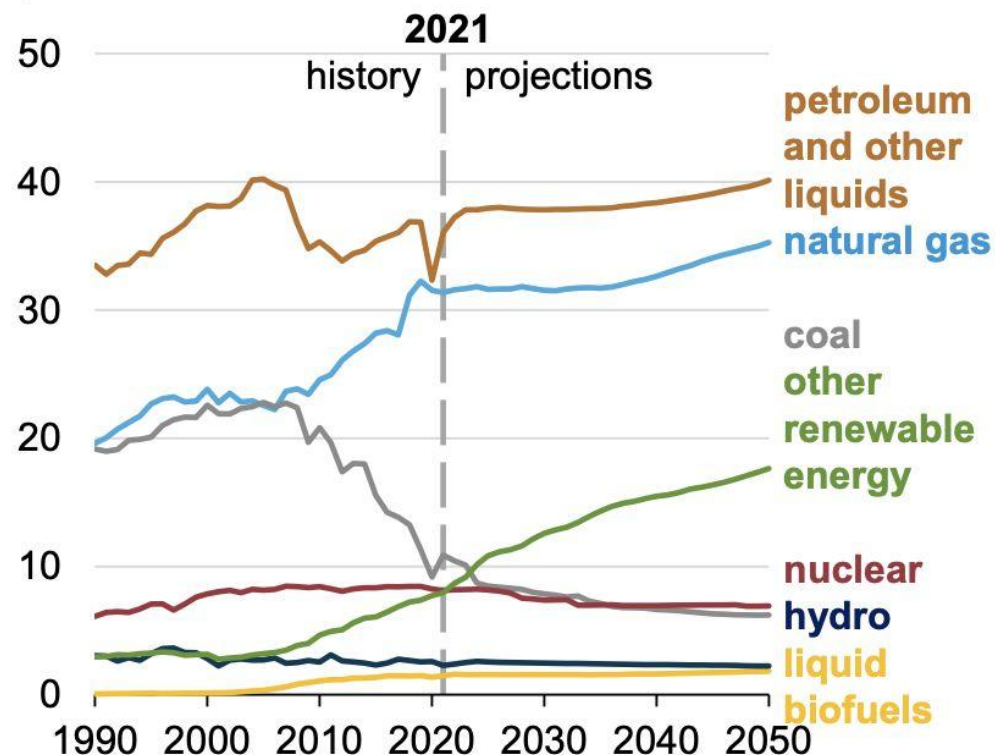
quadrillion British thermal units



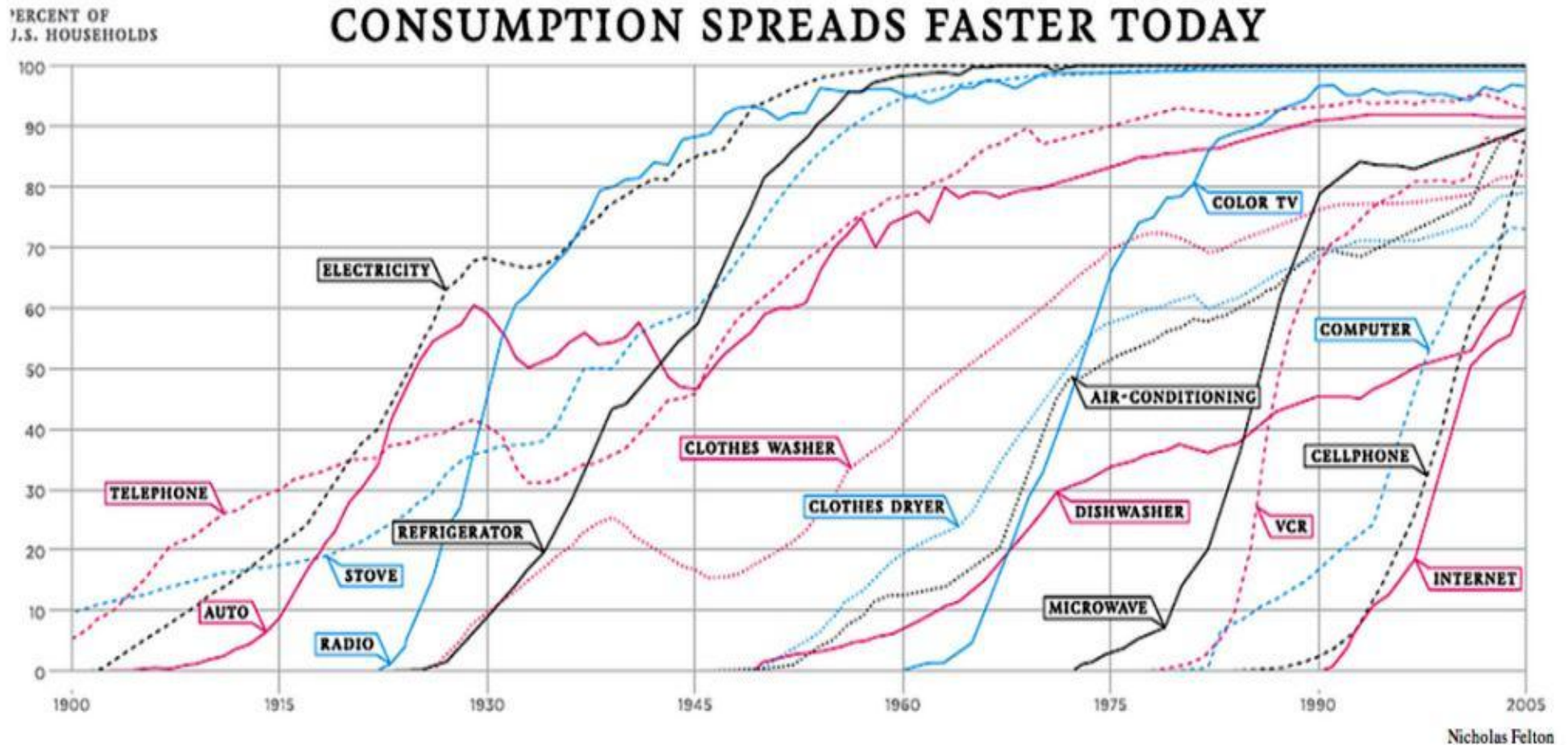
Energy consumption by fuel

AEO2022 Reference case

quadrillion British thermal units



Some technology transitions have been incredibly fast



Outlooks are often wrong! E.g., overpredicted coal...

US Coal Generation – Actual and EIA Forecasts from 2010-2020

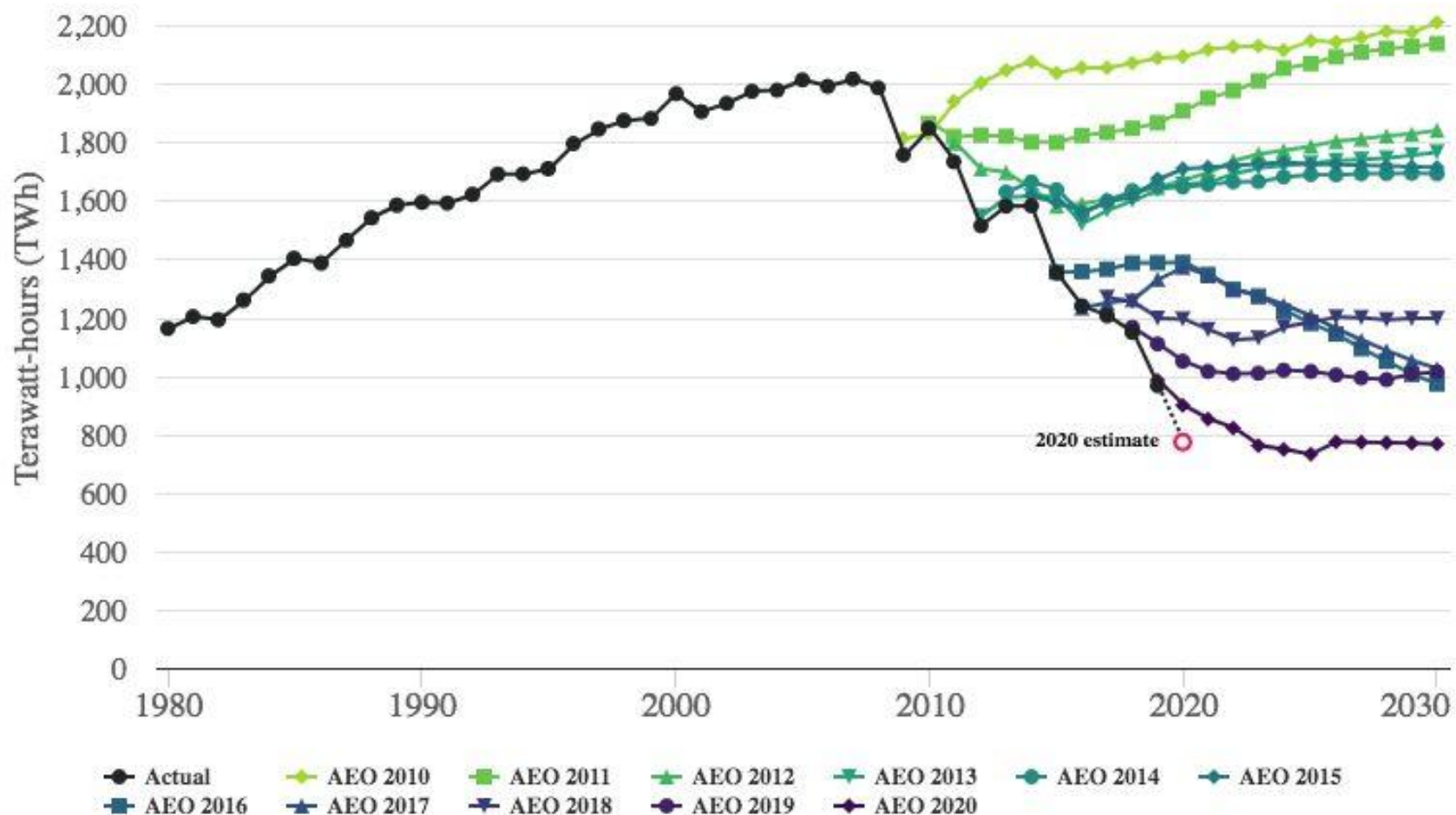
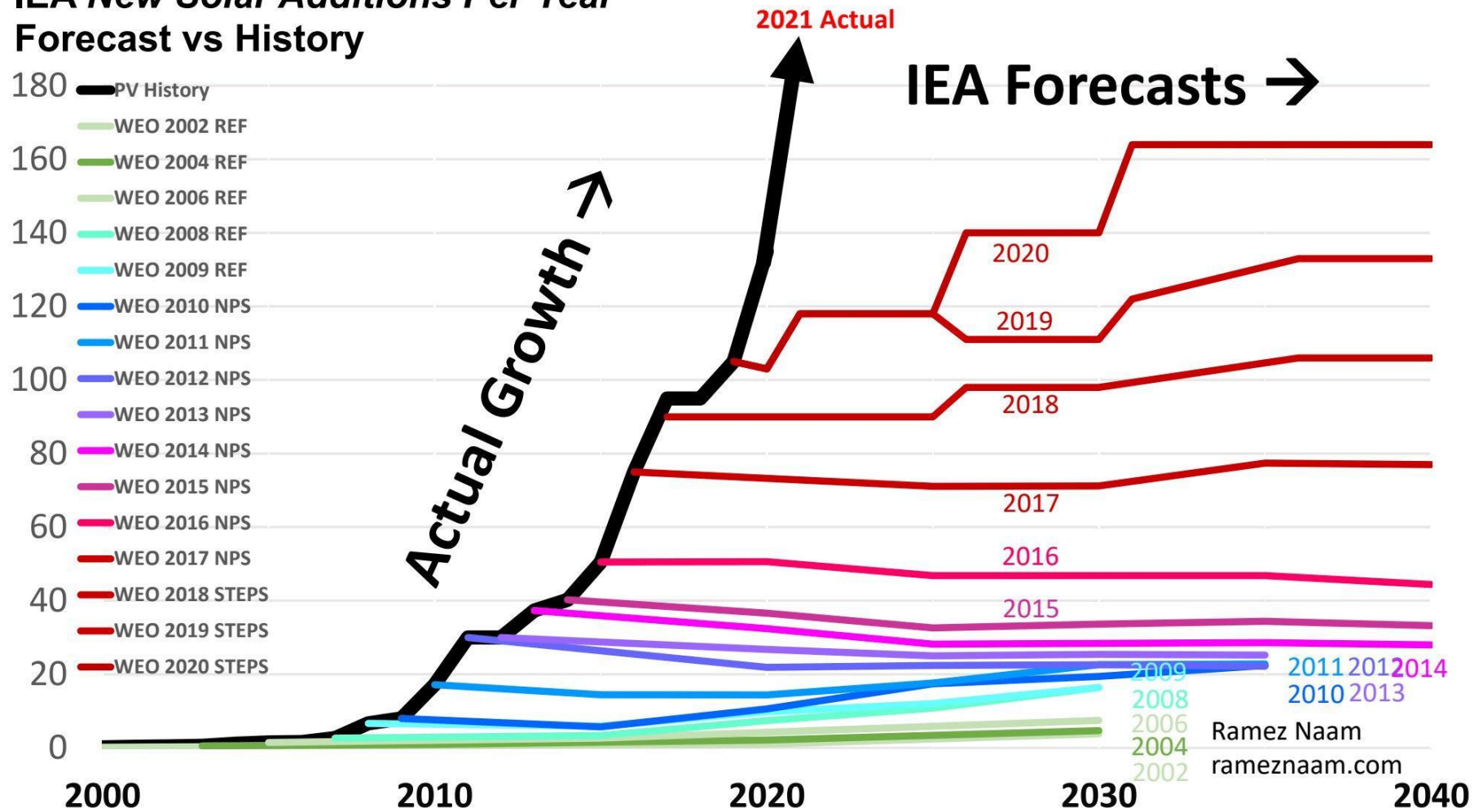


Image from Zeke Hausfather, @hausfath

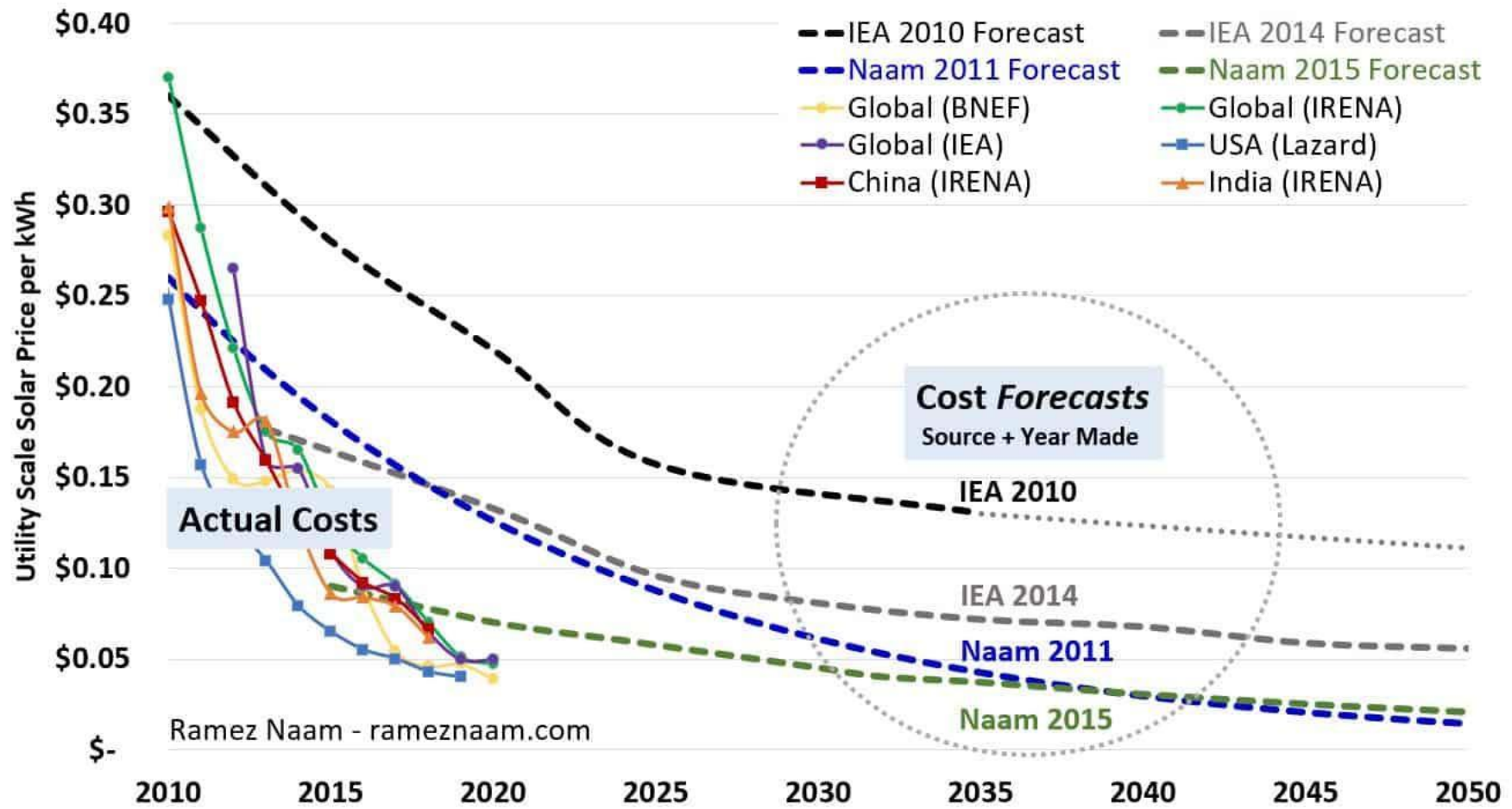
... And underpredicted renewables

**IEA New Solar Additions Per Year
Forecast vs History**



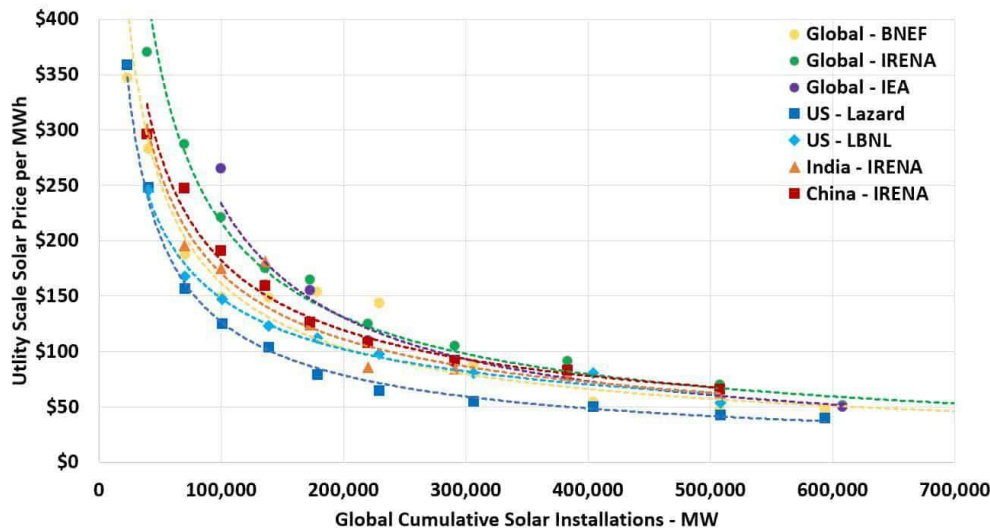
Even optimists failed to foresee cost declines in solar

Solar Costs Are Decades Ahead of Forecasts

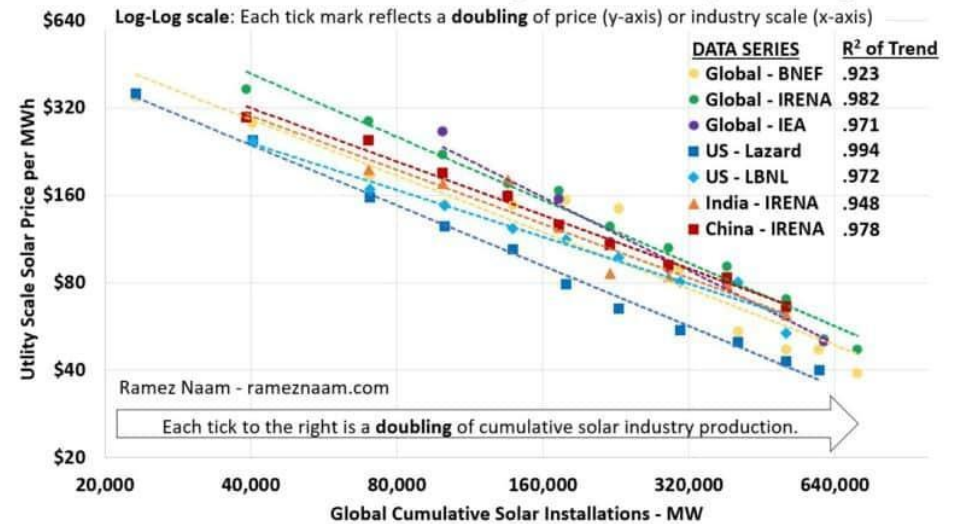


Learning curves tend to be linear on a log-log scale of price and installations

Solar Prices Decline as a Function of *Scale*



Solar Prices Decline Smoothly with Industry Doublings



Learning curves for the Model T

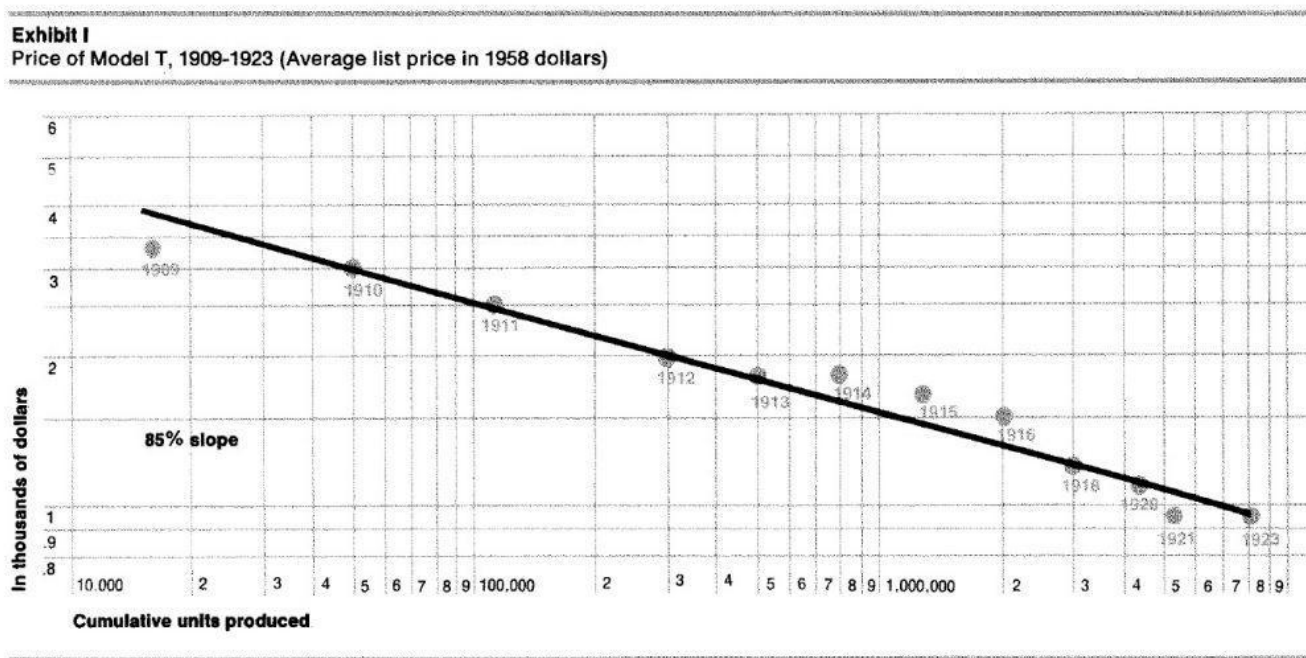


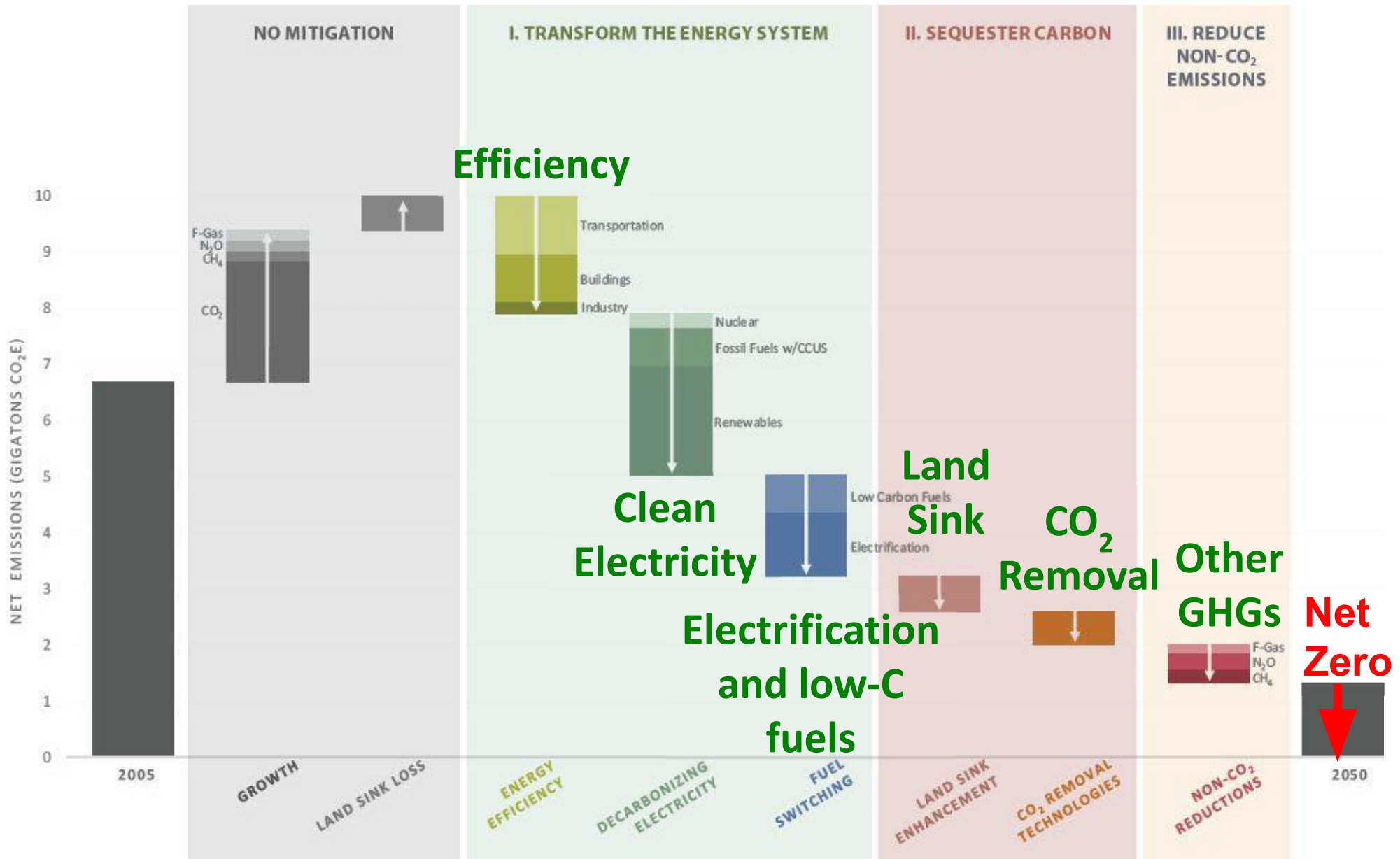
Figure 1. The price of the Ford Model T from 1909-1923[2].

Slides from Ramez Naam: <https://rameznaam.com/2020/05/14/solars-future-is-insanelly>

Neglecting learning curves and policy can have cascading effect on outlooks

- \uparrow Production \square \downarrow Cost \square \uparrow Production \square
- “Technology push” policies: RD&D lowers cost of a technology (\downarrow Cost)
- “Market pull” policies: Create demand for a product (\uparrow Production)
 - Procurement: e.g., Government buys electric cars for fleet
 - Incentives: e.g., electric car tax credits
 - Mandates: e.g., California requires solar on new homes

Steps toward decarbonization

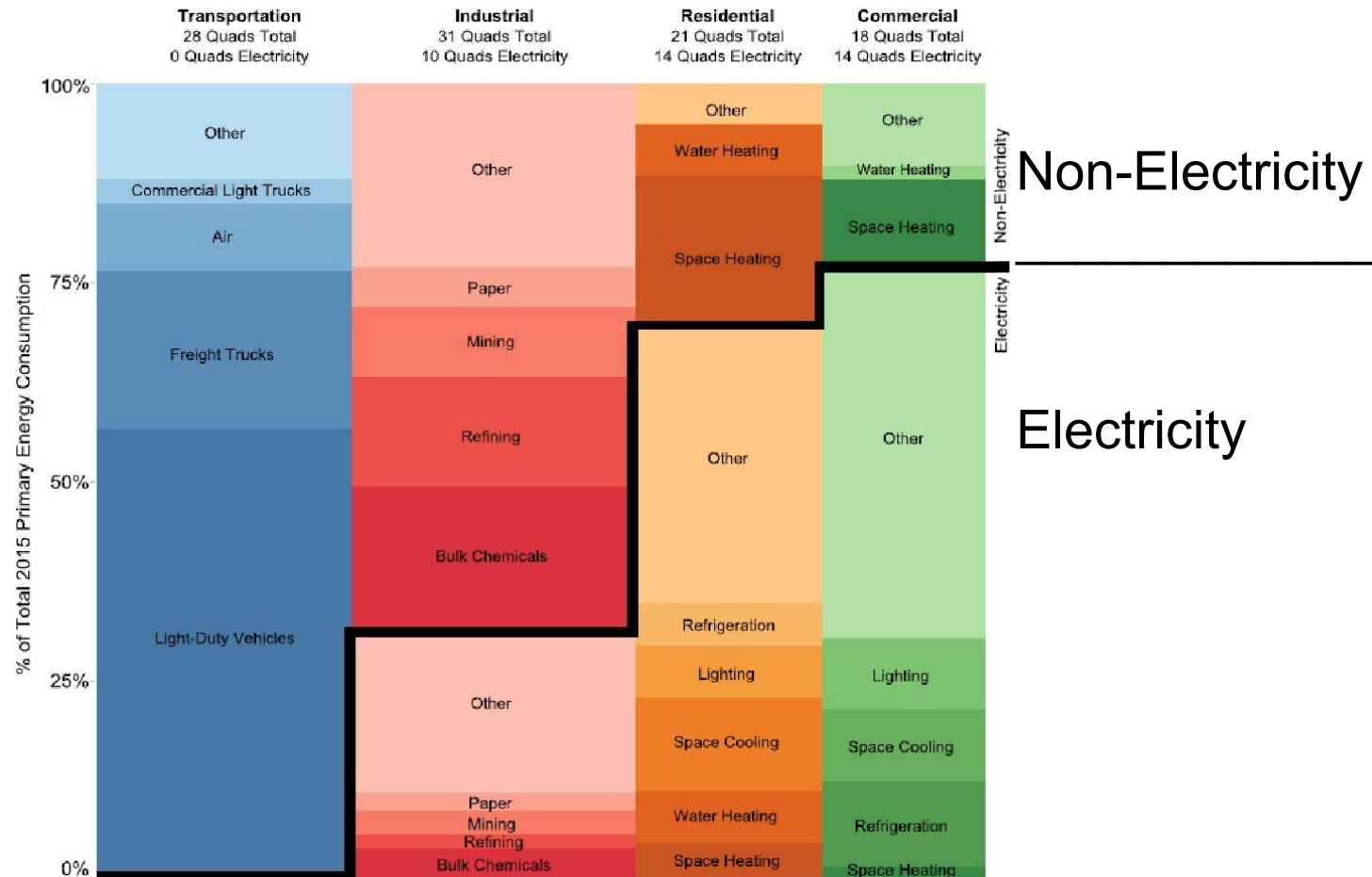


United States Mid-Century Strategy for Deep Decarbonization (White House, Nov. 2016)

Pillars of clean energy

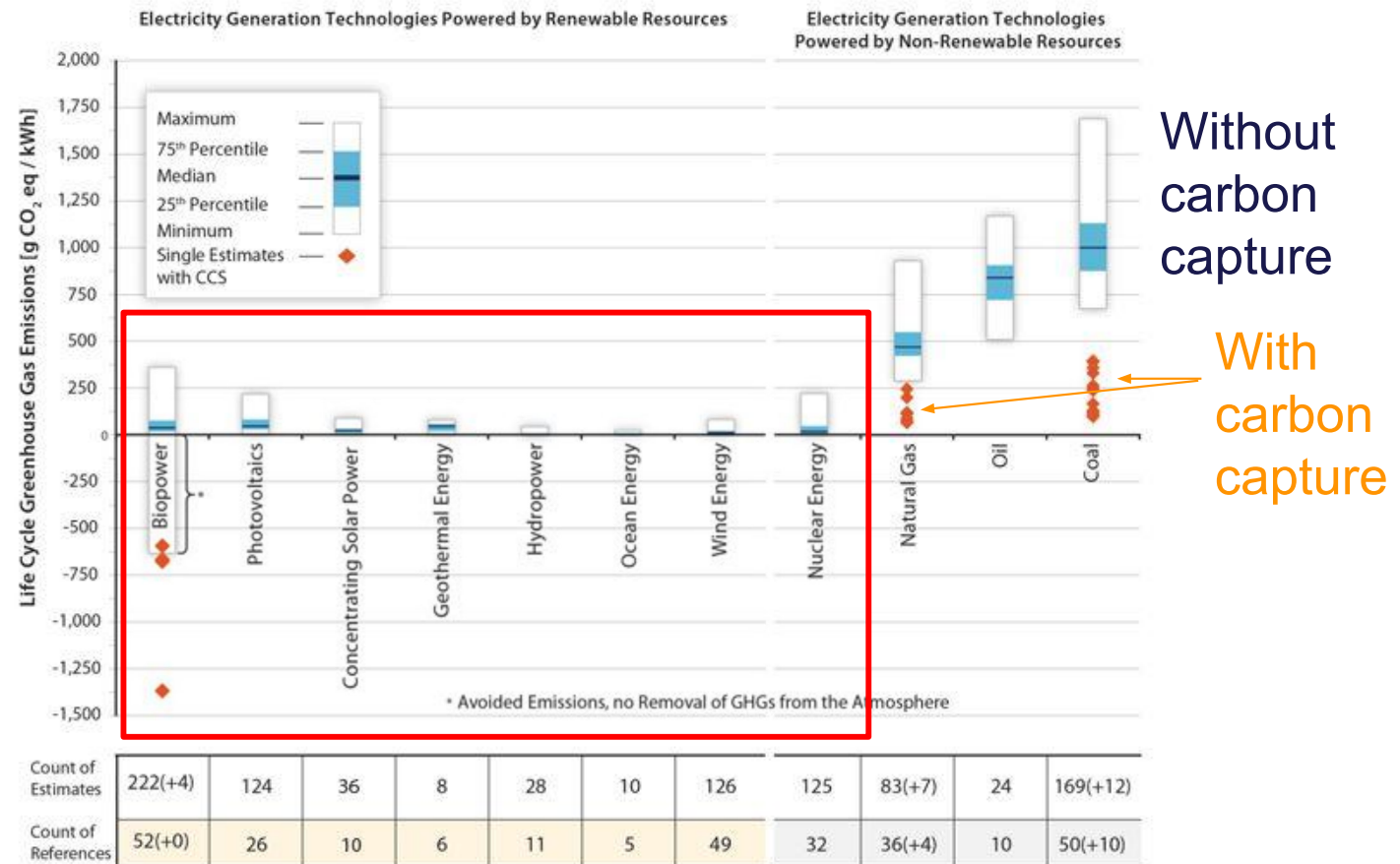
Roles for the pillars of clean energy:

- **Efficiency:** Shrinks all boxes
- **Clean electricity:** Cleans up area below the electric frontier
- **Electrification:** Moves up the electric frontier
- **Other clean fuels:** Decarbonizes above frontier
- **Carbon sinks:** Offset the emissions that remain



Decarbonizing Electricity: Options

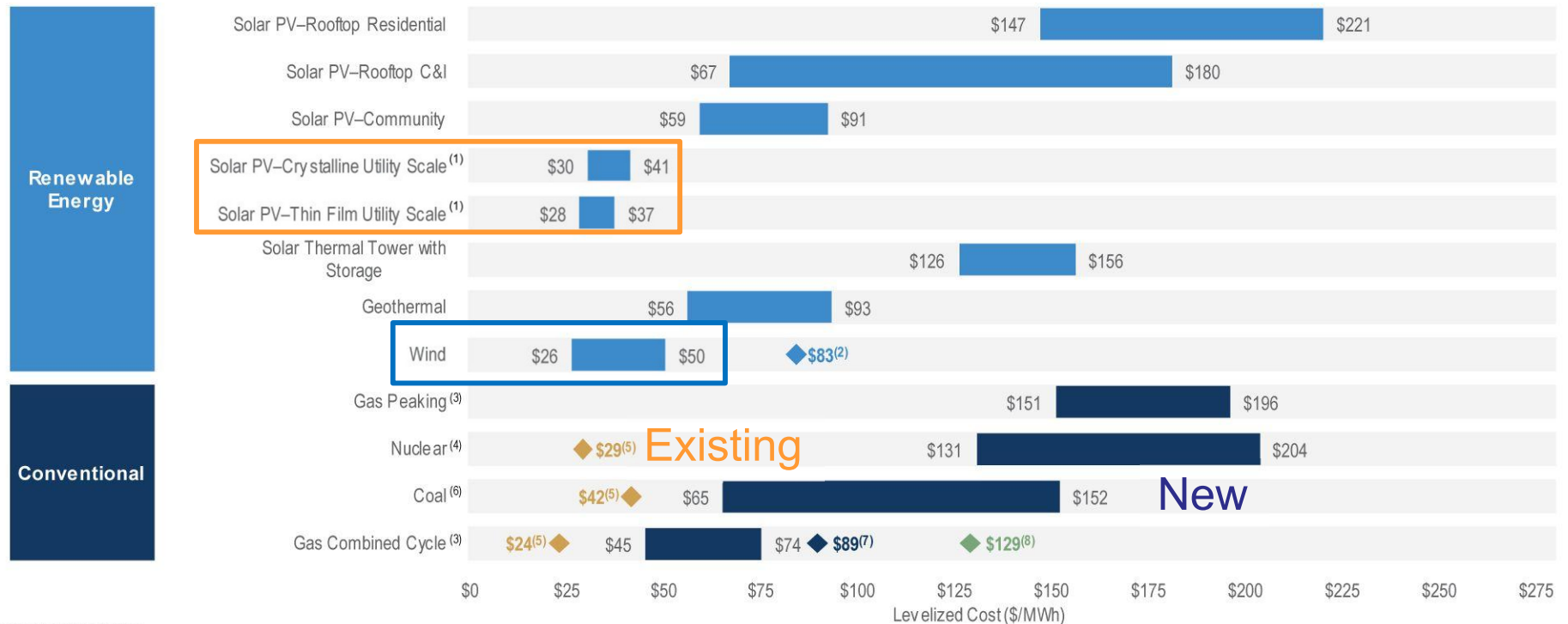
All renewables and nuclear have far lower life cycle emissions than any fossil fuel



Wind and solar are least cost

Levelized Cost of Energy Comparison—Unsubsidized Analysis

Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances



Source: Lazard estimates.

Note: Here and throughout this presentation, unless otherwise indicated, the analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost. Please see page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities. These results are not intended to represent any particular geography. Please see page titled "Solar PV versus Gas Peaking and Wind versus CCGT—Global Markets" for regional sensitivities to selected technologies.

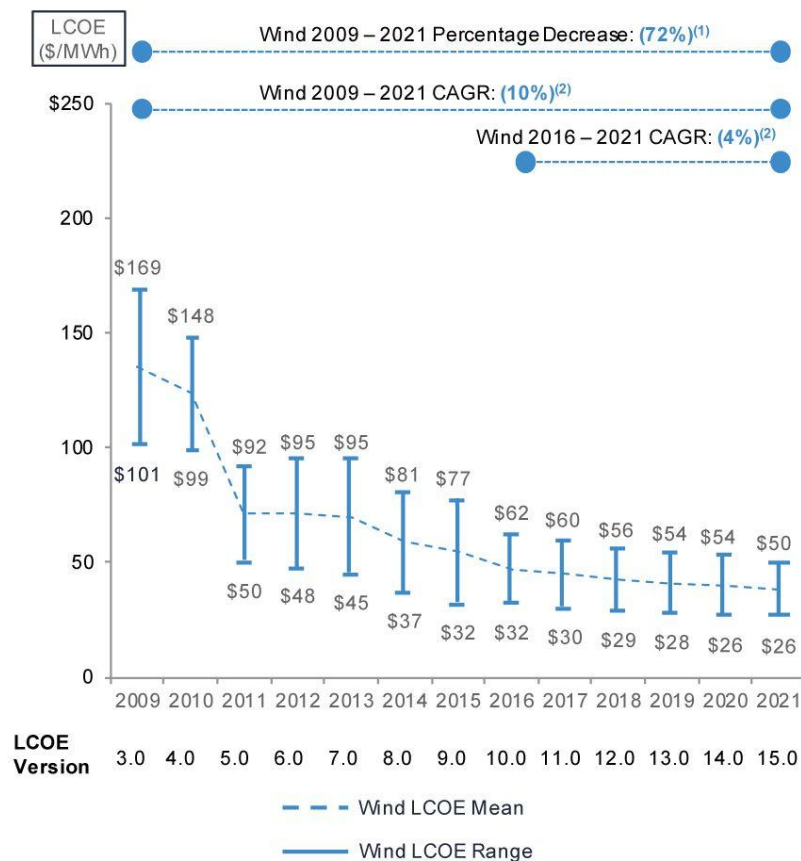
- (1) Unless otherwise indicated herein, the low case represents a single-axis tracking system and the high case represents a fixed-tilt system.
- (2) Represents the estimated implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately \$2,500 – \$3,600/kW.
- (3) The fuel cost assumption for Lazard's global, unsubsidized analysis for gas-fired generation resources is \$3.45/MMBTU.
- (4) Unless otherwise indicated, the analysis herein does not reflect decommissioning costs, ongoing maintenance-related capital expenditures or the potential economic impacts of federal loan guarantees or other subsidies.
- (5) Represents the midpoint of the marginal cost of operating fully depreciated gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas combined cycle or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas combined cycle, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research. Please see page titled "Levelized Cost of Energy Comparison—Renewable Energy versus Marginal Cost of Selected Existing Conventional Generation" for additional details.
- (6) High end incorporates 90% carbon capture and storage. Does not include cost of transportation and storage.
- (7) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Blue" hydrogen, (i.e., hydrogen produced from a steam-methane reformer, using natural gas as a feedstock, and sequestering the resulting CO₂ in a nearby saline aquifer). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is \$5.20/MMBTU, assuming \$1.39/kg for Blue hydrogen.
- (8) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Green" hydrogen, (i.e., hydrogen produced from an electrolyzer powered by a mix of wind and solar generation and stored in a nearby salt cavern). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is \$10.05/MMBTU, assuming \$4.15/kg for Green hydrogen.

Wind costs have fallen 72%, and solar 90% since 2009

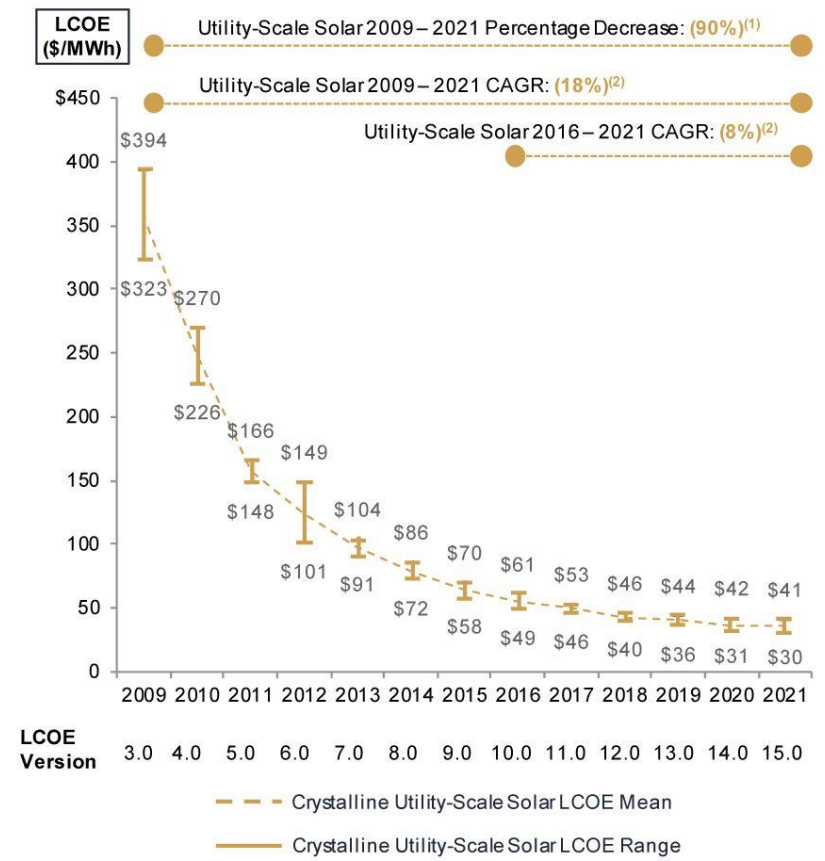
Levelized Cost of Energy Comparison—Historical Renewable Energy LCOE Declines

In light of material declines in the pricing of system components and improvements in efficiency, among other factors, wind and utility-scale solar PV have exhibited dramatic LCOE declines; however, as these industries have matured, the rates of decline have diminished

Unsubsidized Wind LCOE



Unsubsidized Solar PV LCOE



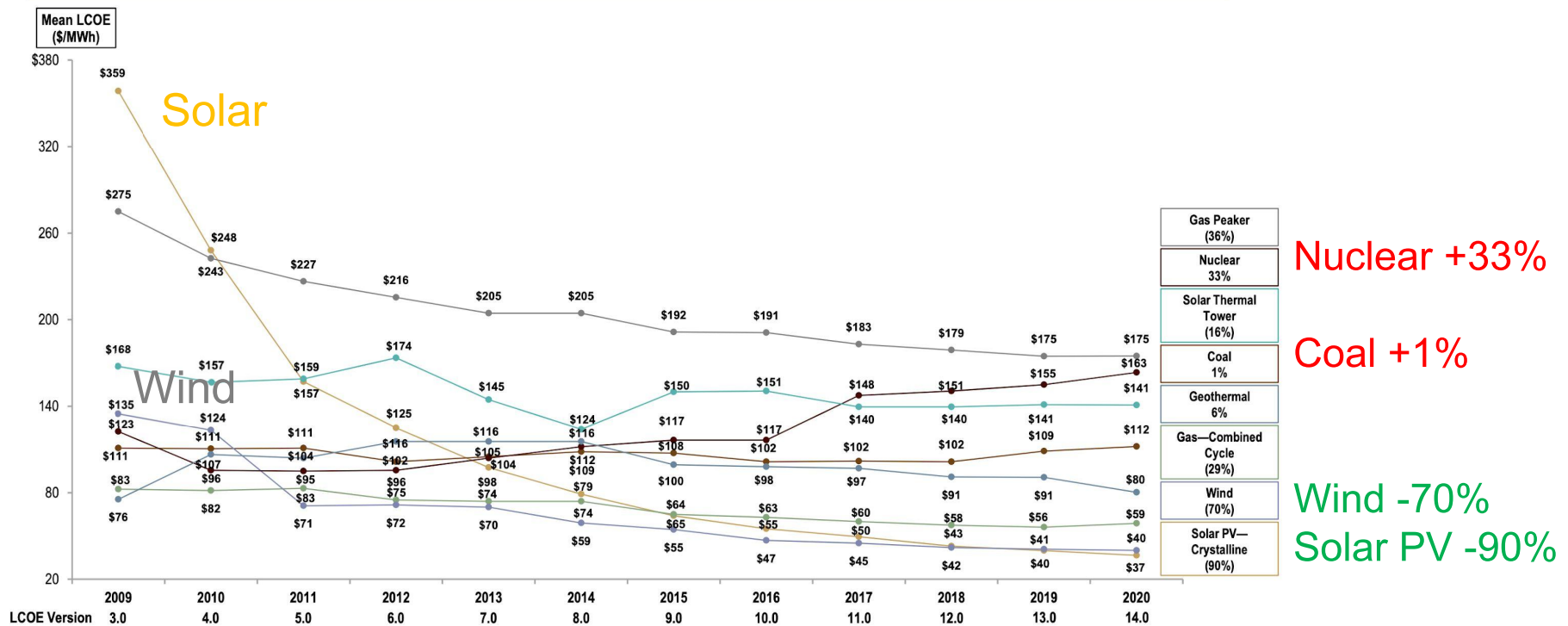
Source: Lazard estimates.
 (1) Represents the average percentage decrease of the high end and low end of the LCOE range.
 (2) Represents the average compounded annual rate of decline of the high end and low end of the LCOE range.

Wind and solar costs down, nuclear and coal up since 2009

Levelized Cost of Energy Comparison—Historical Utility-Scale Generation Comparison

Lazard's unsubsidized LCOE analysis indicates significant historical cost declines for utility-scale renewable energy generation technologies driven by, among other factors, decreasing capital costs, improving technologies and increased competition

Selected Historical Mean Unsubsidized LCOE Values⁽¹⁾

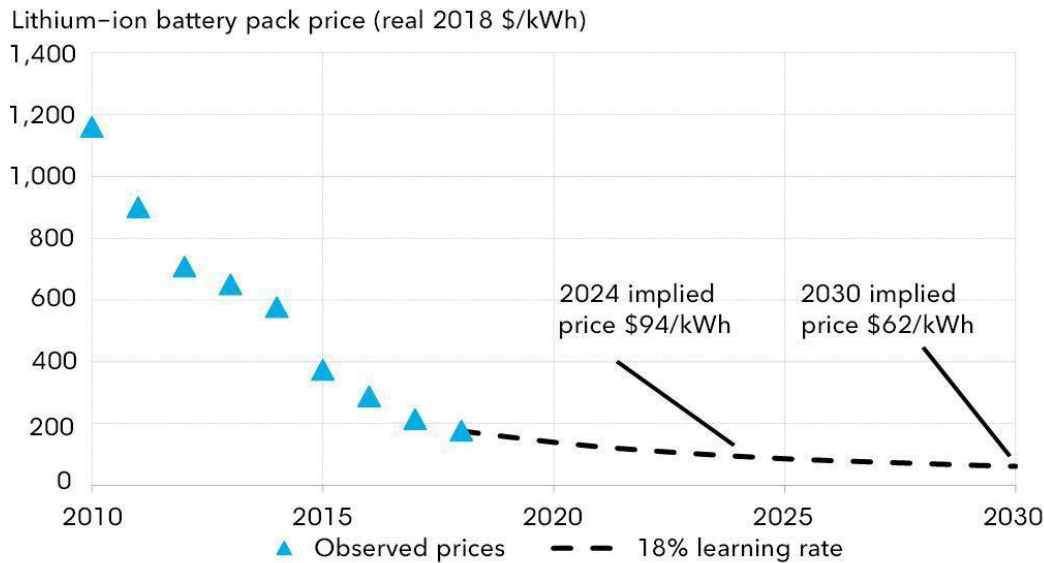


LAZARD Source: Lazard estimates.
 (1) Reflects the average of the high and low LCOE for each respective technology in each respective year. Percentages represent the total decrease in the average LCOE since Lazard's LCOE—
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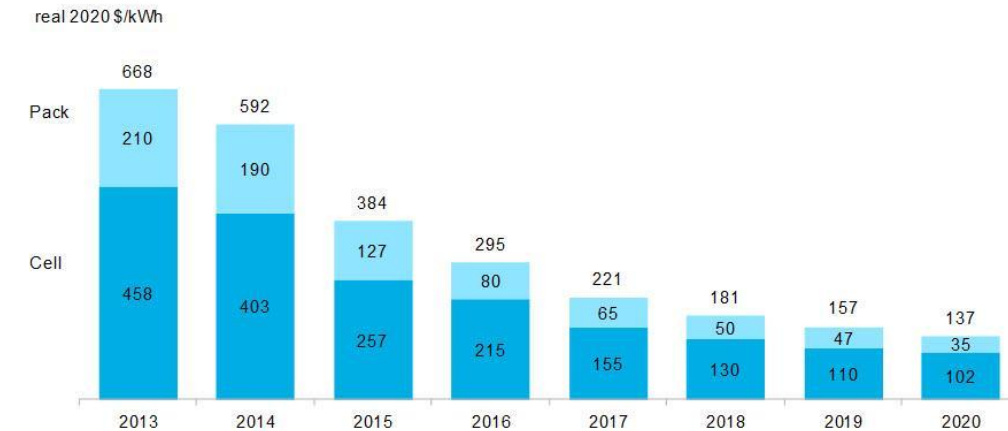
Lithium-ion battery costs

Lithium-ion battery price outlook



Source: BloombergNEF

Figure 1: Volume-weighted average pack and cell price split

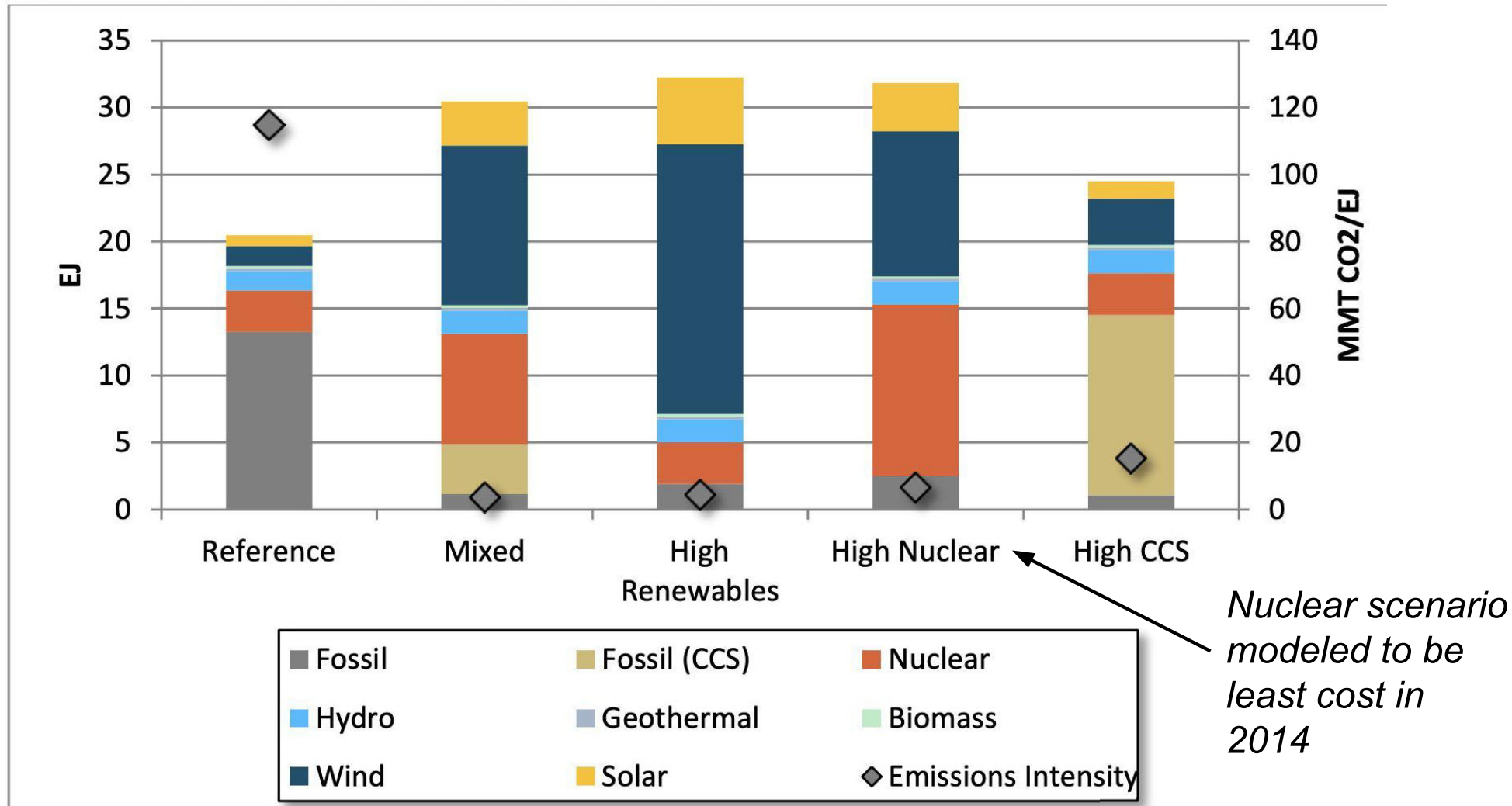


Source: BloombergNEF

BNEF, December 2020,
<https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/>

2014: Renewables, nuclear, and carbon capture pathways all seemed plausible

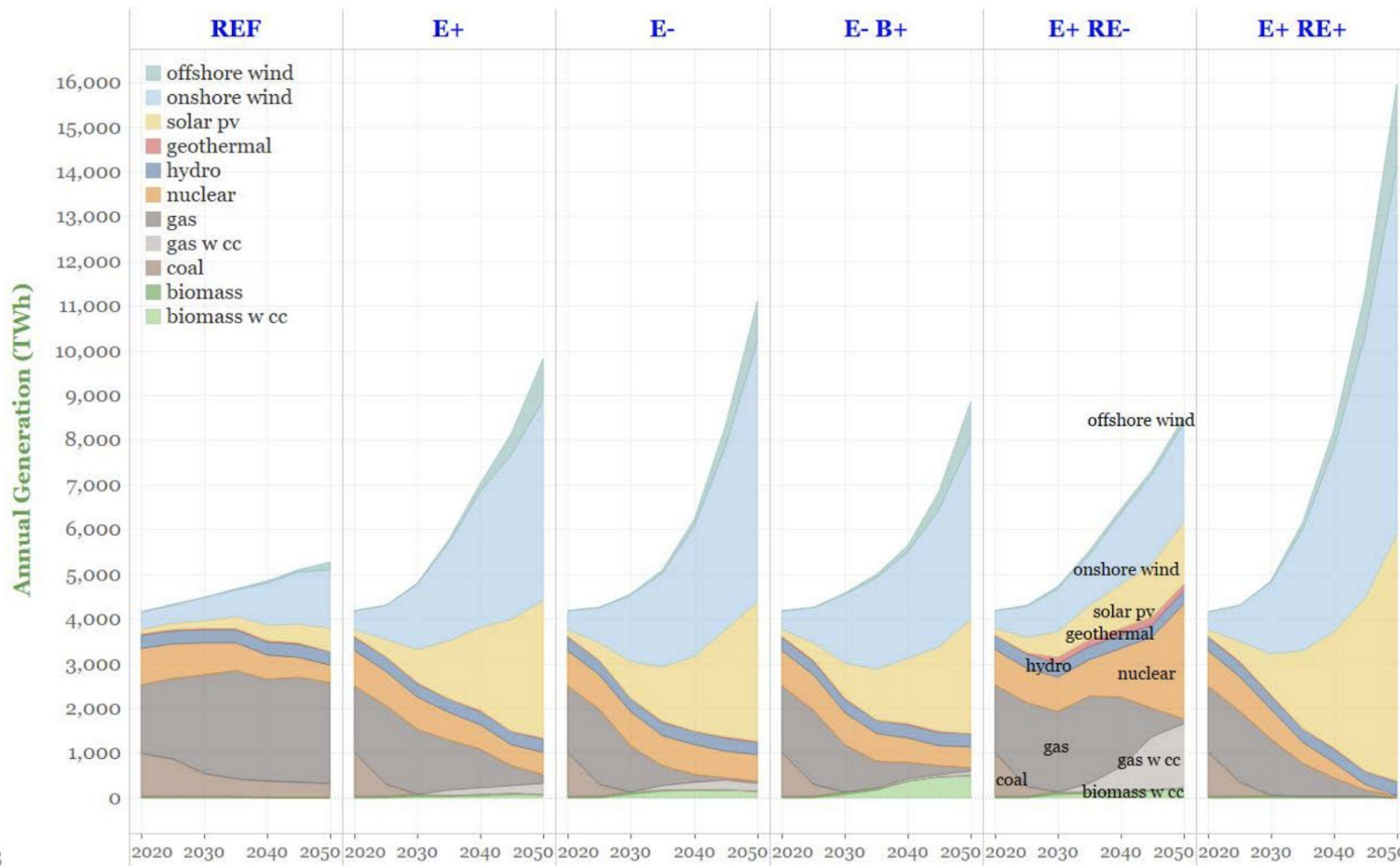
Figure 29. 2050 Electric Generation by Resource Type



Nuclear scenario modeled to be least cost in 2014

2020: Solar and wind lead in all net-zero pathways

Solar and wind generated electricity have dominant roles in all net-zero pathways



- Share of electricity from carbon-free sources roughly doubles from ~37% today to 70-85% by 2030 and reaches 98-100% by 2050.
- Wind + solar grows >4x by 2030 to supply ~1/2 of U.S. electricity in all cases except E+RE-; in that case, growth is constrained, but still triples by 2030 to supply 1/3 of electricity.
- By 2050, wind and solar supply ~85-90% of generation in E+, E-, and E-B+. In E+RE-, 44%; in E+RE+, 98%.

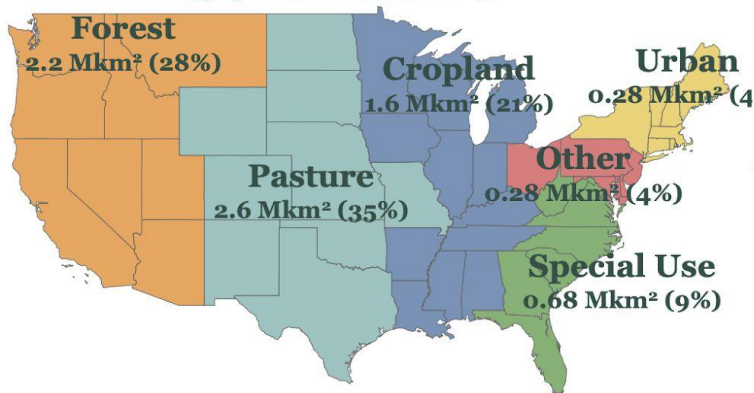
[RETURN TO TABLE OF CONTENTS](#)

Land Use for Solar, Wind, and Biomass in net-zero scenarios

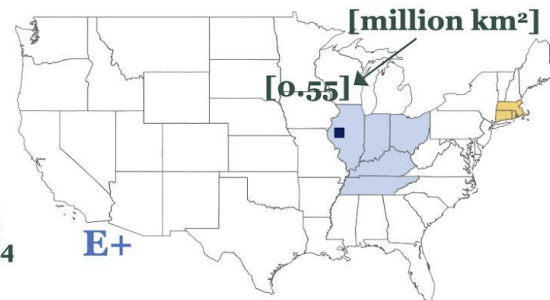
Total land area/visual footprint in 2050 for solar, wind, and biomass across scenarios is 0.25 to 1.1 million km².



U.S. land use today, Lower-48
(7.7 Million km²)



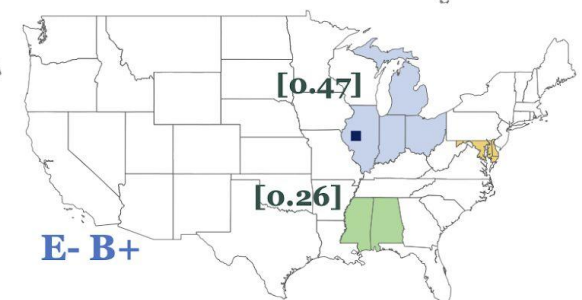
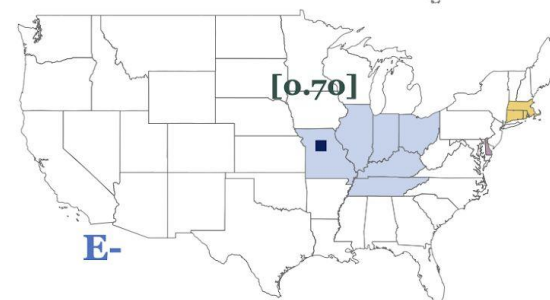
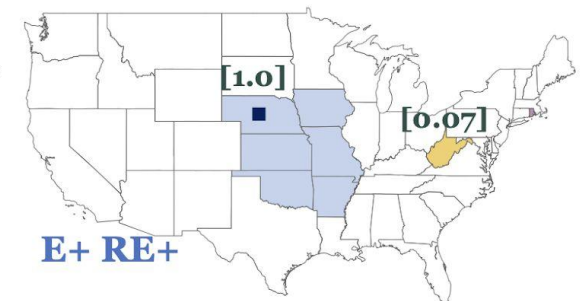
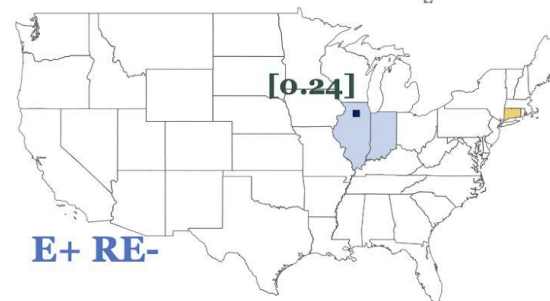
Note: In these maps, the sum of land areas of colored states is roughly the same as the area nationally of the indicated uses.



Equivalent land area for

- Solar farms
- Wind farms
- Biomass farms*
- Direct air capture

Note: Directly impacted land area for wind farms (equipment footprint) is indicated by ■. For solar and biomass, directly impacted areas are 92% and 100% of shaded area shown.



[RETURN TO TABLE OF CONTENTS](#)

* On lands converted from food production.

Emerging option: Enhanced geothermal

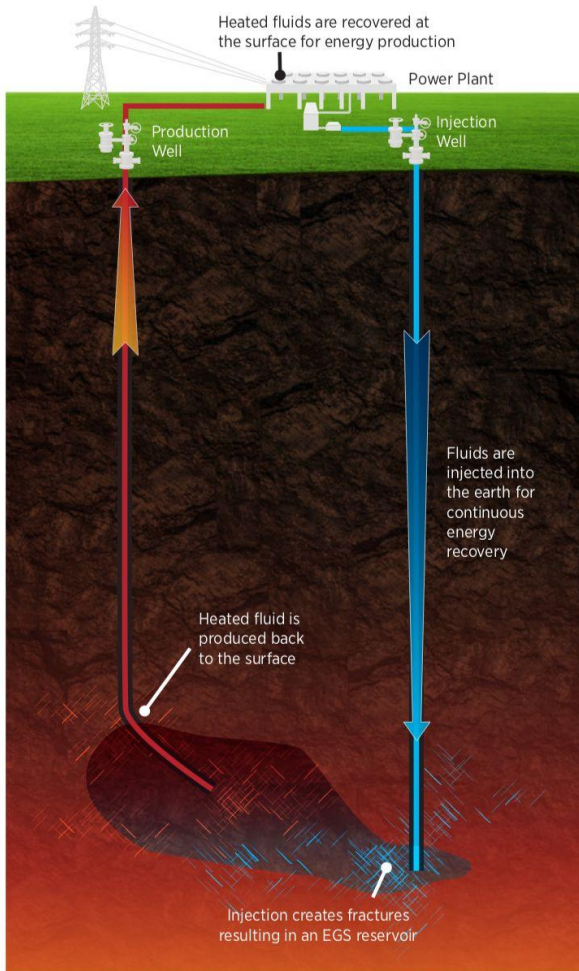


Figure 2-6. Conceptualization of an enhanced geothermal system

DOE GeoVision

GEOHERMAL

Google Taps Fervo Energy To Develop Enhanced Geothermal Systems in Nevada

MIT
Technology
Review

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CLIMATE CHANGE

What it will take to unleash the potential of geothermal power

Four new pilot plants funded by the US infrastructure bill could help expand the range of the "forgotten renewable."

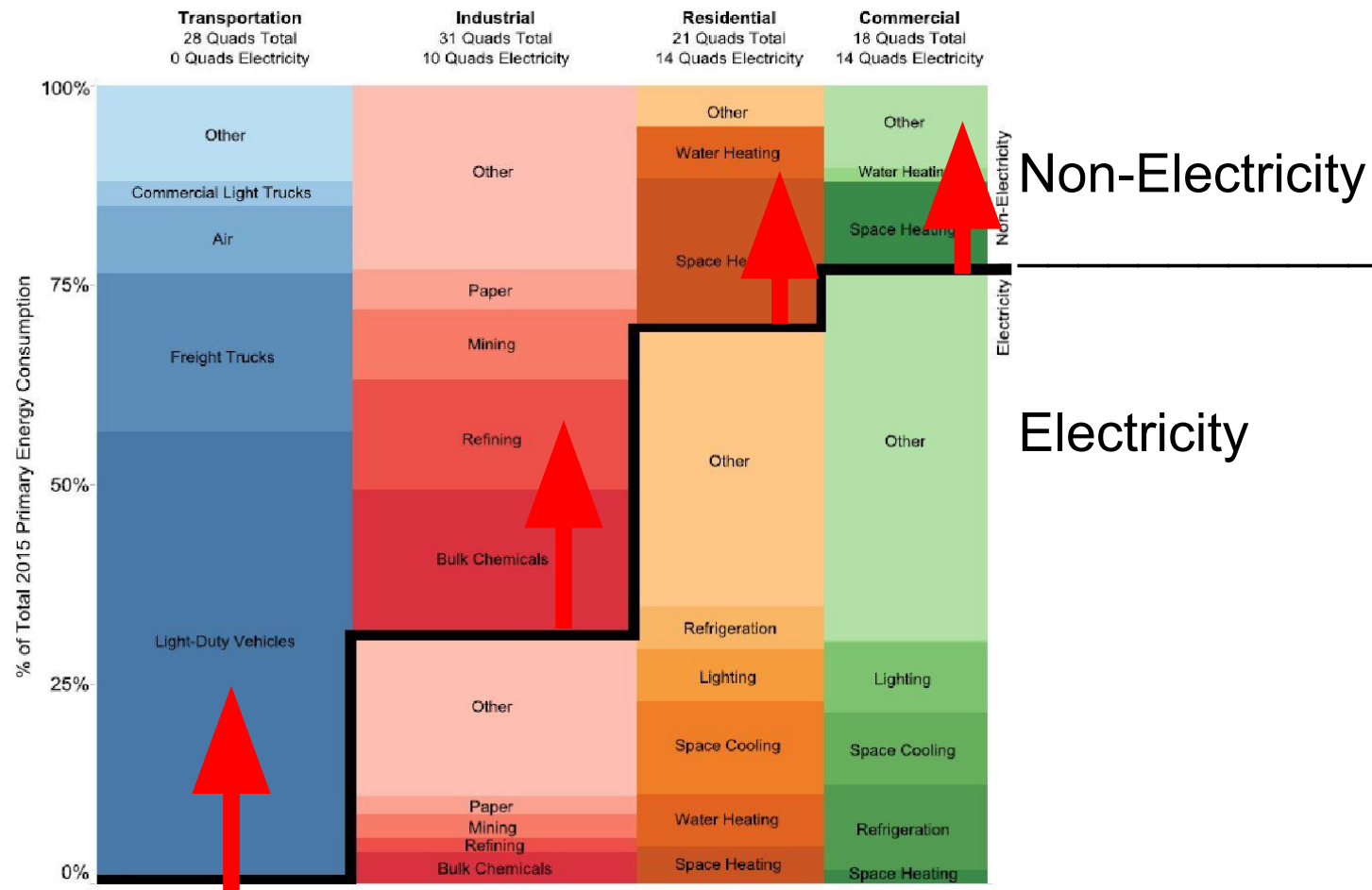
Deep Energy and Eavor forms partnership to deploy closed-loop geothermal technology

Criterion Energy Partners secures strategic investment for geothermal project

Electrification: Shifting the electric frontier

Roles for the pillars of clean energy:


- **Efficiency:** Shrinks all boxes
- **Clean electricity:** Cleans up area below the electric frontier
- **Electrification:** Moves up the electric frontier
- **Other clean fuels:** Decarbonizes above frontier
- **Carbon sinks:** Offset the emissions that remain

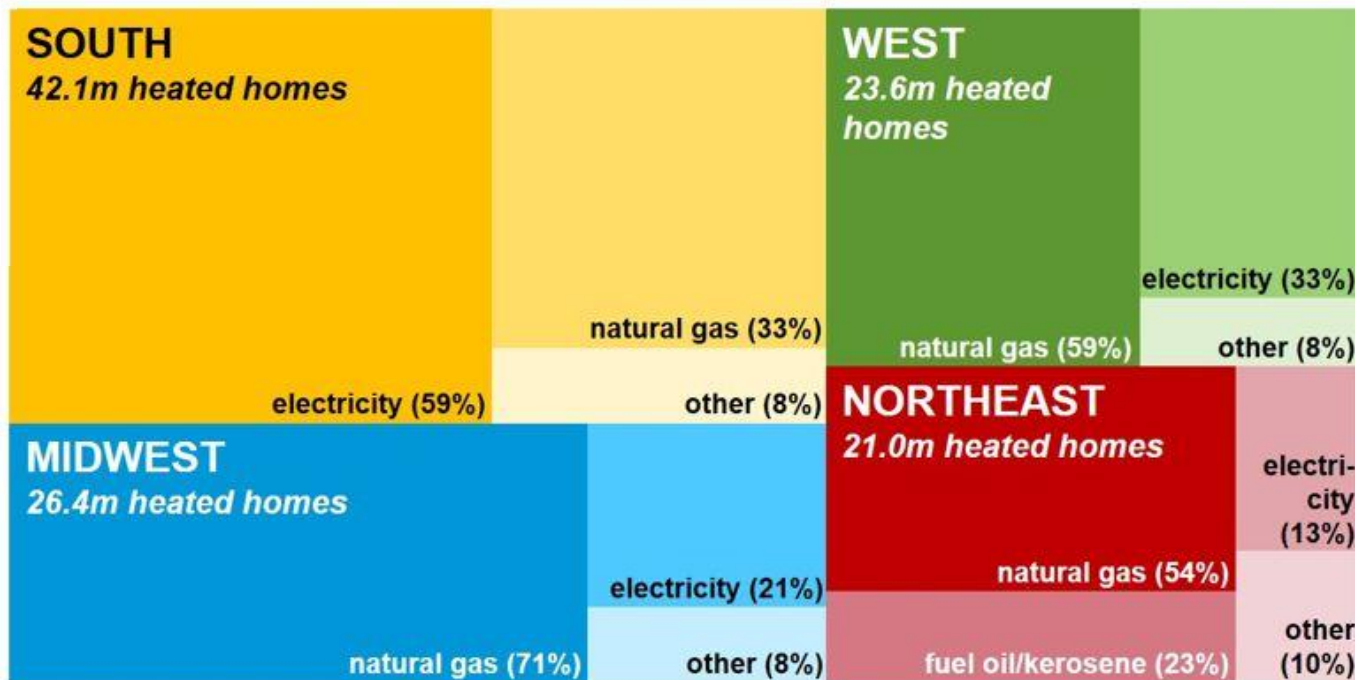


How homes are heated in U.S.

Mostly electricity in the South (~60% electric in Texas)

Mostly natural gas in Midwest

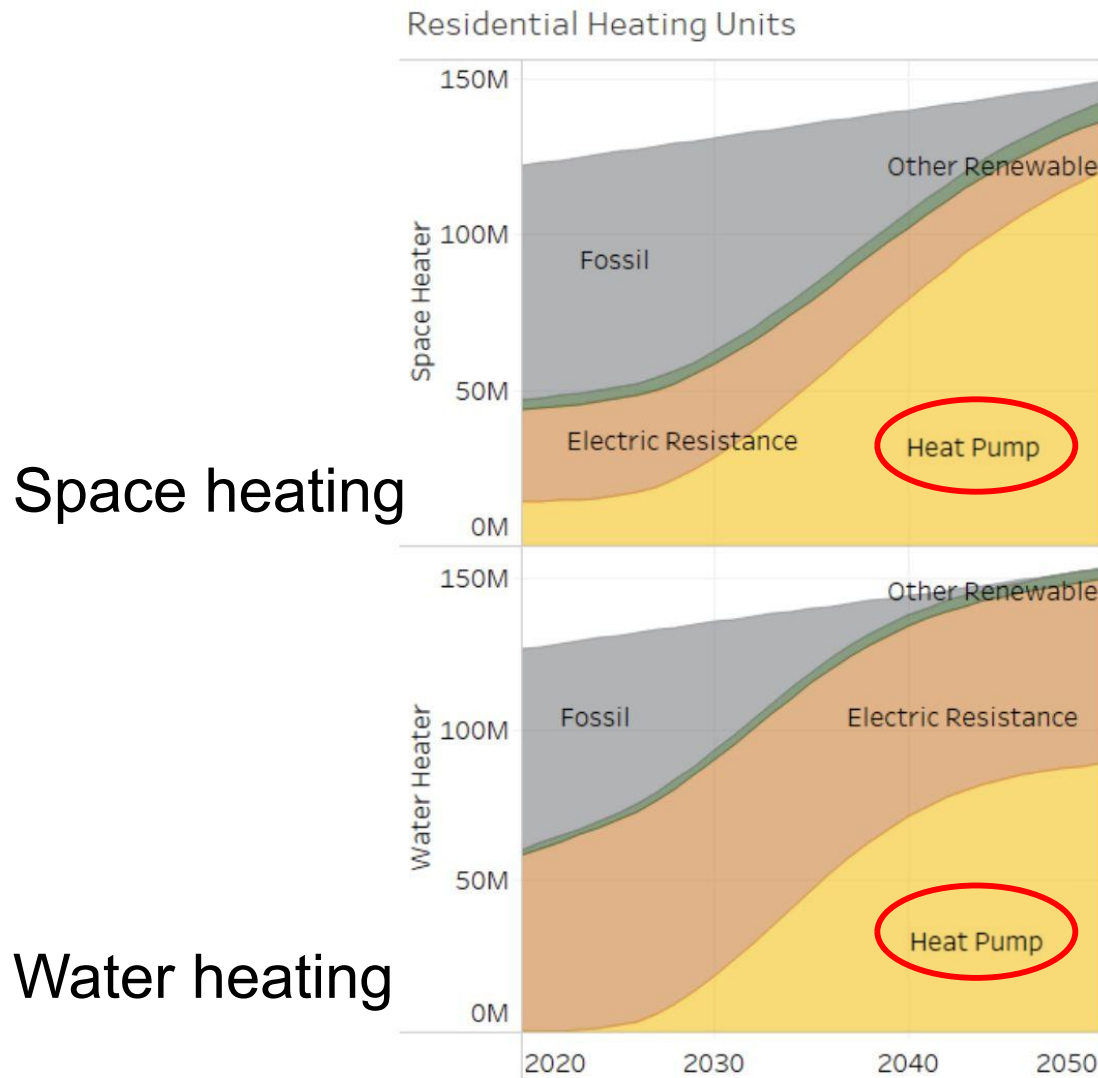
Figure 4. Natural gas is the most-used heating fuel in heated homes in three of four Census regions 
 main space heating fuel by Census region



Mostly natural gas in West

Mostly natural gas and fuel oil in Northeast

Transition to electric heat pumps in most net-zero strategies



Take-home messages

- Decarbonizing the U.S. is necessary but not sufficient for decarbonization globally
 - Diplomacy such as climate clubs can be key
- Efficiency, clean electricity, and electrification are pillars of clean energy
- Solar, wind, EVs, and heat pumps likely to lead the way
- Need to create virtuous cycles of learning by doing to drive technologies forward