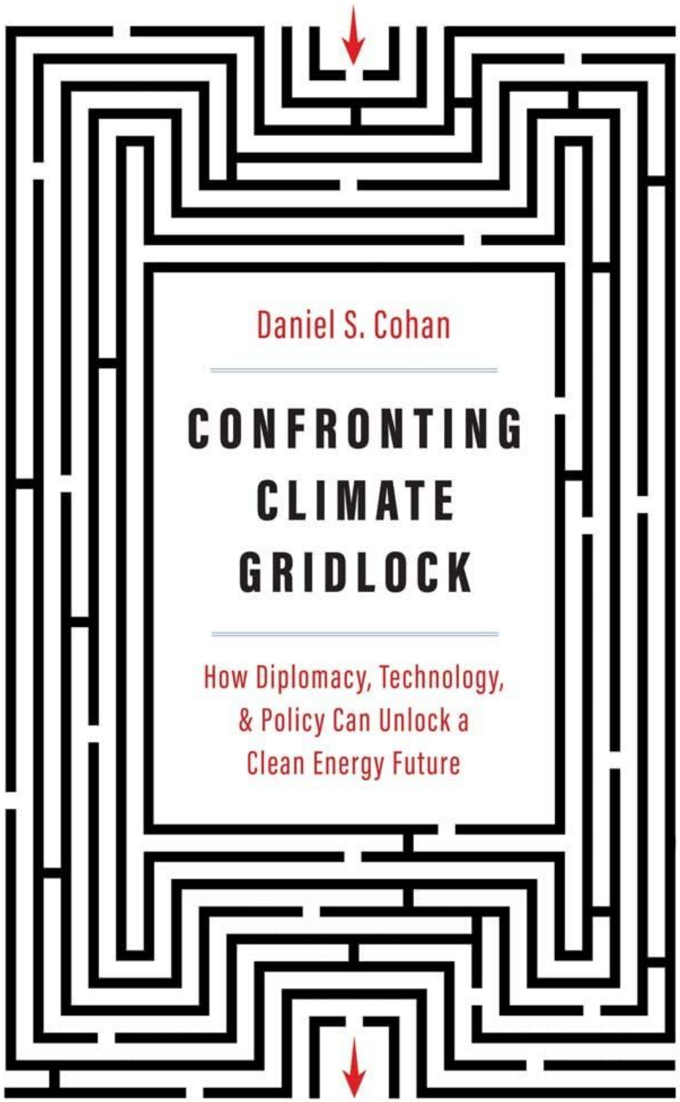
Confronting Climate Gridlock



Prof. Daniel Cohan

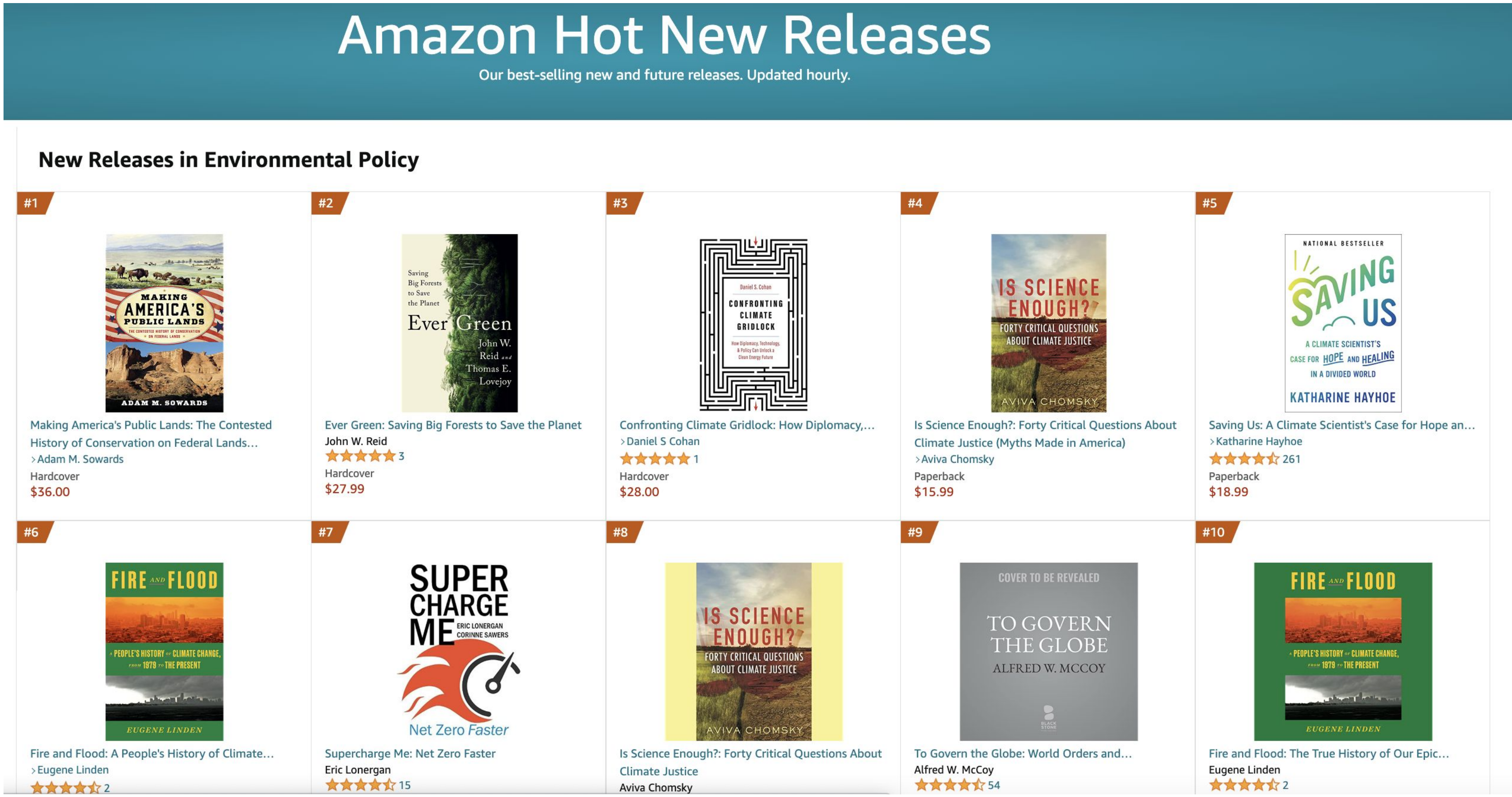
UT Energy Symposium

April 2022

About the speaker

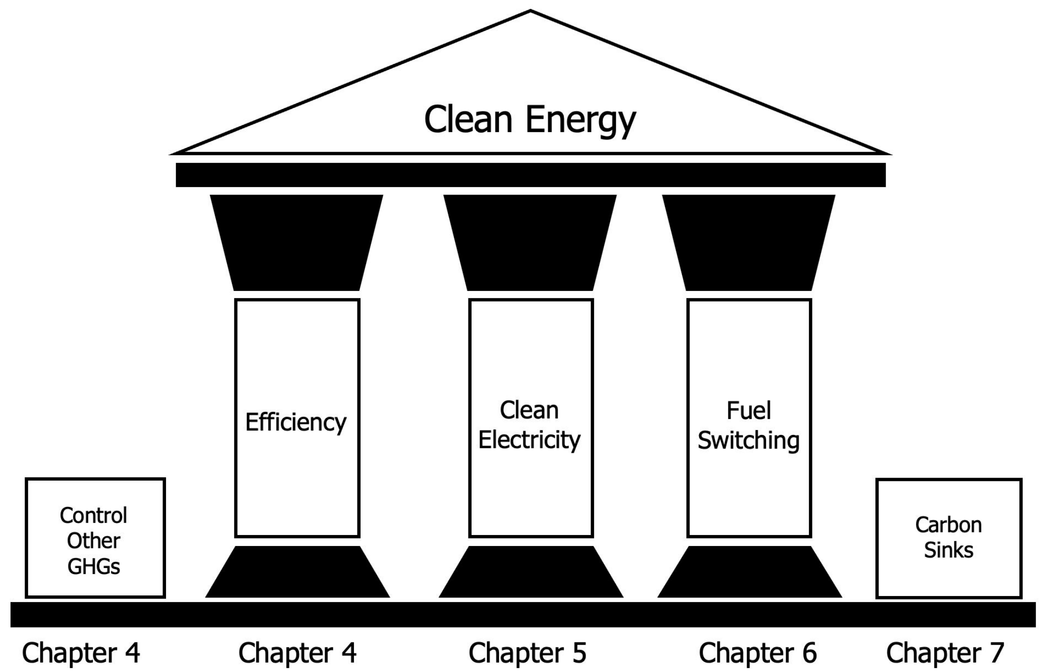
- Associate Professor of Civil and Environmental Engineering at Rice
  - At Rice since 2006
  - A&WMA member
- National Science Foundation CAREER award
- 50+ peer-reviewed publications, 70+ op-eds
- Website: cohan.rice.edu

Available in hardcover, Kindle, Nook, and audio book



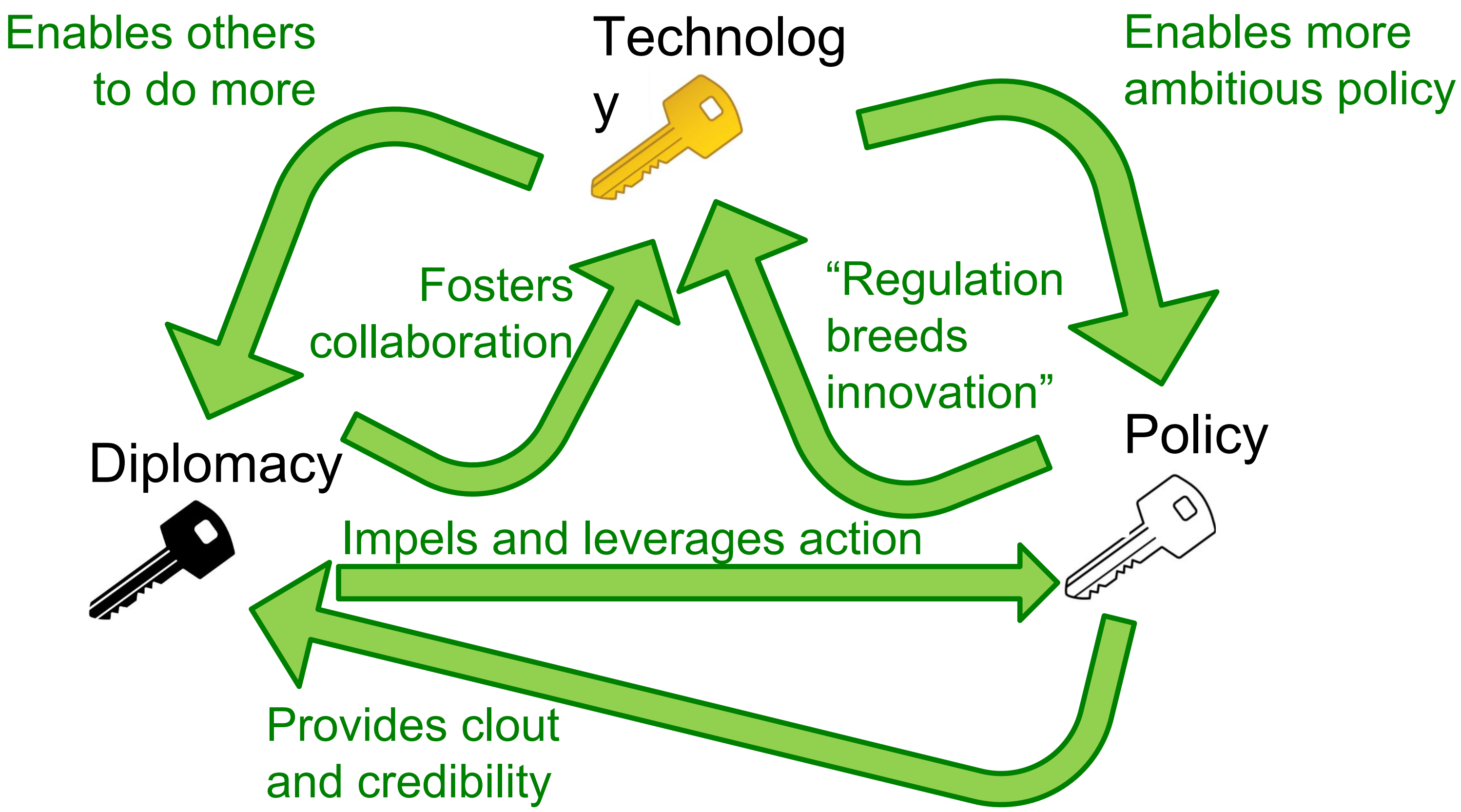
Amazon: https://www.amazon.com/Confronting-Climate-Gridlock-Diplomacy-Technology/dp/030025167X/
Other options: https://yalebooks.yale.edu/book/9780300251678/confronting-climate-gridlock/

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

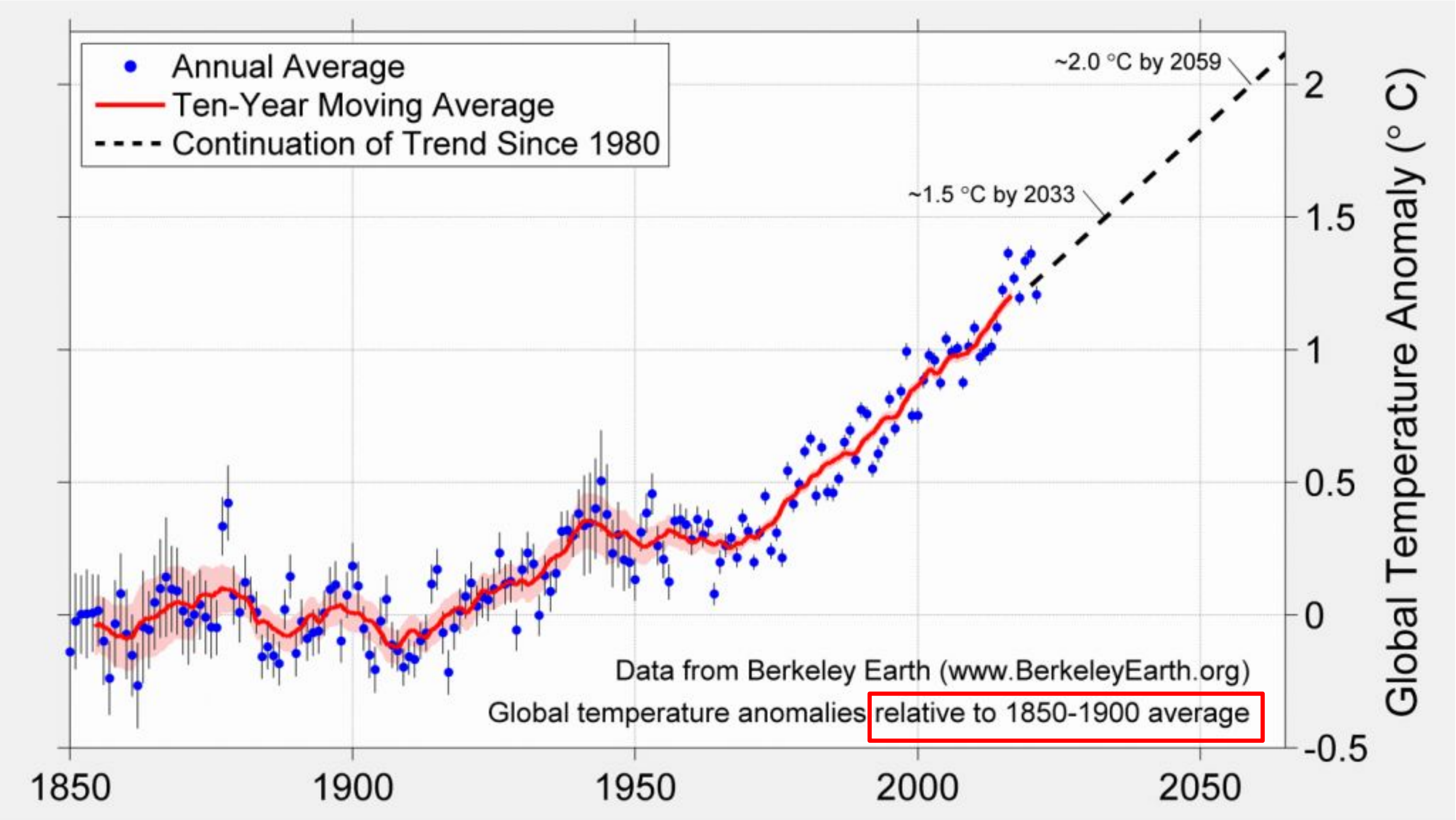


Book draws from >100 interviews with diplomats, scholars, innovators, etc.

How the Keys Interact to Unlock Climate Gridlock



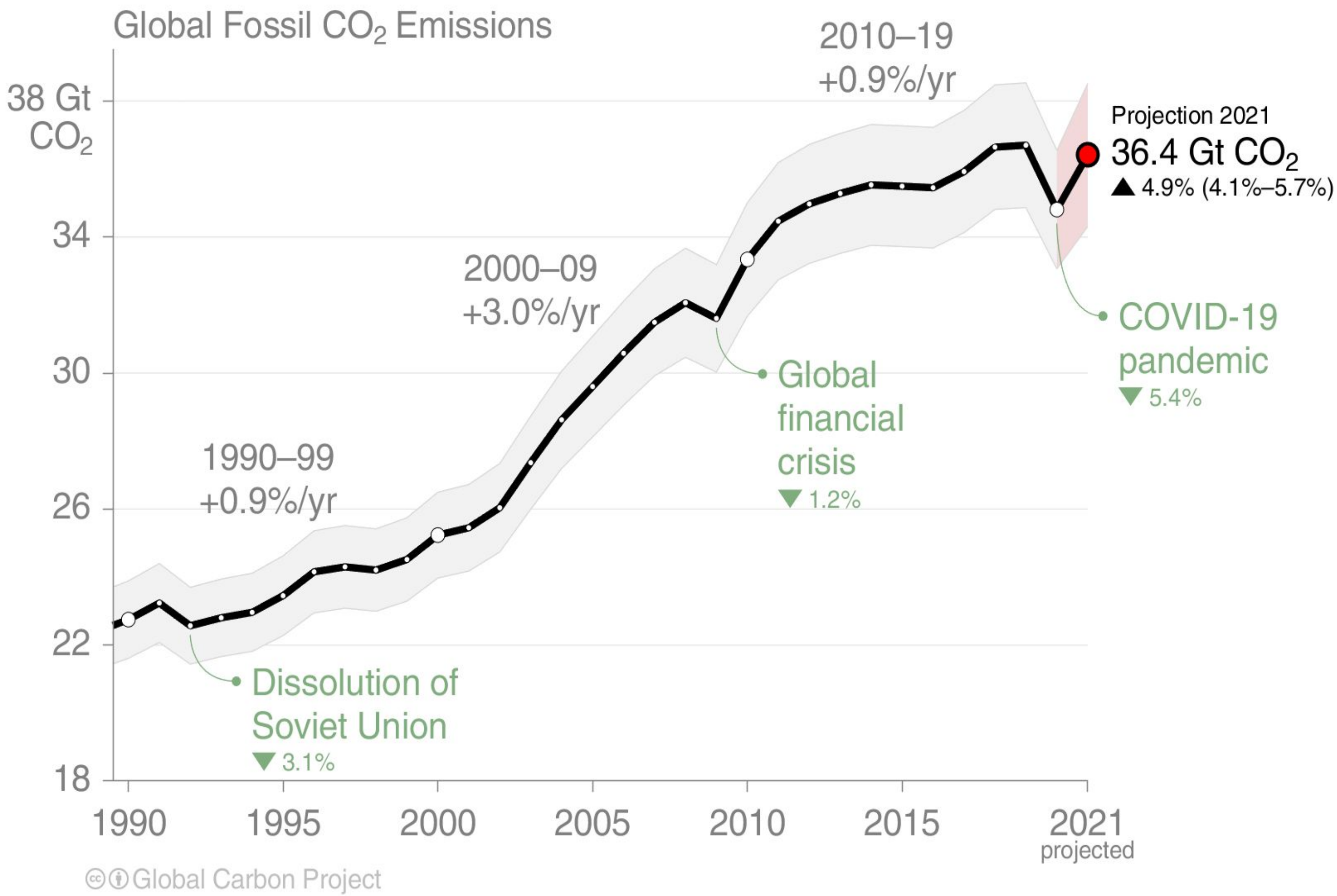
Temperatures are nearing Paris Agreement limits



http://berkeleyearth.org/global-temperature-report-for-2021/

Global fossil CO_2 emissions have been rising relentlessly

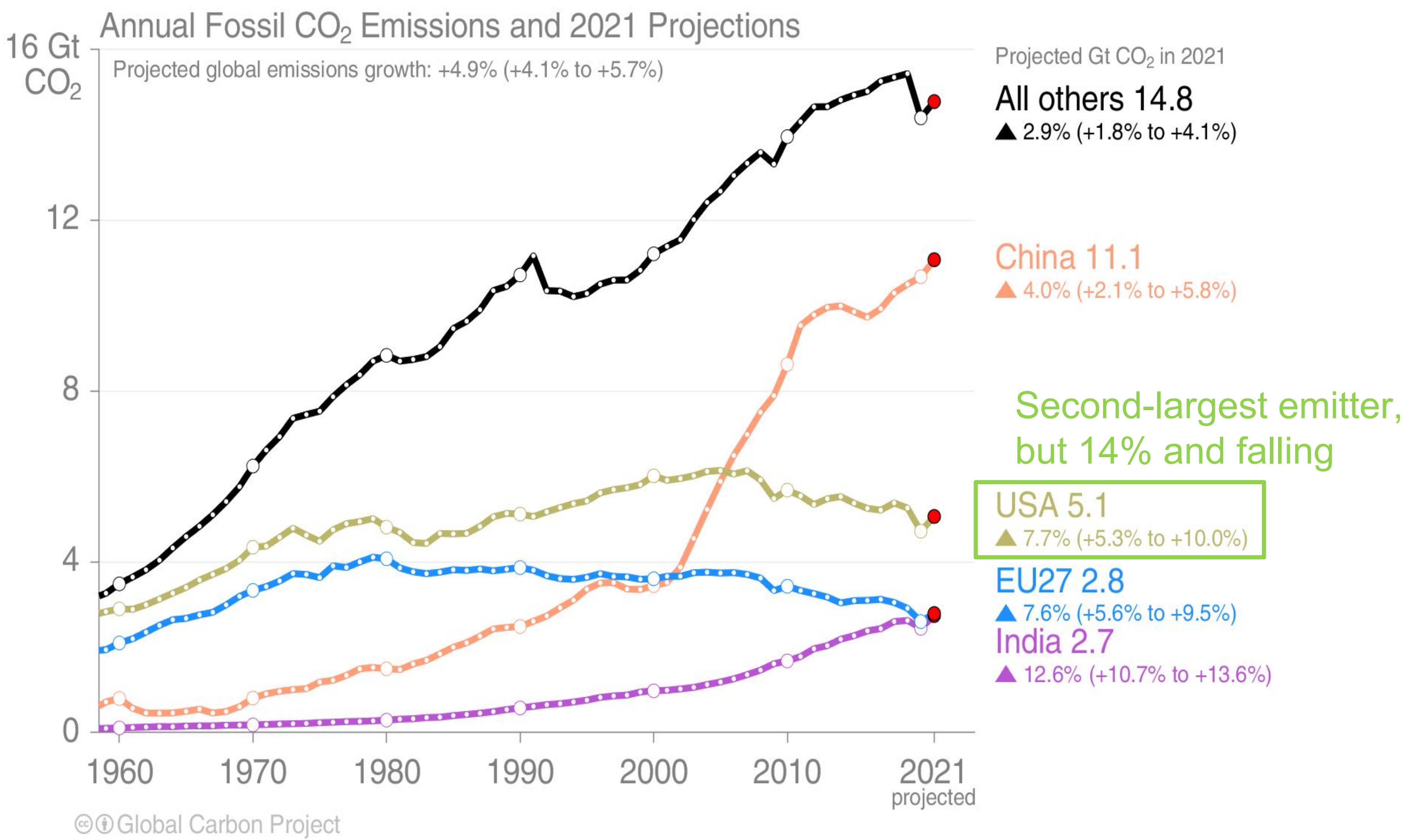
Global fossil CO_2 emissions: 34.8 ± 2 $GtCO_2$ in 2020, 53% over 1990
Projection for 2021: 36.4 ± 2 $GtCO_2$, 4.9% [4.1%–5.7%] higher than 2020



The 2021 projection is based on preliminary data and modelling.
Source: Friedlingstein et al 2021; Global Carbon Project 2021

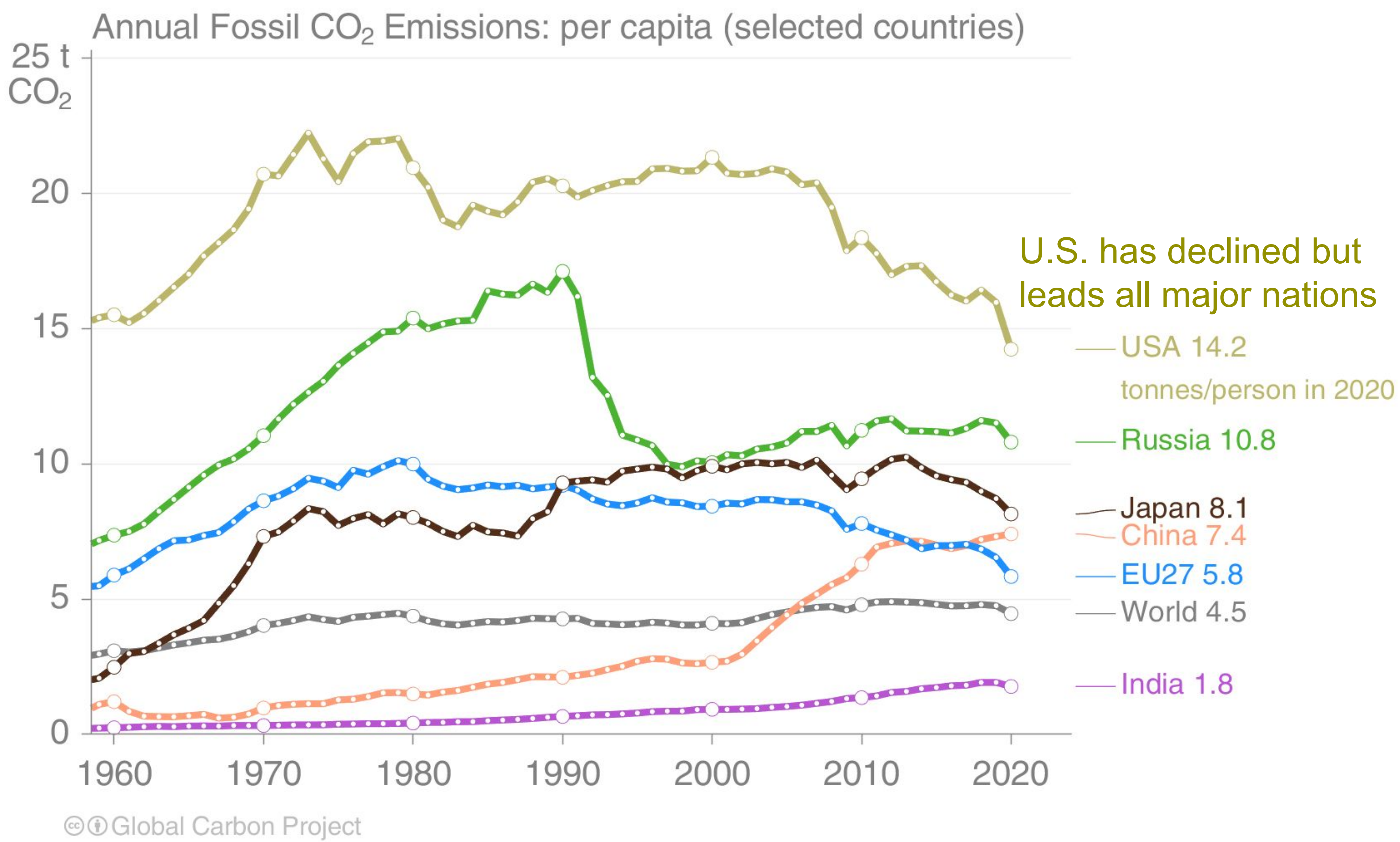
Emissions by country

Global fossil CO_2 emissions are projected to increase by 4.9% [4.1%–5.7%] in 2021



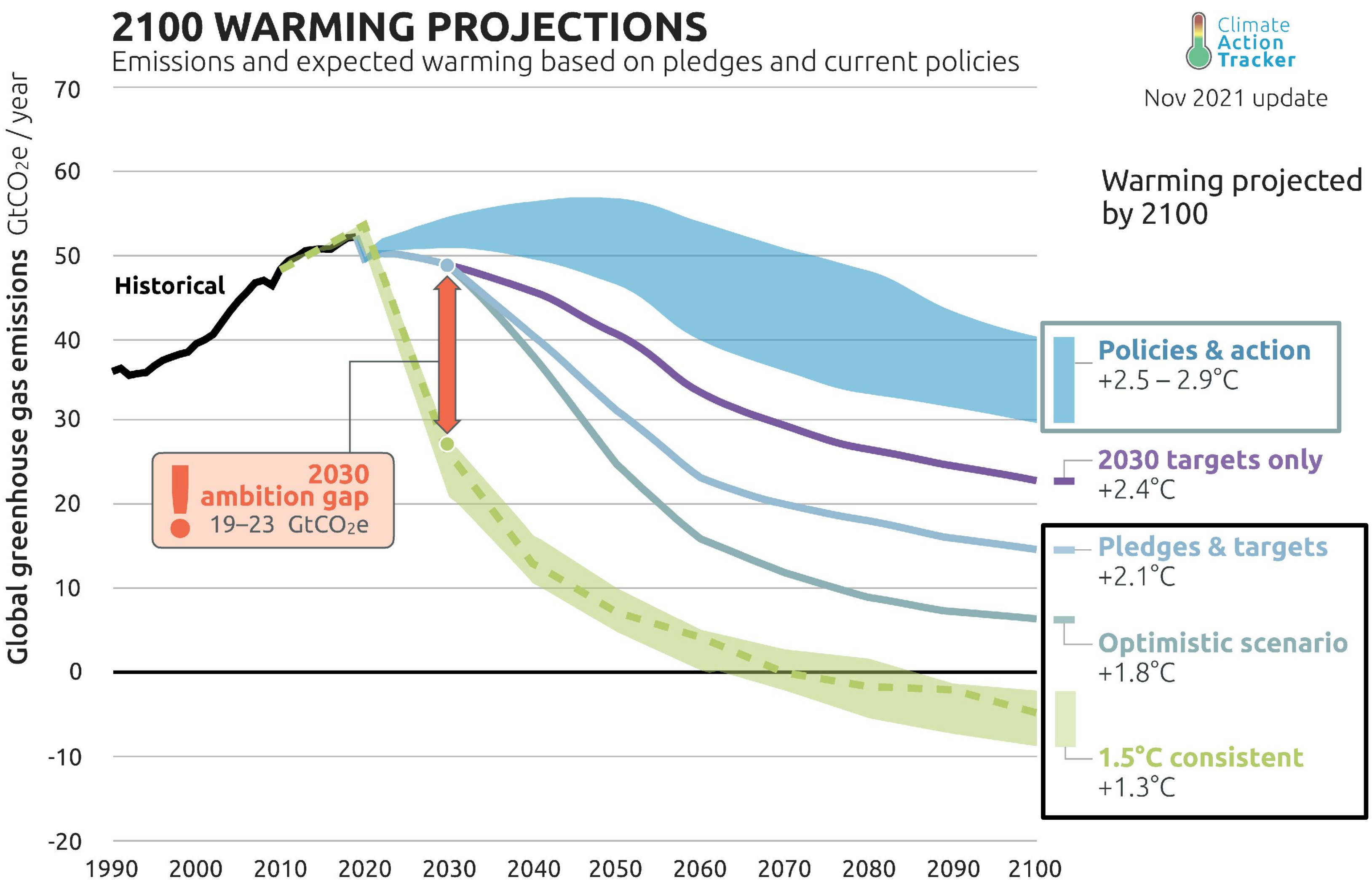
The 2021 projections are based on preliminary data and modelling.
Source: Friedlingstein et al 2021; Global Carbon Project 2021

Fossil CO_2 Emissions per capita



Source: Friedlingstein et al 2021; Global Carbon Project 2021

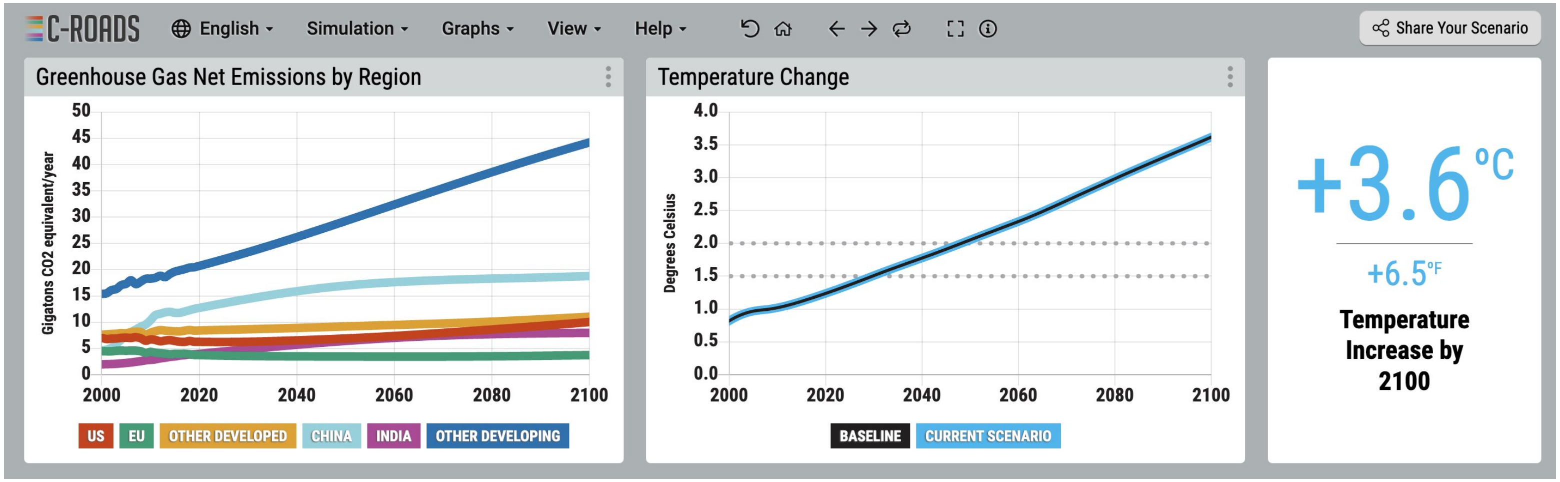
Worst-case scenarios avoided, but not on track for 1.5-2℃



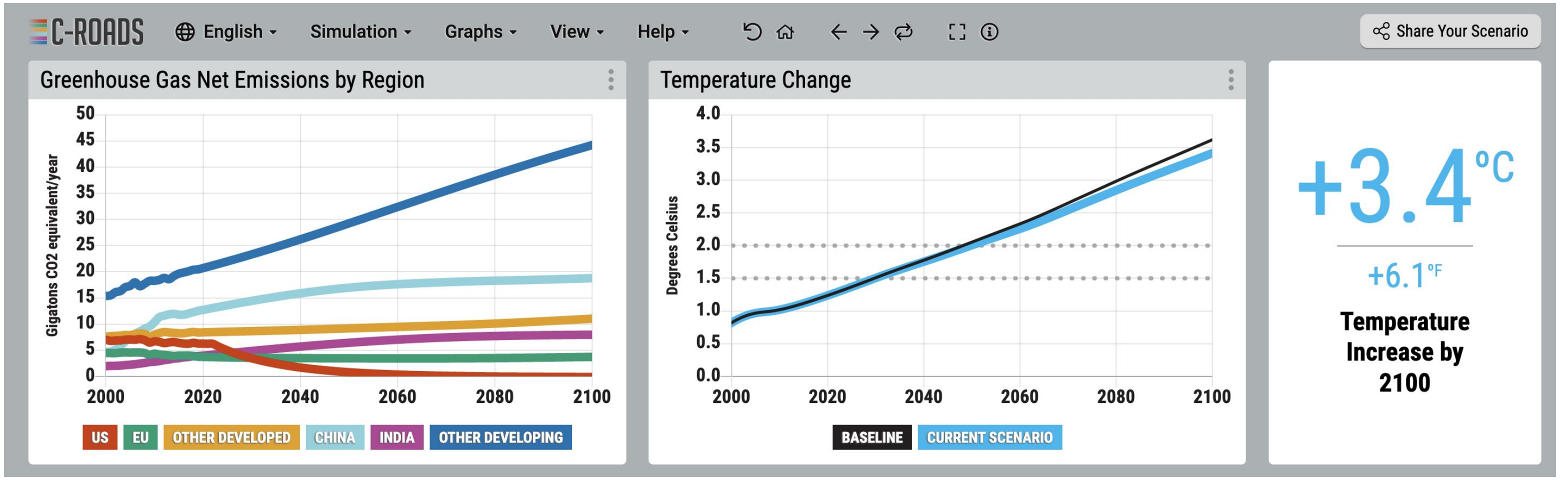
Climate Action Tracker

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

C-ROADS
Base case



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



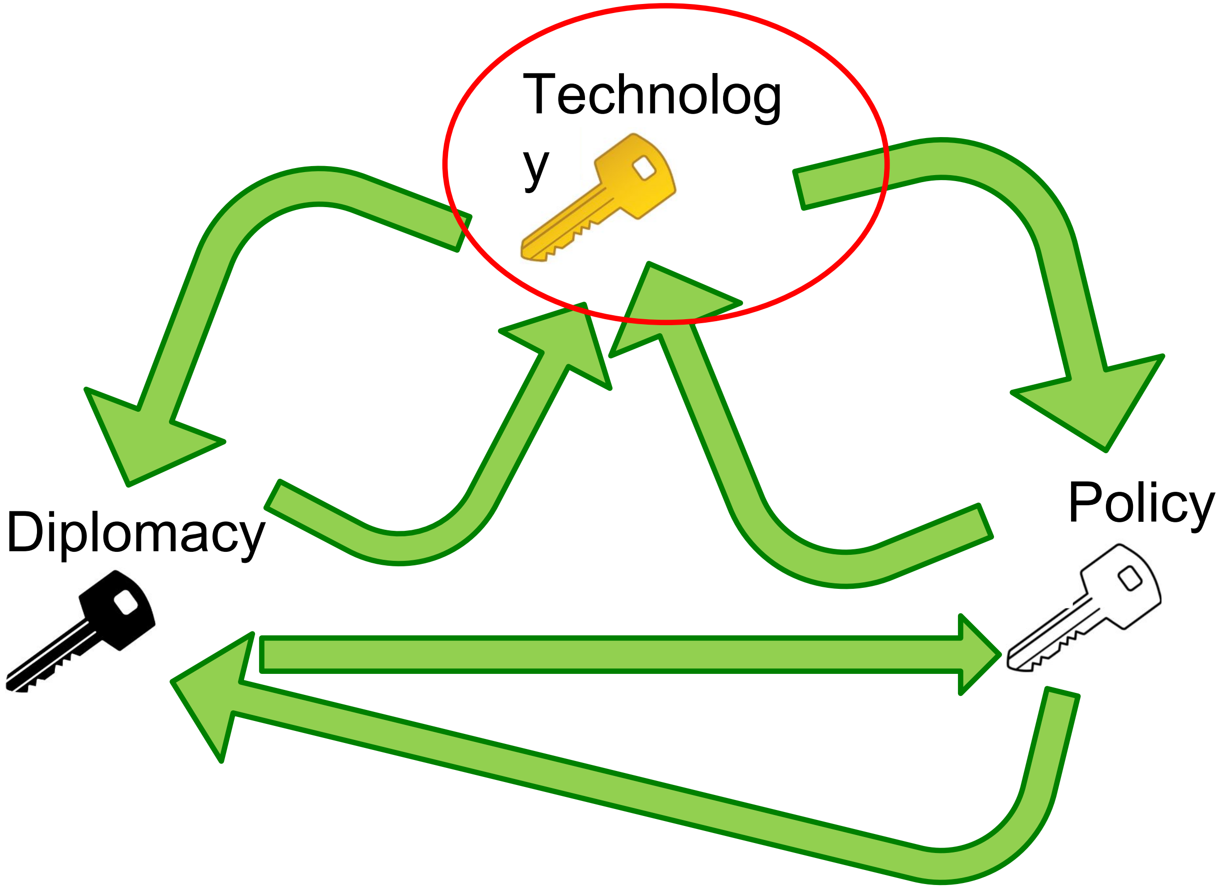
Need to decarbonize energy affordably, reliably, and fast, in ways that make it achievable globally

C-ROADS: Climate Interactive https://c-roads.climateinteractive.org/

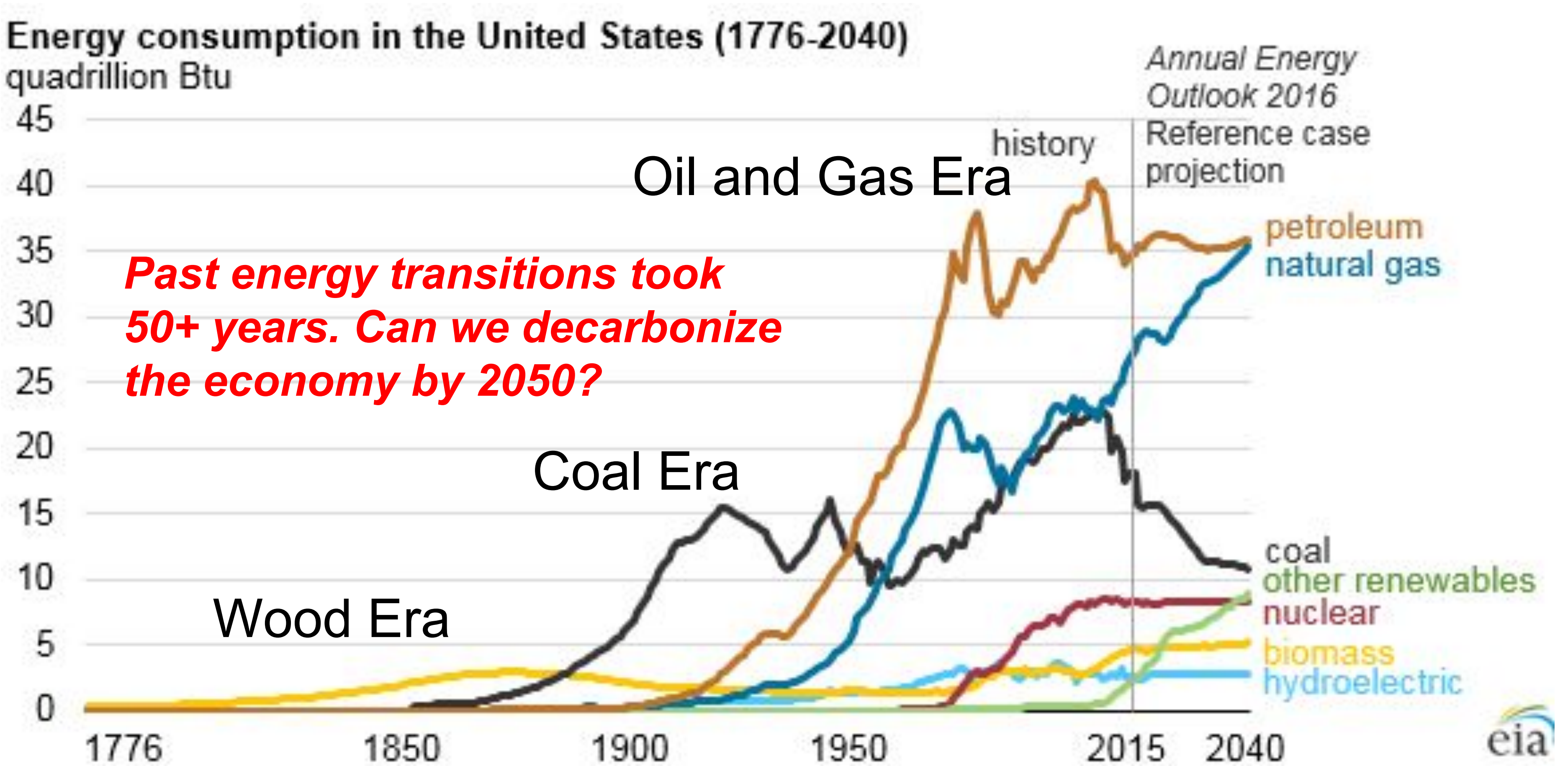
Still, U.S. is crucial

- 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

The Technology Key

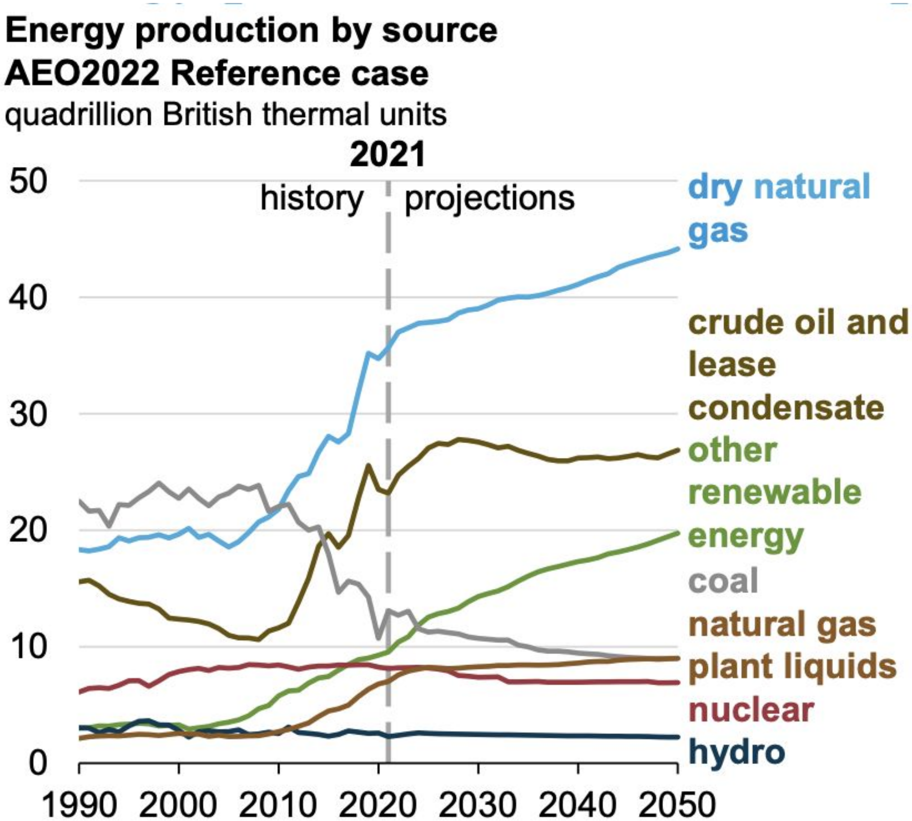


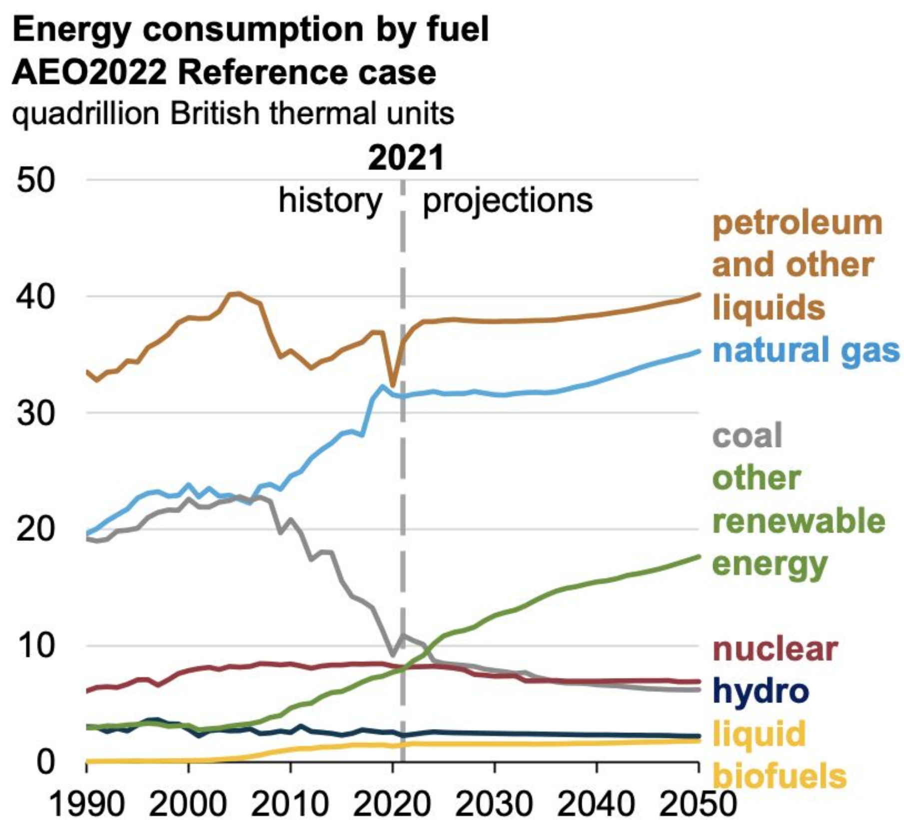
Energy transitions historically have been slow



https://www.eia.gov/todayinenergy/detail.php?id=26912

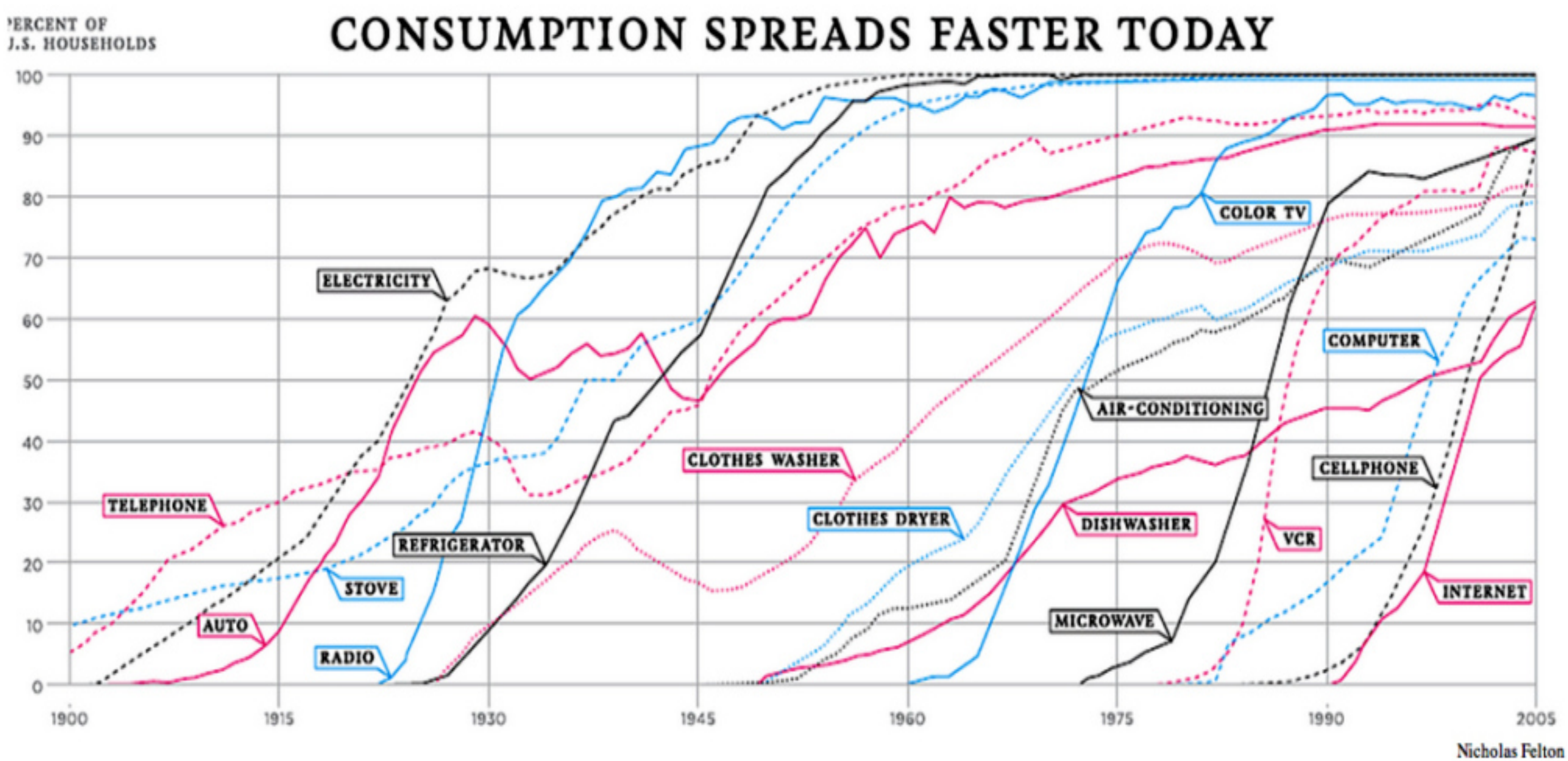
Baseline projections expect fossil fuels to remain dominant





U.S. EIA, Annual Energy Outlook 2022

Some technology transitions have been incredibly fast



https://cleantechnica.com/2018/05/06/tony-seba-charts-out-the-disruptive-path-forward-to-evs-and-out-of-the-i-c-e-age/
https://alearningaday.blog/2017/10/22/horses-cars-and-the-disruptive-decade/

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

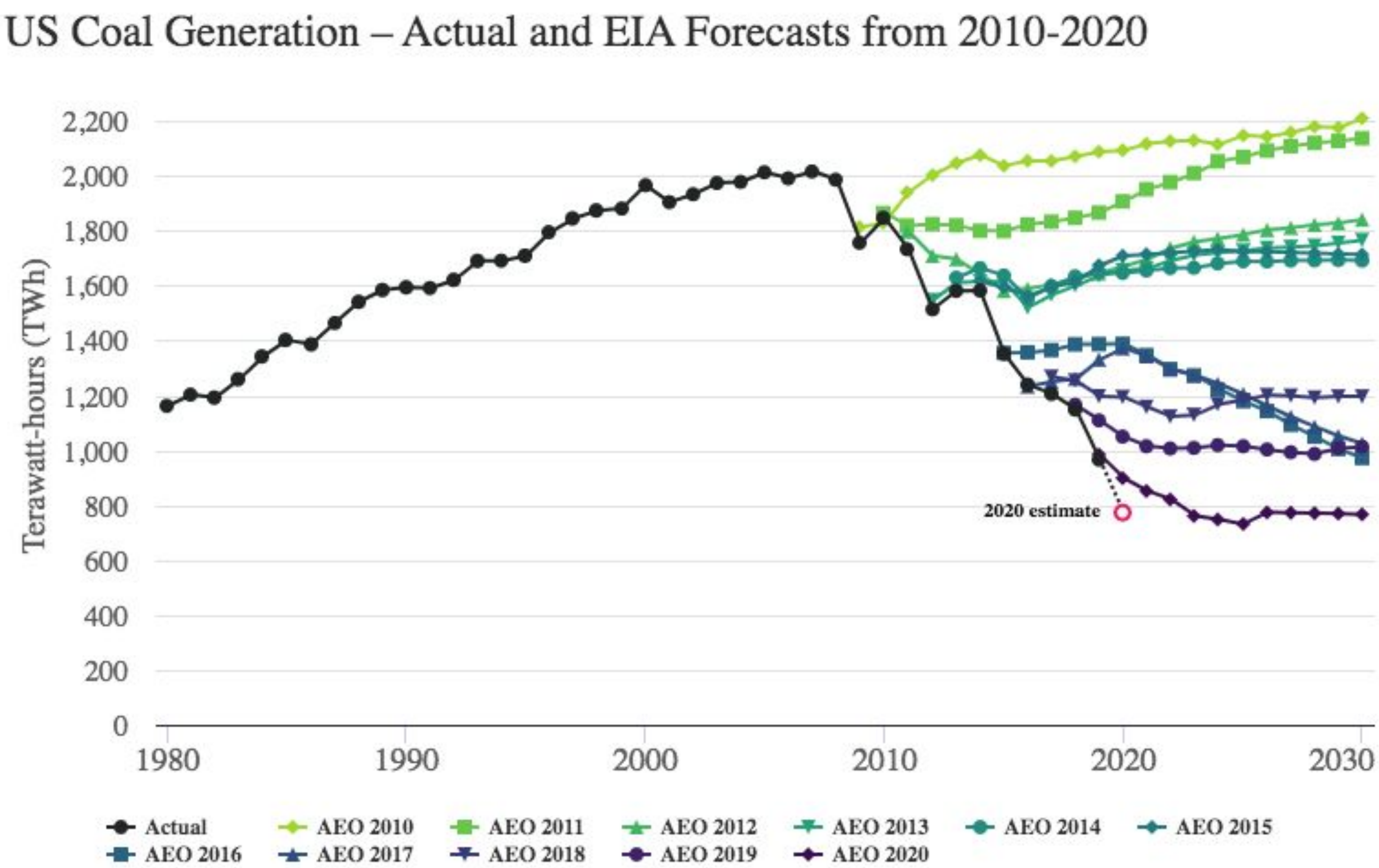
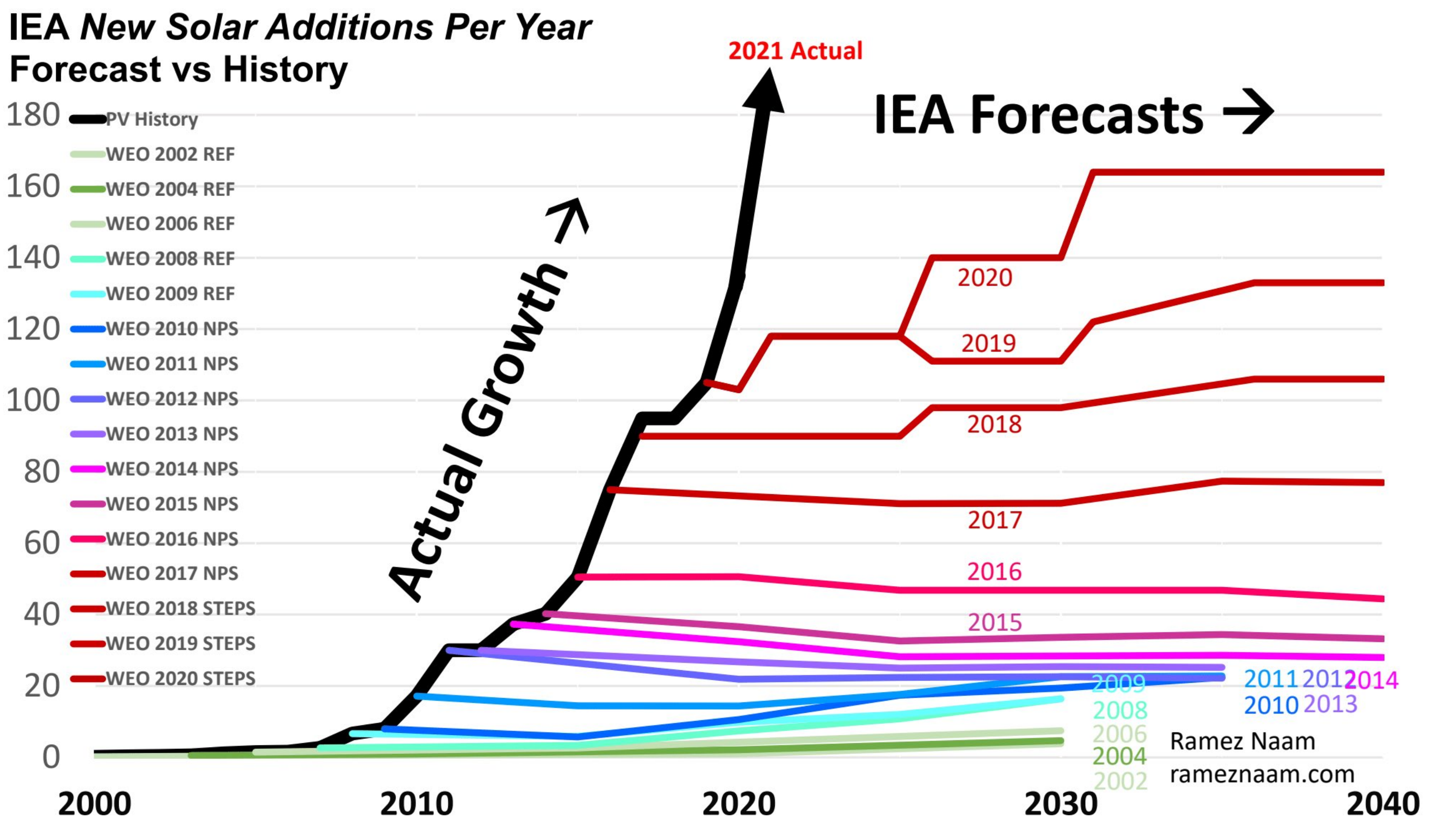
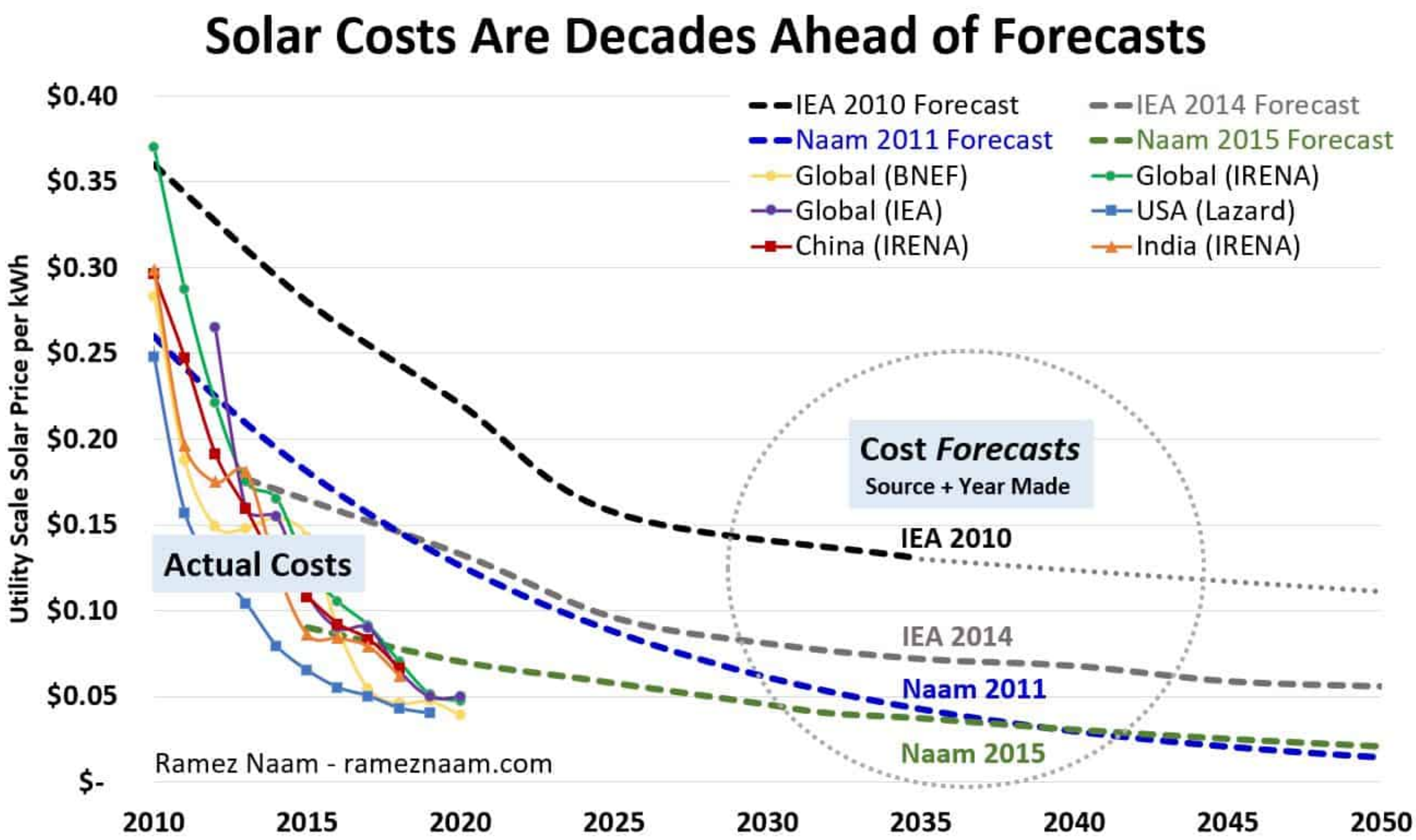


Image from Zeke Hausfather, @hausfath

… And underpredicted renewables



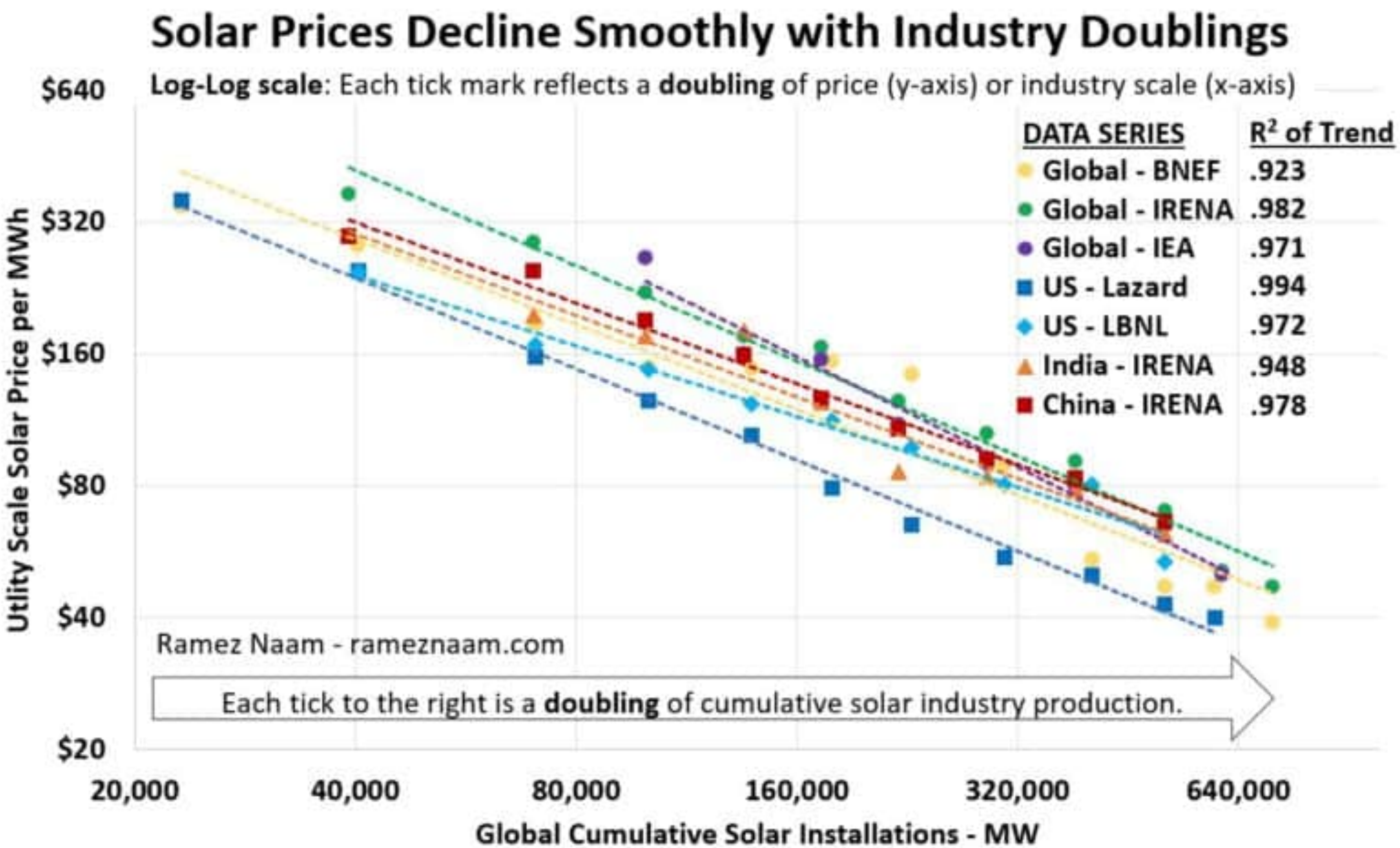
Even optimists failed to foresee cost declines in solar



Slides from Ramez Naam: https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/

Learning curves: Costs tend to fall ~18% per doubling in deployment

Solar prices on a log scale (each tick mark is a doubling)



Each tick mark is a doubling in global cumulative solar

Slides from Ramez Naam: https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/

Learning curves for the Model T

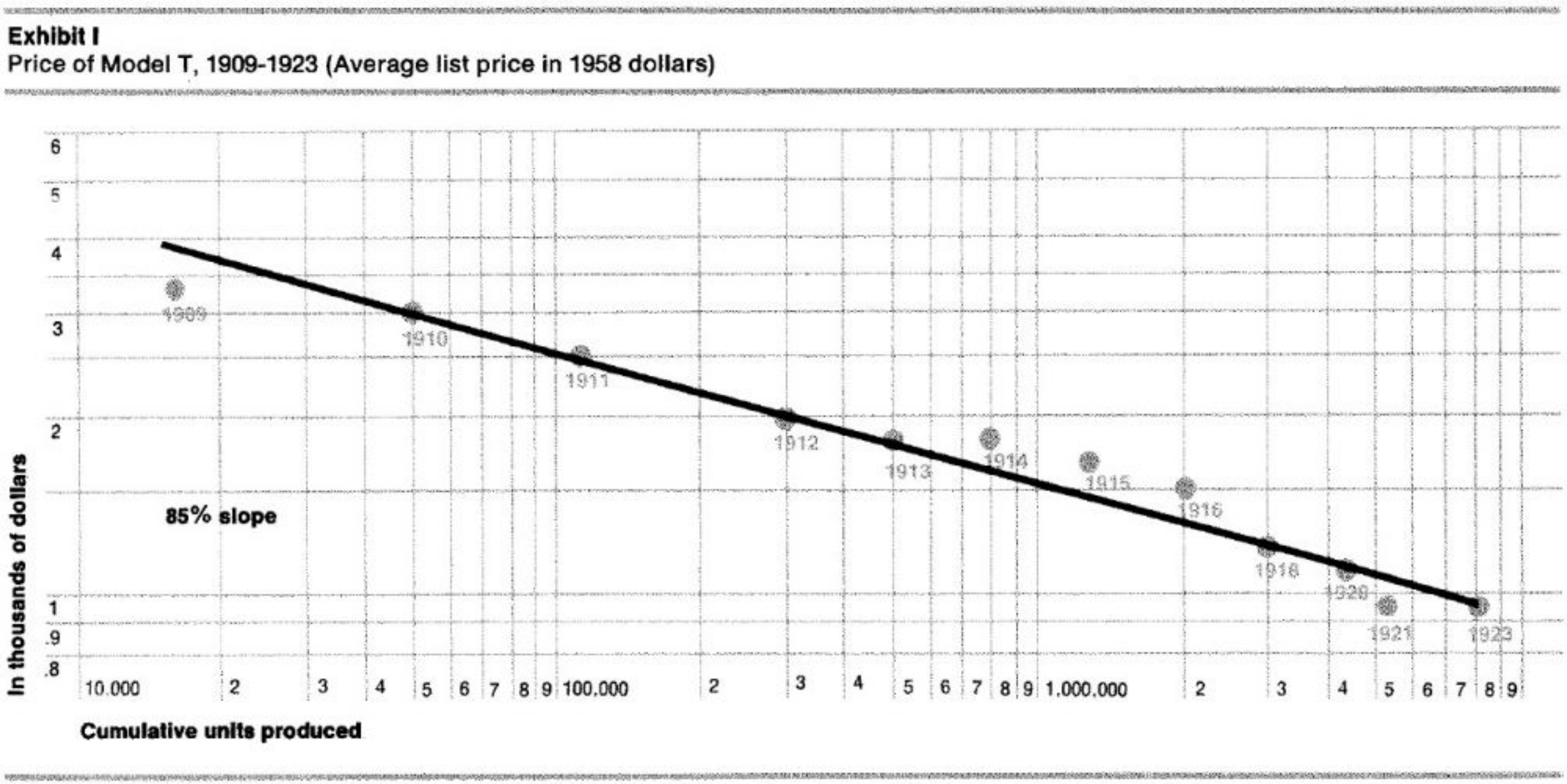
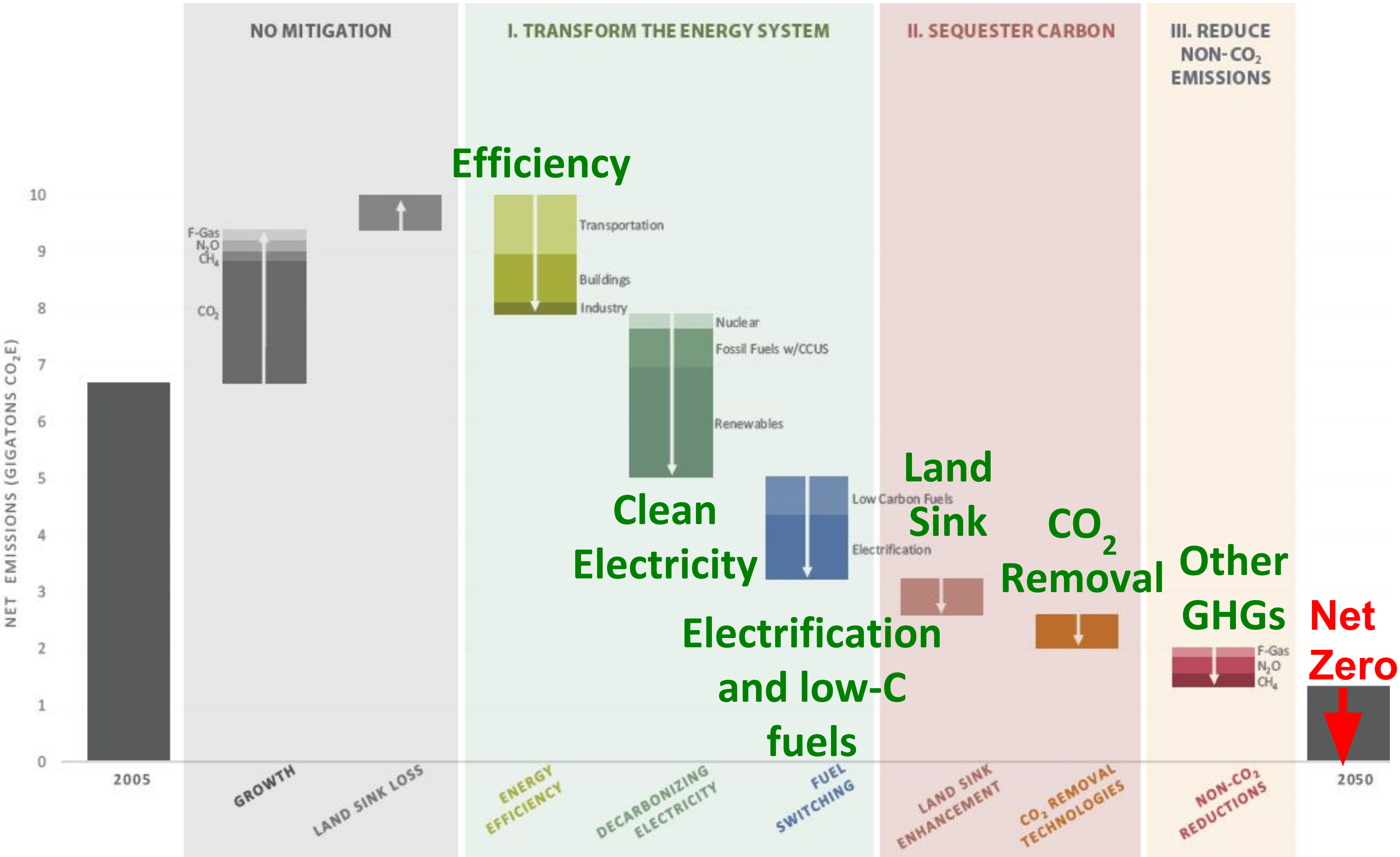


Figure 1. The price of the Ford Model T from 1909-1923[2].

Slides from Ramez Naam: https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/

Steps toward decarbonization

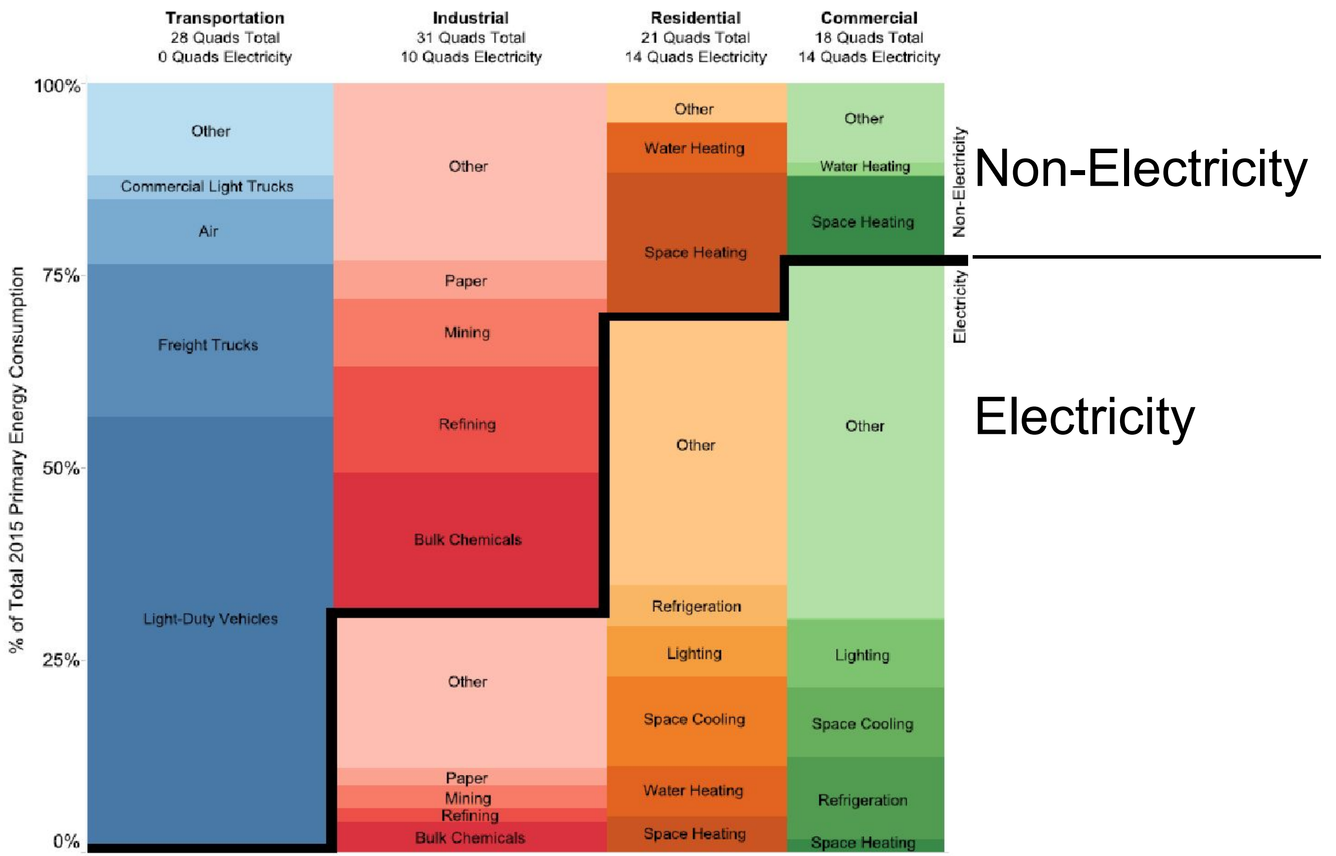


United States Mid-Century Strategy for Deep Decarbonization (White House, Nov. 2016)

Pillars of clean energy

Roles for the pillars of clean energy:

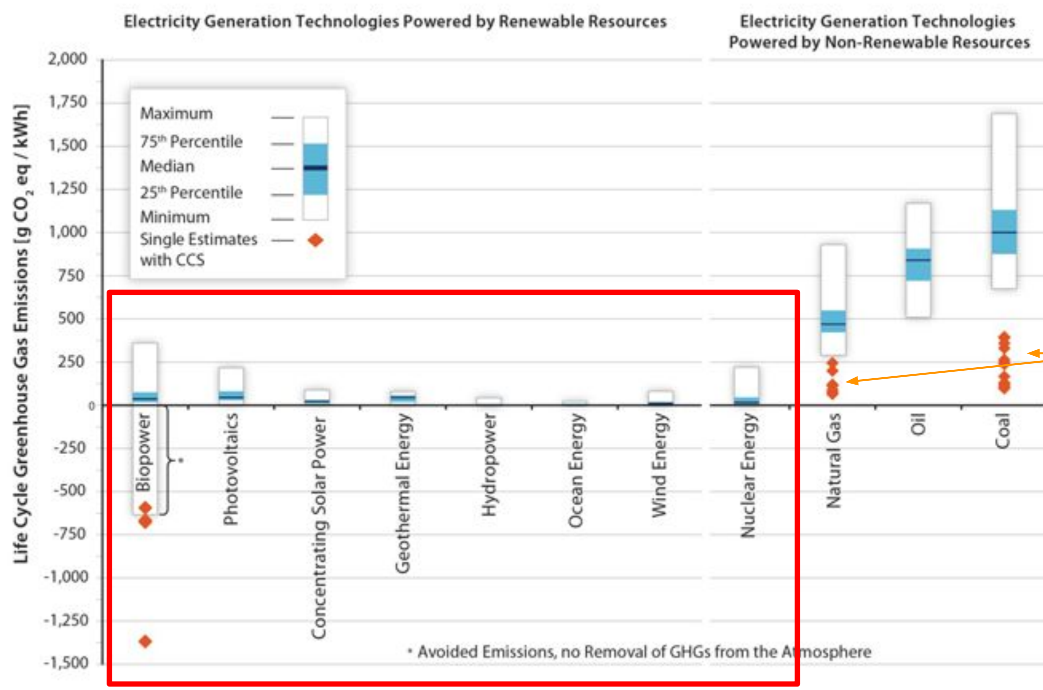
- **Efficiency**: Shrinks all boxes
- **Clean electricity:** Cleans up area below the electric frontier
- **Electrification:** Moves up the electric frontier
- **Other clean fuels:** Decarbonizes above frontier
- **Carbon sinks:** Offset the emissions that remain



NREL Electrification Futures Study

Decarbonizing Electricity: Options

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



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	36	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	10	6	11	5	49	32	36(+4)	10	50(+10)

Without carbon capture

With carbon capture

NREL NATIONAL RENEWABLE ENERGY LABORATORY

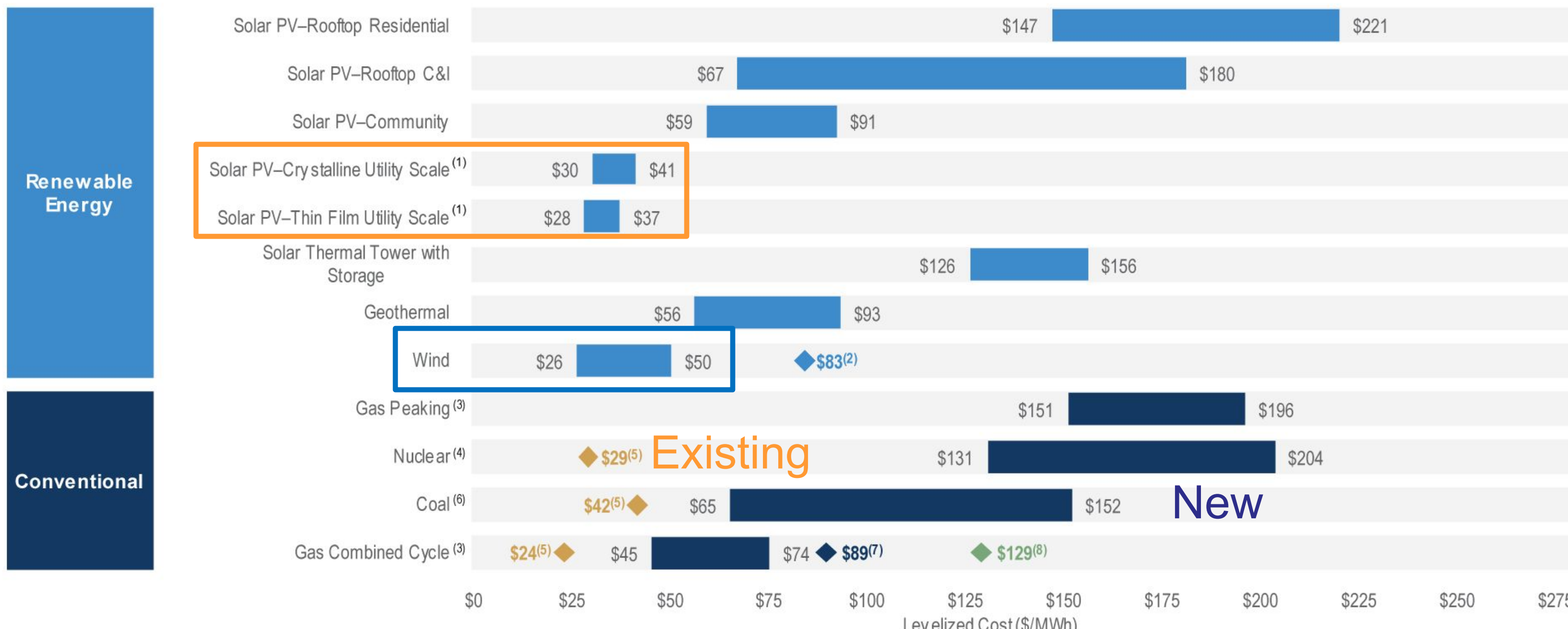
ipcc INTERGOVERNMENTAL PANEL ON climate change

NREL Life Cycle Assessment Harmonization

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



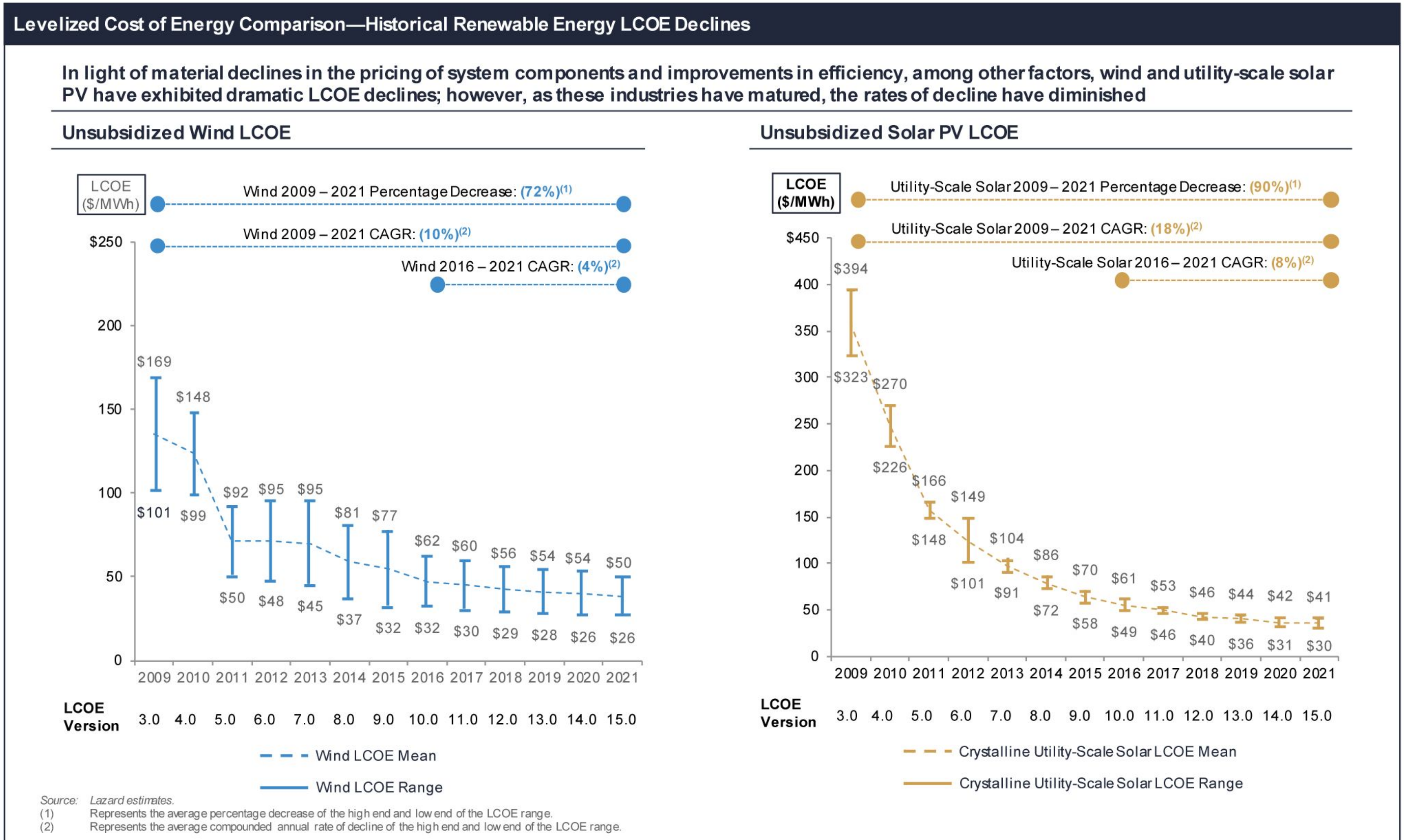
Source: Lazard estimates.

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 CO_2 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.

Lazard 2021, Unsubsidized levelized cost of electricity

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



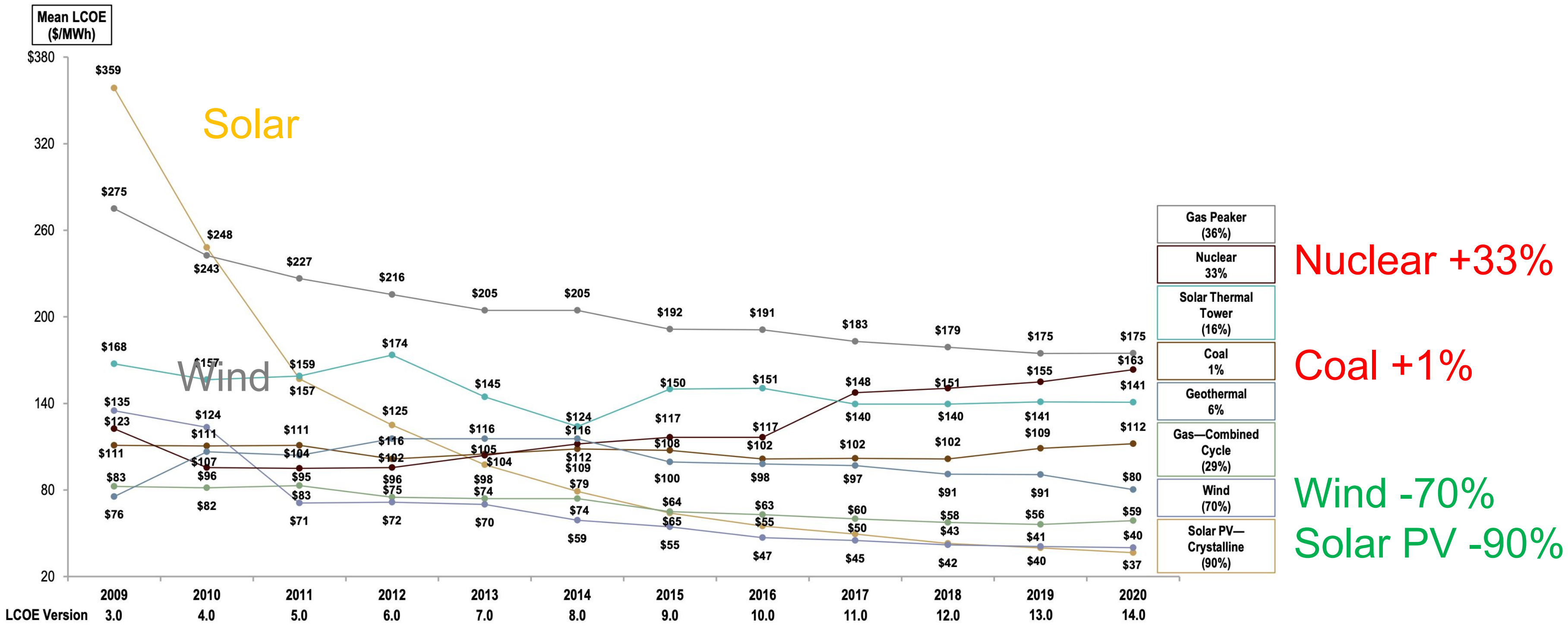
Lazard 2021, Unsubsidized levelized cost of electricity

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

Copyright 2020 Lazard

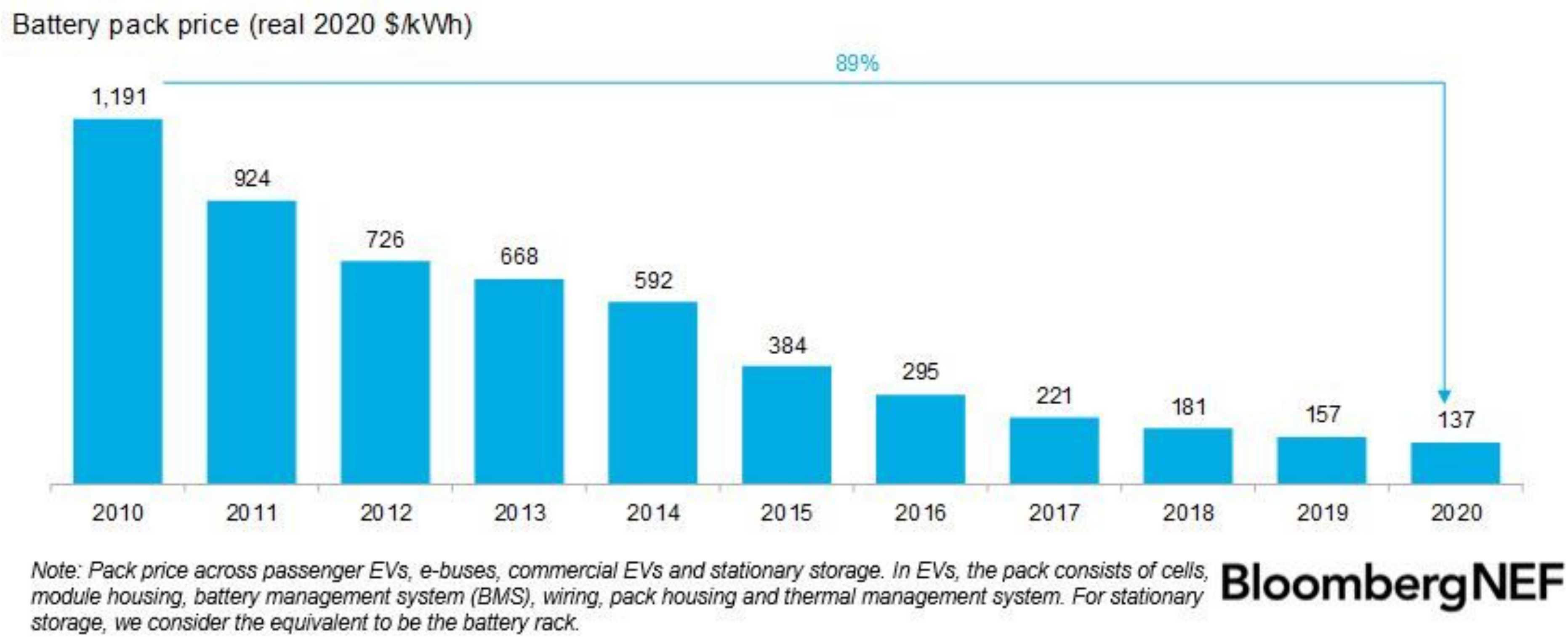
Source: Lazard estimates.

(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—Version 3.0.

8

Lazard 2020: https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf

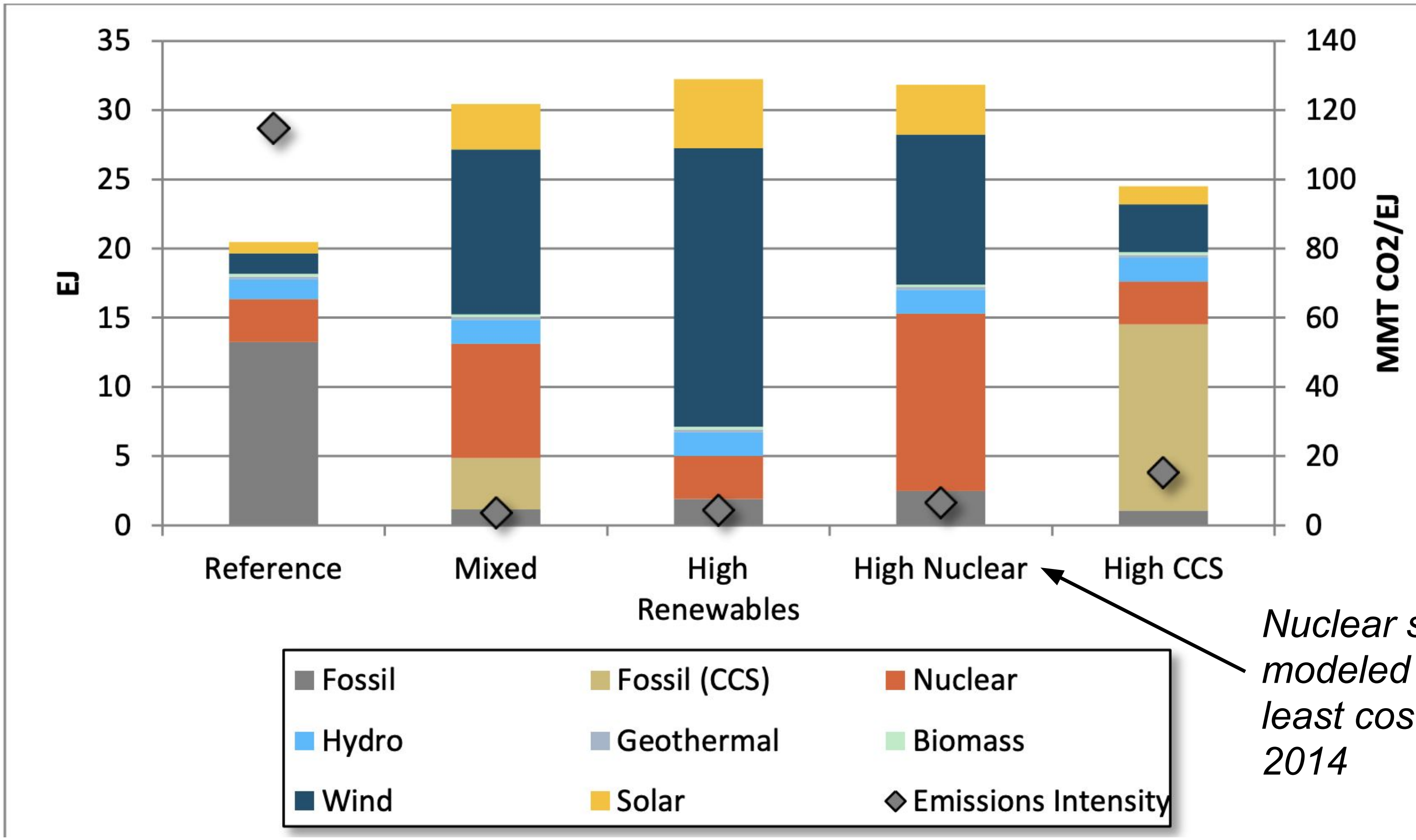
Lithium-ion battery costs



BNEF 2021:
https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/

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

Figure 29. 2050 Electric Generation by Resource Type

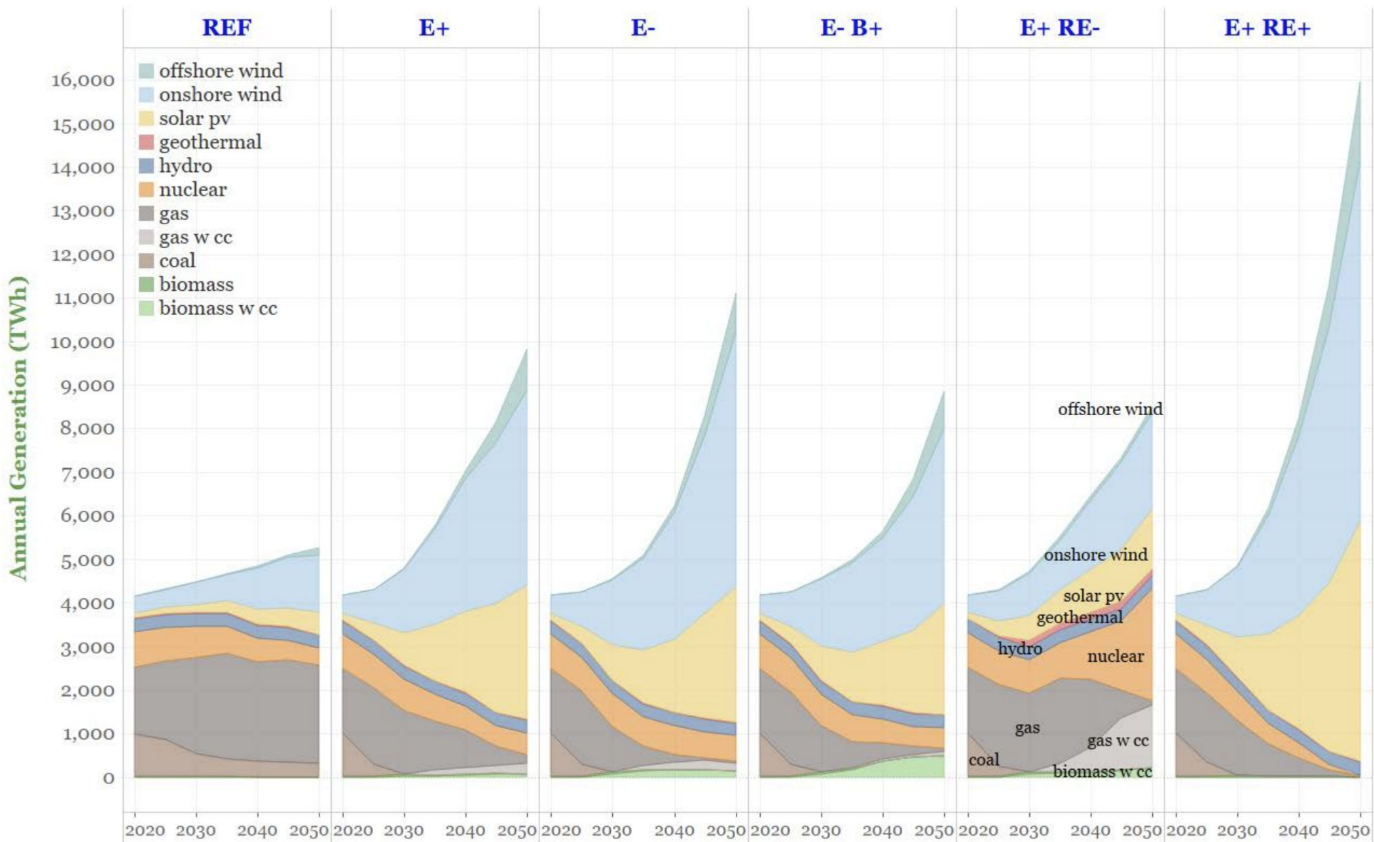


Nuclear scenario modeled to be least cost in 2014

United States Deep Decarbonization Pathways Project 2014

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

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

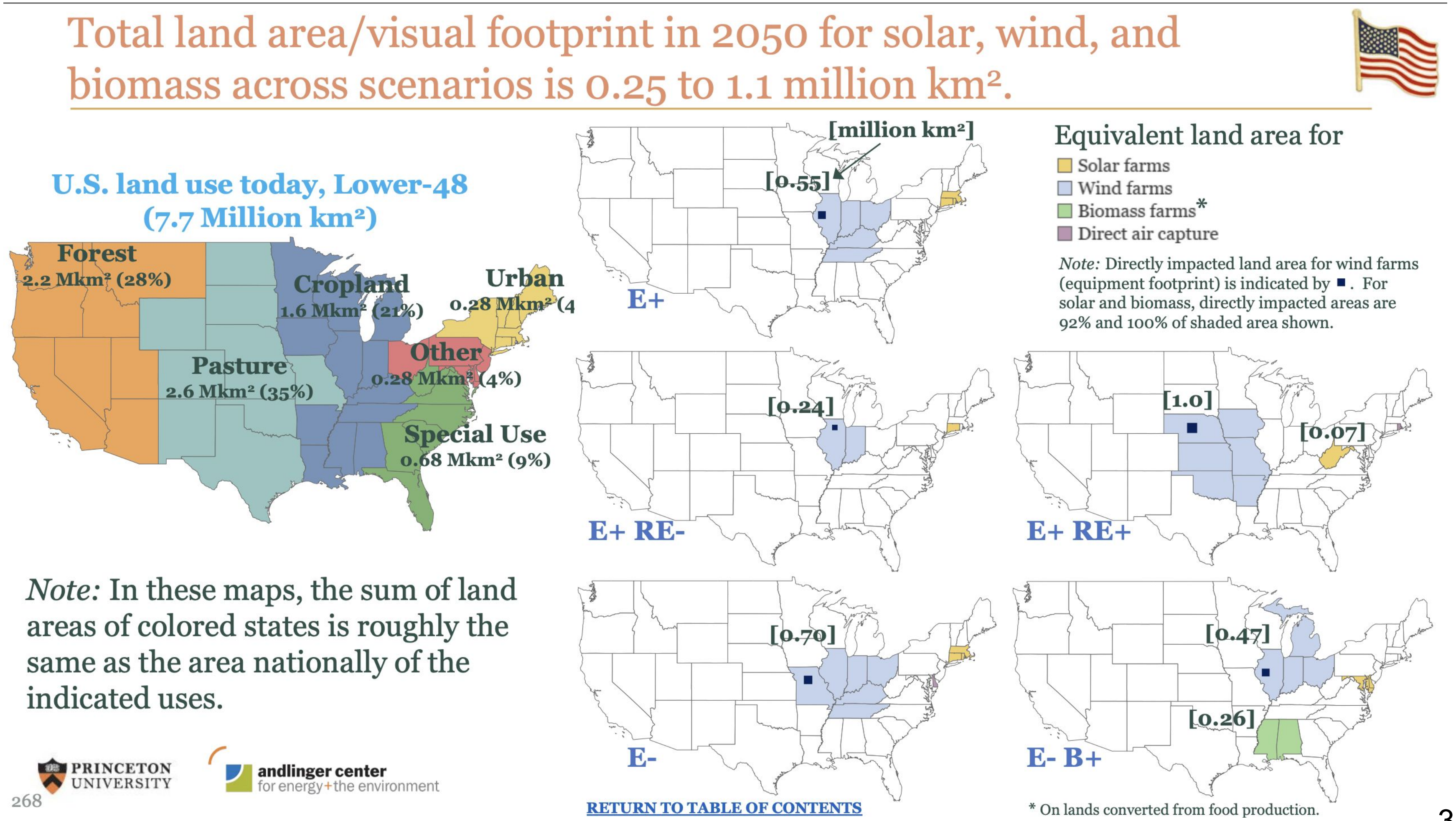


- Share of electricity from carbon-free sources roughly doubles from ~37% today to 70-85% by 2030 and reaches 98-100% by 2050.
- Wind + solar grows >4x by 2030 to supply ~½ of U.S. electricity in all cases except E+RE-; in that case, growth is constrained, but still triples by 2030 to supply ⅓ of electricity.
- 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

Princeton, net-zero pathways: https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

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



Princeton, net-zero pathways: https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Emerging option: Enhanced geothermal

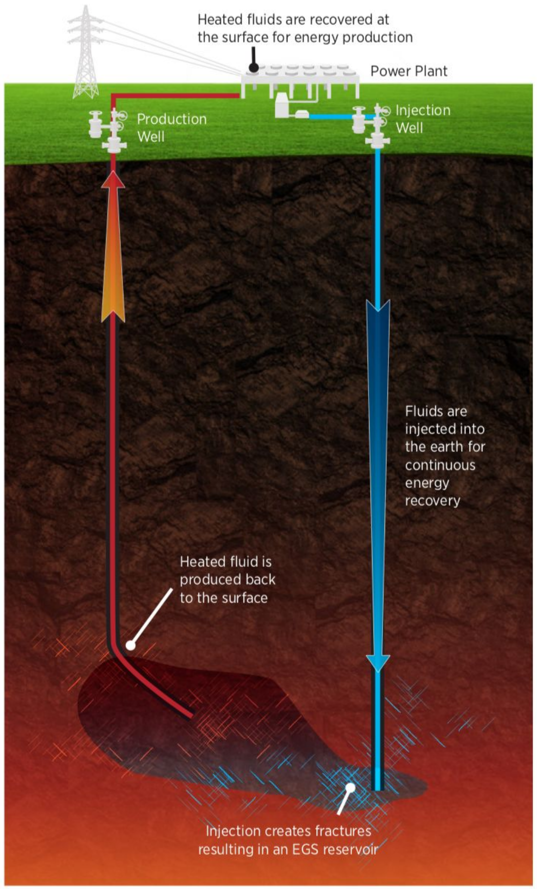


Figure 2-6. Conceptualization of an enhanced geothermal system

DOE GeoVision

GEOTHERMAL

Google Taps Fervo Energy To Develop Enhanced Geothermal Systems in Nevada

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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
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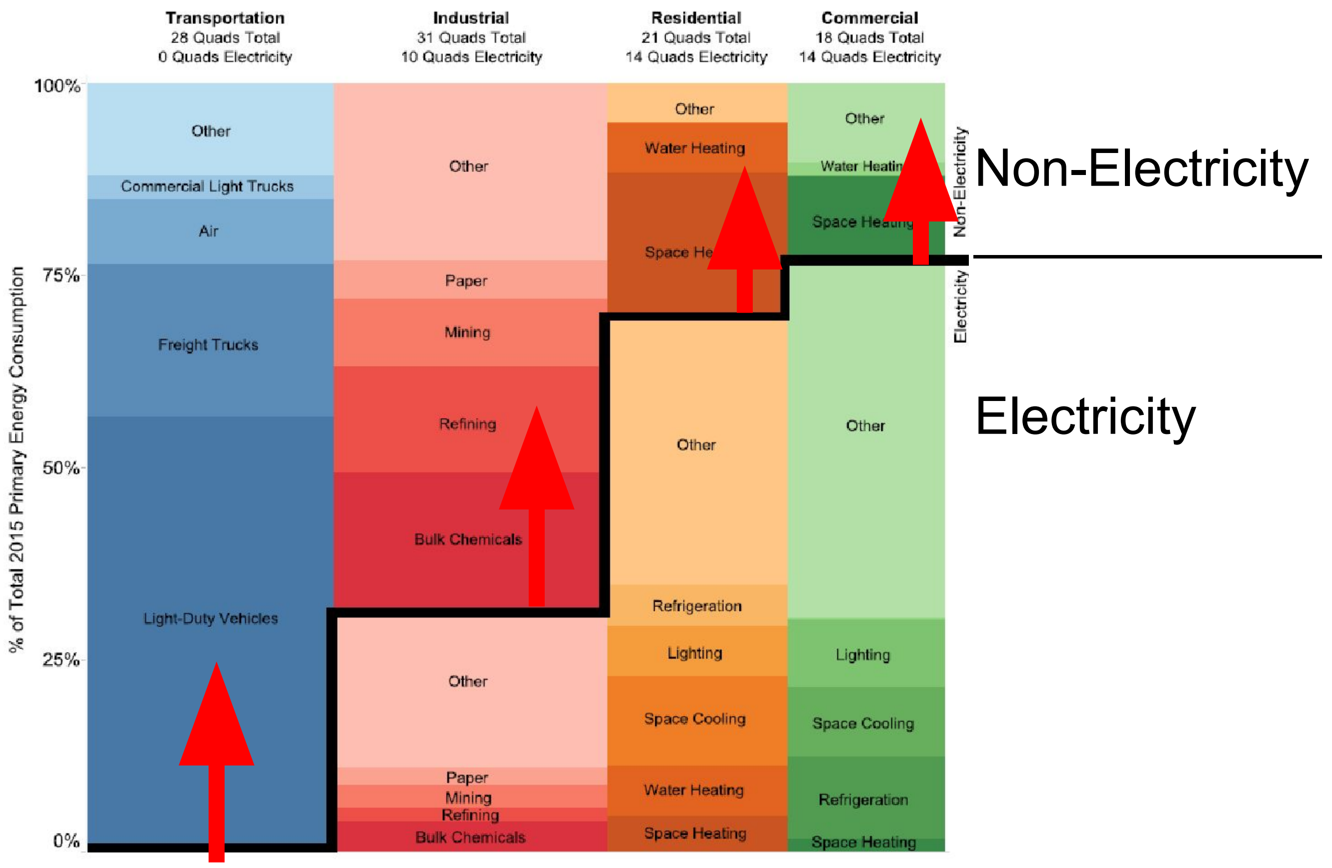
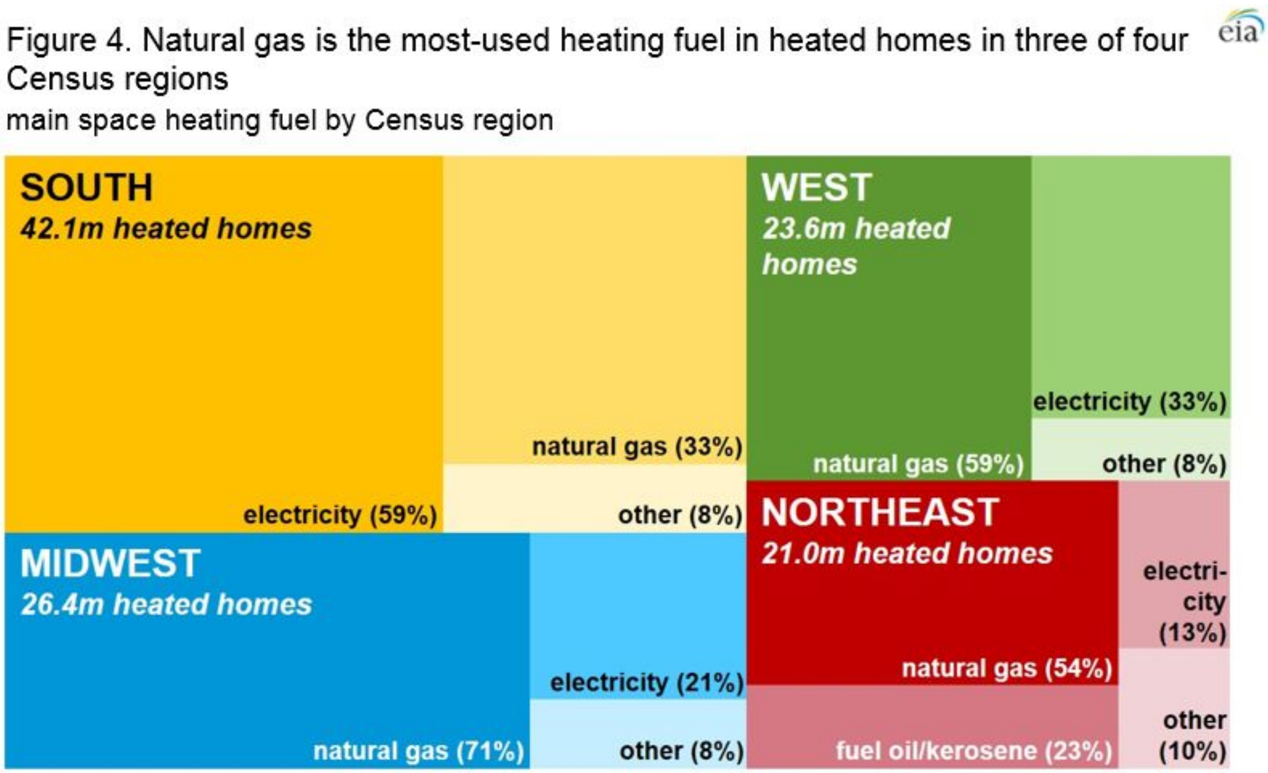


NREL Electrification Futures Study

How homes are heated in U.S.

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



Mostly natural gas in West

Mostly natural gas and fuel oil in Northeast

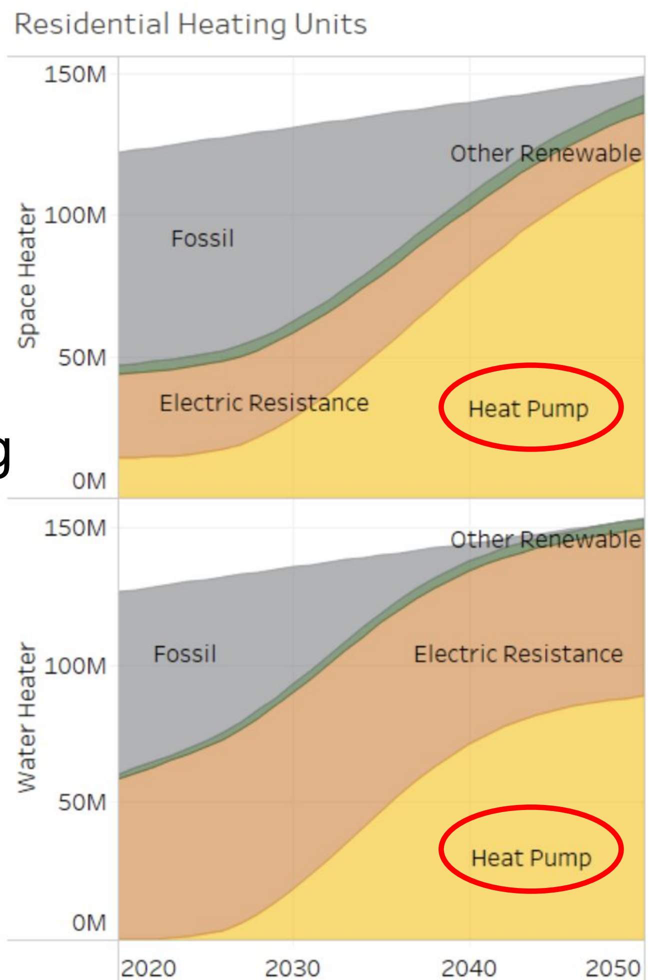
Mostly natural gas in Midwest

[EIA 2015 Residential Energy Consumption Survey]

Transition to electric heat pumps in most net-zero strategies

Space heating

Water heating



America's Zero Carbon Action Plan: https://www.unsdsn.org/Zero-Carbon-Action-Plan

Policies can create virtuous cycle of technology learning curves

- ↑Production □↓Cost □ ↑Production □ ….
- "Technology push" policies: RD&D lowers cost of a technology (↓Cost)
- "Market pull" policies: Create demand for a product (↑Production)
  - Procurement: e.g., Government fleet
  - Incentives: e.g., electric car tax credits
  - Mandates: e.g., California new home solar
  - Emissions taxes

Take-home messages

- Decarbonizing the U.S. is necessary but not sufficient for decarbonization globally
- 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