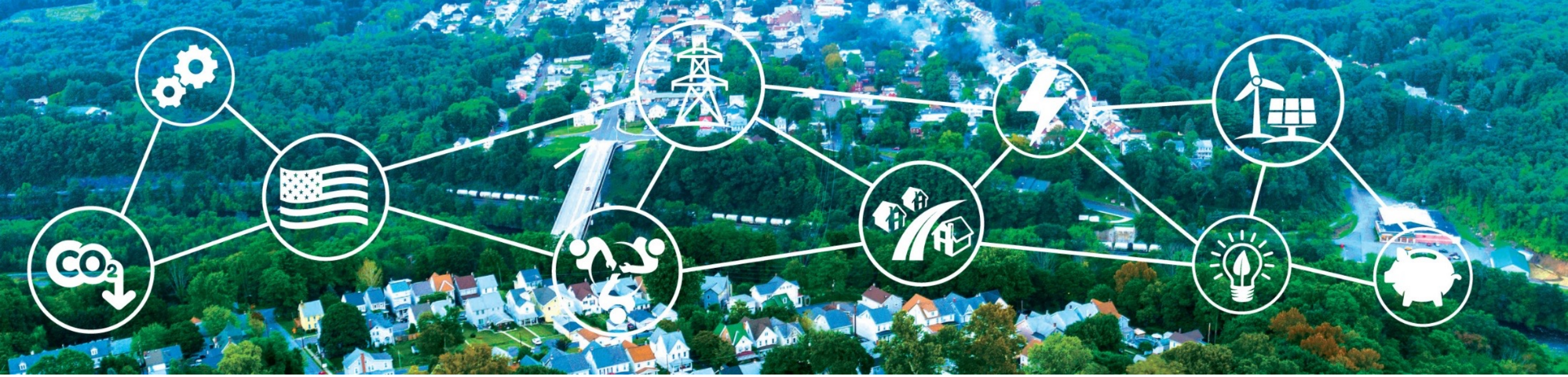


How to Achieve Net-Zero Greenhouse Gas Emissions in the United States by Midcentury

Steve Pacala
Princeton University
March 31, 2021

High Meadows Environmental Institute | Carbon Mitigation Initiative

Outline

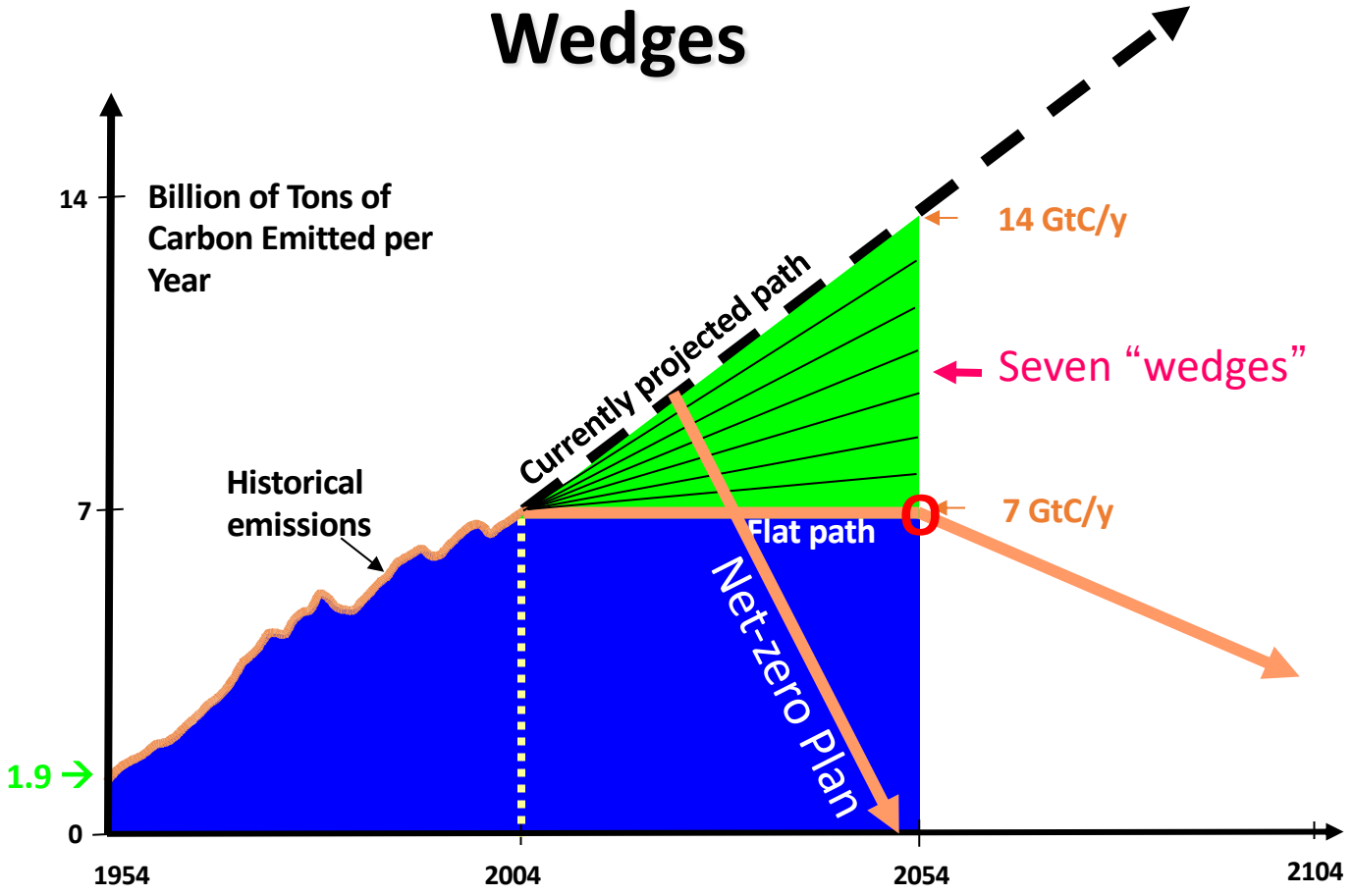
History lesson: an unheralded revolution in energy technology.

> **Subsidies worked in otherwise free markets to reduce the cost of net-zero technology and made implementation economically and perhaps politically feasible.**

A policy manual for a fair, just, feasible and economic transition to net-zero in the US from the National Academies of Science, Engineering and Medicine (2021).

Examples from Princeton Net-Zero America Project (NZAP 2020)

Pacala and Socolow (2004)



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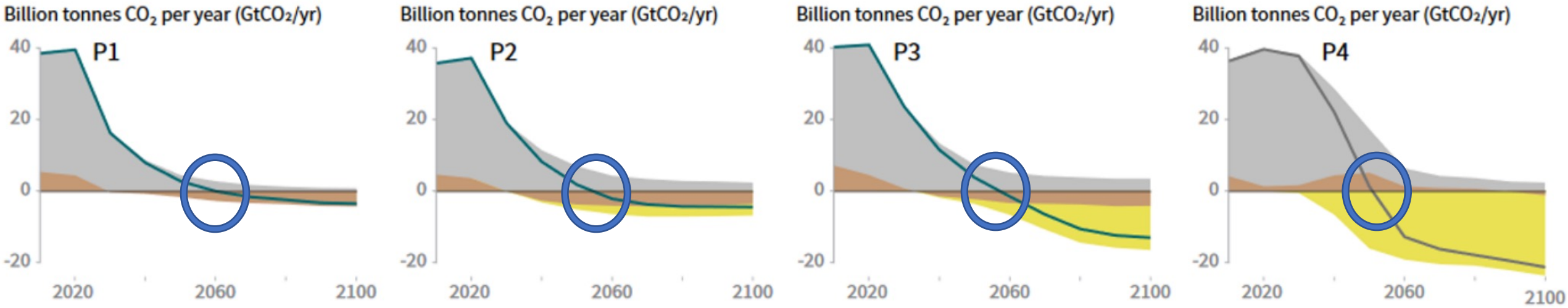
Q: Why did we focus only on getting started along a path to ~3 degrees? A: We didn't have the technology to do anything else.

(Agriculture Forestry and other Land Use)

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways

Fossil fuel and industry AFOLU BECCS (Biomass Energy with Carbon Capture and Storage)



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

IPCC 1.5 Degree Report

Why did the goal posts move?

1. There is no nearby tipping point, as far as we know, but excess CO2 in the atmosphere is known to be dangerous right now.

BAU Problem: Tipping points

~2100

Monsters Behind the Door
Copyright Disney

~2050

2015

1995

ppmv CO2	2100 warming
900	
850	4°
800	
750	
700	
650	3°
550	
500	
450	2°
400	
350	1°
300	0°

- Rapid Deglaciation and Loss of Coastal Cities
- Mass Extinction
- Deep Sea Circulation Stops
- Tropical Famine

Why did the goal posts move?

2. The technology got cheaper, making the cure feasible.

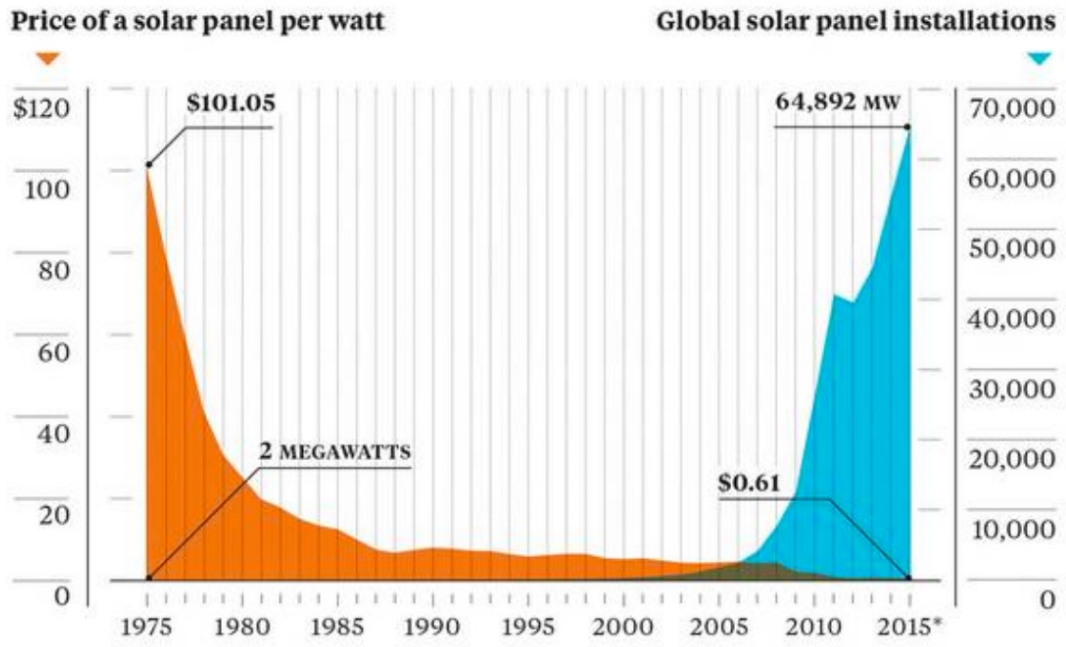
Most promising options… in 1990

The Start

Slide pair: courtesy of Greta Shum, Andlinger Center, Princeton University

2011 Kentucky Derby, AP Photo/Matt Slocum. https://www.cbsnews.com/pictures/2011-kentucky-derby/7

Non-emitting energy sources were either limited (hydro) or expensive. But subsidies were in place across the board. They created markets for wind, solar and unconventional gas, that would not have existed otherwise.



Although, fundamentally, photovoltaic technology has changed very little since the 1950's – the average residential 4kW PV system has fallen in price from roughly £15,000 10 years ago, to an average of c.£5,000 today.

http://solarsouthwest.co.uk/solar-panel-cost/

During the last ten years alone, the cost of:

Solar declined 90%.

Wind declined 70%.

Lithium ion batteries declined 85%

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Most promising options … in 2020

Melbourne Cup, The Foreign Correspondents' Club, Hong Kong. https://www.fcchk.org/event/melbourne-cup

Back Straight

Outline

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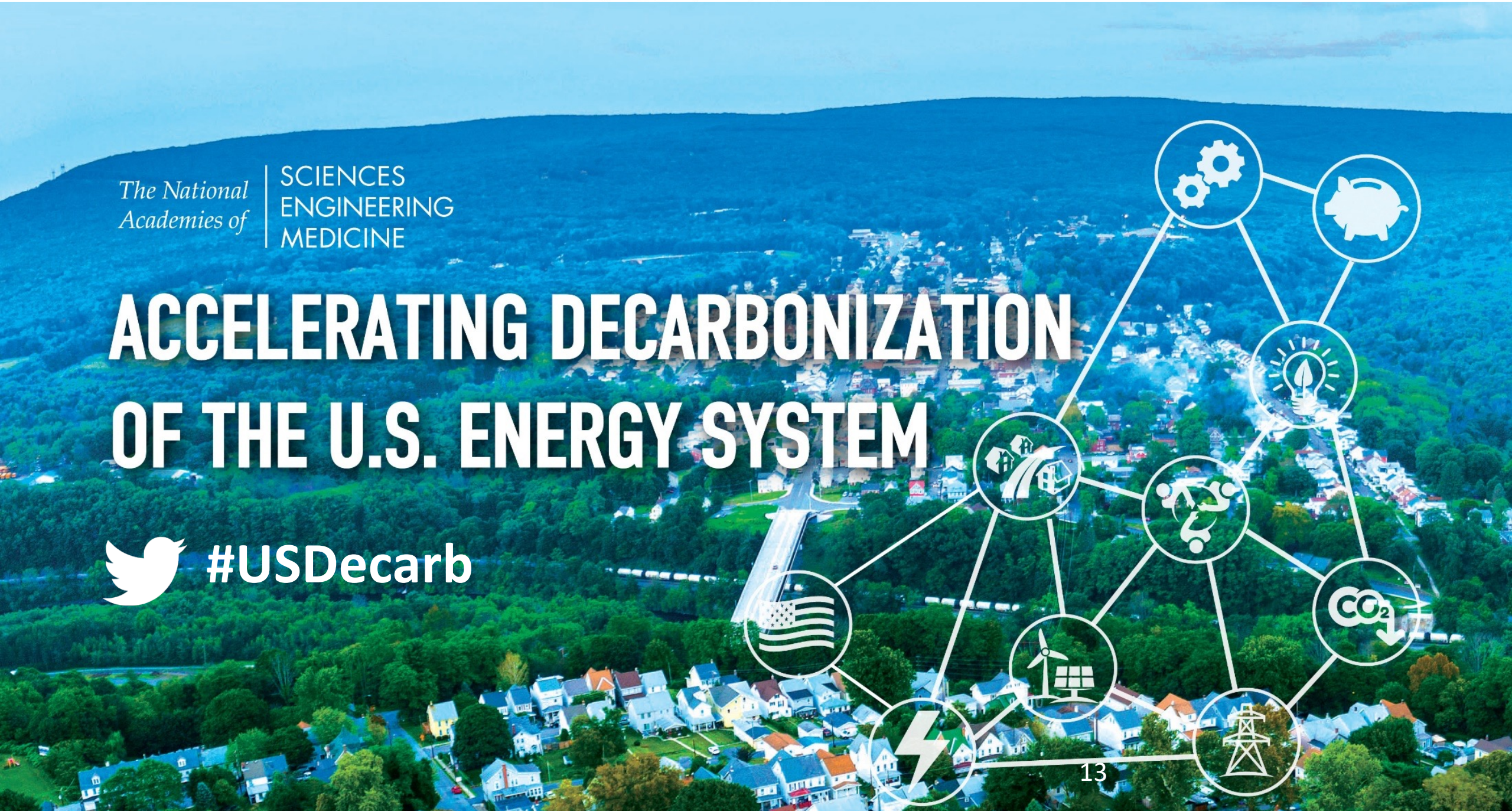
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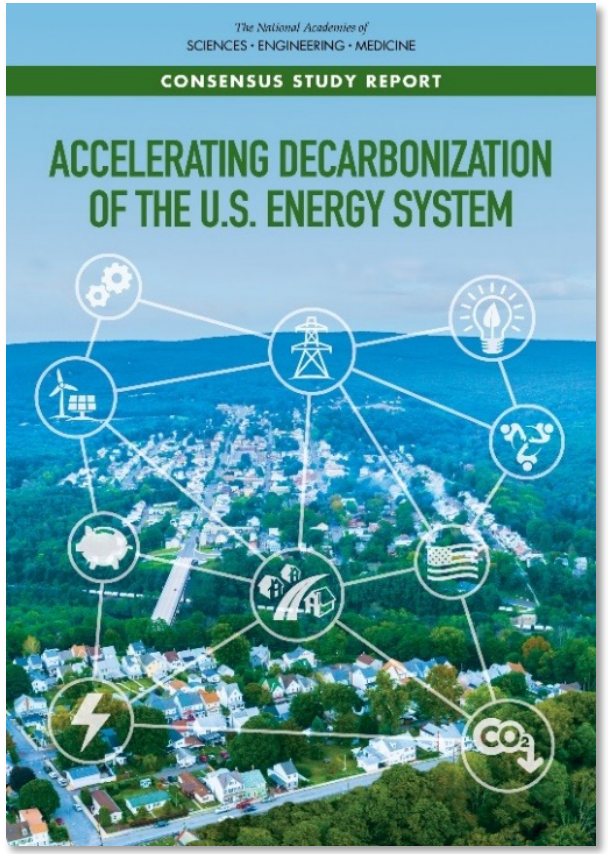
SCIENCES
ENGINEERING
MEDICINE
ACCELERATING DECARBONIZATION OF THE U.S. ENERGY SYSTEM
#USDecarb
CO_2

Report Scope



nap.edu/decarbonization

Federal actions over the next ten years to put the US on a **fair and equitable path to net-zero in 2050**.

Sectors considered include **CO_2, transportation, electricity, industry, buildings, and biofuels**.

Not asked to determine whether the nation should move to net zero, only how to get there. Other GHGs, sinks created by forestry practices, and cropping practices that enhance soil carbon are not discussed in detail.

This report is broadly compatible with recent announcements from the Biden Administration. It was developed by an expert panel without prior consultation with the Administration.

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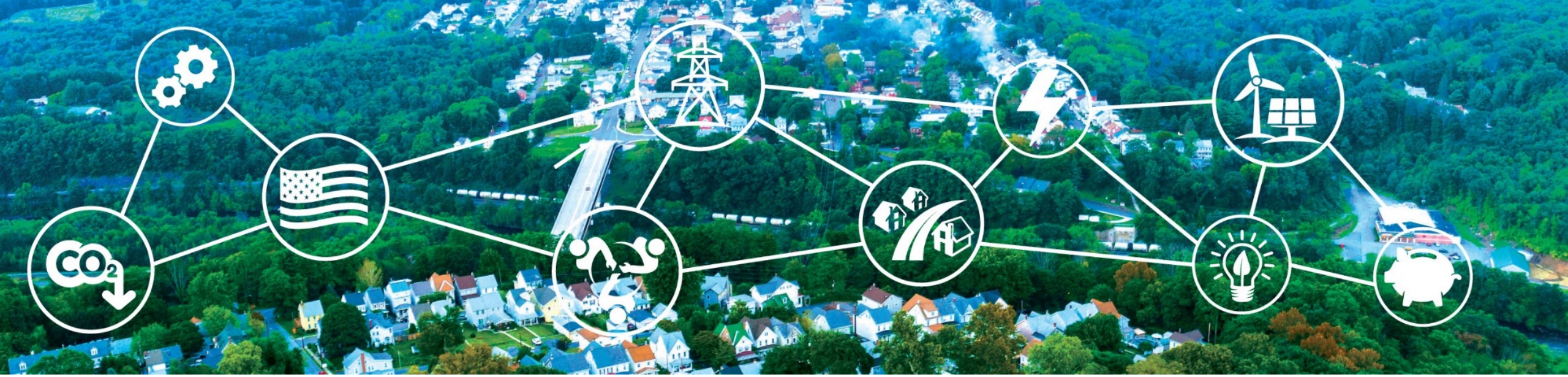

Lessons Learned from Review of Previous Studies

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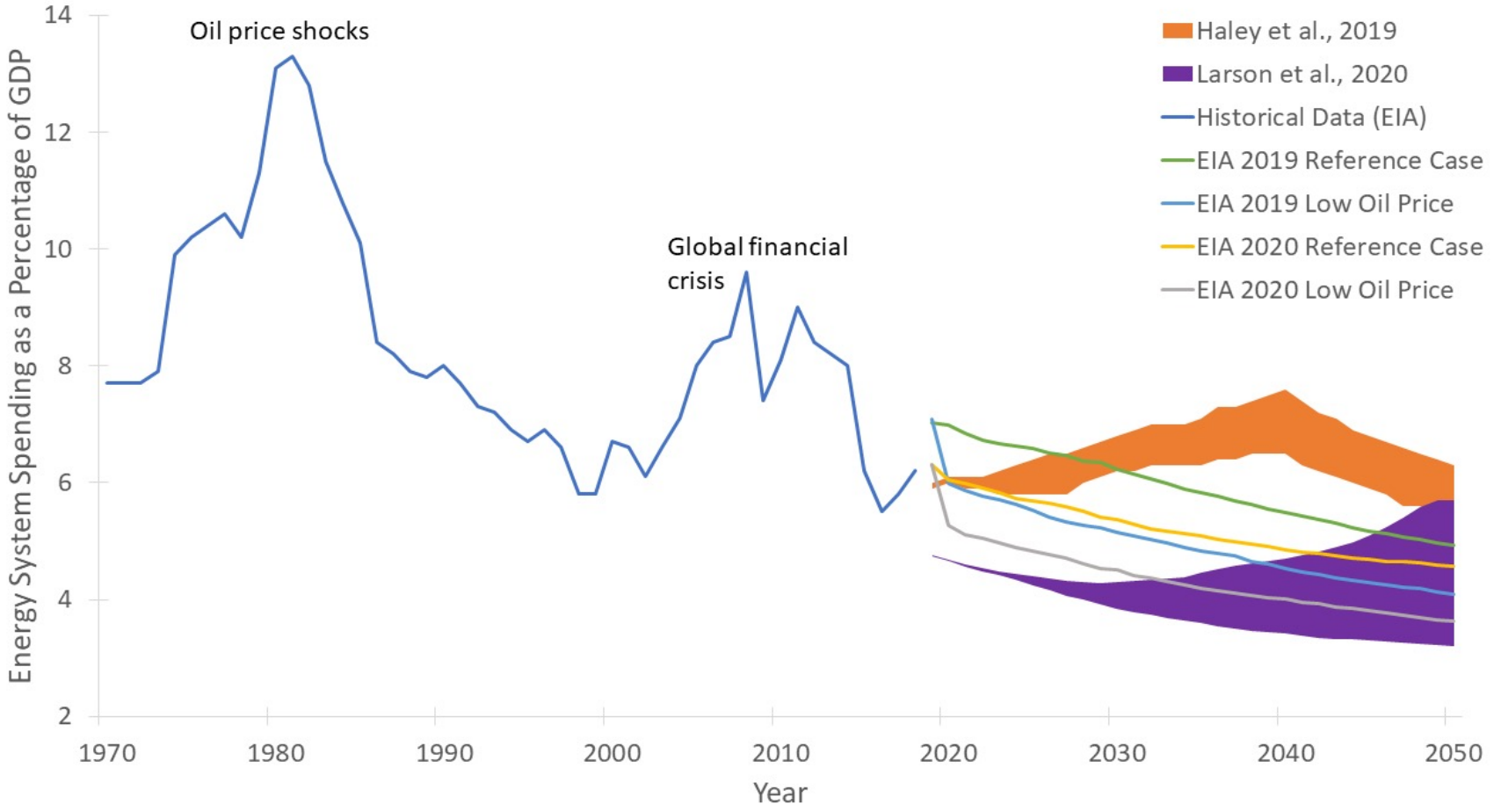
1. Deep decarbonization is feasible and economic.

Projected energy costs during the next 30 years would be less than we spent over the past 30.

$200 billion cumulatively in the 2020's.

Less than the health benefit alone.



Decarbonization Paths Compared to Historical Energy Spending

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Net-Zero America: Potential Pathways, Infrastructure, and Impacts

Princeton University: Eric Larson,[a] Chris Greig,[b] Jesse Jenkins,[c] Erin Mayfield,[d] Andrew Pascale,[e] Chuan Zhang,[e] Joshua Drossman,[f] Robert Williams,[g] Steve Pacala,[h] and Robert Socolow[i]

External collaborators: Ejeong Baik,[j] Rich Birdsey,[k] Rick Duke,[l] Ryan Jones,[m] Ben Haley,[m] Emily Leslie,[n] Keith Paustian,[o] and Amy Swan[p]

(a) Co-Principal Investigator, Senior Research Engineer, Andlinger Center for Energy and the Environment, Princeton University.
(b) Co-Principal Investigator, Senior Research Scientist, Andlinger Center for Energy and the Environment, Princeton University.
(c) Co-Principal Investigator, Assistant Professor, Mechanical and Aerospace Engineering Department and the Andlinger Center for Energy and the Environment, Princeton University.
(d) Post-doctoral Research Associate, High Meadows Environmental Institute, Princeton University.
(e) Post-doctoral Research Associate, Andlinger Center for Energy and the Environment, Princeton University.
(f) Undergraduate student, Class of '22, Operations Research and Financial Engineering Department, Princeton University
(g) Senior Research Scientist Emeritus, Andlinger Center for Energy and the Environment, Princeton University.
(h) Professor, Ecology and Evolutionary Biology Department and Director of the High Meadows Environmental Institute's Carbon Mitigation Initiative, Princeton University.
(i) Professor Emeritus, Mechanical and Aerospace Engineering Department and High Meadows Environmental Institute, Princeton University.
(j) PhD candidate, Department of Energy Resources Engineering, Stanford University.
(k) U.S. Forest Service (retired)
(l) Principal, Gigaton Strategies, LLC.
(m) Principal, Evolved Energy Research.
(n) Principal, Energy Reflections, LLC.
(o) Professor, Department of Soil and Crop Sciences & Senior Research Scientist, Natural Resource Ecology Laboratory, Colorado State University.
(p) Project Scientist, Natural Resource Ecology Laboratory, Colorado State University.

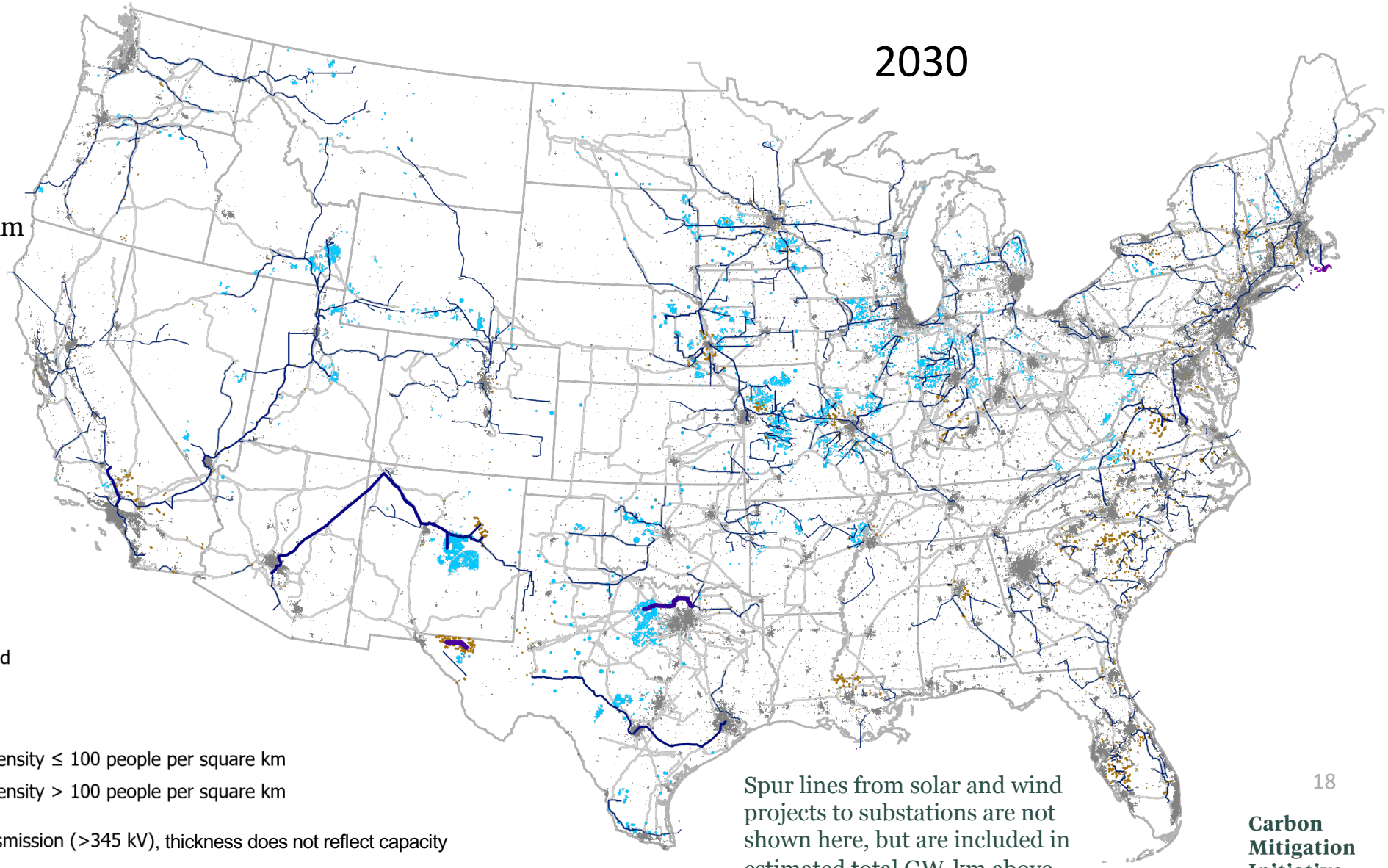
Suggested citation: E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report, Princeton University, Princeton, NJ, December 15, 2020.

Wind and solar projects in 2030, plus new (post-2020) transmission, E+ scenario with Base siting availability

2030 Installed capacity

- Solar: 0.37 TW
- Onshore wind: 0.41 TW
- Offshore wind: 0.005 TW
- Transmission: ~430,000 GW-km (1.3x 2020 level)

Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative, not definitive.



Spur lines from solar and wind projects to substations are not shown here, but are included in estimated total GW-km above.

Carbon Mitigation Initiative

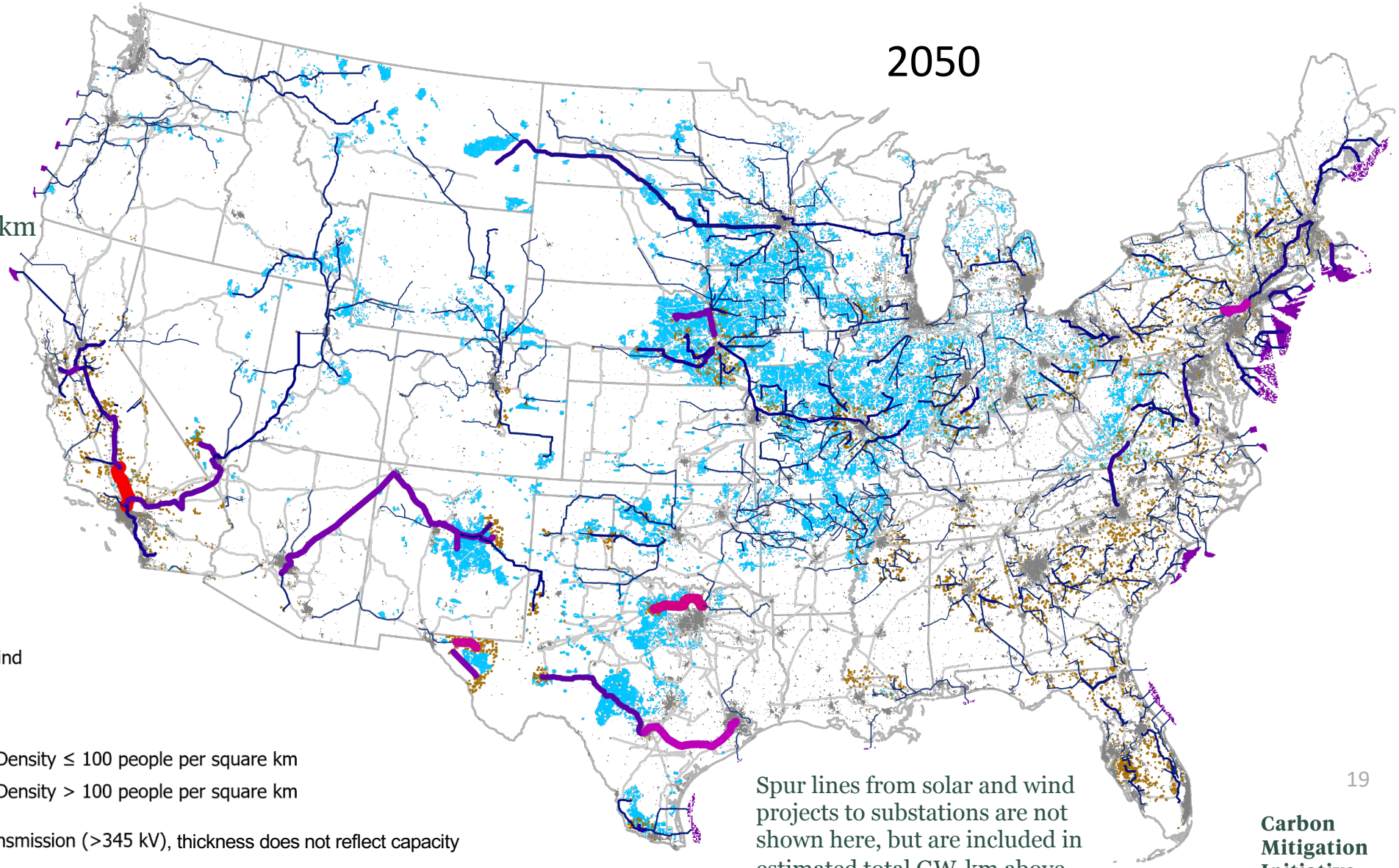
18

Wind and solar projects in 2050, plus new (post-2020) transmission, E+ scenario with Base siting availability

2050 Installed Capacity

- Solar: 1.6 TW
- Onshore wind: 1.3 TW
- Offshore wind: 0.2 TW
- Transmission: ~690,000 GW-km (2.2x 2020 level)

Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative, not definitive.



Spur lines from solar and wind projects to substations are not shown here, but are included in estimated total GW-km above.

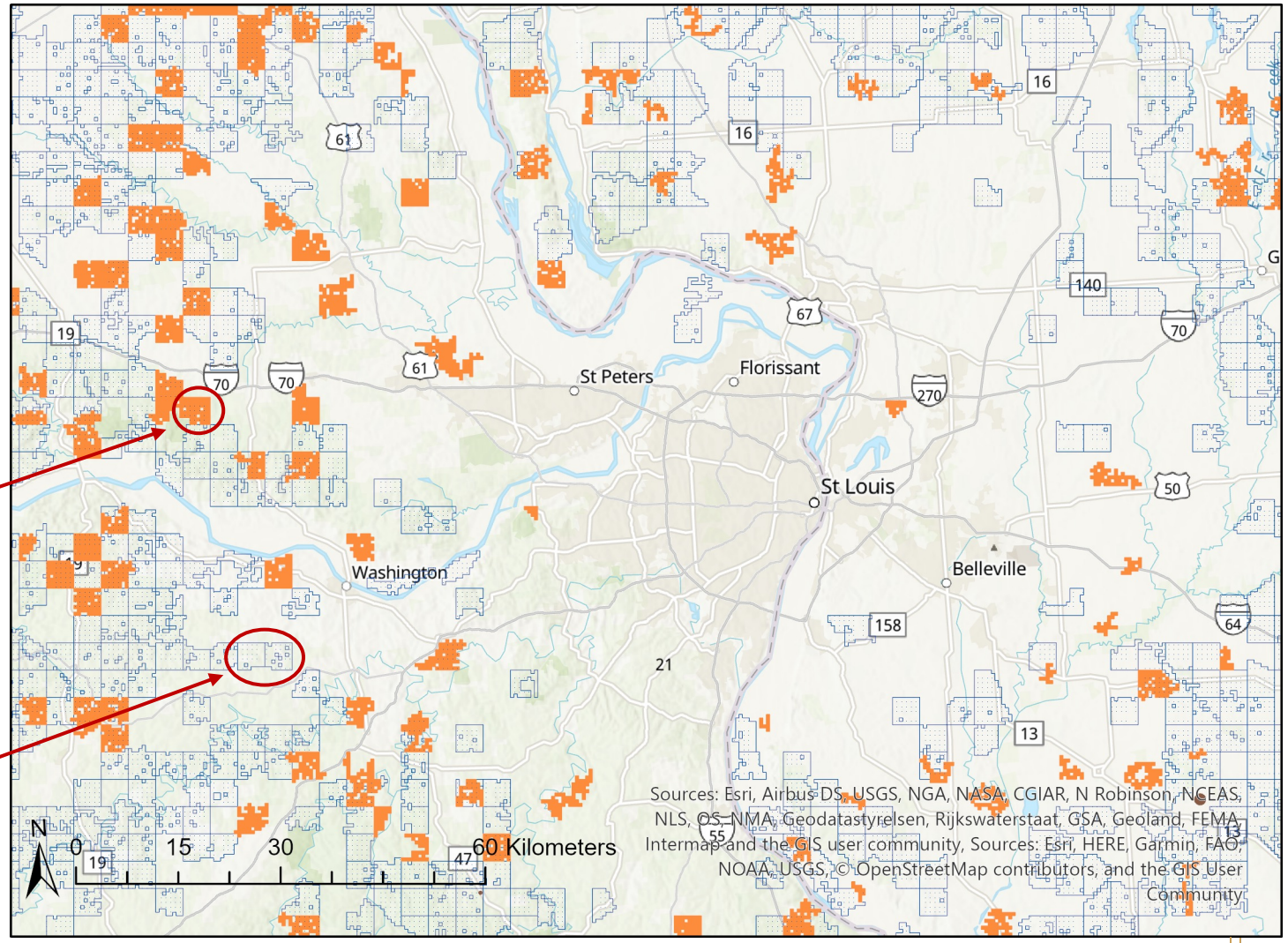
Carbon Mitigation Initiative

Example area detail: St. Louis, MO
2050 E+ wind and solar farms (Base site availability)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

500 MW solar facility
(generic future facility)

80 MW wind facility
(generic future facility)



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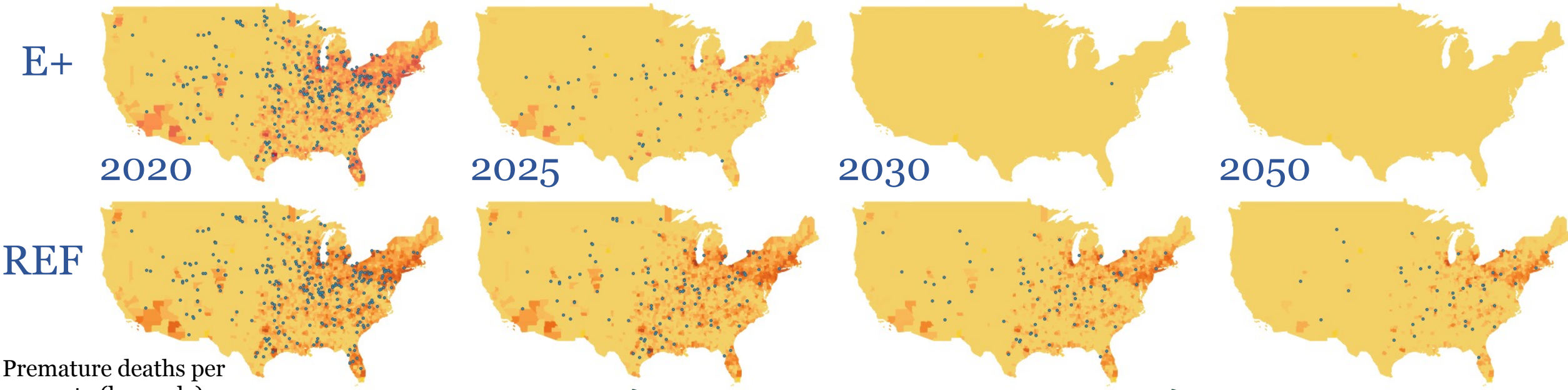
High Meadows Environmental Institute
Carbon Mitigation Initiative

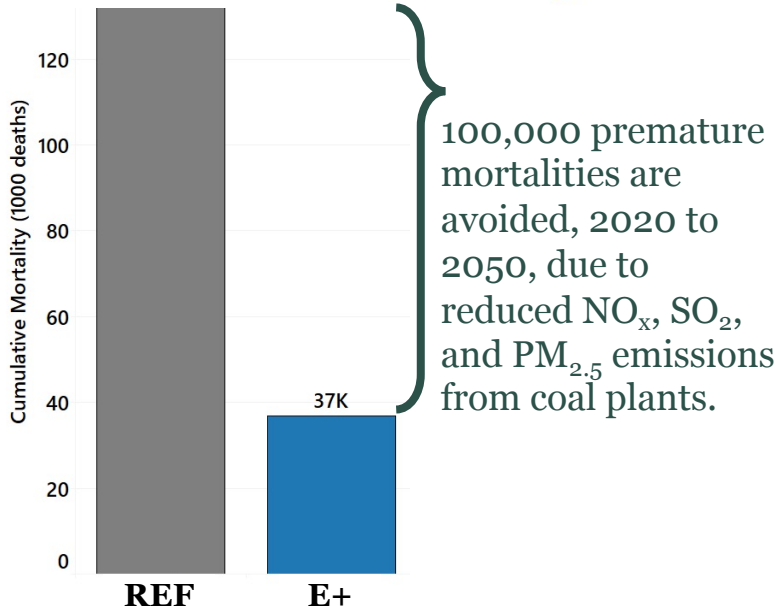
Air quality improves dramatically. About 100,000 air pollution-related deaths (~$930B in damages) are avoided.



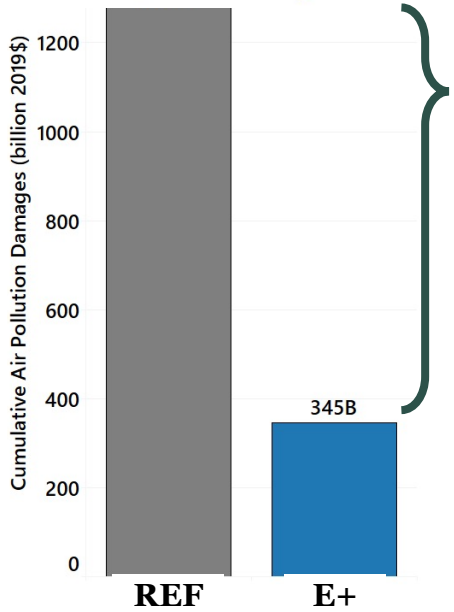
Premature deaths per county (log scale)

0 190

Coal power plant



100,000 premature mortalities are avoided, 2020 to 2050, due to reduced NO_x, SO_2, and $PM_{2.5}$ emissions from coal plants.



$930B in air pollution benefits, 2020 to 2050

Note: Additional analysis forthcoming on air quality impacts of vehicle electrification and natural gas transitions.

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NZAP 2020

Lesson learned 2:
Deep decarbonization could revitalize U.S. manufacturing and increase employment

Technology deployment to achieve a net-zero emissions energy system could revitalize multiple U.S. economic sectors and provide up to **1-2 million net new jobs over the next decade**.

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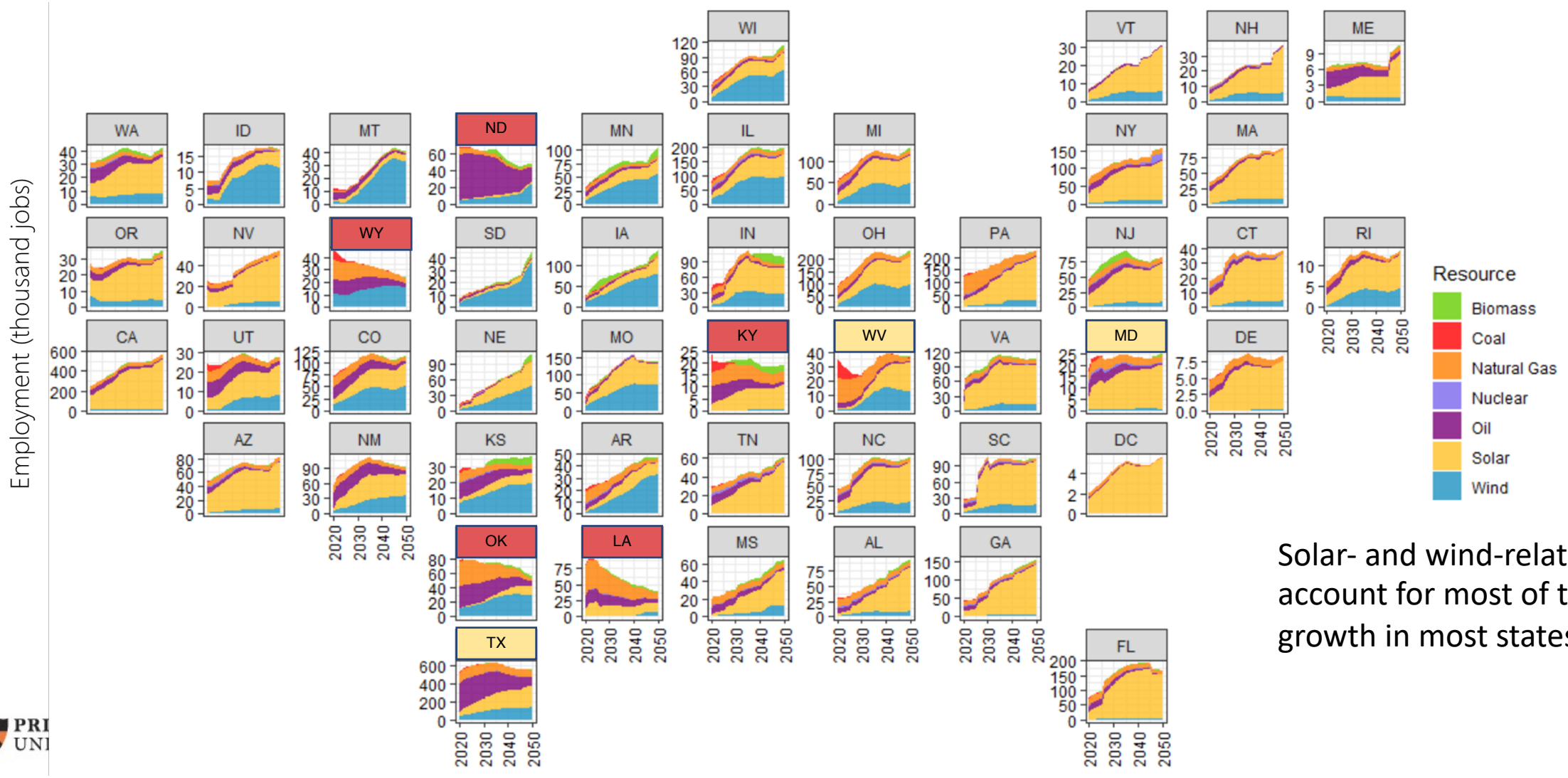
Annual energy-related employment grows substantially in most states, but net declines in five fossil extraction states

Assumes manufacturing follows historic patterns; changes in spatial deployment could offer opportunities to ameliorate losses in fossil extraction states.



Solar- and wind-related jobs account for most of the growth in most states.

Proactive Job Creation

Many more communities gain than lose.

Zero-carbon industrial hubs in communities currently rich in fossil jobs?

Lessons learned 3:
Decarbonization policies must ensure a fair and equitable transition with public participation in decision making

≠

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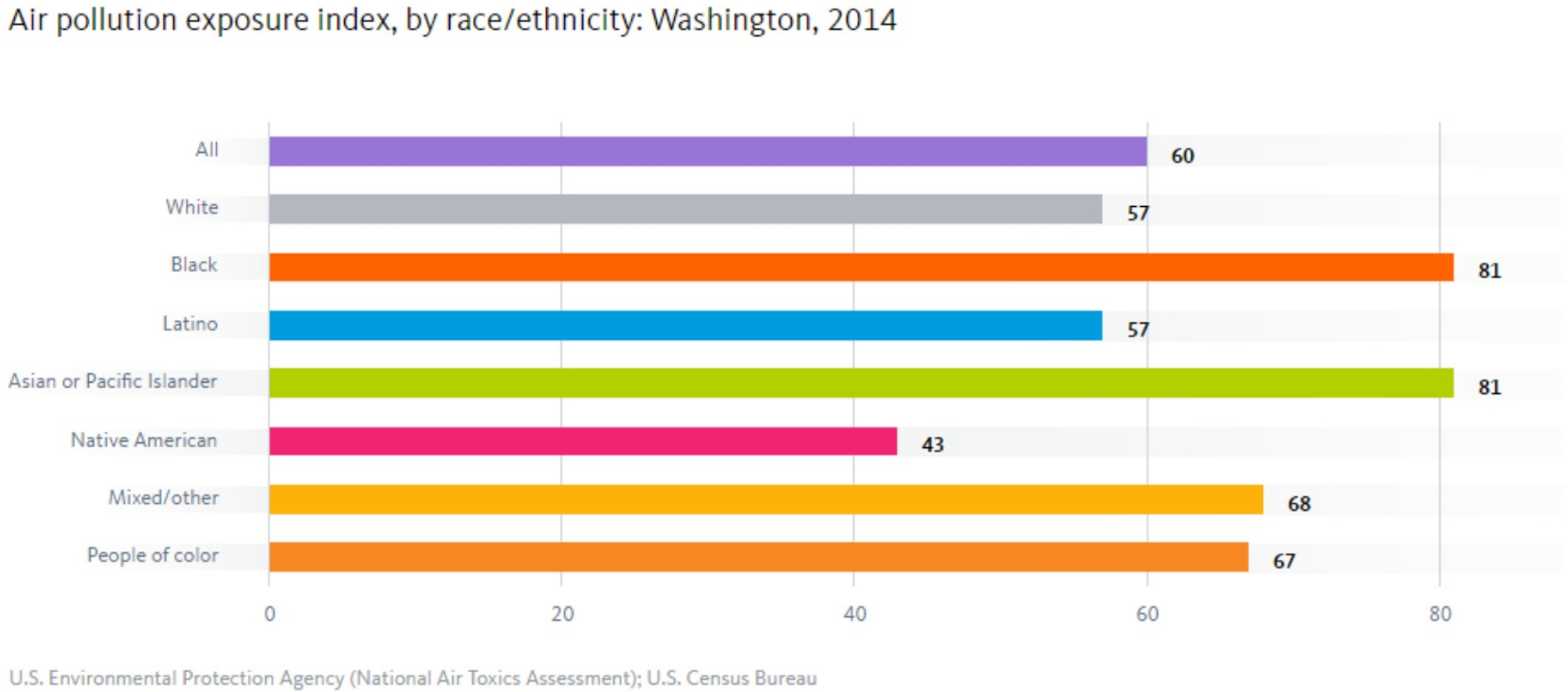

Racial Inequities for Air Pollution Exposure in Washington, 2014. Credit: National Equity Atlas

Lessons learned 4:
Deep decarbonization requires immediate action

Long-lived assets must be replaced by net-zero alternatives when they reach the end of their life cycle.

Actions required during the first ten years are robust to uncertainty about the final make-up of the energy system.

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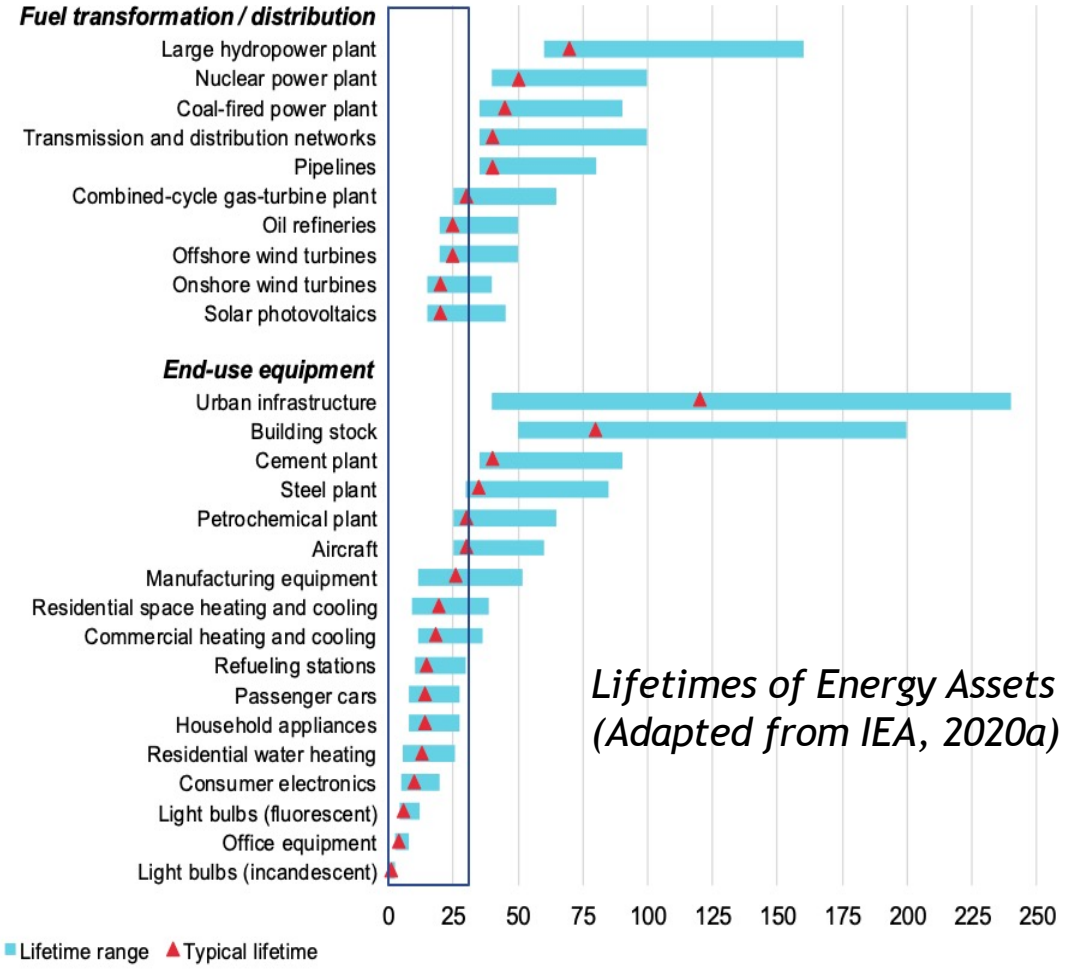
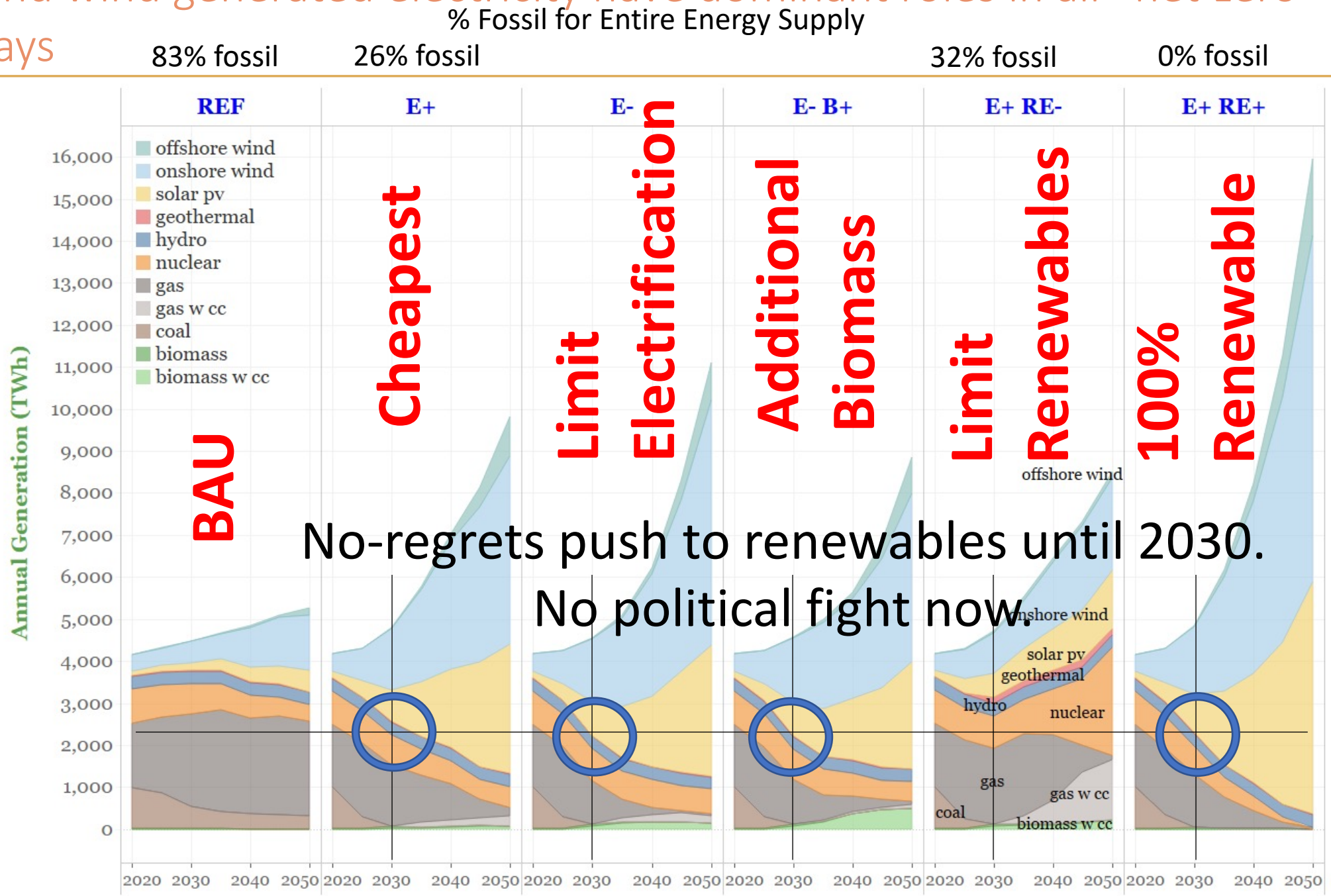


Lifetimes of Energy Assets (Adapted from IEA, 2020a)

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



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Lessoned learned 5:
Expansion of RDD is essential

Net-zero alternatives for some sectors are still pre-commercial, including aviation, shipping, steel, cement, and chemicals manufacturing.

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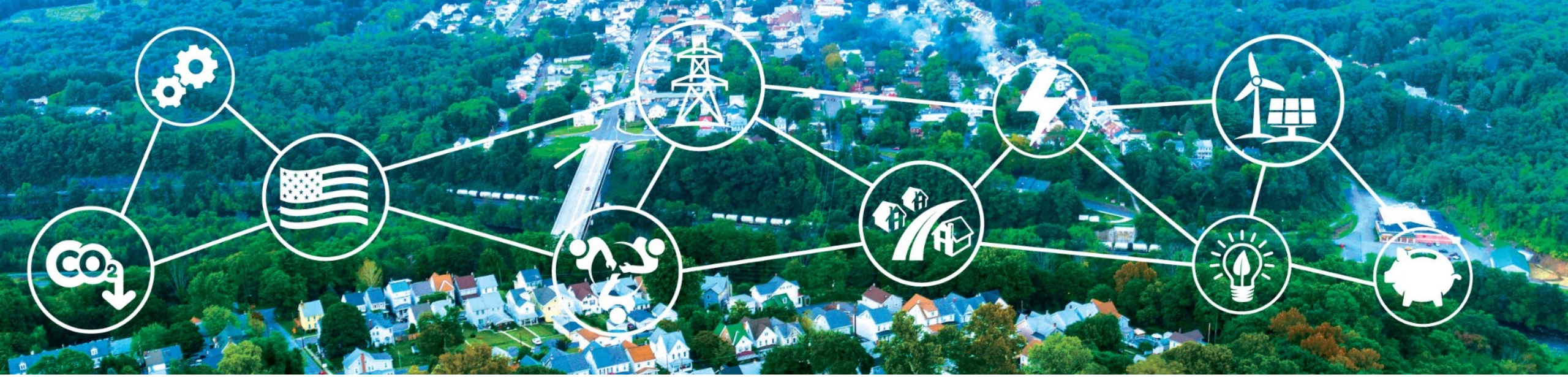

Key Findings and Recommendations from the Report

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Technology Goals

Electrify energy services in transportation, buildings, and industry

Examples include moving half of vehicle sales (all classes combined) to EV's by 2030, and deploying heat pumps in one quarter of residences.

Improve energy efficiency and productivity

Examples include accelerating the rate of increase of industrial energy productivity (dollars of economic output per energy consumed) from the historic 1% per year to 3% per year.

Produce carbon-free electricity

Roughly double the share of electricity generated by carbon-free sources from 37% to 75%.

Expand the innovation toolkit

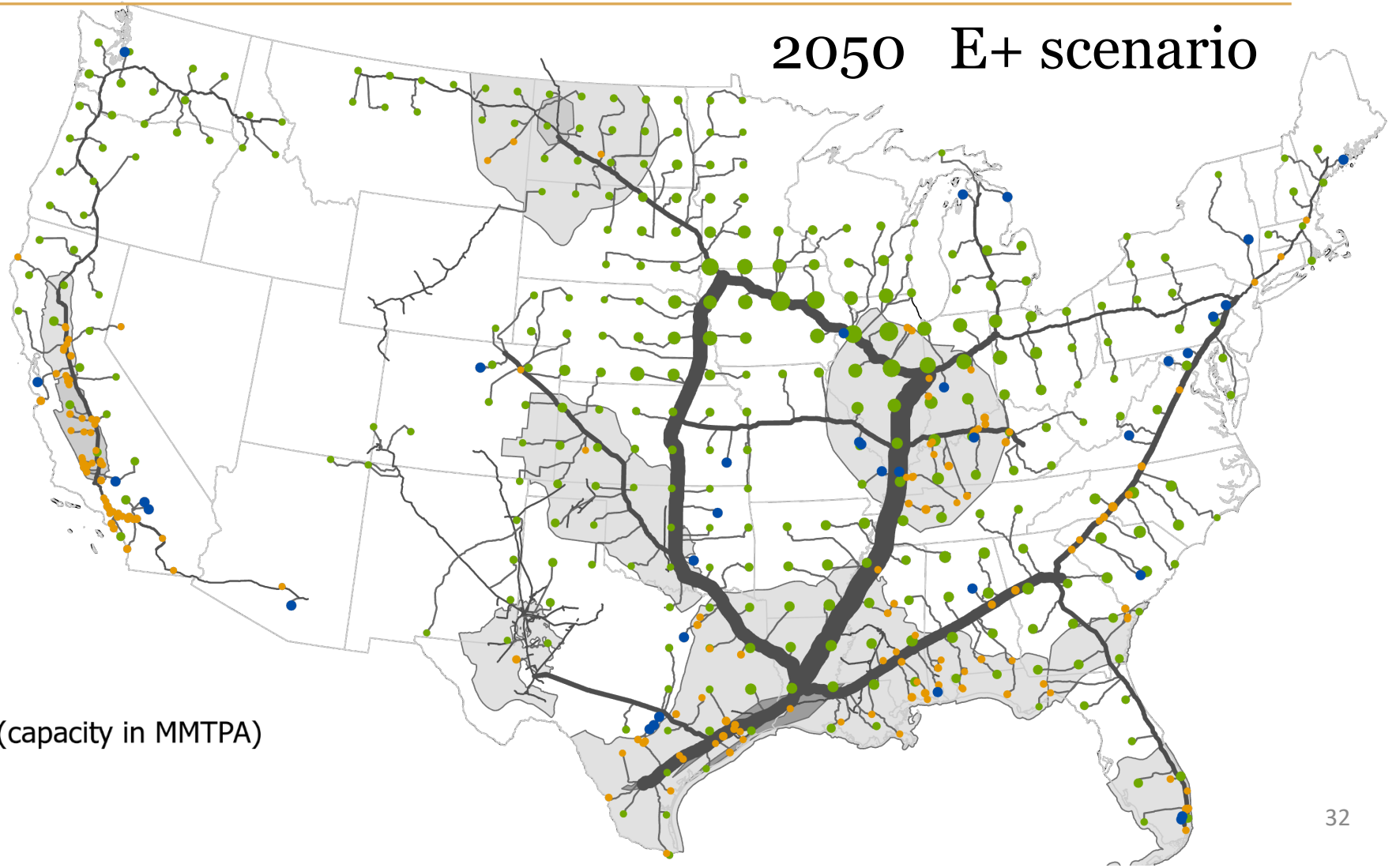
Triple federal support for net-zero RD&D.

Plan, permit, and build critical infrastructure

Examples include new transmission lines, an EV charging network, and a CO_2 pipeline network.

2050 totals: 18,000 km trunk lines + 89,000 km spur lines (equivalent to ~17% of US natural gas transmission pipeline total)

- ~1,000 million tCO_2/y captured
- ~930 million tCO_2/y stored subsurface by 2050
- Average transport and storage cost of $23/t CO_2
- 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.



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Wind and solar projects in 2050, plus new (post-2020) transmission, E+ scenario with Base siting availability

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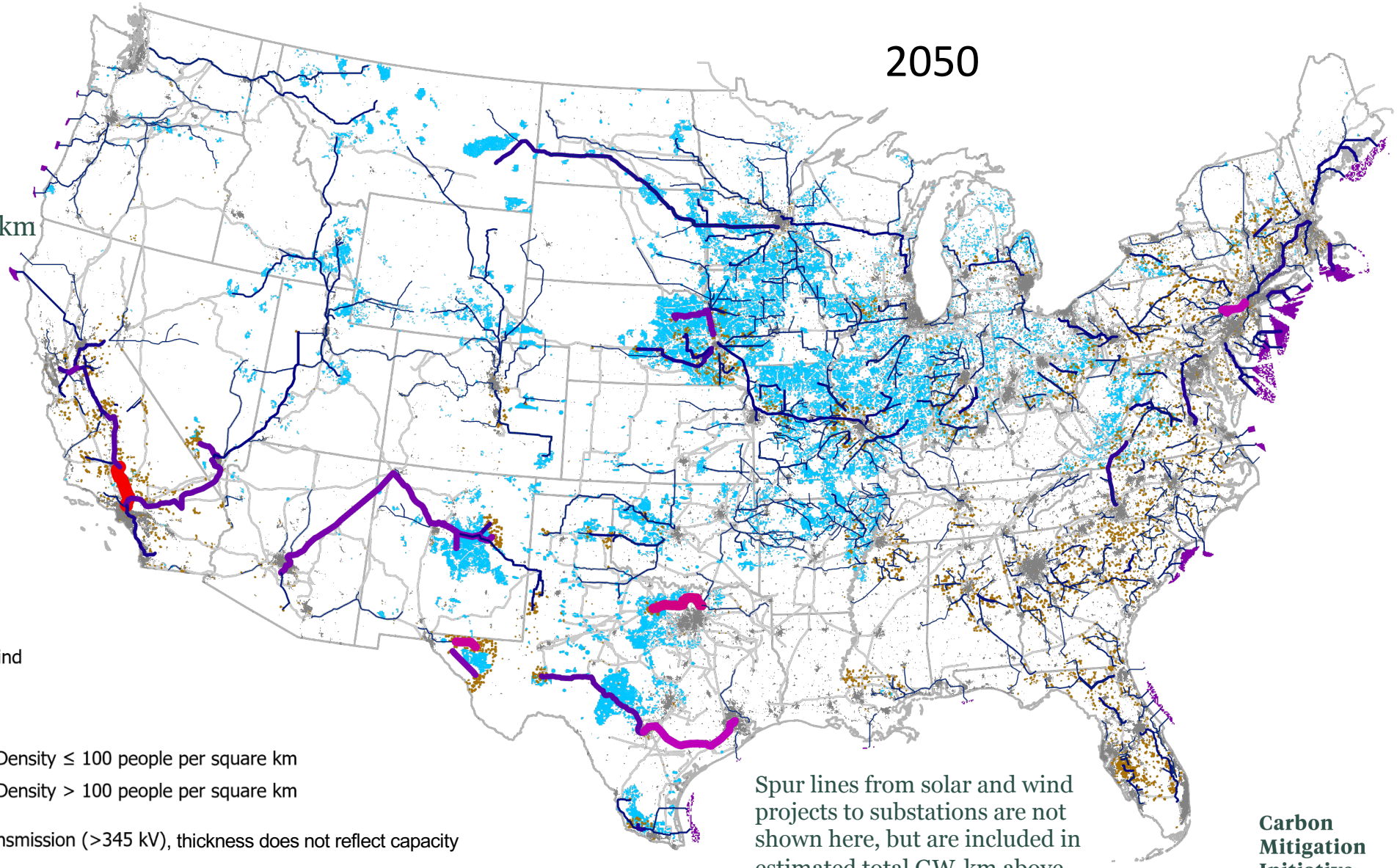

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Socio-Economic Goals

Strengthen the U.S. economy

Use the energy transition to accelerate US innovation, reestablish US manufacturing, increase the nation's global economic competitiveness, and increase the availability of high-quality jobs.

Support communities, businesses, and workers

Proactively support those directly and adversely affected by the transition

Promote equity and inclusion

Ensure equitable distribution of benefits, risks and costs of the transition to net-zero.

Integrate historically marginalized groups into decision-making by ensuring adherence to best practice public participation laws.

Ensure entities receiving public funds report on leadership diversity to ensure non-discrimination.

Maximize cost-effectiveness

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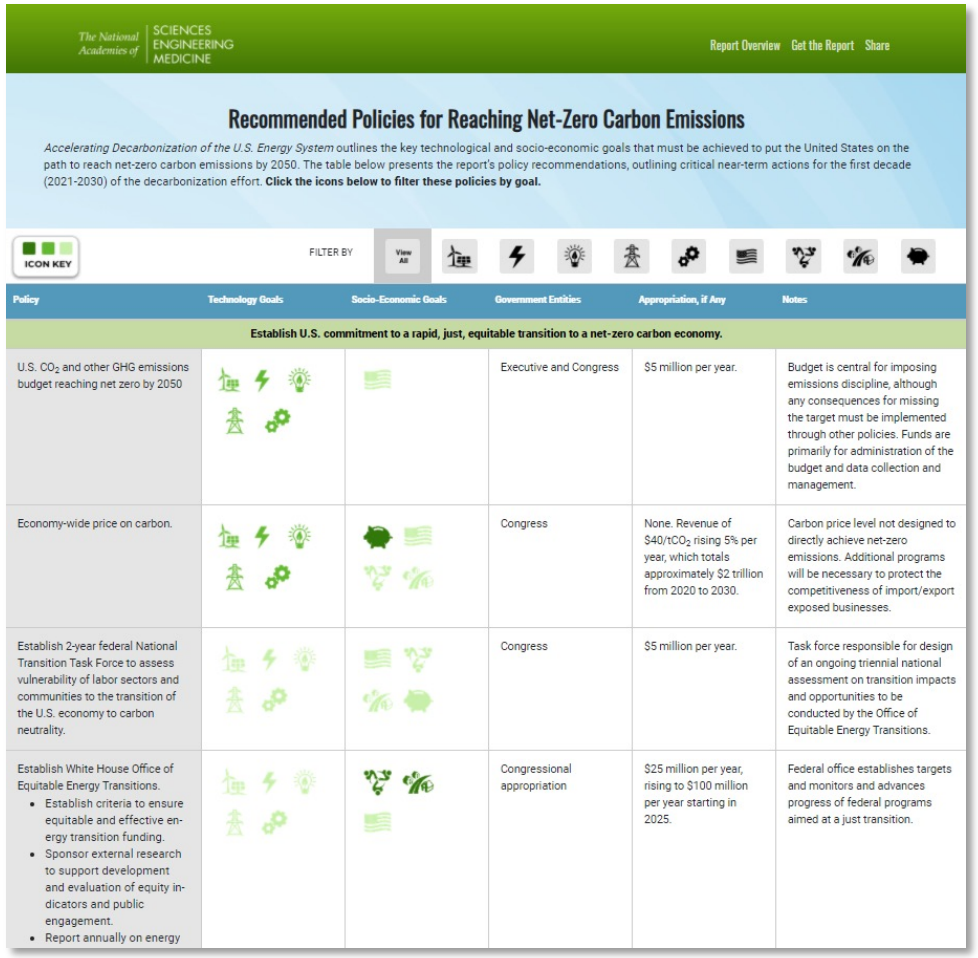

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Report Overview Get the Report Share

Recommended Policies for Reaching Net-Zero Carbon Emissions

Accelerating Decarbonization of the U.S. Energy System outlines the key technological and socio-economic goals that must be achieved to put the United States on the path to reach net-zero carbon emissions by 2050. The table below presents the report's policy recommendations, outlining critical near-term actions for the first decade (2021-2030) of the decarbonization effort. **Click the icons below to filter these policies by goal.**

ICON KEY FILTER BY View All

Policy	Technology Goals	Socio-Economic Goals	Government Entities	Appropriation, if Any	Notes
Establish U.S. commitment to a rapid, just, equitable transition to a net-zero carbon economy.					
U.S. CO_2 and other GHG emissions budget reaching net zero by 2050			Executive and Congress	$5 million per year.	Budget is central for imposing emissions discipline, although any consequences for missing the target must be implemented through other policies. Funds are primarily for administration of the budget and data collection and management.
Economy-wide price on carbon.			Congress	None. Revenue of $40/t$CO_2$ rising 5% per year, which totals approximately $2 trillion from 2020 to 2030.	Carbon price level not designed to directly achieve net-zero emissions. Additional programs will be necessary to protect the competitiveness of import/export exposed businesses.
Establish 2-year federal National Transition Task Force to assess vulnerability of labor sectors and communities to the transition of the U.S. economy to carbon neutrality.			Congress	$5 million per year.	Task force responsible for design of an ongoing triennial national assessment on transition impacts and opportunities to be conducted by the Office of Equitable Energy Transitions.
Establish White House Office of Equitable Energy Transitions. • Establish criteria to ensure equitable and effective energy transition funding. • Sponsor external research to support development and evaluation of equity indicators and public engagement. • Report annually on energy			Congressional appropriation	$25 million per year, rising to $100 million per year starting in 2025.	Federal office establishes targets and monitors and advances progress of federal programs aimed at a just transition.

Policy Recommendations Table

Report contains 30 near-term policy recommendations across 4 main categories.

This presentation covers 12 of these recommendations.

View full policy table at nap.edu/decarbonization-policies

Key System-Wide Actions for the Next 10 Years

Essential and Highest Priority | Important | Supporting Role

Policy	Technology Goals	Socio-Economic Goals	Gov Entities	Appropriation, if Any	Notes
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U.S. CO_2 and other GHG emissions budget reaching net zero by 2050.			Executive and Congress	$5 million per year.	Budget is central for imposing emissions discipline, although any consequences for missing the target must be implemented through other policies. Funds are primarily for administration of the budget and data collection and management.
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Establish 2-year federal National Transition Task Force to assess vulnerability of labor sectors and communities to the transition of the U.S. economy to carbon neutrality.			Congress	$5 million per year.	Task force responsible for design of an ongoing triennial national assessment on transition impacts and opportunities to be conducted by the Office of Equitable Energy Transitions.

Program to promote a fair a and equitable transition:

Ten regional centers

Community block grants for analysis and planning

DOE “extension service”

Independent National Transition Corporation (the primary distributor of aid)

Extensive education and training program

White House Office of Equitable Energy Transitions

Policy	Technology Goals	Socio-Economic Goals	Gov Entities	Appropriation, if Any	Notes
Invest (research, technology, people, and infrastructure) in a U.S. net-zero carbon future.					
Establish a federal Green Bank to finance low- or zero-carbon technology, business creation, and infrastructure.			Congressional authorization and appropriation	Capitalized with $30 billion, plus $3 billion per year until 2030.	Additional requirements include public reporting of both energy equity analyses of investment and leadership diversity of firms receiving funds.
Establish educational and training programs to train the net-zero workforce, with reporting on diversity of participants and job placement success.[g]			Congressional appropriations to Department of Education, DOE, and NSF	$5 billion per year for GI Bill-like program. $100 million per year for new undergraduate programs. $50 million per year for use-inspired and $375 million per year for other doctoral and postdoctoral fellowships. Eliminate visa restrictions for net-zero students. $7 million over 2020–2025 for the Energy Jobs Strategy Council.	Fields covered include science, engineering, policy, and social sciences, for students researching and innovating in low-carbon technologies, sustainable design, and the energy transition.
Increase clean energy and net-zero transition RD&D that integrates equity indicators.[i]			Congressional appropriation for and directions to DOE and NSF	DOE clean energy RD&D triples from $6.8 billion per year to $20 billion per year over 10 years. DOE funds studies of policy evaluation at $25 million per year and regional innovation hubs at $10 million per year; DOE- and NSF-funded studies of social dimensions of the transition should be supported by an appropriation of $25 million per year.	Establish criteria for receiving funds on equity analysis, appropriate community input, and leadership diversity of companies applying for public investments. DOE to report on equity impacts and diversity of entities receiving public funds.

Key Sector- and Community-Specific Strategies

Policy	Technology Goals	Socio-Economic Goals	Gov Entities	Appropriation, if Any	Notes
Set rules/standards to accelerate the formation of markets for clean energy that work for all.					
Set energy standard for electricity generation, designed to reach 75% zero-emissions electricity by 2030 and decline in emissions intensity to net-zero emissions by 2050.			Congress	None.	
Enact five congressional actions to advance clean electricity markets, and to improve their regulation, design, and functioning.[b]			Congress	$8 million per year for Federal Energy Regulatory Commission (FERC) Office of Public Participation and Consumer Advocacy.	Two of these congressional actions involve FERC, and three involve the DOE.
Set national standards for light-, medium-, and heavy-duty zero-emissions vehicles, and extend and strengthen stringency of CAFE standards. Light-duty ZEV standard ramps to 50% of sales in 2030; medium- and heavy-duty to 30% of sales in 2030.			Congress	None.	
Set manufacturing standards for zero-emissions appliances including hot water, cooking, and space heating. Department of Energy (DOE) continues to establish appliance minimum efficiency standards. Standard ramps down to achieve close to 100% all-electric in 2050.			Congress	None.	

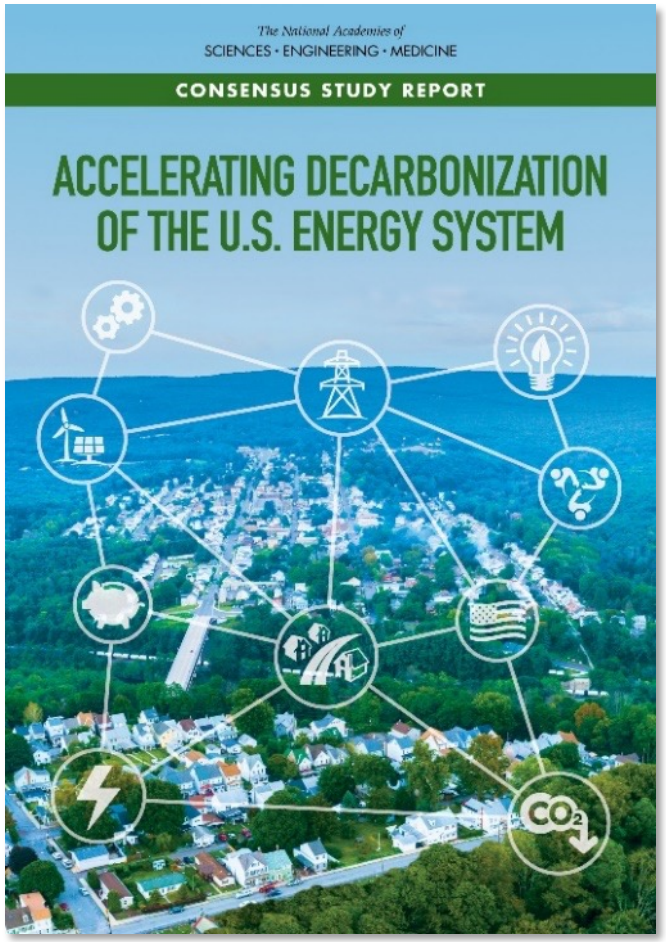
Plans for Second Report

Decisions on topics and structure of second report guided by task statement and informed by committee's discussions.

Topics might include:

- agriculture and forestry carbon sinks
- greater sector-specific detail
- broader range of policy actors (state, local, private sector, non-governmental organizations)
- national security implications
- Granular jobs plan and health impacts analysis

Thank you!



Download the report and report resources at **nap.edu/decarbonization**

Full table of policies at:

- https://www.nap.edu/resource/25932/interactive/table/index.html#top

Interactive summary at:

- https://www.nap.edu/resource/25932/interactive/

Most promising options … in 2050

Home Stretch

Photo by Joe Lewnard