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NET-ZERO AMERICA

POTENTIAL PATHWAYS, INFRASTRUCTURE, AND IMPACTS

FINAL REPORT SUMMARY

October 29, 2021

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Final Report Summary

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

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Foreword (excerpted from foreword in full report)

By John P. Holdren
Professor in the Kennedy School of Government, Department of Earth and Planetary Sciences, and John A. Paulson School of Engineering and Applied Science at Harvard University; formerly (2009-2017) Science Advisor to President Obama and Director of the White House Office of Science and Technology Policy.
December 11, 2020

Long after the terrible challenge of the COVID-19 pandemic has finally been surmounted and (one may hope) greatly improved preparations for inevitable future pandemics have been put in place, the climate-change challenge will be marching on as the 21st century's most dangerous and intractable threat to global society.

It is the most dangerous of threats because the growing human disruption of climate that is already far along puts at risk practically every aspect of our material well-being—our safety, our security, our health, our food supply, and our economic prosperity (or, for the poor among us, the prospects for becoming prosperous).

It is the most intractable of threats because it is being driven, above all, by emissions of carbon dioxide originating from combustion of the coal, oil, and natural gas that still supply eighty percent of civilization's primary energy and over sixty percent of its electricity; and because, for quite fundamental reasons, the shares of electricity and nonelectric energy provided by these fossil fuels cannot be very rapidly reduced, nor can their emissions be easily or inexpensively captured and sequestered away from the atmosphere….

It has been clear for two decades or more that, for the industrialized countries to do something approaching a responsible share of a global effort to limit the average surface temperature increase to 2.0°C, they would need to reduce their emissions of heat-trapping gases by 80 to 100 percent by around 2050. Each year that has passed without countries taking steps of the magnitude needed to move expeditiously onto a trajectory capable of achieving such a goal has increased the challenge that still lies ahead.

At the same time, observations of actual harm from climate change and a continuing flow of bad news from climate science about likely future impacts has increased the sense of urgency in the knowledgeable community, while continuing advances in energy technology have engendered a degree of optimism about what emission reductions might be possible and affordable. The result has been an increasing flow of (mostly) increasingly sophisticated modeling studies of how emissions of CO_2 and other heat-trapping gases might be reduced to near zero by 2050. In the United States, such studies have been conducted by the federal government (not always published), by the National Academies, by national laboratories, by companies, by universities, by NGOs, and by consortia.

I believe that this Princeton Study, *Net Zero America: Potential Pathways, Infrastructure, and Impacts*, sets an entirely new standard in this genre. The superb Princeton team—led by Eric Larson, Jesse Jenkins, and Chris Greig—has done an absolutely remarkable amount of new work, developing new models and new data to provide an unprecedented degree of clarity and granularity about possible pathways to mid-century "net zero" for this country. They have analyzed technological possibilities, as currently understood, in great detail; they have examined the "co-benefit" of reduced disease impacts from conventional air pollutants when fossil-fuel use is reduced; they have examined the employment consequences of alternative trajectories; and, perhaps most importantly, they have called attention to the most important areas where policy measures are needed to enhance and preserve the nation's options going forward, as events evolve and understandings grow.

None of the Princeton scenarios will prove to be "right", but together they provide a compelling picture of possible paths forward. Everybody seriously interested in the crucial question of this country's energy-climate future—not least the new Biden-Harris administration—needs to understand the findings of this extraordinary study.

Preface and Acknowledgments

This *Net Zero America* study aims to inform and ground political, business, and societal conversations regarding what it would take for the U.S. to achieve an economy-wide target of net-zero emissions of greenhouse gases by 2050. Achieving this goal, i.e. building an economy that emits no more greenhouse gases into the atmosphere than are permanently removed and stored each year, is essential to halt the buildup of climate-warming gases in the atmosphere and avert costly damages from climate change. A growing number of pledges are being made by major corporations, municipalities, states, and national governments to reach net-zero emissions by 2050 or sooner. This study provides granular guidance on what getting to net-zero really requires for the U.S. and on the actions needed to translate these pledges into tangible progress.

The work outlines five distinct technological pathways, each of which achieves the 2050 goal and involves spending on energy in line with historical spending as a share of economic activity, or between 4-6% of gross domestic product. The authors are neutral as to which pathway is “best”, and the final path the nation takes will no doubt differ from all of these. A goal of this study is to provide confidence that the U.S. now has multiple genuine paths to net-zero by 2050 and to provide a blueprint for priority actions for the next decade. These priorities include accelerating deployment at scale of technologies and solutions that are mature and affordable today and will return value regardless of what path the nation takes to net zero in the longer term, as well as a set of actions to build key enabling infrastructure and improve a set of less mature technologies that will help complete the transition to a net-zero America.

With multiple plausible and affordable pathways available, the societal conversation can now turn from “if” to “how” and focus on the choices the nation and its myriad stakeholders wish to make to shape the transition to net-zero. These conversations will need to be sensitive to the different values and priorities of diverse communities. That requires insight on how the nation will be reshaped by different paths to net-zero, and the benefits, costs, and challenges for specific locations, industries, professions, and communities. Supporting these decisions requires analysis at a visceral, human scale.

The original and distinguishing feature of this *Net Zero America* study is thus the comprehensive cataloging across all major sectors at high geospatial and temporal resolution of the energy infrastructure deployments and related capital expenditures required for a net-zero transition. This granularity allows assessing the implications for land use, employment, air pollution, capital mobilization, and incumbent fossil fuel industries at state and local levels. The high resolution analysis is aimed at helping inform federal and state policy choices and private-sector decision making in support of a transition to net-zero by 2050.

During the 2+ year research effort, the authors had many informative discussions with individuals in environmental research and advocacy organizations, oil and gas companies, renewable energy companies, national labs, industry trade organizations, universities, and elsewhere. The authors thank those individuals for their time and interest. The authors also thank the hundreds of stakeholders who have attended briefings where preliminary study results were presented. The feedback received as a result of those briefings have helped shape the contents of this report. Of course, any errors or omissions in this study are the responsibility of the authors alone, as are any views or recommendations expressed herein.

For funding support, the authors thank the Andlinger Center for Energy and the Environment, BP and the Carbon Mitigation Initiative within Princeton’s High Meadows Environmental Institute, ExxonMobil, and the University of Queensland.

Synopsis

This study provides high-resolution analysis of what getting to net-zero emissions for the U.S. by 2050 will look like "on the ground" and thereby clarifies specific actions needed in the pursuit of that goal.

Using state-of-the-art modeling tools, five different technologically and economically plausible energy-system pathways for the U.S. to reach net-zero emissions by 2050 are constructed. The model results are then further refined to provide highly-resolved mapping, sector-by-sector, of the timing and spatial distribution of changes in energy infrastructure, capital investment, employment, air pollution, land use, and other key outcomes at a state and local level.

We find that each net-zero pathway results in a net increase in energy-sector employment and delivers significant reductions in air pollution, leading to public health benefits that begin immediately in the first decade of the transition. We also conclude that a successful net-zero transition could be accomplished with annual spending on energy that is comparable or lower as a percentage of GDP to what the nation spends annually on energy today. However, foresight and proactive policy and action are needed to achieve the lowest-cost outcomes.

Building a net-zero America will require immediate, large-scale mobilization of capital, policy and societal commitment, including at least $2.5 trillion in additional capital investment (relative to business as usual) into energy supply, industry, buildings, and vehicles over the next decade. Consumers will pay back this upfront investment over decades, making the transition affordable (total annualized U.S. energy expenditures would increase by less than 3% during 2021-2030), but major investment decisions must start now, with levels of investment ramping up as the transition proceeds.

Each transition pathway features historically unprecedented rates of deployment of multiple technologies. Impacts on landscapes, incumbent industries and communities are significant and planning will need to be sensitive to regional changes in employment and local impacts on communities.

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Project motivation, objectives, and approach

- A growing number of governments and companies are pledging net-zero emissions by 2050. For the US as a whole to achieve this requires eliminating or offsetting today's emissions of ~6 billion tCO_{2e}/year.
- There is a dearth of analysis for understanding requirements, costs, and impacts of this transition.
- The goal of this study is to help fill this gap by providing insights at visceral, human scales of how the nation will look as it transitions to net-zero emissions and the localized benefits, costs, and impacts for different industries, professions, and communities. The analysis aims to inform debates on public and corporate policies needed to support a transition to net-zero emissions economy wide, but specific policy recommendations are not offered.
- Energy service demands projected to 2050 by the EIA for 14 regions across the continental US provide the starting point for modeling. Five different pathways, each of which achieves net-zero emissions by 2050, are constructed for meeting these demands by applying varied exogenous constraints in addition to the net-zero emissions constraint.
    - End-use technologies to meet service demands are exogenously specified in 5-year time steps to determine final energy demands that must be delivered by the energy supply system.
    - Pathways to net-zero emissions by 2050 are constructed by finding the energy supply mix that meets the final-energy demands and minimizes the 30-year NPV of total energy-system costs, subject to the exogenous constraints. The model has perfect foresight and seamless integration between sectors.
- These modeling results are "downscaled," using a variety of methods, to state or sub-state geographies to quantify local plant and infrastructure investments, construction activities, land-use, jobs, and health impacts, 2020 - 2050.
- Methodologies are detailed in 18 technical annexes to the final report.

Energy/industrial pathways analytical framework

Demand for energy services projected

- Geographically-resolved annual demands for energy services projected to 2050 as in U.S. Energy Information Admin. (EIA) *Annual Energy Outlook 2019* "Reference" case
- Same service demands for each net-zero pathway

EnergyPATHWAYS demand-side model

- Exogenously-specified demand-side technology choices
- EP tracks stock turnover with time
- EP calculates final energy by type (electricity, diesel-like, gasoline-like, gas, etc.) to meet projected energy-service demands

RIO supply-side cost-minimization

- Finds *lowest-cost mix* of supply-side technologies that meet final-energy demands under a US-wide carbon constraint.*
- Changing other exogenous constraints leads to construction of different pathways to net-zero.
- 14-region model for lower-48 states

Downscaling analysis

- EP and RIO results serve as inputs for customized high-resolution "downscaling" analysis and modeling of key sectors.
- State and sub-state level geographic resolution.

Example: Annual vehicle-miles → Vehicle types to meet vehicles miles traveled, e.g., gasoline, hybrid, EV, H_2 fuel cell → Mix of sources (solar, nuclear, oil, etc.) that minimizes total energy-system cost → Where are energy assets and infrastructure sited? What are impacts on land use, employment, and air quality/health?

* RIO minimizes net-present value of supply-side costs over the life of the transition, with perfect foresight and seamless cross-sectoral integration

Five scenarios constructed to highlight implications of different pathways for the US economy to reach net-zero emissions by 2050

Assumptions regarding energy-demand and energy-supply technology options available in the future were varied to develop 5 distinct net-zero scenarios (or pathways). The pathways help highlight the role of three key elements in energy-system transitions: 1) extent of end-use electrification in transport & buildings, 2) extent of solar & wind electricity generation, and 3) extent of biomass utilization for energy. Each of the 5 scenarios has its own short-hand label used in presenting results:

E+	Assumes aggressive end-use electrification, but energy-supply options are relatively unconstrained for minimizing total energy-system cost to meet the goal of net-zero emissions in 2050
E-	Less aggressive end-use electrification, but same supply-side options as E+
E- B+	Electrification level of E-; Higher biomass supply allowed to enable possible greater biomass-based liquid fuels production to help meet liquid fuel demands of non-electrified transport
E+ RE-	Electrification level of E+; On the supply-side, RE (wind and solar) rate of increase constrained to 35 GW/y (~30% greater than historical maximum single-year record). More CO_2 storage allowed to enable the option of more fossil fuel use than in E+
E+ RE+	Electrification level of E+; Supply-side constrained to be 100% renewable by 2050, with no new nuclear plants or underground carbon storage allowed, and fossil fuel use eliminated by 2050.

(55 additional scenarios were modeled to test the sensitivity of different input parameters on the results.)

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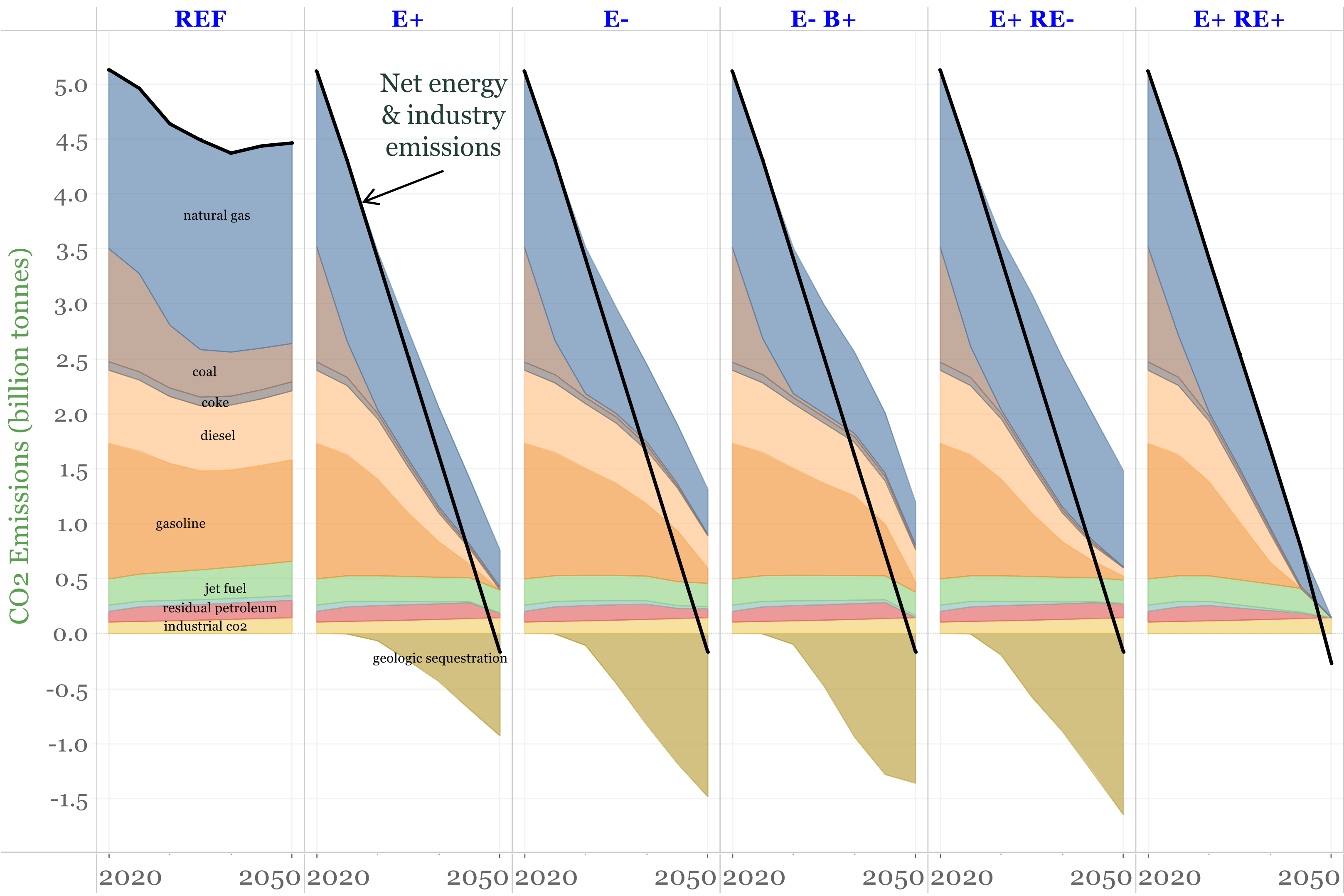
Summary of high-level modeling results for net-zero pathways

- In all five cost-minimized energy-supply pathways, coal use is essentially eliminated by 2030.
- Overall, fossil fuels in the primary energy mix decline by 62% to 100% from 2020 to 2050 across scenarios. Oil and gas decline 56% to 100%.
- In pathways with aggressive electrification (E+, E+RE-, and E+RE+) use of petroleum-derived liquid fuels declines more rapidly than with less-aggressive electrification (E-, E-B+). Natural gas use also declines.
- Oil & gas contributions in 2050 are largest in E+RE-, where fossil, nuclear, and renewables each account for about one-third of primary energy.
- Renewable energy (primarily wind & solar power) accounts for the majority of primary energy in 2050 (60-68%) in the other scenarios, and supply 100% of primary energy in the case of E+RE+.
- Nuclear power is maintained at roughly today's levels in the least-constrained cases (E+, E-, E-B+), expands significantly when renewable energy deployment is constrained (E+RE-) and is eliminated by 2050 in a 100% renewable energy pathway (E+RE+).
- All pathways rely on large-scale CO_2 capture and utilization or storage. In E+RE+, 0.7 Gt/y of CO_2 is captured and utilized to synthesis liquid and gaseous hydrocarbons. In all other scenarios, more than 1Gt/y of CO_2 is captured with the majority being stored in geologic formations.
- Annualized energy spending across the full 30-year transition as a fraction of GDP is similar to spending levels experienced during recent prosperous periods, but all net-zero pathways are much more capital intensive than historical energy sector capital spending.

Energy and industrial CO_2 emissions are net negative by 2050 to deliver net-zero emissions for the full economy

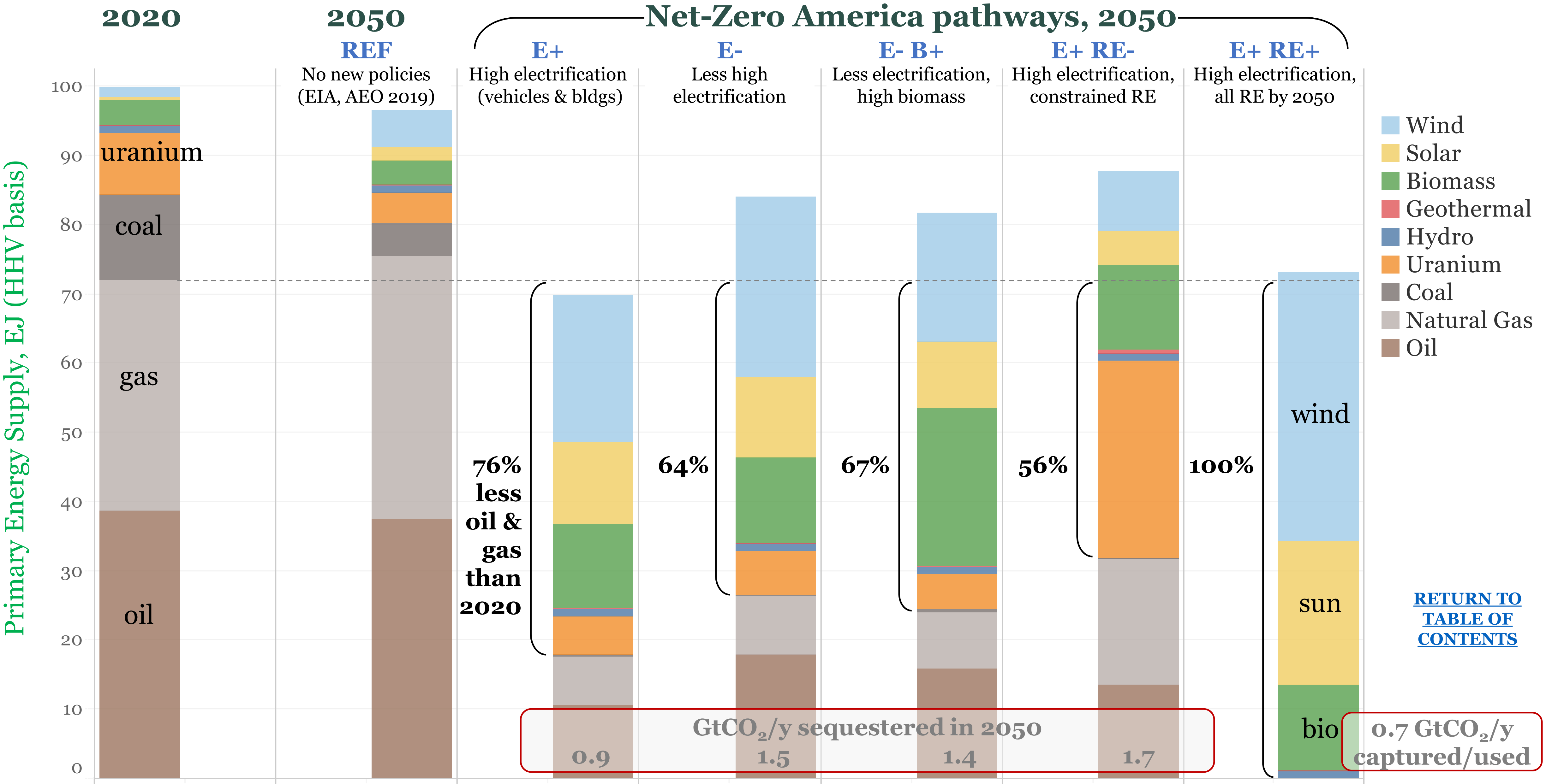


- Modeled energy/industrial system emissions are -0.17 $GtCO_2$ in 2050, supplementing the assumed -0.85 $GtCO_{2e}$ provided by land carbon sinks. Together these offset the assumed 1.02 $GtCO_{2e}$ of remaining non-CO_2 GHG emissions.
- Fossil fuel emissions decline significantly, and annual CO_2 sequestration in 2050 reaches 0.9-1.7 $GtCO_2$ in 4 of the 5 pathways.

natural gas
coal
coke
diesel
gasoline
jet fuel
LPG
residual petroleum
industrial co2
geologic sequestration

Carbon storage in long-lived products is included in the modeling, but is not shown explicitly here.

Primary energy mix in 2050 is ≤38% fossil in net-zero pathways. Coal use all but disappears by 2030. Oil & gas down 56-100%



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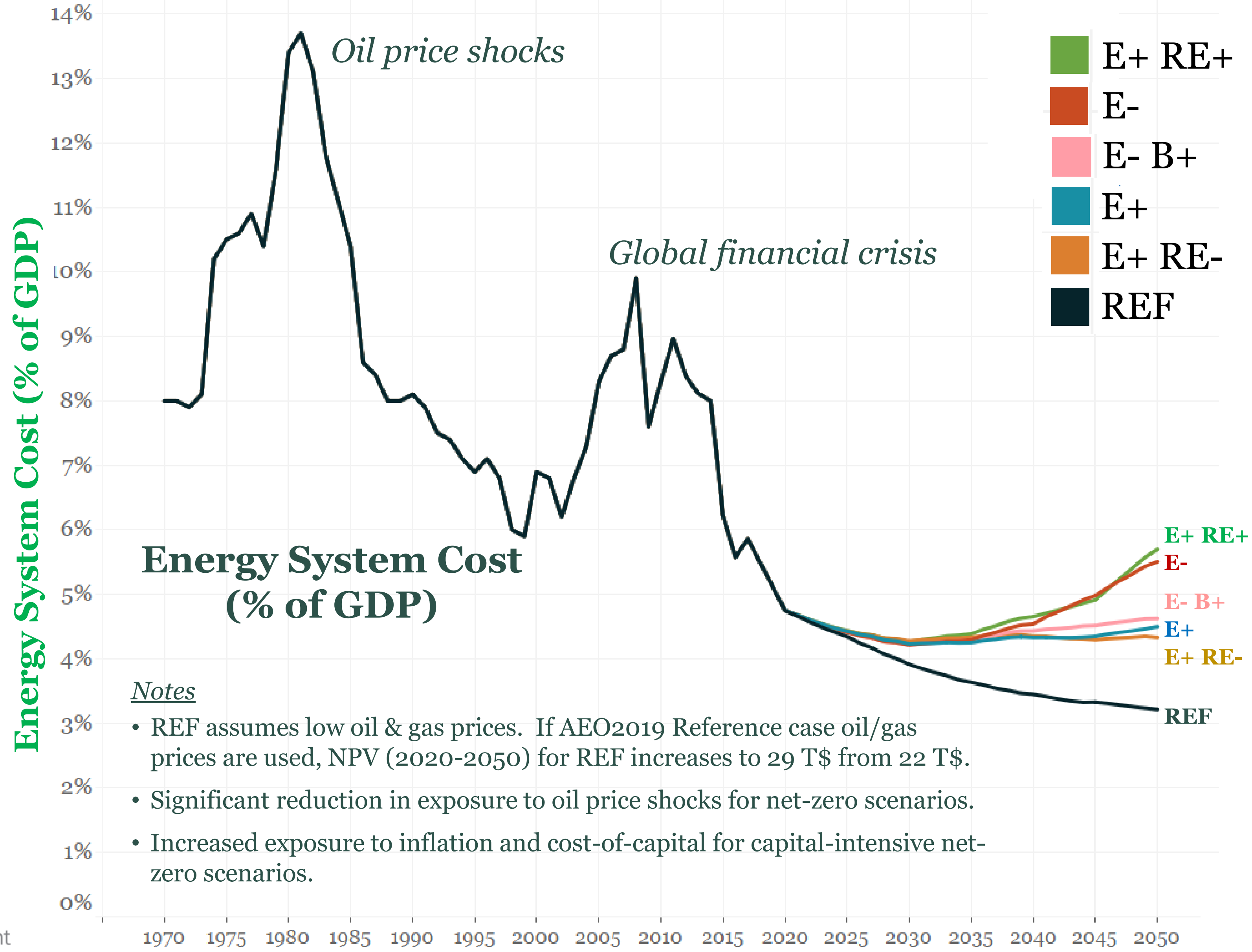
Annualized energy-system costs as % of GDP for net-zero pathways are similar to recent historical levels in prosperous economic times

Societal NPV (2% discount rate) of all energy system costs

	Trillion 2018 $	
	2020 - 2030	2020 - 2050
REF	9.4	22
E+	9.7	26
E-	9.7	28
E- B+	9.7	27
E+ RE-	9.7	26
E+ RE+	9.7	28

Annual costs shift from fuel costs to fixed costs: annualized capital + fixed O&M payments by 2050 are 2 to 4 times those for REF.



Notes

- REF assumes low oil & gas prices. If AEO2019 Reference case oil/gas prices are used, NPV (2020-2050) for REF increases to 29 T$ from 22 T$.
- Significant reduction in exposure to oil price shocks for net-zero scenarios.
- Increased exposure to inflation and cost-of-capital for capital-intensive net-zero scenarios.

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Major Transformations on the Path to Net-Zero Emissions

1. **Physical infrastructure**
2. **Capital mobilization**
3. **Land use**
4. **Energy workforce**
5. **Air pollution and public health**

1. Physical infrastructure

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Six pillars of decarbonization are essential to support the physical transition to net-zero in each of the five pathways

1. End-use energy efficiency and electrification
2. Clean electricity: wind & solar generation, transmission, firm power
3. Clean fuels: bioenergy, hydrogen, and synthesized fuels
4. CO_2 capture and utilization or storage
5. Reduced non-CO_2 emissions
6. Enhanced land sinks

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Rapid expansion is needed, 2020 – 2050, across all six pillars to achieve net-zero emissions. 2050 goals for each pillar include:

1. Efficiency & Electrification

Consumer energy investment and use behaviors change

- Light-duty EVs: 210 million (E-) to 330 million (E+)
- Residential heat pump heaters: 80 million (E-) to 120 million (E+)

Industrial efficiency gains

- Energy intensity declines 1.9%/yr.
- Steel making evolves to all EAF and direct (H_2) reduced iron

2. Clean Electricity

Wind and solar

- 1.3 to 5.9 GW of solar and wind installed, up from 0.2 GW in 2020
- 2x to 5x today's transmission

Nuclear

- In RE- scenario site up to 250 new 1-GW reactors (or 3,800 SMRs).
- Spent fuel disposal.

NGCC-CCS

- In RE-, 300+ plants (@750 MW)

Flexible resources

- Combustion turbines w/high H_2
- Large flexible loads: electrolysis, electric boilers, direct air capture
- 50 - 180 GW of 6-hour batteries

3. Zero-Carbon Fuels

Major bioenergy industry

- 100s of new conversion facilities
- 620 million t/y biomass feedstock production (1.2 Bt/y in E- B+)

H_2 and synfuels industries

- 8-19 EJ H_2 from biomass with CCS (BECCS), electrolysis, and/or methane reforming with CCS
- Largest H_2 use is for fuels synthesis in most scenarios

4. CO_2 capture & storage

Geologic storage of 0.9 – 1.7 $GtCO_2$/y

- Capture at ~1,000+ facilities
- 21,000 to 25,000 km interstate CO_2 trunk pipeline network
- 85,000 km of spur pipelines delivering CO_2 to trunk lines
- Thousands of injection wells

5. Non-CO_2 Emissions

Methane, N_2O, Fluorocarbons

- 20% below 2020 emissions (CO_{2e}) by 2050 (30% below 2050 REF).

6. Enhanced land sinks

Forest management

- Potential sink of 0.5 to 1 $GtCO_{2e}$/y, impacting ½ or more of all US forest area ($\geq$ 130 Mha).

Agricultural practices

- Potential sink ~0.20 $GtCO_{2e}$/y if conservation measures adopted across 1 – 2 million farms.

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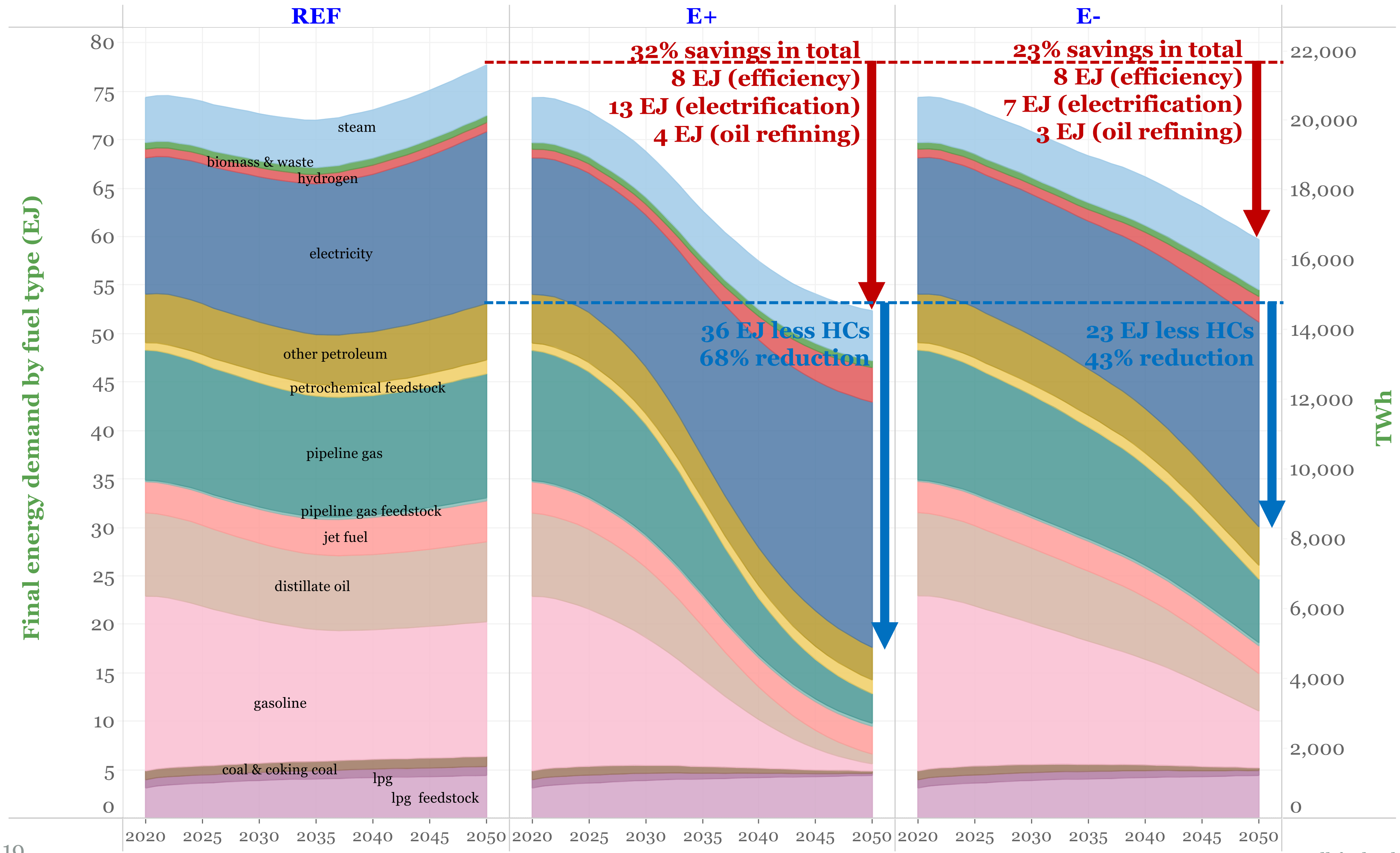
Pillar 1: Improve end-use energy productivity – efficiency and electrification

- End-use efficiency improvements and electrification across all sectors are critical for reducing:
  - the required build out of the energy-supply system to deliver the energy needed to meet the given level of energy service demands.
  - the demand for liquid or gaseous fuels, which are generally more difficult/costly to decarbonize than electricity.
- In transportation and space and water heating, electrification itself provides large reductions in final energy because electric drive trains for vehicles and electric heat pumps for heating are intrinsically more efficient than using fuels to provide the same services.
- In industry, the annual average decline in final-energy intensity is assumed to be nearly double that for the REF scenario. Steel production transitions to be entirely via electric arc furnaces (with scrap steel supplemented by direct reduced iron). Electricity and hydrogen from carbon-free sources substitute some industrial fuel uses.
- To minimize transition costs, equipment replacements are made at economic end-of-life. For long-lived assets, their *next* end-of-life replacement must be with a low-carbon option. Otherwise, in the future, early retirements (and therefore stranding of assets) will be required to reach the 2050 emissions goal.

End-use energy productivity improves via same-fuel efficiency gains and via electrification; energy used for oil refining declines.



U.S. final-energy intensity (MJ/$GDP) falls, 2020 to 2050:
- 1.7%/y in REF
- 3.0 %/y in E+
- 2.6 %/y in E-

Efficiency gains in
- Most of industry
- Buildings non-heating
- Aviation

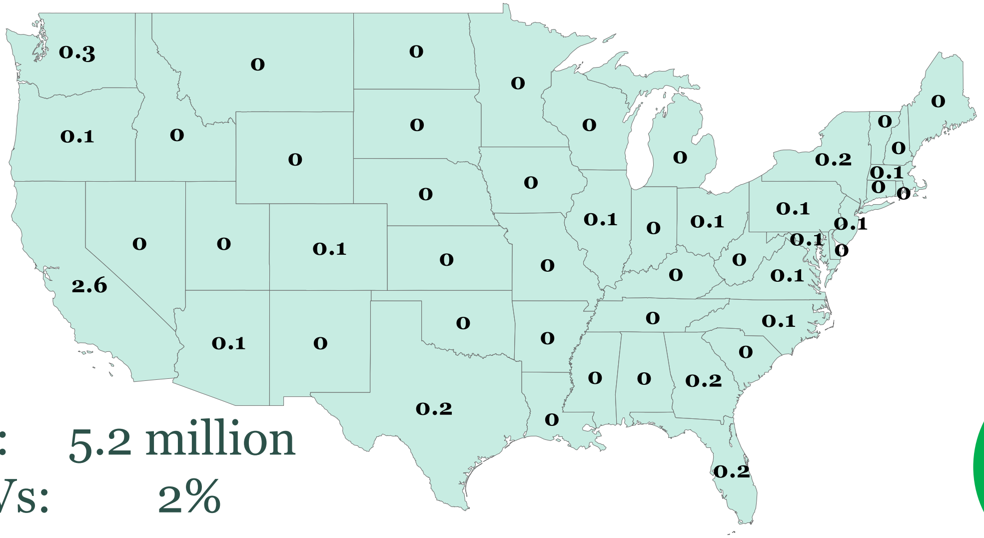
Electrification reduces fuel use and provides efficiency gains in
- Road transport
- Heating of buildings
- Some industry, especially iron and steel.

Oil refining energy use falls from 5.4 EJ in 2020 to 0 to 2.3 EJ in 2050 in net-zero scenarios.

Note: All fuel values reported in this slide pack are on HHV basis.

In E+, the stock of EVs grows to 17% of all light-duty vehicles by 2030 and 96% by 2050.

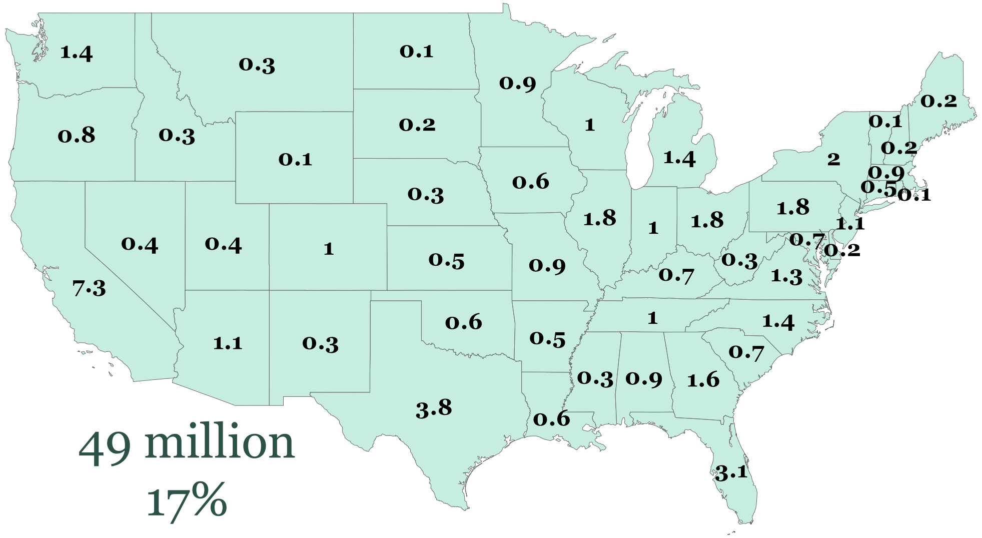
2020



# of EVs: 5.2 million
% of LDVs: 2%

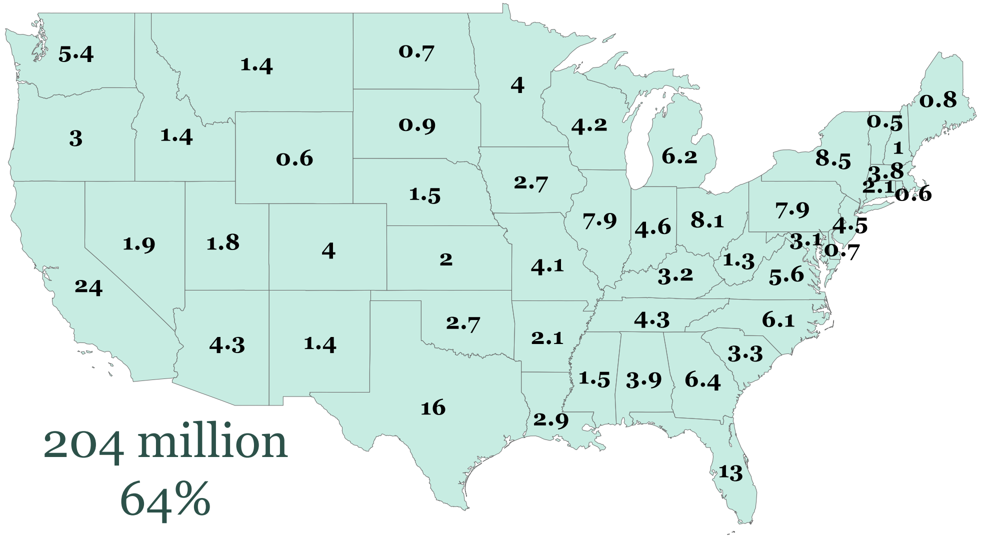
E+

2030



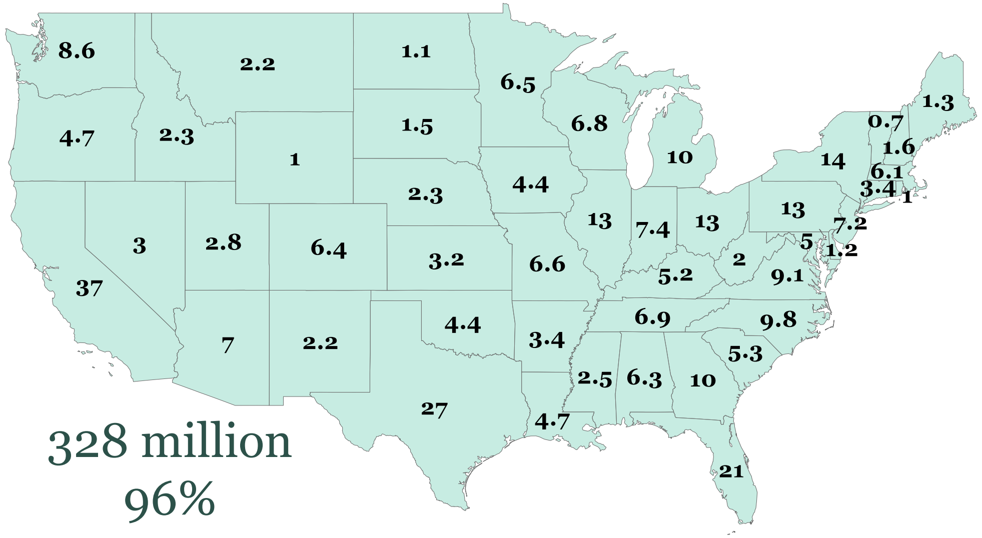
49 million
17%

2040



204 million
64%

2050



328 million
96%

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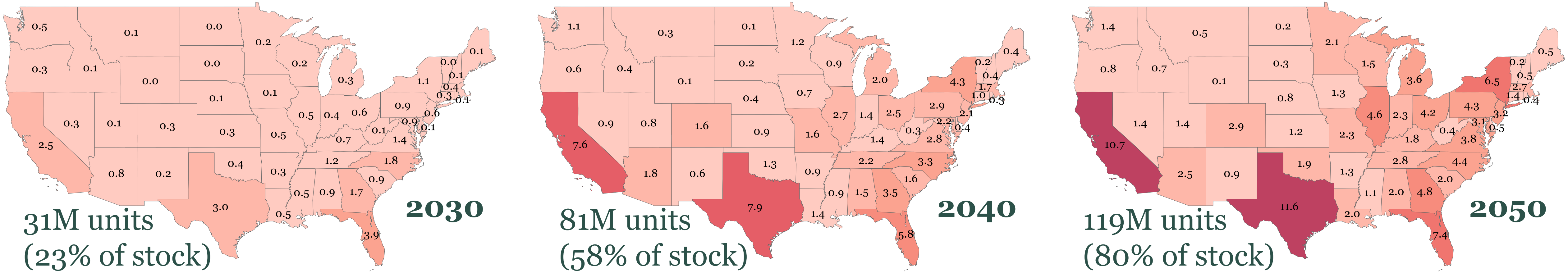
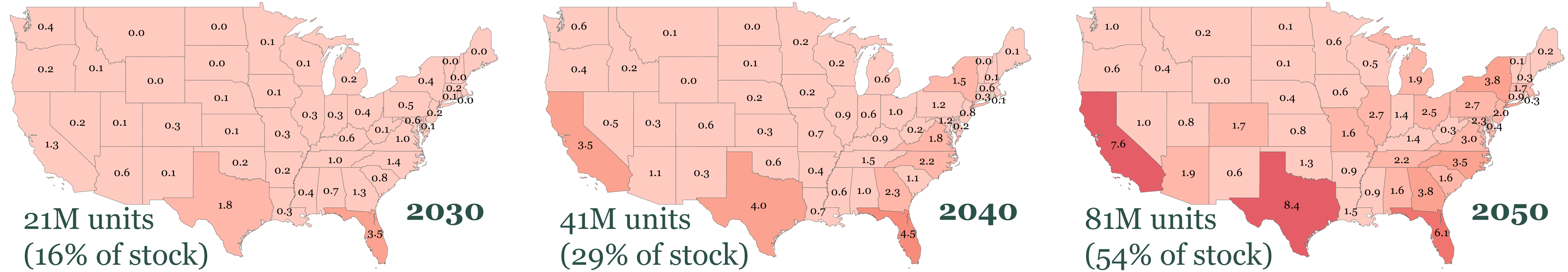
Residential heat pumps grow from ~10% of the space heating stock in 2020 up to 80% (E+) or 54% (E-) by 2050.

E+



E-



Number of homes using heat-pump heating by state: Million Units 0 12

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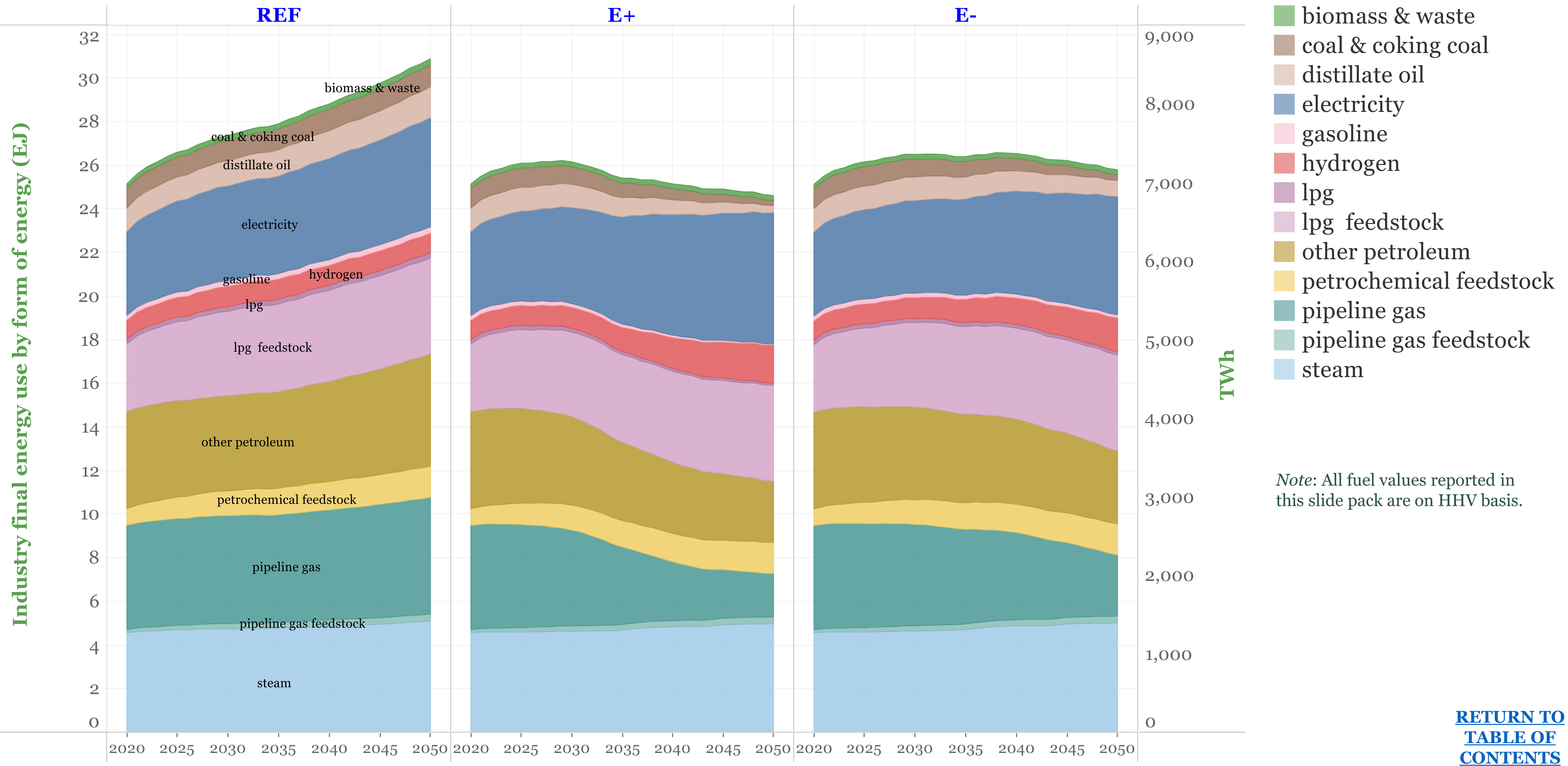
Industrial final energy in 2050 is 15-20% below REF despite growing output. Electricity & H_2 grow; use of liquids & other gases decline.



Note: All fuel values reported in this slide pack are on HHV basis.

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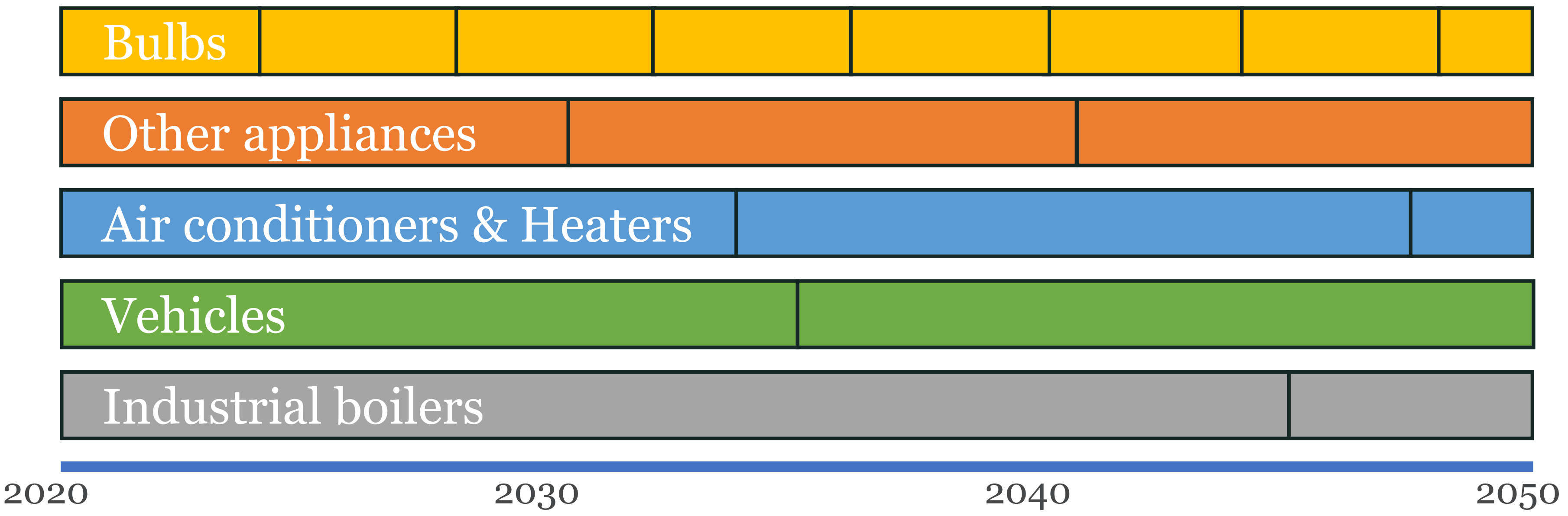
Transitioning to net-zero at least cost relies on replacing long-lived assets with low-carbon alternatives as they reach end-of-life.

- The economically optimal time for replacing physical assets is at the end of their lives.
- For some demand-side technologies, like vehicles and industrial boilers, there will be few opportunities between now and 2050 for end-of-life replacement.
- For such longer-lived assets, their *next* end-of-life replacement must be with a low-carbon option.

Typical asset replacement times for various durable assets



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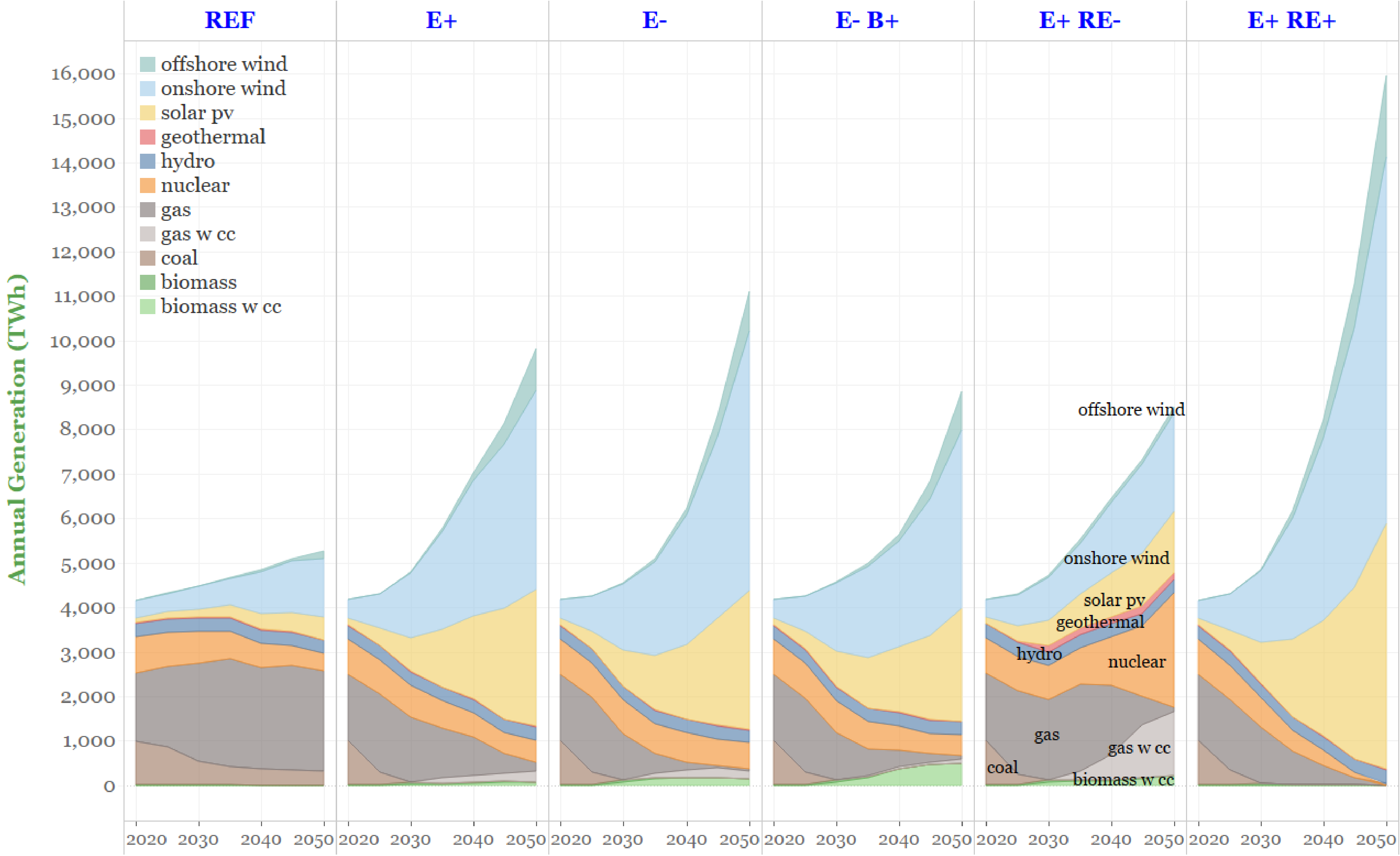
Pillar 2: Clean electricity

- Electricity generation is double to quadruple by 2050 in the net-zero scenarios. Clean electricity is a linchpin.
- Low- or no-carbon electricity roughly doubles from ~37% today to 70-85% by 2030 and hits 98-100% by 2050.
- Wind and solar power play dominant roles in all pathways:
  - Generation grows more than 4-fold by 2030 to supply ~½ of U.S. electricity in 4 scenarios. The 5th scenario (E+RE-) sees a 3-fold growth by 2030 to supply ⅓ of U.S. electricity.
  - By 2050, wind+ solar provide 85-90% of generation in E+, E-, and E-B+. They supply 44% in E+RE- and 98% in E+RE+.
  - Wind and solar capacity deployment rates set new records year after year (unless constrained, as in E+RE-), with extensive deployment across the United States.
- Nearly all coal-fired capacity retires by 2030 in all cases, reducing U.S. emissions by roughly 1 $GtCO_2$/year.
- Some nuclear plants are operated 80 years, except in E+RE+, where existing plants retire after 60 years and no new construction is allowed.
- Natural gas generation declines, except in E+RE-, by 2-30% by 2030, while installed capacities are ±10% of the 2020 level. In E+RE-, gas-fired generation grows through 2035 (up 30% from 2020) before declining to just 7% of 2020 levels by 2050, even as total installed capacity grows to be ⅓ higher than in 2020.
- To ensure reliability, all cases maintain 500-1,000 GW of firm generating capacity through all years (compared to ~1,000 GW today); gas plants burn hydrogen blends and with declining utilization rates through 2050. When wind and solar expansion are constrained (as in E+RE-), natural gas plants w/CO_2 capture and nuclear plants expand to pick up the slack.

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%.

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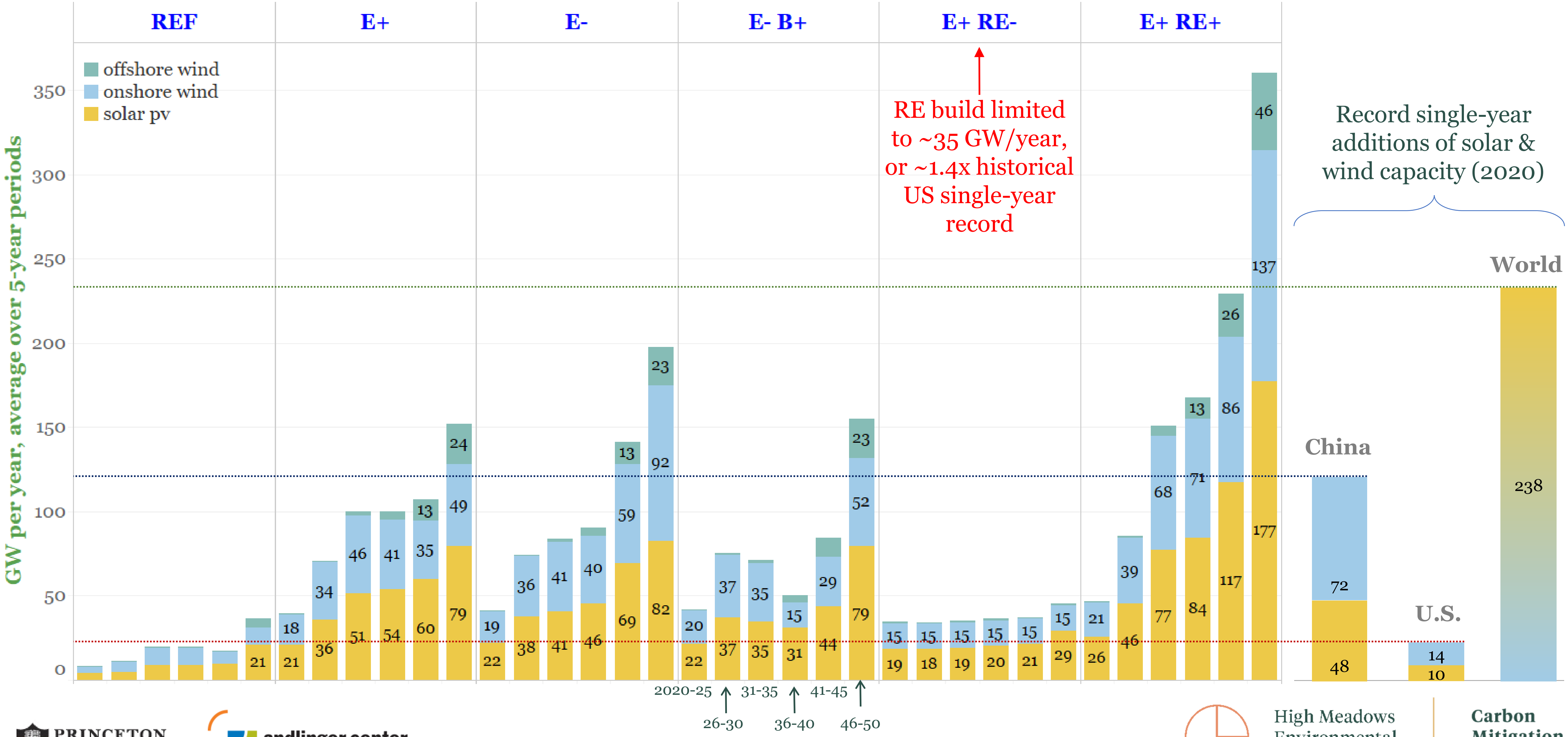
Annual wind and solar capacity additions are sustained over multiple decades at historically-unprecedented rates



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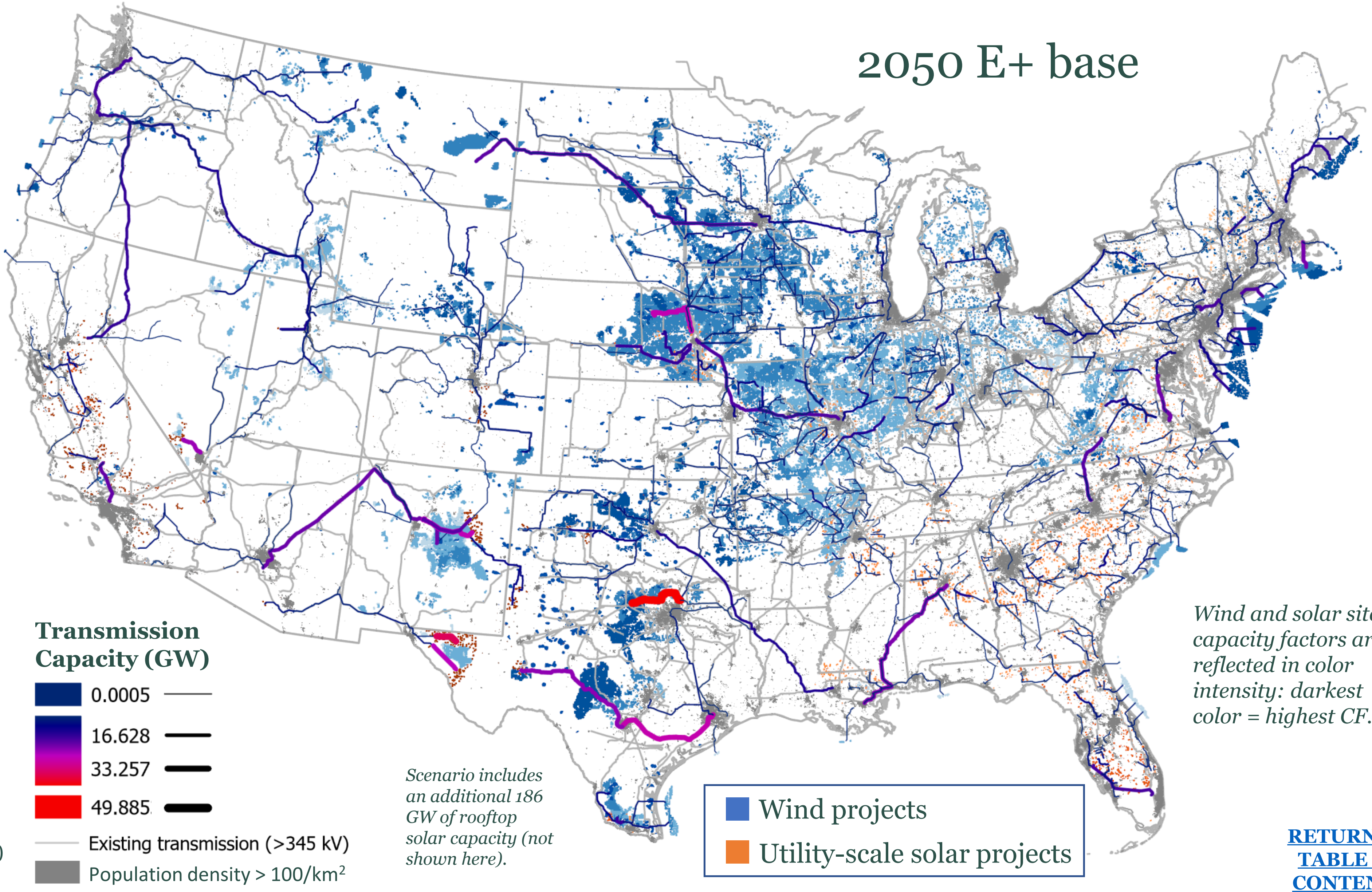
E+: 3.2 TW of wind and solar capacity operating in 2050; transmission capacity more than triples.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	1.67	1.50
Land used (1000 km²)		
Total	551	38.3
Direct	5.51	34.9
Capital invested (Billion $\$_{2018}$)*		
Solar	-	1,488
Onshore wind	1,609	-
Offshore wind	301	-
Transmission added vs. 2020**		
Capacity (GW-km)		673,000
Increase over 2020		210%
Capital in serv (B$\$_{2018}$)		2,210

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Scenario includes an additional 186 GW of rooftop solar capacity (not shown here).

Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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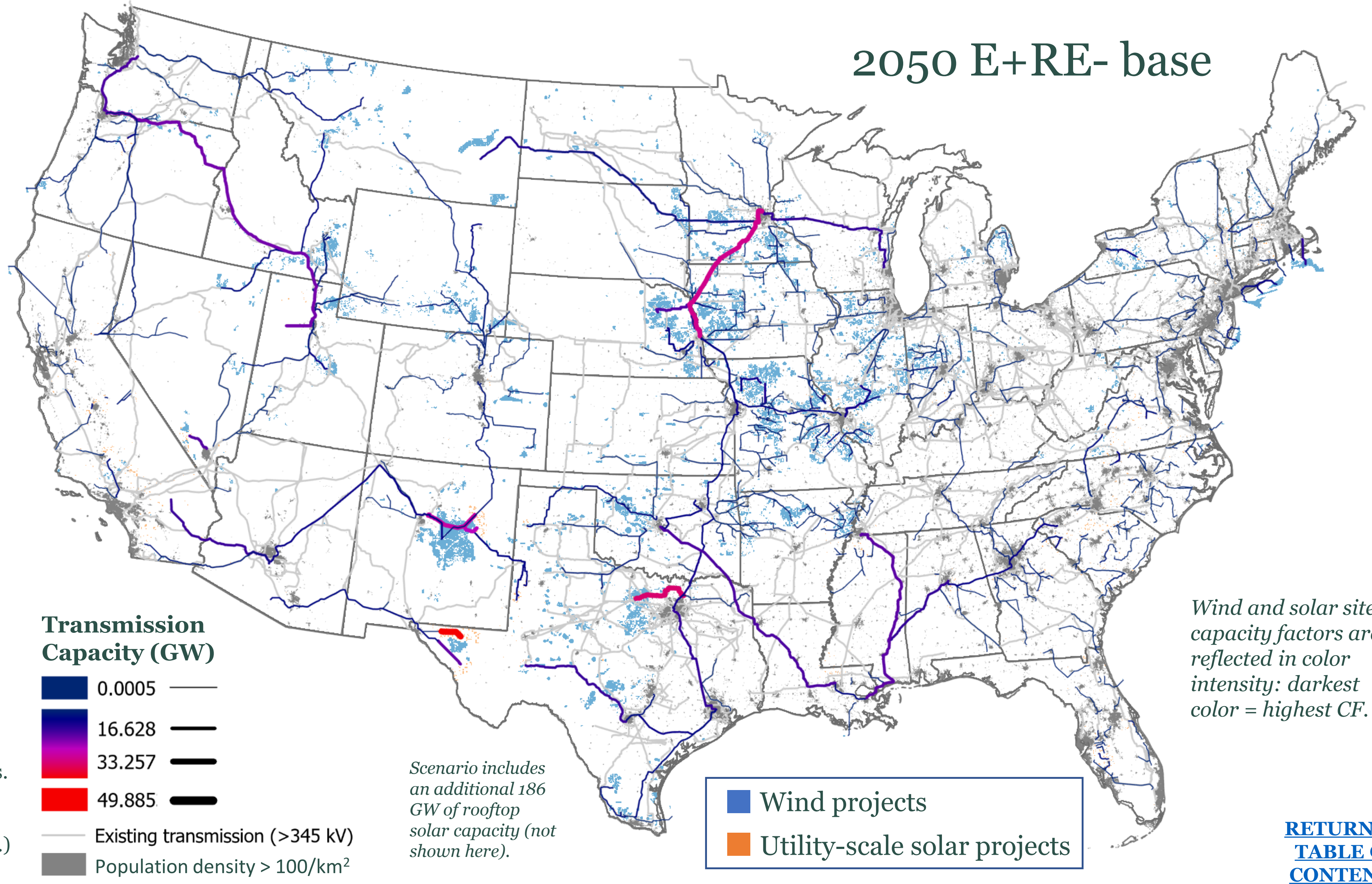
E+ RE-: 1.3 TW of solar and wind capacity operating in 2050; transmission capacity is double the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	0.67	0.64
Land used (1000 km²)		
Total	244	14.2
Direct	2.44	13.0
Capital invested (Billion $\$_{2018}$)*		
Solar	-	655
Onshore wind	658	-
Offshore wind	71	-
Transmission added vs. 2020**		
Capacity (GW-km)		306,000
Increase over 2020		96%
Capital in serv (B$\$_{2018}$)		1,280

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Scenario includes an additional 186 GW of rooftop solar capacity (not shown here).

Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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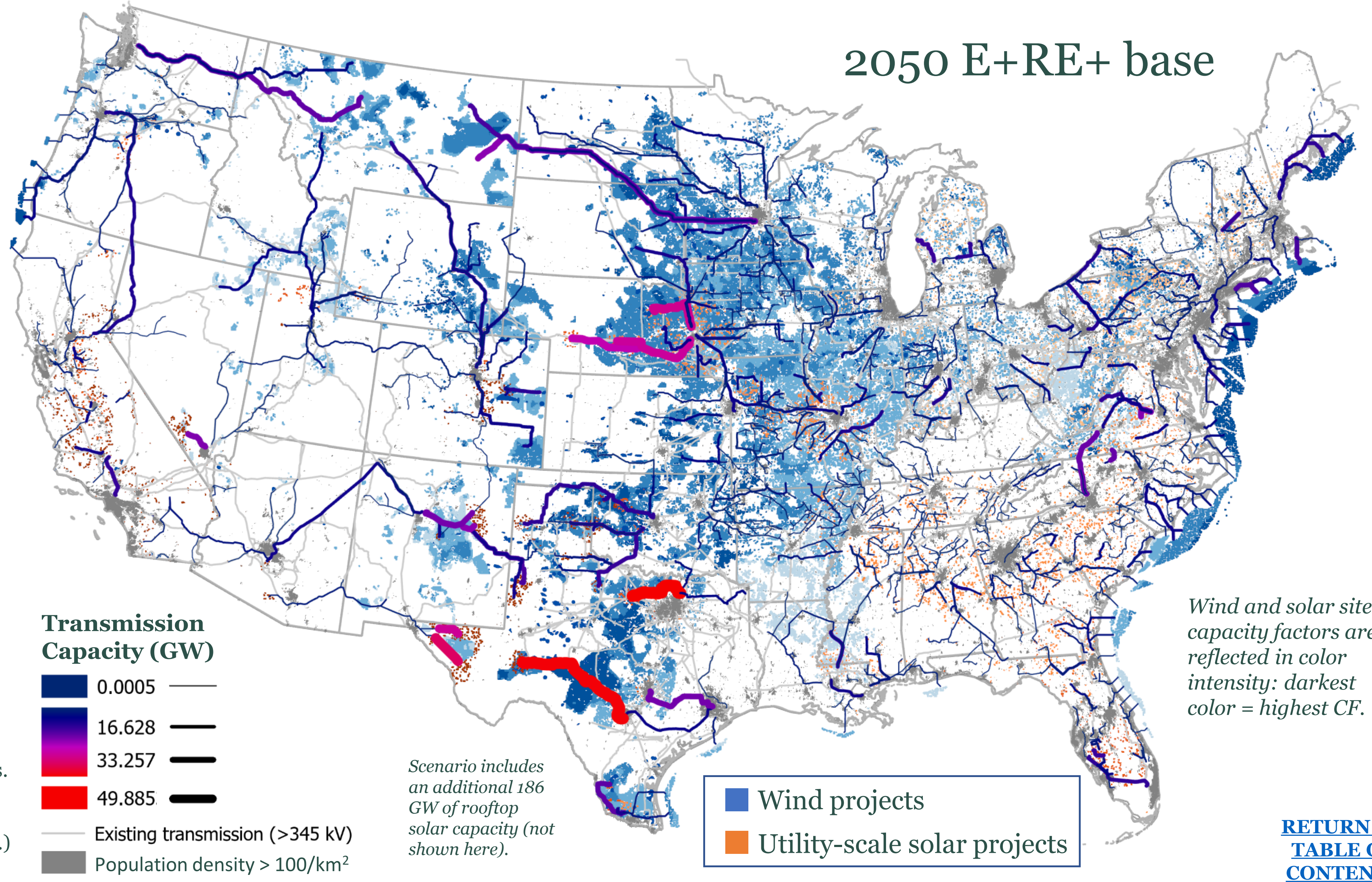
E+ RE+: 5.9 TW of wind and solar capacity operating in 2050; transmission capacity grows to 5.1x the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	3.07	2.75
Land used (1000 km²)		
Total	1,003	61.2
Direct	10.0	55.7
Capital invested (Billion $_{2018}$)*		
Solar	-	2,684
Onshore wind	3,010	-
Offshore wind	594	-
Transmission added vs. 2020**		
Capacity (GW-km)		1,309,000
Increase over 2020		409%
Capital in serv (B$_{2018}$)		3,560

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



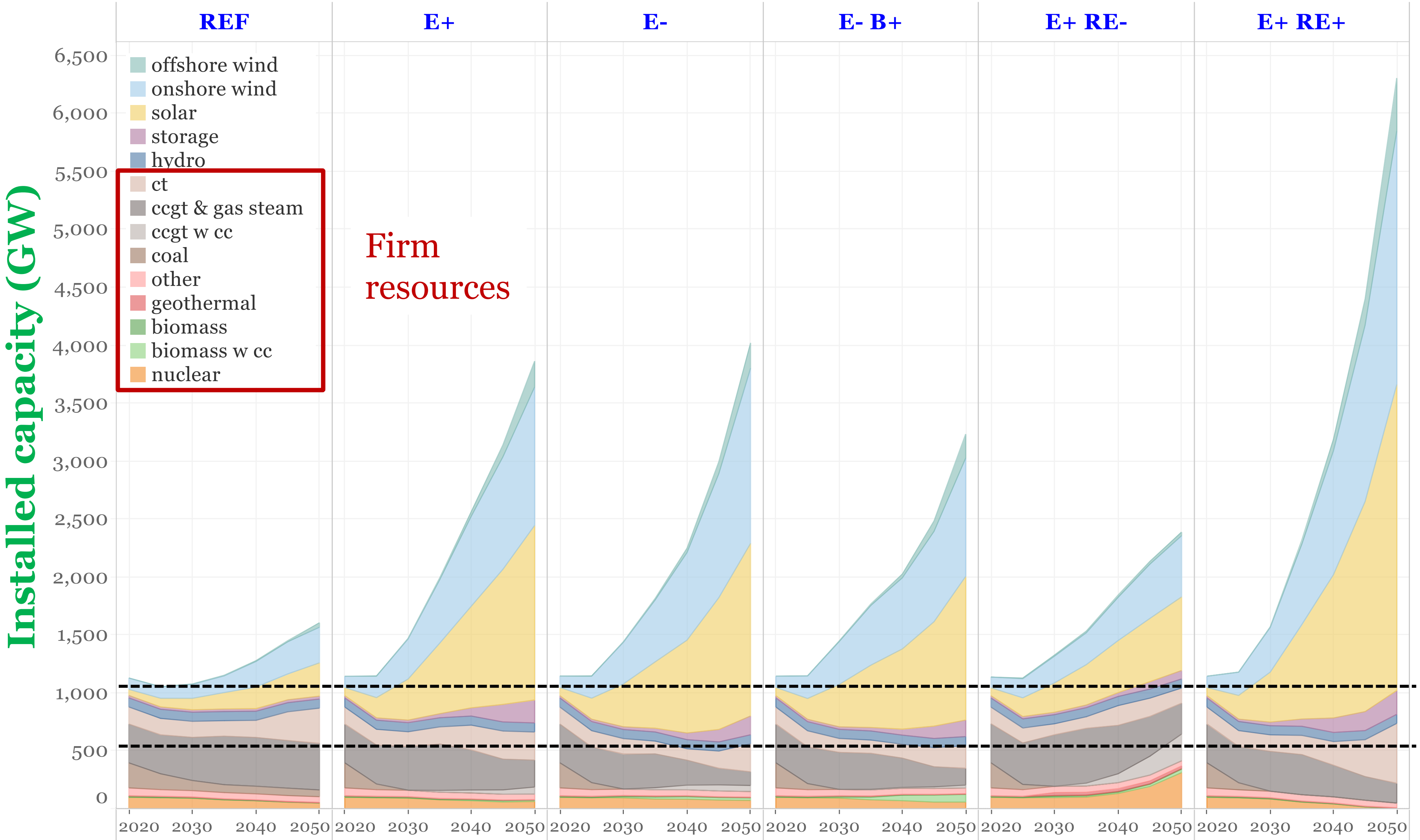
Scenario includes an additional 186 GW of rooftop solar capacity (not shown here).

Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

Clean firm resources and thermal plant retirements

- Installed capacity of "firm" generation sources — technologies that can produce power on demand, any time of year, for as long as required — remains similar to current levels in all scenarios, with ~500-1,000 GW (vs. 875 GW today).
- Coal fired capacity is completely retired by 2030 across all NZA scenarios with decline rates similar across all regions at higher than the historical peak of 21 GW/y in 2015. No new coal fired capacity is added in any scenario.
- About 50% of existing nuclear capacity retires by 2050 in all NZA scenarios (by assumption to reflect age-based retirements); the E+RE+ scenario phases out all nuclear by 2050 with 15 GW retired by 2030.
- New advanced nuclear generation capacity is added in all scenarios except E+RE+; expansion is modest in E+, E- and E+B+ with ~10-20 GW deployed in the 2030s and 2040s. The E+RE- scenario expands new nuclear capacity rapidly from 2025-2050, deploying ~260 GW by 2050, requiring historically unprecedented build rates in the 2040s.
- Natural gas retirements vary across NZA scenarios, with the E+RE+ scenario seeing the most retired (224 GW) and the E+RE- scenario seeing the least (175 GW). By 2050, cumulative retirements are consistent across most NZA scenarios (450 GW) except for the E+RE- scenario (506 GW).
- New natural gas fired capacity is added in all scenarios except E+RE+. The most new capacity is added in E+RE- which sees ~580 GW of new gas capacity (around 230 GW of which includes CO_2 capture) by 2050.
- To meet firm capacity needs in the 100% renewable E+RE+ scenario, ~590 GW of new combustion turbine and combined cycle power plants are deployed and by 2050 are fired entirely with zero-carbon synthetic gas.
- Siting studies indicate that most of the new thermal generation capacity can be sited at existing coal, natural gas and nuclear plant sites with few new sites to be developed, unless safety or environmental criteria currently applicable to new greenfield projects were applied. In that case, many sites would fail to pass one or more of the criteria.
- Batteries for short-duration storage reach 53 to 186 GW installed by 2050.

Firm capacity stays comparable to today; high H_2 fuel blends for gas turbines have important role; nuclear & gas w/CCS key in RE-



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. (See Annex B for additional details.)

Firm capacity (across all years)

~500-1000 GW

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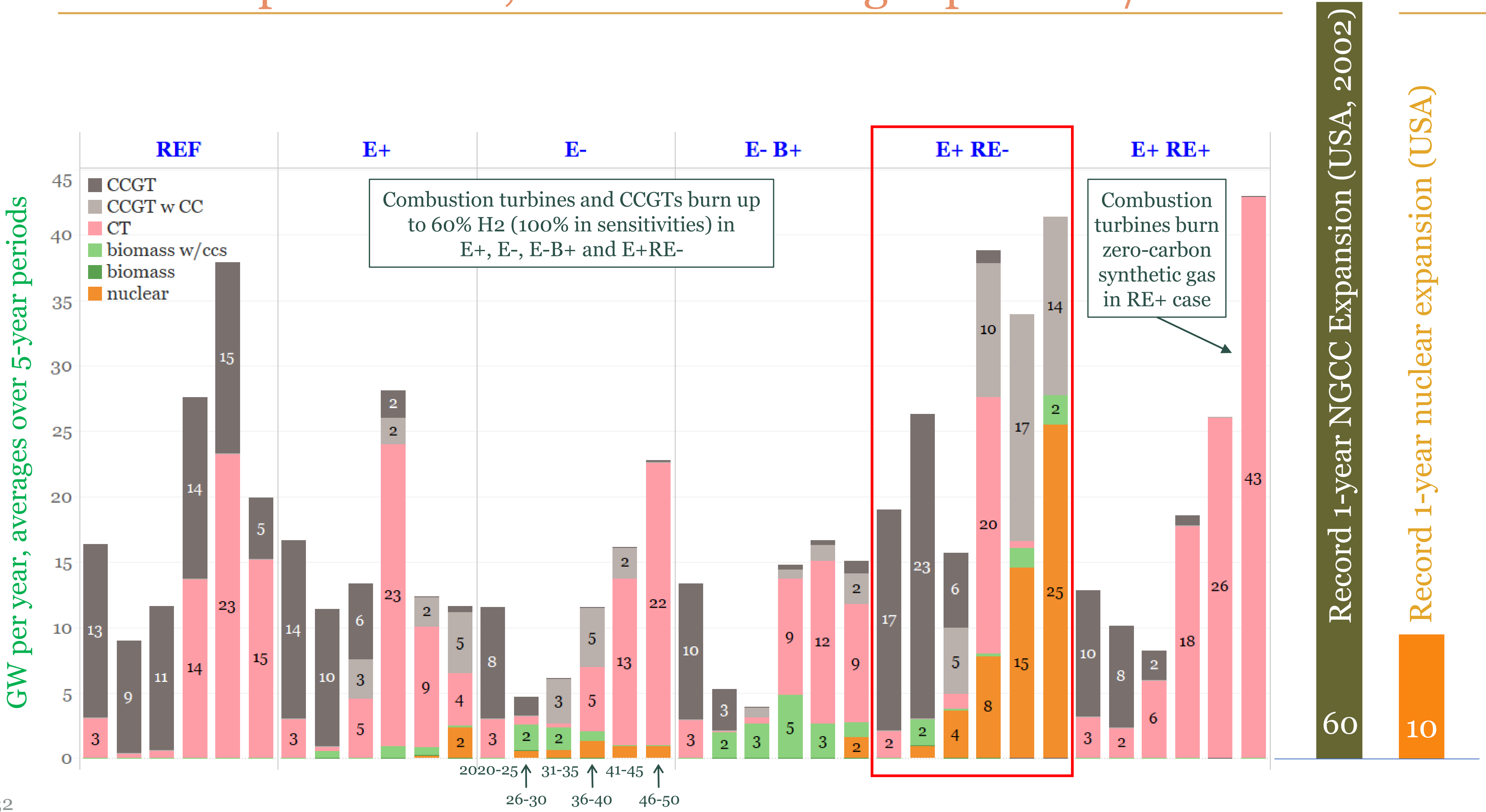
E+ RE- requires historically-unprecedented growth rates, sustained for multiple decades, for nuclear and gas plants w/CCS



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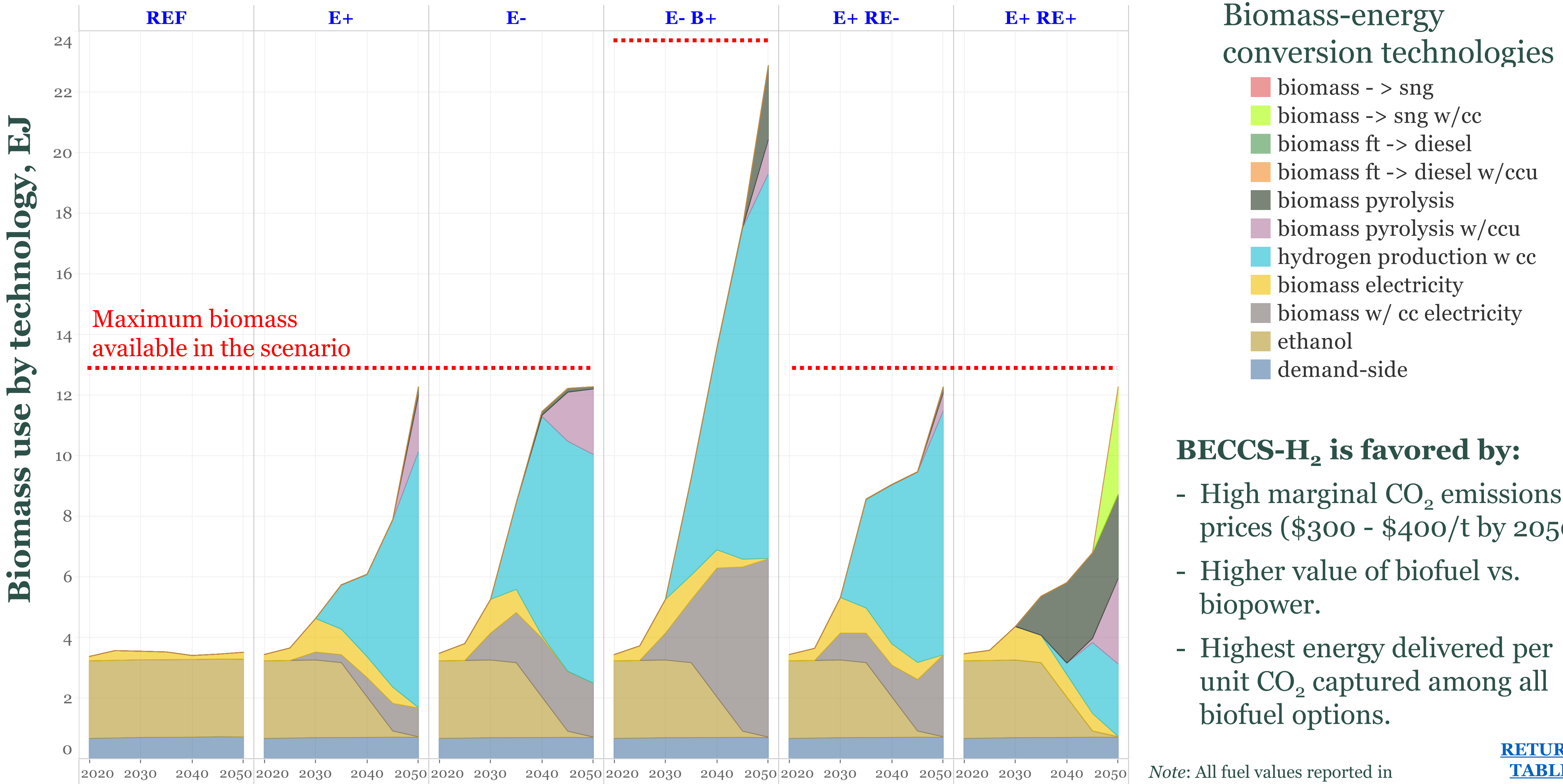
Pillar 3: Clean fuels: Bioenergy, hydrogen, and synthesized fuels

- The net-zero scenarios realize carbon-neutral or carbon-negative fuels derived from fossil fuels, from biomass, and/or from clean electricity. Hydrogen is a key carbon-free intermediate and final fuel.
- Biomass plays an especially important role because *i*) it removes CO_2 from the atmosphere as it grows and so combustion of hydrocarbon fuels made with sustainable-biomass carbon results in no net CO_2 emissions to the atmosphere, *ii*) it can be converted into H_2 while capturing and permanently sequestering its carbon, resulting in a net negative-emissions fuel, and *iii*) it can similarly be used to make negative-emissions electricity and replacements for petrochemical feedstocks (via pyrolysis).
  - The biomass supply in 4 of the 5 net-zero scenarios consists of agricultural and forest residues, plus transitioning land growing corn for ethanol today to growing perennial grasses or equivalent for energy. This supply scenario thus includes no conversion of land currently used for food or feed production.
  - The high biomass supply case (E-B+ scenario) assumes all biomass identified in the US Department of Energy's "Billion Ton Study" is available for energy; this would involve some conversion of cropland and pasture to energy crops.
  - Starting in the 2030s, H_2 from biomass with capture of CO_2 that is permanently sequestered is a highly cost-competitive technology option because of the high value of the associated negative emissions; negative-emissions bio-electricity is less valued because of abundant low-cost solar and wind electricity.

Essentially all available biomass is used in 2050. Rapid growth after 2030. H_2 from biomass with CO_2 capture is a key technology.



BECCS-H_2 is favored by:

- High marginal CO_2 emissions prices ($300 - $400/t by 2050).
- Higher value of biofuel vs. biopower.
- Highest energy delivered per unit CO_2 captured among all biofuel options.

Note: All fuel values reported in this slide pack are on HHV basis.

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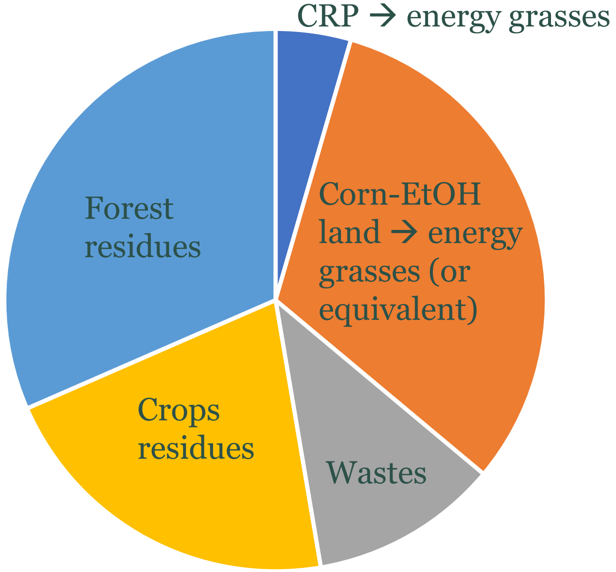
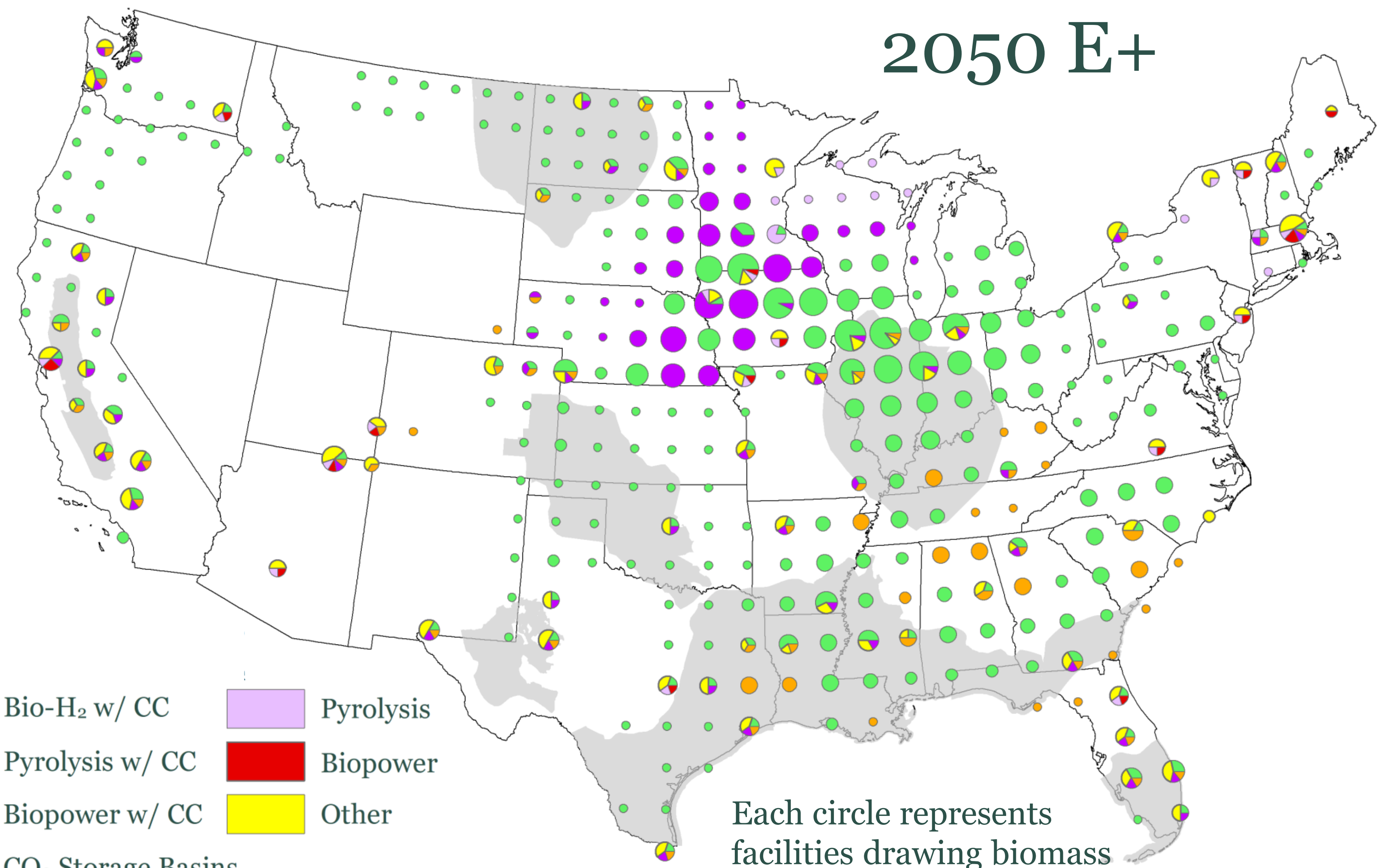
810 B$ of capital is invested across rural America by 2050 to establish an entirely new bioenergy industry

2050 non-food biomass use:

- 618 million dry t (12.2 EJ)
- 17% of primary energy
- Sources:





Average facility capacity is 2,100 dry t/day biomass input

Other includes a collectively small level of biomass converted to diesel, synthetic methane, and/or electricity.

Each circle represents facilities drawing biomass from a surrounding grid cell area 100 mi x 100 mi.

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Hydrogen production and use

- In the net-zero models, H_2 can be made by reforming natural gas (without or with CO_2 capture), gasifying biomass (with CO_2 capture), or electrolyzing water. E+, E-, and E-B+ all favor H_2 from a mix of biomass and electrolysis. H_2 from natural gas is prominent in E+RE-, because electrolysis is less cost competitive when wind and solar capacity growth is restricted. In E+RE+, electrolysis dominates by 2050 because fossil fuel use is disallowed and most biomass is converted into pyrolysis oils used for petrochemicals production.
- As a final energy carrier, H_2 is used in fuel cell trucks and for producing ammonia and other chemicals, direct reduction of iron, and industrial heating. As an intermediate energy, H_2 is an input to synthesis of hydrocarbon fuels, and a small amount supplements natural gas use in gas turbine power generation.
- H_2 systems begin expanding substantially only starting in the mid-2030s, reaching total H_2 volumes in 2050 in the E+ pathway more than six times H_2 flows in the U.S. today. In E+RE+, H_2 flows are more than twice as large again, with most H_2 being combined with captured CO_2 to synthesize hydrocarbon fuels.
- Many industrial H_2 users would likely produce H_2 onsite, as happens today. Distributed users might be served by regional pipeline networks and/or truck delivery, as is also the case in some regions today.
- Design and mapping of future H_2 systems was not done (except for biomass H_2, as described earlier) with as high a resolution as some other features of the net-zero pathways, but coarse (14-region) analysis indicates possible future geographic distribution of this industry.

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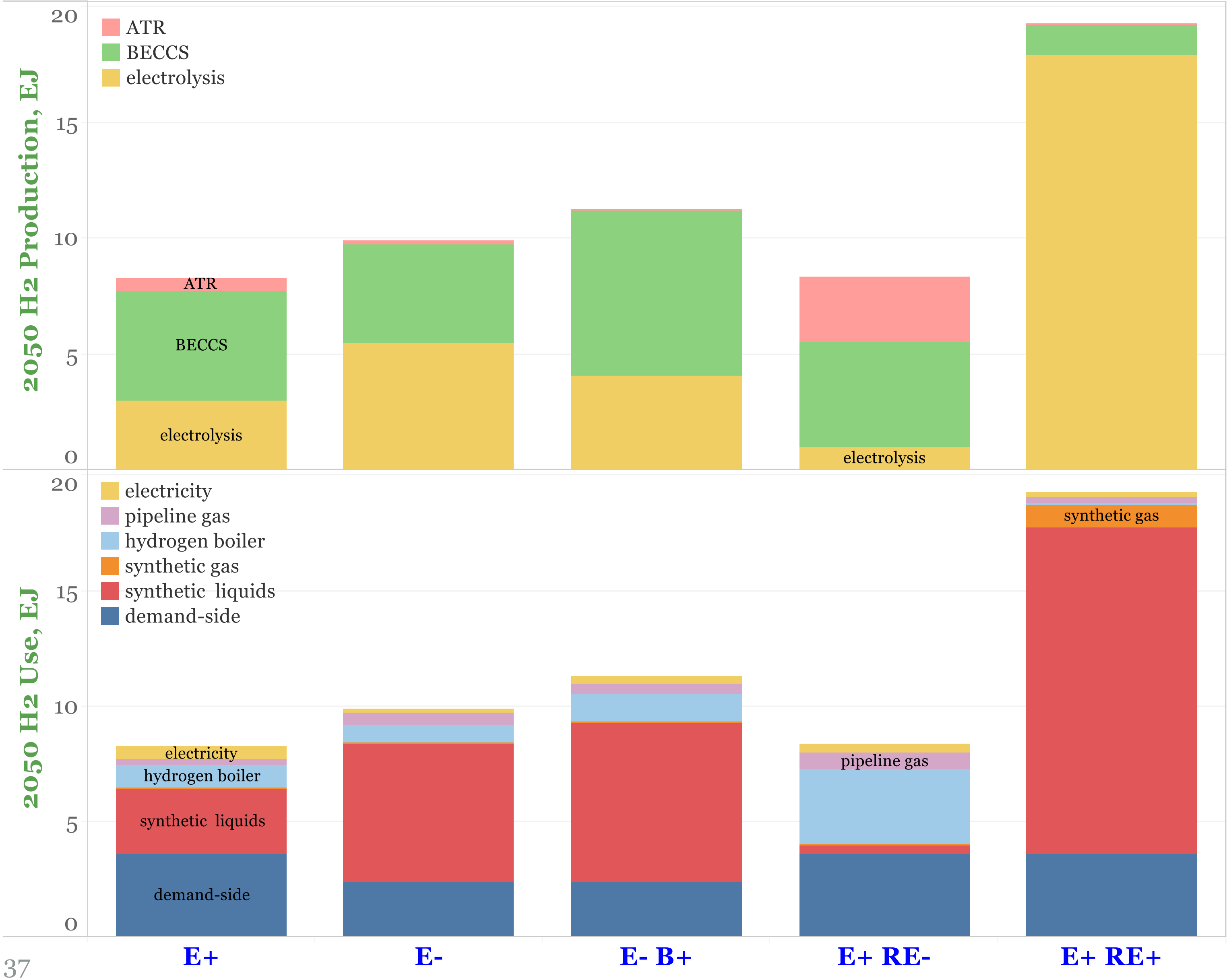
58 to 136 Mtpa of H_2 are produced in 2050; volume-equivalent (at pipeline pressure) to 0.8x to 2.2x today's U.S. natural gas use



H_2 sources

ATR = autothermal reforming of natural gas with CO_2 capture.

BECCS = biomass gasification to H_2 with CO_2 capture (negative net emissions).

Electrolysis = water splitting using electricity.

H_2 uses

Electricity = H_2 burned in gas turbines in high "hythane" blend with CH_4 (60% limit by energy).

Pipeline gas = H_2 used for "hythane" blend in CH_4 pipelines (7% limit by energy).

H_2 boiler = industrial steam generation.

Synthetic gas = CH_4 synthesis from H_2 and CO_2.

Synthetic liquids = Fischer Tropsch fuels from H_2 + CO_2.

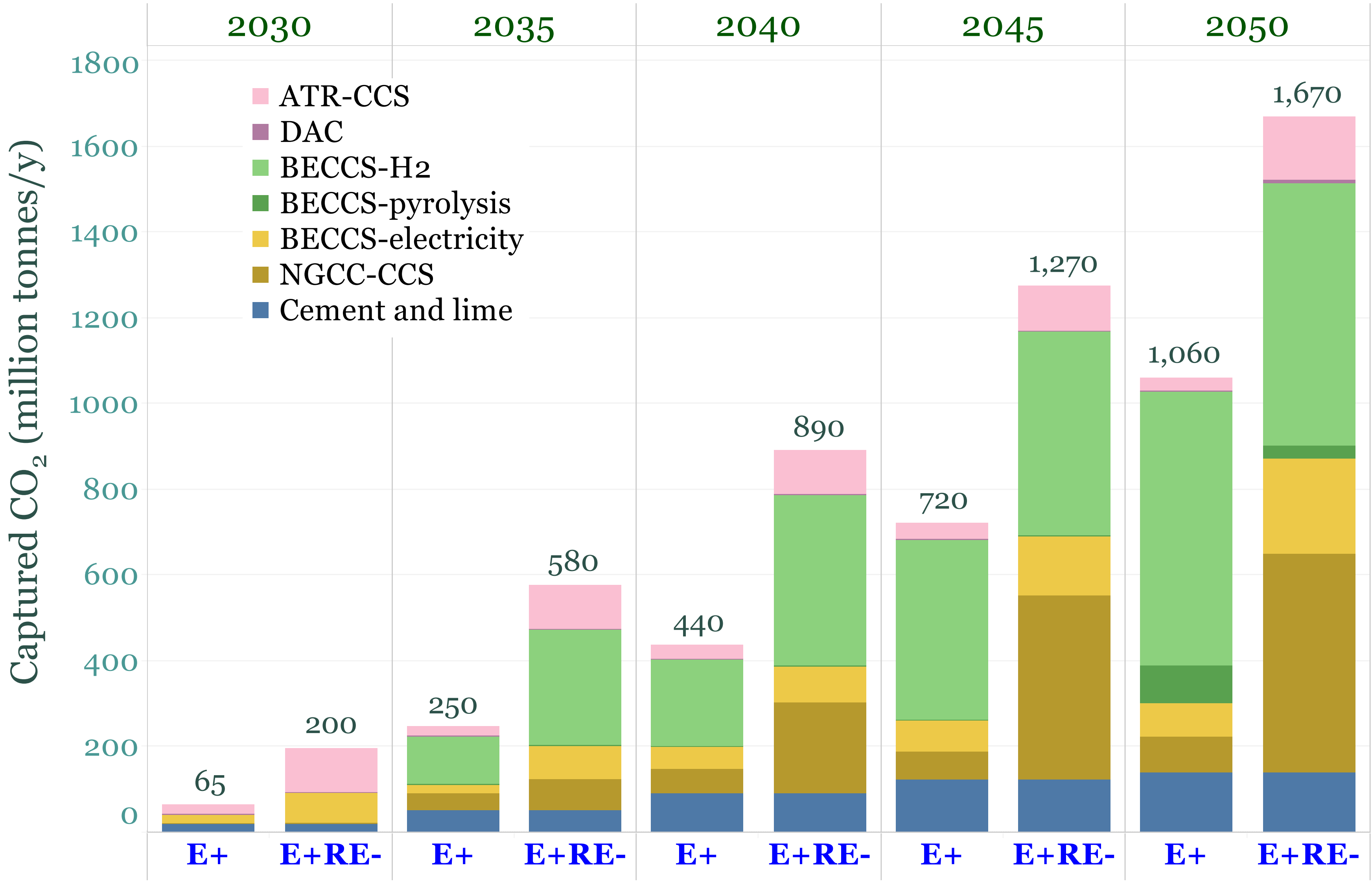
Demand side = H_2 used in transport and for production of chemicals, direct-reduced iron, and process heat in various industries.

Note: All fuel values reported in this slide pack are on HHV basis.

Pillar 4: CO_2 capture, transport, and utilization or geologic storage

- CO_2 capture and utilization is deployed at large scale in all scenarios. Capture and geological storage is deployed at large scale in all except E+RE+, where all captured CO_2 is utilized for synthetic fuels.
- CO_2 capture is deployed on cement production, gas- and biomass-fired power generation, natural gas reforming, biomass derived fuels production, and in some cases from direct atmospheric air capture.
- Geological sequestration rates range from almost 1 to 1.7 billion tonnes of CO_2 per annum by 2050, servicing more than a thousand capture facilities distributed across the nation.
- The majority of geologic sequestration takes place in the Texas gulf coast region, but other basins host sequestration of 10's to more than 100 million tonnes of CO_2 per year.
- An investment of 13 B$ is estimated for stakeholder engagement plus characterization, appraisal and permitting across multiple storage basins and sites before 2035 to enable rapid expansion thereafter.
- The CO_2 capture utilization and storage (CCUS) industry is enabled by > 100,000 km of new CO_2 pipelines having an estimated capital cost of $170 billion (for E+) to $230 billion (for E-B+).
- Estimated unit costs for CO_2 transport and storage average $17 to $23 per tonne stored depending on the ultimate scale of deployment.
- The scale of CO_2 transport and storage in 2050 in these scenarios ranges from 1.3 to 2.4 times current US oil production on a volume-equivalent basis.

Some capture plants online by 2030, followed by rapid growth in 2030s and 2040s. E+ and E+RE- pathways are shown here.



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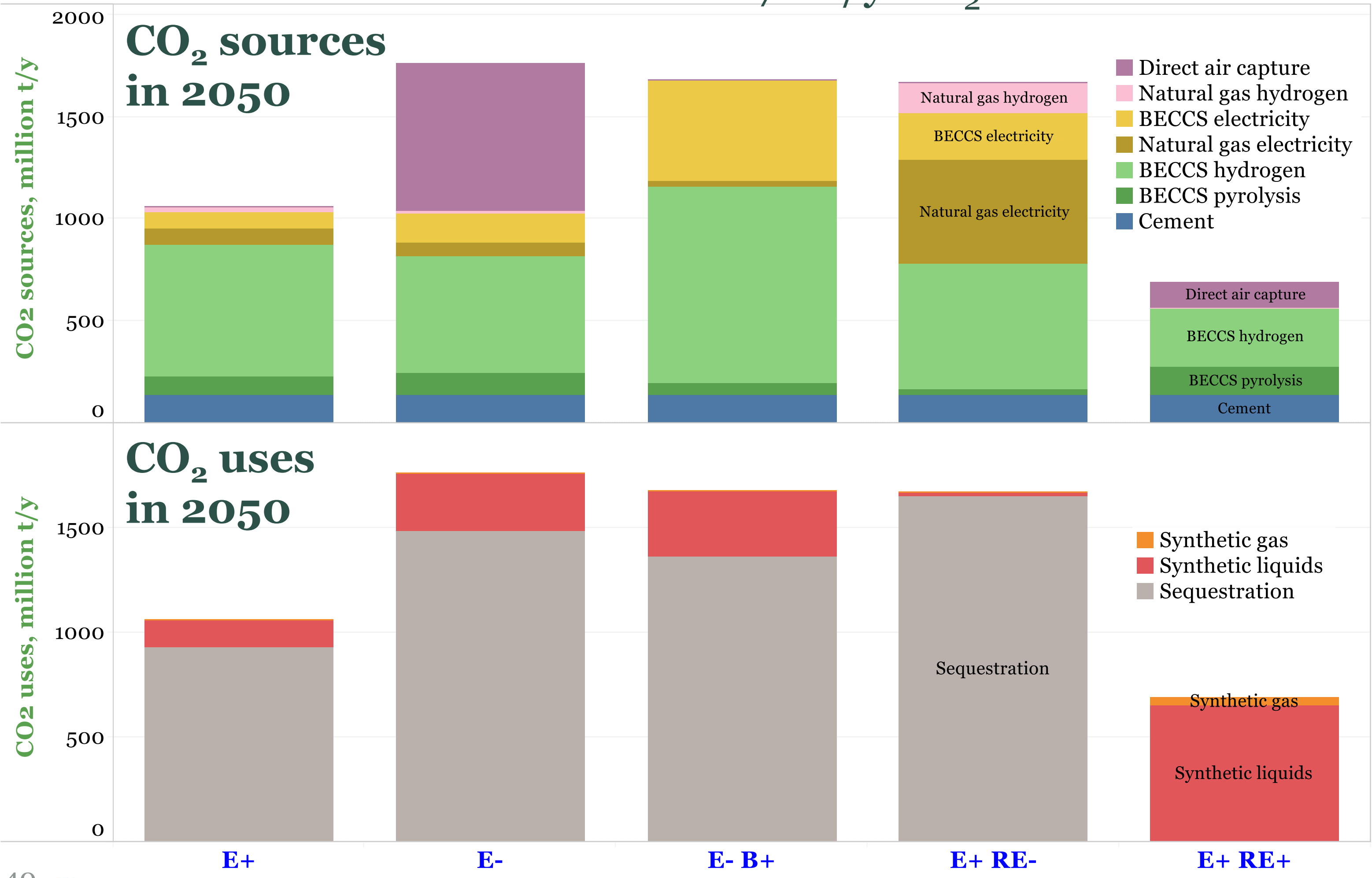
CO_2 capture at multiple facility types and some CO_2 utilization in all pathways; significant CO_2 storage in all but one pathway

By 2050
- 0.7 to 1.8 Gt/y CO_2 captured.
- 0.9 to 1.7 Gt/y CO_2 sequestered.
- 0.1 to 0.7 Gt/y CO_2 converted to fuels.



CO_2 sources

Direct air capture

Natural gas hydrogen (autothermal reforming)

BECCS electricity (gasifier-Allam cycle)

Natural gas electricity (Allam cycle)

BECCS hydrogen (gasifier/water gas shift)

BECCS pyrolysis (hydrocatalytic)

Cement via 90% capture (post-combustion).

CO_2 uses

Synthetic liquids = synthesis of fuels from $H_2 + CO_2$.

Synthetic gas = methane synthesis from $H_2 + CO_2$.

Sequestration = geological storage

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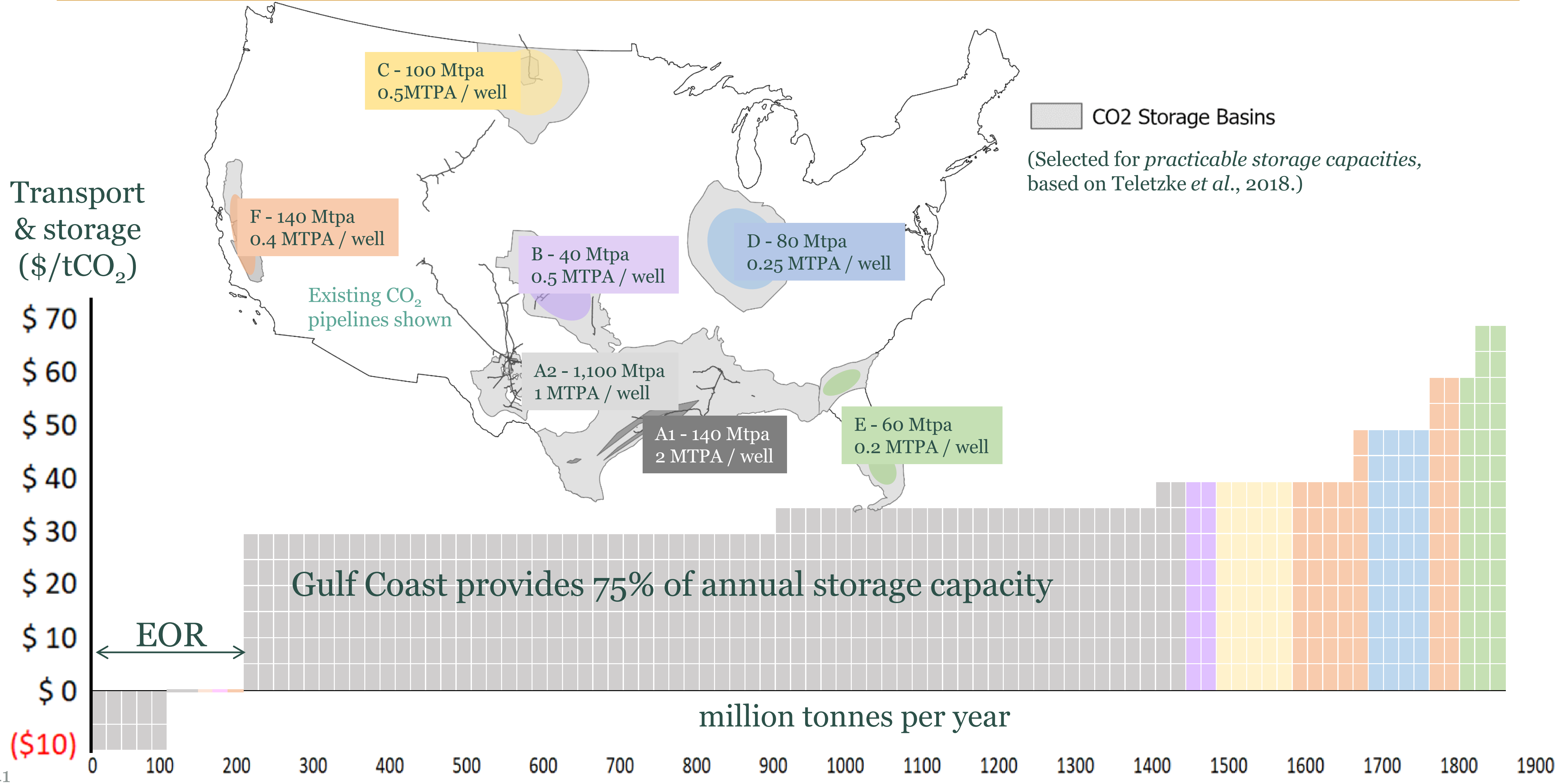
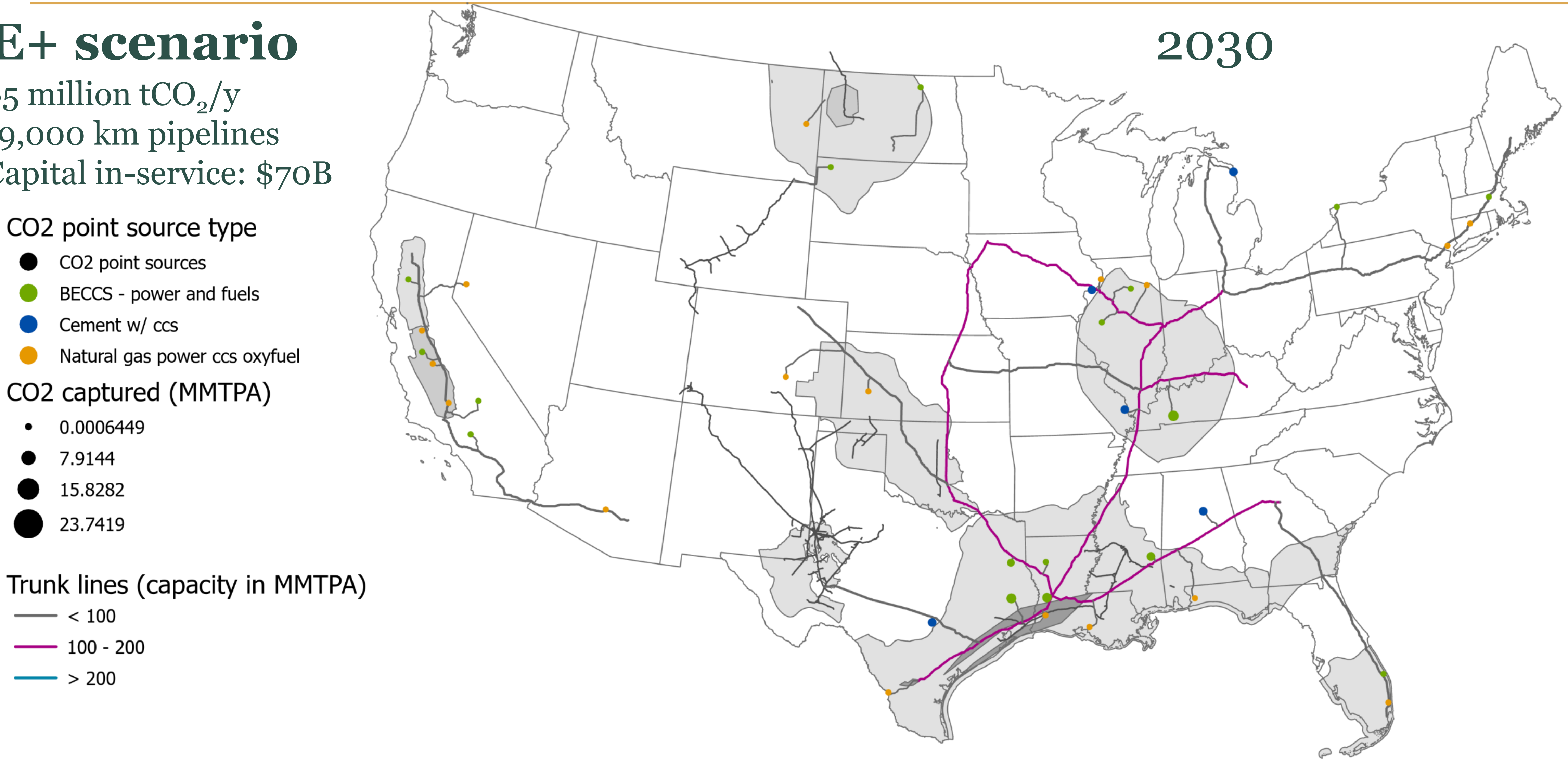
Notional CO_2 storage capacity appraised, permitted and developed in 2050 is 1.8 billion t/y, mostly in Gulf Coast



Significant trunk lines built by 2030; initial CO_2 capture plants come online, with spur lines connecting to trunk network

E+ scenario

65 million tCO_2/y
19,000 km pipelines
Capital in-service: $70B



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2050 totals: 21,000 km trunk lines + 85,000 km spur lines (equivalent to ~22% of US natural gas transmission pipeline total)

E+ scenario

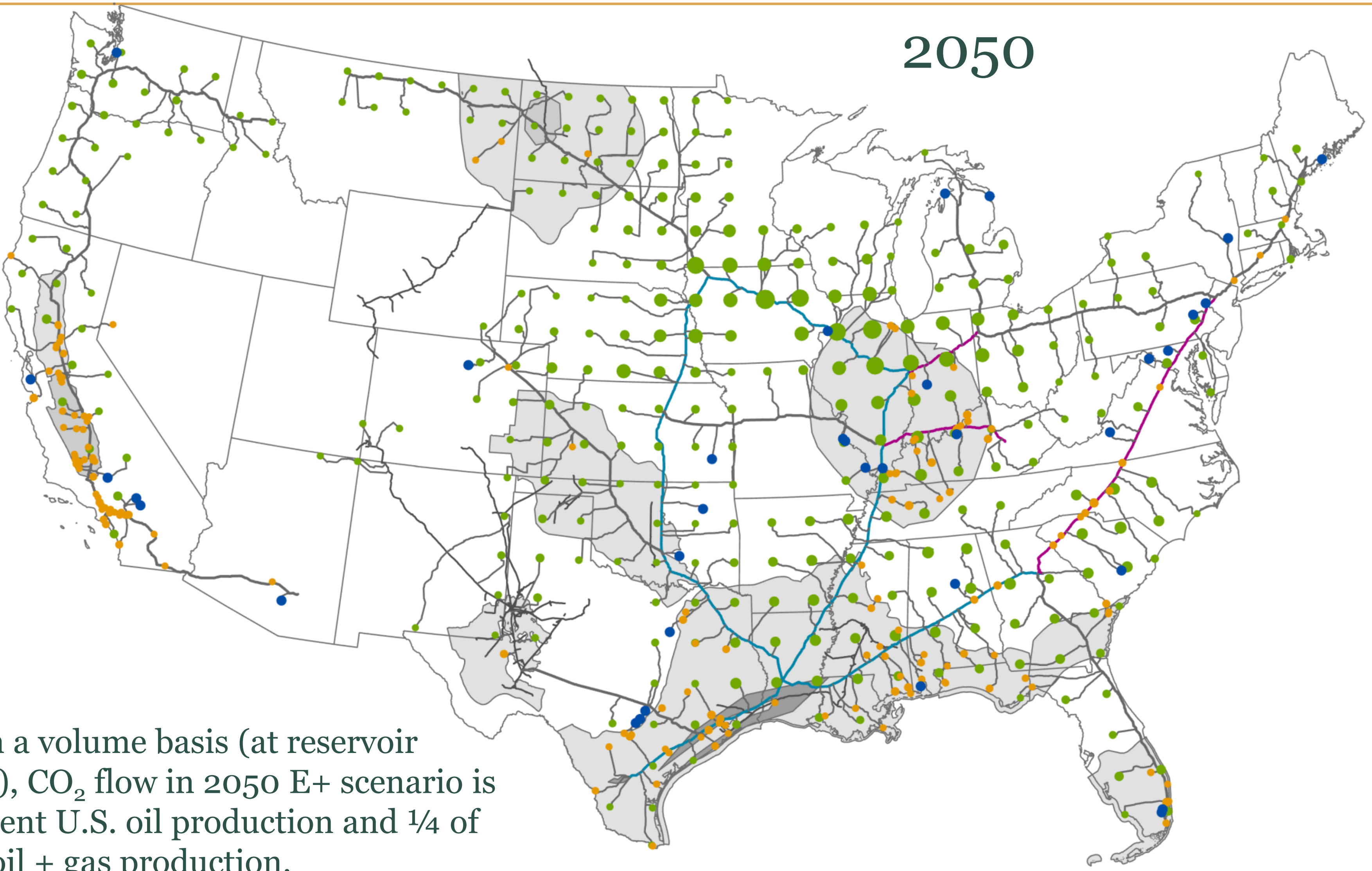
929 million tCO_2/y
106,000 km pipelines
Capital in service: $170B

CO2 point source type
- CO2 point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO2 captured (MMTPA)
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA)
- < 100
- 100 - 200
- > 200

2050



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

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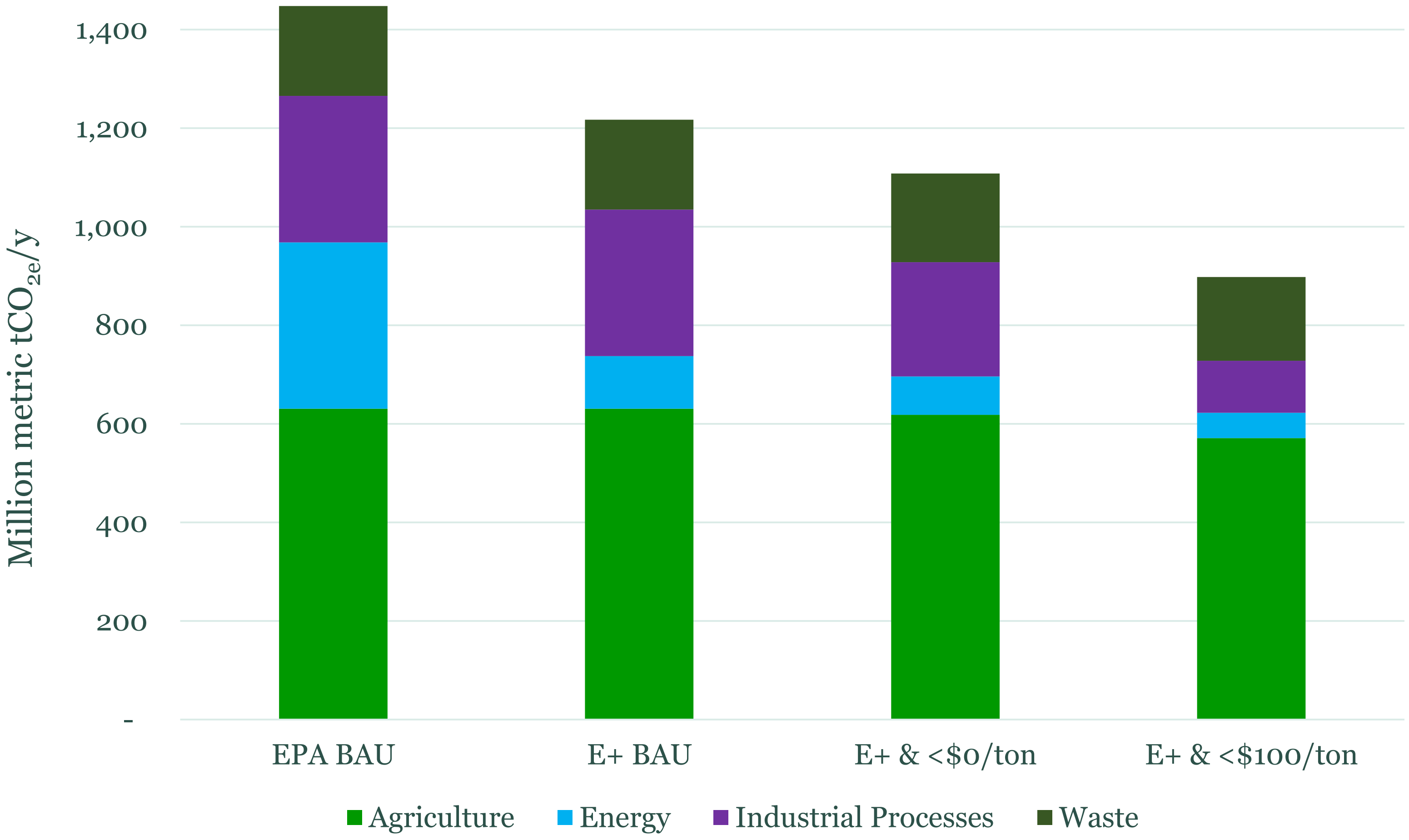
Pillar 5: Reduced non-CO_2 emissions

- In a net-zero future, non-CO_2 greenhouse gas emissions each year must be compensated by removal of an equivalent amount of CO_2 from the atmosphere. In the modeling here, negative emissions can be achieved by permanent storage underground (or in long-lived plastics or similar products) of CO_2 derived from biomass or directly captured from the air, or (as discussed below under Pillar 6) by uptake in soils and trees.
- Sources of methane and nitrous oxides – the majority of non-CO_2 emissions today – are widely dispersed, making mitigation more challenging, and non-CO_2 emissions are projected to grow in the future under business-as-usual.
- The Net-Zero America study team did not conduct original analysis assessing mitigation options, but assumed as an input to the modeling a level of mitigation from 2020 to 2050 consistent with recent analysis from the U.S. Environmental Protection Agency (EPA).
- EPA's mitigation estimates assume future levels of oil and gas use that are closer to those of a "business-as-usual" future than our net-zero scenarios. In the latter, fossil fuel use is at least 70% to 80% lower than today by 2050. The EPA projections assume some mitigation of non-CO_2 emissions associated with producing and transporting fossil fuels. Under a net-zero scenario, these emissions would be significantly lower due to the reduced fossil fuel use.

Mitigation can reduce emissions to ~1 Gt per year by 2050, but beyond that the path to deeper reductions remains uncharted

2050 Non-CO_2 Emissions ($MtCO_{2e}$)



In 2050:

- *EPA BAU*: no mitigation. Non-CO_2 emissions reach 1.45 $GtCO_{2e}$/y
- *E+ BAU*: Non-CO_2 mitigation due to reduced fossil fuel use in E+ net-zero path. Non-CO_2 emissions fall to 1.22 $GtCO_{2e}$/y (coal production essentially ceases and oil/gas output drops ~75%)
- *E+ & <$0/ton*: Very low-cost mitigation yields 1.11 $GtCO_{2e}$/y
- *E+ & <$100/ton*: Higher cost mitigation measures reduce emissions to 0.90 $GtCO_{2e}$/y.

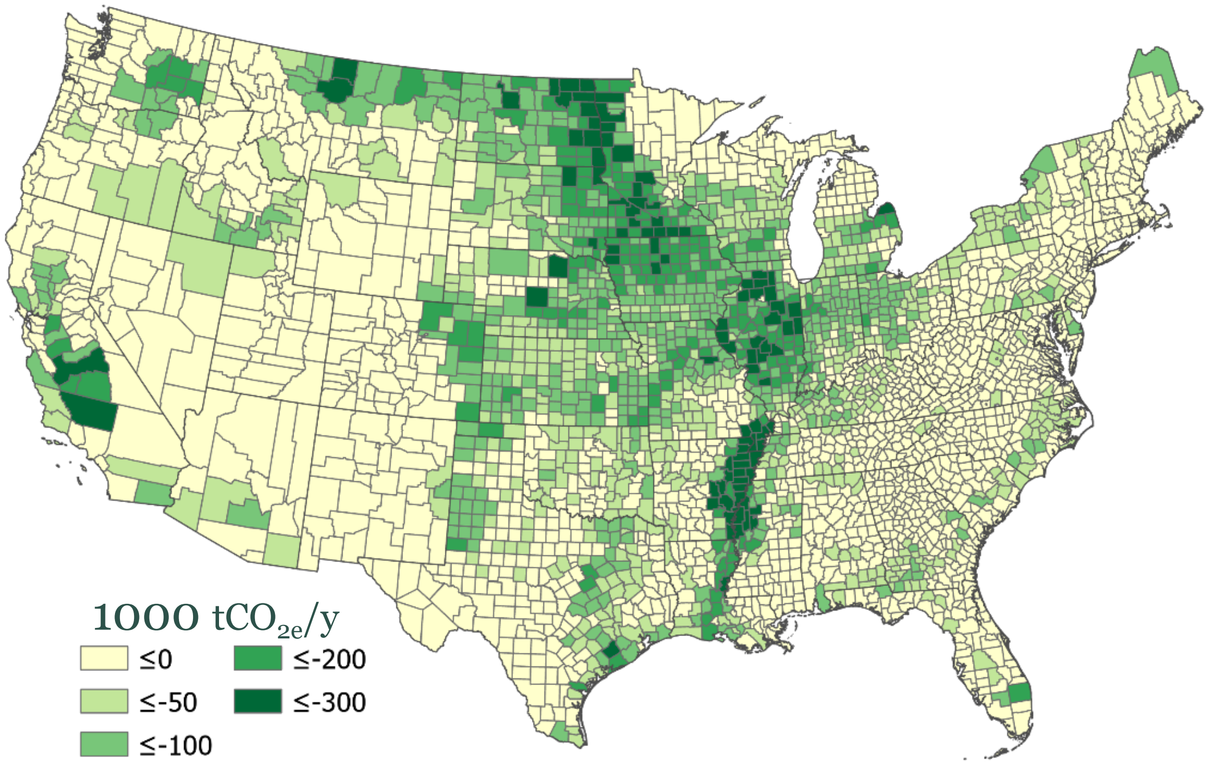
Source: EPA, *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019, with adjustments for E+ scenario.

Pillar 6: Enhanced land sinks

- Land carbon sinks, i.e., annual removal of carbon from the air and permanent storage in soil or trees, are critical for net-zero emission scenarios, because they offset positive greenhouse gas emissions from elsewhere in the economy.
- In the cost-minimized net-zero scenarios developed in this study, the last unit of CO_2 emission avoided from the energy/industrial system is the most expensive one to avoid. Thus, land sinks avoid using the most costly measures for CO_2 emissions reductions in the energy/industrial system.
- There is uncertainty about what the magnitude of the U.S. land sink is today, but 0.7 $GtCO_{2eq}$/y is thought to be a reasonable estimate, and there is an expectation that the natural land sink will weaken in the future to as low as 0.3 Gt/y by 2050 due to maturing of forest regrowth in the U.S.
- Geographically-resolved analysis by Net-Zero America researchers estimates a technical potential for enhanced land sinks by 2050 of up to 0.2 $GtCO_{2eq}$/y in agriculture and from 0.5 to 1.5 $GtCO_{2eq}$/y in forestry.
- The net-zero modeling in this study assumes the land sink as a whole grows to 0.85 $GtCO_{2eq}$/y by 2050, which implies a concerted effort to deploy agricultural and/or forestry land sink enhancement measures from 2020 to 2050.

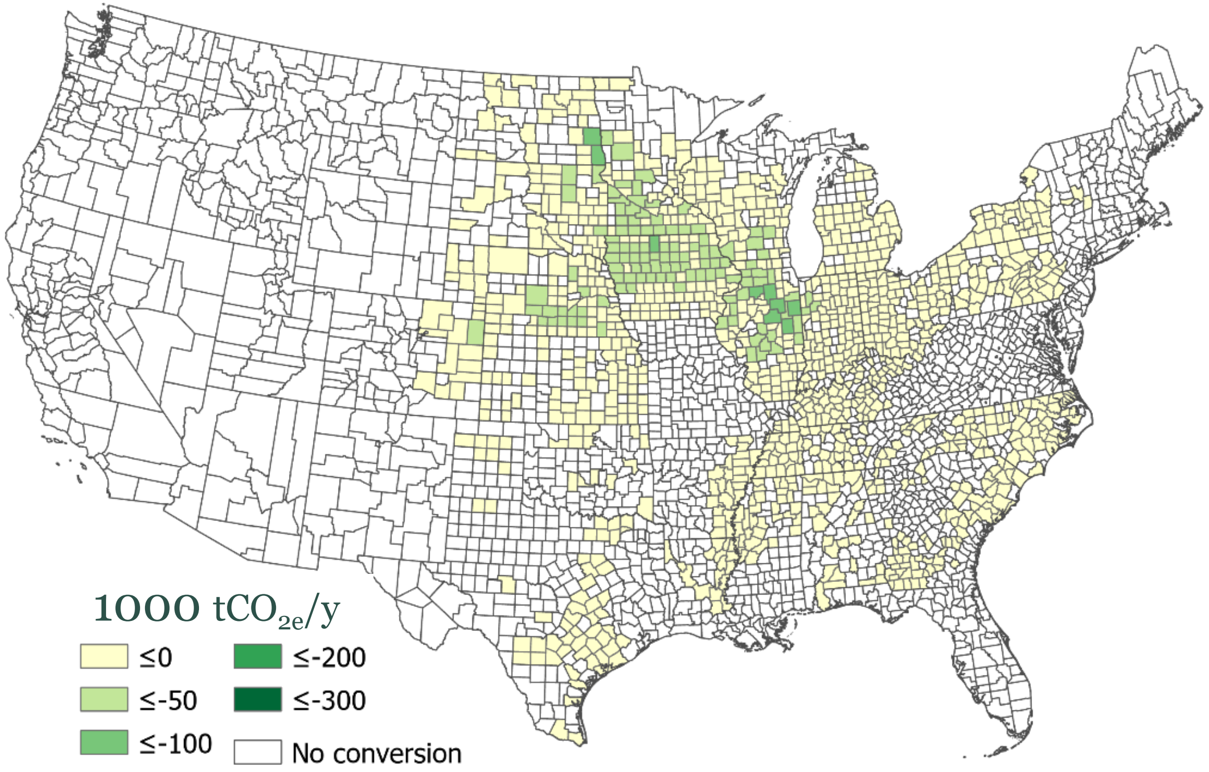
Maximum annual carbon uptake potential on agricultural lands by county; Midwestern states account for >80% of the potential.

Carbon storage across all agricultural lands (160 million ha)



Total U.S. potential: 230 million tCO_{2e}

Carbon storage on ethanol-corn land converted to energy grasses (11 Mha)



Total U.S. potential: 23 million tCO_{2e}

See Swan, et al. (Annex Q).

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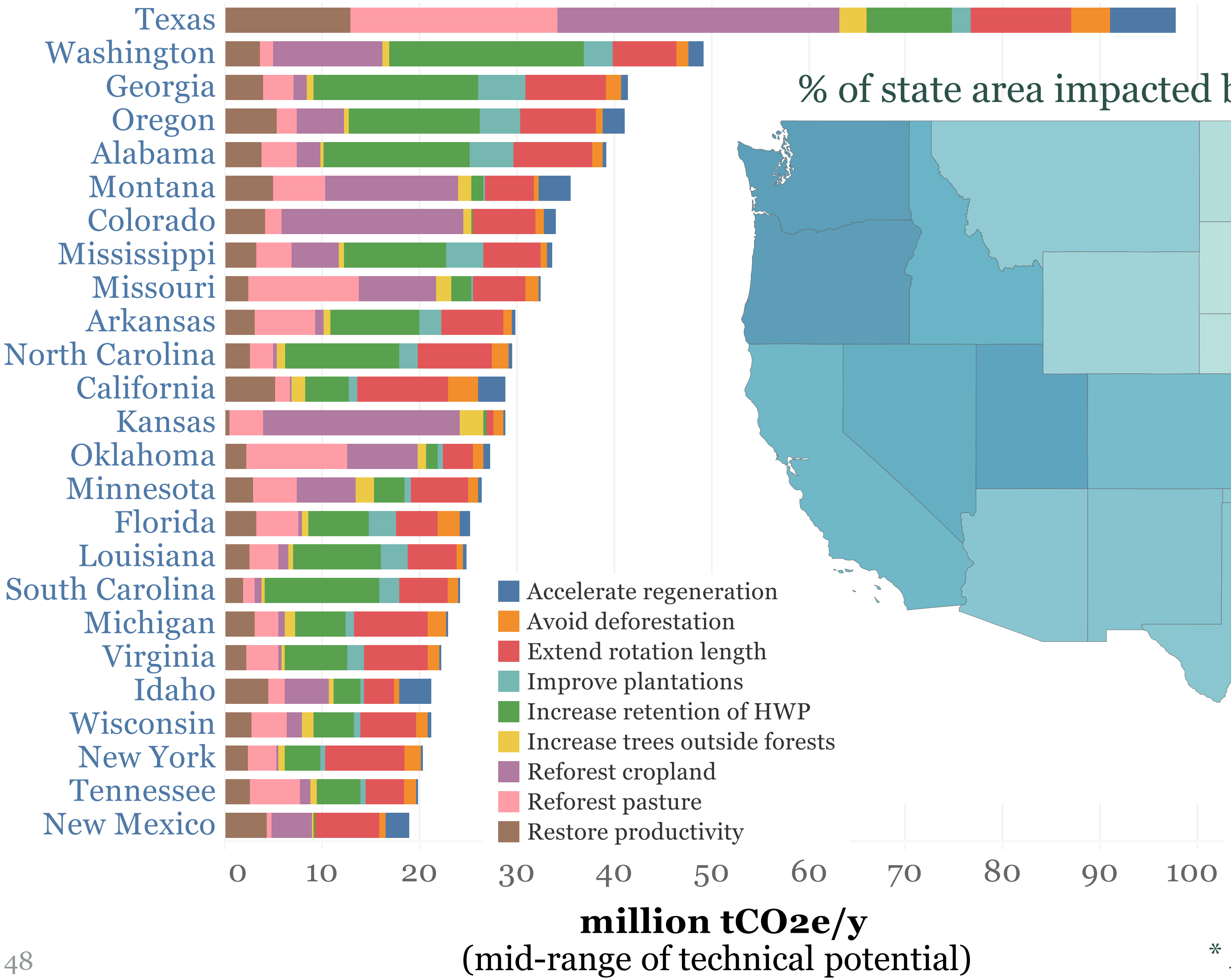
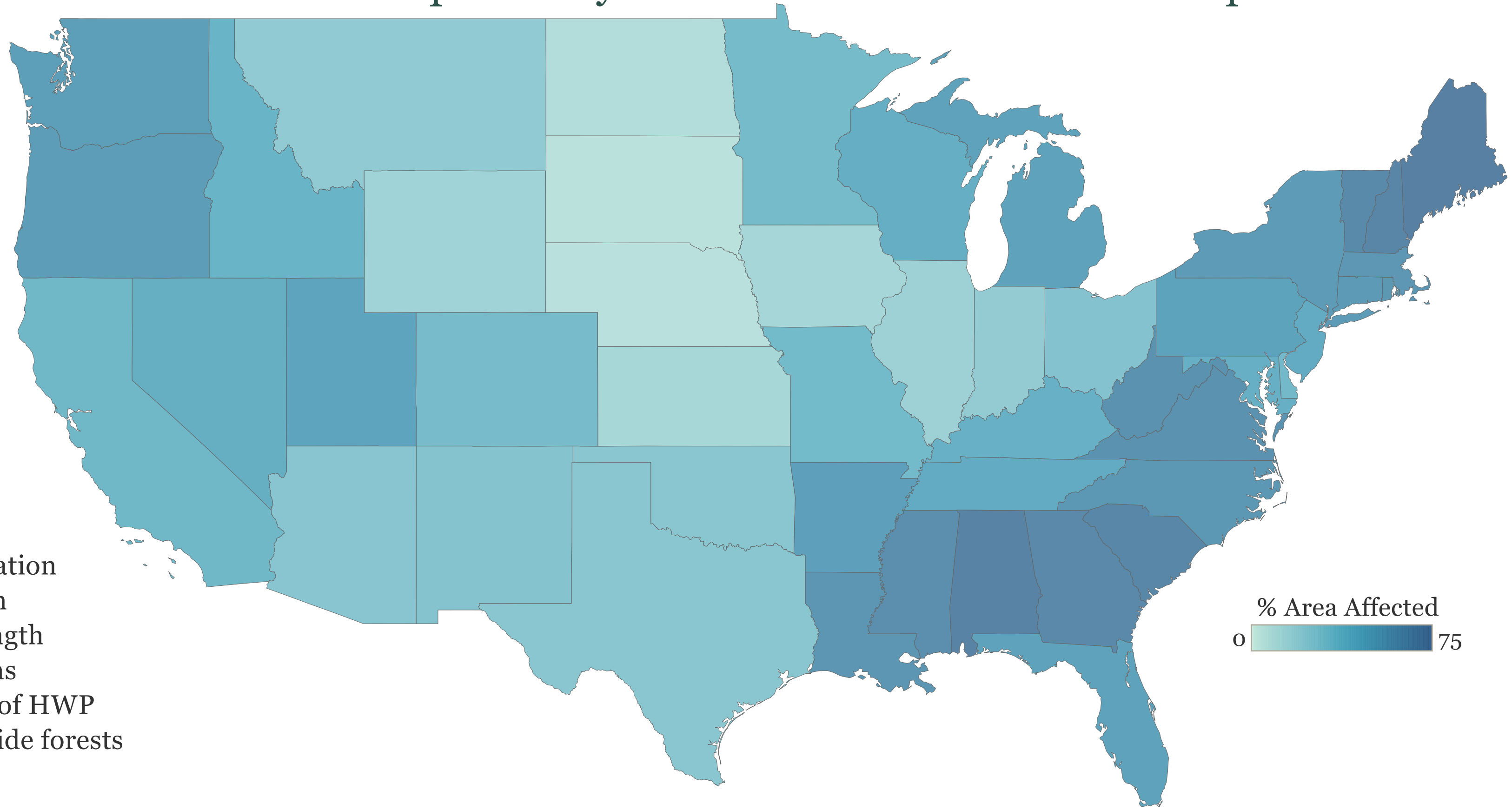
1 $GtCO_{2e}$/yr technical potential for enhanced carbon storage on forest lands (mid-range of estimates)



% of state area impacted by measures to achieve technical potential*



25 states shown in the bar graph have 80% of total US technical potential

* ≥ 130 Mha, or more than ½ of all forest area, are impacted.

2. Capital mobilization

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Capital mobilization

- Net-zero scenarios are 2 – 4 times more capital intensive than REF. E+ requires >2.6 T$ of energy supply-side risk-capital deployed before 2030 and >10 T$ trillion by 2050.
- Capital investments are long-lived, so timing of investments and divestments are critical. NZA models assume rational and efficient markets, and investors responding instantly to incentives to mobilize capital. In reality, capital mobilization requires substantial lead times and resources under considerable uncertainty.
- E+ requires ~190 B$ of investment before financial investment decisions (FID) on energy-supply projects through 2030 and 600 B$ through 2050. Pre-FID investment typically occurs 2-10 years in advance of when projects come online. Pre-FID costs are fully at-risk, since any given project may not proceed past FID to generate value.
- *Risk capital* includes pre-FID capital, as well as all additional capital committed prior to the Commercial Operation Date (COD) of a project. Pre-COD capital is exposed to various development, market, construction and technology performance risks which can impact project cashflows and hence project valuation.
- Investors face deep uncertainty on future technology costs and performance, policies of future governments, investment preferences among peers, customers and competitors, and public acceptance of certain technologies.
- NZA modeling approach obscures key potential challenges to mobilizing risk-capital for project development and construction that must be mitigated through policy mechanisms to meet the 2050 net-zero target.
- Such mechanisms include investment during the 2020's to create *real options* for technologies needed post 2030, including multiple full-scale 'first-N-of-a-kind' projects to de-risk and reduce the cost of less-mature technologies and investment in critical enabling infrastructure (e.g. electricity transmission and CO_2 pipelines) to serve various future supply-side investments.

To avoid lock-in and reduce cost of transition, net-zero pathways capitalize on timing of stock turnover for long-lived assets

Typical asset replacement times for various durable assets

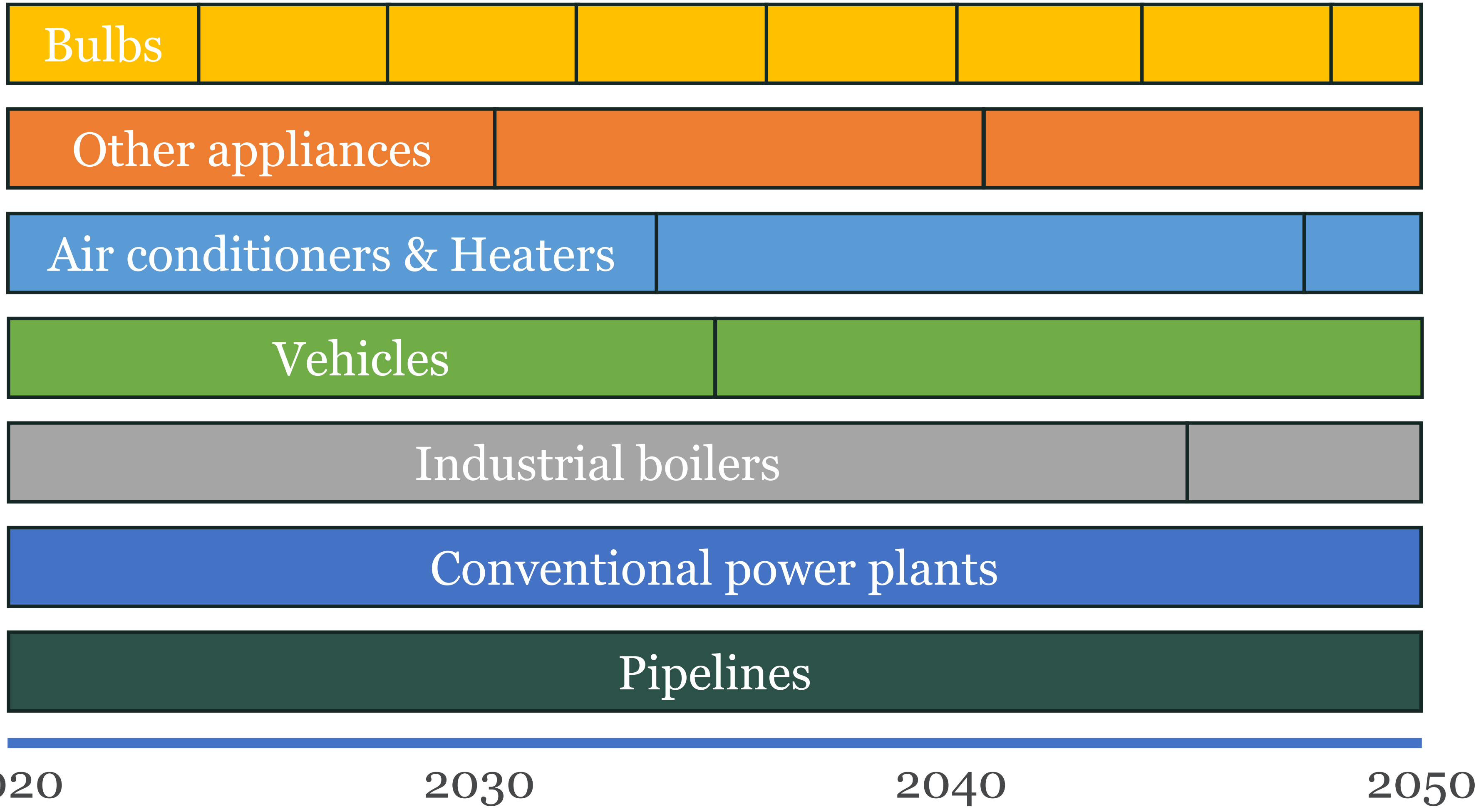

Image credit: Ryan Jones, Evolved Energy Research

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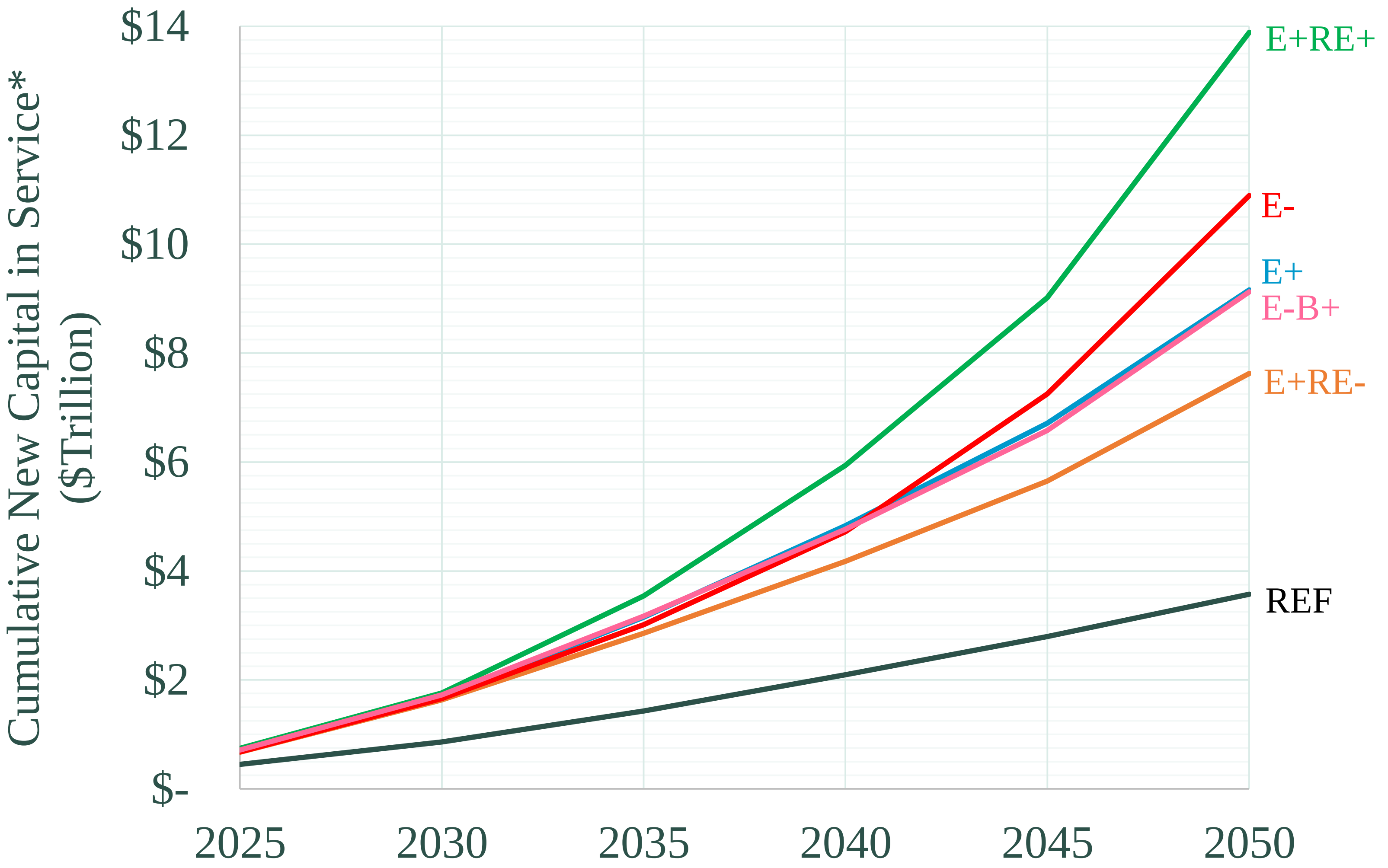
Capital dominates energy system costs in net-zero pathways: Supply-side capital in service by 2050 is 2 to 4 times REF.

- Capital-investment decision processes typically involve greater pre-investment capital-at-risk and corporate scrutiny than operating-cost decisions.
- The sheer number of capital decisions implied in these pathways represents a challenge for the transition schedule.
- Policy environment will be a key determinant of pace/scale of capital investment.



* Estimated capital cost of energy supply assets including power generation, transmission and distribution, fuels conversion assets and CO_2 transport infrastructure. Excludes liquid and gaseous fuel distribution infrastructure for which very significant investments will be needed across all net-zero pathways. Also excludes pre-investment studies, permitting and finance costs.

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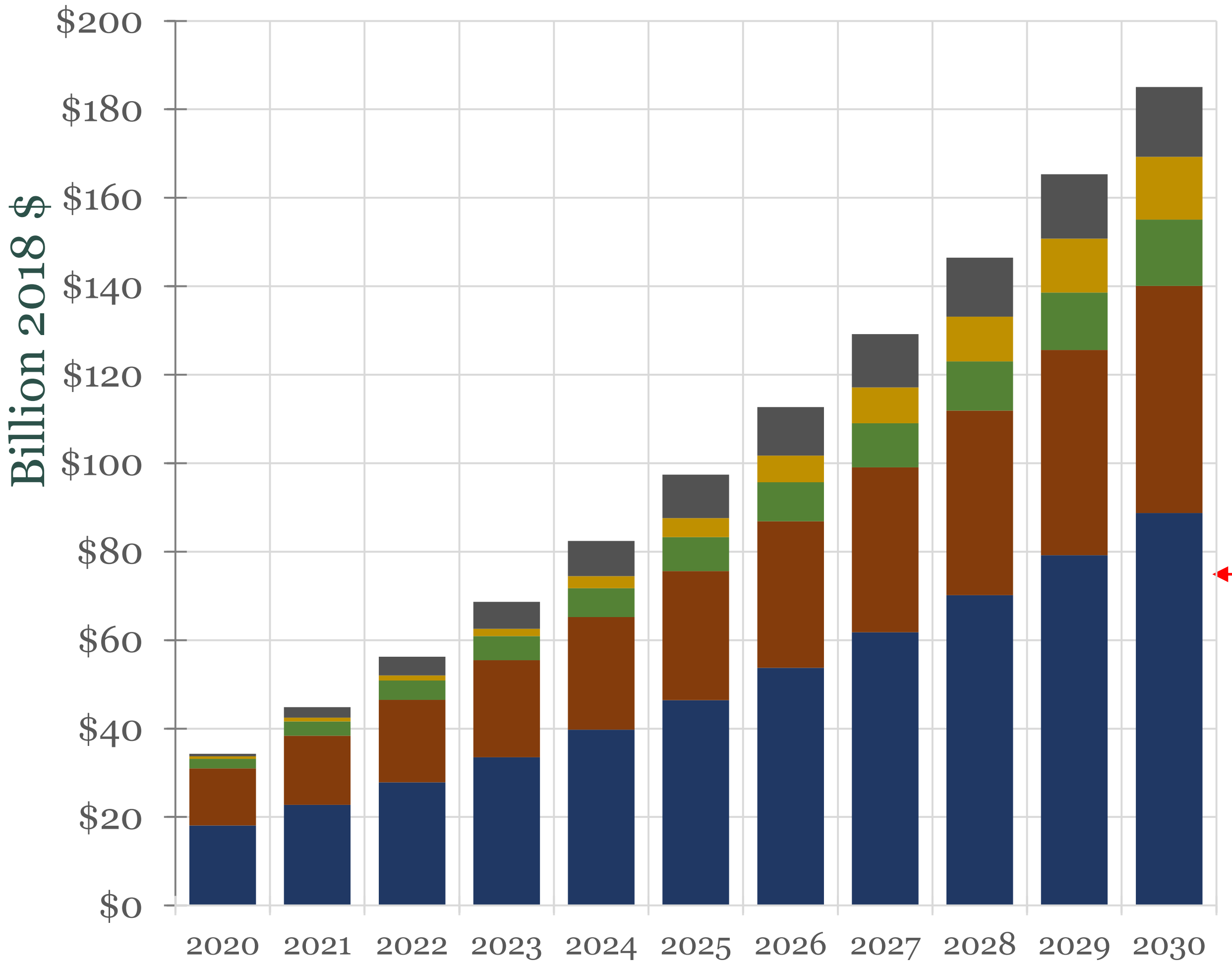
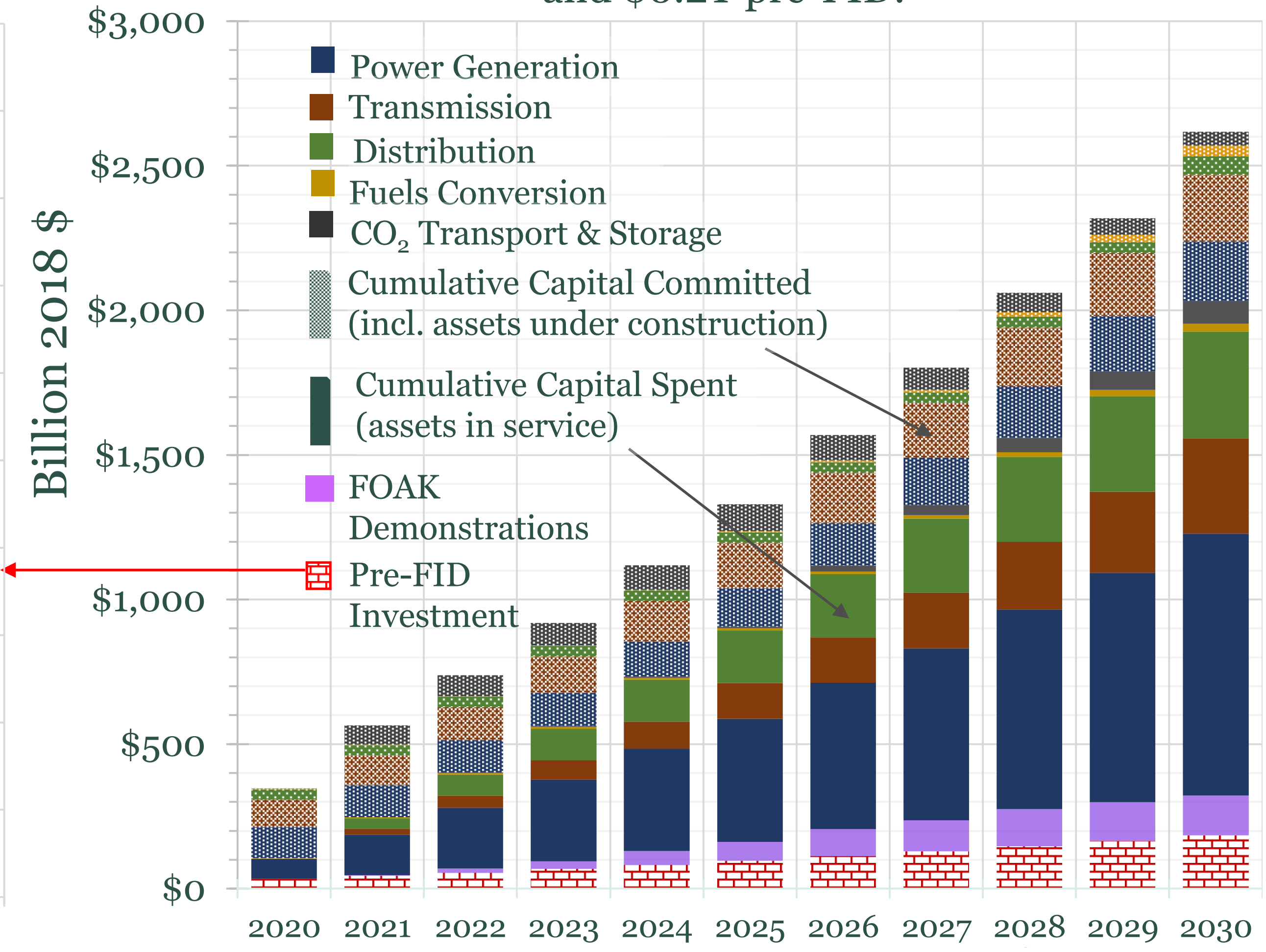
Mobilizing risk capital for development and construction will be a significant challenge for the 2020s (and beyond).

E+

$185 B$ at-risk pre-FID development costs in 2020's to support **supply-side** capital investment decisions



2.6T$ committed to **supply-side** plant & infrastructure in 2020's: $1.8T in service, $0.6T in construction, and $0.2T pre-FID.



Note: Investments in demand-side transport, buildings and industry; fuels distribution systems; biomass crop establishment; and land sink enhancements have not been estimated and are not included in these charts.

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3. Land use

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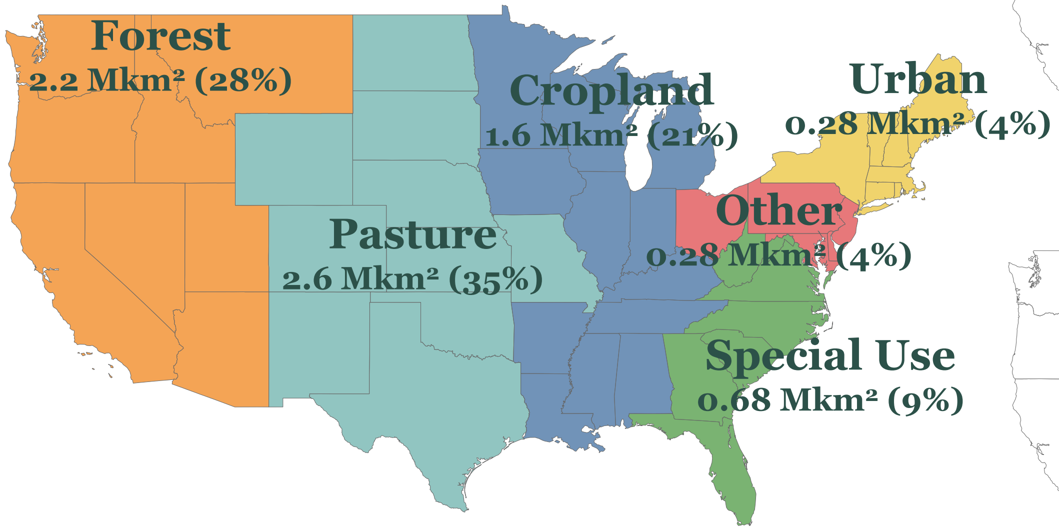
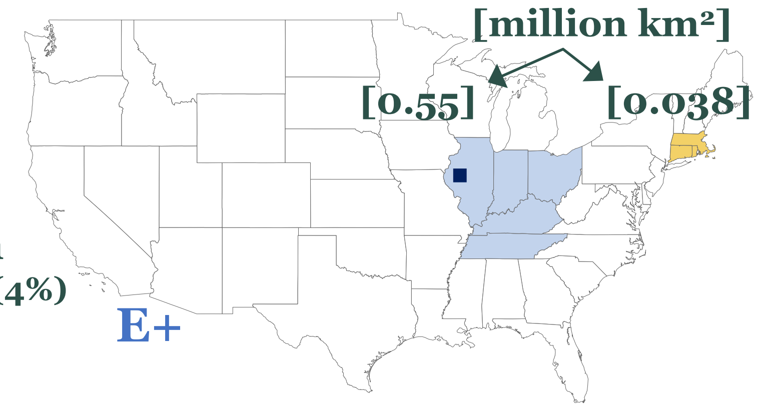
Land use

- Direct land use for wind-turbine pads in net-zero scenarios is small, but the (visual) footprint of wind farms is significant. In 2050, total wind farm visual footprint is smallest for E+RE- at ¼ million km^2, or the equivalent of the combined land areas of Illinois and Indiana. The footprint is largest for E+RE+ at 1 million km^2, or the equivalent of Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma combined. Wind projects are concentrated in the Great Plains, Midwest, and Texas, primarily on crop, pasture, and forested lands.
- Land use for solar farms in 2050 is much smaller than the visual footprint of wind farms, but directly impacted lands are greater, ranging from the equivalent of the area of Connecticut for E+RE- to that of Virginia for E+RE+. Solar deployment is greatest in the Northeast and Southeast, and forested lands make up the largest directly impacted land cover type.
- The only scenario for which there is land-use change associated with biomass use is the E-B+ scenario, where land area equivalent to the combined areas of Alabama and Mississippi (> ¼ million km^2) is converted from crop or pasture land to dedicated cultivation of perennial energy crops.
- Even with constrained site availability, only 6% of solar candidate project areas (CPA) in E+RE+ are used, indicating the potential to substantially reconfigure solar siting in any scenario so as to minimize land-use conflicts. Wind projects use 45% of CPAs in E+ and 90% of CPAs in E+RE+, indicating greater potential for wind to be constrained by siting challenges.

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)

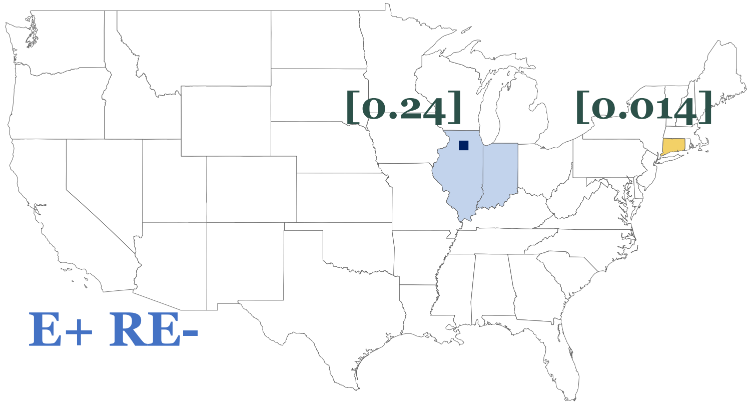


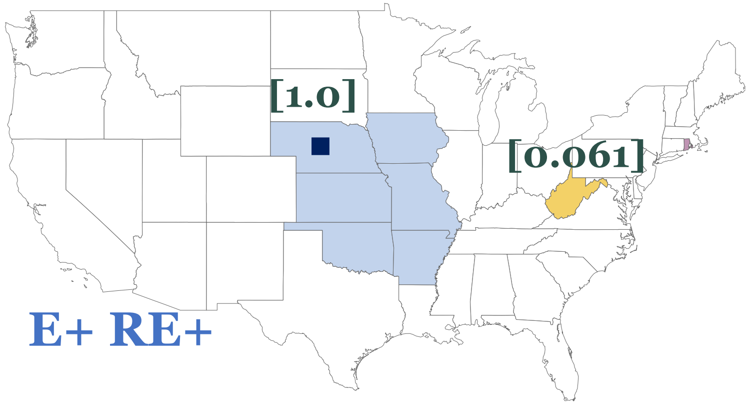


Equivalent land area for

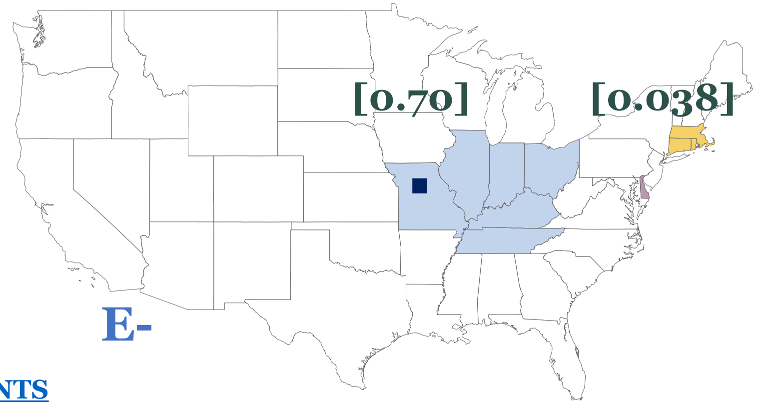
- Solar farms
- Wind farms
- Biomass farms*
- Direct air capture

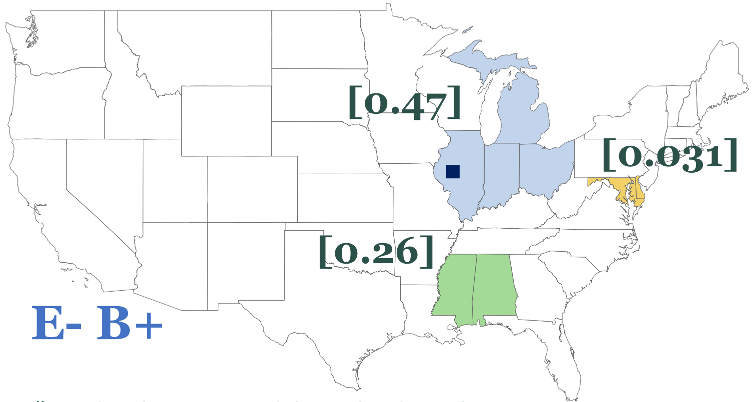
Note: Directly impacted land area for wind farms (equipment footprint) is indicated by ■. For solar and biomass, directly impacted areas are 91% and 100% of shaded area shown.





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





* On lands converted from food production.

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4. Energy workforce

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Modeled employment impacts

- To support a net-zero transition, the supply-side energy workforce expands by 15% in the first decade and by 1.2x to 3x by 2050.
- Net-zero pathways support a net increase of 0.3-0.6 million jobs by 2030 relative to the REF scenario.
- Net job losses in fossil fuel sectors across the transition are more than offset (in aggregate) by increases in low-carbon sectors, especially solar, wind, and electric-grid sectors. Construction comprises an increasing proportion of jobs over time, and mining (i.e., oil, gas, coal upstream activities) comprises a declining portion.
- An annual average of ~$170-180 billion in wages are generated in the 2020s, a net increase of $20-30 billion over the REF scenario.
- A number of modifiable socio-technical factors influence the spatial distribution of labor, such as technology choices, pace of low-carbon infrastructure expansion, infrastructure siting and investment decisions, oil and natural gas exports, and extent of domestic manufacturing. With assumptions used here for these factors, all states see energy-related employment grow as a share of the total state labor force except for a few with very high shares of the current labor force employed in upstream fossil fuel industries (e.g., WY).
- Net-zero transitions have the potential to significantly transform state and local economies. The modifiable socio-technical factors referred to in the prior bullet, can be leveraged to reduce transition risks and to facilitate legislative bargaining.
- Policies that anticipate and leverage the skill, temporal, and locational complementarities between workforces of declining and emerging energy sectors can aid in moderating concentrated unemployment and mitigating labor supply bottlenecks.

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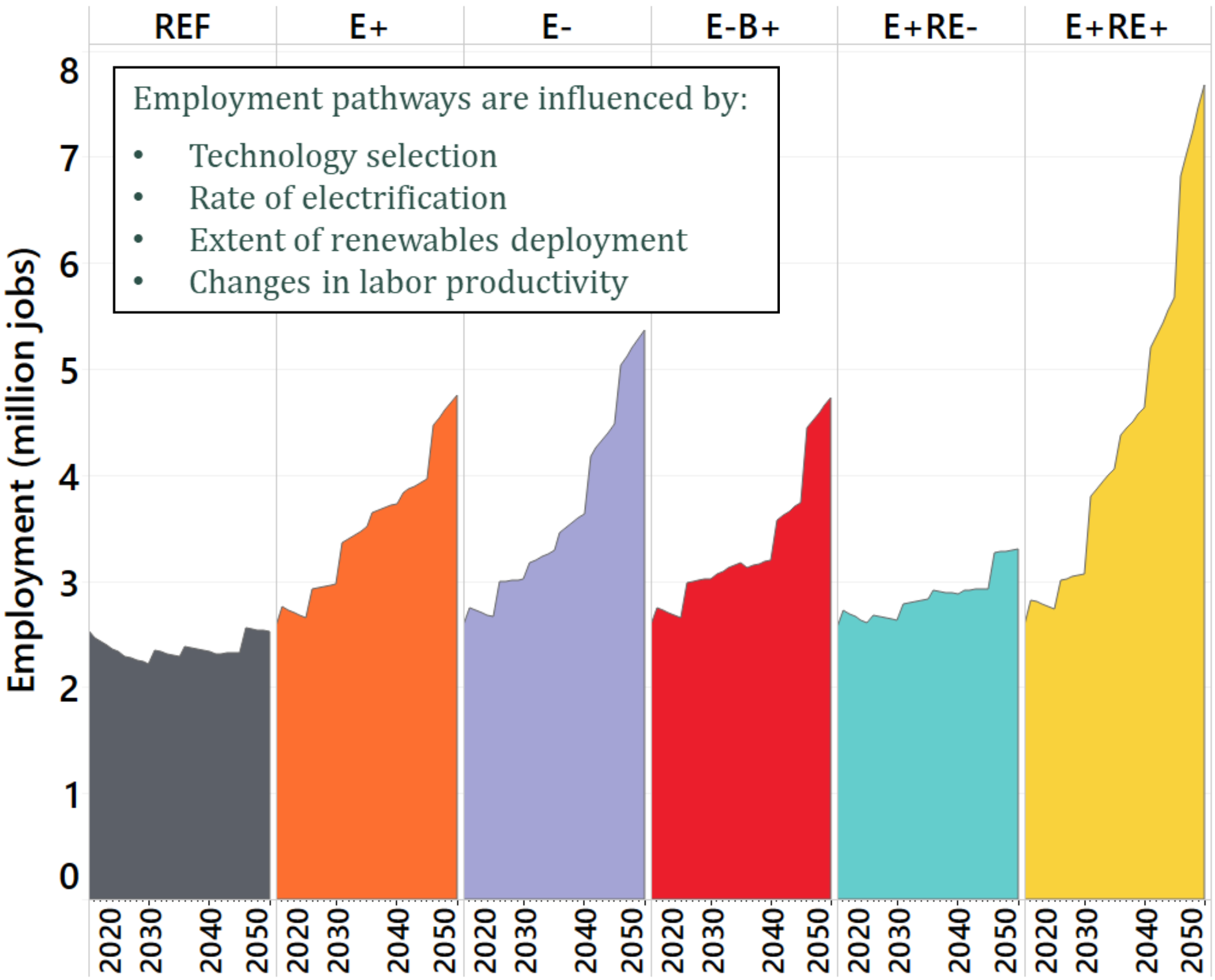
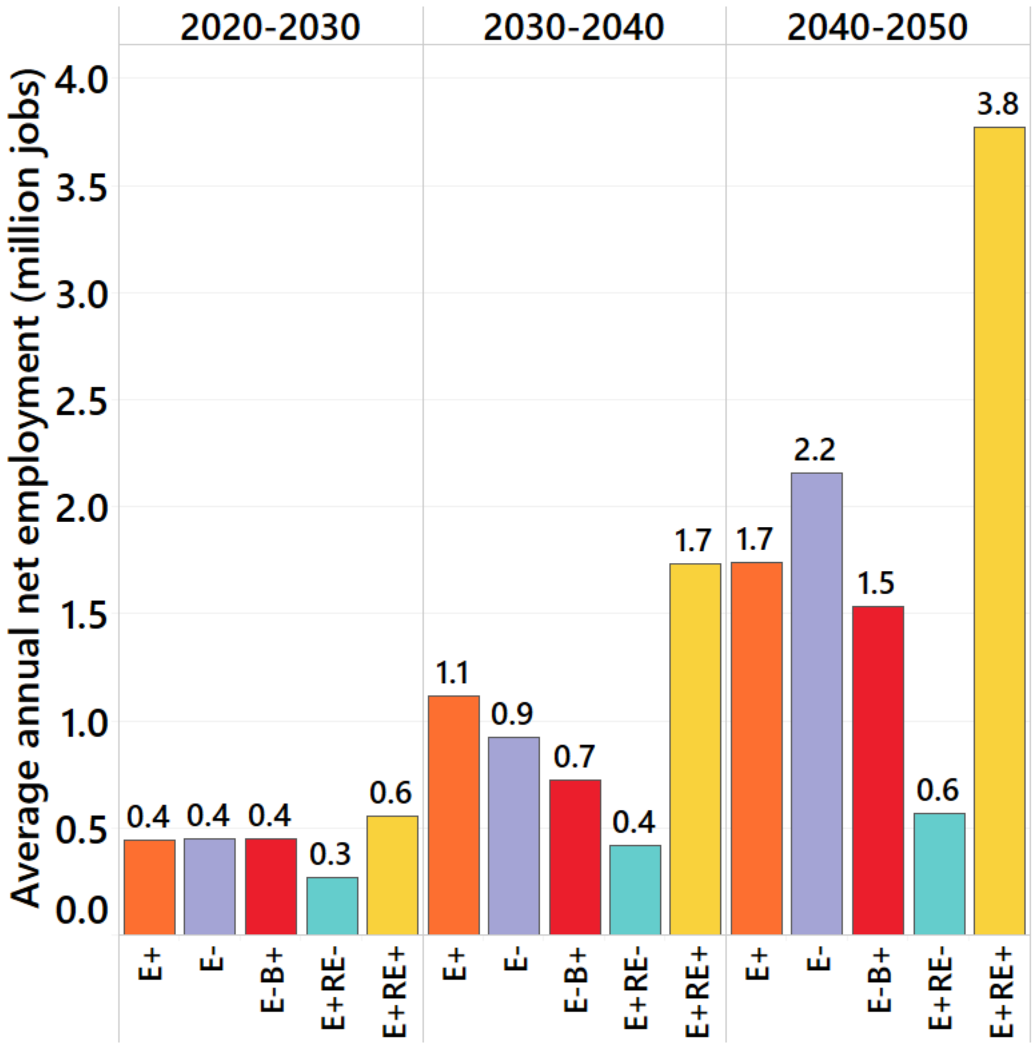
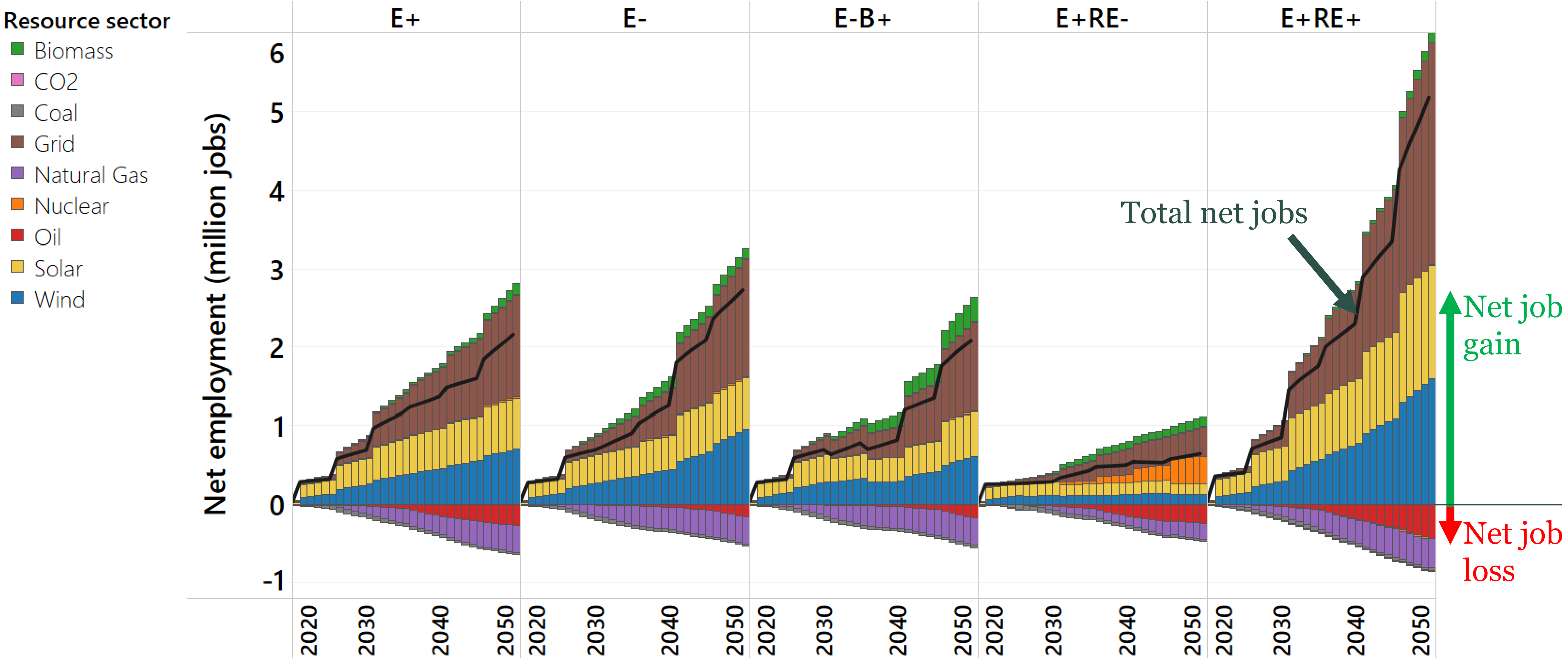
~3 million direct energy-supply jobs annually in the 2020s in net-zero scenarios, or ~0.5 million more than REF scenario.



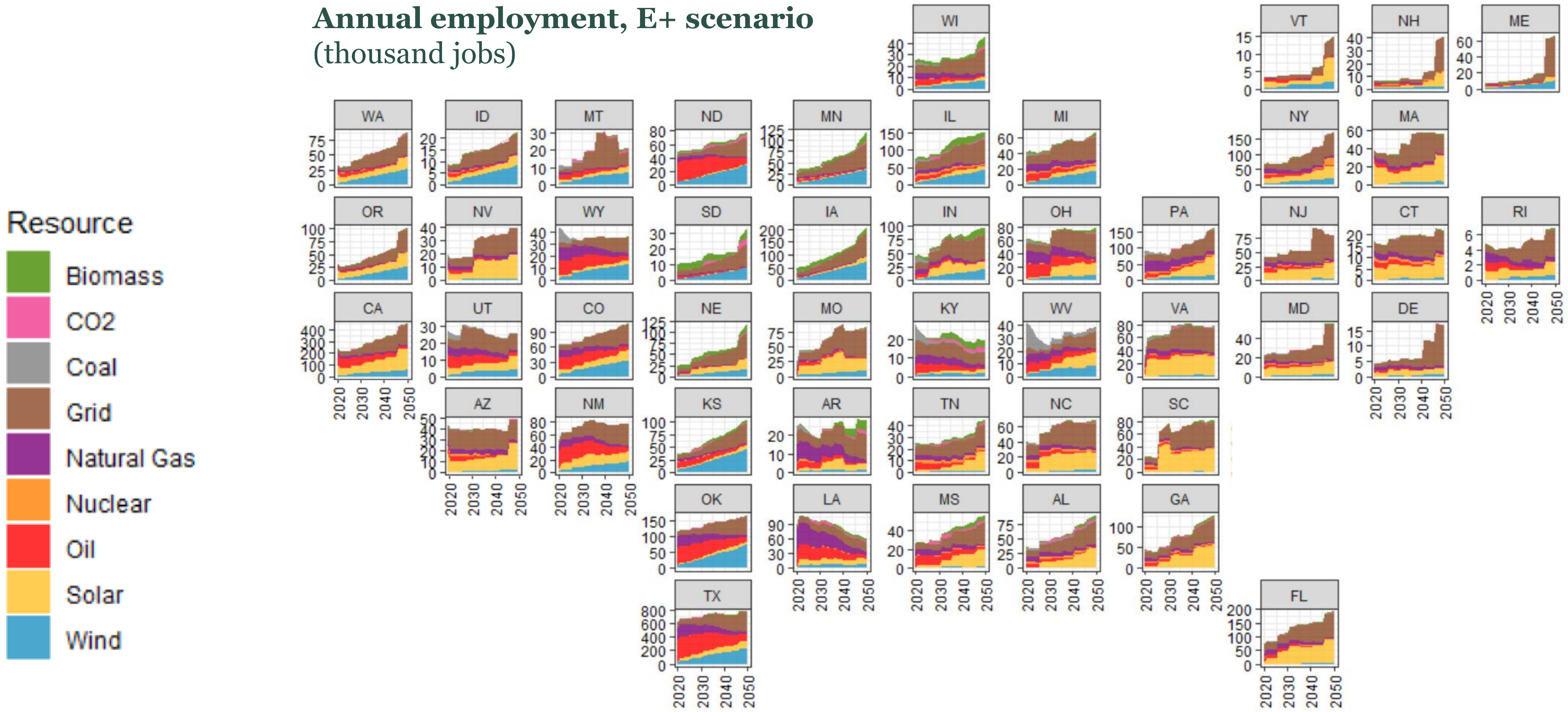


Net job losses in fossil fuel sectors in near- and long-term are more than offset (in aggregate) by increases in low carbon sectors.



Solar, wind, and grid jobs are increasingly dominant in many states, but regional heterogeneity could be a risk to a just transition

Annual employment, E+ scenario
(thousand jobs)



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5. Air pollution and public health

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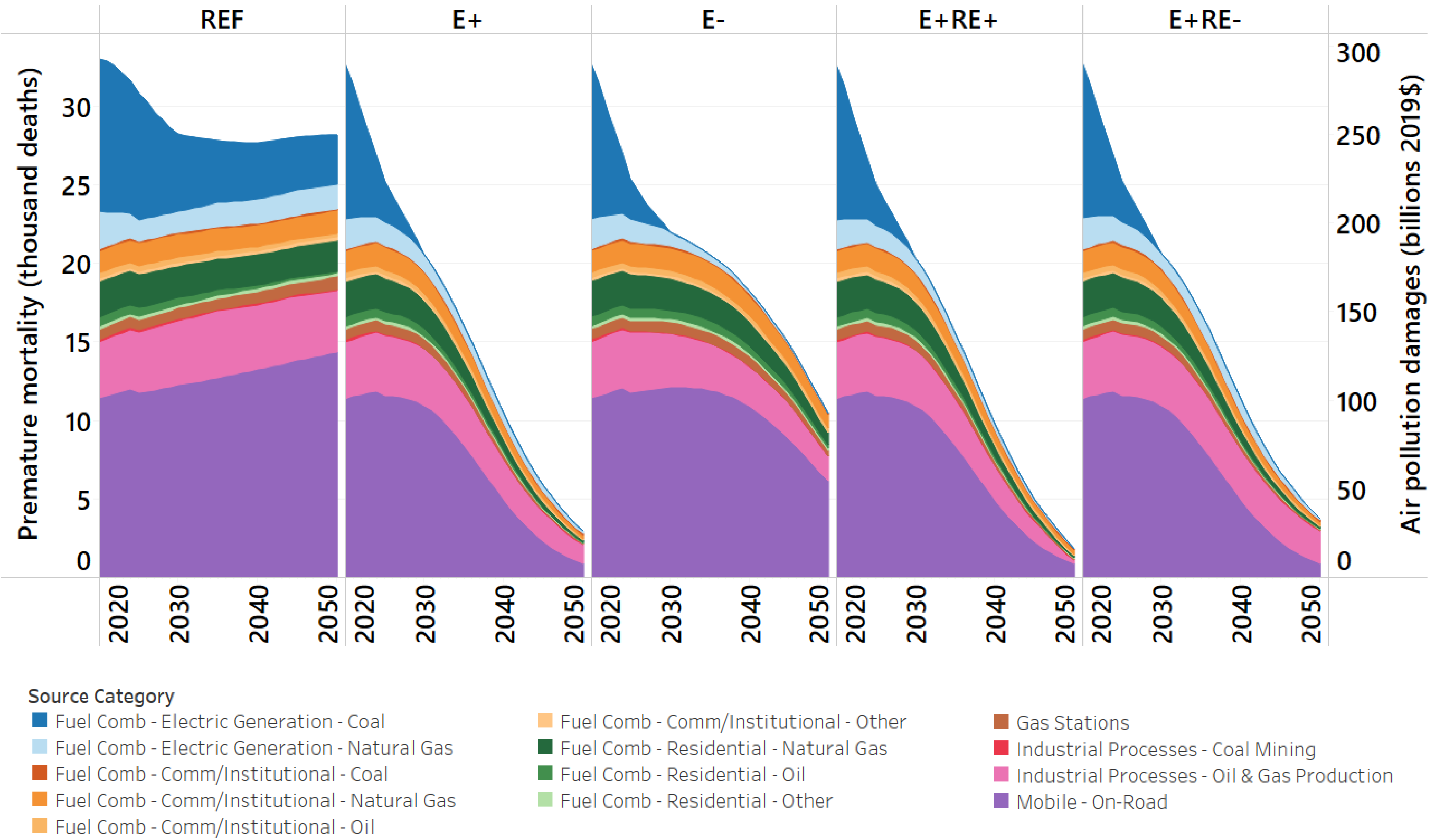
Health impacts related to air quality

- Historically, there have been persistent and large health impacts from fine particulate matter ($PM_{2.5}$) exposure associated with air pollutant emissions from carbon-emitting activities.
- $PM_{2.5}$ exposure disproportionately impacts vulnerable populations, although there is variation in the extent of the disproportionate impacts across different industries.
- Siting decisions, technology selection, air pollutant emissions abatement, and the rate of electrification influence air quality outcomes.
- As a result of changes in coal and natural gas electric power, on-road vehicles, commercial and residential heating and cooling, gas stations, coal mining, and oil and gas production on the path to economy-wide net-zero emissions by 2050, the modeling in this study estimates that
  - Approximately 40,000 to 45,000 premature deaths ($370-410 billion in damages) are avoided in the net-zero scenarios (relative to the REF scenario) in the 2020s
  - Approximately 260,000 to 410,000 premature deaths ($2.3-3.7 trillion in damages) are avoided from 2020 to 2050.

Collectively across all modeled air-pollutant source categories, 260 – 410k deaths (2.3 – 3.7 T$) are avoided from 2020 to 2050.



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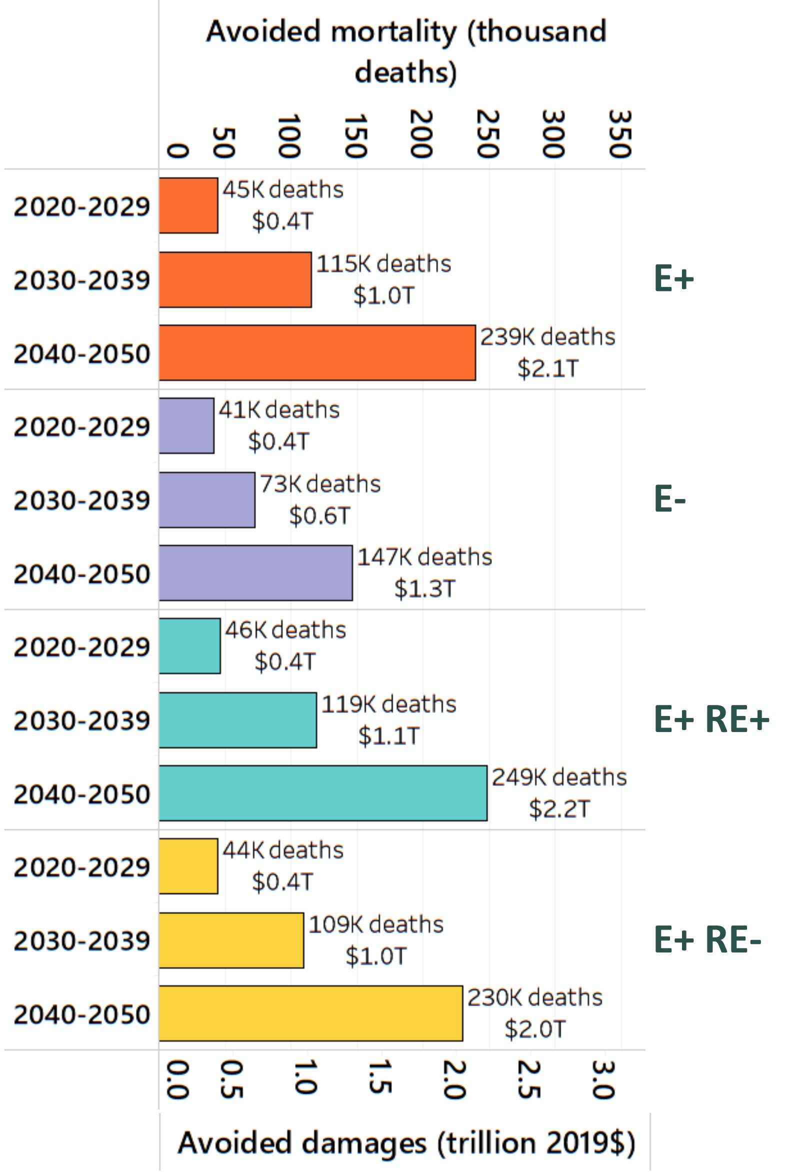
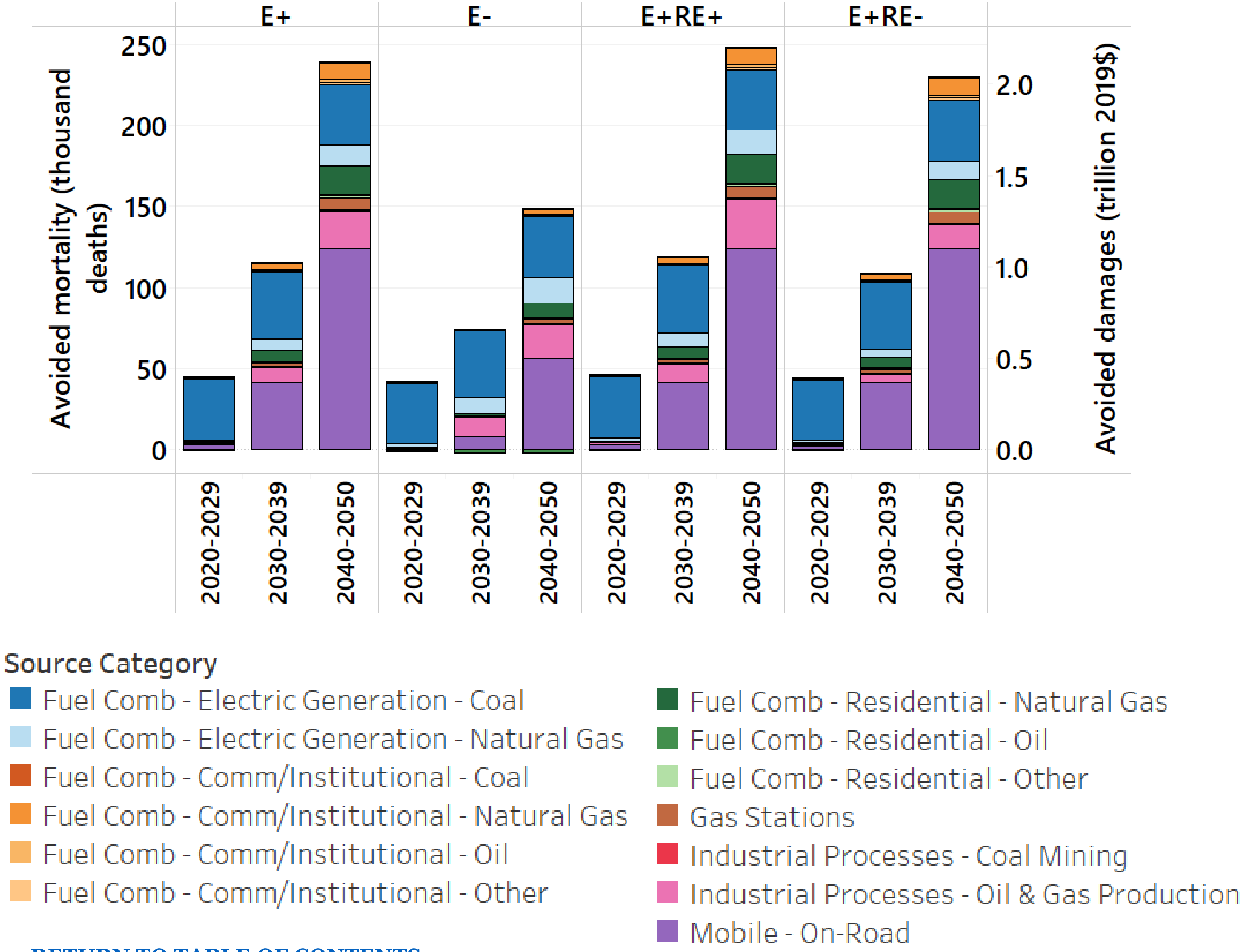
Air quality gains in 2020's are mostly from coal retirements. Vehicle electrification & natural gas transition contribute more after that.





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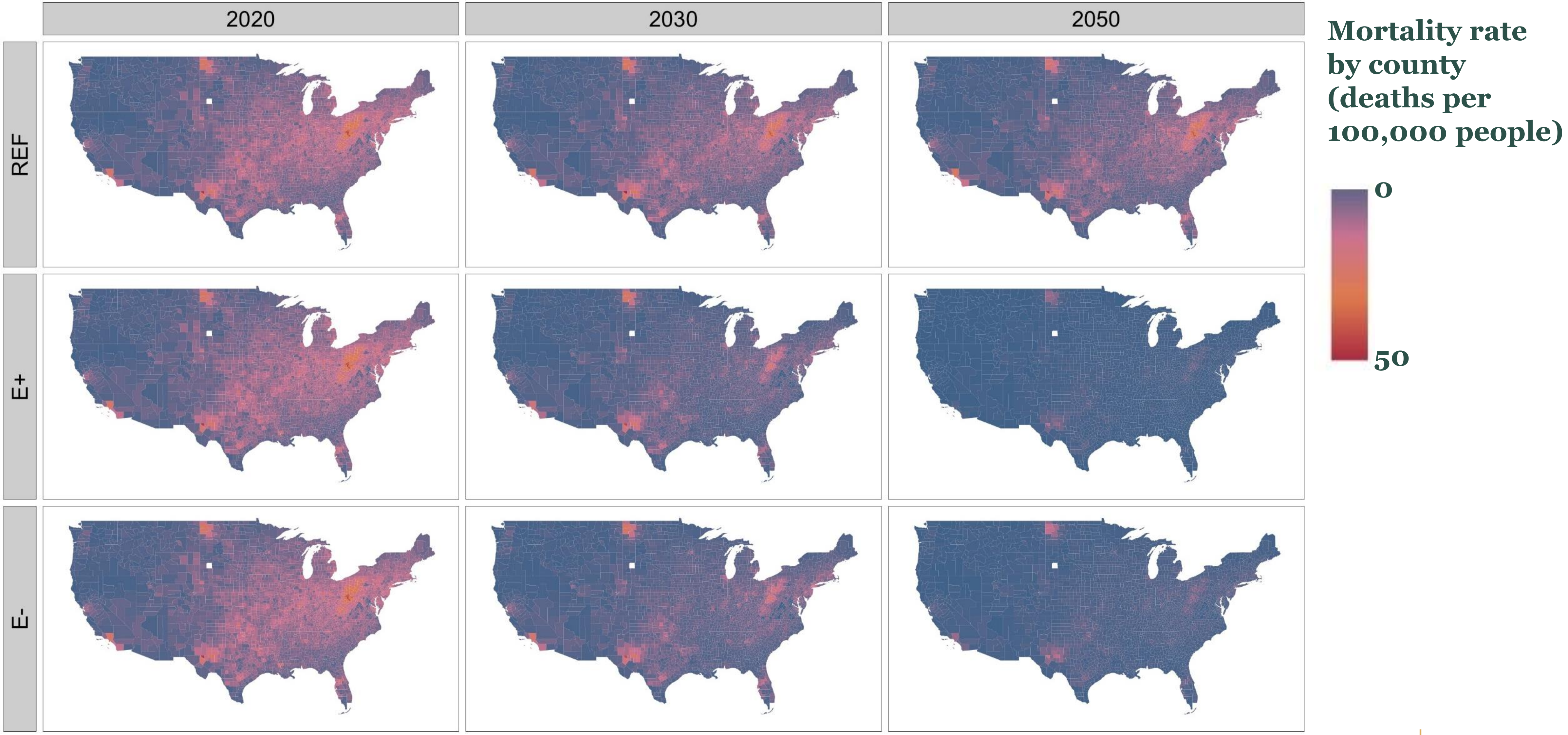
All localities benefit from air pollution reductions in going to net-zero greenhouse gas emissions.



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Key tradeoffs and choices

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Trade-offs and risks in the transition to net-zero emissions for the U.S. by 2050

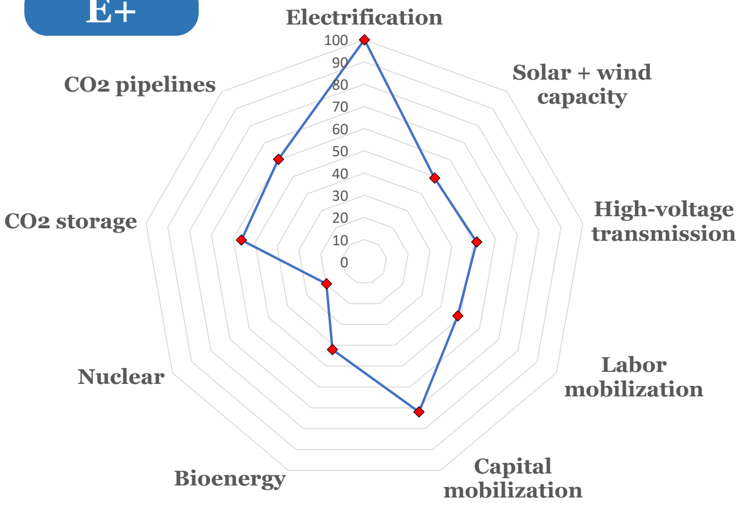
- Each of the five modeled pathways to net-zero emissions by 2050 presents different, but similarly daunting challenges to success
- A successful transition to net-zero emissions by 2050 implies significant cumulative impacts, both positive and negative, that vary across the different net-zero pathways.
- Net-zero emissions for the U.S. by 2050 is achievable and affordable if four key inter-related risks are mitigated through widespread and coordinated actions that begin immediately. The risks are:
  - Failure to deploy physical assets and infrastructure at unprecedented rates;
  - Failure to mobilize capital investments at unprecedented rates;
  - Failure to gain and sustain social license for the transition;
  - Failure to mitigate disruptions to the workforce of fossil fuel industries.

Challenges relative to REF in executing the transition vary across net-zero pathways, implying different trade-offs for each.

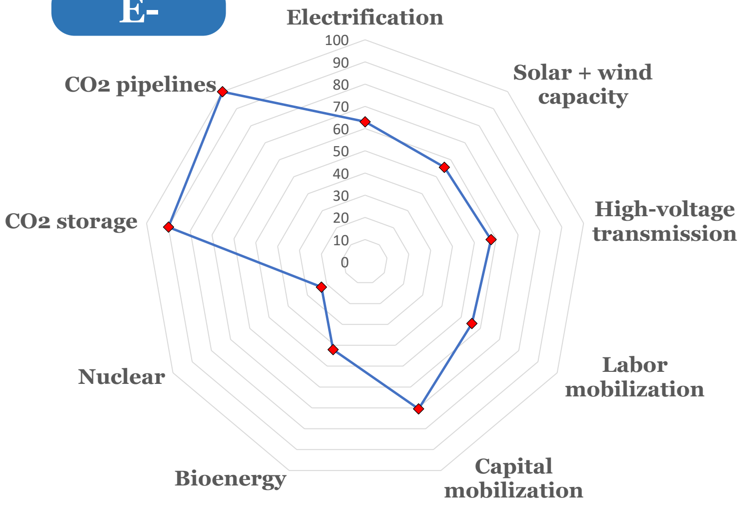
Level of Challenge (ordinal ranking)	
0	Lowest
100	Highest

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

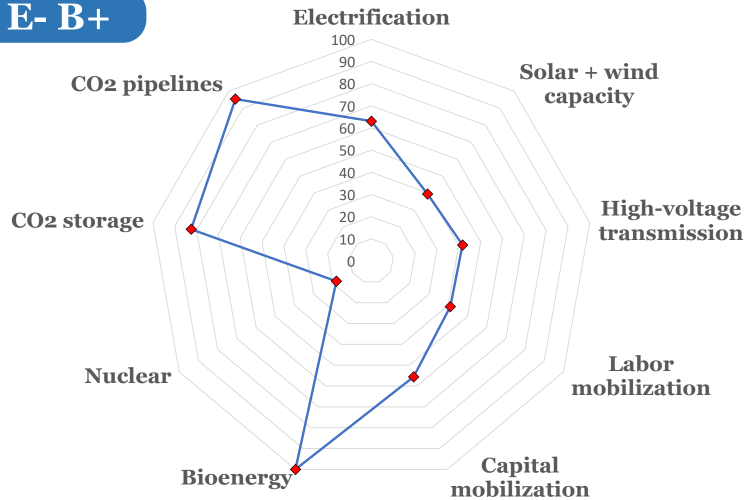
E+



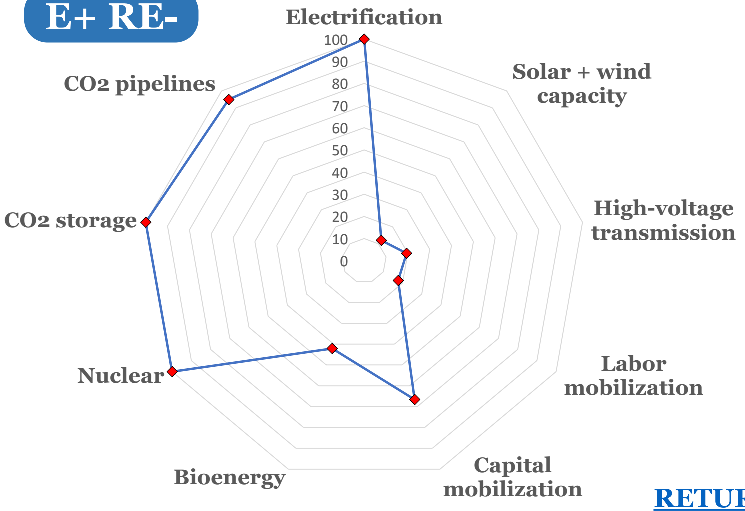
E-



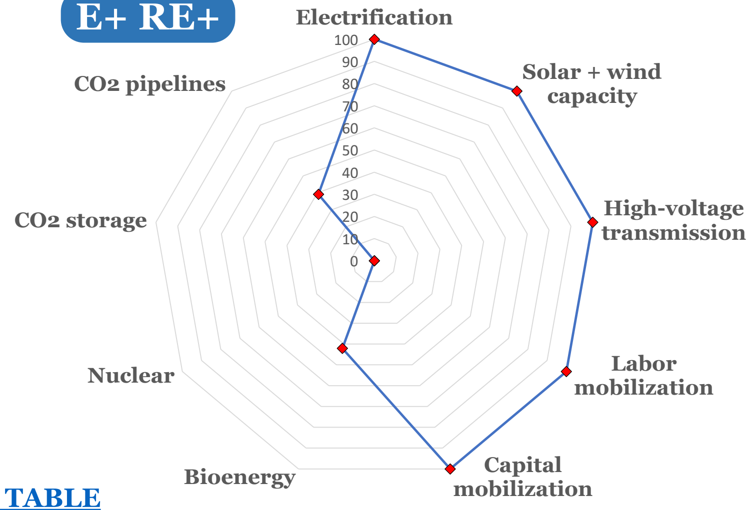
E- B+



E+ RE-



E+ RE+



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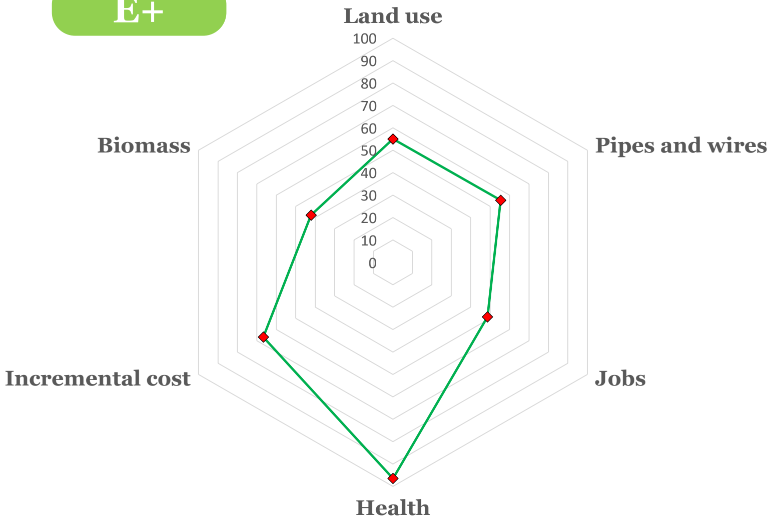
A successful net-zero transition implies cumulative impacts by 2050 (relative to REF) that vary across net-zero pathways

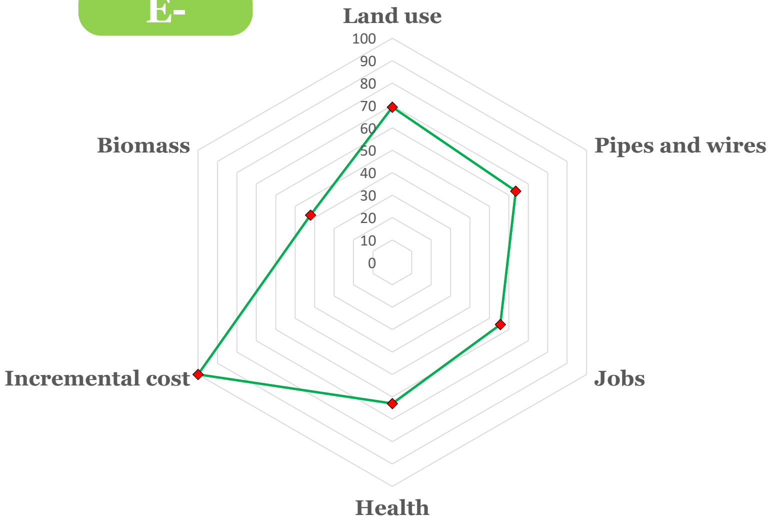
Level of Impact (ordinal ranking)	
0	Lowest
100	Highest

Impact	Comparative metric
Land use	Total km² solar, wind, biomass + DAC, 2050
Pipes & wires	Cumulative capital for HV transmission & CO_2 pipelines, 2020 – 2050
Jobs	Average annual energy jobs in 2040s vs. REF
Health	Cumulative avoided premature deaths, 2020 to 2050.
Cost	NPV of energy-system costs, 2020 – 2050 vs. REF.
Biomass	Bioenergy use in 2050 vs. REF.

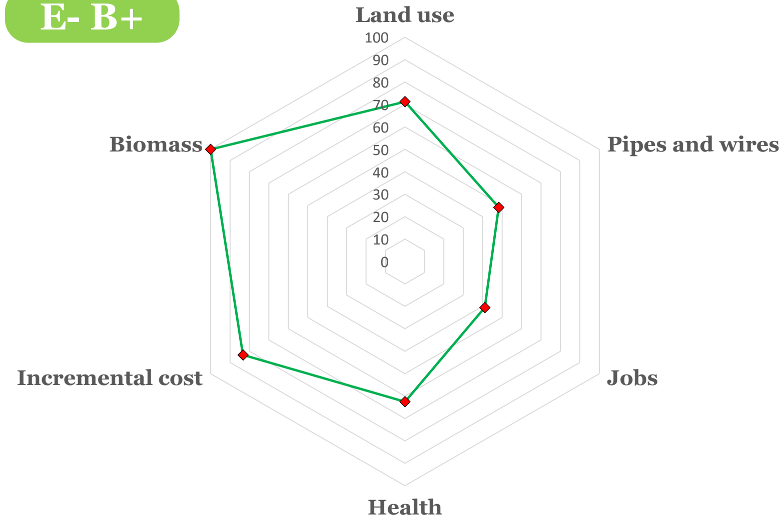
E+



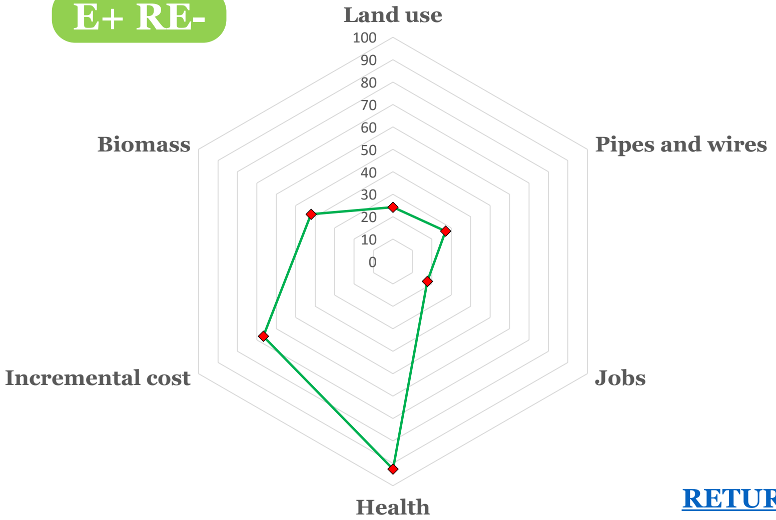
E-



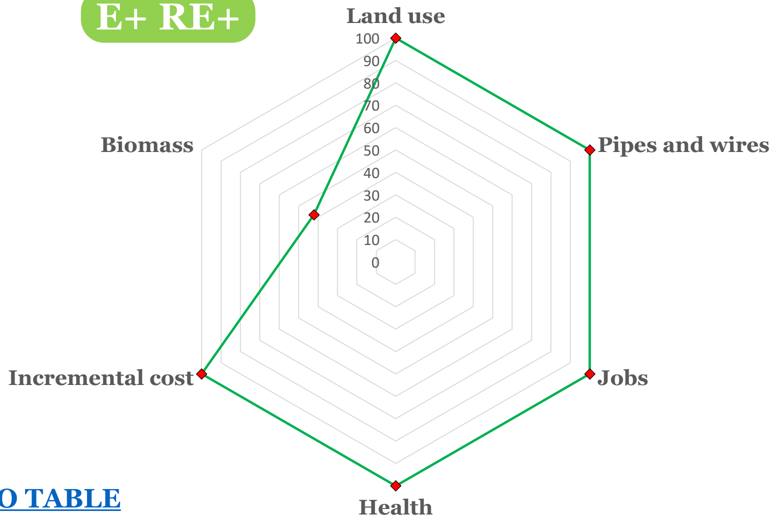
E- B+



E+ RE-



E+ RE+



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High-resolution modeling and visualizations point to 4 key risks for net-zero pathways that must be addressed starting now

1. Failure to deploy physical assets and infrastructure at unprecedented rates

- Many sectors face the challenge of unprecedented growth rates. For example, achieving the required additions by 2030 of utility-scale solar and wind capacity (414 to 739 GW) means installing 38 to 67 GW/y on average. The U.S. single-year record added capacity is 25 GW (achieved in 2020).

2. Failure to mobilize capital investments at unprecedented rates

- Nearly $3 trillion in capital must be mobilized for energy-supply infrastructure in the 2020s, more than double the REF scenario. This includes ~$200 billion of fully at-risk capital to support development of projects.

3. Failure to gain and sustain social license for the transition

- Community support in the face of widespread visual, land-use, and other impacts of wind, solar, grid expansion, CO_2 sequestration, bioenergy industrialization, and nuclear power will be essential.

4. Failure to mitigate disruptions to the workforce of fossil fuel industries

- Most states will see net job gains, but a few will face declines due to loss of fossil fuel jobs. Failure to address the repercussions of declining incumbent industries risks a formidable political backlash.

Blueprint for action

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Net-zero emissions in the U.S. by 2050 is feasible if:

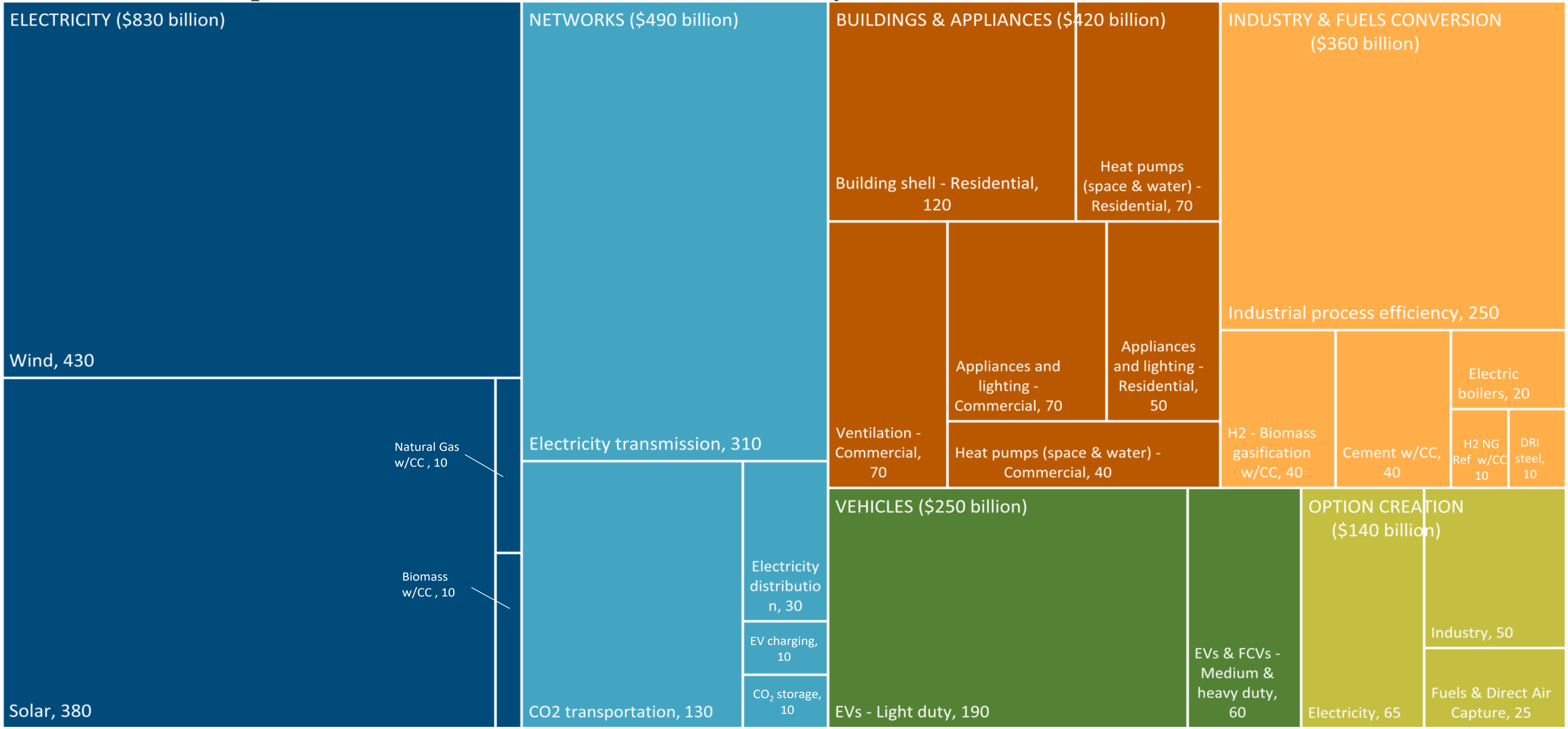
- **Technology and infrastructure are deployed at historically unprecedented rates** across most sectors.
- **Large amounts of risk-capital** are mobilized rapidly by government and private sectors.
- **Expansive impacts on landscapes and communities** are mitigated and managed to secure **broad social license and sustained political commitment**.
- **Electrification uptake by consumers is rapid** across all states (EV's, space heating, etc.).
- **Industry transforms** (electrification, hydrogen, low-carbon steel and cement, etc.)
- **Ambitious expansion of low-carbon technology starts now**, with 2020s used to:
  - Increase and accelerate deployment of wind and solar generation, EVs, heat pumps
  - Invest in critical enabling infrastructure (EV chargers, transmission, CO_2 pipelines)
  - Demonstrate and mature technology options for rapid deployment in the 2030's and 2040's

Net-zero by 2050 requires aggressive action to start now. Eight Key Priorities for the 2020's:

1. Build societal commitment, investment environment, and delivery capabilities
2. Improve end-use energy productivity and efficiency
3. Electrify energy demand, especially transportation and buildings
4. Decarbonize and expand electricity
5. Prepare for major expansion and transformation of the bioenergy industry
6. Build infrastructures: electricity transmission and CO_2 transport/storage
7. Enhance land sinks and reduce non-CO_2 emissions
8. Innovate to create additional *real* options for technologies needed post-2030

Net-zero path requires **$2.5 T additional capital** in 2020s (vs. REF) across energy supply, buildings, appliances, vehicles, industry.

Total additional capital invested and committed, 2021-2030, by sector and subsector for E+ vs. REF (billion 2018 $)



Includes capital invested pre-financial investment decision (pre-FID) and capital committed to projects under construction in 2030 but in-service in later years. All values are rounded to nearest $10b and should be considered order of magnitude estimates. Incremental capital investment categories totaling less than $5B excluded from graphic.

Other potentially significant capital expenditures *not* estimated in this study include investments in fuels distribution systems, establishment of bioenergy crops, and decarbonization measures in other industries besides steel and cement, non-CO_2 GHG mitigation efforts, and establishing enhanced land sinks.

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A Blueprint for the 2020's – bold investment needed this decade to put the U.S. on a path to net-zero by 2050.

Modeling indicates that similar investments are needed regardless of the net-zero path followed after 2030, so investments can be made with confidence that they will deliver value for the long term.

Priority actions from now to 2030 include:

- Get roughly 50 million electric cars on the road and install 3 million or more public charging ports nationwide.
- Double (at least) the share of electric heat pumps in home heating and triple heat pumps in commercial buildings.
- Grow wind and solar electricity capacity fourfold (to approximately 600 gigawatts), to supply ~½ of U.S. electricity.
- Expand high-voltage transmission capacity by roughly 60% to deliver renewable electricity to where it is needed.
- Increase uptake of carbon stored permanently in forests and agricultural soils by 200 million metric tons of CO_{2e}/yr.
- Reduce non-CO_2 greenhouse gas emissions by at least 10%
- Invest in enabling infrastructure and innovative technologies to create real options to complete the transition to net-zero beyond 2030:
    - Plan and permit additional electricity transmission to enable further wind and solar expansion.
    - Plan and begin building a national CO_2 transportation network and permanent underground storage basins.
    - Invest in maturing key technologies to make them cheaper, scalable and ready for widespread use after 2030, including: carbon capture for various industrial processes and power generation technologies; low-carbon industrial processes; clean "firm" electricity technologies, including advanced nuclear, advanced geothermal, and hydrogen combustion turbines; advanced bioenergy conversion processes & high yield bioenergy crops; hydrogen and synthetic fuel production from clean electricity, and from biomass and natural gas with carbon capture; and direct capture of CO_2 from the air.

Net-Zero America (full report and 18 technical annexes) available at https://netzeroamerica.princeton.edu/the-report

Technical annexes:

A. Evolved Energy Research final report
B. Transition pathway sensitivity studies
C. Transport & buildings transitions
D. Solar and wind generation transition
E. Thermal power plants transition
F. Electricity transmission transition
G. Electricity distribution system transition
H. Bioenergy supply industry transition
I. CO_2 transport and storage transition
J. Iron and steel industry transition
K. Cement industry transition
L. Hydrogen transition
M. Mobilizing capital for the transition
N. Fossil fuels transition
O. Non-CO_2 emissions transition
P. Forest land sinks analysis
Q. Agricultural land sinks analysis
R. Employment transition
S. Air quality / health impacts transition