PRINCETON UNIVERSITY

NET-ZERO AMERICA

POTENTIAL PATHWAYS, INFRASTRUCTURE, AND IMPACTS

FINAL REPORT

October 29, 2021

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High Meadows Environmental Institute

Carbon Mitigation Initiative

https://netzeroamerica.princeton.edu

Final Report

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

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Foreword (1/2)

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.

The index used by climate scientists to characterize, in a single number, the state of Earth's climate is the annually and globally averaged temperature of the atmosphere at Earth's surface. The current value is about 1.1°C (2°F) above the value around the beginning of the 20th century. While that increase may strike one initially as modest, it is not. Much like the human body temperature, the average surface temperature of the planet is a very sensitive indicator of the state of a very complex system, with small changes in the index indicative of major disruptions.

At a mere 1°C or so above the average temperature of 120 years ago, the world is experiencing increases in the frequency and intensity of deadly heat waves in many regions; increases in torrential downpours and flooding in many others; large expansions in the annual area burned in regions prone to wildfires (and expansion of wildfires into regions not previously prone to them); an increase in the power of the strongest tropical storms; expanded impacts of pests and pathogens across large parts of the globe; disruptive changes in monsoons; other alterations in atmospheric and oceanic circulation patterns that, together with other impacts, are affecting agriculture and ocean fisheries; an accelerating pace of global sea-level rise; and ocean acidification arising from absorption of some of the excess carbon dioxide in the atmosphere.

The momentum in Earth's climate system and the inertia in society's energy system together ensure that these impacts will grow for some time to come; but <u>how much</u> they grow will depend, above all, on the extent and speed with which human society works to reduce the emissions of carbon dioxide and other heat-trapping gases, to remove them from the atmosphere both biologically and technologically, to adapt our infrastructure and practices to the changes in climate that can no longer be avoided, and, perhaps, to deploy solar-radiation-management technologies to offset some of the heating effect of the heat-trapping gases in the atmosphere (if this approach can be shown to be safe and at least partially effective).

Most of the global community of nations has long embraced a target of limiting the global-average surface temperature increase to 2°C (3.6°) above the "pre-industrial" average. (That average was about the same as the value in the period 1880-1900.) It is clear that this figure would entail climatic disruption and impacts considerably greater than those currently being experienced at just half of that increase. The 2°C figure was agreed not because it would be "safe", but because multiple analyses had indicated that doing much better would be extremely difficult technologically and economically. (Another factor was the view of some that "tipping points" plunging the world into

continues →

drastically different climate regimes were more likely above 2°C than below; in reality, though, the same argument holds for any other choice of target.) As part of the 2015 Paris Agreement of the Conference of the Parties to the UN Framework Convention on Climate Change, the 2°C target was again officially embraced, but a more ambitious, aspirational target of 1.5°C was added in response to arguments that the likely impacts of 2°C, which science has been bringing into clearer focus, would be intolerable.

In the view of most analysts familiar with the technological and economic challenges of very rapid emission reductions, along with the limitations and uncertainties of natural and technological CO_2-removal methods and solar-radiation management, holding the temperature increase to 1.5°C target is very unlikely to be achievable. A large part of the analytical effort on pathways to deep emissions reduction continues to be focused, therefore, on investigating how reductions consistent with a 2.0°C target might be achieved. In any case, though, it is much more important now to focus on what strategies for technological innovation and what policies will move the world more rapidly onto a deep-reductions trajectory than to try to agree on exactly what ultimate temperature limit the world will be able to stay below.

A larger point related to this last one is that the benefit of any attempt to identify and model pathways into the energy-climate future is not in predicting the most likely path on which that future will unfold. It is most improbable that any model will succeed in doing that, given the many respects in which the future is simply not predictable. Rather, models of the ways in which the energy-climate future might evolve are most useful if they can clarify possibilities, using transparent assumptions and algorithms, in ways that help other analysts, policy makers, and publics understand the consequences of different assumptions and choices and, most importantly, help us all shape policies and technological-innovation strategies that can be adjusted over time to respond to new realities as they unfold.

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.

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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 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, 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.

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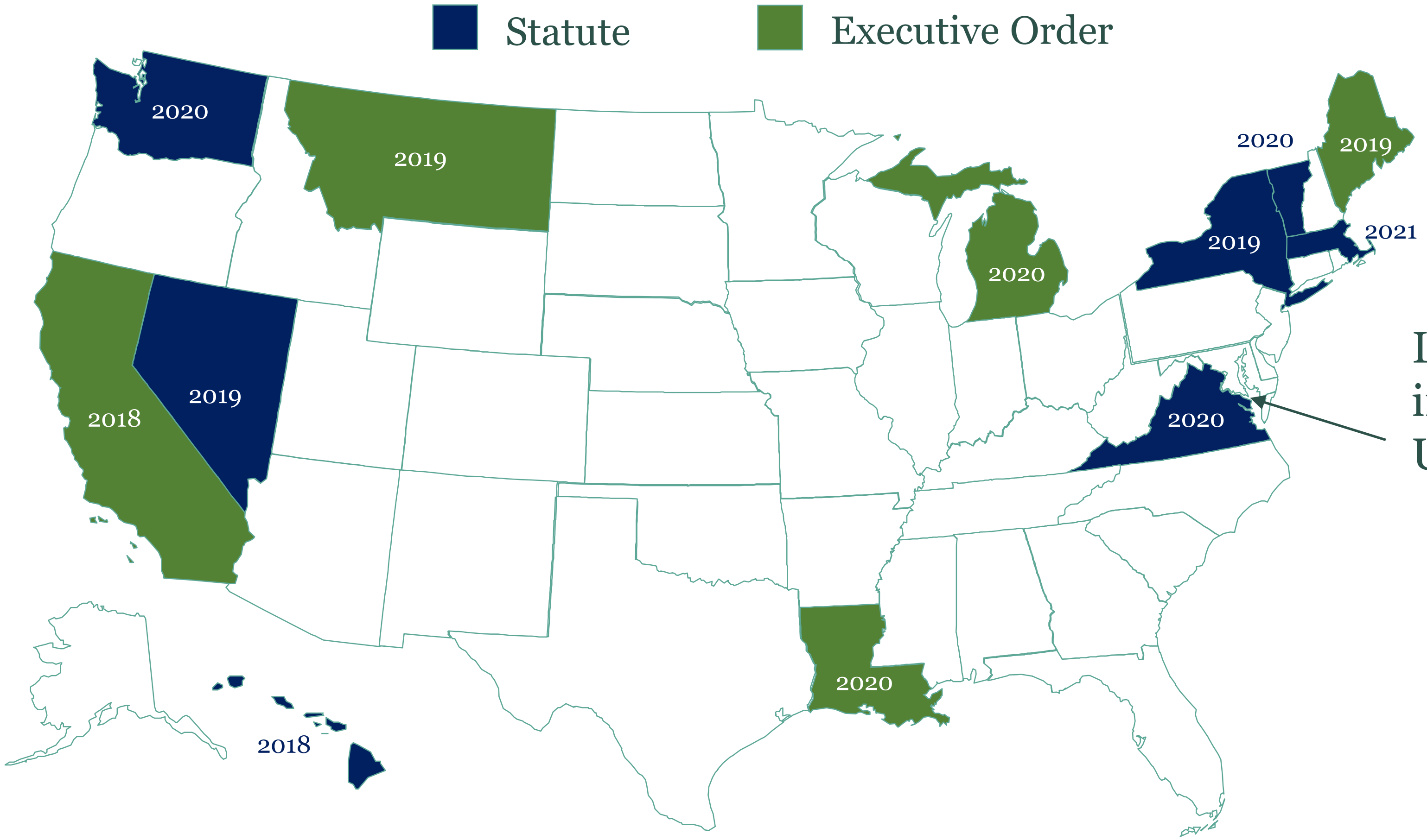
Project motivation, objectives, and approach

Summary of this section

- 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 emission 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 following a pathway to net-zero 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 achieve net-zero, 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 are constructed for meeting these demands by varying exogenously applied constraints to create the different pathways.
  - 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 minimizes the 30-year NPV of total energy-system costs, subject to exogenous constraints. The model has perfect foresight and seamless integration between all sectors.
- These modeling results are "downscaled" to state or sub-state geographies to quantify local plant and infrastructure investments, construction activities, land-use, jobs, and health impacts, 2020 - 2050.

A dozen states have pledged net-zero by 2050 (and counting)



Legislation introduced in both houses of US Congress

Last updated September 6, 2021. Source: https://www.c2es.org/content/state-climate-policy/

The number of companies pledging net-zero by 2050 is growing.

Electric Utilities

- Xcel Energy — Responsible by Nature
- PSEG
- Southern California Edison — Energy for What's Ahead
- Southern Company
- Duke Energy
- DTE Energy
- Dominion Energy
- nrg
- aps
- Consumers Energy
- Green Mountain Power
- Idaho Power — An IDACORP Company
- Hawaiian Electric
- nationalgrid
- Eversource
- PSE Puget Sound Energy
- MGE Madison Gas and Electric
- Avista
- Avangrid
- FirstEnergy

For others, see https://sepapower.org/utility-transformation-challenge/utility-carbon-reduction-tracker/

Oil & Gas*

- Repsol
- Shell
- bp
- OXY

* These companies' pledges include scope 3 emissions.

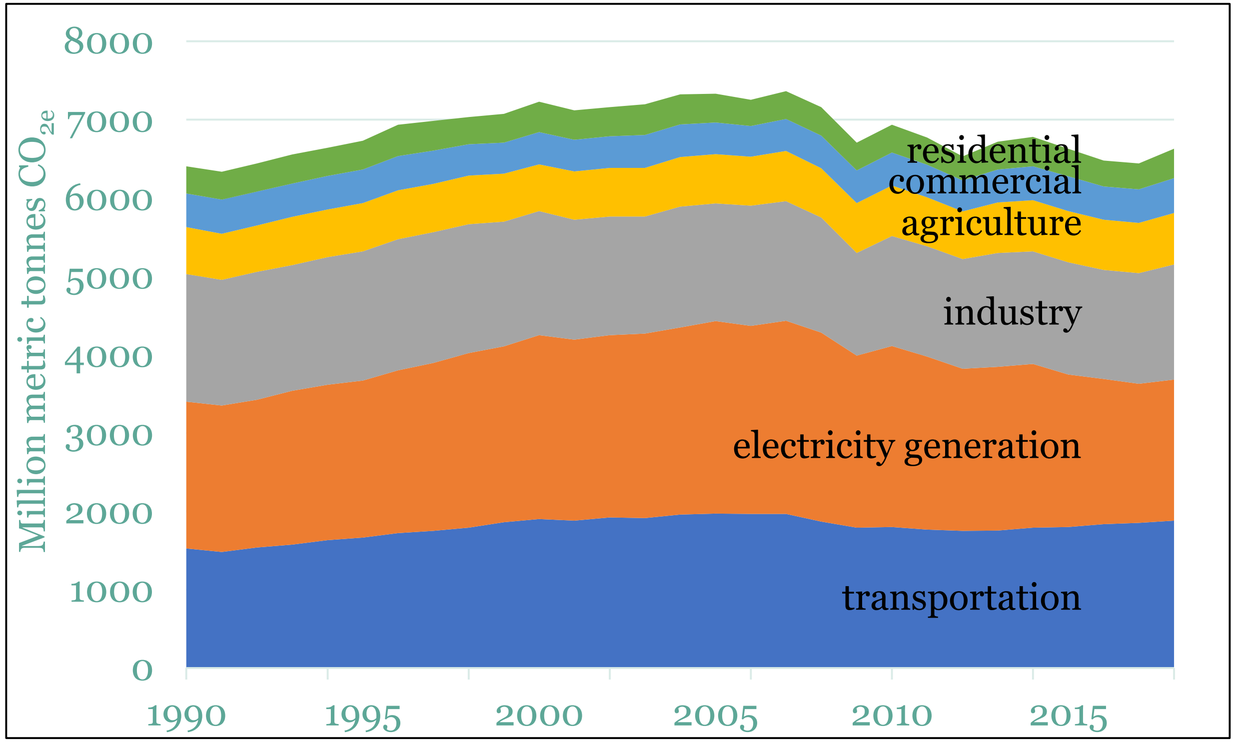
Materials

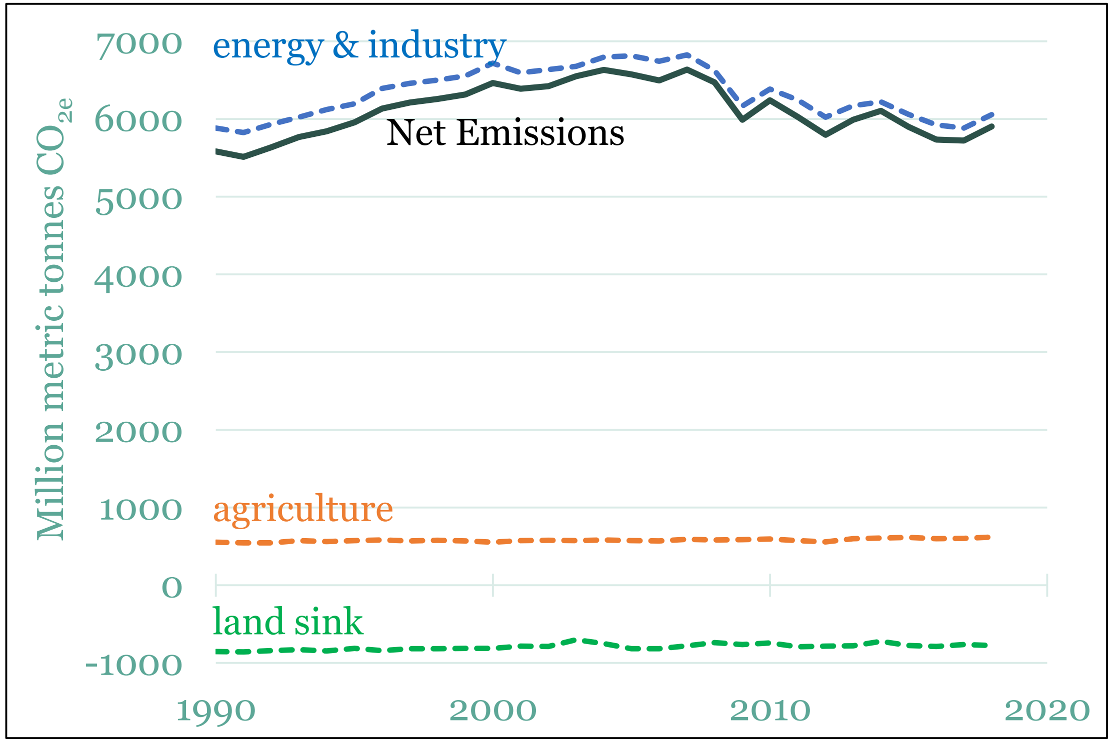
- Vale
- HeidelbergCement
- ArcelorMittal
- USS United States Steel Corporation
- thyssenkrupp

Airlines

- Delta
- Qantas
- jetBlue
- Iberia
- Finnair
- Qatar Airways
- Royal Air Maroc
- S7 Airlines
- American Airlines
- Japan Airlines
- British Airways
- Cathay Pacific
- Malaysia Airlines
- SriLankan Airlines
- Royal Jordanian

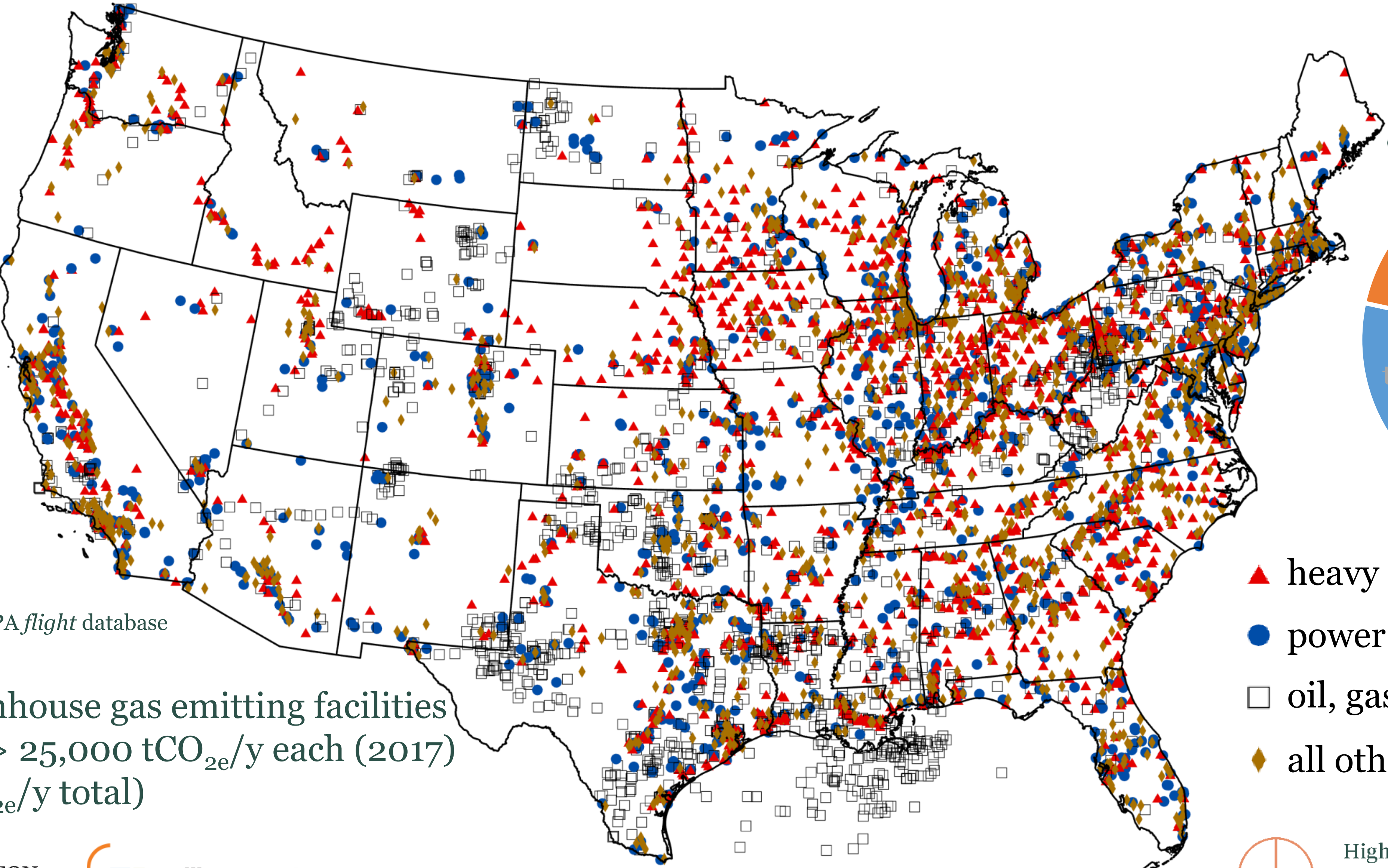
The challenge for the US to reach net-zero emissions: ~ 6 billion tonnes of CO_{2e}/y emissions today (6 $GtCO_{2e}$/y)





EPA GHG Inventory

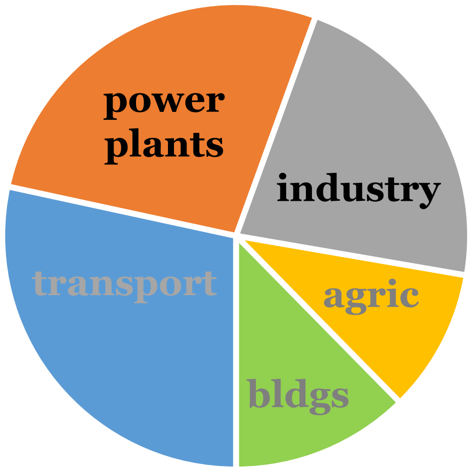
The challenge for the US: Industrial facilities and power plant emission sources are widely dispersed today



heavy industries
power plants
oil, gas, coal operations
all other industries

EPA *flight* database

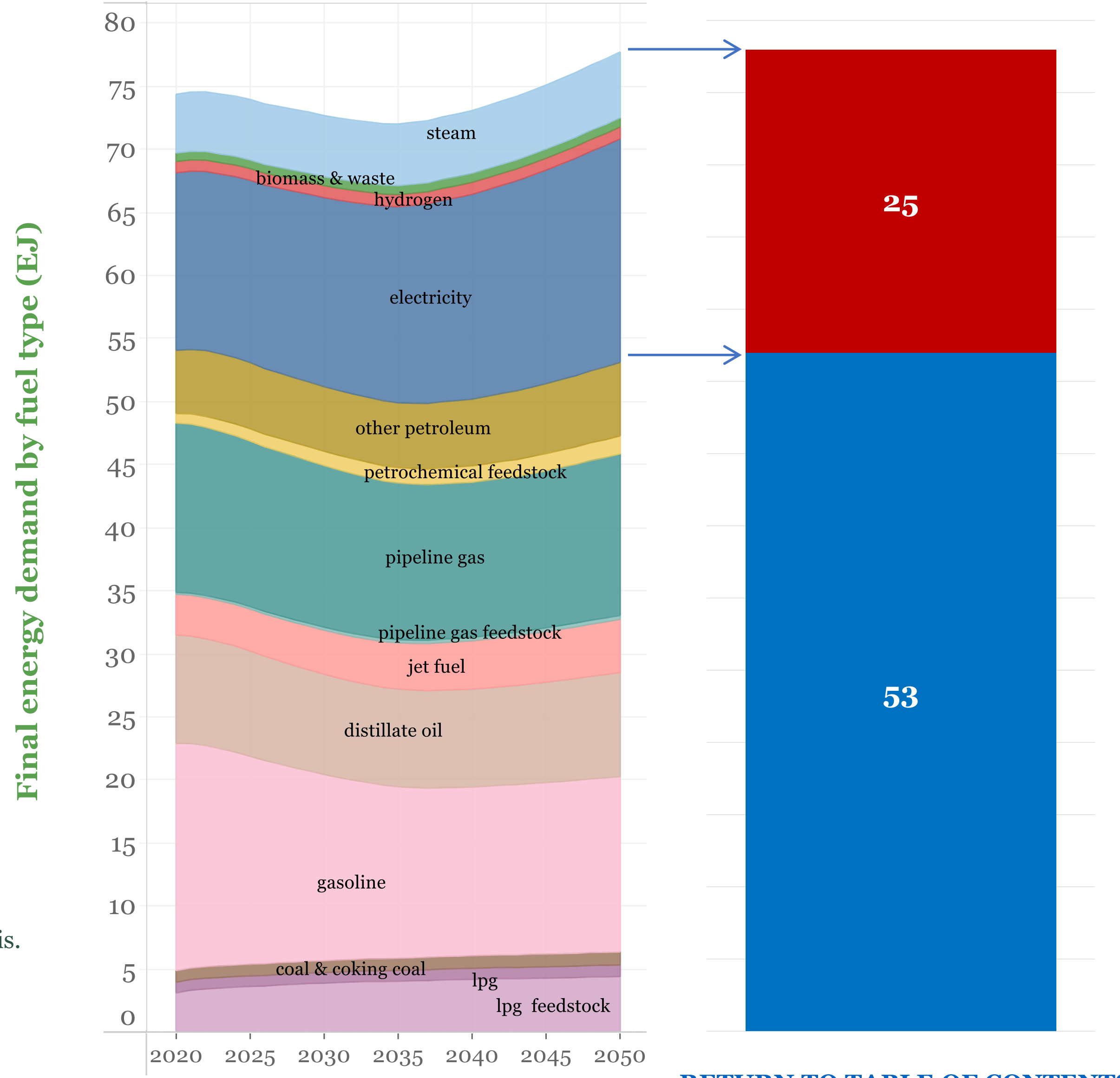
Economy-wise emissions by sector



7,515 greenhouse gas emitting facilities reporting > 25,000 tCO_{2e}/y each (2017) (~ 3 $GtCO_{2e}$/y total)

The challenge for the US: 2/3 of final energy today is hydrocarbons

REFERENCE (EIA AEO 2019)



~ 25 EJ_{HHV} of final energy demands (1/3 of total) are non-hydrocarbon, which could
- be reduced via **efficiency, mode shifting, conservation**
- be met using **zero carbon electricity**

~ 53 EJ_{HHV} (2/3 of total) are hydrocarbons, for which there are the following approaches:
- **Energy productivity (efficiency, mode shifting, conservation)**
- **Electrification**
- **Drop-in zero-carbon fuels**
- **Fossil fuel use with CO_2 capture + some negative emissions to offset**

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

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Decarbonization pathway modeling methodology and key assumptions

Summary of this section

- All net-zero pathways satisfy the same demand for energy services (e.g. vehicle miles traveled, area of building space heated/cooled), consistent with EIA's *Annual Energy Outlook 2019* Reference case.
- The EnergyPATHWAYS model is used to construct two different demand-side scenarios, specifying in 5-year time steps the evolution of energy consuming vehicles, appliances, building stock, etc. to meet those energy service demands: one with nearly complete electrification of most transportation and building and water heating, and another with slower electrification. These scenarios determine final energy demand for electricity, liquid, and gaseous, and other fuels.
- A detailed optimization model, RIO, is then run to determine the lowest-cost (30-year societal net present value) mix of supply-side and network infrastructure to meet demand for fuels and electricity and reach net zero emissions by 2050 (with linearly declining emissions). The model has perfect foresight and seamless integration between sectors, and it models power sector operations at hourly resolution for 41 representative days, while tracking fuels and energy storage volumes across days.
- Only technologies that are commercially available or have been demonstrated at commercial scale are considered; no fundamentally new technologies or scientific breakthroughs are assumed.
- See Annex A for additional details of EnergyPATHWAYS and RIO models and assumptions.
- Modeling results are only the beginning of the analysis, serving as inputs for customized highly-resolved "downscaling" analysis performed sector-by-sector (and reported in subsequent sections).

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

Pathway modeling tools

Modeling performed by EVOLVED ENERGY RESEARCH

EnergyPATHWAYS scenario tool*

Scenario analysis tool used to develop economy-wide energy demand scenarios.

EnergyPATHWAYS produces parameters for RIO's supply-side optimization:

- Demand for fuels (electricity, pipeline gas, diesel, etc.) over time
- Emissions caps by year
- Hourly electricity load shape

* Open-source software.

RIO optimization tool**

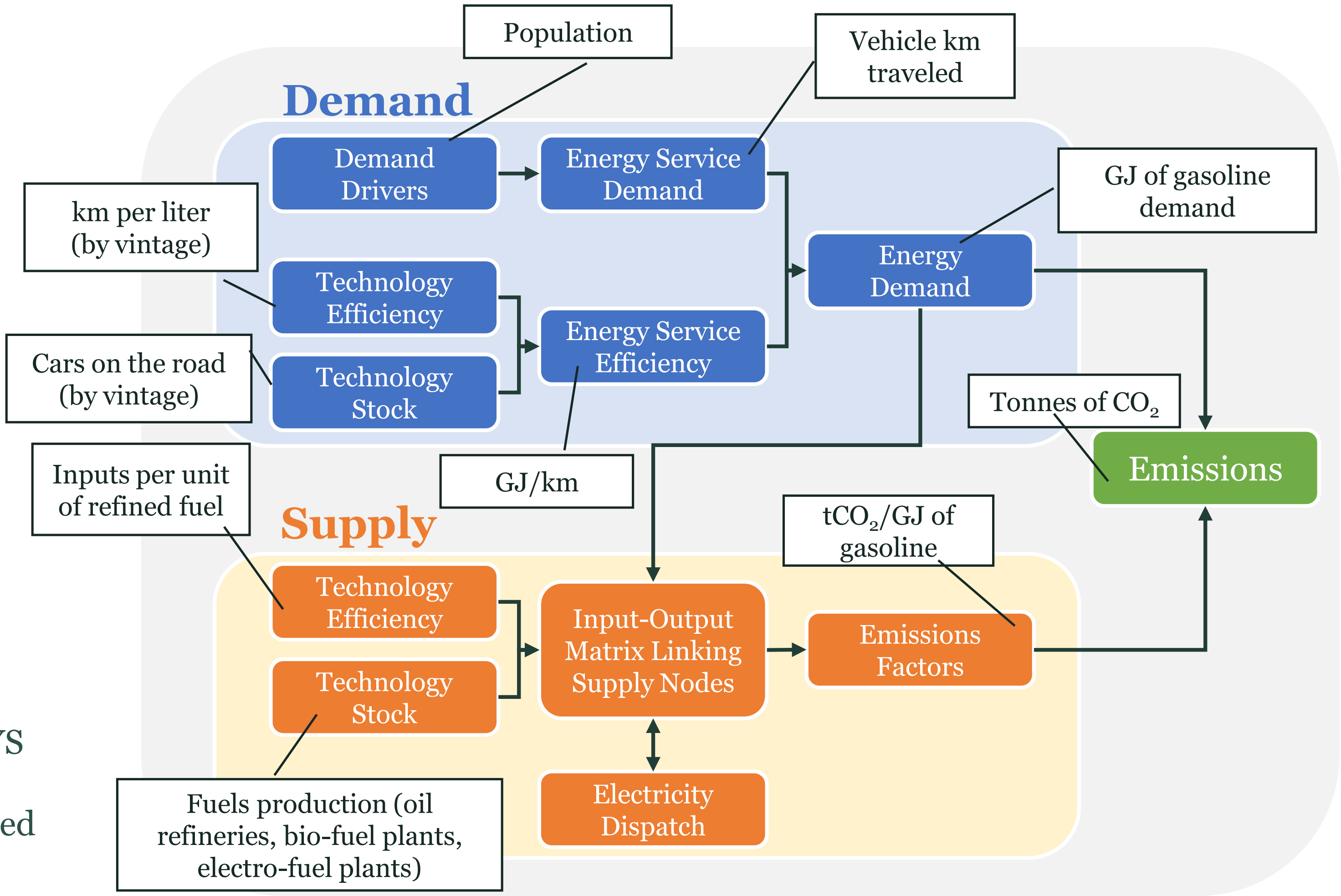
Cost-minimized portfolios of low-carbon technology deployment for electricity generation and balancing, alternative fuel production, and direct air capture.

RIO returns supply-side decisions to EP for cost and emissions accounting:

- Electricity sector portfolios, including renewable mix, energy storage capacity & duration, capacity for reliability, transmission investments, etc.
- Biomass allocations for fuels

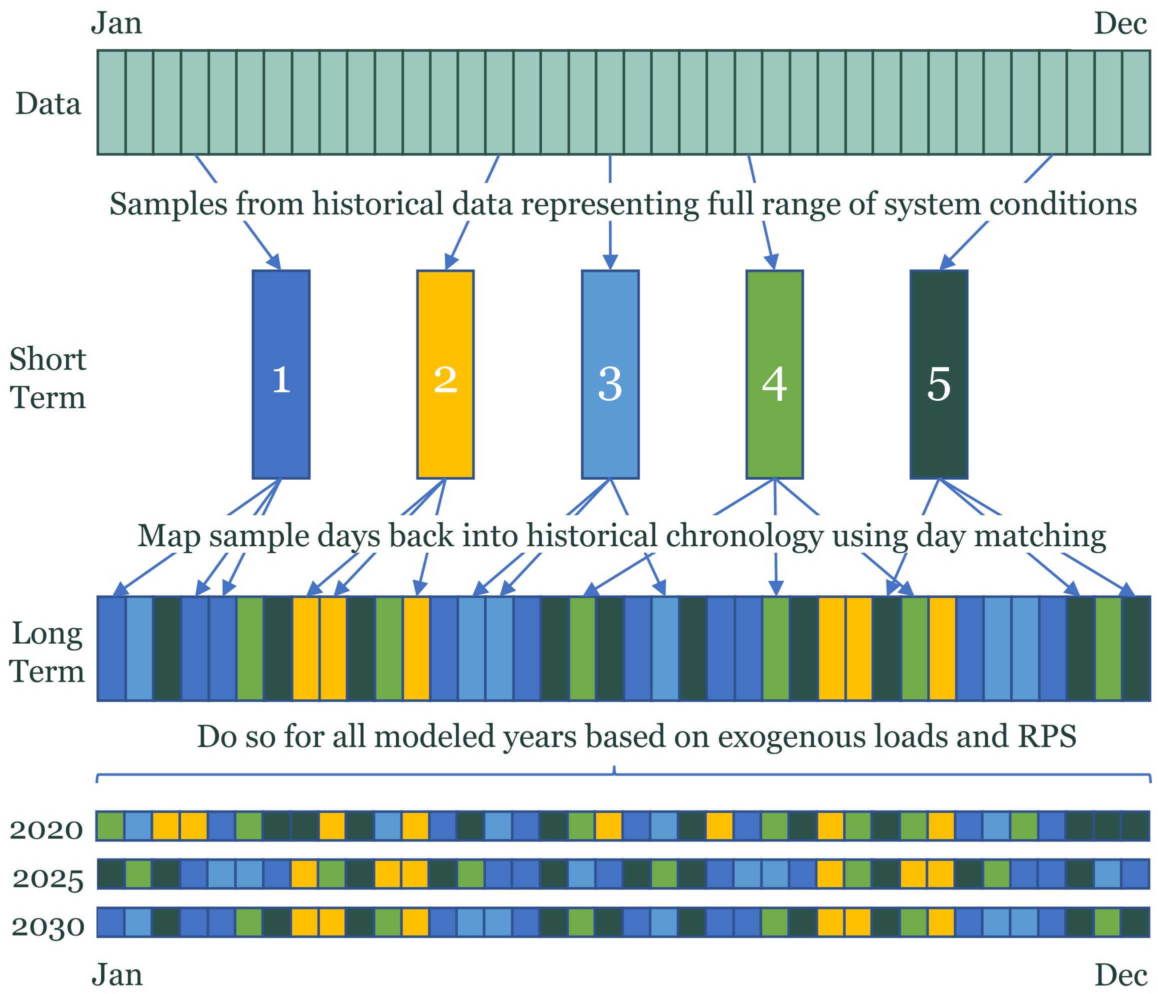
** Evolved Energy Research proprietary.

LIGHT DUTY VEHICLES EXAMPLE

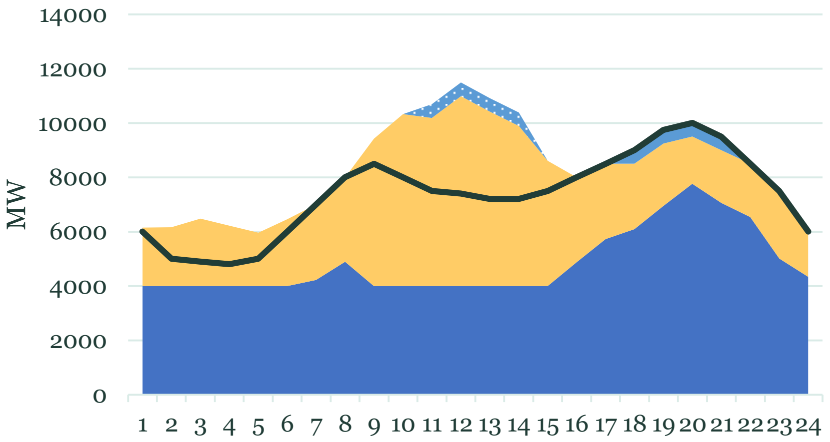


Note: By convention, all fuel values input to EnergyPATHWAYS and RIO are expressed as higher heating values (HHV); all outputs are likewise expressed as HHVs. All fuel values reported in this slide deck are HHVs, unless stated otherwise.

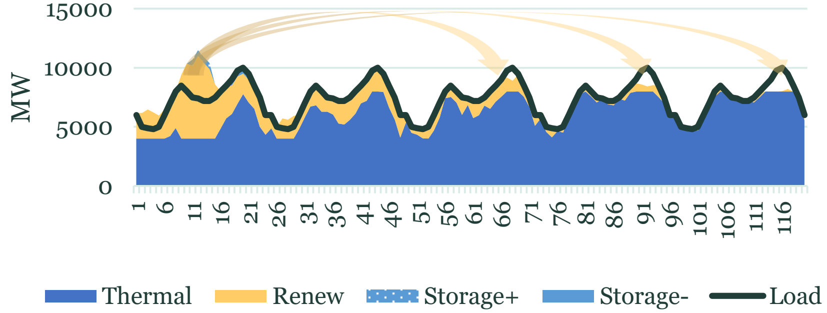
RIO power-sector temporal modeling: Hourly operations for 41 sample days; long-term operations over full chronology

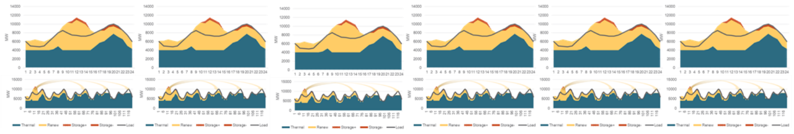


Detailed short term dispatch for every sample day. Dispatch decisions are the same across all days represented by the same sample day.



Time sequential long-term storage operations across sample day dispatches. Long-term dispatch decisions are different across days, based on long term needs.





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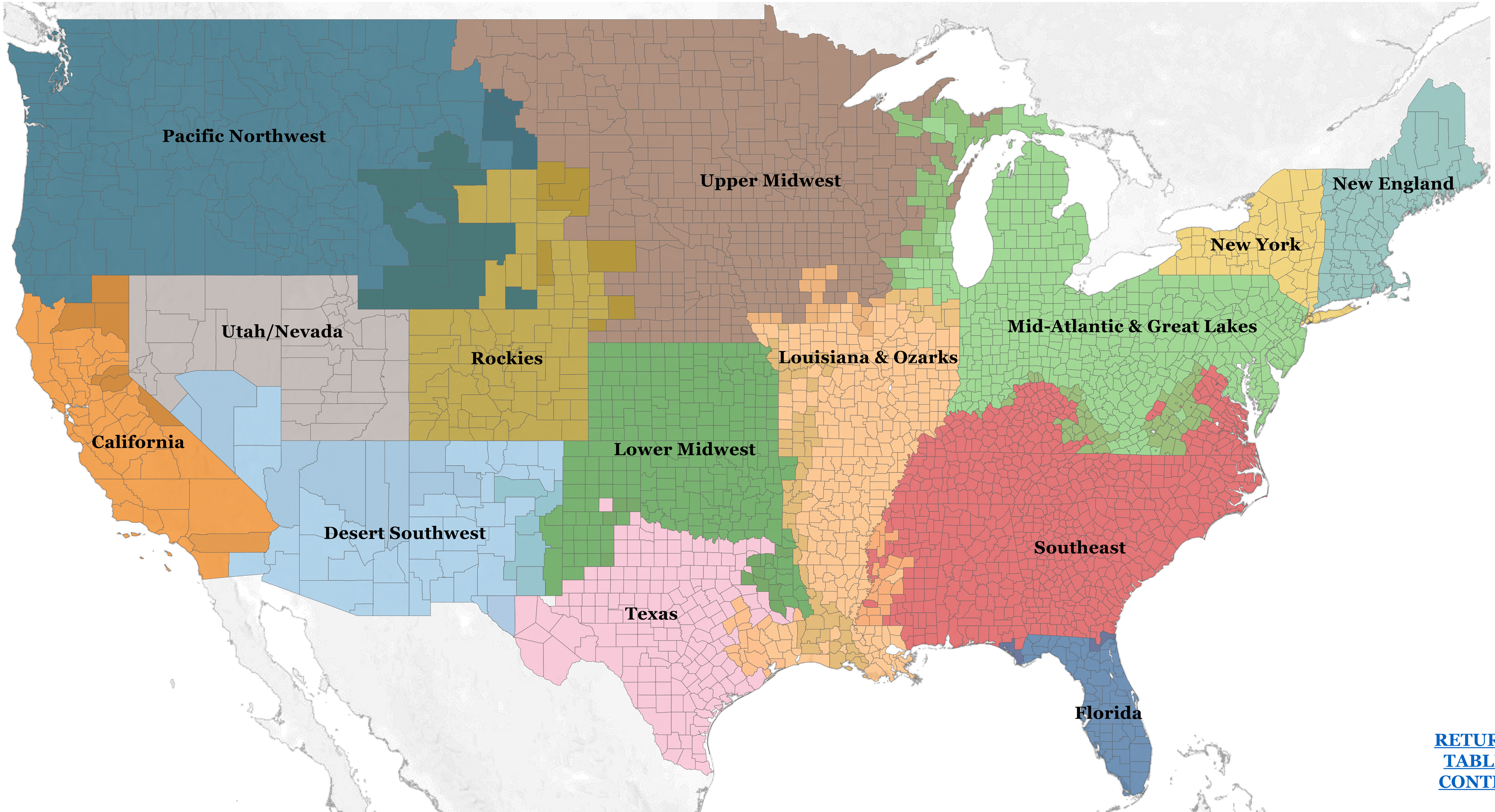
Most model inputs are at state level; outputs are reported for 14 regions (consolidated eGRID regions)



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Key assumptions

- **Same energy-service demands** to 2050 across all scenarios, based on Energy Information Administration *Annual Energy Outlook* (2019) Reference Case
- **Two levels of end-use electrification** (high and less-high) of transportation and buildings.
- **Same-fuel end-use efficiency improvements**: adoption of most-efficient equipment at end-of-life replacement in buildings sector, plus aggressive industrial productivity improvements and reductions in aviation energy use per seat-km.
- **Technology performance and costs**:
  - Light duty EV capex parity with ICE by 2030
  - Power generation and battery storage: NREL 2019 Annual Technology Baseline (mid-range).
  - Biofuels, H_2, synfuels from literature sources.
  - Direct air capture: American Physical Society, 2011.
- **Biomass supply**: DOE "Billion Ton Study" + conversion of ethanol-corn & Conservation Reserve Program (CRP) lands.
- **CO_2 transport and storage costs** developed in consultation with industry experts.
- **Oil and gas prices** are AEO 2019 lowest-price projections.
- Future reductions in **non-CO_2 greenhouse gas emissions** and enhancements of **land sinks** based on expert assessments of potentials for each.
- **Historically-low inflation rate and cost of capital** observed in the past decade persist to 2050.

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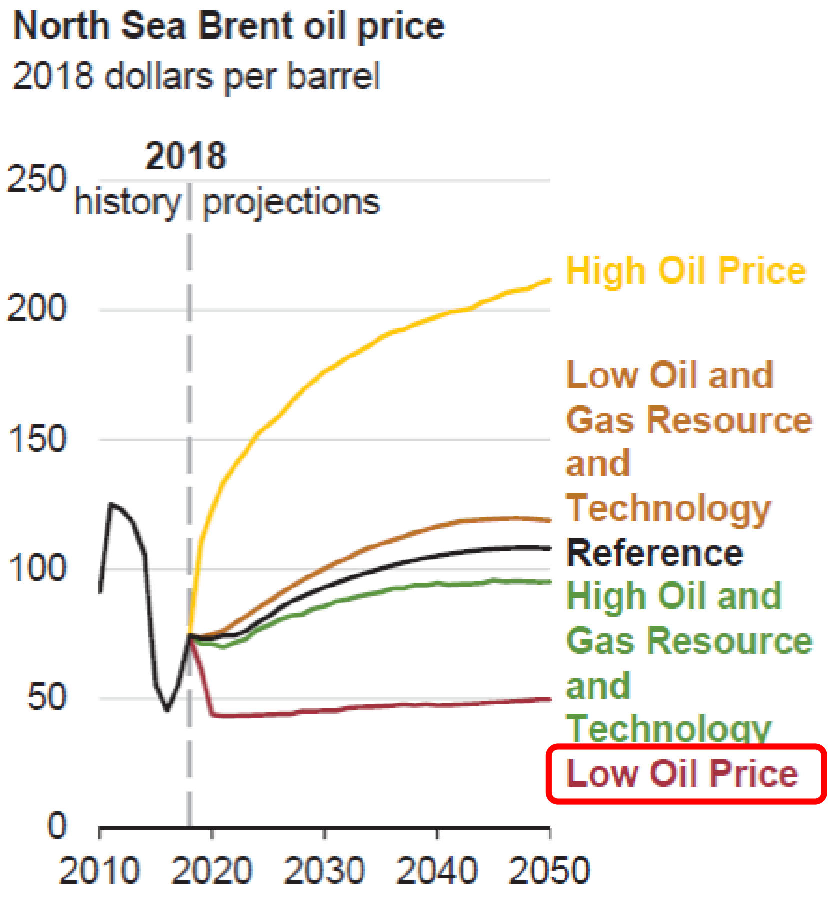
Key assumptions

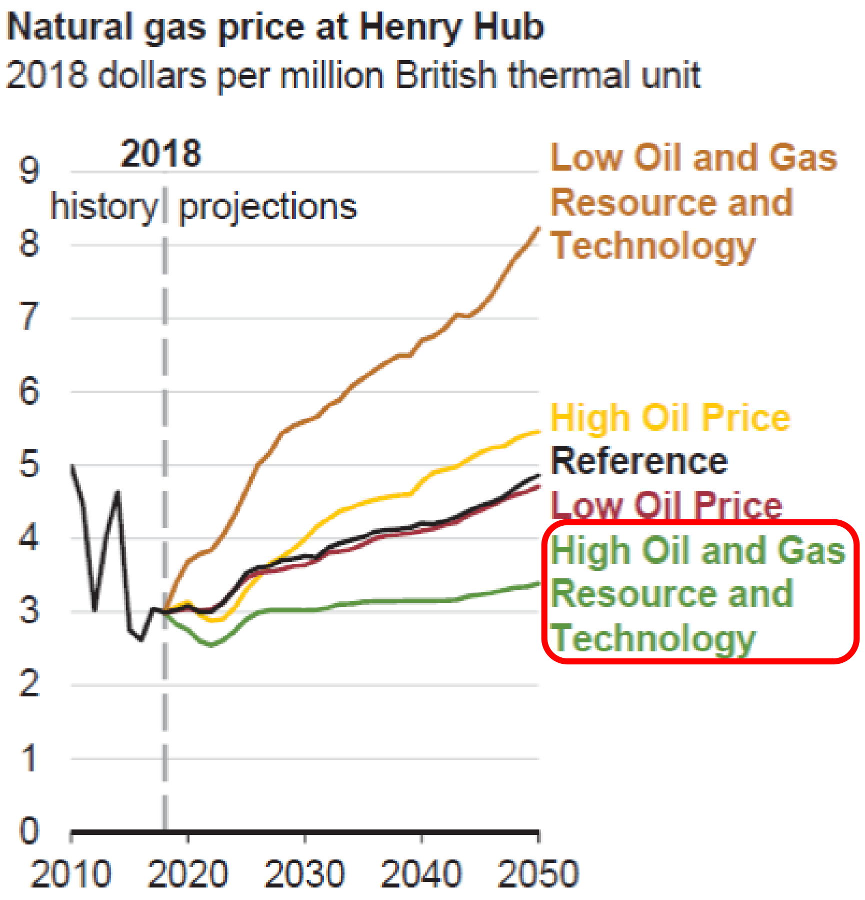
CO_2 emissions	
Land CO_2 in 2050	- 0.85 Gt/y (- 0.7 Gt/y today and declining)
Non-CO_2 in 2050	1 $GtCO_{2e}$/y (25% reduction from today)
Energy/Industry CO_2	- 0.17 GtCO2 in 2050
Technology installed capital costs in 2016$ (some later slides express values in 2018$, assuming 4% escalation from 2016)	
Utility solar, $/$kW_{AC}$	$1,400/kW (2020) → $900/kW (2050) [including grid connection costs]
Onshore wind, $/kW	$1,500 - $2,700/kW (2020) → $1000 - $1,900/kW (2050) [including grid connection costs]
Nuclear power, $/kW	$6,600/kW (2020) → $5,500/kW (2050)
NG power w/CC, $/kW	NGCC-CC, $2,200 (2020) → $1,700 (2050). NG-Allam (99% capture, available from 2030), $2,300/kW.
H_2 capex, $/$kW_{H2HHV}$	Biogasification w/CC, $2,600/kW. NG-ATR w/CC, $800/kW. Electrolysis, $1,700/kW (2020) → $420/kW (2050).
Biopower, $/kW	$3,672/kW (2020) → $3,329/kW (2050)
with CC, $/kW	Bio-IGCC (90% capture), $6,338/kW. Bio-Allam (99% capture, available from 2035), $7,144/kW.
Biopyrolysis, $/$kW_{liq.HHV}$	$2,500/kW
with CC, $/$kW_{liq.HHV}$	$4,000/kW (available from 2035)
Direct air capture, $/tpy	Direct air capture (available from 2035), $2200 per tCO_2/y installed capital cost
Resource costs in 2016$ (some later slides express values in 2018$, assuming 4% escalation from 2016)	
Oil and gas prices	AEO2019 lowest projected prices (2050: crude oil @ $56/bbl & natural gas @ $3.6 - $4.7/$GJ_{HHV}$)
Biomass feedstocks	$30 - $150 per dry tonne delivered, based largely on DOE Billion Ton Study (2016)
CO_2 transport & storage	Cost varies by location and volume stored. Bulk of supply is in the range of $35/$tCO_2$

AEO 2019 low oil and natural gas price projections assumed due to flat or falling demand (as U.S. and other nations decarbonize)

Oil price assumptions



Natural gas price assumptions



- For comparison purposes, all scenarios, *including Reference*, assume the same oil and gas prices.
- This may understate the cost savings from reduced oil and gas use in net-zero scenarios, because the higher oil/gas demand in the Reference scenario would likely mean higher oil/gas prices in that case than in net-zero paths.

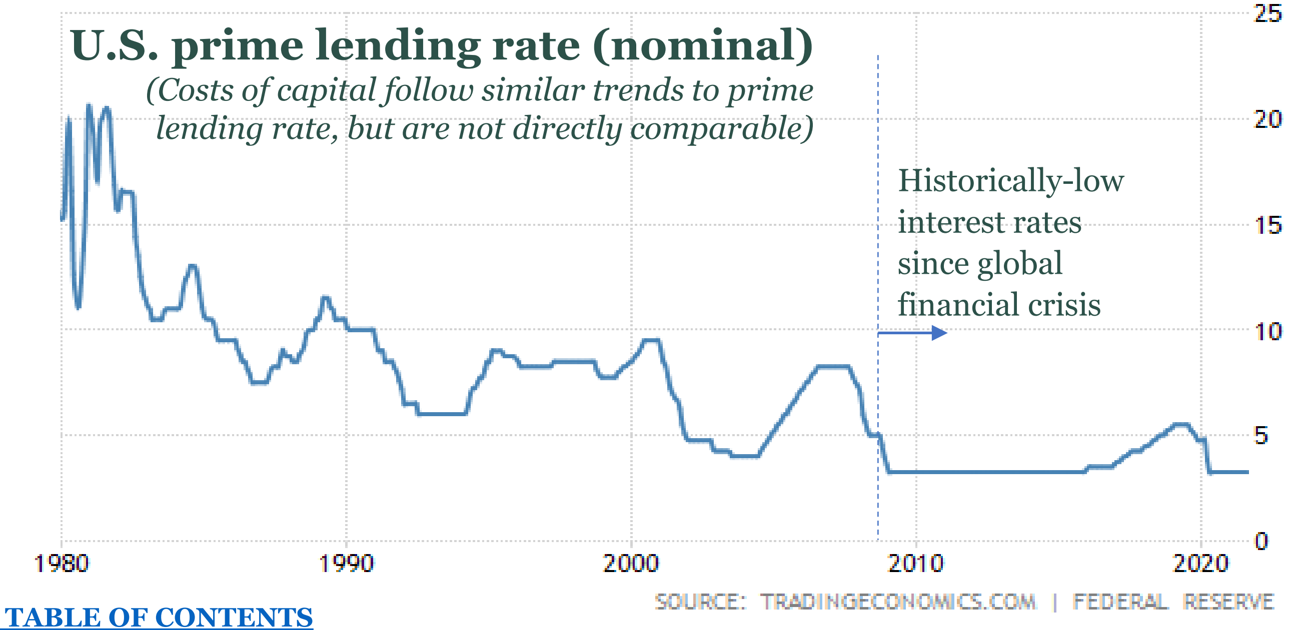
U.S. Energy Information Administration #AEO2019 | www.eia.gov/aeo

Assumed future inflation rate and cost of capital are consistent with the past decade, but low by historical standards.

Inflation and cost-of-capital assumptions in the modeling are consistent with those since the global financial crisis, but are low by historical standards.

Assumed inflation rate, 2020 – 2050

- 1.8% per year



Assumed (weighted-average, real) cost-of-capital for capital investments:

Energy-demand investments

- Range 3-8%, depending on subsector

Energy-supply investments

- Nuclear 6%
- Offshore wind 5%
- Other electricity generators and transmission 4%
- Bioenergy and other fuel conversion technologies 10%

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Net-zero emissions by 2050, together with assumed non-CO_2 emissions and land sink set target for energy/industry emissions

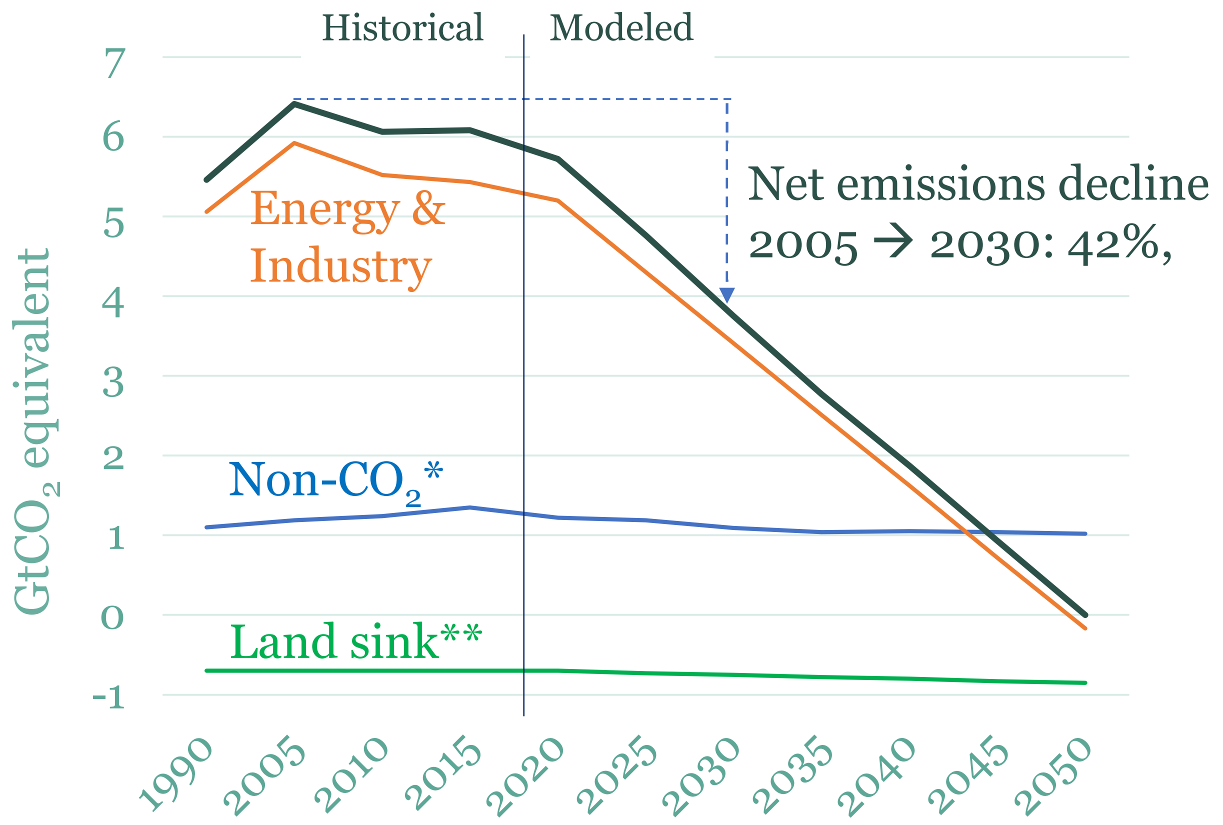
Gt CO_{2e}

Year	Non-CO_2*	Land sink**	Energy & Industrial system
1990	1.1	-0.7	5.06
2005	1.19	-0.7	5.92
2010	1.24	-0.7	5.52
2015	1.35	-0.7	5.43
2020	1.22	-0.7	**5.2**
2025	1.19	-0.73	**4.3**
2030	1.09	-0.75	**3.41**
2035	1.04	-0.78	**2.51**
2040	1.05	-0.8	**1.62**
2045	1.04	-0.83	**0.72**
2050	1.02	-0.85	**-0.17**

* *United States Mid-Century Strategy for Deep Decarbonization* benchmark scenario (U.S. Whitehouse, 2016)

** Natural plus enhanced land sink.

By 2050, land sink ≈ non-CO_2 emissions; requires small net-negative emissions from energy system



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Constructing multiple decarbonization pathways

Summary of this section

We define and model five different net-zero energy-system scenarios (or pathways), each with different assumptions about energy-demand and energy-supply technology options available in the future. 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 supply-side, RE (wind and solar) rate of increase constrained to 35 GW/y (~30% greater than historical maximum single-year total). Higher 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.

A large number of sensitivity cases were run to test the impact of changing input parameter values.

Summary of assumptions used to construct five energy/industry pathways supporting economy-wide net-zero emissions by 2050

	REF ~AEO 2019	E+ high electrification	E- less-high electrification	E- B+ high biomass	E+ RE- renewable constrained	E+ RE+ 100% renewable
CO_2 emissions target		- 0.17 $GtCO_2$ in 2050				
Electrification	Low	High	**Less high**	**Less high**	High	High
Wind/solar annual build	n/a	10%/y growth limit	10%/y growth limit	10%/y growth limit	**Recent GW/y limit**	10%/y growth limit
Existing nuclear	50% → 80-y life	50% → 80-y life	50% → 80-y life	50% → 80-y life	50% → 80-y life	**Retire @ 60 years**
New nuclear	Disallow in CA	Disallow in CA	Disallow in CA	Disallow in CA	Disallow in CA	**Disallowed**
Fossil fuel use	Allow	Allow	Allow	Allow	Allow	**None by 2050**
Maximum CO_2 storage	n/a	1.8 Gt/y in 2050	1.8 Gt/y in 2050	1.8 Gt/y in 2050	**3 Gt/y in 2050**	**Not allowed**
Biomass supply limit	n/a	13 EJ/y by 2050 (0.7 Gt/y biomass) [*No new land converted to bioenergy*]		**23 EJ/y by 2050 (1.3 Gt/y biomass)**	13 EJ/y by 2050 (0.7 Gt/y biomass) [*No new land converted to bioenergy*]	

Slide 1 of 2: Many scenario variants were run to test sensitivity of results to assumptions. Annex B has full details.

Group	Case no.	Shorthand name	Description of input changes
Land & non-CO_2 emissions	1	E+ Land+	Higher net (land sink + non-CO_2) emissions (2050 CO_2 emission cap for energy/industry changes from -0.17 to 0.27 Gt)
	2	E+ Land-	Lower net (land sink + non-CO_2) emissions (2050 CO_2 emission cap for energy/industry changes from -0.17 to -0.73 Gt)
Natural gas prices	3	E+ Gas+	Higher NG prices [AEO2020 'low oil and gas supply' case (e.g., 2050 Texas NG price changes from 3.53 to 6.56 USD/MMBtu)]
	4	E+ Gas-	Lower NG prices [AEO2020 'high oil and gas supply' case (e.g., 2050 Texas NG price changes from 3.53 to 2.54 USD/MMBtu)]
Power sector capital costs (non-nuclear)	5	E+ NGCC+	Higher NGCC-CCS capex (2050 capex changes from 1725 to 2589 $/kW)
	6	E+ NGCC-	Lower NGCC-CCS capex (2050 capex change from 1725 to 1380 $/kW)
	7	E+ Solar_Wind+	Higher solar/wind capex (e.g., 2050 NJ onshore wind TRG1 goes from 1723 to 2280 $/kW; PV TRG1 from 869 to 1144 $/kW)
	8	E+ Solar_Wind-	Lower solar/wind capex (e.g., 2050 NJ onshore wind TRG1 goes from 1723 to 1433 $/kW, PV TRG1 from 869 to 453 $/kW)
	9	E+ Trans+	Higher transmission cost (e.g., 2050 Mid-Atlantic<-->New York transmission cost doubles to 5642 $/kW)
Nuclear power capital costs and build rates	10	E+ Nu+	Higher nuclear capex (2050 capex changes from 5530 to 8295 $/kW)
	11	E+ Nu-	Lower nuclear capex (2050 capex changes from 5530 to 4423 $/kW)
	12	E+ NuRate-	E+ with constrained nuclear capacity built rate (10GW/year maximum from 2030)
	13	E+ Nu--	E+ with lowest nuclear capex (2050 capex changes from 5530 to 1800 $/kW)
	14	E+ Nu--Rate-	E+ with lowest nuclear capex (2050 capex 1800 $/kW) & constrained nuclear capacity built rate (10GW/y maximum from 2030)
	15	E+RE-NuRate-	RE- with constrained nuclear capacity built rate (10GW/year maximum from 2030)
	16	E+RE-Nu--	RE- with lowest nuclear capex (2050 capex 1800$/kW)
	17	E+RE-Nu--Rate--	RE- with lowest nuclear capex (2050 capex 1800$/kW) & lowest nuclear built rate (from 0.36GW/y in 2025 to 8GW/y in 2050)
Wind and transmission build rates	18	E+ TrRate-	Higher transmission capacity constraint (e.g. 2050 Mid-Atlantic<-->New York capacity limit 3830 MW instead of 19145 MW)
	19	E+ Wind-	GW wind installed capacity limits in 2050 (% of E+ capacity): onshore 50%; offshore-wind 100%, except 70% in Mid-Atlantic
	20	E+ Tr&Wind-	Constrained wind build rate + constrained transmission build rate (combines sensitivities 18 and 19)
H_2 turbines	21	E+ H2Turbine	Added constraint of only 100% H_2-firing of GTs allowed starting 2035.
Flexible load technologies	22	E+ EVflex0	No time shifting of EV charging or water heating loads
	23	E+ EVflex+	Increased flexibility in time-shifting loads (100% of EV load can shift; 40% of heat load can shift)
	24	E+ No Electrolysis	Disallows electrolysis, one of the hourly flexible loads
	25	E+ No Electrolysis No E-boiler	Disallows electrolysis and electric boilers, the two hourly flexible load technology options
	26	E+ Electrolysis-	Lower electrolysis capital costs (reaching 220$/kW in 2050)
	27	E+ Electroysis--	Lowest electrolysis capital costs (reaching 96$/kW in 2050)

Note: Unit capital costs for fuels production technologies are given here on a per unit of output, higher heating value basis.

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Slide 2 of 2: Many scenario variants were run to test sensitivity of results to assumptions. Annex B has full details.

Group	Case no.	Shorthand name	Description of input changes
Hydrogen production capital costs	28	E+ NoBioH_2	BECCS-H_2 technology not allowed
	29	E+ BioH_2+	Higher capex for bioconversion to H_2 with carbon capture (4050 $/kW in 2050 instead of 2700 $/kW)
	30	E+ BioH_2-	Lower capex for bioconversion to H_2 with carbon capture (2160 $/kW in 2050 instead of 2700 $/kW)
	31	E+ ATR+	Higher capex for ATR and SMR (both w/CCS) (from 814 to 1221 $/kW for ATR in 2050 and 826 to 1239 $/kW for SMR)
	32	E+ ATR-	Lower capex for ATR & SMR (both with CCS) (ATR: 814 à 651 $/kW in 2050; SMR: 826 à 660 $/kW)
Fuels production capital costs	33	E+ FTS+	Higher FTS/SNG capex (2050 SNG changes from 1155 to 1732 $/kW, FTS changes from 952 to 1428 $/kW)
	34	E+ FTS-	Lower FTS/SNG capex (2050 SNG changes from 1155 to 924 $/kW, FTS changes from 952 to 761 $/kW)
	35	E+ BioFT+	Higher biomass FT w/ccs capex (2050 capex changes from 3962 $/kW to 5948 $/kW)
	36	E+ BioFT-	Lower biomass FT w/ccs capex (2050 capex changes from 3962 $/kW to 3172 $/kW)
Direct air capture	37	E+ DAC-	Lower DAC capex (from $2,164 to $694 per tCO2/year, 2016$)
	38	E+ DAC eff+	Higher DAC electric efficiency (1 instead of 2 MWh/tCO2)
	39	E+ DAC- eff+	Lower DAC capex and higher efficiency (combines sensitivities 37 and 38)
Higher energy efficiency	40	E+ VMT-	15% lower VMT for light duty vehicles (cars/trucks) by 2050
	41	E+ Ieff+	3% per year increase in industrial output ($) per unit energy input (instead of 1.9% per year)
	42	E+ Beff+	1% per year building heating and cooling energy reduction due to greater shell efficiency improvements
	43	E+ EFF+	Combination of sensitivities 40, 41, and 42 (results in 2050 final energy demand ~25% below E+ level)
No new biomass	44	E+ B-	E+ but no additional lignocellulosic biomass beyond today's level
	45	E+ RE- B-	E+ RE- but no additional lignocellulosic biomass beyond today's level
High biomass supply	46	E+ B+	E+ RE+ with high biomass supply (24EJ per year from 13EJ per year)
	47	E- B+	E- with high biomass supply (24EJ per year from 13EJ per year) (This is one of the 5 core scenarios)
	48	E+ RE+ B+	E+RE+ with high biomass supply (24EJ per year from 13EJ per year)
	49	E+ RE- B+	E+RE- with high biomass supply (24EJ per year from 13EJ per year)
	50	E- RE- B+	E-RE- with high biomass supply (24EJ per year from 13EJ per year)
CO_2 emissions trajectory	51	E+SlowStart	Energy/industry CO_2 emissions trajectory to 2030 follows 2005-2020 rate and then linearly declines to -0.17 Gt in 2050.
	52	E+S	Follows slow start emissions rate to 2030, then falls more rapidly to 2040, and then the decline rate slows to reach -0.17 Gt in 2050.
Higher social discount rate	53	E+ 7%	Social discounting @7% instead of 2%
	54	E- B+ 7%	Social discounting @7% instead of 2%
No CO_2 capture	55	E+NoCCUS	No CO_2 capture allowed. (No feasible model solution found with this constraint)

Note: Unit capital costs for fuels production technologies are given here on a per unit of output, higher heating value basis.

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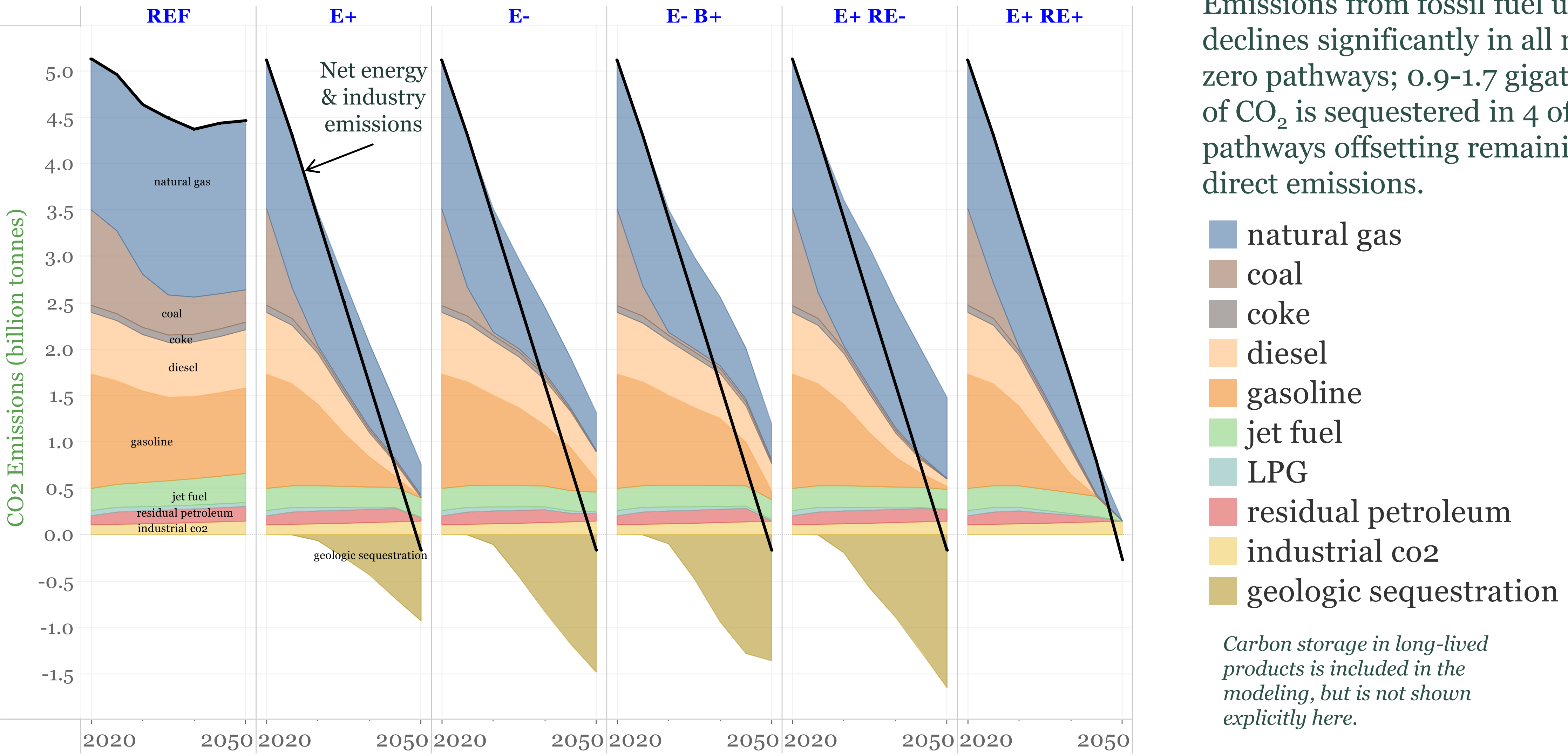
High-level modeling results for net-zero pathways

Summary of this section

- In all five cost-minimized energy-supply pathways, with a linear decline to net-zero emissions by 2050, coal use is essentially eliminated by 2030.
- 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+) petroleum-derived liquid fuels decline more rapidly than in the less-aggressive electrification cases (E-, E-B+).
- 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.

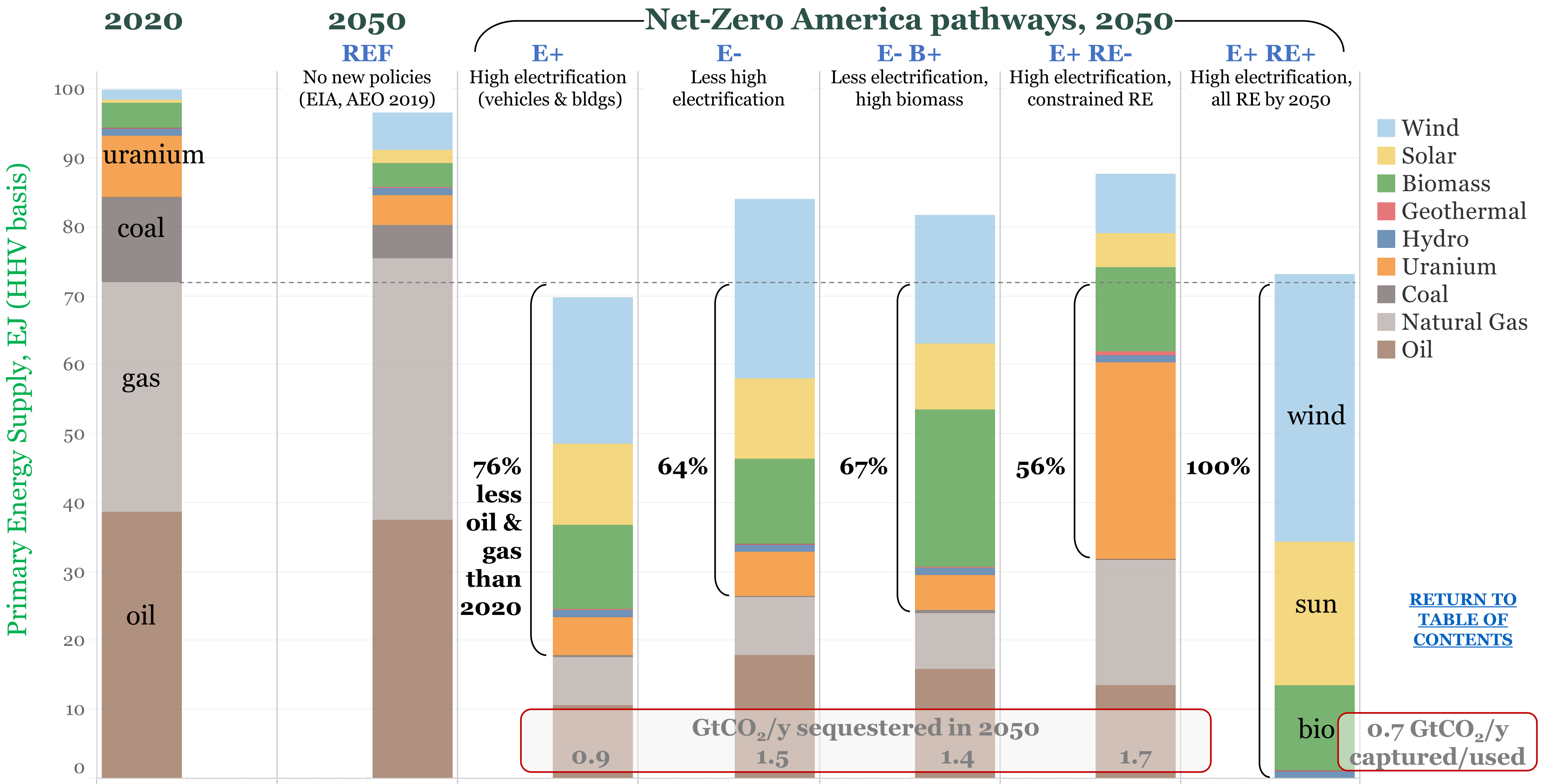
Energy and industrial CO_2 emissions are net negative by 2050 to deliver net-zero emissions for the full economy



Emissions from fossil fuel use declines significantly in all net-zero pathways; 0.9-1.7 gigatons of CO_2 is sequestered in 4 of 5 pathways offsetting remaining direct emissions.

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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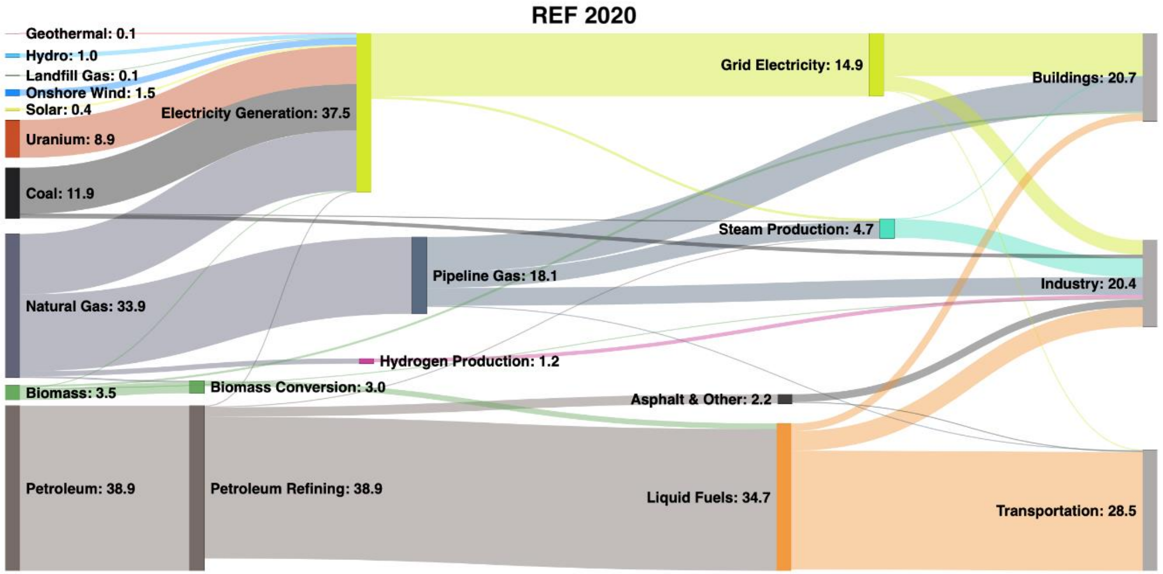
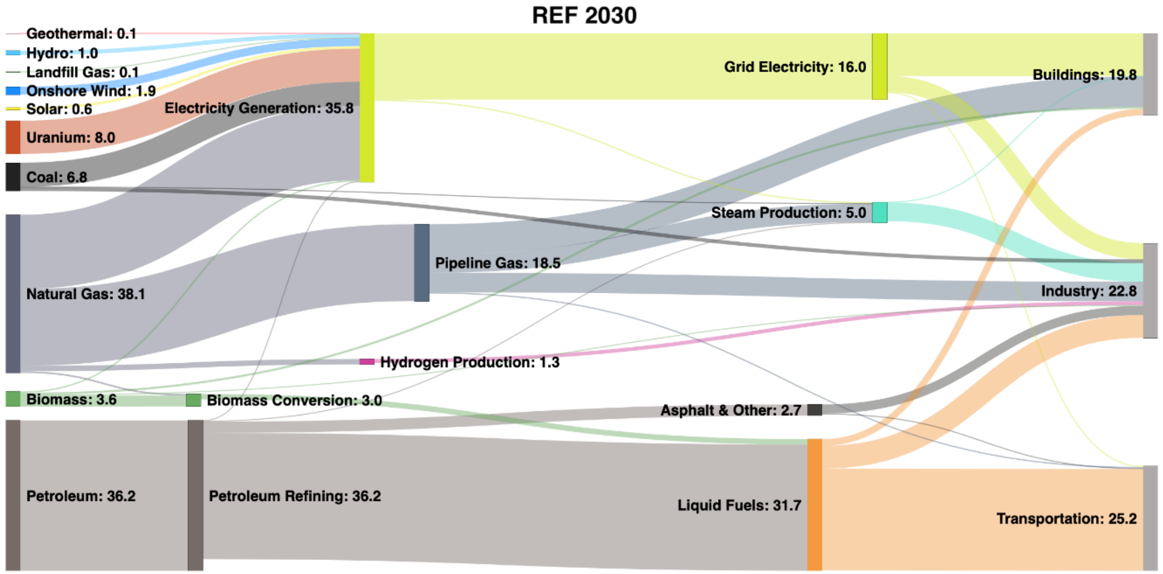
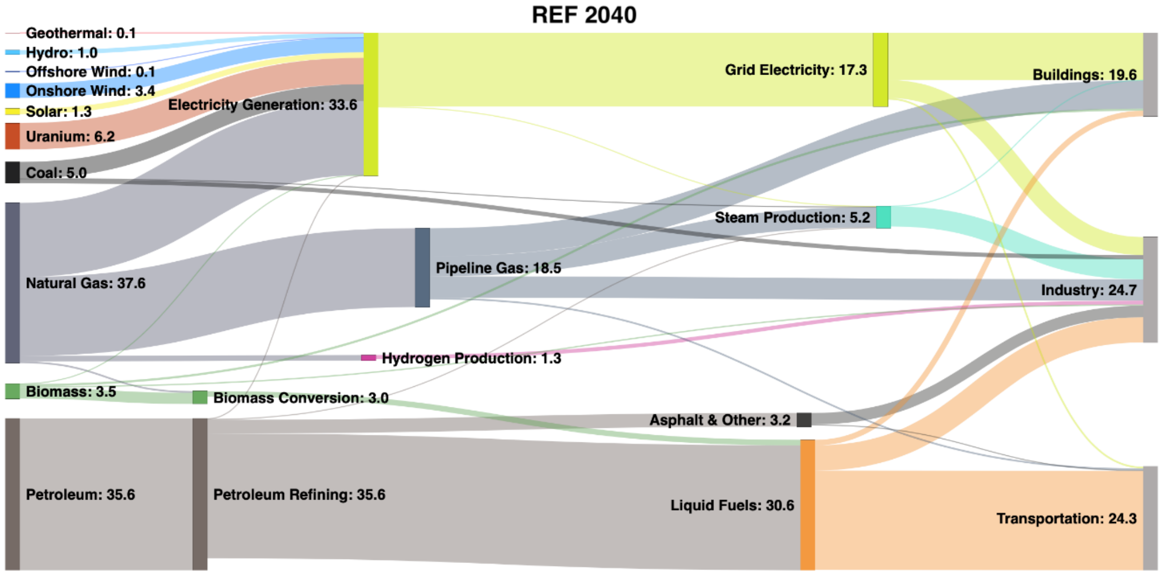
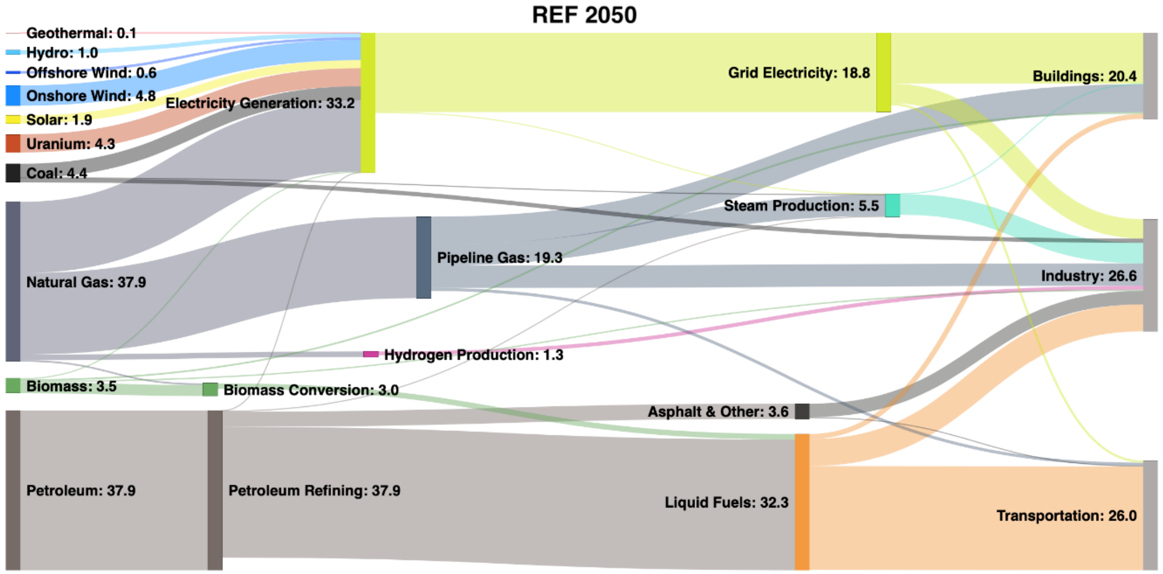
REF primary energy flows (EJ): Relatively little change from 2020 to 2050.









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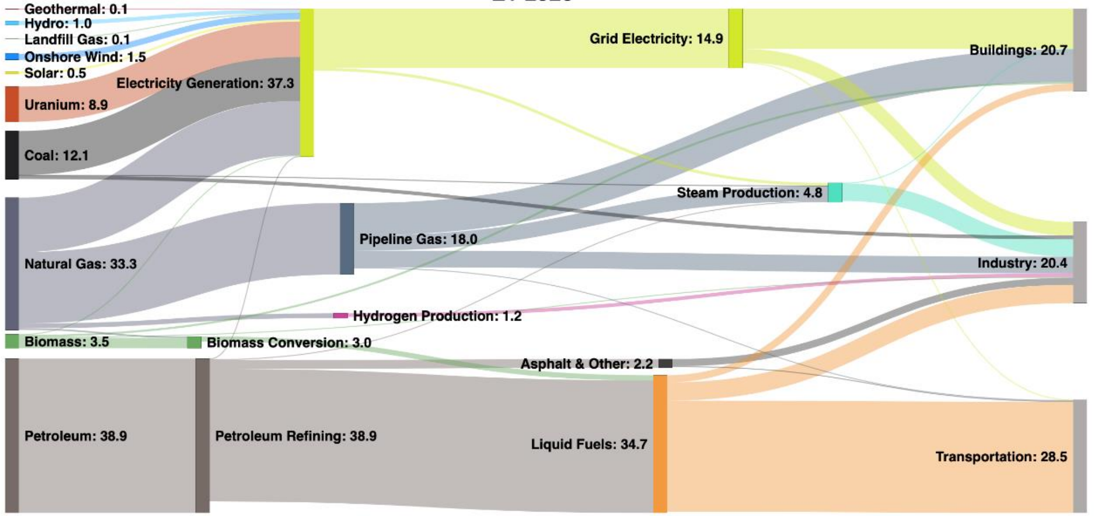
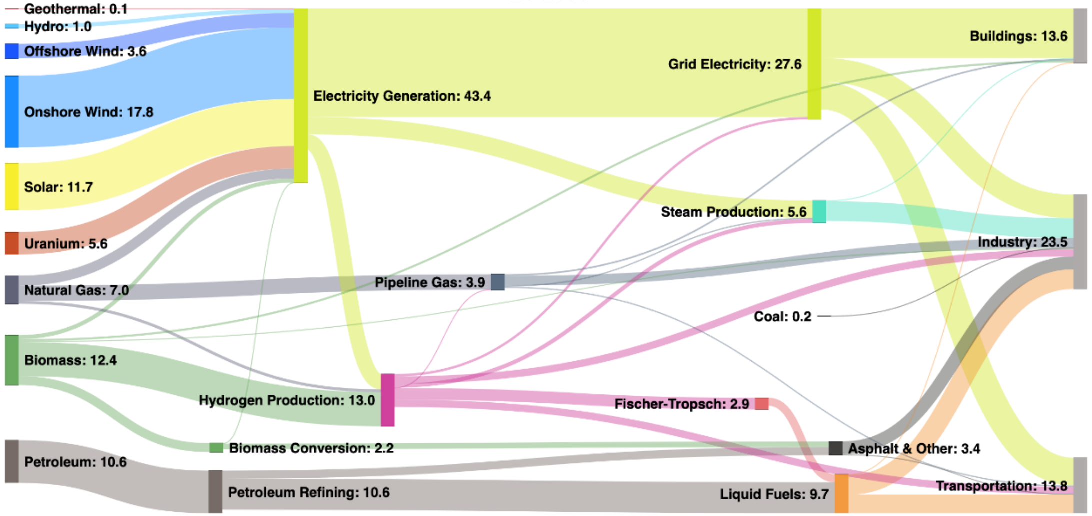
Primary energy flows (EJ) in 2020 & 2050 for E+ and E-. Total energy use declines due to efficiency gains and electrification.

More petroleum in E- (bottom) than E+ (top) by 2050, but also more clean electricity used to synthesize zero net-emission hydrocarbon fuels and to run direct air capture for negative emissions

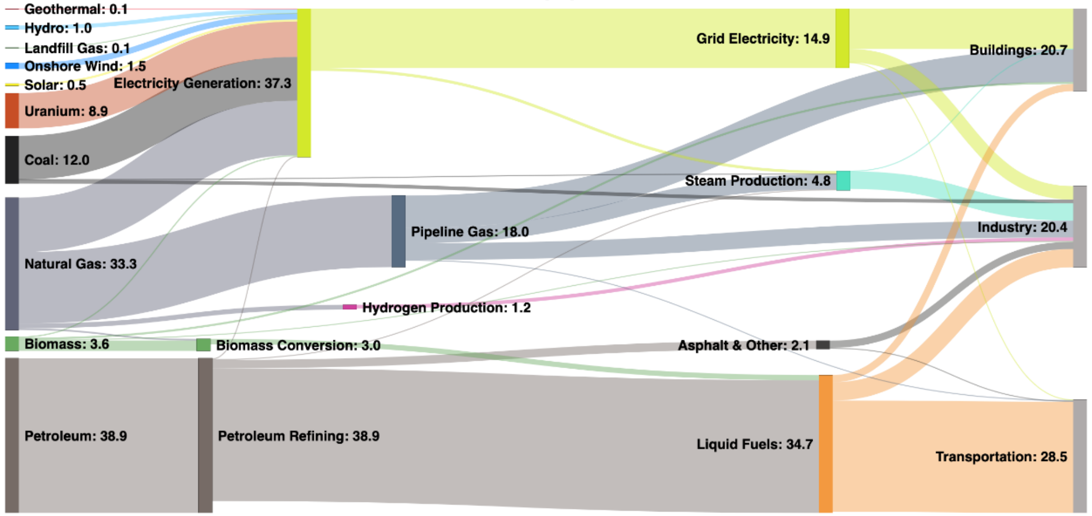
E+ 2020



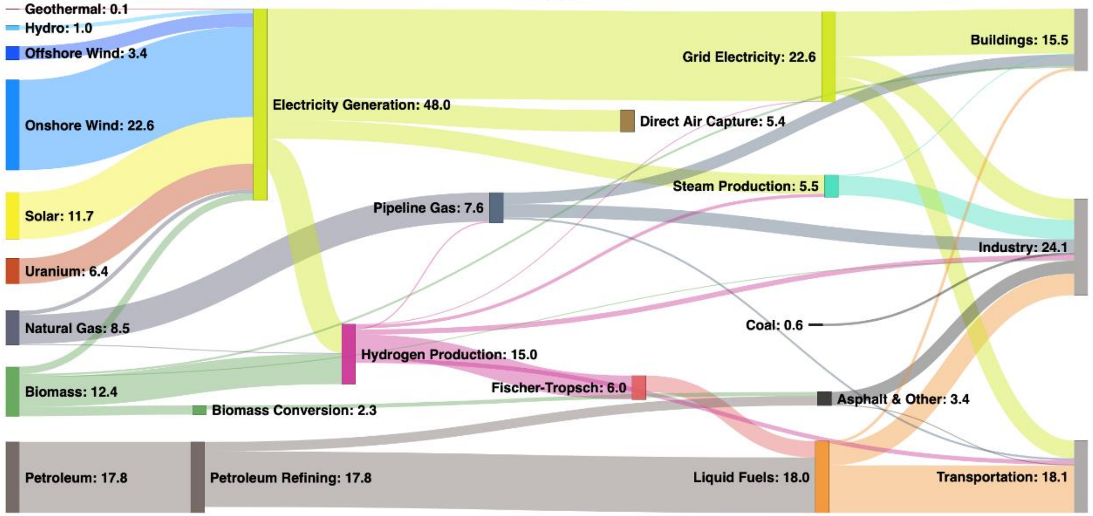
E+ 2050



E- 2020



E- 2050



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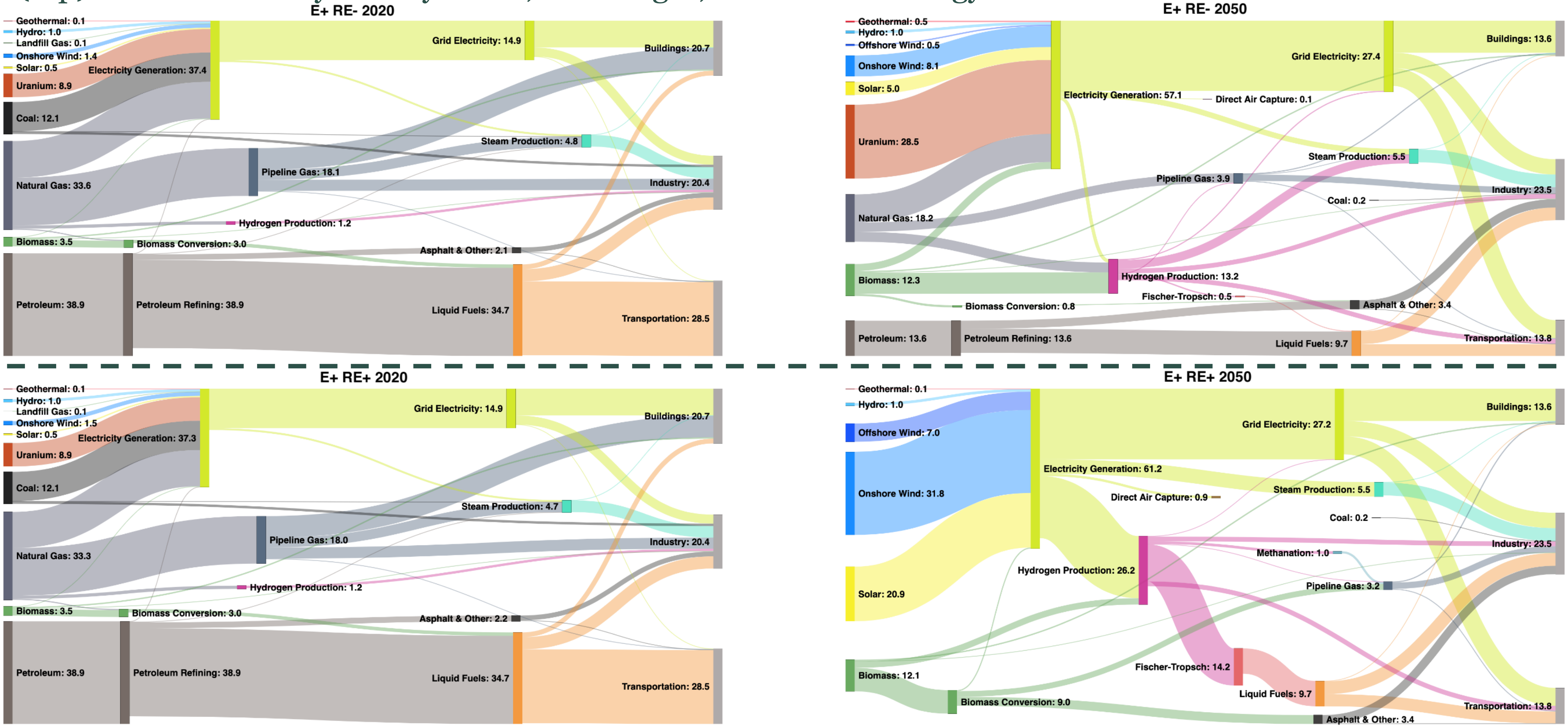
Primary energy flows (EJ) in 2020 & 2050 for E+RE- and E+RE+ highlights large differences in reliance on wind, solar, and nuclear.

E+RE+ (bottom) in 2050 relies entirely on electricity and synthesized fuels for final energy, while E+RE- (top) continues to rely heavily on oil, natural gas, and nuclear energy.



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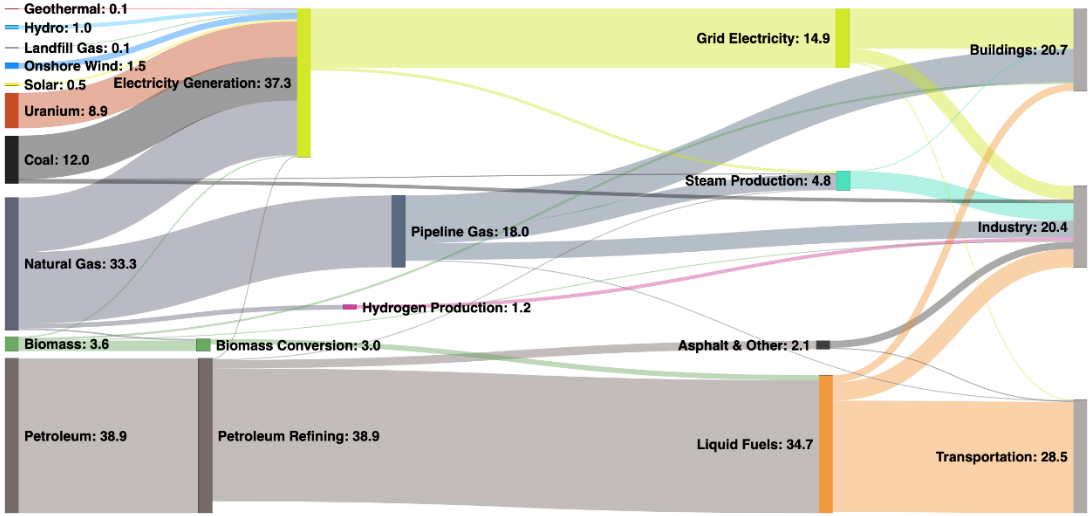
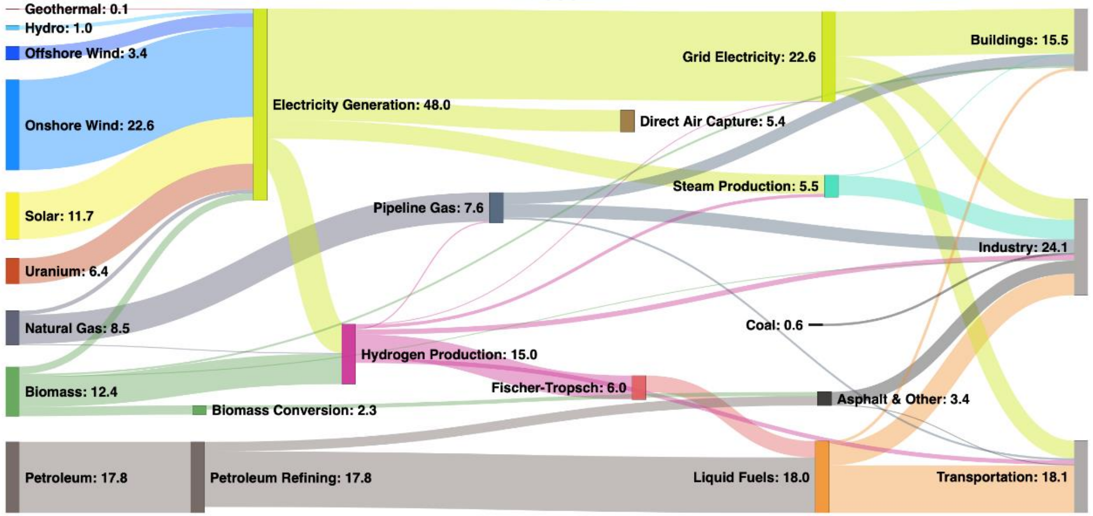
Primary energy flows (EJ) in 2020 & 2050 for E- and E-B+ highlights the impact of biomass resource potential.

In E-B+ (bottom) added biomass is used largely for hydrogen production and power generation (reducing wind, solar, and nuclear). Total electricity generation in E-B+ is lower due to less fuels synthesis and no DAC.

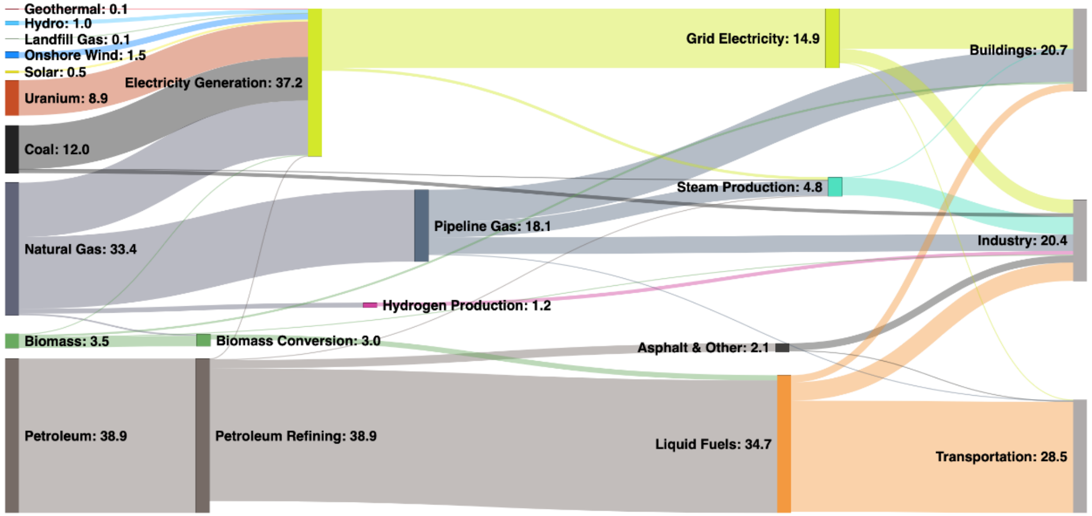
E- 2020



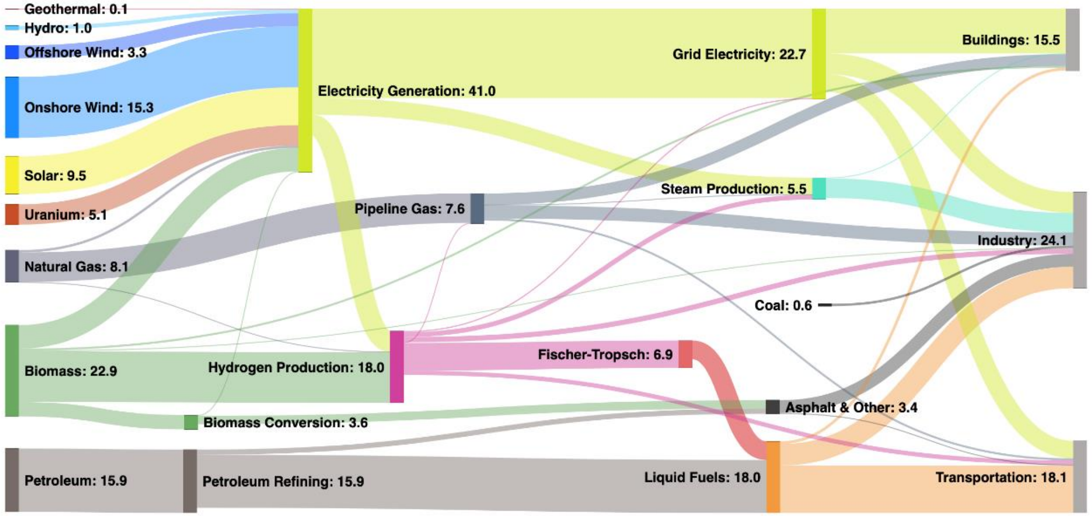
E- 2050



E- B+ 2020



E- B+ 2050



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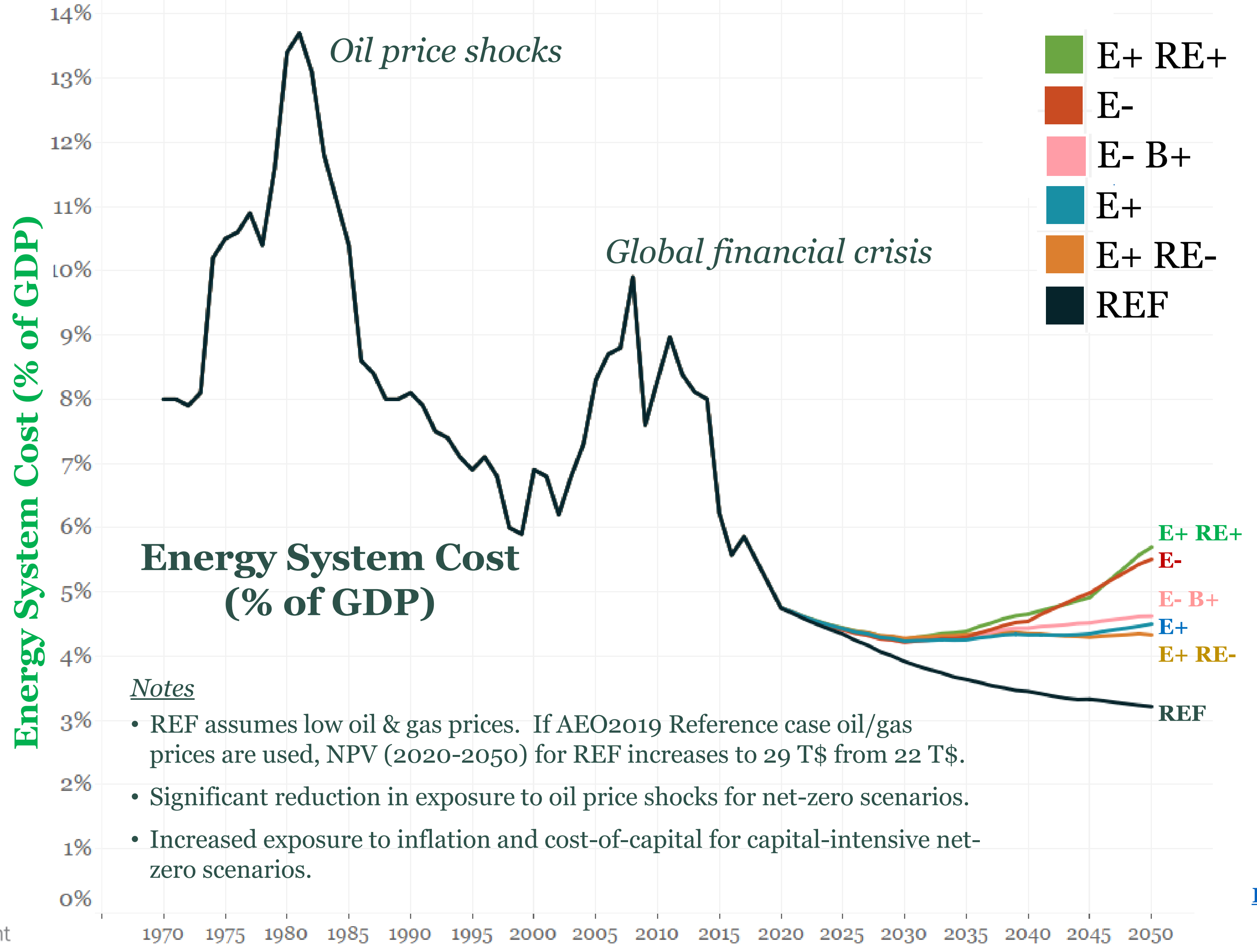
Modeled annualized energy-system costs as % of GDP are comparable to (or less than) in recent prosperous economic times

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



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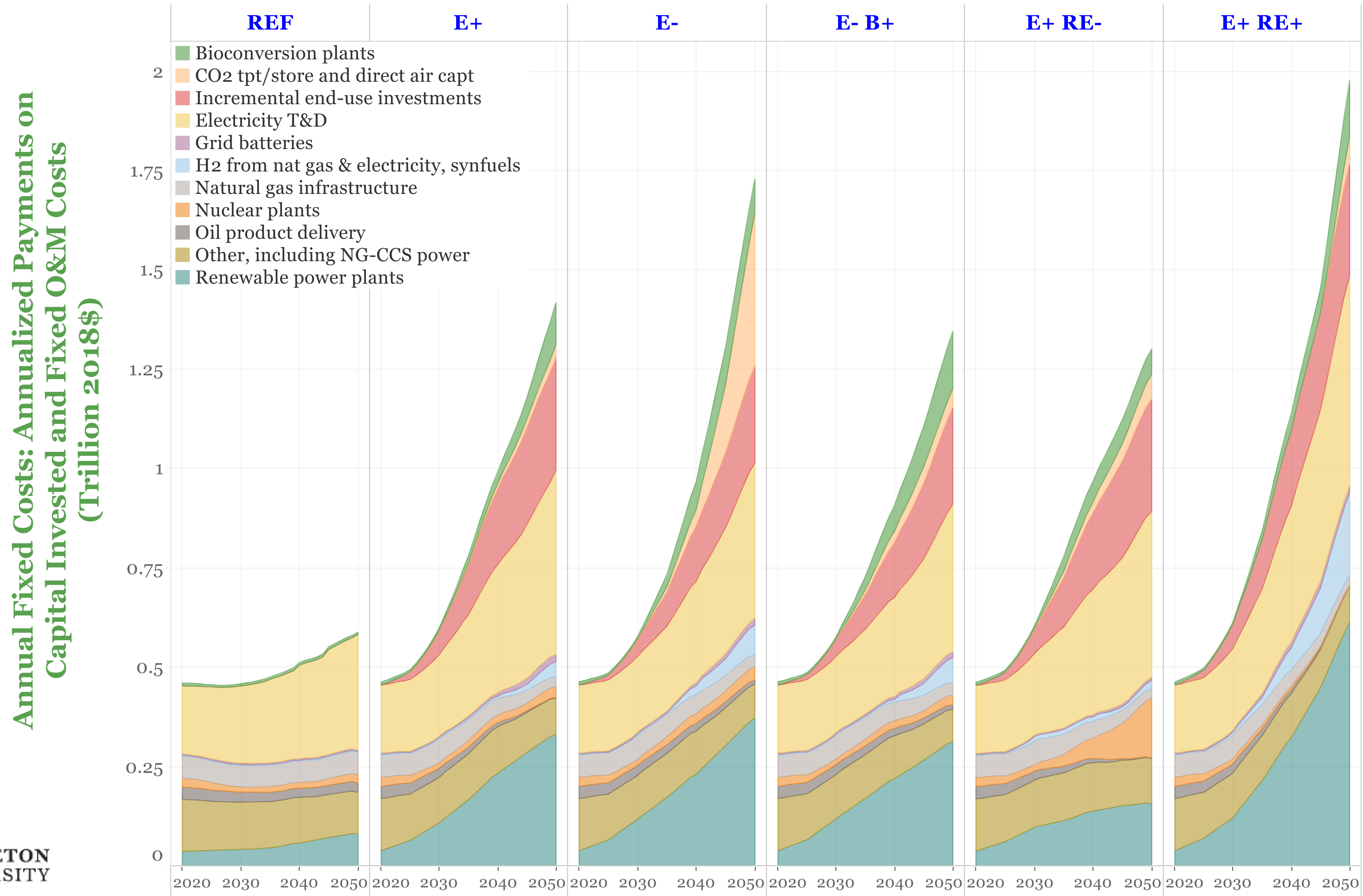
Annual costs shift from fuel costs to fixed costs: annualized capital + fixed O&M payments by 2050 are 2 to 4 times those for REF.



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Six pillars of decarbonization are needed to support the transition to net-zero in any 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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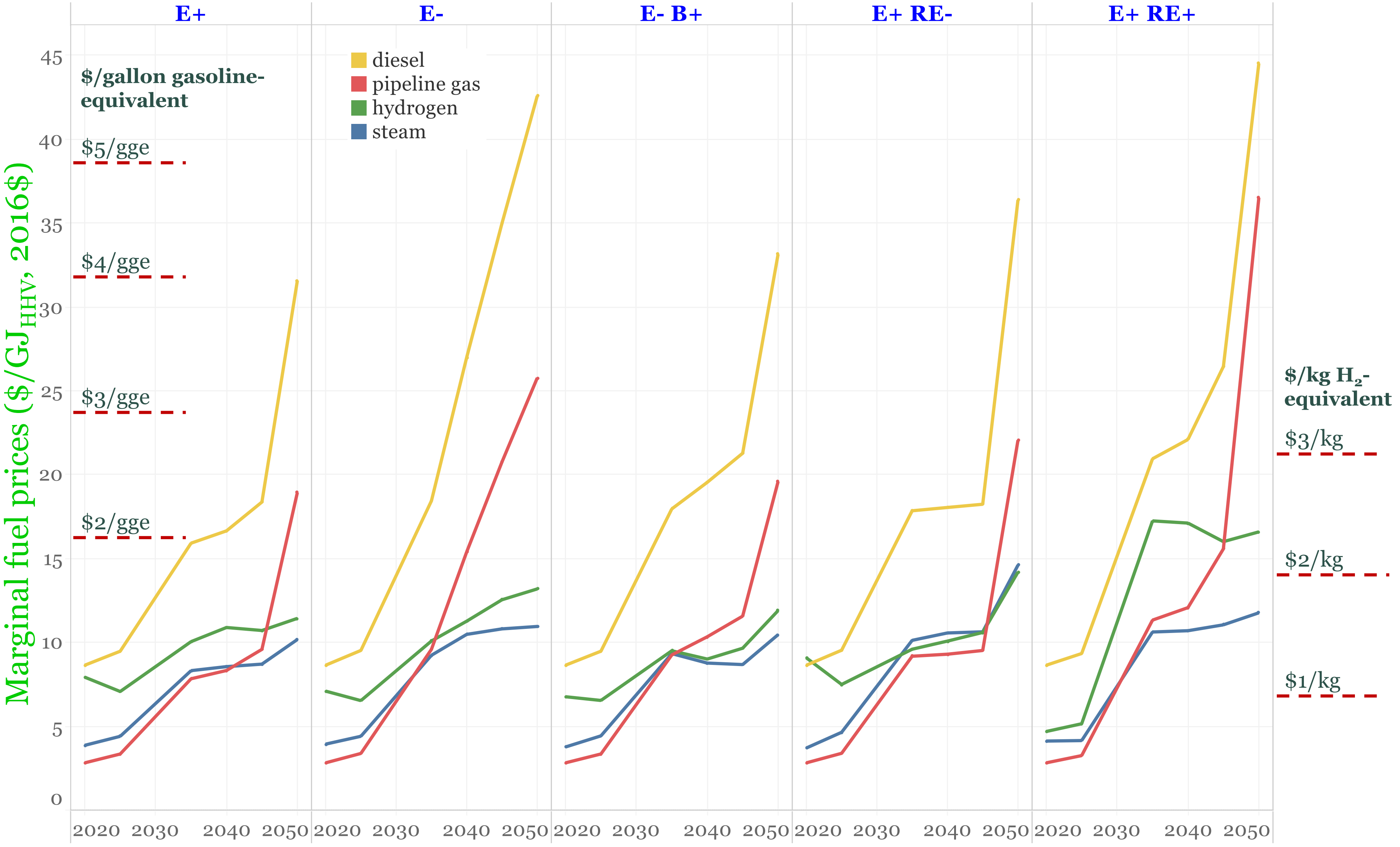
Pillar 1: Improve end-use energy productivity – efficiency and electrification

Summary of this section

- 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, as suggested by the significantly increasing marginal prices for fuels across the different scenarios.
- Electrification itself provides large reductions in final energy needed for transportation and space and water heating because electric drive trains for vehicles and electric heat pumps for heating are intrinsically more efficient than using fuels for these purposes.
- While there is significant electrification of transport and buildings, equipment replacements in our modeling are assumed to occur only at economic end-of-life, which reduces asset replacement costs. More aggressive replacement rates are possible, but would leave some assets stranded and increase transition costs.
- Summaries of the evolution of transportation, residential, commercial, and industrial sector final energy demands are provided in later slides in this section.

Increasing marginal prices for fuels in net-zero pathways imply growing motivation for users to improve efficiencies and electrify.

- Marginal prices reflect the modeled cost of supplying one more increment of fuel.
- Values for 2020 are fossil fuel prices projected for 2020 in AEO2019.
- In later years, values reflect the cost of producing one more unit of zero-carbon fuel; for fossil fuels, values reflect both the cost of the fuel and the implicit cost of CO_2 emissions from fuel combustion given emissions limits imposed in the model.



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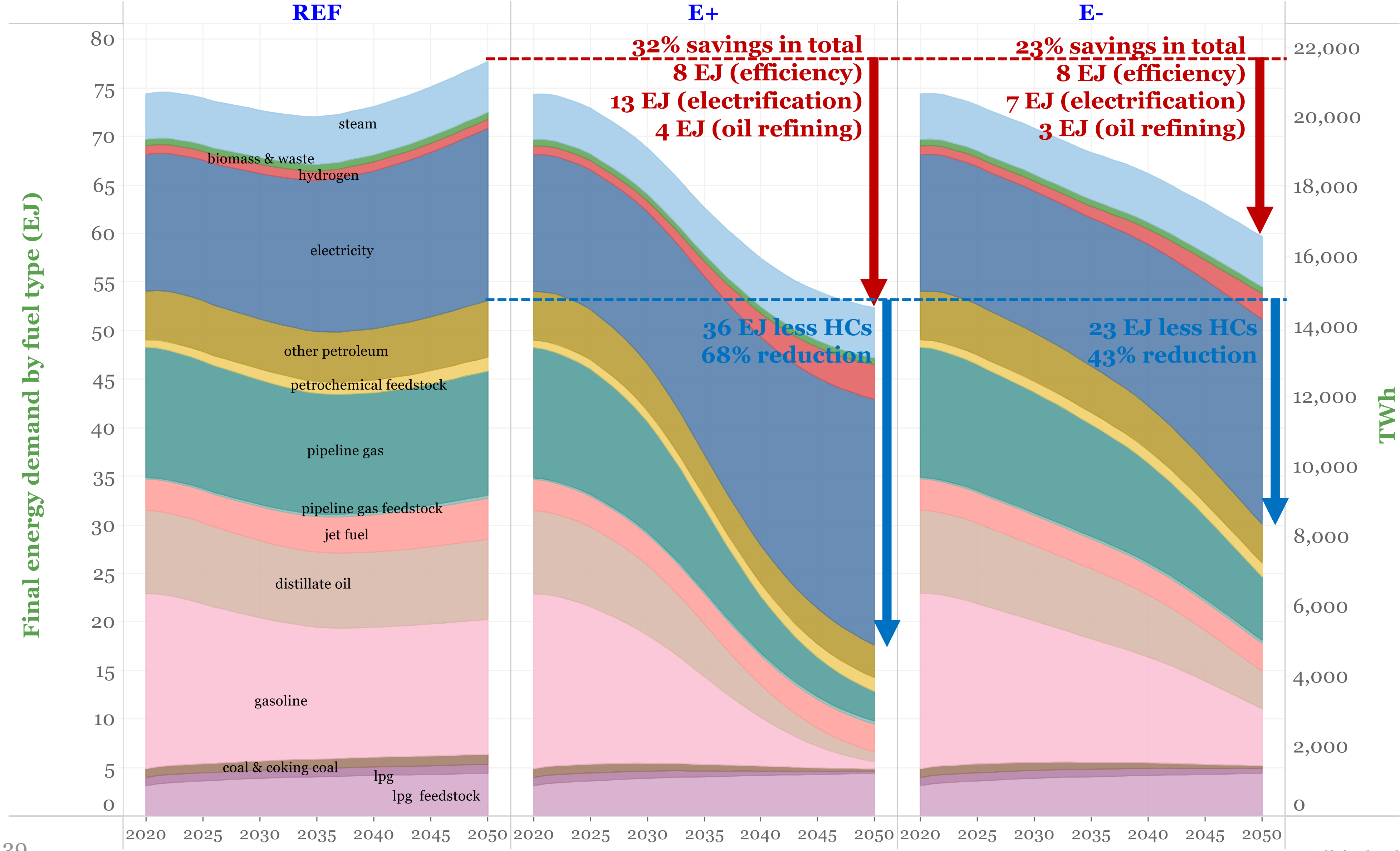
End-use energy productivity improves via same-fuel efficiency gains and via electrification; energy used for oil refining declines.



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.

EVs and heat pumps deliver double benefit: fuel switching to clean electricity *and* reduced final energy use due to greater efficiencies

	Electric Vehicle		Hydrogen Fuel Cell Vehicle		Gasoline Internal Combustion Engine
	100 units of final energy (electricity)		100 units of final energy (hydrogen)		100 units of final energy (gasoline)
Charging equipment	5% energy losses	H_2 to electricity fuel cell efficiency	46% energy losses	Internal combustion engine efficiency	70% energy losses
Battery charge efficiency	5% energy losses				
Inversion DC/AC	5% energy losses	Inversion DC/AC	5% energy losses		
Electric motor efficiency	5% energy losses	Electric motor efficiency	5% energy losses		
% energy delivered to wheels	**81%**		**49%**		**30%**

Adapted from original in Transport and Environment, "Electrofuels? Yes, we can … if we're efficient," December 2020.

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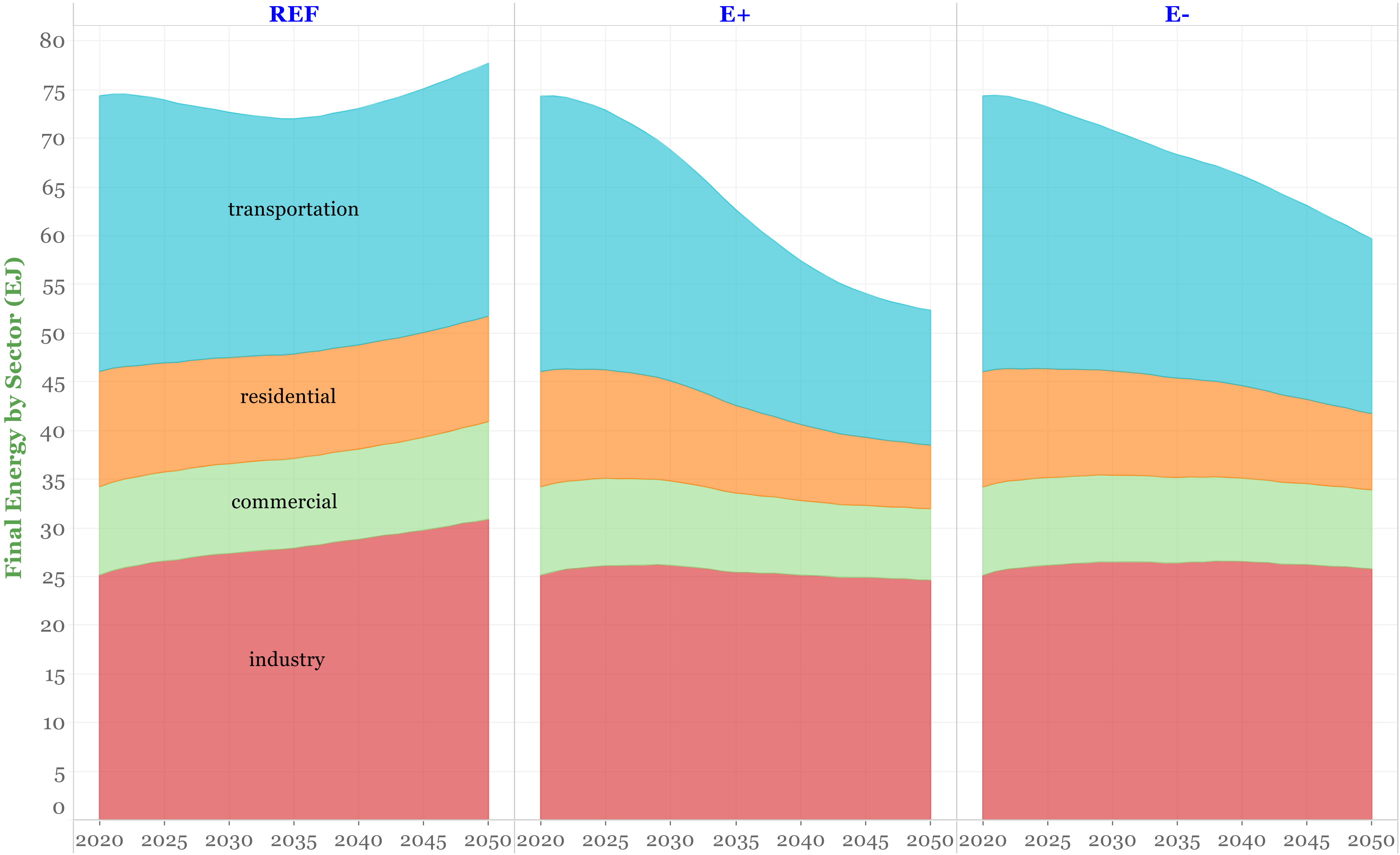
Final-energy demands for transportation decrease dramatically. Other sectors see more modest reductions by 2050.



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

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Efficiency improvements at least cost capitalize on timing equipment/vehicle replacements at end of life.

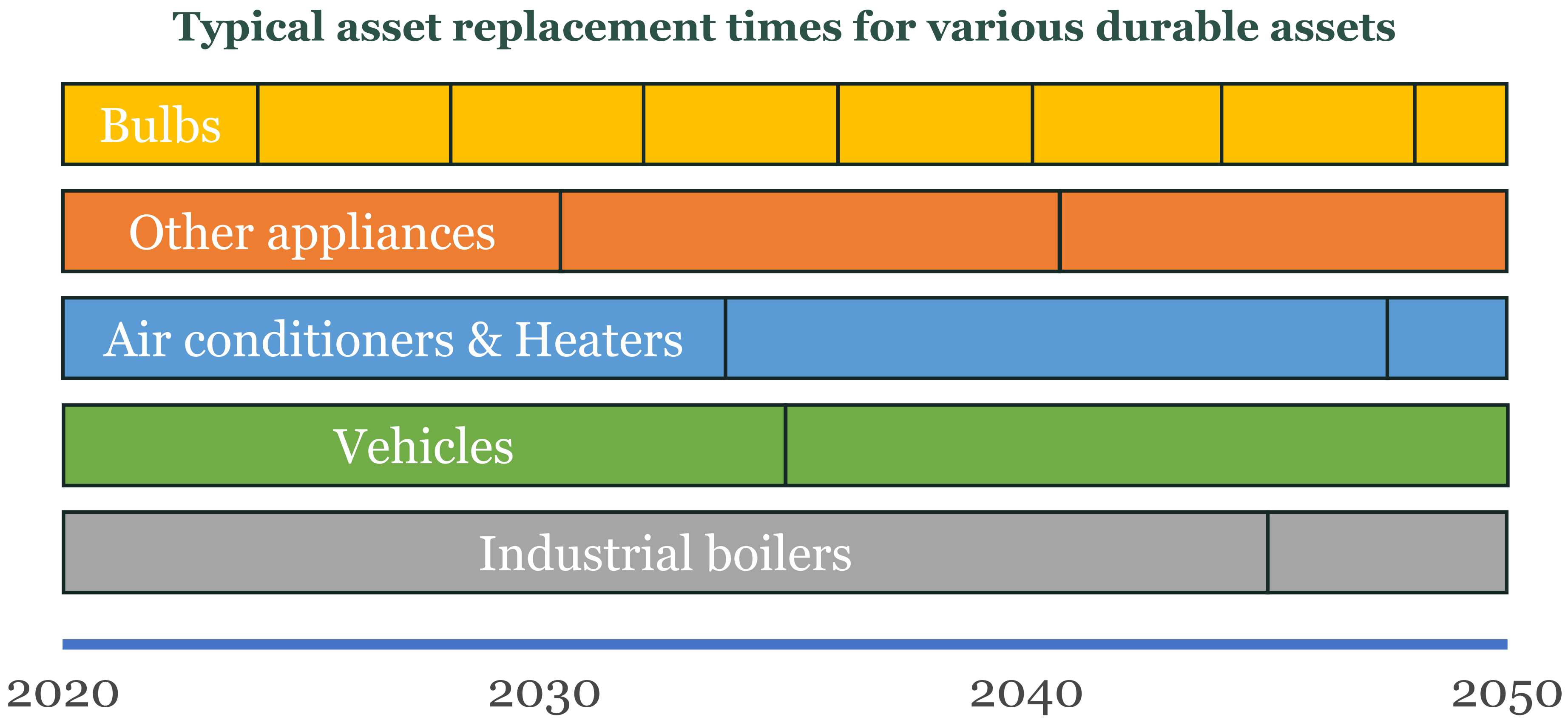


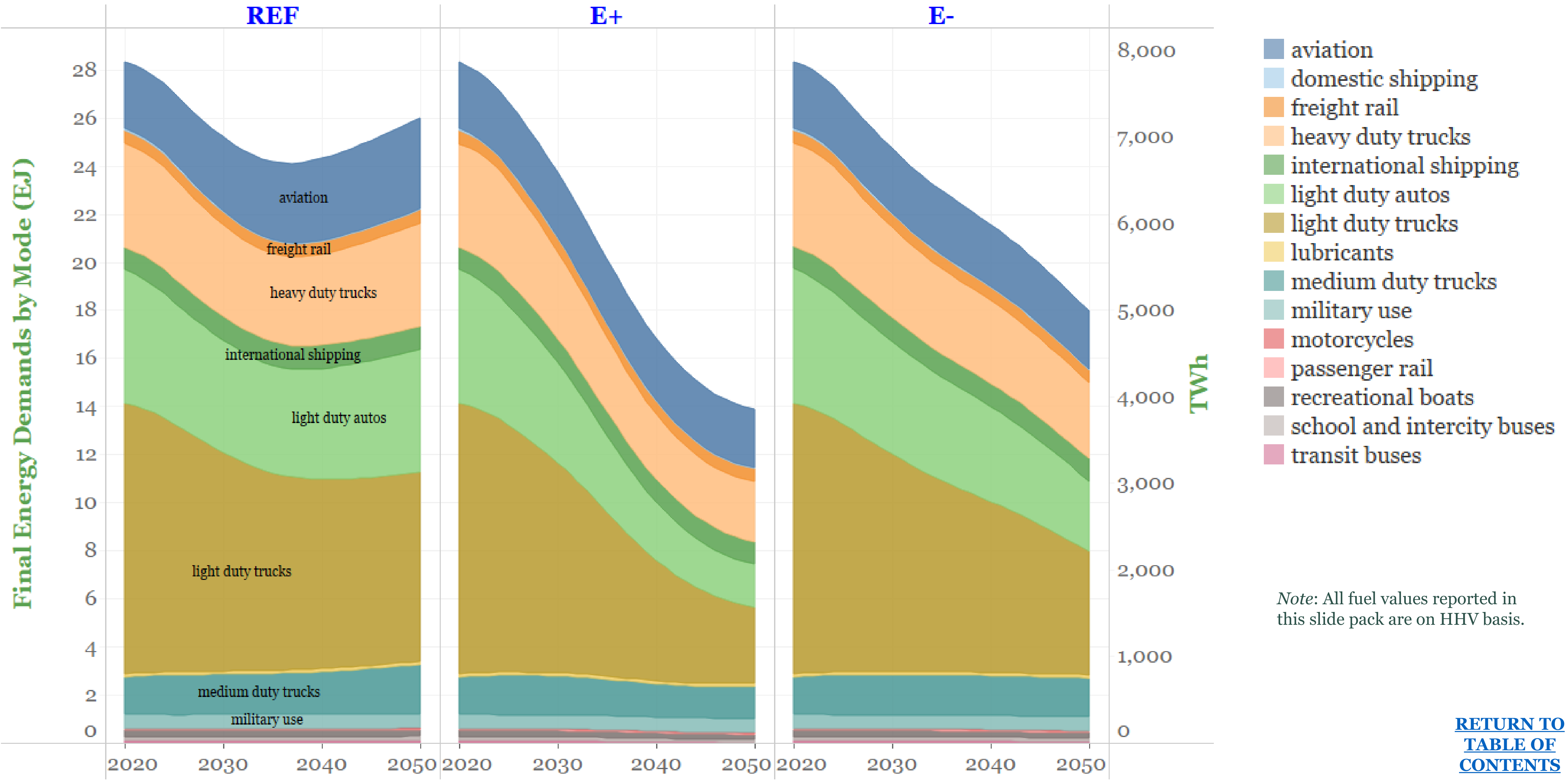
Image credit: Ryan Jones, Evolved Energy Research

Transportation sector

Summary of this section

- Final transportation energy demand in 2050 in the net-zero pathways is one-third to one-half the 2020 level, with reductions in energy use for every mode of transport except aviation. In aviation, the assumed 1.5%/y efficiency improvements offset growing passenger travel demands.
- Energy use by light-duty vehicles (LDV) falls most significantly due to electrification. With aggressive electrification (E+), 17% of the LDVs are electric by 2030 and 96% are electric by 2050. With less aggressive electrification (E-), the 2030 and 2050 electric shares are 6% and 61%.
- Electric LDV costs have been falling in recent years due largely to battery cost reductions, and the model assumes costs reductions will continue, with cost parity with conventional LDVs reached around 2030. The extra upfront costs for electric vs. conventional LDVs in the 2020s cumulatively is $185 billion in the E+ scenario.
- An additional $7 billion of investment (for E+) would be needed during the 2020s in public charging infrastructure to support the EV fleet.
- Medium and heavy-duty truck fleets transition by 2050 to almost entirely electric or hydrogen fuel-cell power. Cost premiums for these vehicles slowly decline over time, but remain relatively high still in the 2030s compared with electric LDV premiums.
- See Annex C for additional details.

Energy use in all transportation modes falls as a result of efficiency gains (e.g., aviation) and/or electrification (e.g., cars and trucks)



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

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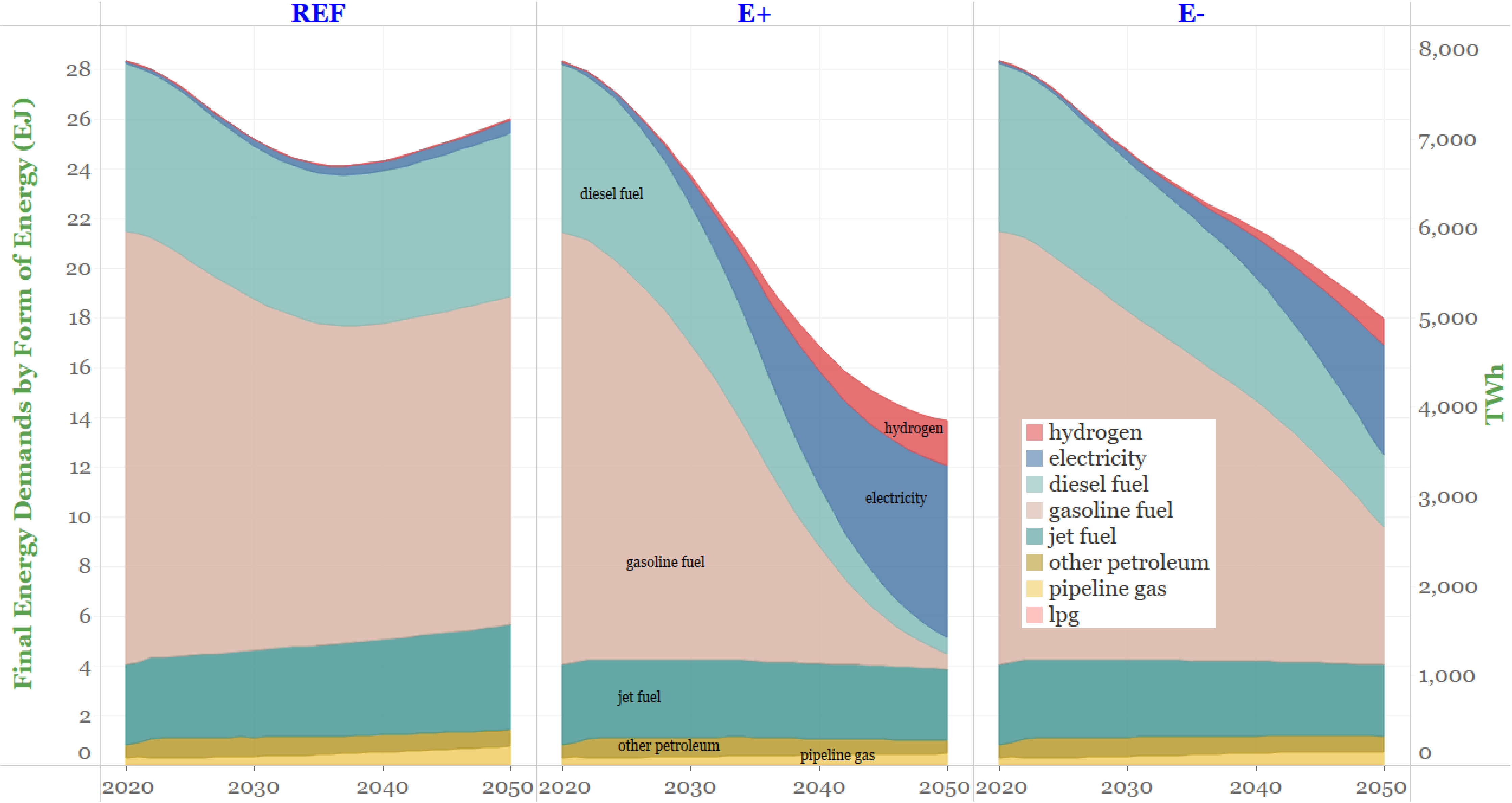
Electricity, jet fuel, and H_2 are predominant transportation fuels in E+ by 2050. Liquid fuels in 2050 are still significant in E-.



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

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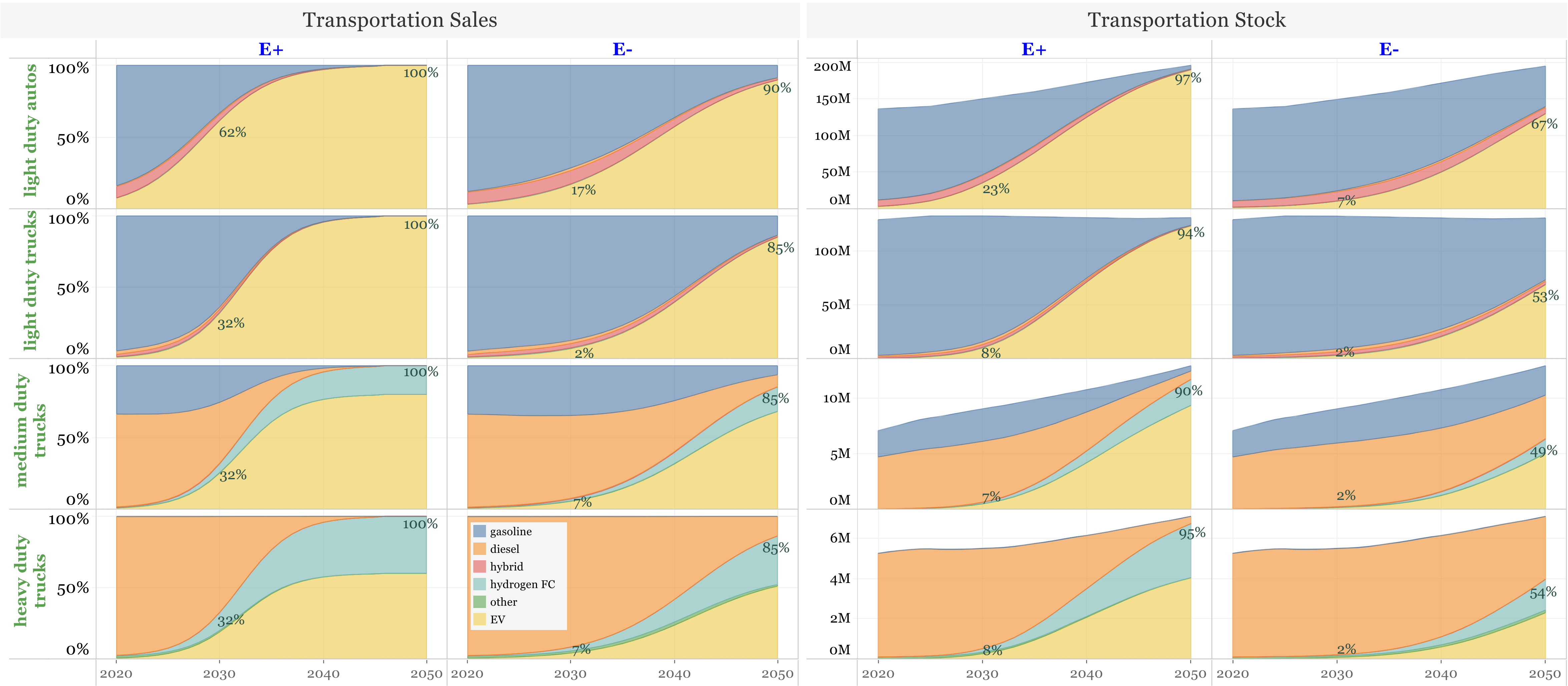
In the 2040s, light duty vehicles sales are 60%-100% EV. Medium & heavy truck sales are 50%-100% electric drivetrain (EV + H_2FCV)



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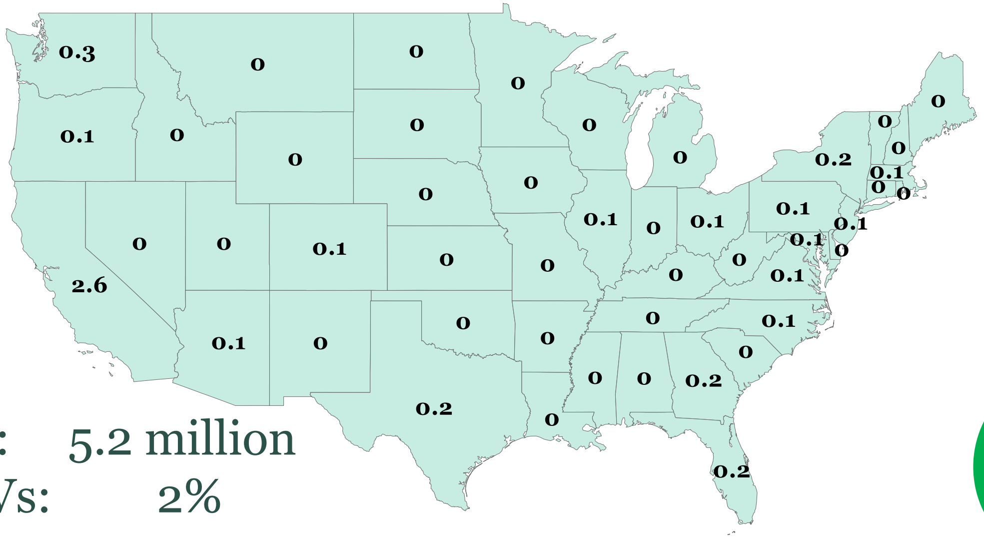
In E+, the stock of EVs grows to 17% of all light-duty vehicles by 2030 and 96% by 2050.

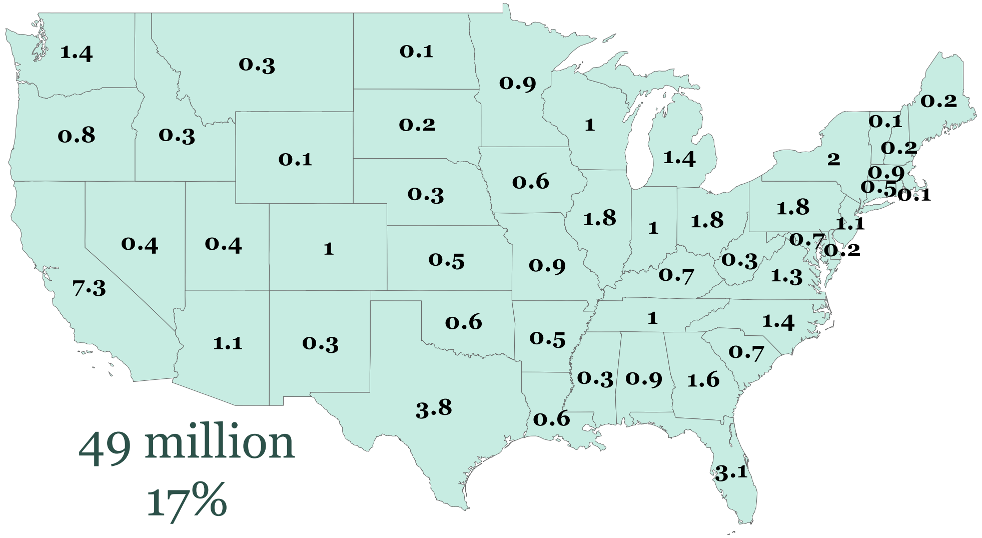
2020



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

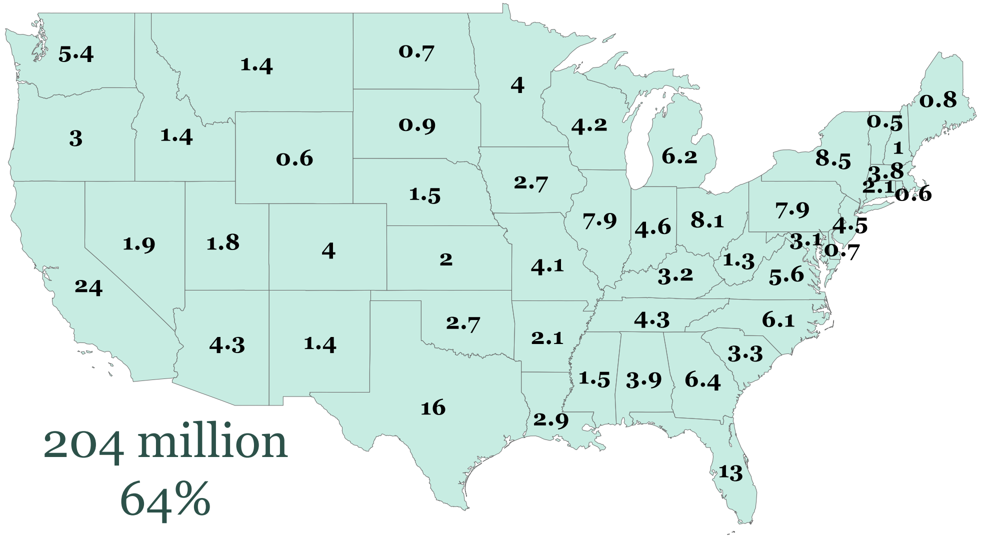
E+

2030



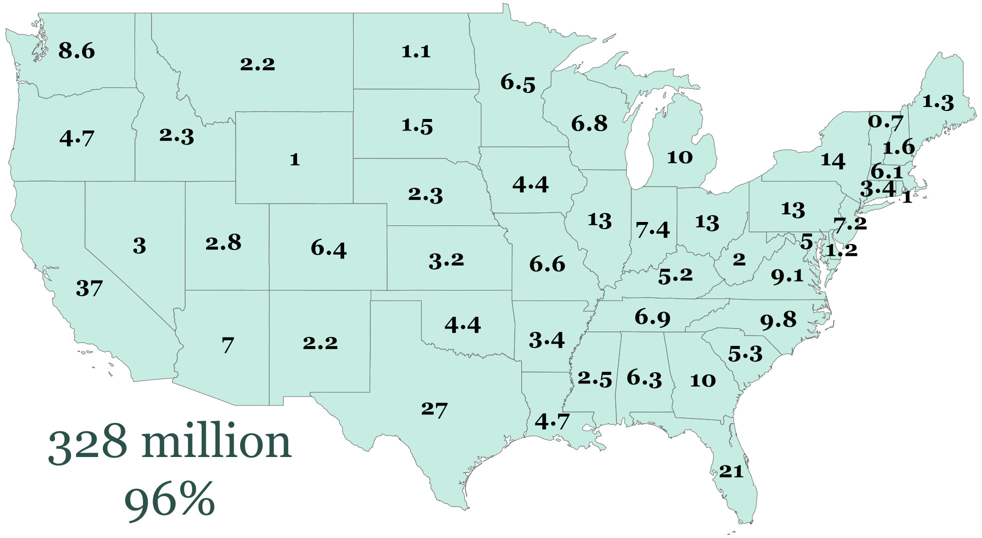
49 million
17%

2040



204 million
64%

2050



328 million
96%

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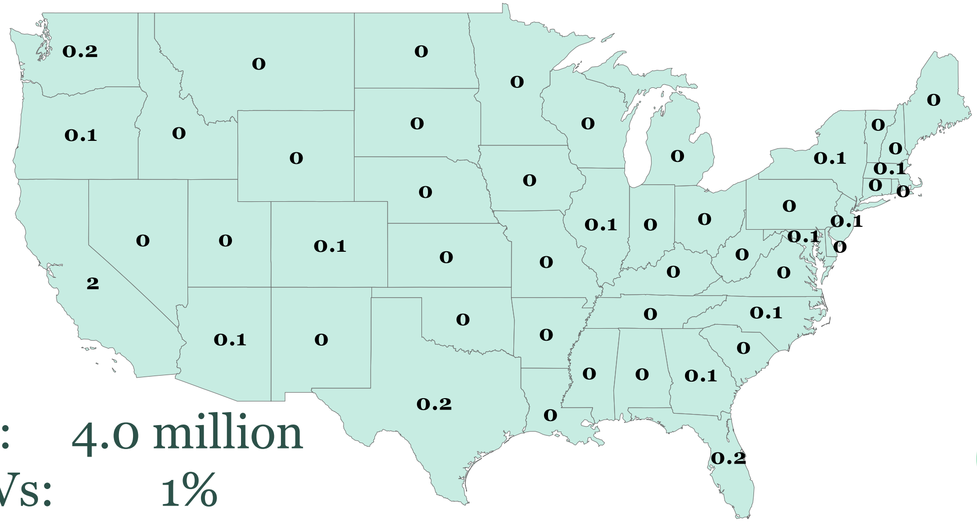
In E-, the stock of EVs grows to 6% of all light-duty vehicles by 2030 and 61% by 2050.

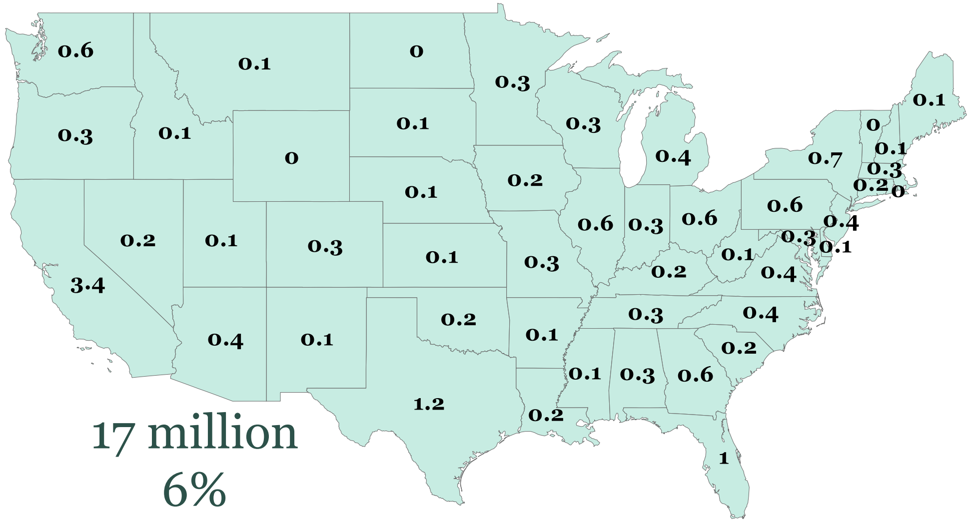
E-

2020



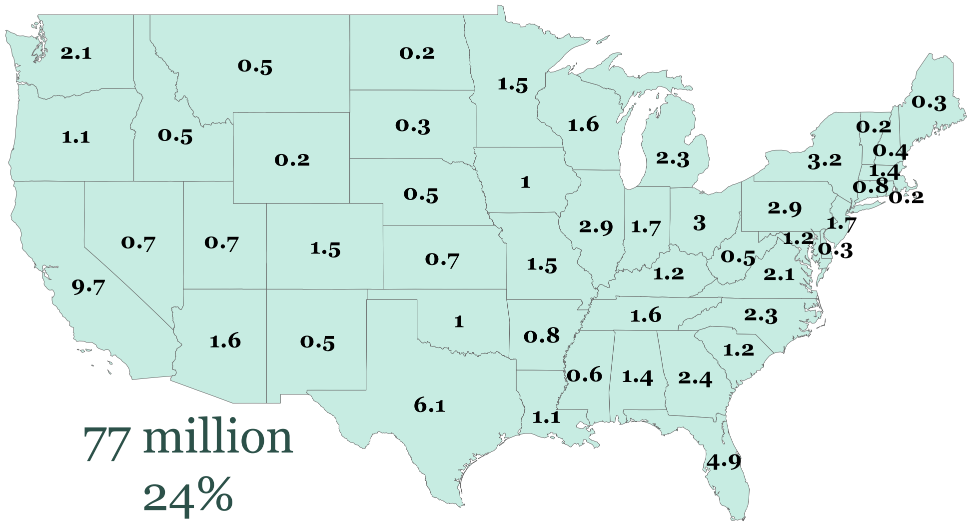
# of EVs: 4.0 million
% of LDVs: 1%

2030



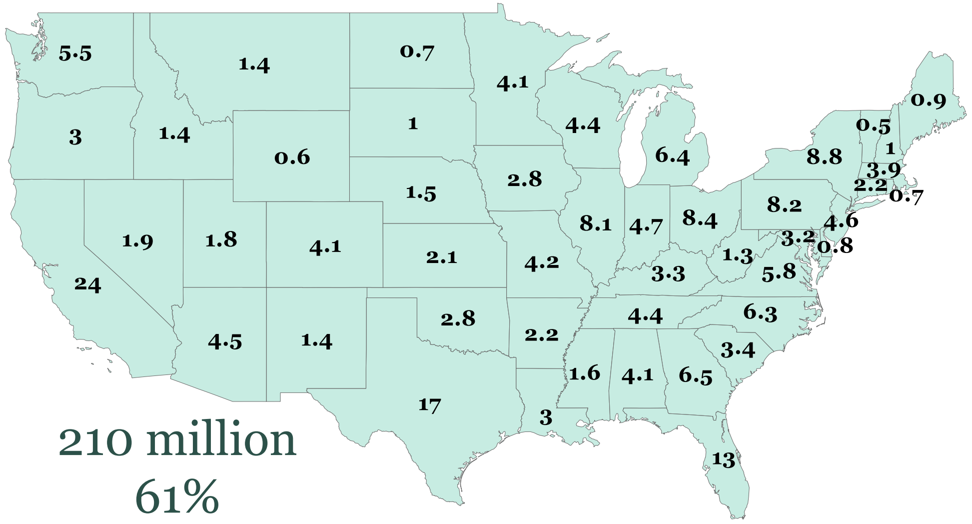
17 million
6%

2040



77 million
24%

2050



210 million
61%

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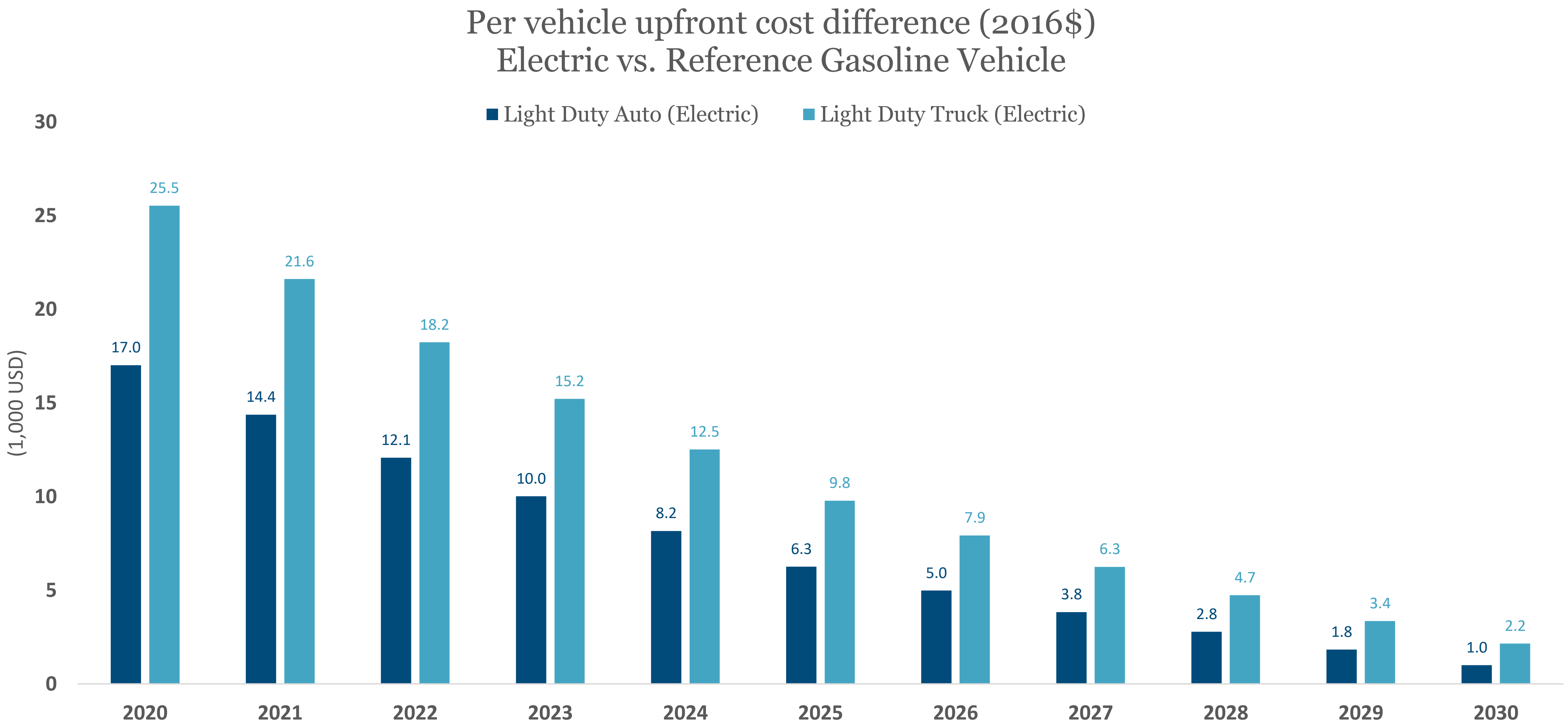
A few states have announced targets for EV registrations in 2025 and/or 2030 that approach E+ levels and generally exceed E- levels.

Green states have announced targets that exceed E- levels.

	State targets	E+	E-
	Battery-EVs in the light-duty vehicle fleet (millions)		
California, 2025	1.5	4.9	2.7
California, 2030	5.0	7.3	3.4
Colorado, 2025	0.055	0.542	0.212
Colorado, 2030	0.94	0.97	0.34
Connecticut, 2025	0.15	0.27	0.10
Maine, 2025	0.007	0.10	0.032
Maryland, 2025	0.3	0.41	0.15
Massachusetts, 2025	0.3	0.49	0.18
New Jersey, 2025	0.33	0.59	0.22
New York, 2025	0.85	1.09	0.39
New York, 2030	2	2.02	0.67
North Carolina, 2025	0.08	0.73	0.25
Rhode Island, 2025	0.043	0.077	0.025
Vermont, 2025	0.06	0.06	0.023

Upfront cost premiums between electric and gasoline light duty vehicles fall through 2020s, reaching close to parity by 2030



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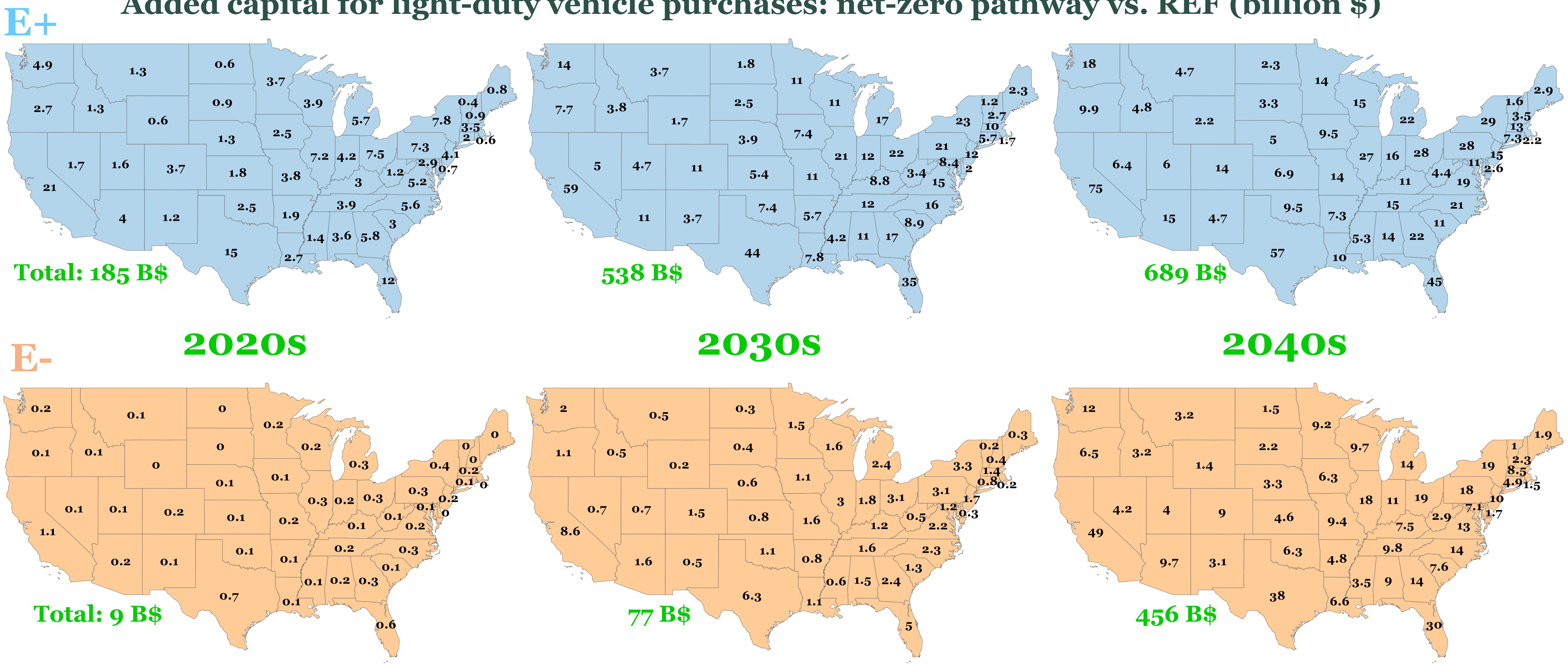
Incremental first costs for light-duty vehicles (E+ vs. REF) is $185B in the 2020s; for E- vs. REF, the increment is $9B.

Added capital for light-duty vehicle purchases: net-zero pathway vs. REF (billion $)



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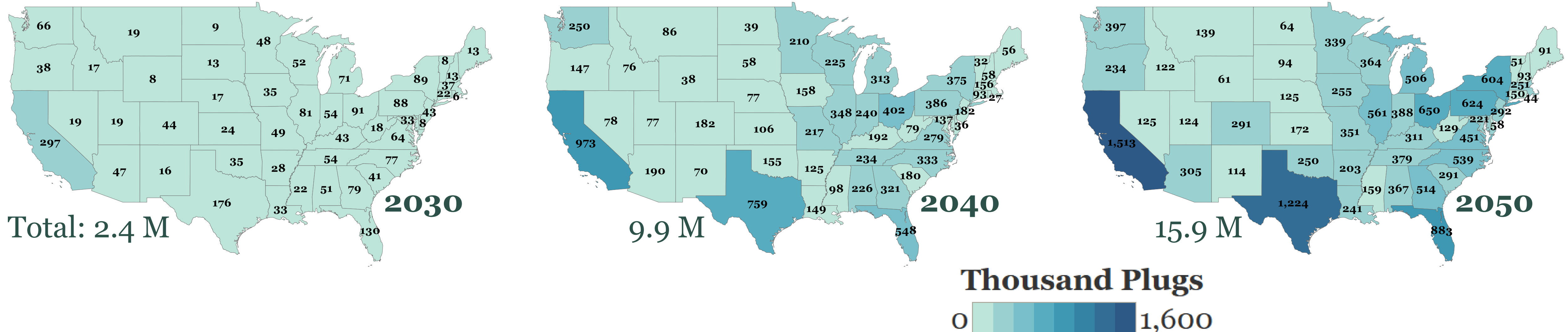
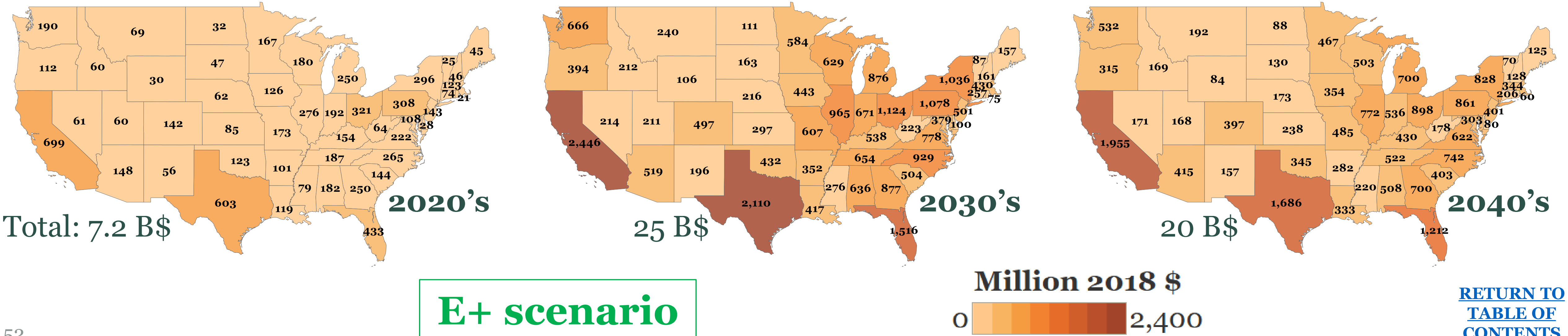
The number of public charging plugs needed to support EV fleets are still modest in 2030 in most states, but grow rapidly after.

Number of public EV charging plugs in operation



Decadal investments in public EV charging plugs



E+ scenario

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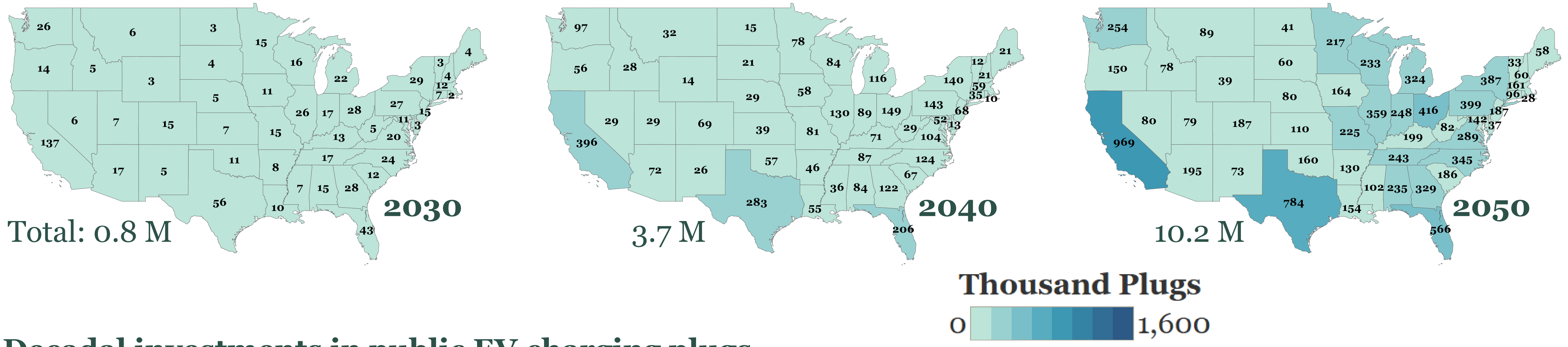
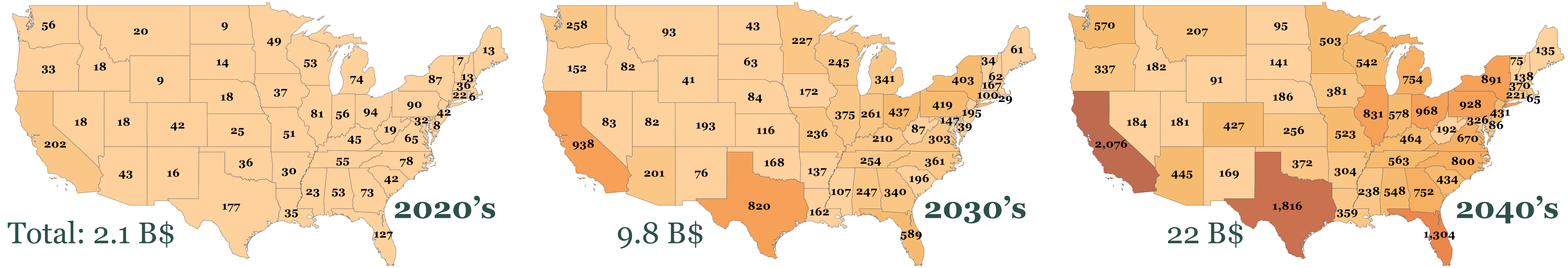
The number of public charging plugs needed to support EV fleets are still modest in 2030 in most states, but grow rapidly after.

Number of public EV charging plugs in operation



Decadal investments in public EV charging plugs



E- scenario

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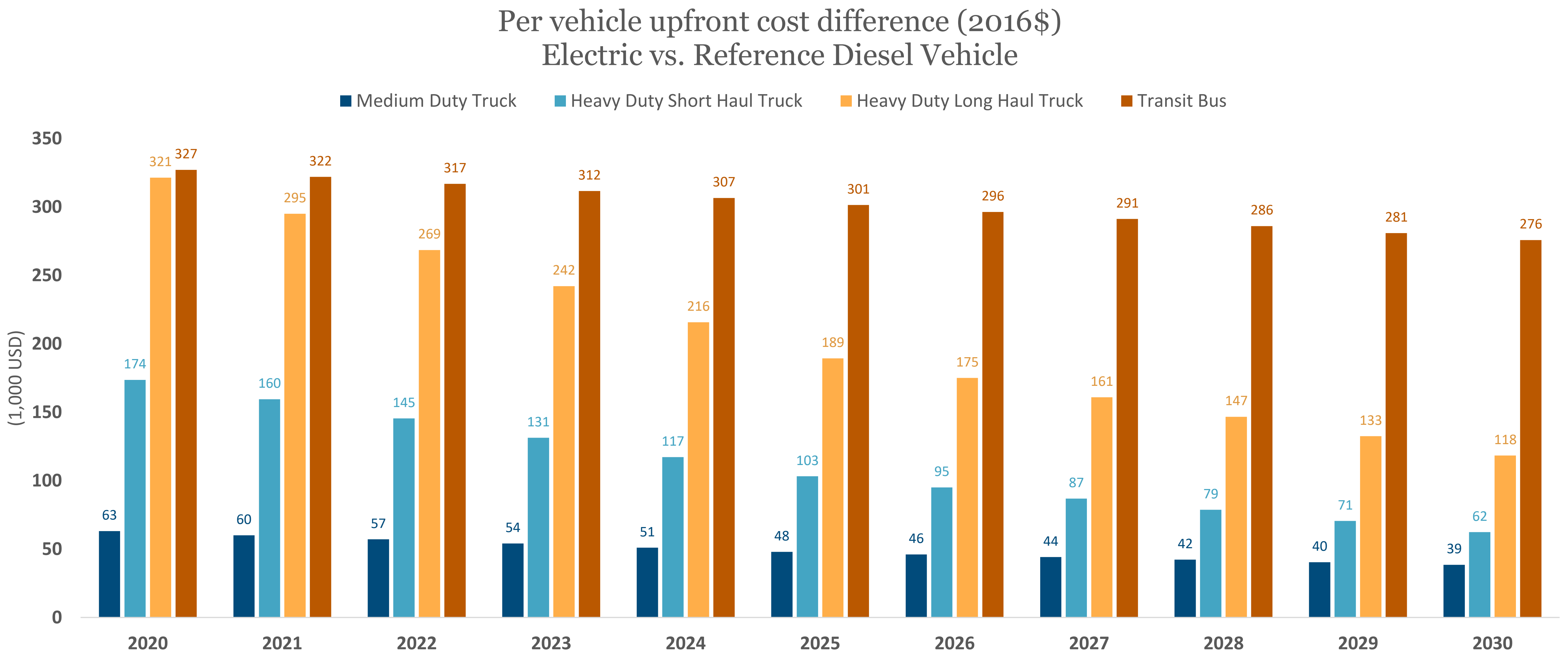
Upfront cost premium for medium and heavy duty electric trucks and transit buses remains significant



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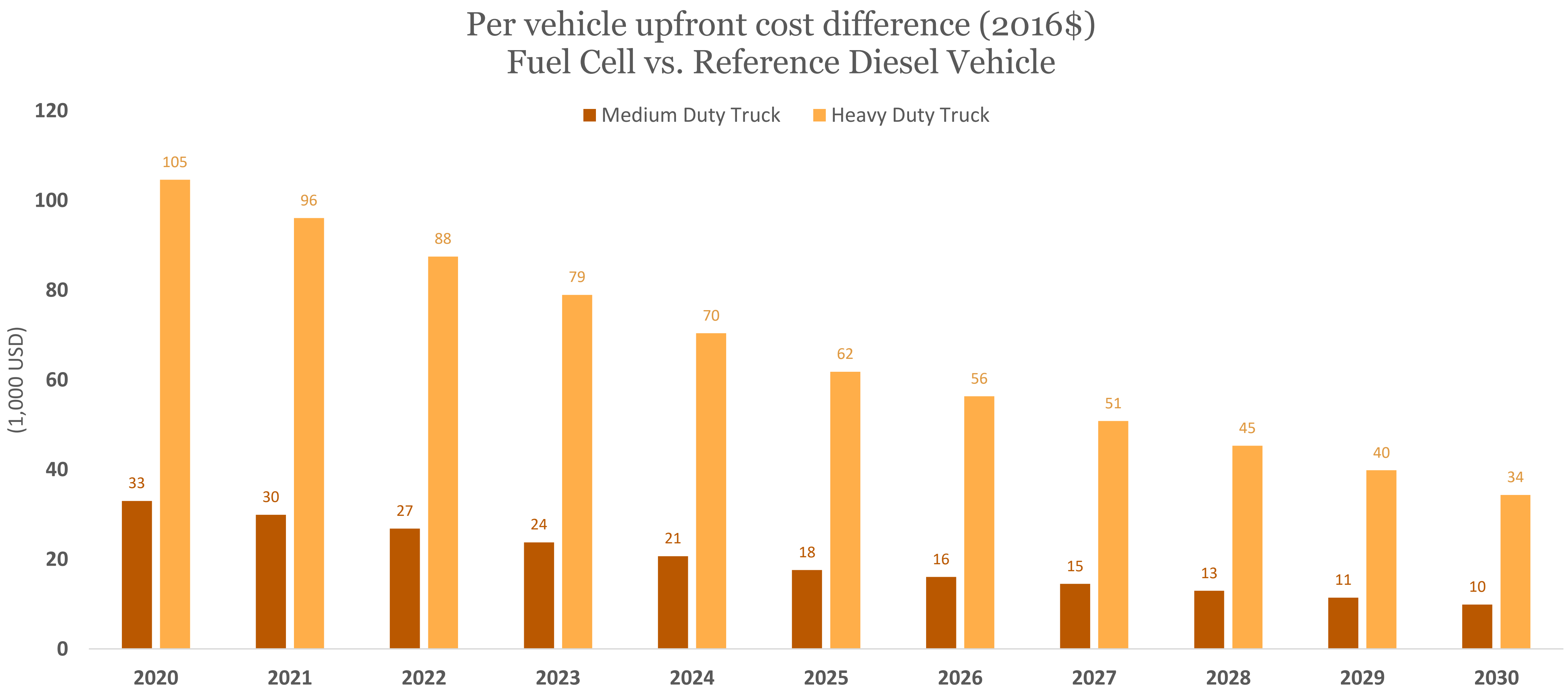
Medium and heavy duty fuel cell vehicles have much lower upfront cost premium than electric but higher fueling costs



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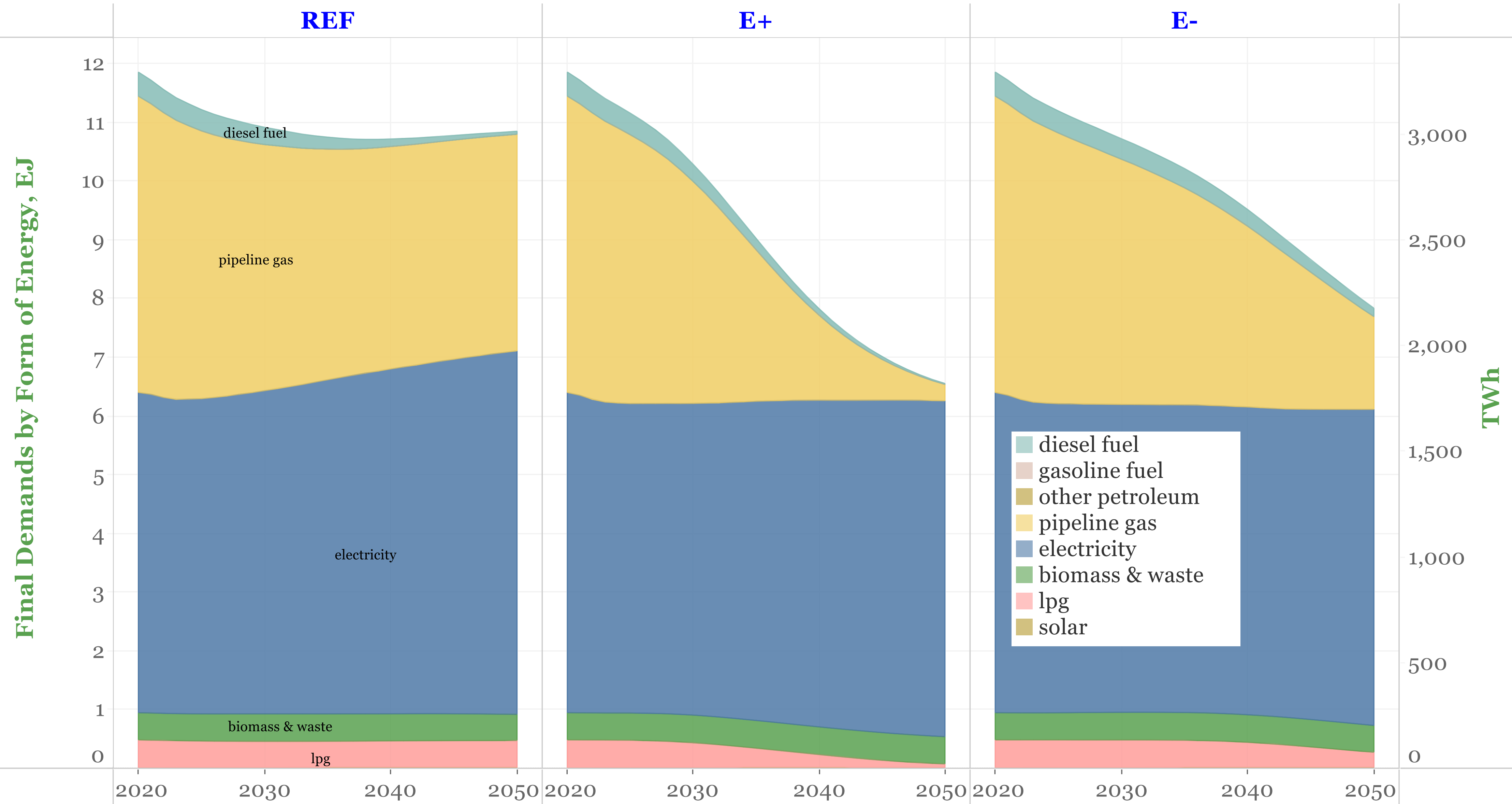
Buildings sector

Summary of this section

- In residential buildings:
  - The use of natural gas for space and water heating and cooking is nearly fully replaced by electricity by 2050 across the net-zero transitions, and final energy use is dramatically lower as a result of heating (and air conditioning) using heat pumps.
  - The market penetration of heat pumps for heating/cooling is highest in warmer climate regions. They are also adopted in colder regions, although they operate somewhat less efficiently.
  - The first-cost premium for space and water heating in the net-zero pathways is $60 to $70 billion in aggregate for the country in the 2020s compared with REF, or 12% to 13% more. The increase is modest because heat pumps heat and cool using the same device, unlike gas-fired heaters.
- Commercial sector final energy use also declines, but not as significantly as for the residential sector:
  - Electricity replaces natural gas in space conditioning, with growing contributions from heat pumps, but also growth in electric resistance heat for which efficiency gains are not as significant as for heat pumps. Electric cooking also grows.
  - The first-cost premium for space and water heating and ventilation in the net-zero pathways is about $110 billion in aggregate for the country from 2021-2030 compared with REF, an increase of about 5%.
- See Annex C for additional details.

Residential sector final energy use declines, and by 2050 electricity accounts for 85% in E+ and 70% in E-.



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

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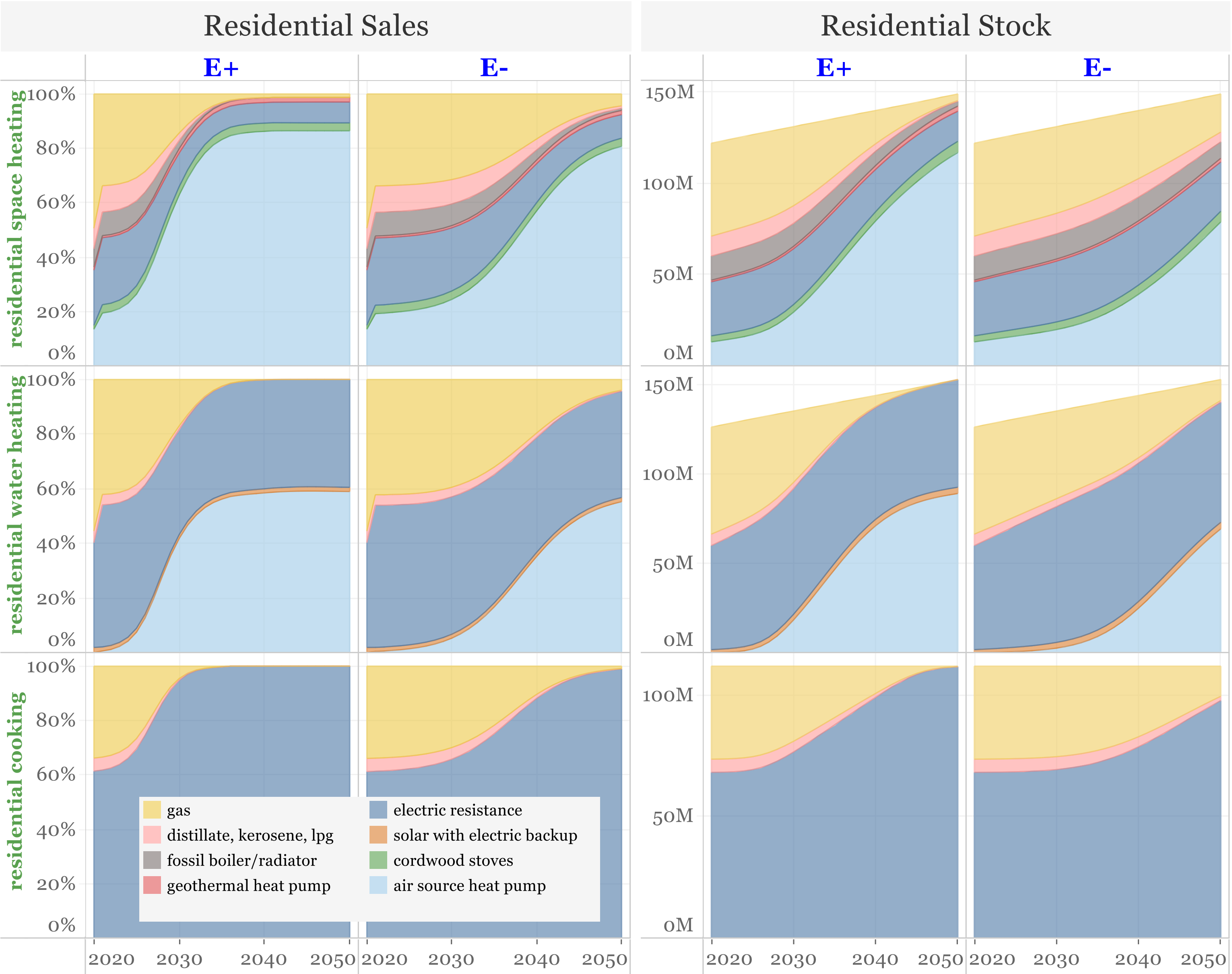
Consumer investment choices shift rapidly to electricity for residential space heating, water heating, and cooking.

- By 2050, space heating, water heating, and cooking are nearly all electric in E+ and 80-90% electric in E-
- In space heating, air-source heat pumps grow to dominate.
- In water heating, growth in heat pumps displaces gas-fired units; resistance heating is generally retained in colder climates.
- Induction cook stoves are 100% of new sales by 2035 in E+ and 2050 in E-.



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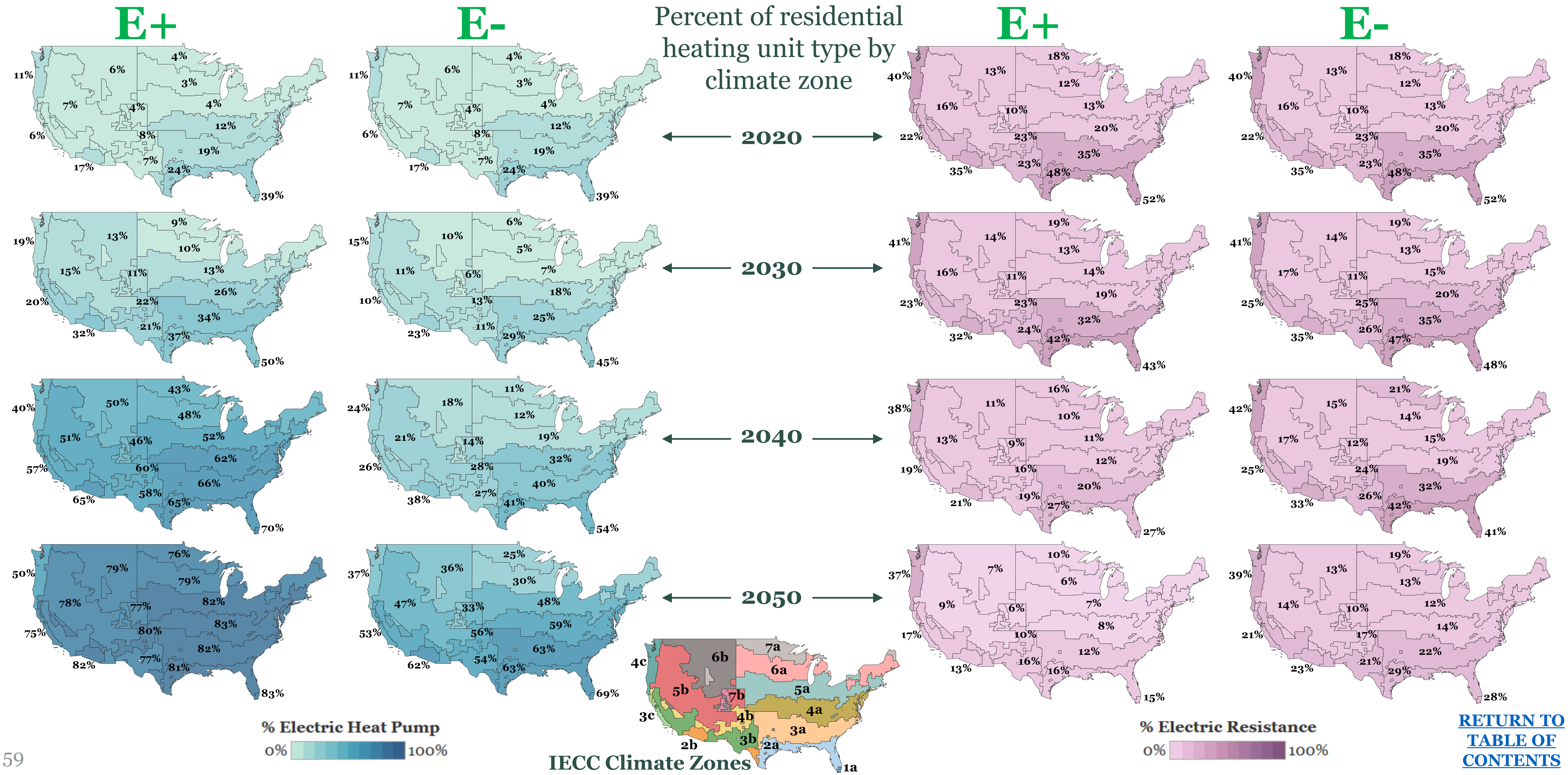
Electric home heating grows significantly, with the fraction adopting heat pumps varying significantly by climate zone.



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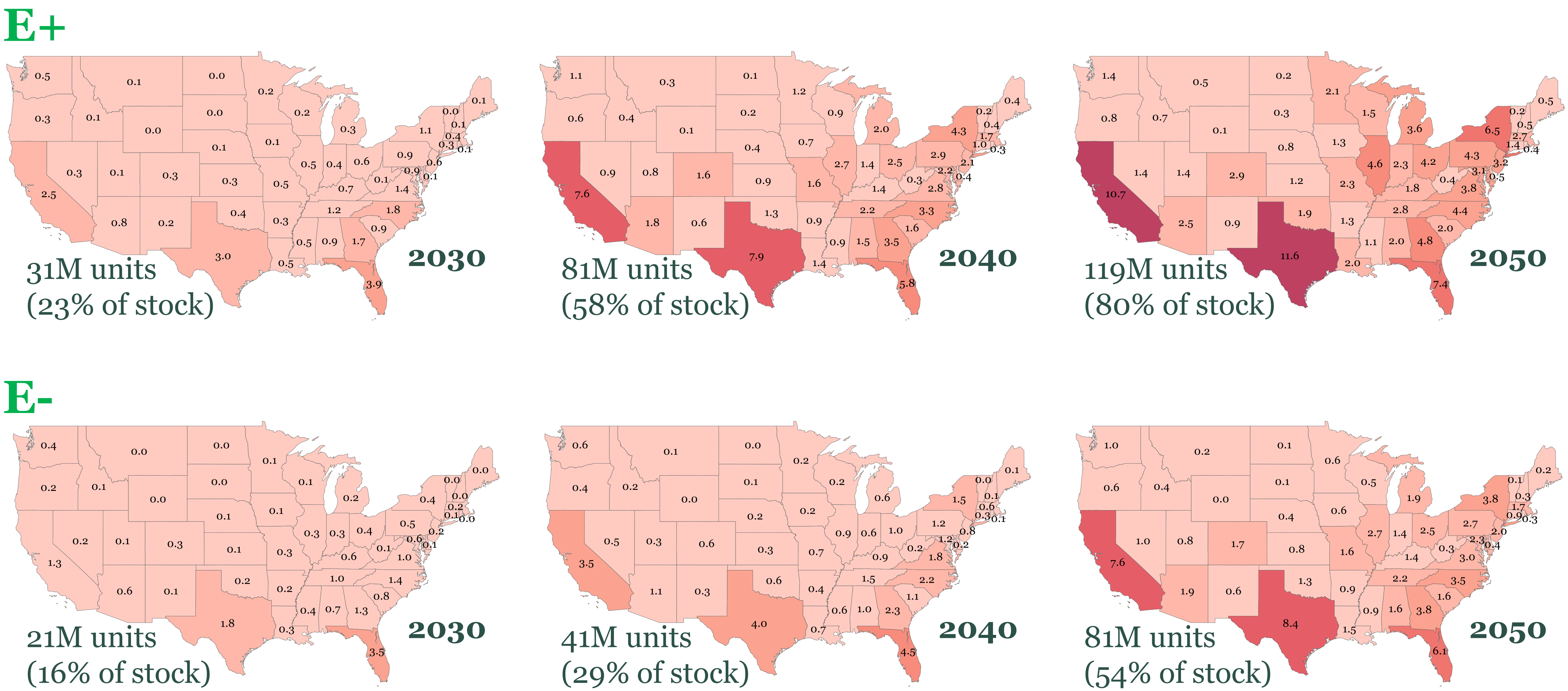
Residential heat pumps grow from ~10% of the space heating stock in 2020 up to 80% (E+) or 54% (E-) by 2050.



Million Units

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

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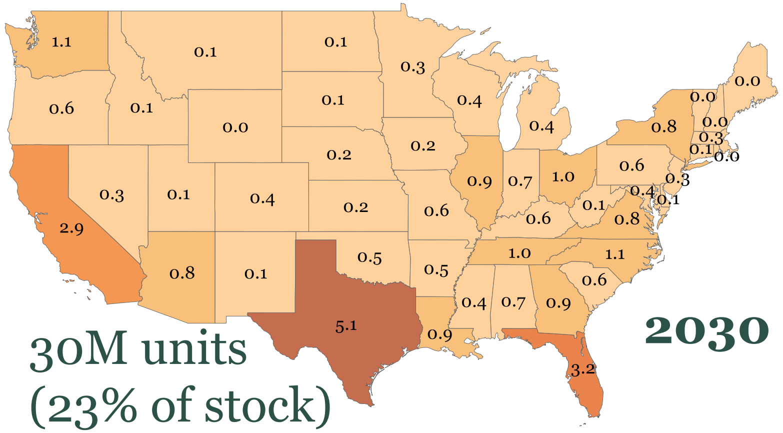
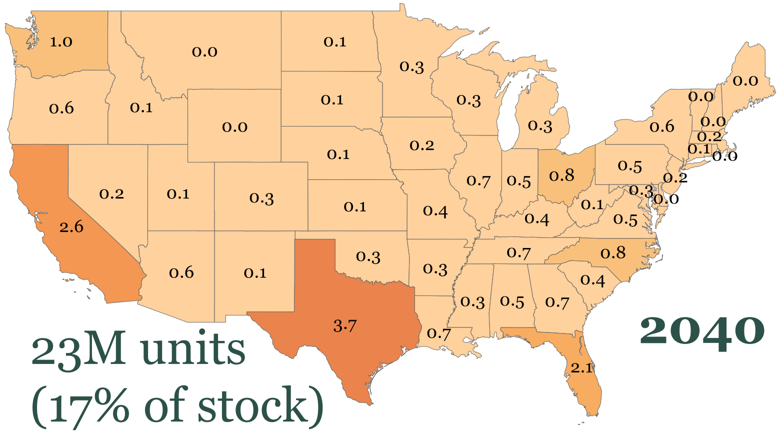
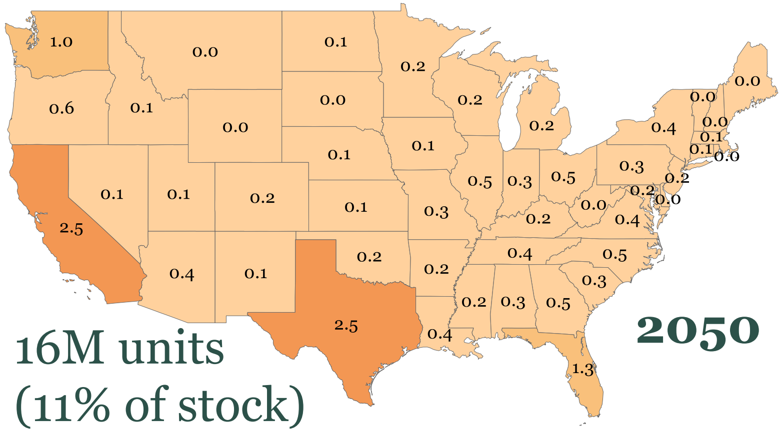
Residential electric resistance units decline from ~25% of the space heating stock in 2020 to 11% (E+) or 18% (E-) by 2050.

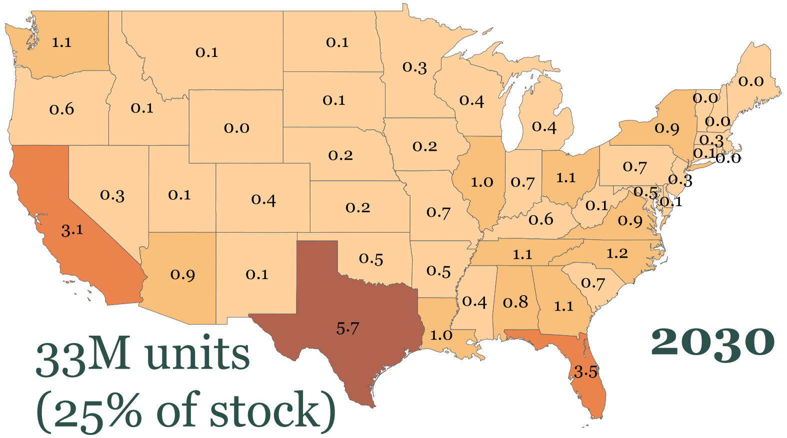
E+

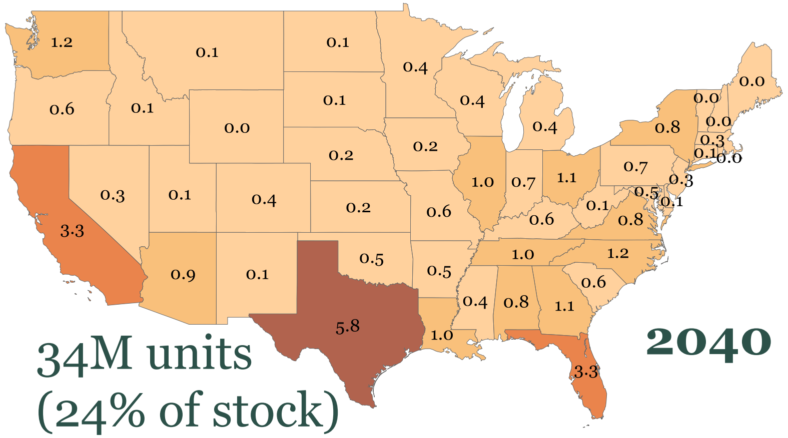


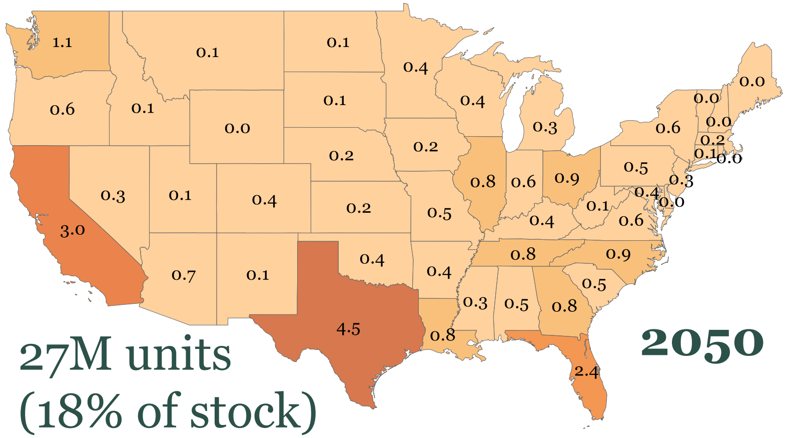




E-







Number of homes using electric resistance heat by state: Million Units 0 6

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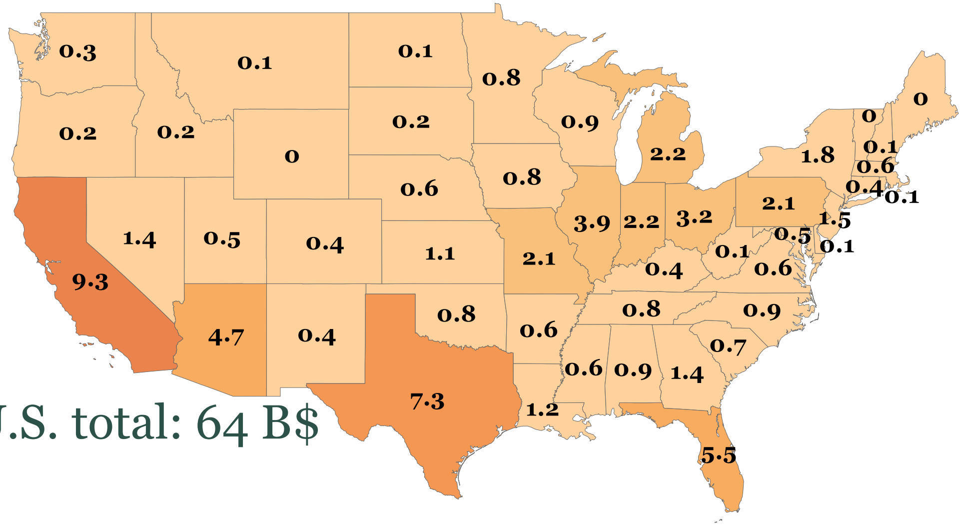
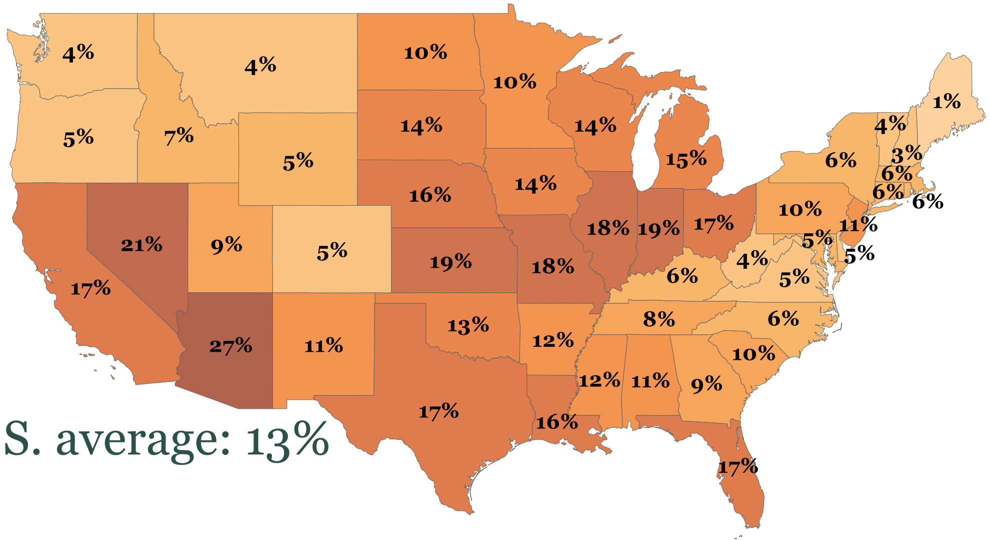
Capital expenditures from 2021-2030 for residential space and water heating are \$60B to \$70B higher than REF.

E+



U.S. total: 64 B\$

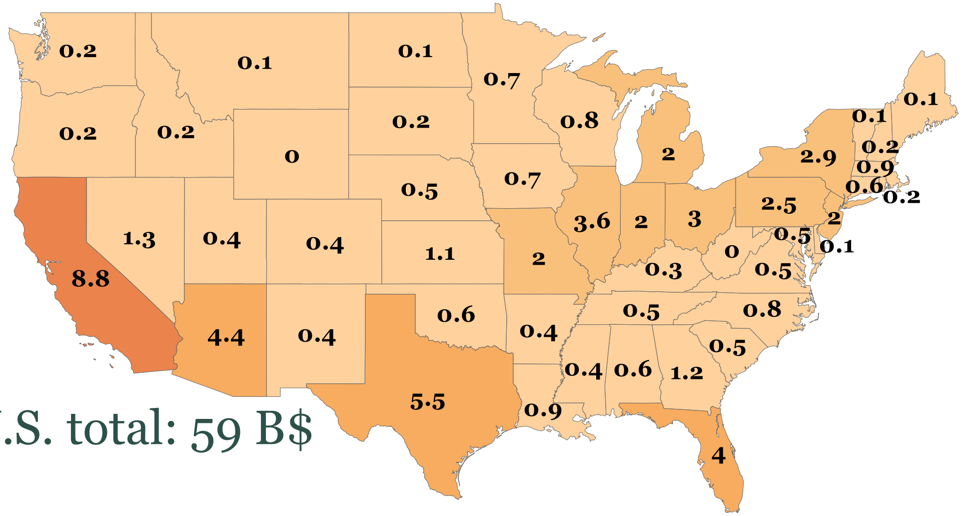
Incremental capital vs. REF



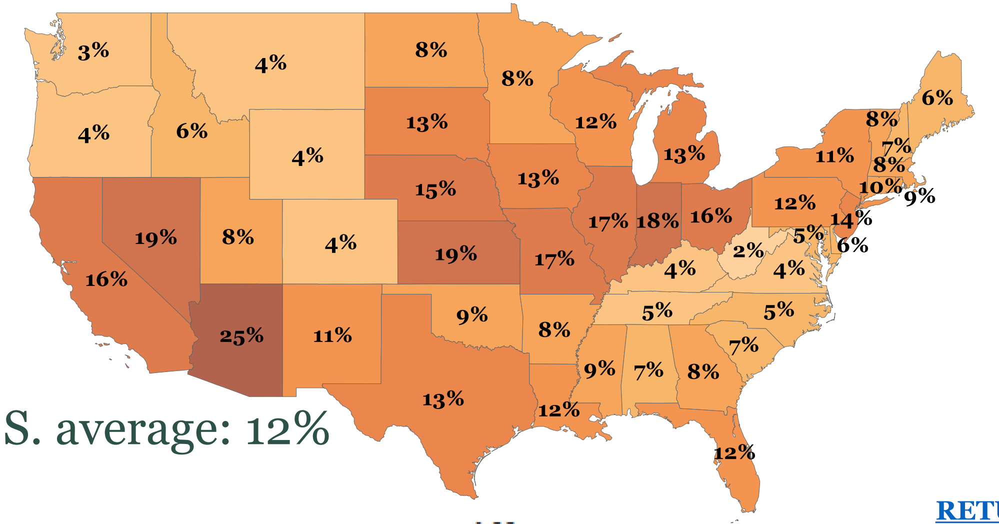
U.S. average: 13%

% increase vs. REF

E-



U.S. total: 59 B\$



U.S. average: 12%

Billion 2018 \$
0 — 16

2021 - 2030

% Difference
0% — 25%

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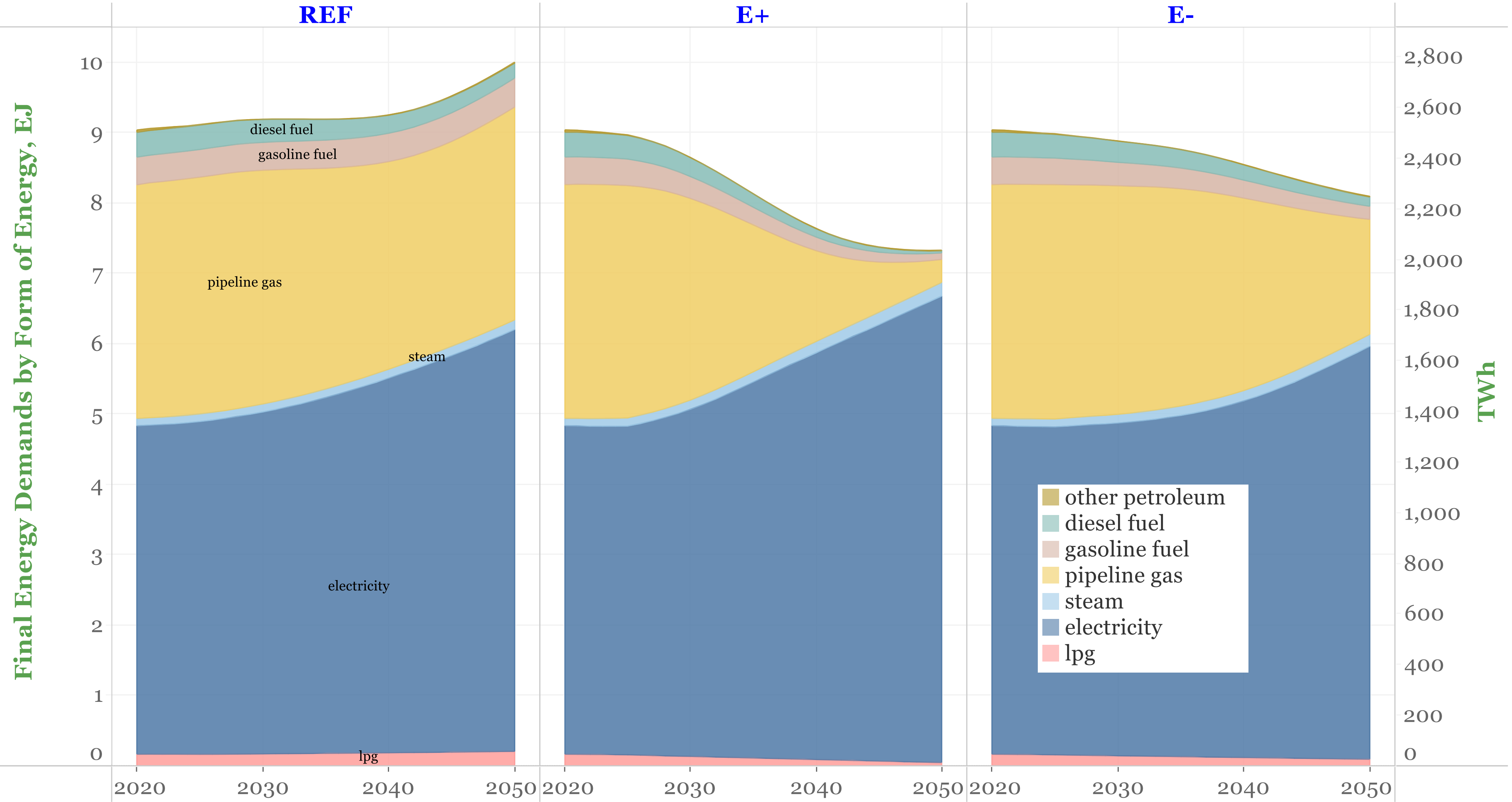
Commercial buildings' final energy use declines, and by 2050 electricity accounts for 90% in E+ and 70% in E-.



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

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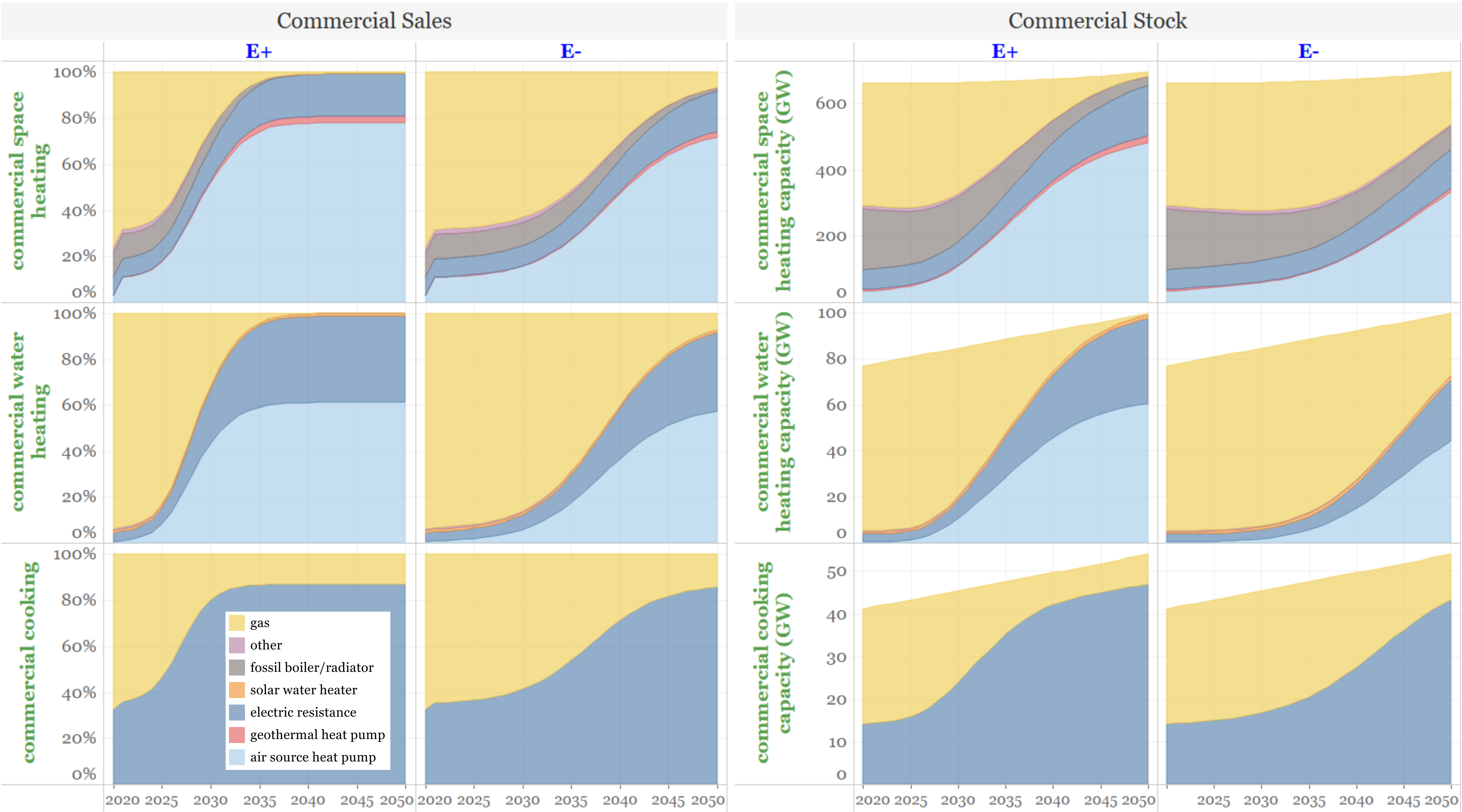
In the commercial sector (as in residential), investment choices shift rapidly to electricity for all energy services.



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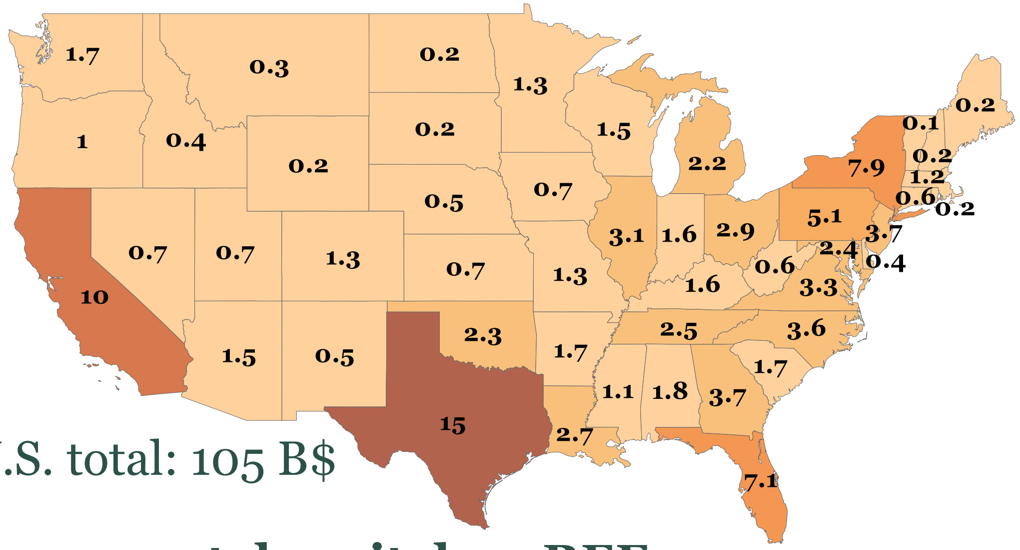
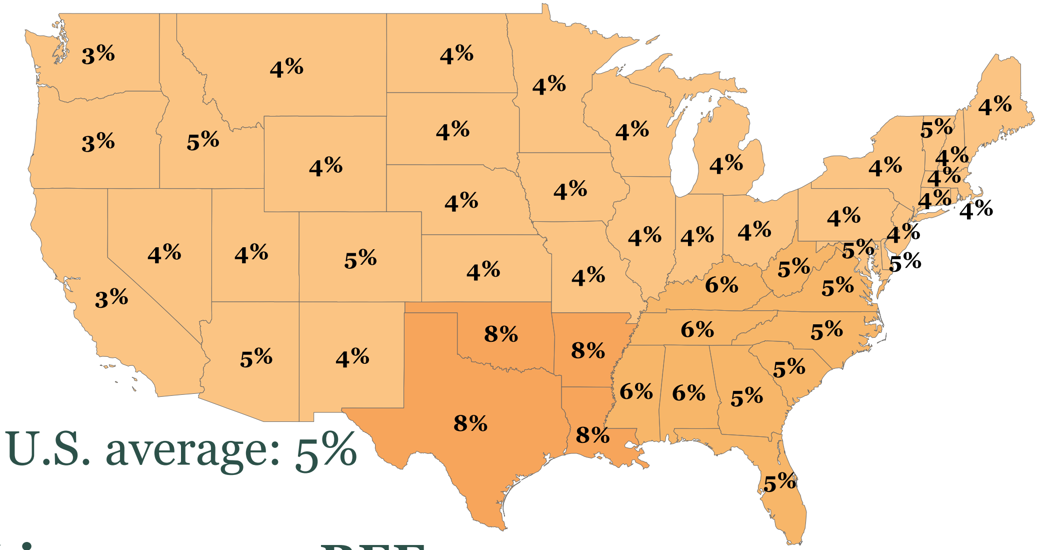
Capital expenditures from 2021-2030 for commercial HVAC and water heating are ~$100B to $110B (5%) higher than REF.

E+



U.S. total: 105 B$

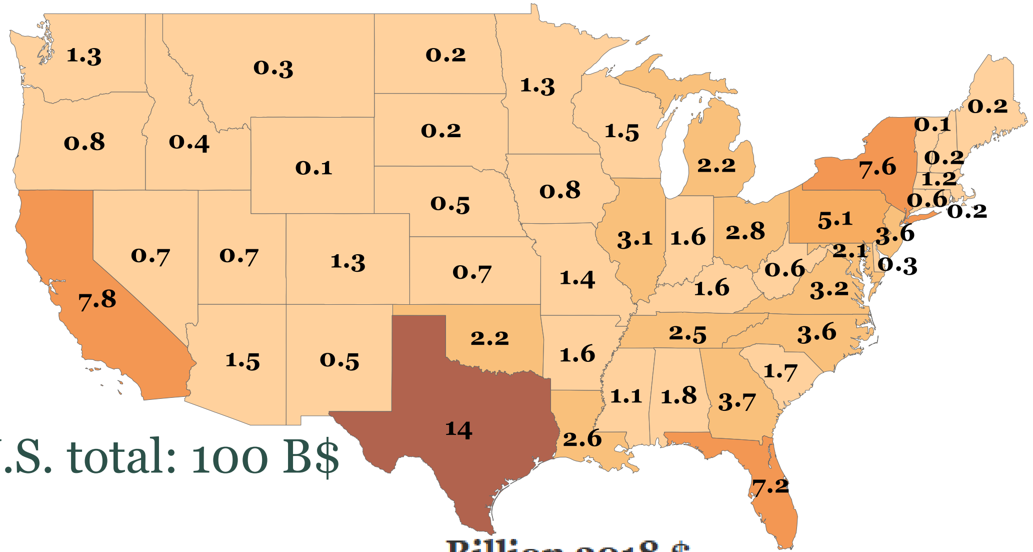


U.S. average: 5%

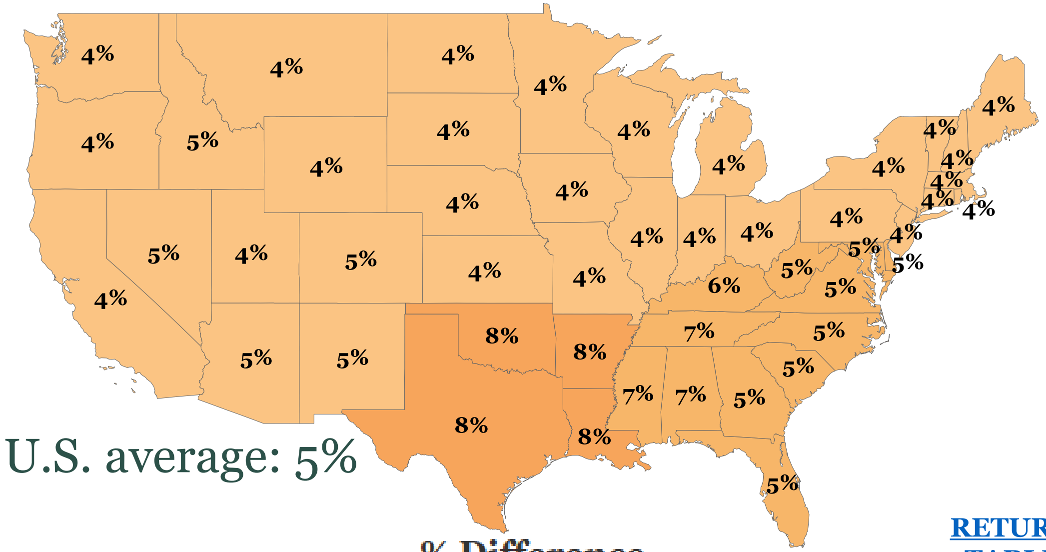
Incremental capital vs. REF

% increase vs. REF

E-



U.S. total: 100 B$



U.S. average: 5%

Billion 2018 $
0 – 16

2021 - 2030

% Difference
0% – 25%

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Electricity distribution system

Summary of this section

- Electrification of vehicles and space and water heating will increase electricity demand and require upgrades to electricity distribution networks
- Flexible demand, including smart charging of EVs and automation of heat pump systems, can reduce coincident peak demand and stress on distribution networks, minimizing costly upgrades
- Even with flexible demand,* distribution networks will likely need to accommodate a ~5-10% increase in peak demand by 2030 and ~40-60% increase by 2050
- In the E+ scenario:
  - Approximately $370b in total distribution network investment is needed in the 2020s, or $15-20b more than in REF.
  - Investments total ~$700b per decade in the 2030s and 2040s, with a cumulative incremental capital investment of $280b relative to REF by 2050.
- In the E- scenario:
  - Due to improvements in energy efficiency (vs REF) and a slower electrification rate (vs E+), peak demand growth is just 2% through 2030 and remains *below* the REF case to 2050.
  - Total distribution network investments through 2030 are ~$300b, or ~$50b *less* than REF.
- See Annex G for additional details.

* Our analysis of required distribution reinforcements assumes 50% of electric vehicle loads and 20% of heat pump water heating loads can be time-shifted to avoid contributing to peak loading of distribution assets

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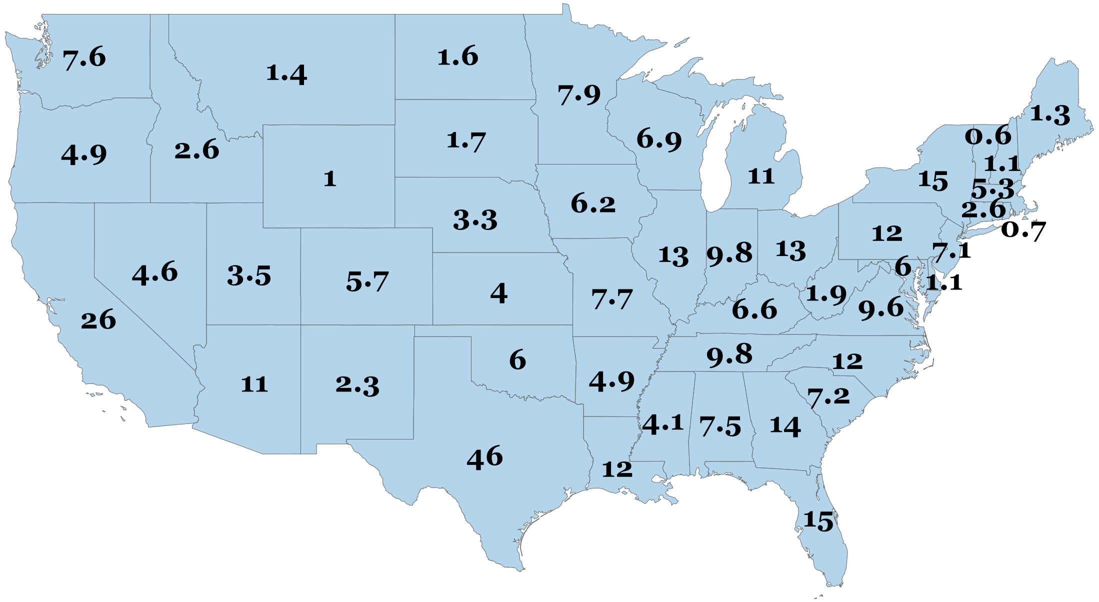
Electricity distribution investments are $370-700B per decade.

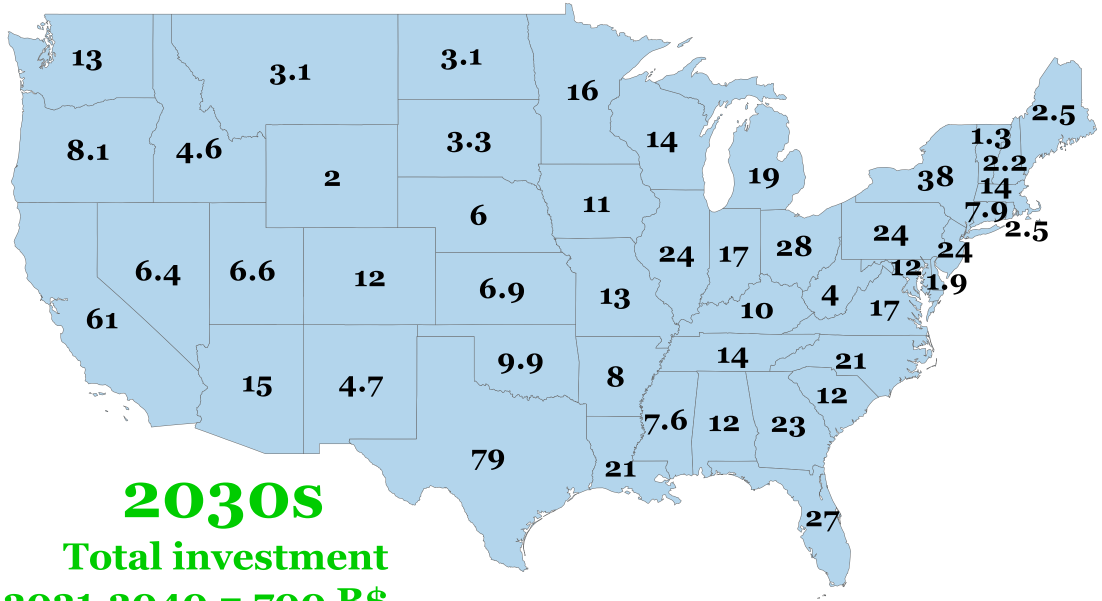
E+ scenario

2020s

Total investment
2021-2030 = 370 B$

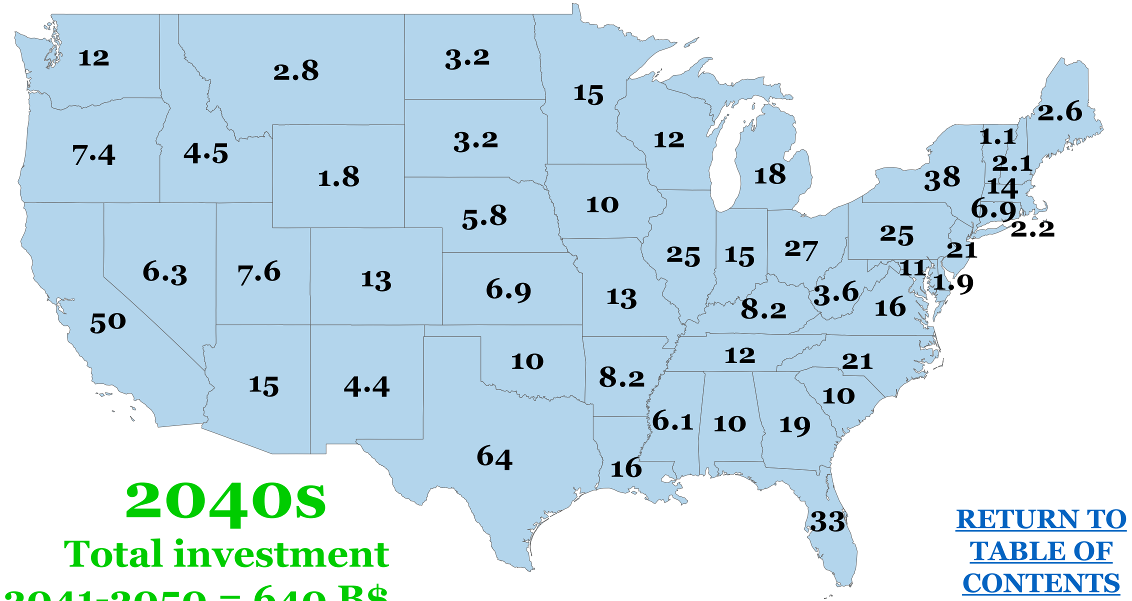


Cumulative *incremental* capital (E+ vs. REF) is ~$15-20B in 2020s, increasing to $280b by 2050.



2030s

Total investment
2031-2040 = 700 B$



(2018 $)

2040s

Total investment
2041-2050 = 640 B$

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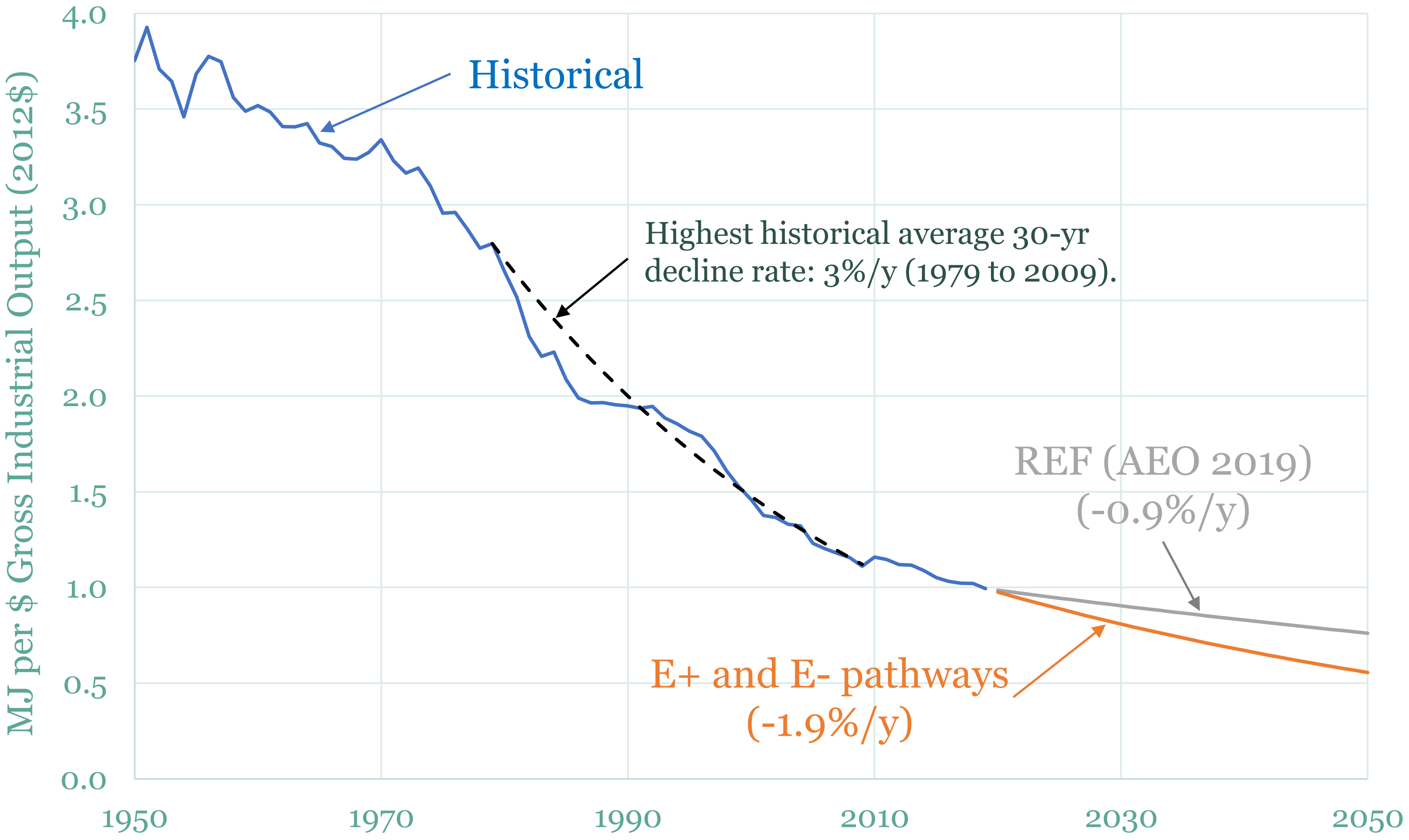
Industrial sector

Summary of this section

- Industrial energy use is roughly constant during the transition in all net-zero scenarios due to:
  - Energy intensity (energy use per $ of industrial output) decreasing at twice the rate in the REF scenario (but more slowly than the fastest recorded historical 30-yr average rate).
  - Declines in petroleum use across the economy reduce the need for petroleum refining, a significant energy-user today.
  - A shift over time toward electric arc furnace steel making and direct-reduced iron production using hydrogen increases electricity and hydrogen use in industry, but these are offset by reductions in fossil fuel use for iron and steel making. See Annex J.
  - Energy use for cement production increases over time as this industry is decarbonized through CO_2 capture applied as a "tailpipe" measure on otherwise conventional cement production. See Annex K.
- During the 2020s, the capital investments in industry for the net-zero pathways include, approximately:
  - 250 B$ for energy intensity reductions (assuming 10 to 15 $/GJ of fuel saved)
  - 60 B$ for new cement plants with carbon capture
  - 8 B$ for new direct-reduced iron facilities that operate using hydrogen for both fuel and reductant.

U.S. industrial energy intensity continues its declining trend of past two decades; electrification has less impact than in other sectors.

- Same-fuel energy productivity improves at double the rate in REF.
- Relatively modest fuel → electricity switching, except for iron and steel, where electric arc furnaces grow to be 100% of steel-making by 2050. Scrap feedstocks are supplemented with direct-reduced iron made using H_2.



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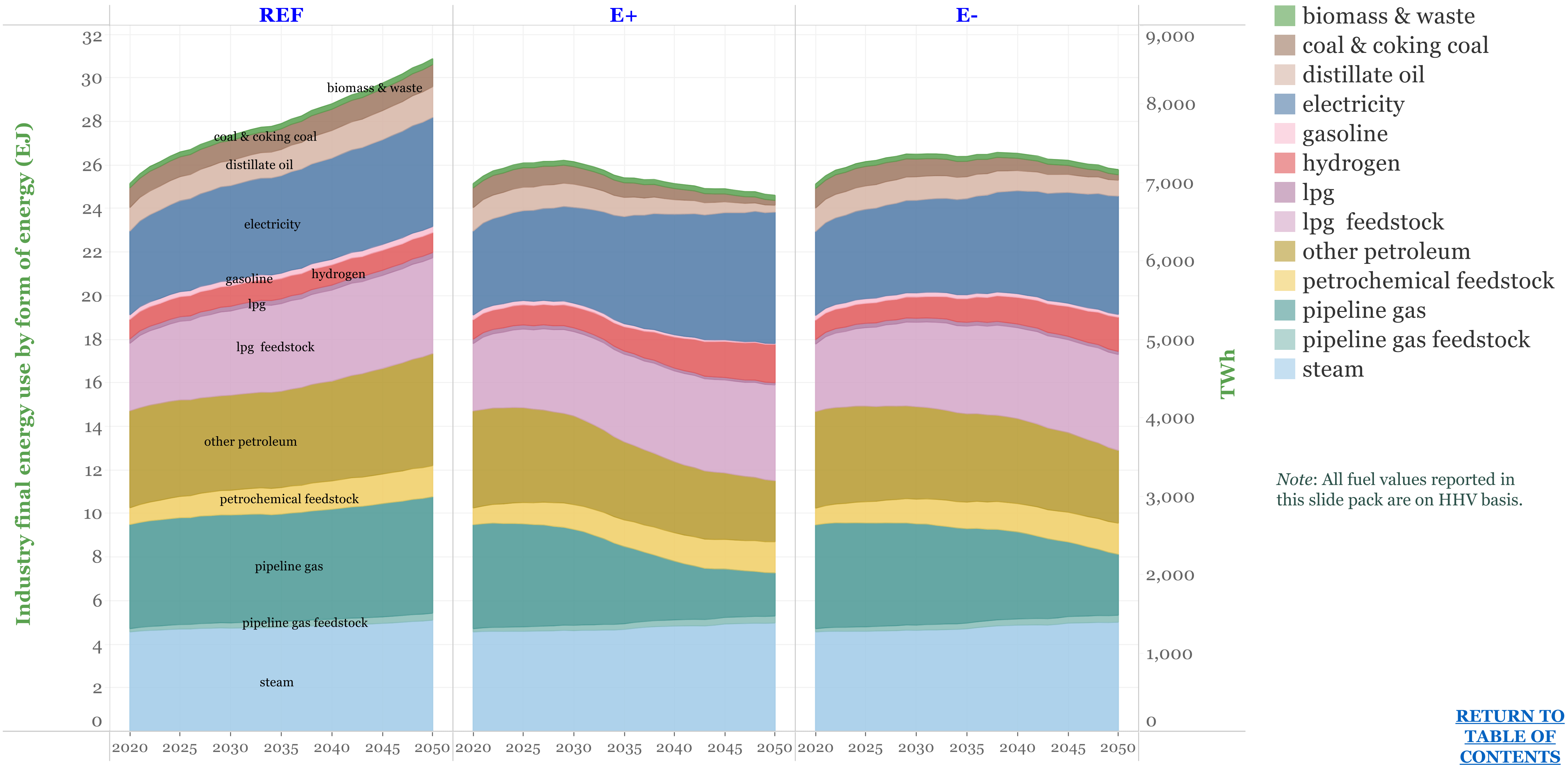
Industrial final energy in 2050 is 15-20% below REF. Roles for electricity and H_2 grow; use of liquids and other gases decline.



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

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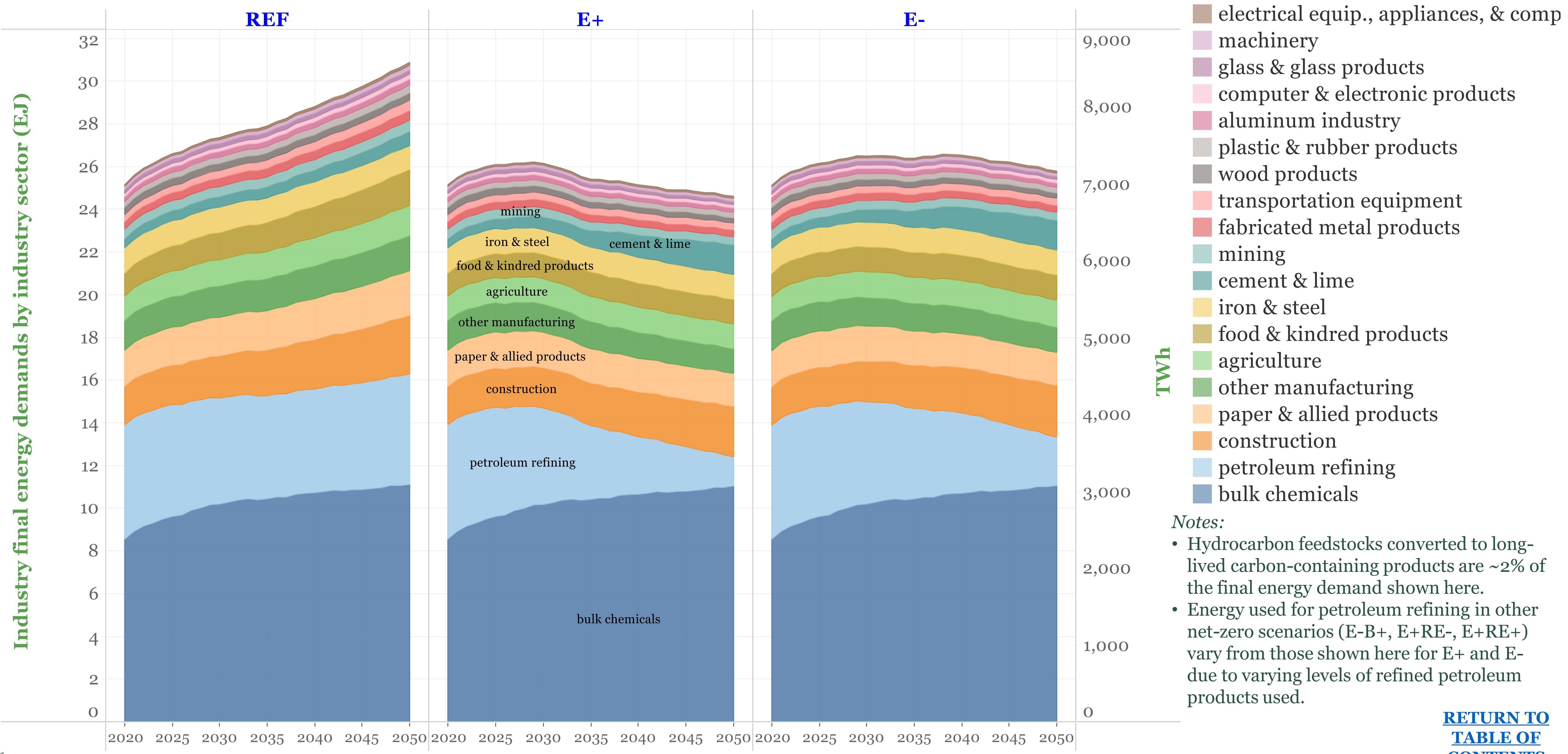
Bulk chemicals remains the largest industrial energy user. Energy use for petroleum refining falls. Cement and lime energy use grows.



Notes:

- Hydrocarbon feedstocks converted to long-lived carbon-containing products are ~2% of the final energy demand shown here.
- Energy used for petroleum refining in other net-zero scenarios (E-B+, E+RE-, E+RE+) vary from those shown here for E+ and E- due to varying levels of refined petroleum products used.

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

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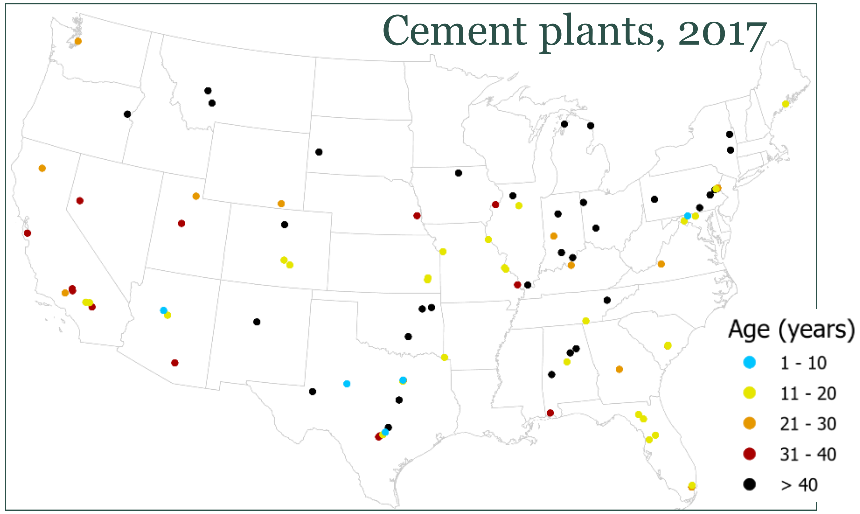
Energy use in cement/lime making grows due to growth in cement demand and use of CO_2 capture to decarbonize



For net-zero, industry consolidates:

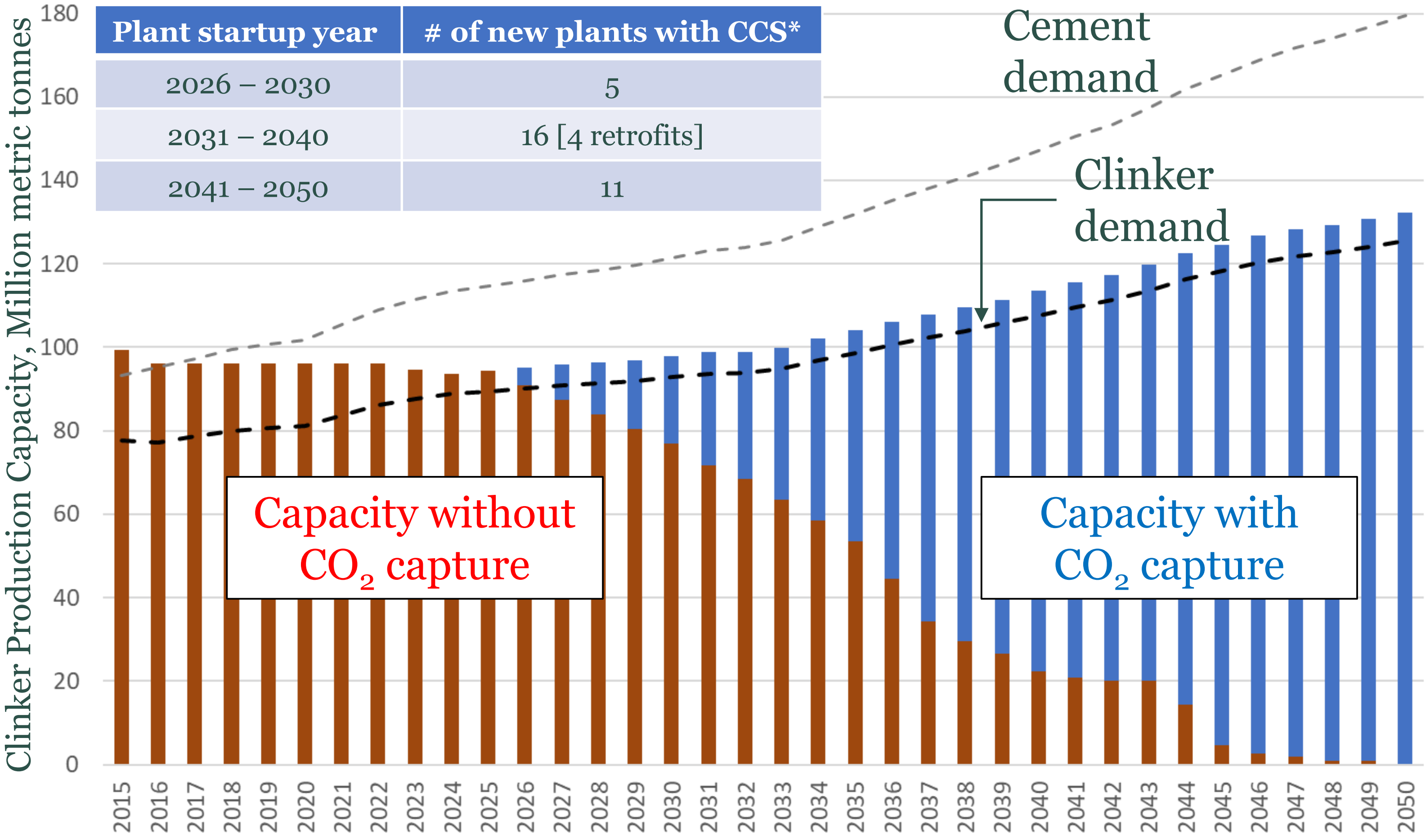
- 92 plants retire when ≥ 35 yrs old.
- 35 world-scale plants with CO_2 capture are built on brownfield sites by 2050, starting in 2020's.

Each world-scale plant:

- Costs ~$3.5 billion to build.
- Captures ~2.5 million tCO_2/y

124 million tCO_2 from cement are captured in 2050 (90% capture rate).

Plant startup year	# of new plants with CCS*
2026 – 2030	5
2031 – 2040	16 [4 retrofits]
2041 – 2050	11



See Annex K for additional modeling details of cement industry decarbonization.

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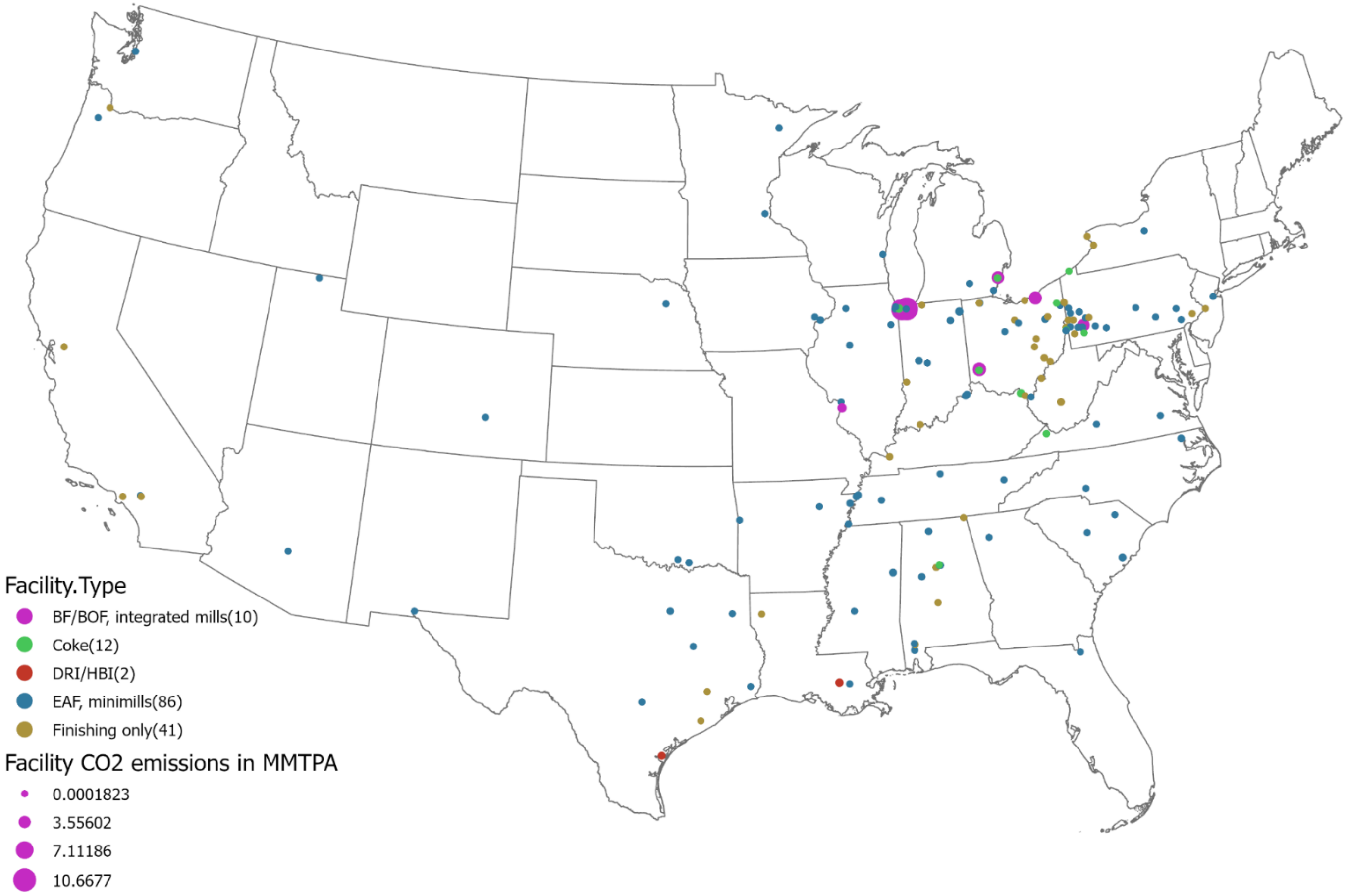
U.S. iron and steel production (~90 million t/y) accounts for 106 million tCO_{2e}/y of emissions today (1.8% of total U.S. emissions).

- Current US steel production is:
  - 32% via integrated iron & steel mills (with blast furnace/basic oxygen furnaces, BF/BOF) accounting for 69% of I&S CO_2 emissions.
  - 68% via electric arc furnaces (EAF) using recycle scrap and some pig iron from BF/BOF, accounting for 31% of I&S CO_2 emissions.
- Distribution of mill types:
  - All nine operating integrated mills are in the Eastern US.
  - Two direct-reduced iron (DRI) facilities are on the Gulf Coast (using natural gas).
  - Approximately 100 electric arc furnace (EAF) steel mills are widely dispersed.



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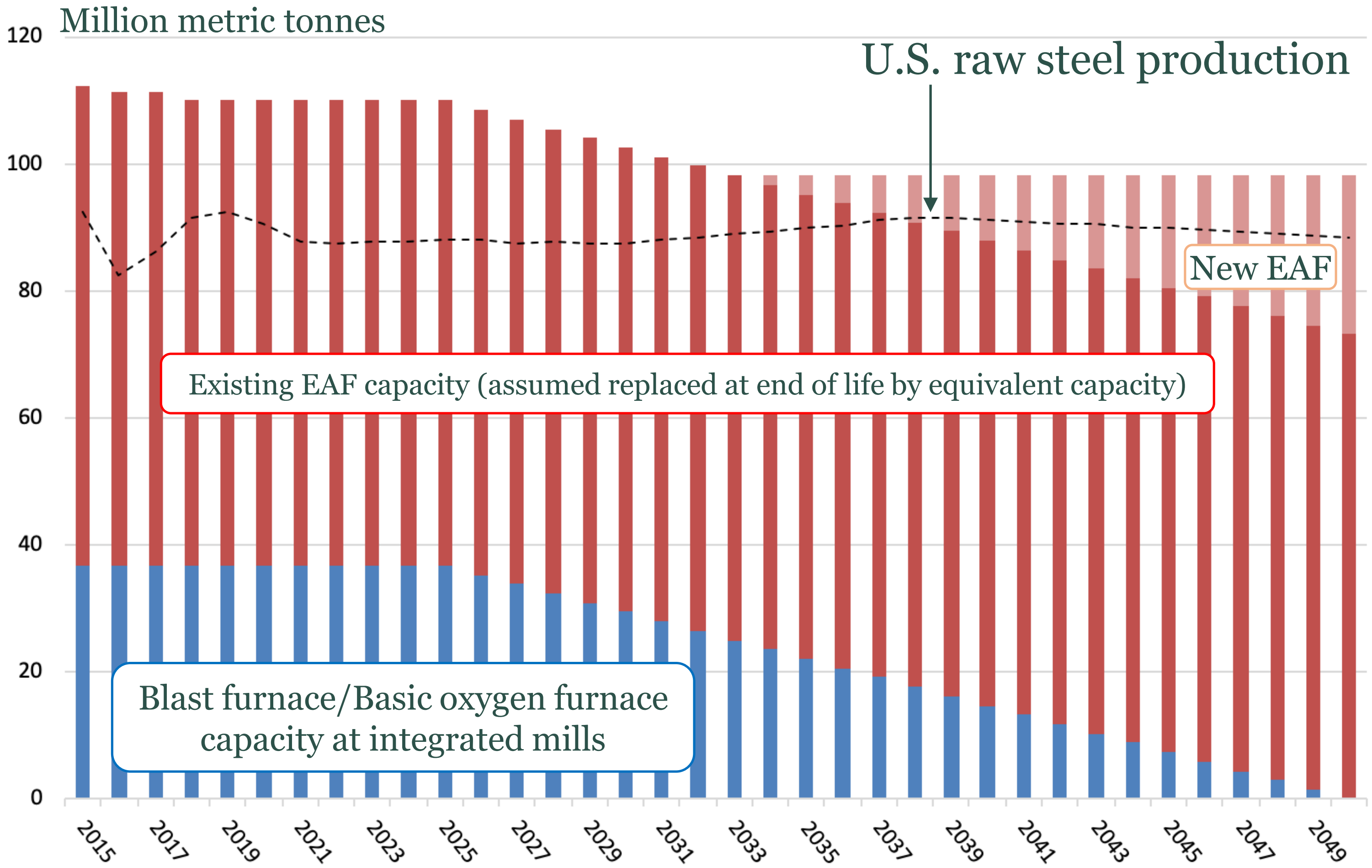
Steel industry evolves to 100% electric arc furnaces (EAF) by 2050; scrap is supplemented by direct-reduced iron (DRI) made using H_2.

- US domestic steel production holds steady at ~90 million t/y to 2050 (AEO2019).
- EAF production grows, producing 100% of domestic steel by 2050.
- Scrap supply for EAF grows to 59 MMT/y by 2030 and plateaus there.
- Scrap is supplemented by raw steel from direct reduction of iron (DRI) using H_2 as fuel and reductant.
- Average of 1.5 MMT/y of DRI capacity comes on line annually from 2030 to 2050 and an equivalent amount of BF/BOF (and associated coke production) retire. All BF/BOF are retired by 2050.
- DRI plants are geospatially distributed in proportion to current installed EAF capacity, except none in Northeast.



See Annex J for additional modeling details of iron & steel industry decarbonization.

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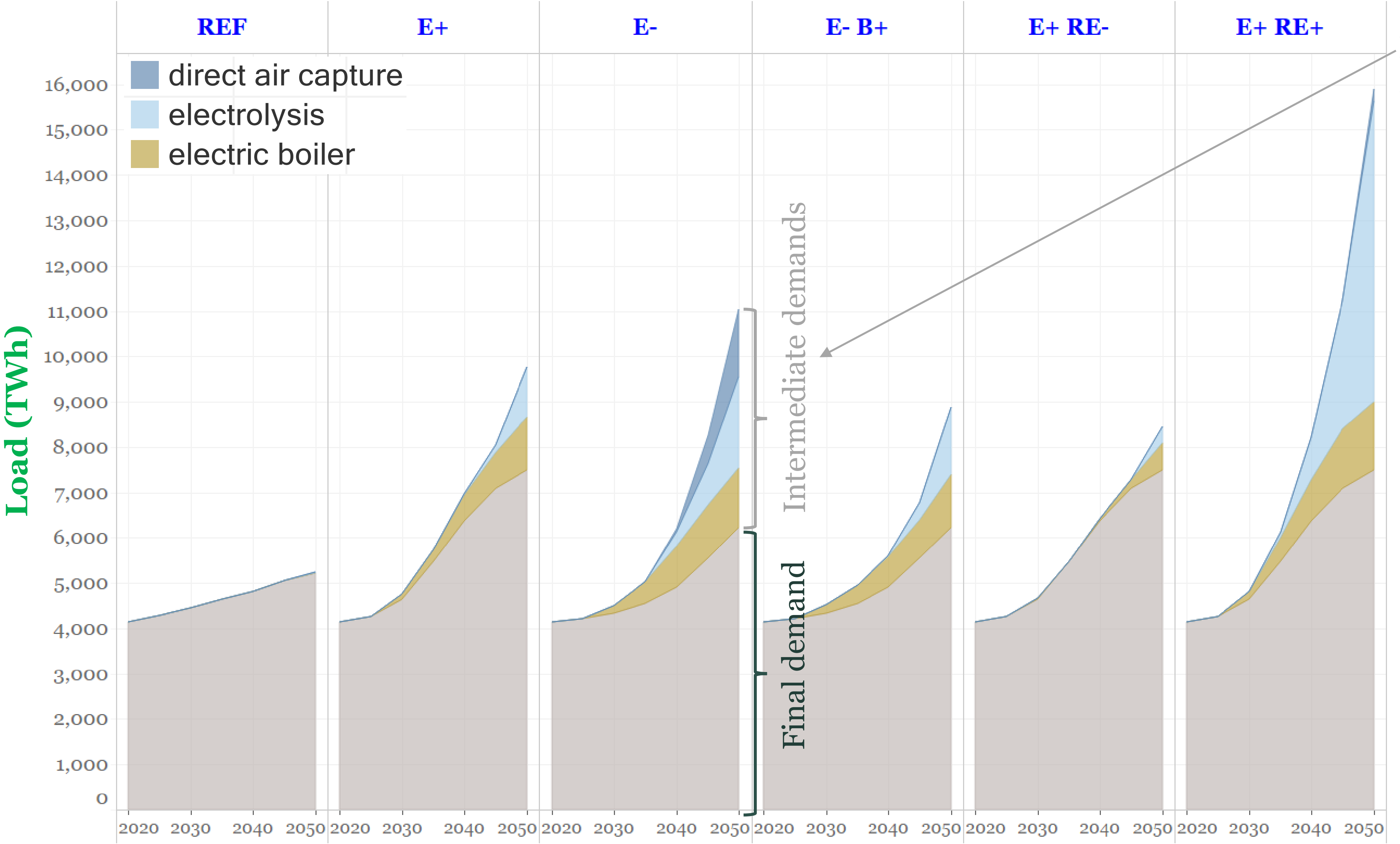
Economy-wide electricity demand and demand-supply balancing

Summary of this section

- Total electricity demand more than doubles by 2050 across all pathways to net-zero: **E+RE-**, +115%; **E-B+**, +125%; **E+**, +145%; **E-**, +170%; and **E+RE+**, +300%.
- End-use demand for electricity grows ~50% in E- scenarios and ~90% in E+ scenarios through 2050, driven by the pace of electrification of transportation and heating.
- Large volumes of *additional* electricity are consumed by several large 'intermediate' demands—electrolysis, electric boilers (installed in parallel with gas boilers) for industrial process heat, and direct air capture—all of which can flexibly consume low-cost, carbon-free electricity (e.g. from wind and solar power) when available and stop consumption when electricity supply is limited.
- If biomass supplies are constrained, falling shorter on electrification of end uses can actually result in *greater* electricity consumption (see E- vs E+). Even more electricity must be devoted to intermediate loads to produce hydrogen and run direct air capture to supply or offset greater demand for liquid and gaseous fuels in transportation and heating. Alternatively, biomass use can expand to supply liquid and gaseous fuels (as in E-B+), but with significant land use implications.
- Flexible scheduling of EV charging and electric water heating, large intermediate flexible loads, batteries, and firm generation technologies all help compensate for variability in wind and solar power and ensure electricity supply and demand are always balanced.

Electricity load grows ~2x – 4x by 2050, including flexible intermediate loads that absorb variable wind and solar generation.



Intermediate demands are flexible loads:

- Electrolysis making H_2 from water (hourly flexibility).
- Electric boilers in parallel with gas-fired units in industry (hourly flexibility).
- Direct air capture (daily flexibility).

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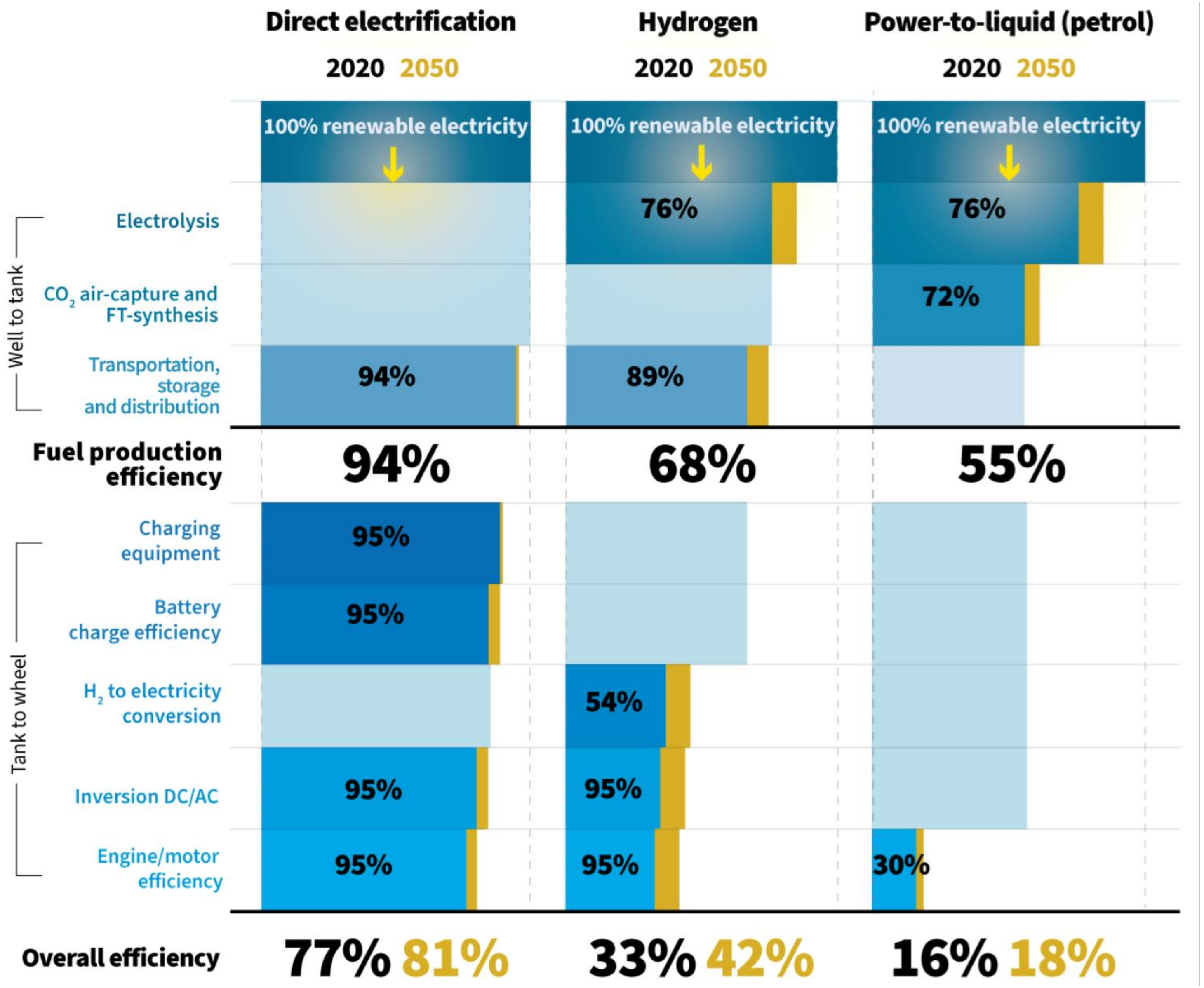
Fueling vehicles with hydrogen or liquids made from electricity requires much more electricity than using it directly in EVs.

Electricity-to-wheels efficiency of various zero-carbon vehicle pathways



Notes: To be understood as approximate mean values taking into account different production methods. Hydrogen includes onboard fuel compression. Excluding mechanical losses.

Adapted, with permission, from Transport and Environment, "Electrofuels? Yes, we can … if we're efficient," December 2020.

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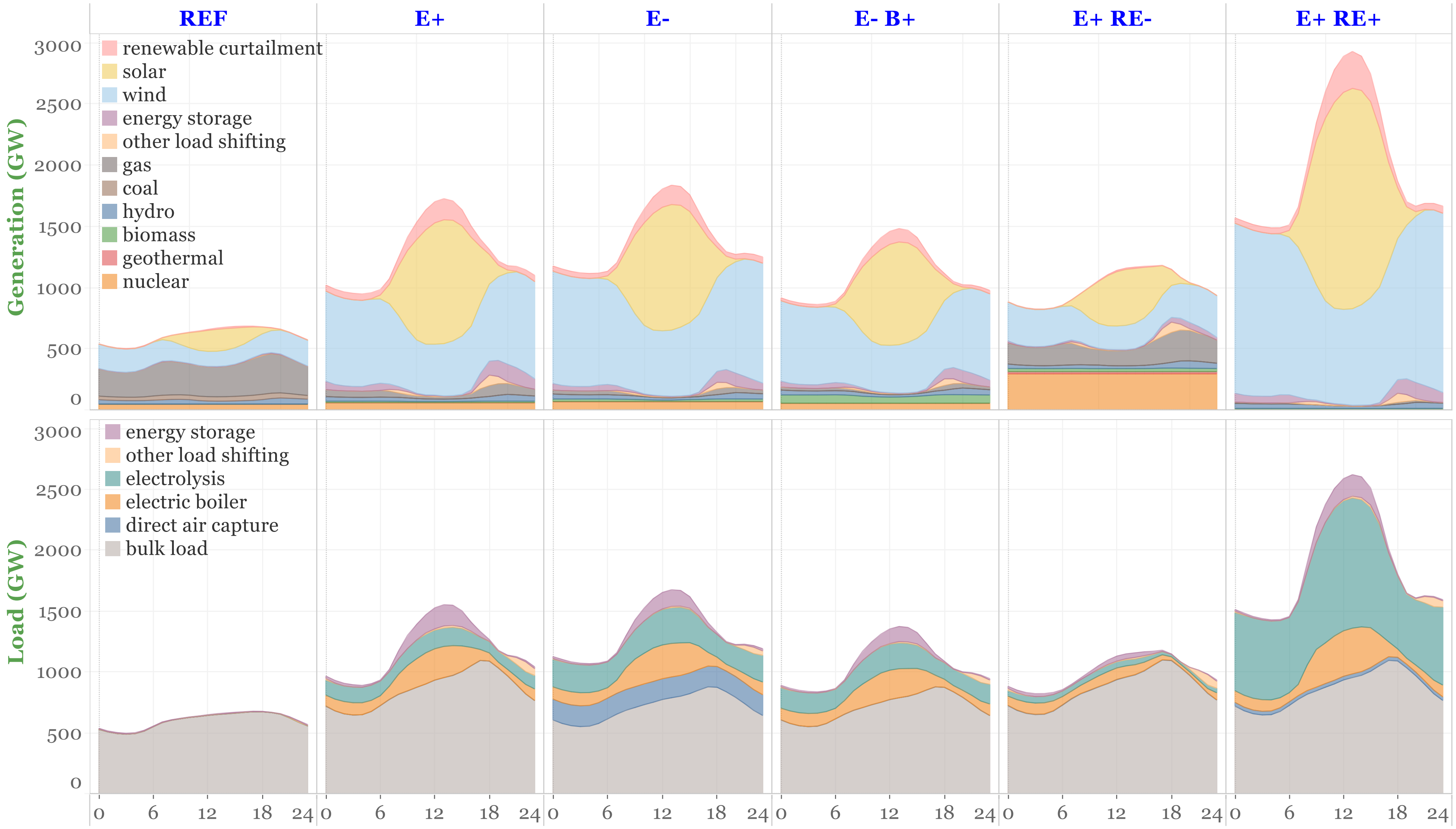
Hourly average grid operations: Short-duration batteries play relatively small roles. Large role for electrolysis in RE+ and E-.



Note: "Other load shifting" represents up to 50% of EV charging load and up to 20% of residential & commercial water heating load that are shifted in time relative to typical consumer patterns. In the RIO model, EV charging can be delayed by up 5 hours and water heating can be advanced or delayed by up to 2 hours. When EV and water heating loads are higher than with typical behavior, they are shown here as load. When they are lower than with typical behavior they are shown as generation. Meanwhile, "bulk load" includes EV and water heating loads under typical consumer behavior. Thus, the "other load shifting" seen here reflects load shifting from early evening to late evening.

If the option of shifting EV and water heating loads were removed, the amount of required energy storage approximately doubles.

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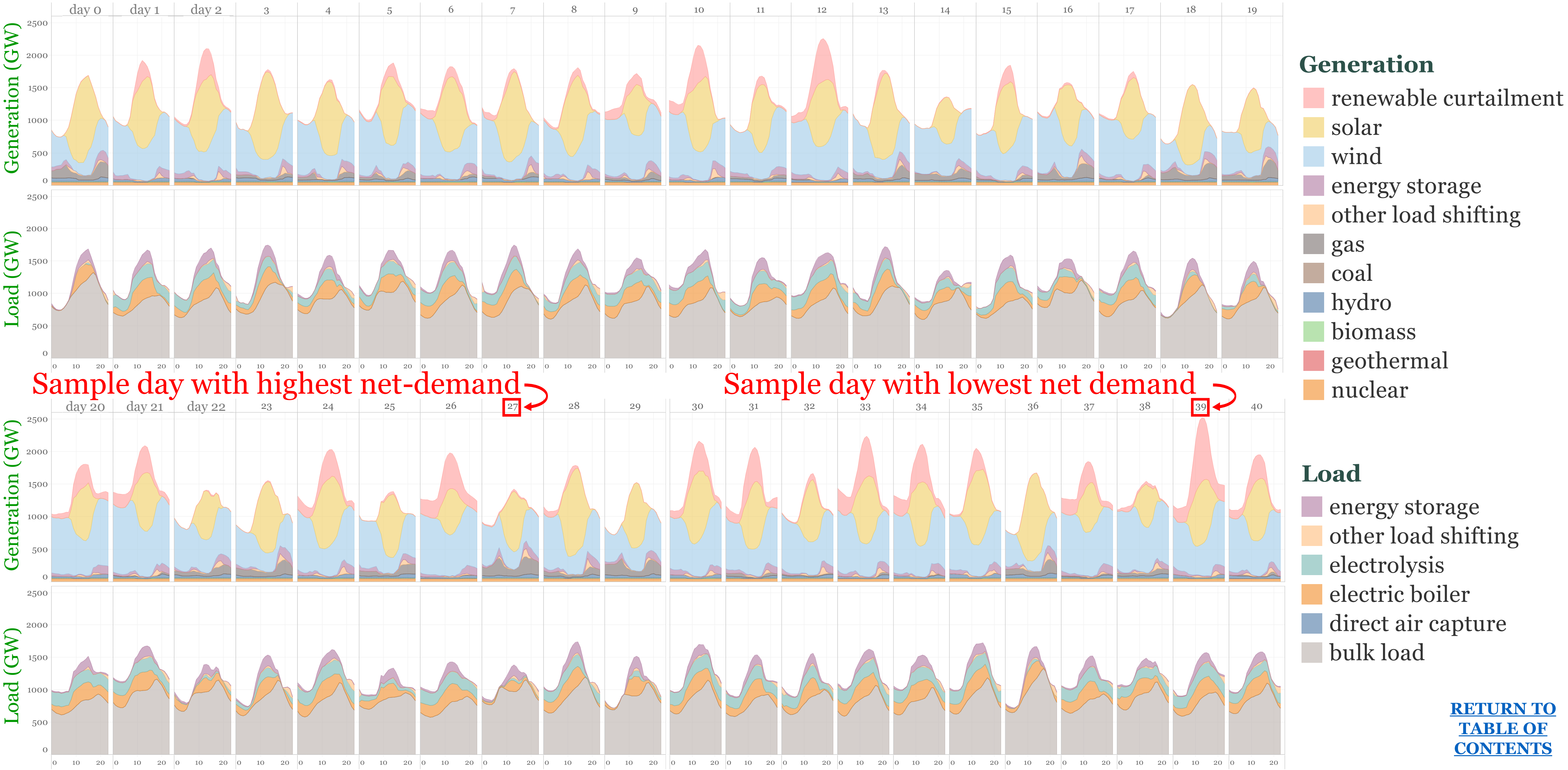
Hourly generation and load profiles in 2050 for each of 41 sample days used to model grid operations, E+ scenario.



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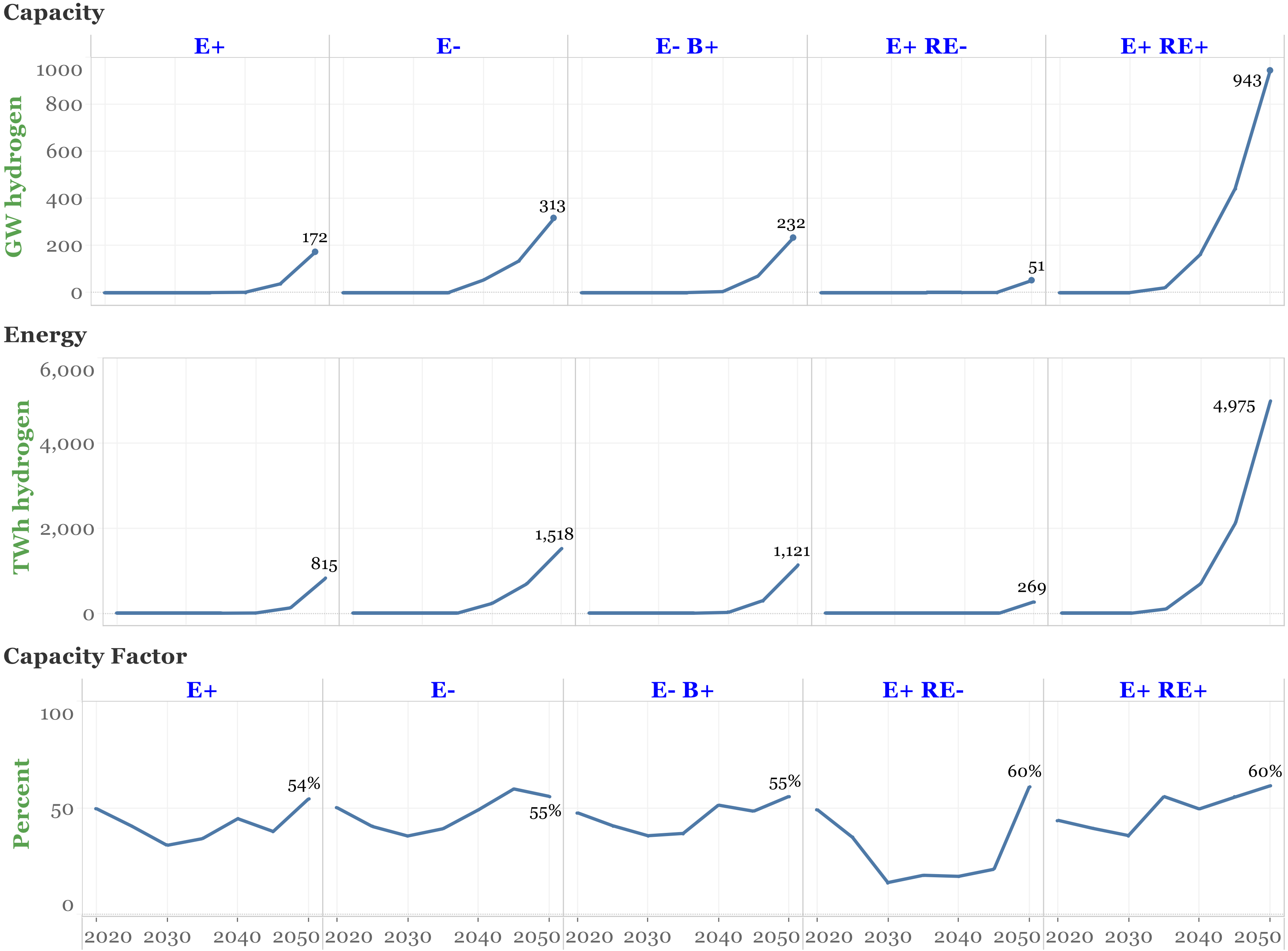
Electrolysis capacity grows primarily in the 2040s in all scenarios, and it grows most significantly in RE+.

- Capacity factors (utilization rates) are in the range of 40-60%
- Plants run frequently, requiring substantial additional wind and solar capacity that primarily supplies electrolysis.
  - In other words: electrolysis doesn't just run on 'excess' or 'free' wind and solar that would otherwise be curtailed.



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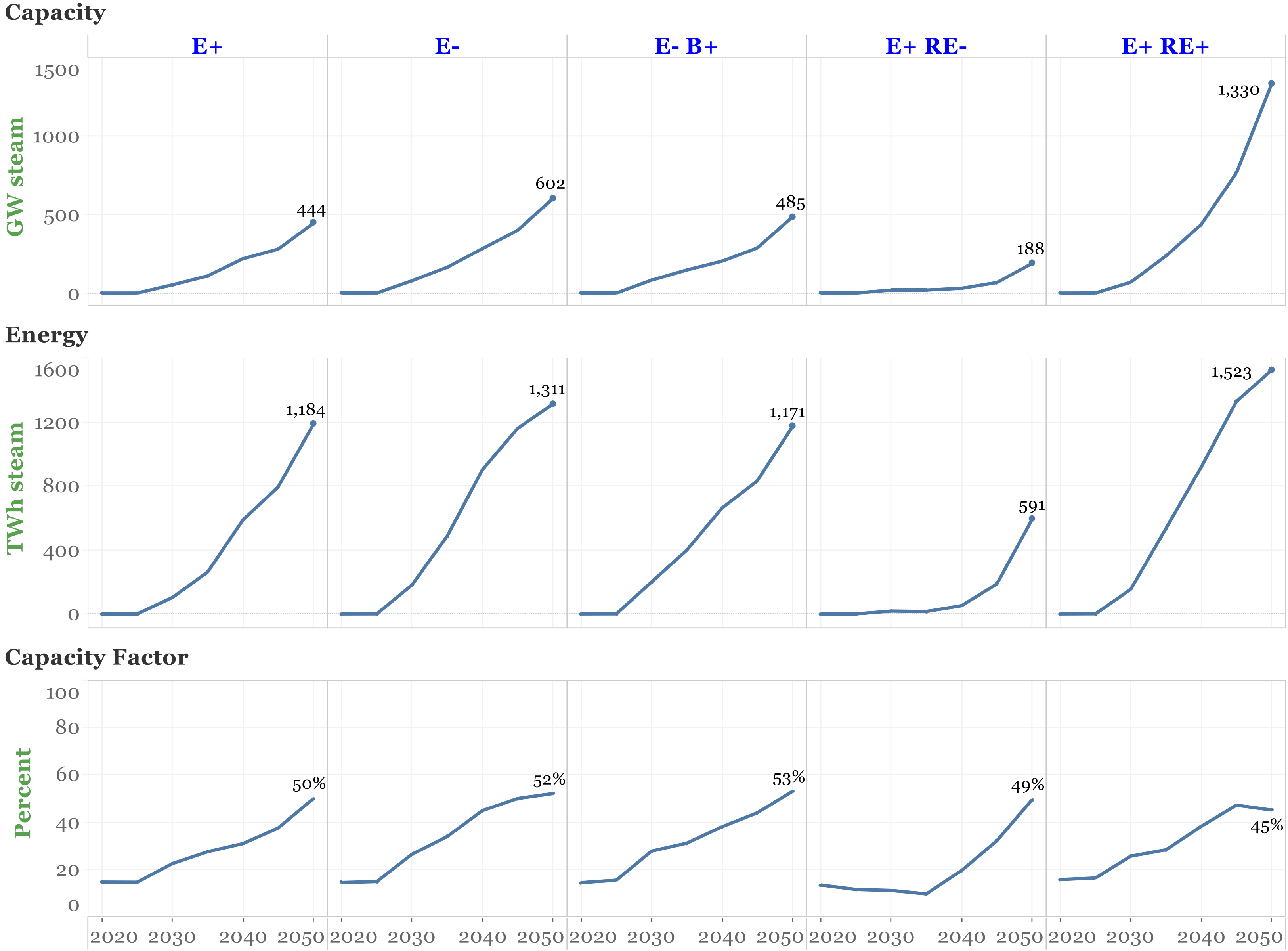
Electric boilers are deployed alongside gas boilers for industrial process heat.

- Allows variable wind and solar generation when available to displace fossil gas while maintaining 100% availability of heat for industrial processes.
- Electric boiler capacity and utilization grow steadily from 2025 to 2050 except in RE-, where growth is delayed until the 2040s.



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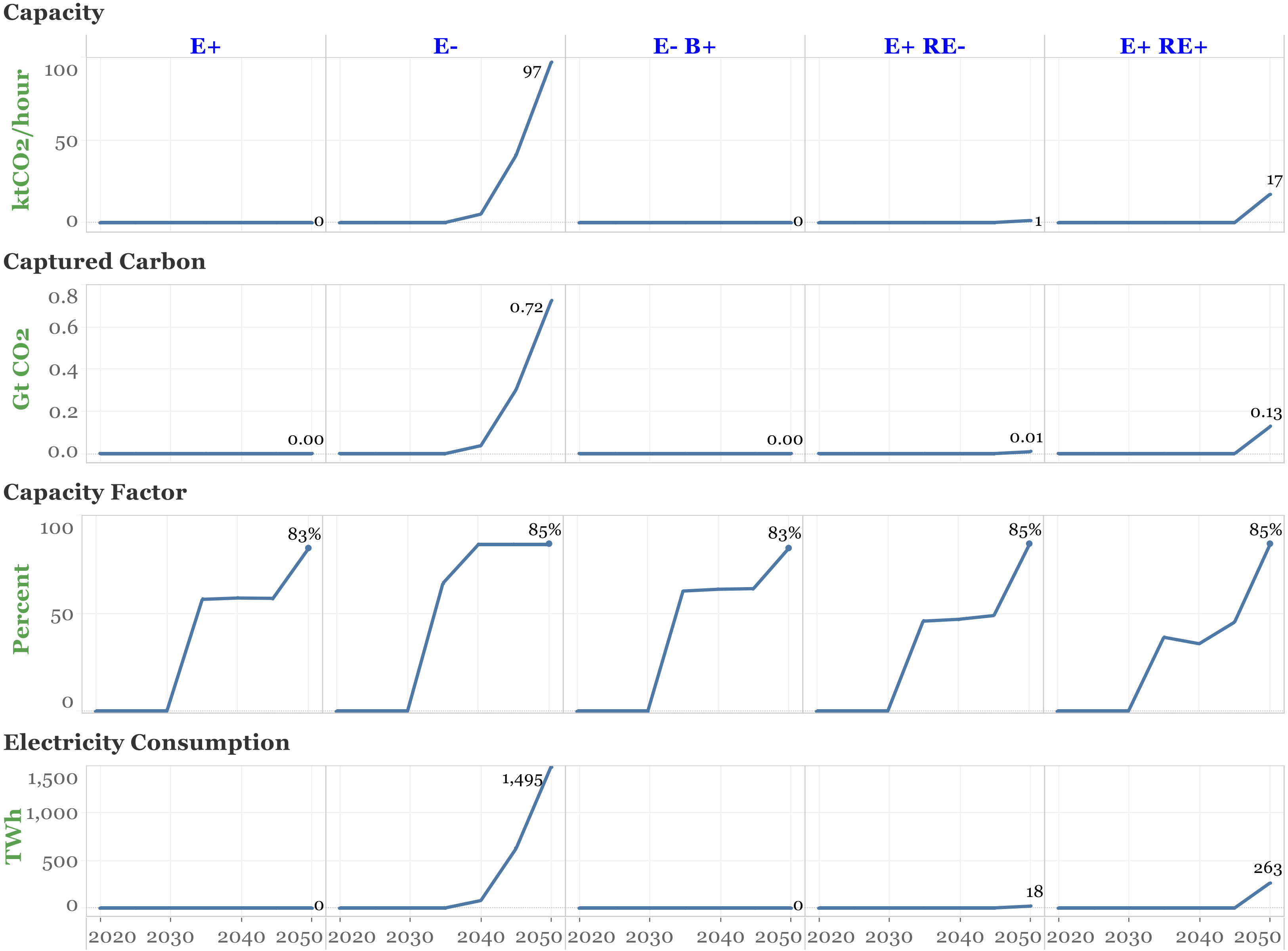
Direct air capture of CO_2 is significant in E- and RE+ scenarios

- With lower electrification of transportation in E- (and with biomass fully utilized), DAC compensates for greater use of liquid and gaseous fossil fuels.
- In RE+, CO_2 from DAC is used as a carbon source for synthetic liquid and gaseous fuels needed to fully displace fossil fuels.
- Given that DAC is a capital-intensive technology, utilization rates are high (50-85%).



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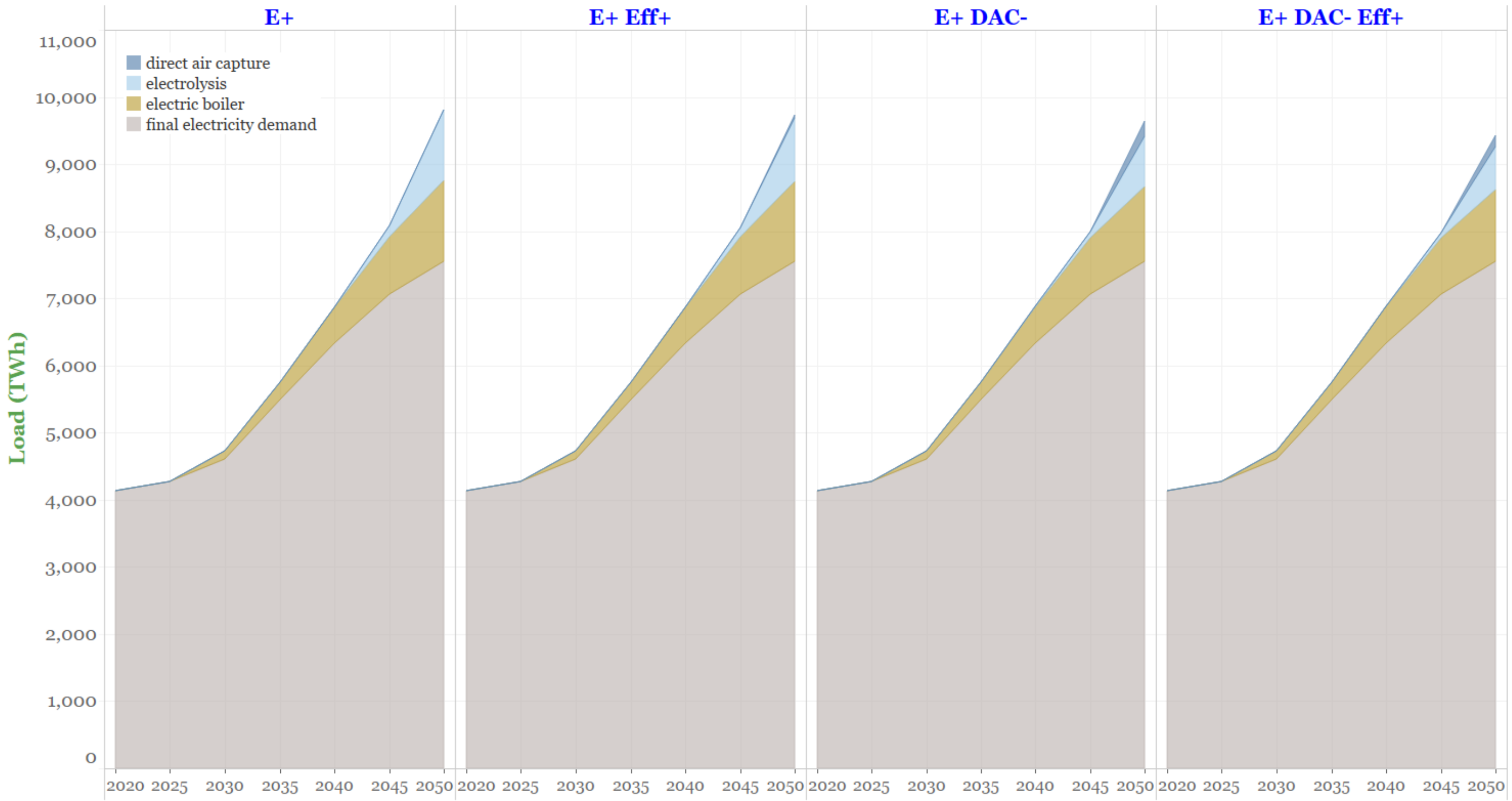
Lower capital cost and/or higher electricity efficiency of direct air capture increases its use slightly in E+ and decreases electrolysis

Role of direct air capture (DAC) was tested in sensitivity analysis. Relative to E+:

- Lowering DAC capital cost to ~1/3 of E+ (E+ DAC-) leads to only a small increase in DAC load because DAC is still more costly for CO_2 removal than other options. Electrolysis is slightly less utilized.
- Halving assumed DAC electricity use per tonne of CO_2 captured (E+ Eff+) leads to an even smaller increase in DAC load, with little change in electrolysis use.
- Combining lower cost *and* higher efficiency for DAC (E+ DAC- Eff+) reduces electrolysis load and total load more appreciably.
- NPV of total energy-supply system costs (2020 – 2050) is nearly the same for all cases shown.



See Annex B for additional discussion of sensitivity results.

Input assumptions that vary between sensitivity cases				
	E+	E+ DAC-	E+ DAC eff+	E+ DEC- eff+
Capital cost, $/(tCO_2/y), 2016$	2,164	694	2,164	694
Electricity use, MWh/tCO_2 captured	2	2	1	1

DAC cost and efficiency in E+ based on Socolow, et al., 2011. DAC cost in DAC- based on Keith, et al, 2018.

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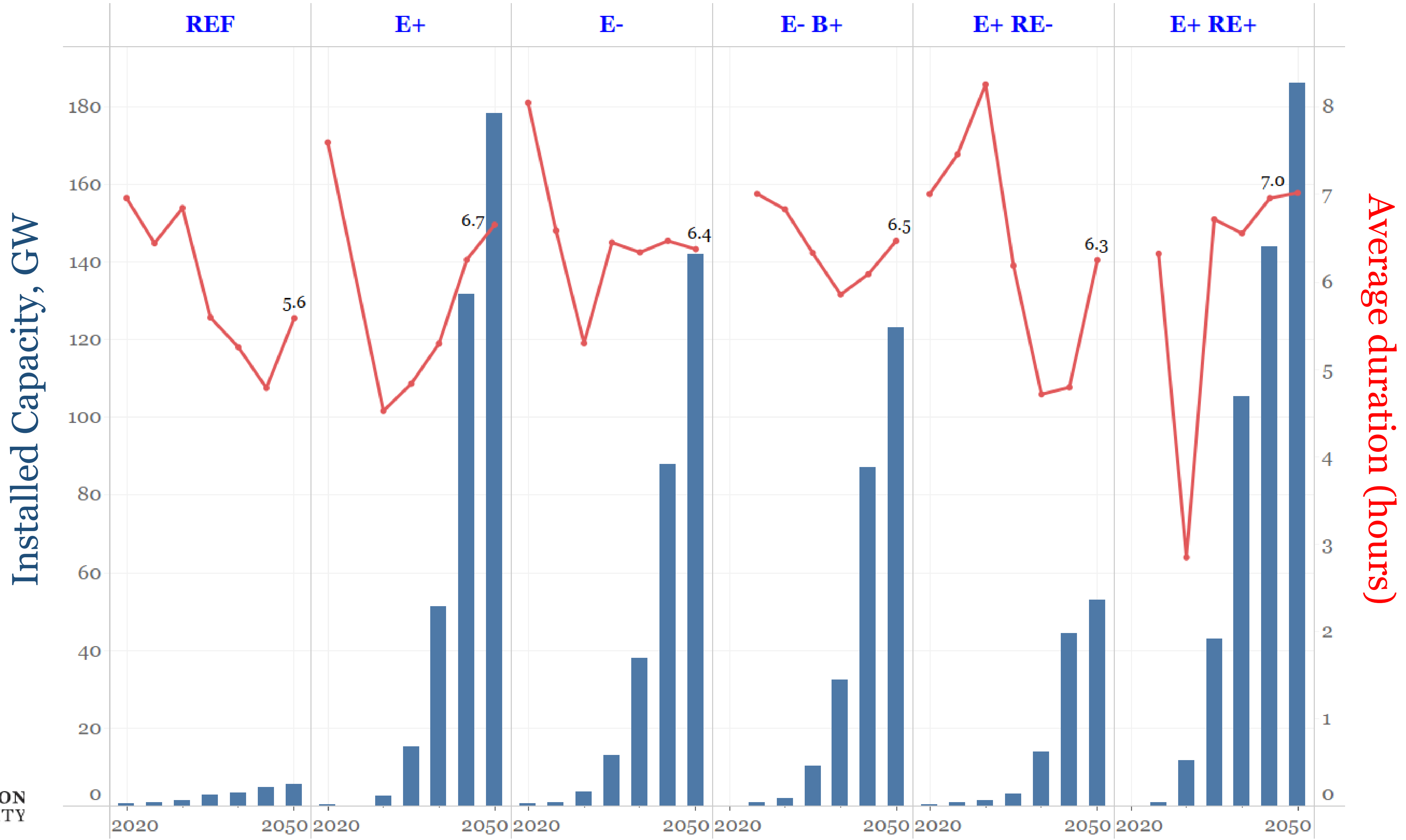
Grid battery capacity grows (mostly after 2030) to handle intra-day flexibility needs (5 to 7 hours storage duration)



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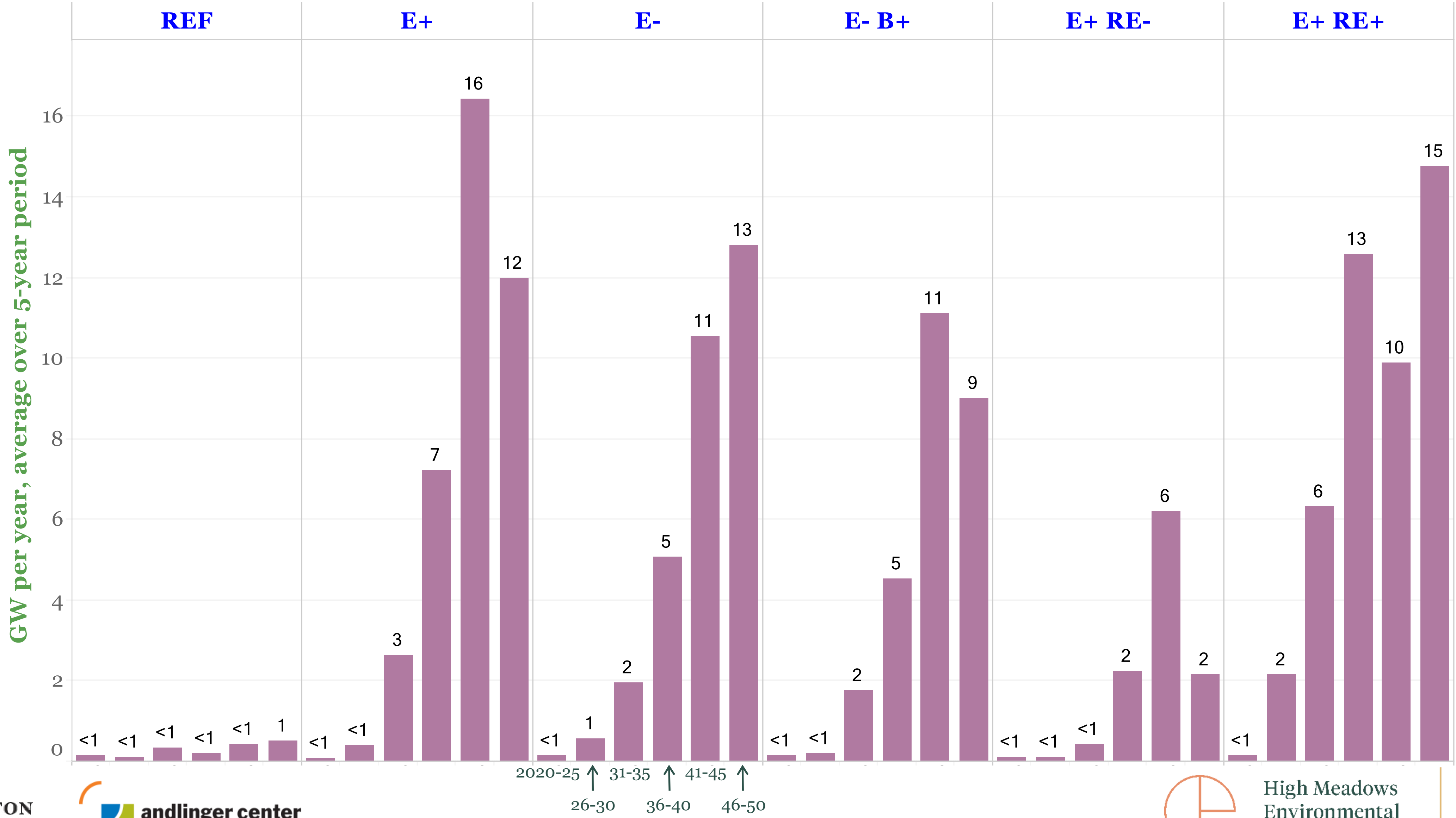
Annual capacity build rates for grid batteries are relatively modest through the 2030s, increasing thereafter.



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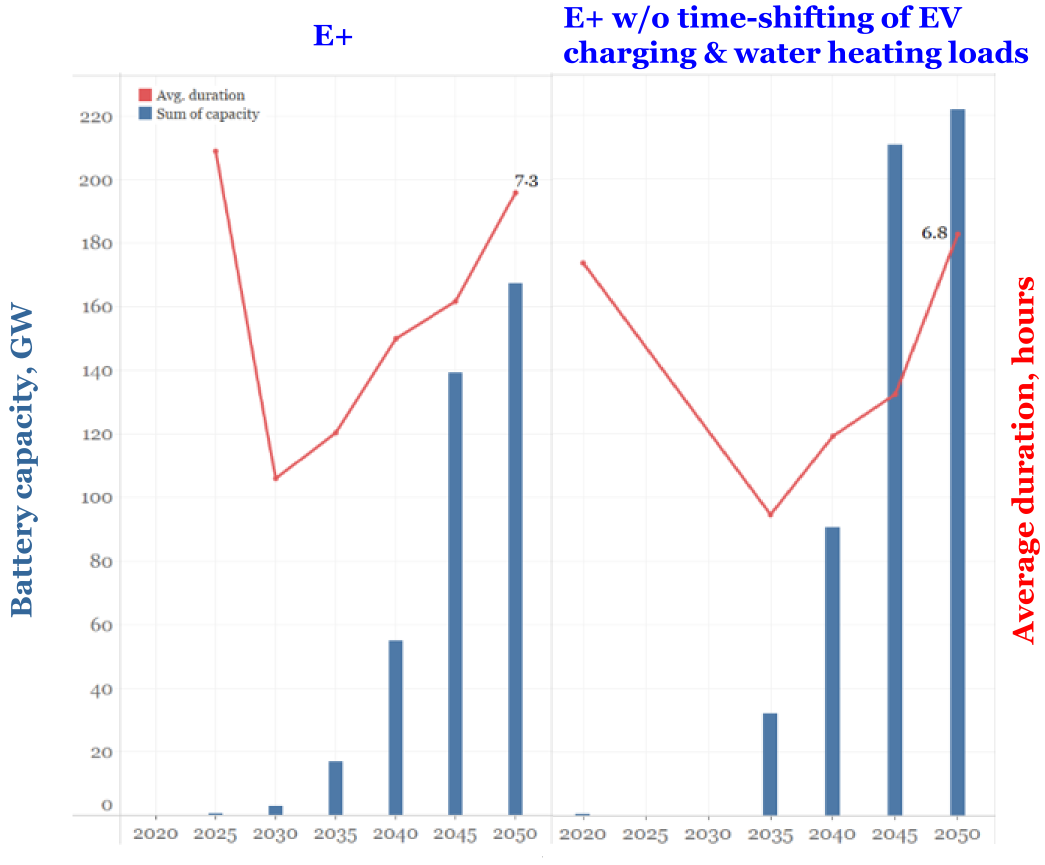
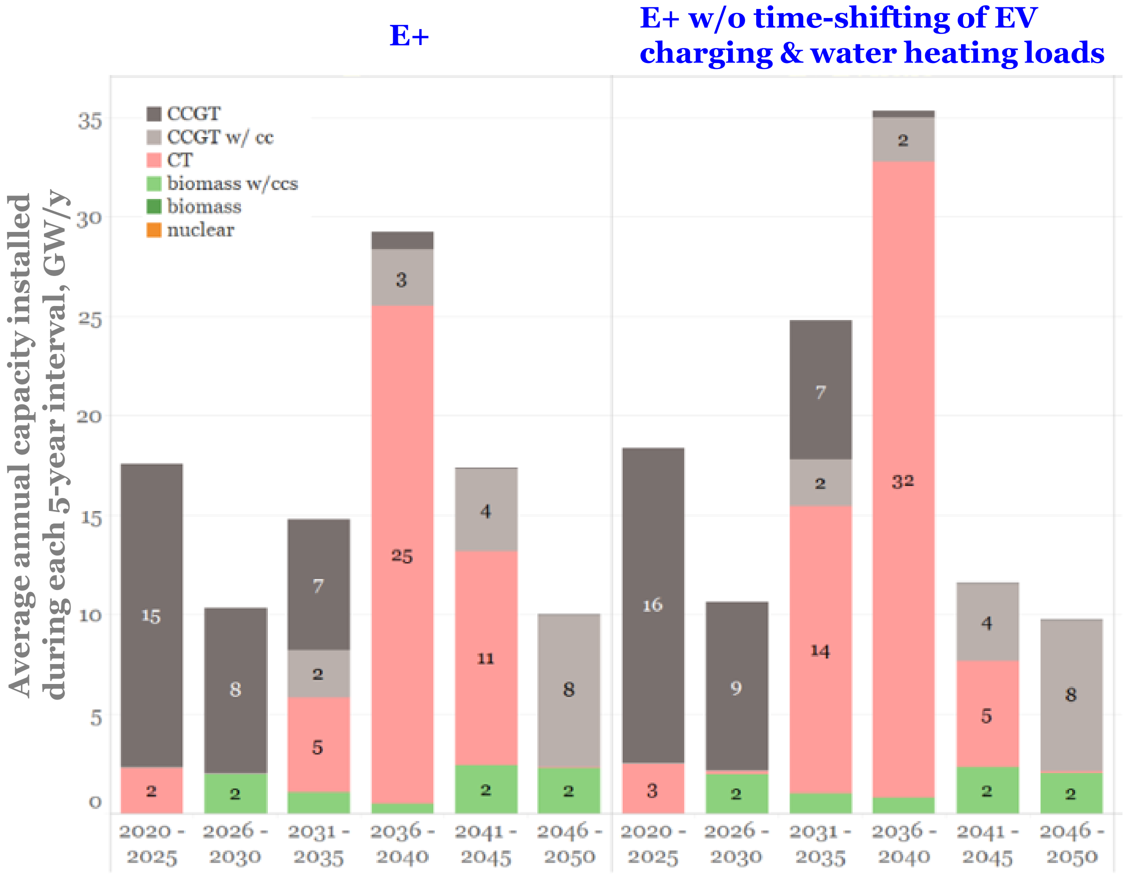
In a sensitivity case w/o time-shiftable EV charging and water heating, capacities of batteries and combustion turbines increase

In the E+ scenario, where some time-shifting of EV charging and electric water heating loads is allowed, deployment of battery storage is relatively modest, but if time-shifting loads is not allowed, additional sources of flexibility are installed, including about 40% more battery storage capacity by 2050 and significantly more combustion turbine capacity in the second half of the transition period.





See Annex B for additional discussion of sensitivity results.

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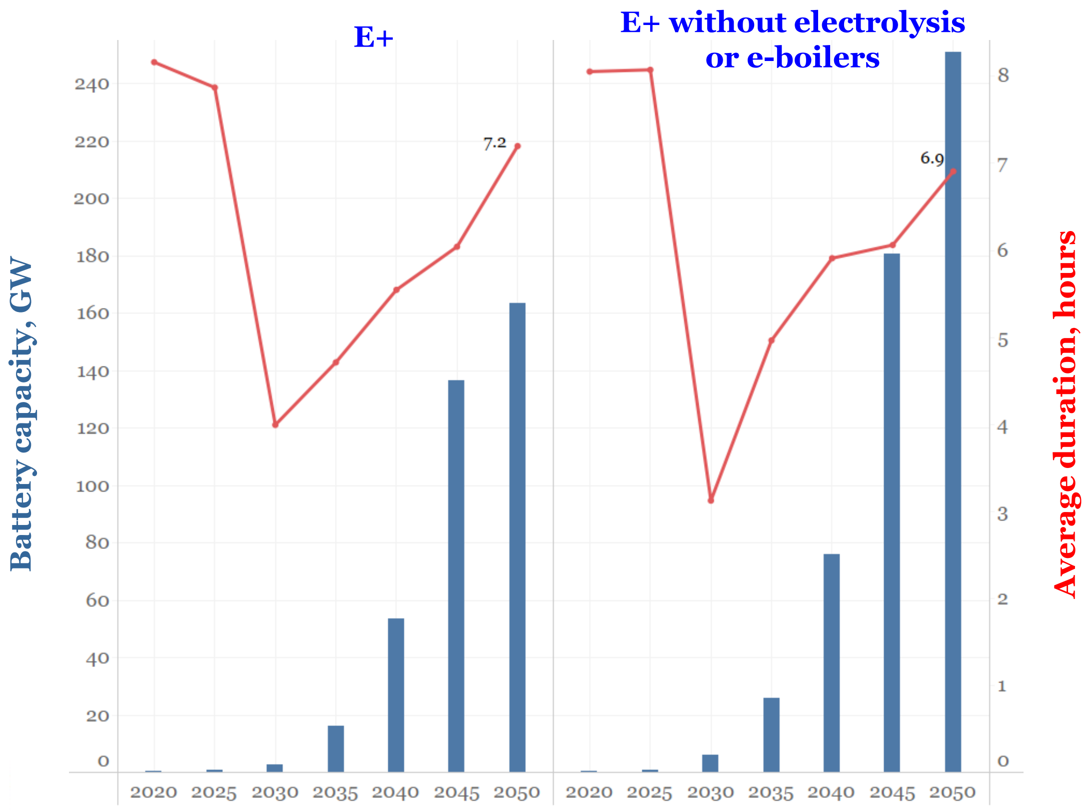
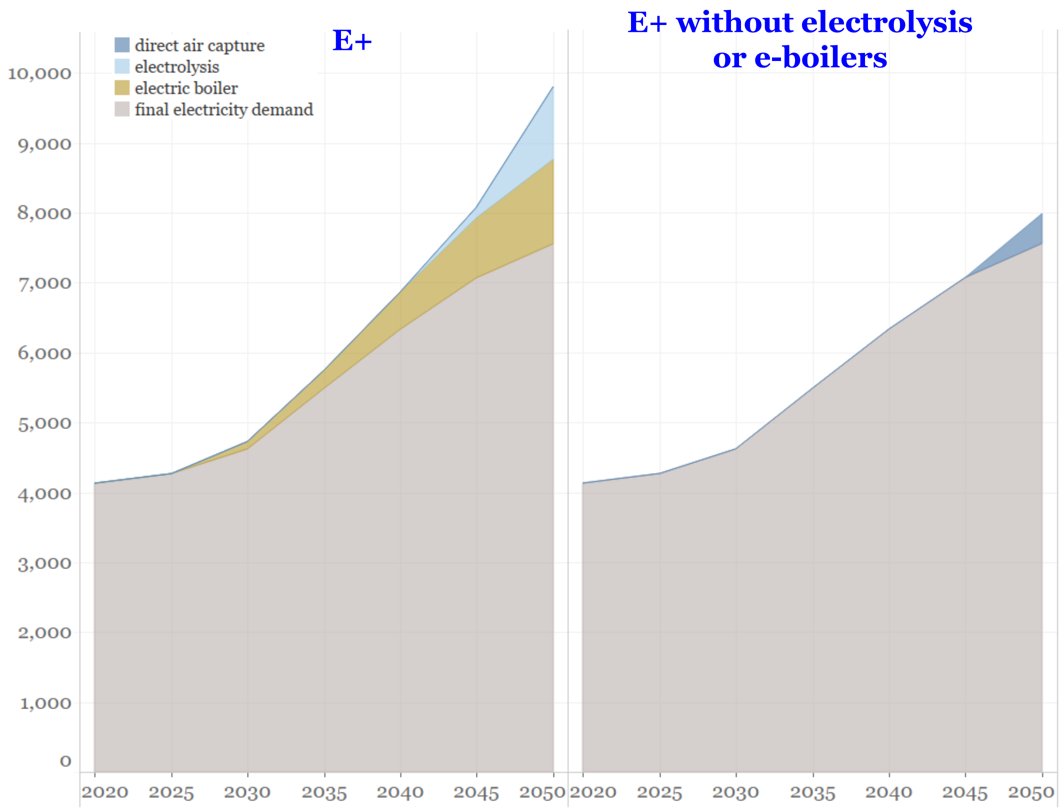
If large intermediate flexible loads are not allowed, battery capacity increases, but there are also other significant impacts

In E+, if flexible electrolysis and electric boilers are not allowed,

- Battery storage capacity increases by about 50% by 2050
- Wind and solar generation are reduced and generation from gas with CO_2 capture increases.
- Direct air capture is deployed in the final time step (2046-2050) to offset emissions from greater use of natural gas combined cycle and combustion turbine power plants without CO_2 capture and gas use in other sectors.





See Annex B for additional discussion of sensitivity results.

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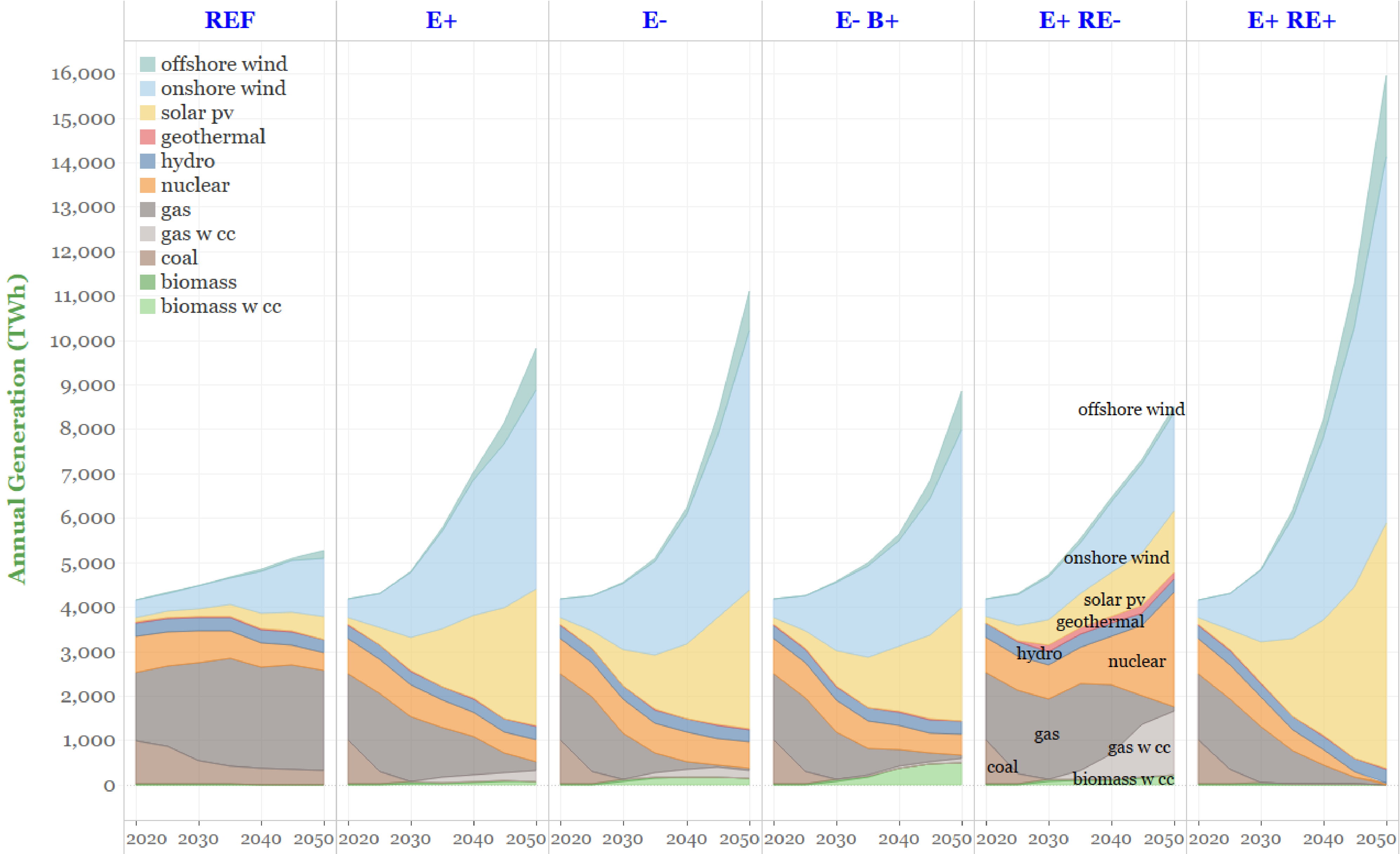
Pillar 2: Clean electricity

Summary of this section

- Expanding the supply of clean electricity is a linchpin in all net-zero paths. The share of electricity from carbon-free sources roughly doubles from ~37% today to 70-85% by 2030 and reaches 98-100% by 2050.
- Wind and solar power have dominant roles in all pathways:
  - Generation grows more than 4-fold by 2030 to supply about ½ of U.S. electricity in all cases except E+RE-; in that case, growth is exogenously constrained in the model, but still triples by 2030 to supply one-third of U.S. electricity.
  - By 2050, they generate ~7,400-9,900 TWh of electricity in E+, E-, and E-B+ (~85-90% of generation). In E+RE-, ~3,700 TWh (44%); in E+RE+, 15,600 TWh (98%). (Context, U.S. generation in 2020 was ~4,000 TWh)
  - 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.
- Nuclear power plants are assumed to operate through 80 years whenever safe to do so, except in E+RE+, where existing plants are retired 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 1/3 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); the model favors gas plants burning an increasing blend of hydrogen and with declining utilization rates through 2050. If wind and solar expansion is constrained, natural gas plants w/CO_2 capture and nuclear 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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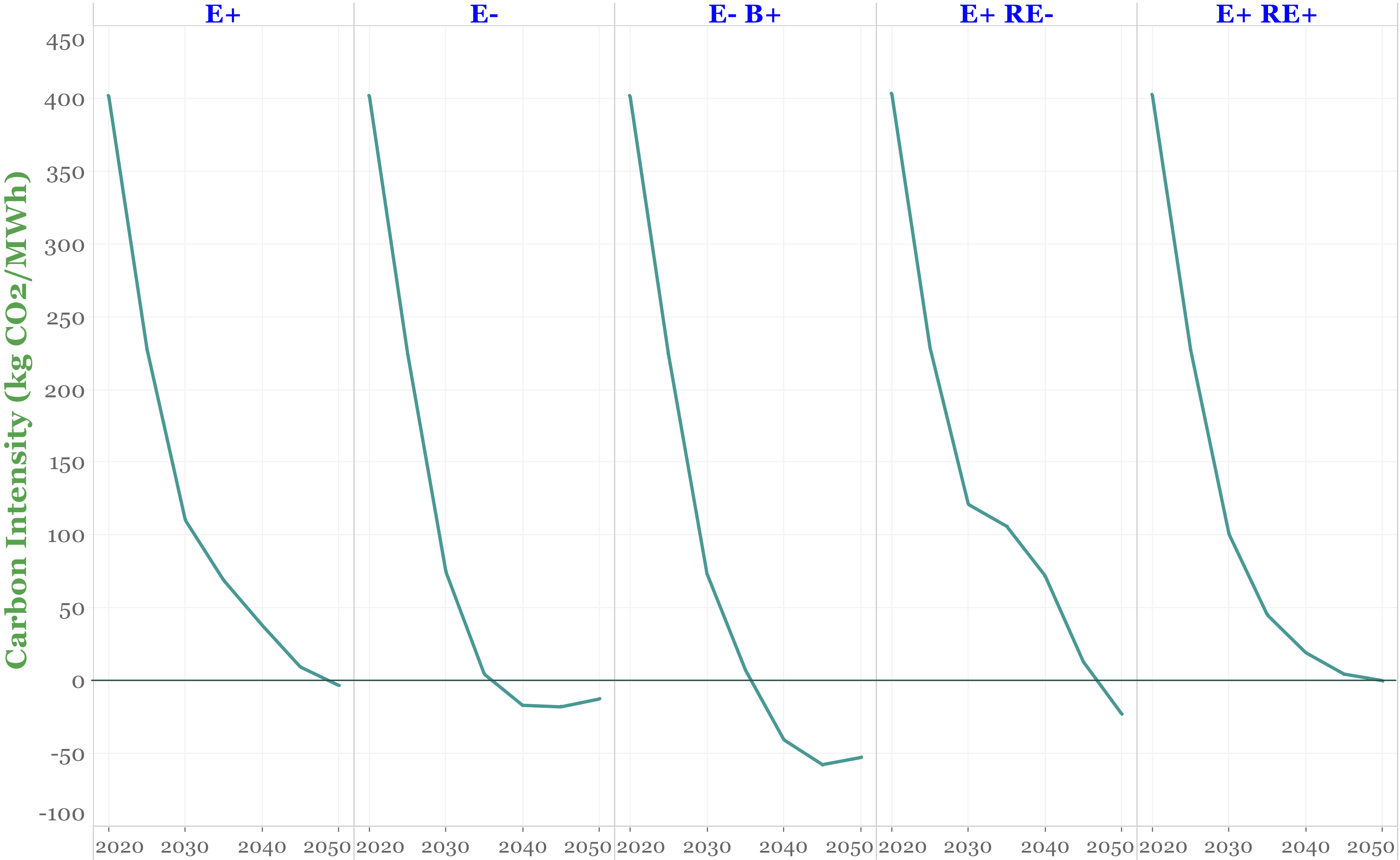
Carbon-intensity of electricity drops rapidly in all cases, reaching net-zero by 2035 in E- and negative values by 2050, except in RE+.



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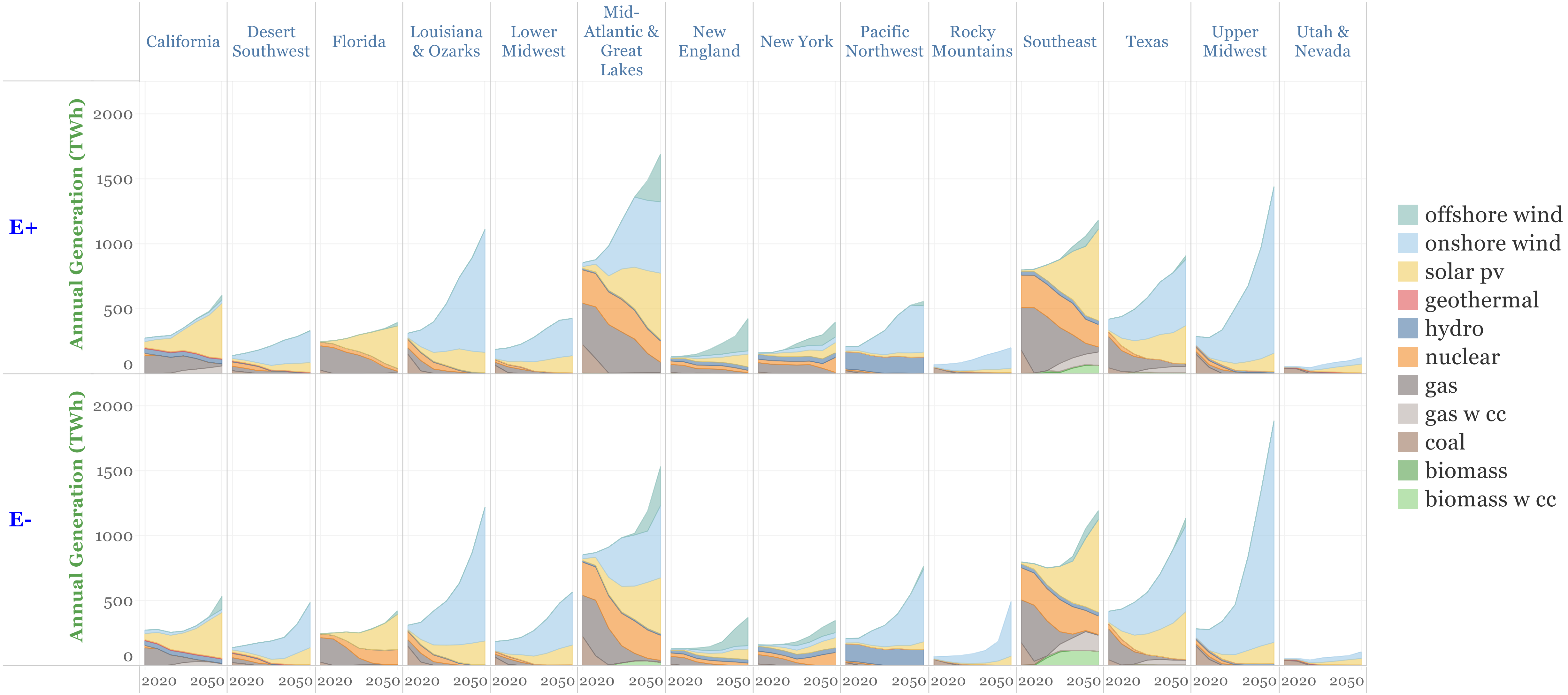
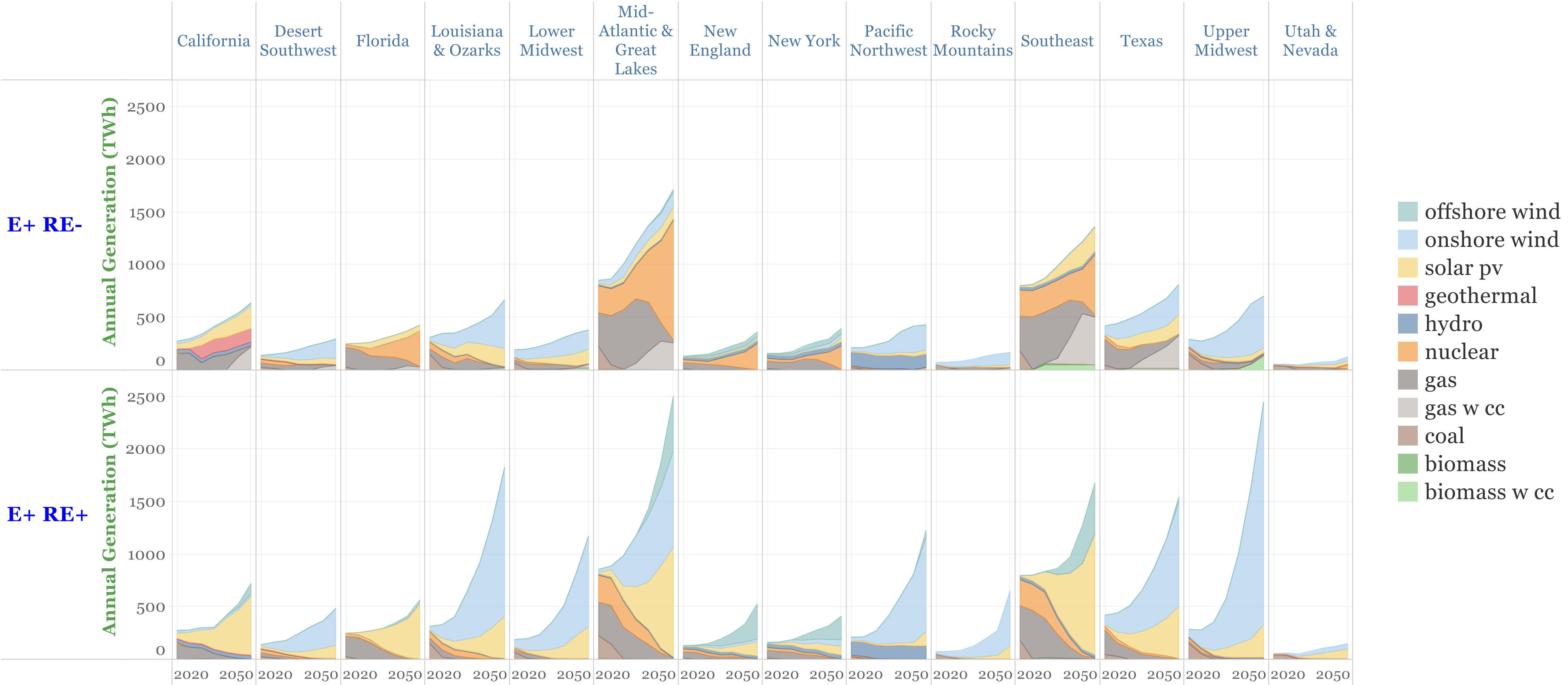
Regional evolution in electricity mix for E+ and E- scenarios.



Regional evolution in electricity mix for RE- and RE+ scenarios.



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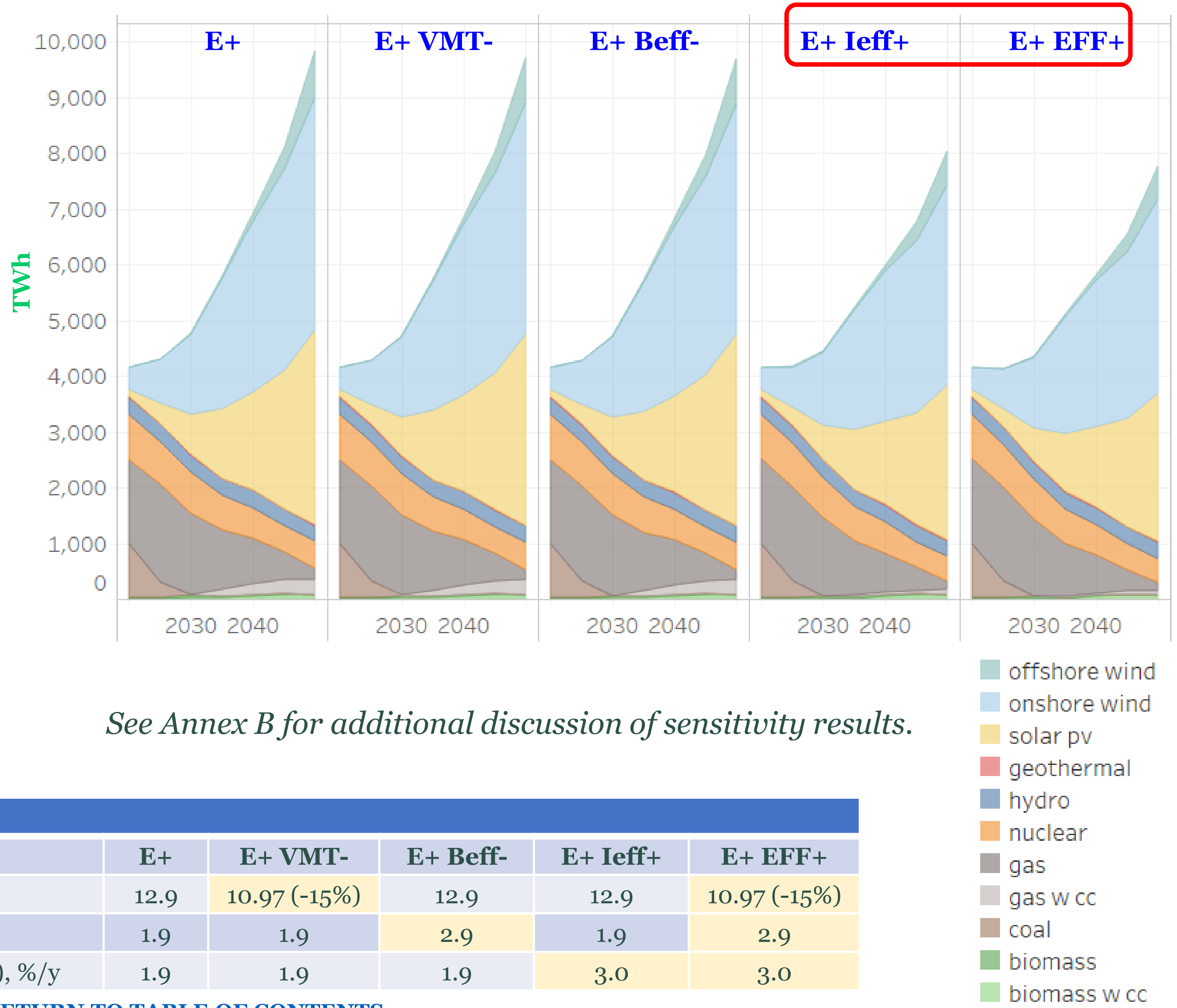
Solar and wind electricity generation in E+ would be reduced with further end-use efficiency improvements, especially in industry

E+ incorporates significant measures for end-use energy efficiency in all sectors, but more aggressive efficiency improvements were tested:

- Further efficiency gains in light-duty vehicles (or equivalent reduction in vehicle miles travelled, E+ VMT-) or building space conditioning (E+ Beff-) don't reduce electricity generation needs significantly, because the efficiencies for these electrified activities are already high.
- However, if industrial productivity improvement is higher (3%/year, the highest historically observed multi-decade rate, E+ Ieff+), wind and solar generation in 2050 would be reduced by over 10% relative to E+ and gas w/CC generation also falls; NPV of total energy-supply system cost declines ~5%.



See Annex B for additional discussion of sensitivity results.

Input assumptions that vary between cases					
	E+	E+ VMT-	E+ Beff-	E+ Ieff+	E+ EFF+
Light duty vehicle-miles traveled in 2050, thousand VMT per vehicle	12.9	10.97 (-15%)	12.9	12.9	10.97 (-15%)
Buildings' heating/cooling final-energy demand reduction rate, %/yr	1.9	1.9	2.9	1.9	2.9
Industrial energy productivity ($ shipments/MJ) increase rate (vs. REF), %/y	1.9	1.9	1.9	3.0	3.0

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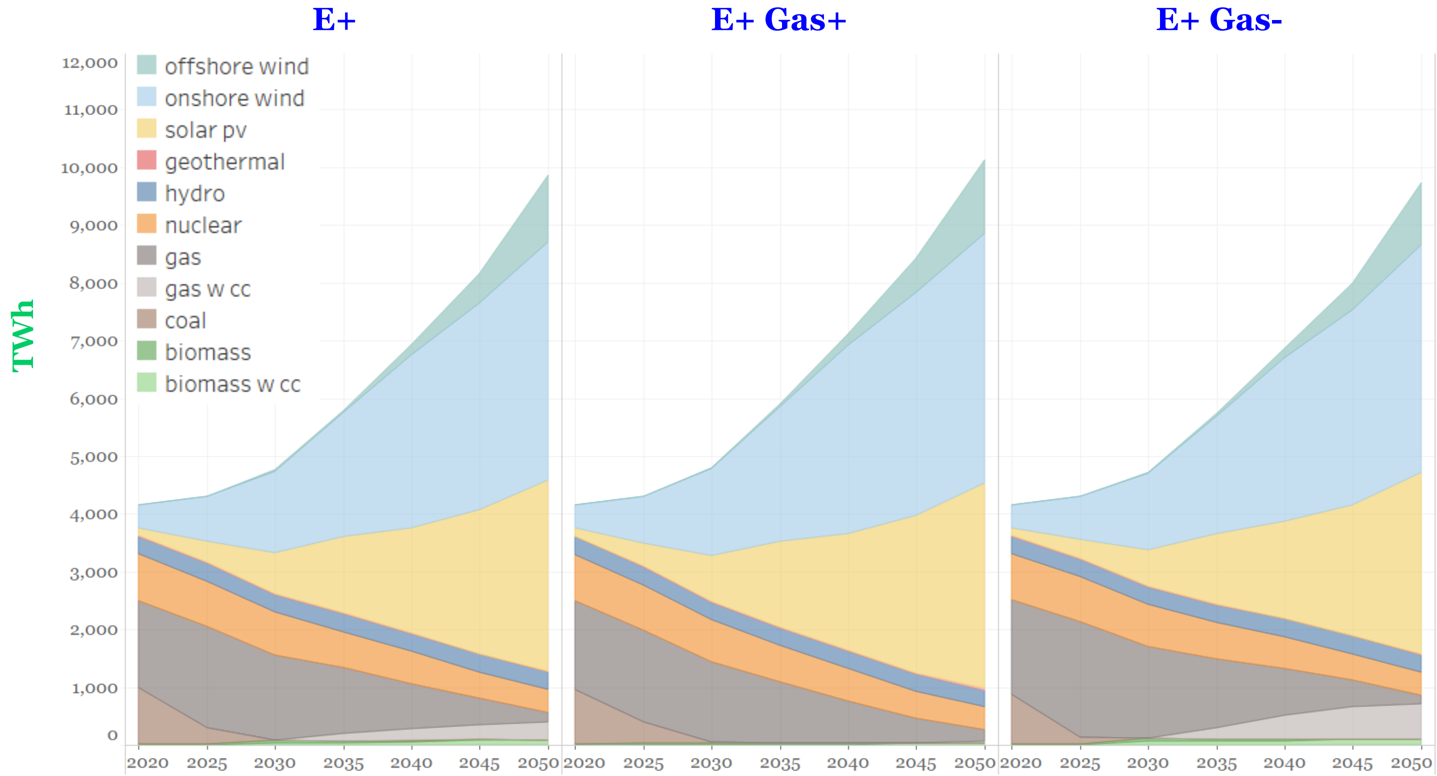
Power generation from natural gas with CO_2 capture plays a larger role if gas prices are lower

Natural gas prices in E+ are as projected in AEO2019 "High Oil and Gas Resource and Technology" scenario. With alternative gas price trajectories:

- With lower gas prices (E+ Gas-), electricity generation by NGCC w/CC increases at the expense of wind/solar and some nuclear. NPV of total energy-supply system cost from 2020 – 2050 (not shown here) is reduced by 2% relative to E+.
- With higher gas prices (E+ Gas+) gas w/CC generation is eliminated and replaced at greater than 1-to-1 by wind and solar due to greater electricity demands from flexible loads (e.g., electrolysis) to balance the added variable generation. NPV of total energy-supply system cost (2020 – 2050) increases ~2% relative to E+.



See Annex B for additional discussion of sensitivity results.

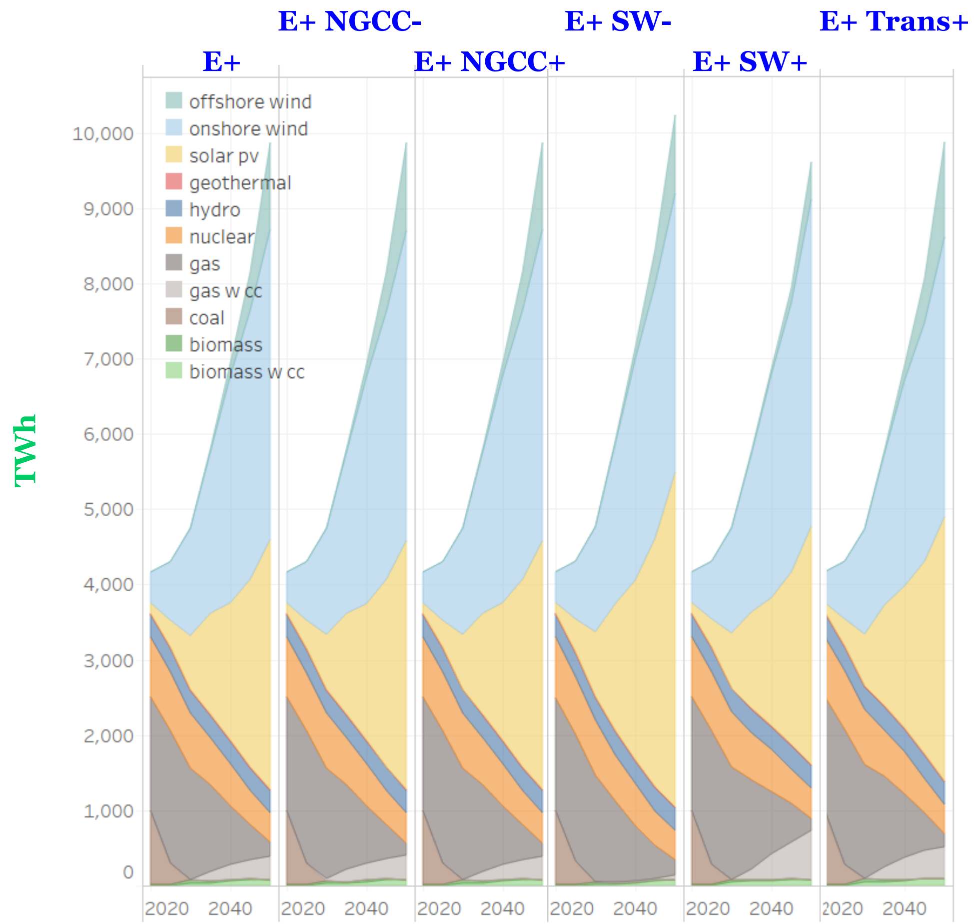
Input assumptions that vary between cases			
2016 $/GJ$_{HHV}$	**E+**	**E+ Gas+**	**E+ Gas-**
Natural gas price projection source	AEO2019 Hi oil/gas tech & resource	AEO2020 Low oil & gas supply	AEO2020 Hi oil & gas supply
Natural gas price in 2020, 25, 30, 35, 40, 45, 50 (*)	2.5, 2.8, 3.0, 3.1, 3.1, 3.1, 3.3	2.5, 3.5, 4.4, 4.9, 5.2, 5.6, 6.2	2.3, 2.3, 2.5, 2.5, 2.5, 2.4, 2.4

* Natural gas price inputs vary between regions. The prices shown here are for the Texas region in the RIO model.

Higher or lower capital costs for solar and wind mostly impact the balance between NGCC w/CC and solar/wind generation

Future capital costs for power sector technologies are uncertain. E+ was tested with higher and lower power-sector capital cost assumptions:

- Changes in solar/wind capital costs have the largest impacts due to the large installed capacity:
    - Lower costs (E+ SW-) lead to more wind/solar and less NGCC w/CC. NPV of total energy-supply system (2020 – 2050) is ~2% lower than for E+.
    - Higher costs (E+ SW+) drive more NGCC w/CC into the generating mix.
- Higher transmission costs (E+ Trans+) have a similar impact as higher solar/wind costs.
- Lower or higher costs for natural gas w/CC have little impact because the amount of firm capacity needed does not change and, with low natural gas prices, gas w/CC retains an advantage over nuclear (the main other firm option) at all of these cost combinations.



See Annex B for additional discussion of sensitivity results.

Input assumptions that vary between cases				
$/kW in 2050	**E+**	**E+ NGCC -/+**	**E+ SW -/+**	**E+ Trans+**
NGCC w/CC (+50% / -20%)	1,725	1,380 / 2,589	1,725	1,725
Solar/wind (TRG1 NJ, e.g.)*	PV: 869 / Wind: 1,723	PV: 869 / Wind: 1,723	PV: 453 / 1,144, Wind: 1,433 / 2,280	PV: 869 / Wind: 1,723
Trans. (Mid-Atl → NY, e.g.)	2,821	2,821	2,821	5,642

* E+ uses NREL Annual Technology Baseline (ATB2019) mid-range cost projections. For SW- and SW+, ATB2019 low-cost and average of mid- and constant-cost projections are used, respectively.

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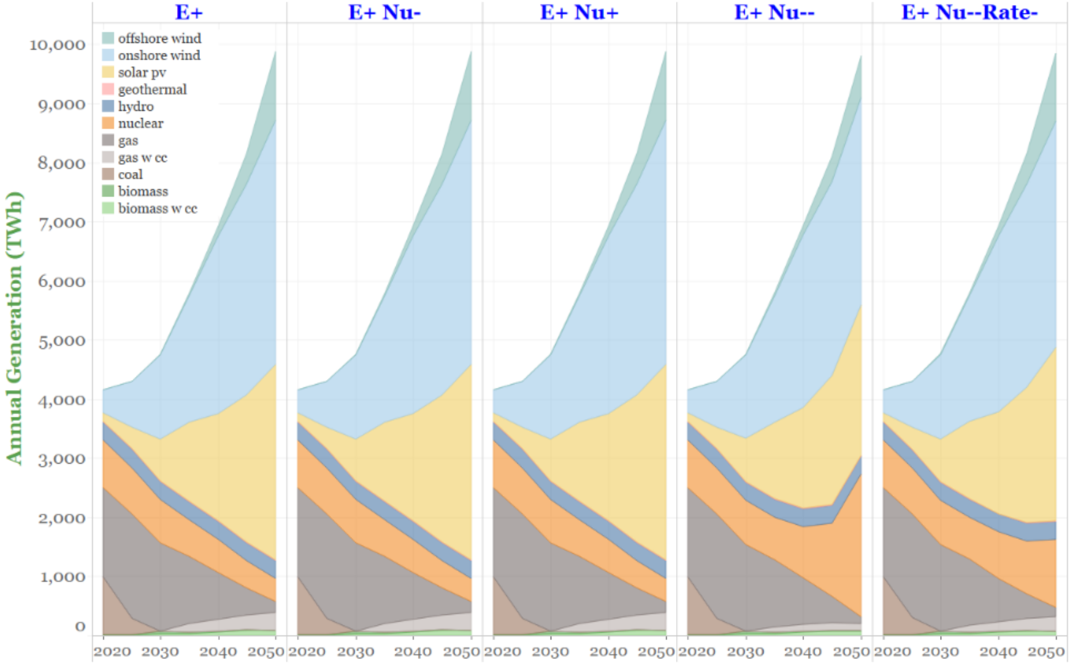
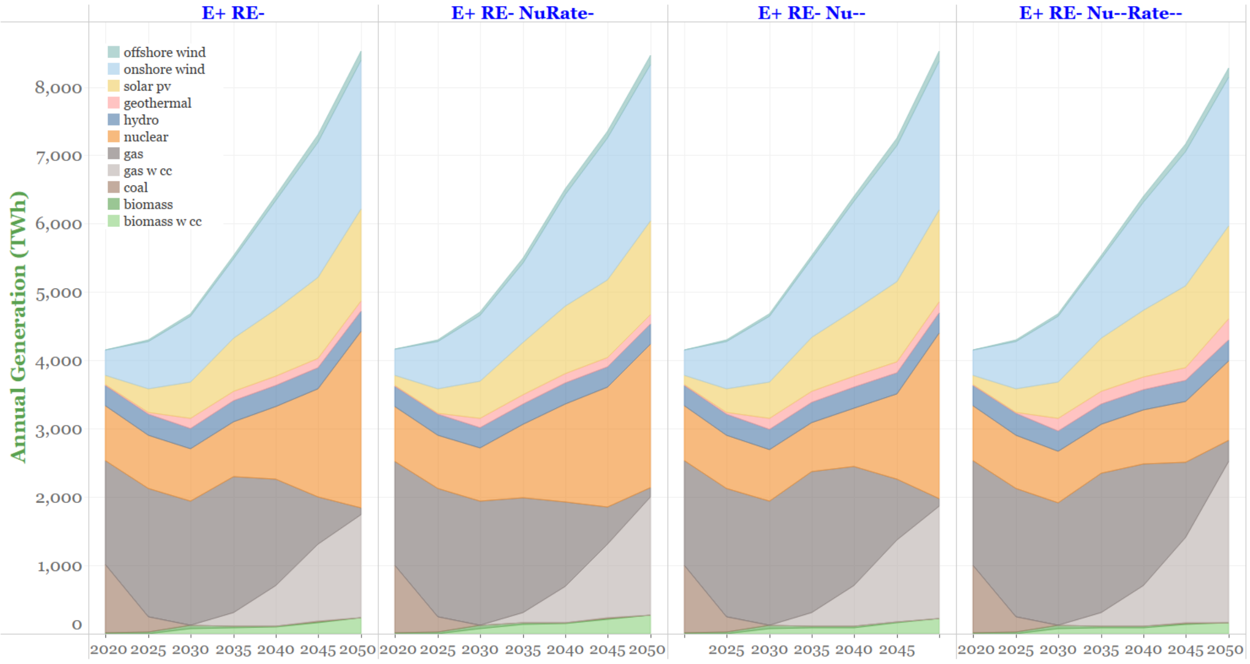
Dramatically reduced capital cost (e.g., for small modular reactors) significantly changes the generating mix in E+, but not E+RE-.

- In E+, nuclear capital costs of -20%/+50% (E+ Nu- / E+ Nu+) relative to the base value have little impact on the generation mix, but there is significant expansion if nuclear costs fall to $1800/kW by 2050 (E+ Nu--). If the rate at which nuclear capacity is allowed to be added is constrained to prospectively plausible levels (E+ Nu--Rate-), nuclear generation still grows, but not as rapidly. In cases when nuclear generation grows, it primarily displaces wind and solar generation.
- In E+RE-, nuclear grows similarly regardless of assumed capital cost, because nuclear additions are driven by the need for significant amounts of zero-carbon electricity other than from wind and solar. When annual growth of low-cost nuclear is constrained (E+RE- Nu—Rate--), gas-fired generation with and without carbon capture increases.





	E+	E+ Nu-	E+ Nu+	E+ Nu--	E+ Nu-- Rate-
CAPEX 2050, 2016$/KW	5,530	4,423	8,295	1,800	1,800
Build rate cap, GW/y	None	None	None	None	10, from 2030

See Annex B for full discussion of sensitivity results.

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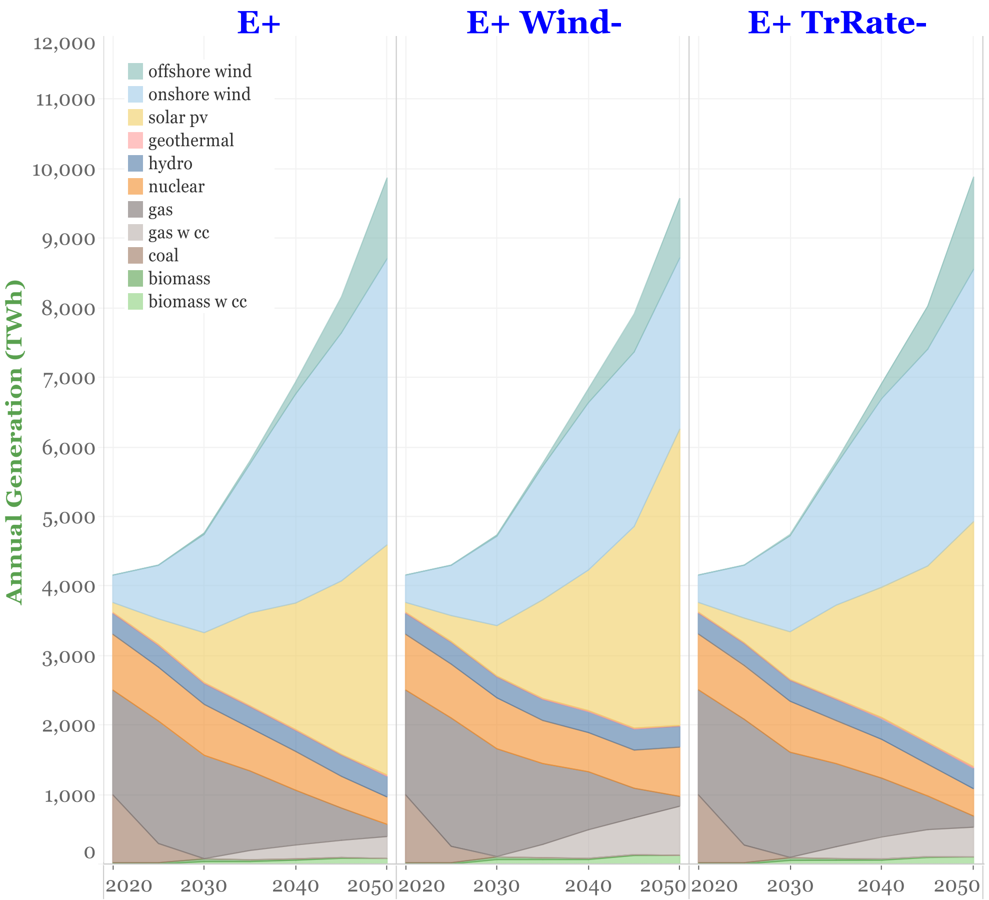
	E+RE-	E+RE- NuRate-	E+RE- Nu--	E+RE- Nu--Rate-
CAPEX 2050, 2016$/KW	5,530	5,530	1,800	1,800
Build rate cap, GW/y	None	10, from 2030	None	0.36 in 2025, 8 in 2050

Constrained wind or transmission growth in E+ case leads to more nuclear and/or gas w CC deployed by 2050

Siting or supply-chain constraints may slow the rate of plant and infrastructure deployment. We tested constraints on cumulative wind and transmission capacity in the E+ scenario:

- Limiting total wind capacity (E+ Wind-) results in more solar and gas w/CC and also spurs deployment of new nuclear capacity in the 2040s.
- Limiting inter-regional transmission capacity to a maximum of 2x current capacity (E+ TrRate-) leads to slightly more gas w/CC and less wind than in E+.



See Annex B for full discussion of sensitivity results.

Input assumptions that vary between cases

	E+	E+ Wind-	E+ TrRate-	E+ RE-	E+ RE- NuRate-
Wind total capacity limit (% of E+ capacity)	None	Onshore 50%; Offshore: 100% (except Mid-Atlantic: 70%)	None	None	None
Nuclear build-rate cap	None	10 GW/y	None	None	10 GW/y
Transmission cumulative build cap	10x current	10x current	2x current	10x current	10x current

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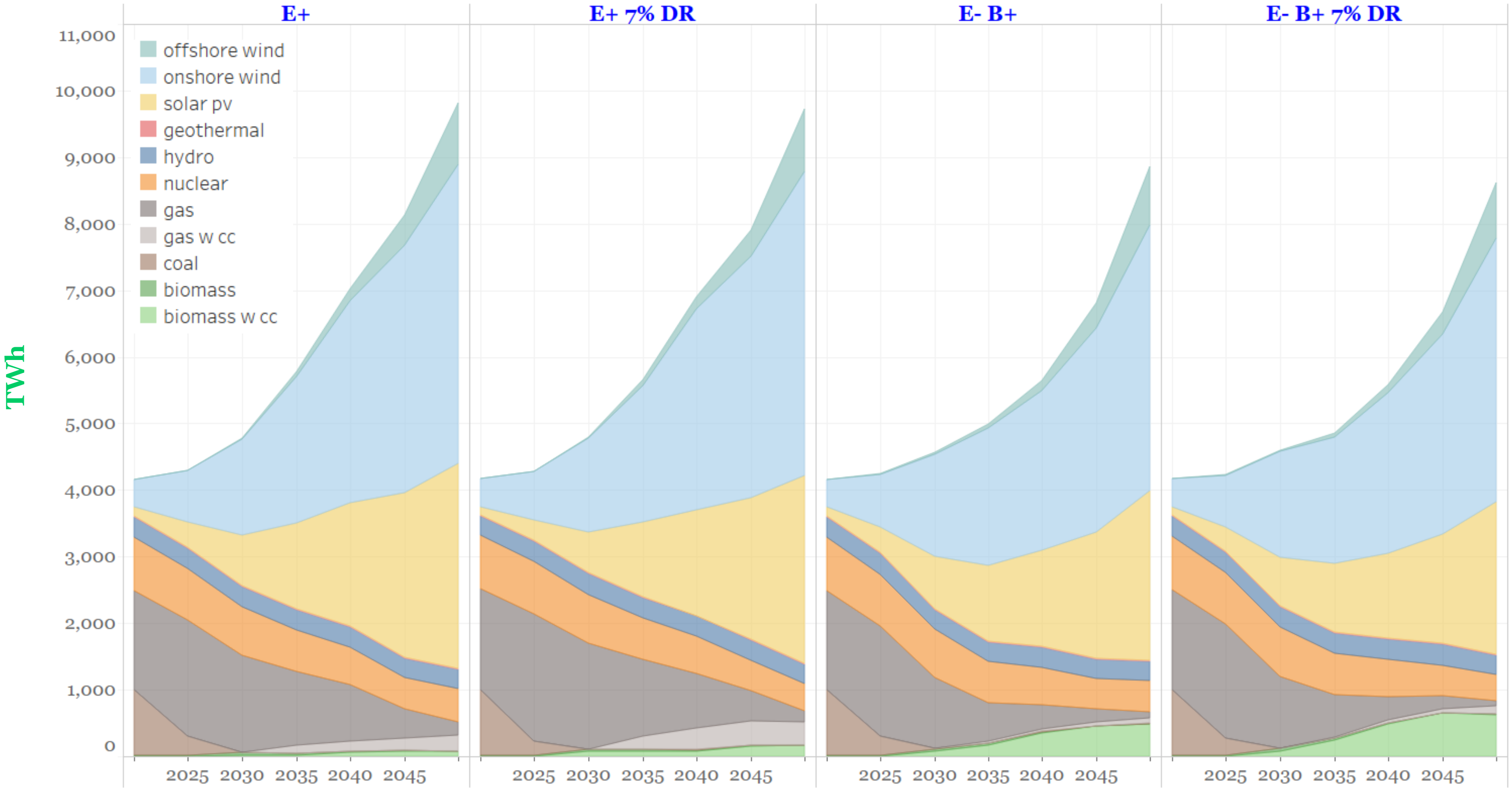
Higher discount rate dramatically reduces the NPV of total energy-system costs, but has no substantial impact on the generating mix

Use of 7% social discount rate instead of 2% results in:

- Only a small increase in deployment of capital-intensive generators (NGCC w/CC or biopower w/CC) late in the modeling period.
- NPV of total energy-supply system cost (2020 – 2050) being reduced by roughly half due to higher discounting of future costs.



See Annex B for additional discussion of sensitivity results.

Input assumptions that vary between cases				
	E+	E+ 7%	E- B+	E- B+ 7%
Social discount rate	2%/y	7%/y	2%/y	7%/y

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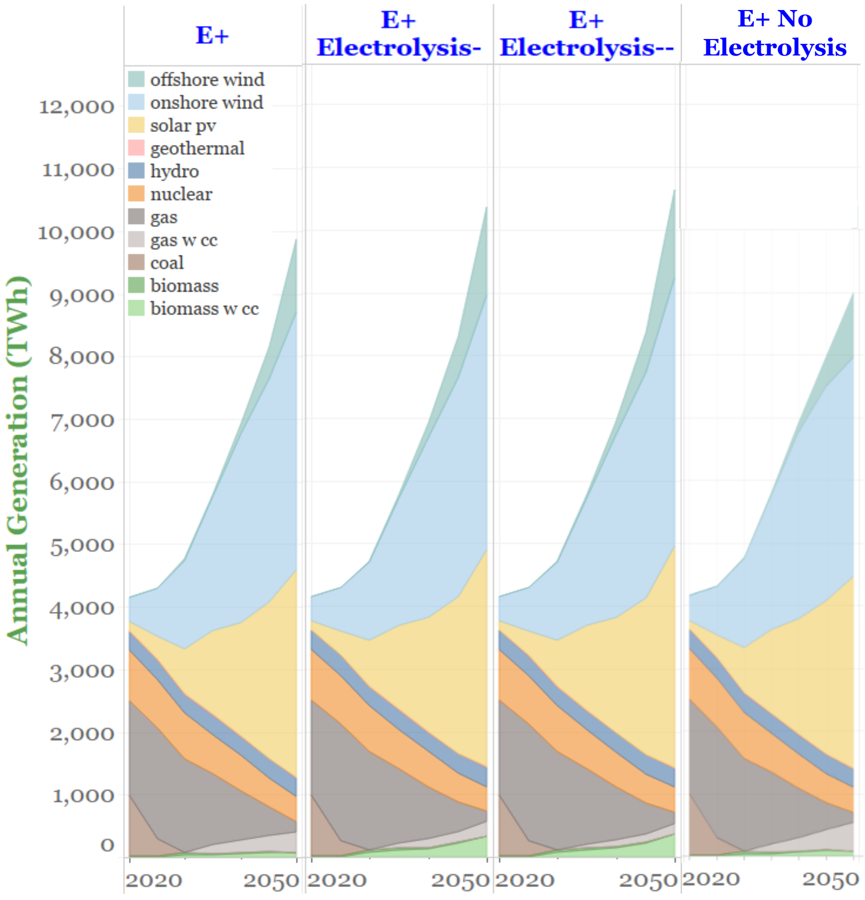
Electrolysis supports wind and solar generation, but the amount generated varies only modestly for a 6x spread in electrolysis cost.

- In the E+ scenario, as the assumed cost for electrolysis is reduced, incrementally more wind and solar electricity are generated. There is also additional generation from biomass with carbon capture (CC) and reduced generation from gas with CC.
- If electrolysis is disallowed completely (simulating very high cost), solar and wind generation in 2050 is substantially lower and generation from gas with CC increases slightly. Total electricity generation in 2050 is about 10% lower than in E+.

See Annex B for additional discussion of sensitivity results.



Input assumptions that vary between cases

	E+	E+ No Electrolysis	E+ Electrolysis-	E+ Electrolysis--
Electrolysis technology capital cost, $\$/kW_{H2,HHV}$	572	Prohibitively high cost	220	96

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Evolution of solar and wind generating capacity

Summary of this section

- Wind and utility-scale solar PV capacity additions accelerate, setting new record deployment rates year after year. The only exception is E+RE- where annual capacity additions are limited by the scenario design to about 1.4x the maximum capacity installed previously in the U.S. in a single year (25 GW in 2020).
  - For distributed (rooftop) PV, we exogenously specify 33 GW of capacity installed in 2020 growing to 185 GW in 2050, as projected by AEO2019. (RIO would not endogenously choose to install any rooftop PV capacity because its costs are higher than for utility-scale PV.)
- The deployment rate for utility-scale PV and wind during 2021-2025 (~40 GW/year average) exceeds the U.S. single-year record rate to date, and deployment rates nearly double to 70-75 GW/year average from 2026-2030.
  - A total of ~250-280 GW of new wind (~2x current capacity) and ~285-300 GW of new utility-scale solar (~4x current capacity) are installed from 2021-2030 in E+, E- and E-B+ pathways.
  - E+ RE+ deploys 290 GW of wind and 360 GW of solar; E+RE- installs 150 GW of wind and 185 GW of solar from 2021-2030.
- Later in the transition period, most cases are deploying more wind and solar annually than the world record for a single nation (set by China in 2020).
- The E+RE+ pathway reaches annual deployment rates in the late 2040s exceeding the total global wind and solar capacity added in 2020 (238 GW/year).

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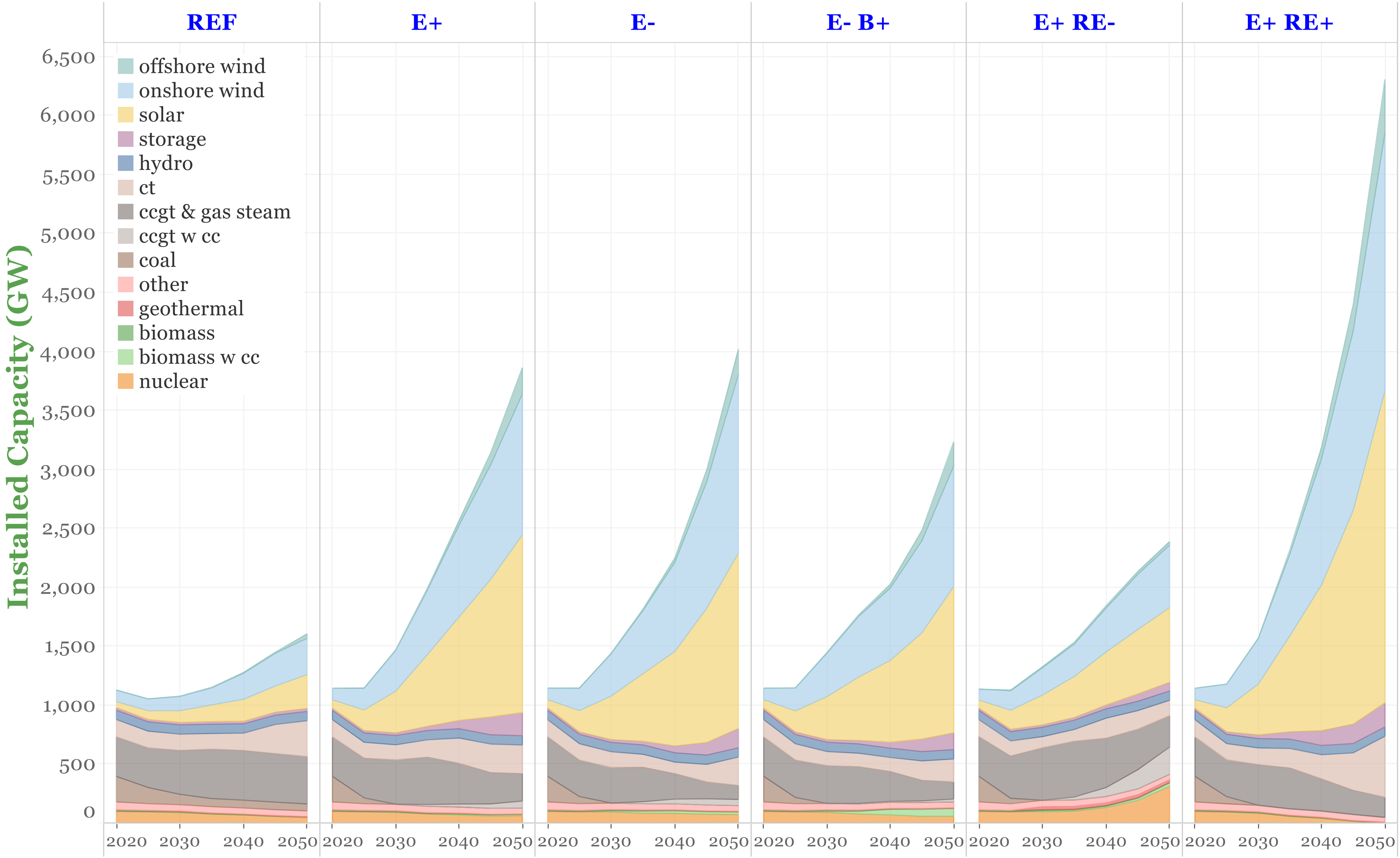
By 2050 installed solar capacity is 9 to 39 times larger than today, and installed wind capacity is 6 to 28 times larger.



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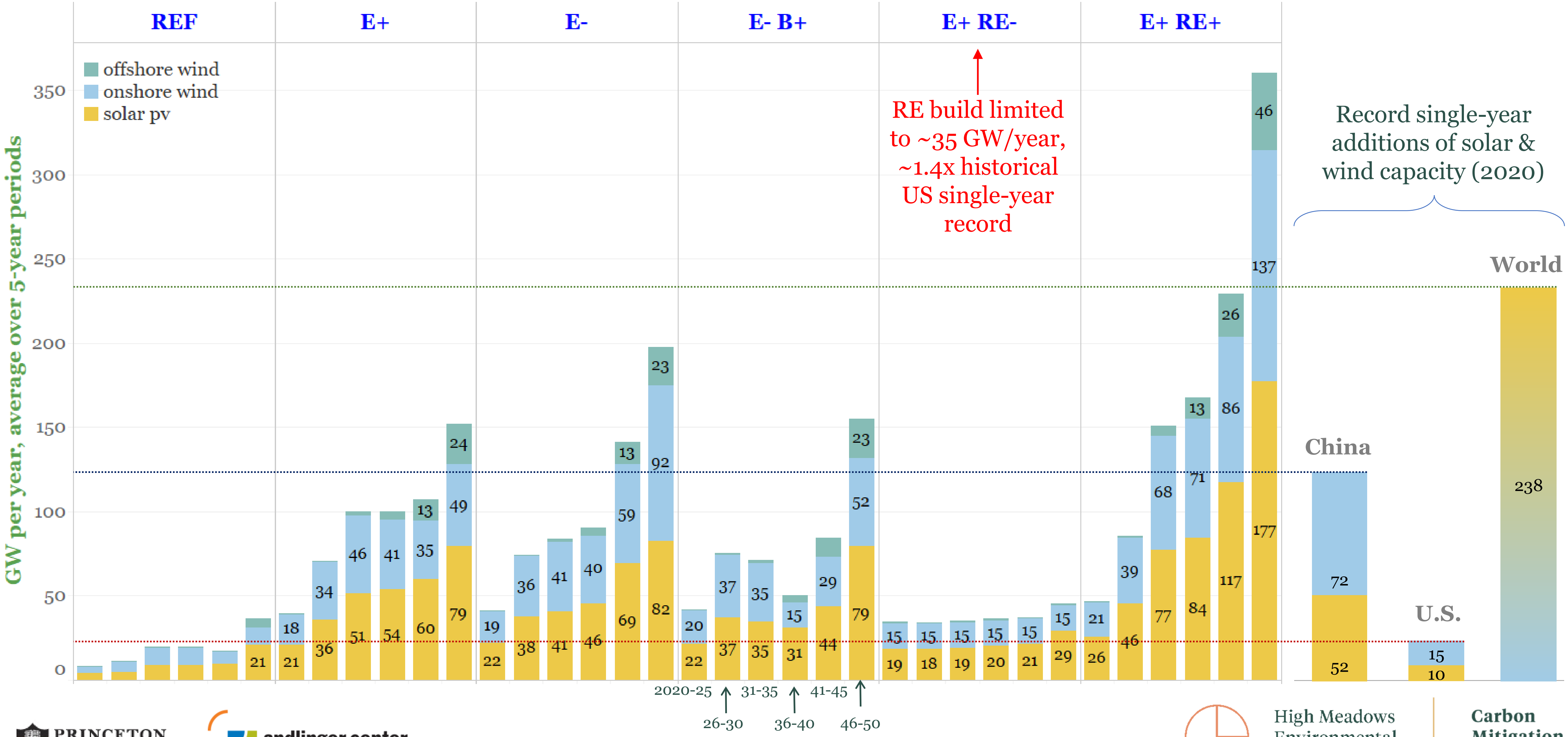
Annual wind and solar capacity additions are sustained over multiple decades at historically-unprecedented rates



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Downscaling methodology for solar and wind and transmission siting in net-zero pathways

Summary of this section

- Wind and solar capacity is deployed extensively across the United States in all cases. Finding sites suitable to develop projects presents a potential bottleneck to wind and solar deployment.
- To assess availability of lands for wind and solar development, we conduct a high resolution (4km x 4km) evaluation of the entire continental U.S. (and offshore wind development areas) using ~50 total geospatial screens to exclude areas with potentially conflicting land uses, including high population density areas, protected lands (e.g. parks, wilderness), the most productive farm lands, or areas with high environmental conservation value, as well as areas unsuitable for construction (e.g. wetlands, mountain slopes).
- To visualize the extent of wind and solar deployment and supporting transmission expansion over time, we downscale RIO's coarse-resolution model results (14-regions for continental U.S.). "Candidate project areas" (CPA) that pass all land use screens are selected in order of least delivered electricity cost (including approximated transmission costs) from solar or wind farms at those CPAs to demand centers until sufficient capacity has been selected to meet the regional level of solar and wind generation modeled by RIO.
- We also visualize a notional expansion of the transmission capacity required to connect wind and solar projects sites to demand centers (e.g. major metropolitan areas).
- These downscaling results, driven by least-cost objectives, are only one of many possible siting configurations for generation projects and transmission lines. Configurations whose siting is driven by other objectives, e.g., minimizing land-use conflicts and/or maximizing local benefits, would be different from these results.
- Annexes D and F provide additional details of methodology and results.

Candidate solar and onshore wind project sites mapped for "base" and "constrained" land availability.

Methodology similar to Wu, *et al.*, *Power of Place: Land Conservation and Clean Energy Pathways for California*, The Nature Conservancy, 2019.

* Exclusion categories that distinguish Base from Constrained land availability are shown in red.

Constrained scenarios are designed to limit development on intact landscapes. Theobald's HMI is used to quantify intactness. HMI is derived from analysis of North America at 0.09 km^2 resolution, with each cell assigned a value from 0 to 1 based on multiple metrics. HMI values < 0.082 identify highly intact landscapes.

Constrained scenarios also restrict onshore wind development on prime farmlands (this is permitted in Base).

	Solar	Onshore Wind
NREL capacity factor map resolution, km	**10**	**2**
Average power density (MW/km^2)	**45**	**2.7**
Land areas excluded from siting of wind / solar projects		
Slope	**> 17%**	**> 34%**
Intactness: Theobald Human Modification index*	**HMI < 0.082 for CONSTRAINED only**	
Population density	> 100 people/km^2 excluded; density of solar/wind projects in other areas is restricted in inverse proportion to population density	
Urban areas + buffer, km	**0.5**	**1**
Water bodies + buffer, km	**0.25**	**0.25**
Military installations + buffer, km	**1**	**3**
Active mines + buffer, km	**1**	**1**
Airports and runways + buffer, km	**1**	**3**
Railways + buffer, km	**0.25**	**0.25**
Prime soils (prime farmland)	**Not allowed**	**Allowed in BASE. Not allowed in CONSTRAINED**
FEMA 1% annual flood hazard areas	**Not allowed**	
Areas of critical environmental concern	**Not allowed**	
National forests (except for wind on ridgecrests), parks, wilderness, recreation, and other federal protected areas	**Not allowed**	
State parks, forests, wilderness & other protected areas	**Not allowed**	
Wetlands and watershed protected areas	**Not allowed**	
Private conservation & forest stewardship areas	**Not allowed, except for wind on ridge crests**	
Native American areas	**Not allowed**	
BLM *High* and *Moderate* sensitivity areas	**Not allowed**	

~50 total environmental, cultural, and economic exclusions. See full list here

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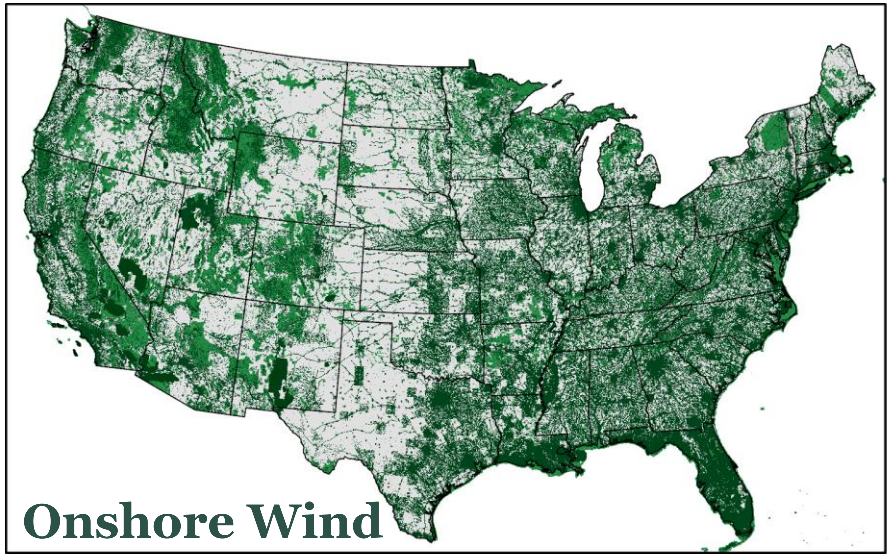
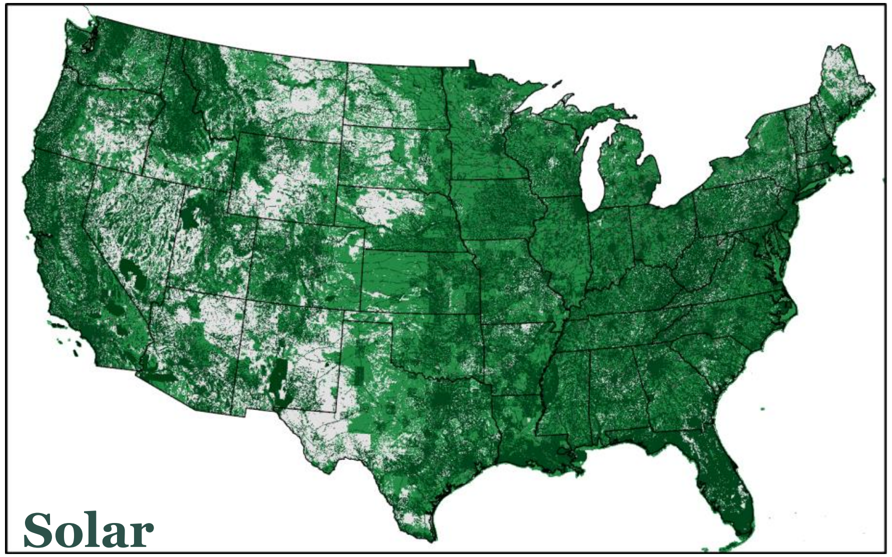
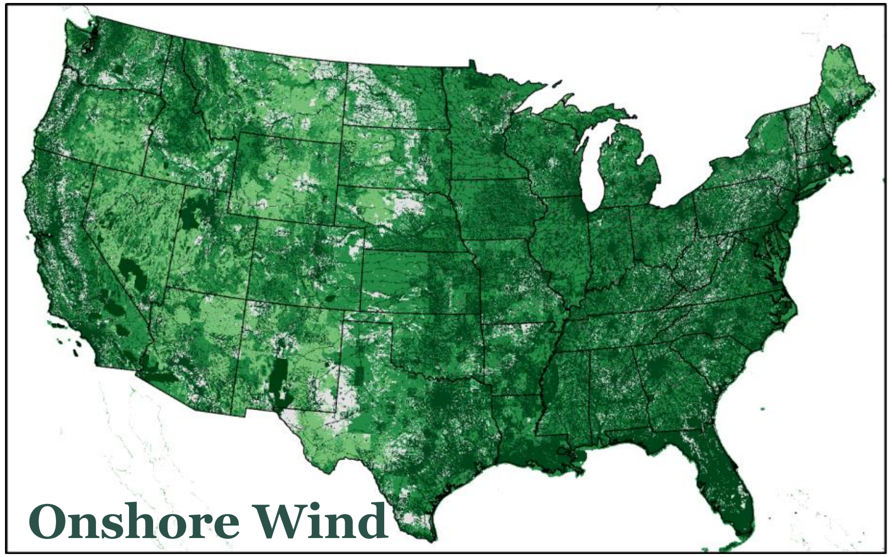
Other land use priorities limit where solar and wind projects can be sited and built.

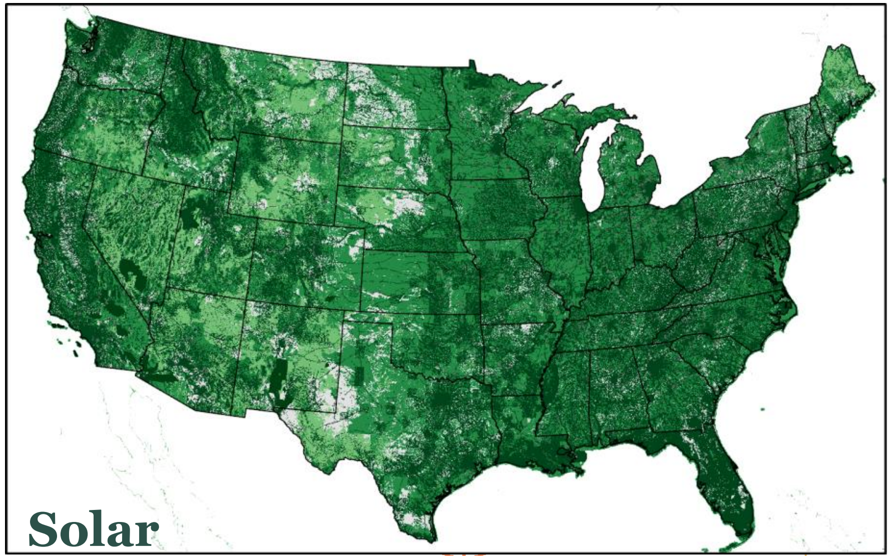
Base siting options





Constrained siting options





Shaded regions are excluded from development.

Unshaded regions are suitable for siting projects (candidate project areas)

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Offshore wind exclusion areas and capacity siting process

Exclusion areas

- Shipping lanes
- Marine protected areas
- Gap status 1 for West, Gulf, and East coasts; Gap status 2 for West and Gulf coasts only (gap status relates to level of sensitivity/administrative protection)
- Military installations + 3 km buffer
- Military danger zones + 3 km buffer
- Outside BOEM-designated zones, candidate area further reduced by 40% (at random) to account for uncertainty about additional exclusions not explicitly geo-specified
- Areas closer than 30 km to shore or greater than 100 km from shore (similar to current BOEM lease zones)

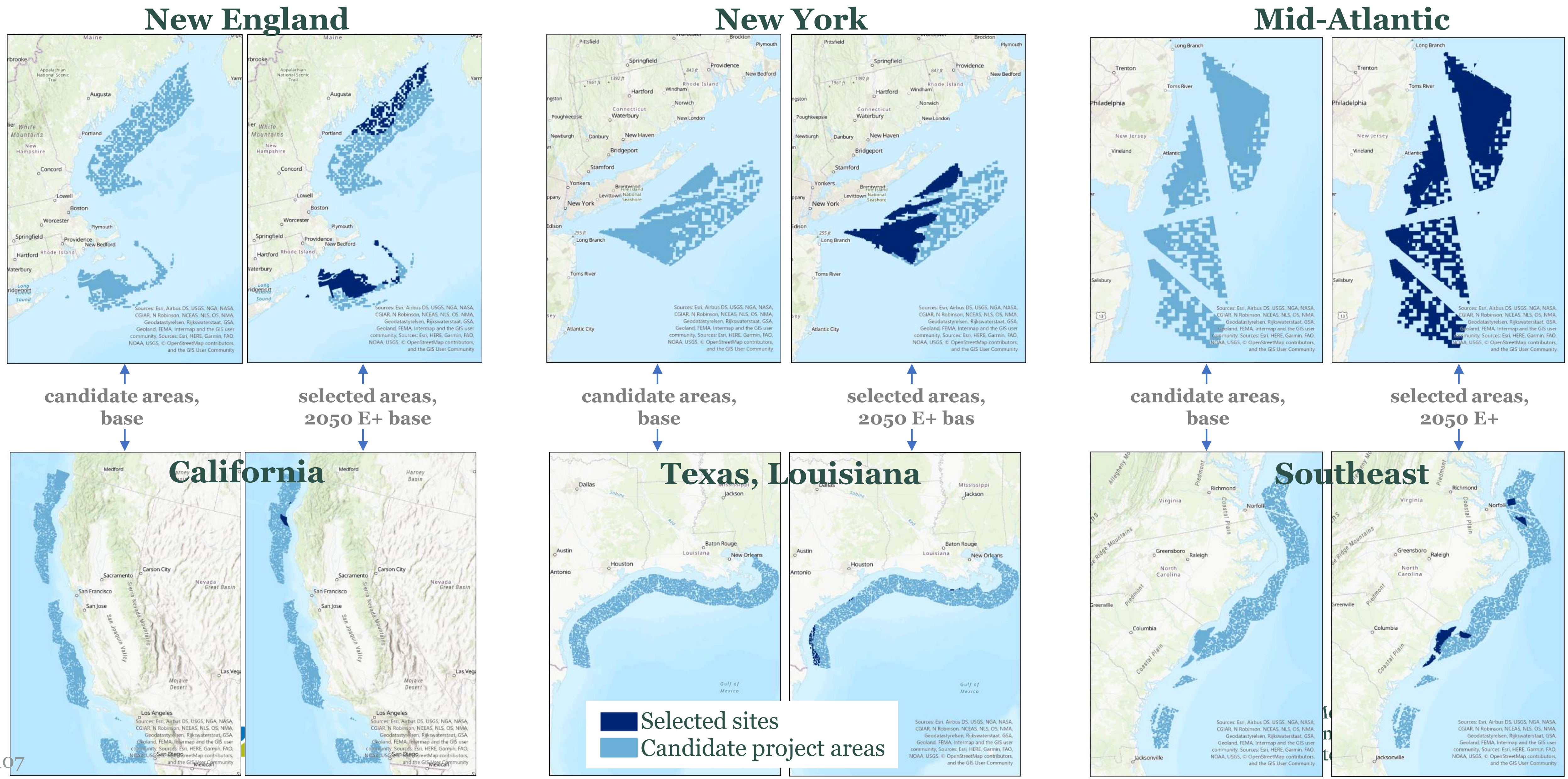
Wind farm technical characteristics

- Power density: West coast, 8 MW/km^2 (floating turbines, seafloor depth > 50 m); East & Gulf coasts: 5 MW/km^2 (fixed turbines, most areas have depth < 50m).
- Capacity factors at 13-km spatial resolution from Vibrant Clean Energy

Sites selected for farms by lowest approximate LCOE until total supply fulfilled

- Turbine capex (avg for 2021-2050 used for ordinal ranking): $3,105/kW (sea depth < 50m); $4,519/kW (> 50 m) (NREL, ATB2019 mid)
- Sub-sea transmission: $20,500/MW-km (< 50m); $28,300/MW-km (> 50m) (ATB2019 mid)

Offshore-wind candidate project areas and selected sites for E+, with base siting constraints



Mapping of solar and wind generators and transmission for the E+ pathway with base site availability

Summary of this section

- In E+, over 300 GW of utility-scale solar, 400 GW of onshore wind, and 5 GW of offshore wind capacity are installed across the U.S. by 2030; by 2050, these grow to 1.5 TW, 1.5 TW, and 200 GW, respectively;
- Following a least-cost siting method subject to the Base land availability screen (see Annex D):
  - The top 10 states for wind capacity by 2050 are: Texas, Missouri, Iowa, Illinois, Nebraska, Minnesota, New Mexico, Montana, Oklahoma, and Arkansas
  - The top 10 states for solar capacity by 2050 are: California, Texas, Florida, Georgia, Pennsylvania, South Carolina, Virginia, Alabama, Missouri, Nebraska
  - Over $800 billion is invested in wind and solar capacity through 2030 and $3.5 trillion by 2050.
- Onshore wind and solar farms span a total area of nearly 600,000 km^2; wind farms account for ~94% of this, with extensive visual impact.
- Lands directly impacted by wind and solar farms (e.g., under roads, turbine pads, solar arrays, inverters, and substations) are only a fraction of the total site area: about 40,000 km^2 (an area roughly twice the size of New Jersey), with solar farms accounting for about 85% of this.
- High voltage transmission capacity expands ~60% by 2030 and triples by 2050 to connect wind and solar facilities to demand (see Annex F); total capital invested in transmission is $330 billion through 2030 and $2.2 trillion by 2050.

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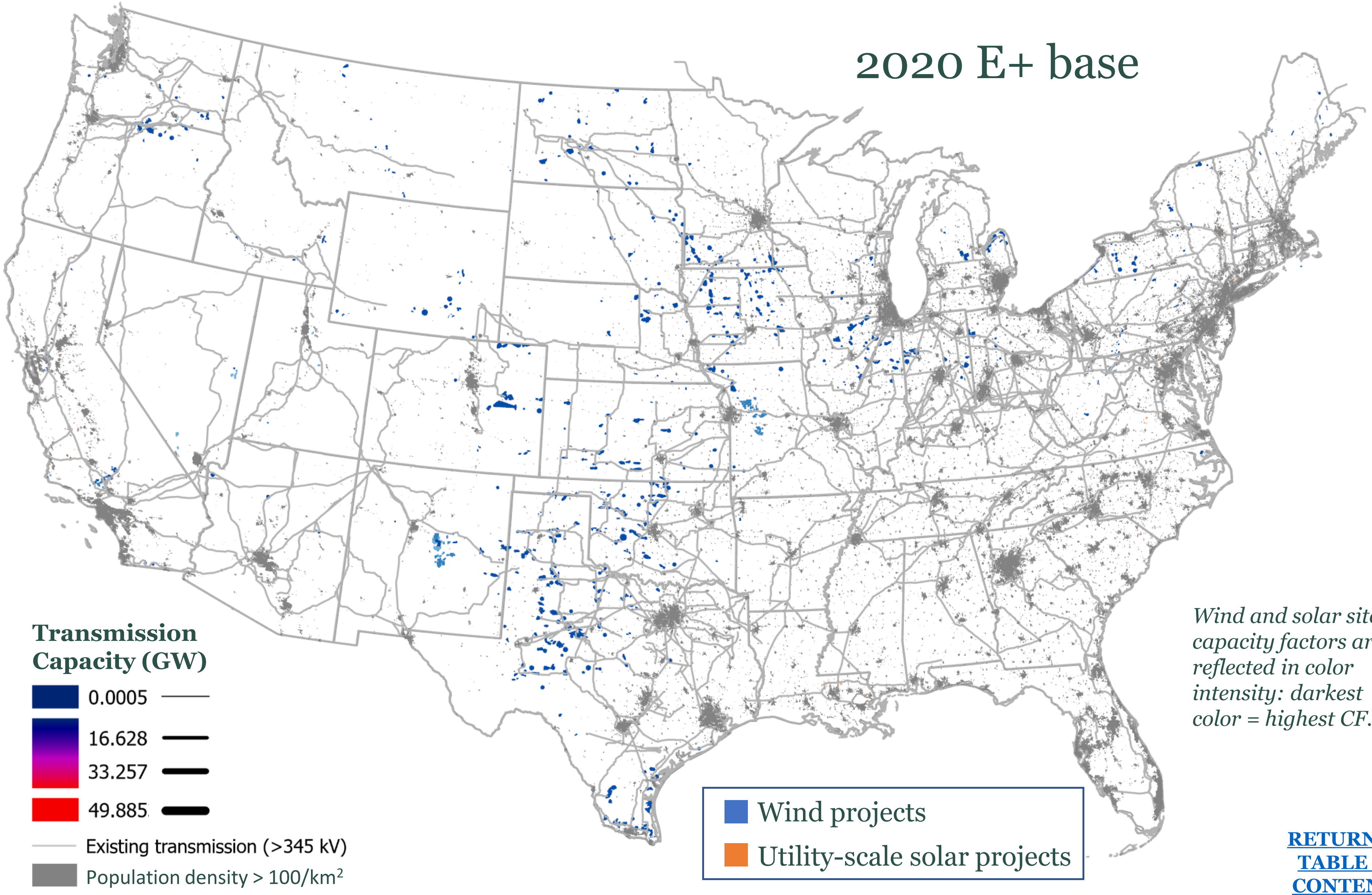
Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	Solar
Cumulative capacity (TW)		
	0.13	0.07
Land used (1000 km²)		
Total	57.9	1.08
Direct	0.58	0.98
Cumulative capital (B$$_{2018}$)*		
Solar	-	48
Onshore wind	55	-
Offshore wind	0	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

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

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, [Renewable Electricity Futures Study, 2012](#).



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

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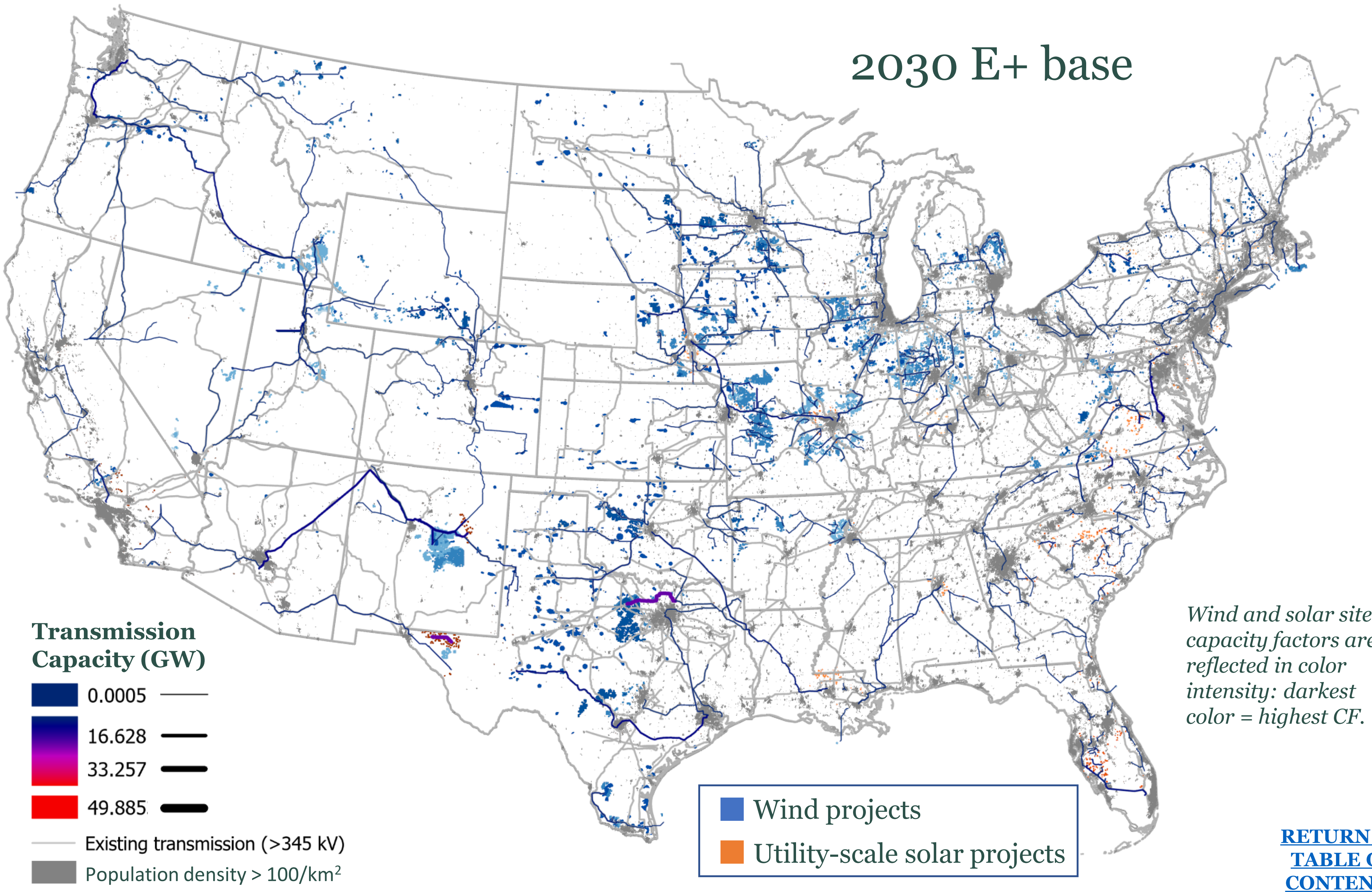
739 GW of wind and solar capacity operating in 2030; transmission capacity grows by 62%.

2030		
	Wind	Solar
Capacity installed (TW)		
	0.41	0.32
Land used (1000 km²)		
Total	157	7.75
Direct	1.57	7.06
Capital invested (Billion $\$_{2018}$)*		
Solar	-	353
Onshore wind	427	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		200,000
Increase over 2020		62%
Capital in serv (B$\$_{2018}$)		330

* 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.)



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

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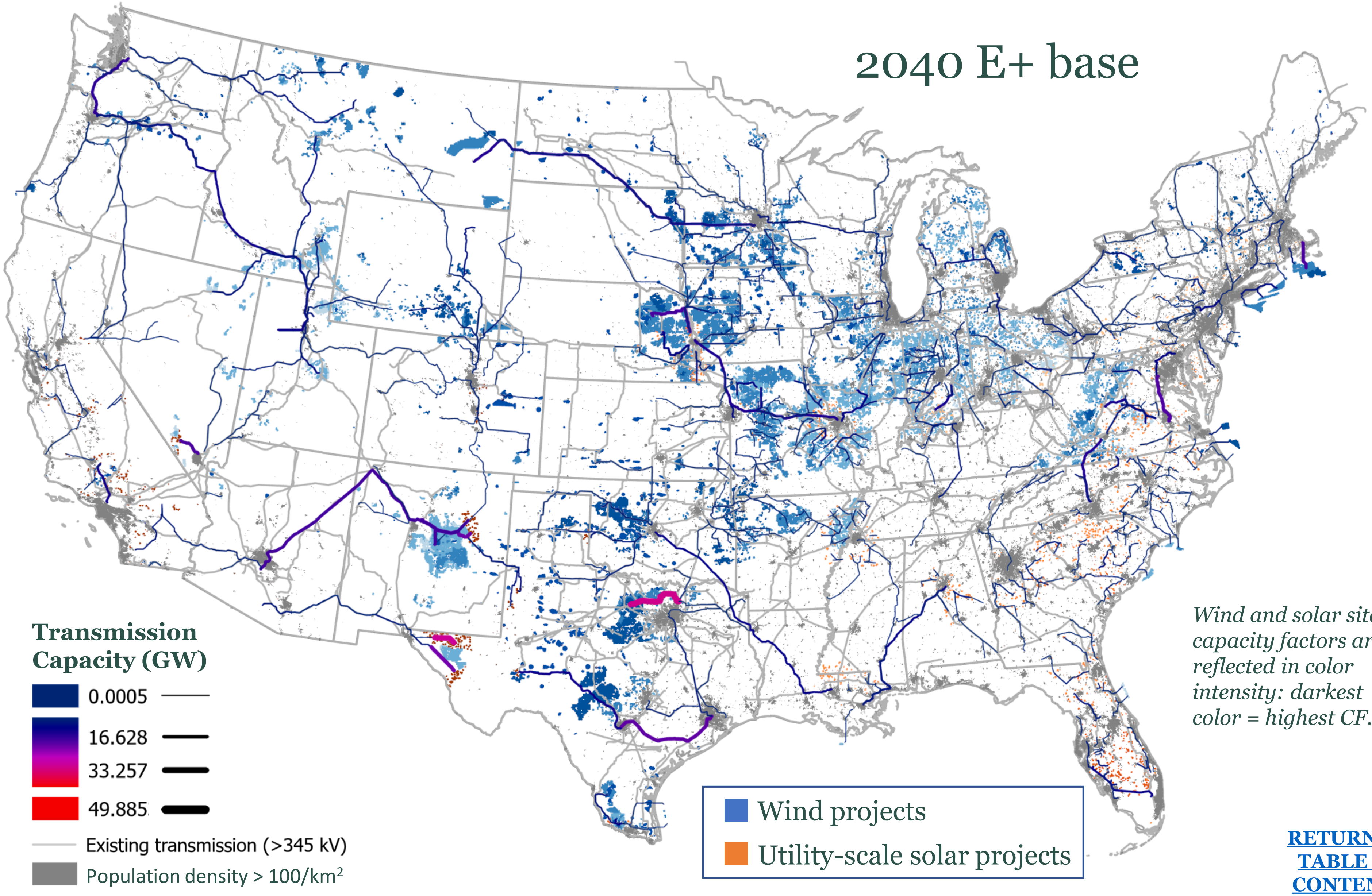
1.8 TW of wind and solar capacity operating in 2040; transmission capacity grows to 1.5x the 2020 level.

2040		
	Wind	Solar
Capacity installed (TW)		
	0.99	0.85
Land used (1000 km²)		
Total	355	21.5
Direct	3.55	19.6
Capital invested (Billion $$_{2018}$)*		
Solar	-	898
Onshore wind	1,053	-
Offshore wind	94	-
Transmission added vs. 2020**		
Capacity (GW-km)		480,000
Increase over 2020		150%
Capital in serv (B$$_{2018}$)		1,020

* 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.)



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

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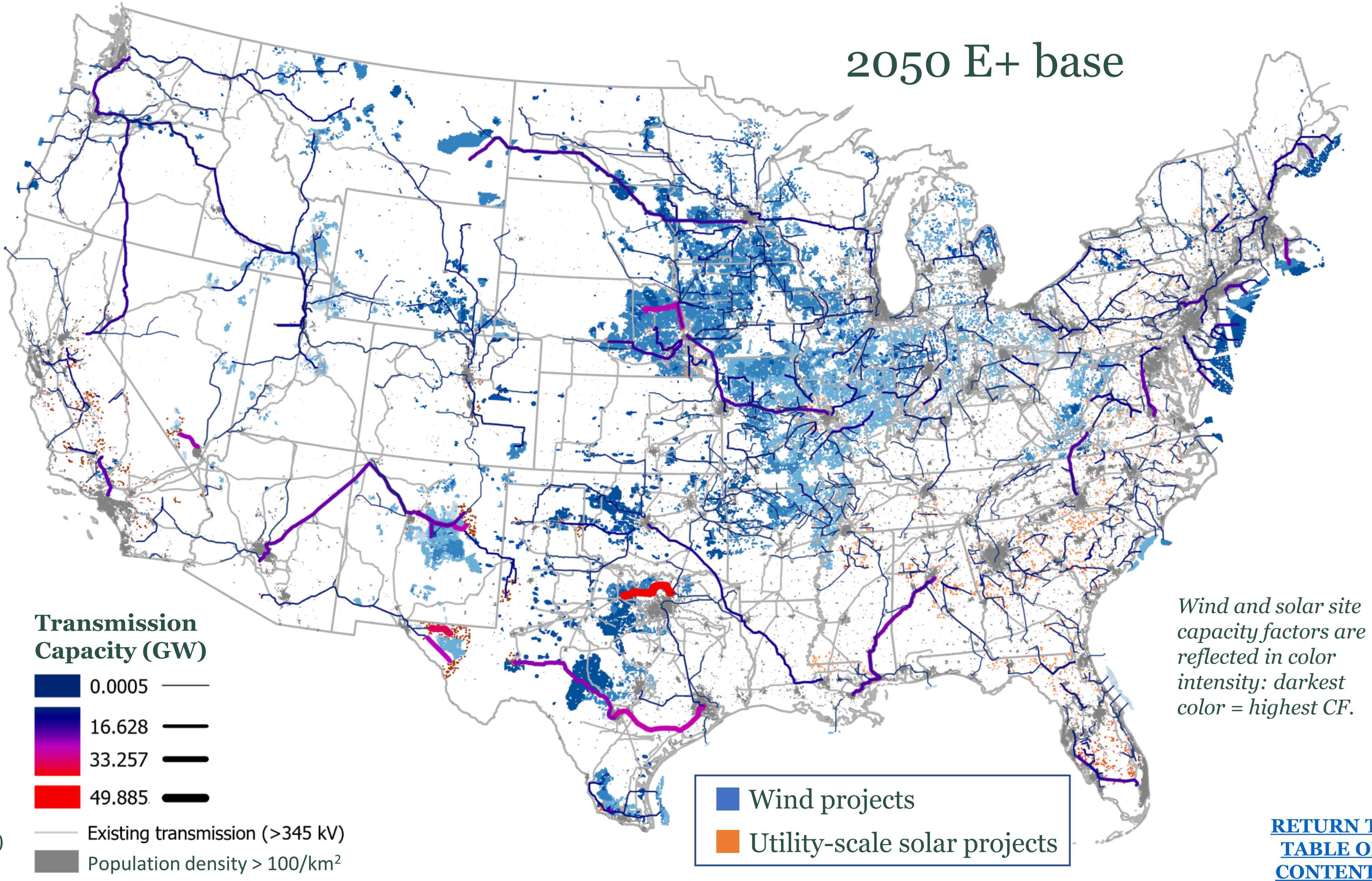
3.2 TW of wind and solar capacity operating in 2050; transmission capacity grows to 3.1x the 2020 level.

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.)



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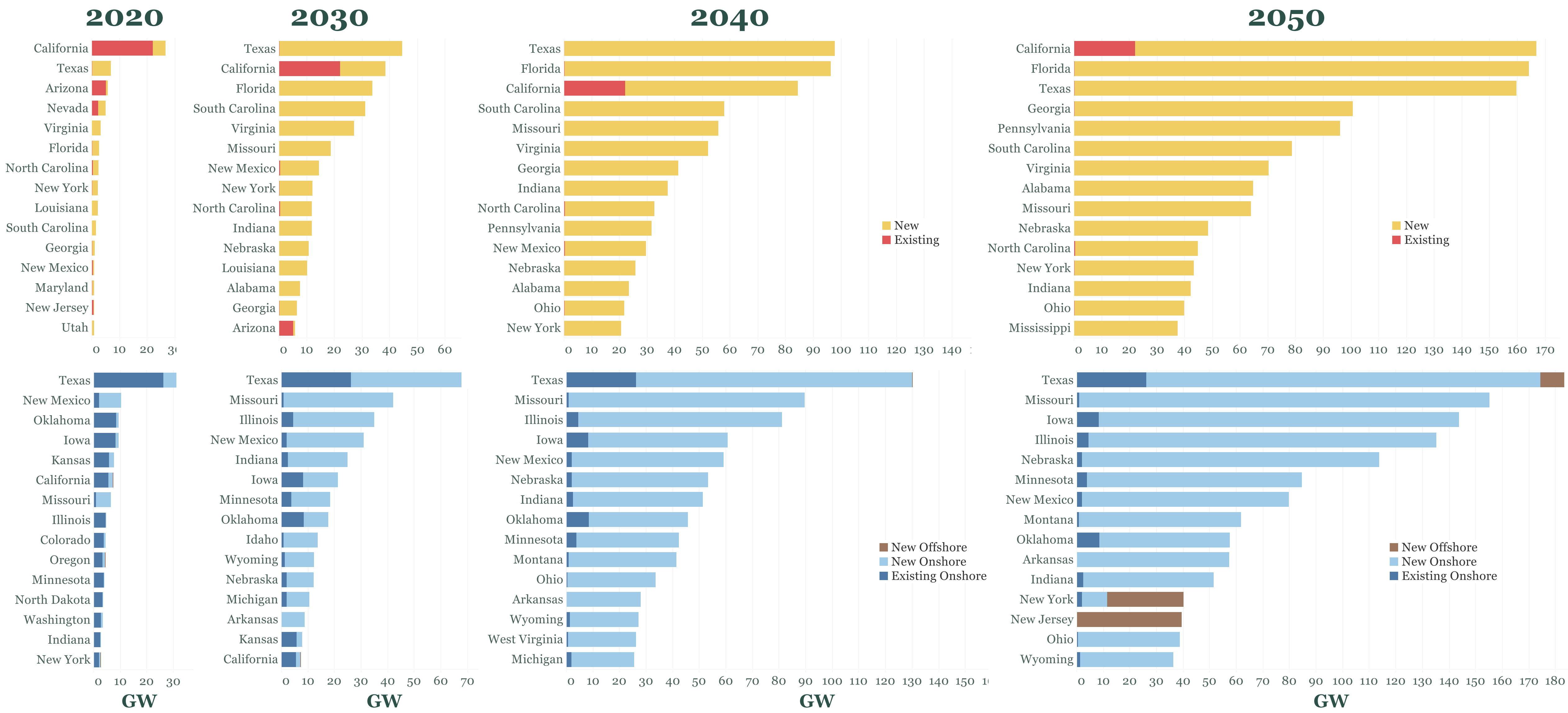
Top 15 states for installed wind and utility-scale solar capacity each decade, E+ (base siting)



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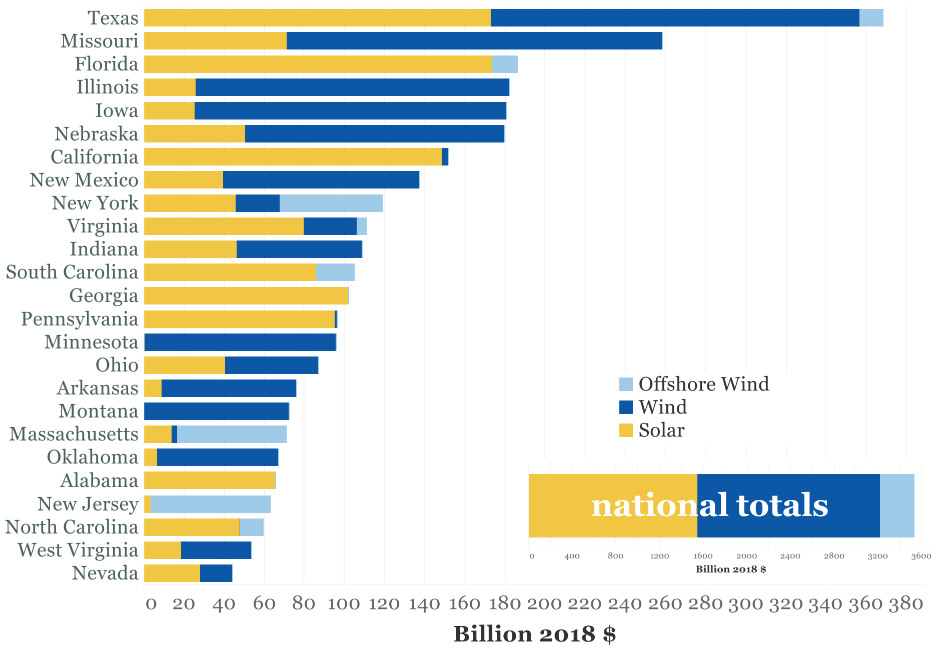
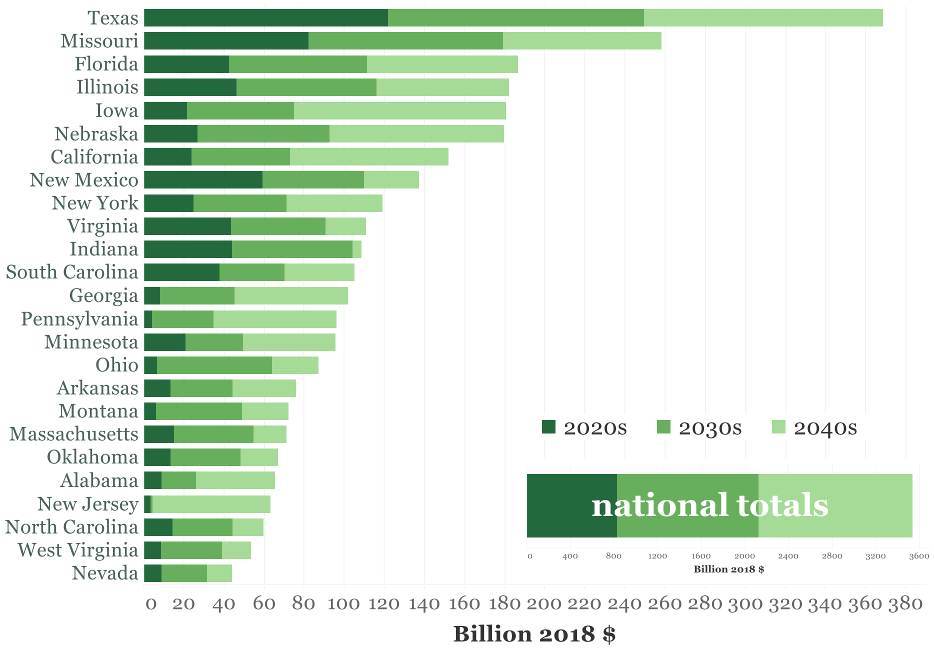
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+ (base siting)

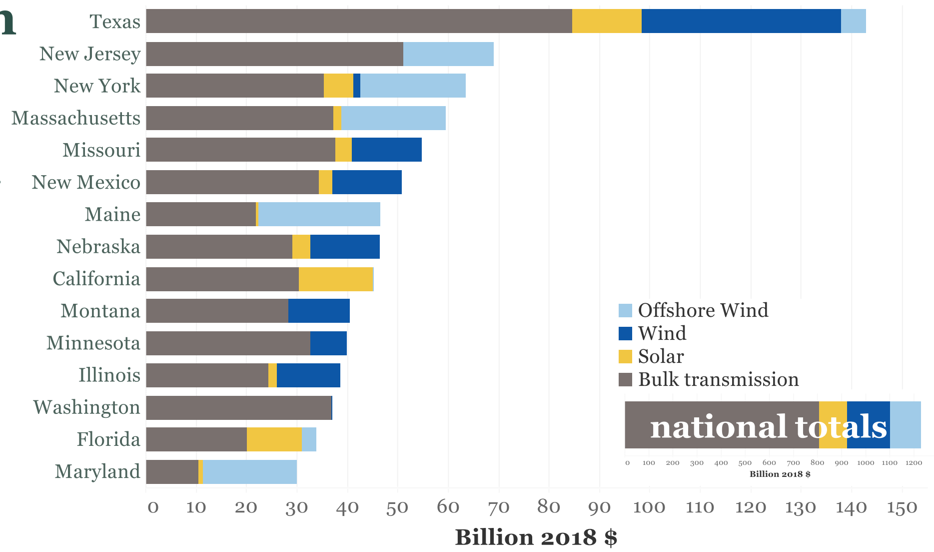
Wind & solar capacity investments, top 25 states

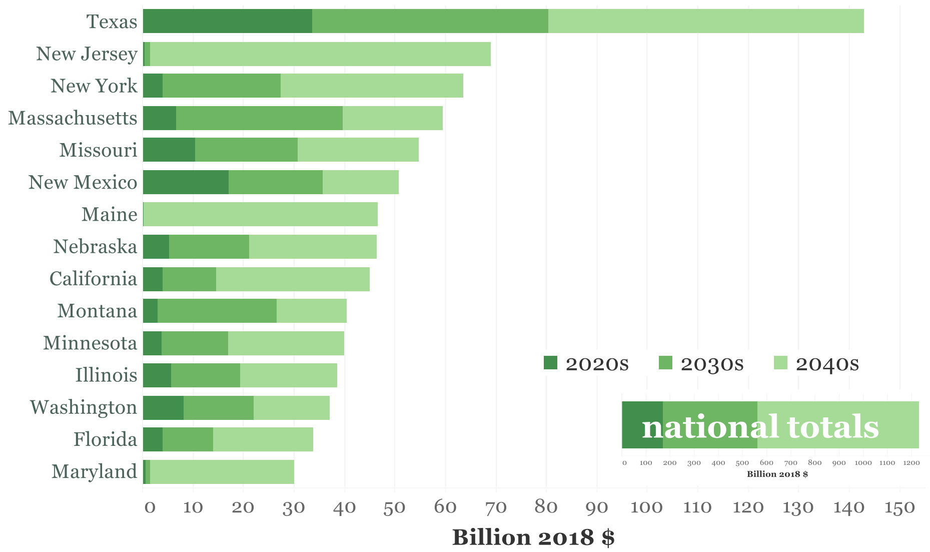




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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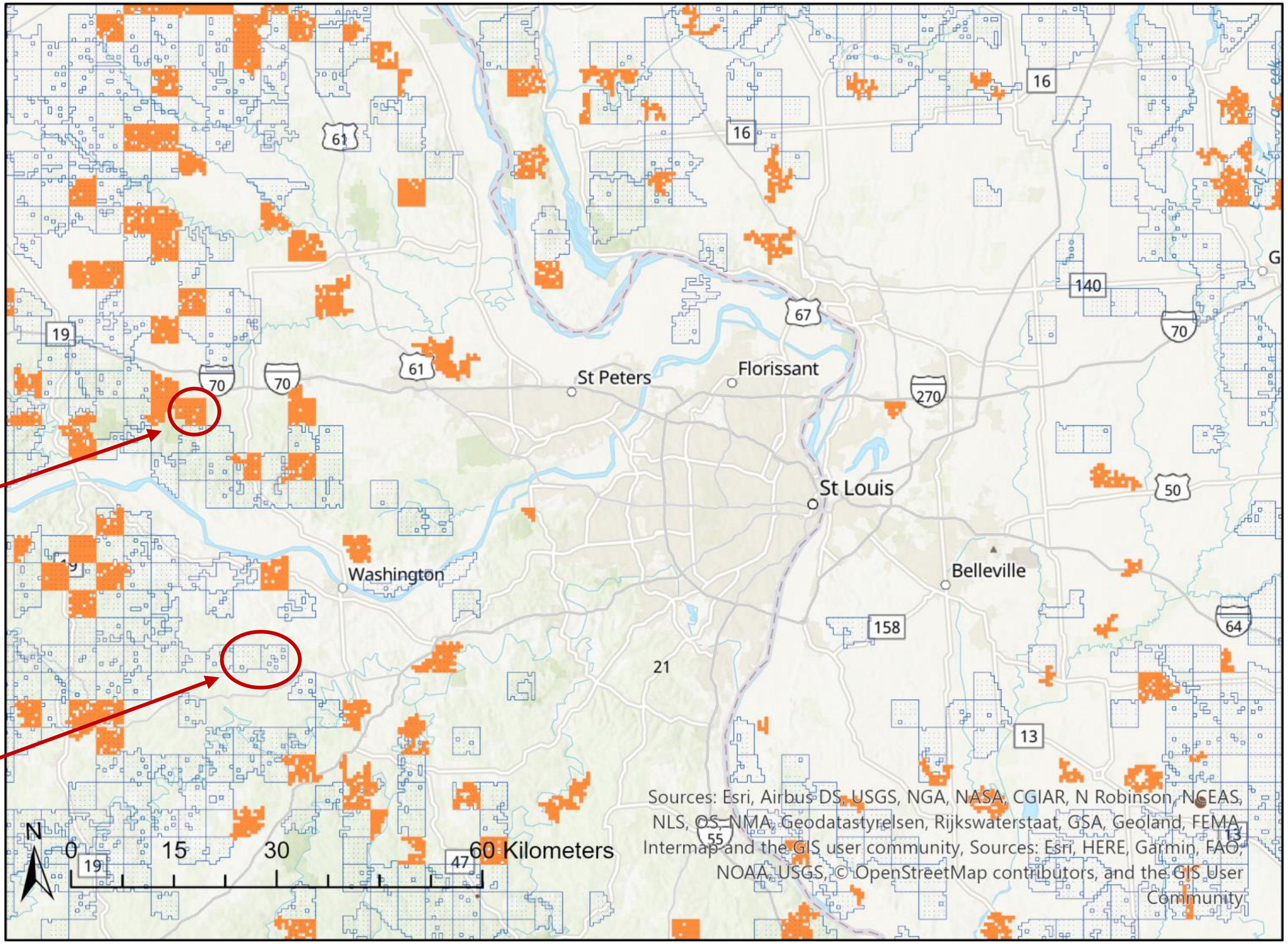
Example area detail: St. Louis, MO
2050 wind and solar farms (E+ base siting)

- 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)

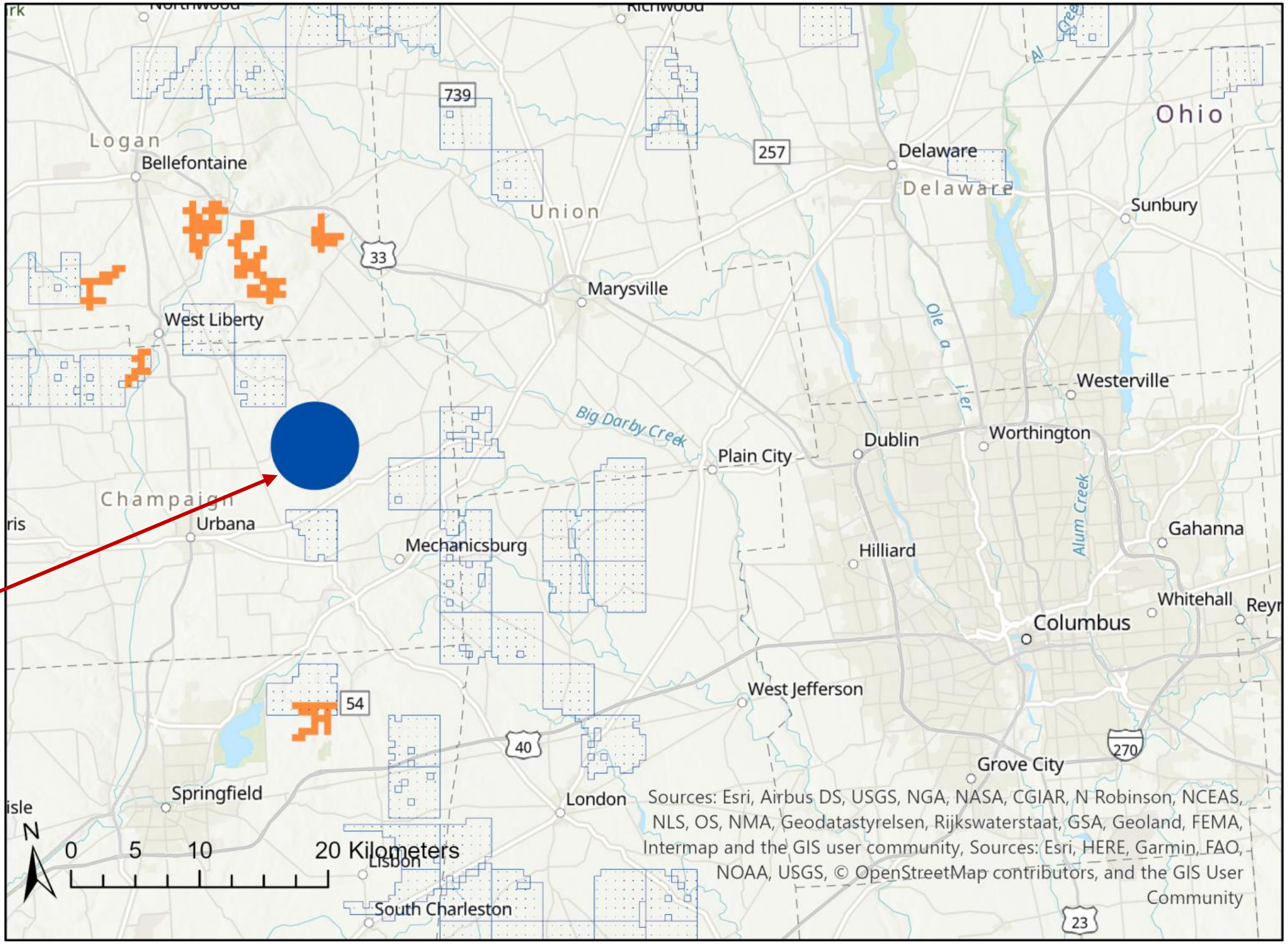
80 MW wind facility (generic future facility)



Example area detail: Columbus, OH
2050 wind and solar farms (E+ base siting)

- 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)

Buckeye Wind
99 MW proposed facility
Scheduled online date = 2021
Population density = 14 people / km²



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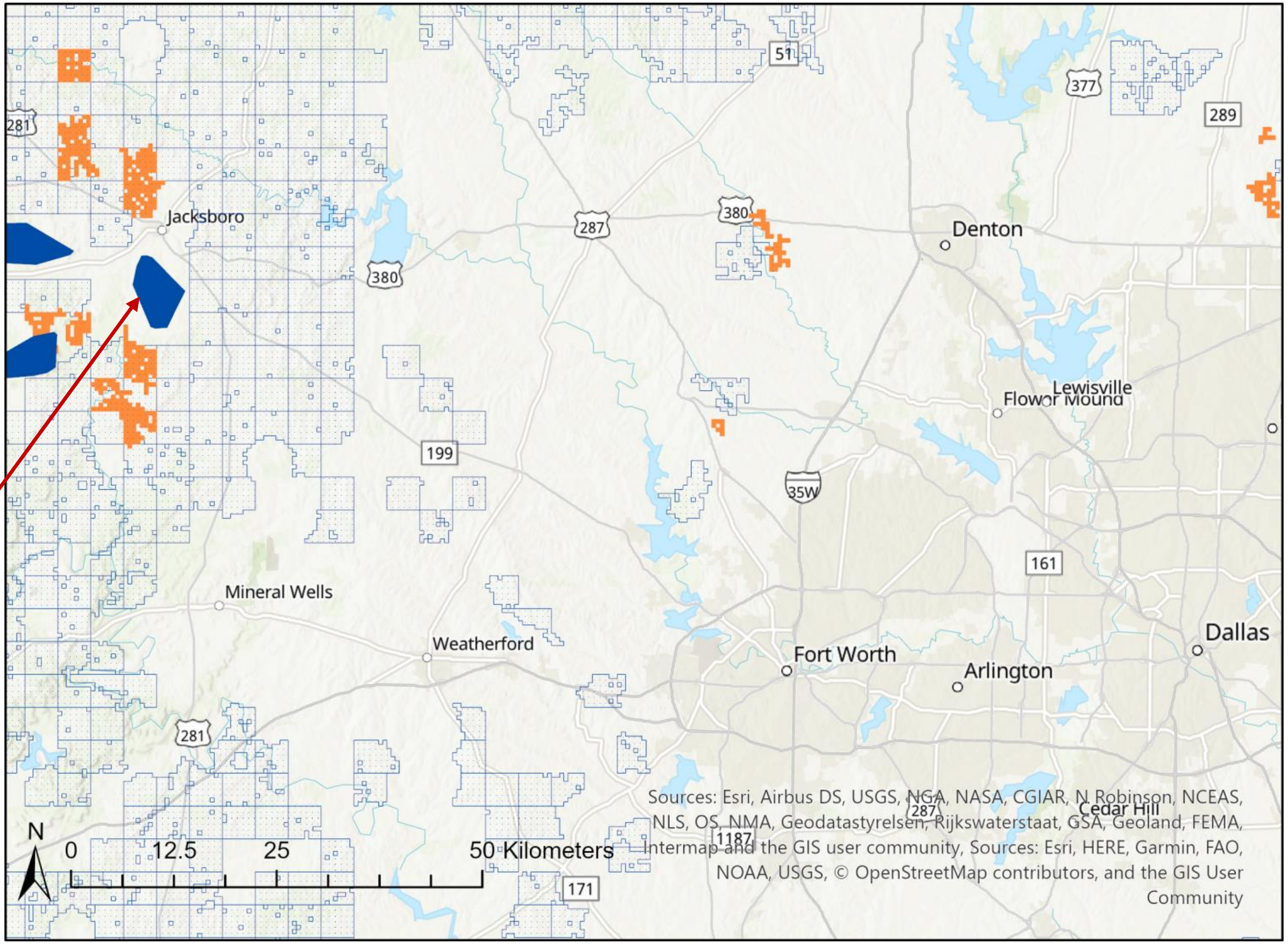
Example area detail: Dallas – Fort Worth, TX 2050 wind and solar farms (E+ base siting)

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)

Keechi Wind
110 MW existing facility
Online date = 2015
Population density = 0 people / km²

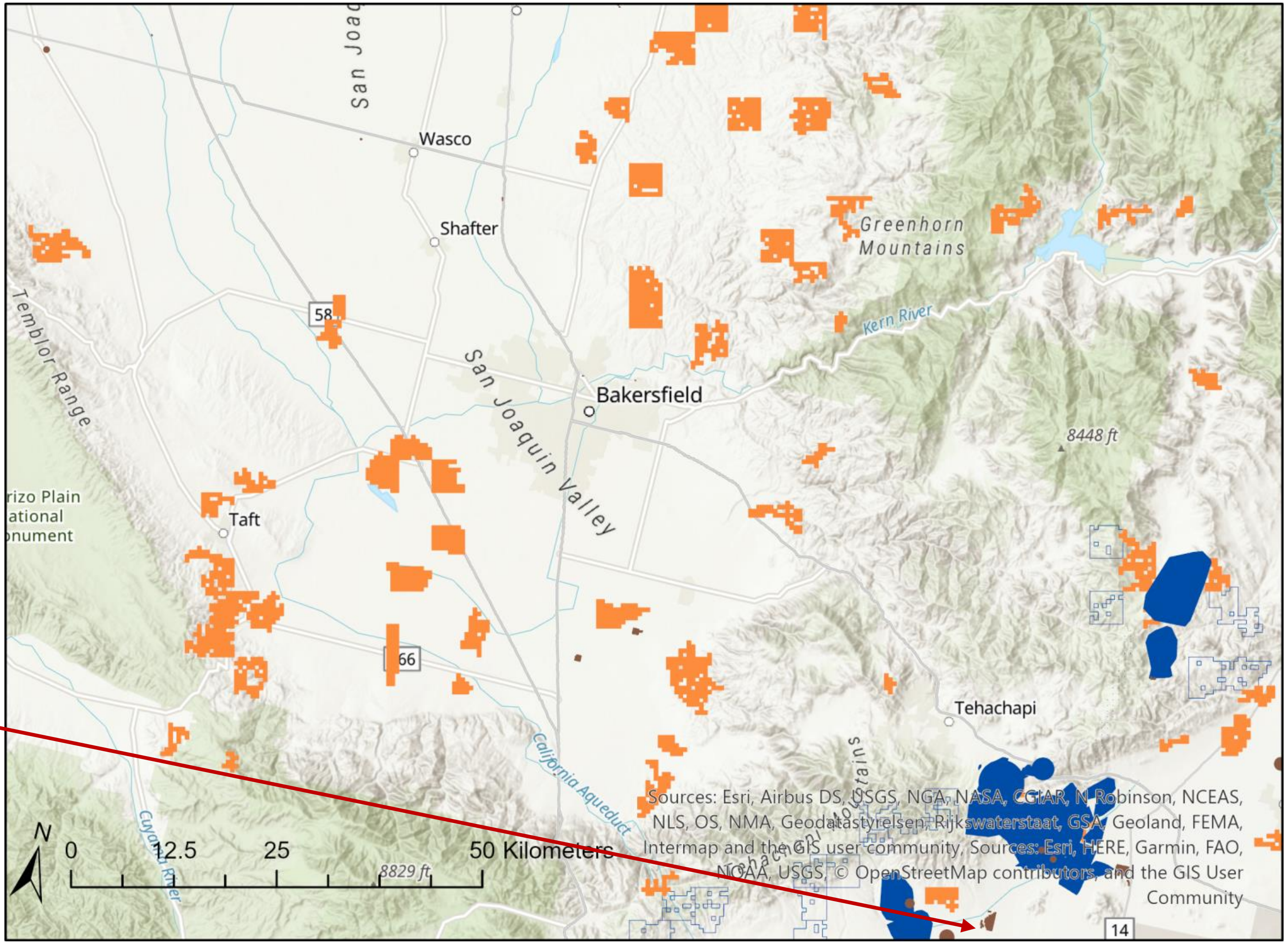
[Town of Jacksboro (7 km away) has population density > 100 p/km²]



Example area detail: Bakersfield, CA
2050 wind and solar farms (E+ base siting)

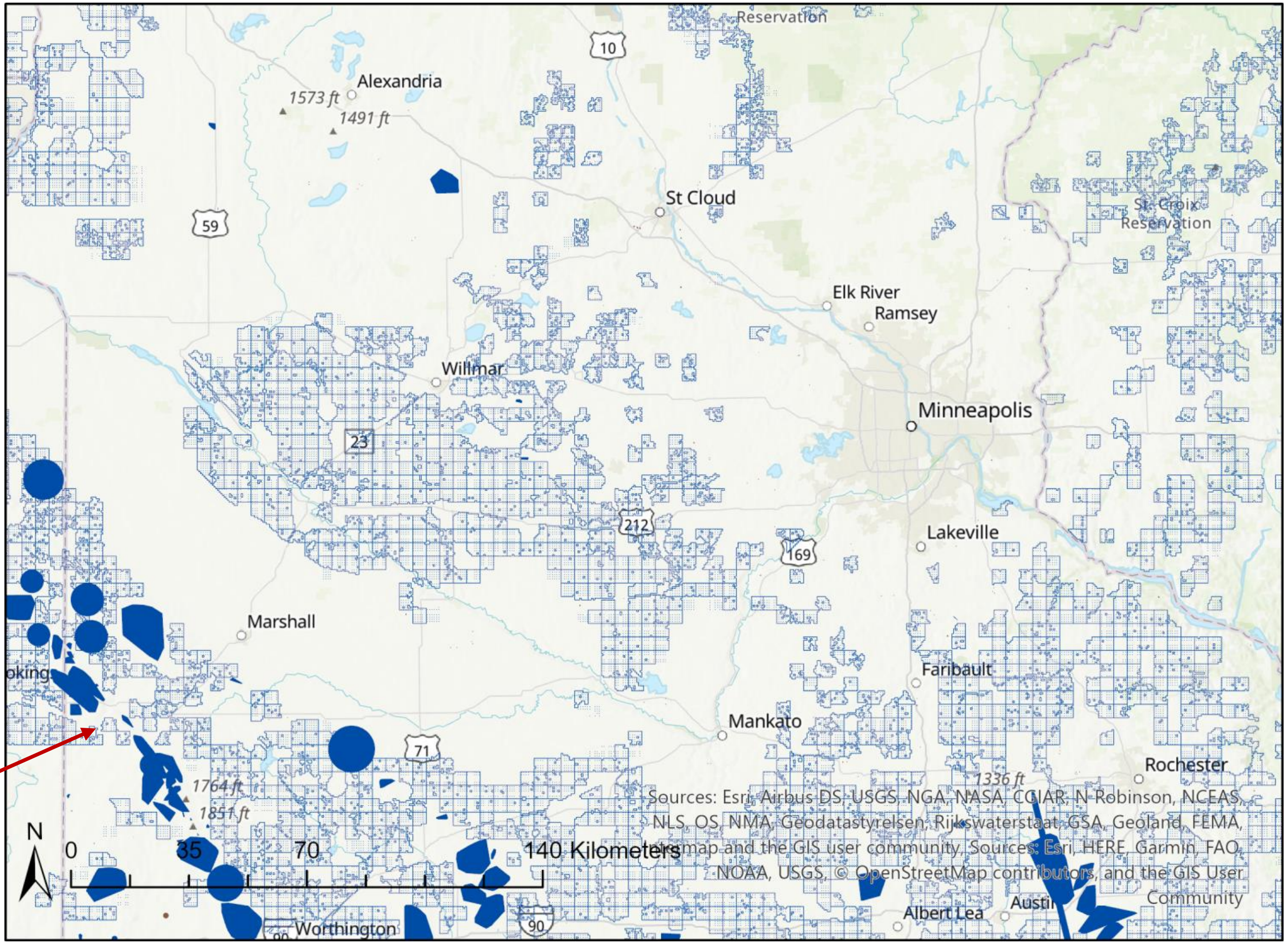
Solar, existing and planned
Solar, additional selected sites 2050 E+ base
Wind, existing and planned
Wind, additional selected sites 2050 E+ base
(dots indicate approximate turbine footprint)

Catalina Solar
110 MW existing facility
Online date = 2014
Population density = 4 people / km²



Example area detail: Minneapolis, MN
2050 wind and solar farms (E+ base siting)

- 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)



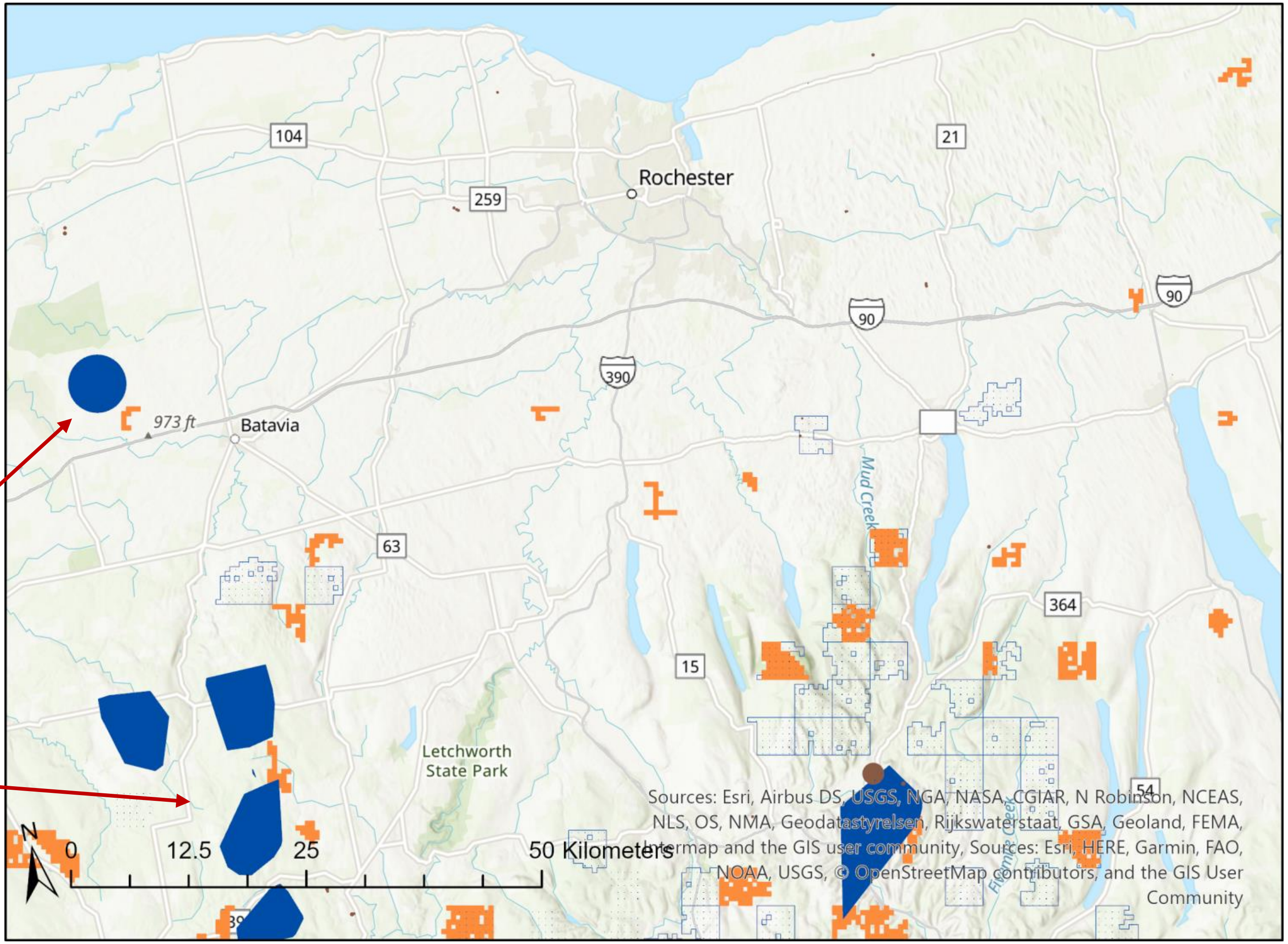
Note siting of new wind farm adjacent existing facilities

Example area detail: Rochester, NY
2050 wind and solar farms (E+ base siting)

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)

Alabama Ledge Wind
80 MW proposed facility
Scheduled online date = 2021

Existing wind facilities



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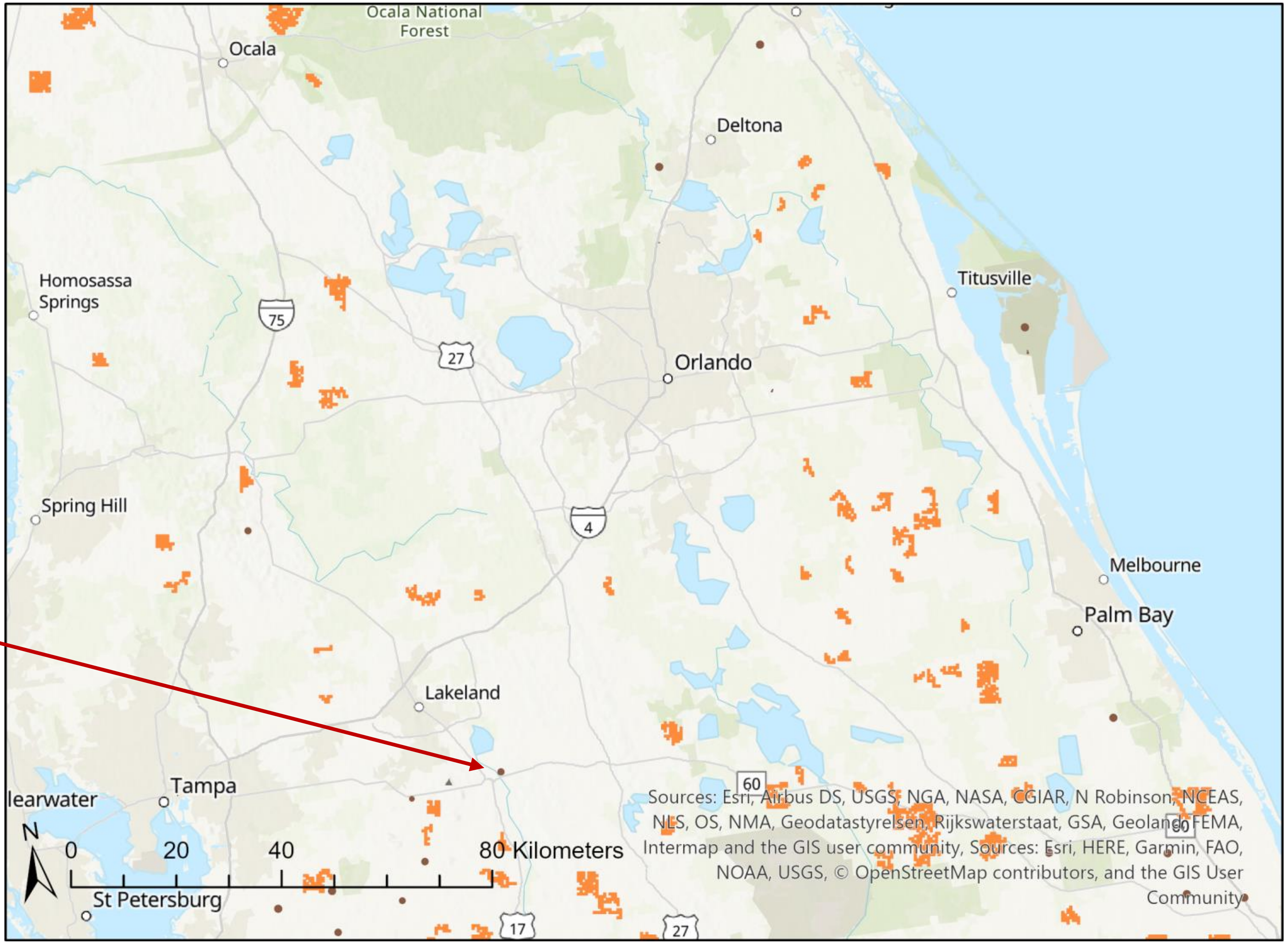
Example area detail: Orlando, FL
2050 wind and solar farms (E+ base siting)

- 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)

Peace Creek Solar
57 MW proposed facility
Scheduled online date = 2020



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Siting of solar and wind generators and transmission for the E+ pathway with constrained land availability

Summary of this section

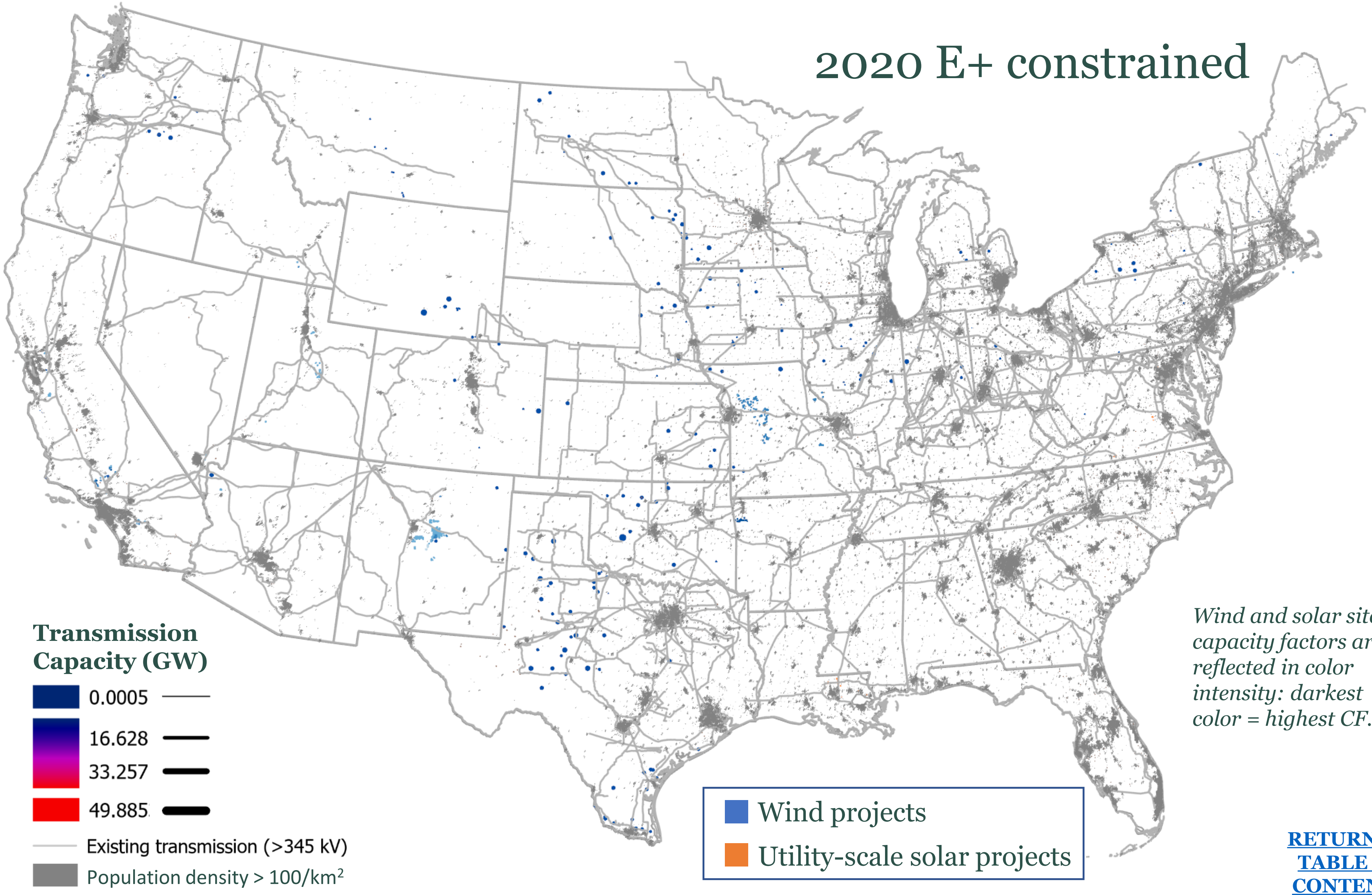
- The constrained site availability case was run to reflect more restrictive permitting and/or other factors that might constrain where solar and wind resource can be deployed.
- In the Constrained land availability scenario, wind farms cannot be deployed on prime farmlands and neither wind nor solar can be sited in relatively intact landscapes (in addition to all land use screens applied in the Base scenario).
- These additional constraints, particularly the prime farmlands exclusion for wind power, requires a more dispersed deployment of wind across the Great Plains states, shifting capacity from Iowa, Minnesota and Oklahoma to North Dakota, South Dakota and Texas.
- The ranking of top 10 solar states in 2050 is nearly unaffected from the Base land availability case.
- About $3.3 trillion is invested in ~3.0 TW of wind and solar capacity by 2050.
- By 2050 total onshore wind and solar farm area is 543,000 km² and directly impacted land area is ~40,000 km² (an area roughly twice the size of New Jersey).
- Constrained land availability requires greater transmission expansion than Base availability, as wind farms push into more remote areas of the Great Plains states. Transmission capacity expands by ~75% by 2030 and 230% by 2050.
- Total capital invested in transmission is ~$390b through 2030 and $2.5 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	Solar
Capacity installed (TW)		
	0.14	0.06
Land used (1000 km²)		
Total	55	0.94
Direct	0.55	0.85
Capital invested (Billion $$_{2018}$)*		
Solar	-	42
Onshore wind	75	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

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

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



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

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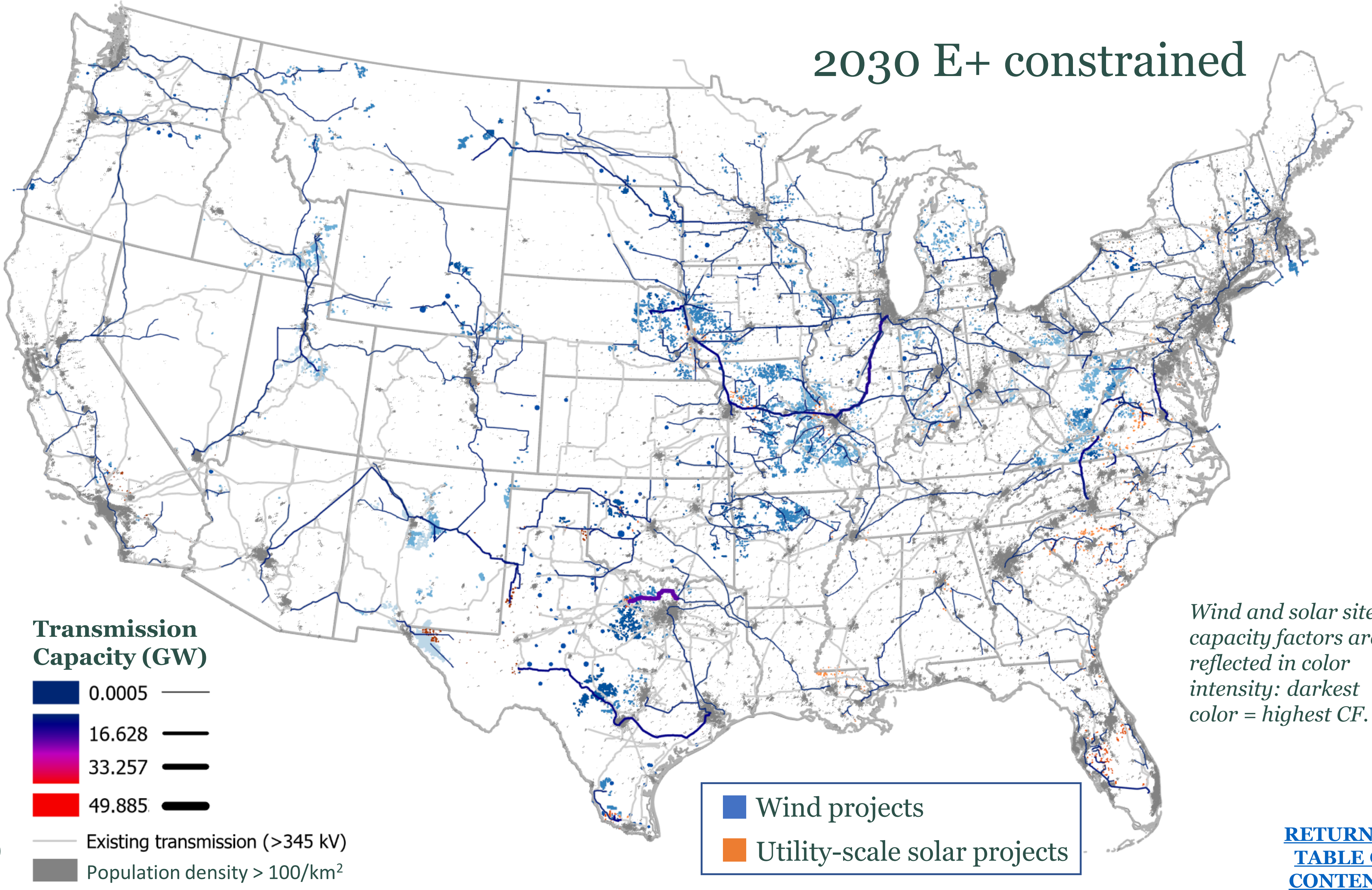
765 GW of wind and solar capacity operating in 2030; transmission capacity grows by 73%.

2030		
	Wind	Solar
Capacity installed (TW)		
	0.43	0.34
Land used (1000 km²)		
Total	158	8.02
Direct	1.58	7.30
Capital invested (Billion $_{2018}$)*		
Solar	-	367
Onshore wind	448	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		234,000
Increase over 2020		73%
Capital in serv (B$_{2018}$)		385

* 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.)



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

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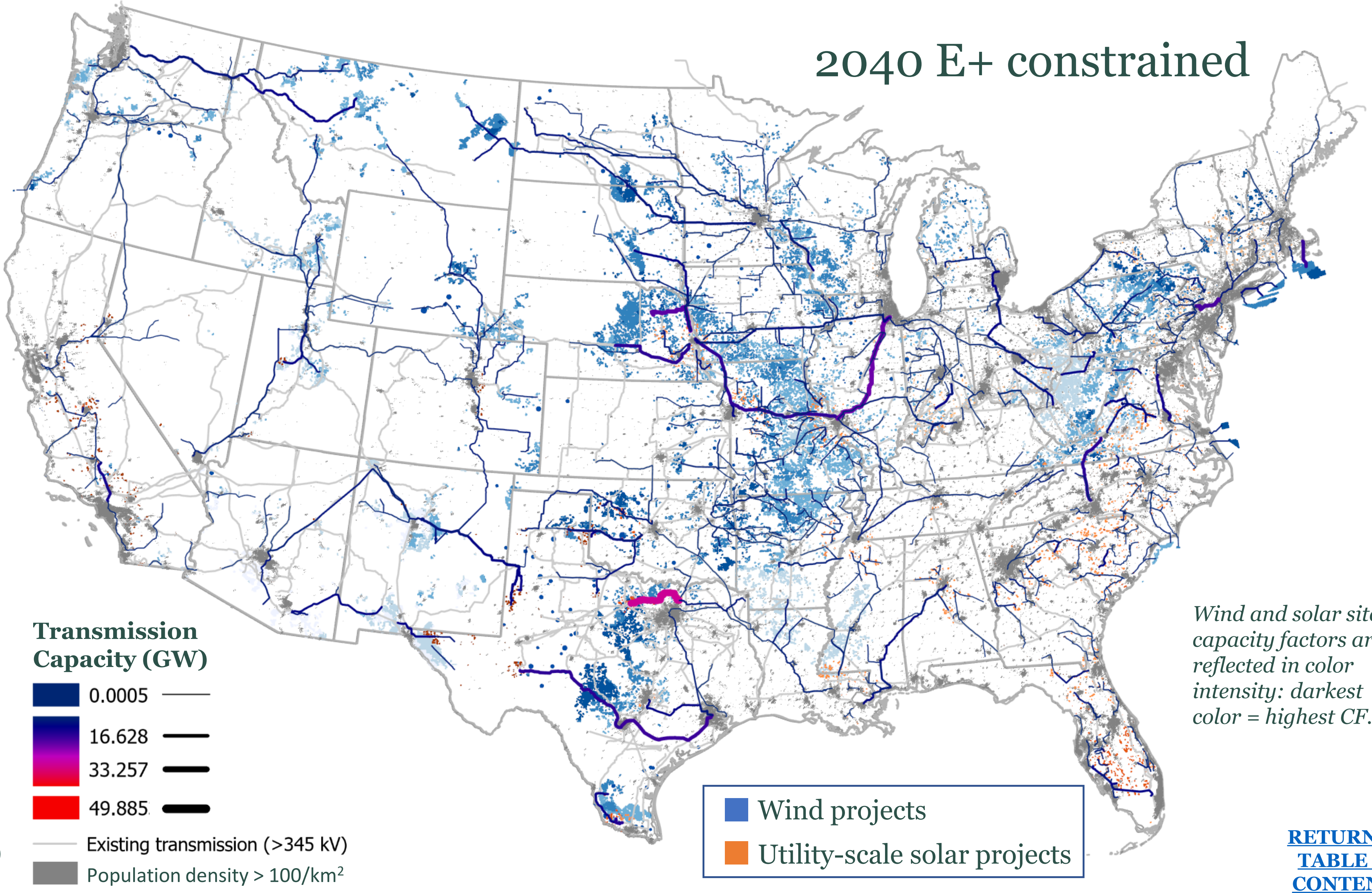
1.9 TW of wind and solar capacity operating in 2040; transmission capacity grows to 1.6x the 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	1.01	0.85
Land used (1000 km²)		
Total	362	21.3
Direct	3.63	19.4
Capital invested (Billion $$_{2018}$)*		
Solar	-	891
Onshore wind	1,141	-
Offshore wind	87	-
Transmission added vs. 2020**		
Capacity (GW-km)		524,000
Increase over 2020		164%
Capital in serv (B$$_{2018}$)		1,110

* 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.)



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

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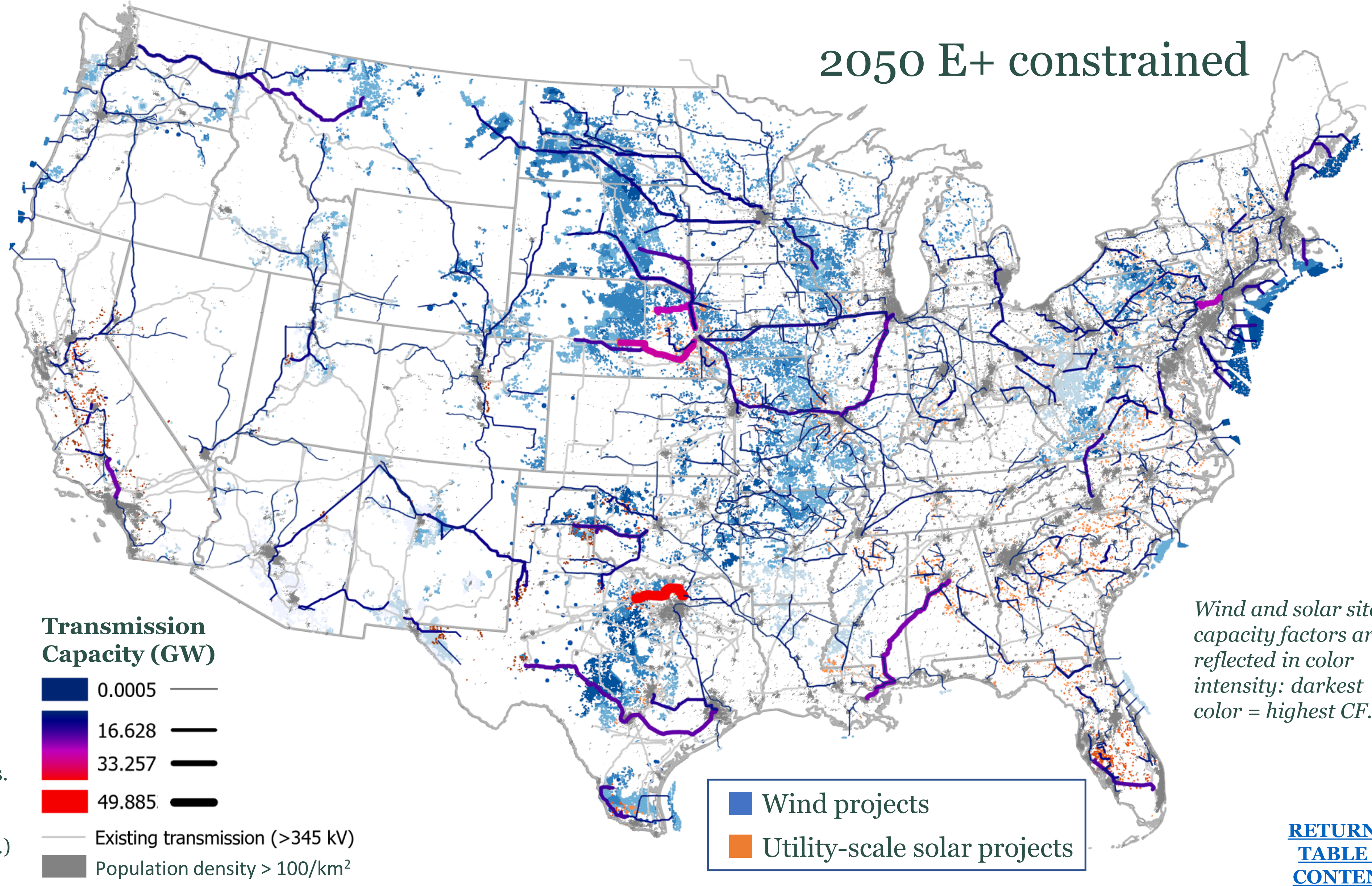
3 TW of wind and solar capacity operating in 2050. Constraining site availability results in more dispersed development.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	1.55	1.48
Land used (1000 km²)		
Total	505	37.8
Direct	5.05	34.4
Capital invested (Billion $_{2018}$)*		
Solar	-	1,473
Onshore wind	1,548	-
Offshore wind	297	-
Transmission added vs. 2020**		
Capacity (GW-km)		749,000
Increase over 2020		234%
Capital in serv (B$_{2018}$)		2,460

* 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.)



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

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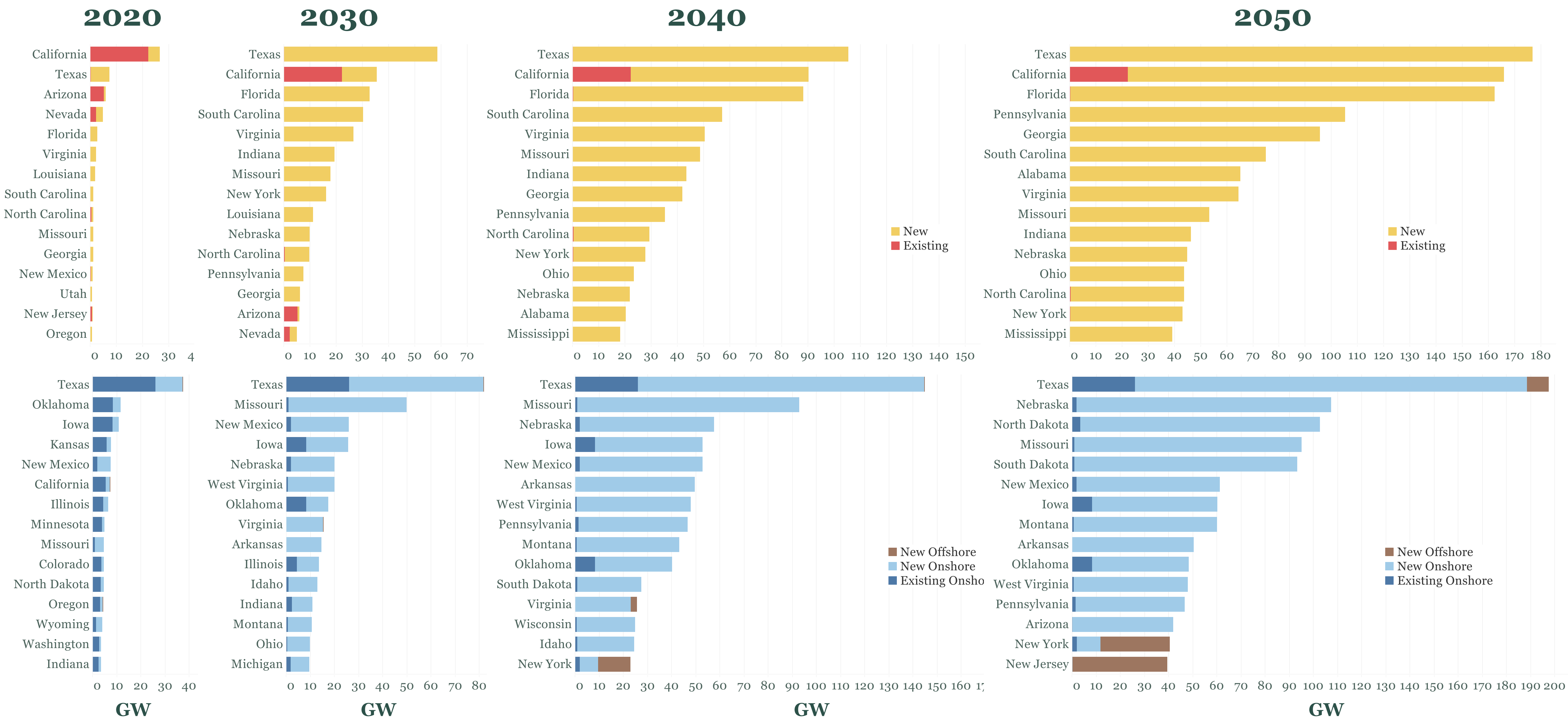
Top 15 states for installed wind and utility-scale solar capacity each decade, E+ (constrained siting)



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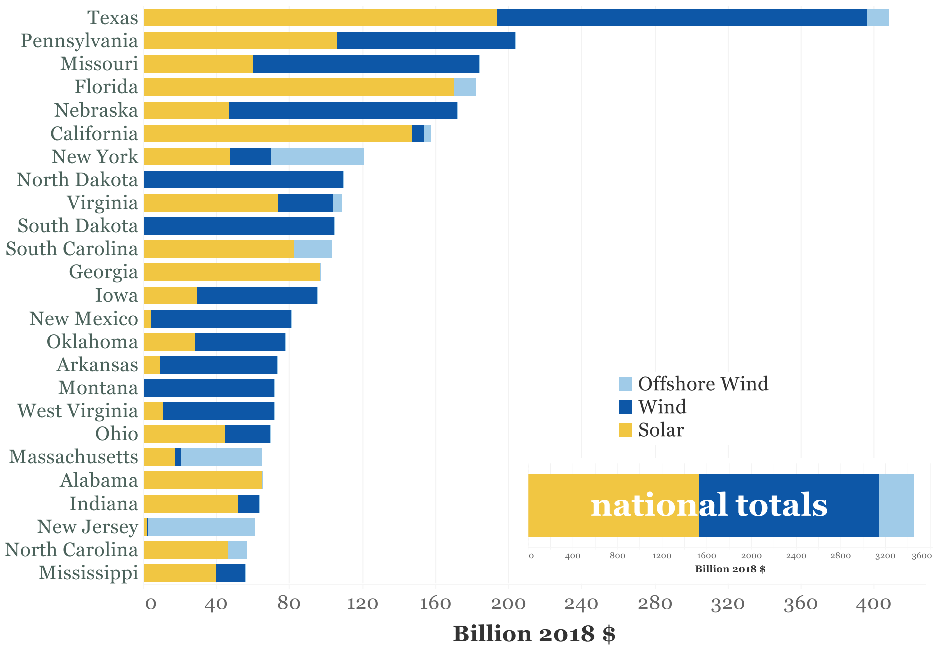
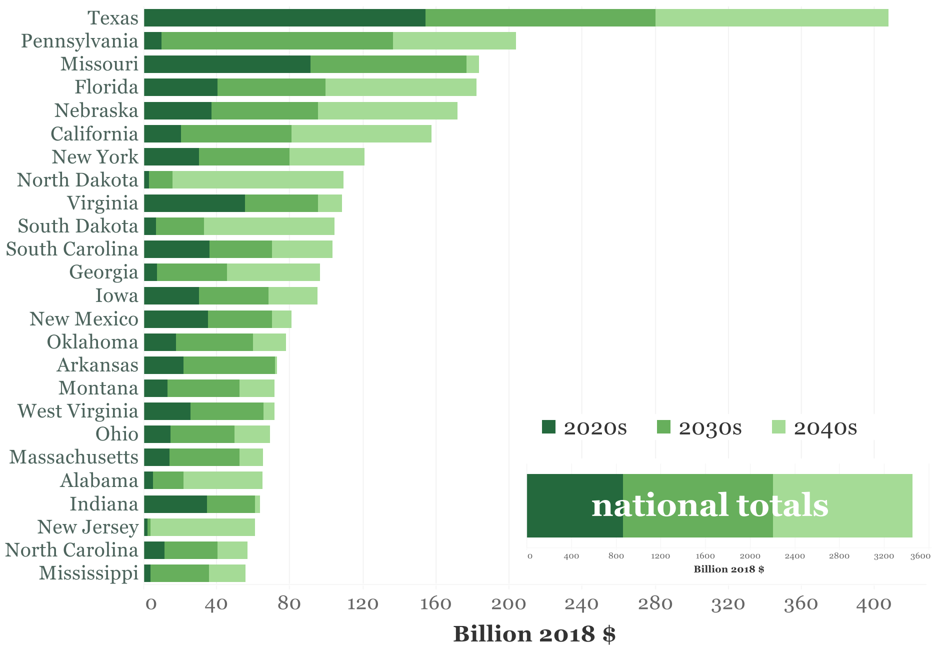
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+ (constrained siting)

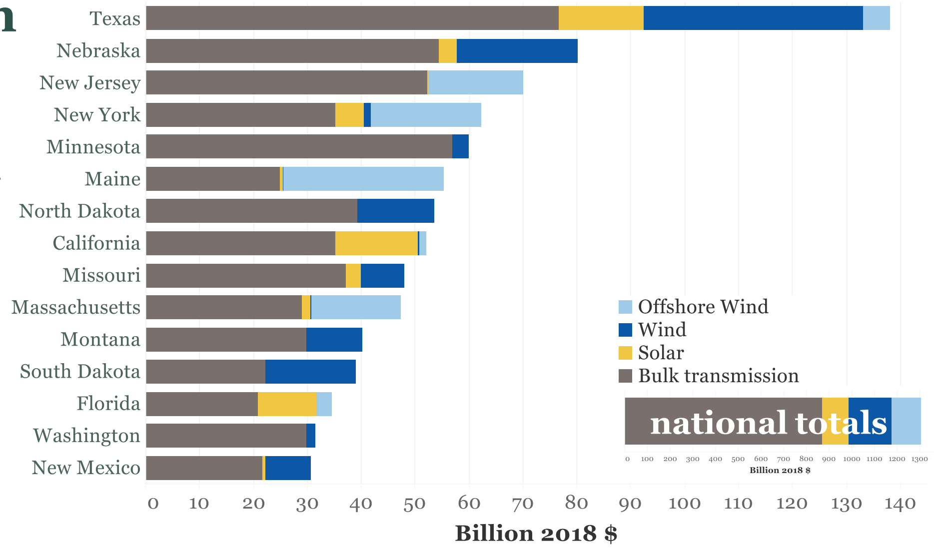
Wind & solar capacity investments, top 25 states





Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.



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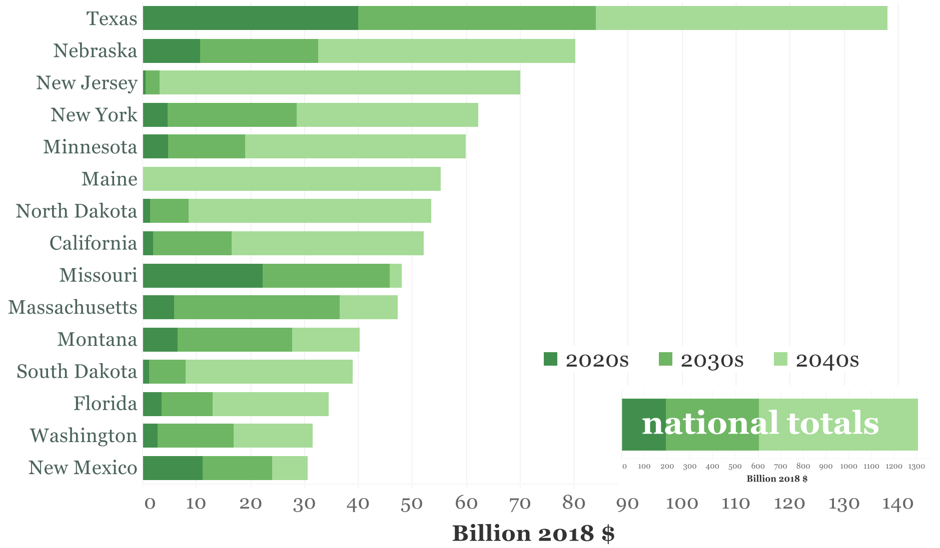


Siting of solar and wind generators and transmission for the E+ RE+ pathway with base land availability

Summary of this section

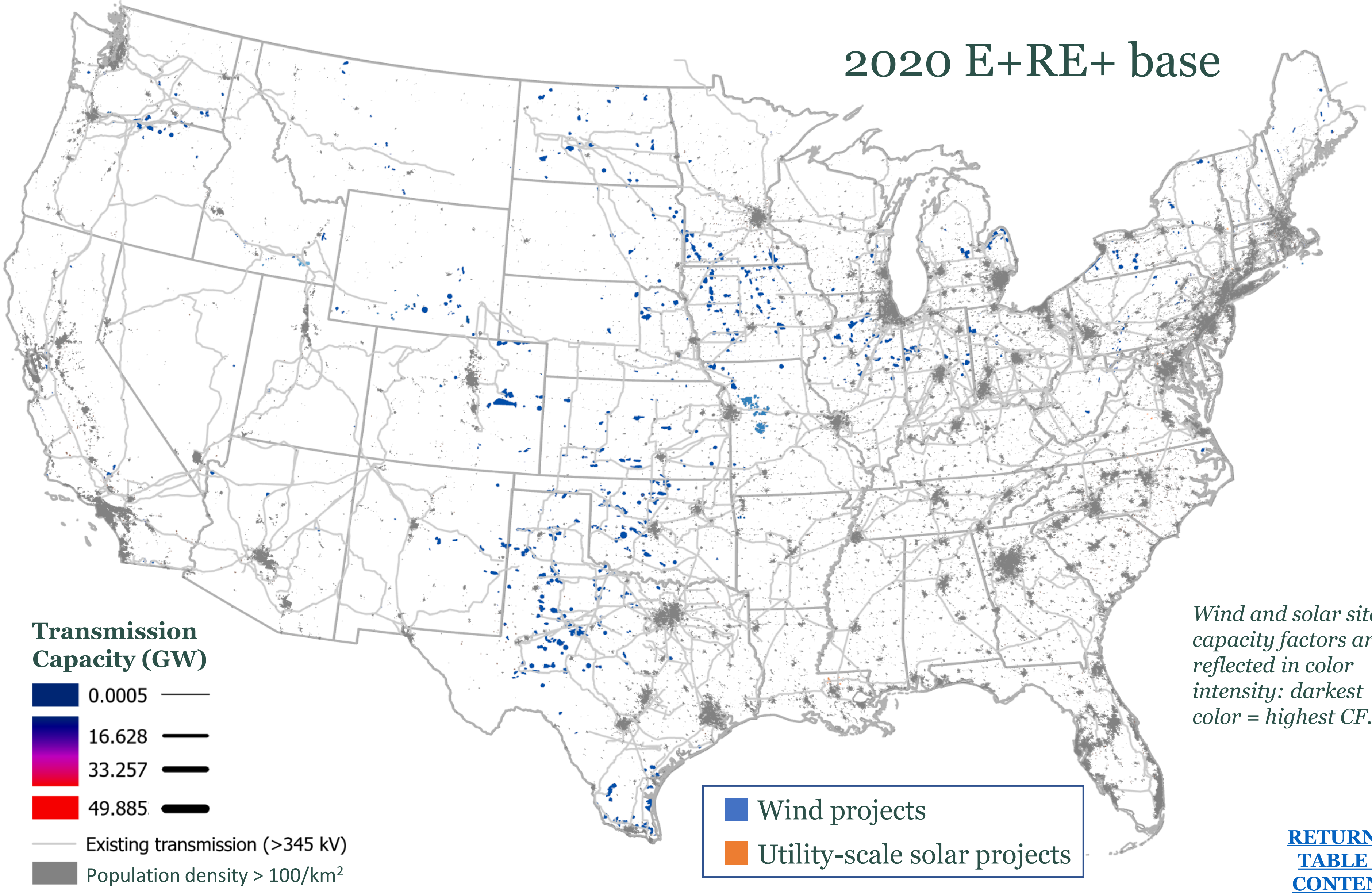
- The E+ RE+ case relies exclusively on renewable energy by 2050, and requires 5.8 TW of wind and solar capacity to meet economy-wide demands (nearly double the capacity in the E+ case). This represents $6.3 trillion of investment.
- The ranking of top 10 states for solar and for wind capacity installed in 2050 are both similar to those in the E+ case.
- By 2050, wind and solar farms span a total area of more than 1 million km², with wind farms accounting for 94% of this.
- Offshore wind farms span another 64,000 km² and are built extensively along the entire Atlantic Coast, as well as some areas in the Gulf of Mexico and floating turbines on the Pacific coast.
- Lands directly impacted by onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals 66,000 km² (an area larger than West Virginia).
- Transmission capacity expands ~75% by 2030 and ~400% by 2050 (to over 1.6 million GW-km installed). The needed expansion from 2020 to 2050 is about double that of the E+ case.
- Total capital invested in transmission is ~$320 billion through 2030 and $3.6 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.14	0.07
Land used (1000 km²)		
Total	57	1.12
Direct	5.8	1.02
Capital invested (Billion $_{2018}$)*		
Solar	-	47
Onshore wind	69	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

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

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, [Renewable Electricity Futures Study, 2012](#).



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

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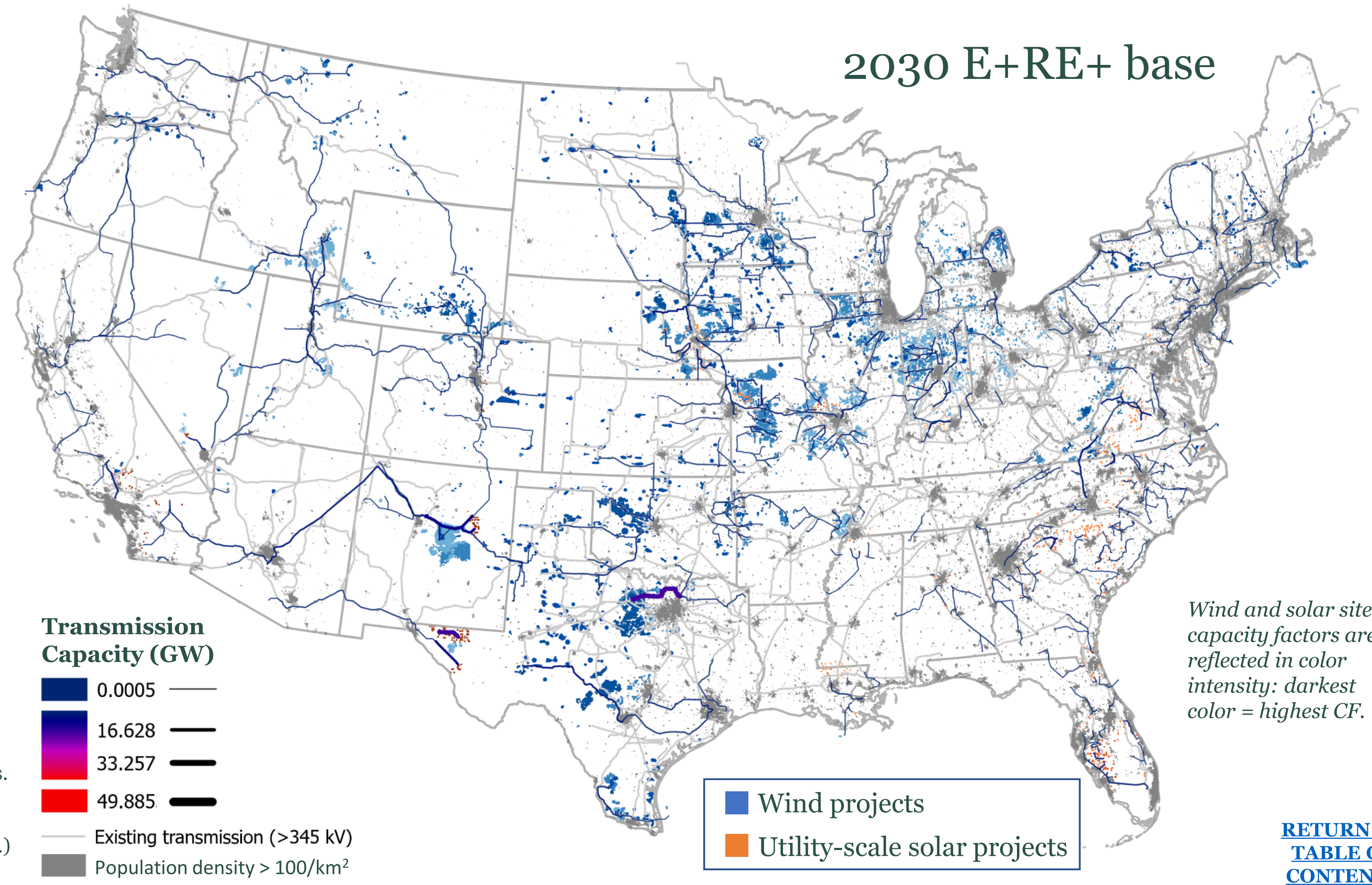
866 GW of wind and solar capacity operating in 2030; transmission capacity grows by 74%.

2030		
	Wind	Solar
Capacity installed (TW)		
	0.46	0.40
Land used (1000 km²)		
Total	174	8.7
Direct	1.74	7.9
Capital invested (Billion $$_{2018}$)*		
Solar	-	450
Onshore wind	490	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		235,000
Increase over 2020		74%
Capital in serv (B$$_{2018}$)		320

* 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.)



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

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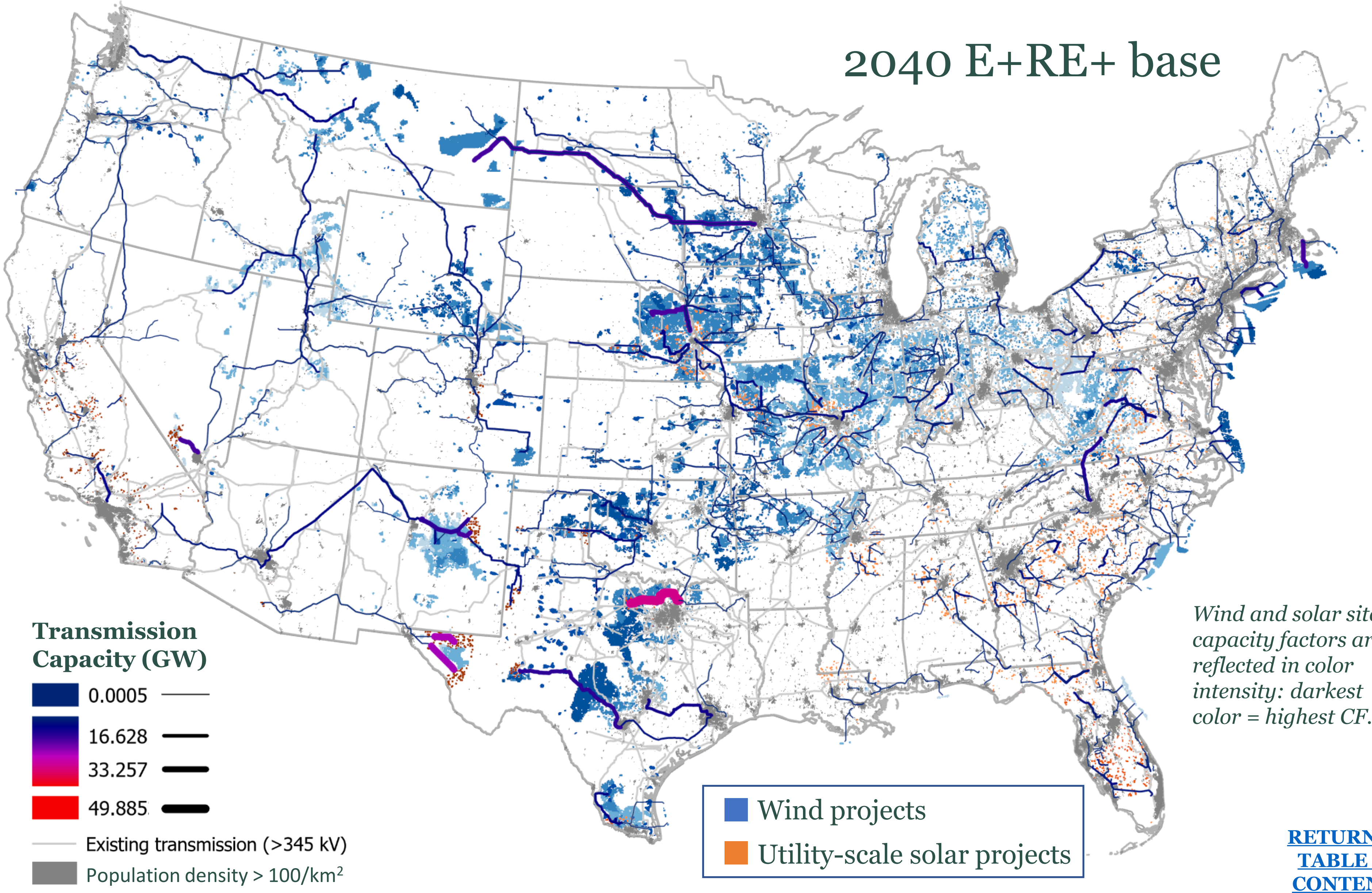
2.7 TW of wind and solar capacity operating in 2040; transmission capacity grows to 2.4x the 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	1.42	1.23
Land used (1000 km²)		
Total	493	26.9
Direct	4.9	24.5
Capital invested (Billion $$_{2018}$)*		
Solar	-	1,305
Onshore wind	1,497	-
Offshore wind	223	-
Transmission added vs. 2020**		
Capacity (GW-km)		760,000
Increase over 2020		237%
Capital in serv (B$$_{2018}$)		1,320

* 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.)



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

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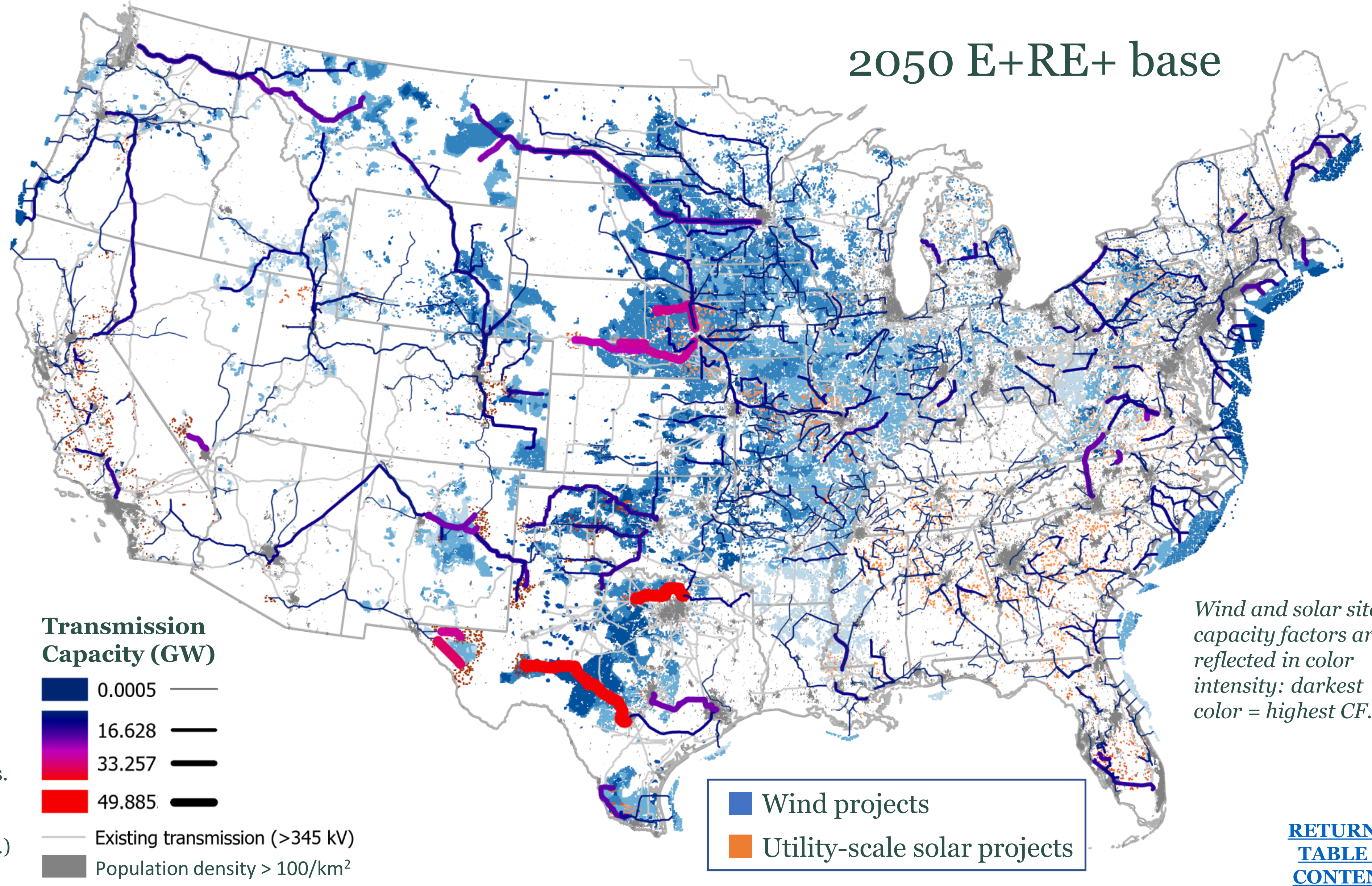
5.9 TW of wind and solar capacity operating in 2050; transmission capacity grows to 5.1x the 2020 level.

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.)



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

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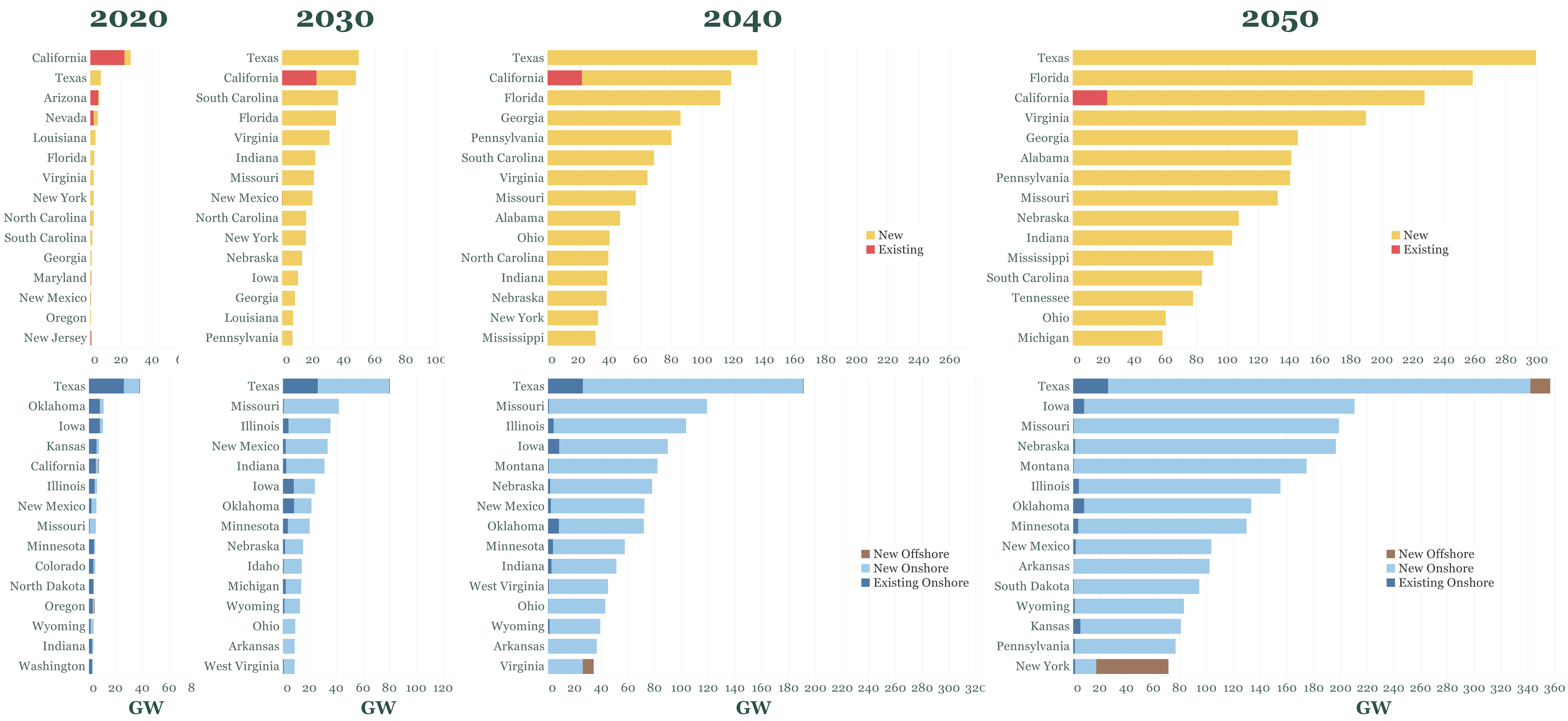
Top 15 states for installed wind and utility-scale solar capacity each decade, E+RE+ (base siting)



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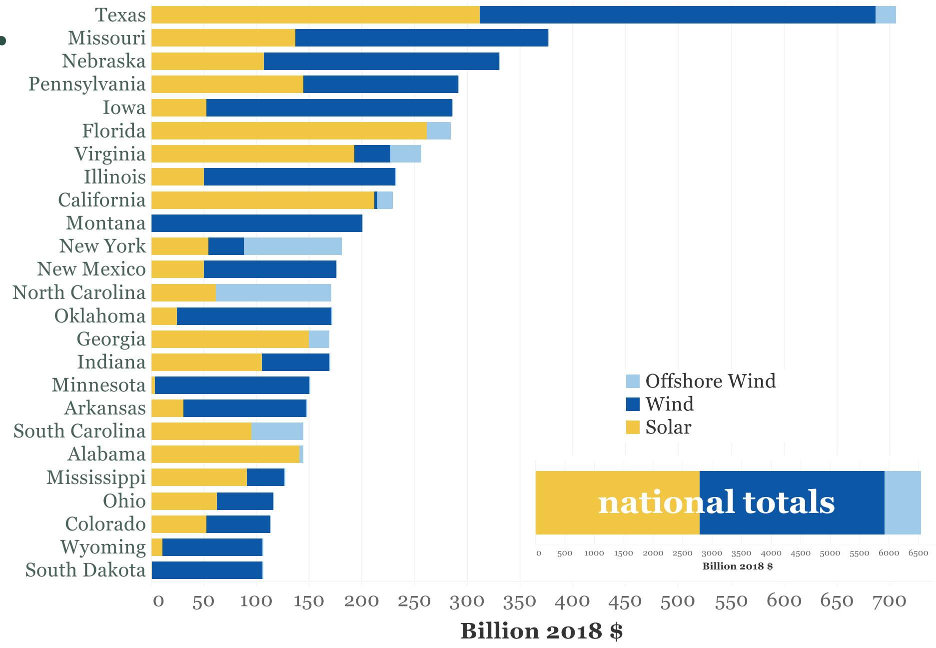
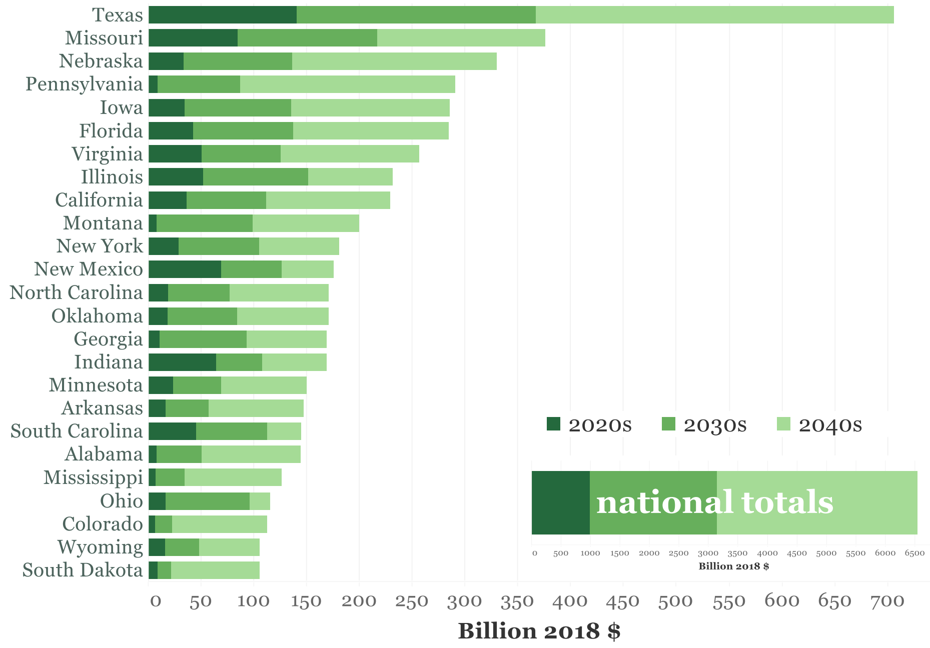
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+RE+ (base siting)

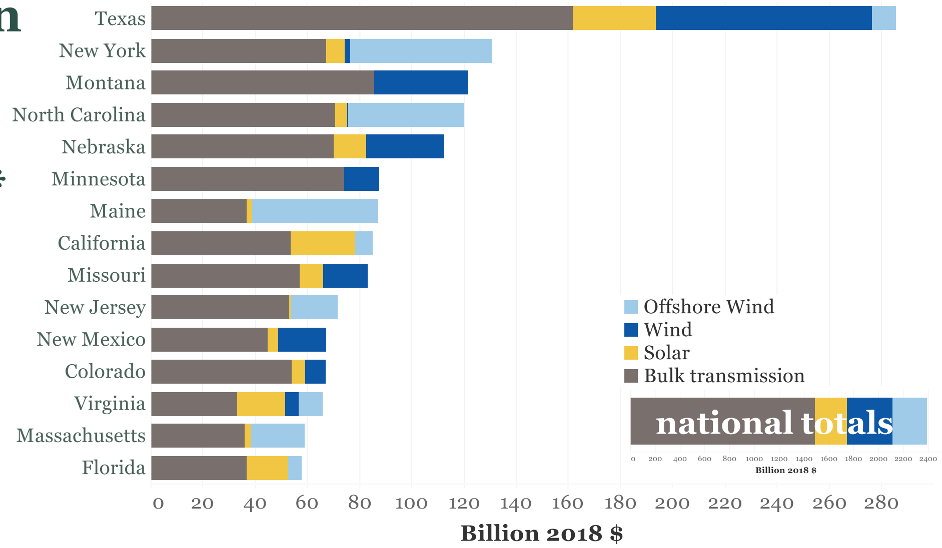
Wind & solar capacity investments, top 25 states

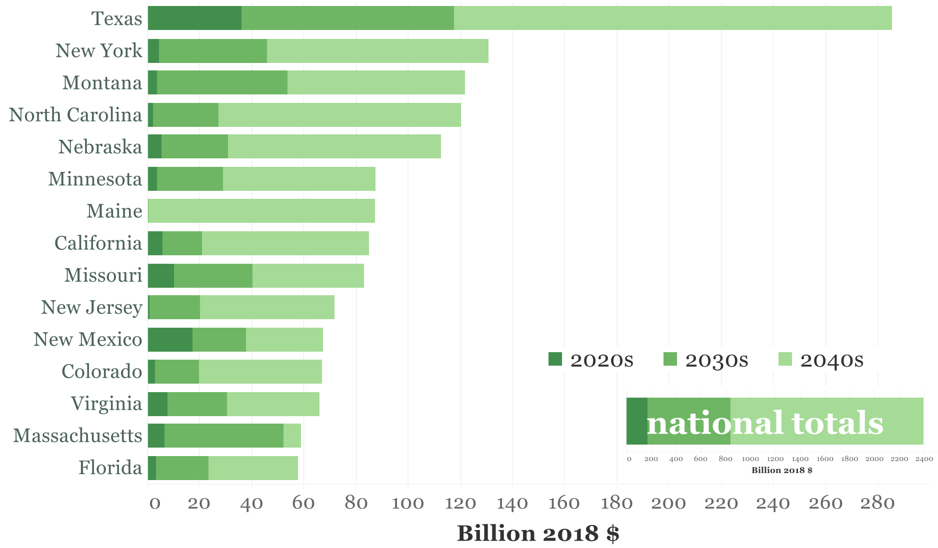




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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Siting of solar and wind generators and transmission for the E+ RE- pathway with base land availability

Summary of this section

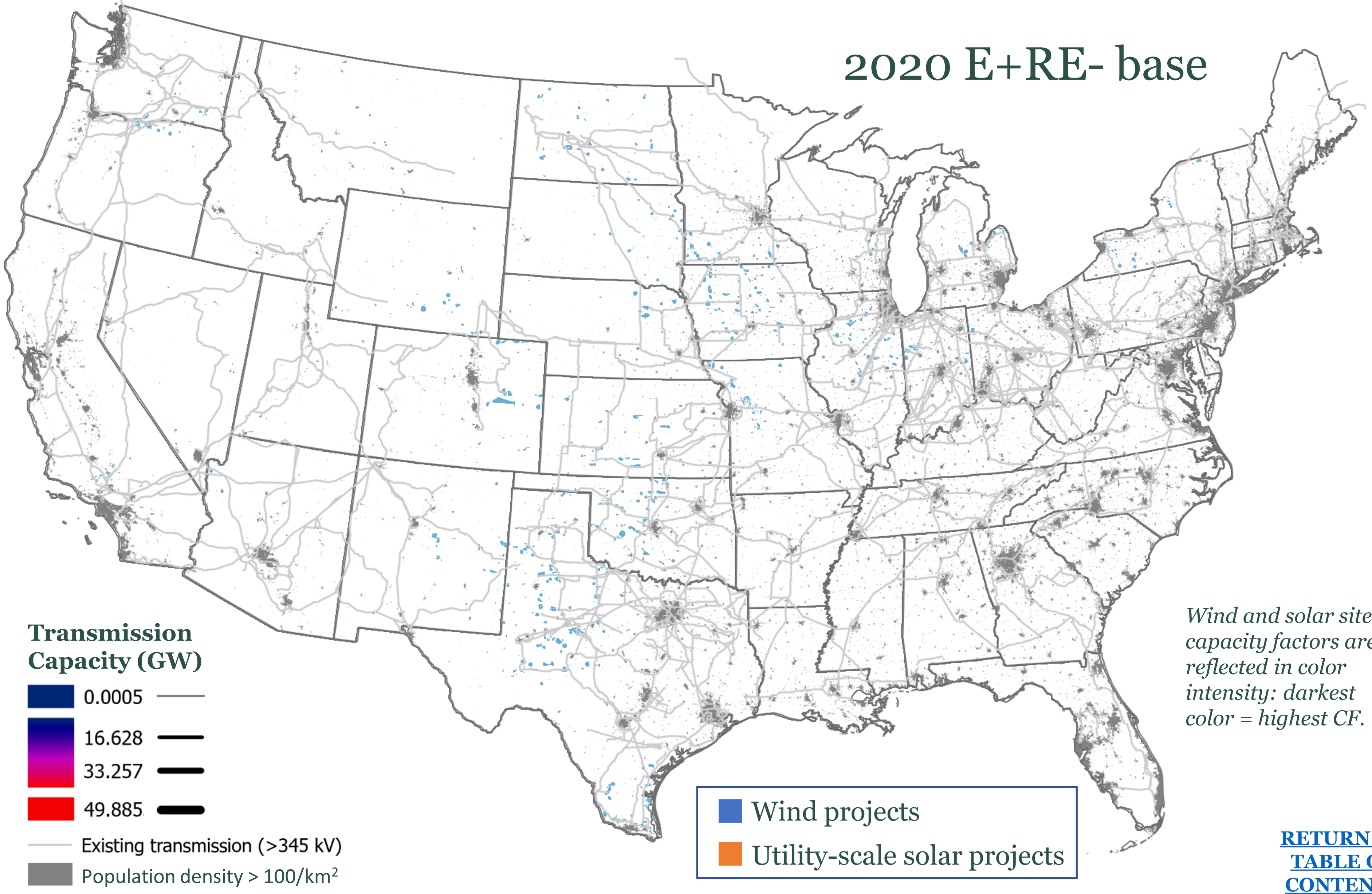
- The E+RE- case limits the allowed annual rate of solar and wind capacity expansion to 35 GW, resulting in 270 GW each of solar and onshore wind installed by 2030 and about 650 GW of each in 2050. Cumulative capital invested by 2050 is $1.4 trillion.
- The ranking of top 10 states for solar and for wind capacity installed in 2050 are both similar to those in the E+ case, but with significantly lower installed capacities.
- By 2050 wind and solar farms span a total area of about 260,000 km^2, with wind farms accounting for 95% of this.
- The direct land impact of onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals about 16,000 km^2 (an area larger than Connecticut).
- Offshore wind farms span an area of 5,700 km^2 (57 km^2 of directly-impacted area), primarily off the U.S. Northeast coast.
- Transmission capacity expands ~40% by 2030 and ~100% by 2050. The needed expansion from 2020 to 2050 is about half of that in the E+ case.
- Total capital invested in transmission is ~$290 billion through 2030 and $1.3 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	Solar
Capacity installed (TW)		
	0.14	0.08
Land used (1000 km²)		
Total	56	1.39
Direct	0.56	1.26
Capital invested (Billion $$_{2018}$)*		
Solar	-	60
Onshore wind	72	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

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

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



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

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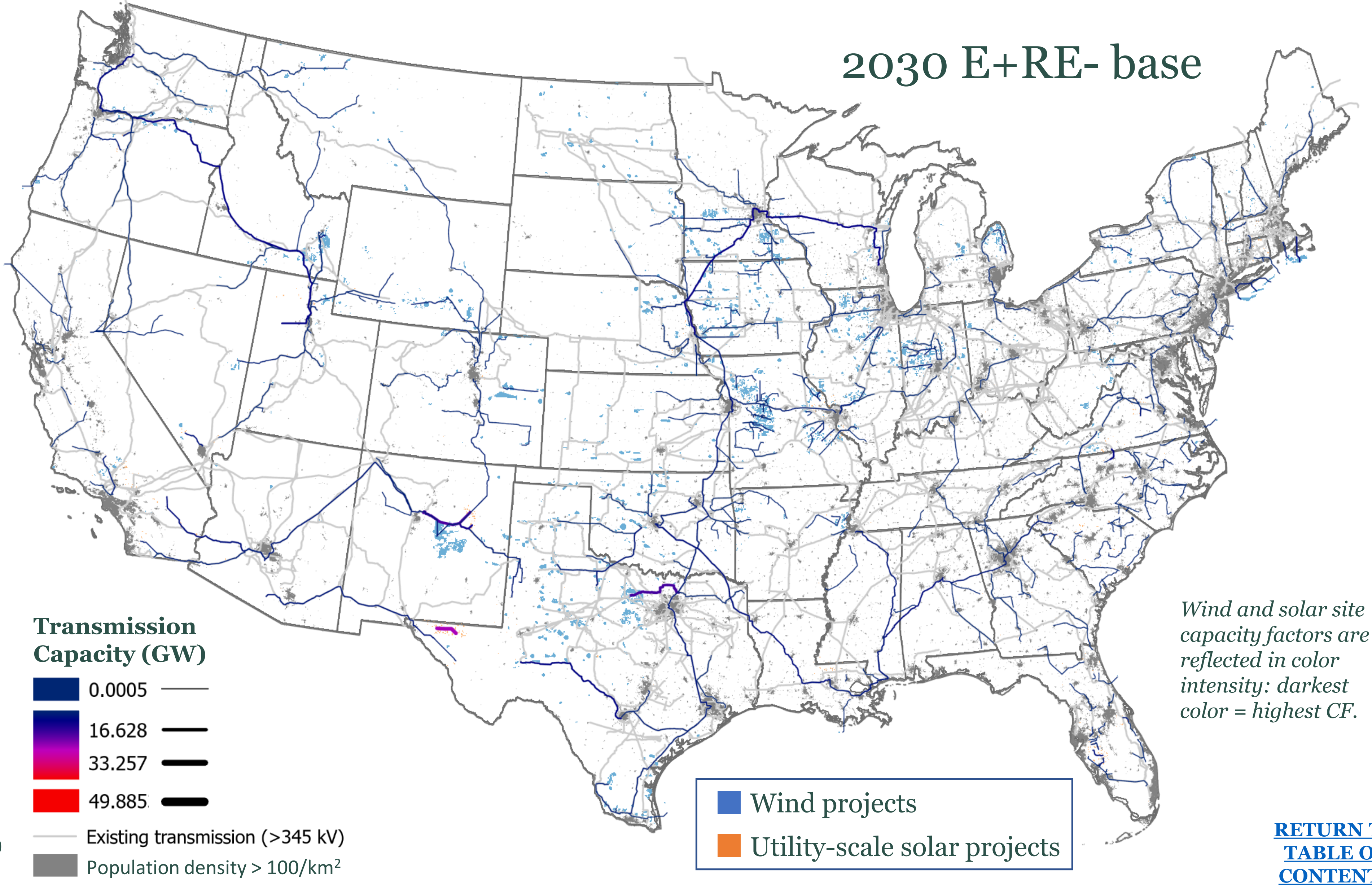
539 GW of wind and solar capacity operating in 2030; transmission capacity grows by 39%.

2030		
	Wind	**Solar**
Capacity installed (TW)		
	0.27	0.27
Land used (1000 km²)		
Total	102	5.8
Direct	1.03	5.3
Capital invested (Billion $\$_{2018}$)*		
Solar	-	292
Onshore wind	229	-
Offshore wind	33	-
Transmission added vs. 2020**		
Capacity (GW-km)		125,000
Increase over 2020		39%
Capital in serv (B$\$_{2018}$)		290

* 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.)



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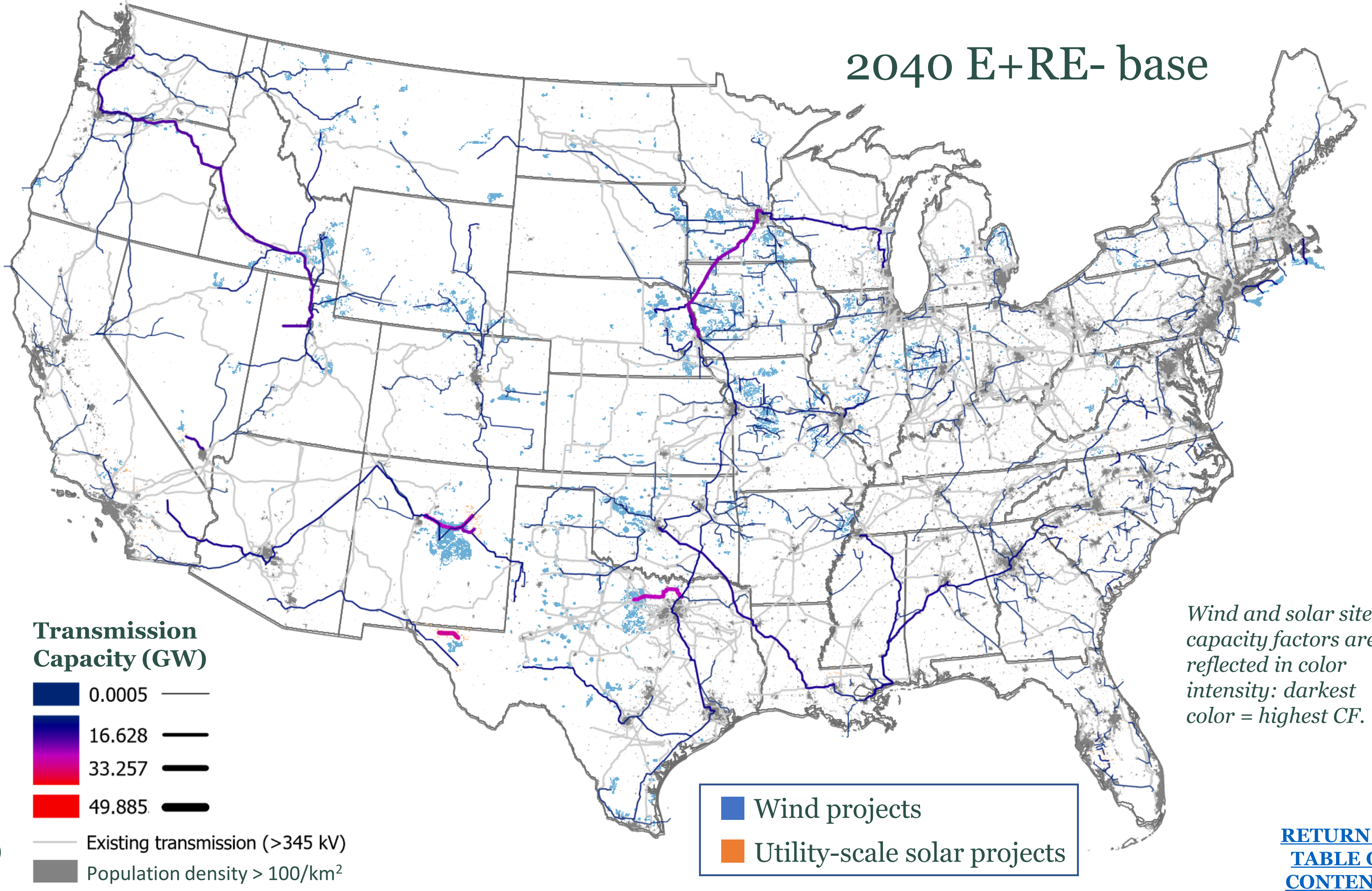
924 GW of wind and solar capacity operating in 2040; transmission capacity grows by 81% over 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	0.47	0.46
Land used (1000 km²)		
Total	170	10.1
Direct	1.7	9.19
Capital invested (Billion $\$_{2018}$)*		
Solar	-	489
Onshore wind	443	-
Offshore wind	57	-
Transmission added vs. 2020**		
Capacity (GW-km)		260,000
Increase over 2020		81%
Capital in serv (B$\$_{2018}$)		990

* 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.)



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

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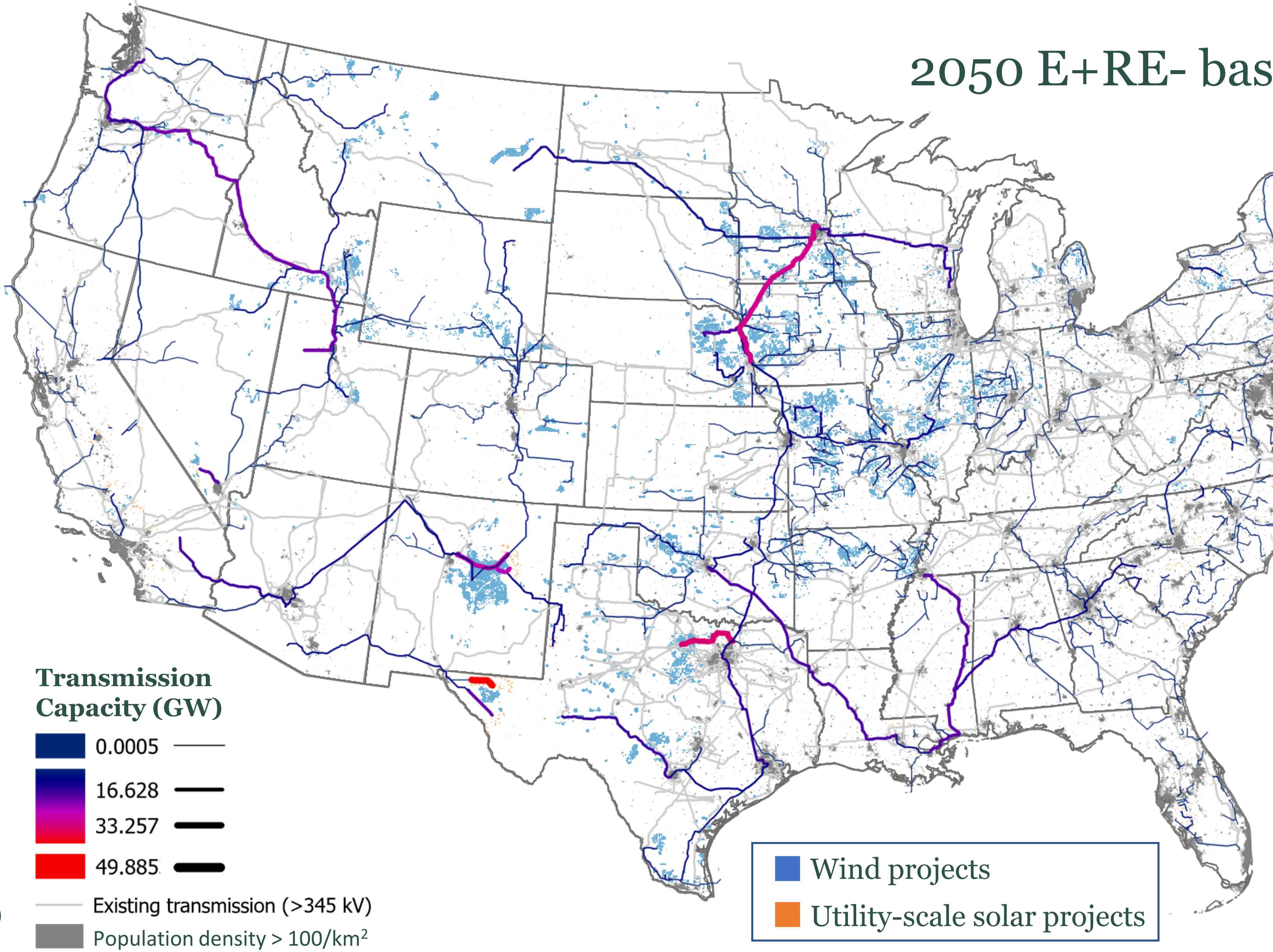
1.3 TW of solar and wind capacity operating in 2050; transmission capacity is 2x the 2020 level.

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.)



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

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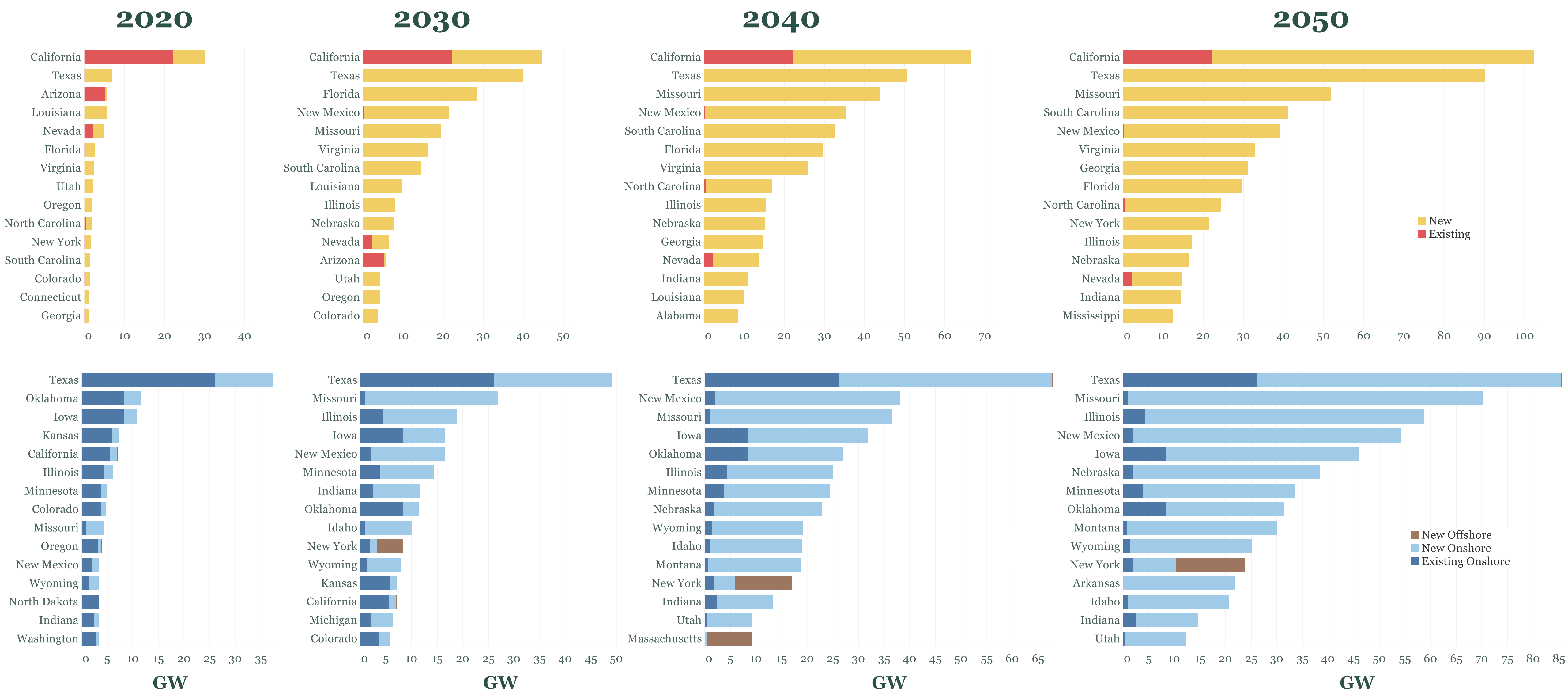
Top 15 states for installed wind and utility-scale solar capacity each decade, E+RE- (base siting)



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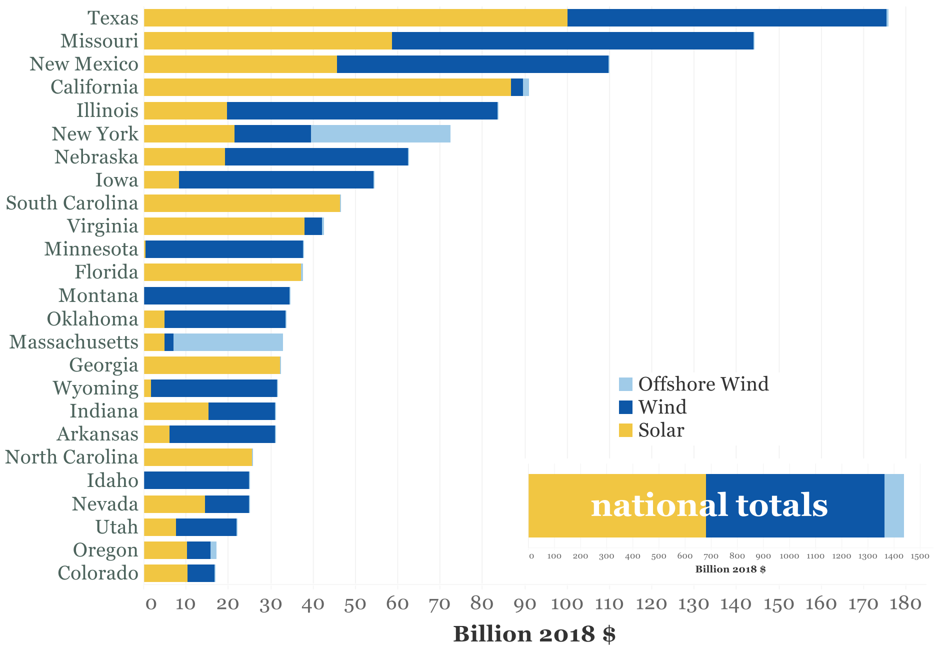
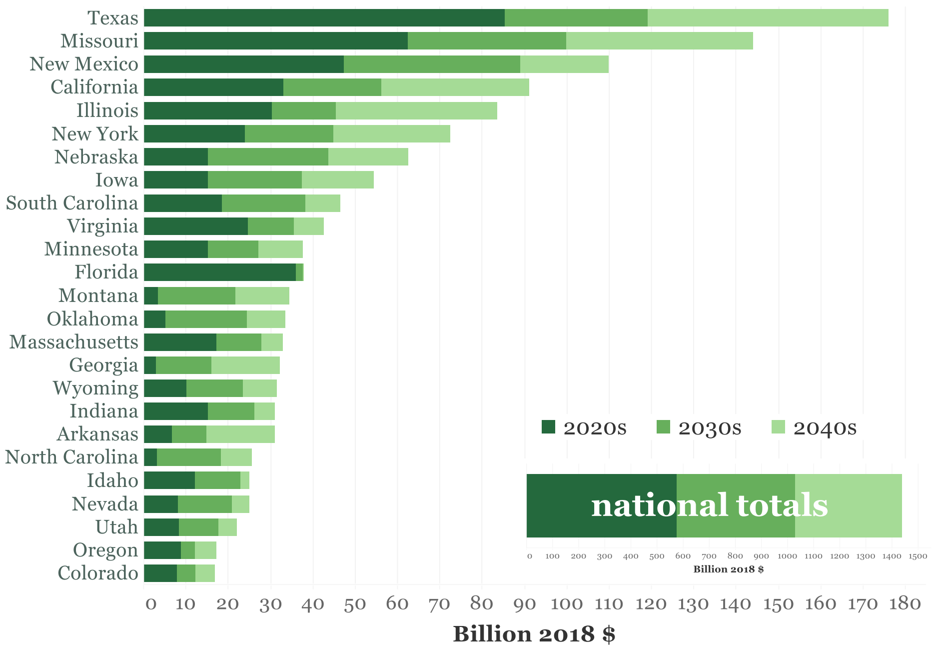
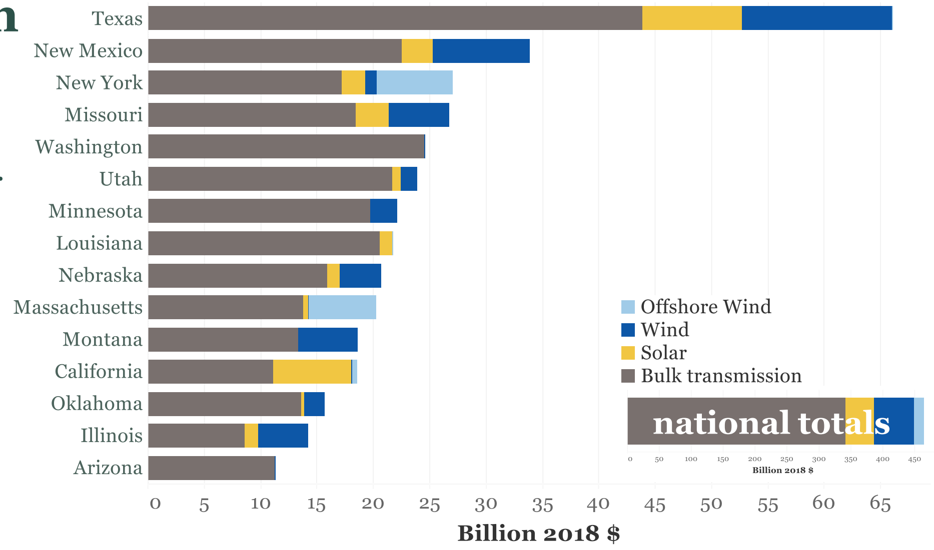
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+RE- (base siting)

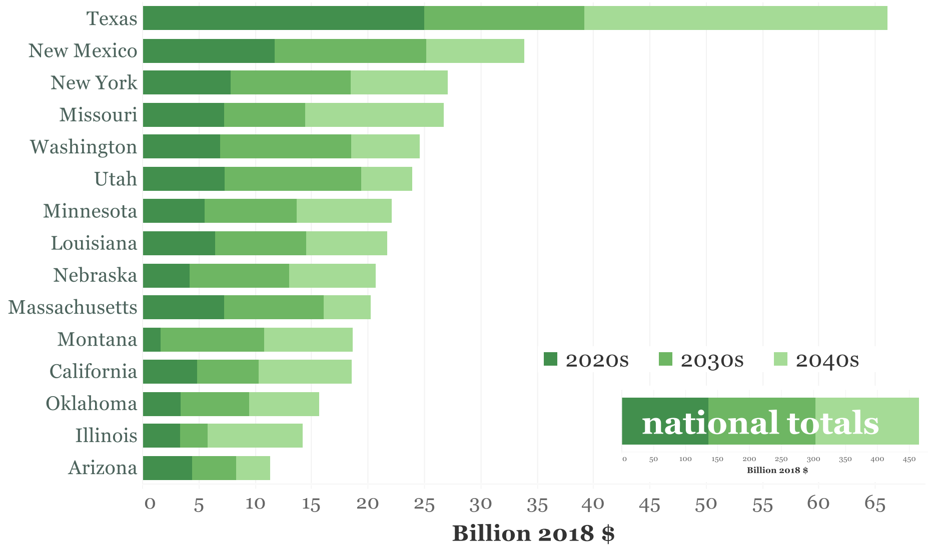
Wind & solar capacity investments, top 25 states





Transmission capacity investments, top 15 states*





* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.

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Siting of solar and wind generators and transmission for the REF pathway with base land availability.

Summary of this section

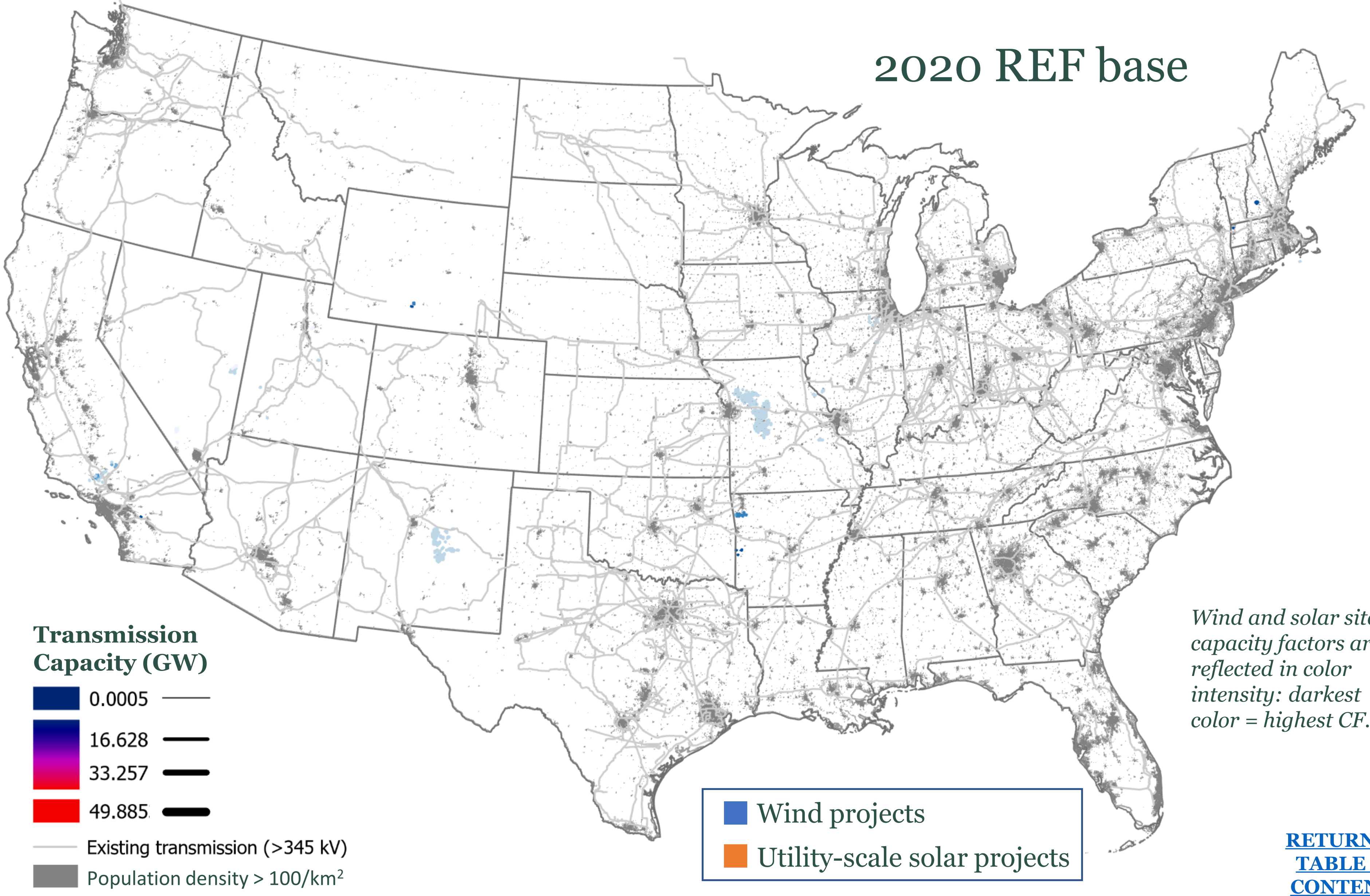
- REF is a "no new policy" case, with no greenhouse gas emissions reduction goals. Solar and wind capacity expand much more slowly than in the modeled decarbonization cases. Less than 250 GW of combined solar and wind capacity are installed in by 2030 and less than 600 GW by 2050. Cumulative capital invested by 2050 is about $520 billion.
- The ranking of top 10 states for solar and for wind installed in 2050 varies considerably from those in the E+ case.
- By 2050 wind and solar farms span a total area of less than 150,000 km^2, with wind farms accounting for most of this.
- The direct land impact of onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals about 4,200 km^2 (slightly larger than Rhode Island).
- Transmission capacity expands ~18% by 2030 and ~47% by 2050. The needed expansion from 2020 to 2050 is about a quarter of that in the E+ case and half that in the E+ RE- case.
- Total capital invested in transmission is ~$210 billion through 2030 and $0.95 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	Solar
Capacity installed (TW)		
	0.15	0.06
Land used (1000 km²)		
Total	61.5	0.95
Direct	0.62	0.86
Capital invested (Billion $$_{2018}$)*		
Solar	-	36
Onshore wind	84	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

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

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



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

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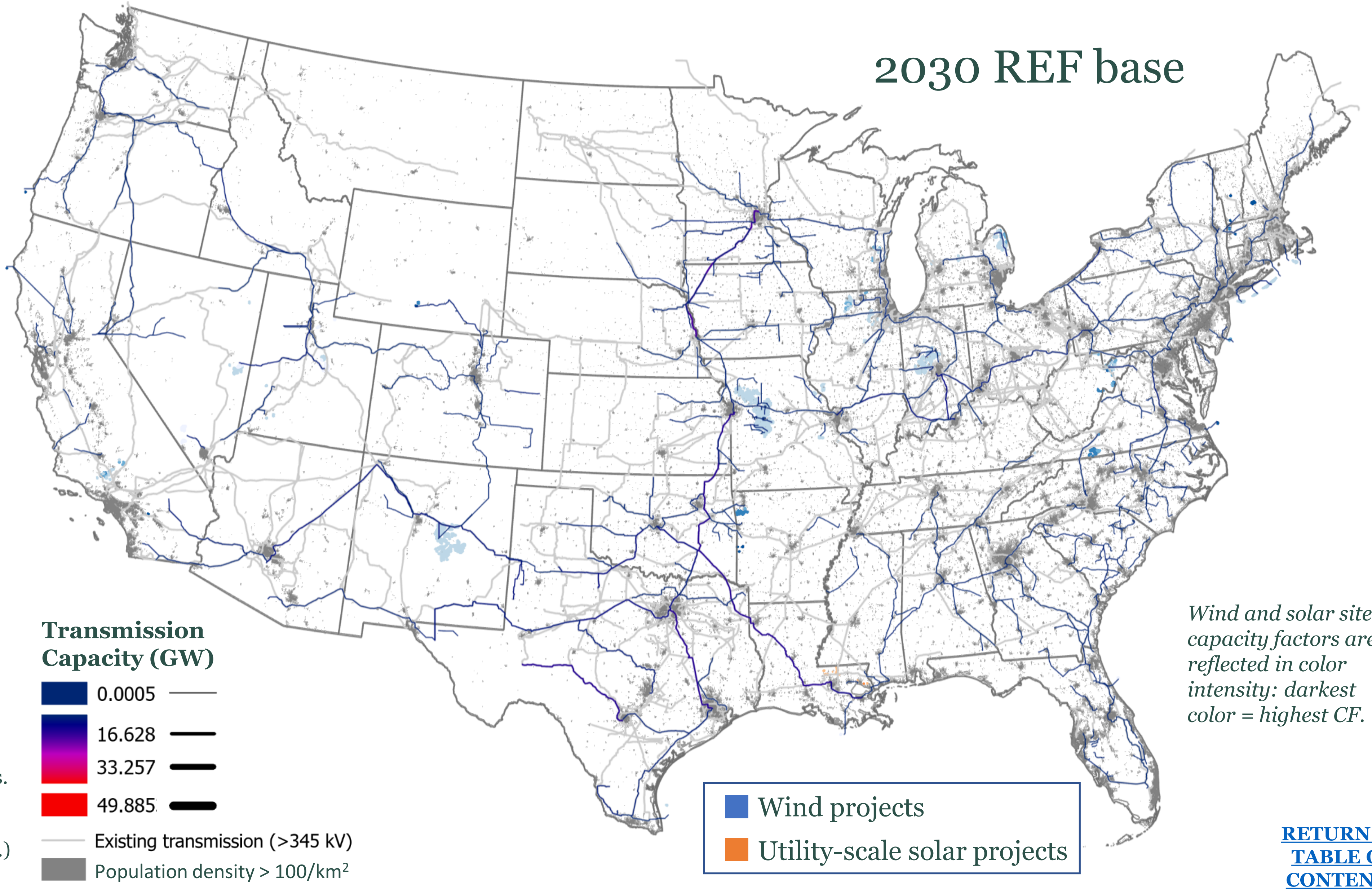
239 GW of wind and solar capacity operating in 2030; transmission capacity grows by 18%.

2030		
	Wind	Solar
Capacity installed (TW)		
	0.17	0.06
Land used (1000 km²)		
Total	69.1	1.02
Direct	0.69	0.92
Capital invested (Billion $\$_{2018}$)*		
Solar	-	41
Onshore wind	110	-
Offshore wind	9	-
Transmission added vs. 2020**		
Capacity (GW-km)	60,000	
Increase over 2020	18%	
Capital in serv (B$\$_{2018}$)	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.)



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

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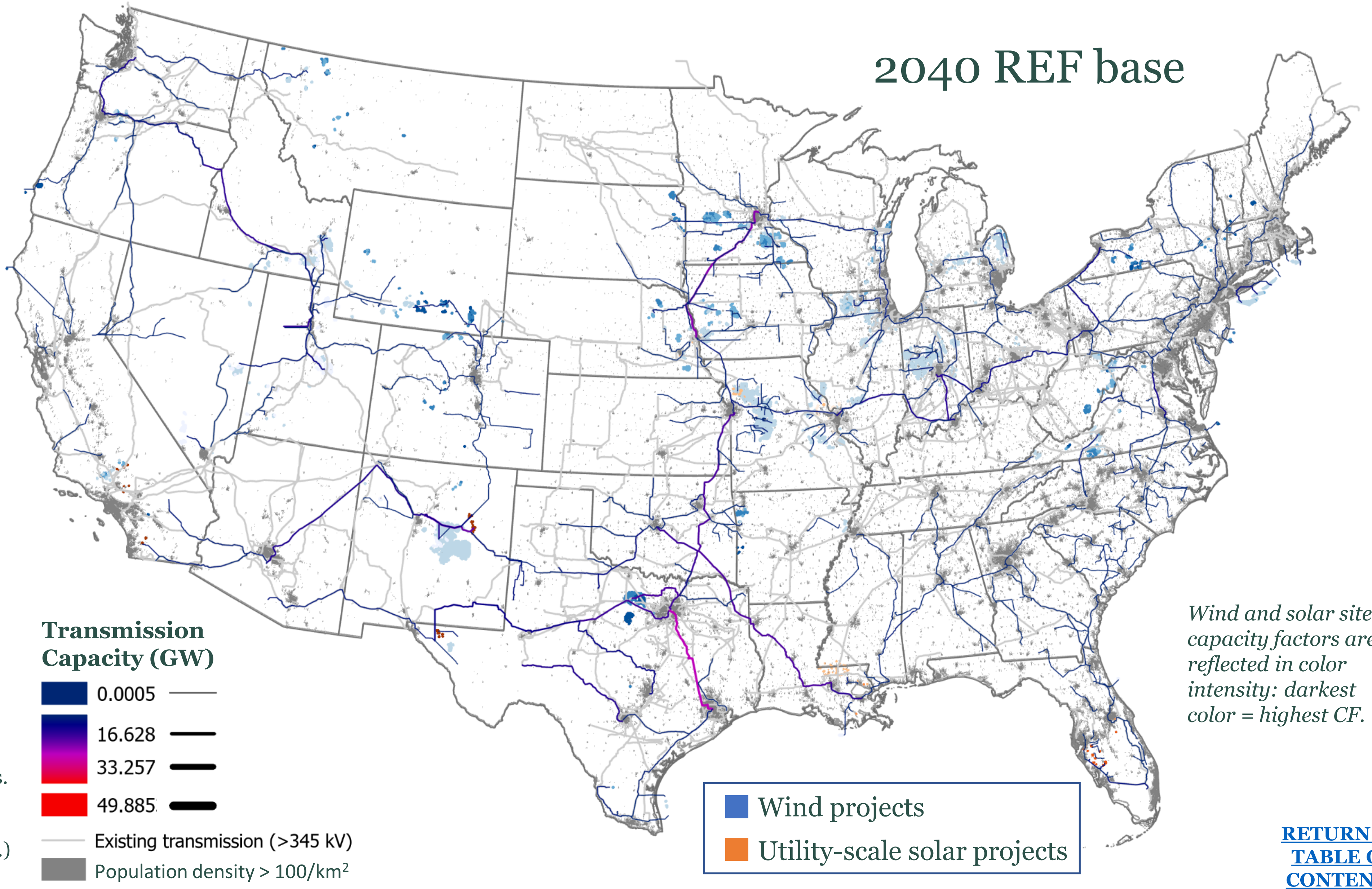
373 GW of wind and solar capacity operating in 2040; transmission capacity grows by 38% over 2020 level.

2040		
	Wind	Solar
Capacity installed (TW)		
	0.27	0.11
Land used (1000 km²)		
Total	102	1.87
Direct	1.02	1.70
Capital invested (Billion $$_{2018}$)*		
Solar	-	83
Onshore wind	213	-
Offshore wind	19	-
Transmission added vs. 2020**		
Capacity (GW-km)		122,000
Increase over 2020		38%
Capital in serv (B$$_{2018}$)		510

* 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.)



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

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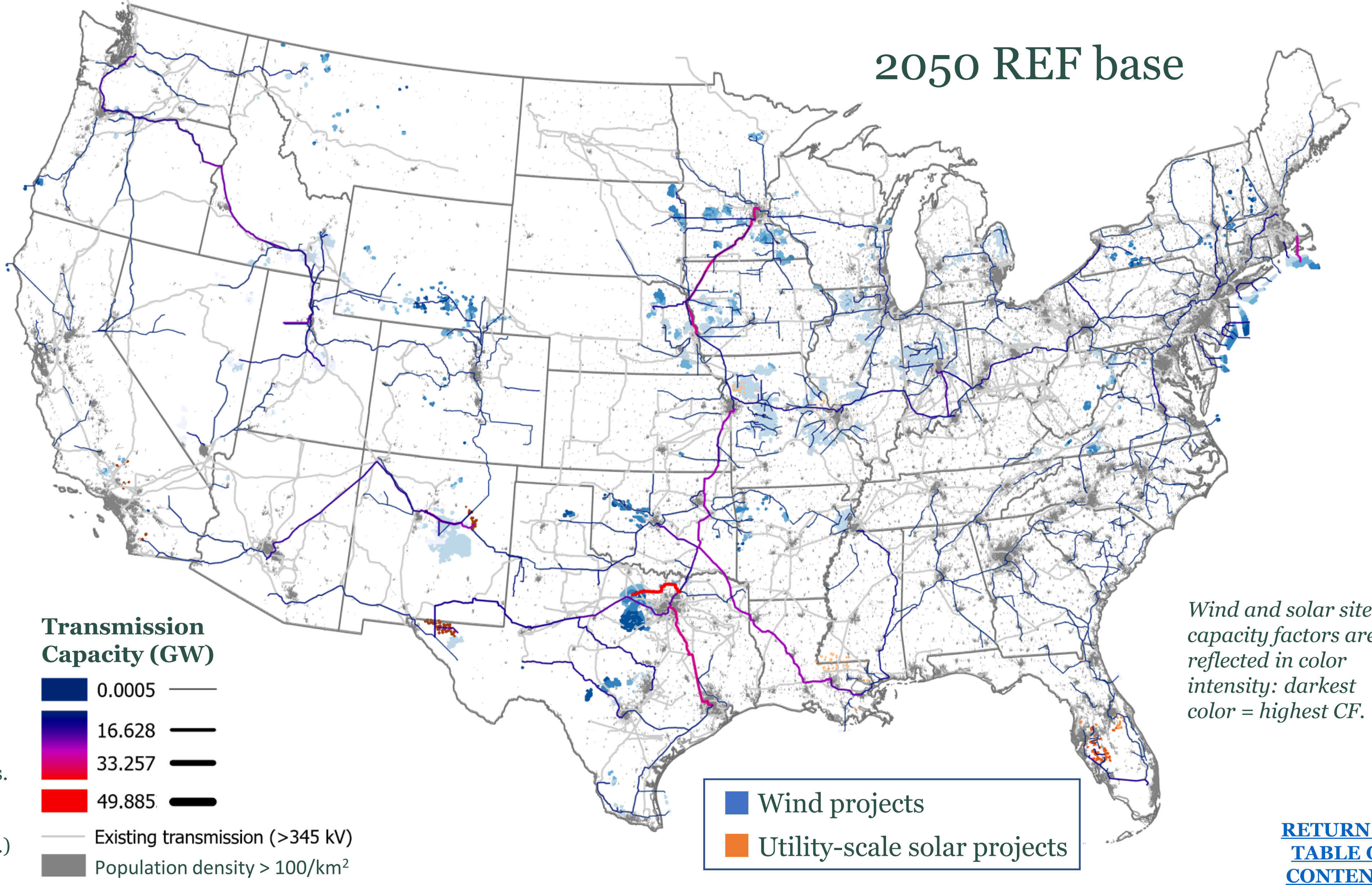
562 GW of wind and solar capacity operating in 2050; transmission capacity is 1.5x the 2020 level.

2050		
	Wind	Solar
Capacity installed (TW)		
	0.41	0.16
Land used (1000 km²)		
Total	142	3.05
Direct	1.42	2.77
Capital invested (Billion $$_{2018}$)*		
Solar	-	128
Onshore wind	327	-
Offshore wind	62	-
Transmission added vs. 2020**		
Capacity (GW-km)		152,000
Increase over 2020		47%
Capital in serv (B$$_{2018}$)		945

* 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.)



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

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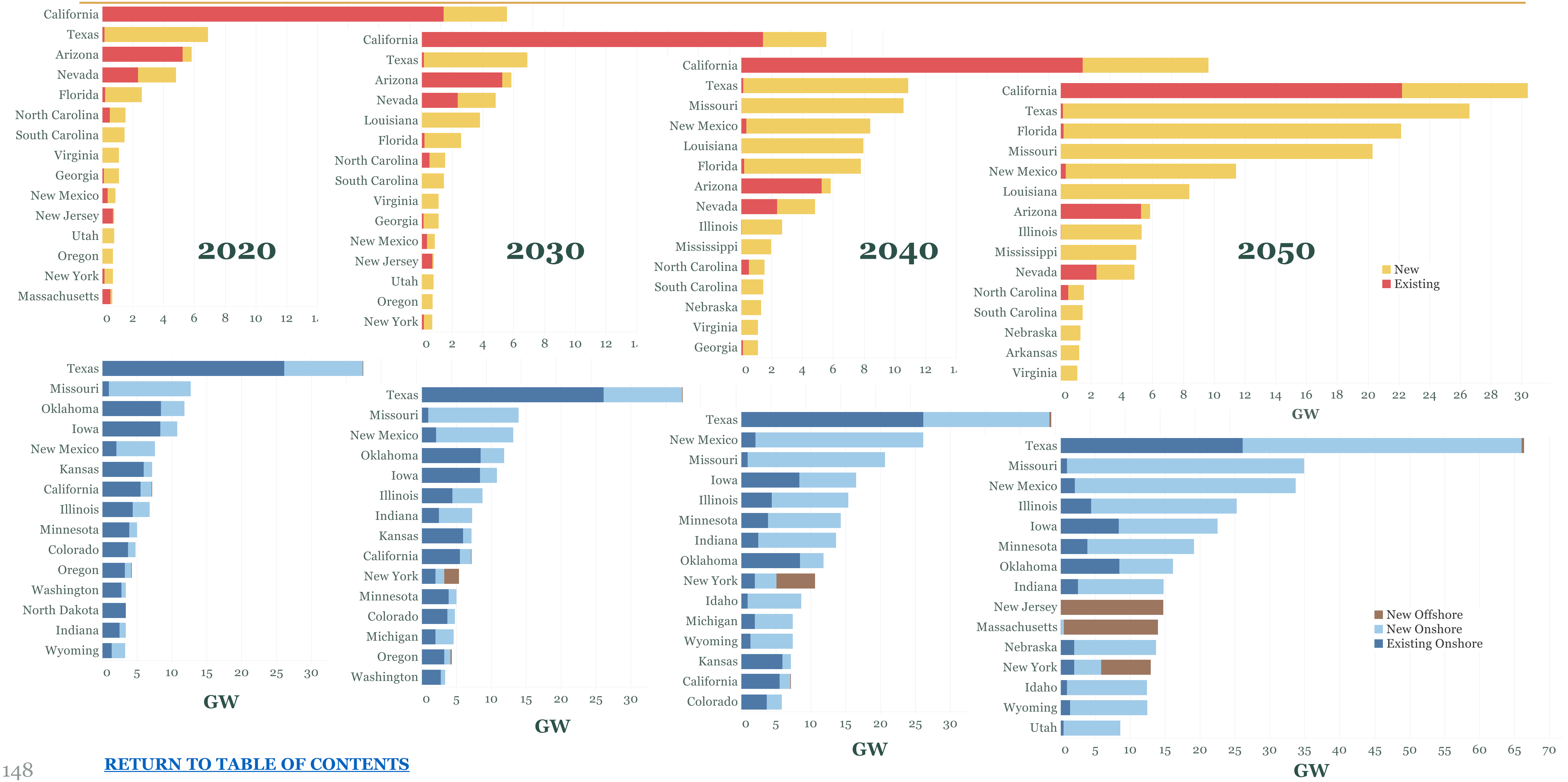
Top 15 states for installed wind and utility-scale solar capacity each decade, REF (base siting)



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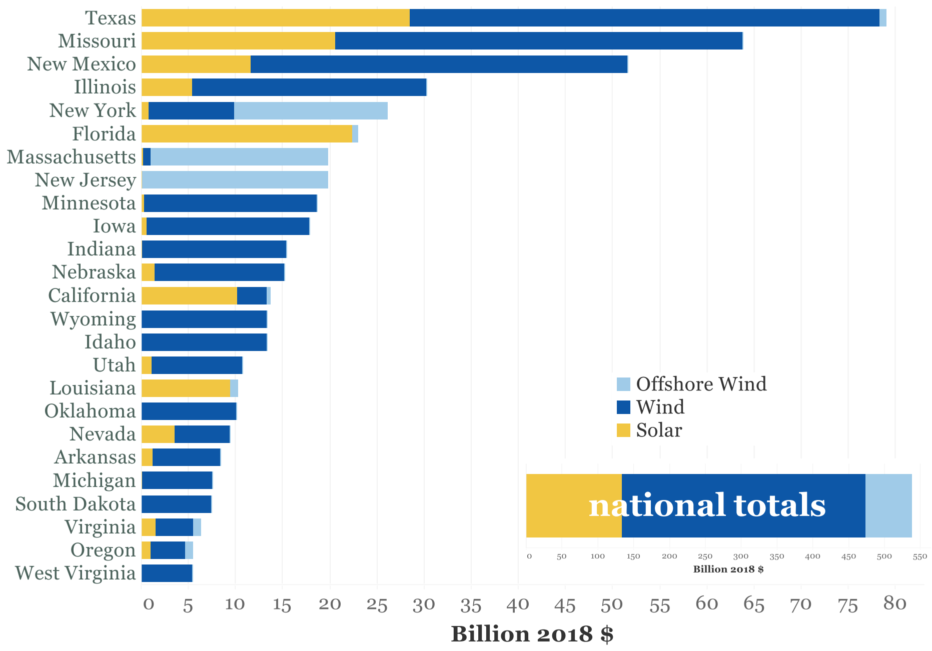
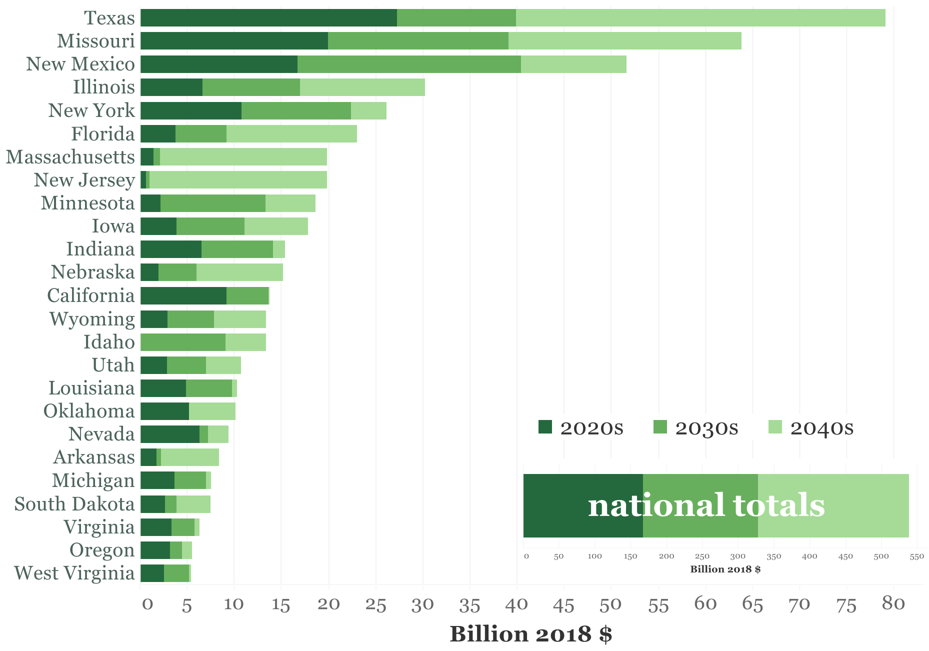
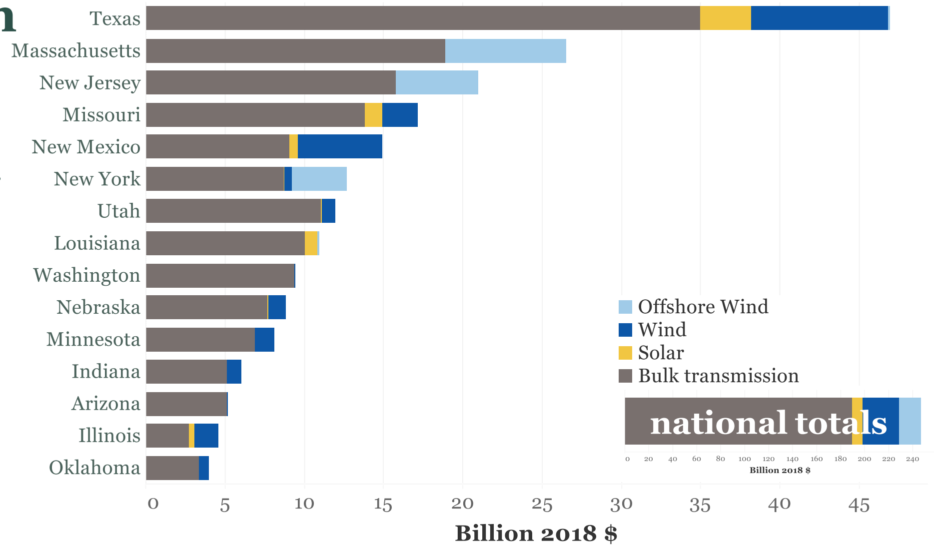
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, REF (base siting)

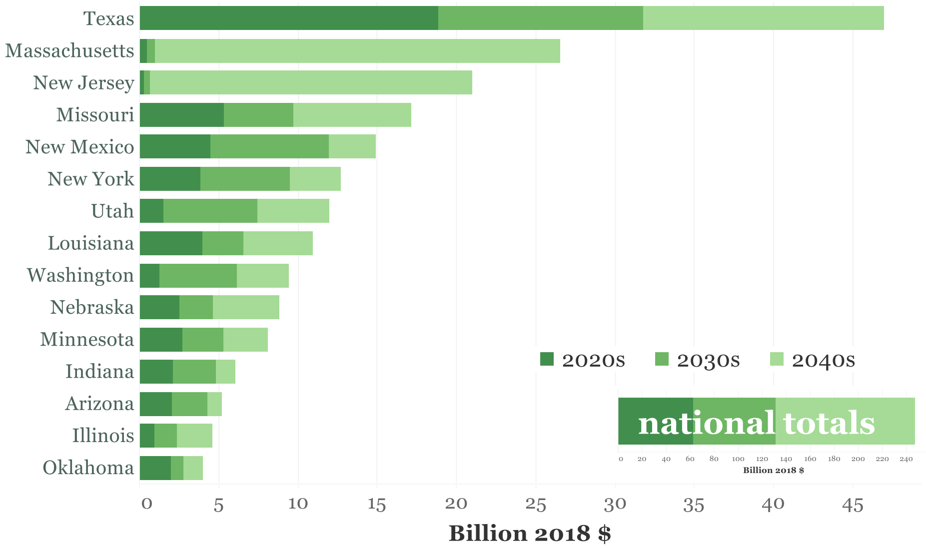
Wind & solar capacity investments, top 25 states





Transmission capacity investments, top 15 states*





* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.

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Clean firm resources and thermal plant retirements

Summary of this section

- 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 (224 GW) and the E+RE- scenario seeing the least capacity retired (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 and are fired entirely with zero-carbon synthetic gas.
- Siting studies indicated 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, but many existing sites would fail on at least one safety or environmental criteria currently applicable to new greenfield projects.

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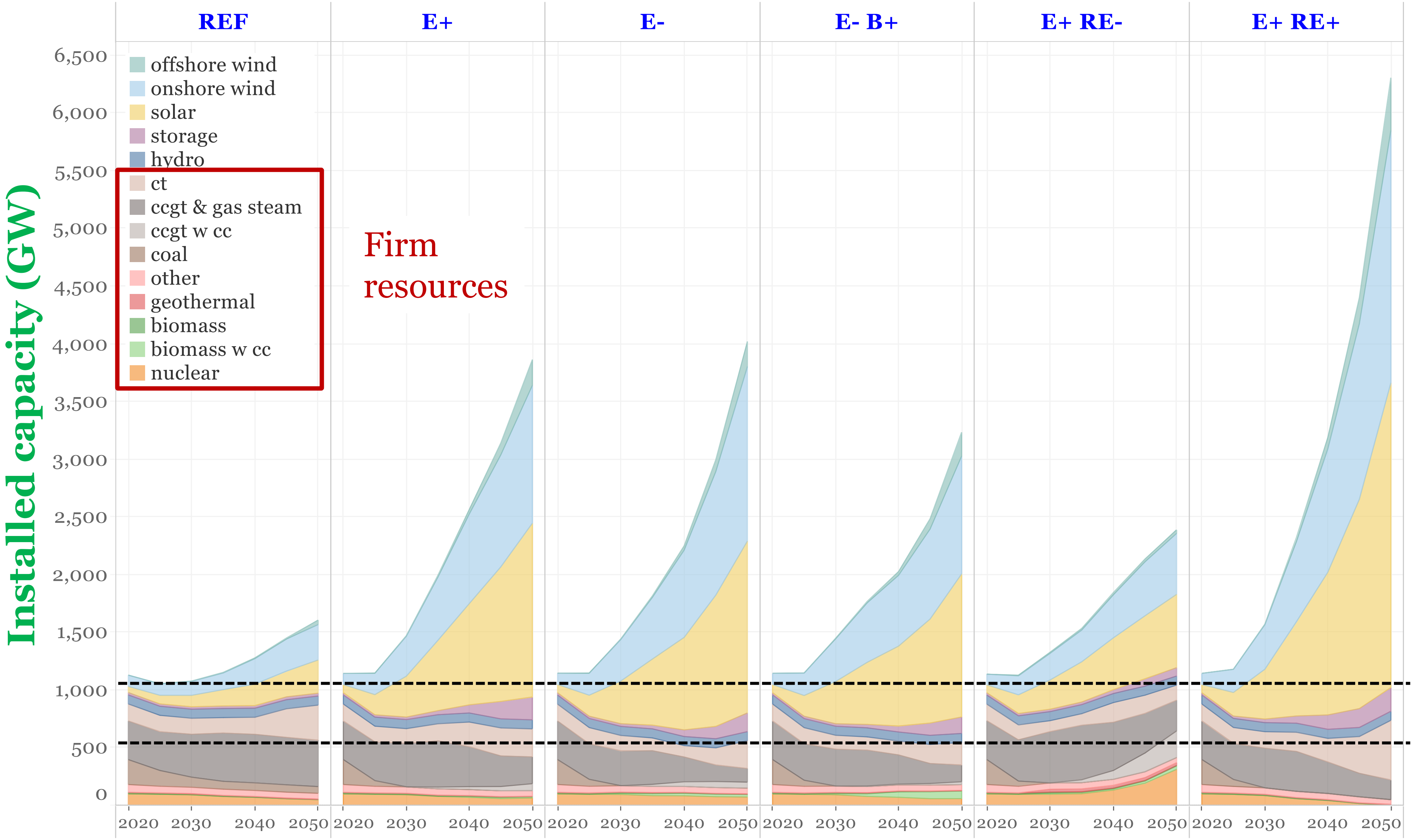
Firm capacity stays comparable to today; high H_2 fuel blends for gas turbines have important role; nuclear & gas w/CCS key in RE-



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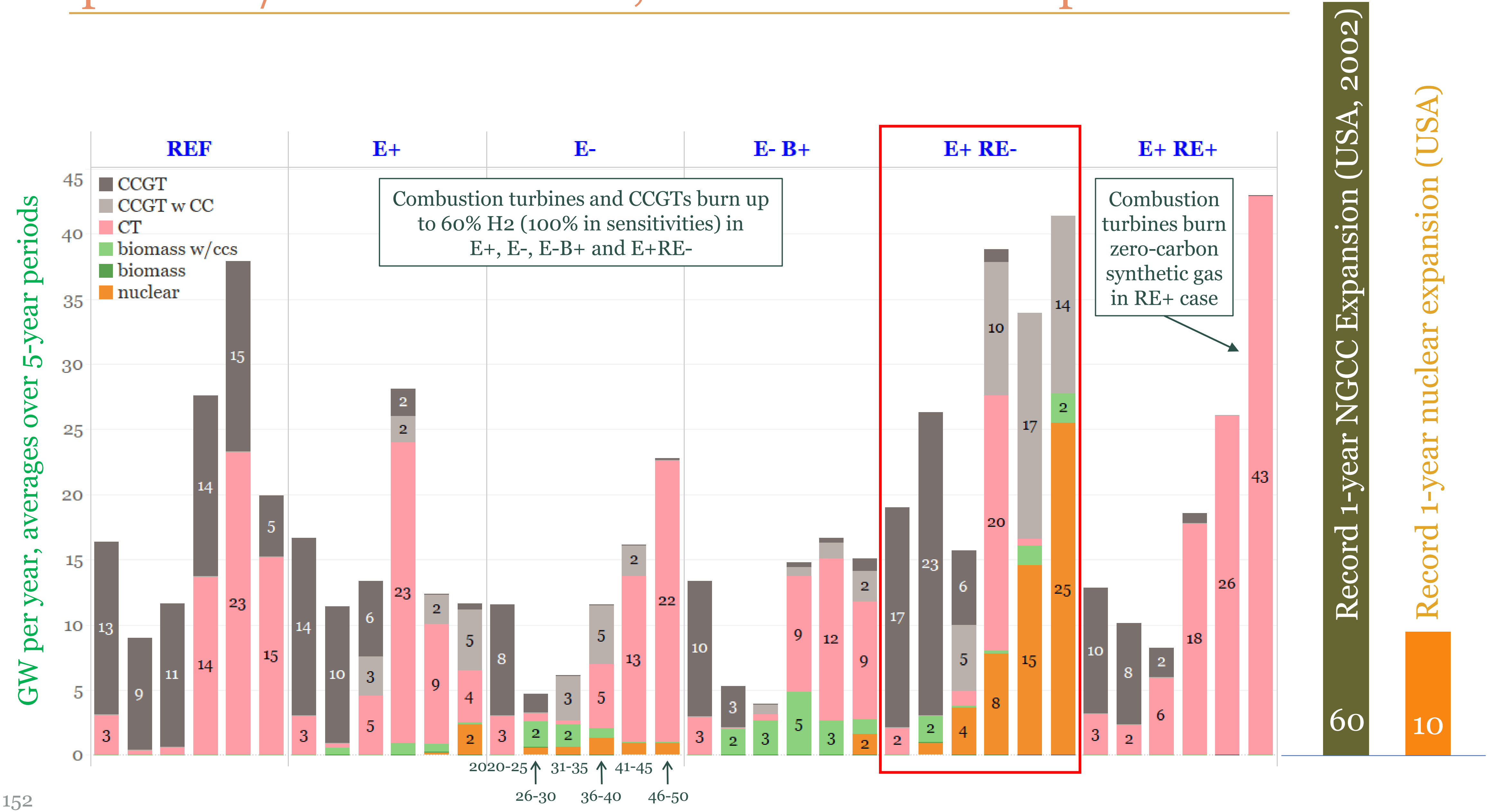
E+ RE- requires historically-unprecedented growth rates for gas plants w/CCS and nuclear, sustained for multiple decades



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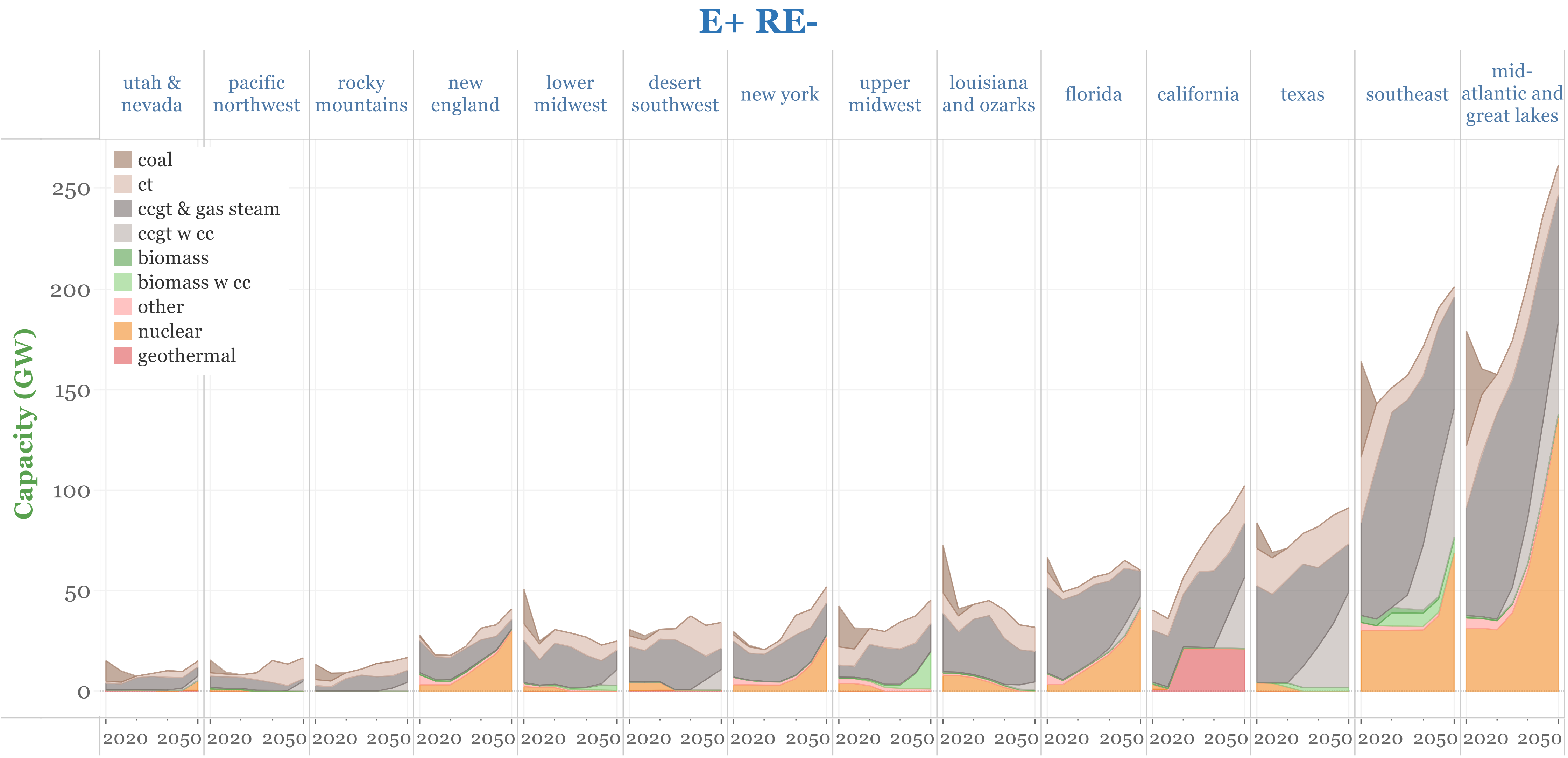
New England, New York, California, Florida, Southeast and Mid-Atlantic/ Great Lakes regions see largest nuclear growth in RE-



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Modeling conversion and retirement of coal, gas, and nuclear plants and sites considers operating costs and site suitability criteria.

Site suitability assessment

Evaluate potential sites based on suitability and exclusion criteria

- Safety
- Environmental / cultural
- Water intake
- Site size
- CO_2 infrastructure
- Environmental justice

Retirement simulation

Timing and location by plant type

- Regional & temporal retired capacity constraints
- Prioritize based on operating costs

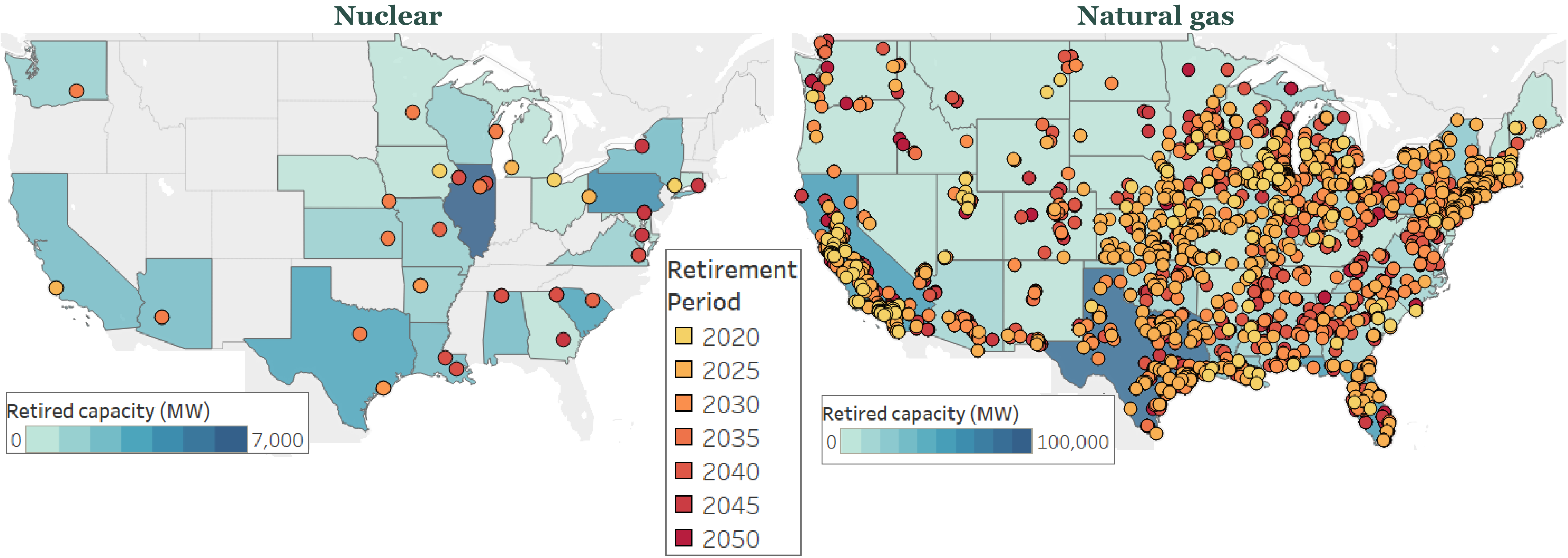
Site conversion simulation

Conversion of existing thermal sites to new natural gas or nuclear sites

- Site conversions prioritized by extent of siting constraints for each technology
- Retirement of existing plants
- Regional & temporal incremental capacity constraints
- Site suitability constraints
- Re-development temporal lag constraints

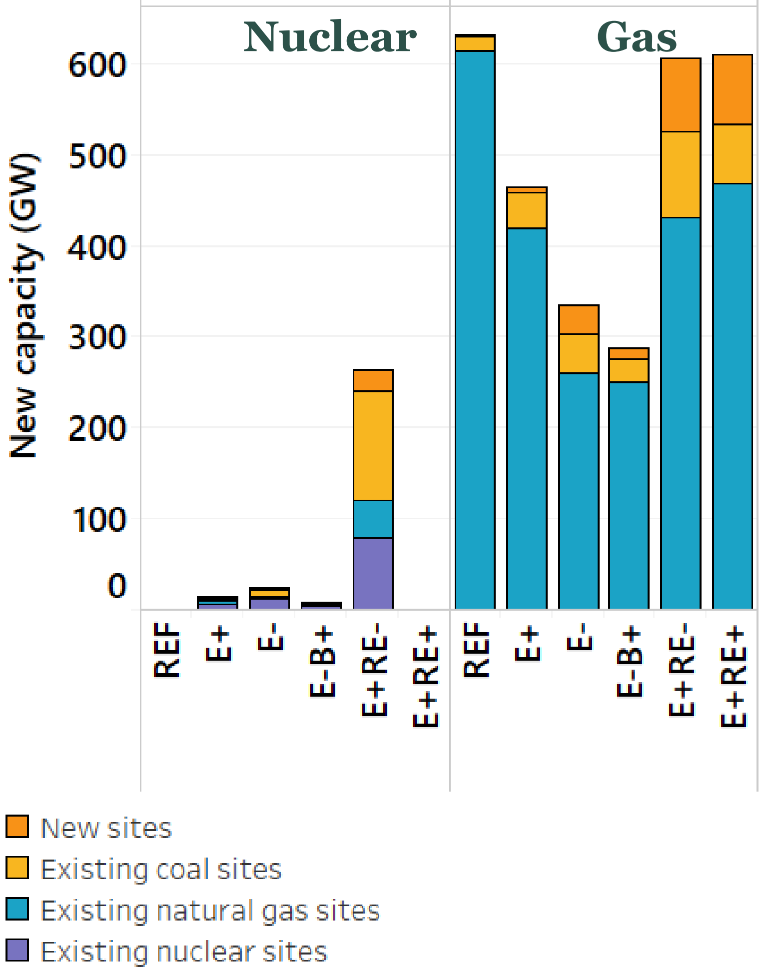
See Annex E for additional discussion of thermal plant siting analysis.

Due to age, 45% of nuclear and 80% of gas capacity retire by 2050; site repowering or conversion to low-carbon generators is possible.

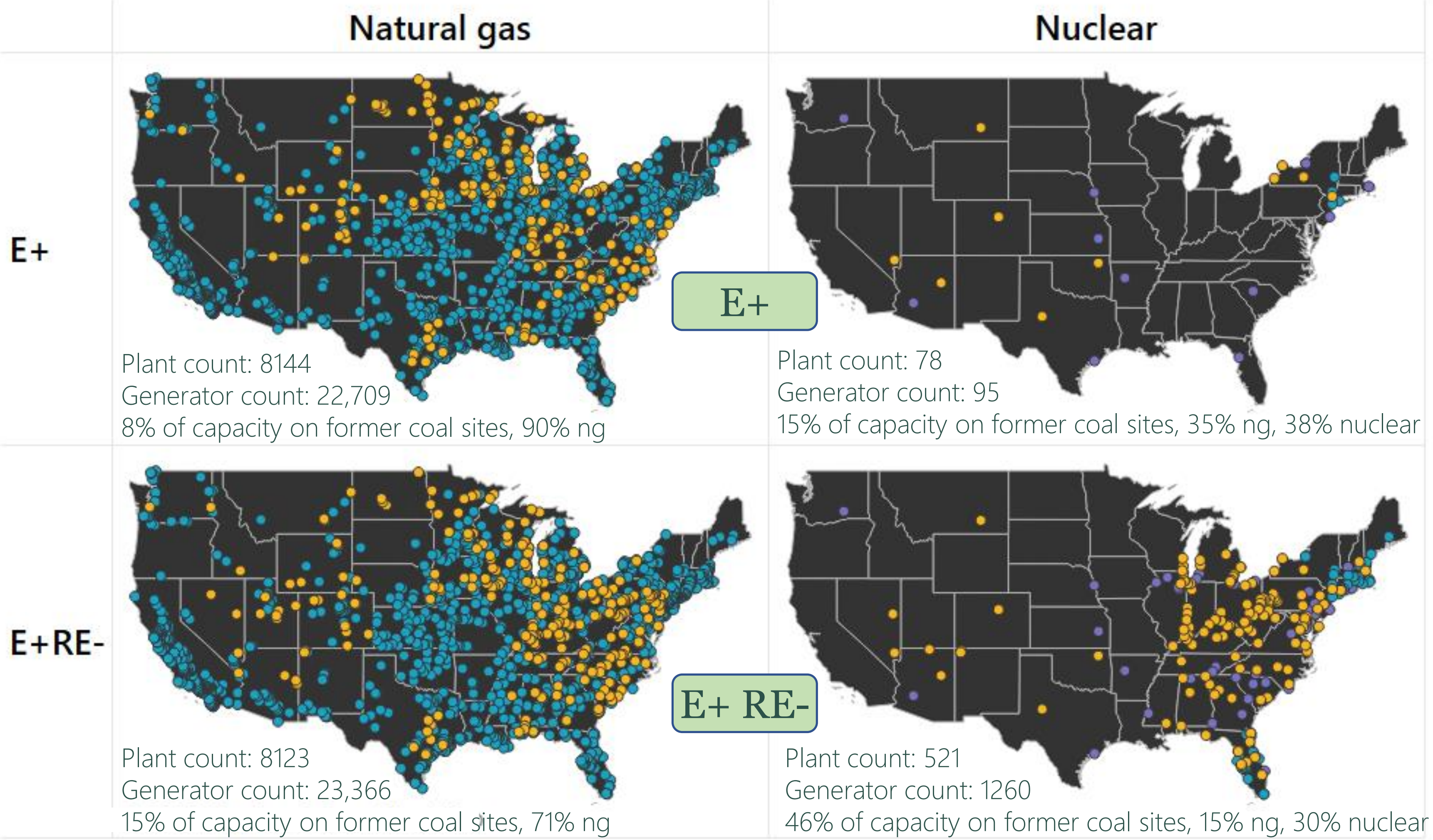


Most new gas and nuclear capacity can be accommodated at existing thermal plant sites, if no new siting restrictions are applied.

New capacity by site type cumulative 2020 - 2050



Site conversions by site type by 2050



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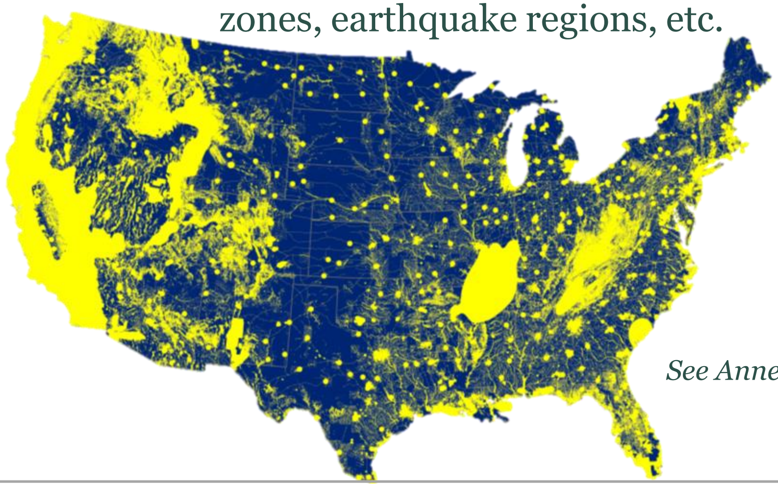
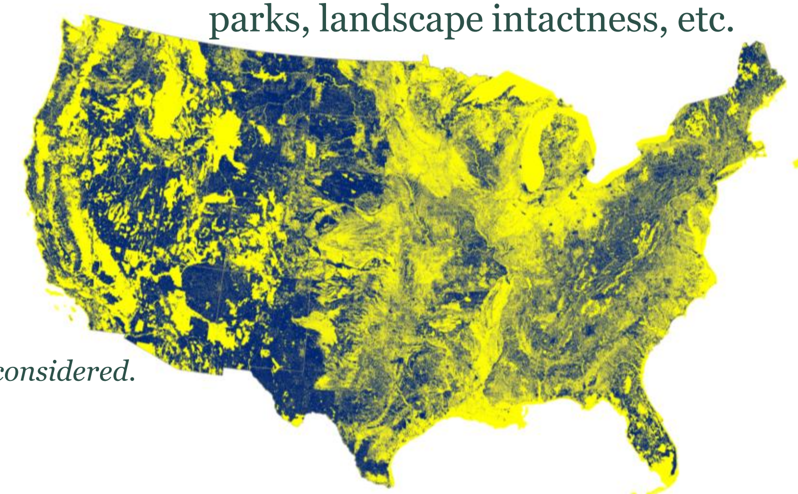
Siting constraints vary by region and are uncertain for emerging technologies (e.g., advanced nuclear).

Many brownfield sites may not meet all environmental and safety-related land-use criteria in a restrictive land use planning regime.

Safety exclusions *(12)*: urban areas, flood zones, earthquake regions, etc.

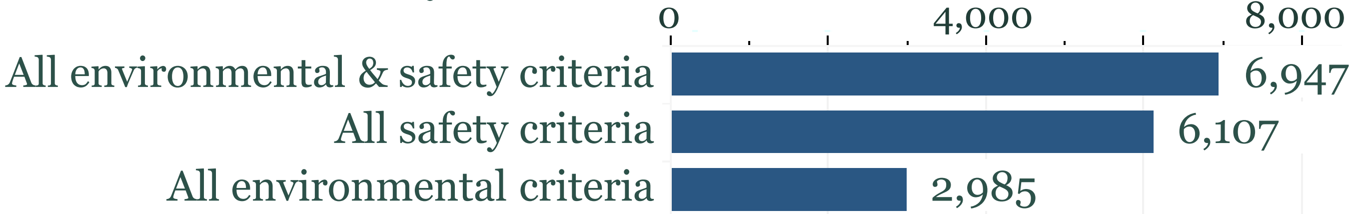


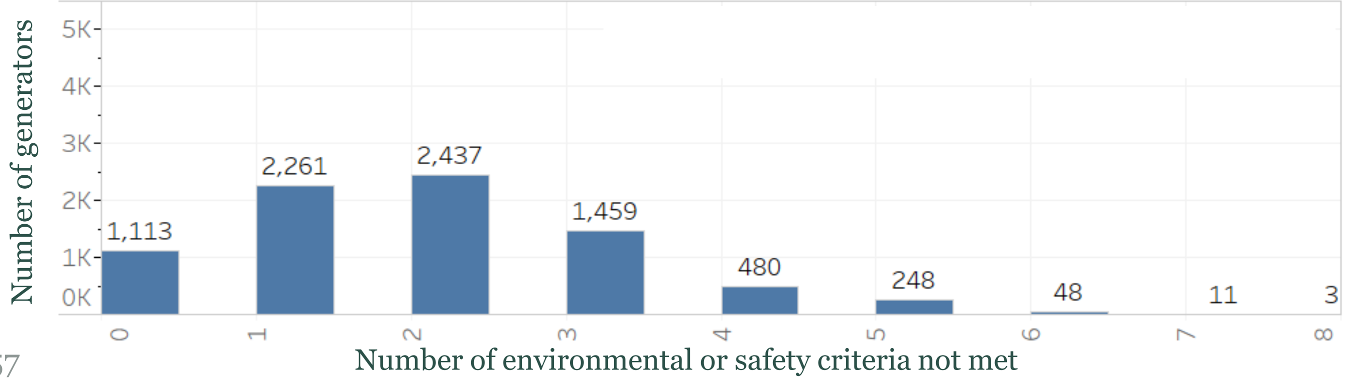
Environmental exclusions *(35)*: wetlands, national parks, landscape intactness, etc.

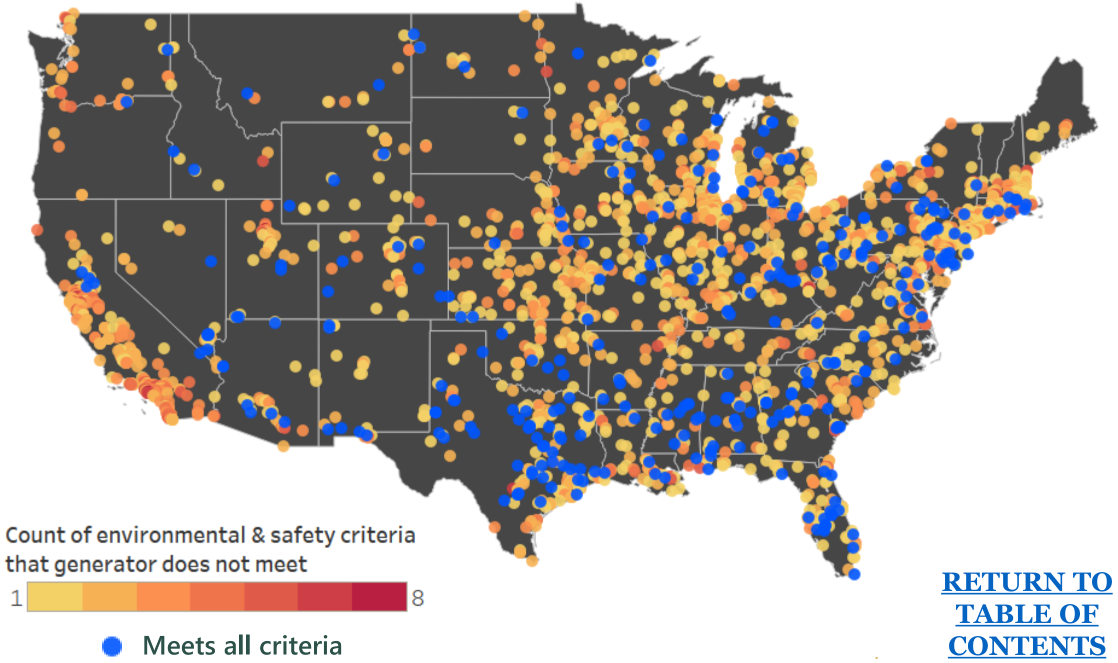


See Annex E for full list of exclusions considered.

Number of current generator locations that would fail to meet site suitability criteria







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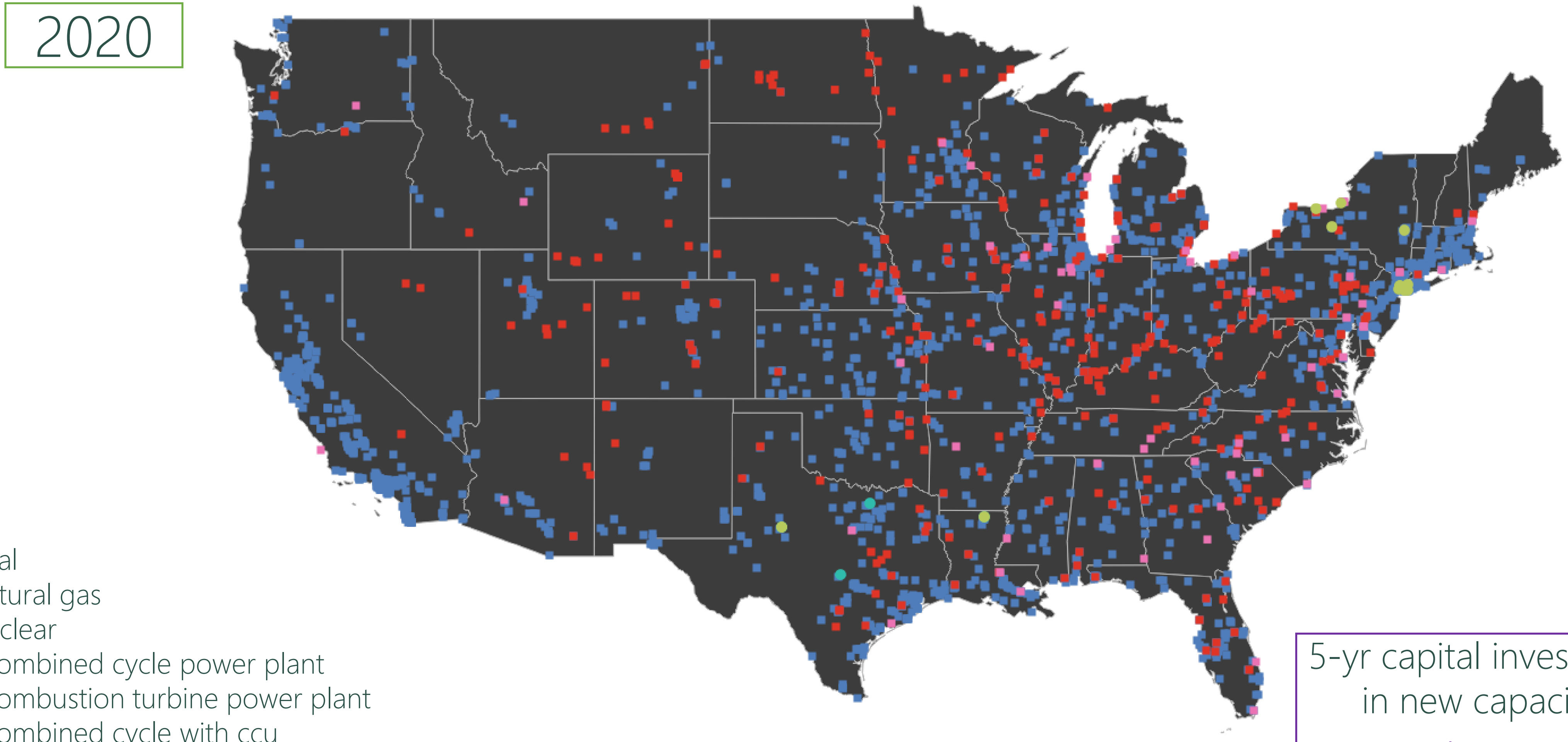
Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2020

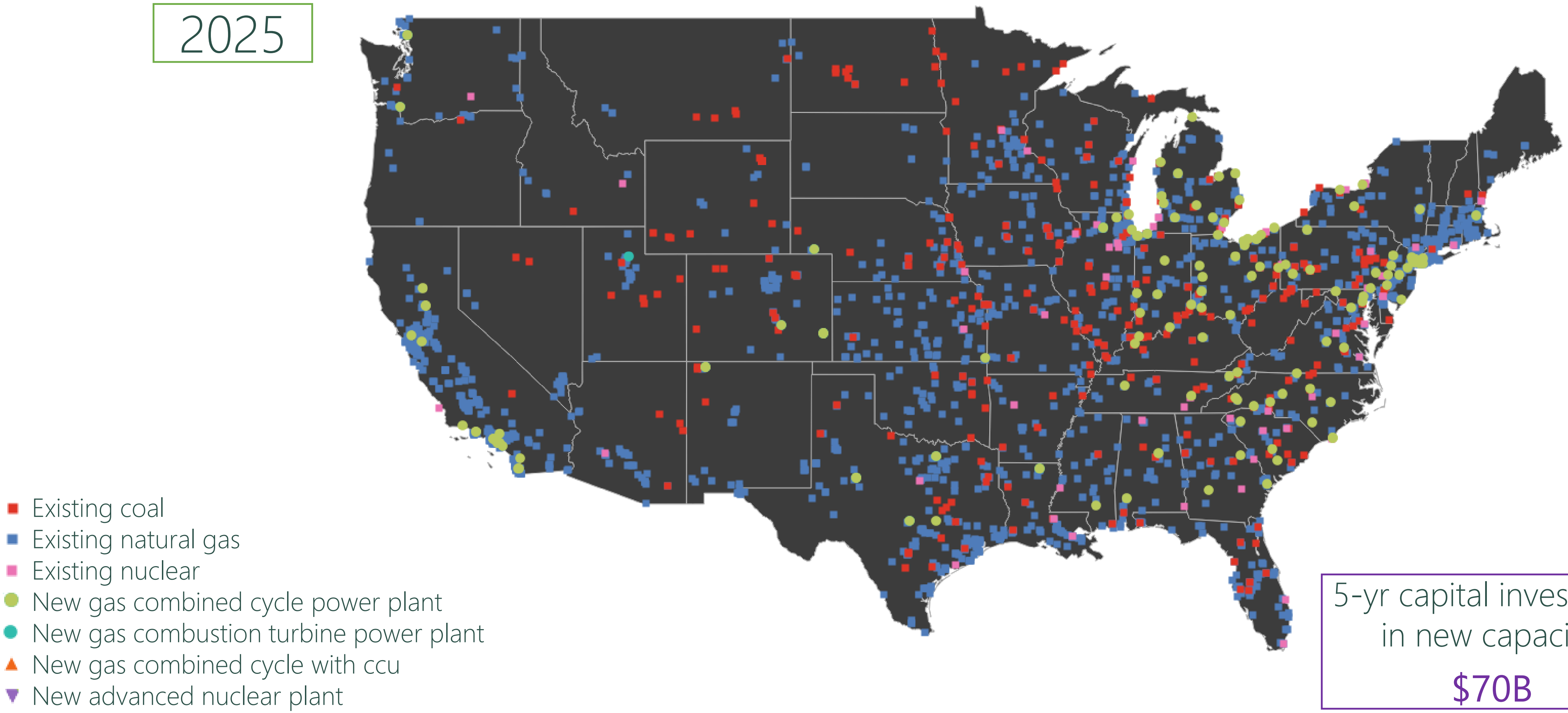


- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$11B

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2025



5-yr capital investment in new capacity:

$70B

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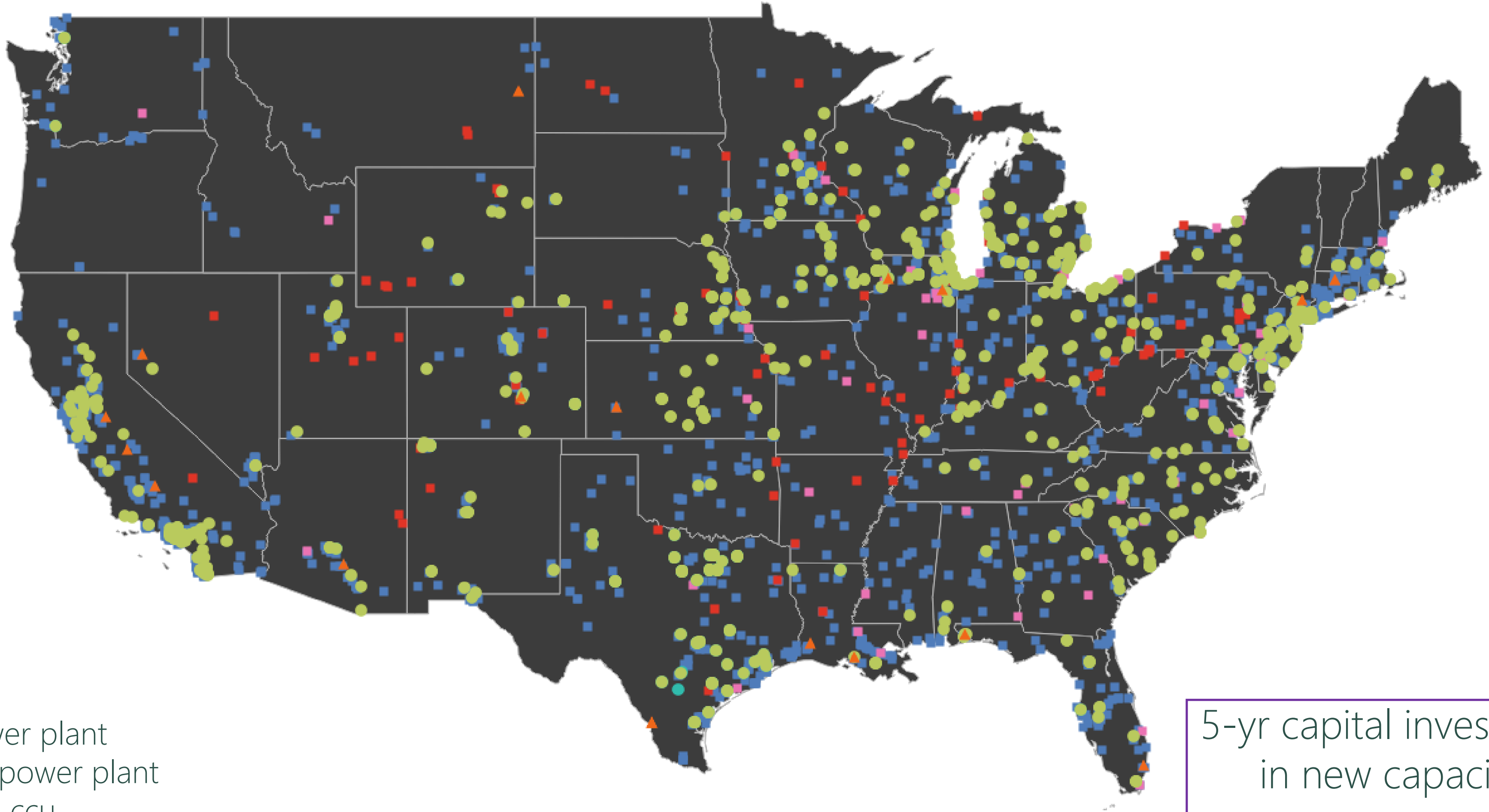
Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2030

2030



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$46B

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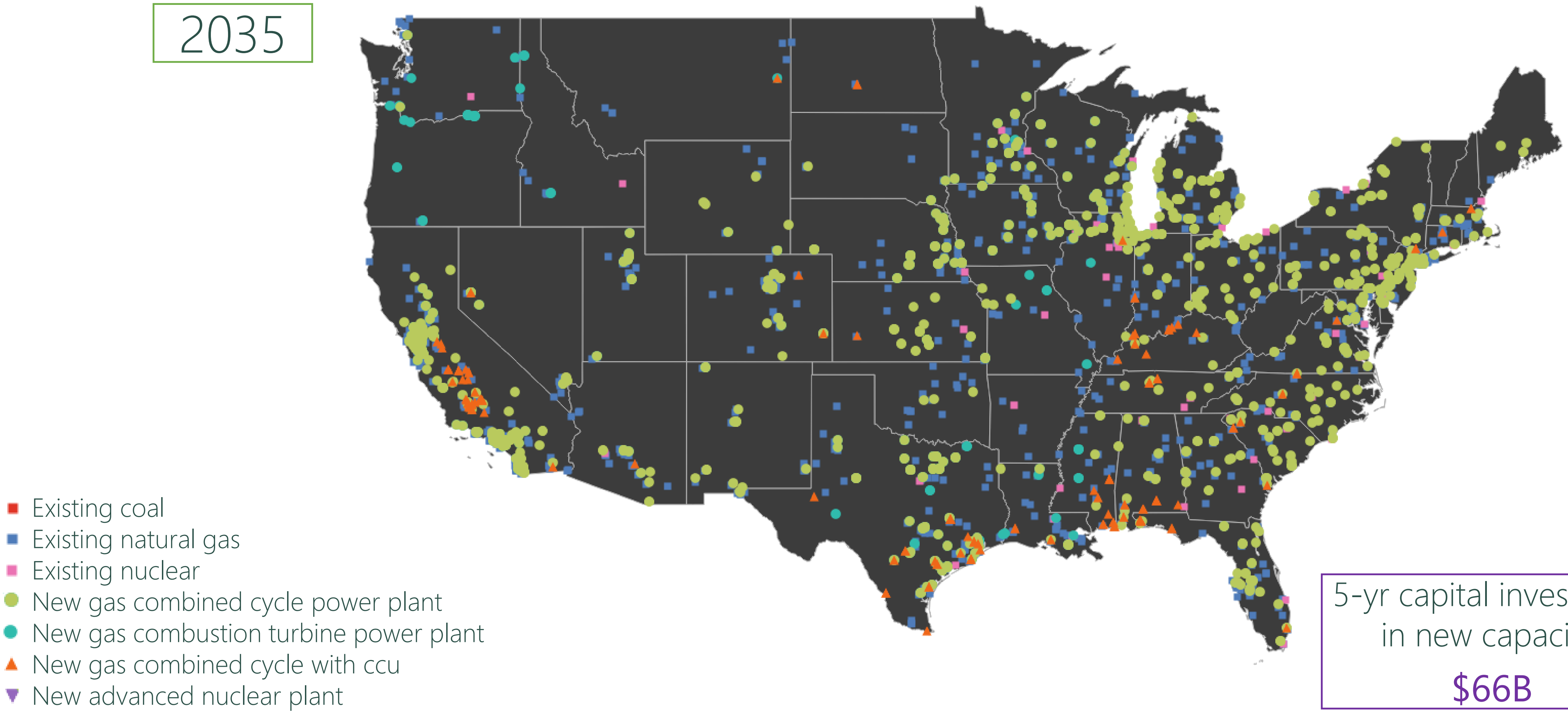
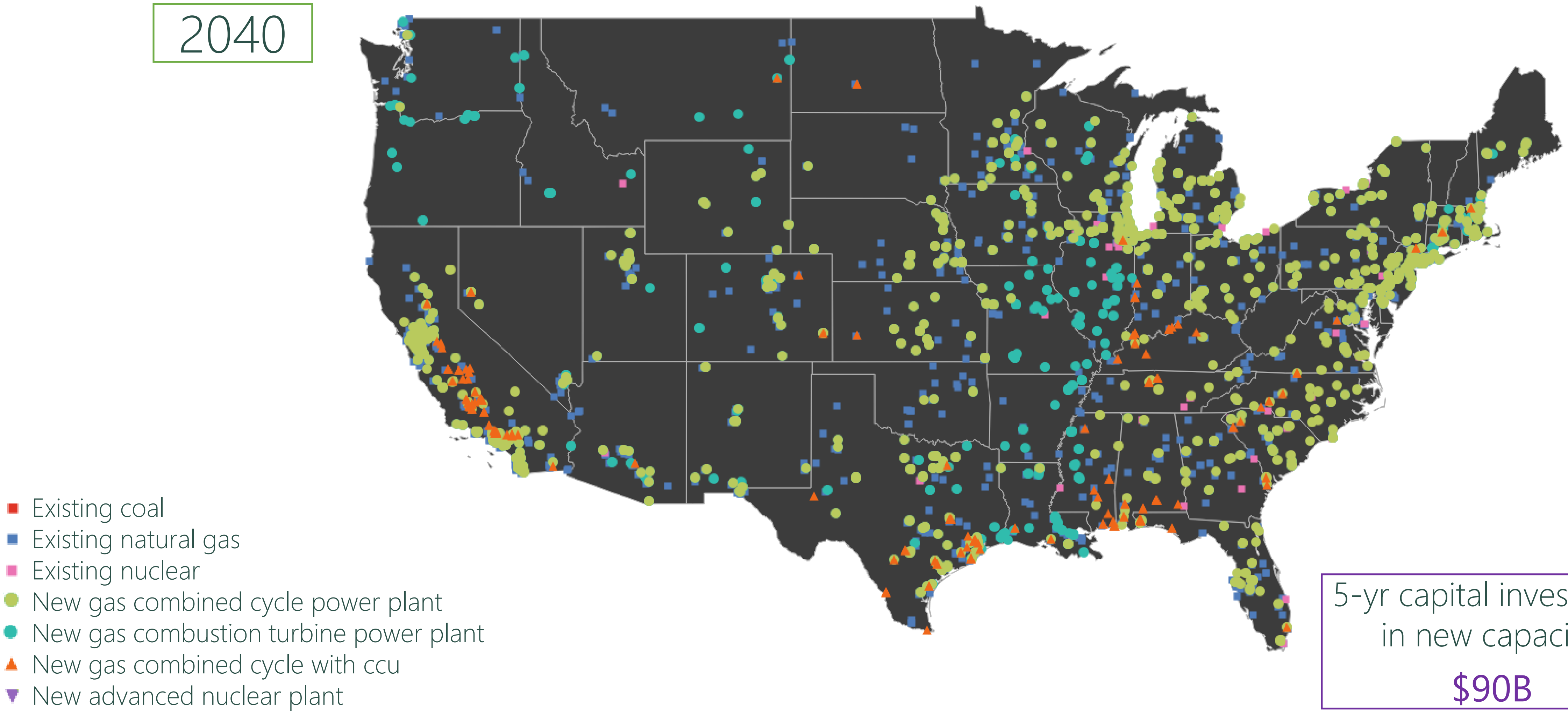
Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2035



5-yr capital investment in new capacity:

$66B

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2040

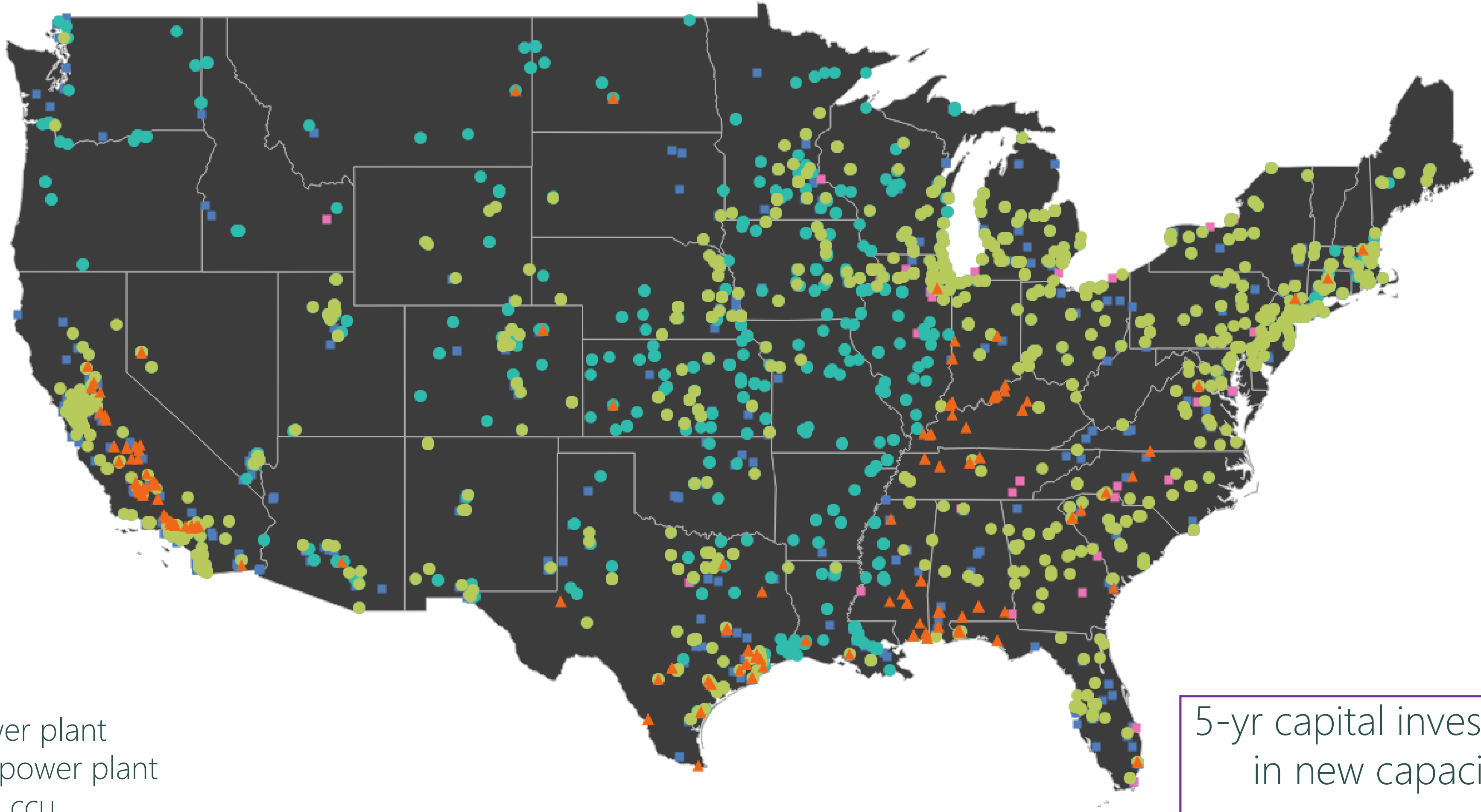


5-yr capital investment in new capacity:

$90B

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2045

2045



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$54B

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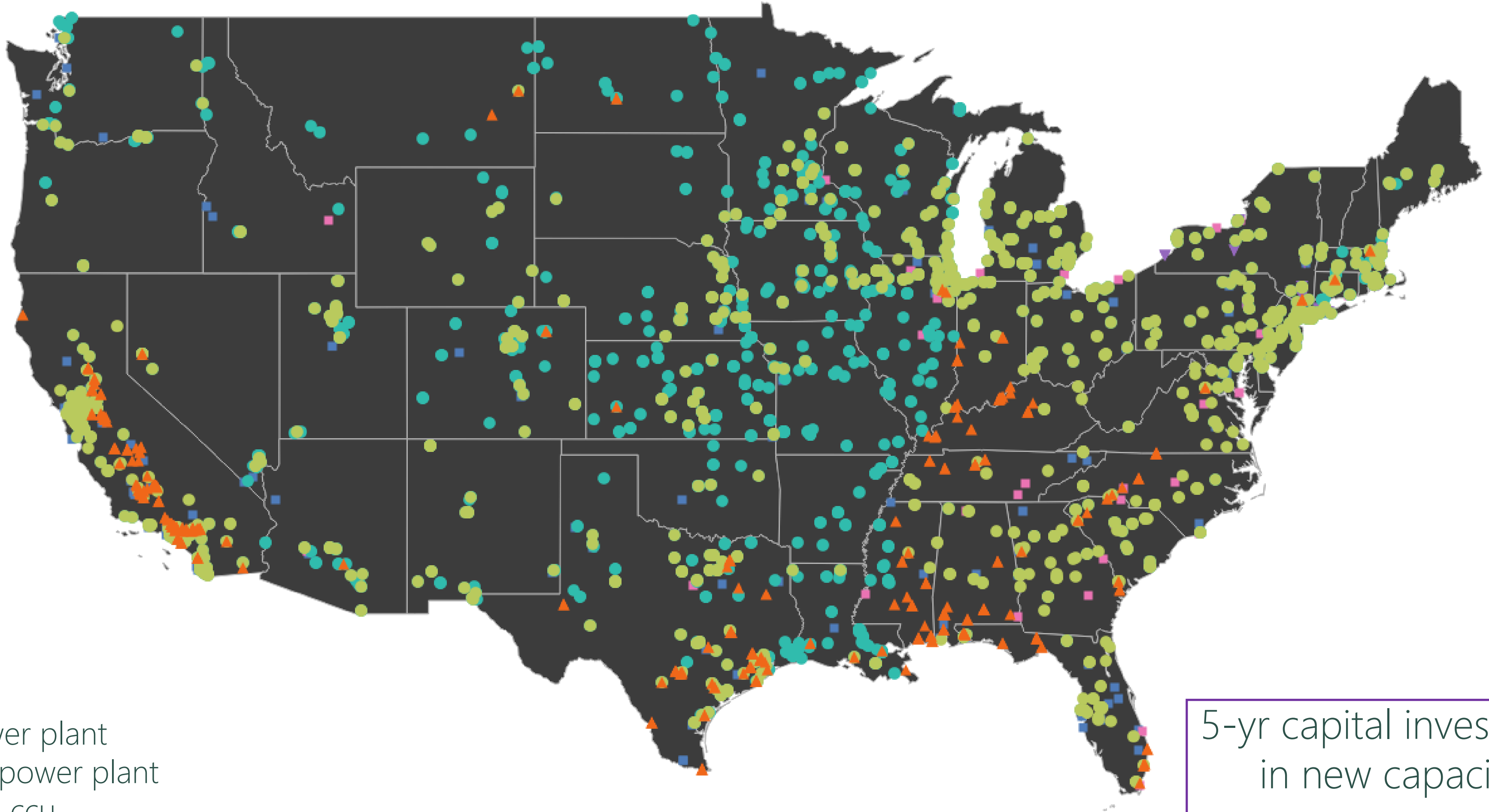
Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2050

2050

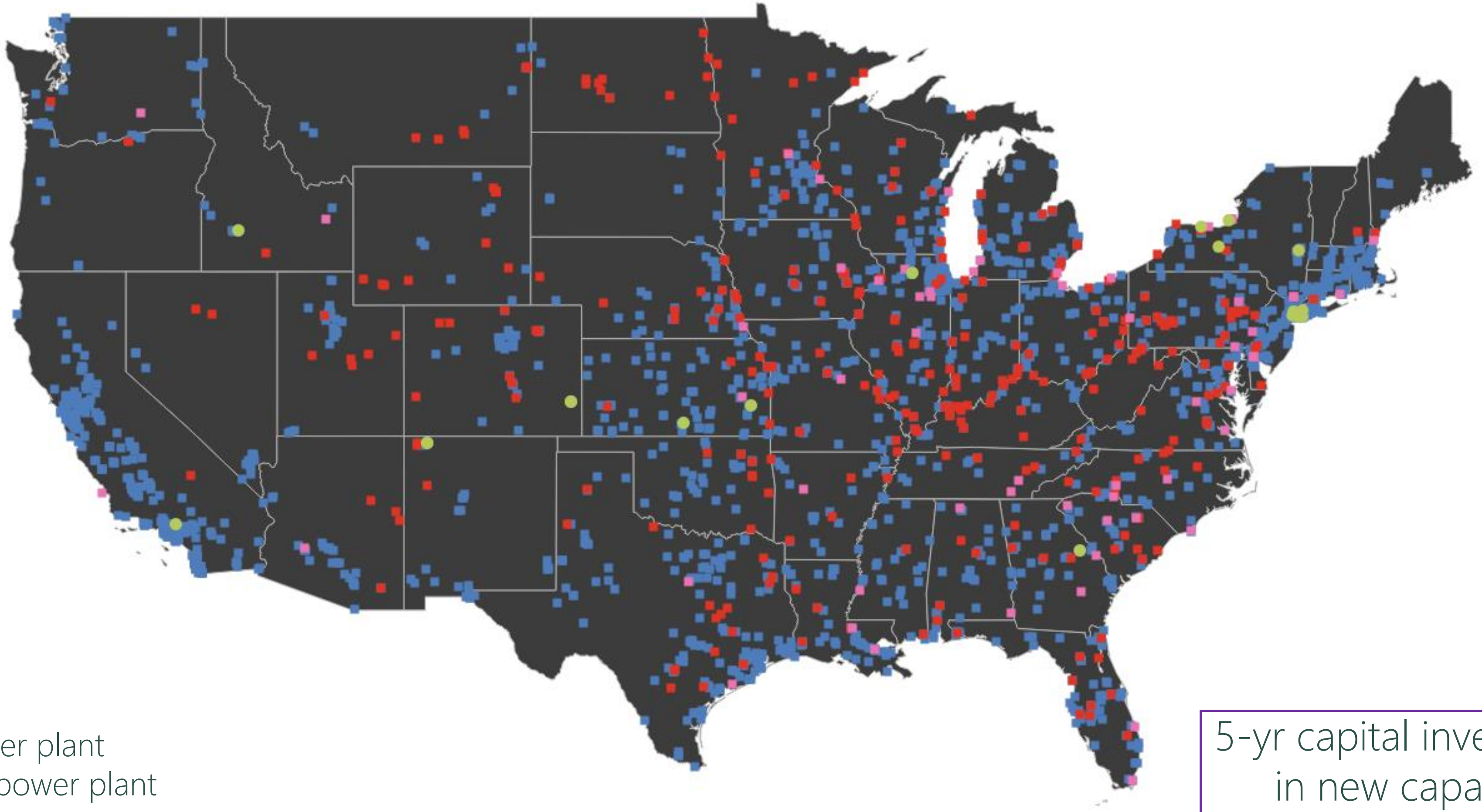


- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$123B

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2020

2020



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$12B

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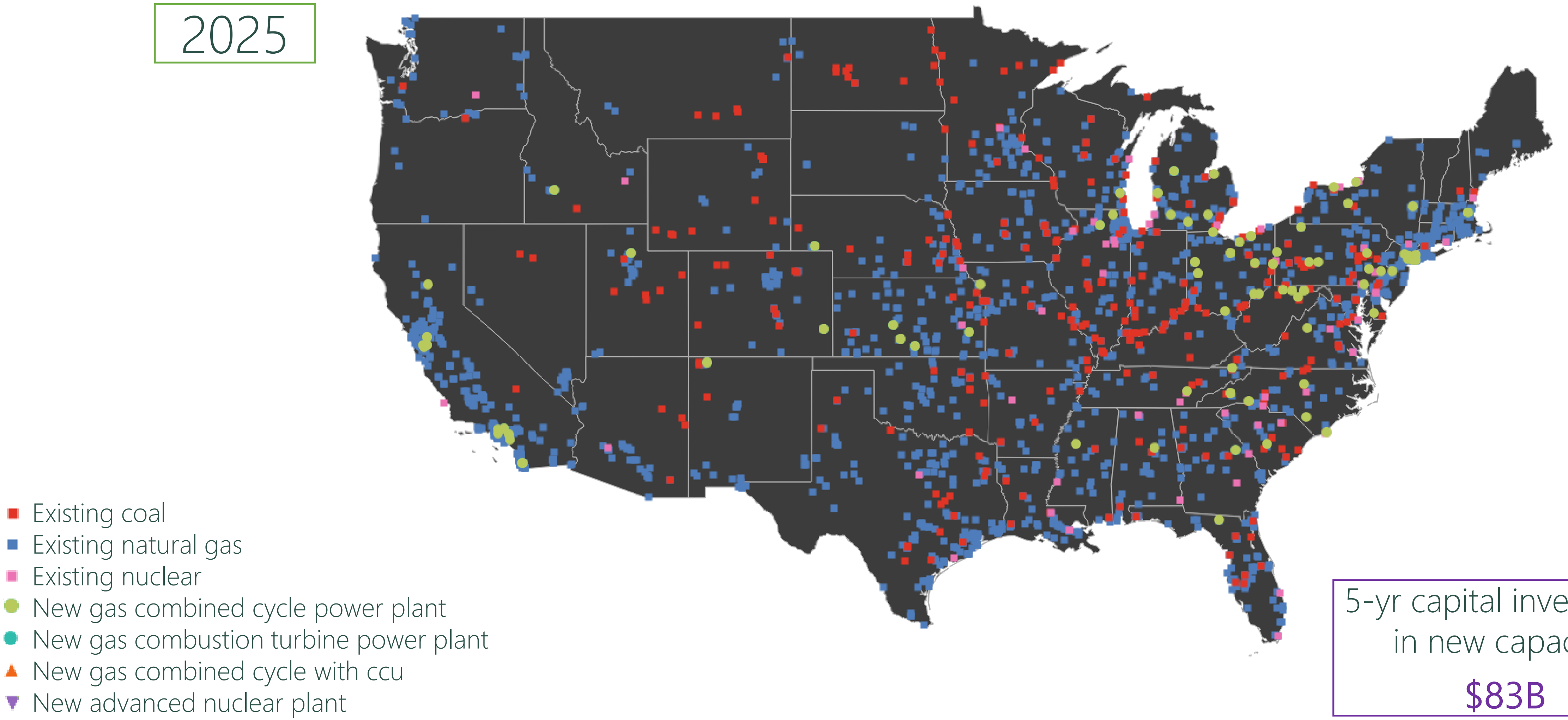
Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2025



5-yr capital investment in new capacity:
$83B

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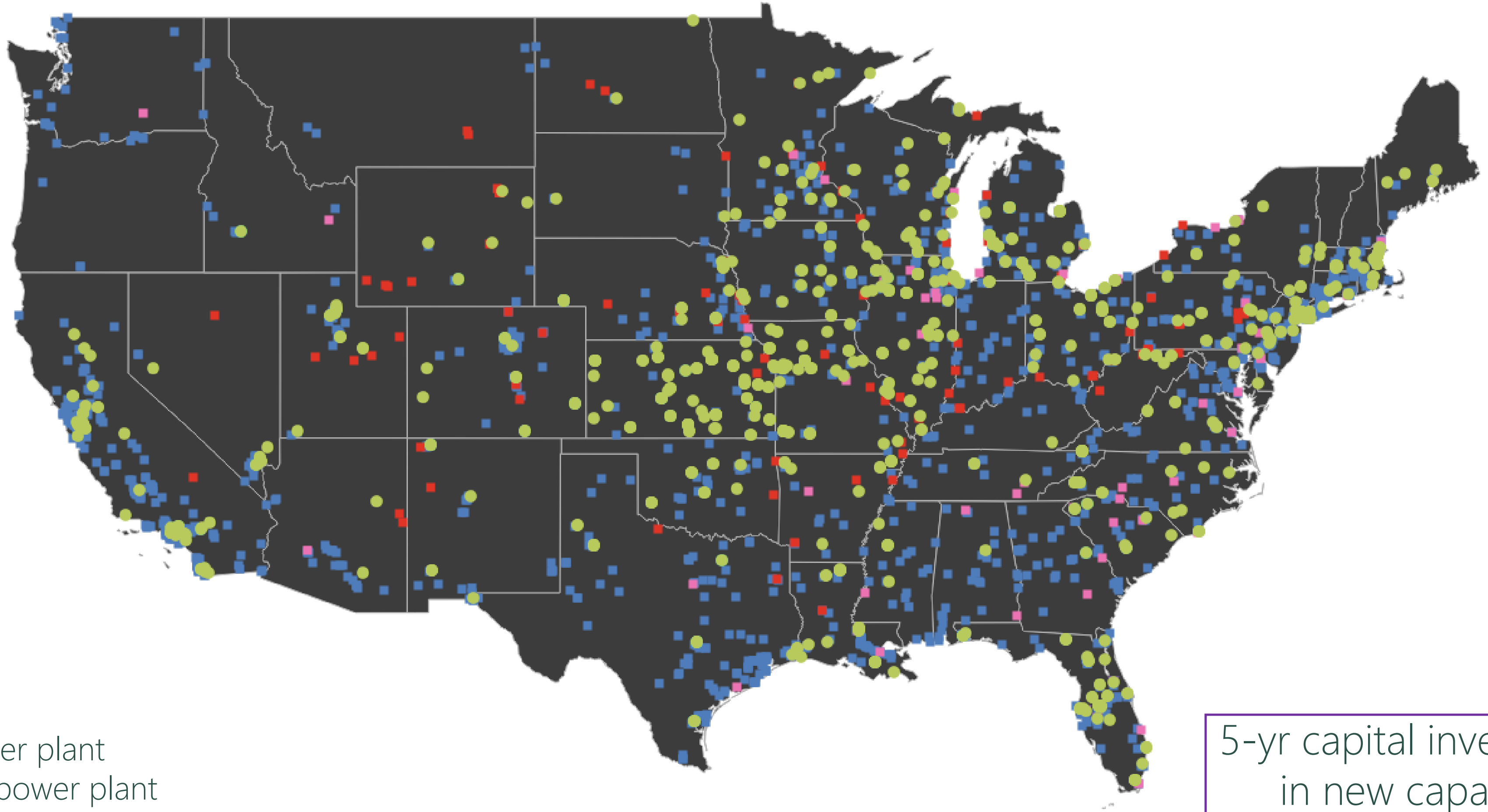
Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2030

2030



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$129B

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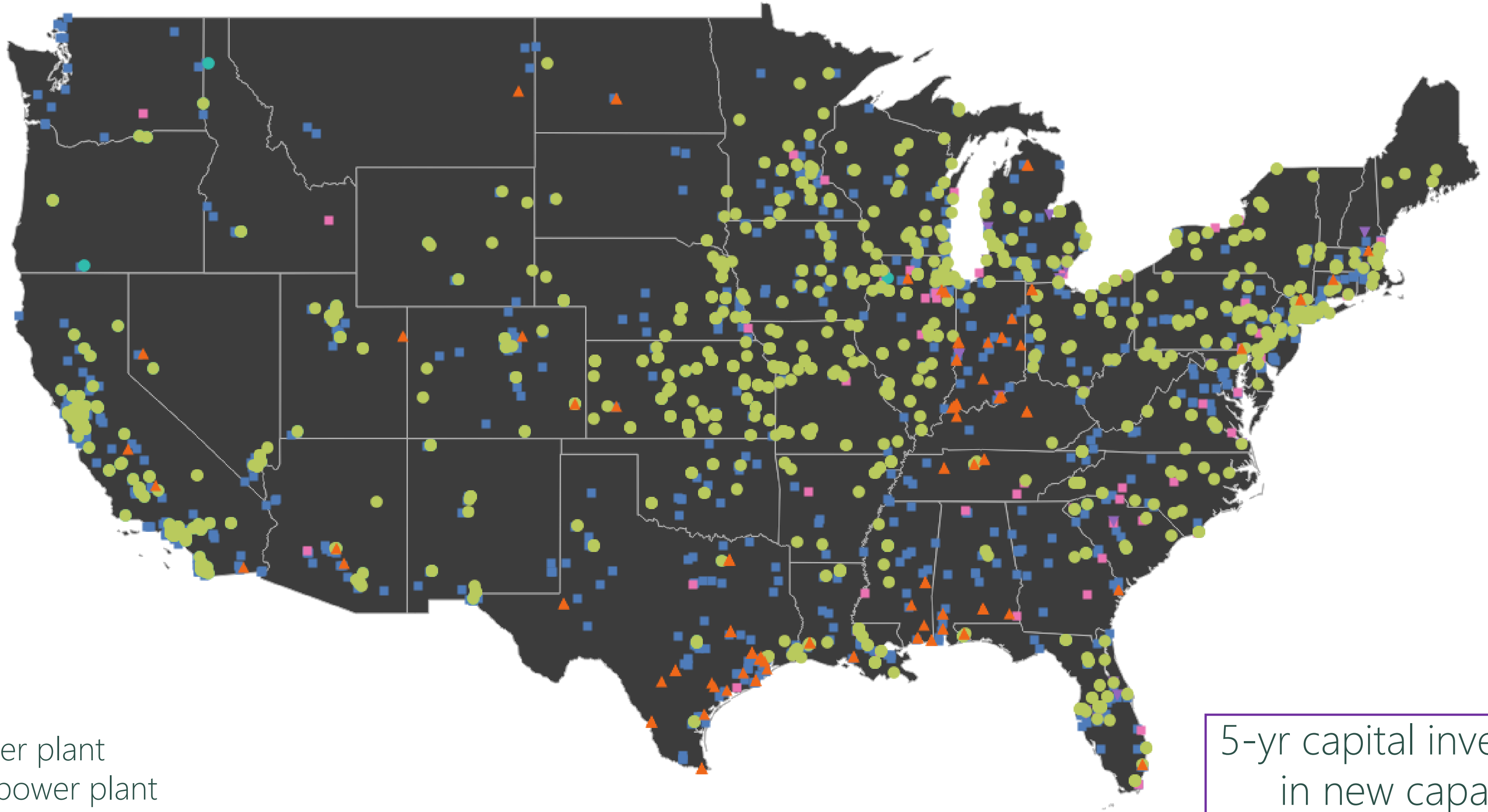
Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2035

2035



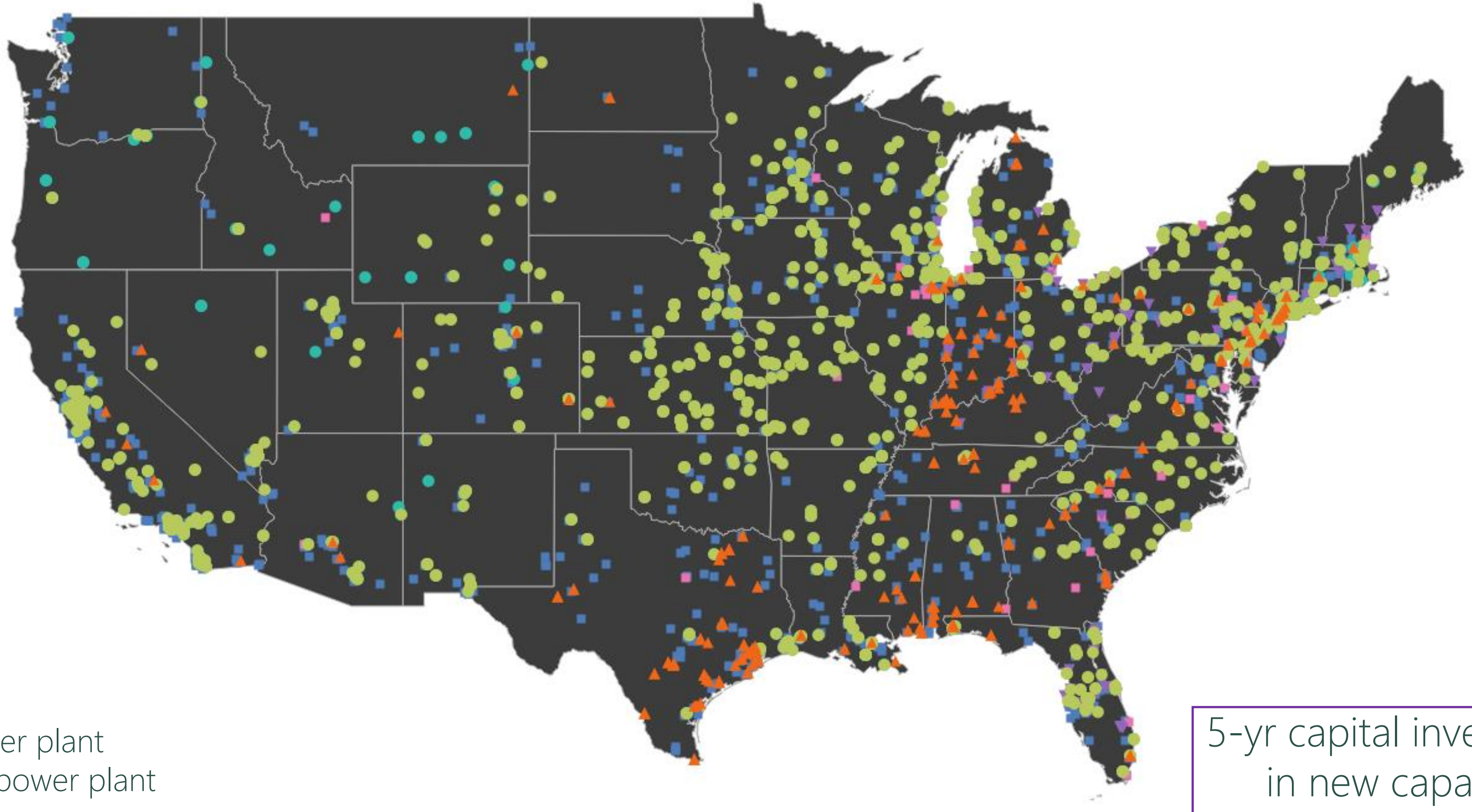
- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$184B

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2040

2040

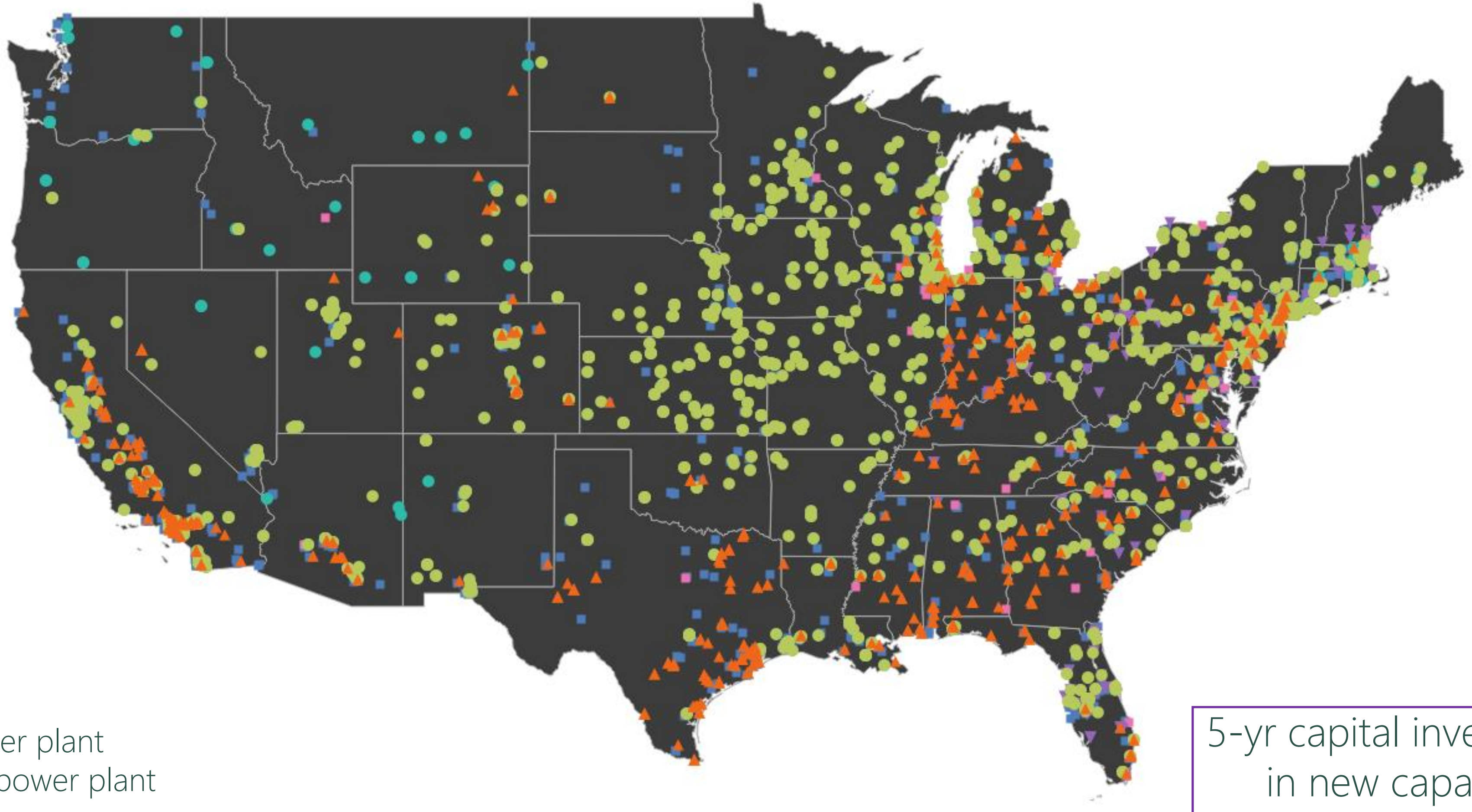


- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$382B

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2045

2045



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$583B

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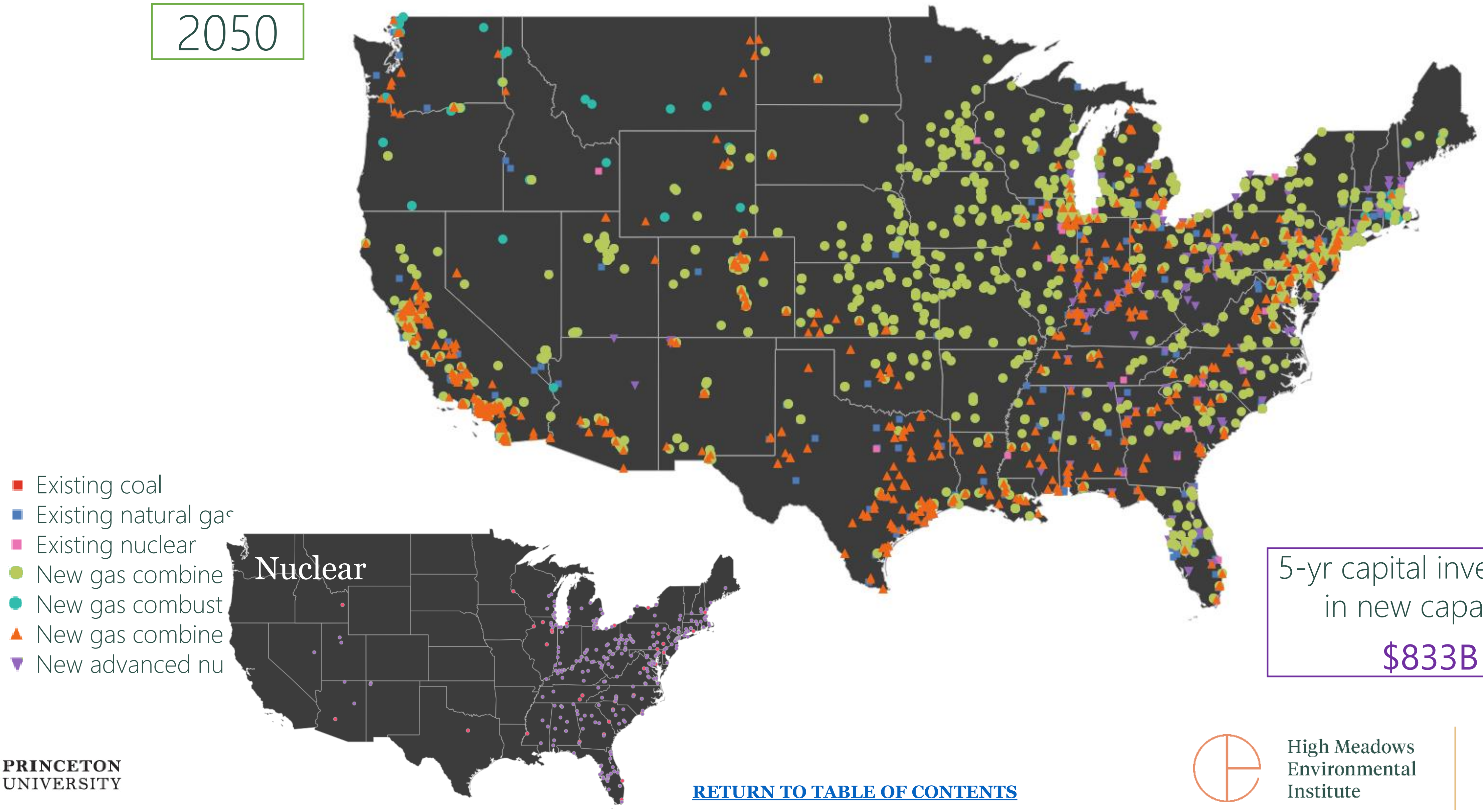
Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2050



5-yr capital investment in new capacity:
$833B

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

Summary of this section

- The net-zero scenario modeling includes ways to 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 or 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 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 area growing corn for ethanol 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 involves some cropland and pasture being converted 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.

* The average rain-fed harvestable yield (t/ha/y, dry basis) of perennial energy grasses on former corn-growing land assumed in the modeling here is about ¾ of today's U.S. average whole-plant yield for corn. Conceptually, therefore, the biomass assumed to be supplied from converted corn-growing lands could equivalently be whole-corn-plant biomass with ¼ of the material left on the field for soil maintenance purposes.

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Key zero-carbon fuels and feedstocks

1. Fossil-derived fuels with negative emissions offsets

Zero-carbon & negative-carbon fuel & feedstock options

2. Hydrogen made from biomass, NG w/CCS, or electrolysis and used directly or as hythane (blend of H_2 + CH_4)

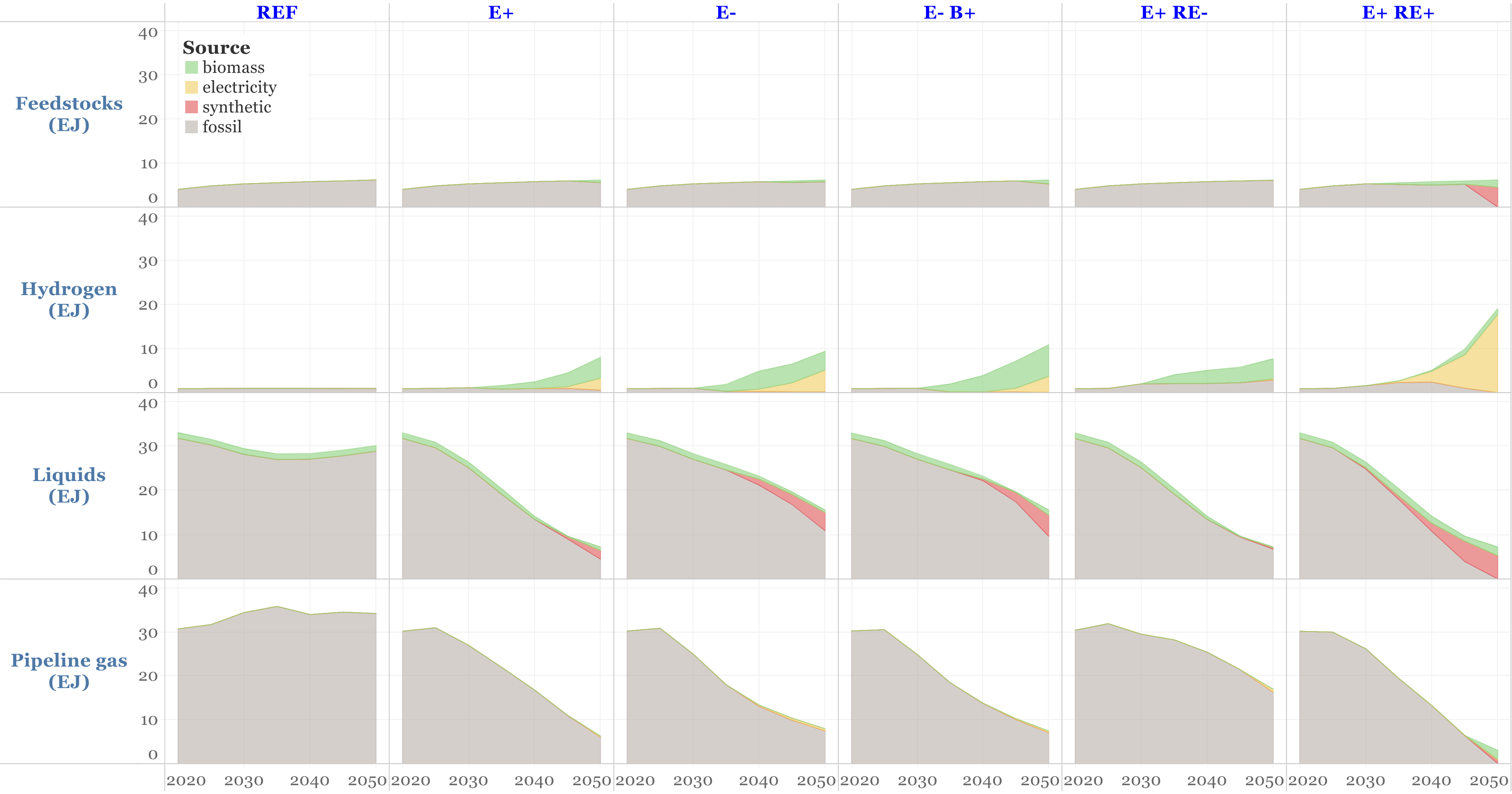
3. Drop-in liquid & gaseous fuels made from biomass or synthesized from H_2 + captured CO_2

Use of fuels decreases substantially in all scenarios, and by 2050 zero-carbon fuels and feedstocks come from a diversity of sources

Zero-carbon fuel options include

1. Fossil fuels plus negative emission offsets
2. Hydrogen made from biomass, NG w/CCS, or electrolysis
3. Synthesized fuels (from biomass or H_2 + captured CO_2)

Mix of fuels and feedstocks by source



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

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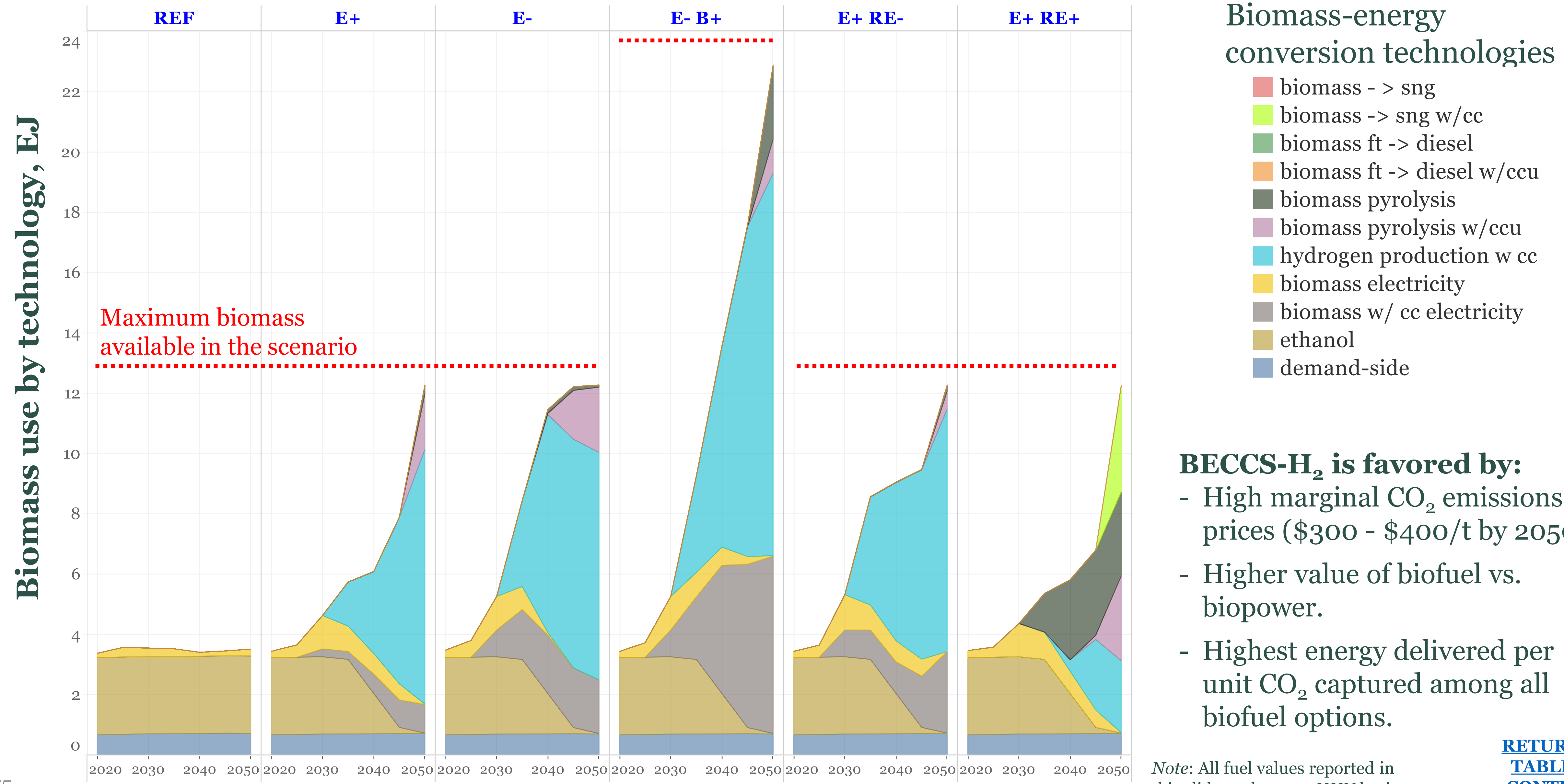
Essentially all available biomass is used in 2050. Rapid growth after 2030. H_2 from biomass with CO_2 capture is a key technology.



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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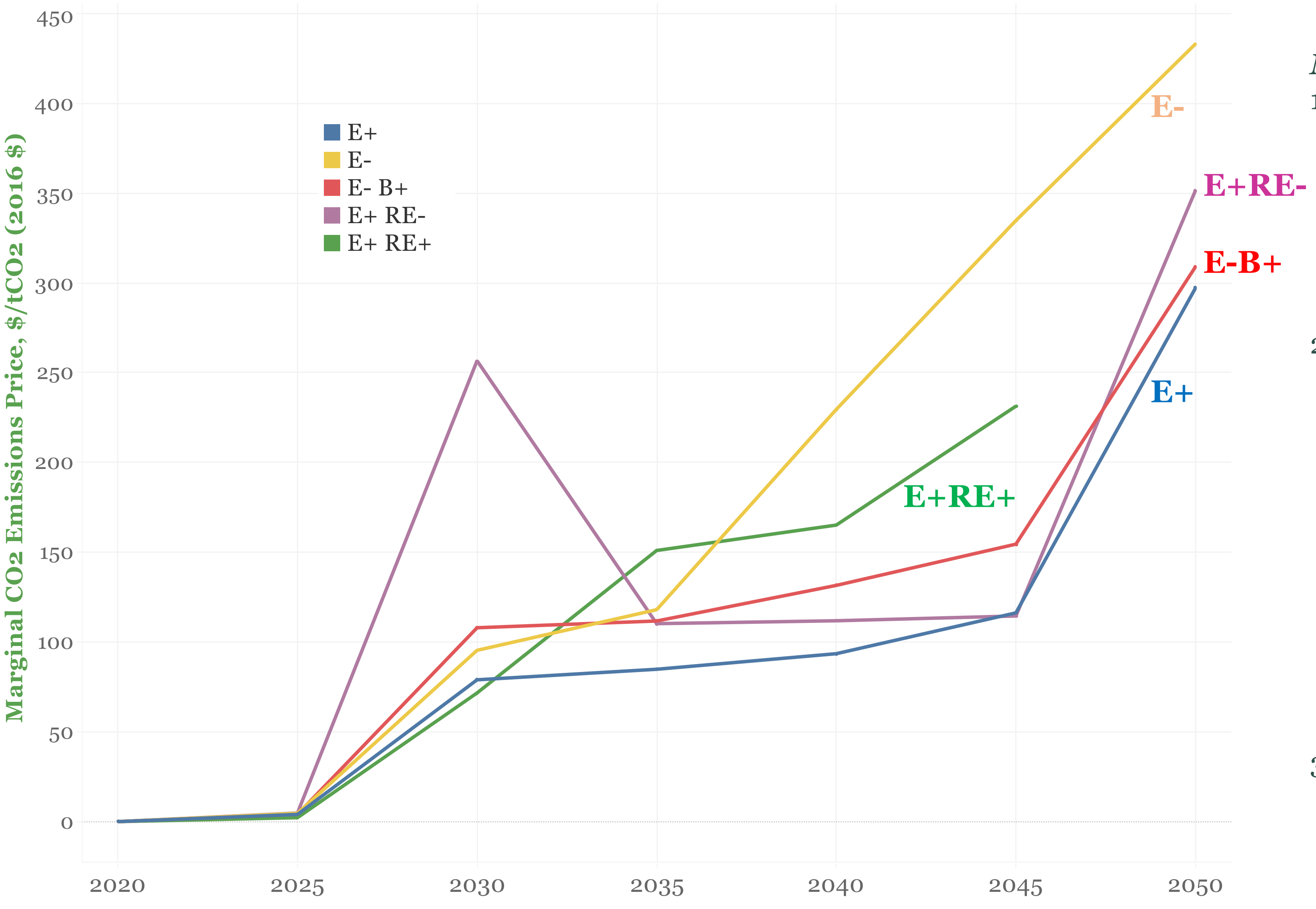
High marginal CO_2 emission prices benefit negative emissions technologies & explain preference for biomass use in BECCS-H_2



Notes:

1) These prices represent overall supply-side system costs for reducing CO_2 emissions by one additional tonne. They do not take into consideration demand-side costs such as added costs for transport electrification in E+ compared with E-. As such, these prices should be interpreted as lower bound estimates of economy-wide carbon emission prices.
2) For E+RE-, the main factors contributing to the non-monotonic behavior from 2025-2035 are: (i) the exogenously imposed linear net-emissions reduction trajectory requires significant reductions by 2030, (ii) the limit on solar and wind power generation build rates means more nuclear and NG-CCS need to be installed; and what can be built of these by 2030 is costly, (iii) post-2030, things get easier because more nuclear and CCS can be built at lower cost, and the electrification of vehicles and buildings that started slowly in the 2020s (limited by stock turnover rates) begins to more significantly reduce fuel demands.
3) For E+RE+, no value is shown for 2050, because the constraint prohibiting fossil fuel use in 2050 is more binding than the annual emissions constraint, implying that the carbon price would (unrealistically) be zero in 2050.

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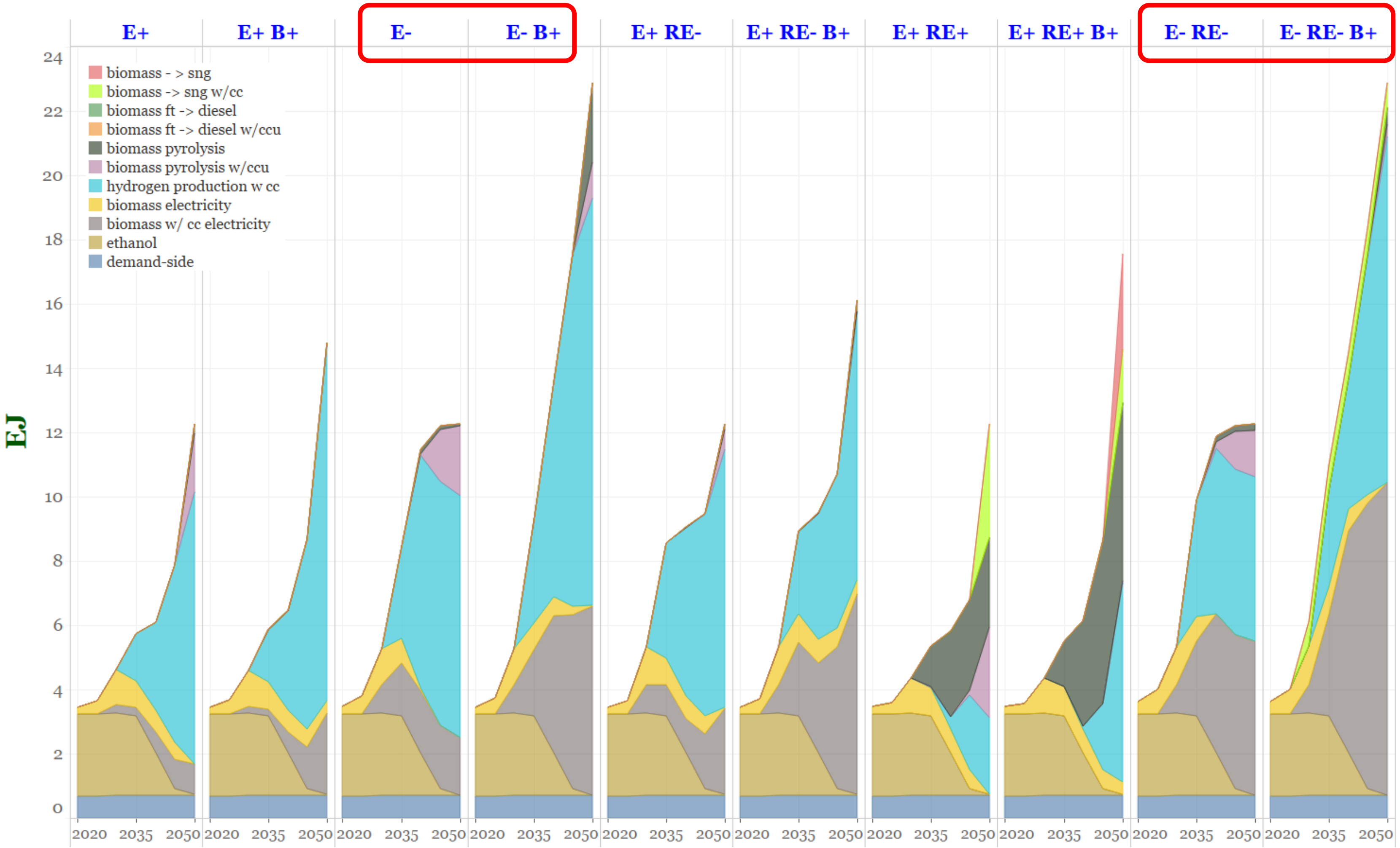
High Meadows Environmental Institute

Carbon Mitigation Initiative

Sensitivity modeling runs: Allowing potential for higher biomass supply results in more biomass use to make electricity and H_2

Biomass is a key resource in all scenarios.

- With the lower biomass supply potential, all available biomass is utilized in all 5 scenarios shown here, including E-RE- (run as a sensitivity to E+RE-).
- With the high biomass supply potential :
  - all available biomass is used in E-B+ and E-RE-B+ cases, which underlines the importance of electrification in reducing reliance on biomass in net-zero pathways.
  - Most of the additional biomass in E+RE-B+, E+RE+B+, and E-RE-B+ is used to produce additional negative emissions via power generation or H_2 production.



Input assumptions that vary between cases		
	E+, E-, E+RE-, E+RE+	E+B+, E-B+, E+RE-B+, E+RE+B+
Biomass potential (by 2050)	0.7 Gt/y (13 EJ)	1.3 Gt/y (24 EJ)

See Annex B for additional discussion of sensitivity cases.

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If no new bioenergy is allowed, more oil and gas are used and direct air capture and sequestration of CO_2 increase to compensate

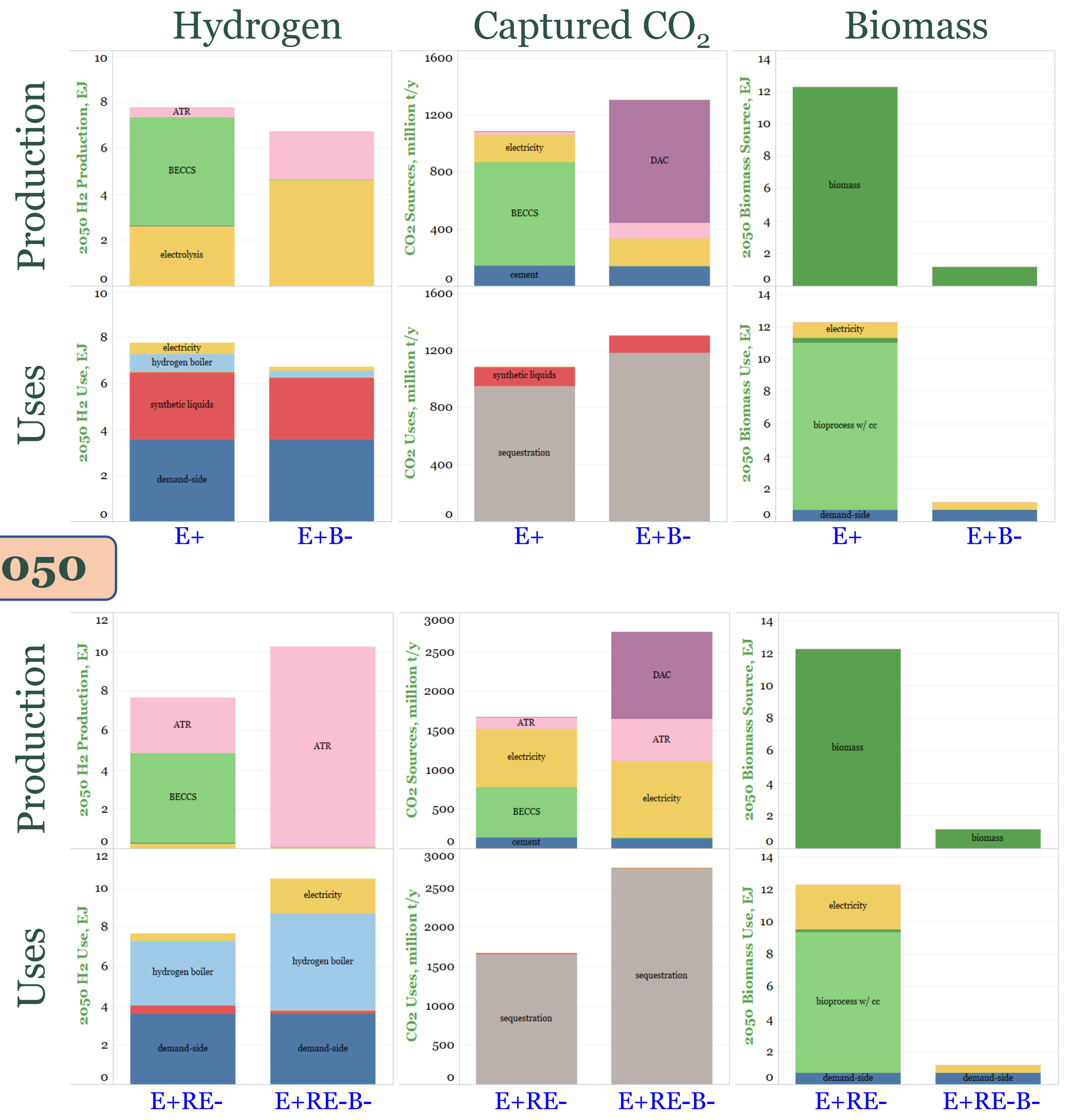
Not allowing new bioenergy removes a key pathway for making net-zero or net-negative emission fuels and leaves only direct air capture (DAC) as an option for achieving negative emissions:

For the E+ case with no new bioenergy (E+B-, upper panel)

- electrolysis and natural gas reforming with CO_2 capture offset the loss of H_2 production from biomass.
- DAC use increases dramatically to offset the added emissions from greater natural gas use and negative emissions from BECCS. Stored CO_2 increases.
- 30-yr NPV of energy-supply system costs increase ~5%.

For E+RE- with no new bioenergy (E+RE-B-, lower panel)

- More hydrogen is produced and all by natural gas reforming with CO_2 capture. More H_2 is used for power generation and industrial steam generation; less for liquid fuels synthesis.
- DAC deployments starts in the early 2030s and ramps up dramatically by 2050, along with CO_2 capture from gas-fired power plants.
- CO_2 storage nearly doubles relative to E+ RE-.
- 30-yr NPV of energy-supply system cost increases by ~25%.



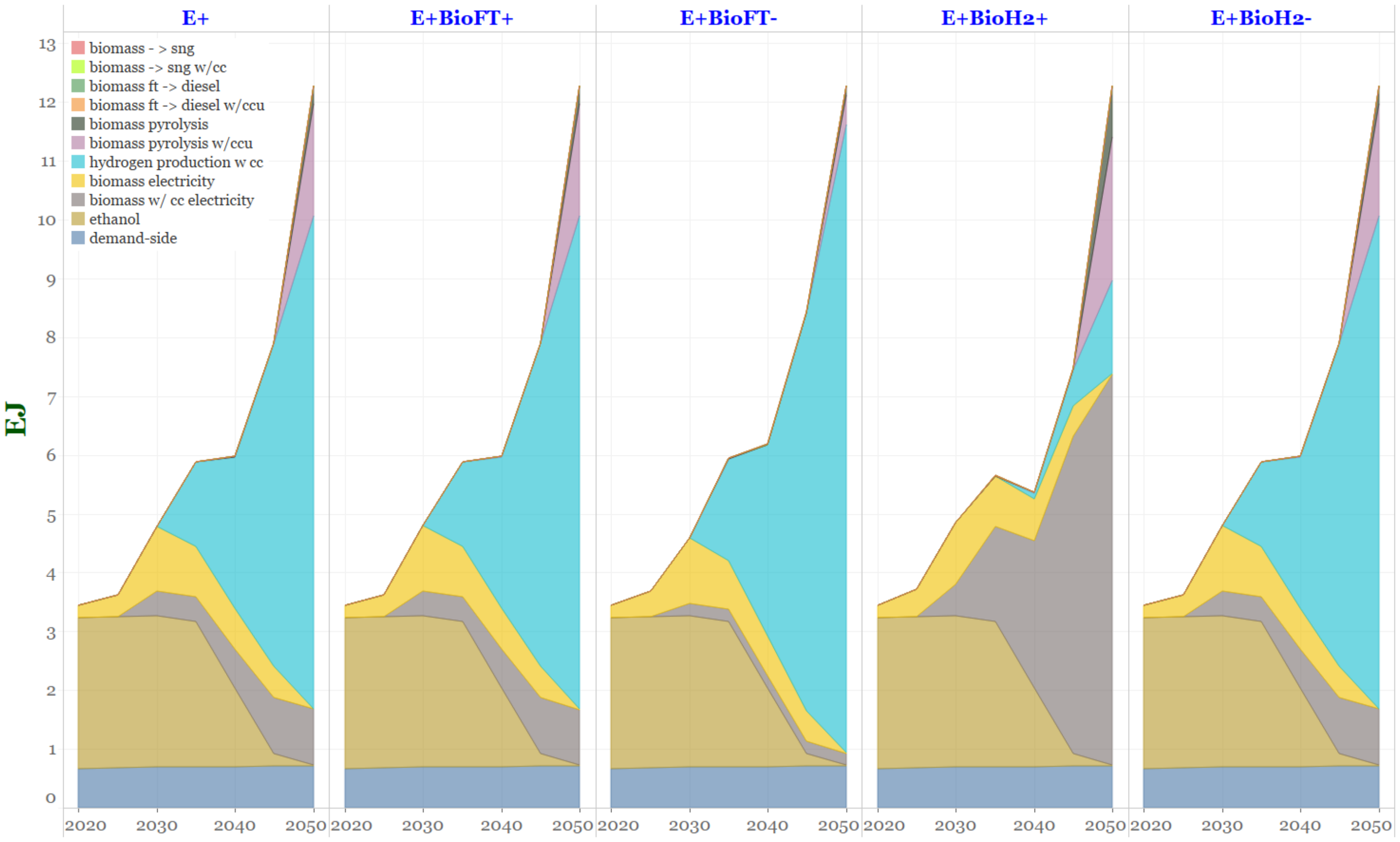
Input assumptions that vary between cases

	E+	E+ B-	E+ RE-	E+ RE-B-
Biomass potential (increase from today to 2050)	0.7Gt/y	0 Gt/y	0.7Gt/y	0 Gt/y

Higher capital costs for biomass conversion to hydrogen drives more biomass use for electricity, but not for bio-derived liquid fuels

Gasification-based integrated biomass conversion to Fischer-Tropsch fuels or H_2 with CO_2 capture are pre-commercial technologies, with inherently uncertain capital costs for future commercial-scale plants. Sensitivity runs tested the impact of 50% higher and 20% lower assumed capital costs for these technologies:

- Neither higher nor lower biomass-FT costs impacted results, because other routes to liquid fuels are less costly for meeting liquid fuel demands within carbon emission constraints.
- A similar result is observed with lower capital costs for biomass-H_2 with CO_2 capture.
- But with higher costs for biomass-H_2, biomass use shifts away from H_2 production to electricity generation with CO_2 capture. Notably, biomass-FT technology is still not deployed even in this case.
- The 30-yr NPV of energy-supply system costs are similar for all cases shown here



See Annex B for additional discussion of sensitivity cases.

Input assumptions that vary between cases					
$\$/kW_{out,HHV}$ in 2050	E+	E+ BioFT+	E+ BioFT-	E+ BioH2+	E+ BioH2-
BECCS-H_2 capital cost	2700	2700	2700	4050	2160
Biomass FT capital cost	3962	5984	3172	3962	3962

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Summary of this section

- For the E+ pathway, the geographic distribution of agricultural and forestry residues used for energy is based on county-level projections from the "Billion Ton Study". Land transitioned from growing corn for ethanol to growing perennial grasses or equivalent for energy is assumed to be distributed among counties in proportion to their corn production level in 2018.*
- Transporting biomass long distances to conversion facilities is costly, so our downscaling approach uses the county-level biomass supply estimates to establish 100 mile x 100 mile cells, within each of which all available biomass is assumed to be used in conversion facilities located in that cell. Most bioconversion facilities, regardless of technology, are assumed to have an input capacity of 0.7 million t_{dry}/y of biomass.
- Bioconversion capacity within a given RIO modeling region is deployed first in cells within that region that have the highest biomass supply density (as a surrogate for lowest biomass feedstock cost), and facilities that capture CO_2 are sited near CO_2 storage reservoirs or pipelines (see CO_2 pipeline maps later).
- Facilities are located primarily in the upper Midwest and in the Southeast, corresponding to the spatial distribution of biomass resources.
- Cumulative investment in bioconversion facilities is ~$810 billion (2018$) nationwide by 2050, and farmer revenues from sale of biomass are more than double today's revenues for corn sold into ethanol production.
- See Annex H for details of the bioenergy downscaling analysis.

* The average rain-fed harvestable yield (t/ha/y, dry basis) of perennial energy grasses on former corn-growing land assumed in the modeling here is about ¾ of today's U.S. average whole-plant yield for corn. Conceptually, therefore, the biomass assumed to be supplied from converted corn-growing lands could equivalently be whole-corn-plant biomass with ¼ of the material left on the field for soil maintenance purposes.

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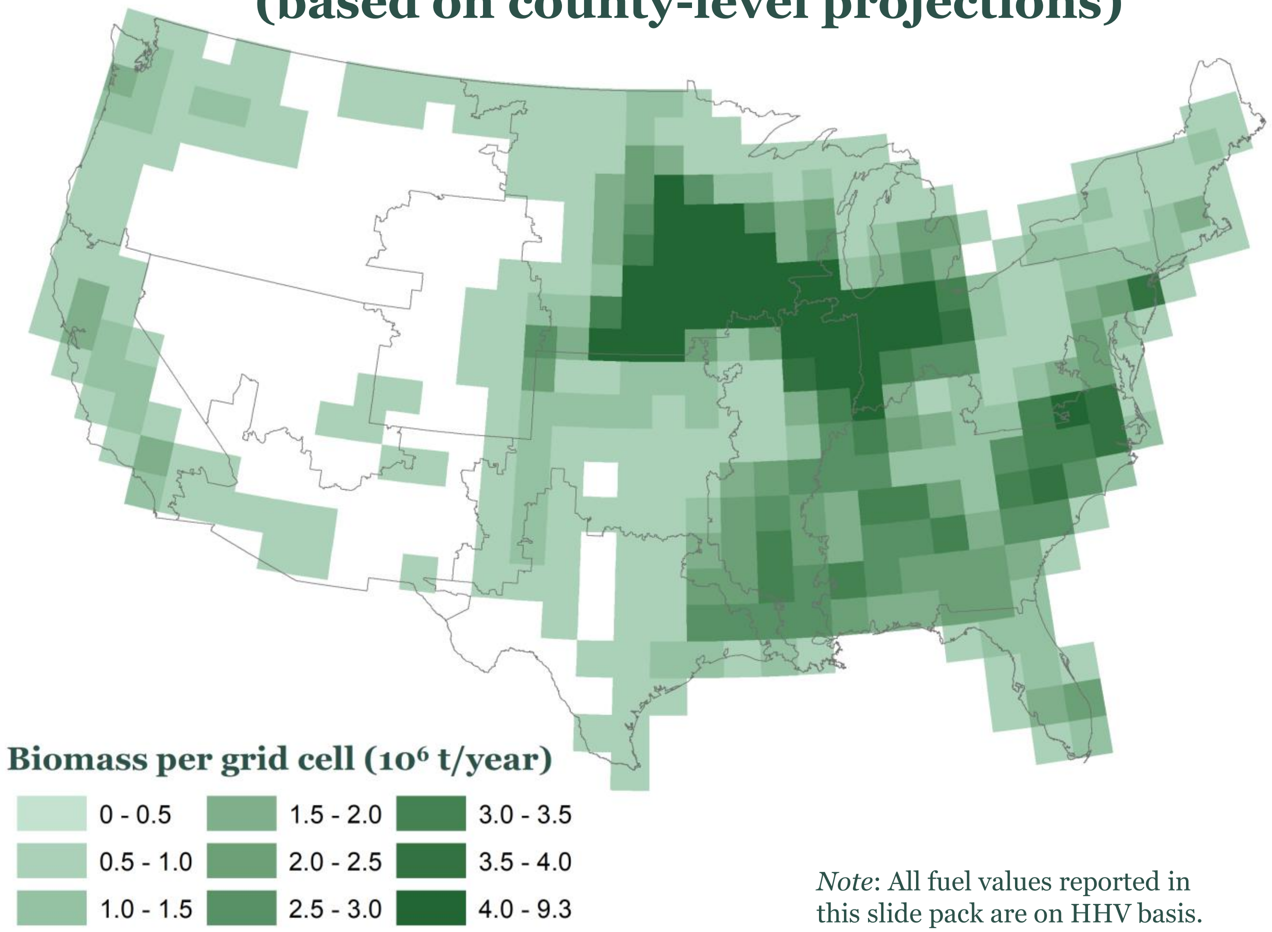
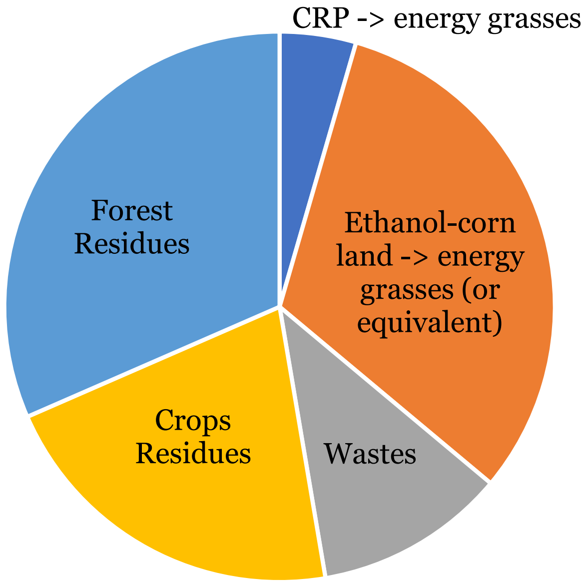
E+ Scenario: Biomass supply with no increase in land use for energy. Midwest and Southeast are largest sources.

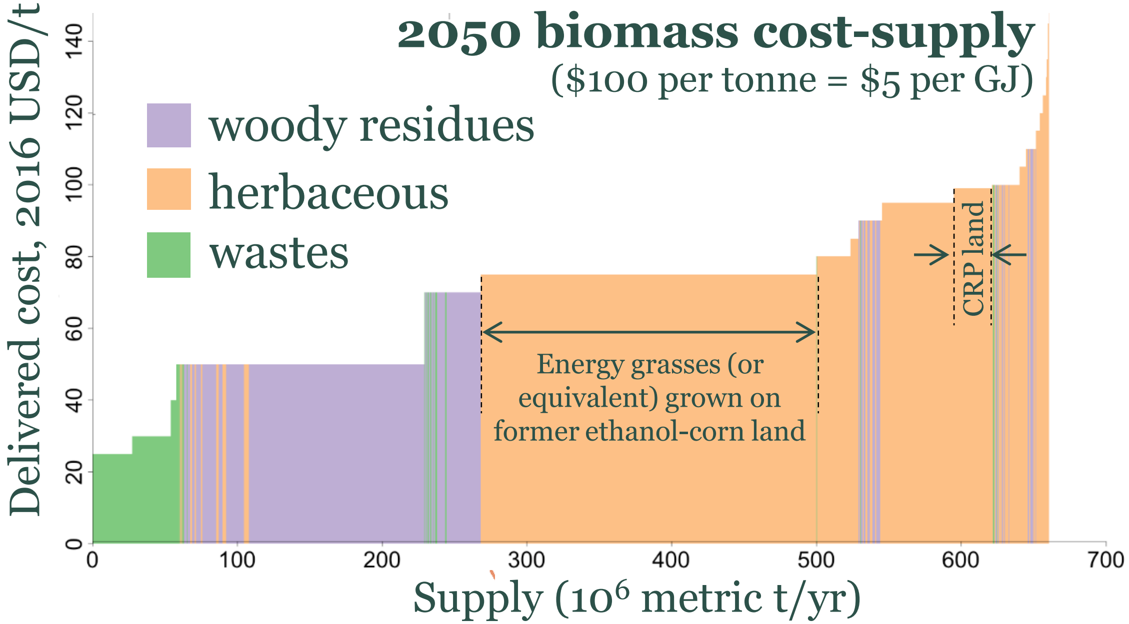
2050 biomass availability, 100 x 100 mi cells (based on county-level projections)



2050 supply by resource (13 EJ total)



2050 biomass cost-supply
($100 per tonne = $5 per GJ)



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

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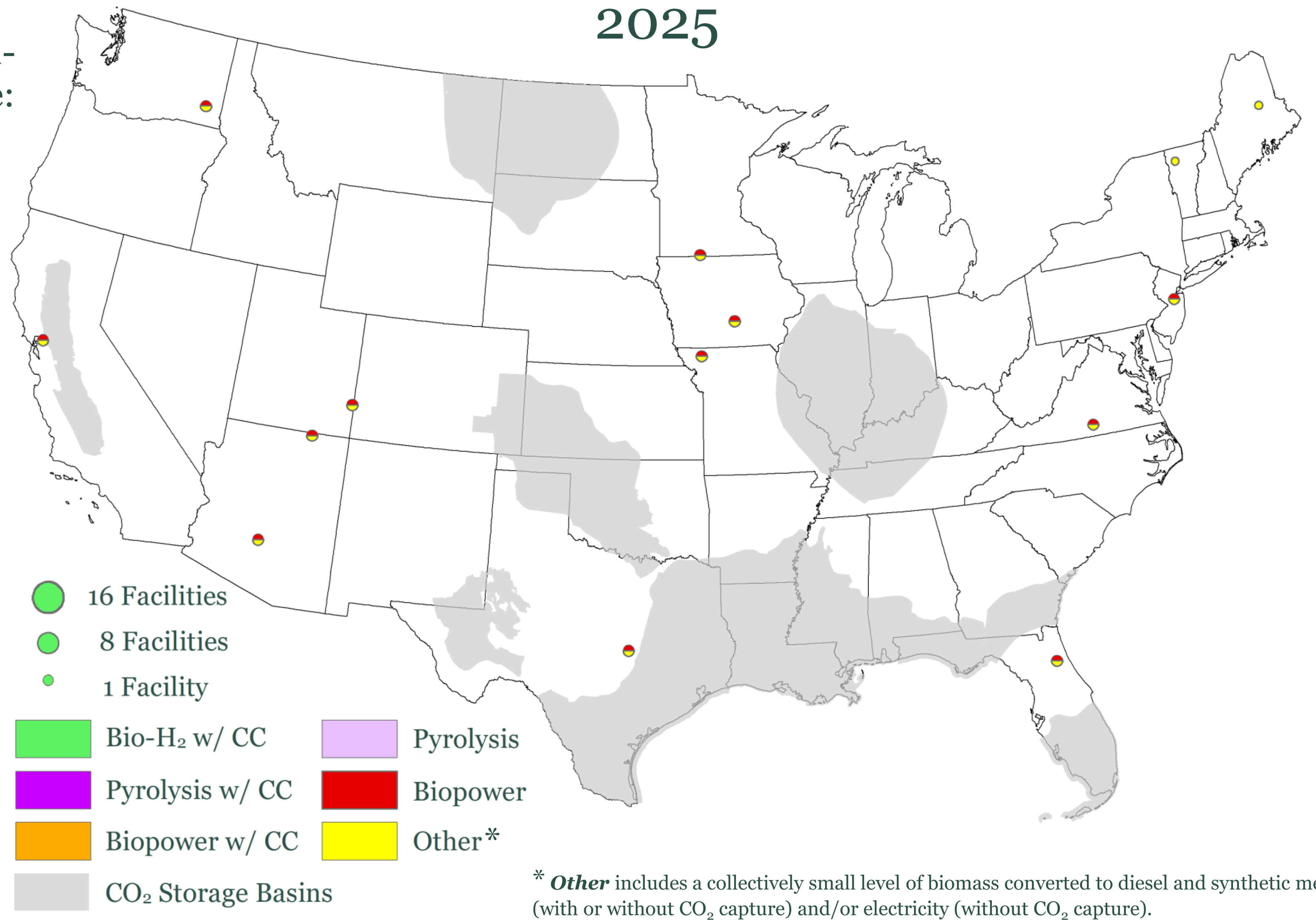
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 44 million t
- 0.9 EJ



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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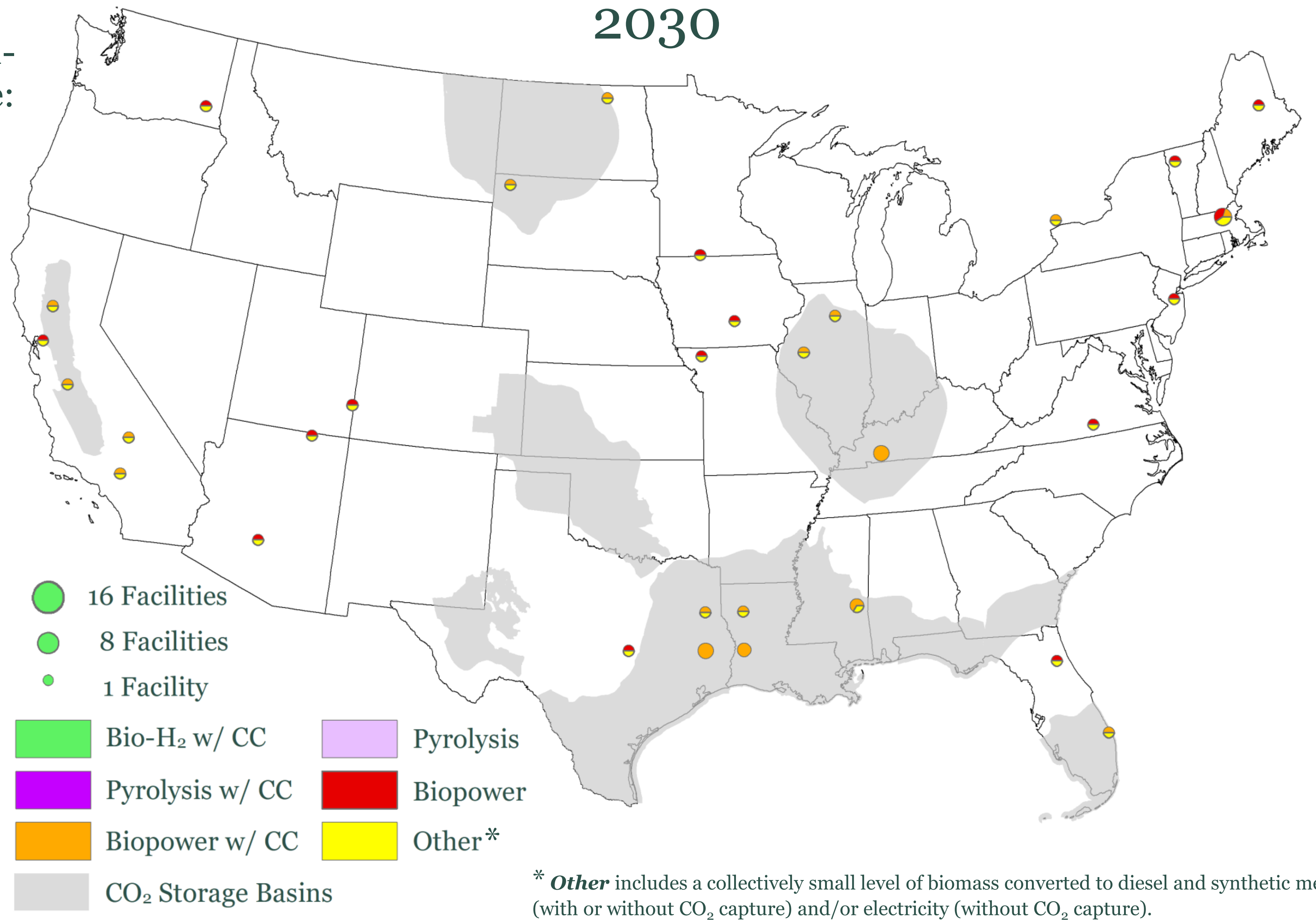
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 79 million t
- 1.6 EJ



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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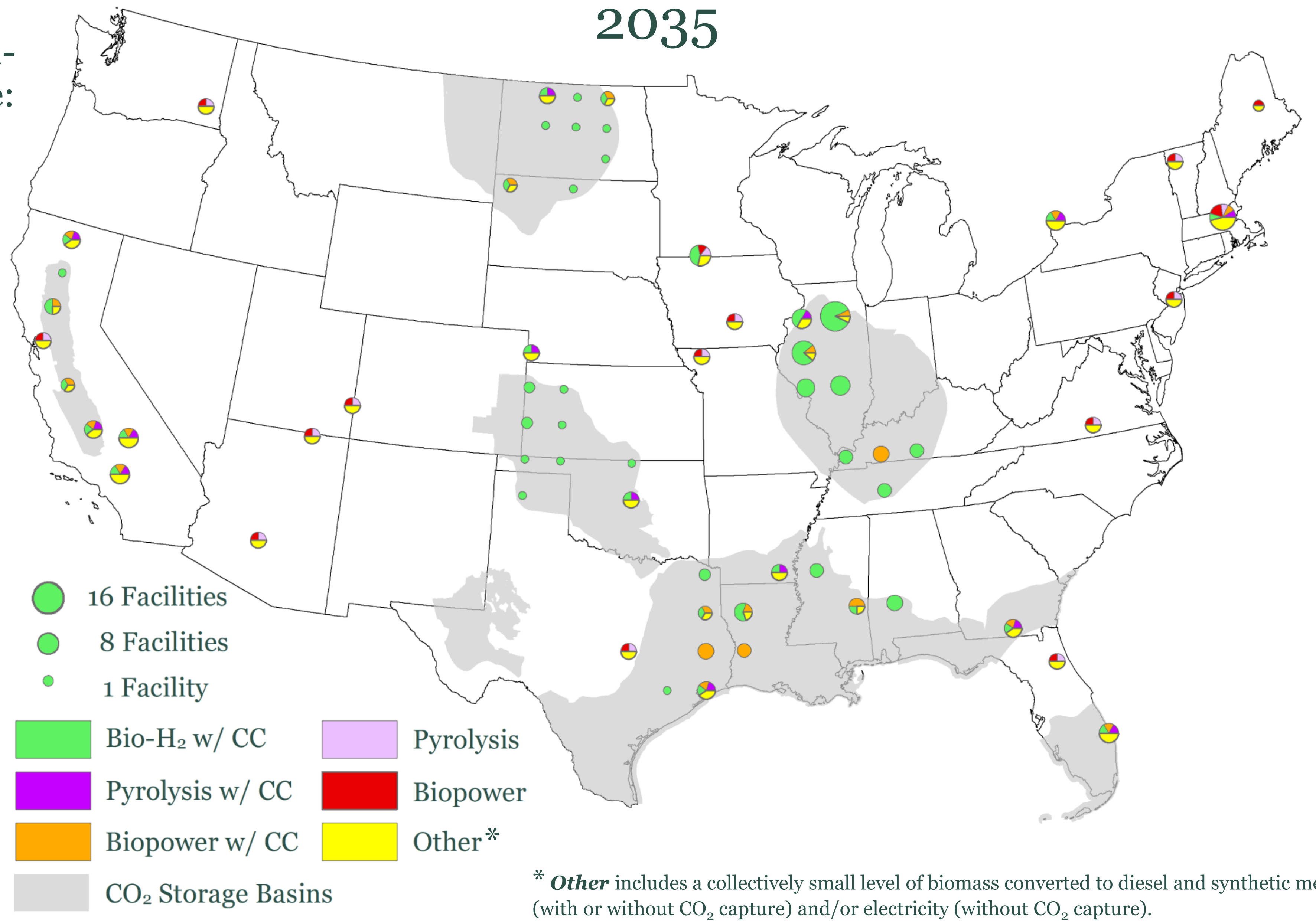
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 145 million t
- 2.9 EJ



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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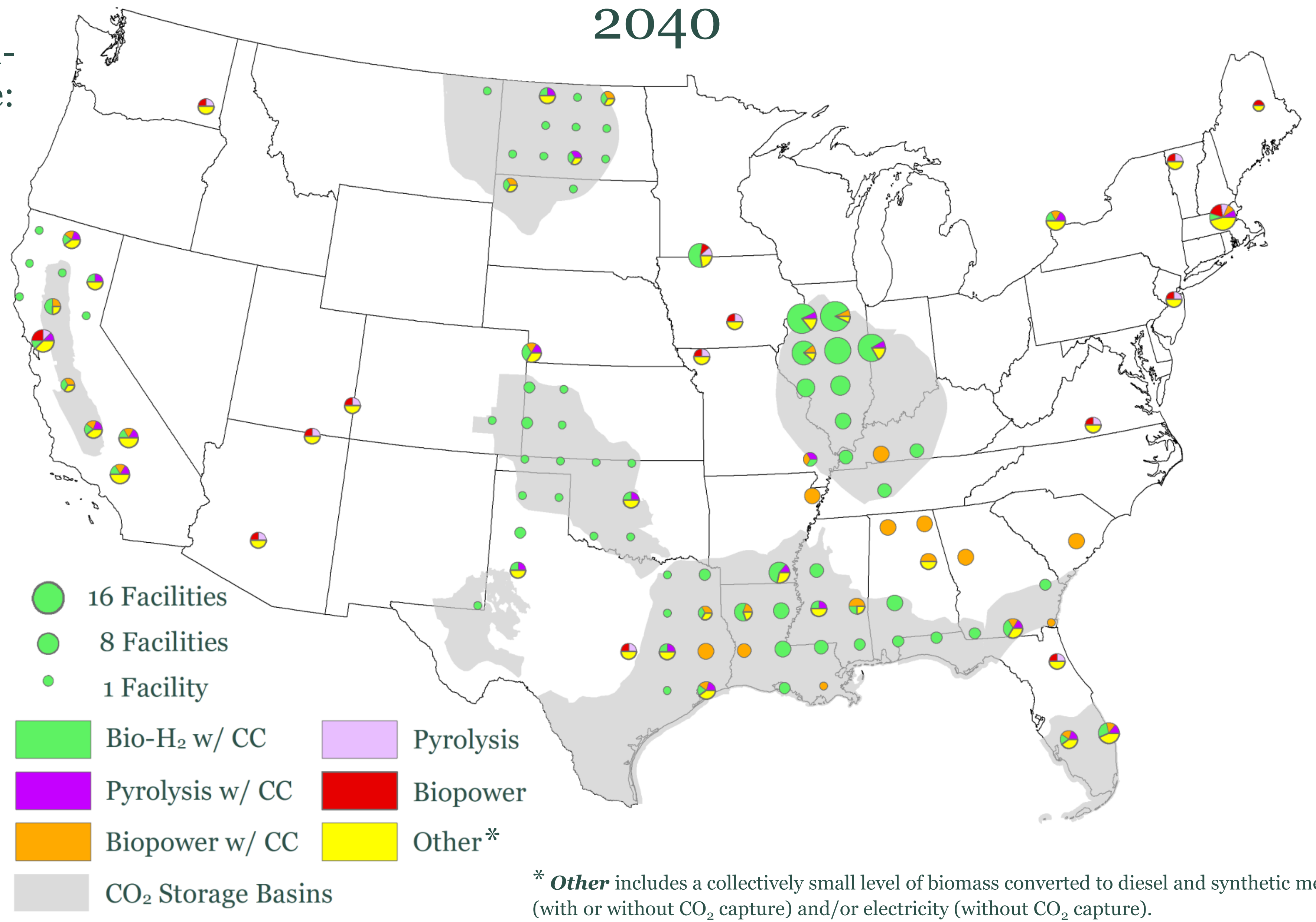
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 223 million t
- 4.4 EJ



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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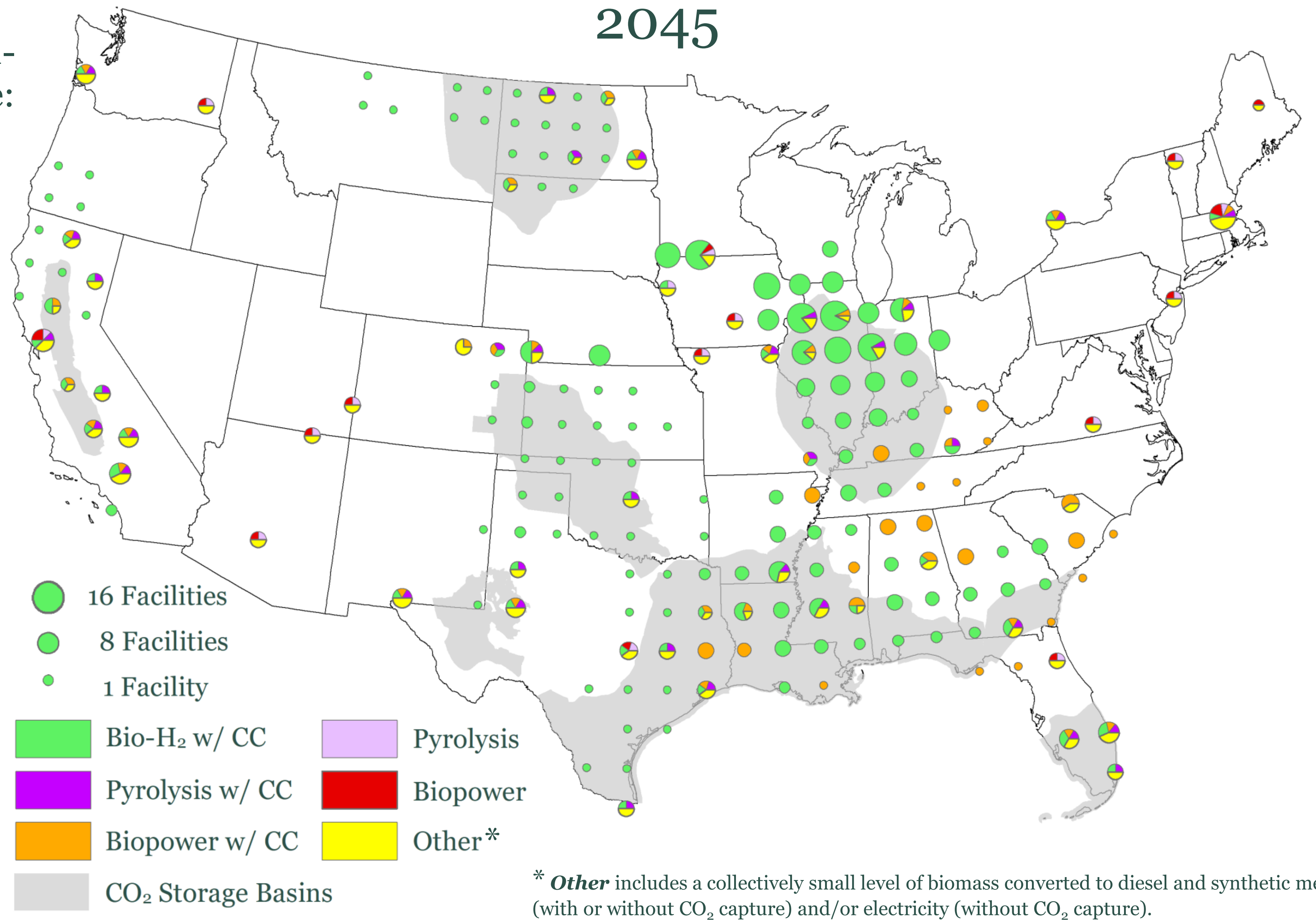
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 375 million t
- 7.4 EJ



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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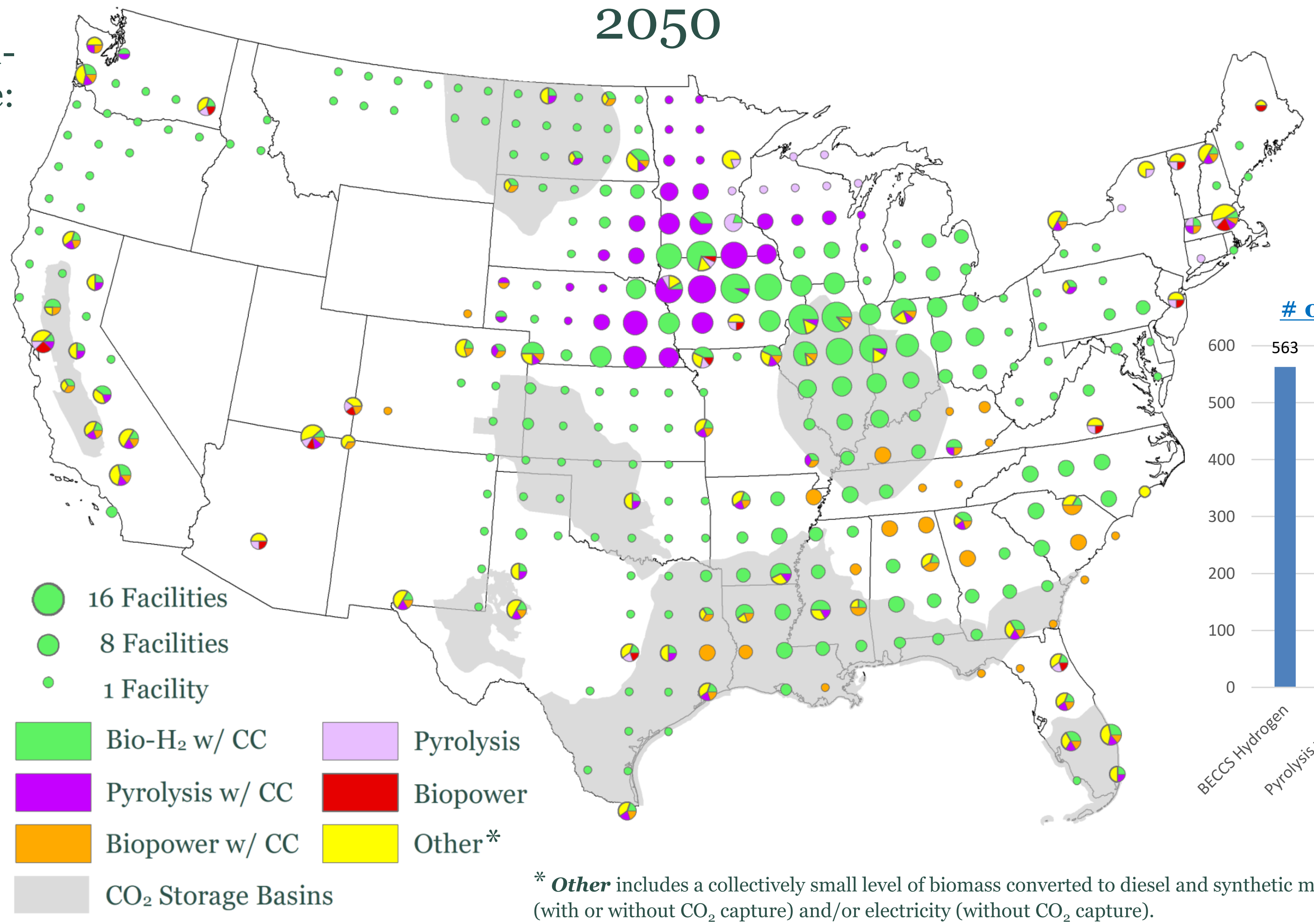
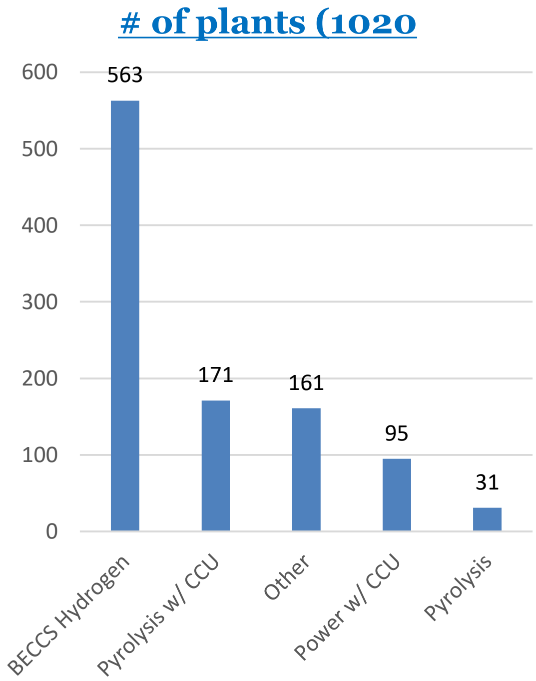
Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 618 million t
- 12.2 EJ





* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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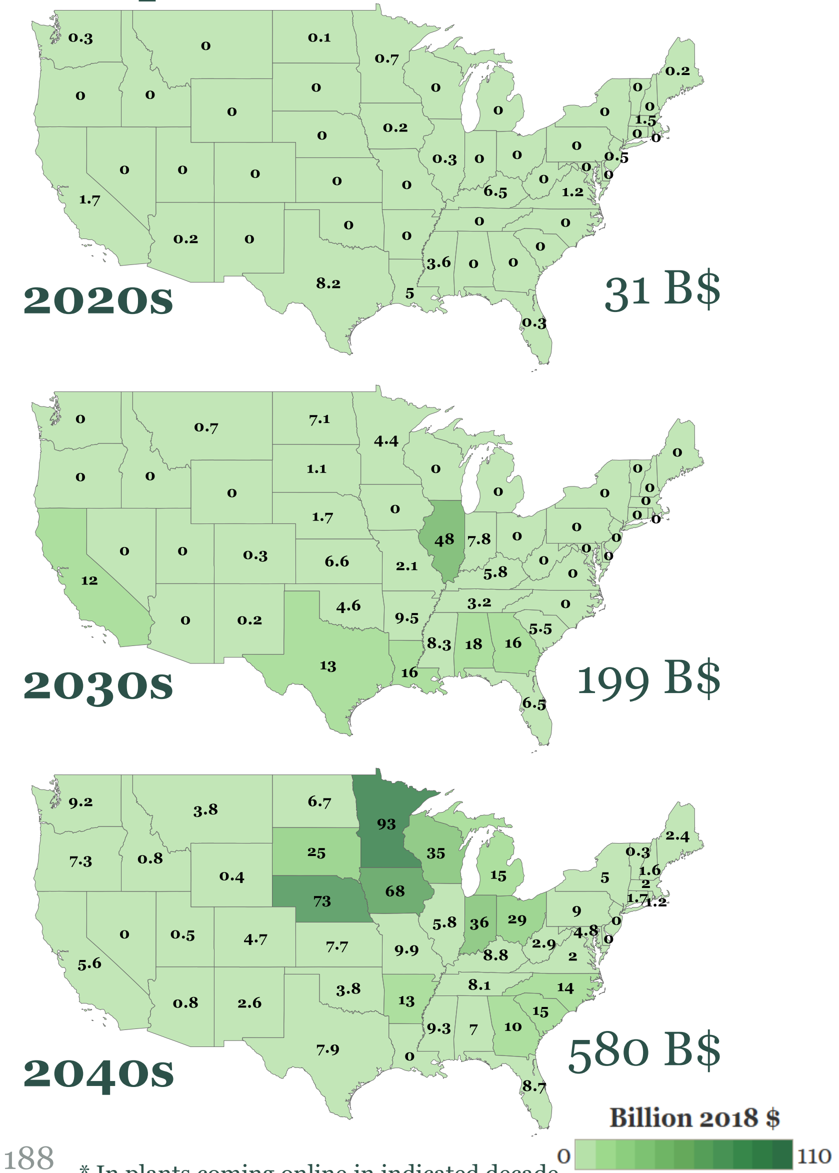
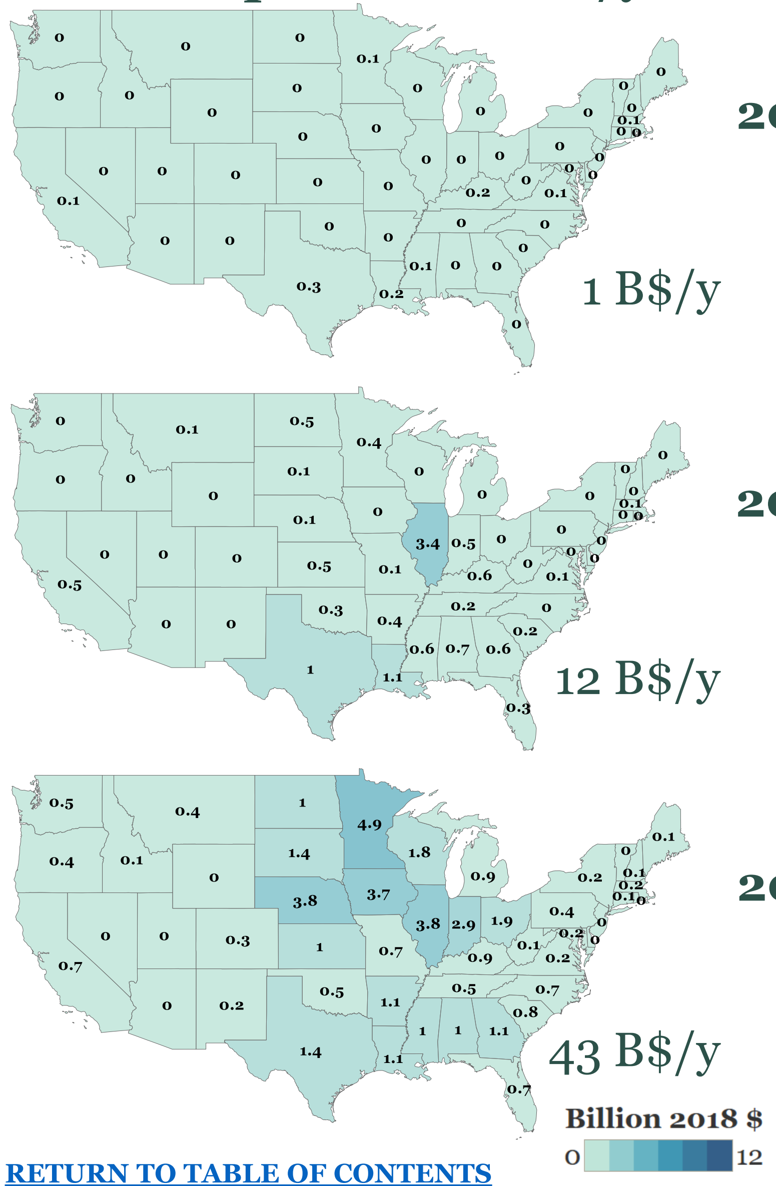
810 B$ capital invested in bioconversion by 2050, largely in Midwest and Southeast. Biomass purchases grow, displacing corn for ethanol.

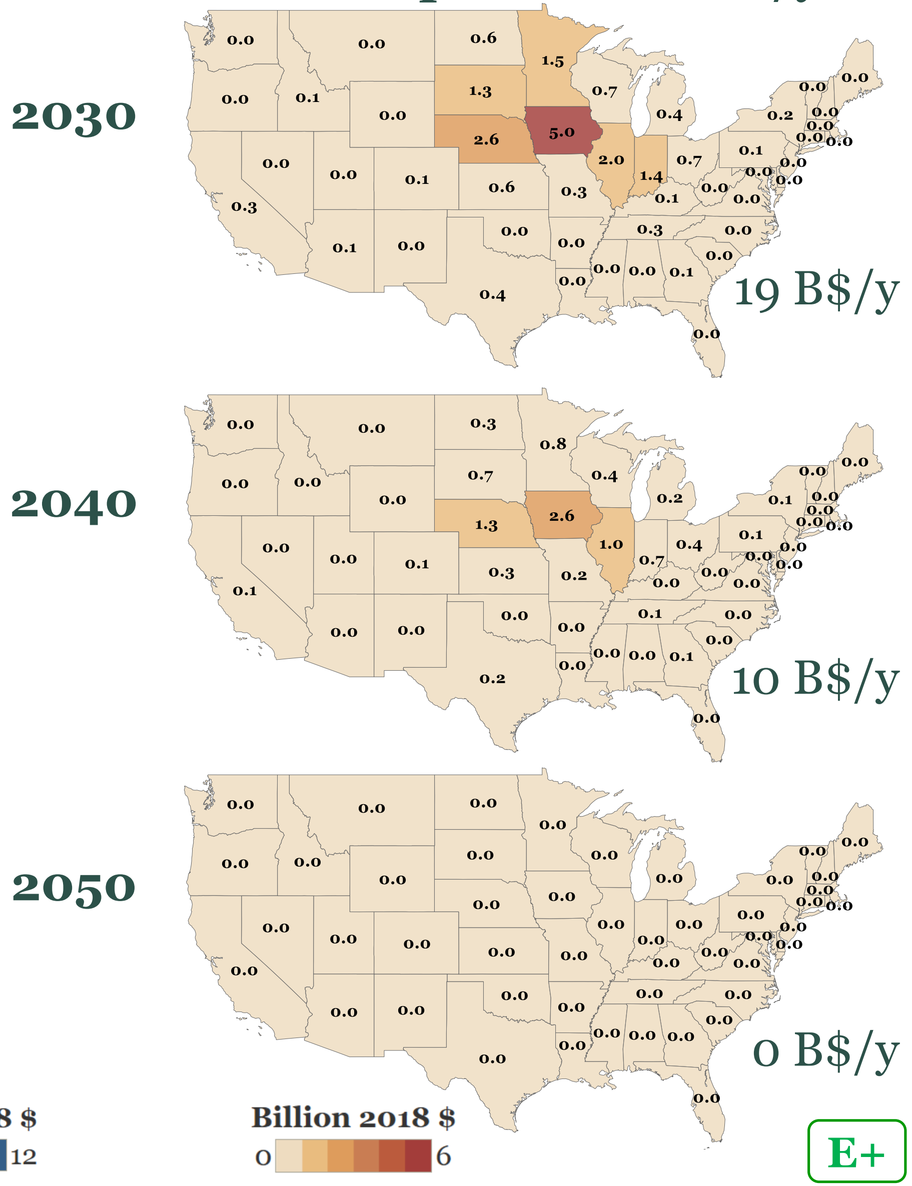
Capital invested (B$)*



Biomass purchases (B$/y)



Corn (for eth.) purchases (B$/y)



* In plants coming online in indicated decade.

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E+

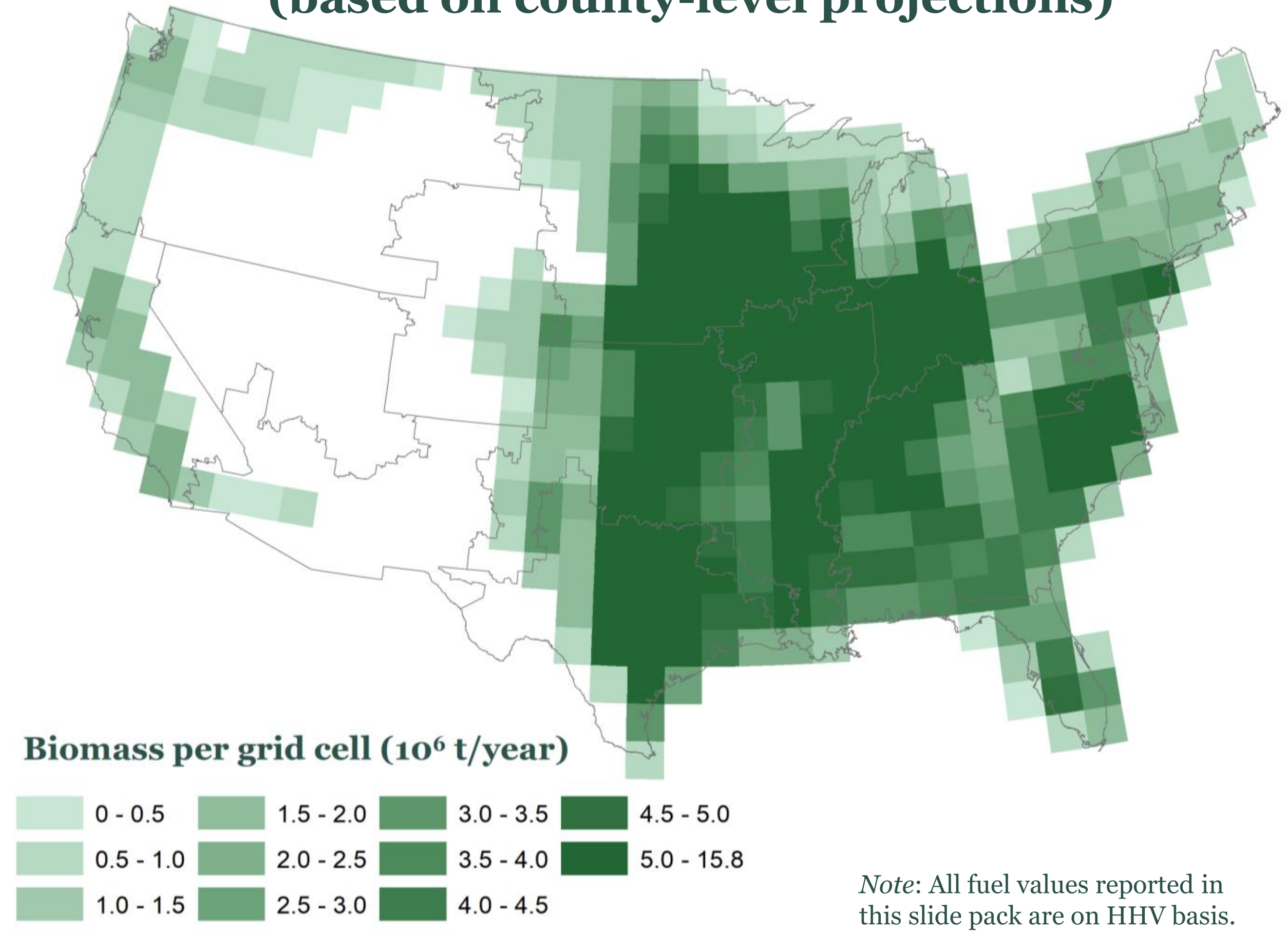
Spatial downscaling and analysis of bioenergy production and use in the E-B+ pathway

Summary of this section

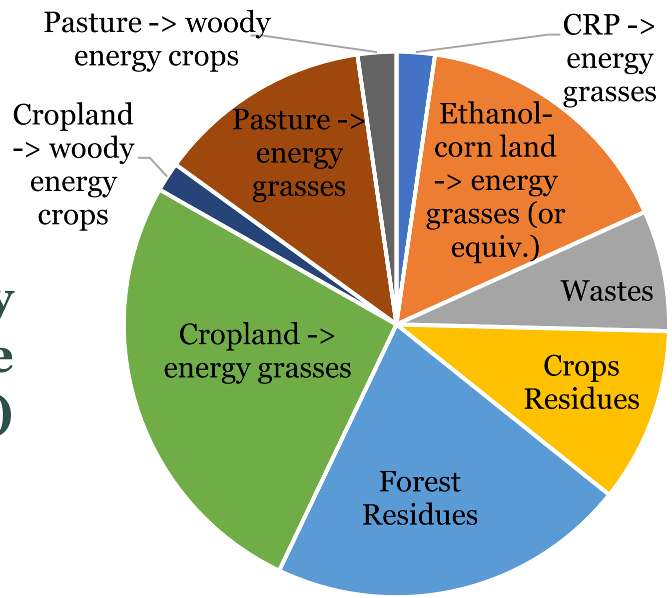
- For the E- B+ pathway, the geographic distribution of biomass supplies, including dedicated energy crops grown on converted crop or pasture land, is based on county-level projections from the "Billion Ton Study". Additionally, production of dedicated energy grasses on lands converted from growing corn for ethanol is assumed to be distributed among counties in proportion to their corn production level in 2018.
- The same downscaling methodology and assumptions are used as for the E+ case reported above.
- Cumulative investment in bioconversion capacity by 2050 totals $1.6 trillion nationwide.
- Farmer revenues from sale of biomass for energy are more than quintuple today's revenues for corn sold into ethanol production.
- See Annex H for details of the bioenergy downscaling analysis.

E- B+ Scenario: Biomass supply is nearly doubled via conversion of some pasture and cropland to energy crops.

2050 biomass availability, 100 x 100 mi cells (based on county-level projections)

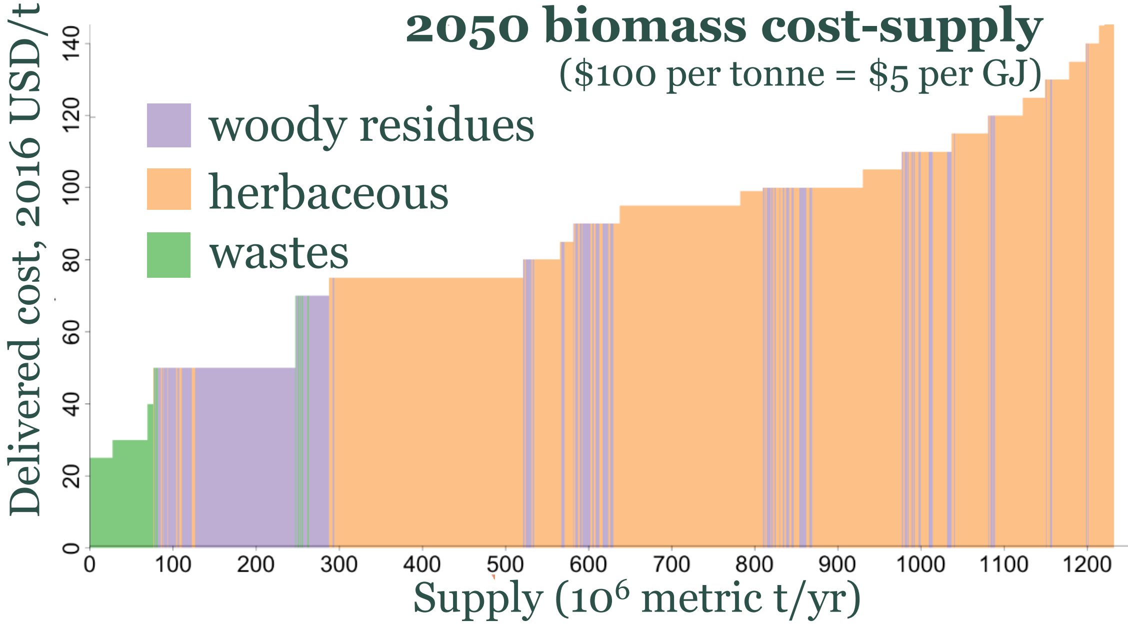


2050 supply by resource (24 EJ total)



2050 biomass cost-supply

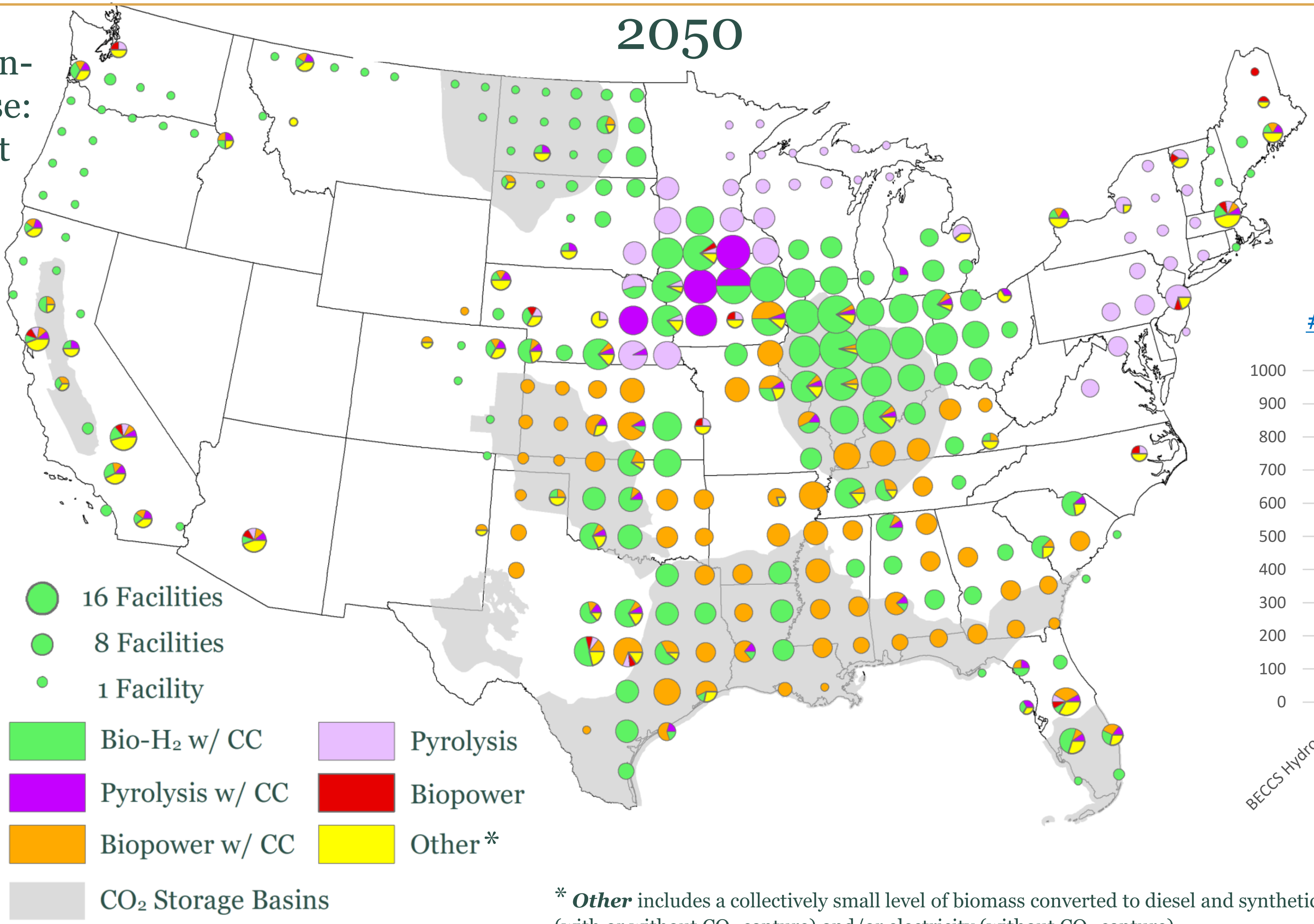
($100 per tonne = $5 per GJ)



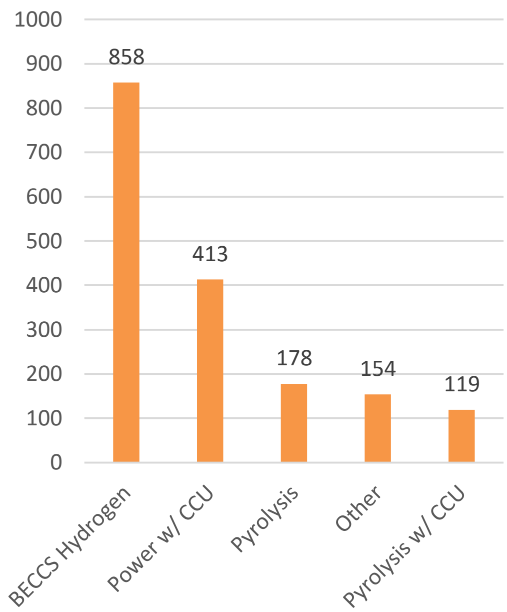
Note: All fuel values reported in this slide pack are on HHV basis.

Bioconversion industry, E- B+ scenario

Total annual non-food biomass use:
- 1,153 million t
- 22.8 EJ



# of plants (1,760 total)



* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

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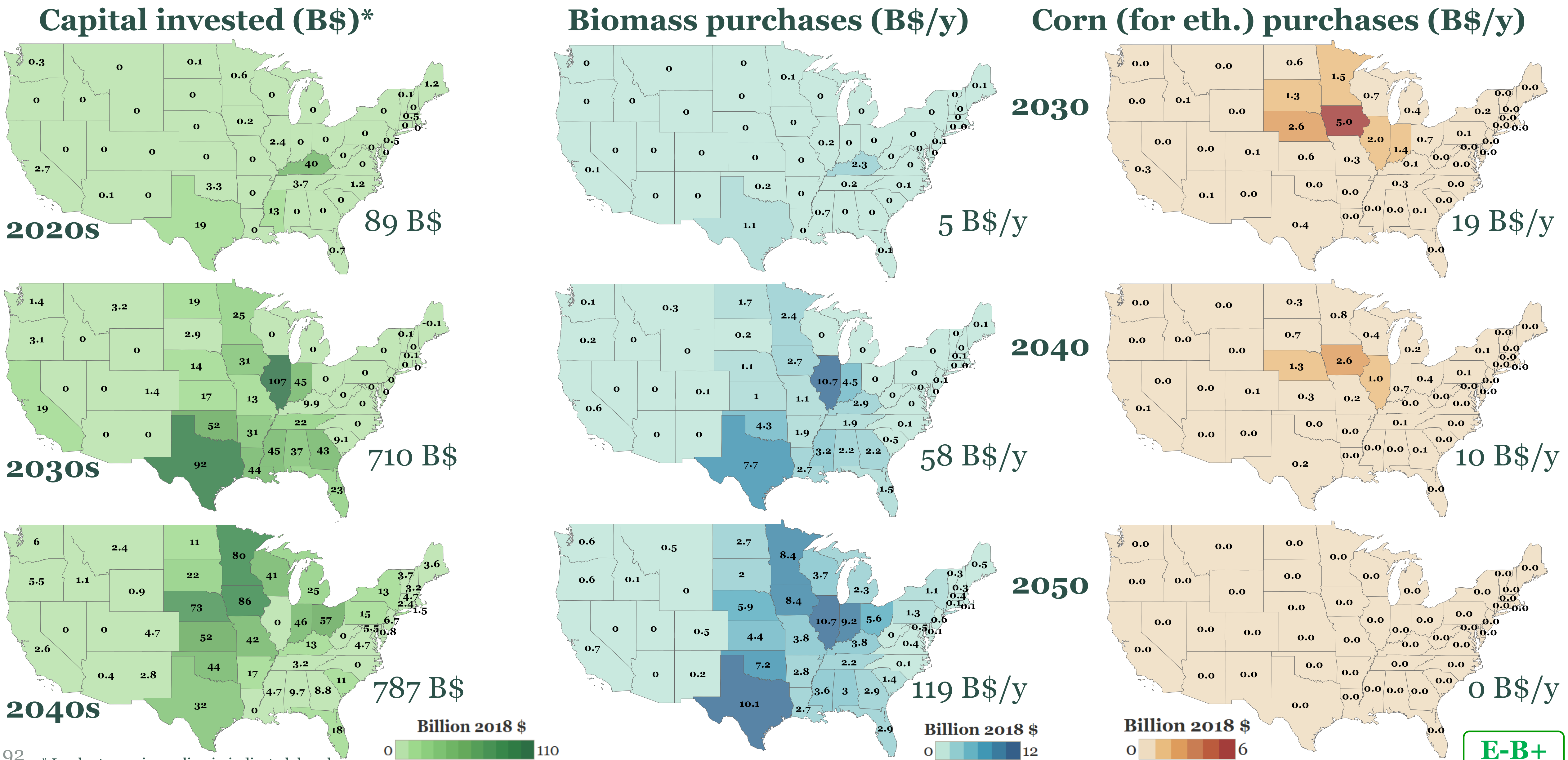
1.6 T$ capital invested in bioconversion by 2050, largely in Midwest and Southeast. Biomass purchases grow, displacing corn for ethanol.



* In plants coming online in indicated decade.

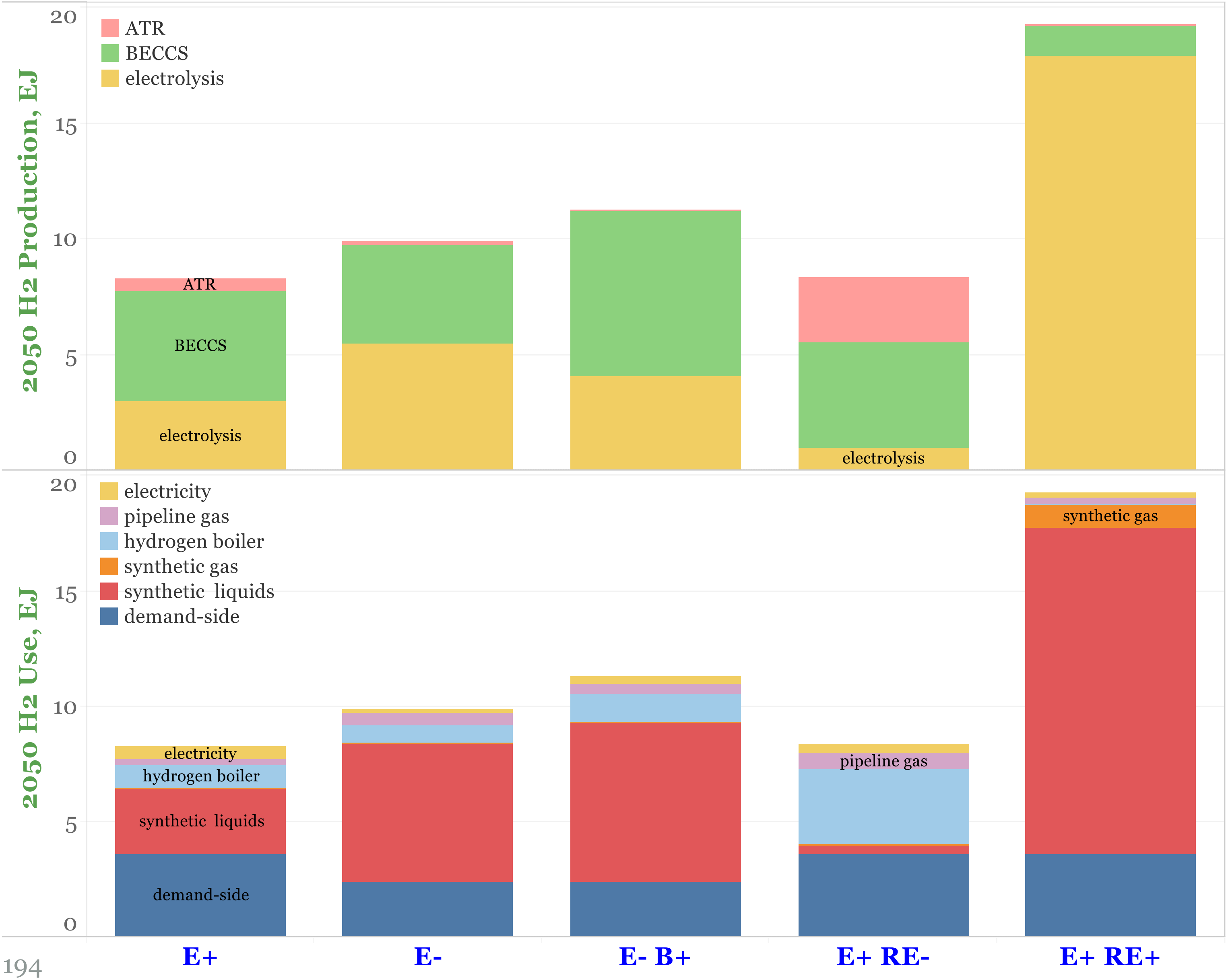
E-B+

Hydrogen production and use

Summary of this section

- 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 given more limited wind and solar capacity. 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. Vignettes of notional future industry-serving regional H_2 pipelines are sketched to illustrate.
- 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.
- See Annex L for additional details relating to hydrogen in the net-zero pathways.

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.

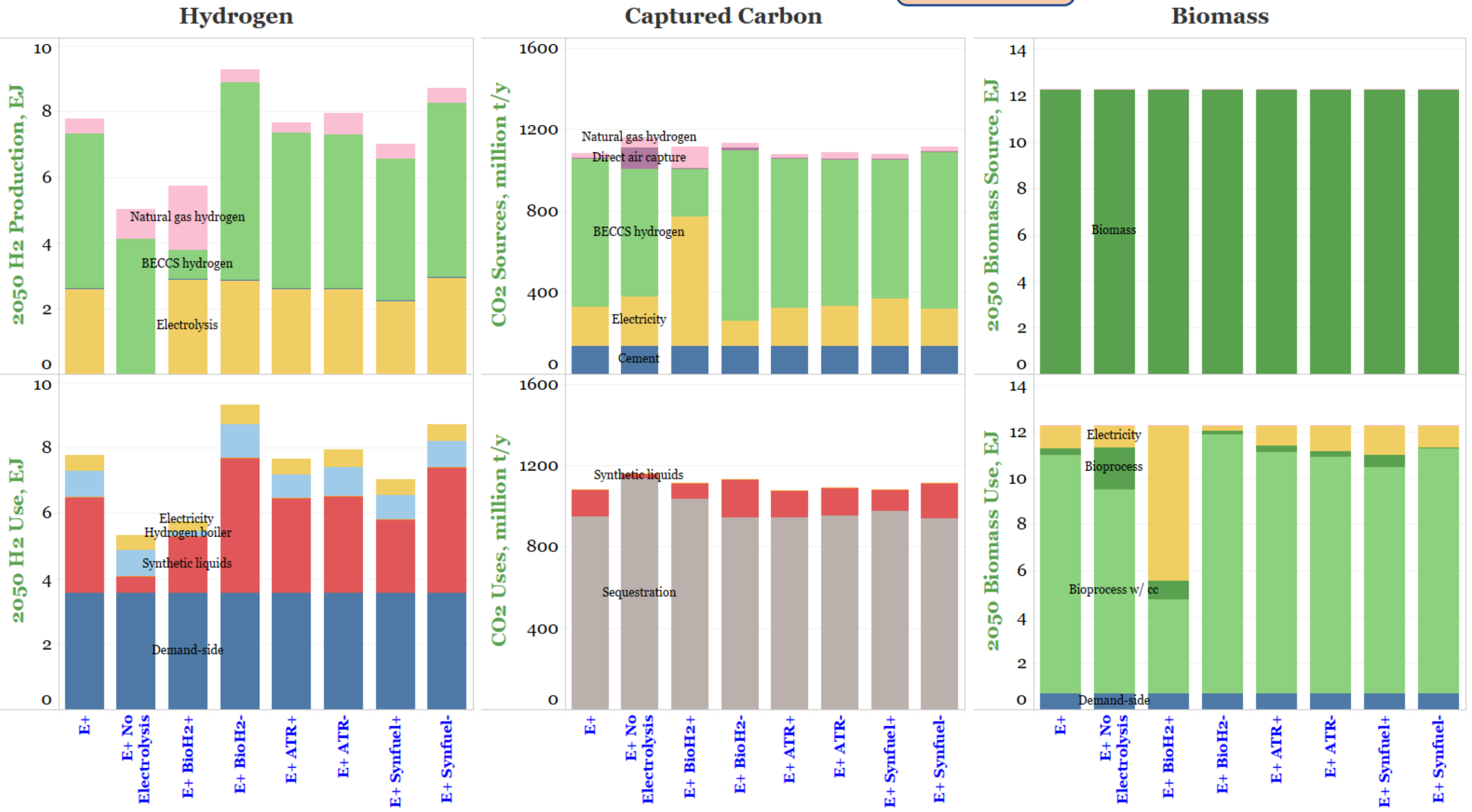
Demand side = H_2 used in transport and for production of chemicals, direct-reduced iron, and process heat in various industries.

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

Sensitivity model runs on E+: Cost/availability of technologies for H_2 production and related fuels synthesis impacts results.

- If electrolysis is disallowed, total H_2 produced is 35% lower, while H_2 from natural gas (ATR-CCS) doubles. Synthetic liquids production is much lower. Direct air capture is deployed to offset residual emissions from greater ATR and use of more petroleum fuels.
- Higher bio-H_2 capital cost drives biomass use from H_2 production to electricity generation with CO_2 capture. More gas is used for H_2 production, and synthetic liquids output falls modestly.
- Results are insensitive to different ATR costs.
- Higher FT synthesis cost reduces output of H_2 and synthetic liquids by ~25%. Lower FT synthesis cost increases H_2 from biomass and via electrolysis.
- NPV of total energy-supply system costs (2020-2050) are about the same for all cases shown.
- See Annex B for additional details.

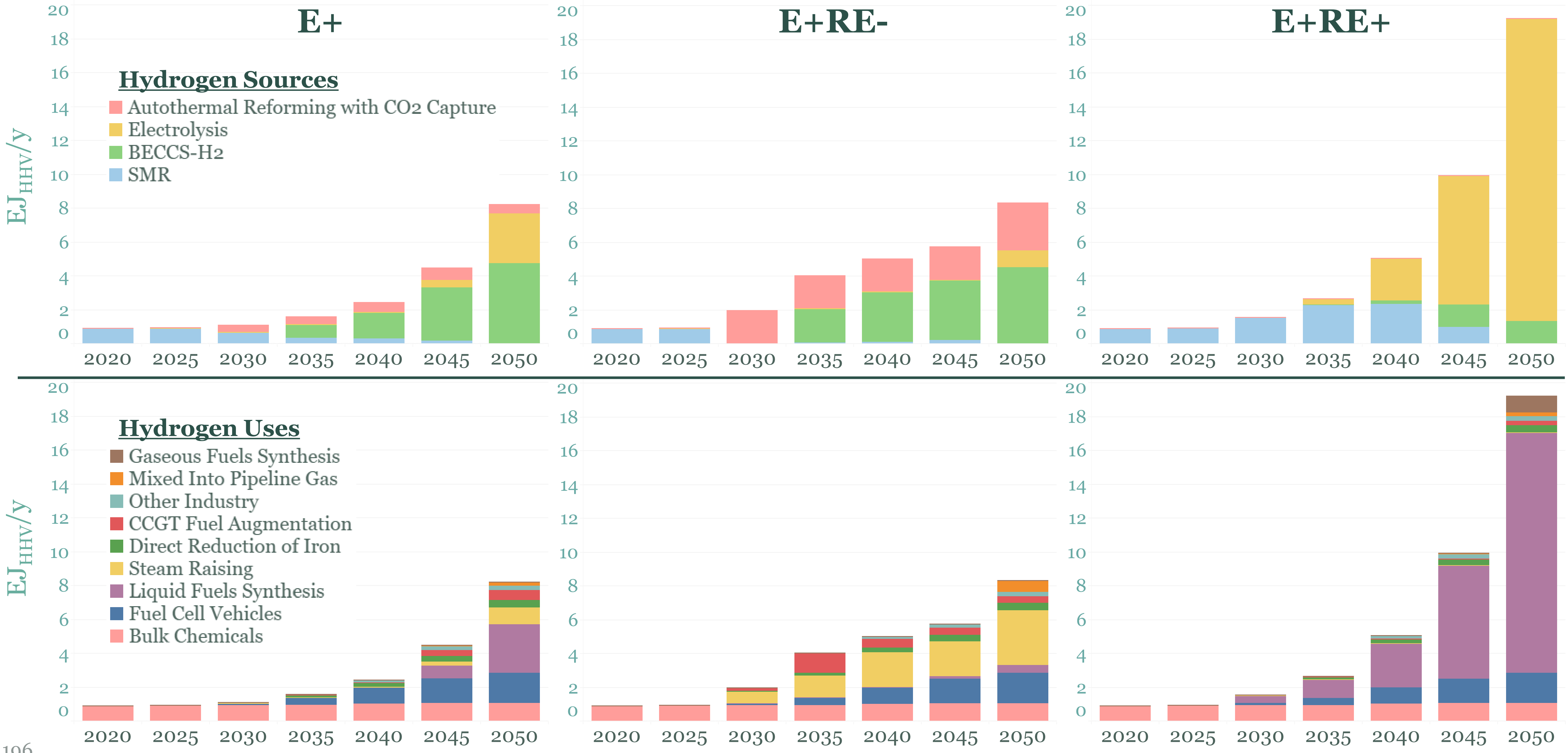
2050



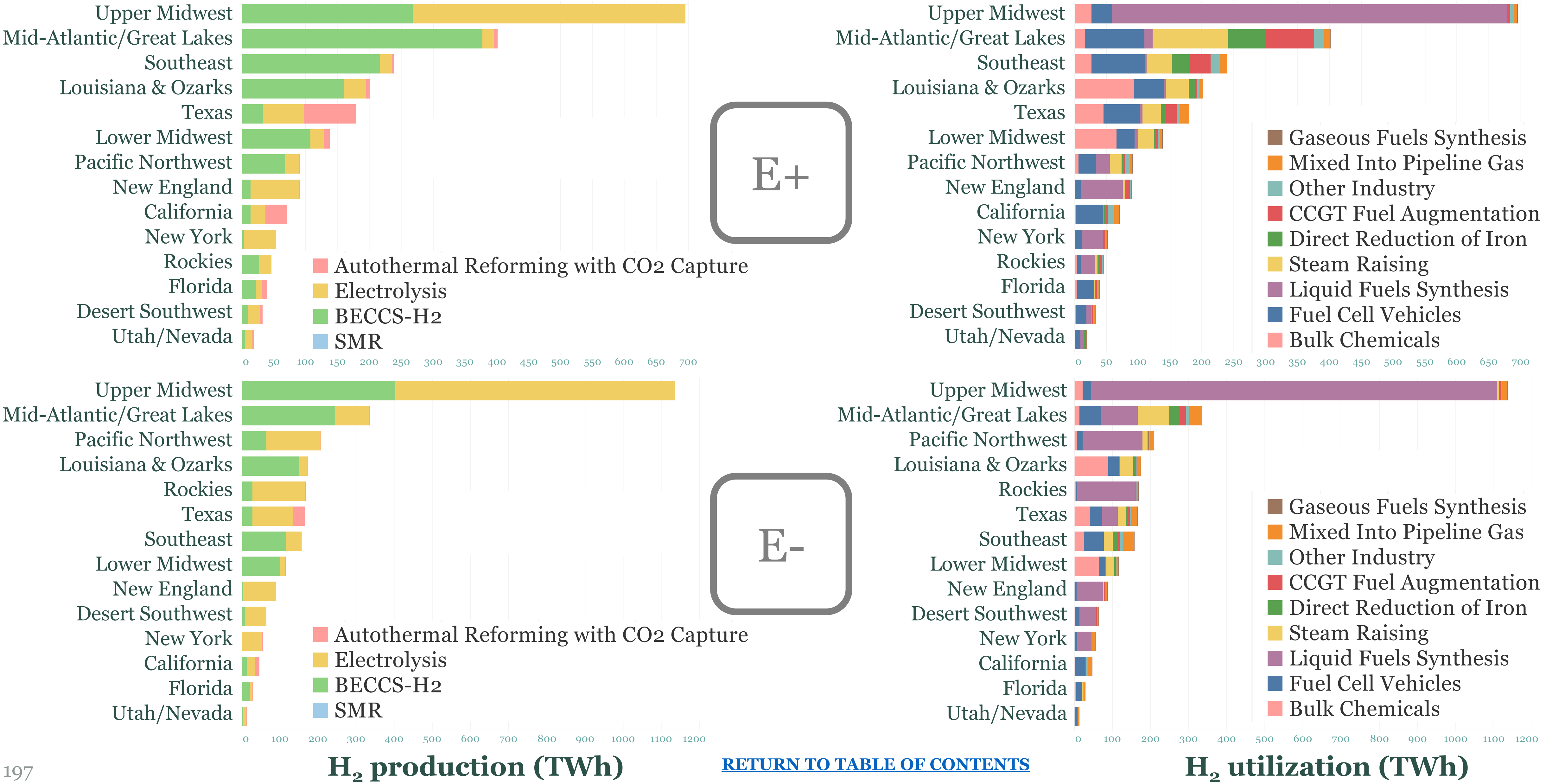
Input assumptions that vary between cases, installed capital cost in 2050 (2016$)

$\$/kW_{H2}$ (HHV)	E+	E+ No Electrolysis	E+ BioH2+	E+ BioH2-	E+ ATR+	E+ ATR-	E+ Synfuel+	E+ Synfuel-
BECCS-H_2	2700	2700	4050	2160	2700	2700	2700	2700
ATR-CCS (H_2 from nat. gas)	814	814	814	814	1221	651	814	814
FT (Fischer-Tropsch) synth.	1155	1155	1155	1155	1155	1155	1732	924
Electrolysis	420	not allowed	420	420	420	420	420	420

Growth accelerates after 2030. Mix of H_2 sources and uses varies by pathway. Total is largest by far in E+RE+.



H_2 sources and uses vary by region for different net-zero pathways. 2050 results compared here for E+ and E-.



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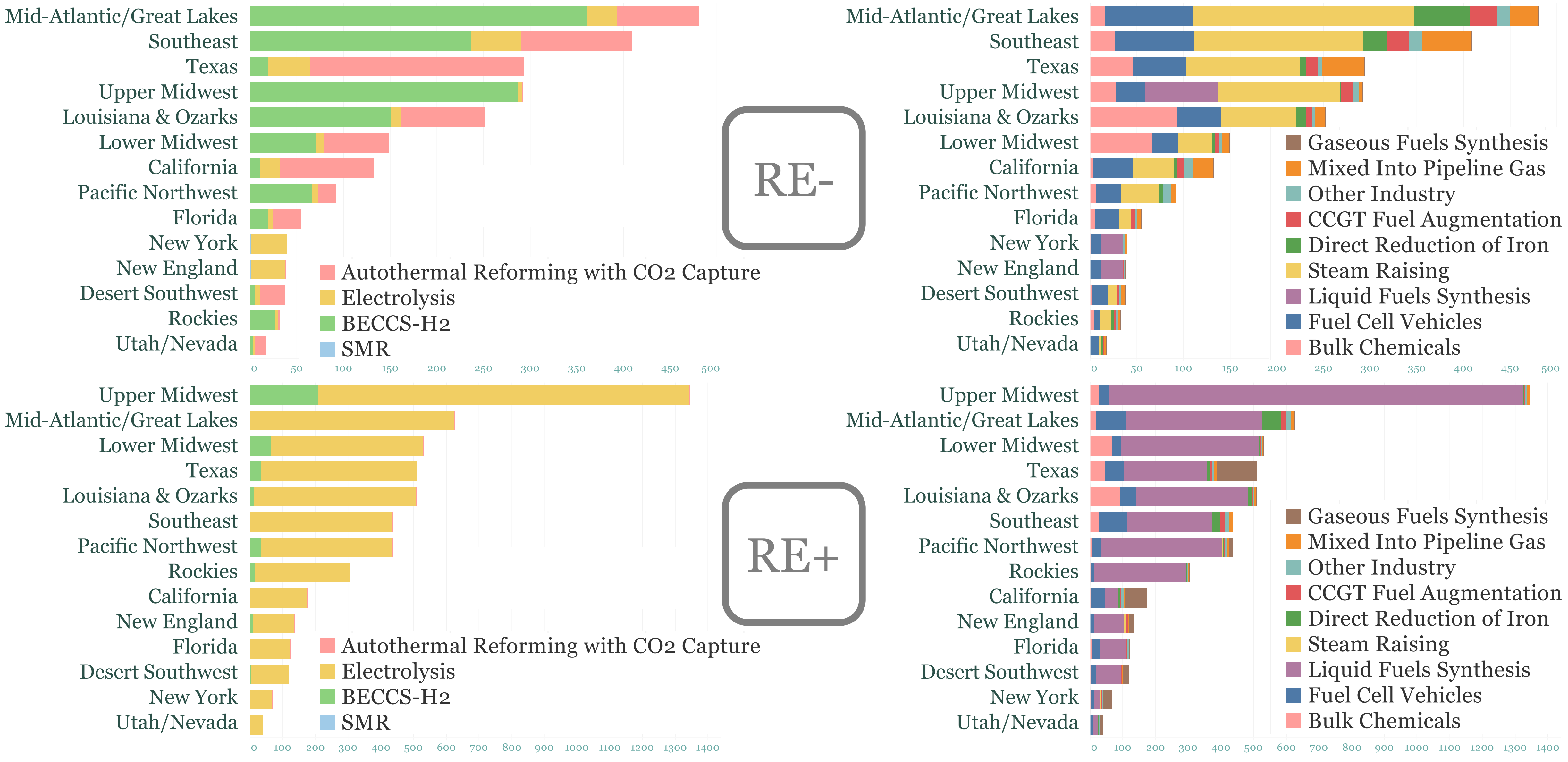
H_2 sources and uses vary by region for different net-zero pathways. 2050 results compared here for E+RE- and E+RE+.



H_2 production (TWh)

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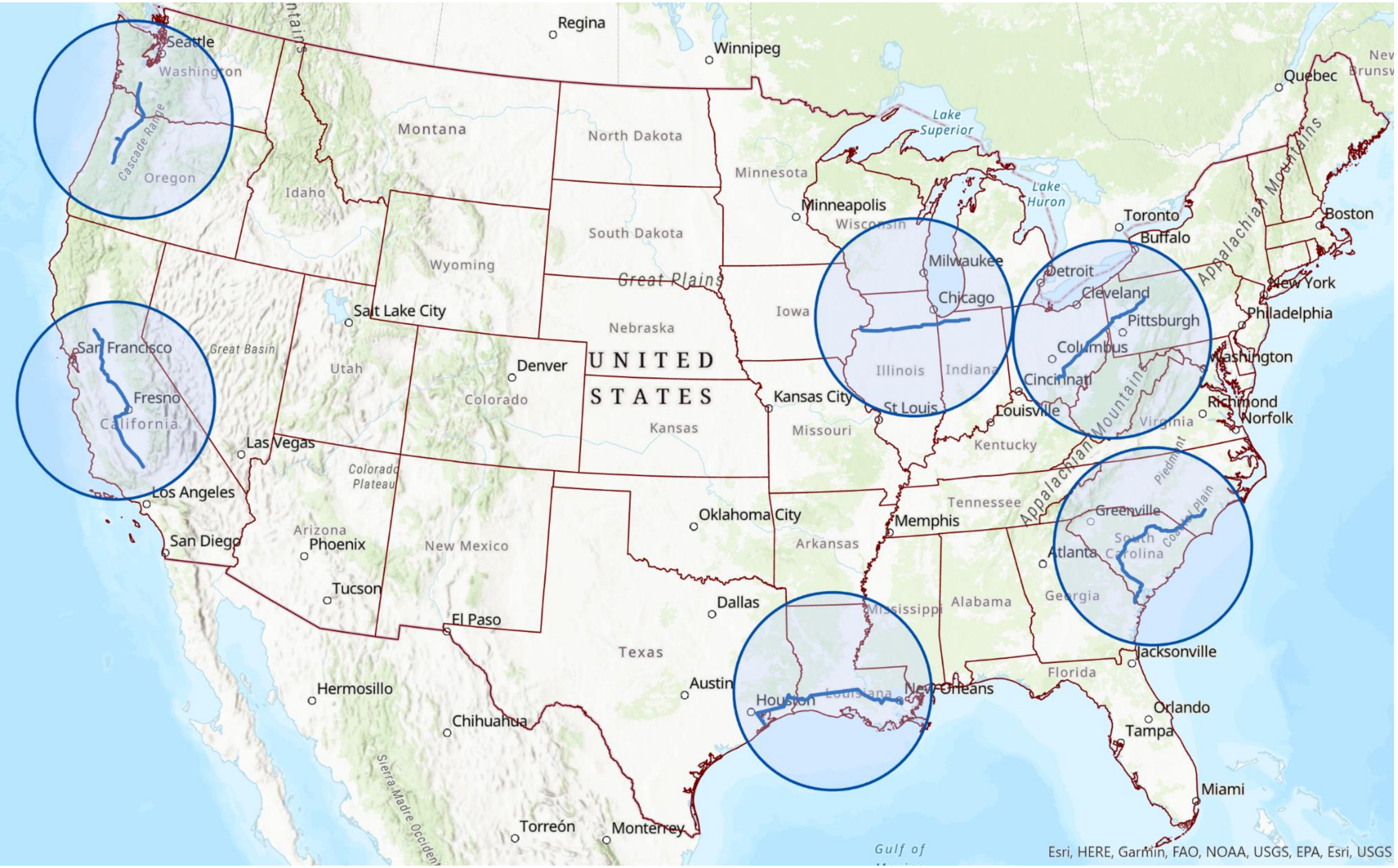
H_2 utilization (TWh)

Notional views of potential H_2 production and use clusters



Industrial H_2-using clusters operate today in U.S. and elsewhere. Here, Air Products & Chemicals Gulf Coast H_2 infrastructure.

- A total of about 2,500 km of H_2 pipelines are in service in the US today
- The most significant H_2-using clusters today are on the Gulf Coast

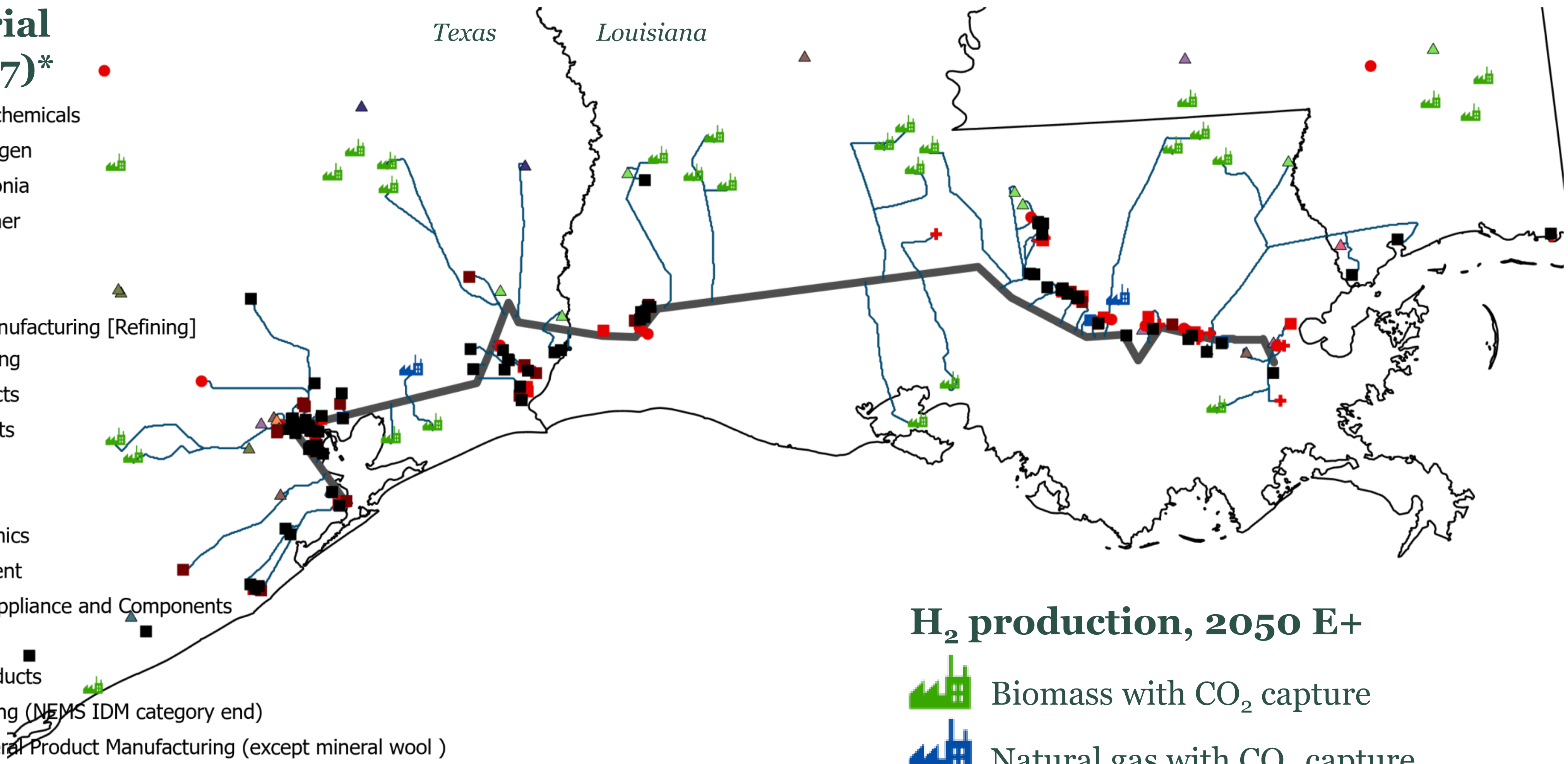
Source: *[Air Products & Chemicals, 2012](#).*

Air Products H_2 Plants - USGC	
Capacity	1.2+ BSCFD
No. of Plants	22
Pipeline Length	~ 600 miles

Notional view of 2050 H_2 production and use: Gulf Coast vignette.

Large industrial facilities (2017)*

- Bulk Chemicals - petrochemicals
- Bulk Chemicals - Hydrogen
- Bulk Chemicals - Ammonia
- Bulk Chemicals - All other
- Cement and Lime
- Iron and Steel
- Petroleum Products Manufacturing [Refining]
- Food products/processing
- Paper and Allied Products
- Glass and Glass Products
- Fabricated Metals
- Machinery
- Computers and Electronics
- Transportation Equipment
- Electrical Equipment, Appliance and Components
- Wood Products
- Plastic and Rubber Products
- Balance of Manufacturing (NEMS IDM category end)
- Other Nonmetallic Mineral Product Manufacturing (except mineral wool)



H_2 production, 2050 E+

- Biomass with CO_2 capture
- Natural gas with CO_2 capture

* Source: Environmental Protection Agency, Facility Level Information on GreenHouse gases Tool (FLIGHT) database.

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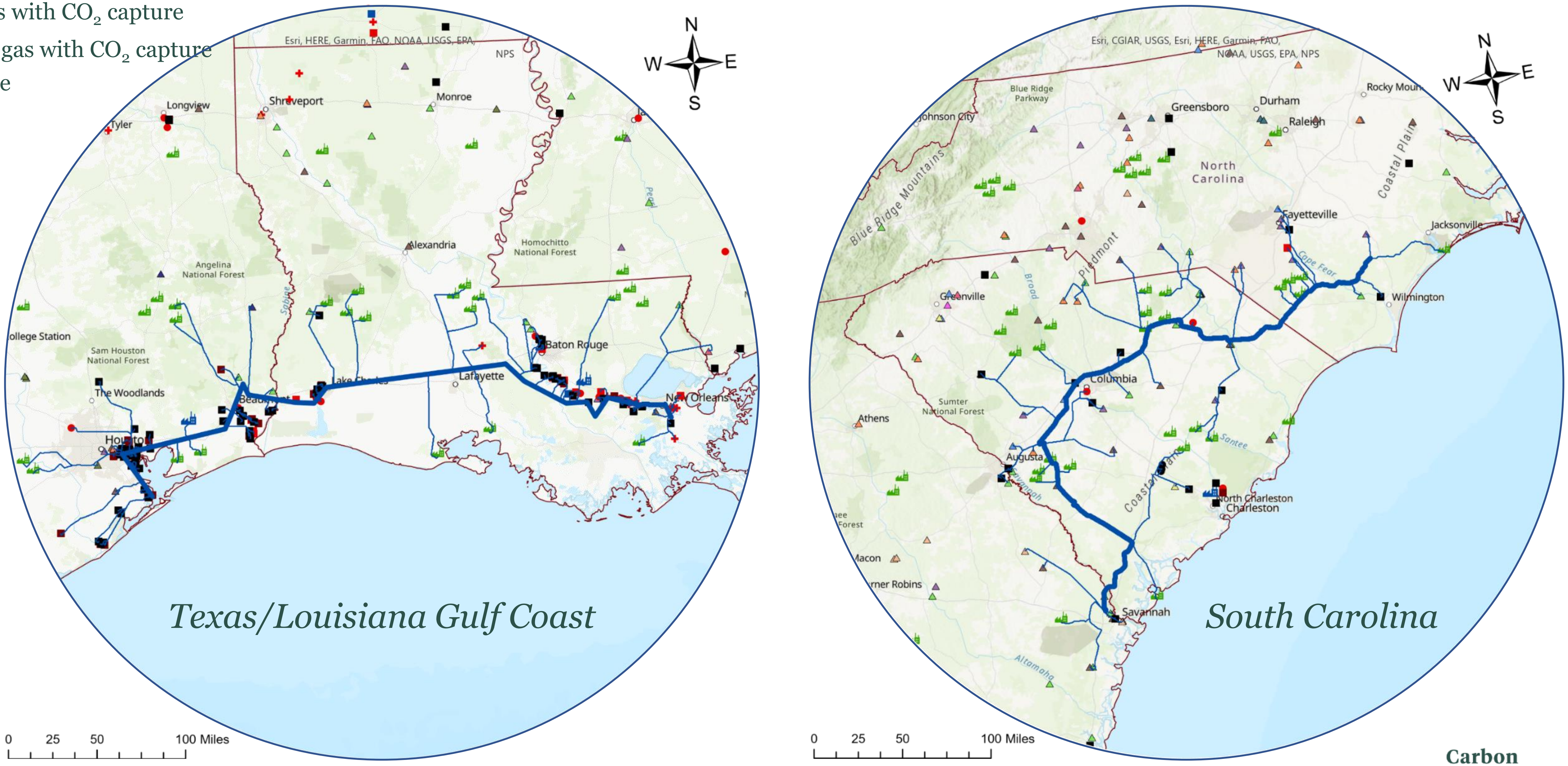
Notional 2050 H_2 production and use clusters: South/SE vignettes.

2050 H_2 supply system (E+)

- H_2 from biomass with CO_2 capture
- H_2 from natural gas with CO_2 capture
- H_2 trunk pipeline
- H_2 spur pipeline
- Large industrial facilities (2017)



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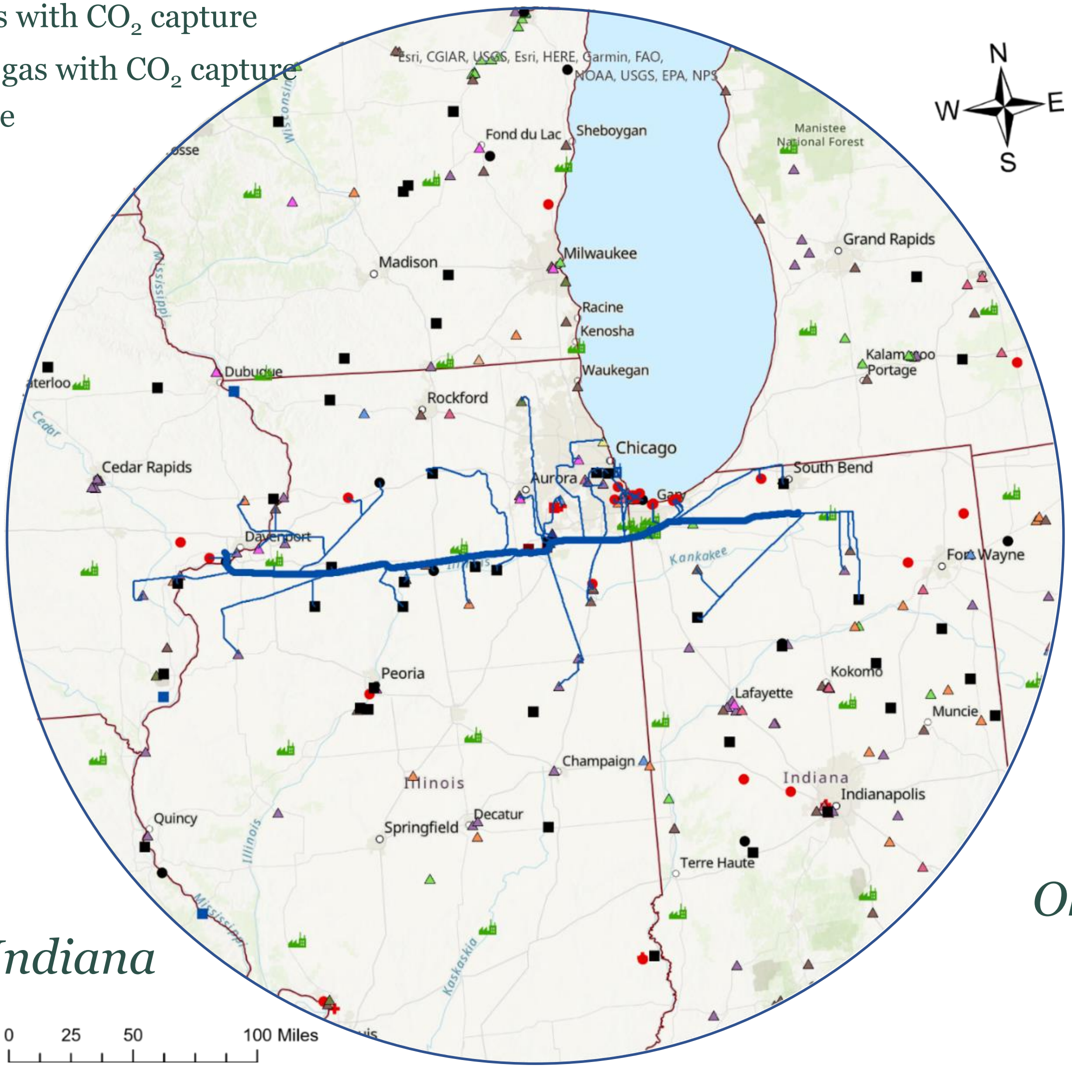
Carbon Mitigation Initiative

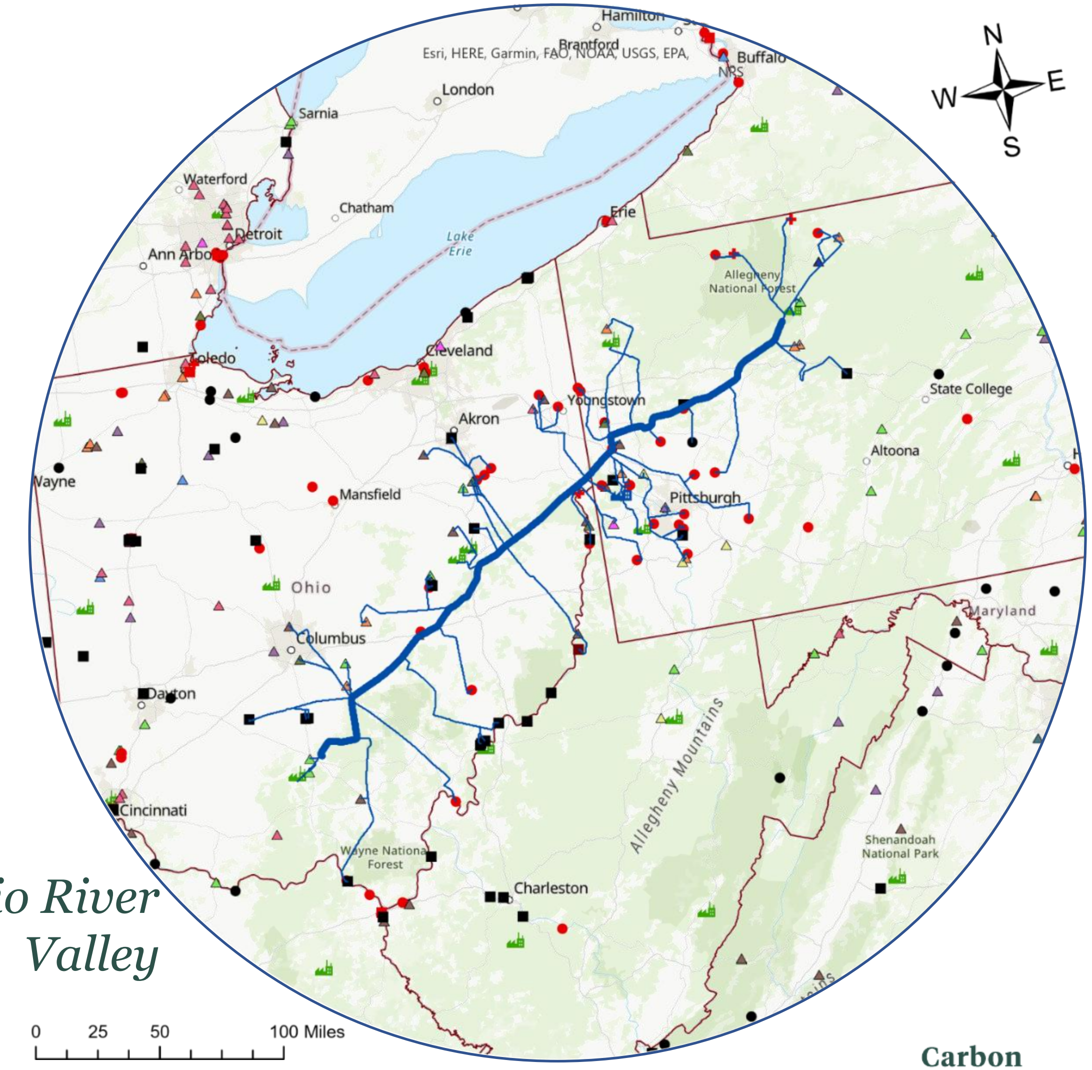
Notional 2050 H_2 production and use clusters: Midwest vignettes.

2050 H_2 supply system (E+)

- H_2 from biomass with CO_2 capture
- H_2 from natural gas with CO_2 capture
- H_2 trunk pipeline
- H_2 spur pipeline
- Large industrial facilities (2017)



Illinois/Indiana



Ohio River Valley

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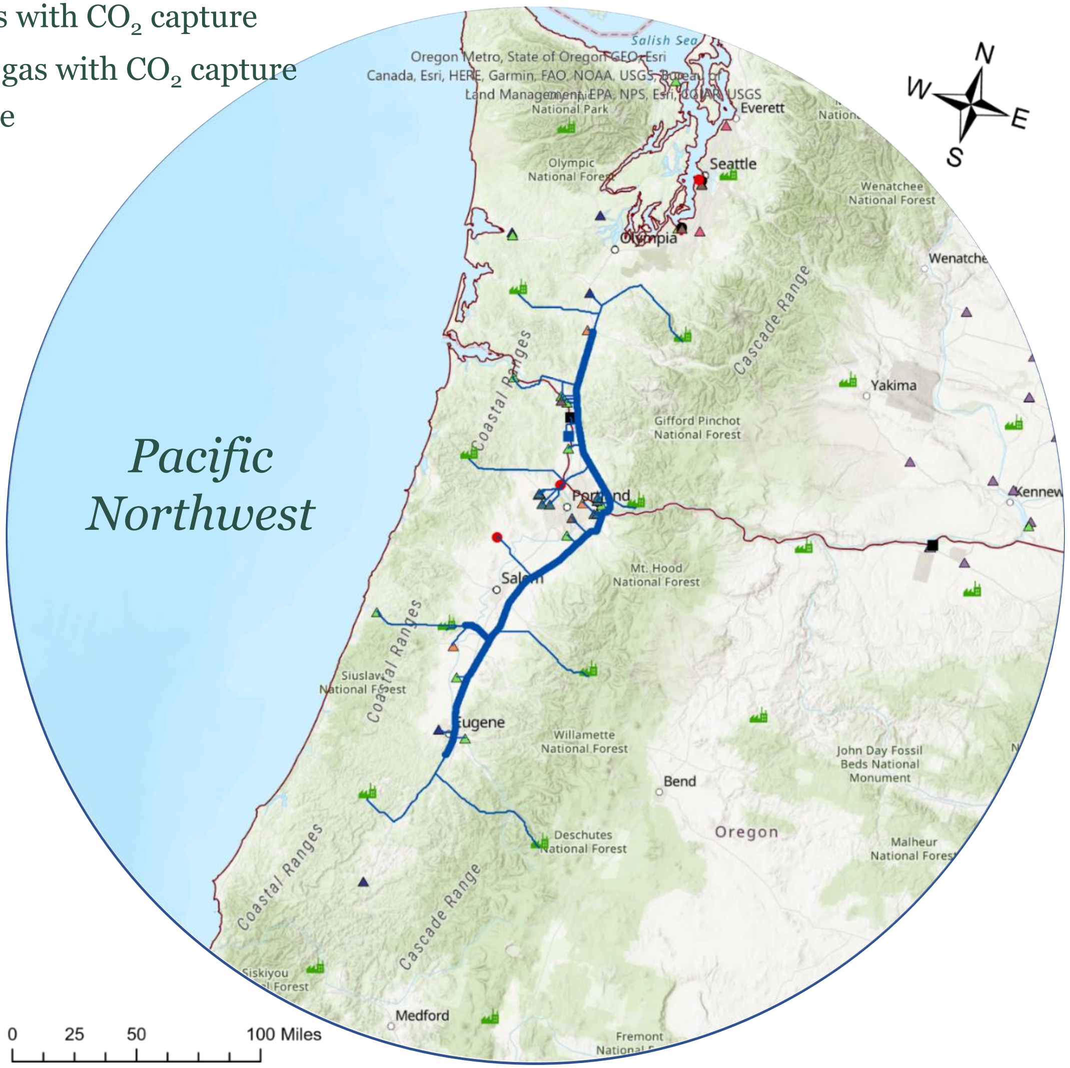
Carbon Mitigation Initiative

Notional 2050 H_2 production and use clusters: West Coast vignettes.

2050 H_2 supply system (E+)

- H_2 from biomass with CO_2 capture
- H_2 from natural gas with CO_2 capture
- H_2 trunk pipeline
- H_2 spur pipeline
- Large industrial facilities (2017)



Carbon Mitigation Initiative

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

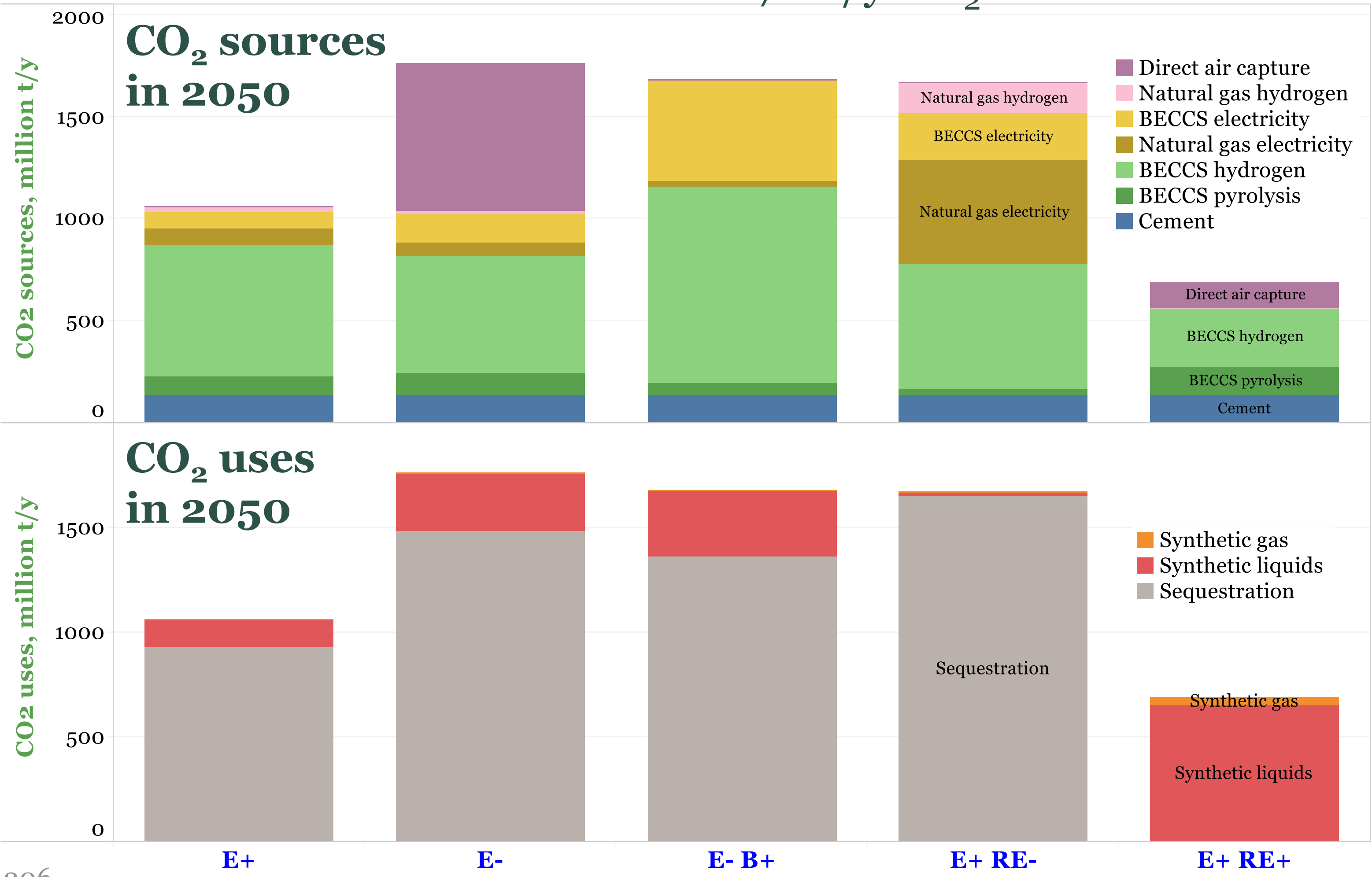
Summary of this section

- CO_2 capture is deployed at large scale in all NZA scenarios. Geological storage is deployed at large scale in all NZA scenarios, 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 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 injection sites before 2035 to enable rapid expansion thereafter.
- The CO_2 capture utilization and storage (CCUS) industry is enabled by around 110,000 km of new CO_2 pipeline infrastructure with 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 these scenarios ranges from 1.3 to 2.4 times current US oil production on a volume equivalent basis.
- See Annex I for details around downscaling analysis of CO_2 transport and geologic storage.

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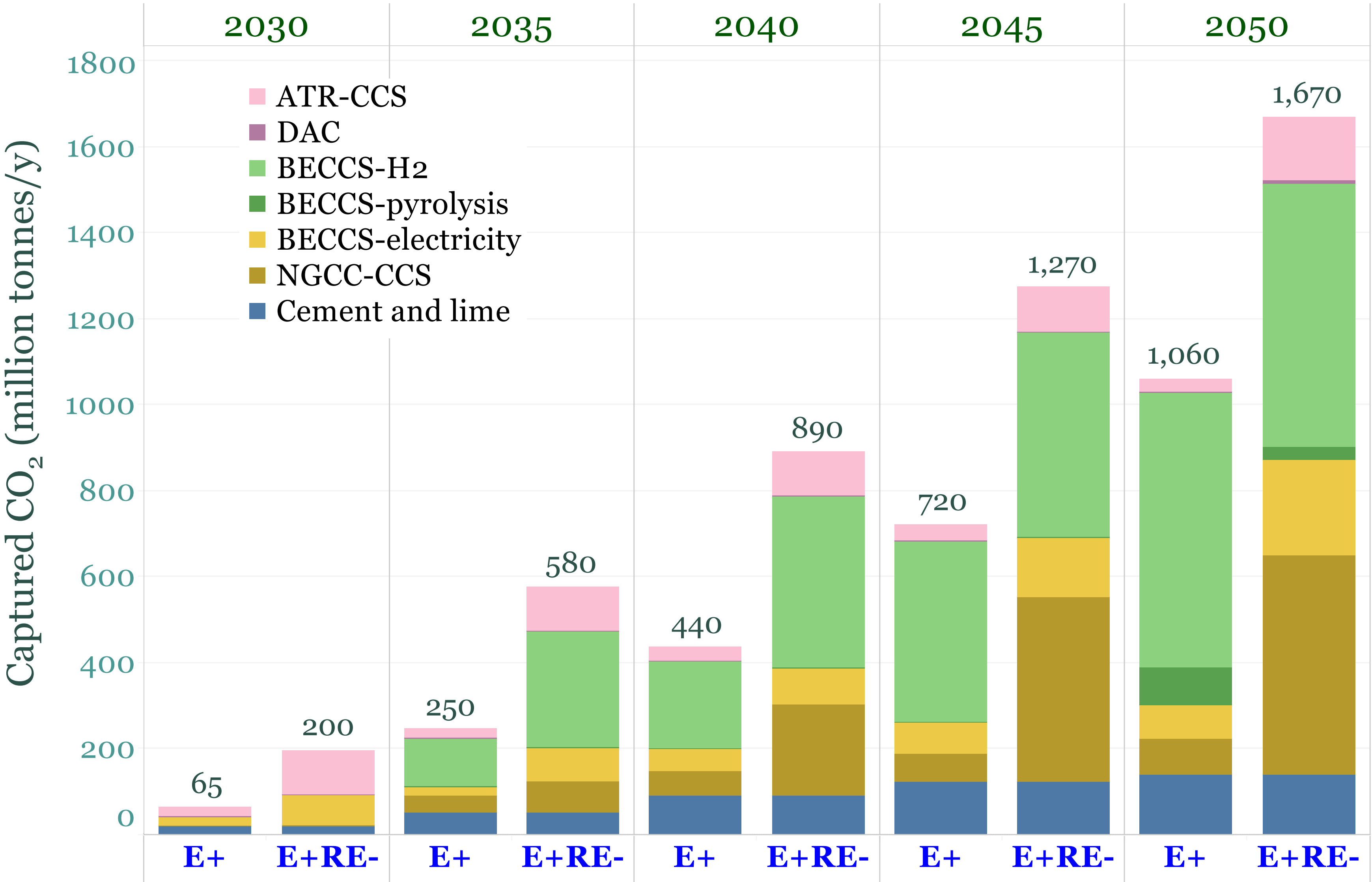
Some capture plants online by 2030, followed by rapid growth in 2030s and 2040s. E+ and E+RE- pathways are shown here.



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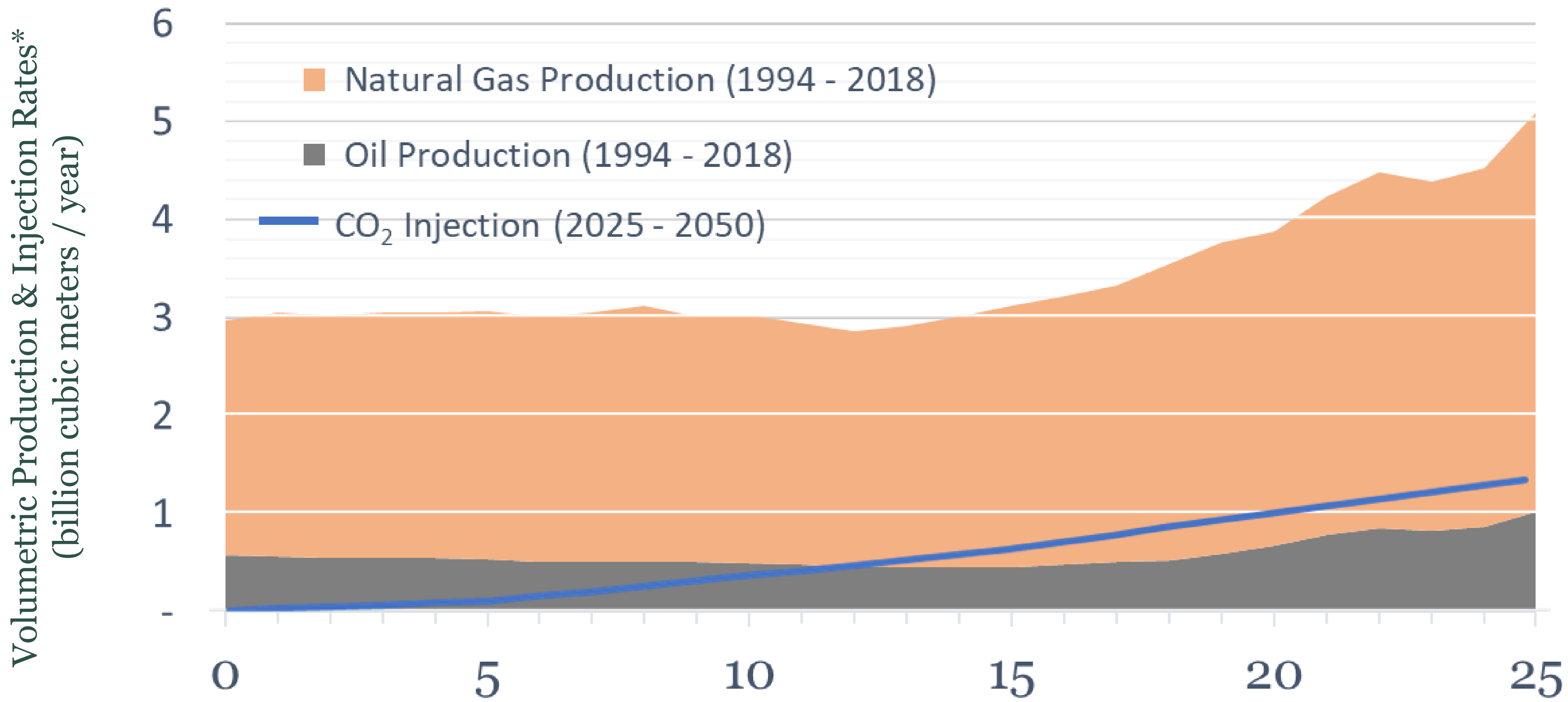
Carbon Mitigation Initiative

CO_2 injection rates grow from small today to 27% of 2018 oil & gas extraction rates in 2050 (at notional in situ reservoir conditions)



Years (1994-2019 for oil & gas; 2025-2050 in E+ scenario for CO_2)

* At notional in situ reservoir conditions (2,000 m depth)

Oil & gas production data from BP Statistical review of Energy

CO_2 transport network design combines state-of-art understanding of storage basins and geospatial downscaling of CO_2 point sources.

1. The most prospective CO_2 storage basins were identified based on practicable storage capacity (accessible, sustainable annual injection rates) estimates of Teletzke *et al*. (2018).
2. Notional supply-cost curve for CO_2 transport and storage established using expert judgement and industry consultation (BP, ExxonMobil, Occidental), assuming shared transport infrastructure.
3. RIO chooses CO_2 capture and storage (CCS) to mitigate emissions from power sector, fuels production and industry sectors across 14 regions, where economically competitive for scenarios that allow CCS.
4. Downscaling defines locations for each capture facility at county level.
5. Notional CO_2 trunk line network drawn 'by eye' to pick up major clusters of point sources, with build program to deliver CO_2 transport infrastructure in advance of start of CO_2 capture activity.
6. Point source downscaling repeated to locate all point sources within 200 km of trunk lines.
7. Spur lines connect point sources to trunk lines using minimum distance and following existing ROWs.*
8. Trunk lines sized and costed using FE/NETL CO_2 Transport Cost Model, and build-out programmed to meet expansion of CO_2 point sources for all trunk line catchment areas. Spur lines costed using a simple *Cost = f(tpa, km)* equation derived from the FE/NETL CO_2 Transport Cost Model.
9. Levelized cost of CO_2 transport established based on capital cost estimates, build schedules, and CO_2 expansion using discounted cash flow model.
10. Cost-supply curves calculated for different potential capacity-charge arrangements.

See Annex I for additional details

* Existing ROWs include natural gas, NH_3 and CO_2 pipelines, railways, interstate highways, and > 220kV electricity transmission lines, as mapped in Edwards and Celia, "Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States," *PNAS*, 115(38): E8815-E8824, 2018.

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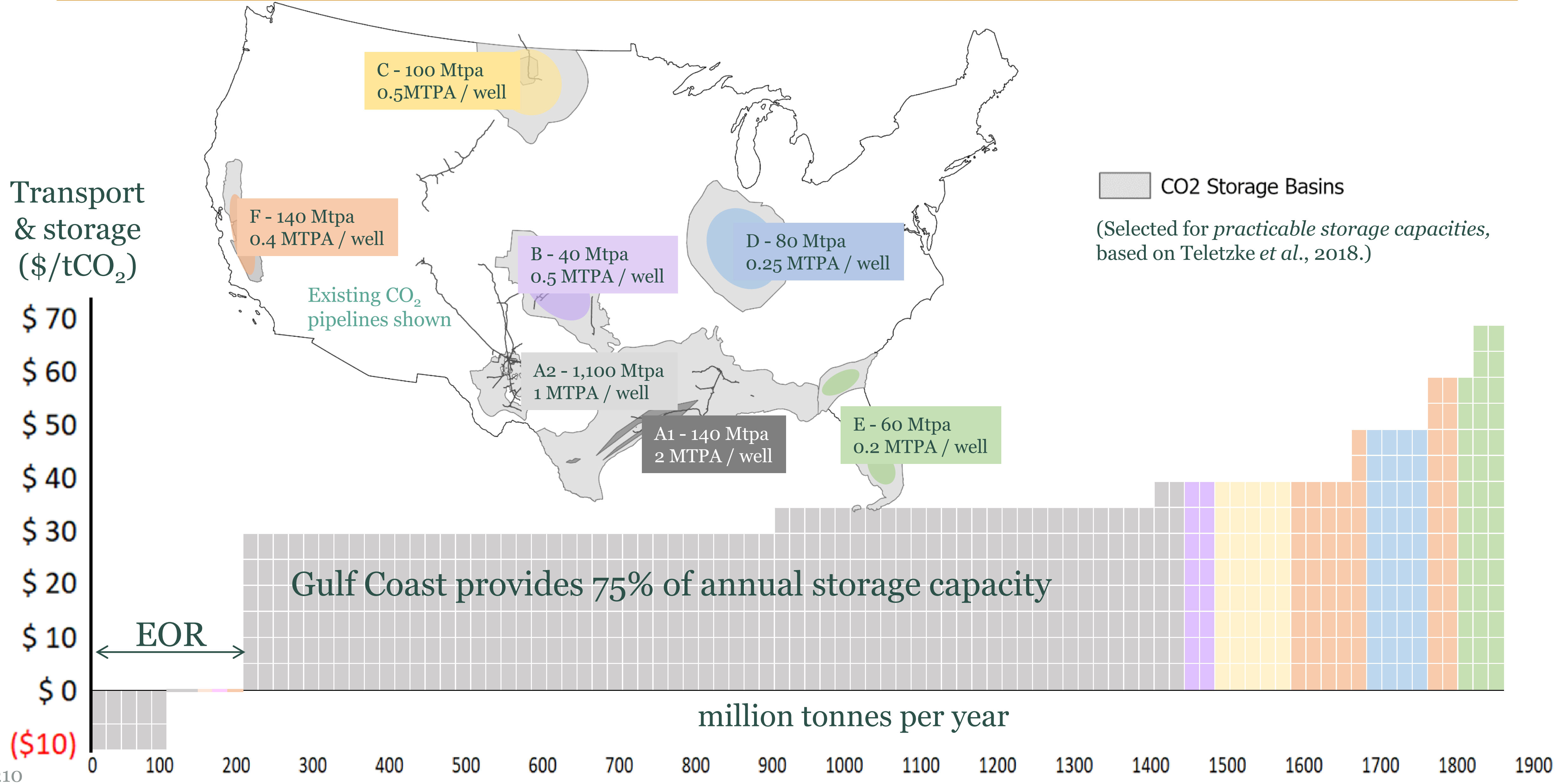
Notional CO_2 storage capacity appraised, permitted and developed in 2050 is up to 1.8 billion t/y, mostly in Gulf Coast



13 B$ invested in stakeholder engagement and characterization, appraisal & permitting pre-2035 enables rapid expansion thereafter.

Item	2021-25 Investment (Million $)	2026-30 Investment (Million $)	2031-35 Investment (Million $)	Notional Capacity Appraised (MMtpa)
CO_2 Basin-wide Assessments*	1,500	1,500		
CO_2 Site Appraisal and Permitting**				
Area A1	0	700	400	110
Area A2	0	4,000	2,700	670
Area B	0	100	100	20
Area C	0	200	300	50
Area D	0	200	200	40
Area E	0	100	200	30
Area F	0	300	500	80
Totals	**1,500**	**7,100**	**4,400**	**1,000**

* Estimated to be $500 million per basin (basins A – F identified in prior slide).
** See previous slide for basin labels.

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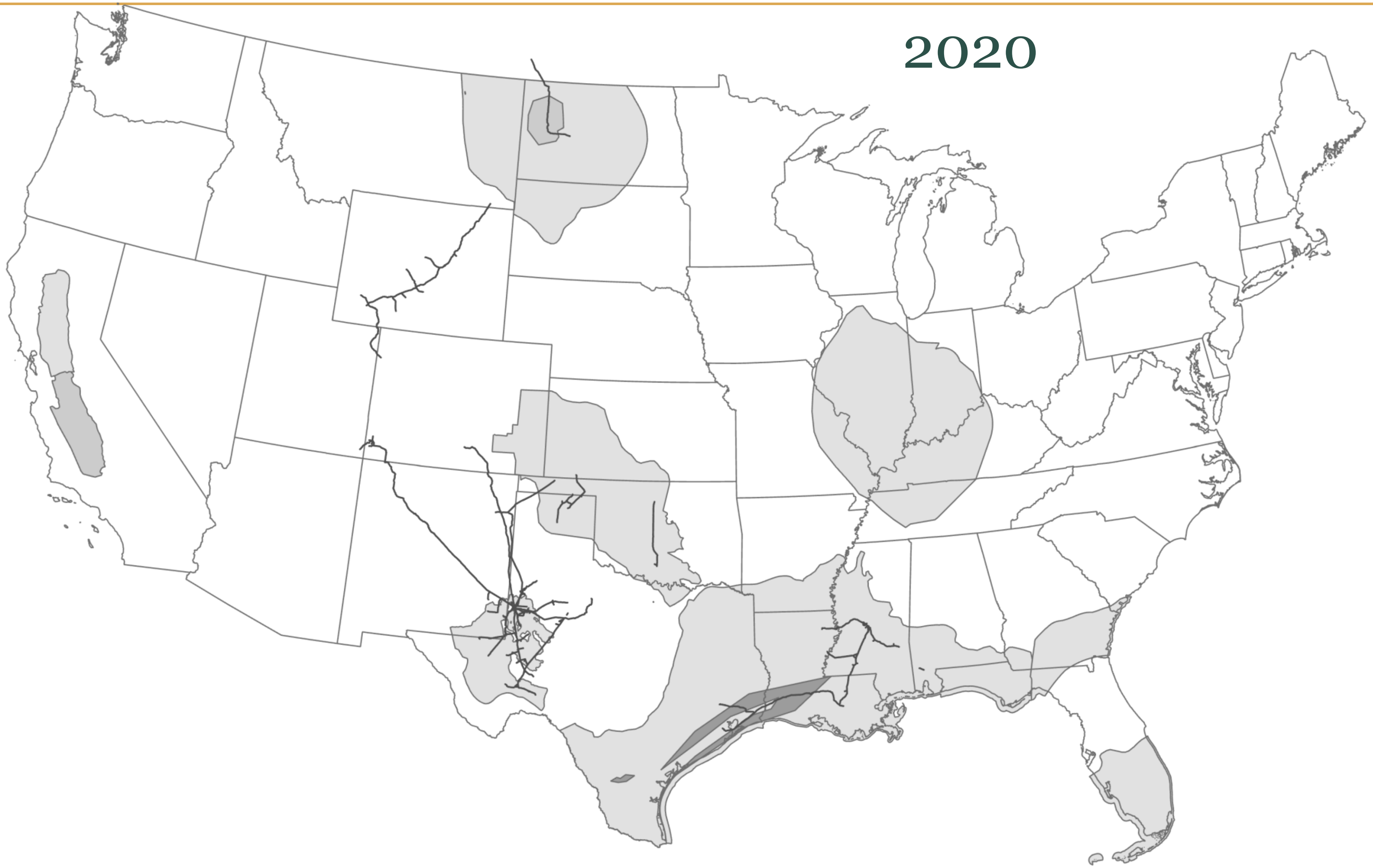
Existing CO_2 pipeline network

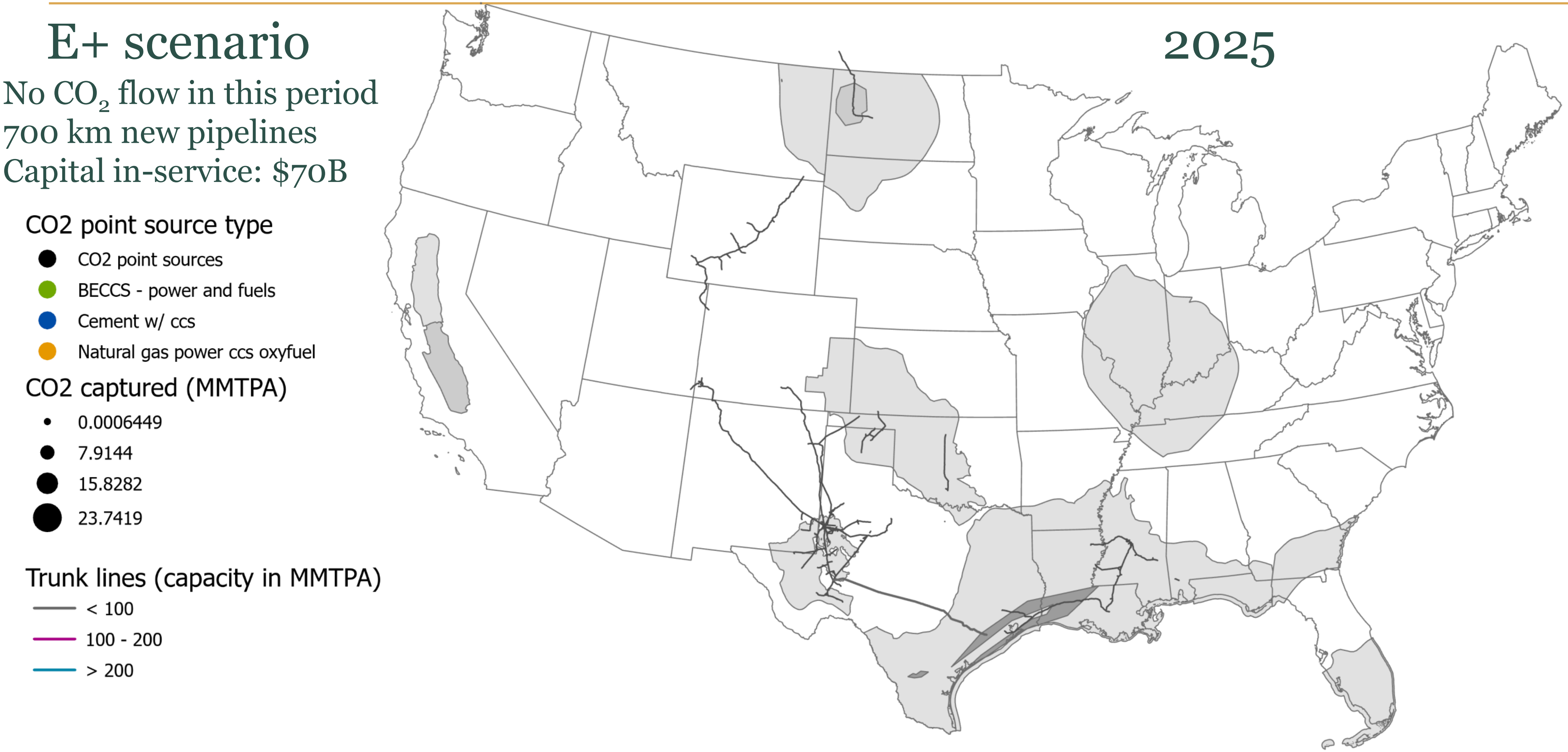
- ~ 80 million tCO_2/yr transported
- ~ 8,500 km of pipelines
- Servicing enhanced oil recovery operations
- Majority in Permian Basin (West Texas and southeast New Mexico)



Trunk line construction begins before 2025 with connection between Permian Basin and Gulf Coast

E+ scenario

No CO_2 flow in this period
700 km new pipelines
Capital in-service: $70B



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Trunk line build out continues and initial CO_2 capture plants come online, with spur lines connecting to trunk network

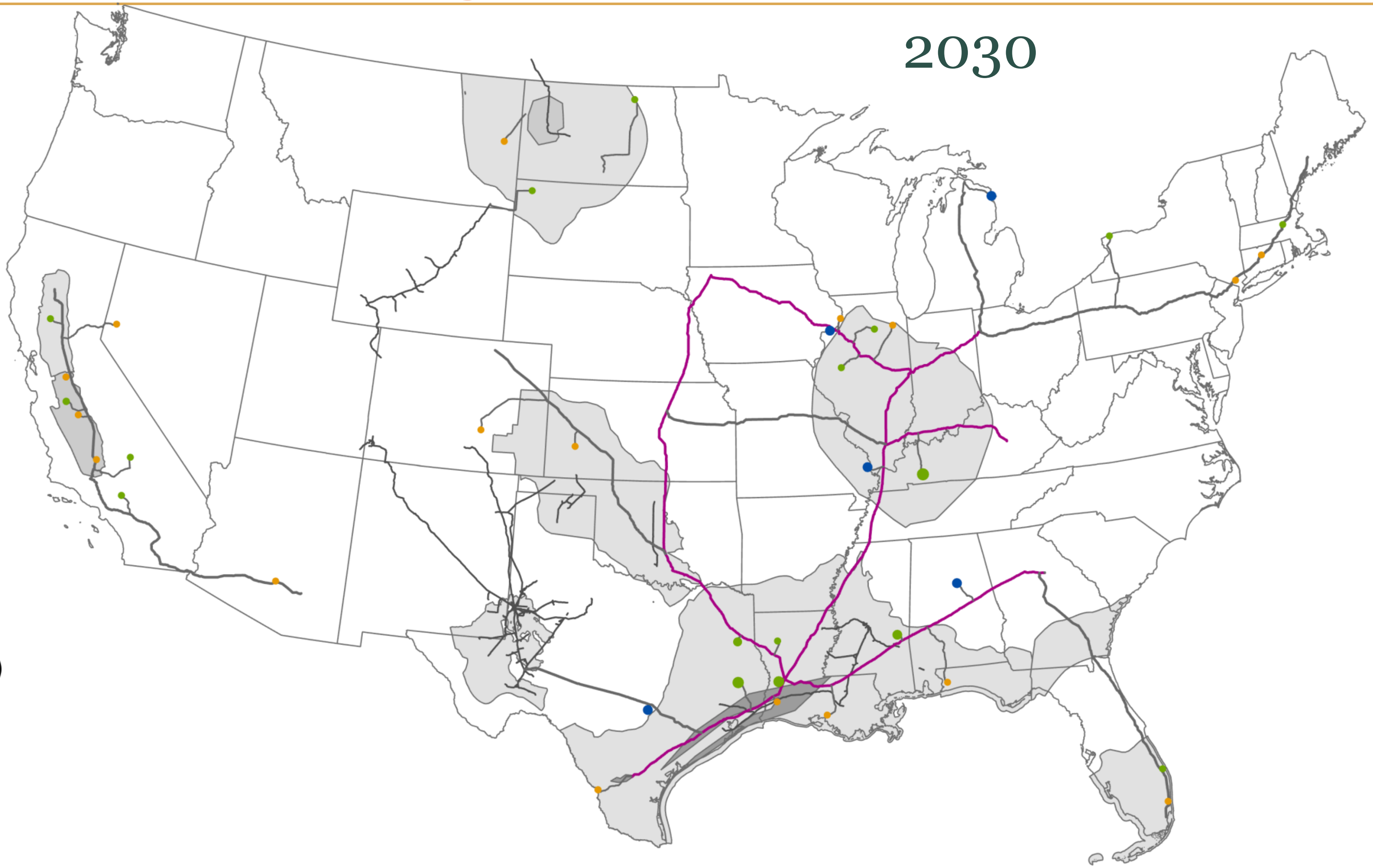
E+ scenario

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

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



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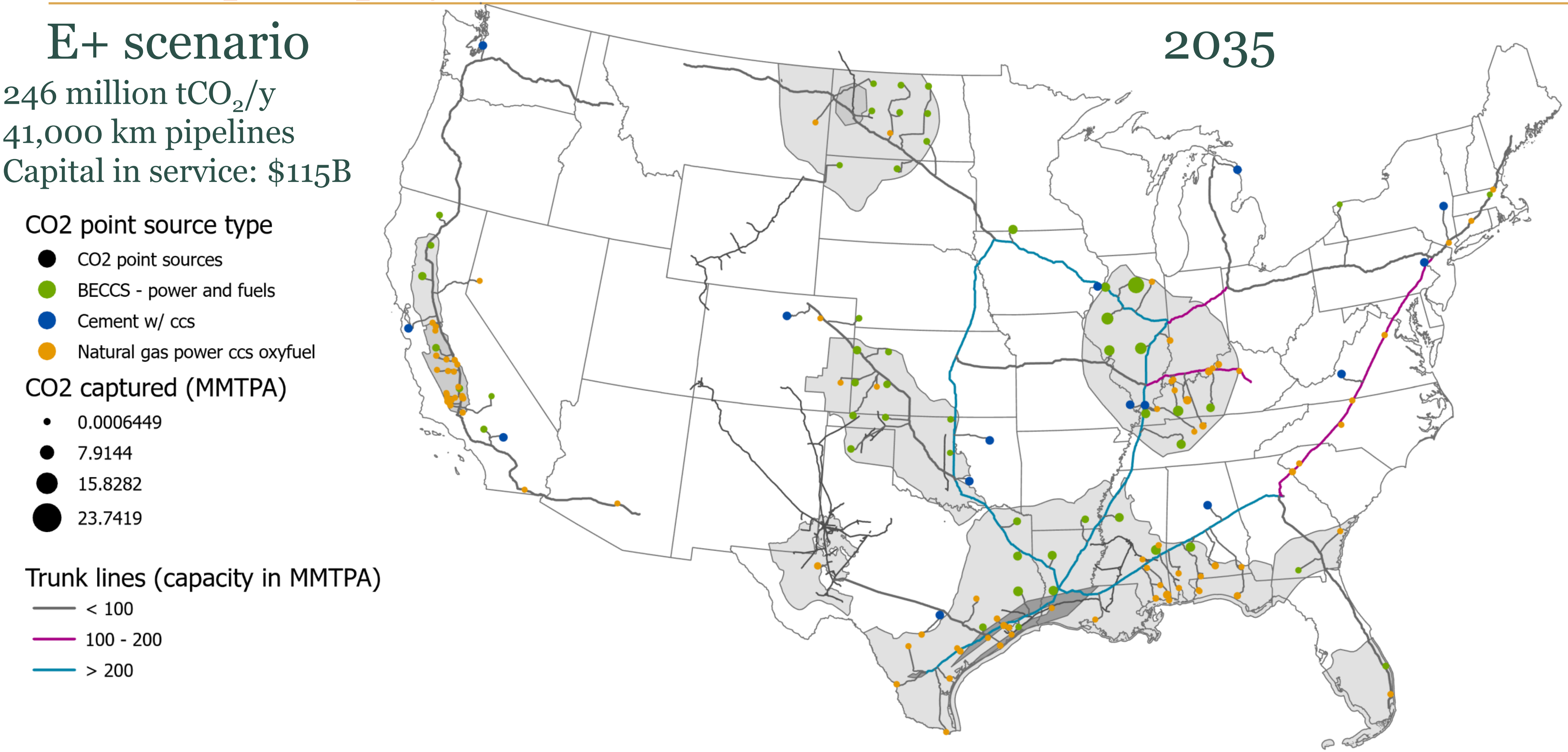
Trunk network routes complete; some sections add parallel lines as more capture projects are built and connected

E+ scenario

246 million tCO_2/y
41,000 km pipelines
Capital in service: $115B



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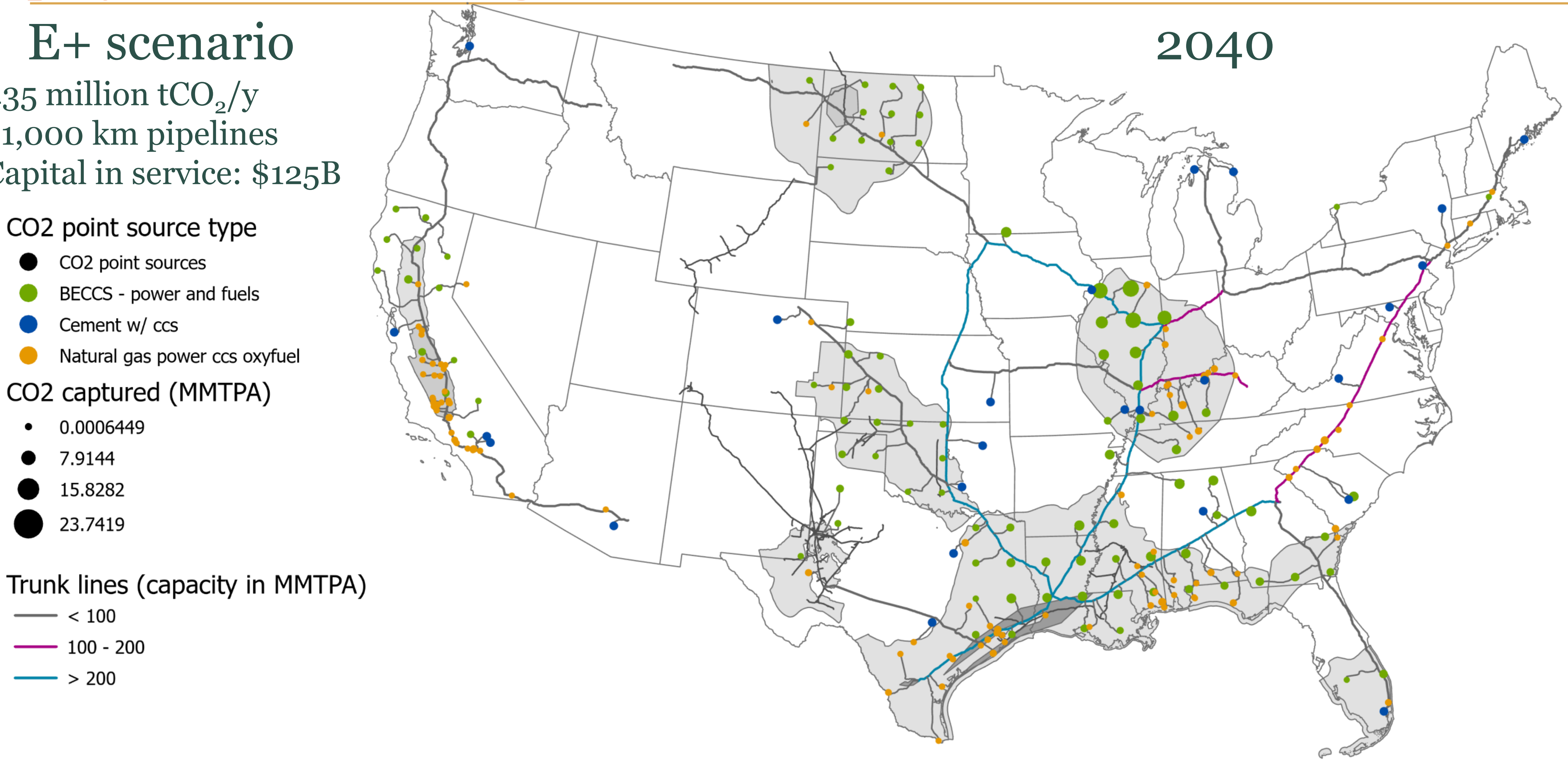
More individual trunk line duplications as number of capture projects continues to grow

E+ scenario

435 million tCO_2/y
51,000 km pipelines
Capital in service: $125B



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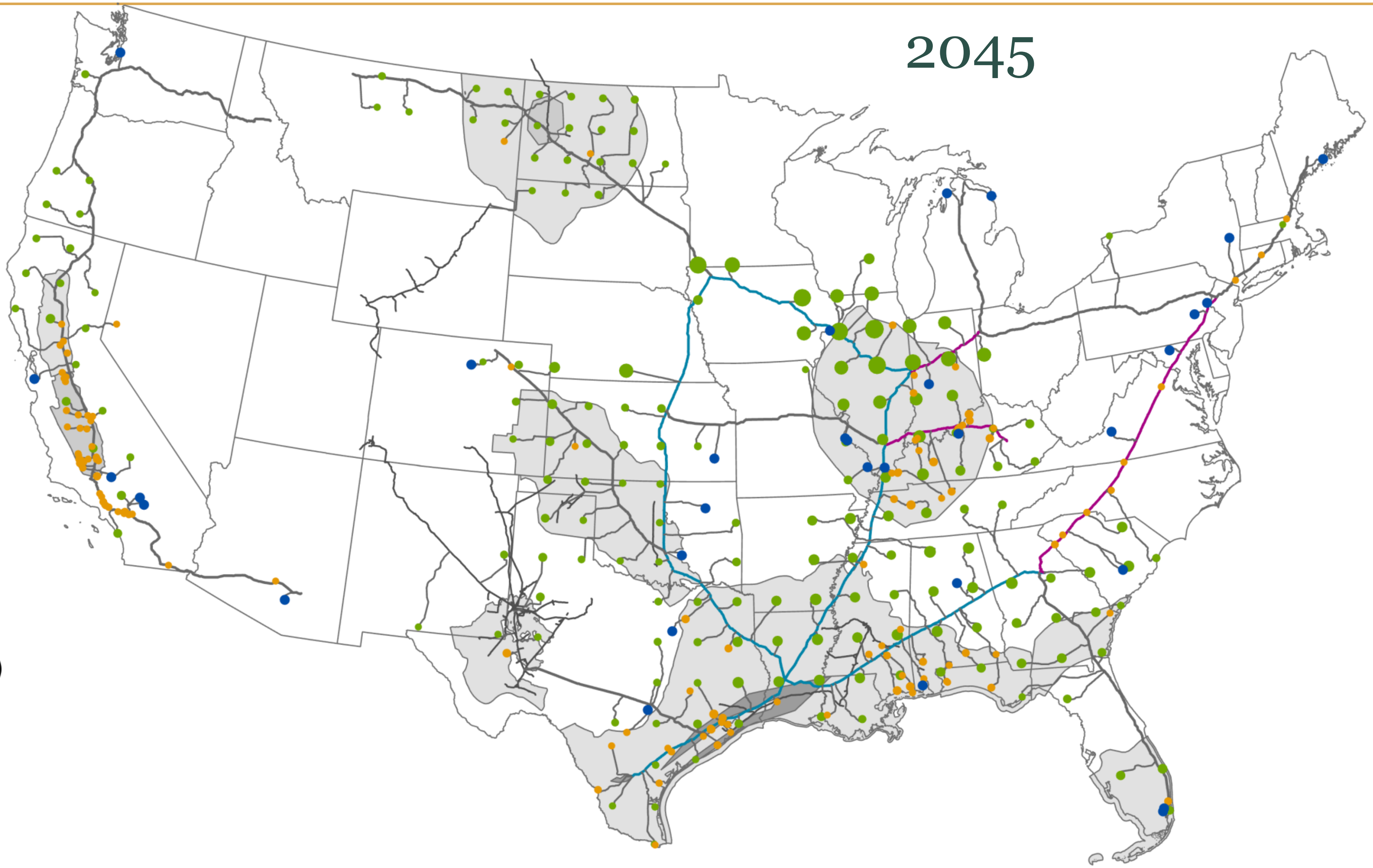
CO_2 capture plants connected to trunk lines grow rapidly

E+ scenario

687 million tCO_2/y
70,000 km pipelines
Capital in service: $135B



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

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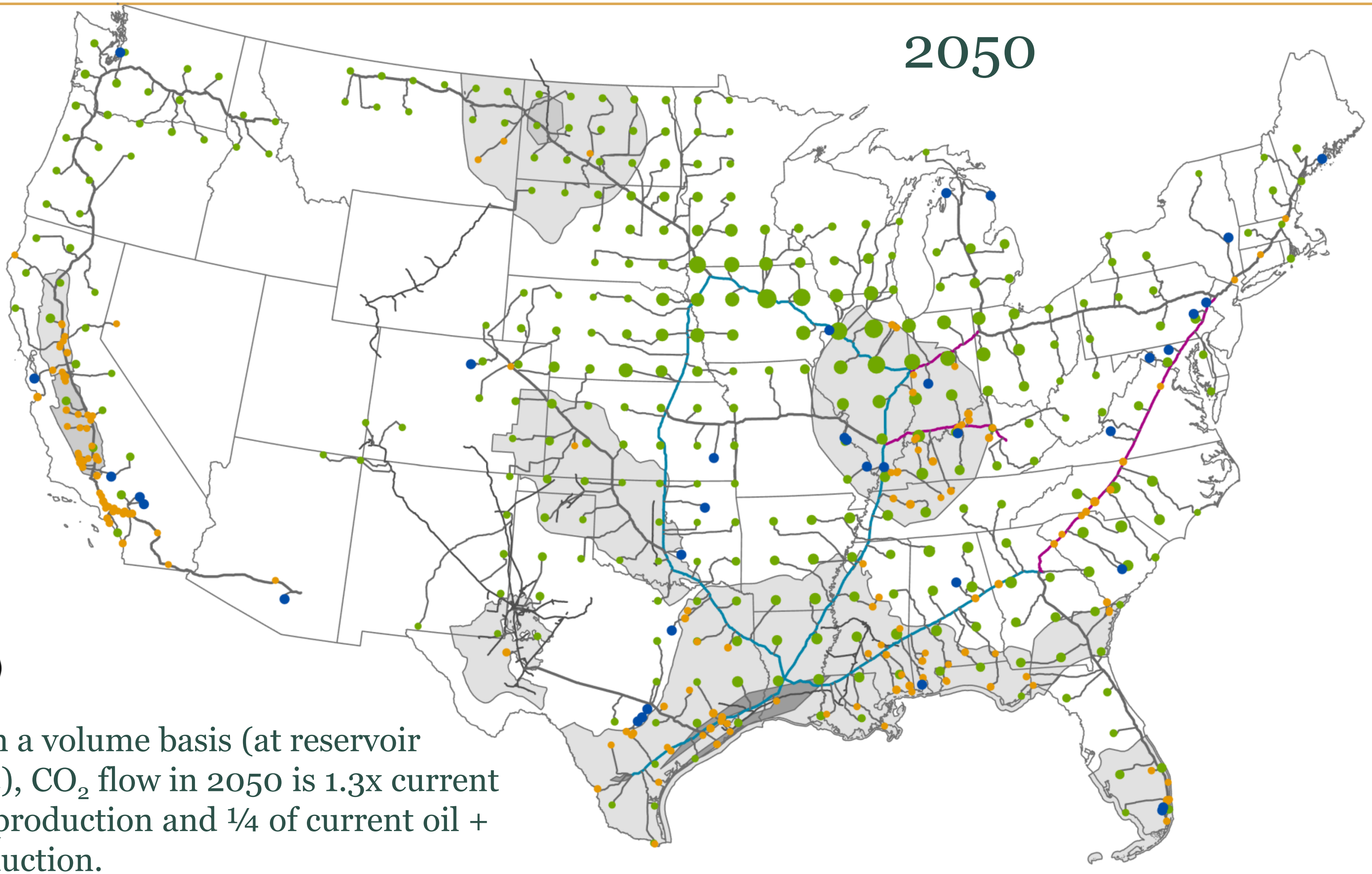
2050 totals: 21,000 km trunk lines + 85,000 km spur lines (equivalent to ~22% of US natural gas transmission pipeline total)

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

Note: 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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E-B+ utilizes the same trunk network, but with some additional parallel pipes in some corridors

E-B+ scenario

1,361 million tCO_2/y
111,000 km pipelines
Capital in service: $220B

CO2 point source type

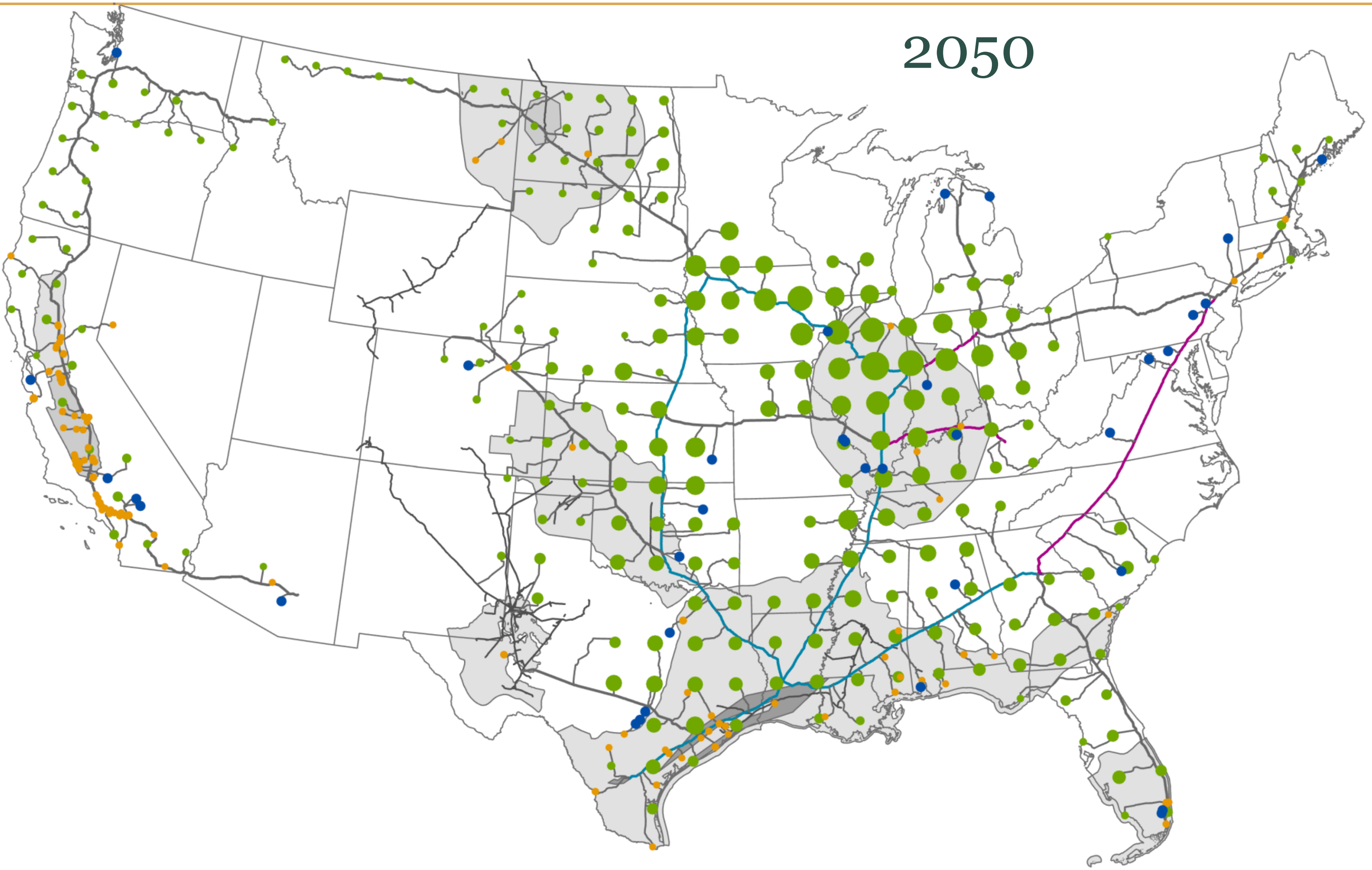
- CO2 point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO2 captured (MMTPA)

- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA)

- < 100
- 100 - 200
- > 200



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Capital for national CO_2 collection and transport network is $170 to $230 billion, or ~ $11 to $16/t$CO_2$ when amortized across all users

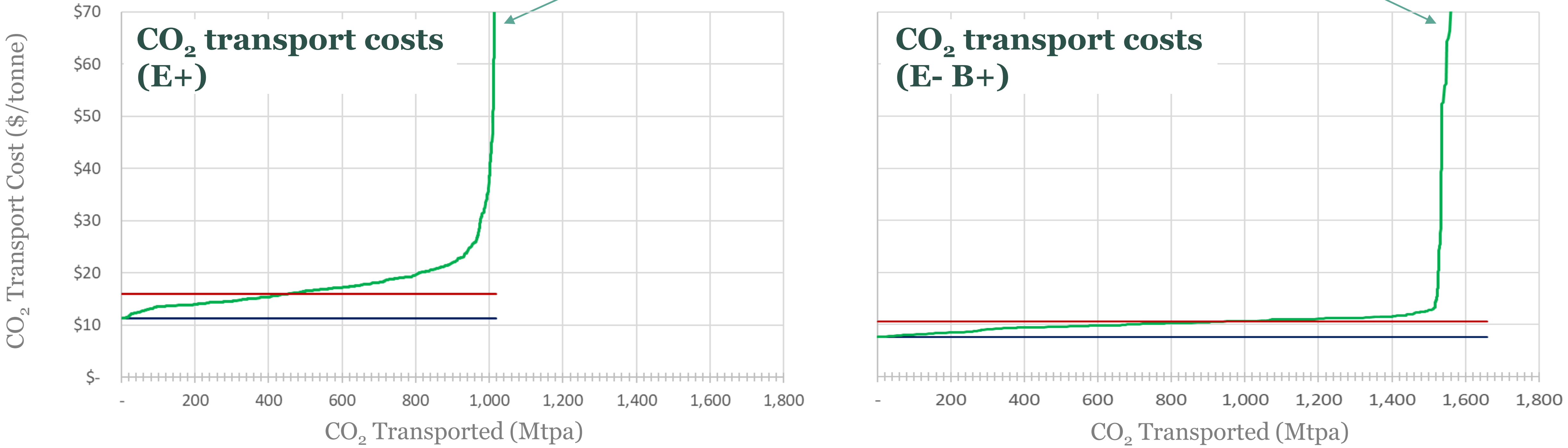
Costs (2020$)*	E+	E- B+
Trunk lines		
Total length, km	21,100	25,400
Total installed capital cost, billion 2020$	101	135
National network-access charge, $/t$CO_2$ delivered	11.3	7.6
Center-East network-access charge, $/t$CO_2$ delivered	11.3	7.4
West network-access charge, $/t$CO_2$ delivered	11.6	10.4
Spur lines		
Total length, km	85,800	85,700
Total installed capital cost, billion 2020$	69	88
National network-access charge, $/t$CO_2$ delivered	4.6	3.0
Total trunk + spur lines		
National network-access charge, $/t$CO_2$ delivered	15.9	10.6

Higher charge for West than for Center-East trunk network

* Costs, including pipelines and compressors, were estimated using the DOE/NETL CO_2 Transport Cost Model (version 2b),.

Amortizing investments across all users avoids prohibitively high costs of small-capacity point sources financing their own spur lines.

Rapidly rising transport costs for smaller point sources with longer spur lines

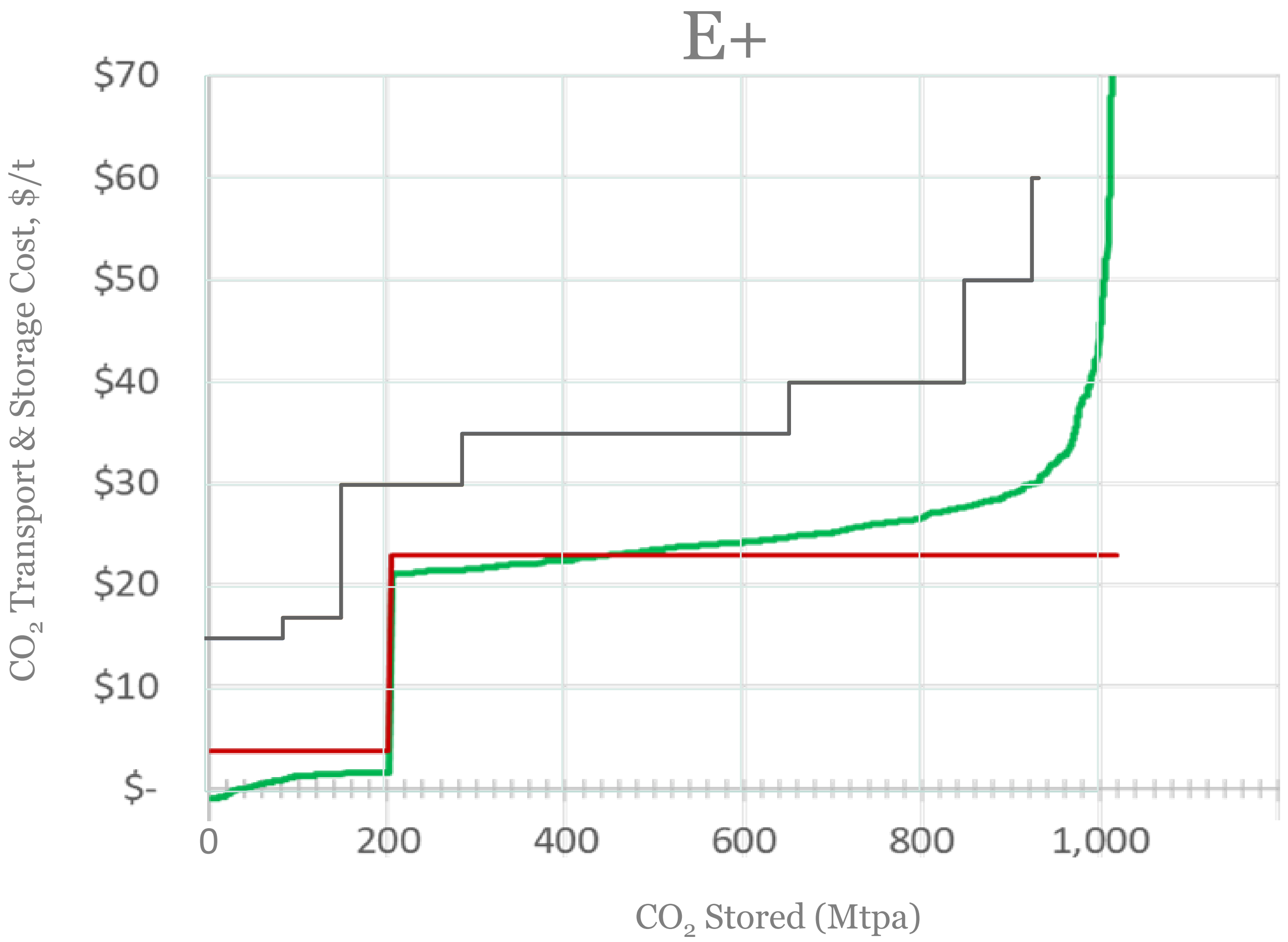


Trunk + spur line network-access charge. (All point sources charged equally, regardless of scale, location, or on-stream date.)

Trunk line network-access charge. (All point sources charged equally, regardless of scale, location, or on-stream date.)

Cost-supply curve assuming trunk line network-access charge + spur line investment by individual point sources.

Storage adds \$7/tCO_2 (DOE low-end estimate) and EOR provides credit of \$19/tCO_2 (for \$50/bbl oil*).



CO_2 transport and storage costs calculated from the downscaling analysis are somewhat lower than the costs assumed in the RIO modeling of E+ pathway.

- Transport and storage cost assumed for 2050 in original RIO modelling of E+ pathway
- Calculated trunk + spur line network-access charge. (All point sources charged equally, regardless of scale, location, or on-stream date.)
- Calculated assuming trunk line national network-access charge + spur line investment by individual point sources.

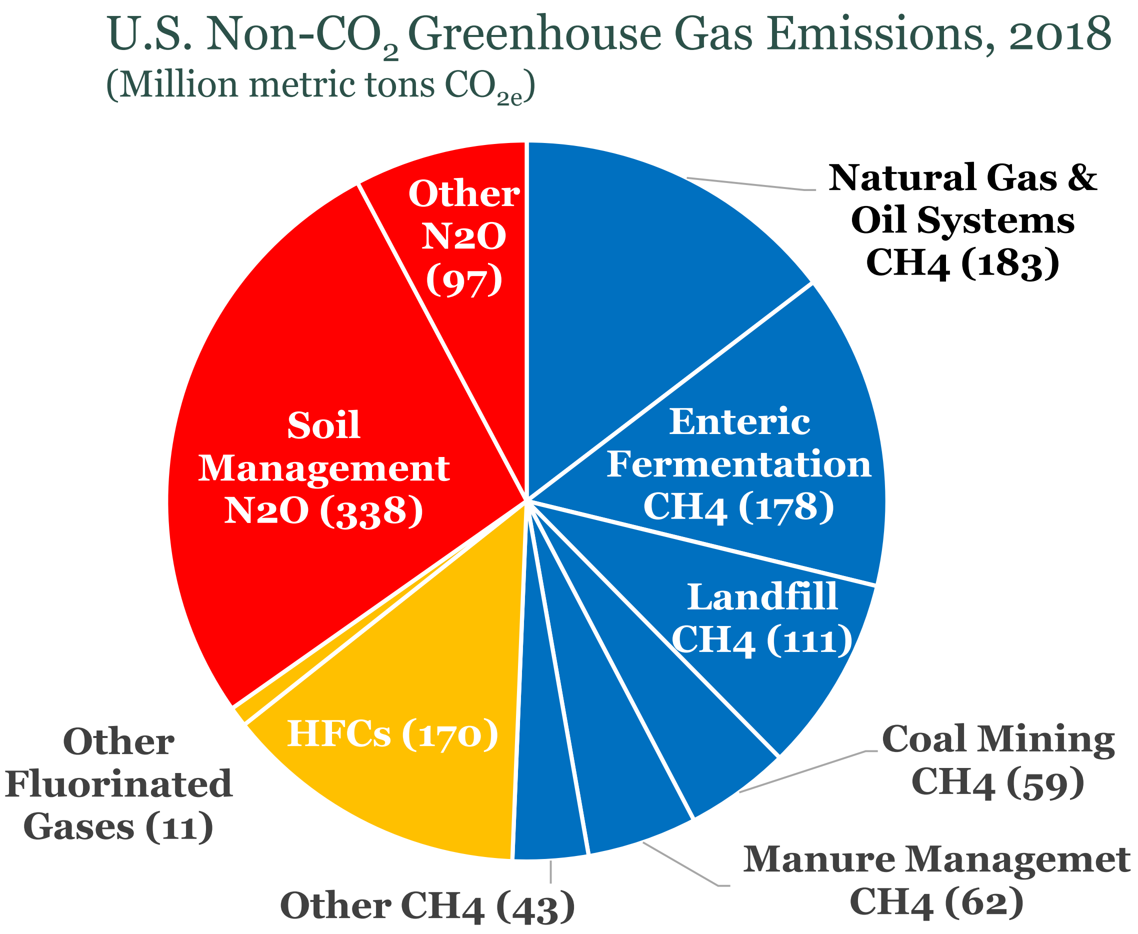
* Rubin, et al. (2015) wrote that "conventional wisdom suggests that the price that EOR projects can afford to pay for CO_2 (in \$/1000 standard ft³) is 2% of the oil price in \$/bbl."

Pillar 5: Reduced non-CO_2 emissions

Summary of this section

- 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).
- We also note that EPA's mitigation estimates assume future levels of oil and gas use that are closer to those of a "business-as-usual" future than a net-zero emissions future. 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.
- See Annex O for additional discussion of non-CO_2 emissions.

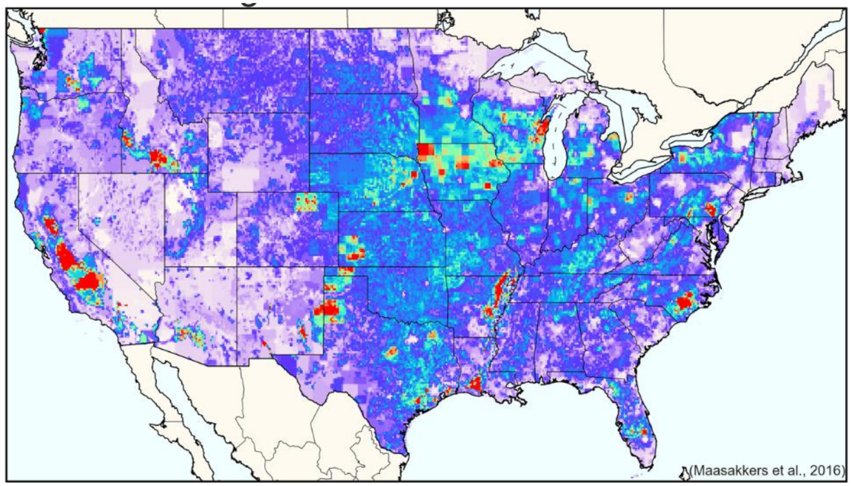
Non-CO_2 emissions today are 1.25 $GtCO_{2e}$/year



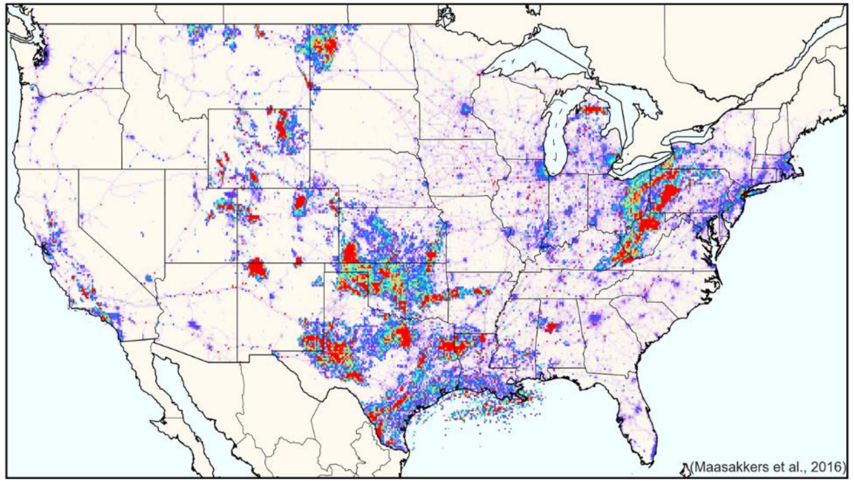
Source: EPA, *2020 GHG Inventory*

Methane emissions follow energy and agricultural production patterns and population densities

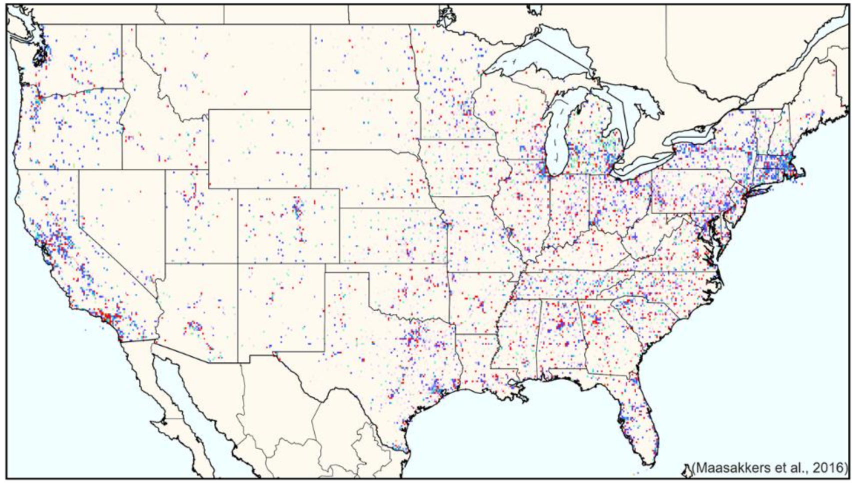
Agricultural emissions are dominated by livestock and dairy production



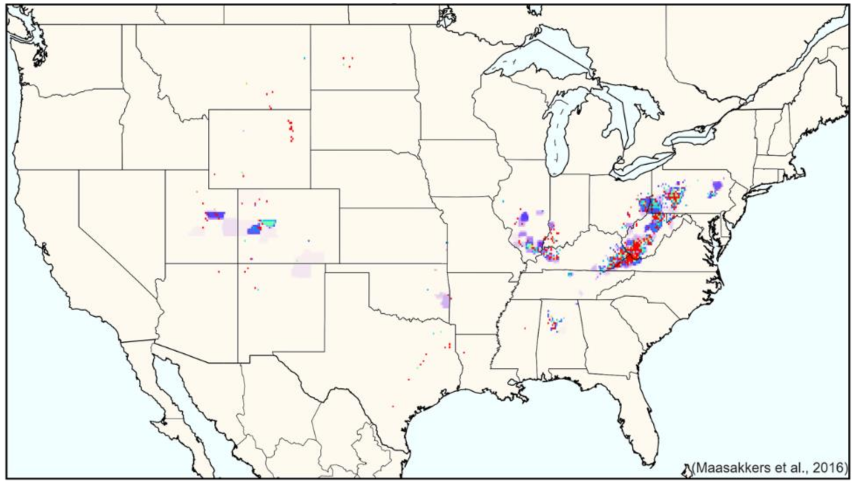
Oil and gas upstream emissions align with production & processing; downstream with pop.



Waste emissions are aligned with population density



Coal upstream emissions are dominated by Appalachian subsurface mining.



Source: EPA

2012 emissions (tCH_4/km^2)
(All emissions in the National GHG Inventory)

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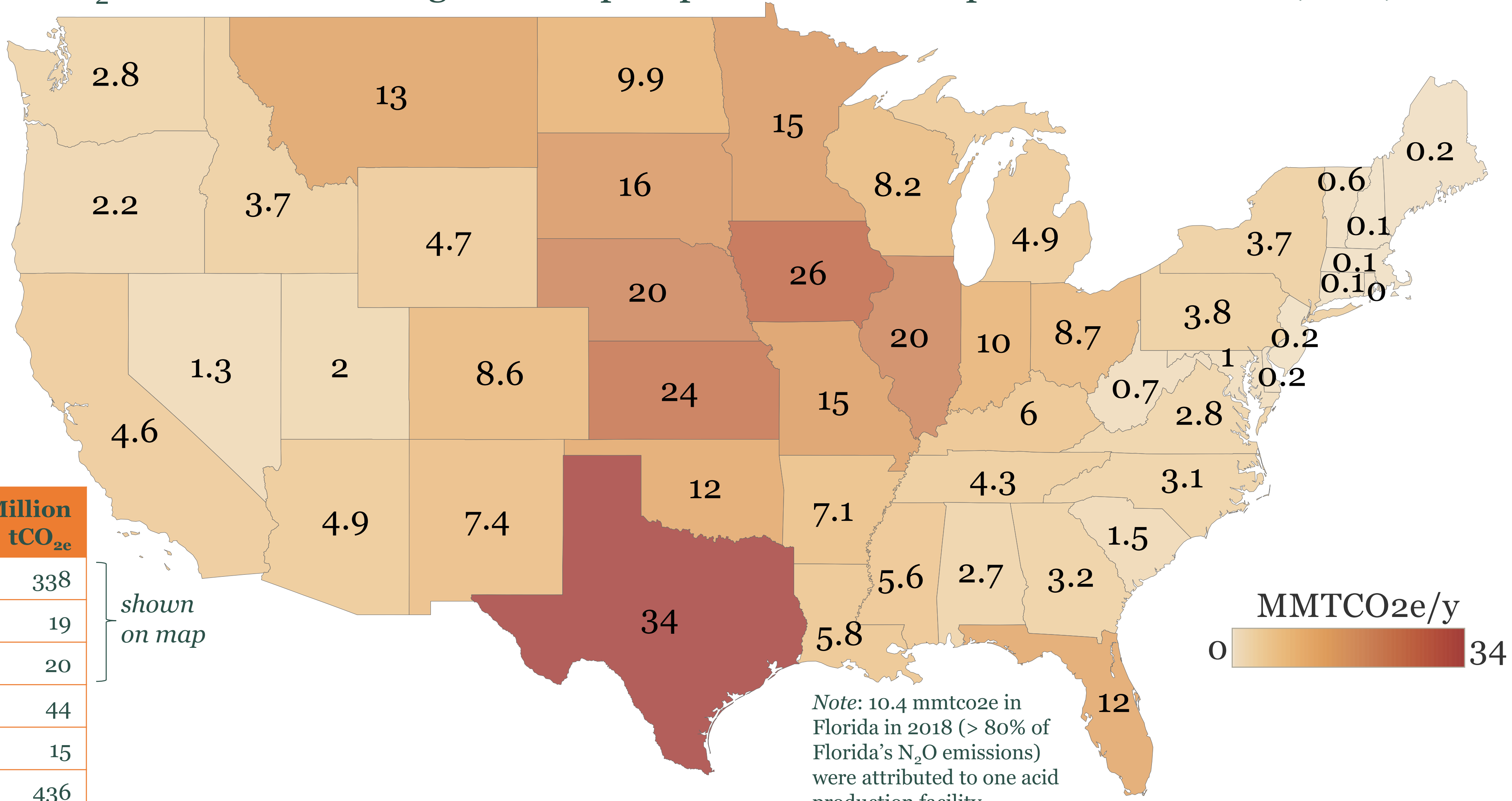
N_2O emissions occur mostly outside of the energy sector and in states with significant agricultural production.

N_2O emissions from agriculture plus production of adipic and nitric acids (2018)



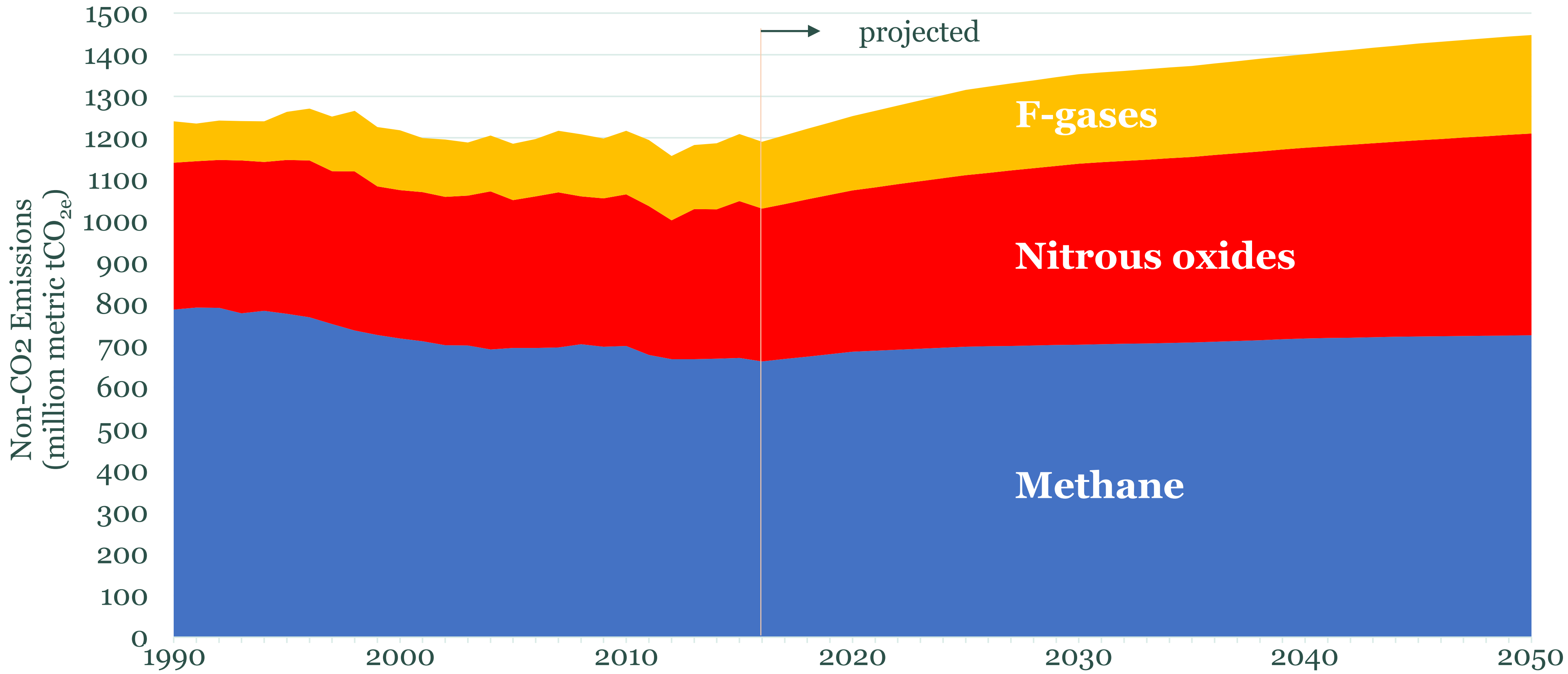
N_2O emissions (2018)	Million tCO_{2e}
Agricultural soil management	338
Manure management	19
Adipic & nitric acid production	20
Stationary & mobile combustion	44
Other	15
Total	436

shown on map (first three rows)

Note: 10.4 mmtco2e in Florida in 2018 (> 80% of Florida's N_2O emissions) were attributed to one acid production facility.

Without mitigation efforts, non-CO_2 emissions grow gradually to 1.45 $GtCO_{2e}$ by 2050, with CH_4 and N_2O contributing most

Historical and projected non-CO_2 emissions by gas type under business as usual (BAU)



Source: EPA, *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019.

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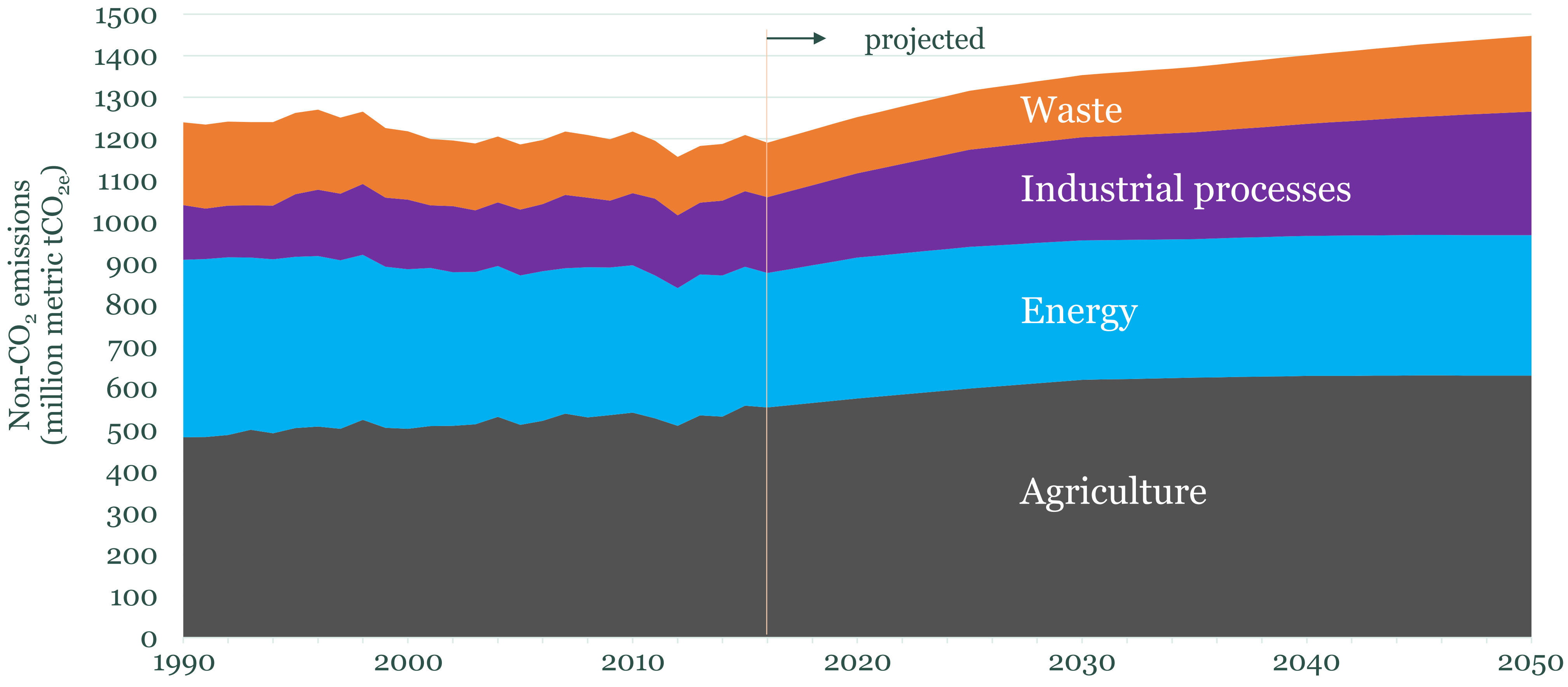
Without mitigation, non-CO_2 emissions grow gradually to 1.45 $GtCO_{2e}$ by 2050, with agriculture and energy remaining dominant

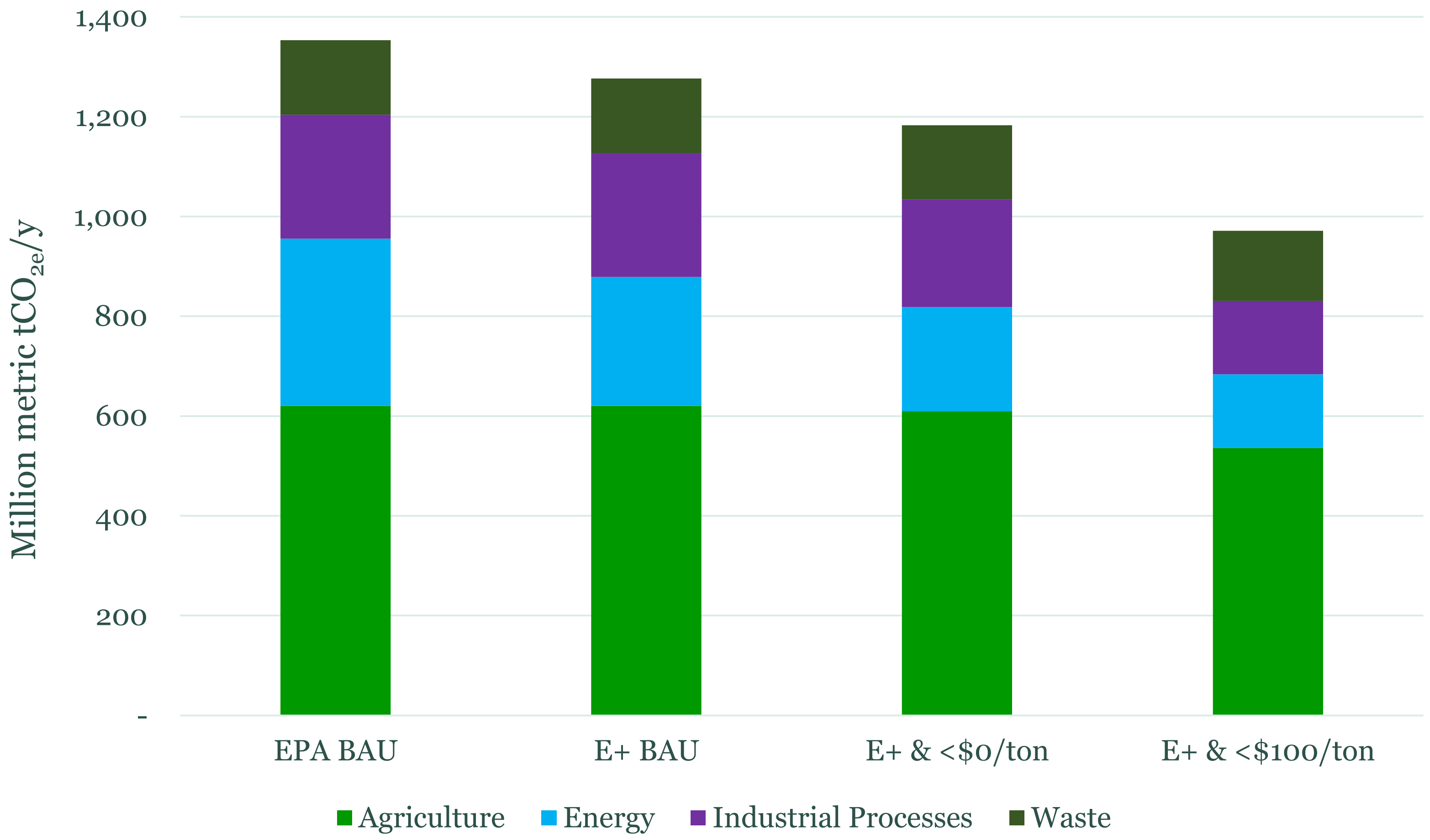
Historical and projected non-CO_2 emissions by sector under business as usual (BAU)



Source: EPA, *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019.

Mitigation can reduce non-CO_2 emissions substantially by 2030

2030 Non-CO_2 Emissions ($MtCO_{2e}$)



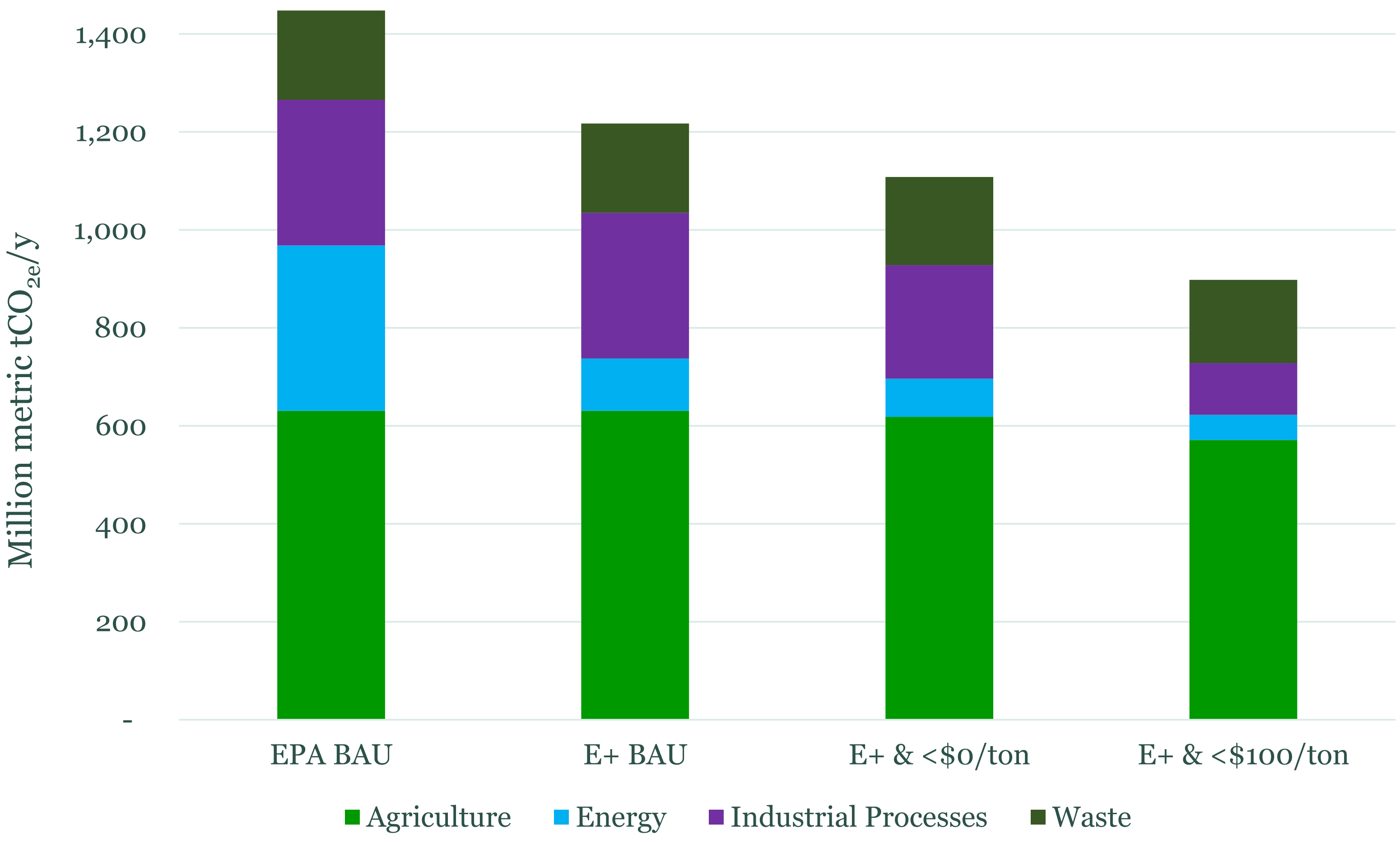
By 2030, EPA projects:

- Under EPA BAU (no mitigation), non-CO_2 emissions reach 1.35 $GtCO_{2e}$/y
- Under E+ BAU (energy mitigation but no non-CO2 mitigation), non-CO_2 emissions fall to 1.28 $GtCO_{2e}$/y as nearly all coal production ceases and oil/gas output drops ~10%
- Very low-cost mitigation yields 1.18 $GtCO_{2e}$/y while measures costing <$100/$tCO_{2e}$ yield 0.97 $GtCO_{2e}$/y
- Further research needed to identify additional reductions

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

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 ($MtCO_{2e}$)



By 2050, EPA projects:

- Under EPA BAU (no mitigation), non-CO_2 emissions reach 1.45 $GtCO_{2e}$/y
- Under E+ BAU (energy mitigation but no non-CO2 mitigation), non-CO_2 emissions fall to 1.22 $GtCO_{2e}$/y as nearly all coal production ceases and oil/gas output drops ~75%
- Very low-cost mitigation yields 1.11 $GtCO_{2e}$/y while measures costing <\$100/tCO_{2e} yield 0.90 $GtCO_{2e}$/y
- E+ scenario assumes non-CO2 abatement efforts yield ~1 $GtCO_{2e}$/y by 2050

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

Non-CO_2 emissions are assumed to be reduced to 1 $GtCO_{2e}$ by 2050, or ~20% below 2020 and ~30% below EPA's BAU forecast for 2050.

Estimated abatement potential by 2050 @ ≤ \$100/tCO_{2e} avoided

	Source	2050 Abatement (10^6 tCO2e/y)
Agriculture	Croplands/Rice	11
	Livestock	49
Energy	Coal	5
	Oil and gas	48
Industrial	Nitric & Adipic Acid Production (N_2O)	36
	Refrigerants/AC (F-gases)	146
	Other	9.0
Waste	Landfill	13
	Total	**316**

Non-CO_2 Abatement Potential:

- Mitigation measures costing <\$100/tCO_{2e} can drive non-CO_2 emissions from 1.45 to 0.90 $GtCO_{2e}$/y by 2050
- F-gases account for nearly half of this mitigation potential

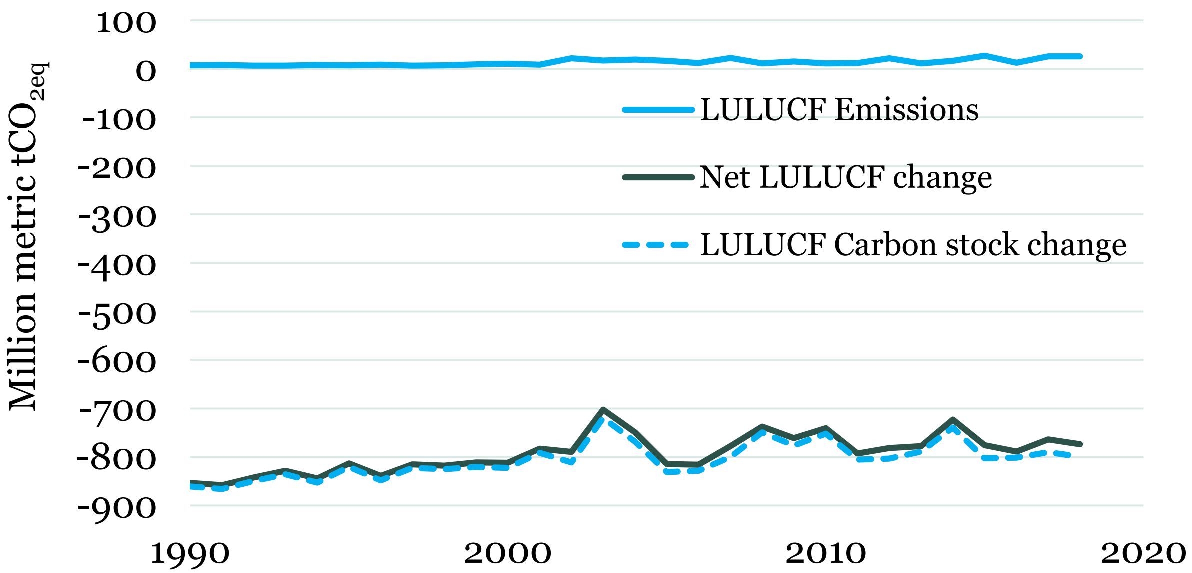
Source: EPA, *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019, but with coal and oil and gas adjustments to reflect E+ scenario: coal abatement is limited to mitigation of abandoned mines and oil/gas abatement is reduced by ~75% to account for lower oil production under E+.

Pillar 6: Enhanced land sinks

Summary of this section

- 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 (see Annex Q) and from 0.5 to 1.5 $GtCO_{2eq}$/y in forestry (see Annex P).
- 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 maintenance/enhancement measures from 2020 to 2050.

Extent of carbon uptake in soils and trees impacts the decarbonization challenge for the energy/industrial system



(EPA, *2020 GHG Emissions Inventory*)

- The current natural land sink is uncertain, but estimates are in the range of 0.7 $GtCO_{2e}$/y.
- Without efforts to enhance the natural land sink, it is projected to decline to 0.3 $GtCO_{2e}$/y by 2050.
- Significant modification of agricultural and forestry practices, if widely adopted, can help maintain/enhance the land sink.

2050	E+ (and other scenarios)
Land sink, $GtCO_{2e}$/y (assumed)	- 0.85
Non-CO2 emissions, GtCO2e/y (assumed)	1.02
Energy/industry emissions, $GtCO_2$/y	- 0.17

Sensitivity model runs: Magnitude of land carbon sink impacts the costs and emissions reductions needed in energy/industrial system

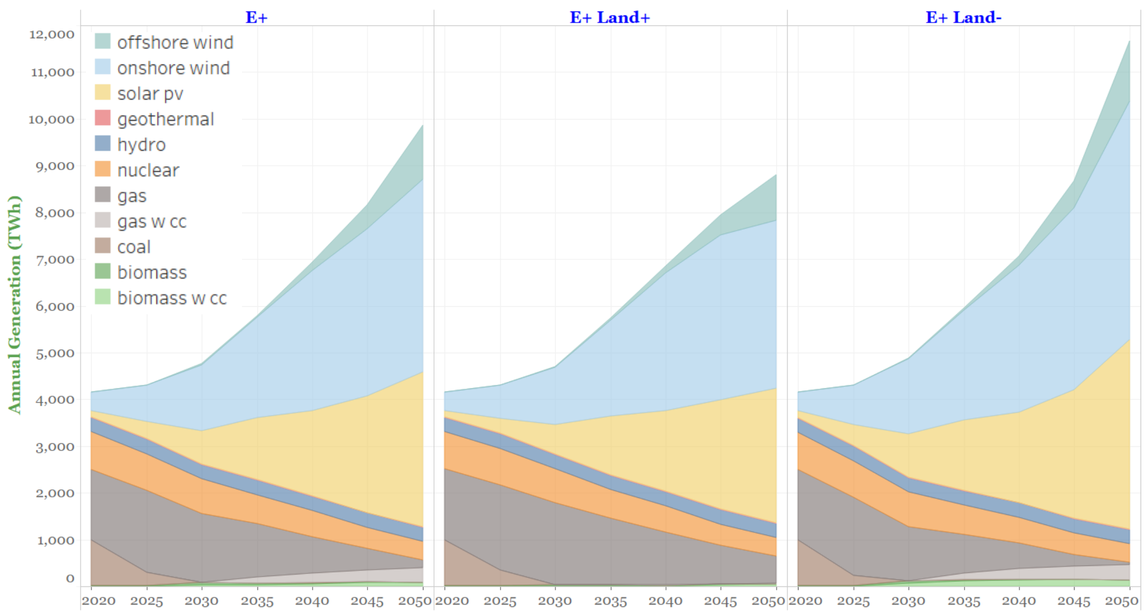
To reach net-zero emissions economy wide in 2050, emissions "allowed" by the energy/industrial system in 2050 depend on the net emissions occurring outside of energy/industry, i.e., land sinks and non-CO_2 emissions. The degree of net land sinks + non-CO_2 emissions that will be achieved is uncertain. Compared with E+:

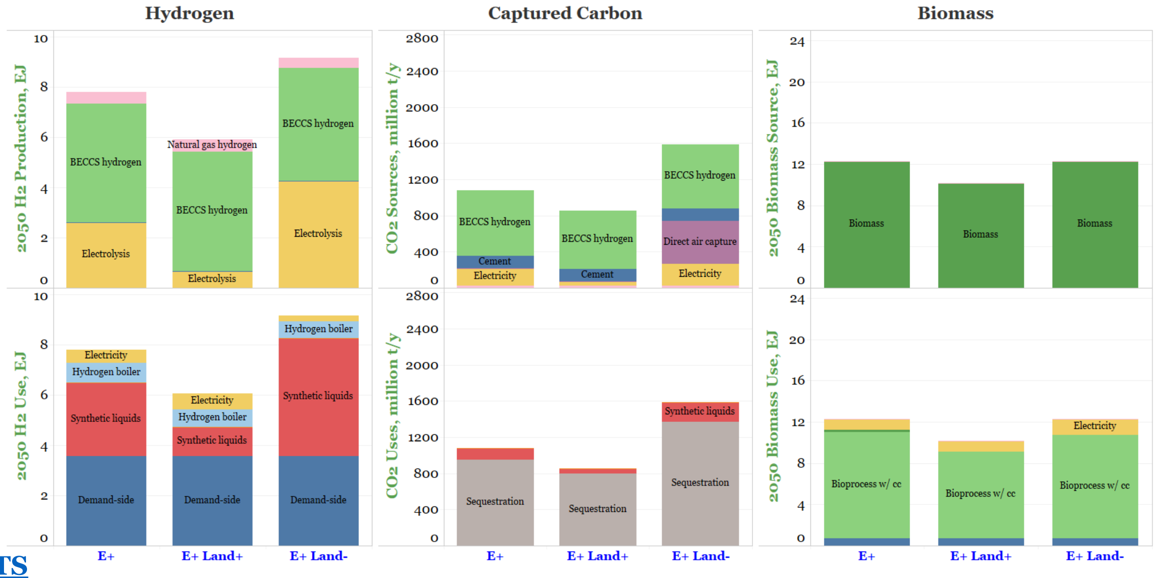
- If the net outside emissions are higher (E+ Land-), electricity generation is much higher by 2050, with most of the increase being solar and wind. Electrolytic H_2 production is also higher, deployment of direct air capture is significant, and about 60% more CO_2 sequestration is required. NPV of the total energy-supply system (2020 – 2050) increases by 3%.
- If the net outside emissions by 2050 are lower (E+ Land+), less total electricity is needed in 2050, and a greater fraction comes from NGCC without CC. There is also less H_2 demand because more petroleum-derived fuels can be used. NPV of the total energy-supply system (2020 – 2050) decreases by 2%.

See Annex B for additional details.

Input assumptions that vary between cases

Billion metric tCO_{2e} in 2050	E+	E+ Land+	E+ Land-
Land sink	- 0.85	- 1.30	- 0.30
Non-CO2 emissions	1.02	1.02	1.02
Net emissions outside of energy/industry system	0.17	- 0.27	0.73
Allowed energy/industrial CO_2 emissions in 2050	- 0.17	0.27	- 0.73





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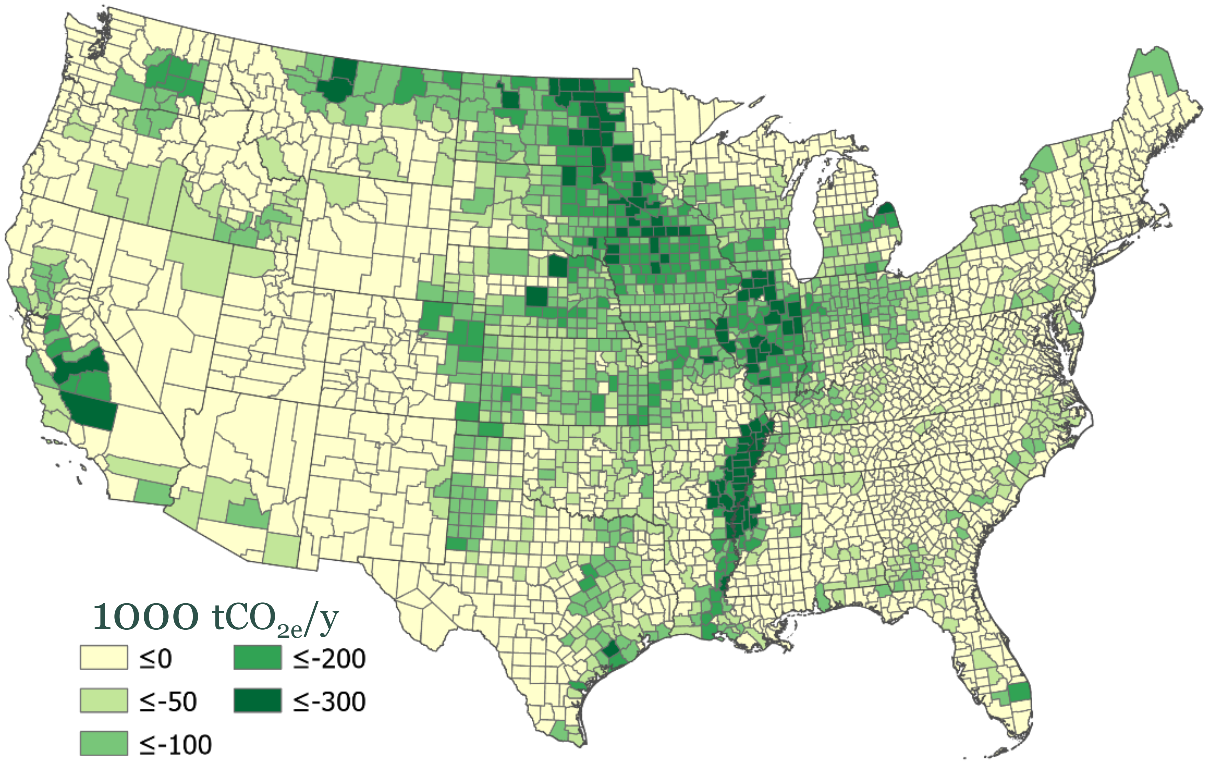
Agricultural measures can yield > 200 million tCO_{2e}/year of additional carbon storage in soils by 2050*

With 100% adoption of conservation measures	E+		E- B+	
	10^6 ha	10^6 tCO_{2e}/y	10^6 ha	10^6 tCO_{2e}/y
Ethanol-corn land → perennial energy grasses	11	23	11	23
CRP area converted to perennial energy grasses	12	0	12	0
Other croplands converted to				
perennial energy grasses	0	0	10	16
woody energy crops	0	0	1	no estimate
permanent herbaceous cover	13	7	12	7
Pasture converted to perennial energy crops	0	0	15	no estimate
Other croplands remaining as cropland	136	204	127	189
Pasture remaining as pasture	155	no estimate	140	no estimate
Totals	**327**	**234**	**327**	**233**

* See Swan, et al. (Annex Q).

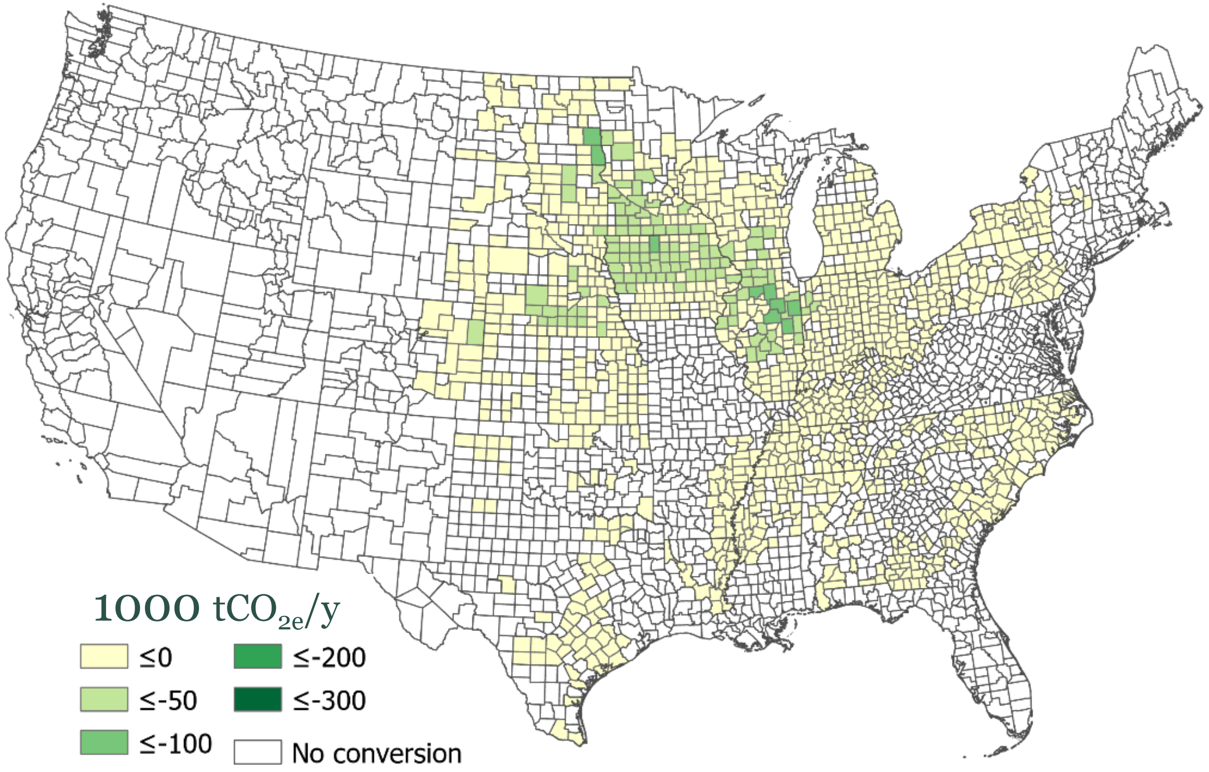
Maximum annual carbon uptake potential on agricultural lands by county; Midwestern states account for >80% of the potential.

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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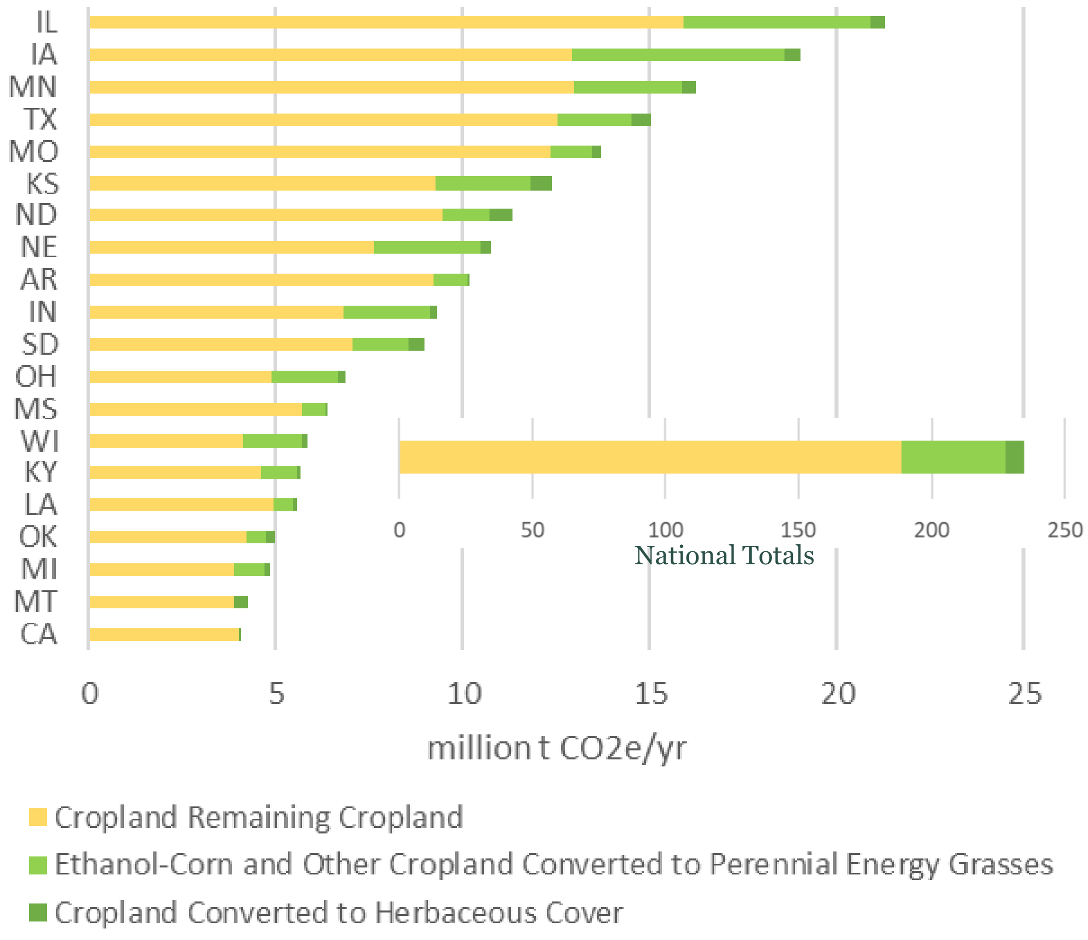
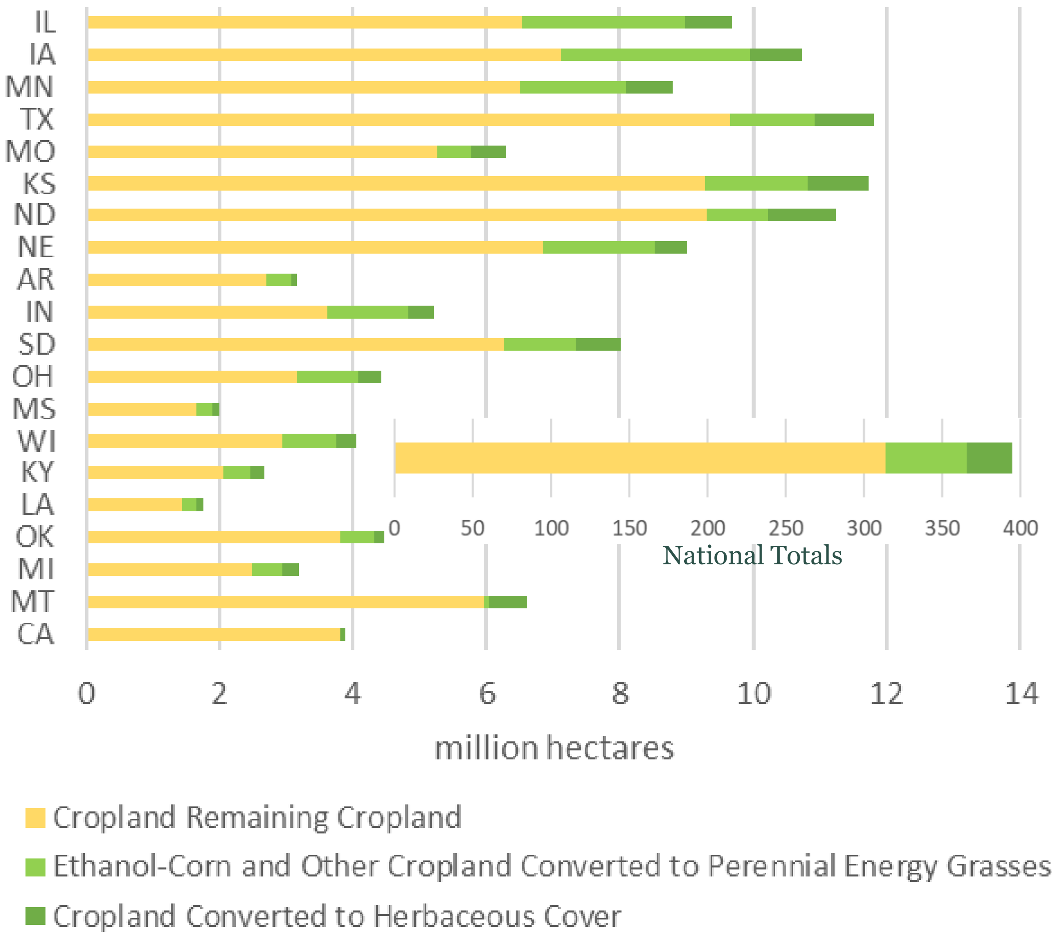
Top 20 states account for > 85% of the carbon storage potential on agricultural lands in 2050 (E+ scenario)

Most of the potential is in measures applied to cropland, with carbon storage per acre averaging 1.5 tCO_{2e}/ha/yr; ethanol-corn land conversion to energy grasses is highest (2.1 tCO_{2e}/ha/yr).

Annual C Storage & GHG Emission Reductions



Land area impacted



Technical potential for carbon uptake by forest measures is estimated to be 0.5 to 1.5 $GtCO_{2e}$/y.*

Activity	Low Estimate ($GtCO_{2e}$/y)	High Estimate ($GtCO_{2e}$/y)	Land area affected (million ha)
Reforestation of agricultural lands (a)	**0.141**	**0.506**	**9 – 34**
Croplands	0.121	.242	8 – 16
Pasture	0.020	.264	1.3 – 17.5
Improved forest management	**0.250**	**0.644**	**112 – 297**
Accelerate regeneration	0.025	0.049	4 – 8
Restore productivity of degraded forests	0.060	0.178	36 – 154
Extend rotation lengths	0.116	0.302	59 – 154
Improve productivity of plantations	0.029	0.057	11 – 21
Increase stocking of trees outside forests	0.021	0.060	3 – 6
Increased C retention in harvested wood	**0.100**	**0.300**	**n/a**
Reduced deforestation	**0.014**	**0.084**	**11**
Total potential	**0.500**	**1.53**	**132 – 342**

(a) Agricultural lands that are assumed to otherwise be enrolled as Conservation Reserve Program acreage.

* See Birdsey, 2020 (Annex P).

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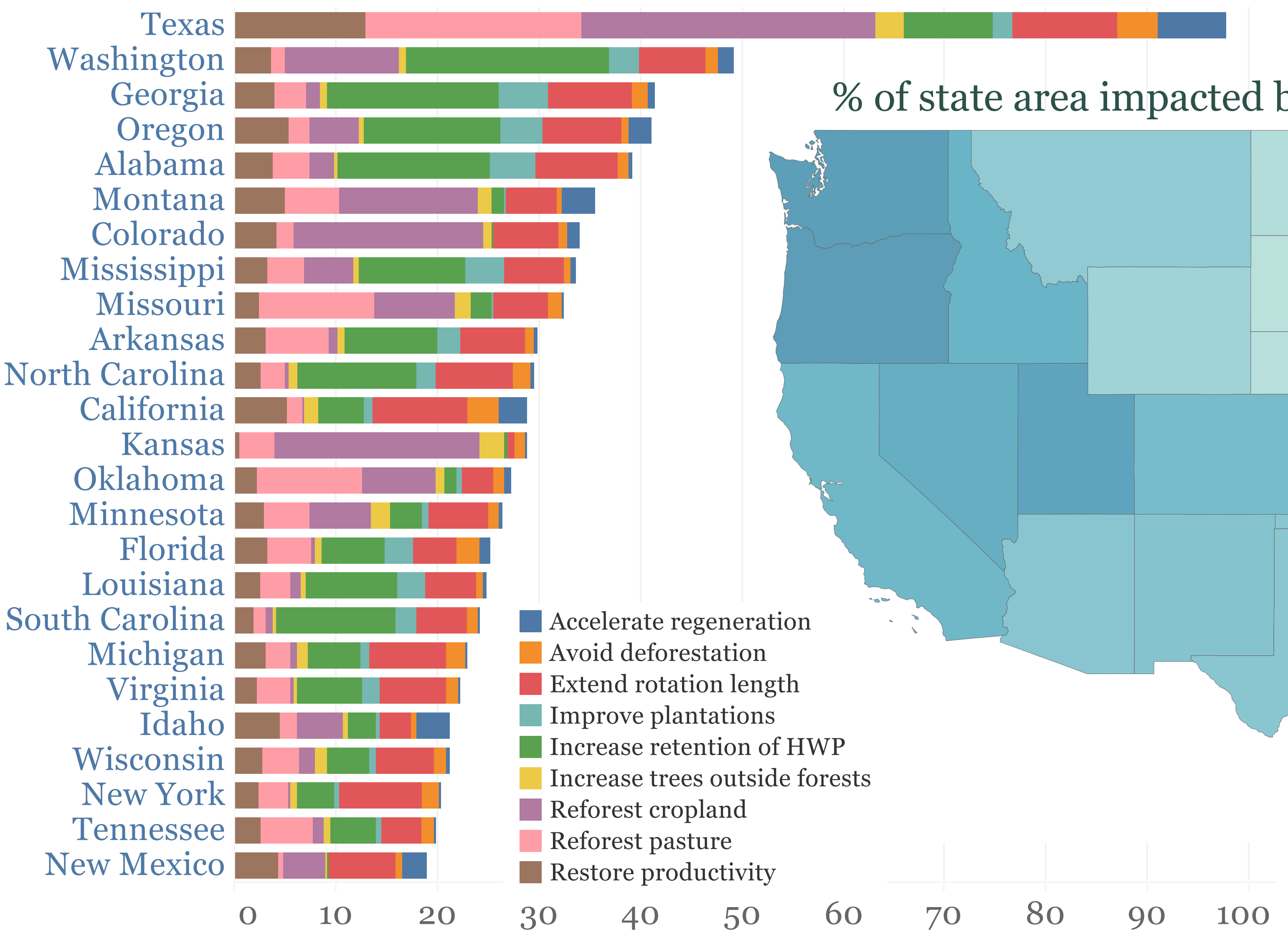
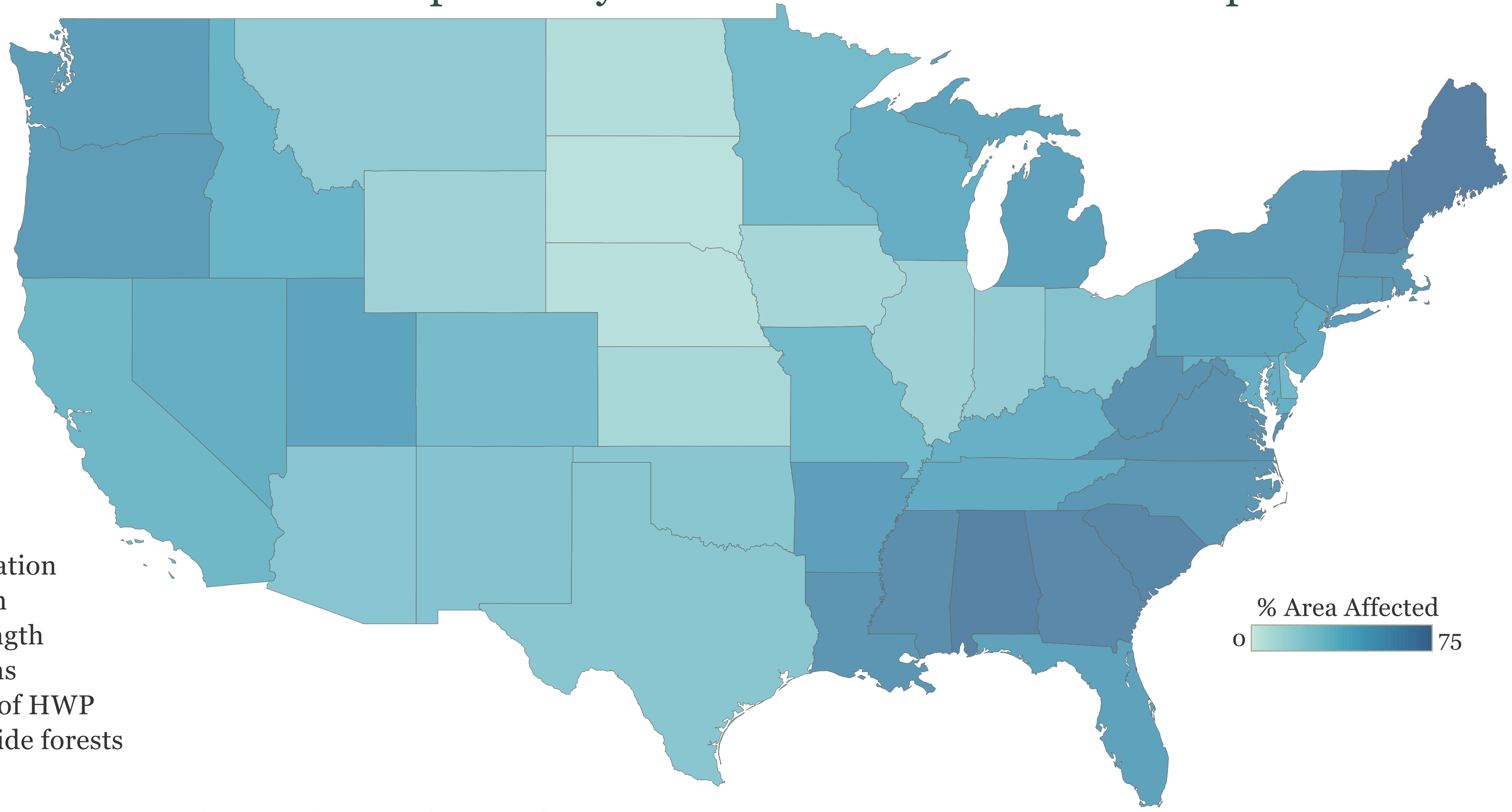
1 $GtCO_{2e}$/yr technical potential for enhanced carbon storage on forest lands (mid-range of estimates)



million tCO2e/y
(mid-range of technical potential)

% 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.

Summary of goals for the six pillars

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 (≥ 130 Mha).

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

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Summary of this section

- Significant implications of transitions to net-zero emissions are illustrated quantitatively here for land use, capital mobilization, fossil fuel industries, employment, and air pollution-related health impacts.

Land use

Summary of this section

- Direct land use for wind turbine construction in net-zero scenarios is small, but the (visual) footprint of wind farms is significant. In 2050, total wind farm area 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+ @ 1 million km^2, or the equivalent of land areas 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, ranging from an area equivalent to the area of Connecticut for E+RE- to that of West 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 significant land-use change associated with biomass use is in 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.
- With constrained site availability, only 6% of solar candidate project areas (CPA) in E+RE+ are selected, indicating potential to substantially reconfigure solar siting in any scenario to minimize 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.

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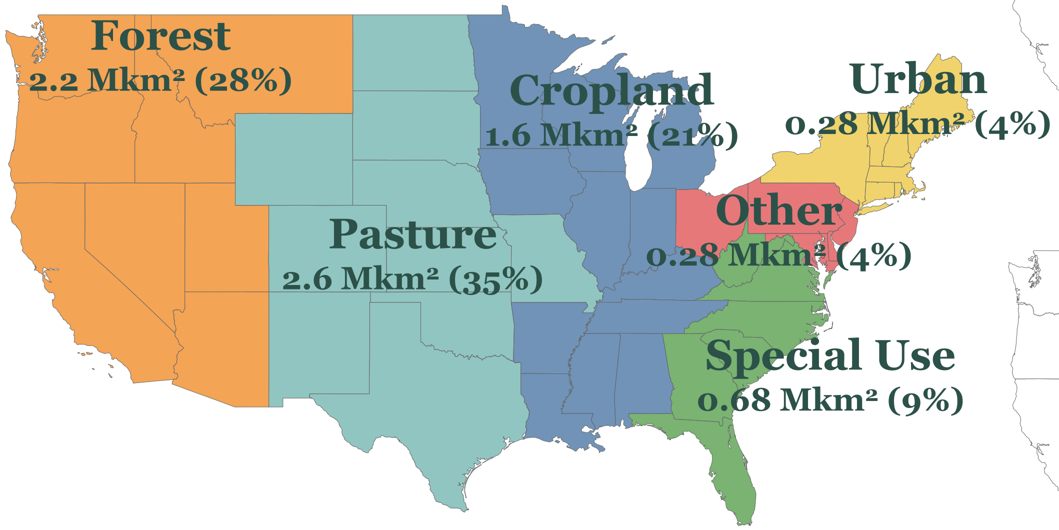
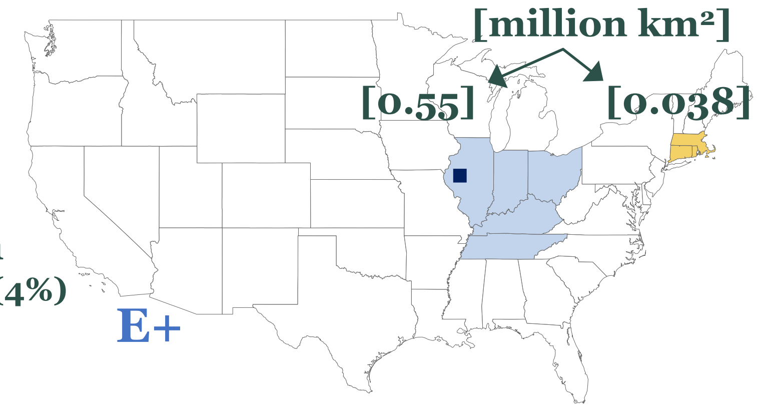
Total land area/visual footprint in 2050 for solar, wind, and biomass across scenarios is 0.25 to 1.1 million km².

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

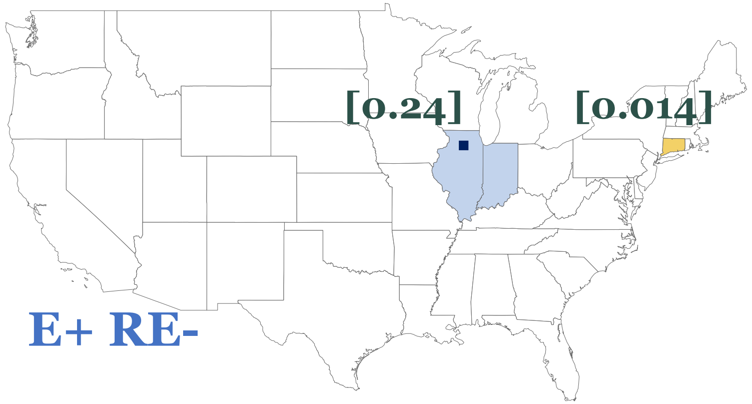


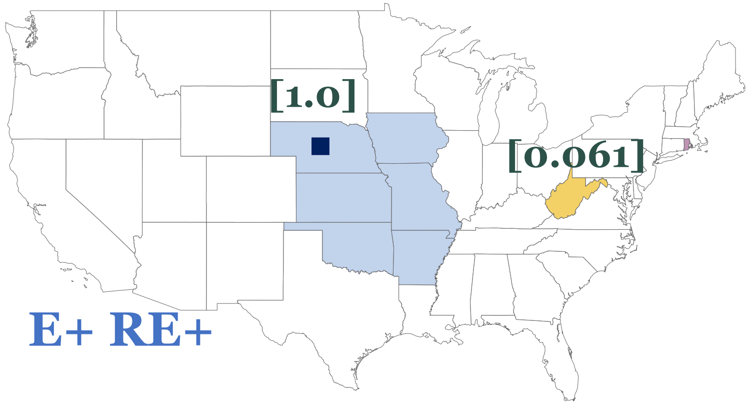
Notes: In these maps, the sum of land areas of colored states is roughly the same as the area nationally of the indicated uses.

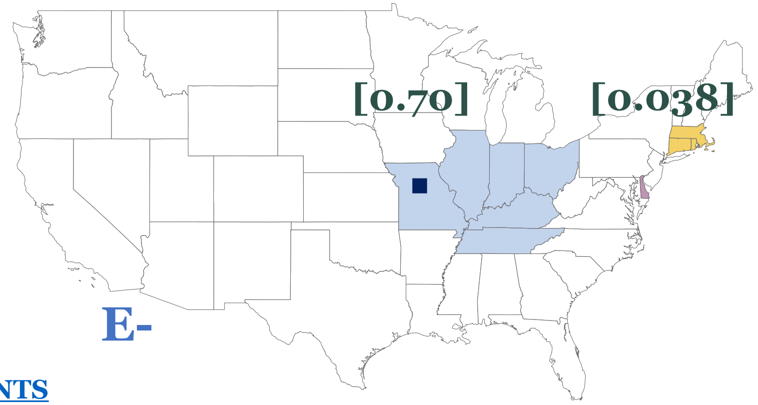


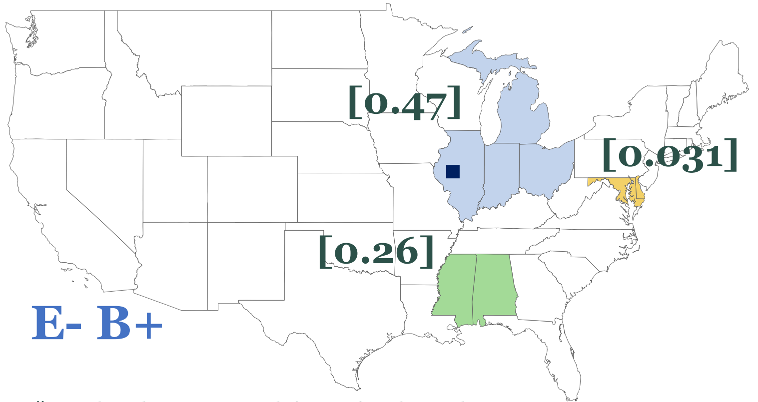
Equivalent land area for
- Solar farms
- Wind farms
- Biomass farms*
- Direct air capture

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









* On lands converted from food production.

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Land use summary for wind and solar capacity for downscaled net-zero pathways.

		E+				E+ RE-				E+ RE+			
		2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Base land availability assumptions	**Solar**												
	Installed capacity (MW)	63,093	319,791	849,698	1,494,953	75,786	265,380	457,047	638,177	65,638	401,952	1,232,705	2,750,263
	Total solar farm area (km2)	1,078	7,752	21,530	38,307	1,387	5,788	10,100	14,241	1,122	8,671	26,937	61,212
	Direct land use (km2)*	981	7,055	19,592	34,859	1,262	5,267	9,191	12,959	1,021	7,891	24,512	55,703
	Total land, % of Candidate Project Areas	0.0%	0.3%	0.7%	1.3%	0.0%	0.2%	0.3%	0.5%	0.0%	0.3%	0.9%	2.0%
	Land-based wind												
	Installed capacity (MW)	147,364	414,298	948,379	1,479,035	142,976	267,651	450,686	650,670	146,120	461,584	1,322,129	2,699,955
	Total wind farm extent (km2)	57,913	156,777	354,585	551,124	56,288	102,464	170,254	244,323	57,452	174,291	493,011	1,003,317
	Direct land use (km2)*	579	1,568	3,546	5,511	563	1,025	1,703	2,443	575	1,743	4,930	10,033
	Total land, % of Candidate Project Areas	1.3%	3.5%	7.9%	12%	1.3%	2.3%	3.8%	5.5%	1.3%	3.9%	11%	22%
	Offshore wind												
	Installed capacity (MW)	70	5,289	45,030	202,562	70	10,827	22,125	31,933	70	5,323	109,121	385,665
	Total wind farm area (km2)	14	1,044	7,708	33,077	14	2,151	4,117	5,691	14	1,051	19,665	64,670
	Direct area used (km2)*	0	10	77	331	0	22	41	57	0	11	197	647
	Total area, % of Candidate Project Areas	0.0%	0.4%	3.2%	14%	0.0%	0.9%	1.7%	2.4%	0.0%	0.4%	8.1%	27%
Constrained land availability assumptions	**Solar**												
	Installed capacity (MW)	56,456	329,044	839,108	1,474,990	73,049	266,950	469,629	664,068	65,919	417,727	1,223,766	2,763,554
	Total solar farm area (km2)	936	8,023	21,285	37,818	1,310	5,652	10,239	14,817	1,139	9,389	28,249	63,784
	Direct land use (km2)*	852	7,301	19,369	34,414	1,192	5,143	9,317	13,484	1,036	8,544	25,707	58,044
	Total land, % of Candidate Project Areas	0.1%	0.8%	2.0%	3.6%	0.1%	0.5%	1.0%	1.4%	0.1%	0.9%	2.7%	6.0%
	Land-based wind												
	Installed capacity (MW)	147,786	427,662	978,766	1,363,177	143,104	271,649	466,163	682,229	146,416	479,664	1,313,032	2,872,596
	Total wind farm extent (km2)	54,735	158,377	362,489	504,864	56,335	103,944	175,986	256,011	57,562	180,987	489,642	1,015,149
	Direct land use (km2)*	547	1,584	3,625	5,049	563	1,039	1,760	2,560	576	1,810	4,896	10,151
	Total land, % of Candidate Project Areas	4.9%	14%	32%	45%	5.0%	9.3%	16%	23%	5.1%	16%	44%	90%
	Offshore wind												
	Installed capacity (MW)	70	5,289	45,030	202,562	73	10,334	21,811	31,666	73	4,981	80,277	366,878
	Total wind farm area (km2)	14	1,044	7,708	33,077	15	2,058	4,353	6,261	15	987	16,044	64,372
	Direct area used (km2)*	0	10	77	331	0	21	44	63	0	10	160	644
	Total area, % of Candidate Project Areas	0.1%	4.1%	30%	129%	0.1%	8.0%	17%	24%	0.1%	3.9%	63%	252%

* Direct use of land or ocean area in this table refers to land on which equipment, roads, and other infrastructure are physically placed.

Total wind and solar farm area by 2050 is small in most states, with the exception of the Midwest, Great Plains, and Texas.

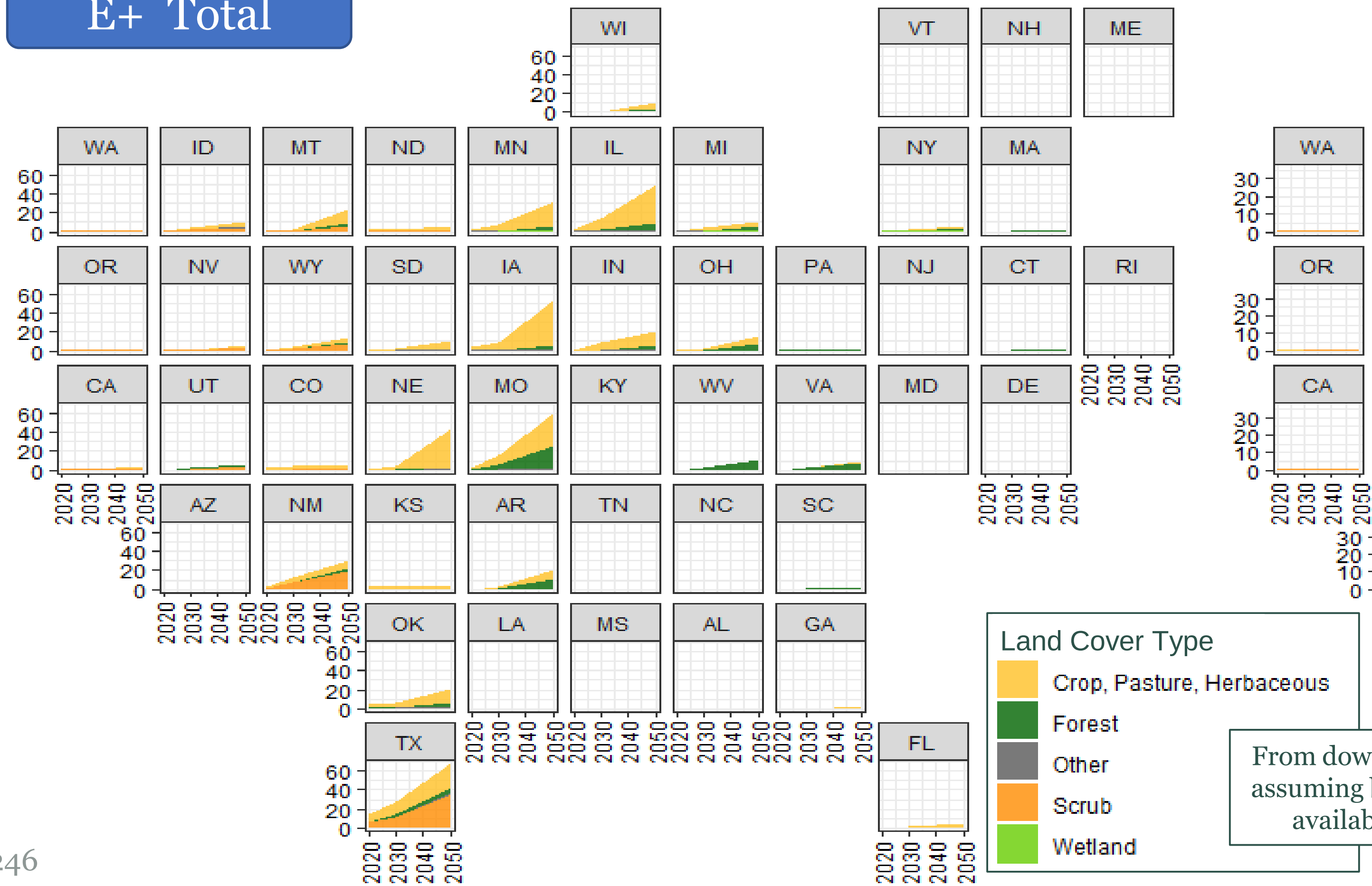
Total area impacted by solar and wind development (1,000 km²)

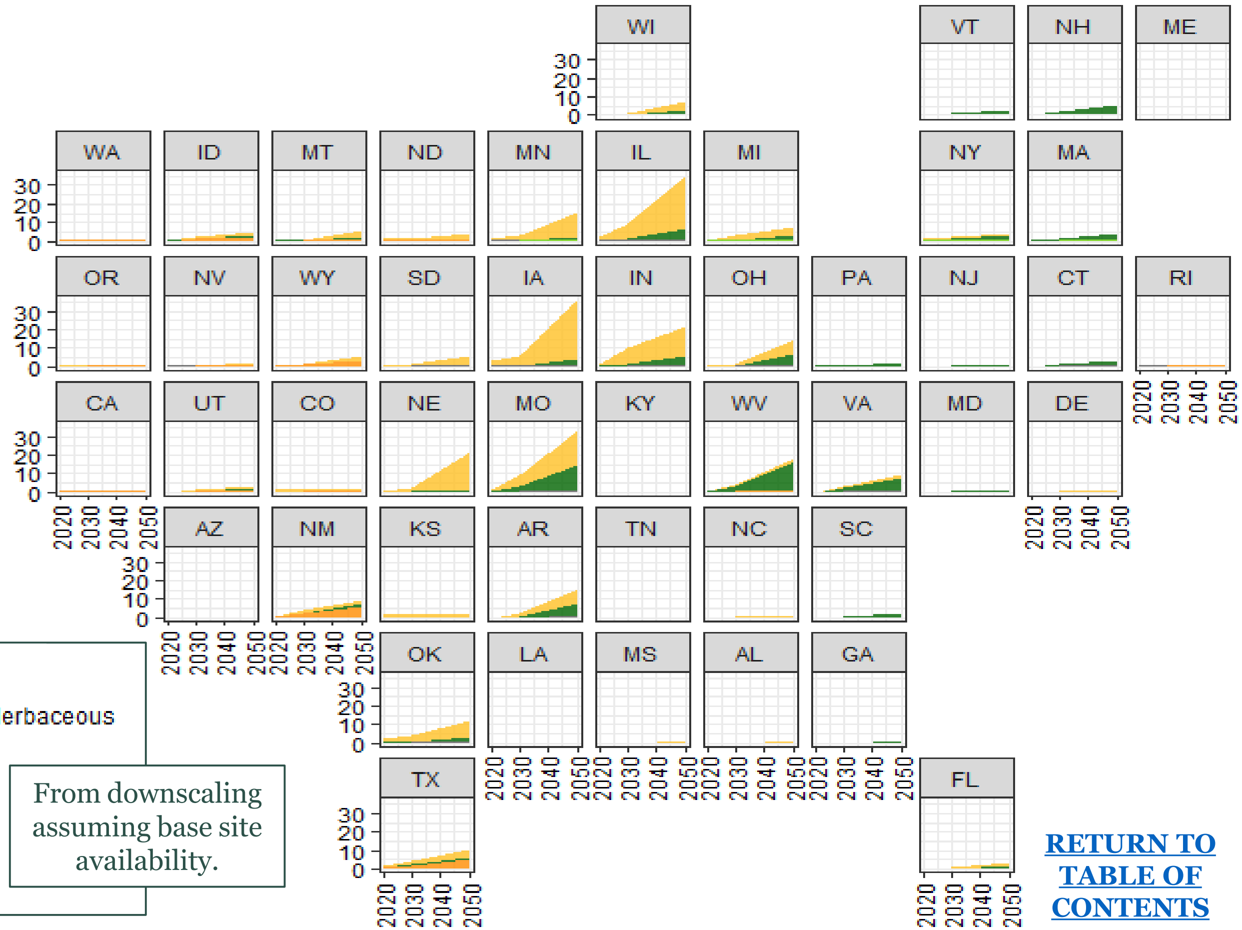
The impacted area by 2050 ranges from ~10 km² in Delaware to ~68,000 km² in Texas.

Percent of state land area

The share of land area impacted by mid-century ranges from <1% in Kentucky to ~37% in Iowa.

E+ Total





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Direct land impacts by 2050 are greatest in states with high amounts of solar deployed, including in the Northeast and Southeast.

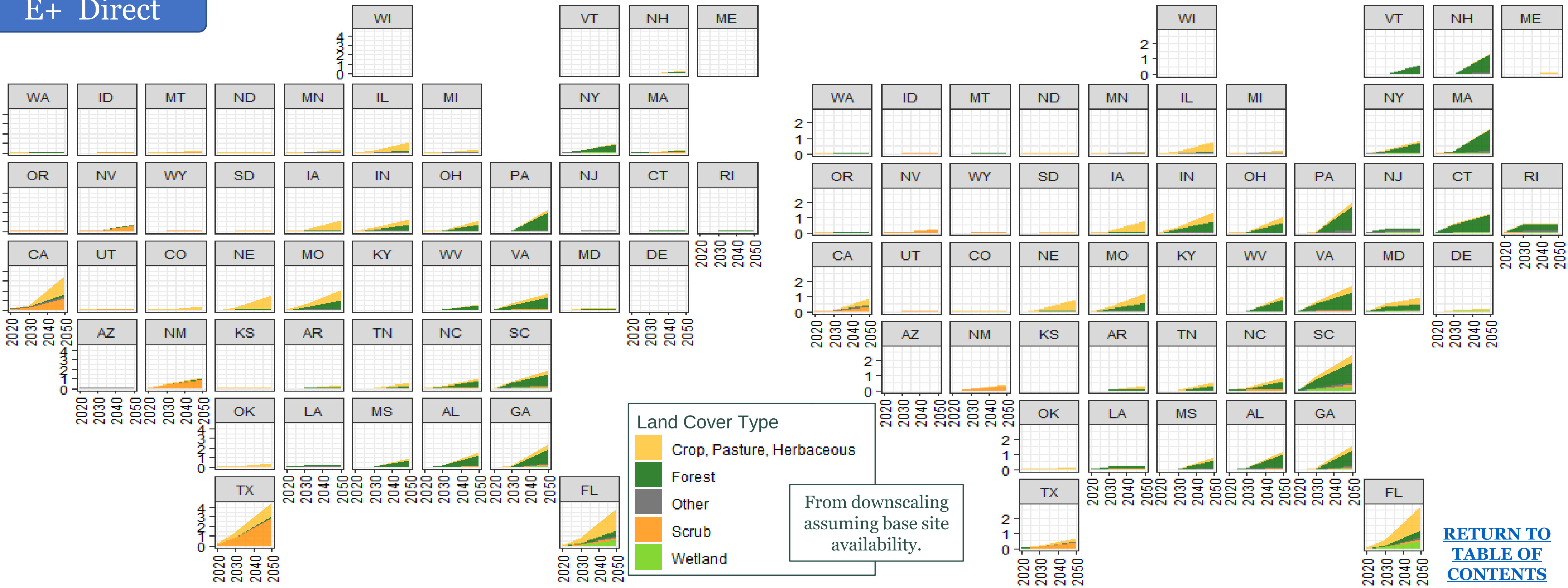
Land area directly impacted by solar and wind development (1,000 km²)

The impacted area by 2050 ranges from ~4 km² in Kentucky to ~4,400 km² in Texas.

Percent of state land area

The share of land area impacted by mid-century ranges from <<1% in Kentucky to ~3% in Florida.

E+ Direct



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States and land types impacted by wind and solar farms in E+RE+ by 2050 are similar to E+, but with much larger areas affected.

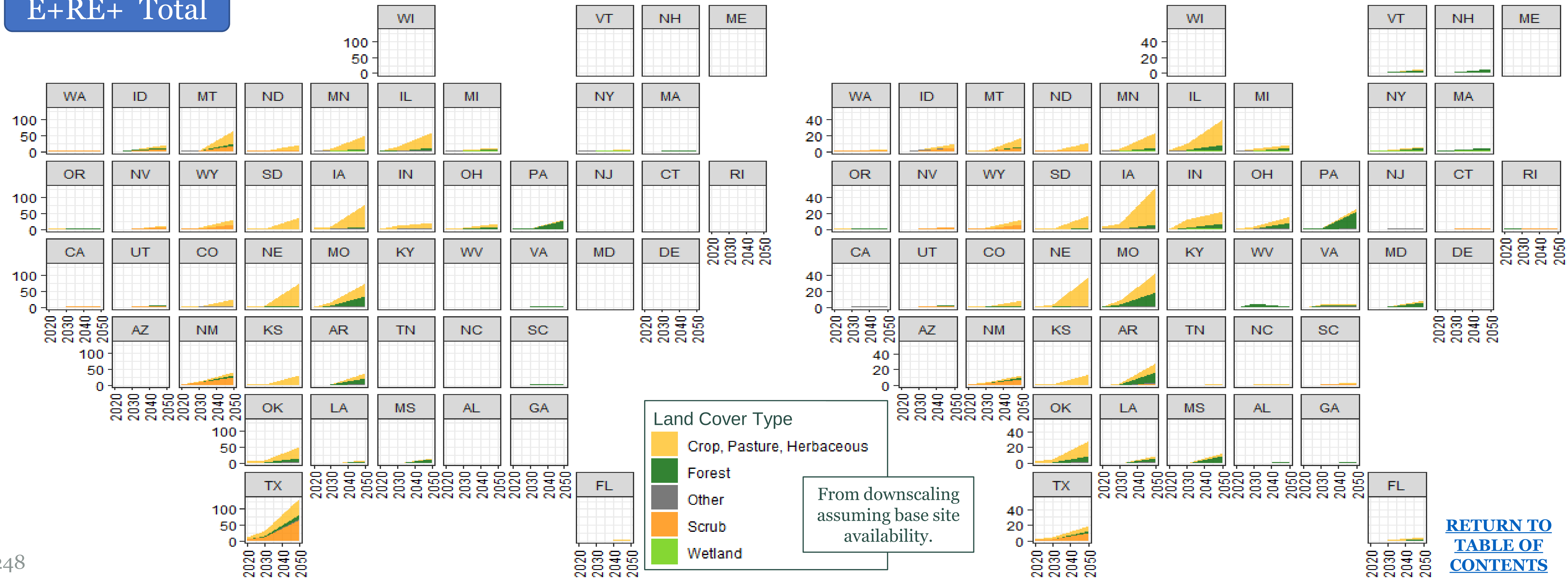
Total area impacted by solar and wind development (1,000 km²)

The impacted area by 2050 ranges from very little in several states up to 140,000 km² in Texas.

Percent of state land area

The share of land area impacted by 2050 ranges from very small in several states to over 50% in Iowa.

E+RE+ Total



From downscaling assuming base site availability.

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Direct land impacts by 2050 in E+RE+ are greatest in states with highest solar deployed, including in the Northeast and Southeast.

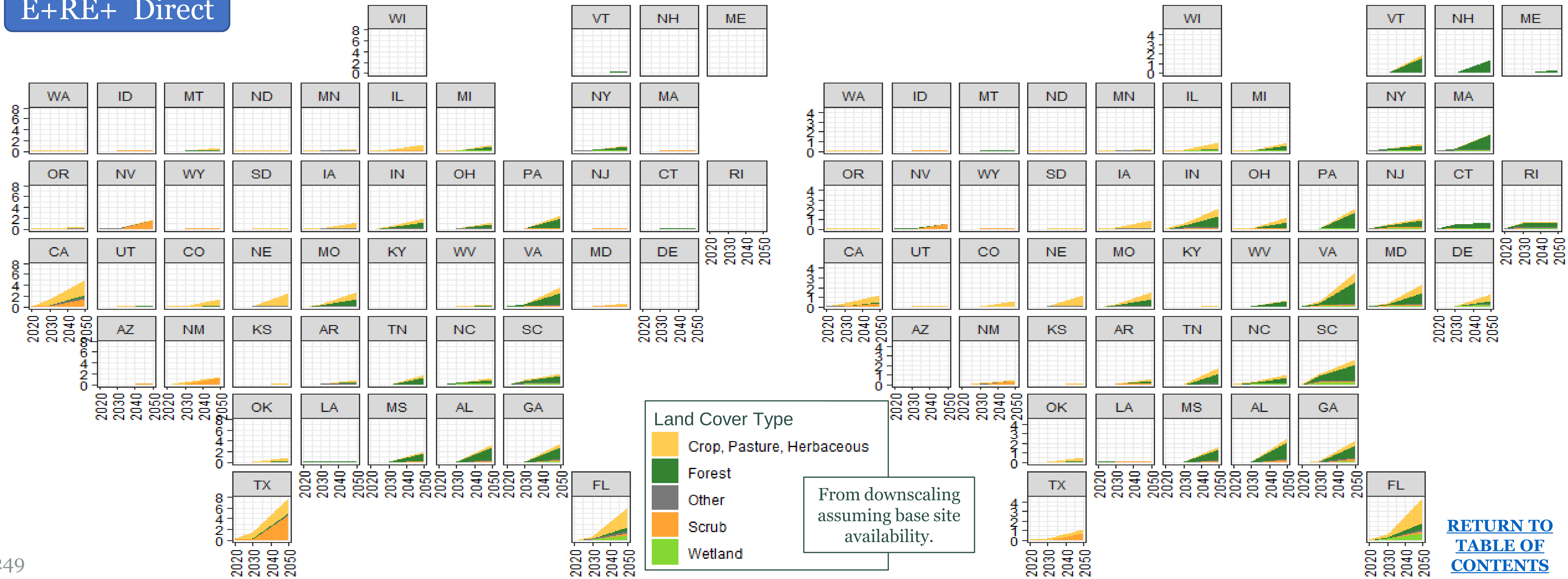
Land area directly impacted by solar and wind development (1,000 km²)

The impacted area by 2050 ranges from very small in some states to ~8,000 km² in Texas.

Percent of state land area

The share of land area impacted by 2050 ranges from very small in some states to nearly 5% in Florida.

E+RE+ Direct



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More western states and fewer eastern states are impacted in E+RE- by 2050 than in E+ or E+RE+.

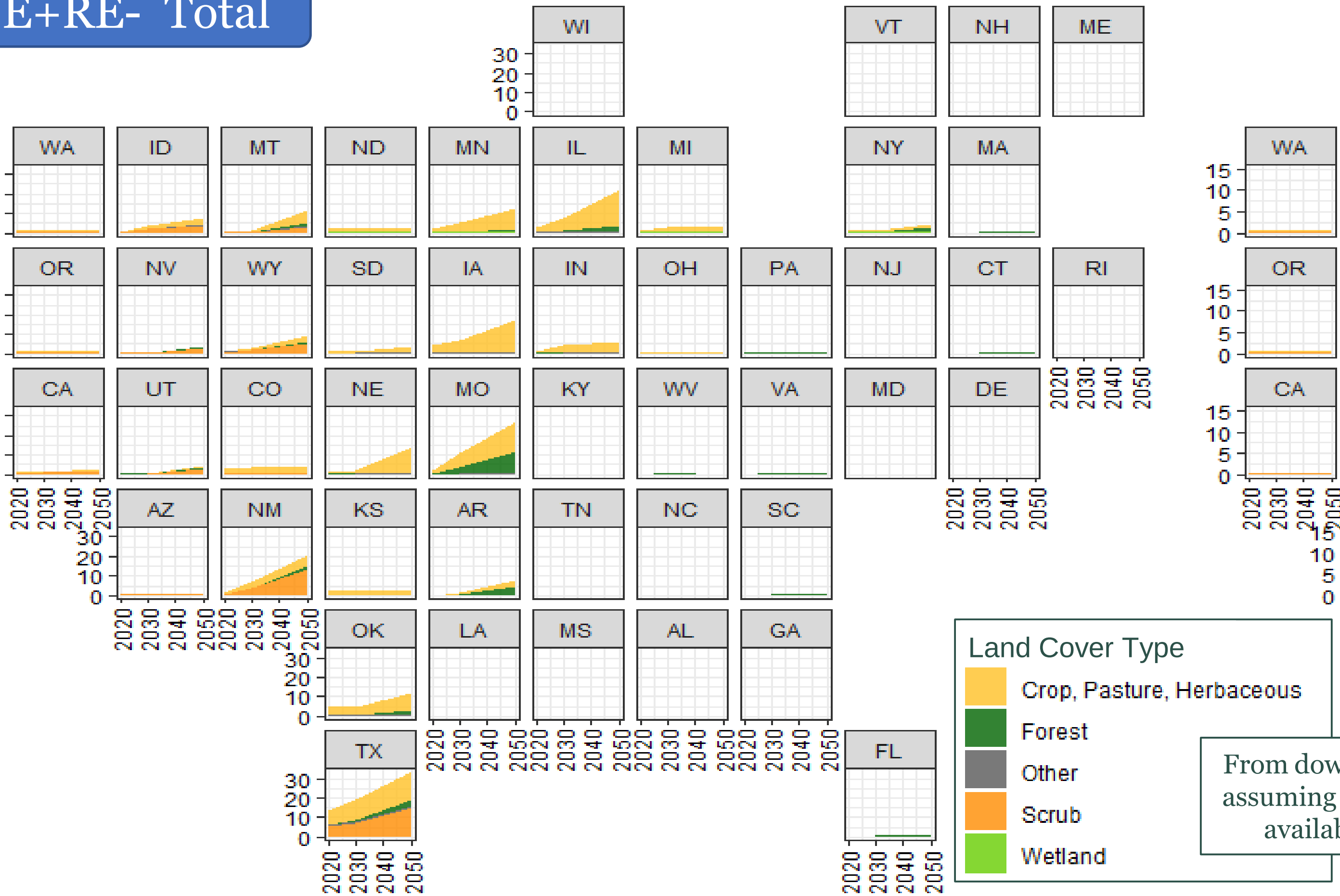
Total area impacted by solar and wind development (1,000 km²)

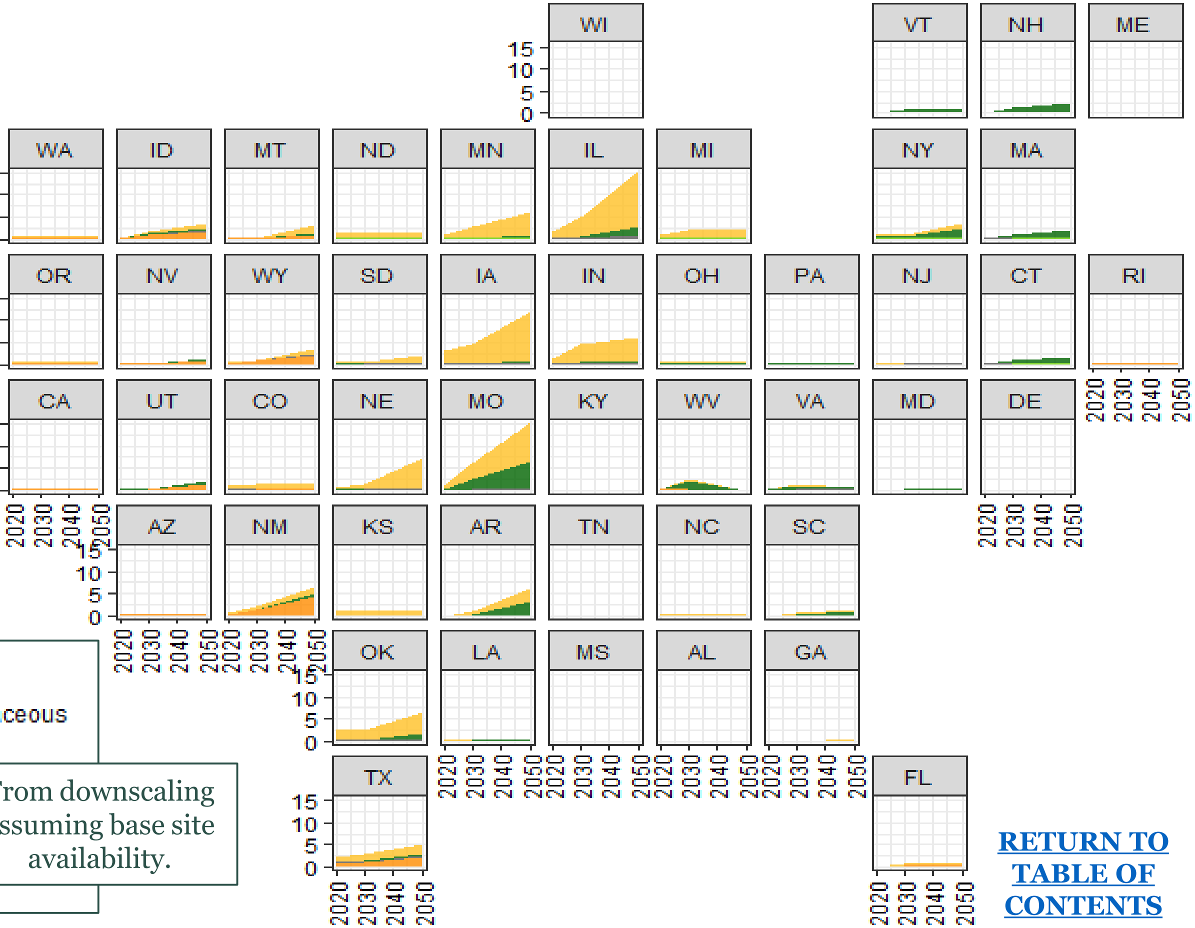
The impacted area by 2050 ranges from hardly any in several states to over 30,000 km² in Texas.

Percent of state land area

The share of land area impacted by 2050 ranges from very small in some states to 15% in Illinois and Missouri.

E+RE- Total





From downscaling assuming base site availability.

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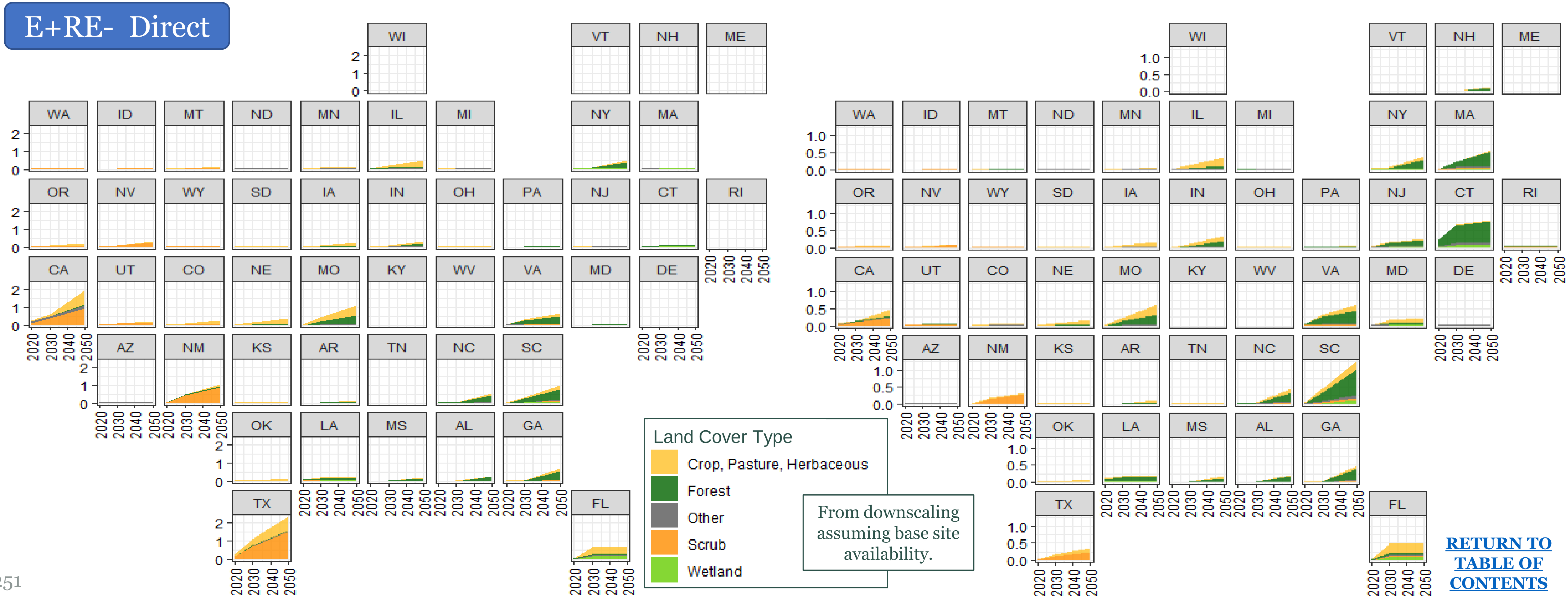
Direct land impacts by 2050 in E+RE- as percent of states' areas are largest for states in the Northeast and Southeast.

Land area directly impacted by solar and wind development (1,000 km²)

The impacted area by 2050 ranges from negligible in some states to ~2,000 km² in Texas and California.

Percent of state land area

The share of land area impacted by 2050 is about 1% or less in all states.



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Capital mobilization

Summary of this section

- Modeled net-zero scenarios are 2 to 4 times more capital intensive than the REF scenario. E+ requires > 2.6 T$ of energy supply-side risk-capital before 2030 and >10 T$ trillion by 2050 (in addition to demand-side capital investments such as vehicles).
- Net-zero scenarios depend critically on timely mobilization of large sums of capital. Capital investments are long-lived, so timing of investments and divestments are critical. The macro-energy systems optimization model used in this study assumes rational and efficient markets that see investors respond instantly to incentives to mobilize capital. In reality, capital is mobilized through a sequence of decisions and activities which require considerable lead times and resources.
- E+ requires on the order of 190 B$ of investment before financial investment decisions (FID) are made on energy-supply projects through 2030 and 600 B$ by 2050. Pre-FID investment typically occurs 2-10 years in advance of when projects come online. Pre-FID costs are fully at-risk, since as there is no guarantee that a given project will 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. These risks can limit the availability, and increase the cost, of investment capital.
- Net-zero scenarios are characterized by a high degree of foresight and seamless integration between sectors; but investors face deep uncertainty around future technology costs and performance, policy priorities of future governments, investment preferences among peers, customers and competitors, and public acceptance of certain technologies.
- Gaps between optimization modeling and the real investment decision making obscure a number of 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.
- See Annex M for details of capital mobilization analysis.

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

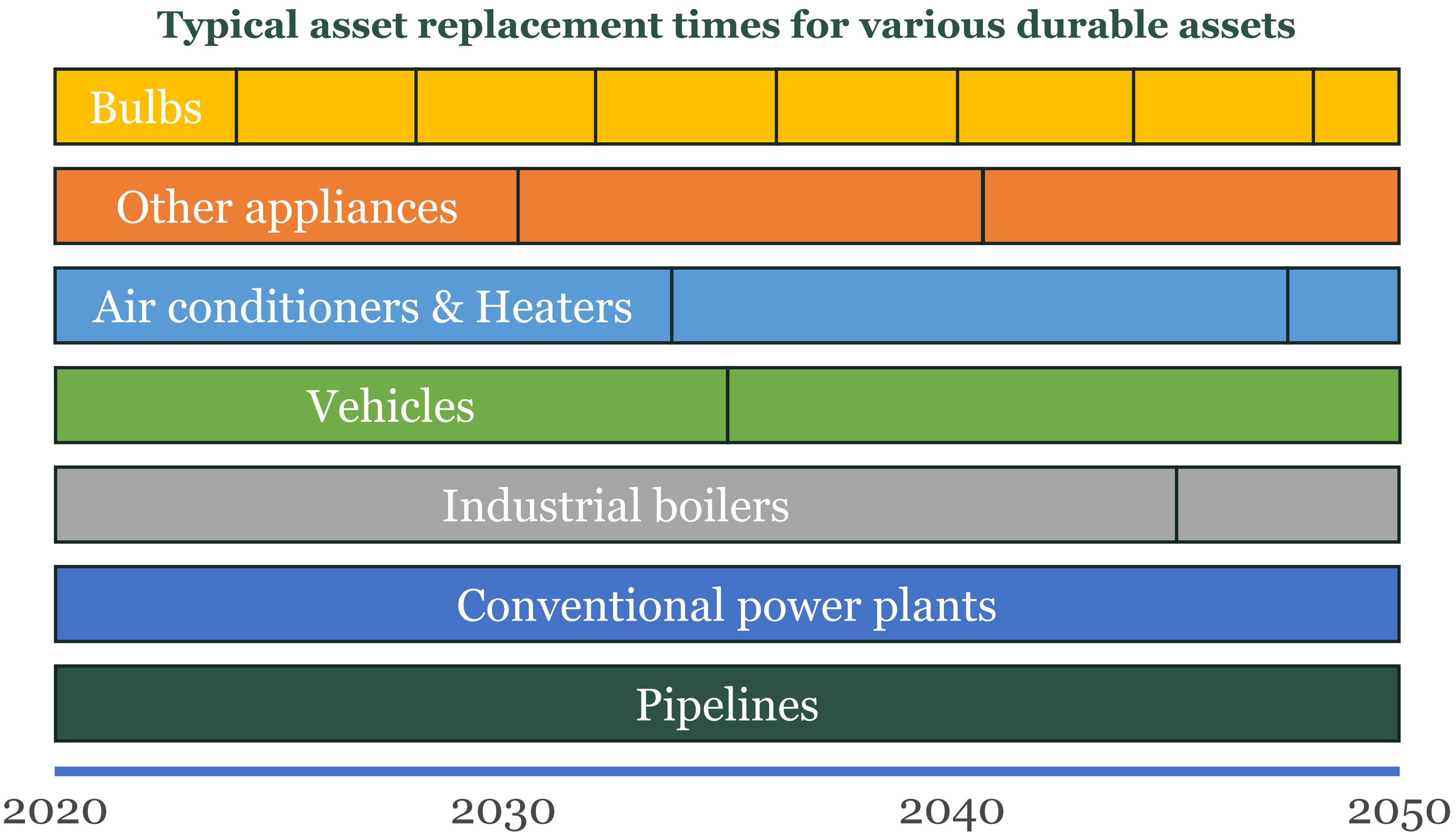

Image credit: Ryan Jones, Evolved Energy Research

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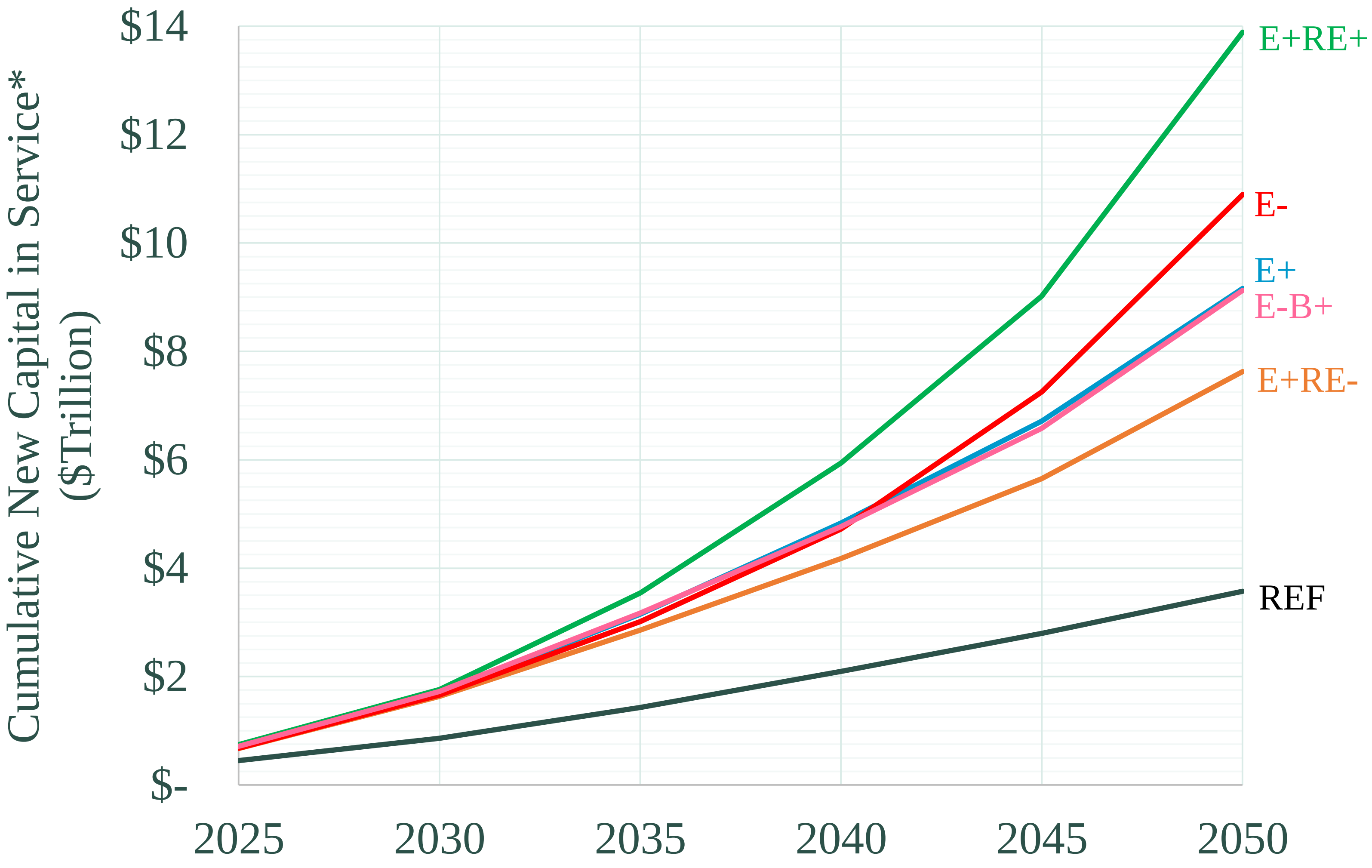
Capital dominates energy system costs in net-zero pathways: Supply-side capital in service by 2050 is 2 to 4 times REF.

- 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.



* Estimatef 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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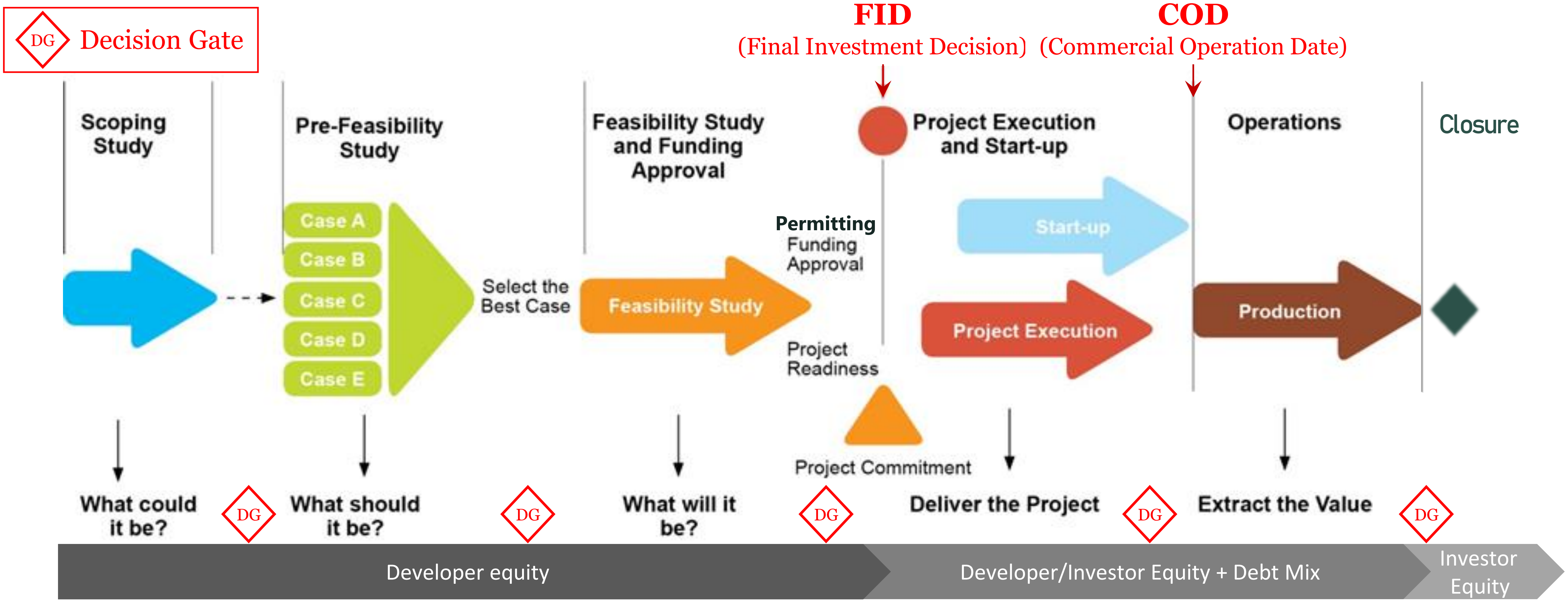
RIO assumes that energy supply assets come online 'overnight' as needed to meet demands; but investment lead times are significant

Stylized decision-gated sequence, where stages feature increasing investment to reduce risk and uncertainty, implies that substantial sums of risk capital will need to be mobilized:



Graphic based on Figure 3 in W. Mackenzie and N. Cusworth, "The use and abuse of feasibility studies," in *Proceedings Project Evaluation 2007*, pp 65-76, The Australasian Institute of Mining and Metallurgy, Melbourne, 2007.

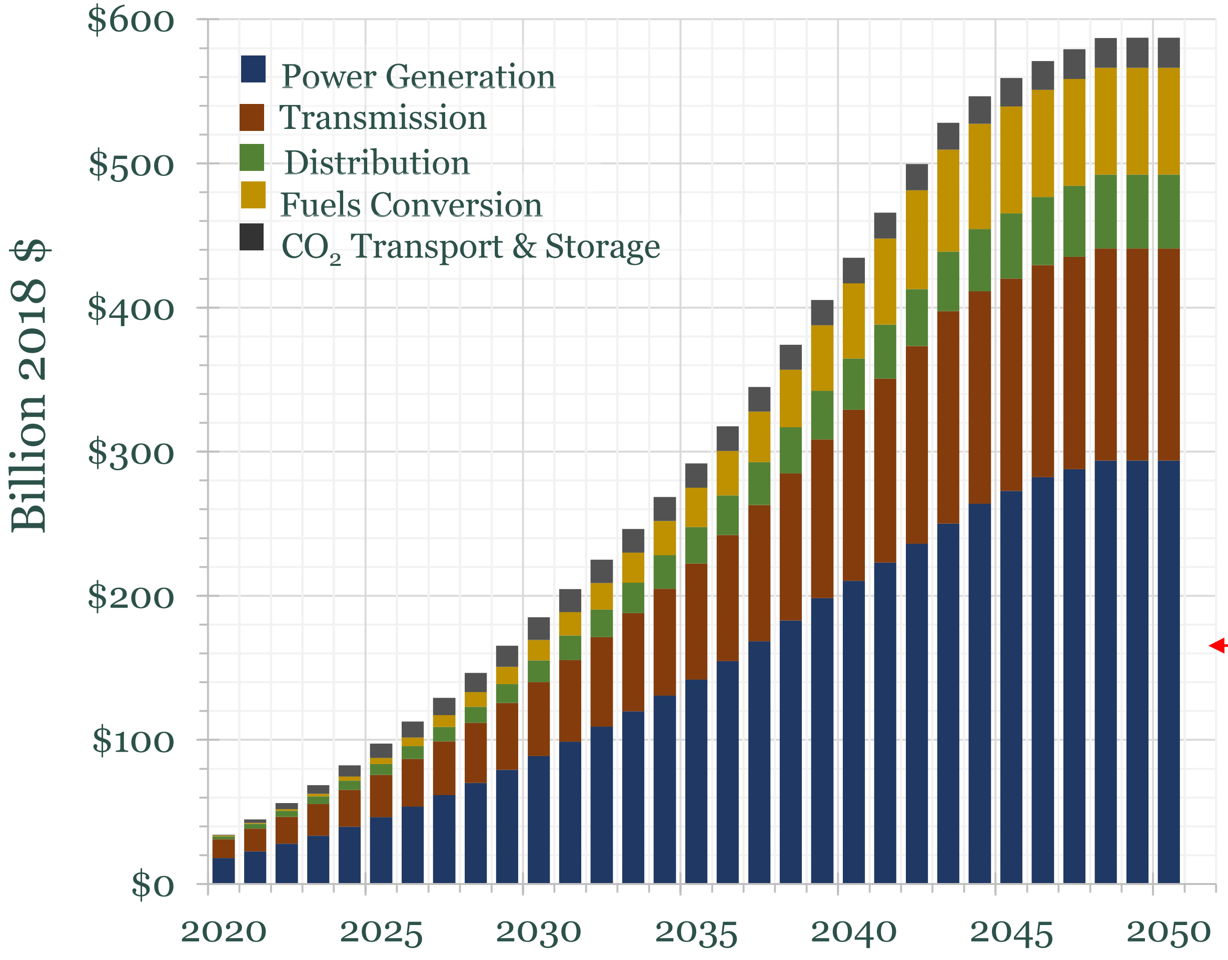
An extensive set of activities must happen before final investment decision (FID)

- Stage-gate decisions are informed by activities, the scopes of which include, but aren't limited to:
  - Engineering, logistics and cost estimating;
  - Resource characterization;
  - Site evaluation and selection;
  - Environmental and social impact assessments;
  - Stakeholder engagement;
  - Land access agreements
  - Market analysis and offtake agreements;
  - Technology license agreement;
  - EPC contract negotiations;
  - Permitting & licensing.
- Pre-FID activities are generally equity funded and entirely 'at-risk'; not all proposed projects will achieve FID, so estimation of study costs must allow for a percentage of 'failure cases'.
- Post-FID, the majority of projects will be project financed using a mix of debt and equity; debt finance will be subject to finance fees that must be paid before first drawdown (i.e., at FID).
- Historical experience is that depending on the risk profile, debt funds and some classes of equity investment funds may be attracted to invest only after the date commercial operations have commenced (COD).
- Pre-FID investment costs, lead-times and success rates (in moving from FID to COD), along with construction times for each technology were estimated on the basis of the NZA team's industrial experience, and in consultation with expert practitioners.

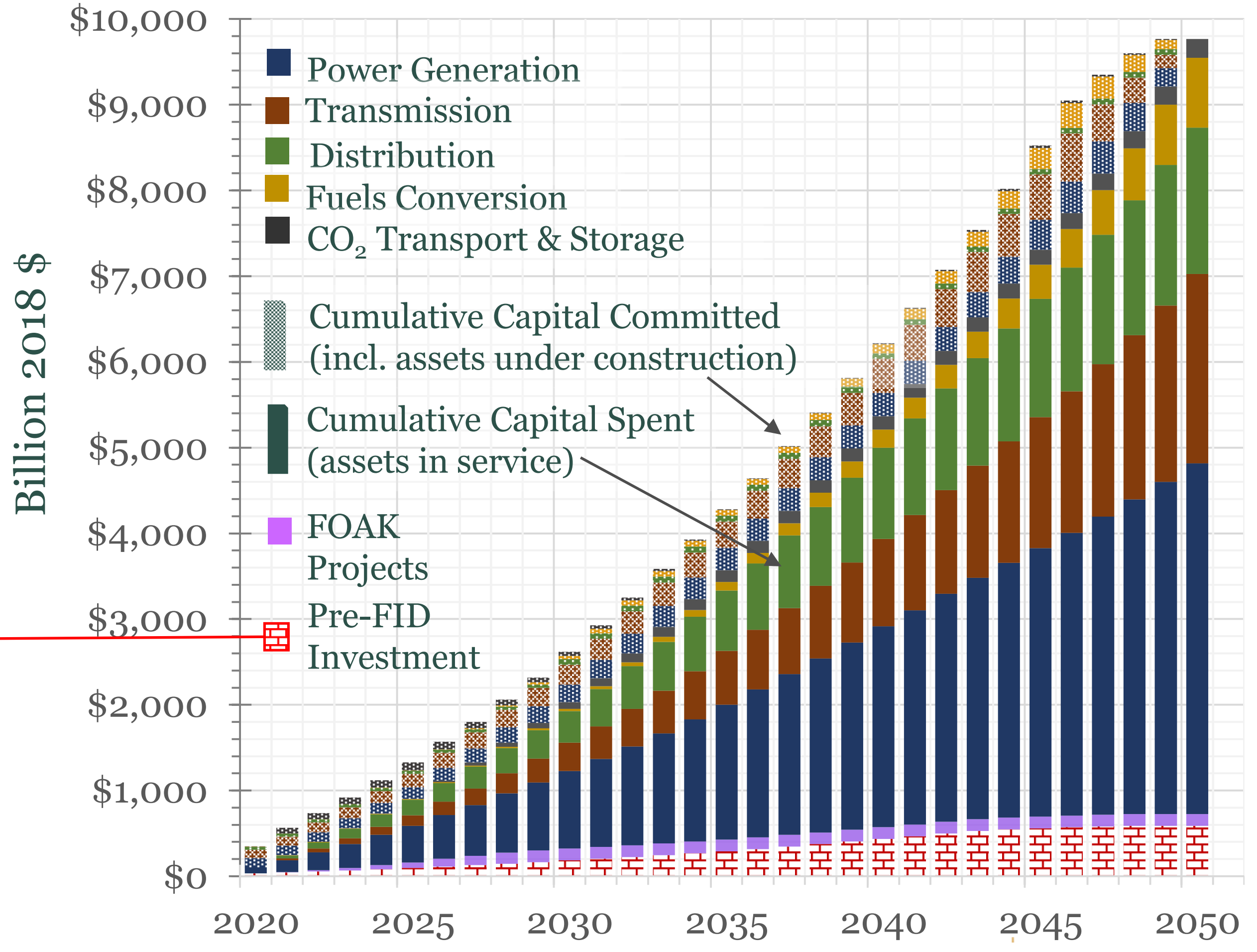
All net-zero scenarios are capital intensive. Mobilizing risk capital for development and construction will be a significant challenge

E+

$600 billion at-risk Pre-FID development costs to support >$9 trillion in capital investment decisions



Almost $10 trillion cumulative capital investment in supply-side plant & infrastructure (incl. pre-FID and FOAK demonstration costs)



Note: Excludes investments in demand-side transport, buildings and industry; fuels transport & distribution systems; biomass crop establishment; and land sink enhancements.

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Average project development times and pre-FID costs used to estimate E+ capital mobilization requirements in the power sector.

POWER SECTOR

Generation Assets	Pre-FID Study Time (years)	PreFID Cost (% of TIC)	Financing Cost (% of TIC)	Total Pre-FID Cost (% of TIC)	Financial Close (years)	Construction Time (years) FID to COD	Overall Dev Time (years) Concept to COD
biomass w cc	2.5	9.0%	1.5%	10.5%	0.5	4	7
CCGT	1	4.5%	1.0%	5.5%	0.5	2	3.5
CCGT w CC	2.5	9.0%	1.5%	10.5%	0.5	4	7
CT	1	4.5%	1.0%	5.5%	0.5	1	2.5
geothermal	2	9.0%	1.0%	10.0%	0.5	2	4.5
nuclear	5	24.1%	3.0%	27.1%	1	5	11
offshore wind	2.5	10.0%	1.5%	11.5%	0.5	3	6
onshore wind	1.5	5.5%	1.0%	6.5%	0.5	2	4
solar pv	1	5.5%	1.0%	6.5%	0.5	1	2.5
storage li-ion	1	4.5%	1.0%	5.5%	0.5	1	2.5
Transmission and Distribution Assets							
Transmission (average)	2.5	5.7%	1.0%	6.7%	0.5	4	7
Distribution networks	1	2.5%	0.5%	3.0%	0.5	1	2.5

Average project development times and Pre-FID costs used for fuel conversion, CO_2, and industry sectors

	Pre-FID Time (years)	Pre-FID Cost (% of TIC)	Financing Cost (%of TIC)	Total Pre-FID Cost (% of TIC)	Financial Close (years)	Construction Time (y) FID to COD	Overall Dev Time (y) Concept to COD
FUEL CONVERSION							
ATR Hydrogen	2	4.5%	1.0%	5.5%	1	2	5
ATR Hydrogen with CCU	2	9.0%	1.5%	10.5%	2	3	7
BECCS Hydrogen	2	9.0%	1.0%	10.0%	2	4	8
Biomass to Syngas	2	9.0%	1.5%	10.5%	2	3	7
Biomass to Syngas with CCU	2	9.0%	1.0%	10.0%	2	4	8
Biomass FT to Diesel	2	9.0%	1.0%	10.0%	2	3	7
Biomass FT to Diesel with CCU	2	9.0%	3.0%	12.0%	2	4	8
Biomass Pyrolysis	2	4.5%	1.5%	6.0%	2	3	7
Biomass Pyrolysis with CCU	2	9.0%	1.0%	10.0%	2	4	8
Electrolysis	2	4.5%	1.0%	5.5%	1	2	5
DAC for Synfuels	2	9.0%	1.0%	10.0%	1	2	5
Electric Boiler	2	9.0%	1.0%	10.0%	2	1	5
Hydrogen Blend	1	4.5%	1.0%	5.5%	1	1	3
Industrial Hydrogen Boiler	2	4.5%	1.0%	5.5%	1	2	5
Industrial Pipeline Gas Boiler	2	4.5%	1.0%	5.5%	1	1	4
Power to Liquids	2	9.0%	1.0%	10.0%	1.5	3	6.5
Power to Gas	2	9.0%	1.0%	10.0%	1.5	3	6.5
CO_2 TRANSPORT & STORAGE							
Inter-Regional Trunk Lines	5	13.0%	1.5%	14.5%	1	5	11
Spur Lines	2.5	4.2%	1.0%	5.2%	0.5	3	6
E&A, Wells & Facilities	1	5.0%	0.0%	5.0%	0	1	2
INDUSTRY							
Cement	2.5	4.2%	1.0%	5.2%	0.5	4	7
Steel	2.5	4.2%	1.0%	5.2%	0.5	3	6

The 2020s is the decade to invest in maturing and improving a range of technologies that improve options for the longer term.

- Several technologies will require multiple full-scale ‘first-N-of-a-kind’ (FOAK) projects to reduce costs and technology risks in order to make them ‘commercial ready’ for deployment at scale.
- Assumed investment premium is estimated at 150% over and above reference costs across pre-FID, design, construction and commissioning.

	FOAK Project unit Capacity	No. of Projects	Mature cost* (used in RIO model)	FOAK cost multiplier on mature cost**	Total FOAK Investment (B$)
Power		**27**			**63.3**
Advanced Nuclear	300 MW	4	6,465 $/kW	2.5	19.4
CCGT with CC	300 MW	5	2,176 $/kW	2.5	8.2
CCGT with CC (Oxy)	300 MW	5	1,924 $/kW	2.5	7.2
Bio-gasifier GT with CC	300 MW	5	6,338 $/ kW	2.5	23.8
High-H_2 GT	100 MW	5	520 $/kW	2.5	0.7
Advanced Geothermal	100 MW	3	5,472 $/kW	2.5	4.1
Fuels		**30**			**24.8**
ATR Hydrogen with CC	300 MW	5	782 $/kW	2.5	2.9
Bio-gasifier H_2 with CC	300 MW	5	2,599 $/kW	2.5	9.7
Biomass Pyrolysis	100 MW	5	3,991 $/kW	2.5	5.0
Electrolysis	100 MW	10	1,790 $/kW	2.5	4.5
Direct Air Capture	100 ktpa	5	18,954 $/ktph CO_2	2.5	2.7
Industry		**10**			**48.8**
Cement with CC	2.8 Mtpa	5	3.5 B$/plant	2.5	43.8
H_2-Direct Reduced Iron	2.25 Mtpa	5	400 M$/plant	2.5	5.0
Total		**67**			**136.9**

* Overnight installed capital cost per unit output. For fuels, output is expressed on a higher heating value basis.
** Including pre-FID, based on Guidelines for First-of-a-kind Cost estimation [1.5 applies to FOAK plants already committed in 2020’s]

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Fossil fuel industries

Summary of this section

All fossil fuel industries see rapidly declining consumption and production throughout the transition.

Thermal coal consumption and production ceases by 2030.

- Over 700 coal mines close and some 500 coal-fired power plants are retired.
- The majority of coal plants retire at >30 years age, with just 8% retiring at <20 years and 50% retiring at >50 years.

Oil production declines 25% to 85% across the suite of NZA scenarios, relative to the REF scenario

- Consumption declines 60% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Oil production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on recent growth rates indicating the need to slow pace of exploration and development over time to avoid stranded assets.

Natural gas production declines between 20% and 90% across the suite of NZA scenarios, relative to the REF scenario

- Consumption declines 50% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Revenues decline significantly for producers, and remediation costs of some $25 billion are brought forward.
- Gas production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on historical growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.
- Significant stranded asset risks for gas transmission and distribution networks. A declining customer base over time will challenge cost recovery and raise equity concerns, especially in high electrification scenarios.

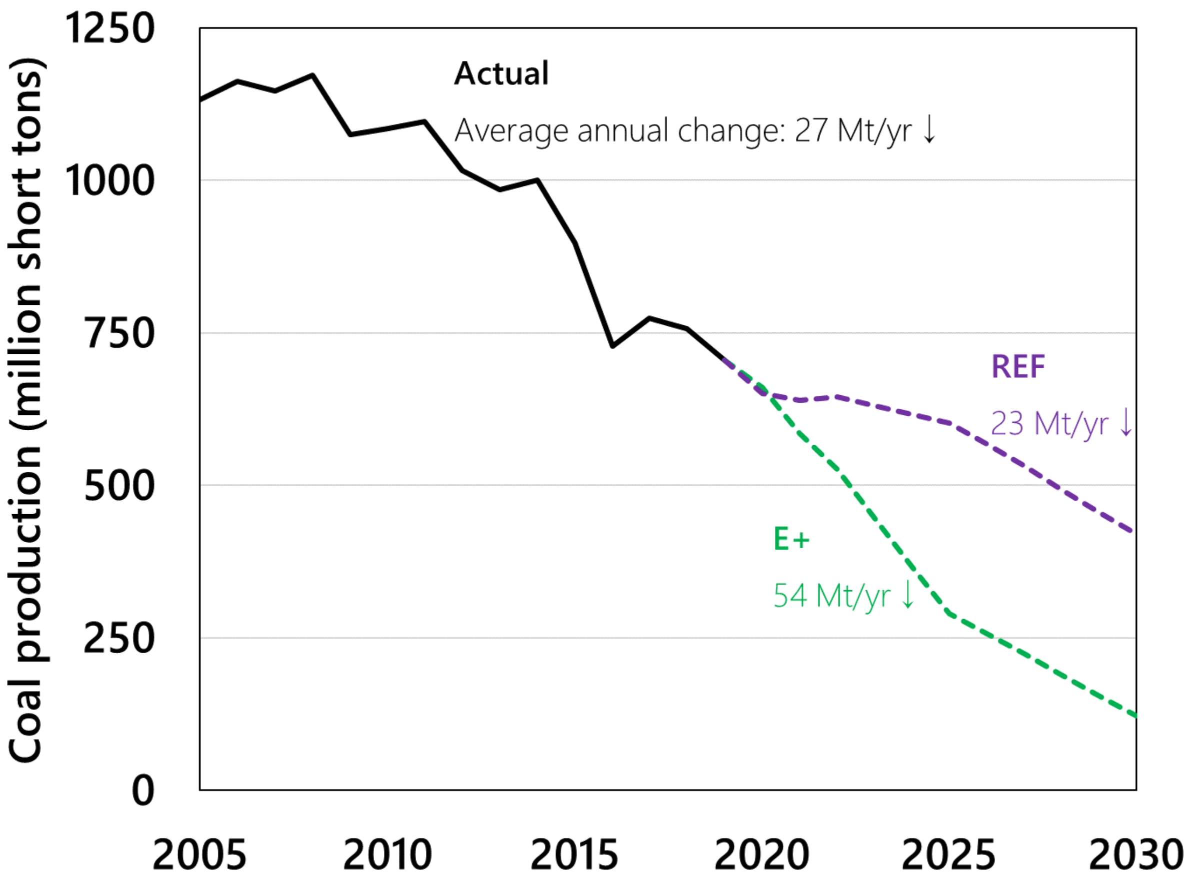
See Annex N for details.

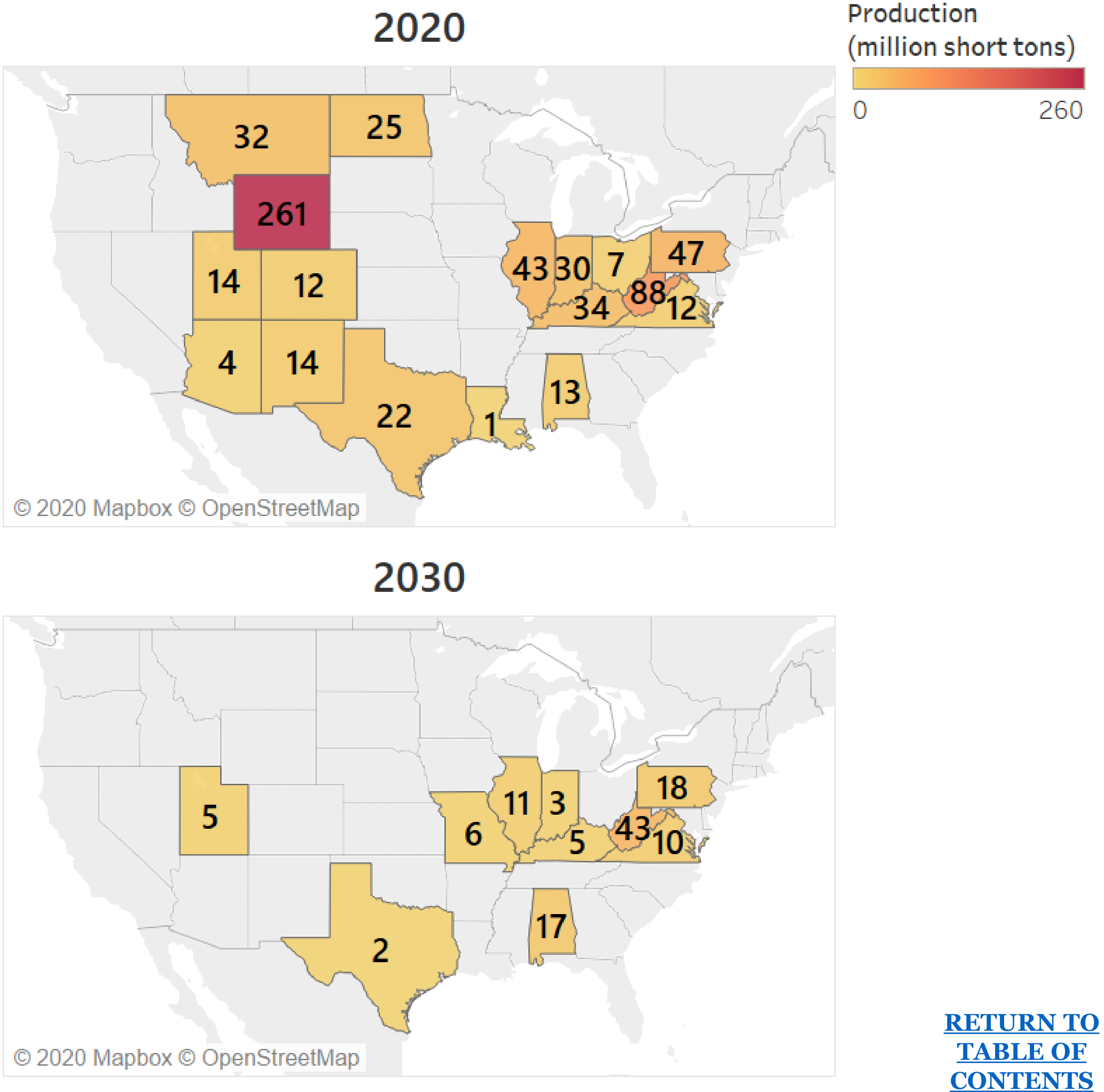
Summary of this section

Thermal coal consumption and production ceases by 2030.

- Over 700 coal mines close and some 500 coal-fired power plants are retired.
- The majority of coal plants retire at >30 years age, with just 8% retiring at <20 years and 50% retiring at >50 years.
- By assumption, the US continues to produce coal post-2030 to meet domestic non-power demands as well as projected exports consistent with the EIA projections to 2050.

In all net-zero pathways most of the nearly 700 mines close by 2030, impacting all coal-producing regions.





Note: We assume that the US continues to produce coal post-2030 to meet domestic industrial and coking demand as well as projected exports consistent with the EIA 2020 AEO Reference case projections. We assume that coal imports are trivial. In 2030 for the E+ scenario, we assume that continued coal production to meet export demand occurs in states that have historically produced coal for export; we use the 2019 historical state origin of exports to spatially allocate future production.

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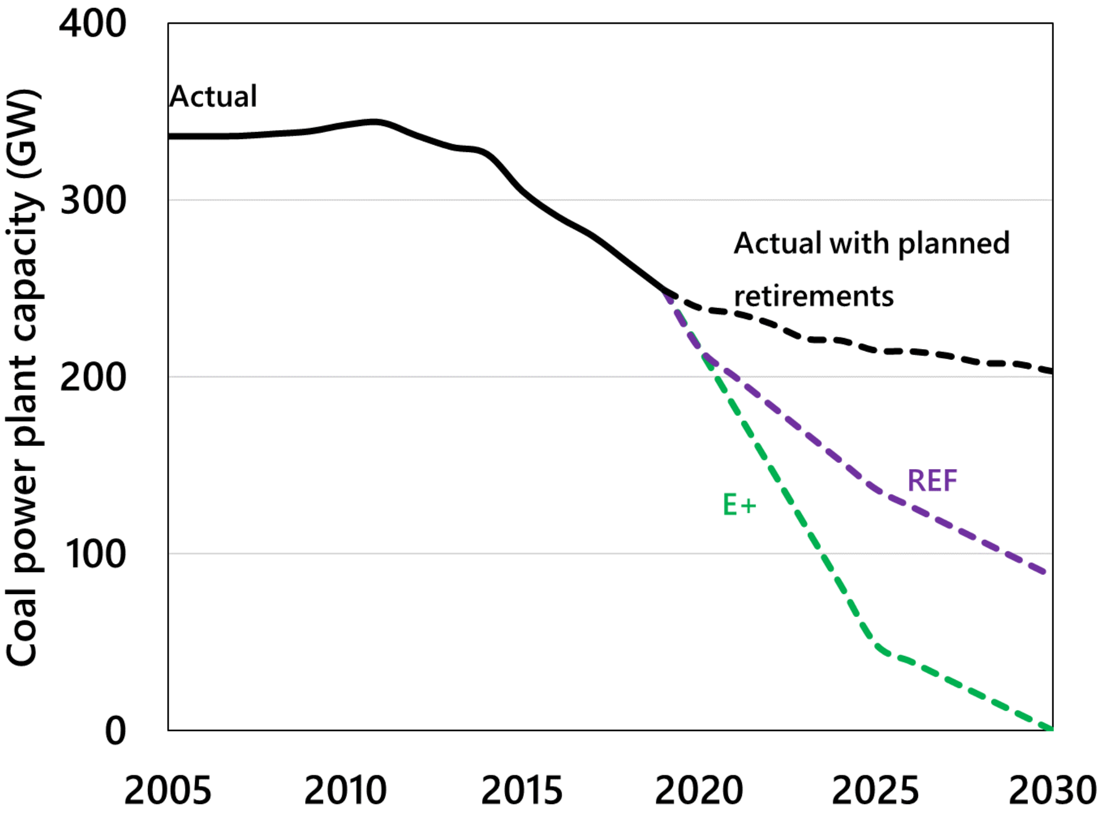
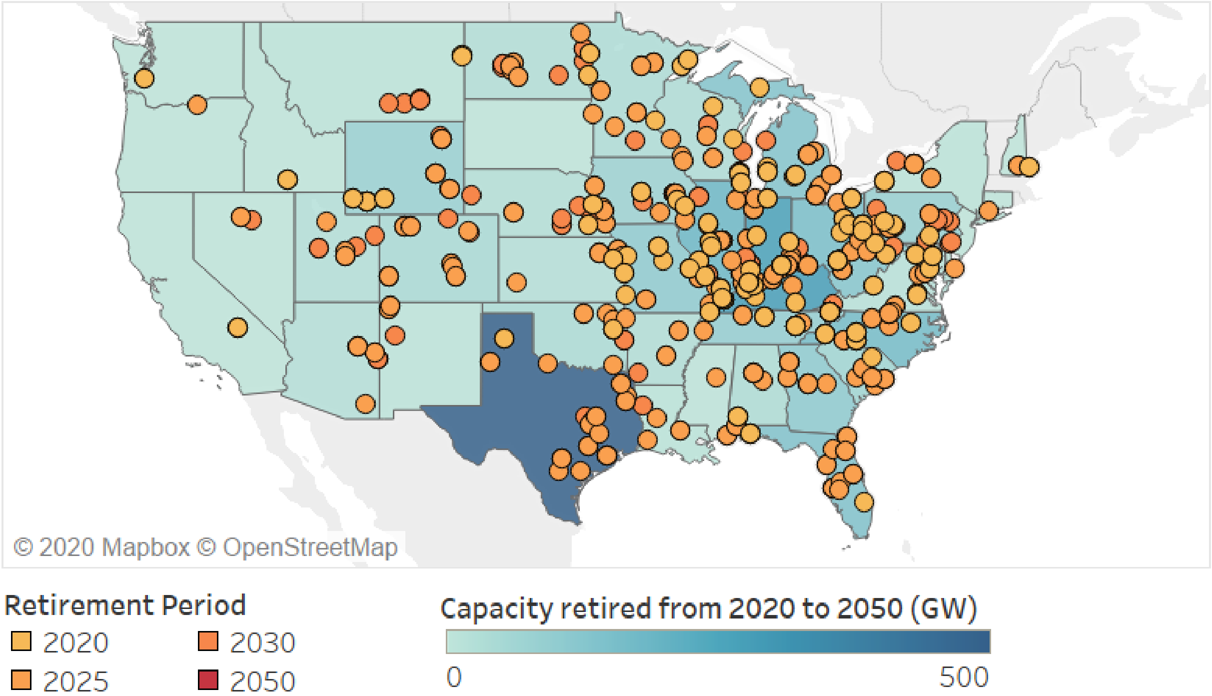
All coal power plants (500+) close by 2030.



Retirement period of coal generators in E+ scenario



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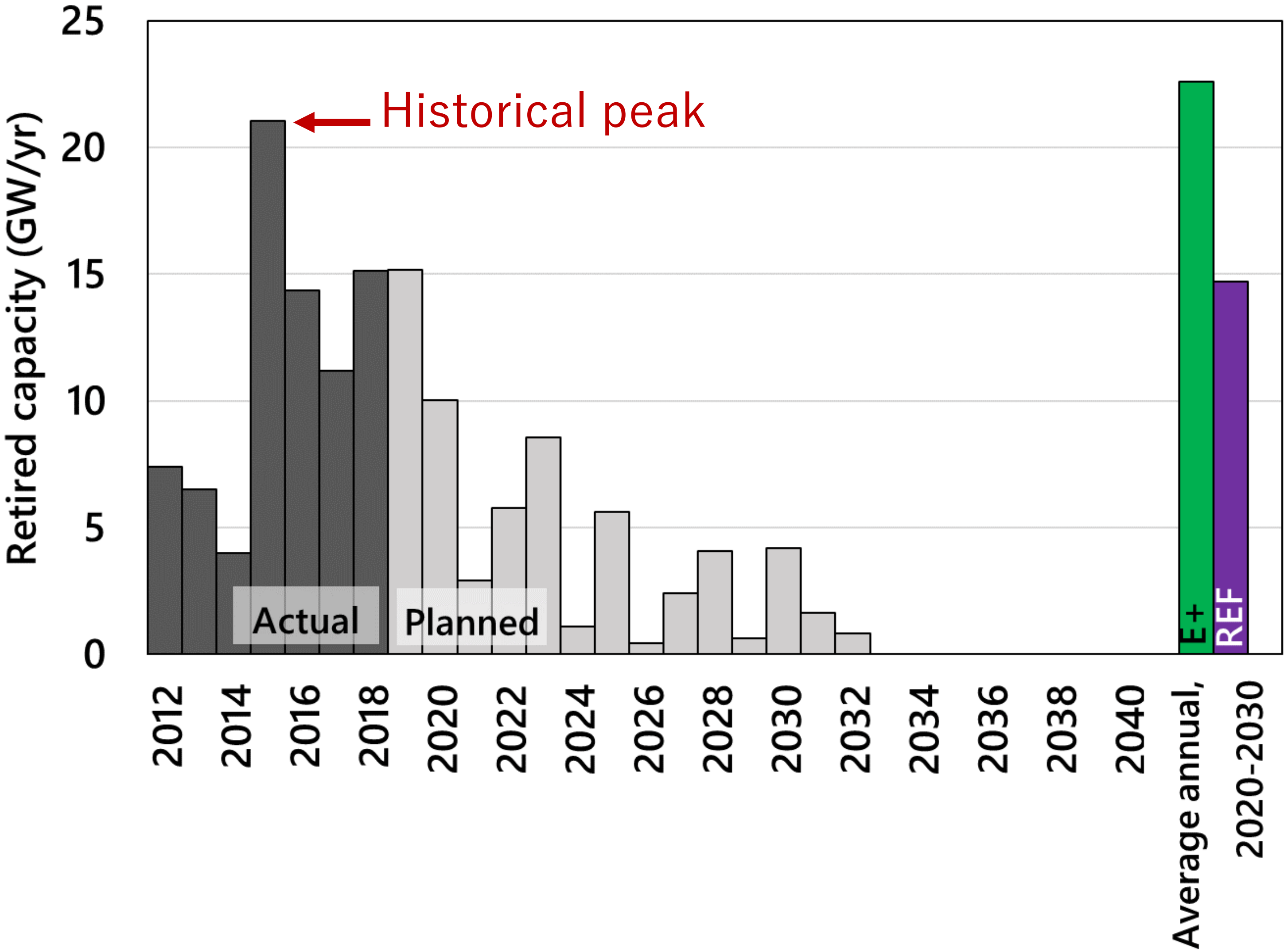
Average annual coal retirements in all net-zero scenarios is close to the historical peak rate observed in 2015.



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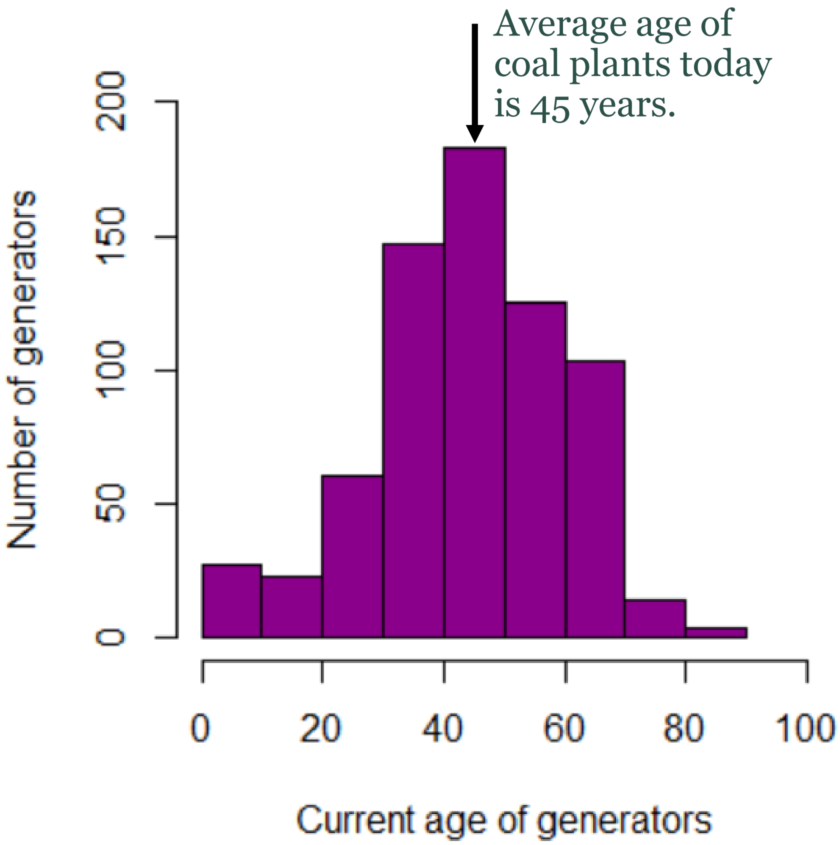
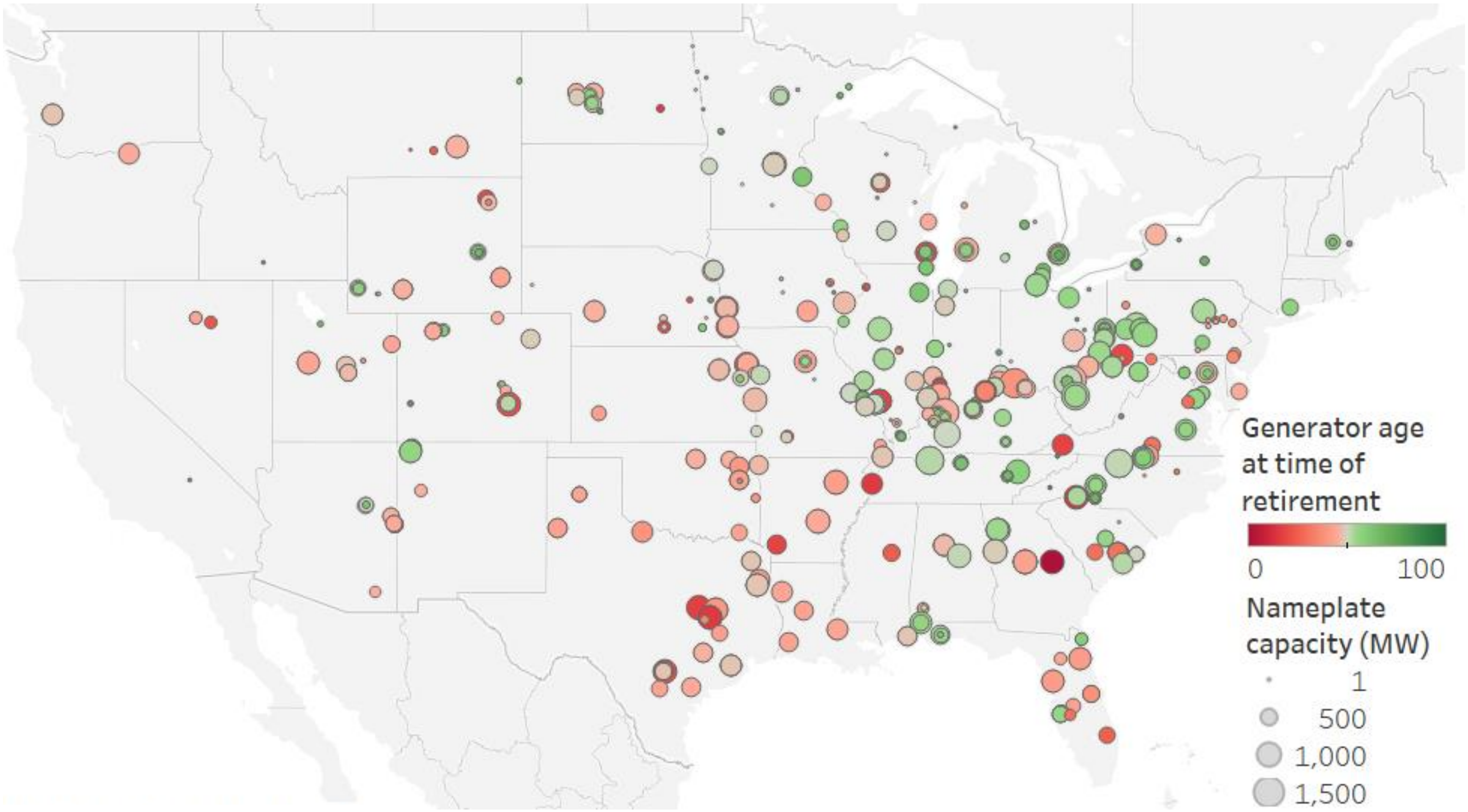
The U.S. coal fleet is old. Half of plants retire 50+ years old in the 2020's. Less than 8% (23 GW) retire before reaching 20 years.



Retirement of coal generators for E+ scenario

Generators indicated in red retire prior to the typical 50-year lifespan of coal generators, consistent with Grubert (2020).



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Summary of this section

- Oil production declines 25% to 85% across the suite of NZA scenarios, relative to the reference scenario
- Consumption declines 55% to 100% by 2050 in net-zero scenarios.
- By assumptions, exports remain in line with AEO projections to 2050.
- Oil production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on recent growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.

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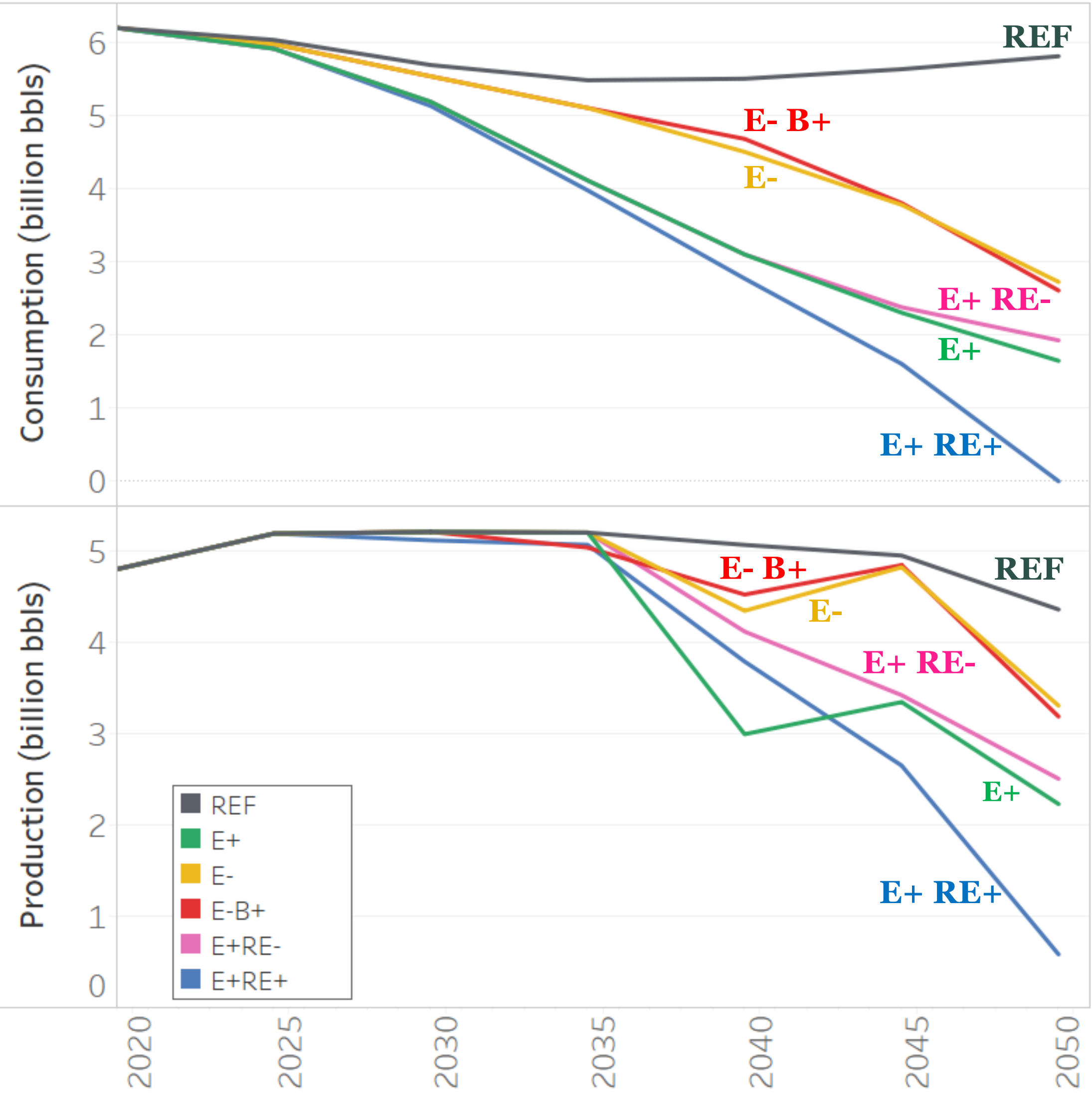
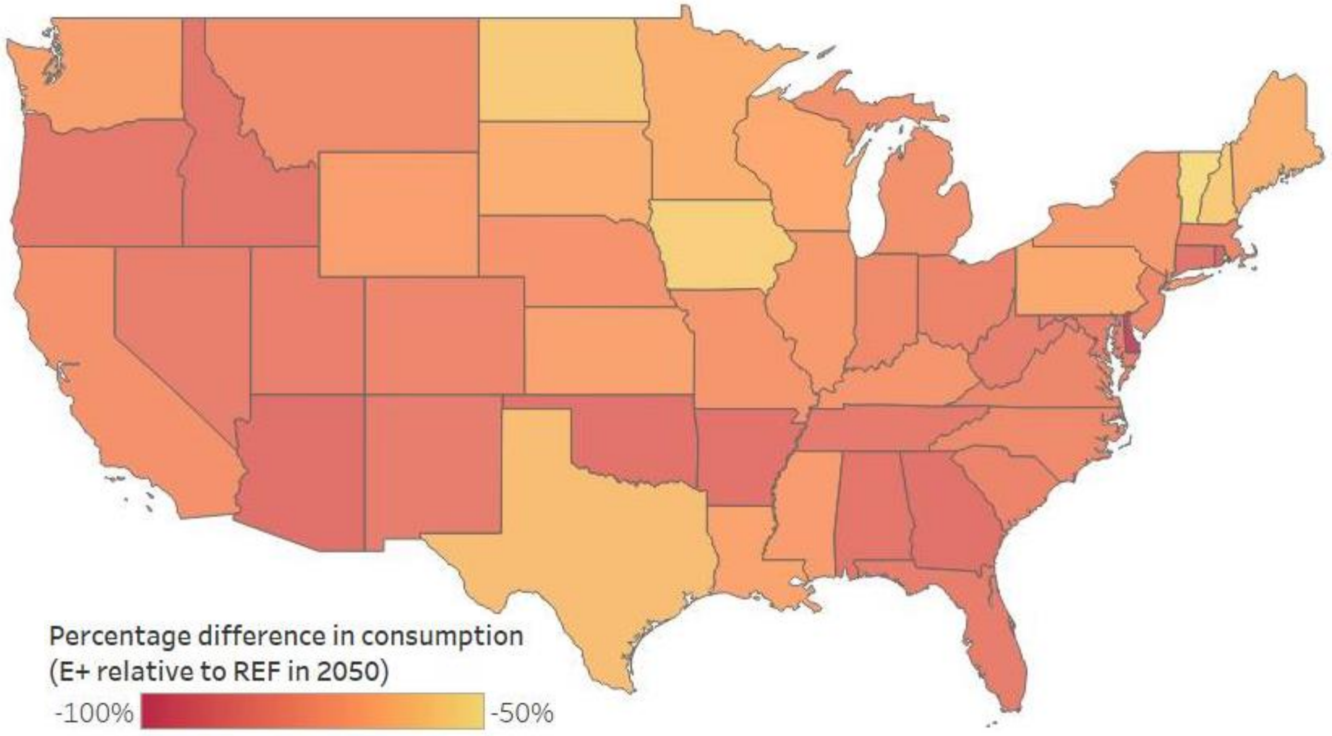
Oil consumption declines 55% to 100% by 2050 for net-zero scenarios relative to REF; production declines 25% to 85%.



Change in oil consumption in E+ case relative to REF



Note: Production projections assume US produces at a rate consistent with or lower than the 2019 EIA AEO Reference case and continues to export oil at rate consistent with the AEO projection. As domestic consumption declines, an increasing share of demand is met through domestic production and a decreasing share of oil is imported. Starting around 2035, domestic demand has fallen to the point that oil imports are no longer needed, and with further demand declines thereafter, US production also declines.

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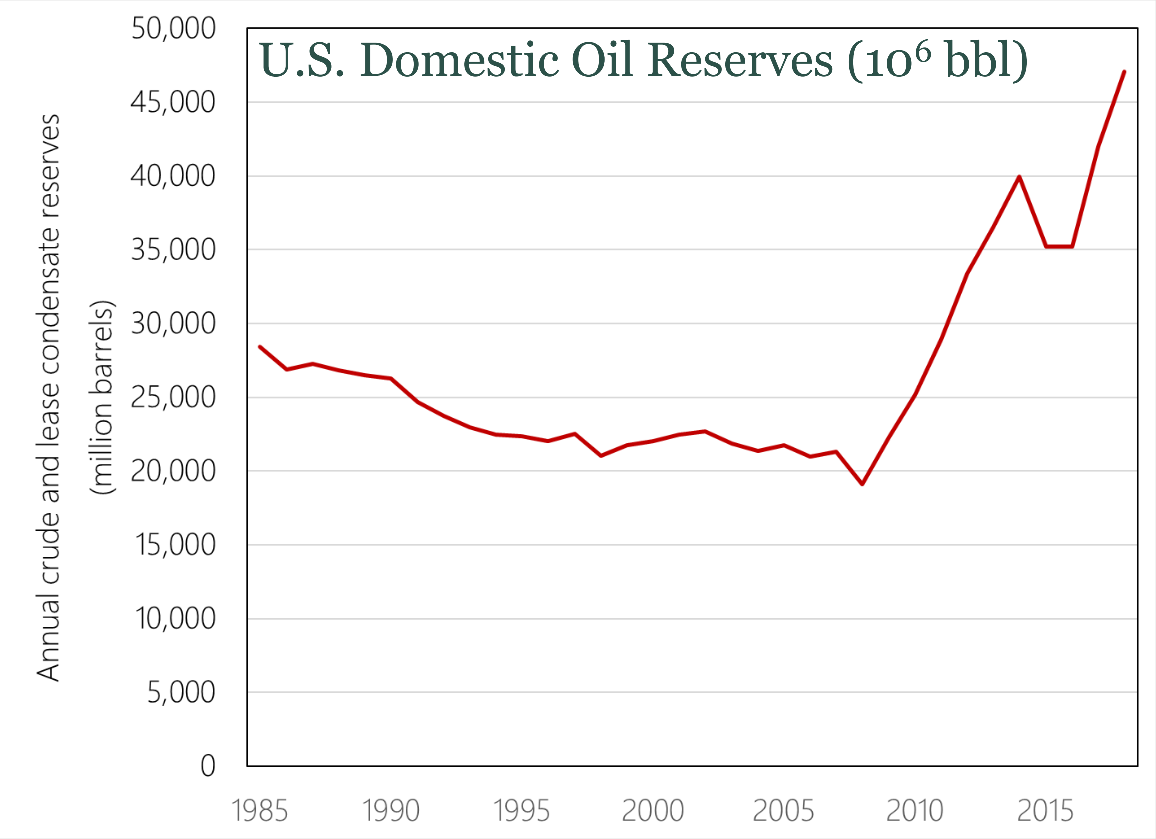
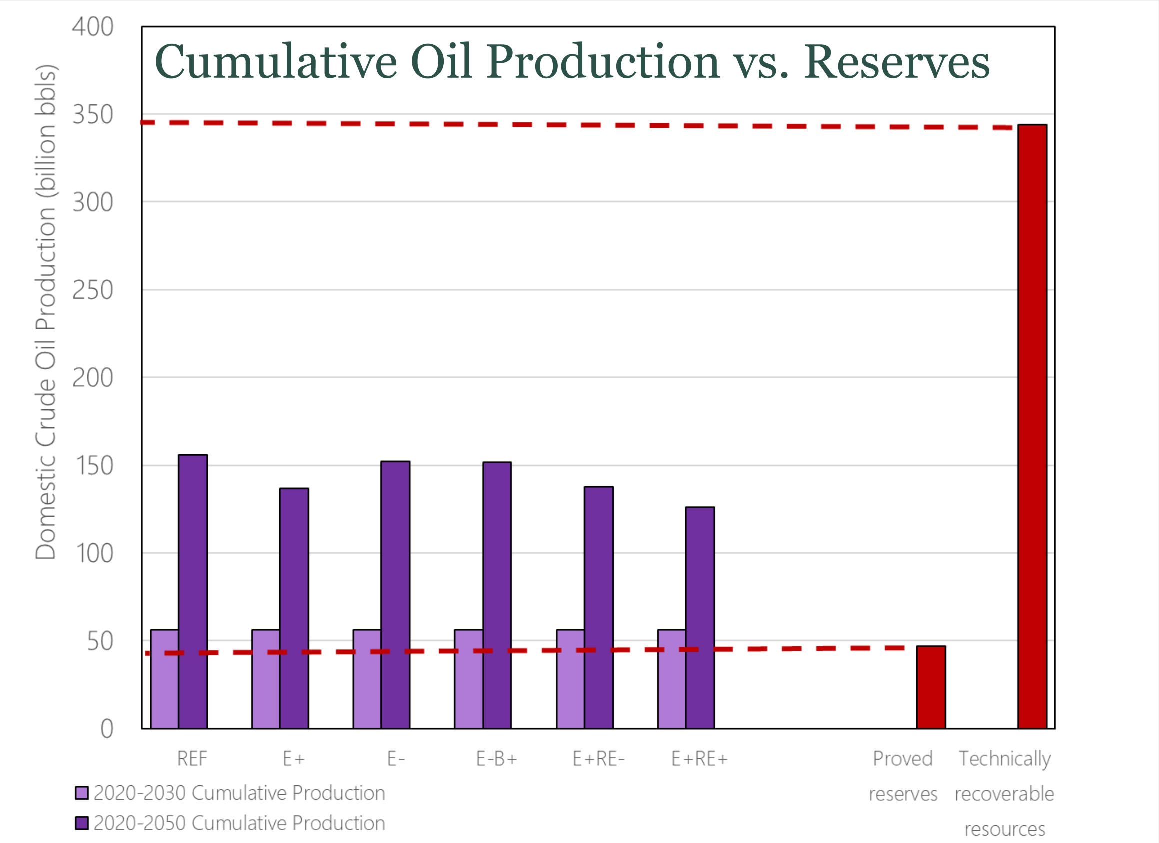
Cumulative oil production through 2030 exceeds current proved reserves, but continued additions could risk stranding assets.





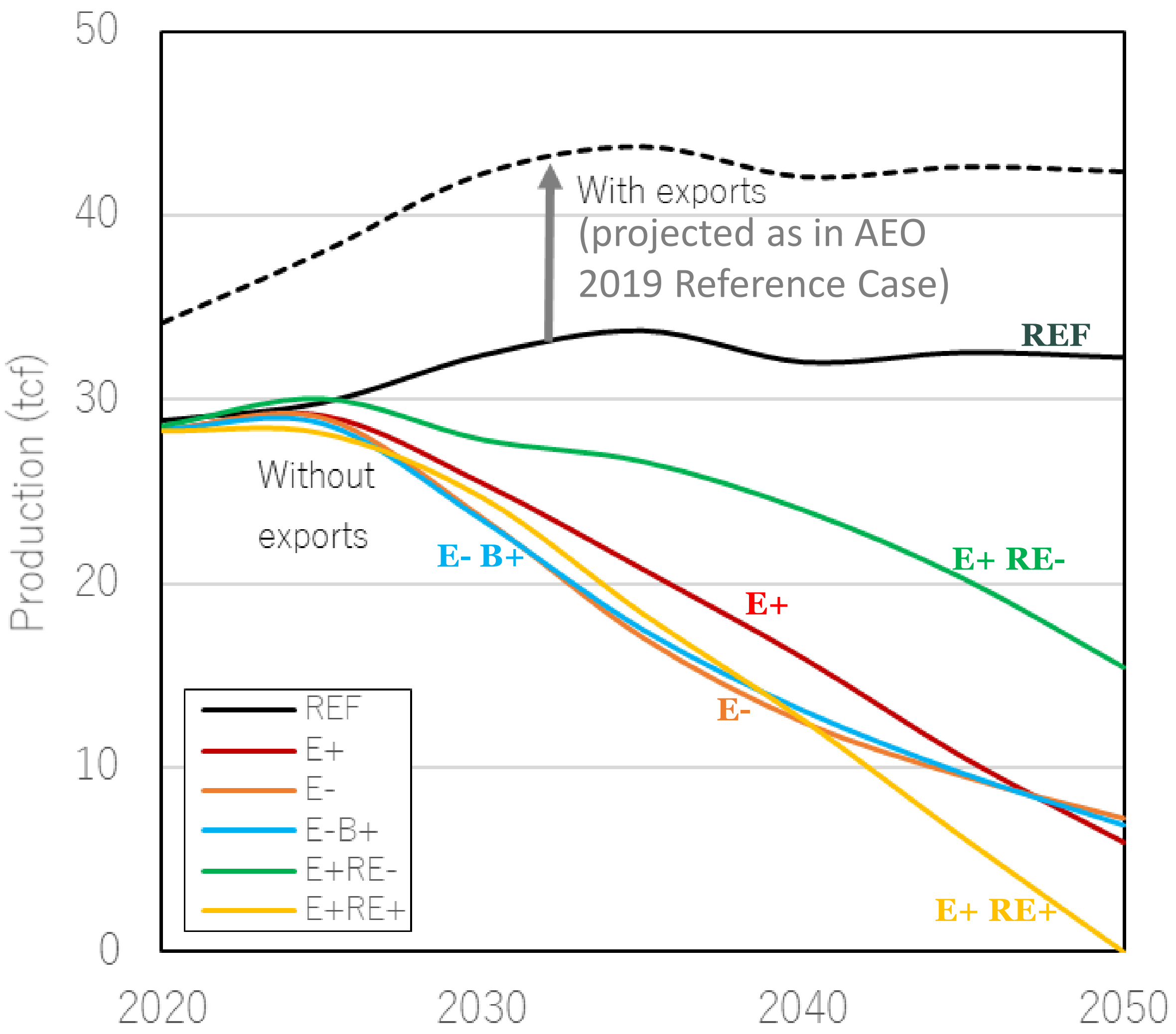
- Cumulative oil production to 2050 in REF and net-zero scenarios exceeds current proven reserves, indicating that all current reserves can be produced in these scenarios.
- If recent annual rates of reserve addition persist, however, proved reserves could surpass projected cumulative oil production and result in some stranded assets.

Natural Gas

Summary of this section

- Natural gas production declines between 25% and 85% across the suite of NZA scenarios, relative to the reference scenario.
- Consumption declines 50% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Significant declines in revenues for producers and bringing forward some $25 billion in remediation costs.
- Gas production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on historical growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.
- Significant stranded asset and write-down risks for transmission and distribution networks. A declining customer base over time will challenge cost recovery and raise equity concerns, especially in high electrification scenarios.

Natural gas consumption declines 50% to 100% by 2050 in net-zero scenarios relative to REF.

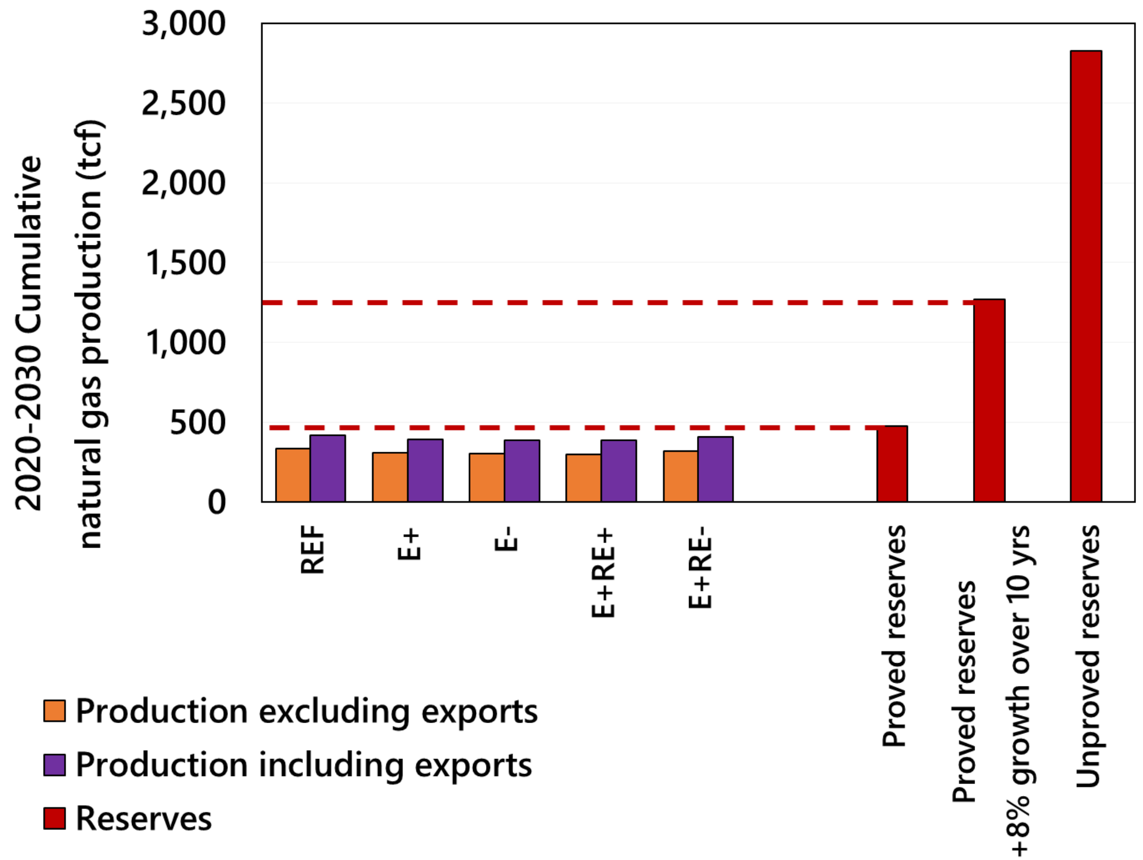


- Over ½ million gas wells close in 2020's; plug and abandonment costs are estimated to be ~$25 billion.

Natural gas production through 2030 is less than current proved reserves, but continued reserve additions could risk stranding assets.

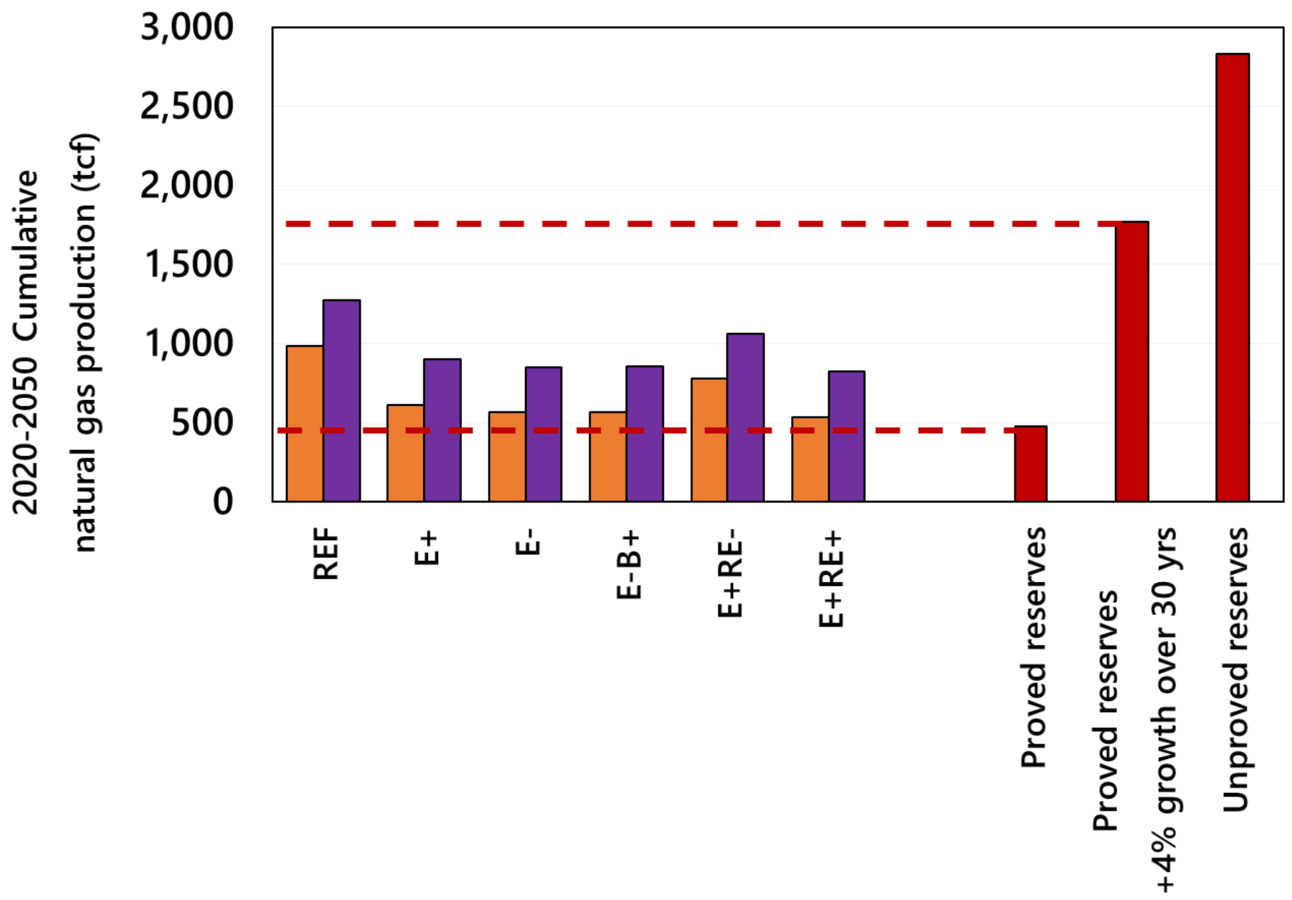
2020-2030 Near-term production and reserves

Cumulative gas production to 2030 in E+ is less than today's proved reserves, even without reserve additions at short-term historical growth rates (8%/year).



2020-2050 Long-term production and reserves

Cumulative gas production to 2050 in E+ exceeds today's reserves, but is less than reserves if reserves grow at long-term historical rate (4%/year).



EIA reserves estimates.

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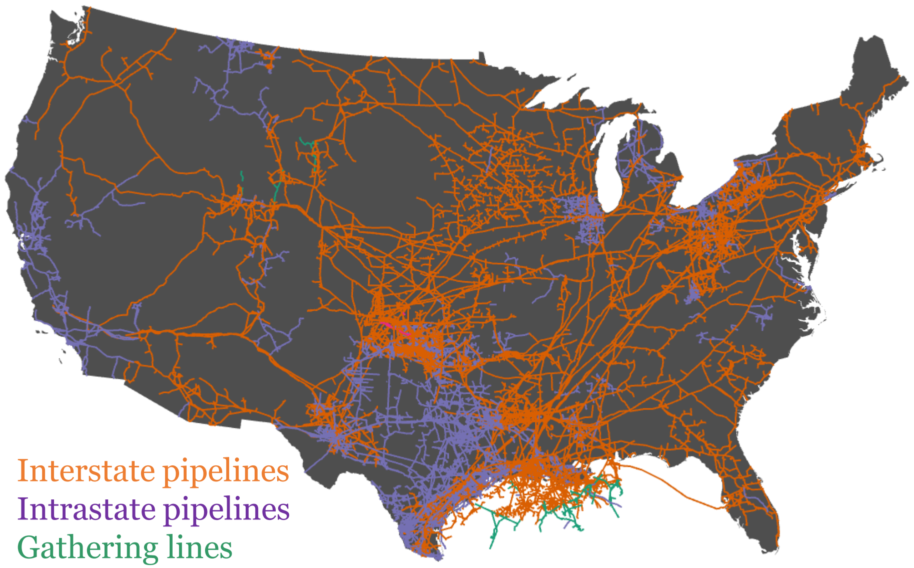
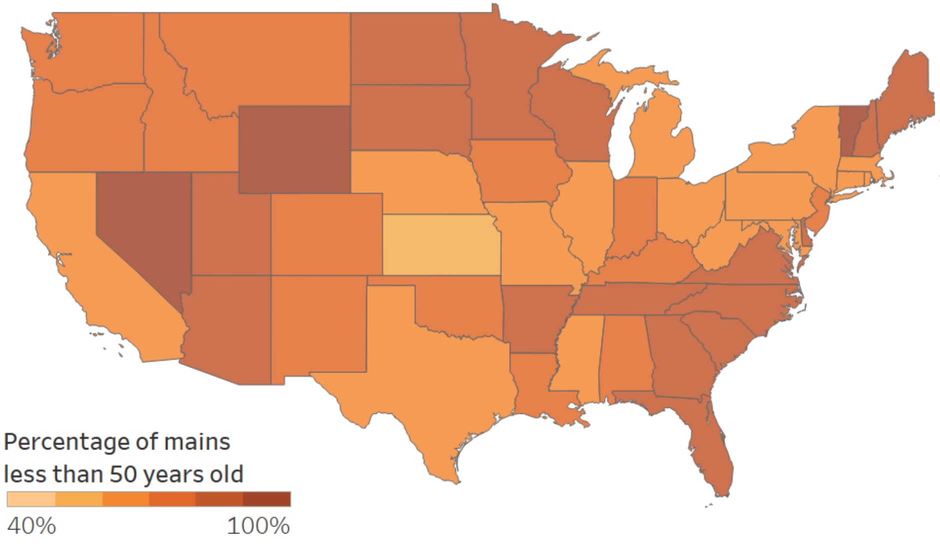
Declines in natural gas consumption will impact gas transmission and distribution infrastructure.



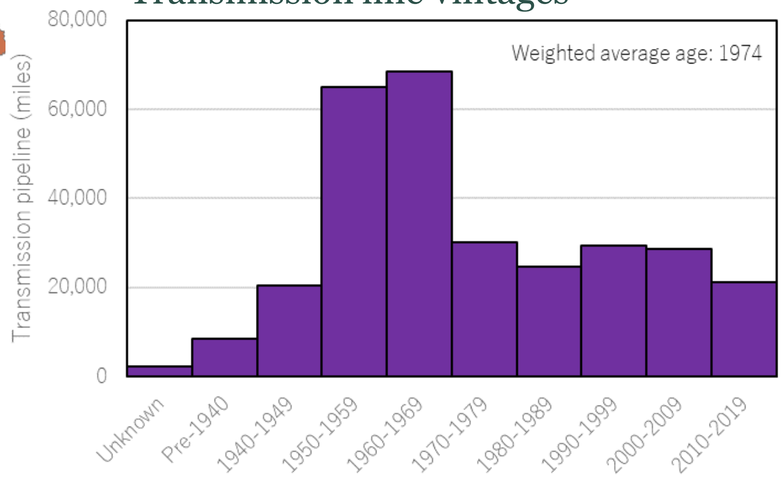


The existing gas pipeline network is vast:

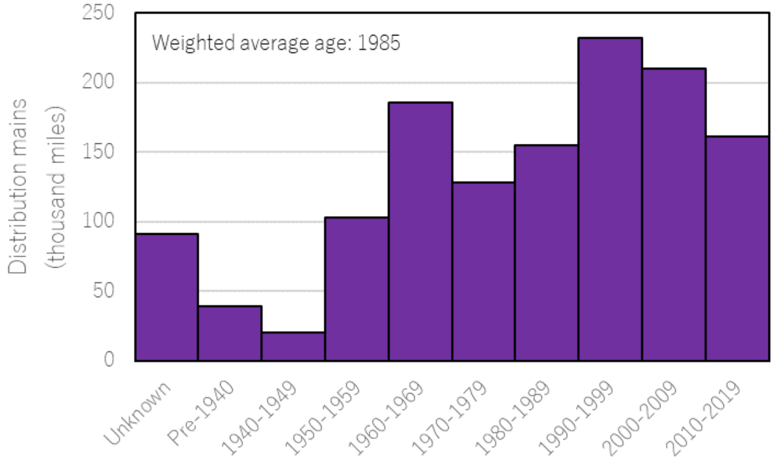
- 20,000 miles of gathering lines (50% >30 years old)
- 300,000 miles of transmission lines (70% >30 years old)
- 1,300,000 miles of distribution mains (50% > 30 years old)
- 70,000,000 service lines

The transmission network is aging, but some distribution system replacements have accompanied the shale gas boom:

Transmission line vintages



Distribution main vintages



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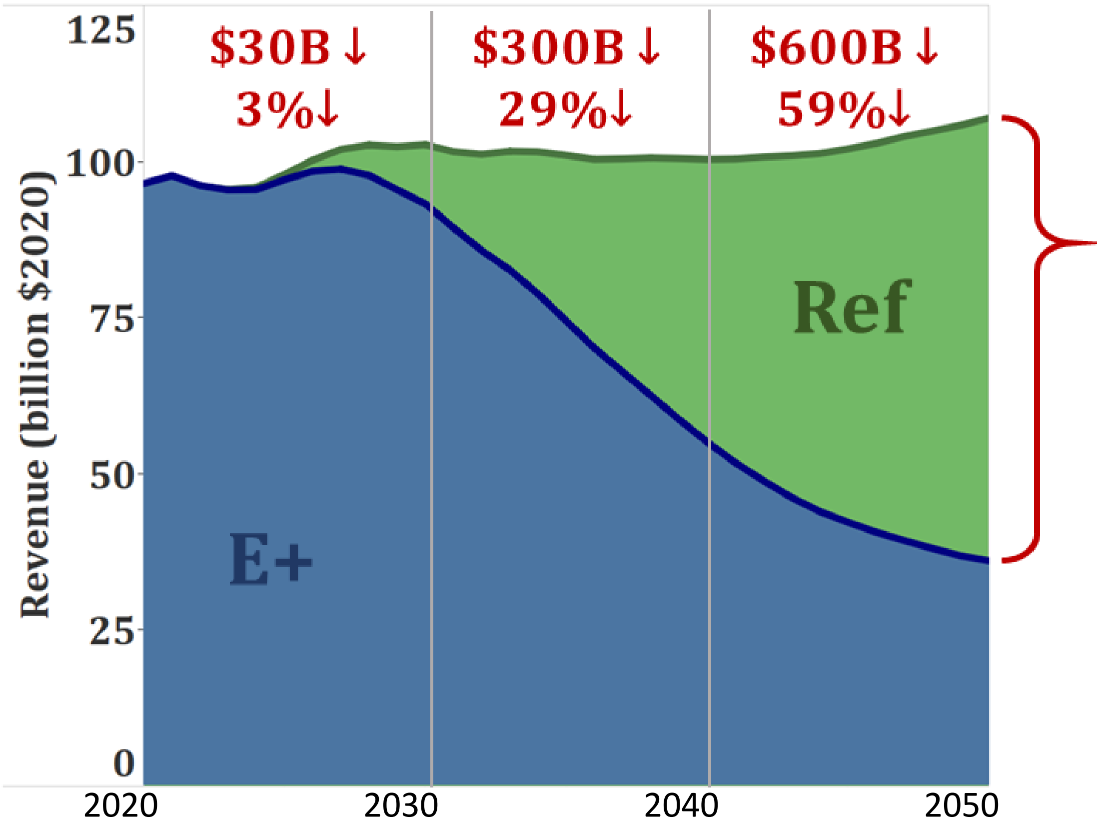
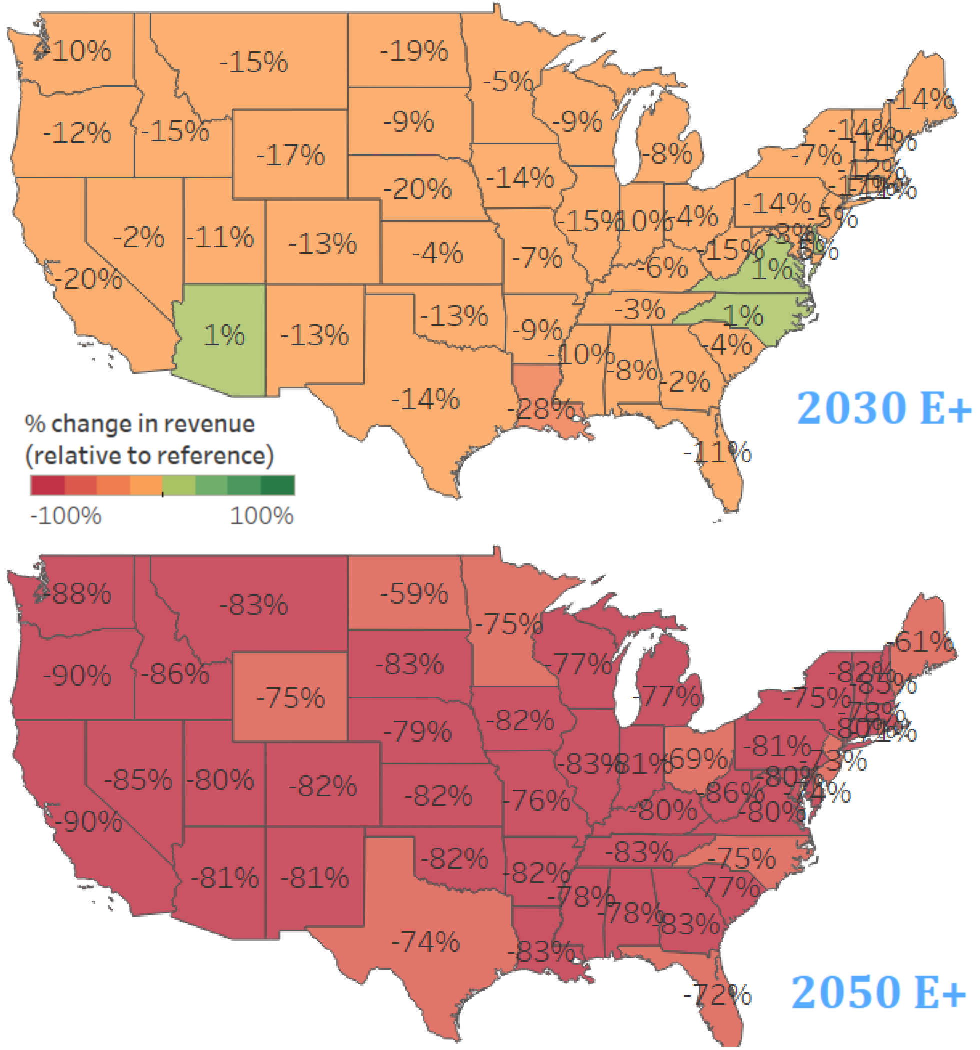
As gas use falls, volumetric revenues will decline, prompting need to review rate design and network asset valuations

Decline in natural gas market revenue (E+ vs. REF) assuming volumetric rates



Reduced spending, assuming gas prices constant across scenarios

*Revenue includes pass-through commodity cost.



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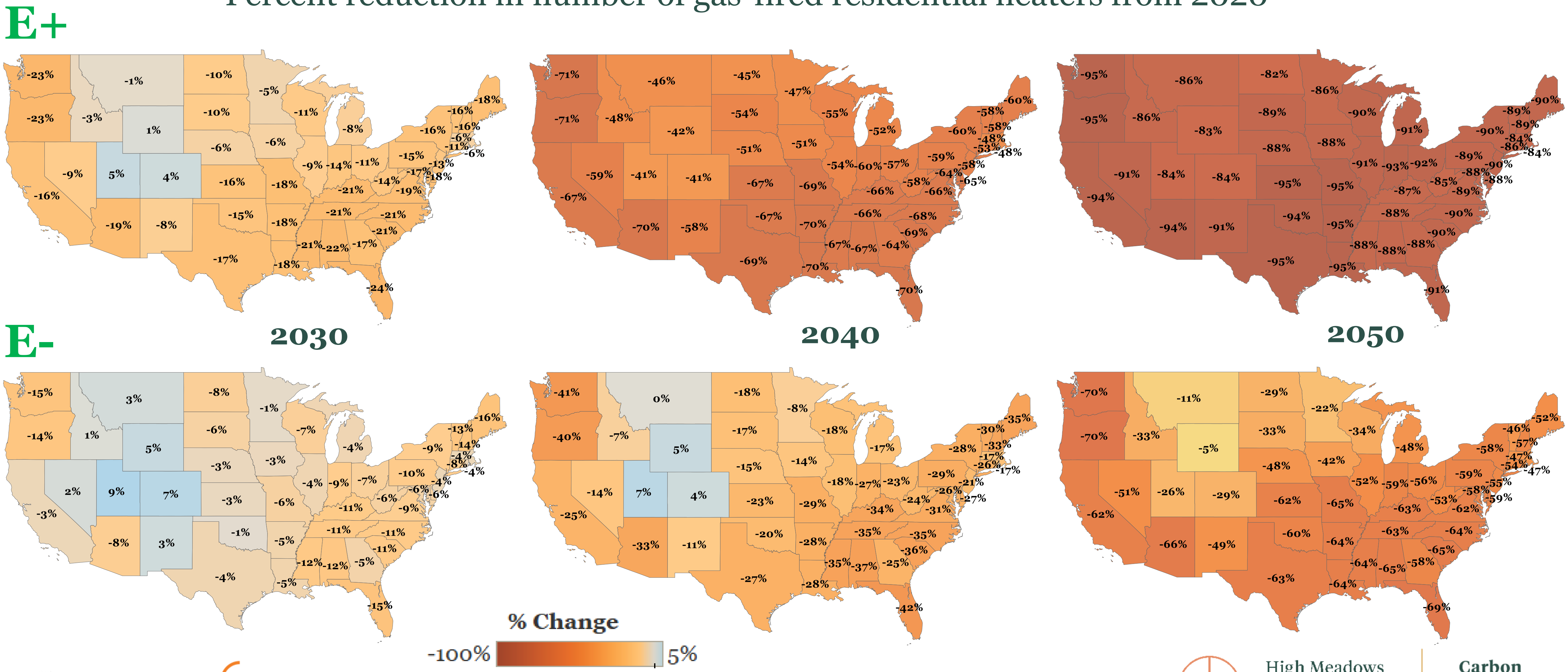
Declining customer base over time will challenge cost recovery and raise equity concerns.

Percent reduction in number of gas-fired residential heaters from 2020



Employment impacts

Summary of this section

- A model was built to assess energy supply-related employment, wages, and workforce development requirements in energy-system transitions. (Energy efficiency, vehicle and appliance related employment is not modeled in this study.)
- To support modeled net-zero transitions, the supply-side energy workforce expands 12-24% in the 2020s across different net-zero scenarios and by 24-152% by 2050. Today ~1.5% of the labor force is directly employed in energy supply-related jobs. By 2050, this grows to 2-4% across different net-zero scenarios.
- Net-zero pathways support ~3 million energy supply-related jobs by 2030, a net increase of 0.3-0.6 million jobs 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.
- All employment modeling assumes current domestic content shares persist for major manufactured components.
- This modeling explicitly considers impacts of labor productivity changes on future employment. Changes in productivity have a large influence on modeled employment outcomes and more broadly on the energy transition as whole.
- 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. Supply-side energy sector employment generates ~2% of total U.S. wages, rising to as much as 4.5% by mid-century.
- A number of modifiable sociotechnical factors influence the spatial distribution of labor. With assumptions used here, 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). In some states with high renewable resource quality (e.g., NE, MT, IA), energy industries grow to become dominant employers.
- There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

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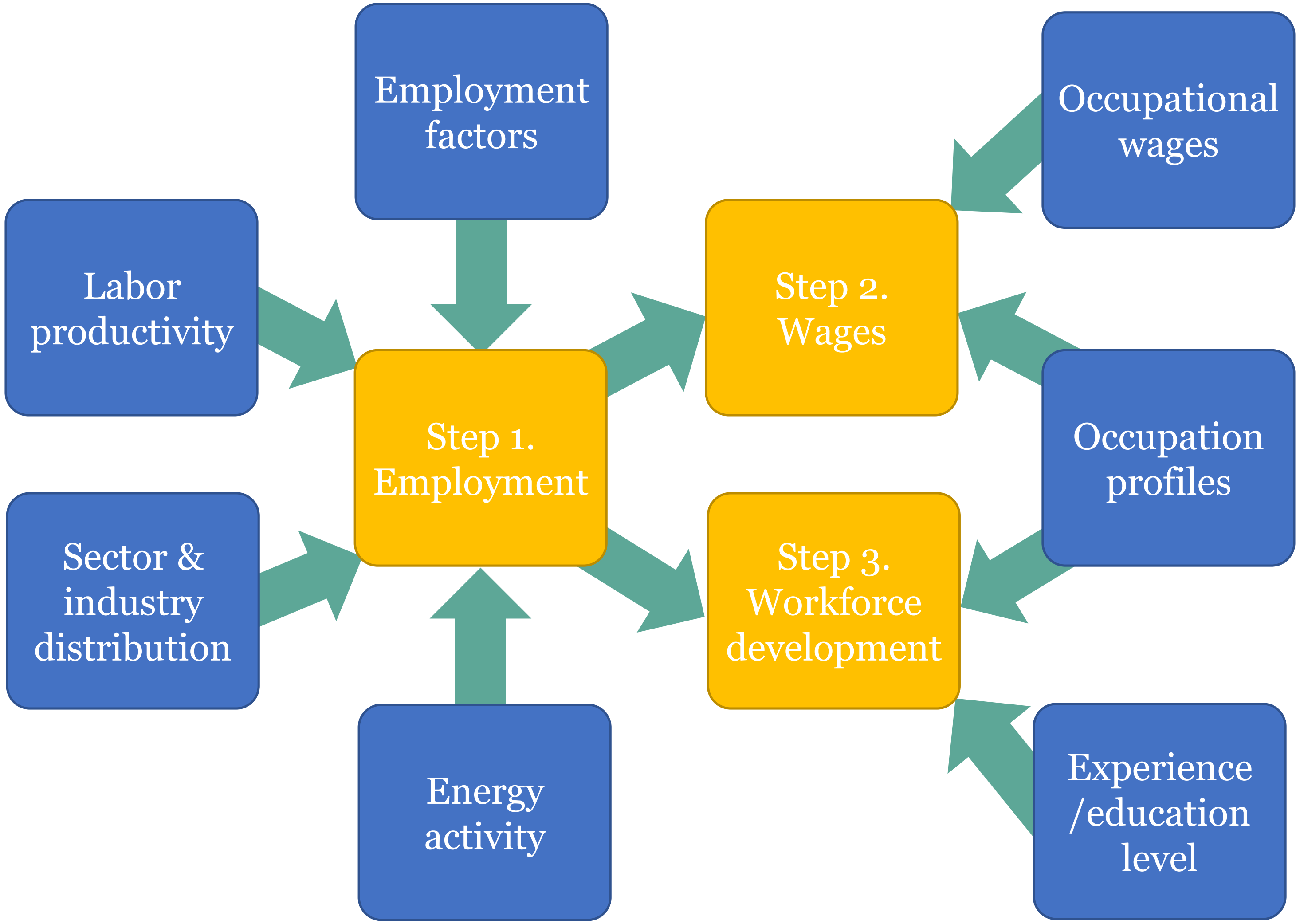
Decarbonization Employment & EneRgy Systems model (DEERS)

Labor model assesses supply-side employment, wages, and workforce development requirements associated with energy-system transitions.

- Pairs with output of economy-wide or spatially downscaled macro-energy system modeling.
- Architecture largely derived based on current data of economic accounts and energy activity.
- Models the distribution of labor impacts across 50 states, 9 economic sectors, 9 resource supply chains, 50 industries, and 1000+ occupations.
- Includes time-variant factors, such as labor productivity and wage inflation, relevant for long-term planning.
- Can be used to evaluate policy and planning decisions, such as just-transition funds, workforce development needs, domestic manufacturing, oil/gas exports, and facility siting.

See Annex R for DEERS model details.



***Note*:** In this analysis, we focus on energy supply-related resource supply chains (i.e., biomass, CO_2, coal, electric power grid, natural gas, nuclear, oil, solar, wind). We do not model employment related to energy efficiency, electric vehicles, or consumer electronics/appliances.

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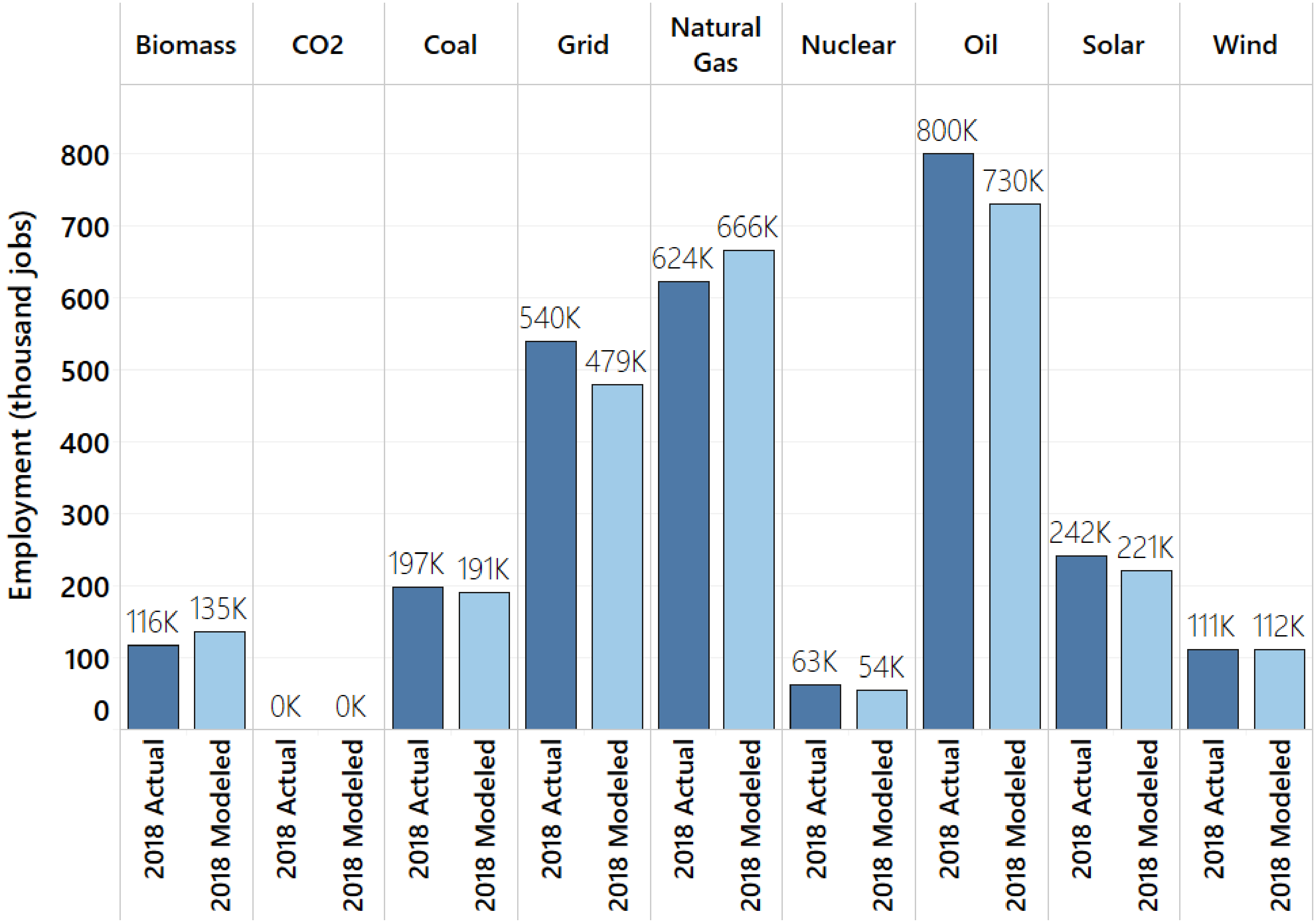
Employment simulated using DEERS (based on actual 2018 activity data) compares well with actual 2018 employment.

Model calibration results



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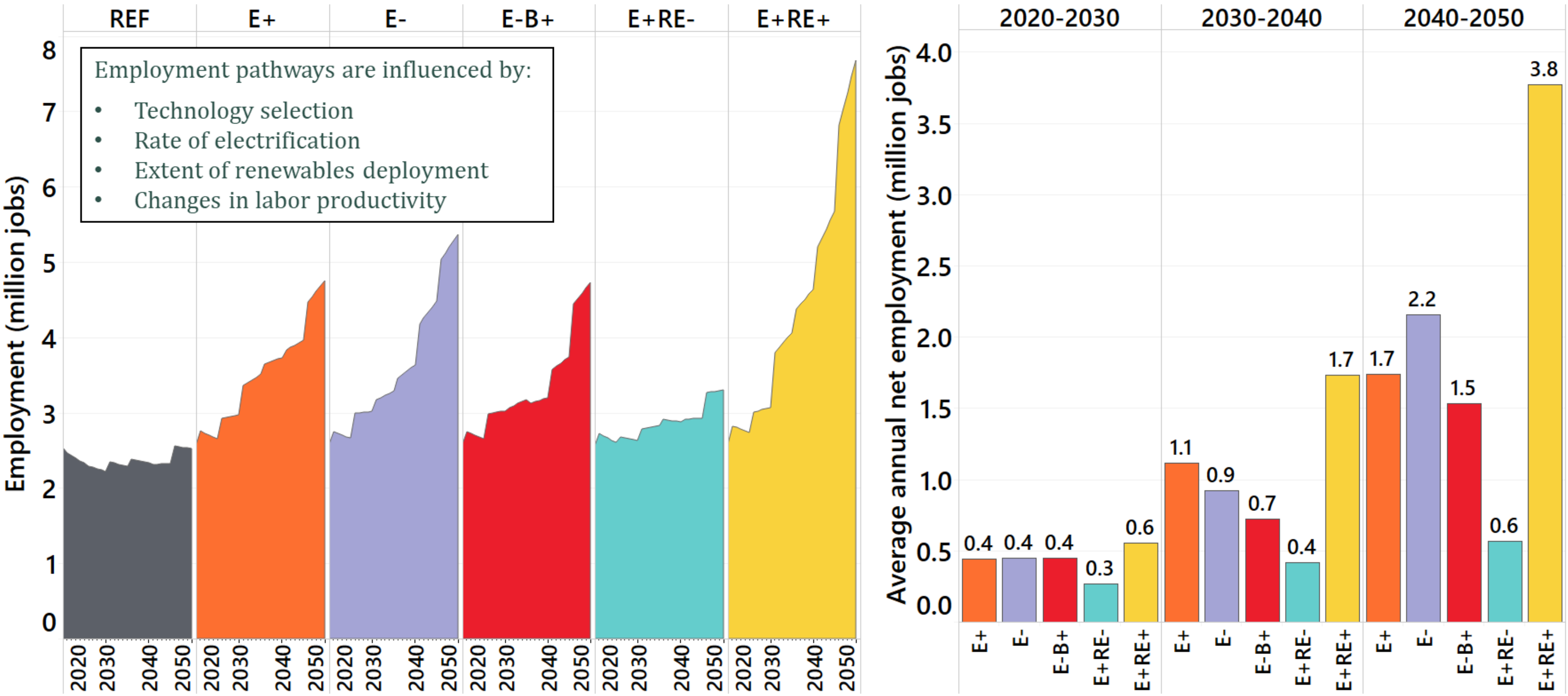
~3 million direct energy supply-related jobs annually in the 2020s in net-zero scenarios, or ~0.5 million more than REF scenario.



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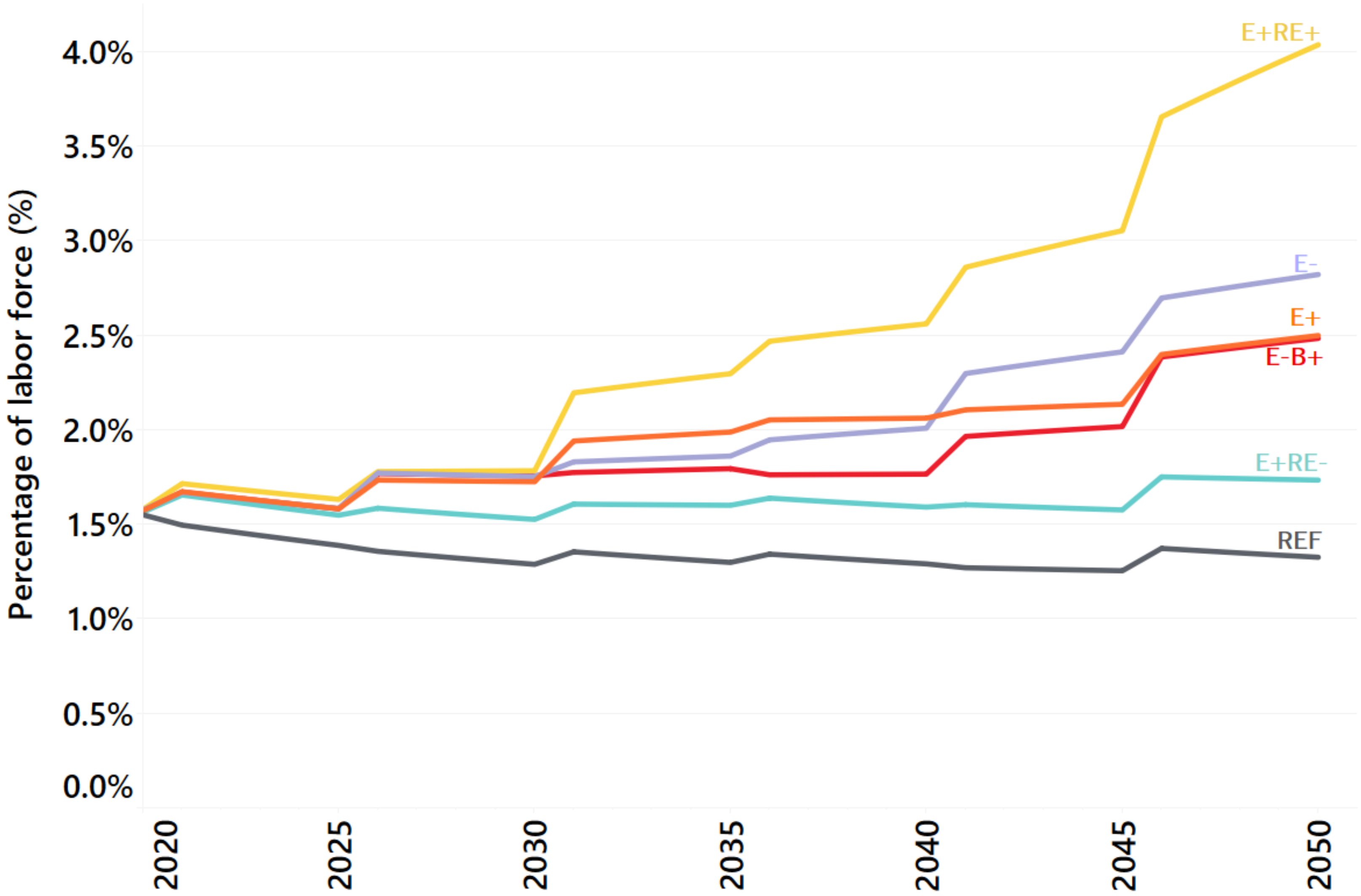
1.5% of the U.S. labor force is directly employed in energy-supply today, increasing to 2-4% by 2050 in net-zero scenarios.



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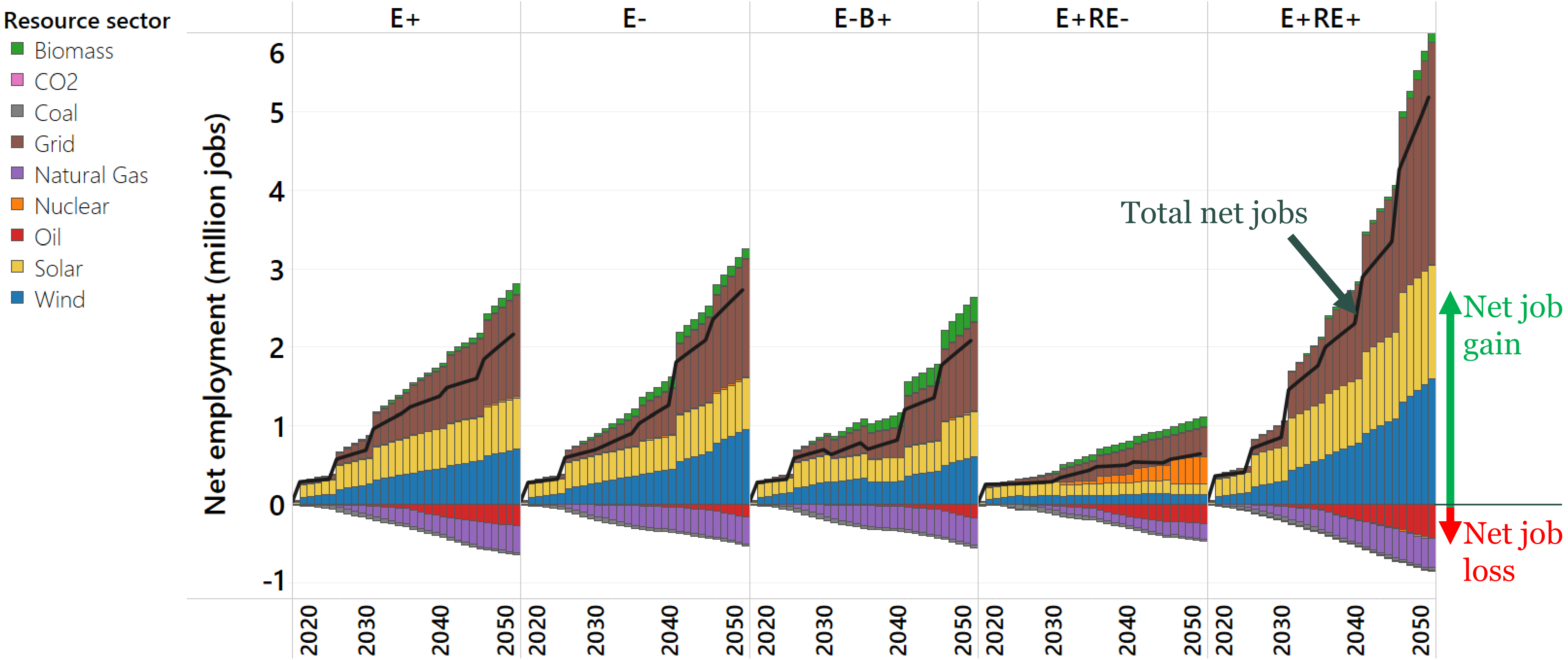
Net job losses in fossil fuel sectors in near- and long-term are more than offset (in aggregate) by increases in low carbon sectors.



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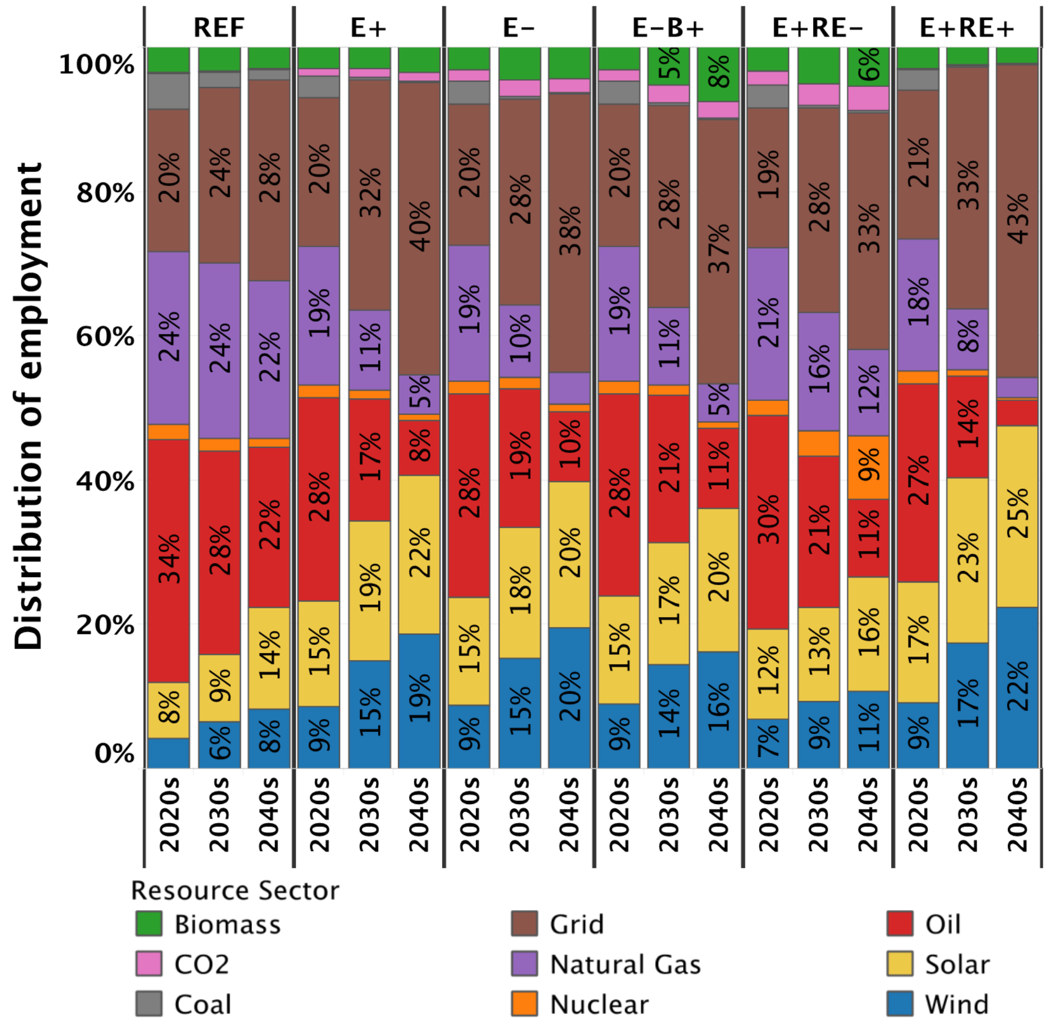
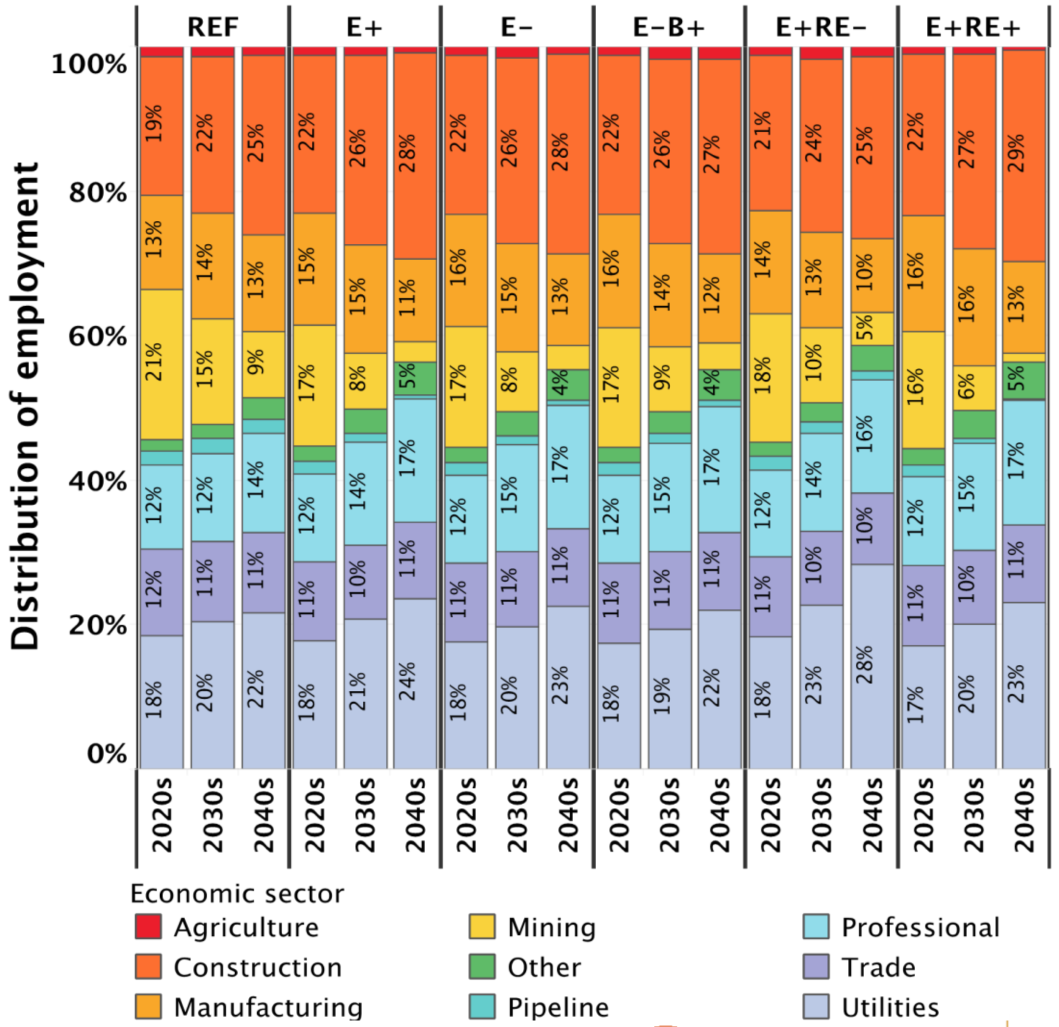
Solar, wind, and grid dominate energy-sector jobs. Construction share increases over time, while mining (upstream fossil) declines.

Distribution of jobs by resource sector



Distribution of jobs by economic sector



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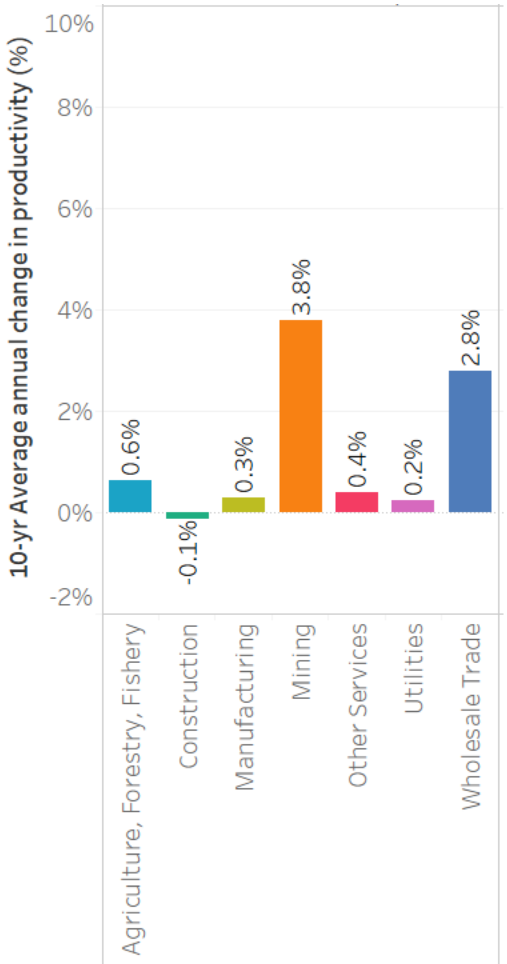
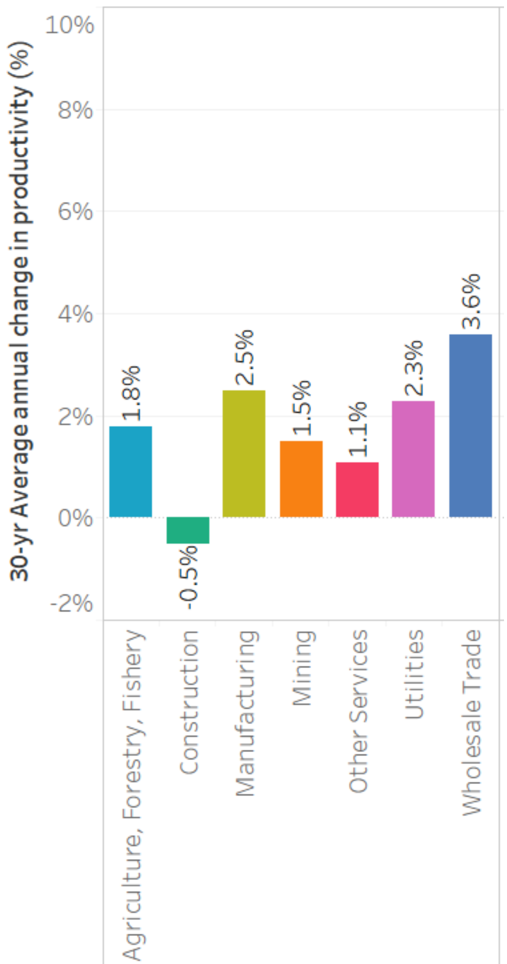
Changes in labor productivity have a large influence on employment outcomes and more broadly the energy transition as whole.

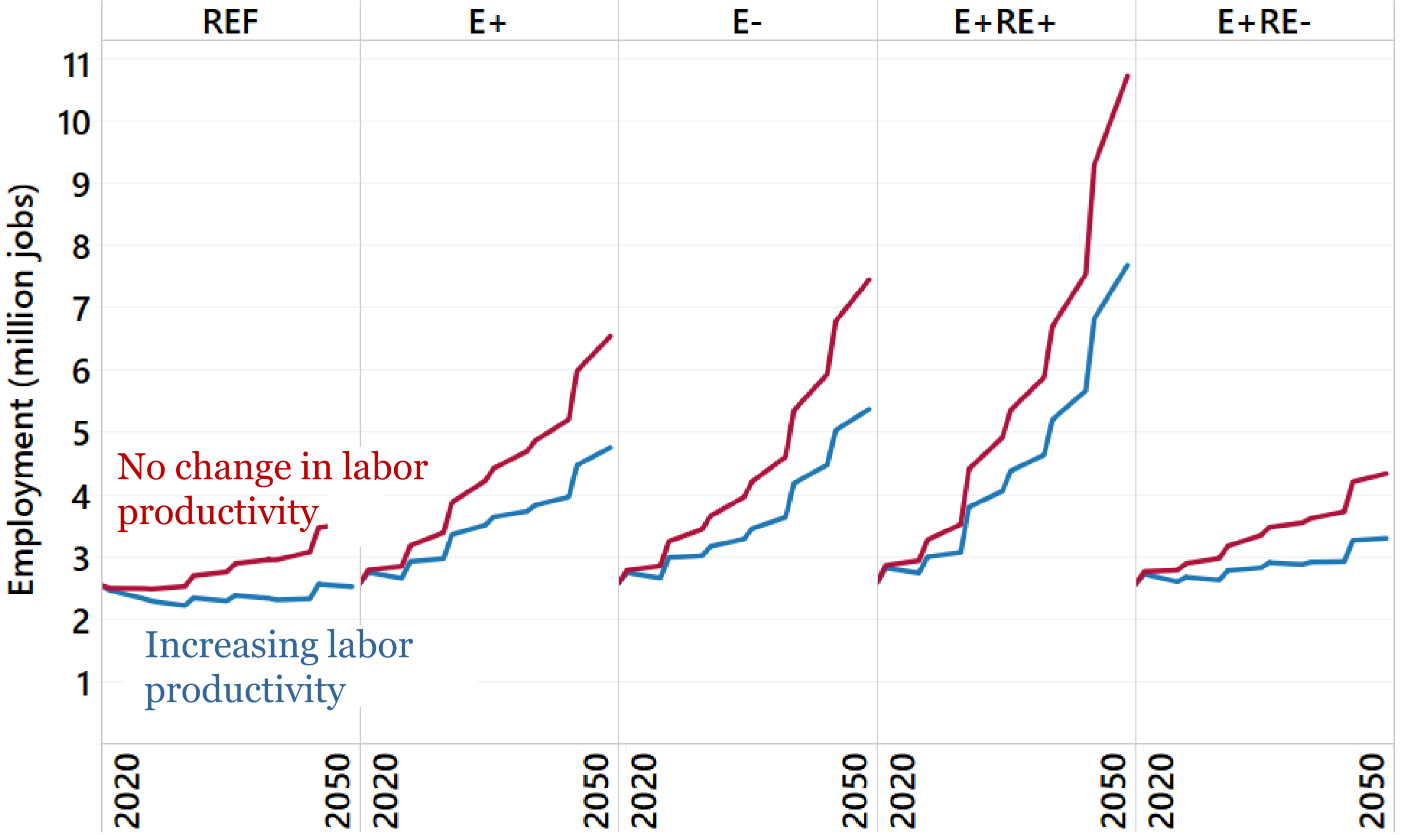
Historical changes in labor productivity

Short-term



Long-term

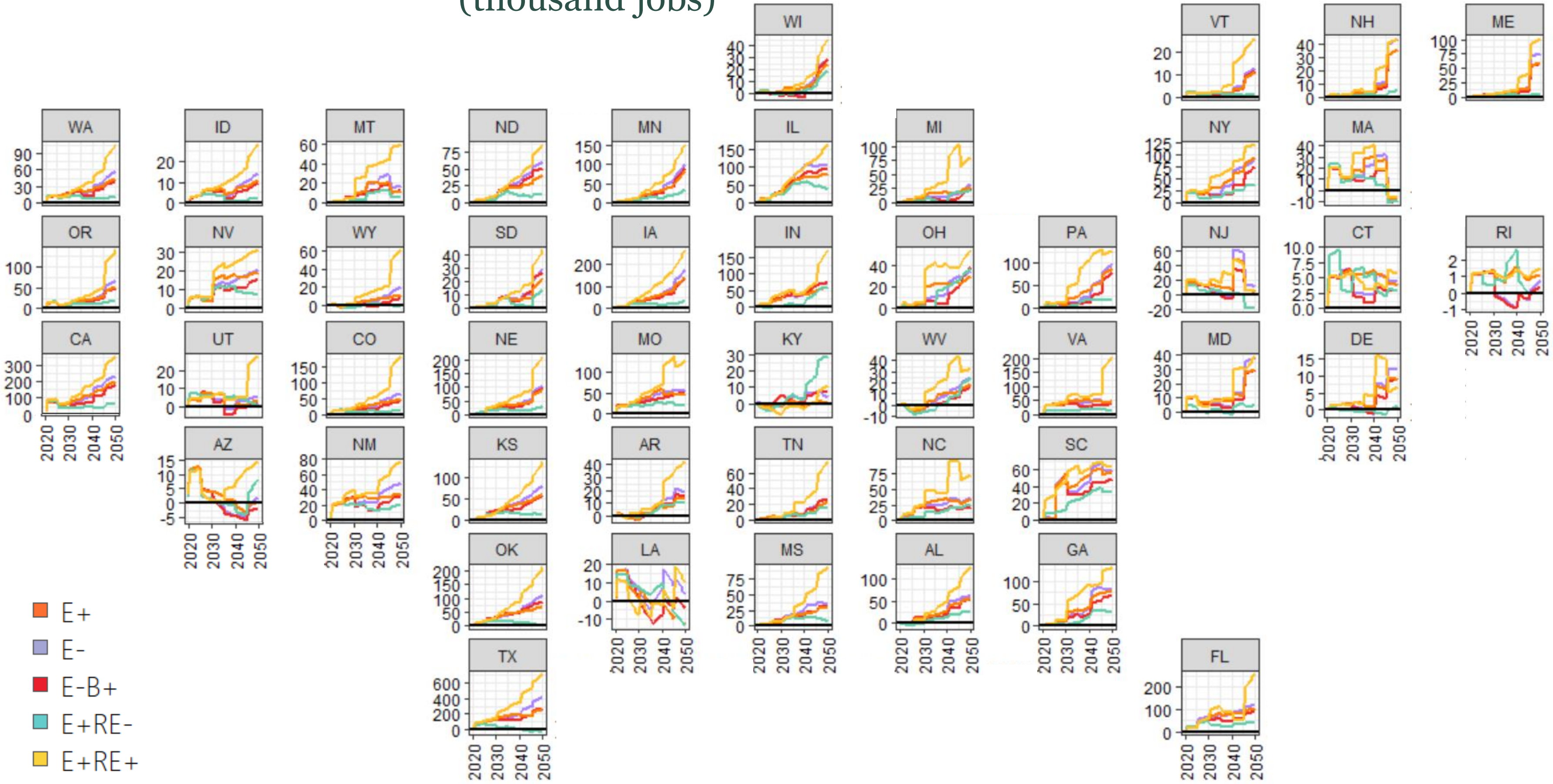




Note: Other employment modeling results shown in this report correspond to the results with increasing labor productivity shown on this slide.

Modifiable socio-technical factors influence spatial distribution of employment. Below is one instantiation of the future (out of many).

Net annual employment by state (relative to REF scenario)
(thousand jobs)

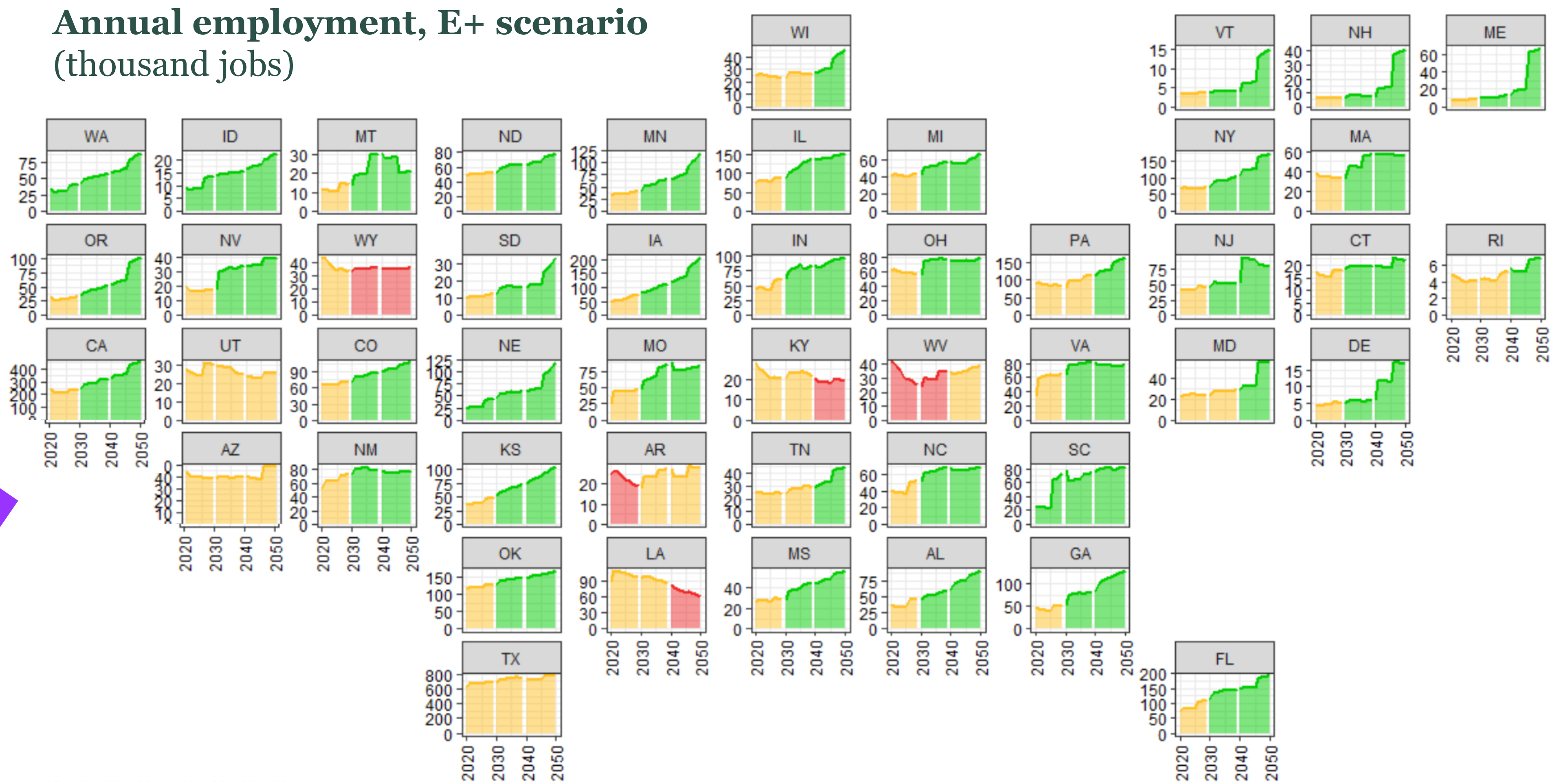


Modifiable sociotechnical factors that influence the spatial distribution of employment:

- Resource quality and availability
- Rate of electrification
- Technology selection
- Domestic manufacturing
- Siting constraints
- Oil and gas exports
- Political and policy processes and constraints

There are several degrees of freedom that can reduce transition risks and be leveraged for political bargaining.

Transitioning to a net-zero energy system has the potential to transform state and local economies.



Color indicates change in average decadal employment:

> 15% above 2021

within ± 15% of 2021

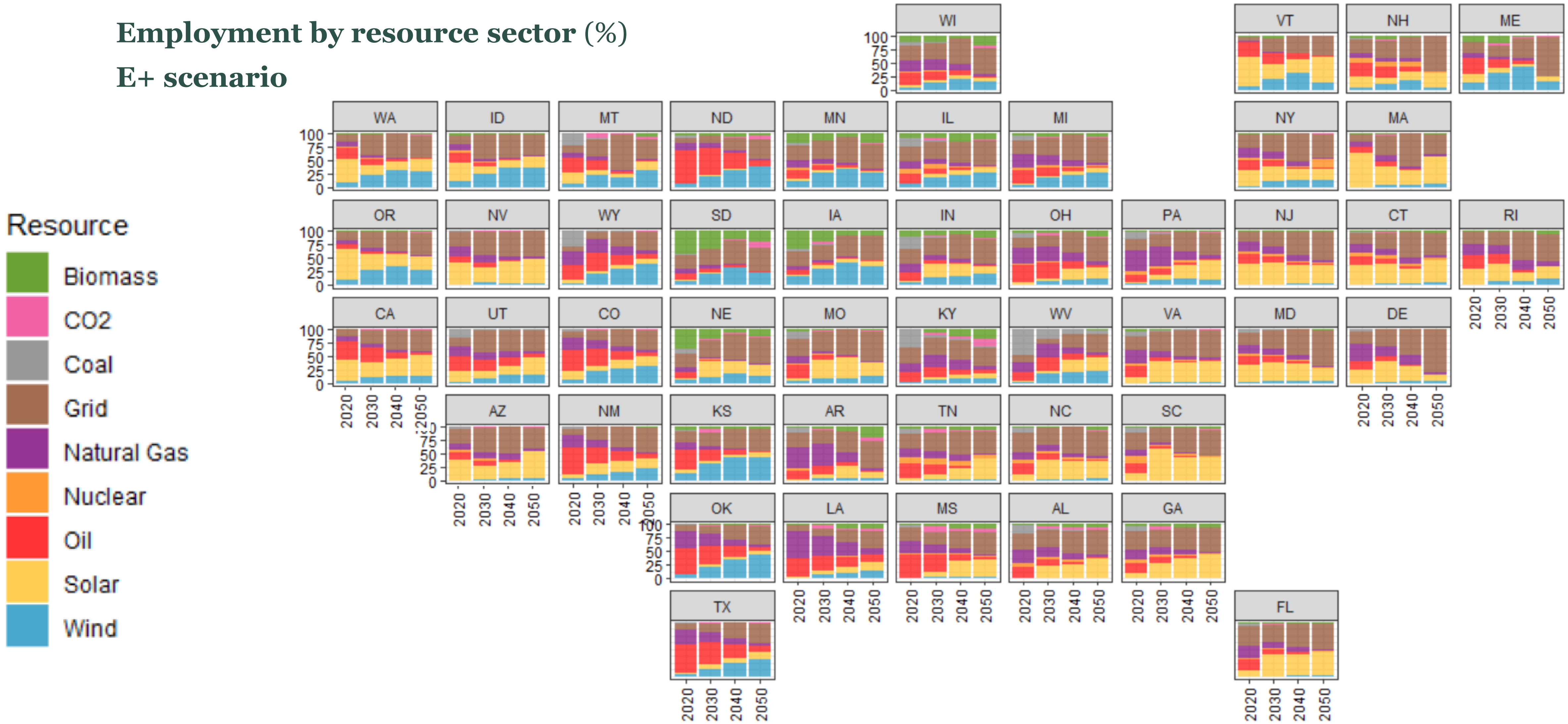
> 15% below 2021

Note: Spatial redistribution of solar and wind manufacturing facilities and increasing the domestic manufacturing share offer opportunities to ameliorate losses in fossil fuel extraction states. For assumptions used here in siting solar and wind manufacturing jobs, see this slide.

State-level distributions of employment by resource sector change dramatically over the transition.

Employment by resource sector (%)

E+ scenario



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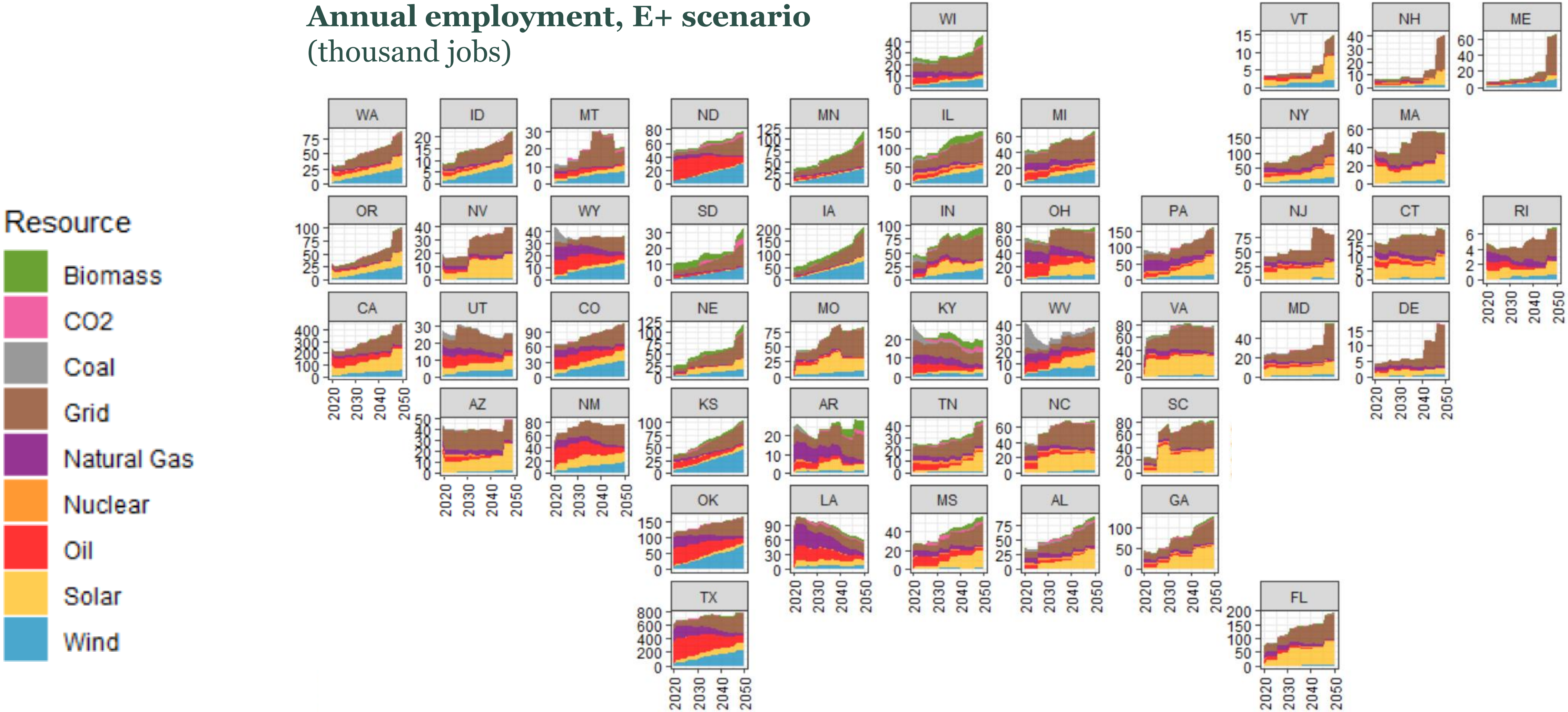
Solar, wind, and grid jobs are increasingly dominant in many states, but regional heterogeneity could be a risk to a just transition

Annual employment, E+ scenario
(thousand jobs)



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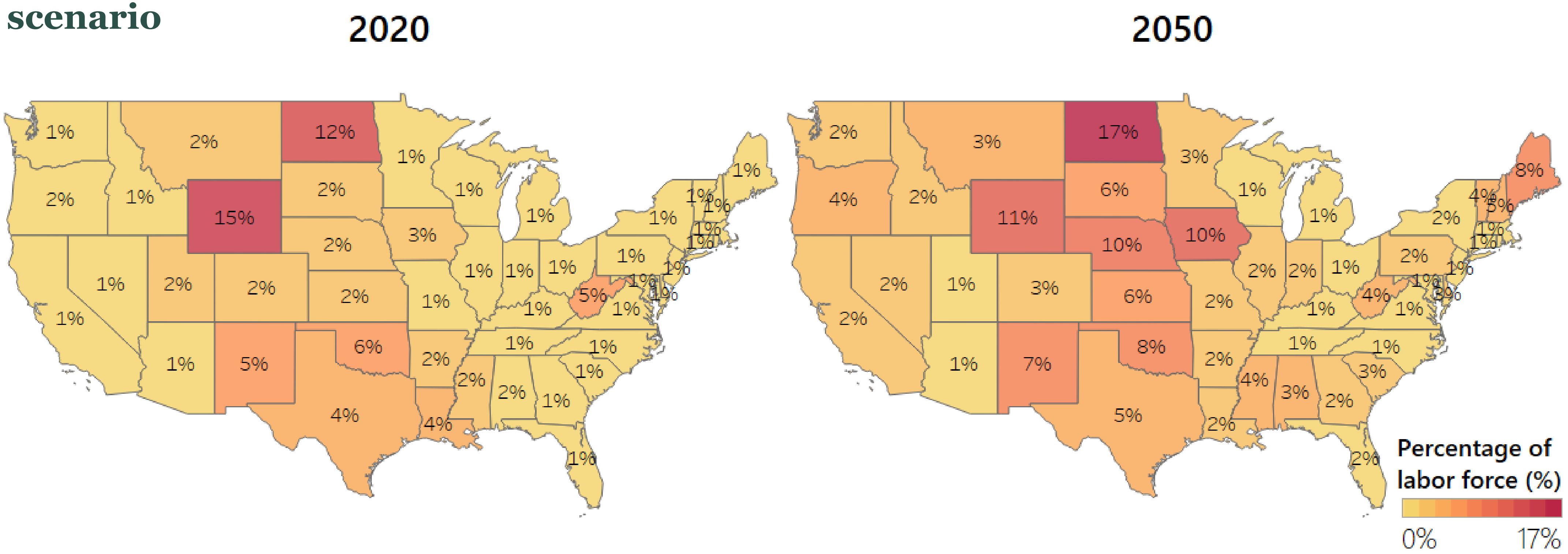
In most states, energy-related employment grows as a share of total employment through the transition to 2050.

E+ scenario



- In a few states with a very high share of the current labor force employed in upstream fossil fuel industries (e.g., WY), energy-related employment decreases as a share of the total employment through the transition.
- In states with high renewable resource quality (e.g., NE, MT, and IA), energy industries grow to become major employers.

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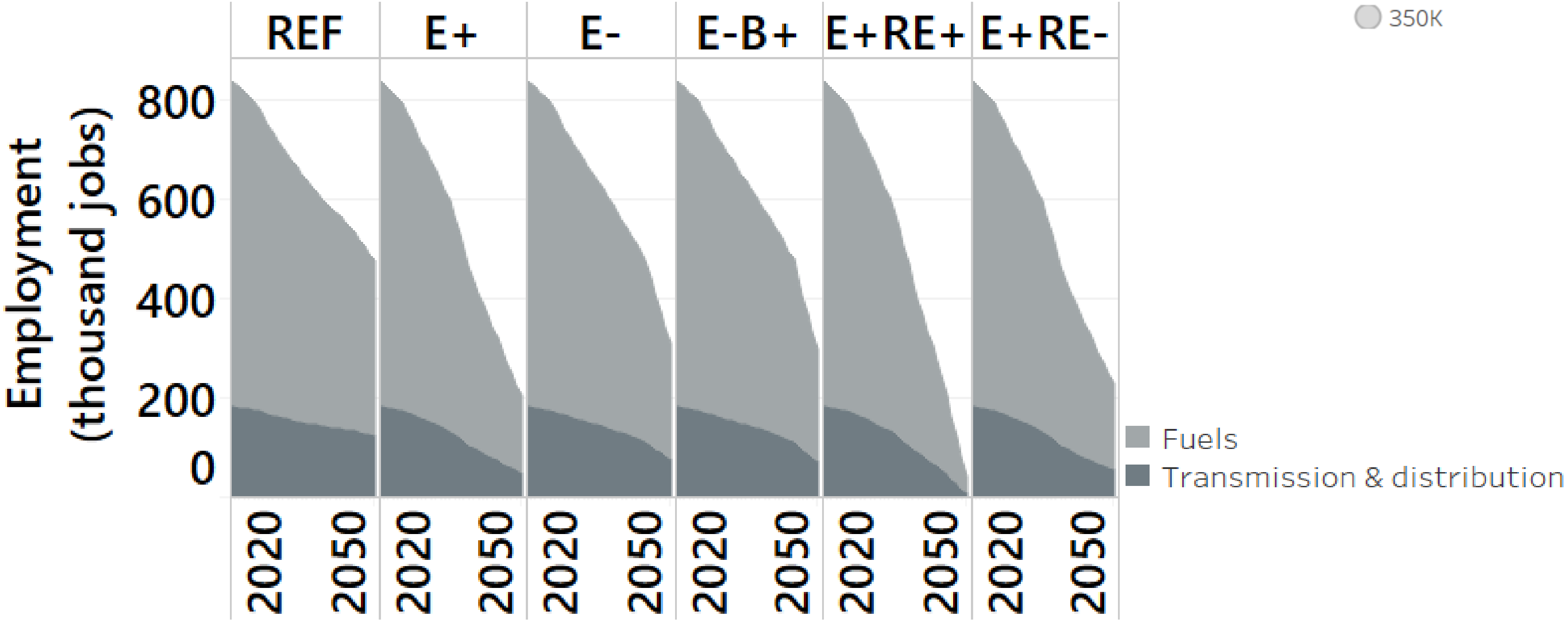
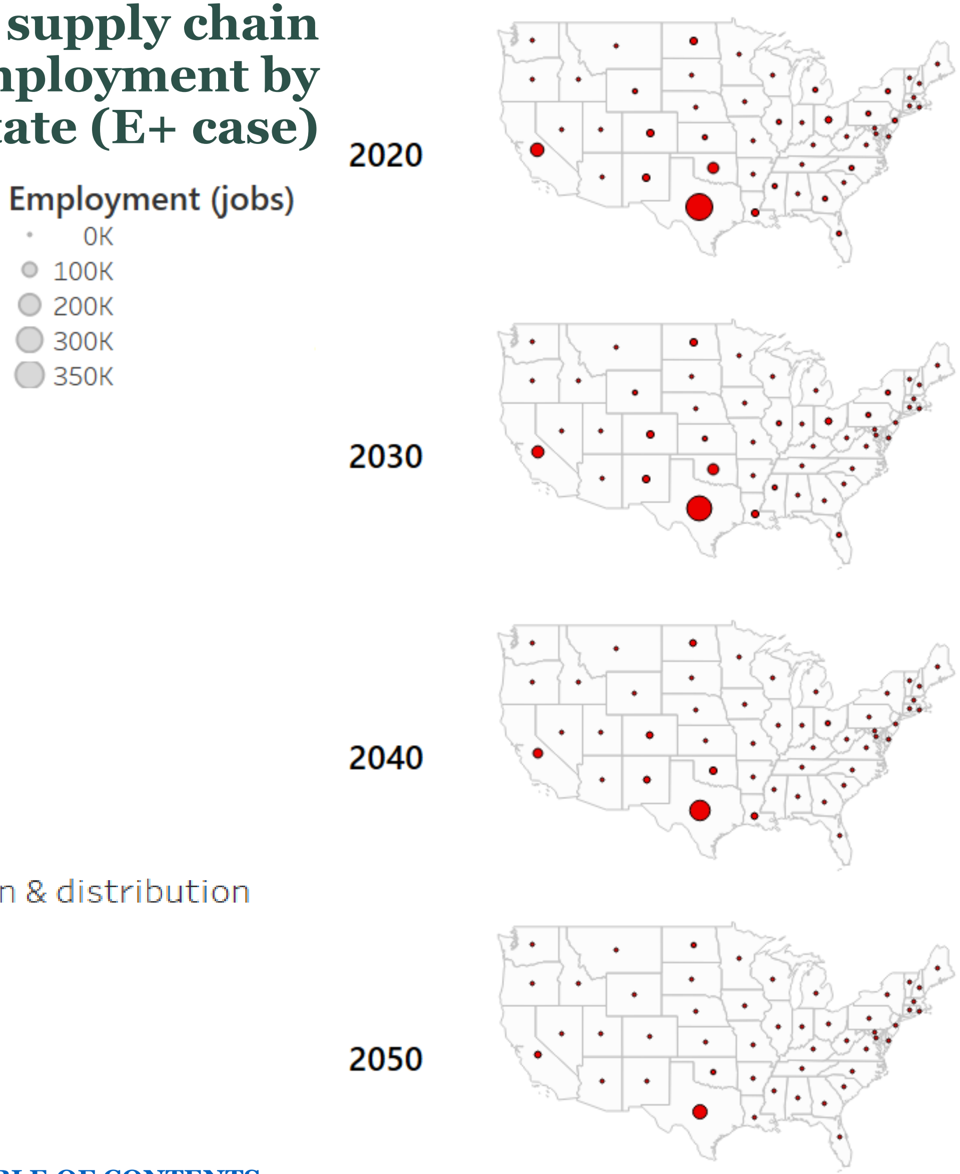
Oil is the largest resource sector today, with ~⅓ of supply-side energy jobs: ~800,000 oil-sector jobs today (model estimate)

Oil employment declines in both REF and net-zero scenarios, influenced by the rate of electrification, extent of renewables deployment, and oil imports and exports. By 2050, employment in the REF scenario is approaching half that today, and in the net-zero scenarios it declines by 60-95%.



Note: all fossil energy sectors are assumed to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.

Oil supply chain employment by state (E+ case)



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The natural gas sector is the 2nd largest energy-employer, but upstream jobs have been rapidly declining for several years.

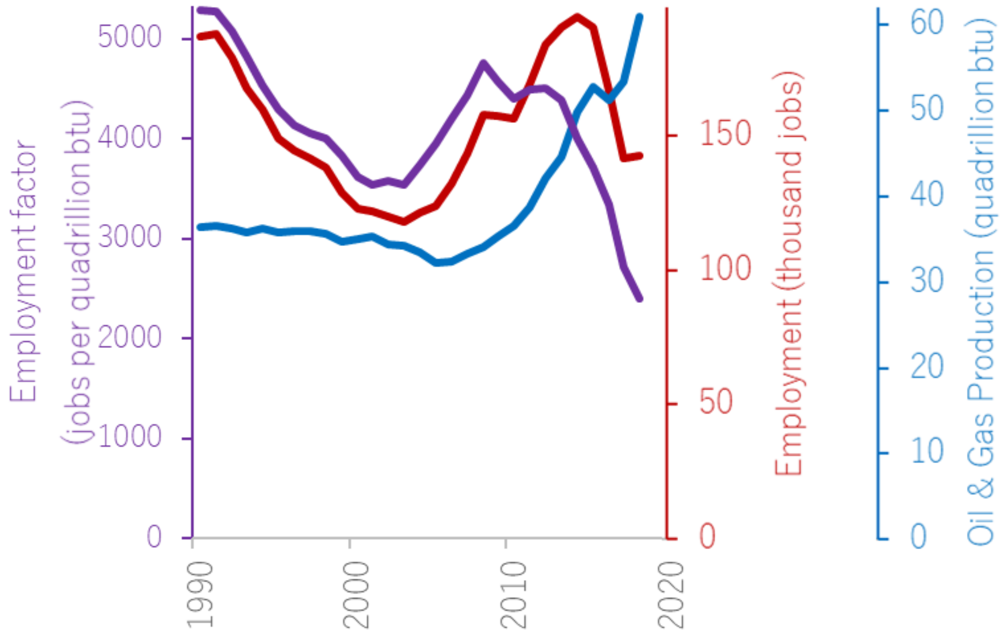
Natural gas sector supports 600,000 jobs associated with production (60%), transmission & distribution (30%), and power generation (10%) in model year 2021.

Source: NPR

Source: theint.net

Natural gas extraction industry currently is a major employer in several counties, although part of the workforce is transient. During the peak of the shale gas boom, the natural gas industry comprised upwards of 60% of combined direct, indirect, and induced employment in one West Virginia county.

Employment in oil & gas extraction industry has been rapidly declining for years, and has accelerated during the COVID-19 pandemic.



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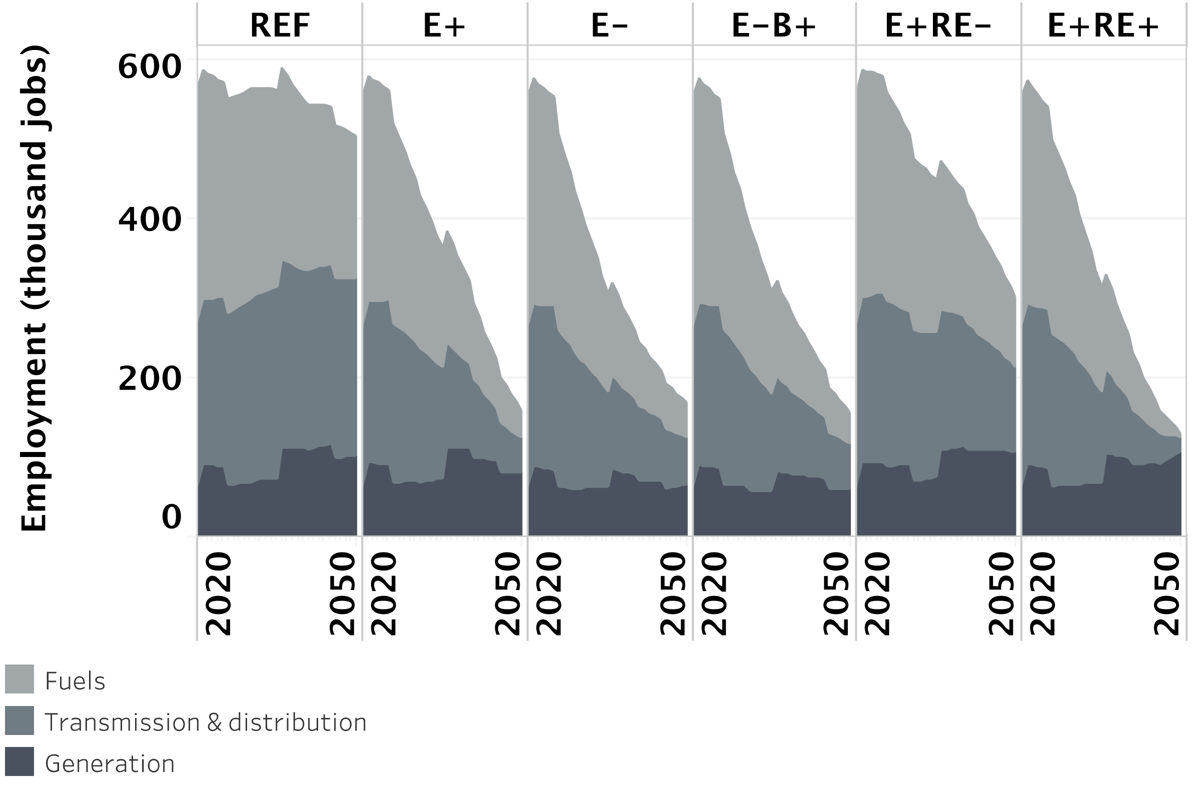
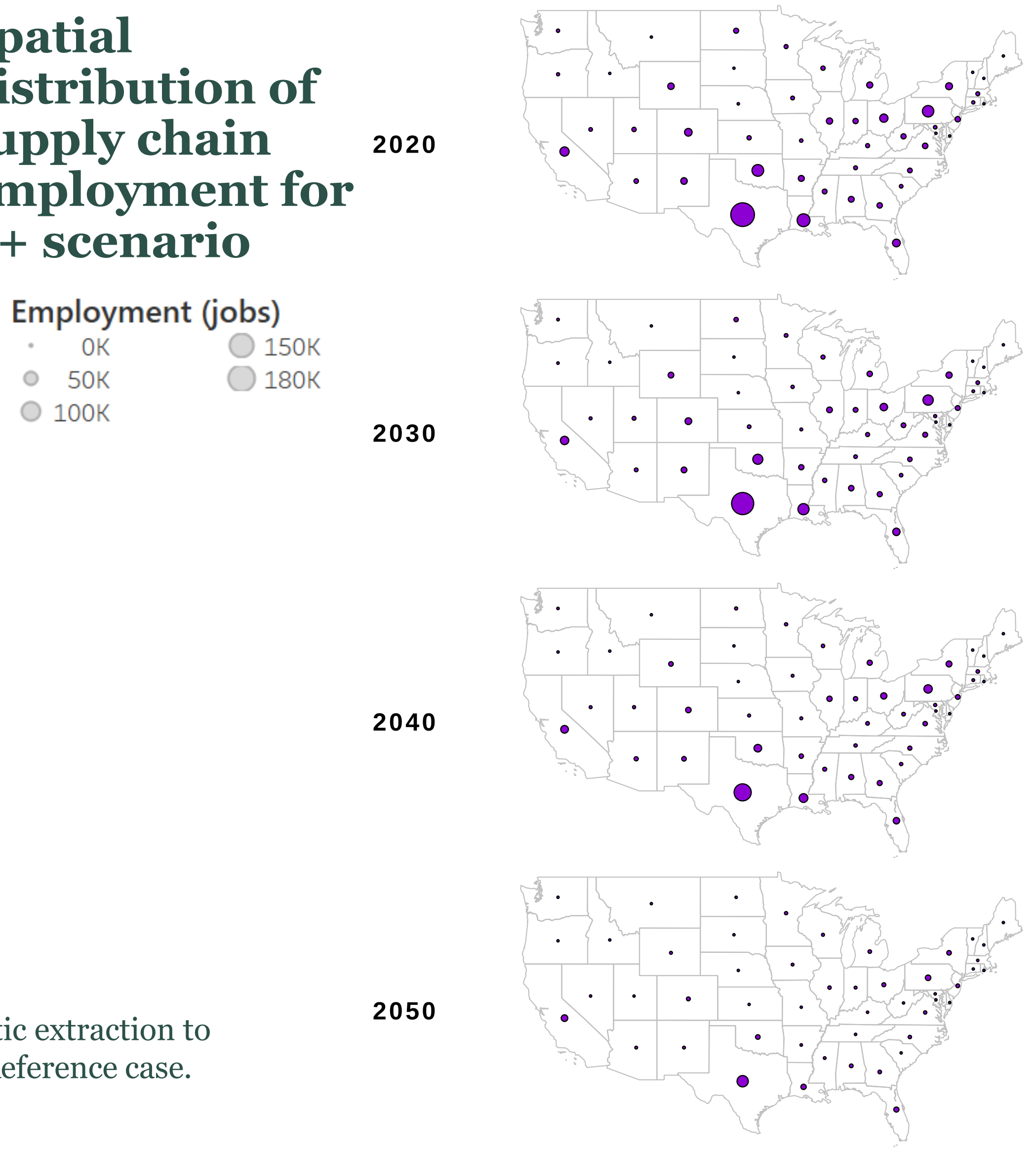
Jobs in natural gas value chain decline to 2050, except for gas power generation. The Appalachian and Permian basins are most affected.

Natural gas employment decline is influenced by the rate of electrification, extent of renewables deployment, and natural gas exports.



Spatial distribution of supply chain employment for E+ scenario



Note: all fossil energy sectors are assumed to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.

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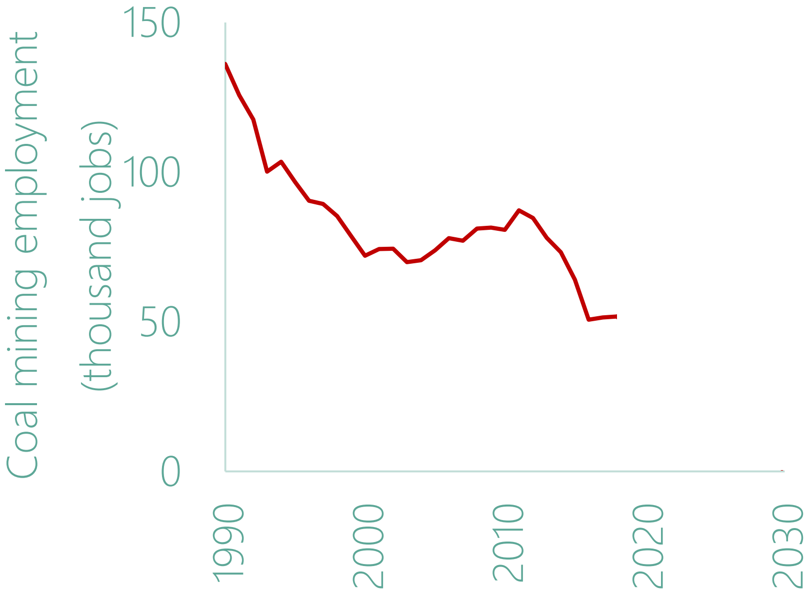
Coal mining jobs have been declining for 3 decades. Phasing out coal has greatest impact on resource-dependent rural labor markets.

At the national-scale, the coal sector is relatively small, representing 5% of the energy workforce in 2021. For model year 2021, there are 150,000 jobs associated with production (40%), transport (20%), and power generation (40%).

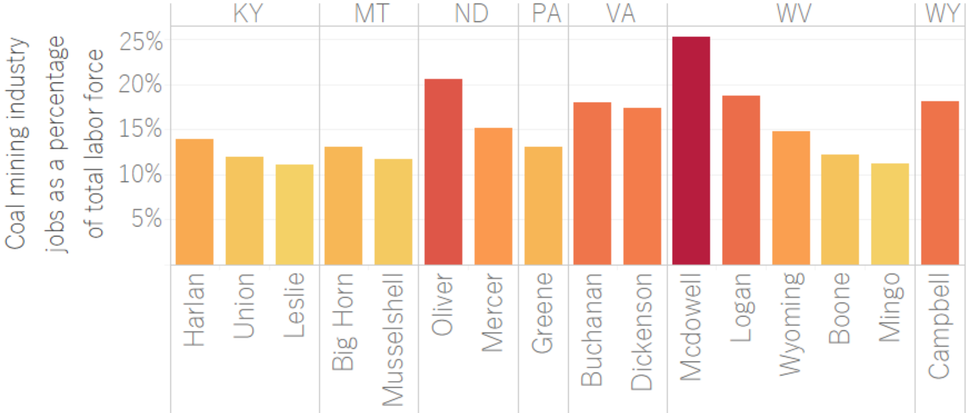

Source: Johnson Group


Source: power-technology.com

Over past three decades, employment in coal mining industry has declined dramatically (62%). Average decline rate of 3%/yr (3,000 jobs/yr) and peak decline rate in 2016 of 21%/yr (13,000 jobs/yr).



Coal mining industry currently is a major employer in several counties. The coal sector represents 5% or greater of labor force in 35 counties. This includes only jobs within the mining industry, not indirect and induced employment.



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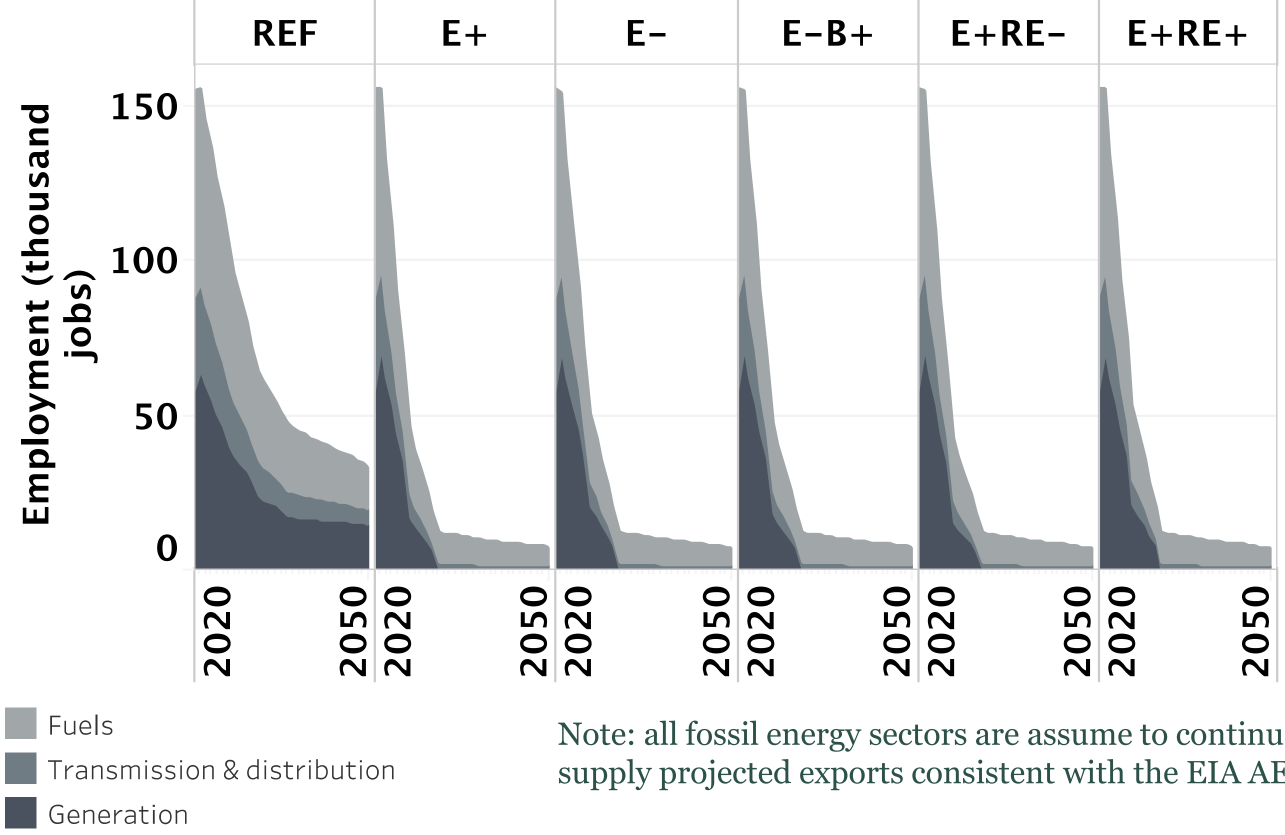
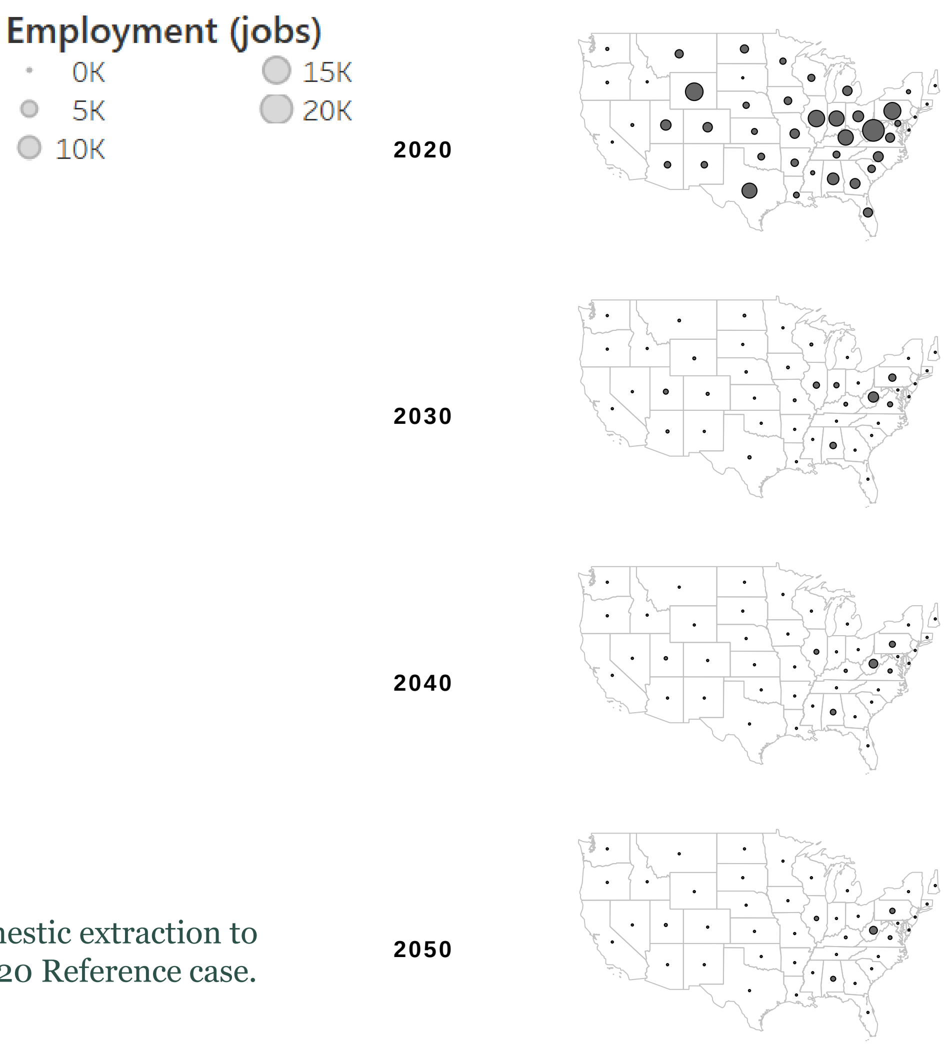
Coal jobs continue to decline at recent historical rate. Impacts are concentrated in the Appalachian & Powder River basins.

Eliminating coal for power by 2030 implies an annual decline rate of 14,000 jobs/yr, compared to a decline rate of 8,000 jobs/yr in the reference scenario over the first decade

(6,000 jobs/yr mining/upstream, 2,000 jobs/yr transportation, 7,000 jobs/yr power generation)



Job losses concentrated in mining regions.



Note: all fossil energy sectors are assume to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.

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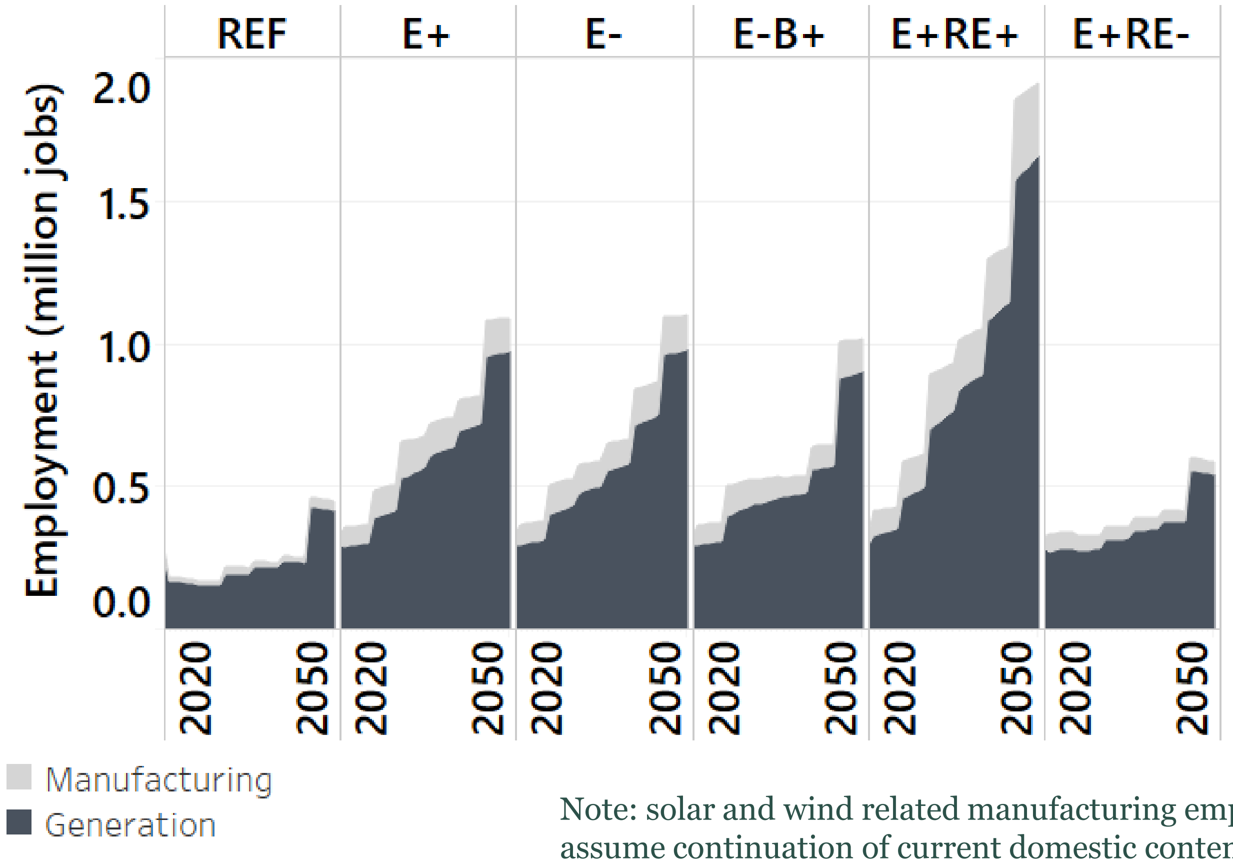
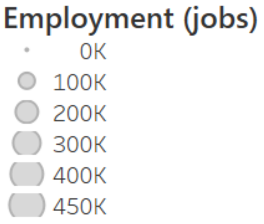
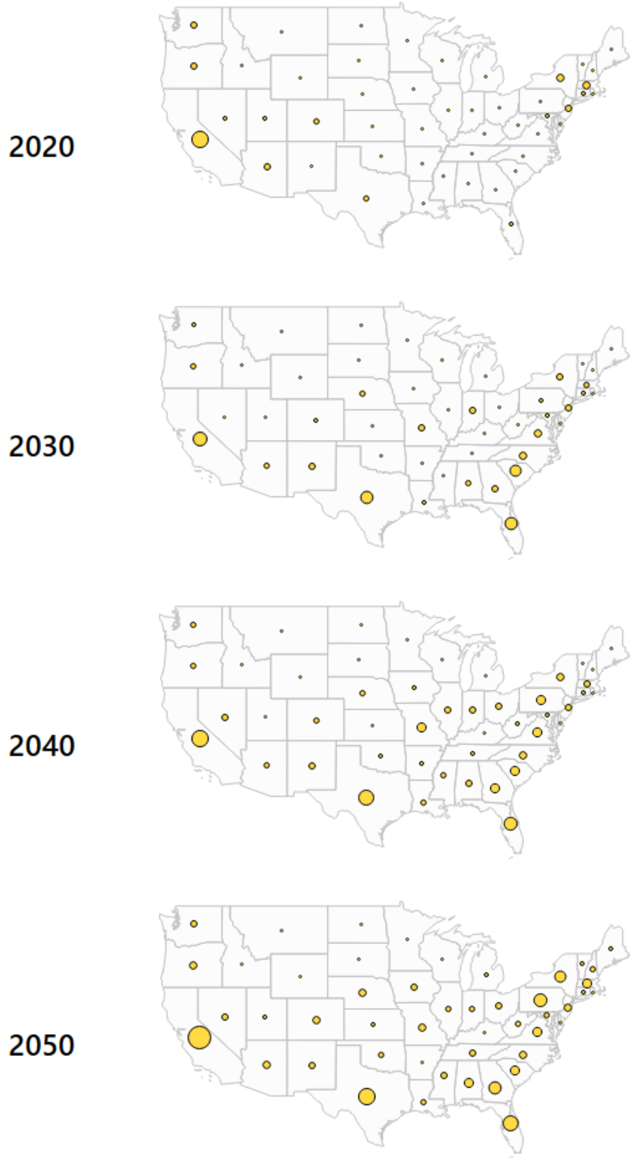
~300,000 solar jobs in model year 2021. In 2030, solar is 2nd or 3rd largest employer, with 80% in generation & 20% in manufacturing.

By 2050, employment in solar comprises a quarter of energy-related jobs in net-zero scenarios. Even in the reference scenario, solar emerges to be equivalent in size to the oil sector.



Spatial distribution of employment is influenced by resource quality, siting constraints and decisions, and extent and location of domestic manufacturing.





Note: solar and wind related manufacturing employment estimates assume continuation of current domestic content shares.

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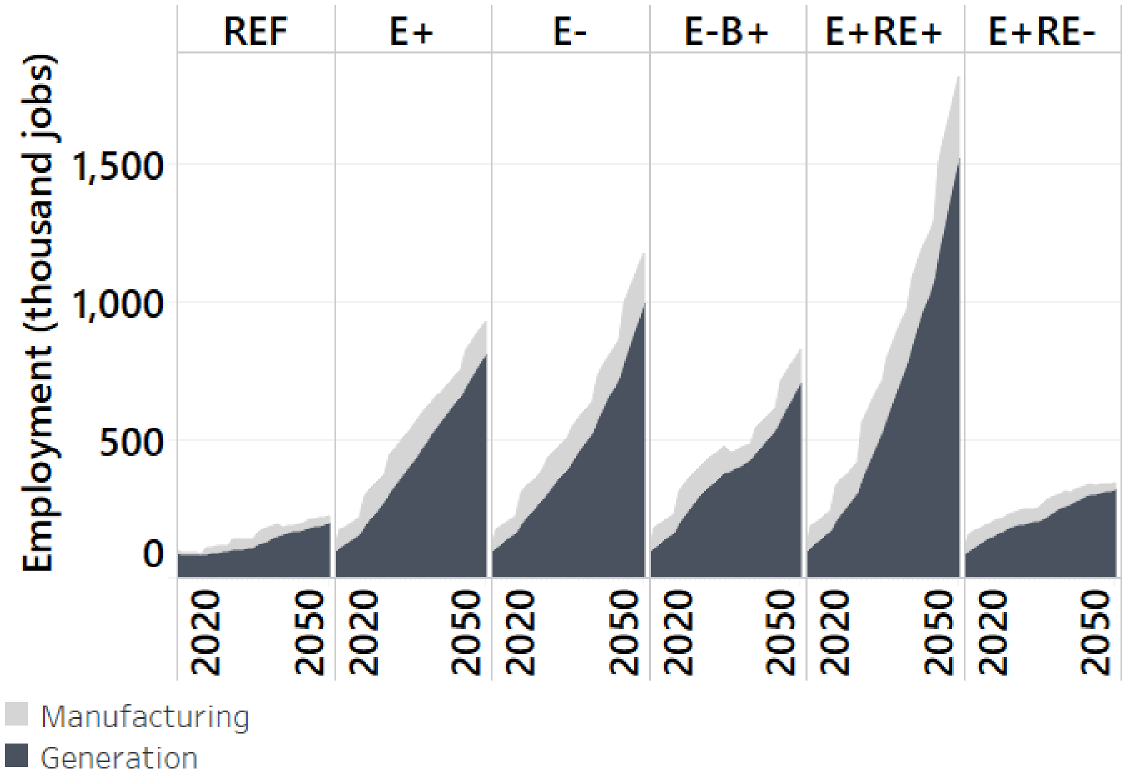
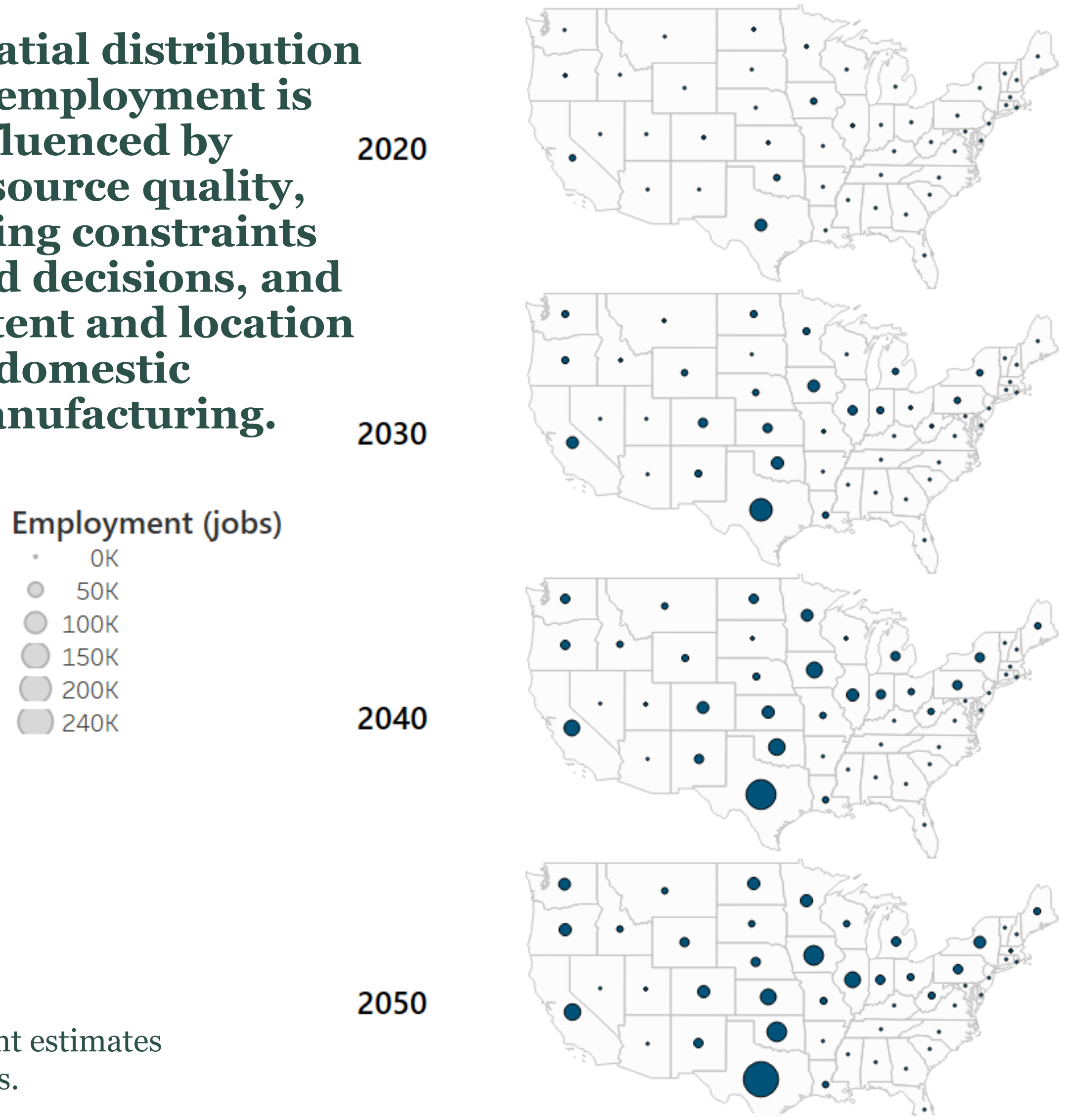
Wind sector employs ~100,000, or <5% of the energy supply-related workforce today but grows to exceed current natural gas employment

By 2050, employment in the wind sector comprises 10 to 25% of energy-related jobs in the net-zero scenarios, surpassing the size of the current natural gas sector.



Spatial distribution of employment is influenced by resource quality, siting constraints and decisions, and extent and location of domestic manufacturing.



Note: solar and wind related manufacturing employment estimates assume continuation of current domestic content shares.

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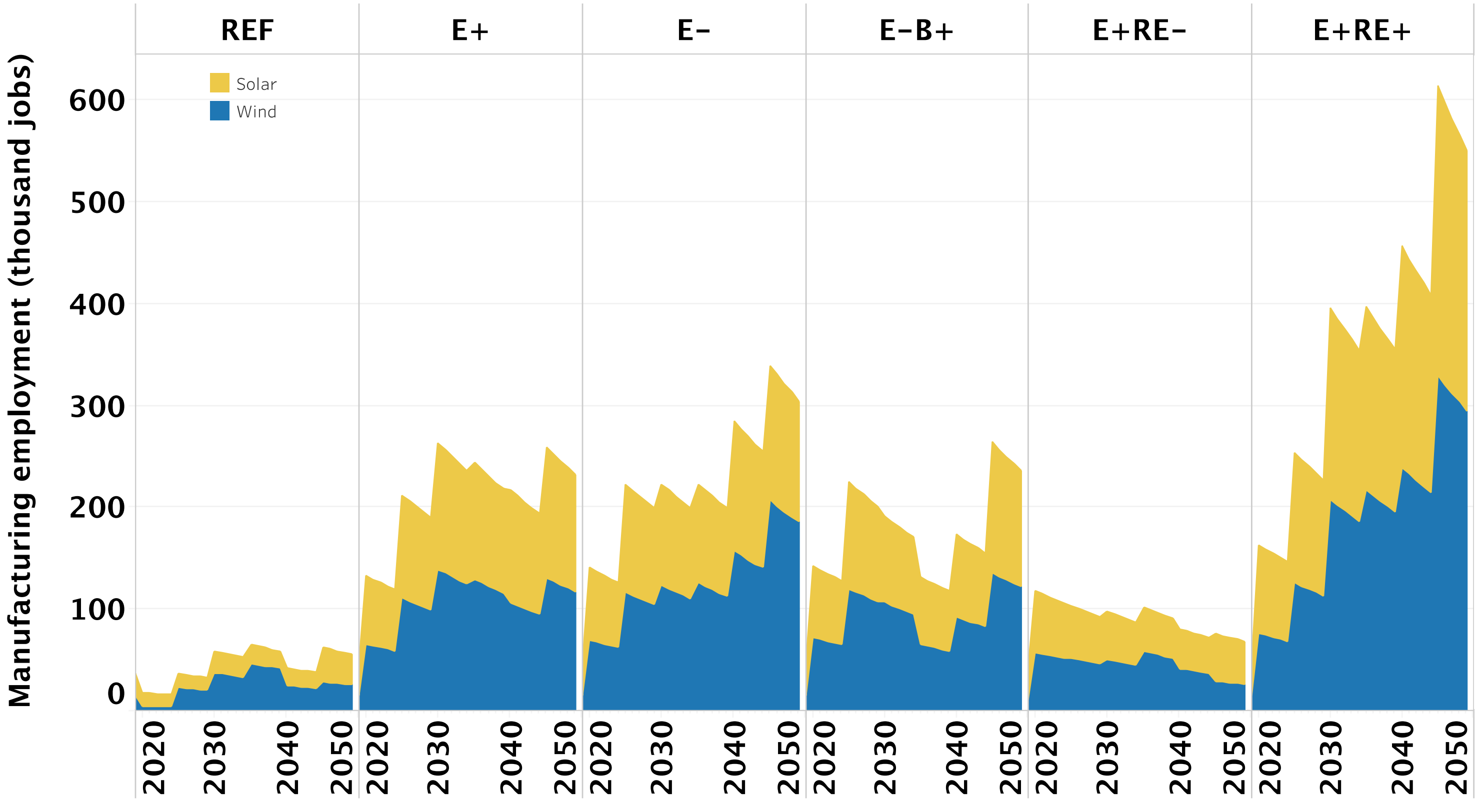
Solar and wind manufacturing offer opportunities to distribute employment benefits across multiple states



Note: Spatial redistribution of solar and wind manufacturing facilities and increasing the domestic manufacturing share offer opportunities to ameliorate losses in fossil fuel extraction states. The estimates here assume 1) manufacturing is sited within the logistic region (see next slide) where solar and wind generation are sited to account for transport between manufacturing and generation, 2) the distribution of manufacturing by state within a logistic region is consistent with the distribution of 2018 energy-related jobs (next slide), and 3) the domestic share of manufacturing is consistent with the historical domestic share (i.e., 79% wind, 15% solar).

There are degrees of freedom in siting solar and wind manufacturing facilities and the amount of manufacturing done domestically. This flexibility can be leveraged to offset job losses in communities, build coalitions, and facilitate legislative bargaining.

- To maintain current domestic shares of manufacturing (79% wind, 15% solar), manufacturing capacity must increase in most scenarios:
  - by 2030: 3-7X for wind, 1-4X for solar
  - by 2050: 2-20X wind, 1-8X solar
- Increasing domestic content share has minimal impact on technology costs, while supporting additional domestic jobs.

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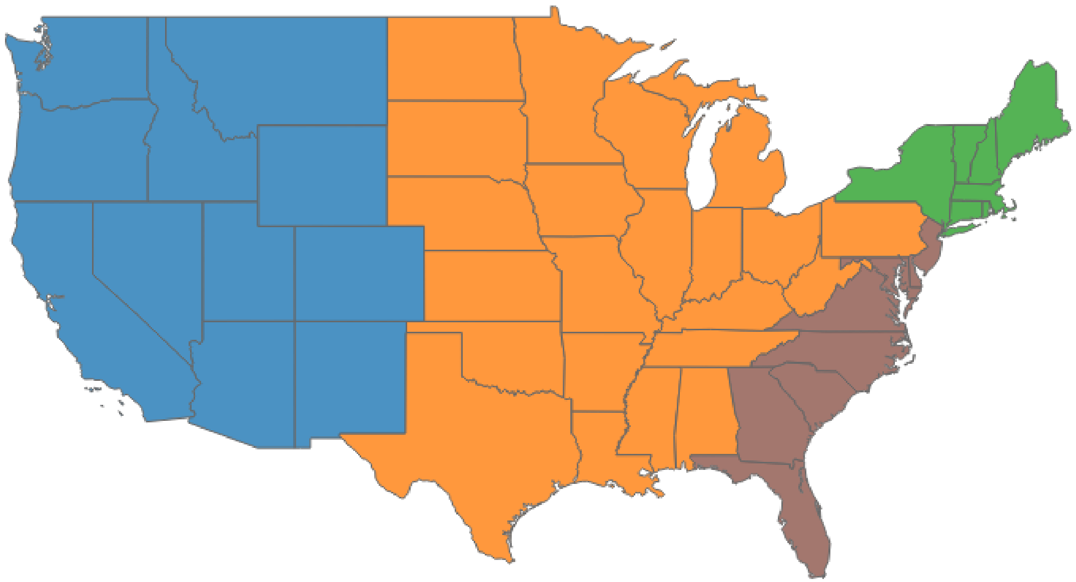
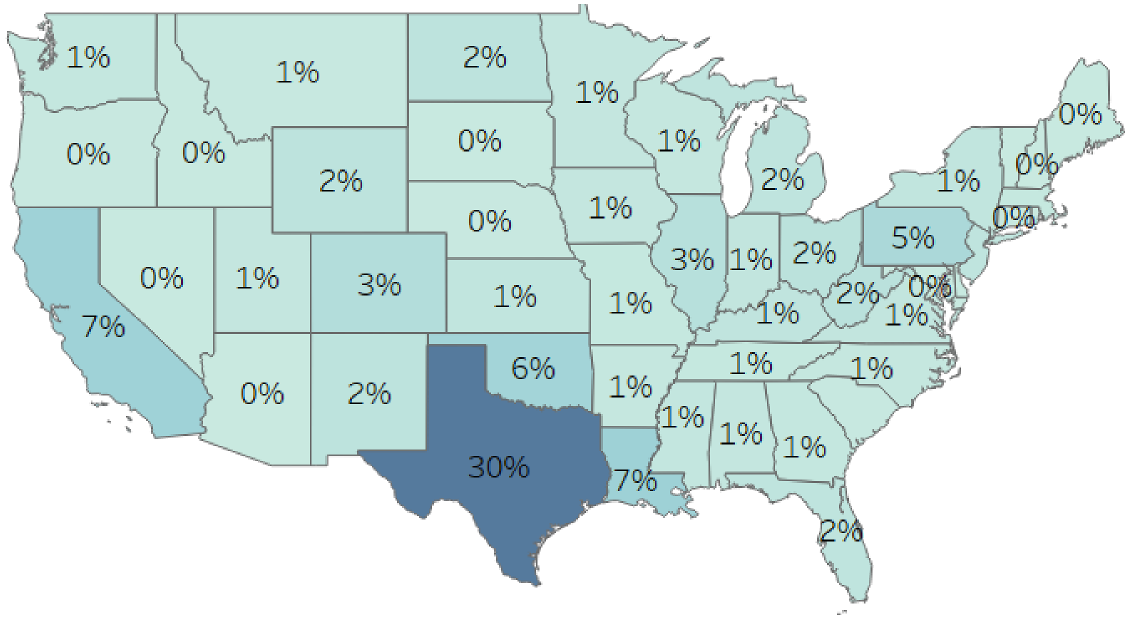
Assumptions for modeling the state-wise distribution of solar and wind manufacturing jobs

The state-wise distribution of solar and wind manufacturing jobs assumes 1) manufacturing is sited within the logistic region where solar and wind generation are sited, 2) the distribution of manufacturing by state within a logistic region is consistent with the distribution of 2018 energy-related jobs, and 3) the domestic share of manufacturing is consistent with the historical domestic share (i.e., 79% wind, 15% solar).

Logistic regions



2018 distribution of energy labor force



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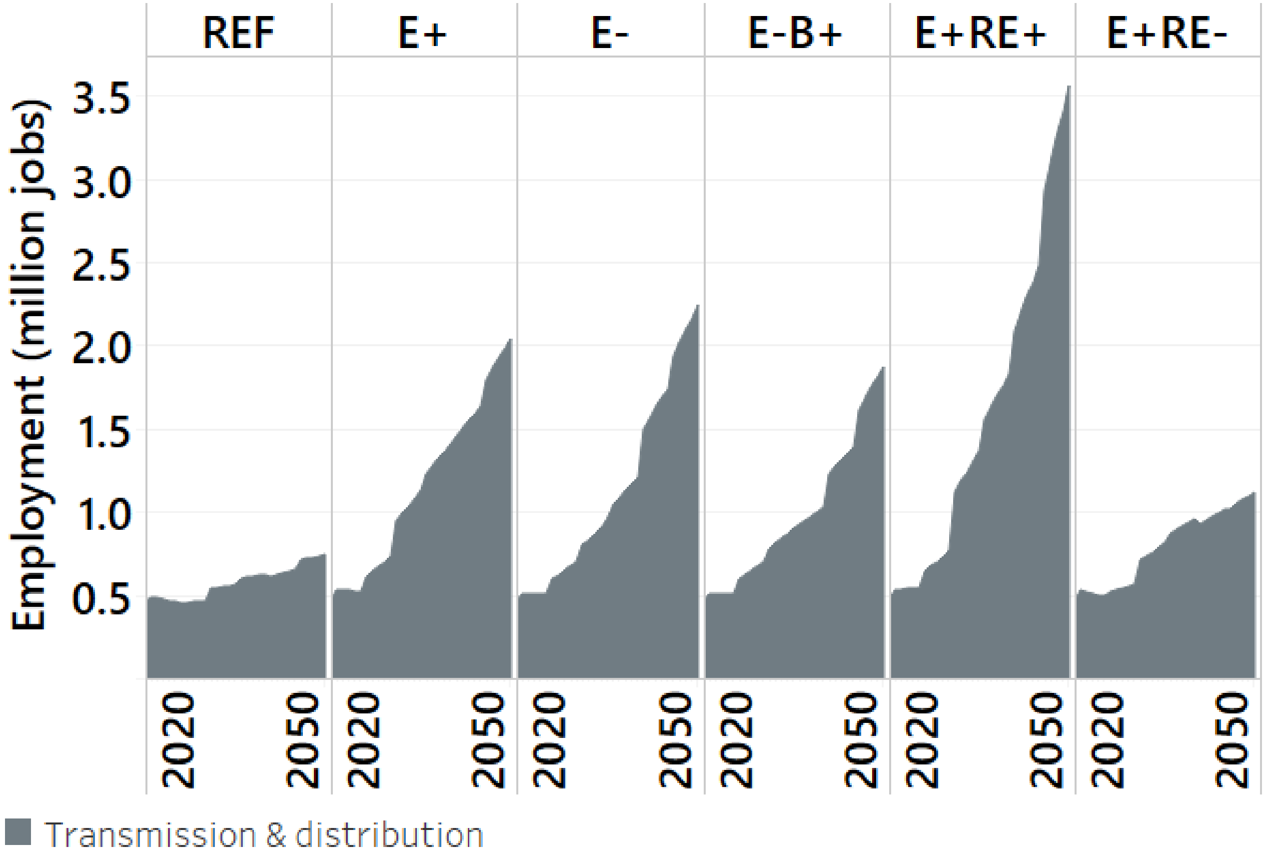
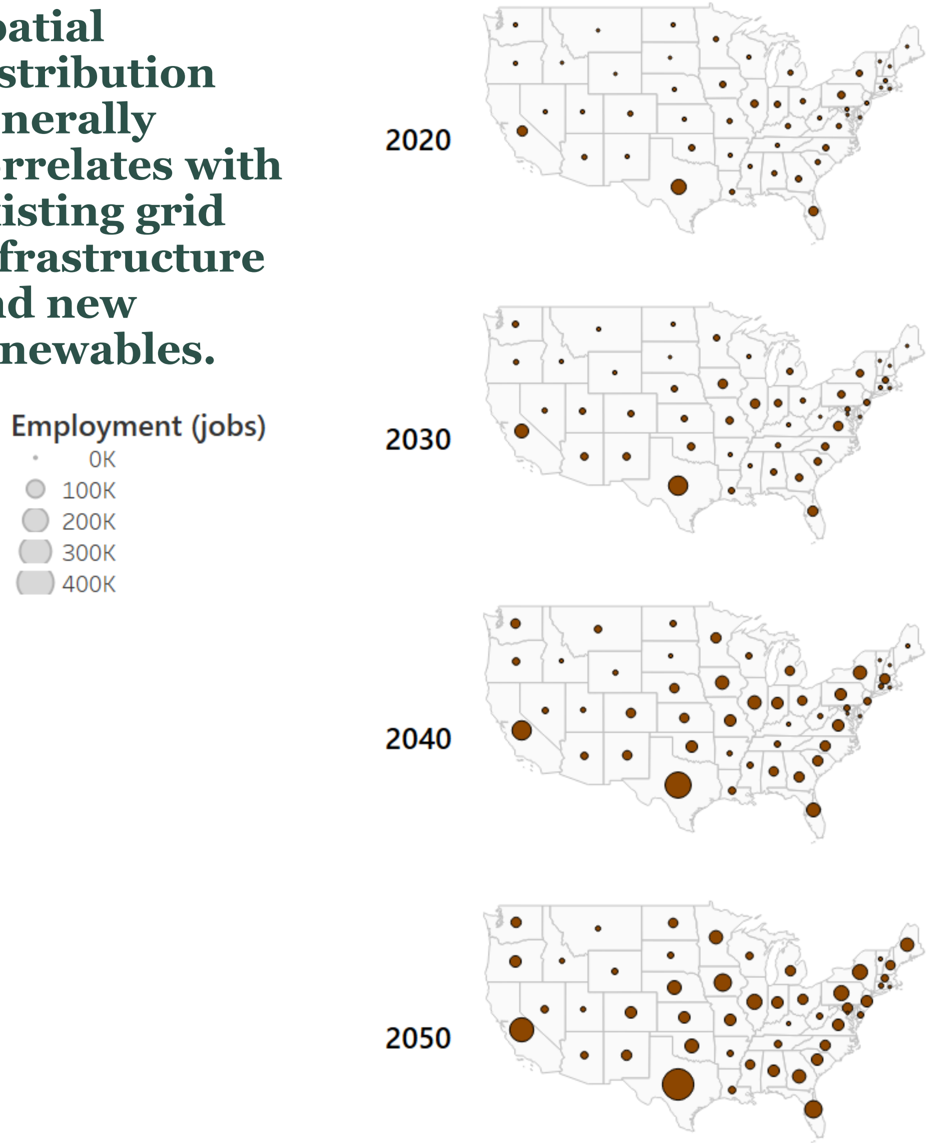
~450k grid-related jobs today represent ~20% of energy supply-related workforce. By 2050, these grow to 35-45%.

Growing employment is largely associated with the 2-4x expansion of the grid and ongoing O&M of existing and expanding grid infrastructure. Employment growth is generally correlated with renewables deployment.



Spatial distribution generally correlates with existing grid infrastructure and new renewables.



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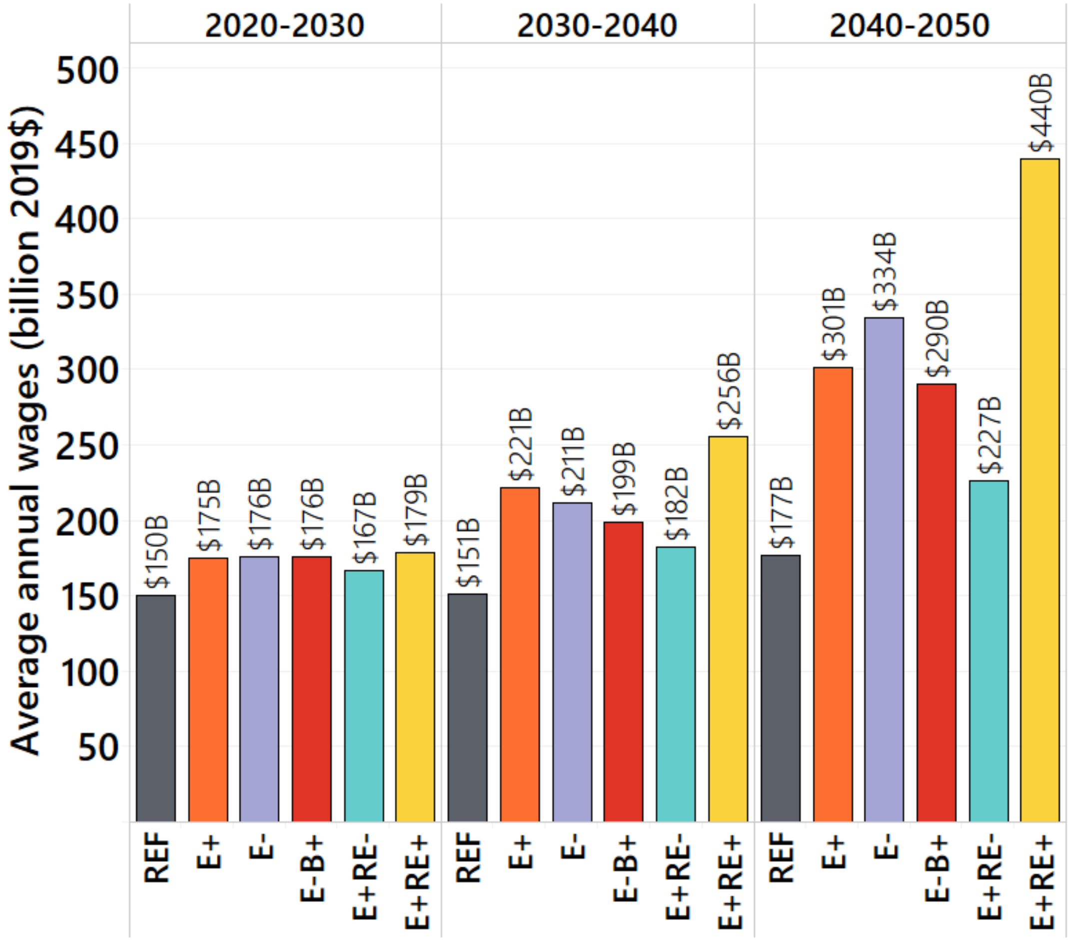
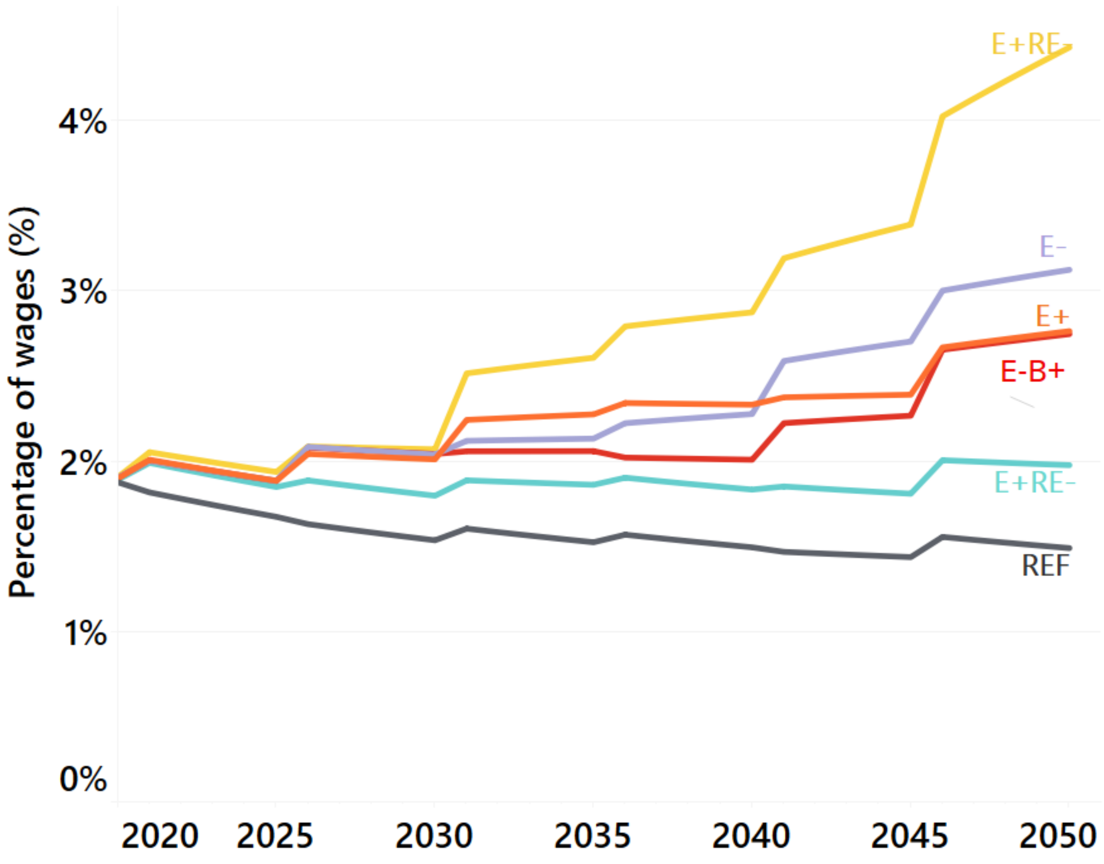
Wages for energy-supply related employment increase through net-zero transitions.

Annual wage income is 170 to 180 B$ in net-zero scenarios in the 2020s, an increase of 20-30 B$ over REF



Energy-related wages represent ~2% of total wages today and 2-4.5% by mid-century in net-zero scenarios



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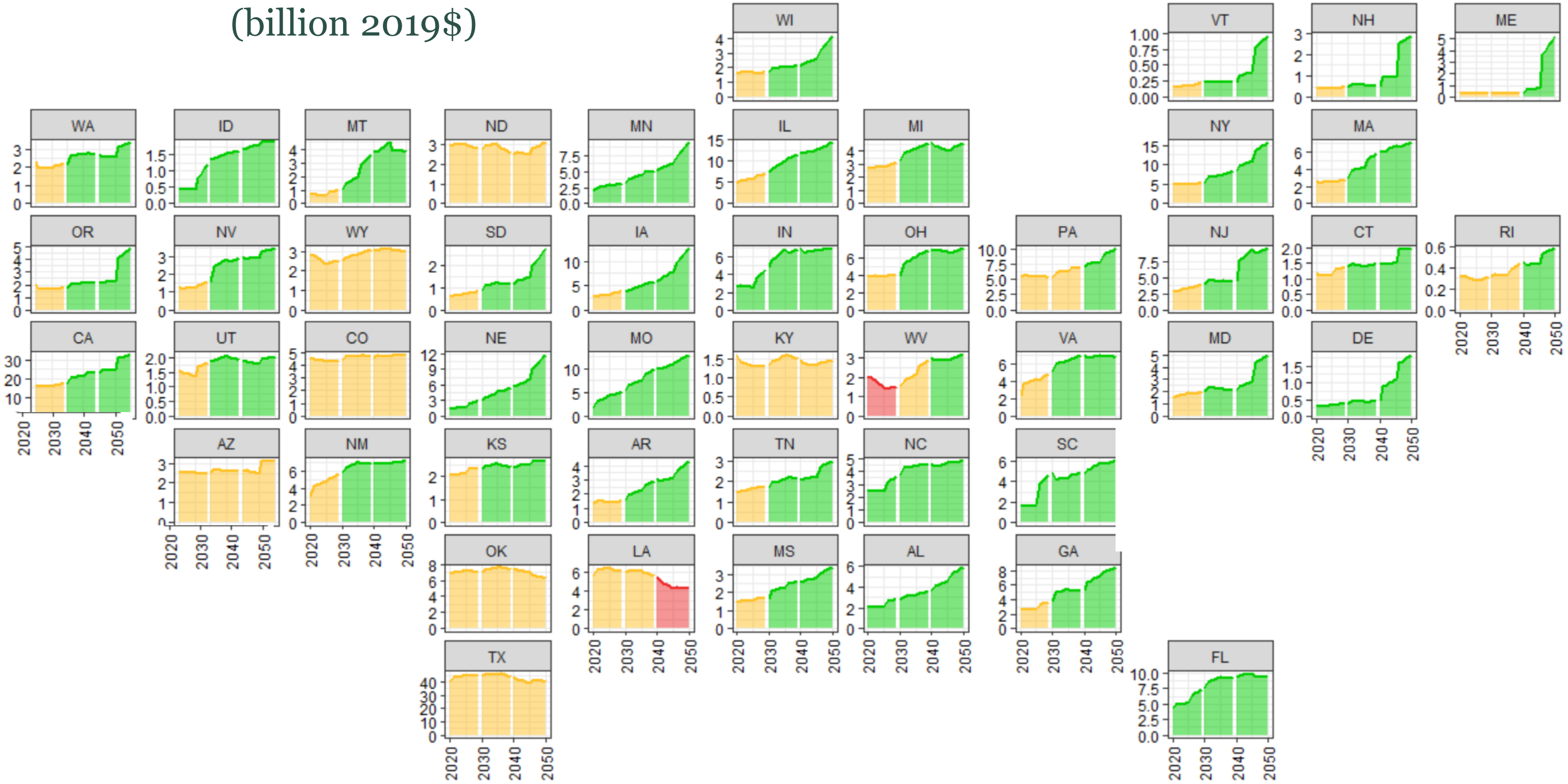
Modifiable socio-technical factors influence spatial distribution of wages. Below is one instantiation of the future.

Annual wages based on downscaled E+ scenario

(billion 2019$)



Note: Green, yellow, and red coloring indicate whether average annual wages within a decade is more than 15% higher, within 15%, or more than 15% lower than 2021 wages, respectively.

Modifiable sociotechnical factors that influence the spatial distribution of wages:

- Resource quality and availability
- Rate of electrification
- Technology selection
- Domestic manufacturing
- Siting constraints
- Oil and gas exports
- Political and policy processes and constraints

There are several degrees of freedom that can reduce transition risks and be leveraged for political bargaining.

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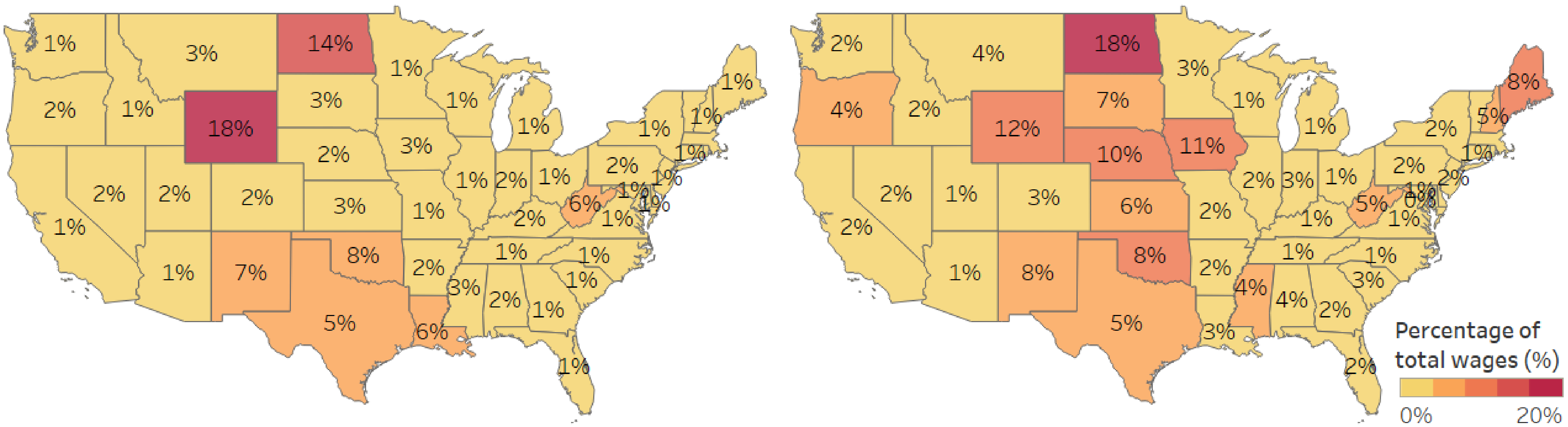
In most states, energy-related wages grow as a share of total wages through the transition period.

E+ scenario

2020 | 2050



- In a few states with a very high share of the current labor force employed in upstream fossil fuel industries (e.g., WY, WV), energy-related employment wages decrease as a share of the total employment wages through the transition.
- In states with high renewable resource quality (e.g., NE, SD, MT, and IA), wages for energy-related employment as a share of total-employment wages grow considerably.

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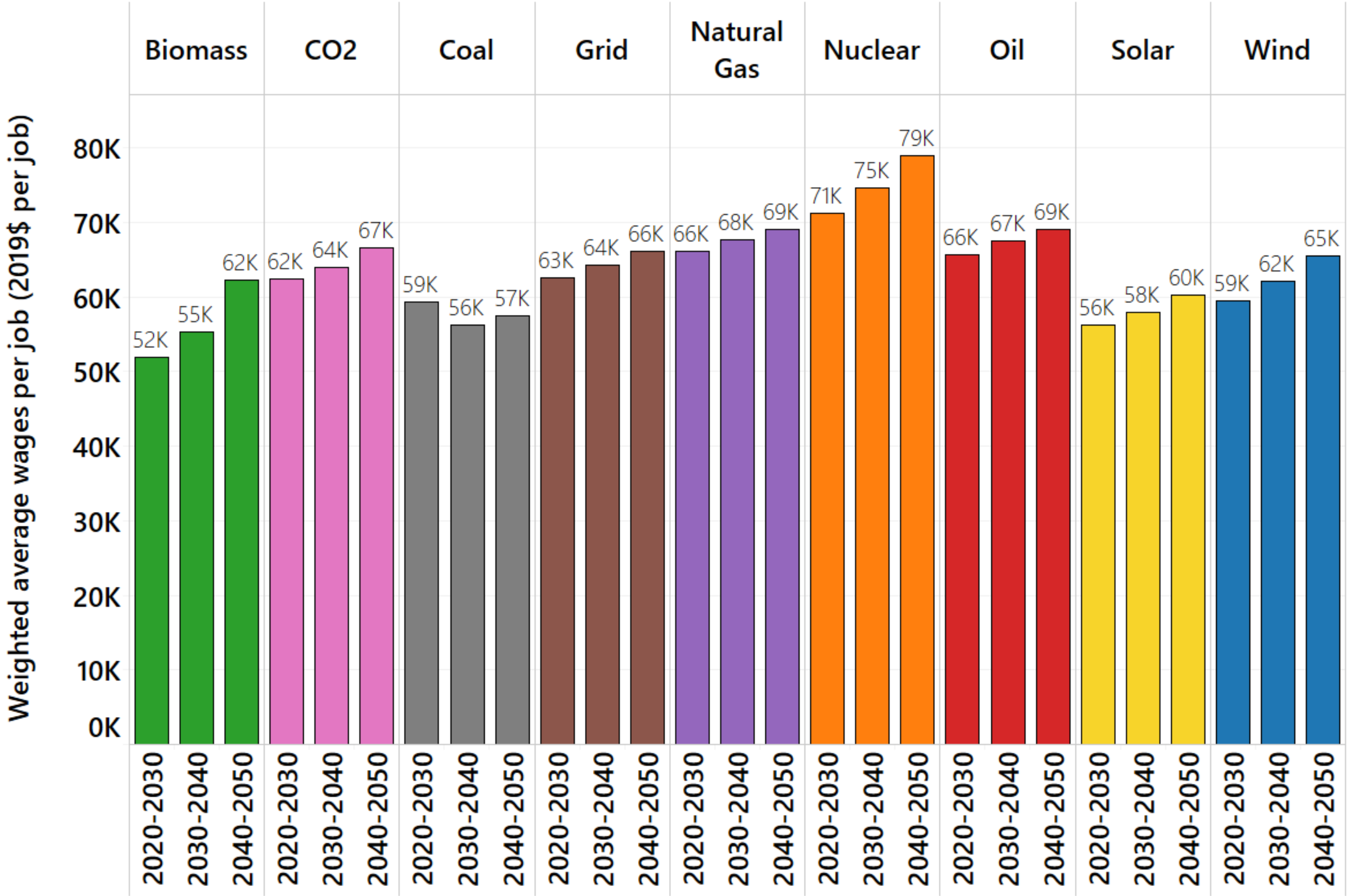
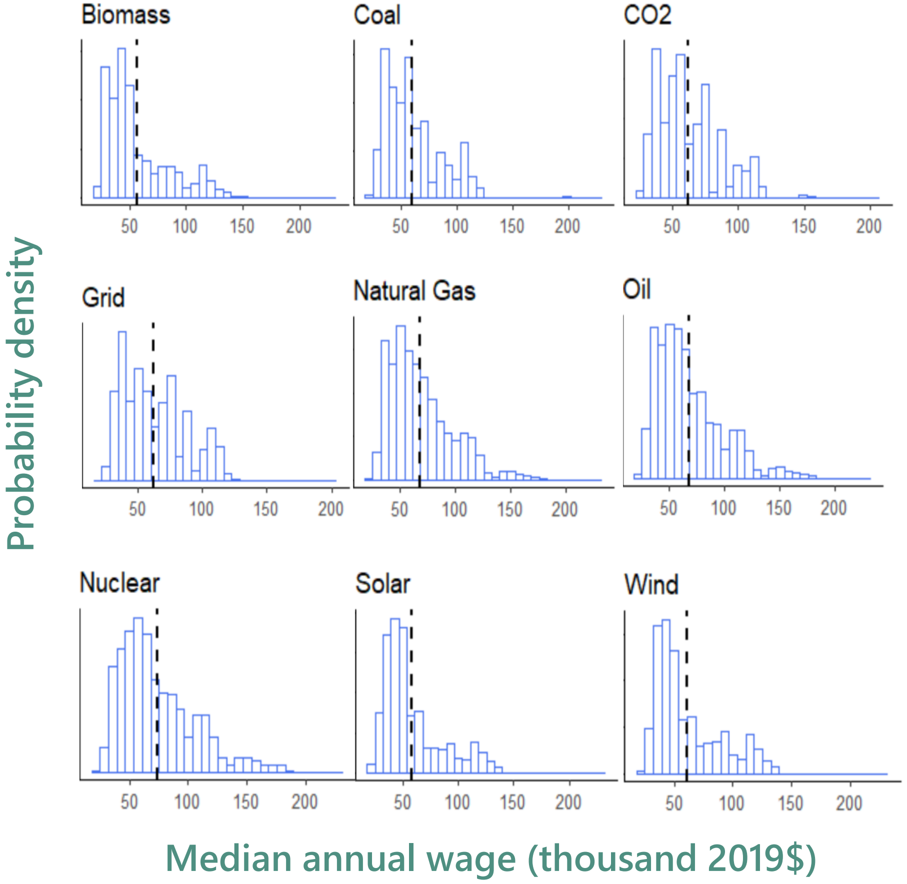
Wages per job for a given resource sector are similar for REF and net-zero scenarios, with some variations between sectors.

E+ scenario



Energy-related jobs are largely middle-income jobs, but there is a range across the income spectrum.



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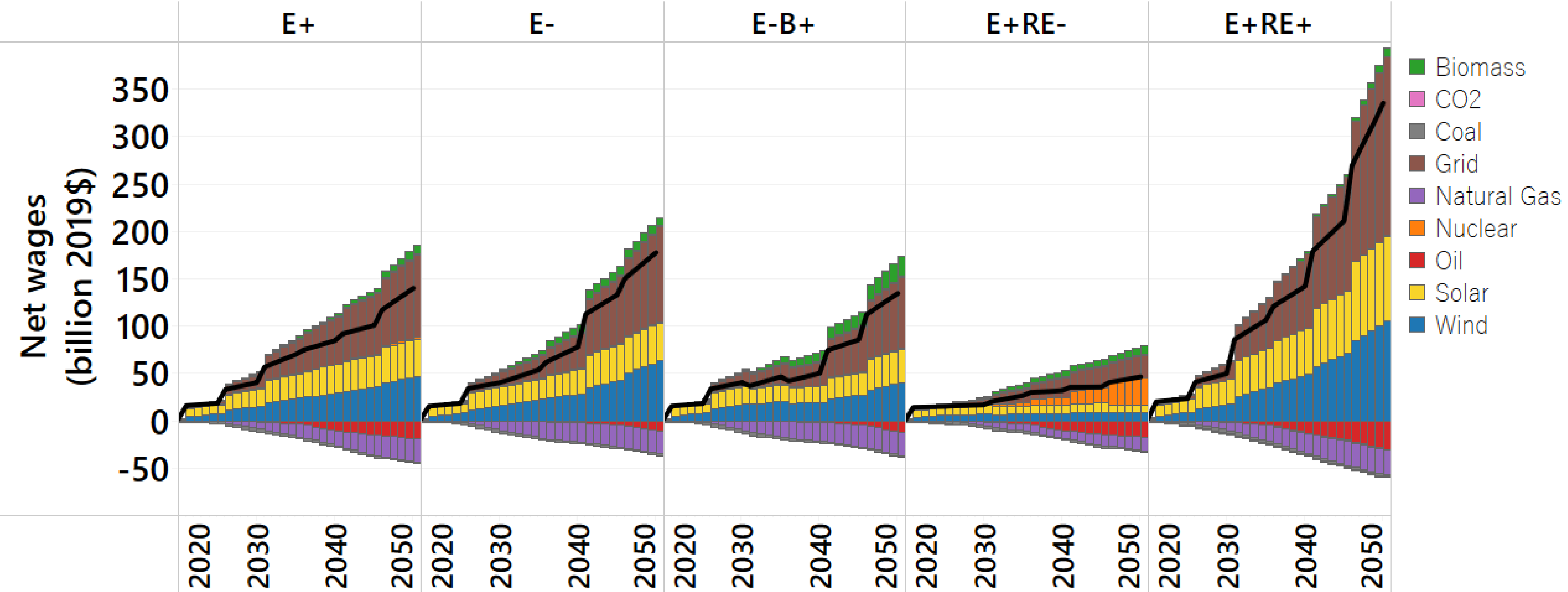
Wages losses in fossil fuel sectors are offset (in aggregate) by added wages in low carbon sectors.

- There is minimal wage loss in fossil fuel sectors in the first decade of the transition.
- By the 2040s, the loss is substantially higher (though much of the current fossil fuel workforce will have reached normal retirement age by that time).



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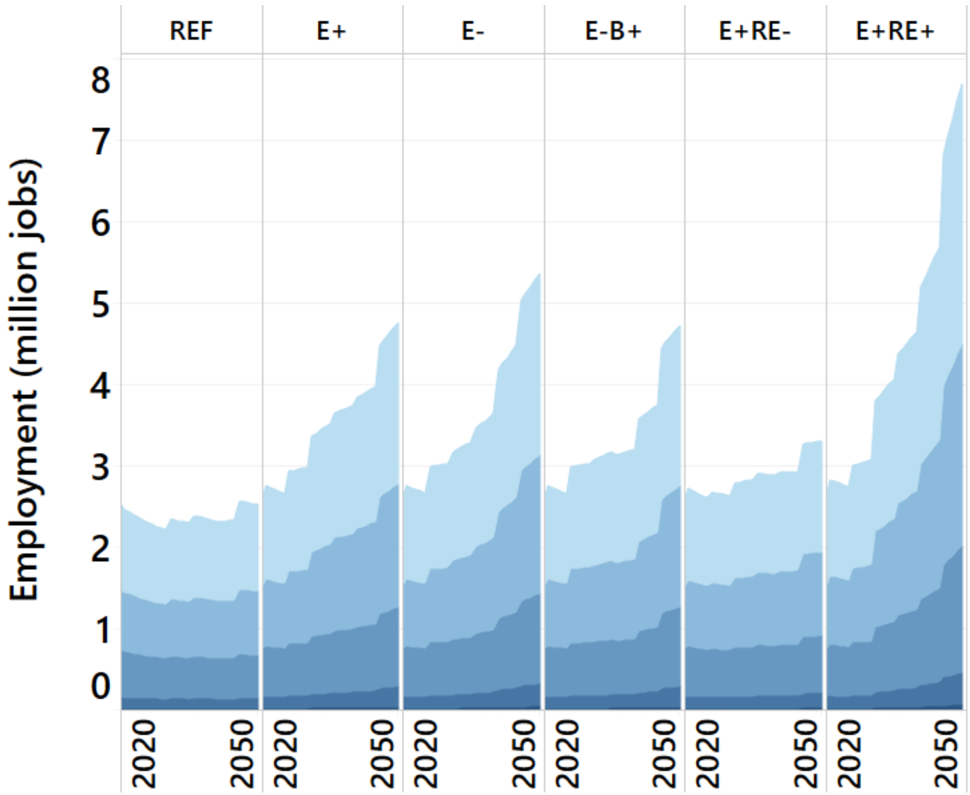
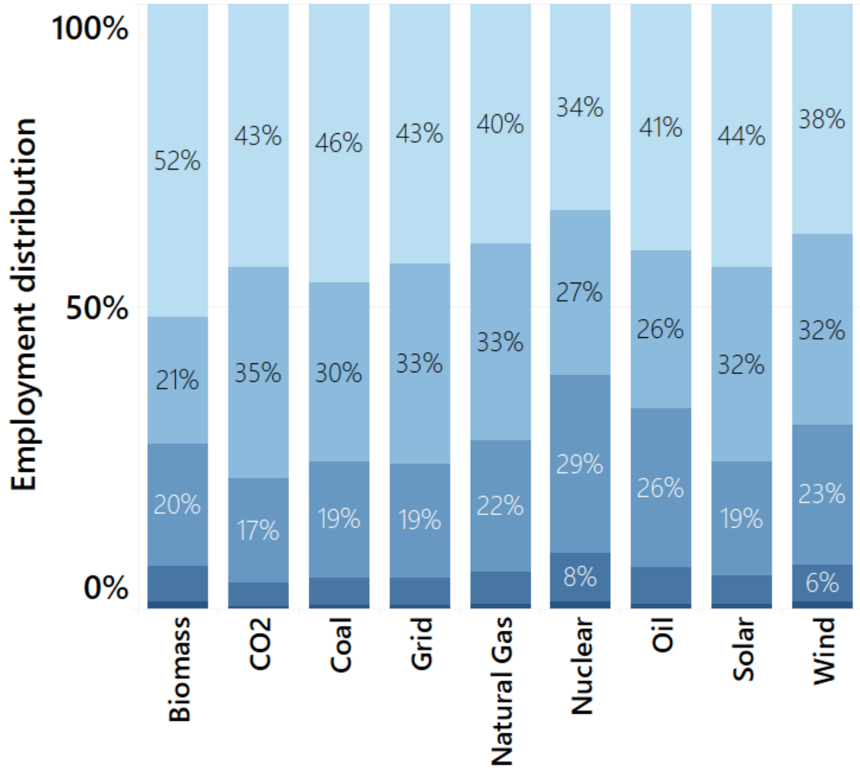
There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

Employment by required level of education



Distribution of employment by required level of education

(results are for E+ scenario aggregated over 30-yr transition period)

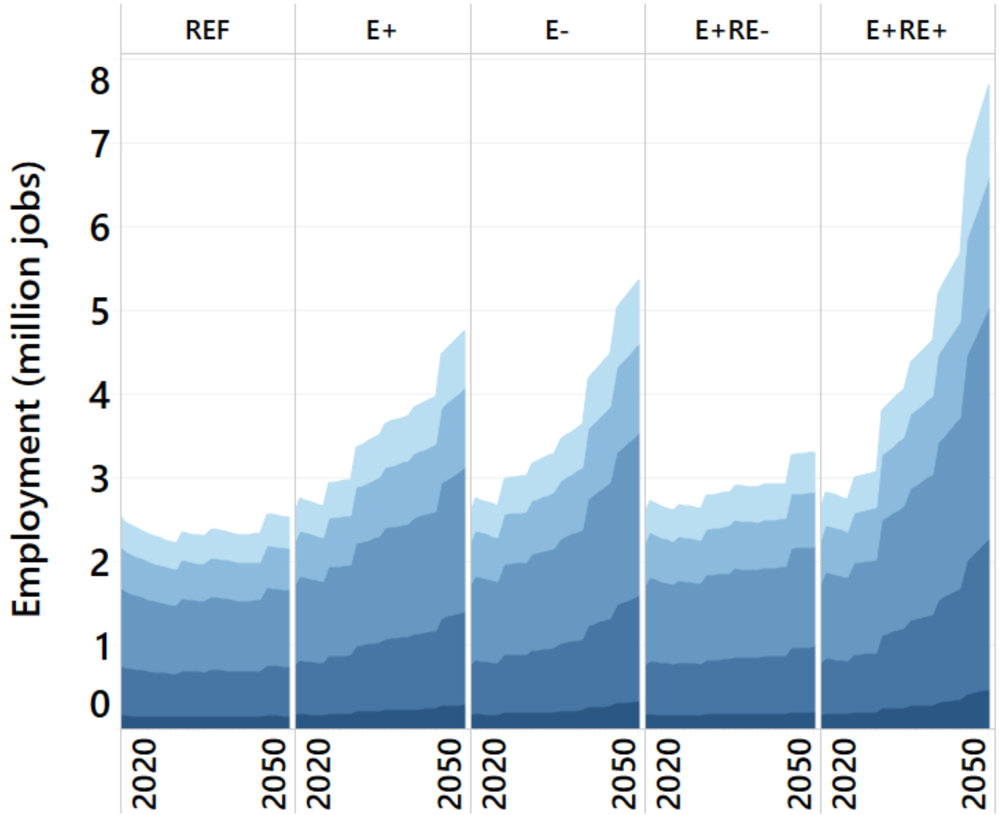


- 30% of the energy workforce will require a bachelor's degree or higher
- Similar distribution of education requirements across REF and net-zero scenarios and over time
- Heterogeneity in education requirements across resource sectors

- High school diploma or less
- Associates degree or some college
- Bachelors degree
- Masters or professional degree
- Doctoral degree

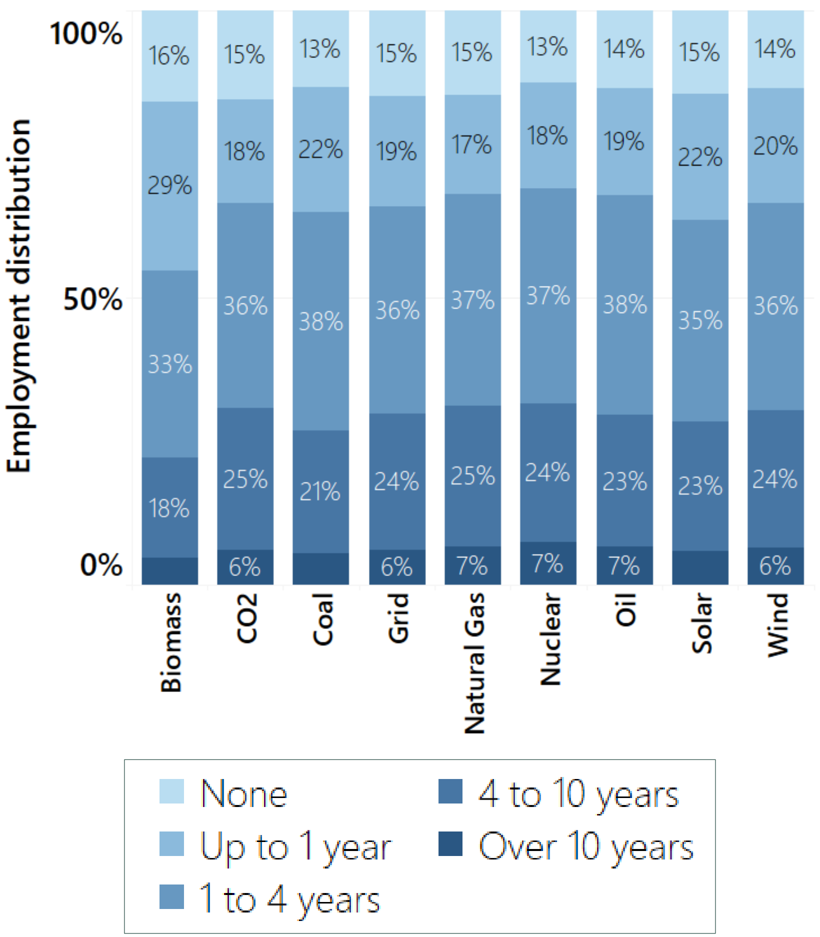
There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

Employment by required years of experience



Distribution of employment by required years of experience

(results are for E+ scenario aggregated over 30-yr transition period)



- 70% of the energy workforce requires less than 4 years of related work experience, suggesting minimal lead time required to prepare individual workers.
- Similar distribution of experience requirements across REF and net-zero scenarios and over time.
- Heterogeneity in experience requirements across resource sectors.

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Considerations for workforce development programs in net-zero transitions

- The rate of decarbonization is influenced by the organization and availability of labor.
- In established fossil fuel and emerging renewable labor markets, there is evidence of difficulty in hiring, which portends continued employment bottlenecks without countervailing policies and organization.
- Findings suggest that diverse workforce programs (e.g., occupational skills training, college training, apprenticeships, and internships) are needed to re-train workers in declining sectors and train and educate the future workforce.
- Findings suggest that there is minimal lead time required to prepare individual workers.
- Given the magnitude of future labor demand to support a decades-long transition, large-scale and sustained workforce programs and corresponding federal support will be required.
- Substantial coordination between unions, public agencies, firms, and workers will be needed to meet the evolving needs of both workers and employers and mitigate labor supply bottlenecks.
- A diversity of programs will be needed to account for the heterogeneity of existing workforces and types of sectors and industries that will be expanded in different regions and communities.
- Beyond training, workforce programs can include recruitment and job placement assistance.

Implications of findings on energy-related employment

- To support a net-zero transition, the supply-side energy workforce will need to expand by 15% in the first decade (to 2030) and by 1.2x to 3x by 2050.
- Net-zero transitions have the potential to significantly transform state and local economies.
- Labor pathways and the distribution of labor are influenced by several modifiable socio-technical factors, such as technology selection, pace of low carbon infrastructure expansion, infrastructure siting and investment decisions, oil and natural gas exports, and domestic manufacturing.
- Modifiable factors can be leveraged to reduce transition risks and to facilitate legislative bargaining.
- Designing 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.
- Given the magnitude of future labor demand to support a decades-long transition, large-scale, sustained, and diverse workforce programs and corresponding federal support will be required.
- Policy can mitigate the impacts of employment losses for fossil fuel workers and communities.

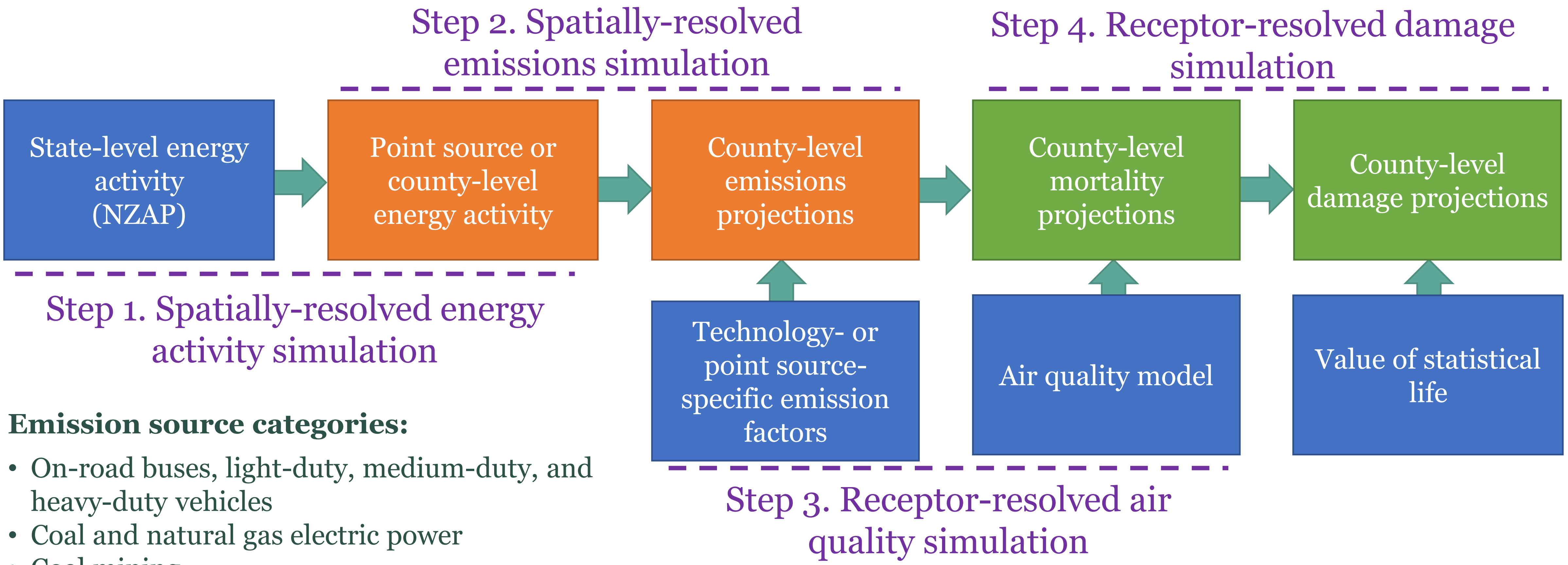
Health impacts related to air quality

Summary of this section

- Historically, there have been persistent and large health impacts from fine particulate matter (PM2.5) exposure associated with air pollutant emissions from carbon-emitting activities.
- PM2.5 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. This is on par with estimated increases in energy-related expenditures over the decade.
  - Approximately 260,000 to 410,000 premature deaths ($2.3-3.7 trillion in damages) are avoided from 2020 to 2050.

See Annex S for details of the health impact analysis.

Modeling framework for estimating air pollution and associated health impacts

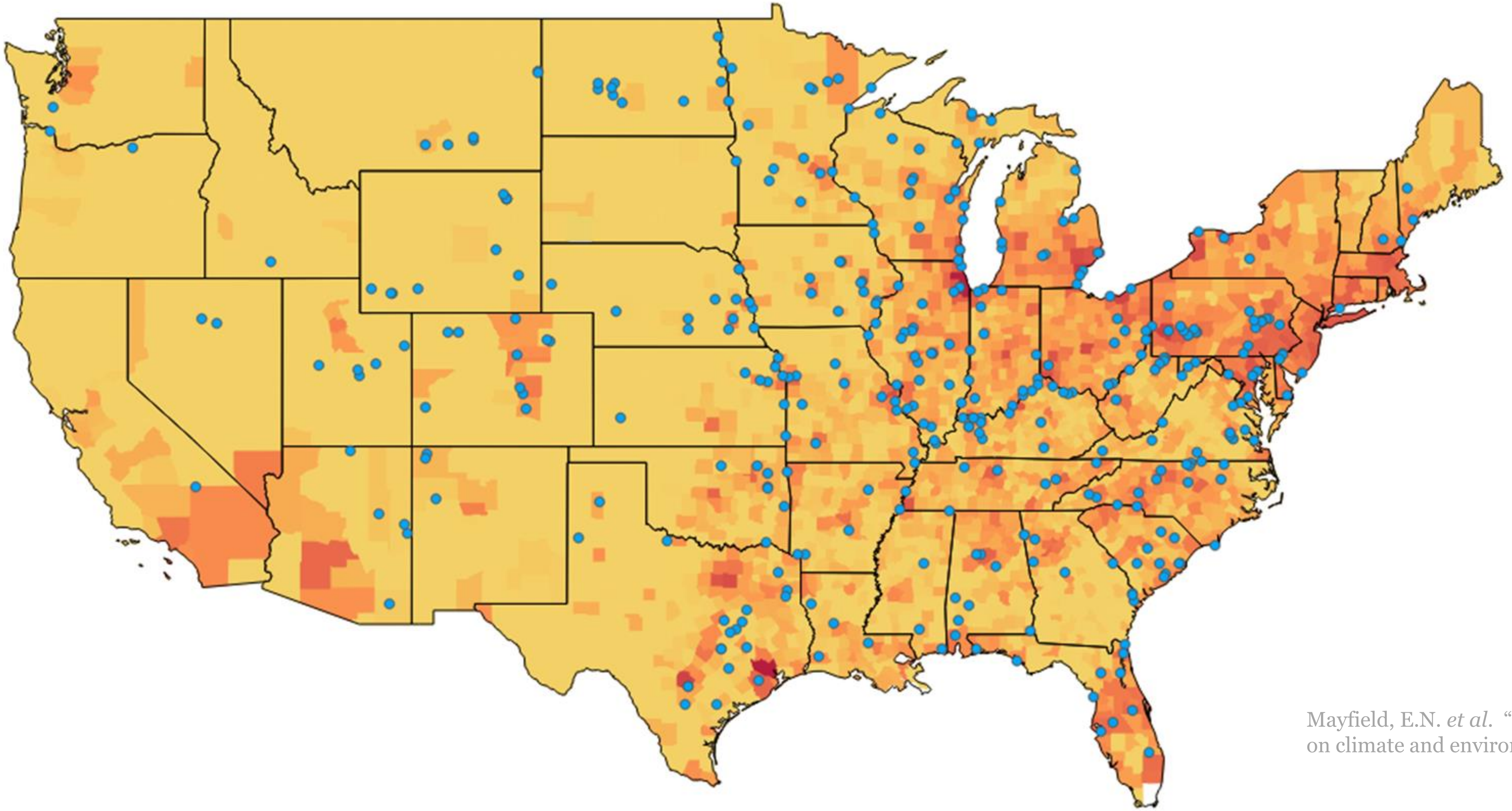


Emission source categories:

- On-road buses, light-duty, medium-duty, and heavy-duty vehicles
- Coal and natural gas electric power
- Coal mining
- Oil & gas production
- Commercial sector fuel combustion
- Residential sector fuel combustion
- Gas stations

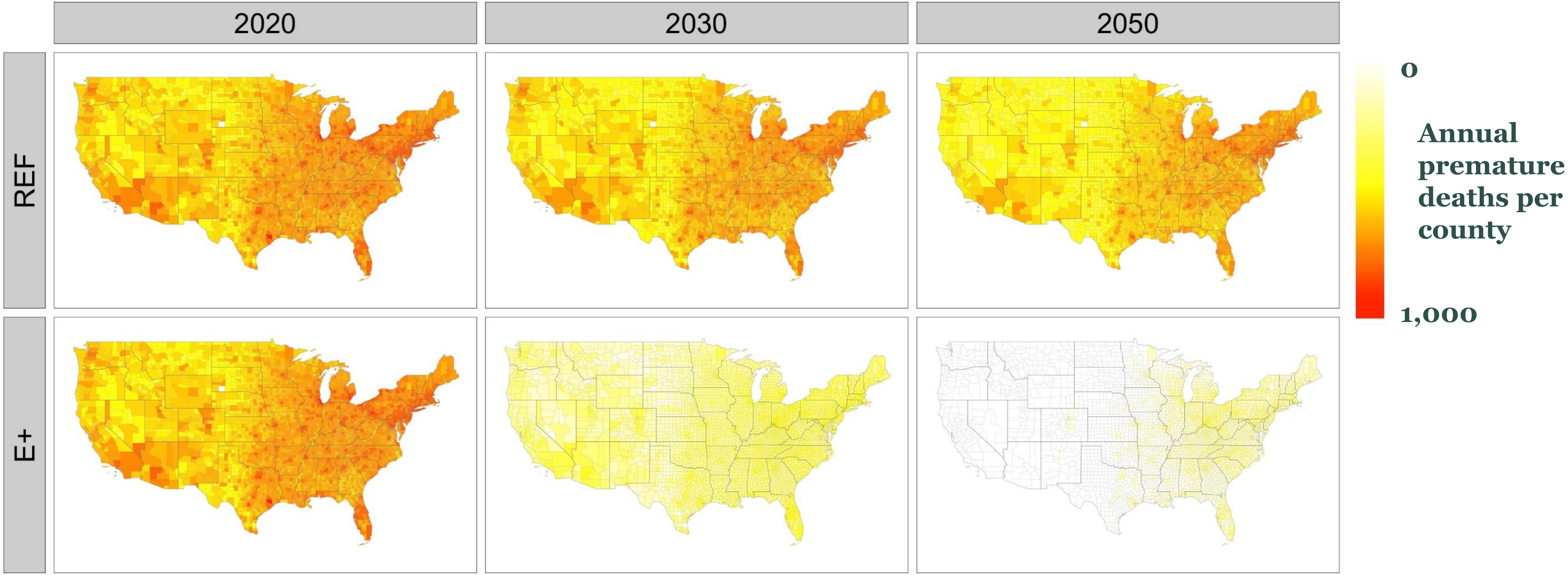
Criteria pollutants: NO_x, $PM_{2.5}$, SO_2, VOC
Air quality model: AP3
Health outcomes: premature mortality and damages
Dose-response relationship: American Cancer Society

In 2018, 11,000 premature mortalities (~$100B damages) were associated with emissions from 390 coal power plants.



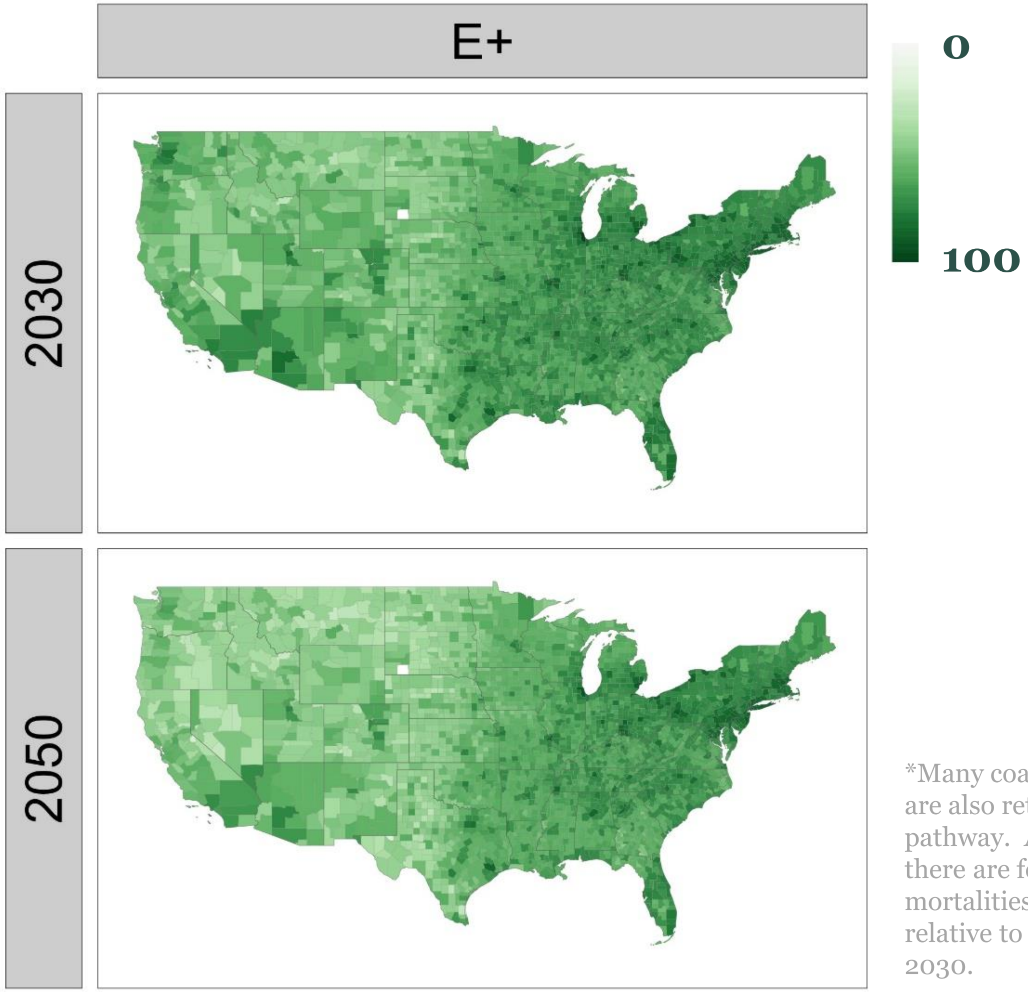
Mayfield, E.N. *et al*. "Sequencing coal retirements based on climate and environmental objectives." *forthcoming*.

Over 100,000 coal electric power-related air pollution deaths (~1 T$ in damages) are avoided by 2050 with any of the net-zero pathways.

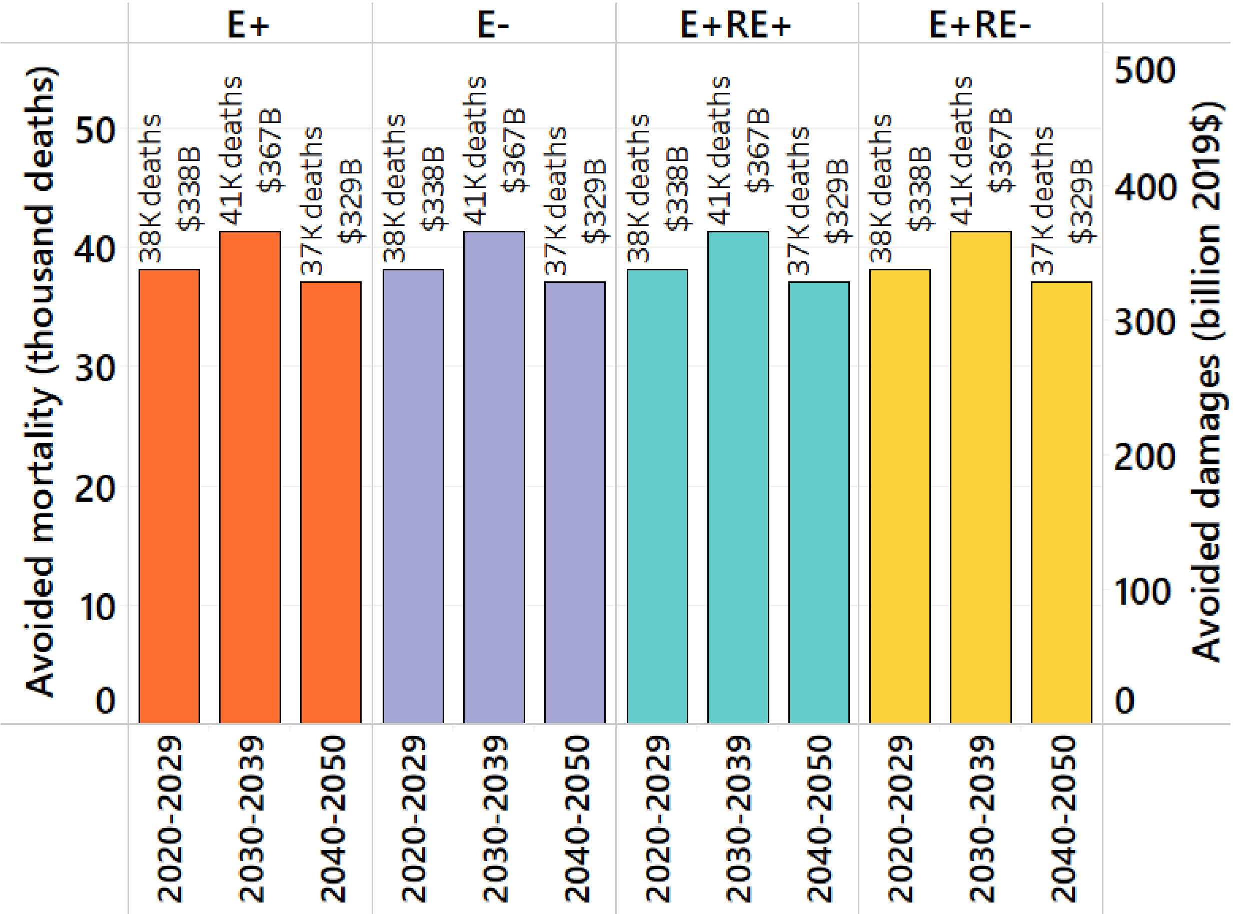


Over 100,000 coal electric power-related air pollution deaths (~1 T$ in damages) are avoided by 2050 with any of the net-zero pathways.

Annual avoided premature deaths per county [relative to REF*]



Avoided premature mortalities by decade [relative to REF]



*Many coal power plants are also retired in the REF pathway. As a result, there are fewer avoided mortalities in 2050 relative to REF than in 2030.

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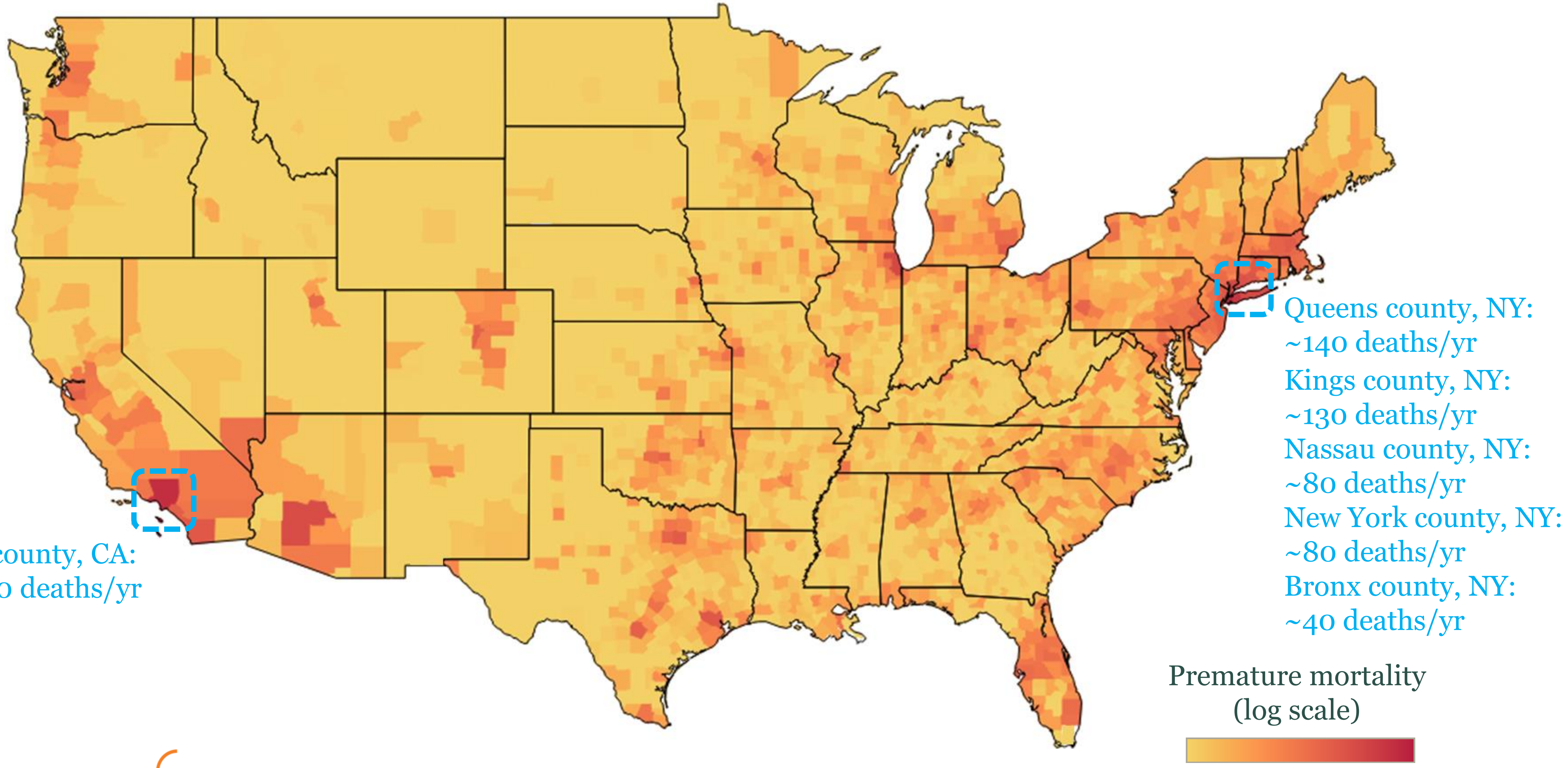
In 2019, ~1,800 premature mortalities ($16B damages) were associated with air pollution from natural gas power plants.



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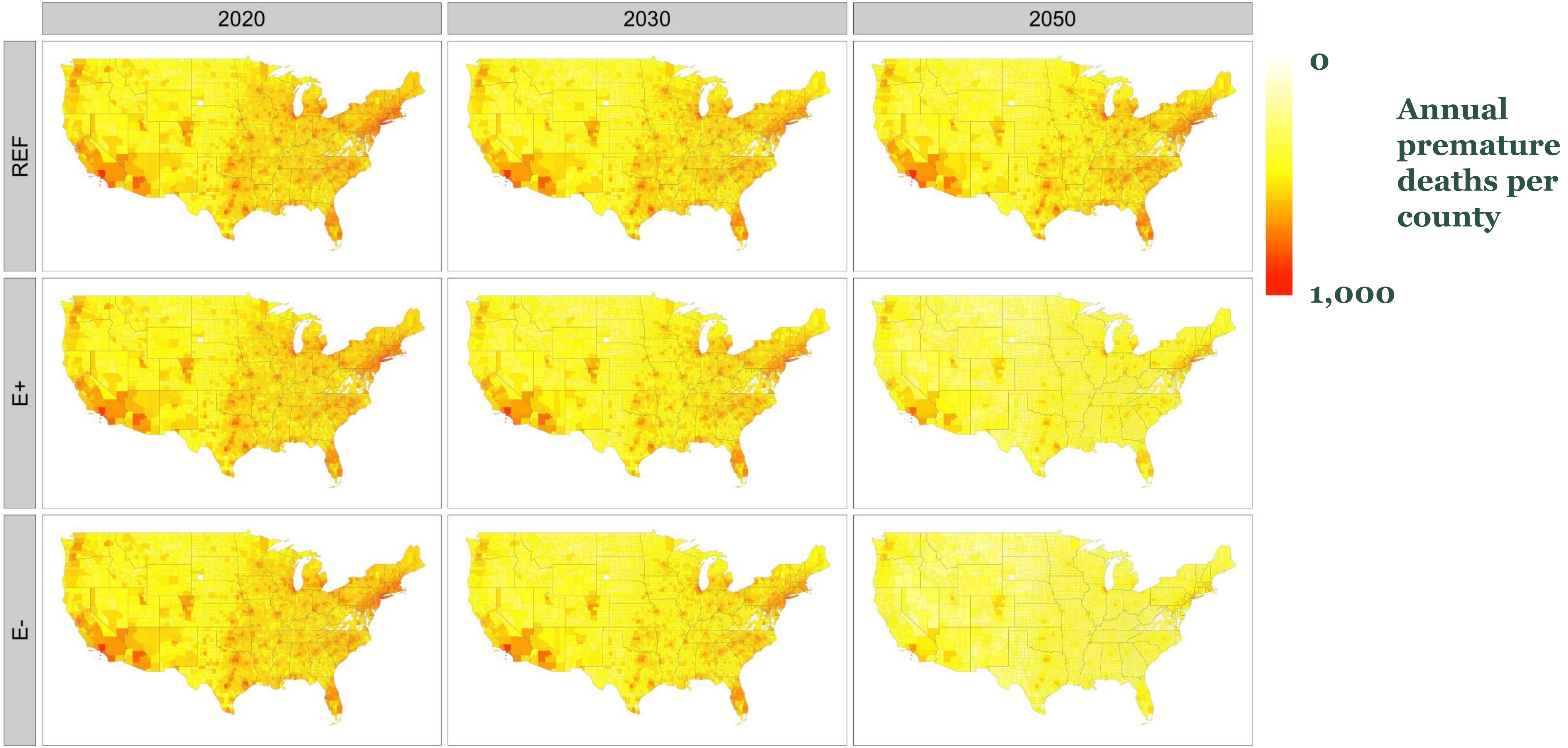
18 – 28k deaths (159 – 244B$ damages) are avoided from 2020 to 2050 by natural gas power plant retirements and conversions.



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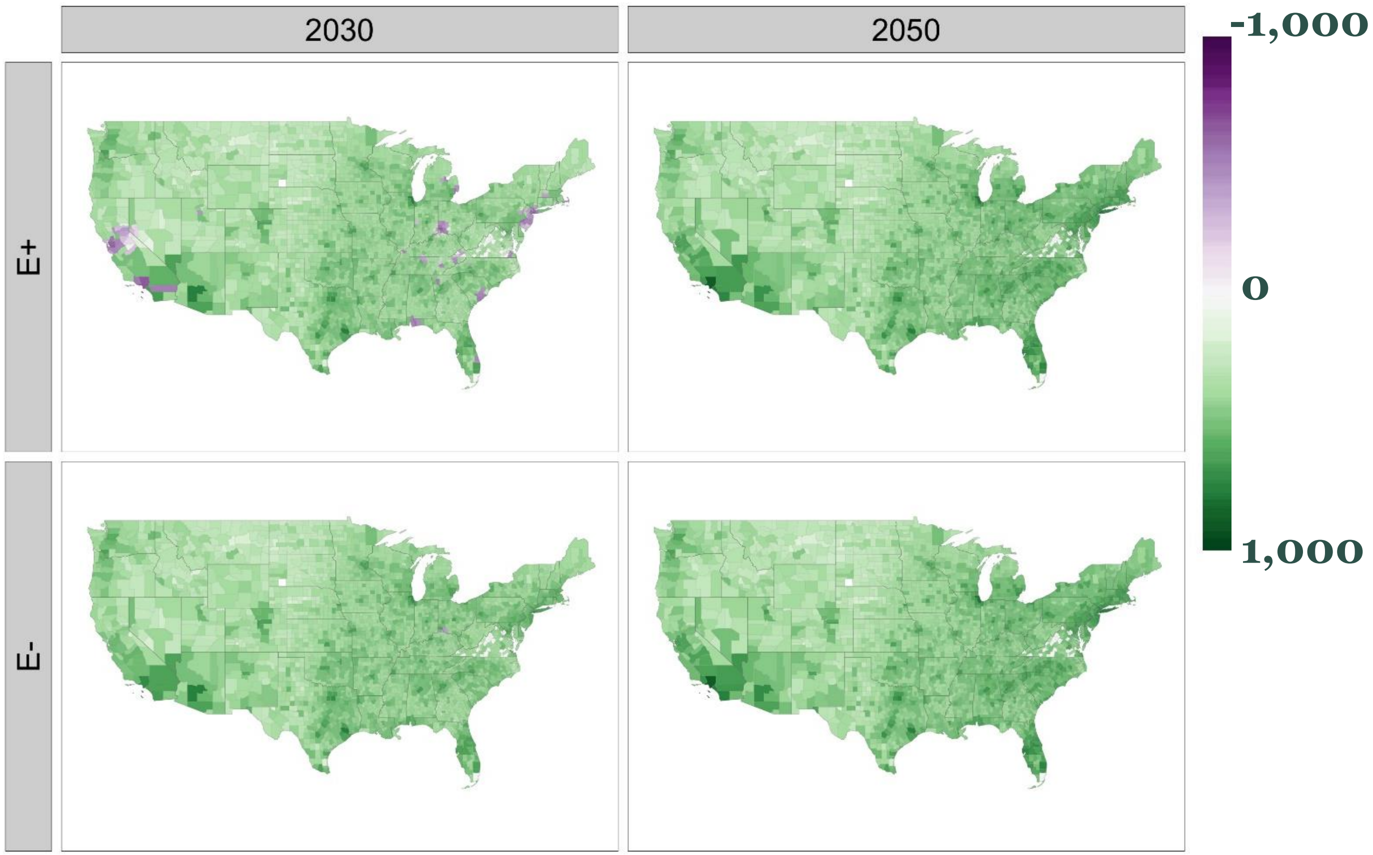
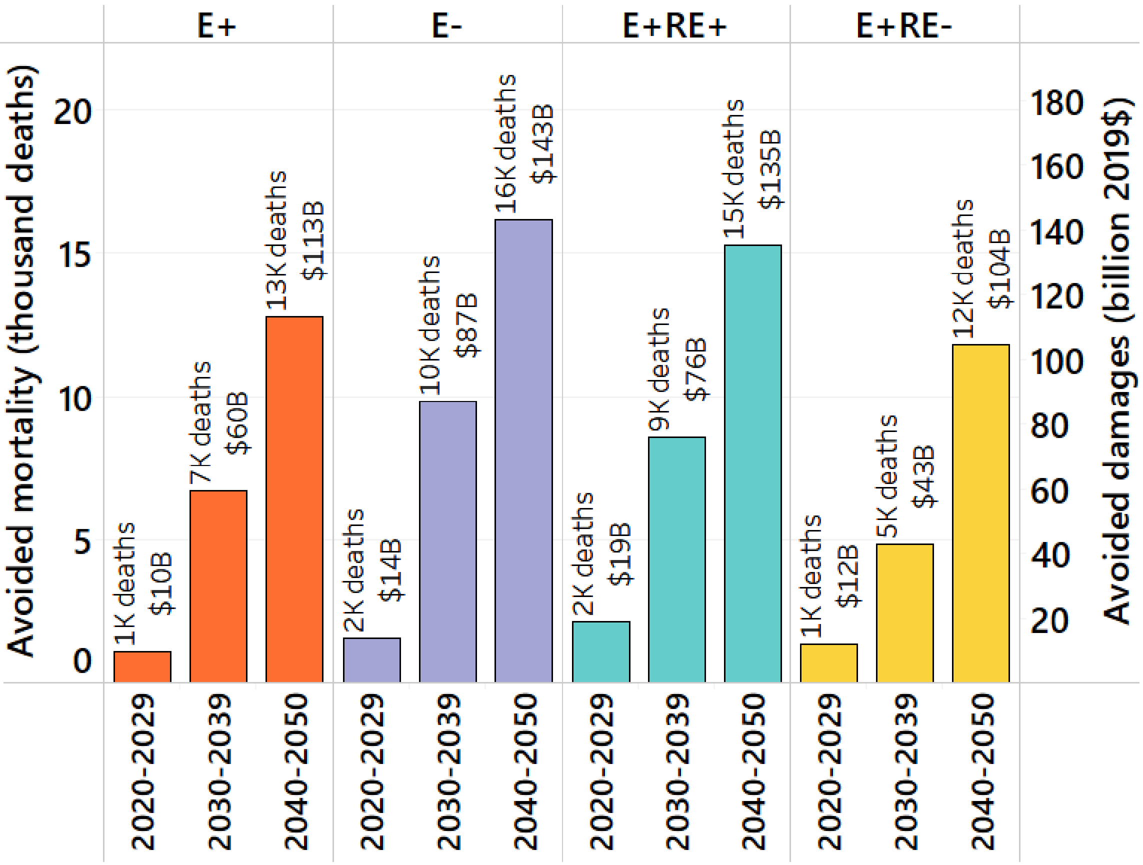
18 – 28k deaths (159 – 244B$ damages) are avoided from 2020 to 2050 by natural gas power plant retirements and conversions.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



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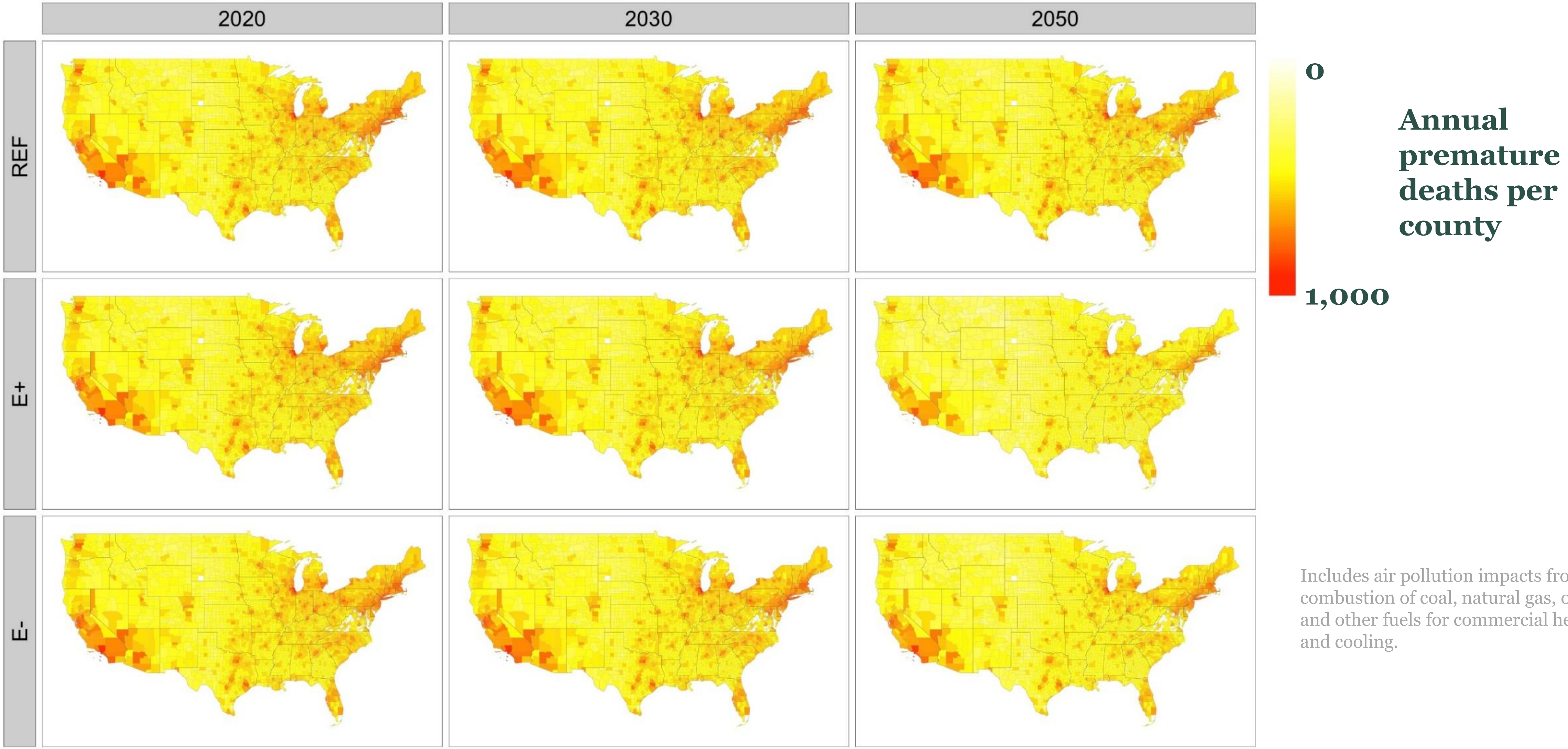
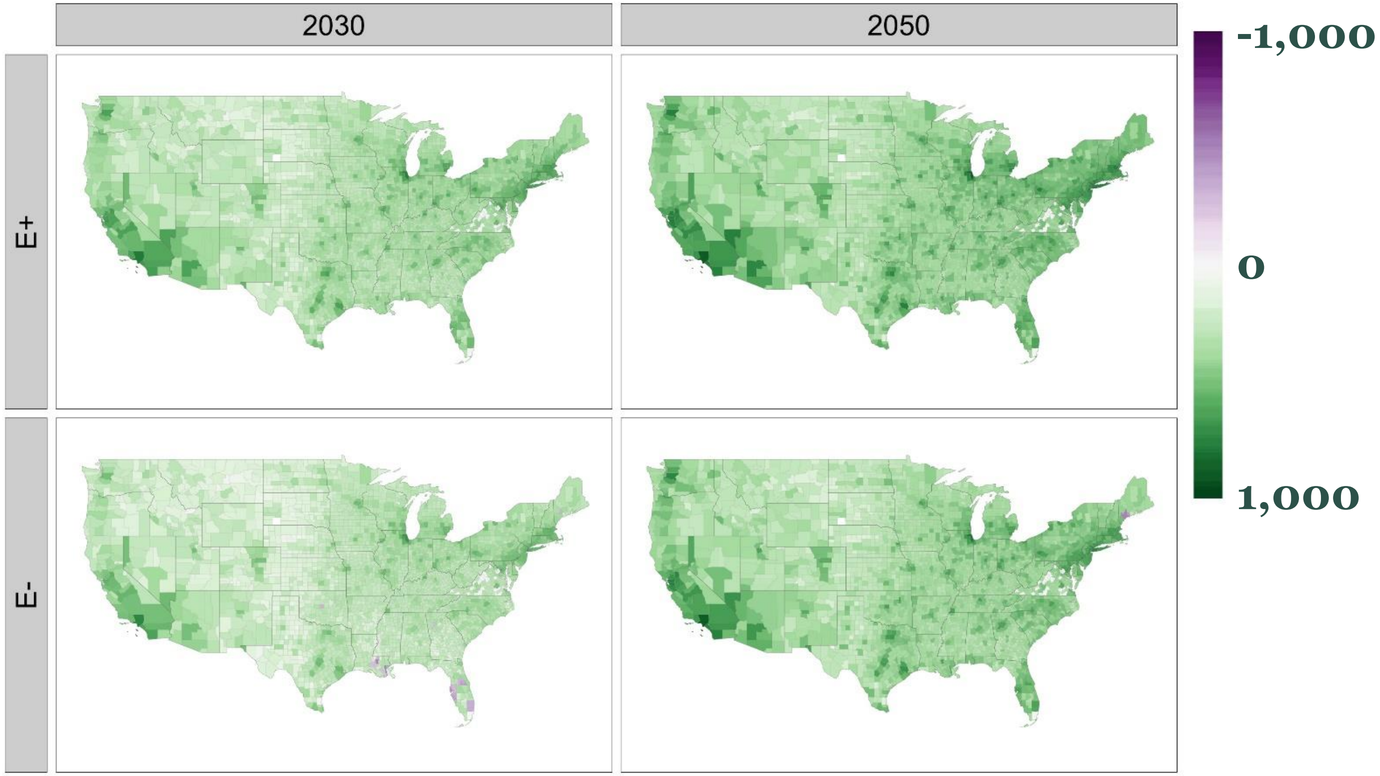
7 – 21k deaths (58 – 183B$ damages) associated with commercial heating & cooling are avoided from 2020 to 2050 by electrification.



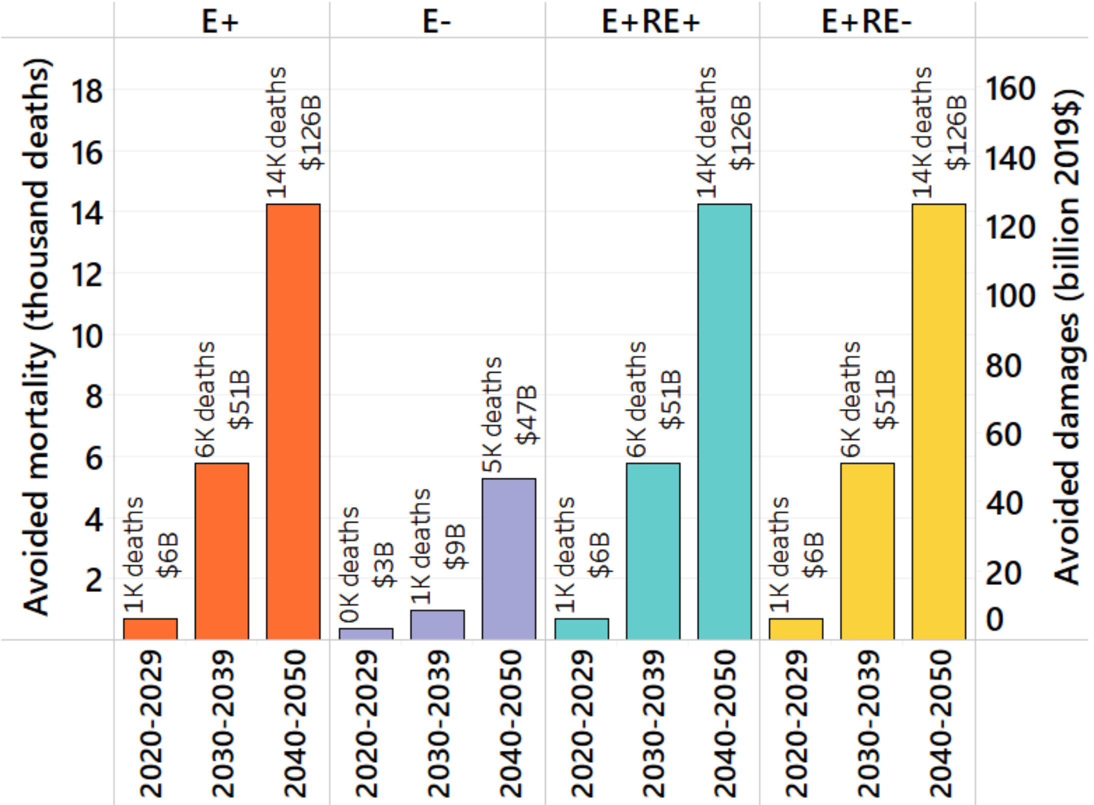
Includes air pollution impacts from combustion of coal, natural gas, oil, and other fuels for commercial heating and cooling.

7 – 21k deaths (58 – 183B$ damages) associated with commercial heating & cooling are avoided from 2020 to 2050 by electrification.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



Includes air pollution impacts from combustion of coal, natural gas, oil, and other fuels for commercial heating and cooling.

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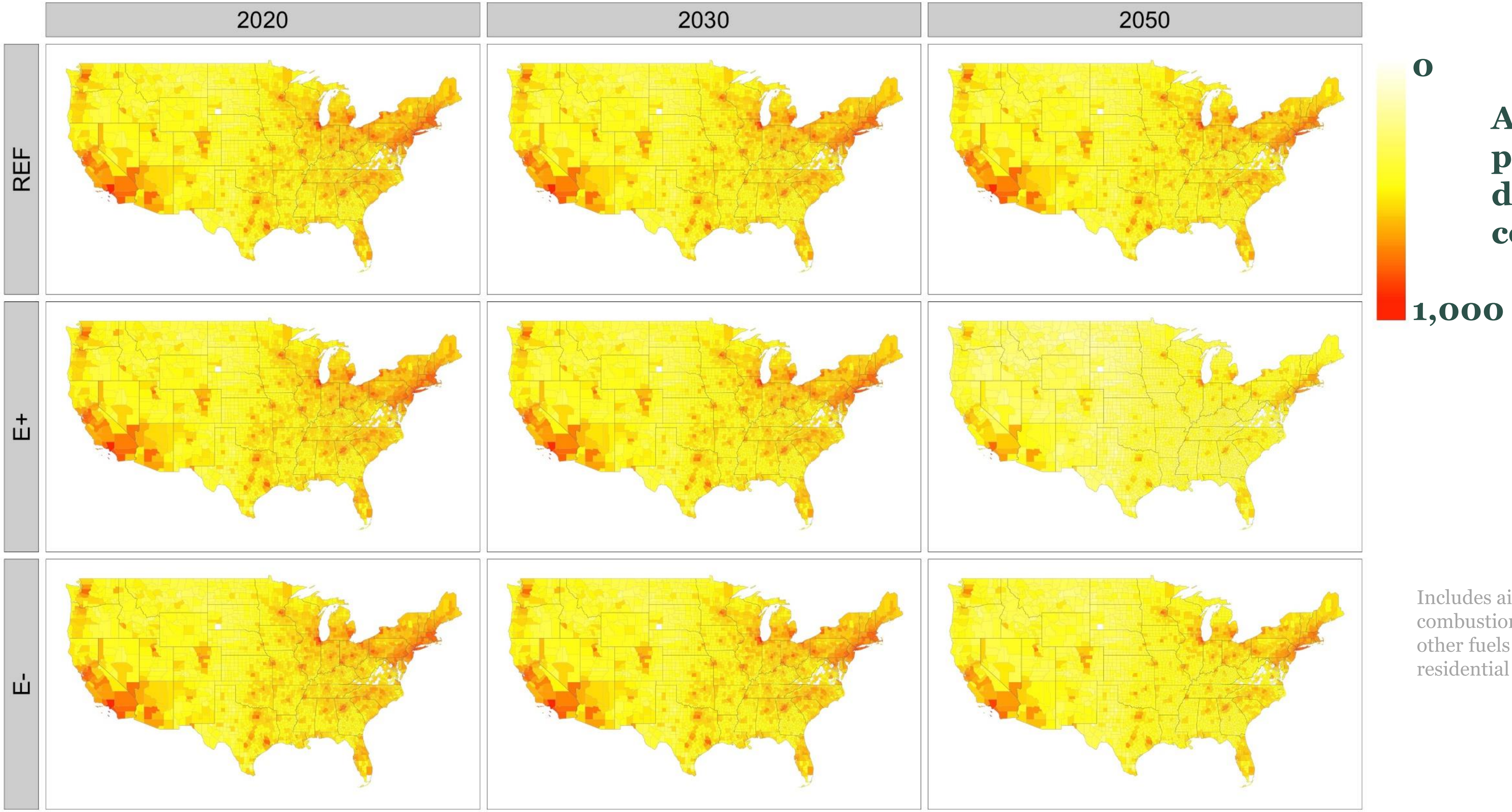
6 – 28k deaths (55 – 246B$) associated with residential heating and cooling are avoided from 2020 to 2050 by electrification.

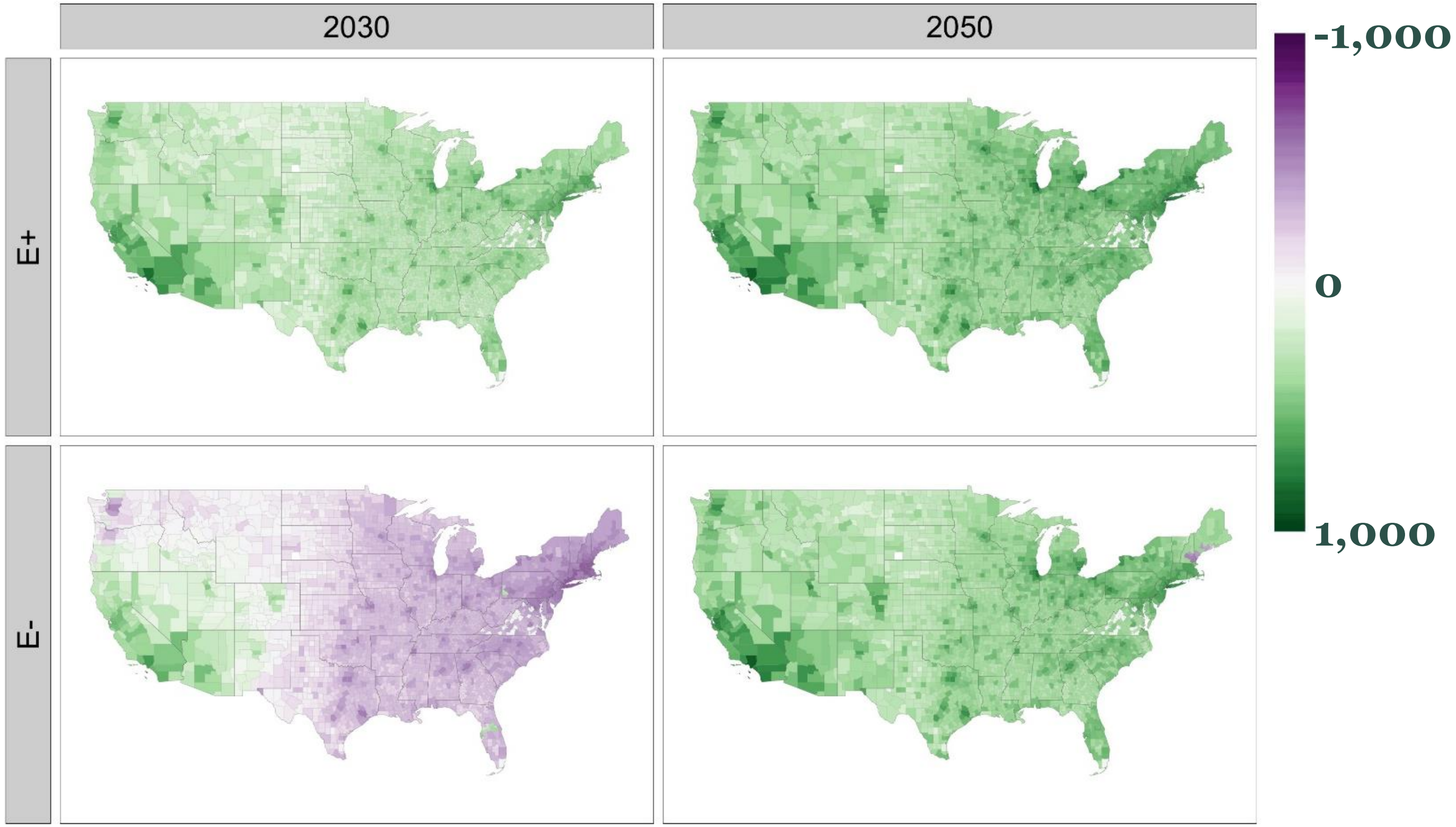


Annual premature deaths per county

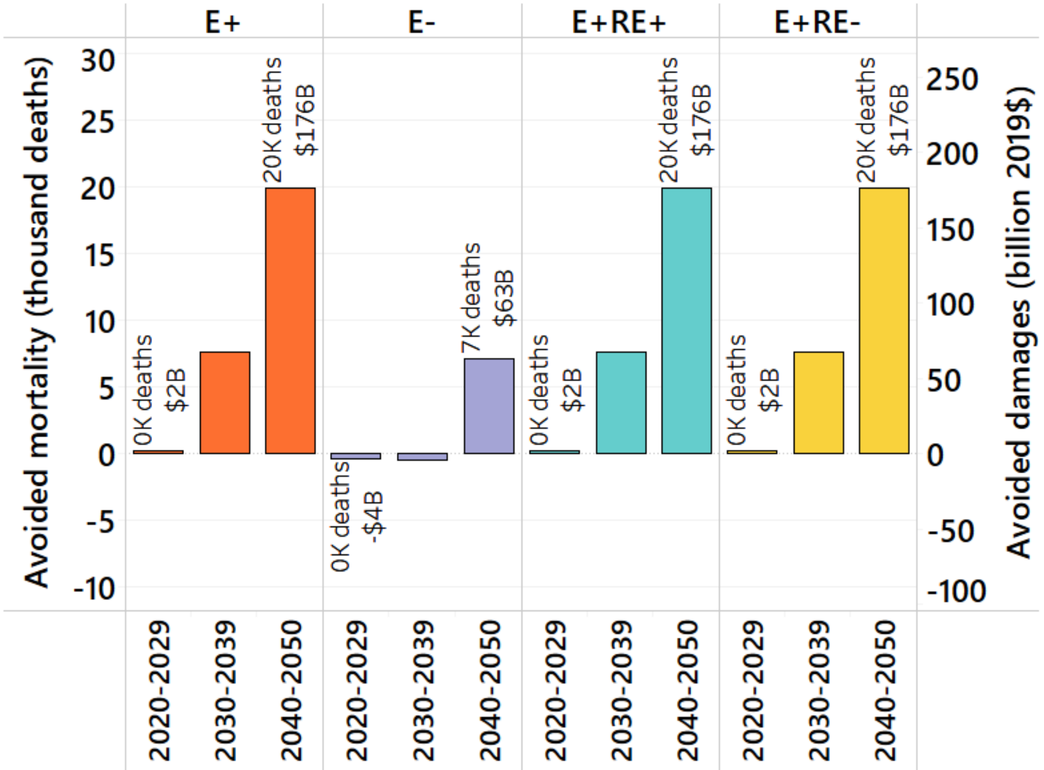
Includes air pollution impacts from combustion of natural gas, oil, and other fuels except wood for residential heating and cooling.

6 – 28k deaths (55 – 246B$) associated with residential heating and cooling are avoided from 2020 to 2050 by electrification.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



Includes air pollution impacts from combustion of natural gas, oil, and other fuels except wood for residential heating and cooling.

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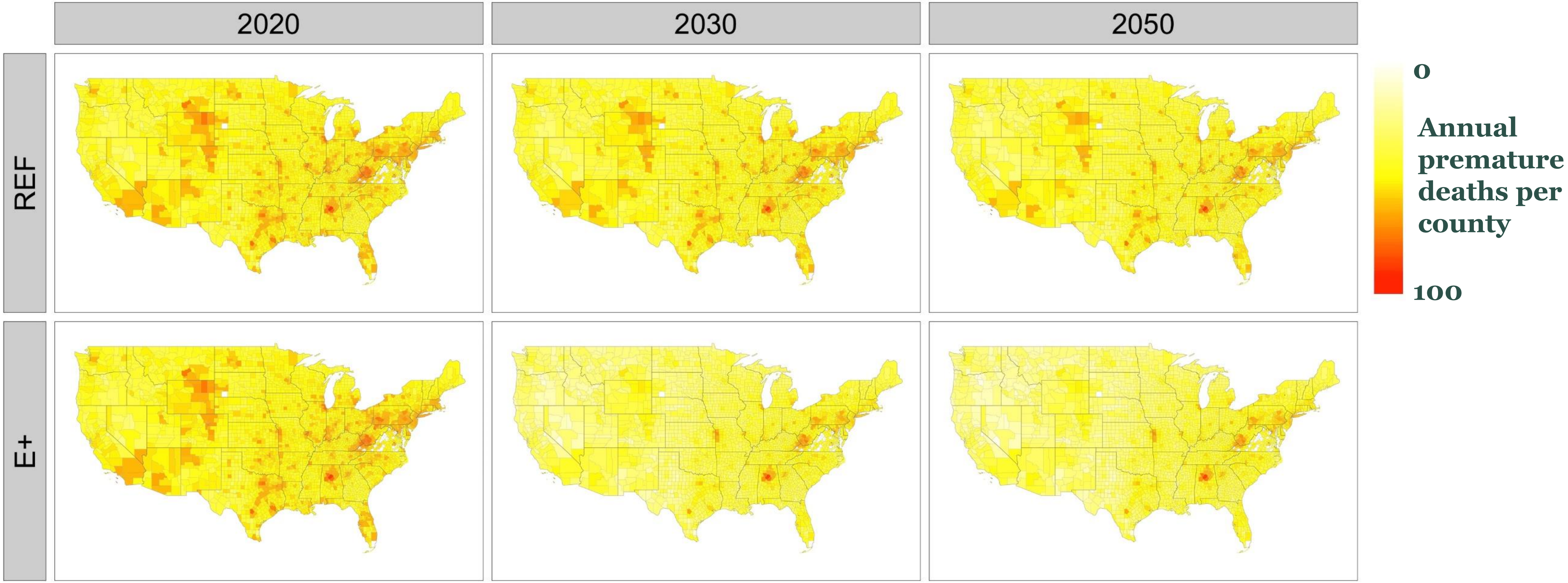
2k deaths (14B$ damages) due to air pollution from coal mining are avoided from 2020 to 2050 as a result of reductions in coal use.



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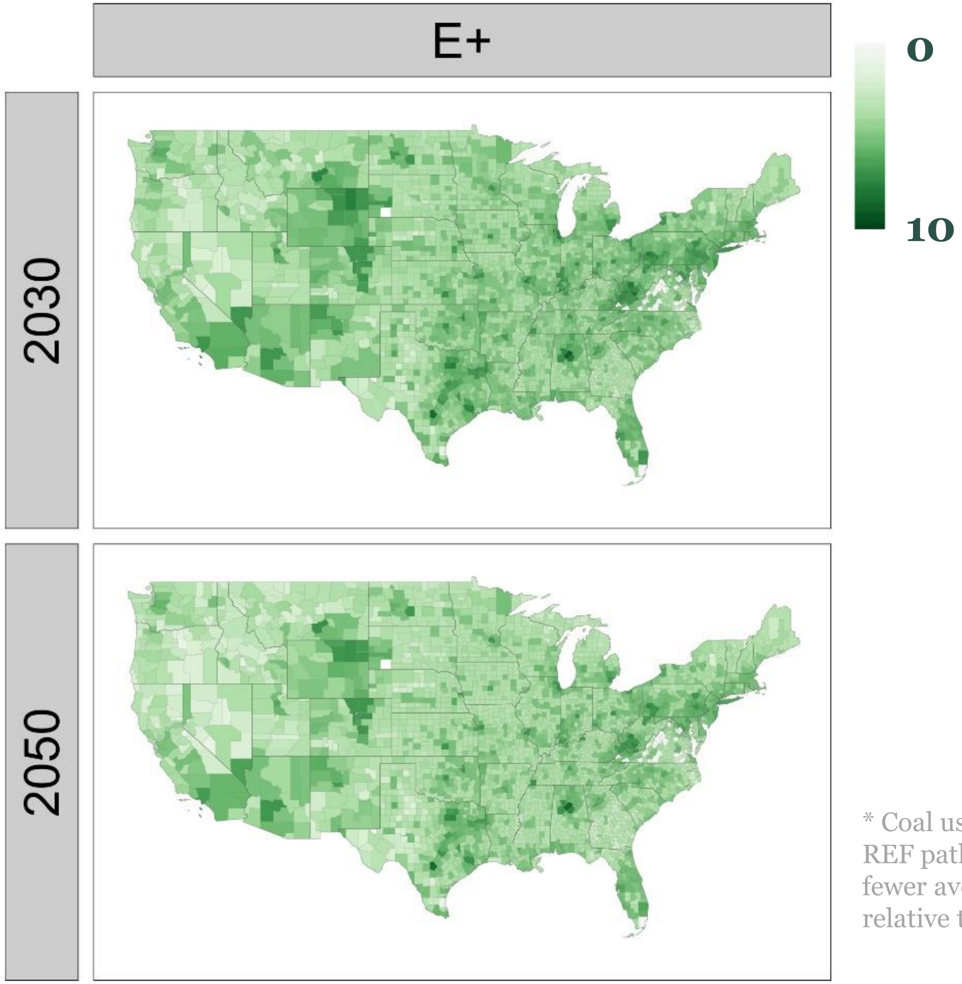
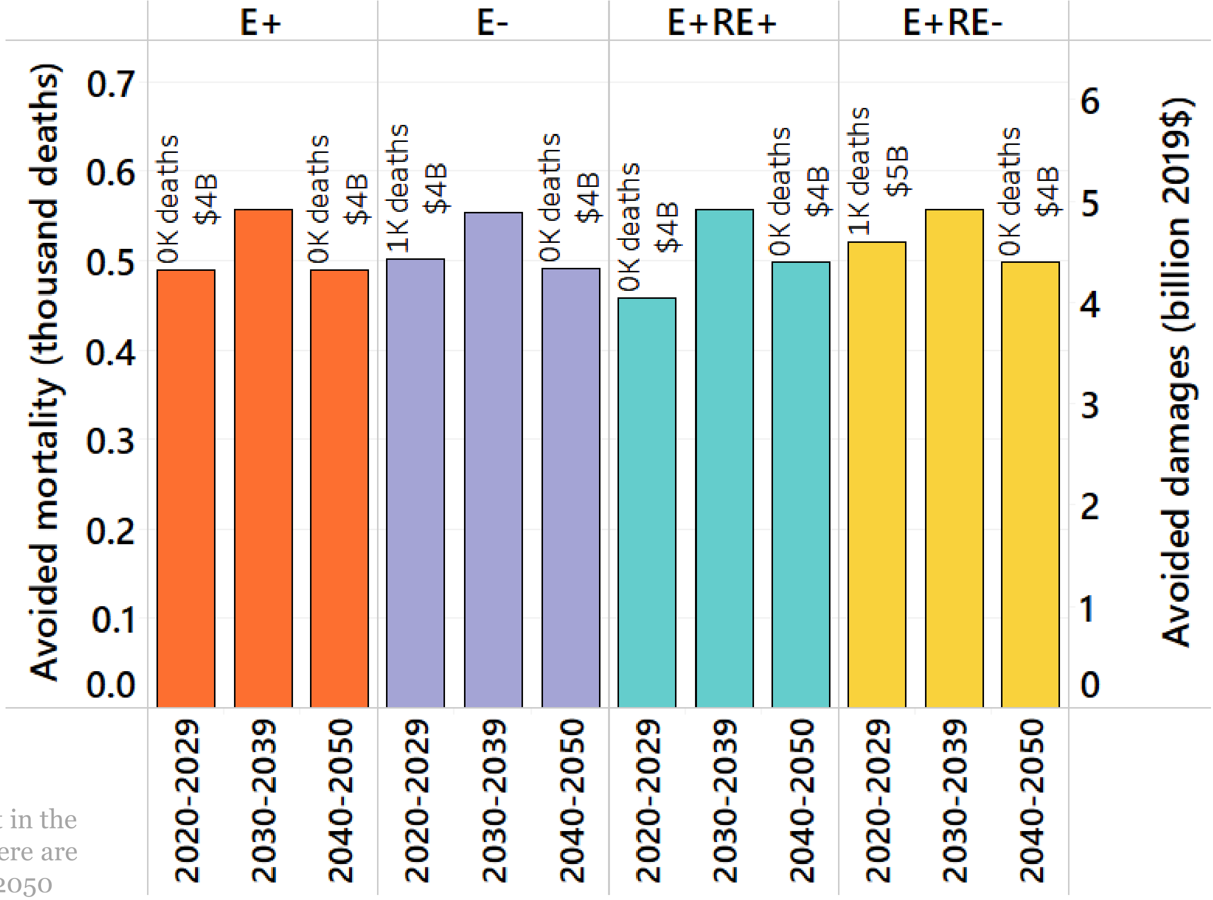
2k deaths ($14B damages) due to air pollution from coal mining are avoided from 2020 to 2050 as a result of reductions in coal use.

Annual avoided premature deaths per county [relative to REF*]



Avoided premature mortalities by decade [relative to REF]



* Coal use declines somewhat in the REF pathway. As a result, there are fewer avoided mortalities in 2050 relative to REF than in 2030.

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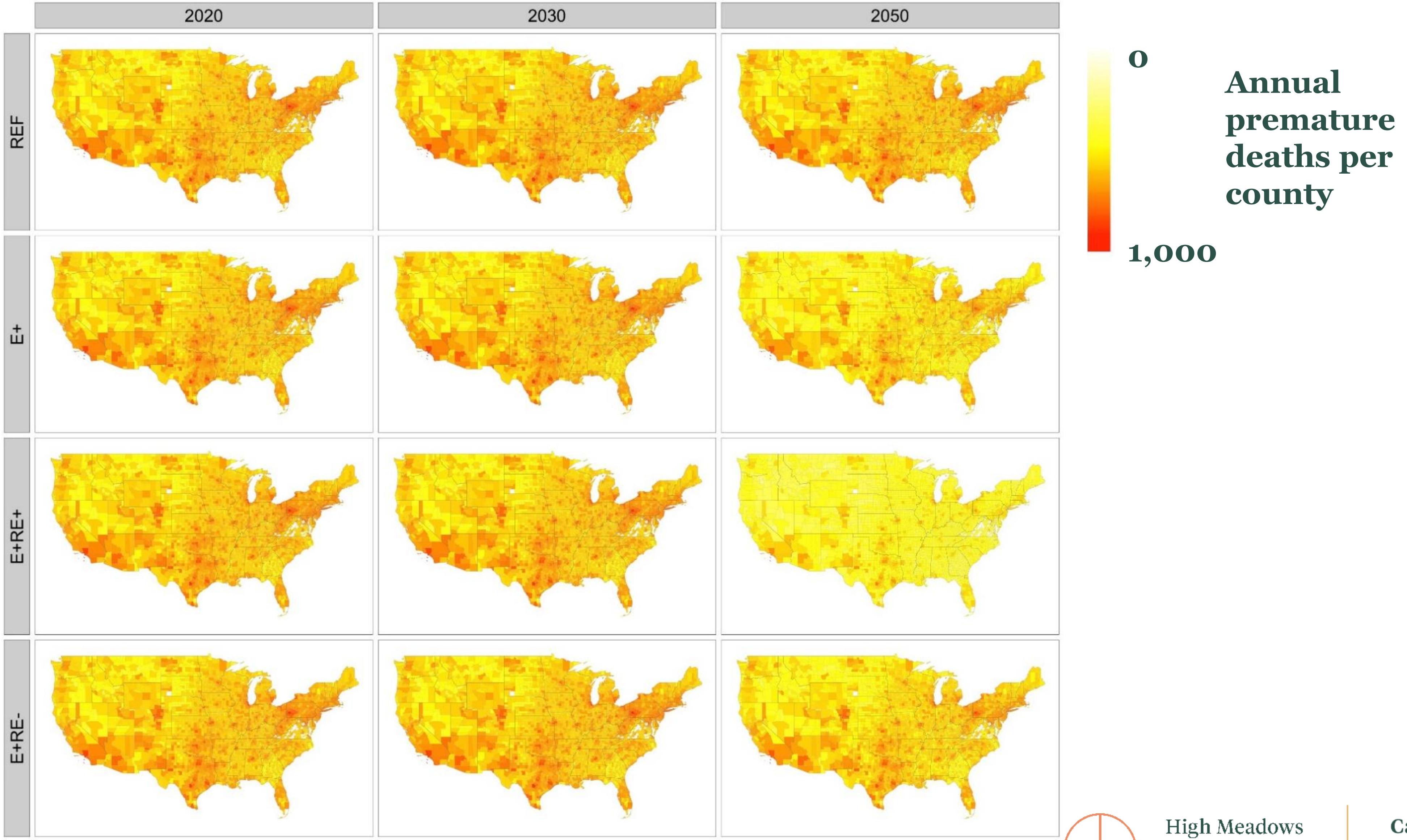
22 – 45k deaths (193 – 395B$ damages) due to emissions from oil and gas production are avoided from 2020 to 2050.



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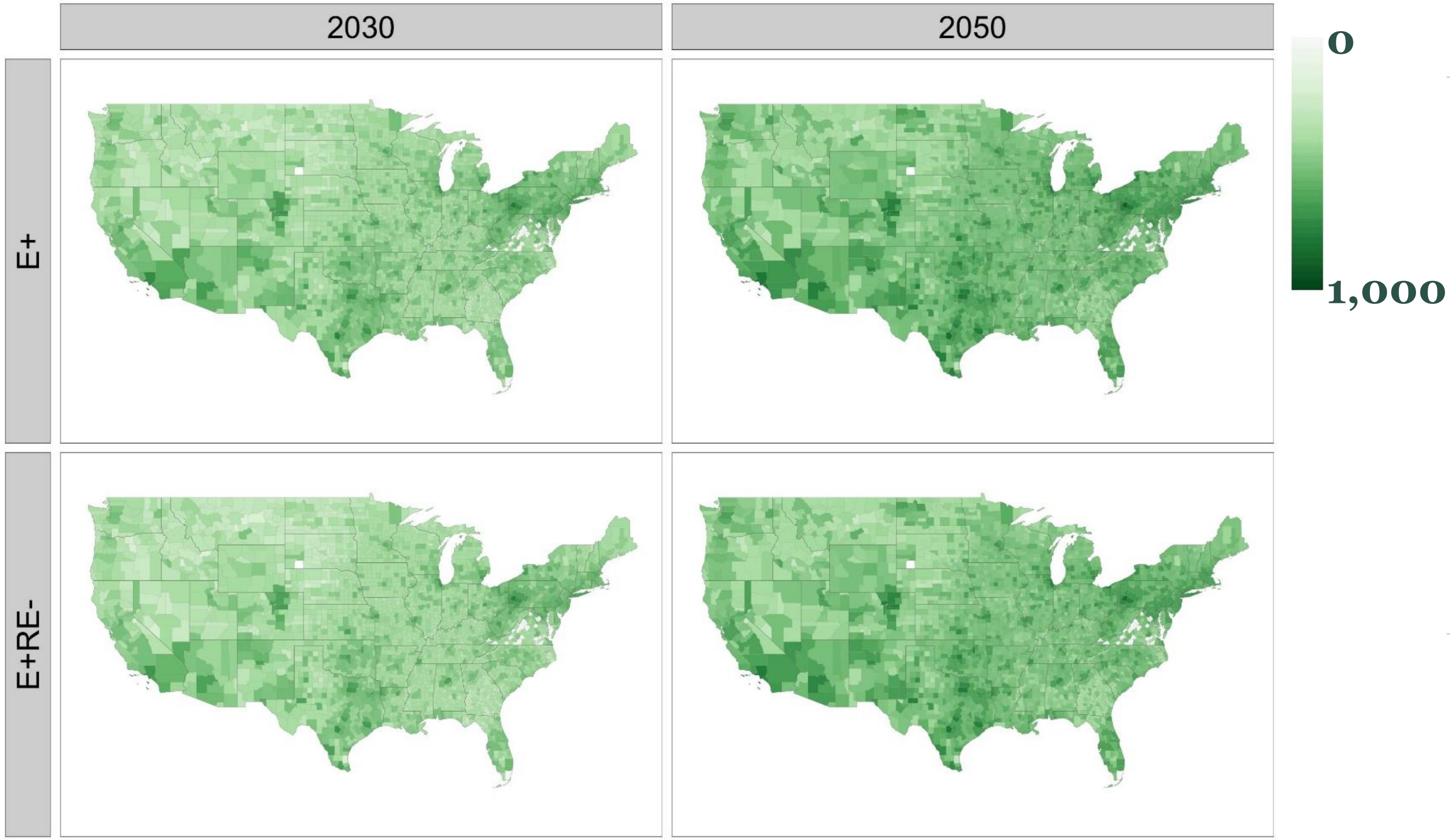
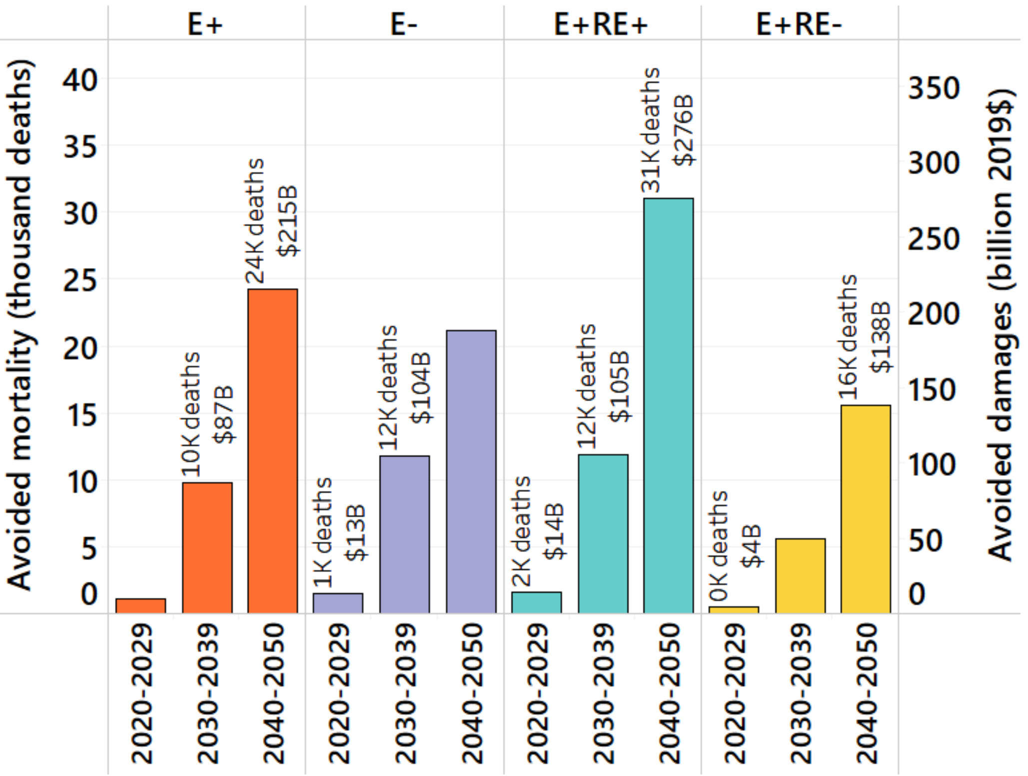
22 – 45k deaths (193 – 395B$ damages) due to emissions from oil and gas production are avoided from 2020 to 2050.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



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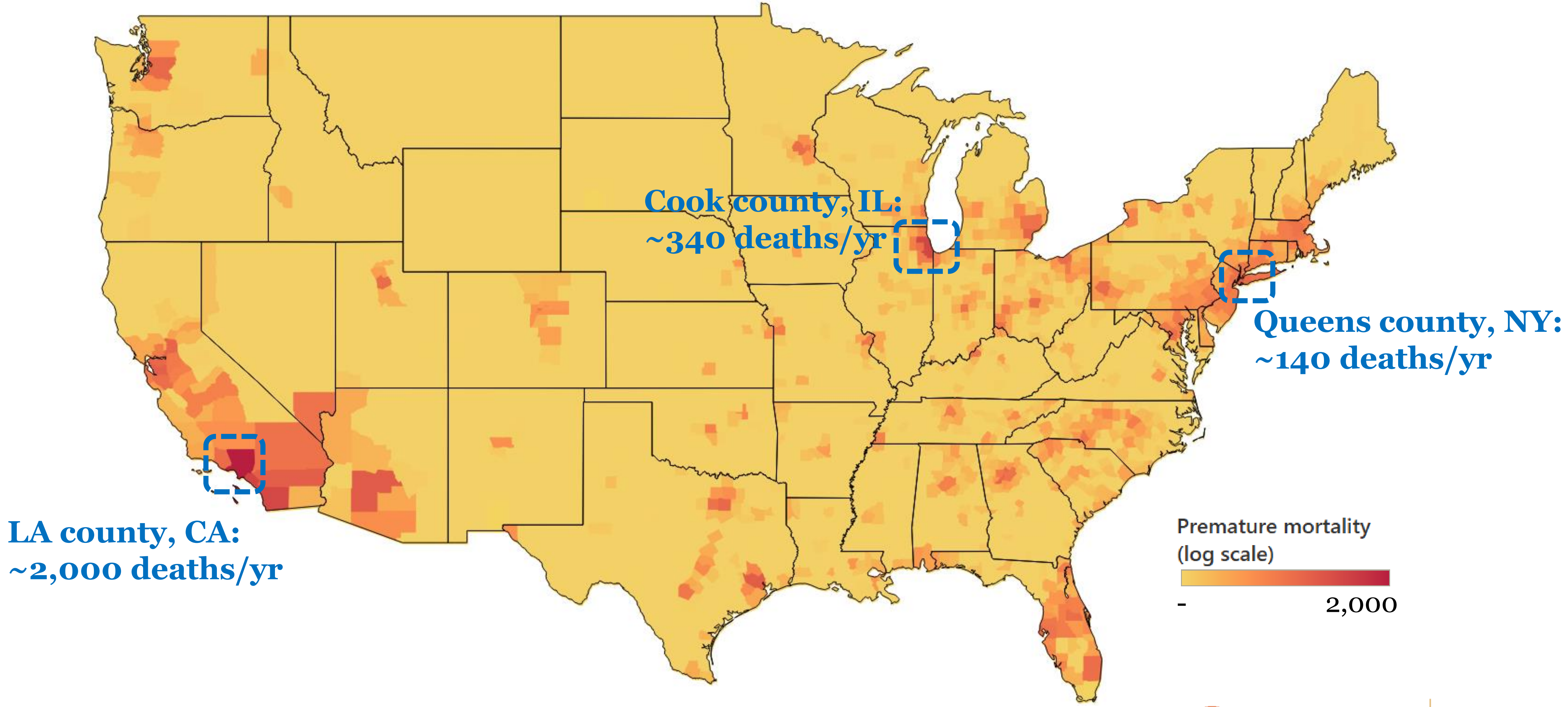
In 2019, ~11,000 premature mortalities (100B$ damages) were associated with emissions from the on-road mobile sources.



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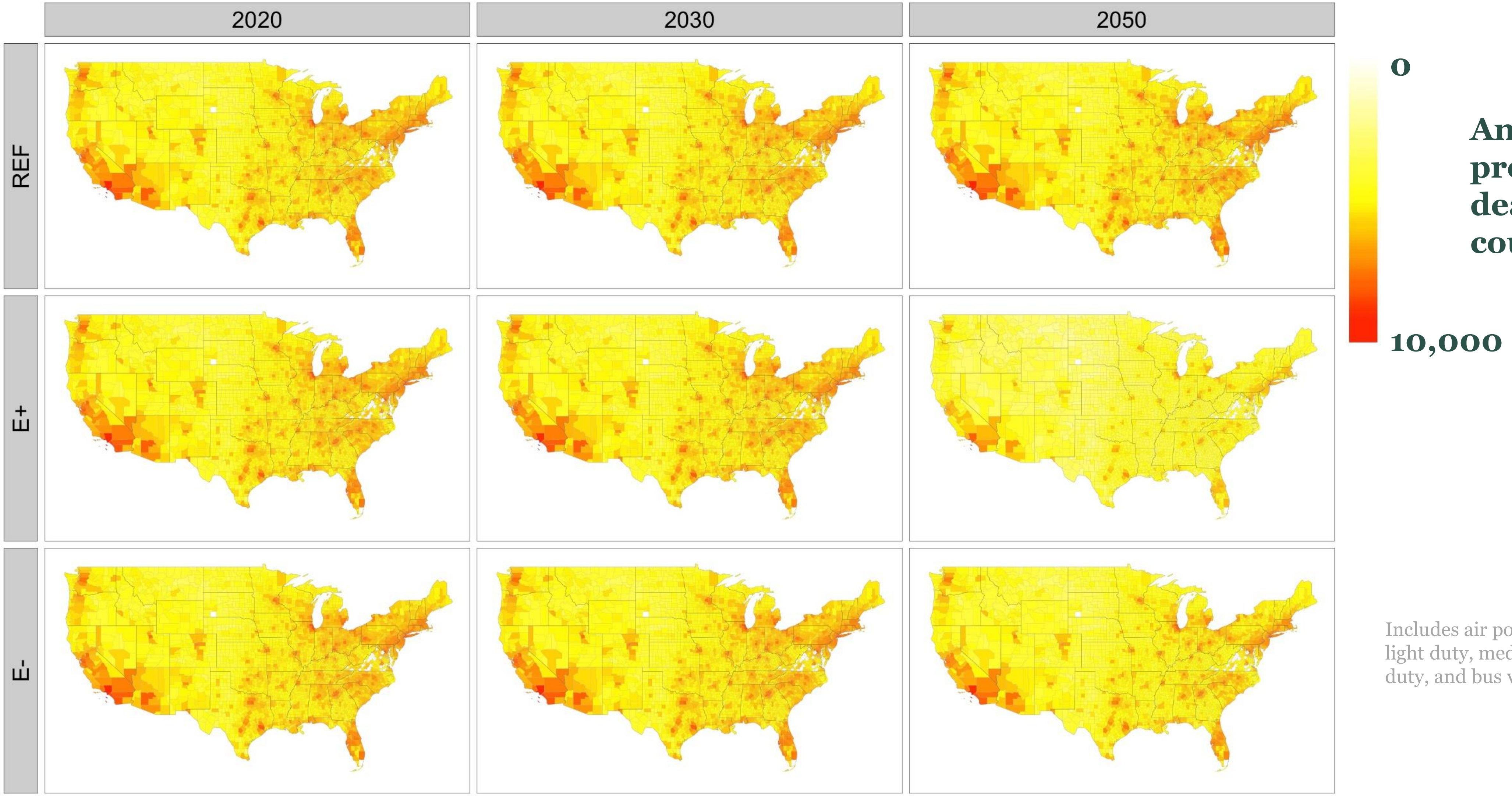
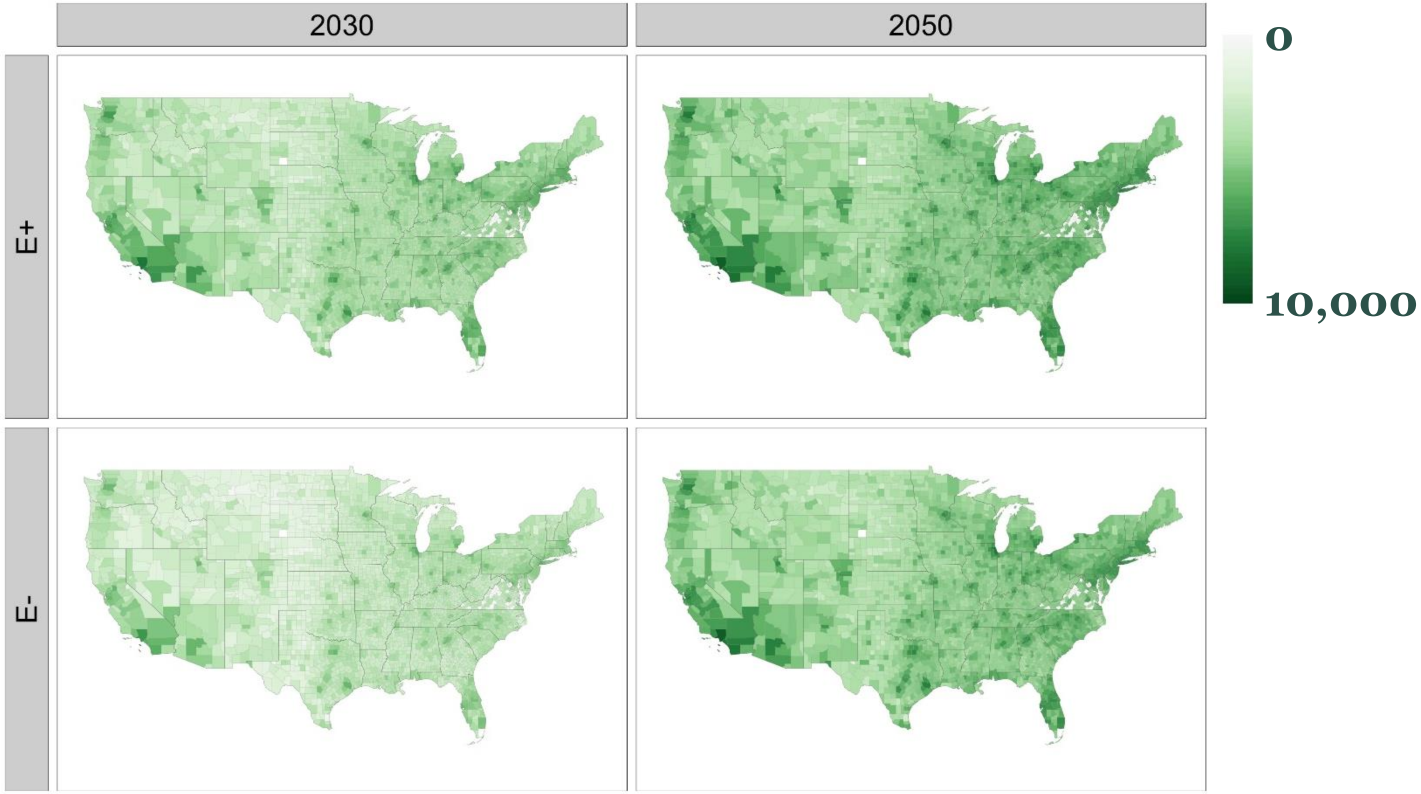
Air pollution benefits from vehicle electrification largely accrue after 2030 and accelerate through to 2050.



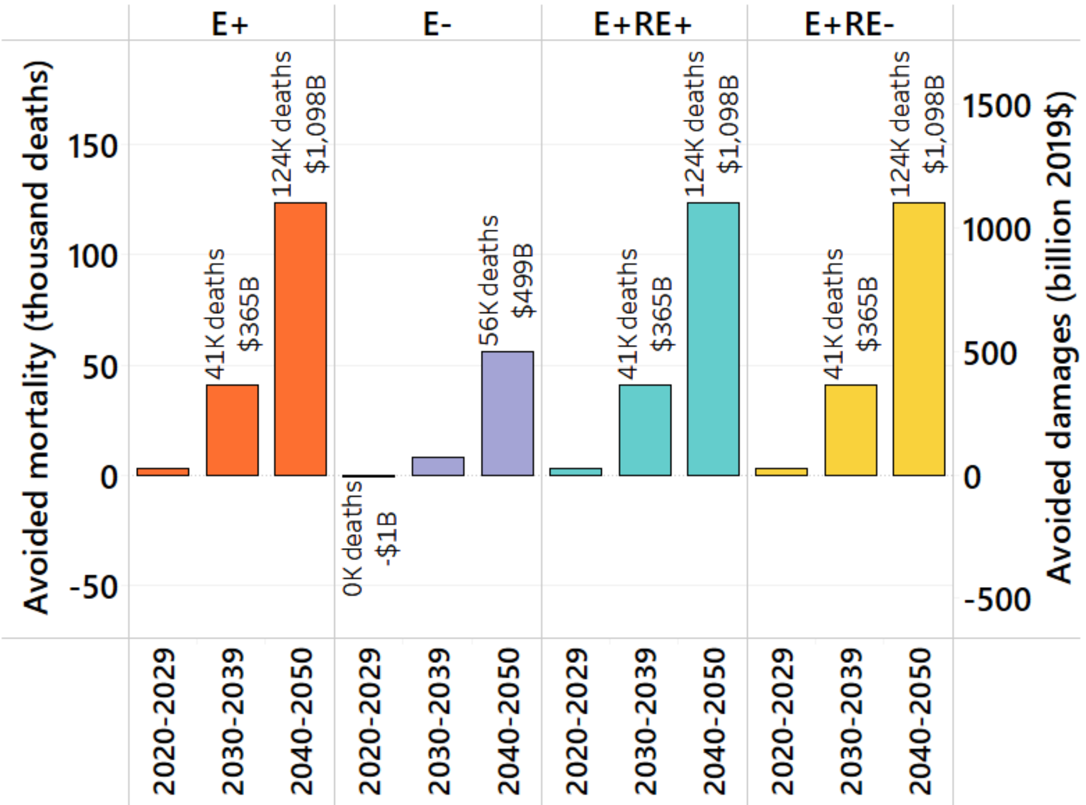
Includes air pollution impacts from light duty, medium duty, heavy duty, and bus vehicle classes.

64 – 167k deaths (570 – 1,490B$ damages) are avoided from 2020 to 2050 by electrification of on-road vehicles.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



Includes air pollution impacts from light duty, medium duty, heavy duty, and bus vehicle classes.

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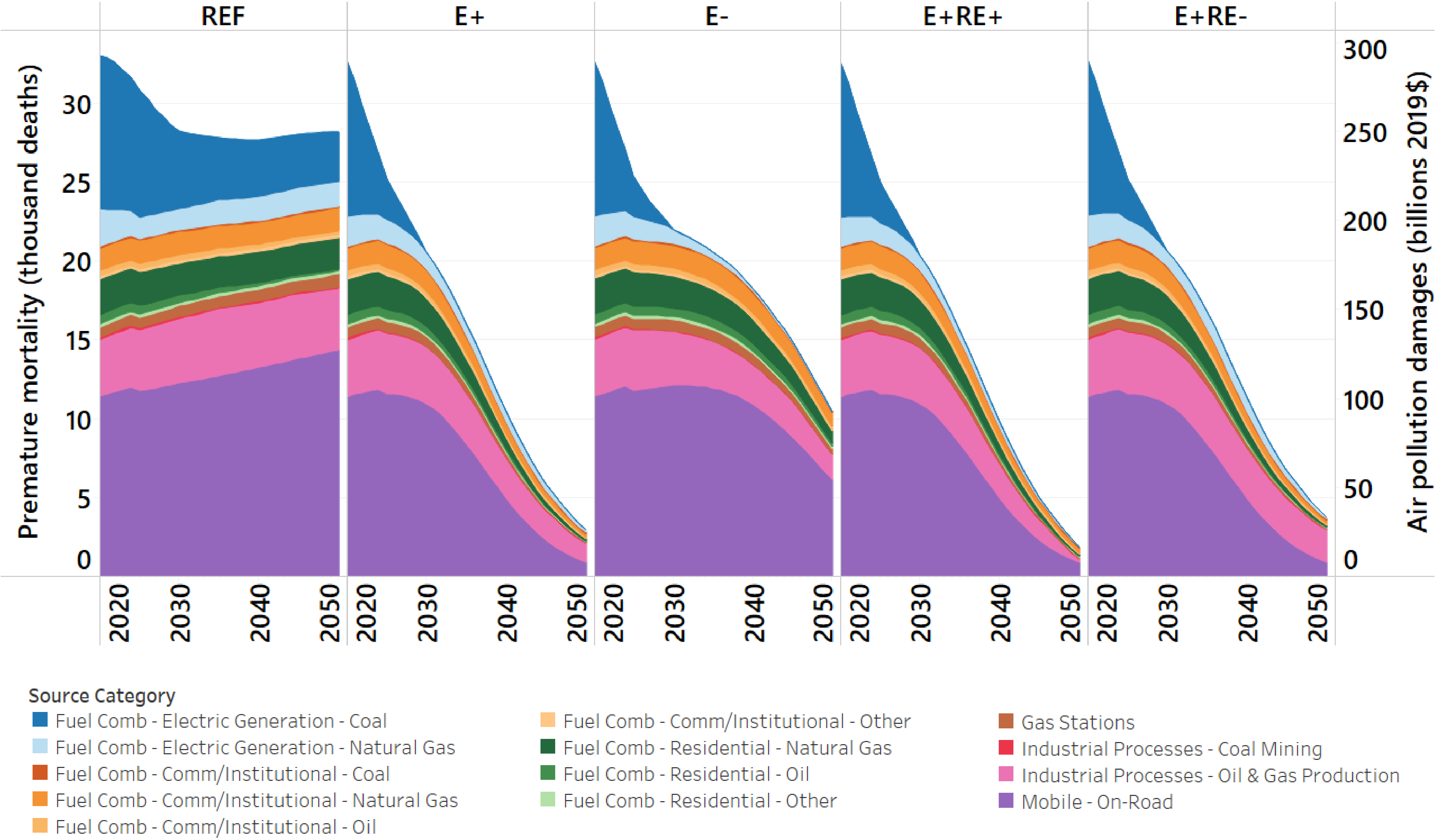
Collectively across all modeled air-pollutant source categories, 260 – 410k deaths (2.3 – 3.7 T$) are avoided from 2020 to 2050.



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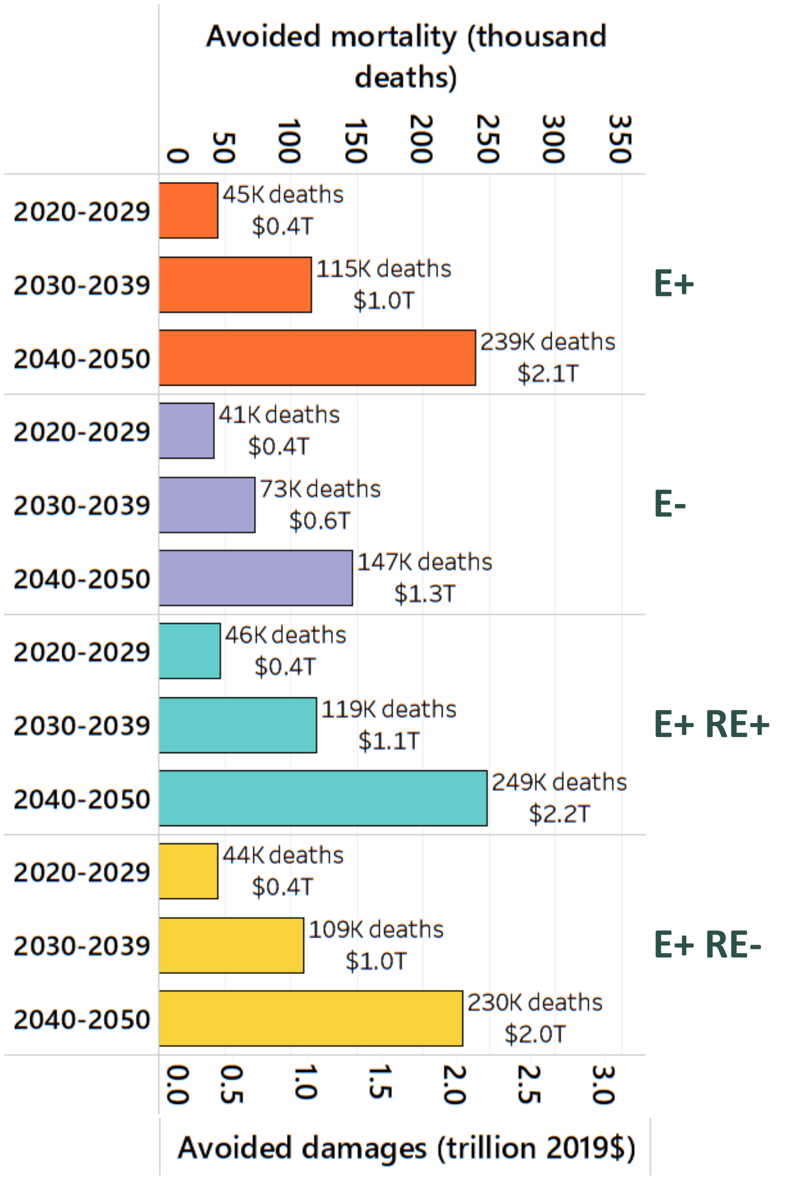
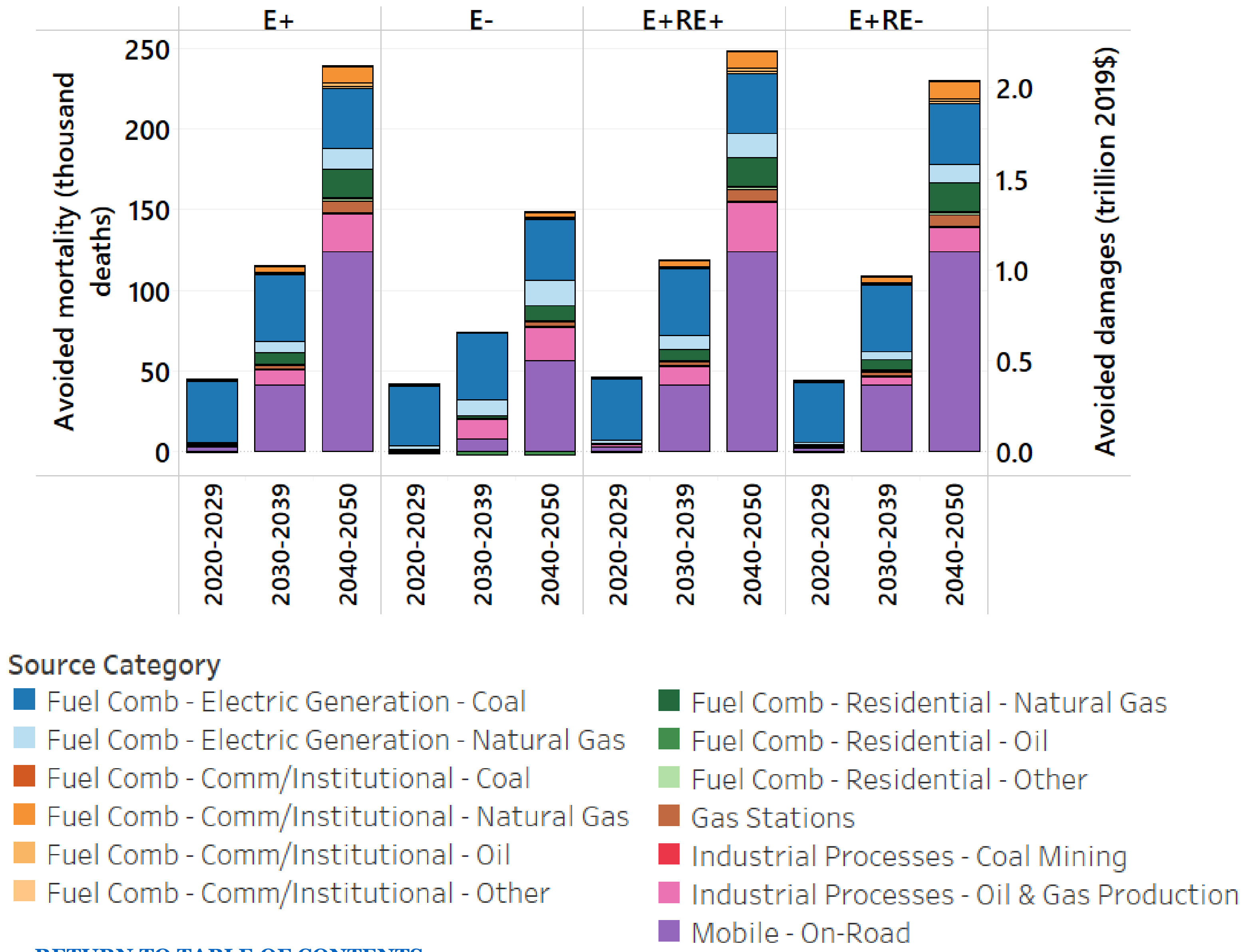
Air quality gains in 2020's are mostly from coal retirements. Vehicle electrification & natural gas transition contribute more after that.





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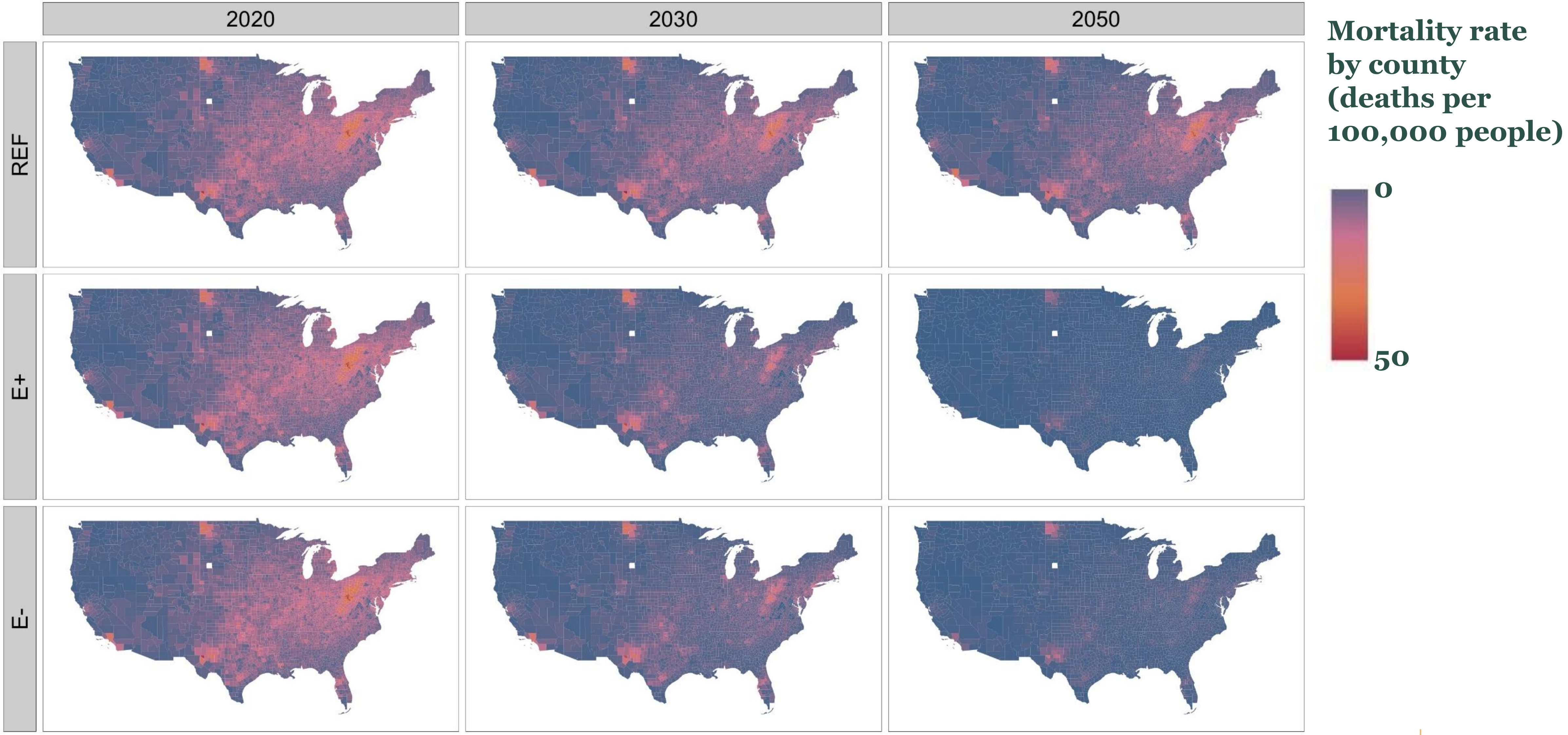
All localities benefit from air pollution reductions in going to net-zero greenhouse gas emissions.



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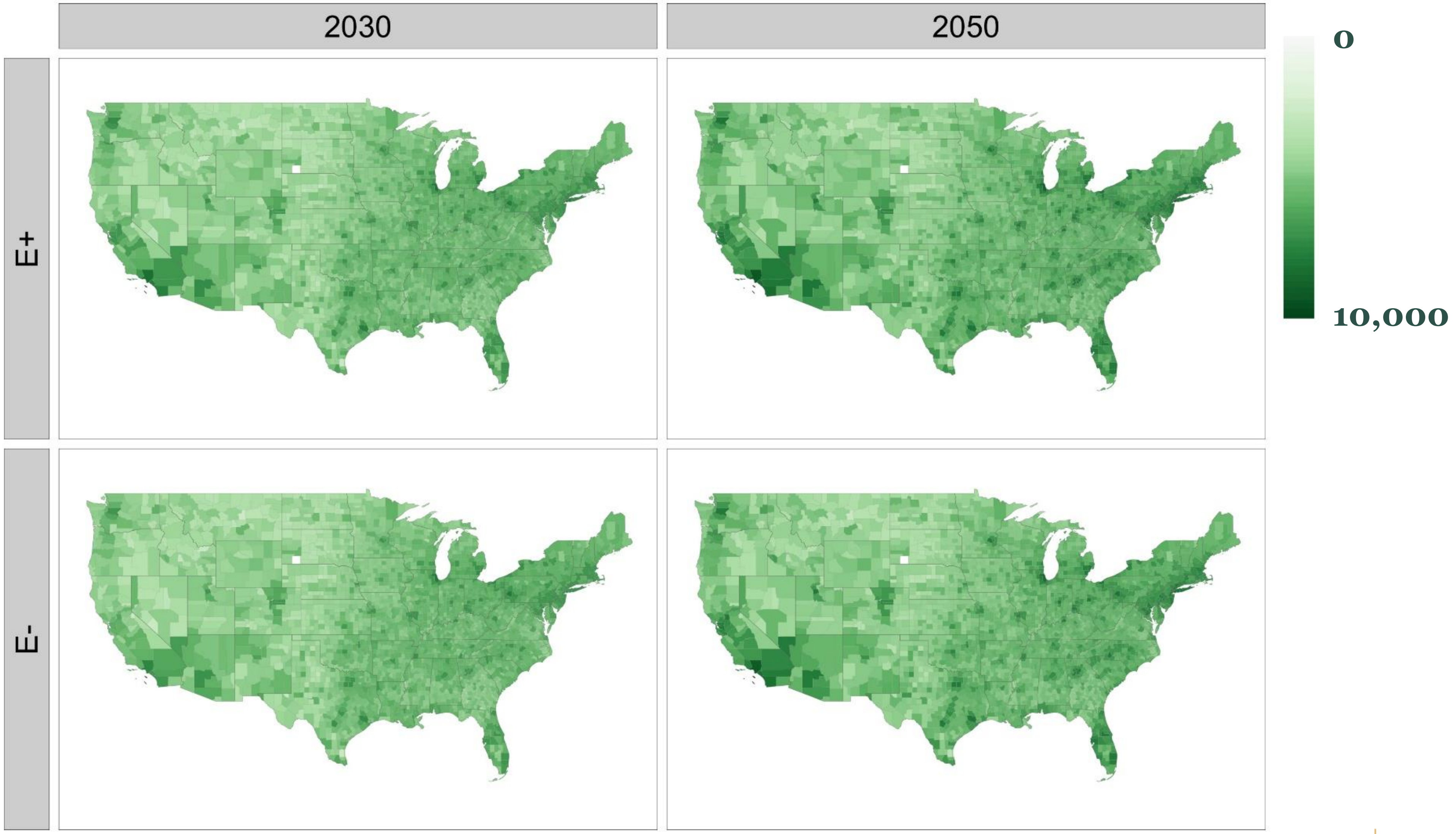
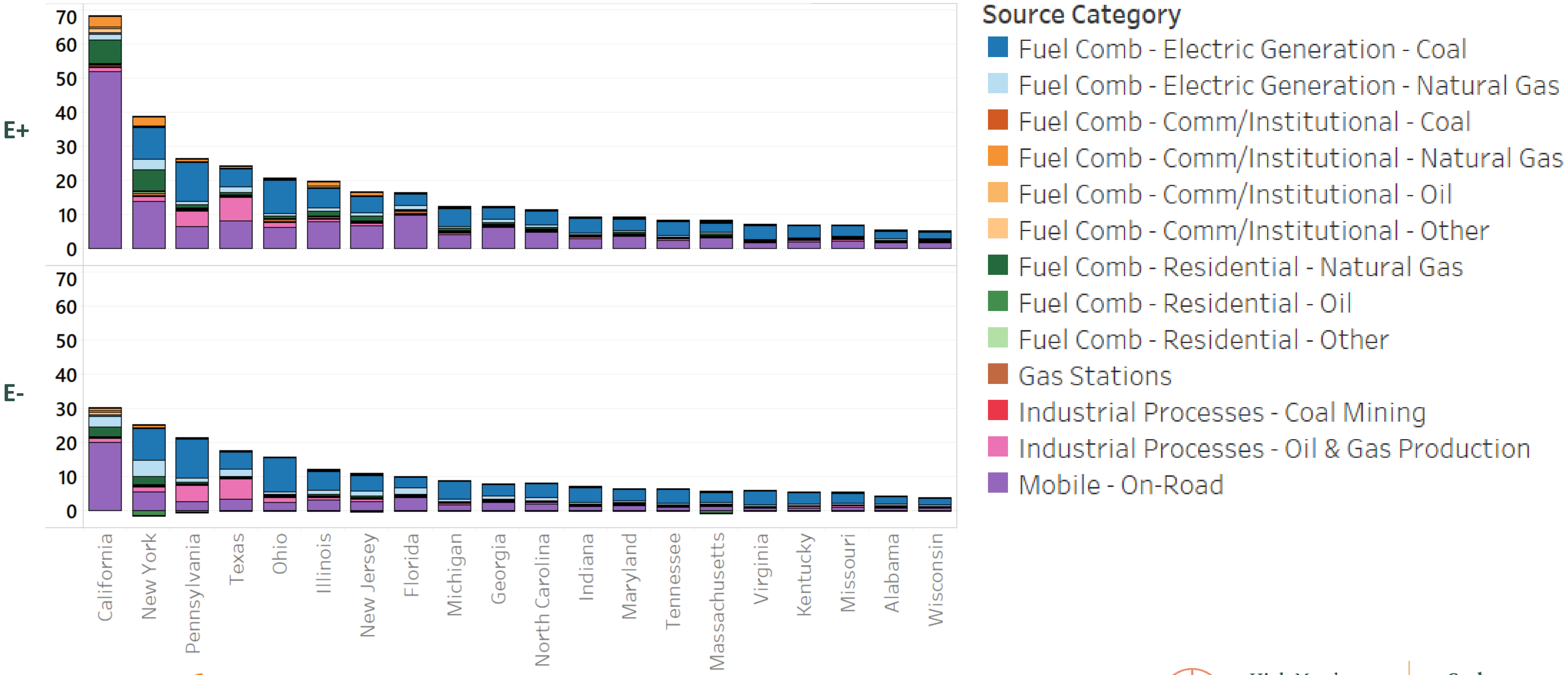
All localities benefit from air pollution reductions in going to net-zero greenhouse gas emissions.

Annual avoided premature deaths per county [relative to REF]



Cumulative air pollution-related health benefits at the state-level are significant in the transition to net-zero.

Avoided mortality, 2020-2050 (1,000 deaths)



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Summary of this section

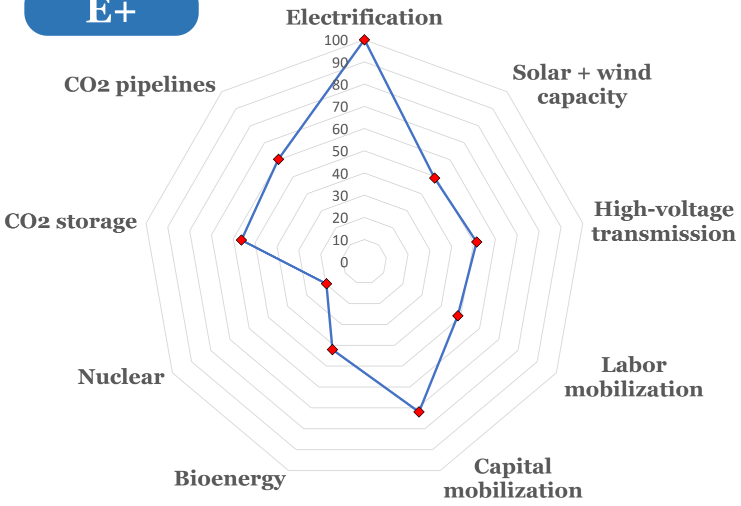
- Each of the five modeling pathways to net-zero emissions by 2050 presents different, but similarly daunting challenges to success.
- A successful transition to net-zero emissions by 2050 implies significant cumulative impacts, both positive and negative, that vary across the different net-zero pathways.
- Net-zero emissions for the U.S. by 2050 is achievable and affordable if four key risks are mitigated through widespread and coordinated actions that begin immediately:
    1. Failure to deploy physical assets and infrastructure at unprecedented rates
    2. Failure to mobilize capital investments at unprecedented rates
    3. Failure to gain and sustain social license
    4. 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+



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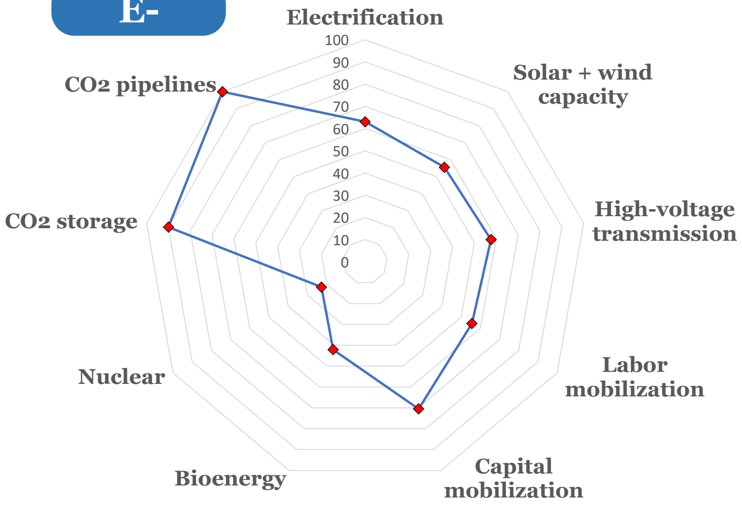

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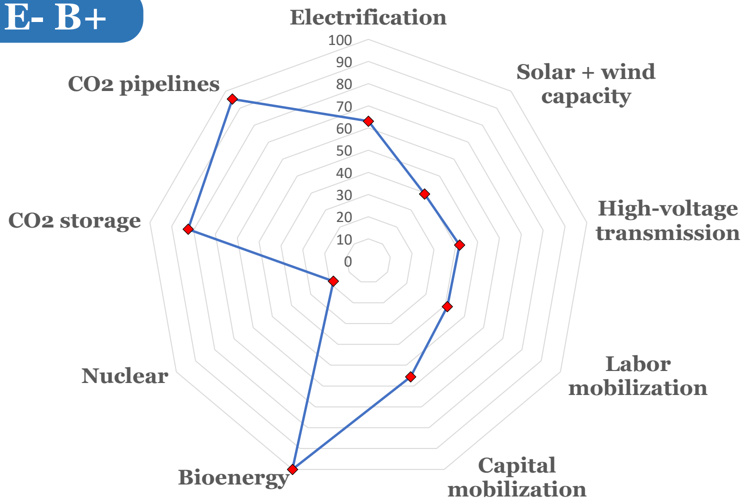
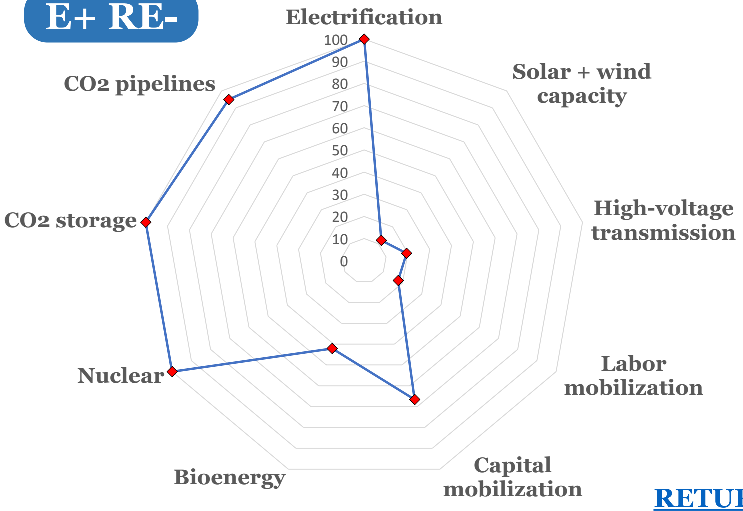
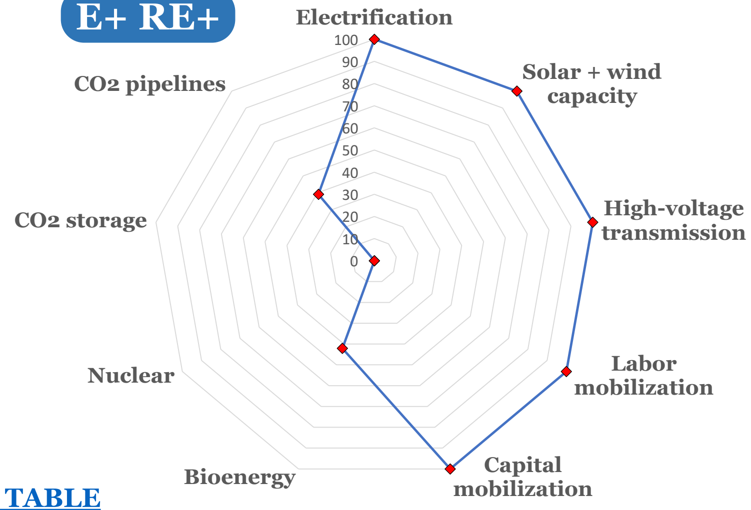


E+ RE-



E+ RE+



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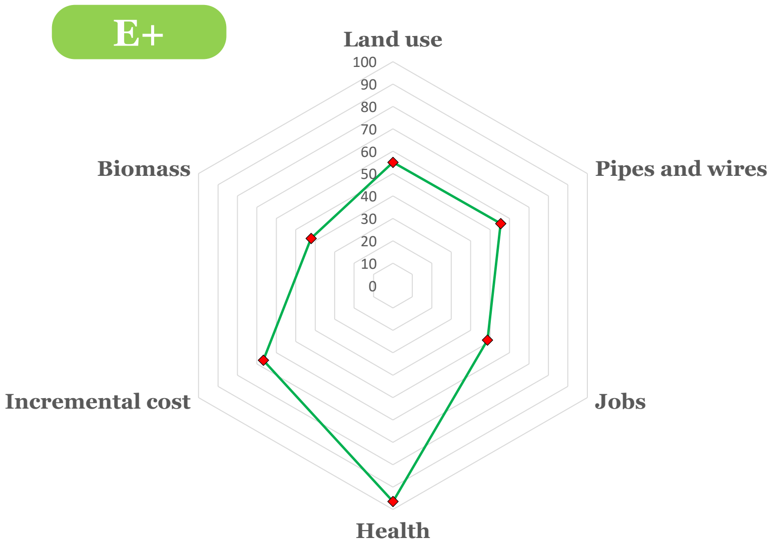
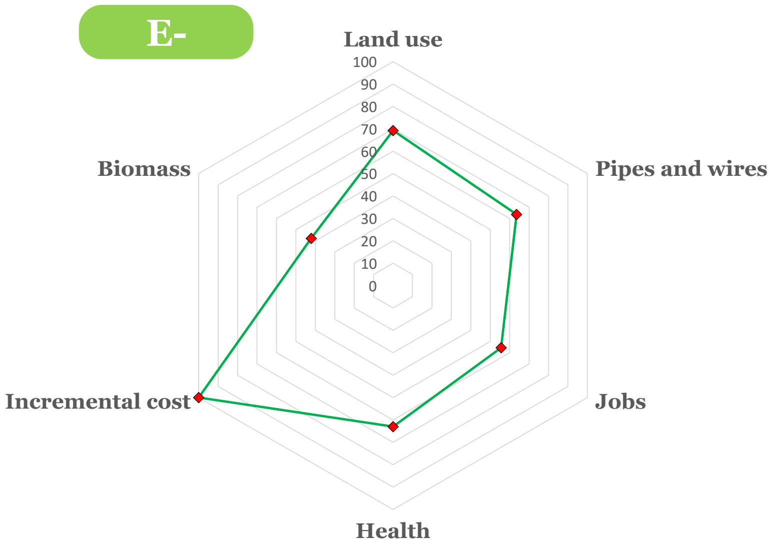
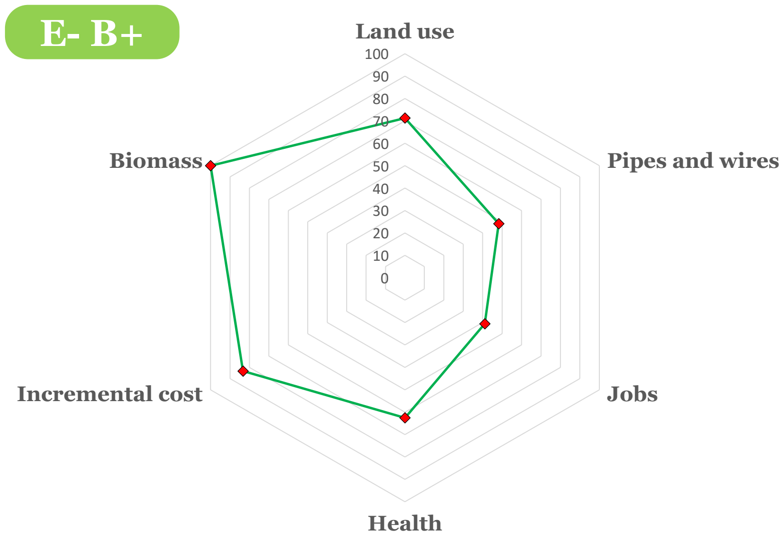
A successful net-zero transition implies cumulative impacts by 2050 (relative to REF) that vary across net-zero pathways

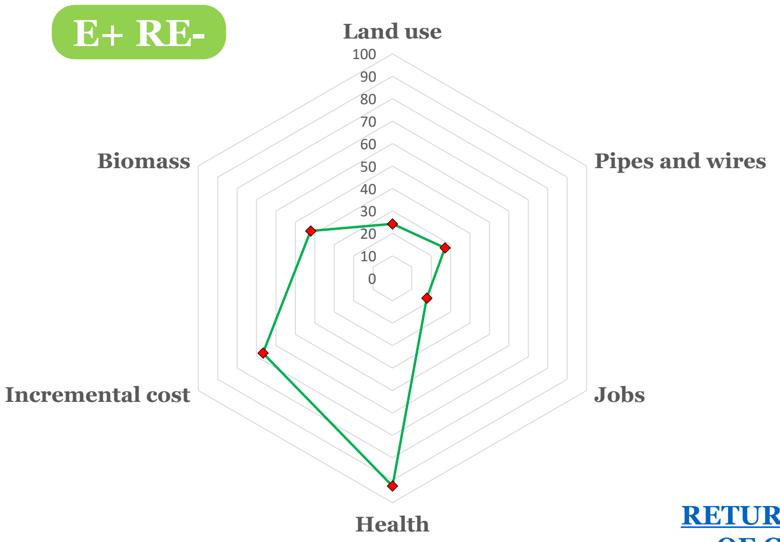
Level of Impact (ordinal ranking)	
0	Lowest
100	Highest

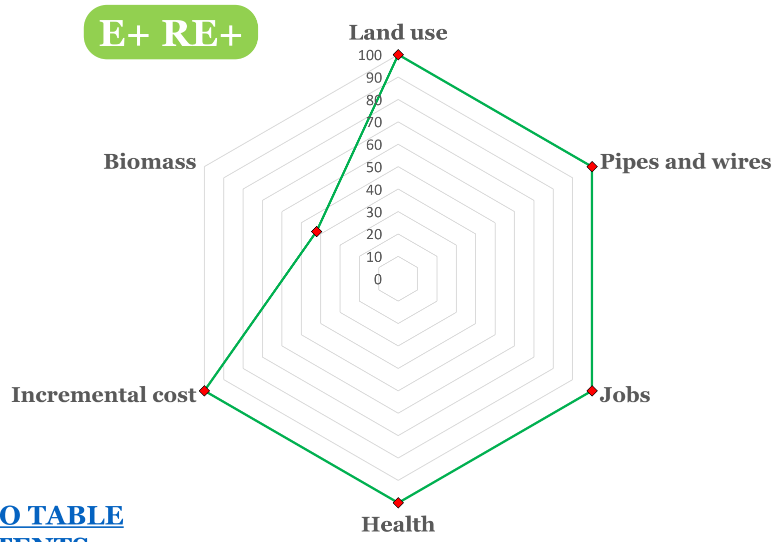
Impact	Comparative metric
Land use	Total km² solar, wind, biomass + DAC, 2050
Pipes & wires	Cumulative capital for HV transmission & CO_2 pipelines, 2020 – 2050
Jobs	Average annual energy jobs in 2040s vs. REF
Health	Cumulative avoided premature deaths, 2020 to 2050.
Cost	NPV of energy-system costs,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











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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

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 project developments.

3. Failure to gain and sustain social license

- 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.

A blueprint for action in the 2020s: key priorities

Summary of this section

- This section presents a blueprint for action in the 2020s.
- Priority actions include a set of robust investments needed this decade to get on track to net-zero emissions by 2050, regardless of which net-zero pathway the country follows in the longer term. These can be made with confidence that they will deliver value over the long term:
  - Renewable electricity generation and transmission
  - Electrification of end uses, including vehicles and building heat
  - Industrial productivity improvement
  - Increase carbon uptake and storage in forests and in agricultural soils
  - Reduce non-CO_2 greenhouse gas emissions
- Actions for the 2020s also include a set of important investments in enabling infrastructure and innovative technologies to create real options to complete the transition to net-zero beyond 2030:
  - Plan and begin building:
    - Additional electricity transmission to enable accelerating wind and solar expansion
    - A nationwide CO_2 transportation network and permanent underground storage basins
  - Invest in maturing a range of technologies to make them cheaper, scalable and ready for widespread use in the 2030s and beyond.

Net-zero by 2050 would require 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

Priorities for the 2020's: Behaviors, institutions, markets

1 Build societal commitment, investment environment, and delivery capabilities

- Major stakeholder engagement campaigns to build:
  - i. *Broad societal awareness* of local, state and national benefits of net-zero energy pathways; and
  - ii. *Acceptance, management, and mitigation of impacts* on landscapes and communities associated with the transition.
- Major consumer awareness campaigns and incentives to drive low-carbon energy investment decisions
- Redesign markets and institutions for a low-carbon future
  - i. *Reform electricity markets* to ensure electricity supply reliability as solar and wind contributions increase; and to value flexibility on both the supply side and the demand side
  - ii. *Improve permitting efficiency* to accelerate successful project and infrastructure siting without compromising quality of environmental and social impact assessment.
  - iii. *De-risk spending of at-risk capital* to accelerate investment decision processes in support of rapid capital expansion
- Develop workforce to support net-zero pathways
  - i. *Signal state-by-state demand and future priorities* to education and training institutions
  - ii. *School outreach programs* to encourage uptake of key STEM degrees, vocational training and trades
  - iii. *Incentive programs* to encourage workforce shifts both between industries and between states
- Major stakeholder engagement campaigns and support programs to mitigate impacts on incumbent sectors and communities and organizations impacted by transitions
- Support for development and rapid expansion of project development capabilities and new industrial capacity and supply chains

Priorities for the 2020's: Demand-Side

2 Improve end-use energy productivity and efficiency

- Industry: Achieve 2% (or greater) per year sustained improvement in industrial end-use energy productivity
- Buildings: Reduce building space conditioning (heating/cooling) energy use through improved building shells, electric heat pumps, and controls
- Appliances: Ensure adoption of most efficient end-use appliances and consumer devices, including conversion of fuel-using devices to electricity
- Vehicles: Increase energy productivity by shifting transportation from single occupancy light duty vehicles to multi-occupancy vehicles, transit, cycling and walking; shift on-road trucking to rail freight; and steadily improve fuel efficiency of new ICE vehicles.

3 Electrify, especially transportation and buildings

- Electric vehicles: By 2030, half of all new light-duty vehicles sold are battery-electric; medium and heavy-duty trucks and bus sales are 15% battery-electric and 10% fuel cell. By 2030, there are ~50 million electric light duty vehicles on the road and ~1M medium and heavy duty trucks and buses. (These targets correspond to E+ scenario. Targets for E- would be lower.)
- Charging infrastructure: Build-out of publically-accessible EV charging infrastructure (ahead of EV adoption rate), including 2.4 million charging ports nationwide by 2030 for E+ scenario or 0.8 million ports by 2030 for E- scenario.
- Space heating: Deploy electric heat pumps in ¼ of current residences by 2030 (25-30 million households) plus ~15% of commercial buildings. Focus on new builds and end-of-life replacement of current stock in climate zones 1 through 5.
- Hot water: Deploy electric heat pump residential water heaters as end-of-life replacements for existing units.
- Automation: Expand automation and controls across electricity distribution networks and end-use devices to unlock flexibility of EV charging, space and water heating loads, and distributed energy resources and minimize distribution network expansion required to support electrification.

Priorities for the 2020's: Supply-side

4 Decarbonize and expand electricity

- Carbon-free electricity: Increase total U.S. electricity generation 10-20% by 2030, and double the carbon-free share (to ~75%).
- Wind and solar: Deploy about 300 GW of wind (3x existing) and 300 GW of solar (~4.5x existing) by 2030, supplying 45-55% of U.S. electricity (vs. ~10% today).
- Coal power: Retire all existing coal-fired power plants, reducing U.S. CO_2 emissions by ~1 billion tons (1/6 of total net U.S. greenhouse gas emissions), while avoiding ~40,000 deaths and ~$400 billion in air pollution damages through 2030. Manage associated operational reliability and local economic transition challenges and impacts. Ready retiring sites for redevelopment as new zero-carbon thermal power plants.
- Nuclear power: Preserve existing nuclear power plants wherever safe, and ready retiring nuclear plants for redevelopment as new zero-carbon thermal power plants.
- Natural gas power plants: Modest decline in generation (10-30%) through 2030 with installed capacity at ±10% of 2020. Existing gas plants play key role providing firm capacity and system flexibility. Avoid new commitments to long-lived natural gas pipeline infrastructure to avoid lock-in.
- Energy storage: 5 to 15 GW of battery energy storage deployed by 2030.

5 Prepare for transformation and expansion of bioenergy industry

- Establish biomass collection/transportation infrastructure: Sustainably use about 80 million t/y of residue biomass for energy by 2030.
- Prepare for dedicated bioenergy feedstock production: Develop high-yield energy crop systems (e.g., switchgrass, miscanthus) for converted (corn) cropland toward commencement of commercial harvests in 2035 and ramping up to 80 million tonnes/year of production by 2040 across 4 million hectares.
- Prepare bioconversion industry transition: Demonstrate advanced gasification-based bioconversion technologies for fuels production and design commercial-scale facilities to be deployed in the 2030's.

Priorities for the 2020's: Network Infrastructures

6 a. Expand critical electric network infrastructure

- Electric transmission: Build 200,000 GW-km of new transmission lines connecting solar / wind projects to loads by 2030 (~60% increase over current US transmission capacity). Strengthen and expand U.S. long-distance electricity transmission by identifying corridors needed to support wind and solar deployment (through 2030 and beyond given long lead time for transmission), reform siting/cost allocation process, and develop stakeholder consensus/support to site transmission connecting high renewable-potential development zones.
- Electric distribution: Strengthen distribution system planning, investment, and operations to allow for greater use of flexible demand and distributed energy resources, improve distribution network asset utilization, and efficiently accommodate 5-10% increase in peak electricity demand from EVs, heat pumps, and other new loads by 2030. Prepare for more rapid electrification and peak demand growth after 2030.

6 b. Expand critical CO_2 capture, transport and storage infrastructure

- Interstate CO_2 trunk line network: Plan, site, and construct an "interstate CO_2 highway system" (trunk line network) by 2030 (~19,000 km), connecting all regions to CO_2 storage basins in Gulf Coast, West Texas (Permian), Midwest (IL, IN, MO, KY), Dakotas/Eastern MT (Bakken), and California Central Valley.
- CO_2 storage regulations: Finalize national and/or state regulatory conditions governing: pore space ownership and access; well standards; injection operations; measurement, monitoring and verification of CO_2 containment (during- and post-injection); and long-term liability.
- CO_2 reservoir exploration and appraisal: Characterize with high confidence all major basins for CO_2 sequestration and identify sites suitable for injection of approximately 250 million metric tons of CO_2 per year by 2030. Advance field development planning and permitting.
- Carbon capture and sequestration: Capture and sequester 65 million metric tons of CO_2 /year by 2030, including CO_2 capture at 5 world-scale cement plants, 5-10 natural gas power plants, and 5-10 large-scale steam- or autothermal-reforming plants making hydrogen.

Priorities for the 2020's: Land Sinks and Non-CO_2 Emissions

7 a. Protect and enhance land carbon sinks

- Grow the land sink: Deploy measures to achieve 200 million tCO_{2e} per year of additional sequestration in 2030 compared with 2020 so as to offset reduction of land sinks absent any action and achieve a net increase in the land sink of 50 million tCO_{2e} per year.
    - i. *Forestry sector*: Target 160 million tCO_{2e} per year additional sequestration through deployment of a variety of measures.
    - ii. *Agriculture*: Target 40 million tCO_{2e} per year additional sequestration, primarily through measures employed on croplands.
- Prepare for future land-sink growth: Establish institutional mechanisms to ensure additional land sink enhancements beyond the 2020's.

7 b. Reduce non-CO_2 emissions

- Non-CO_2 GHGs: Reduce non-CO_2 greenhouse gases by at least 10% by 2030, including
    - i. *Reducing HFC production and consumption* consistent with the Kigali Amendment to the Montreal Protocol.
    - ii. *Identifying and eliminating largest CH_4 leakage sources in oil and gas* production, processing, and pipelines.
    - iii. *Improving management of N_2O and CH_4 in agriculture.*
    - iv. *Managing N_2O emissions from nitric and adipic acid production.*

8 Innovate to create additional *real** options for technologies needed post-2030

- Technology option creation: Pursue maturation, scale-up, and cost/performance improvements in clean-energy technologies, including:
  - *Clean firm electricity resources*, including advanced nuclear, advanced geothermal, natural gas power plants with CO_2 capture, biopower plants with CO_2 capture, hydrogen and ammonia combustion turbines; ultra-cheap long duration energy storage;
  - *Hydrogen production* via electrolysis, natural gas reforming with CO_2 capture, and biomass gasification with CO_2 capture;
  - *Synthesis of fuels from biomass and* $H_2 + CO_2$, including methane and liquid hydrocarbons (e.g., Fischer-Tropsch fuels);
  - *Direct hydrogen-reduced iron* and other carbon-free alternatives for primary steel production;
  - CO_2 *capture* in a range of industrial applications, including cement, ammonia, biofuels, and hydrogen;
  - *High-yield bioenergy crops* such as miscanthus
  - *Direct air capture* methods

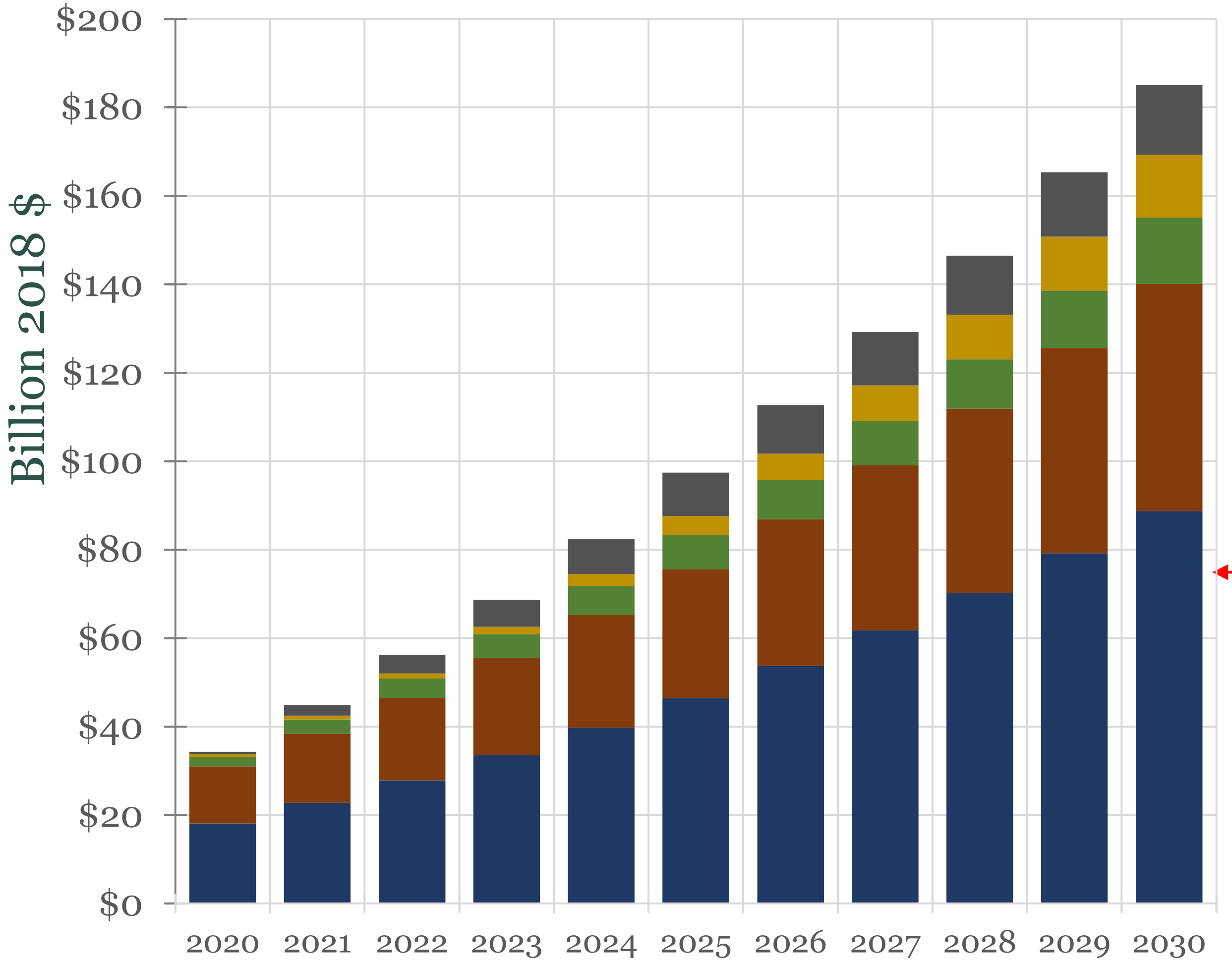
  $140 Billion: Order-of magnitude capital cost estimates for up to 5 first-N-of-a-kind (FOAK) demonstrations for each technology above, including FOAK premiums.
- Technology innovation to reduce siting challenges: Increase investment in research and technology solutions that reduce network infrastructure siting challenges, including repurposing existing natural gas or oil pipelines for hydrogen or CO_2 transport, low-cost underground transmission lines and increasing utilization/transfer capacities of existing electricity transmission.

* We define real options as those developed to a relatively high execution readiness such that the options are able to be rapidly deployed at scale, if and when needed.

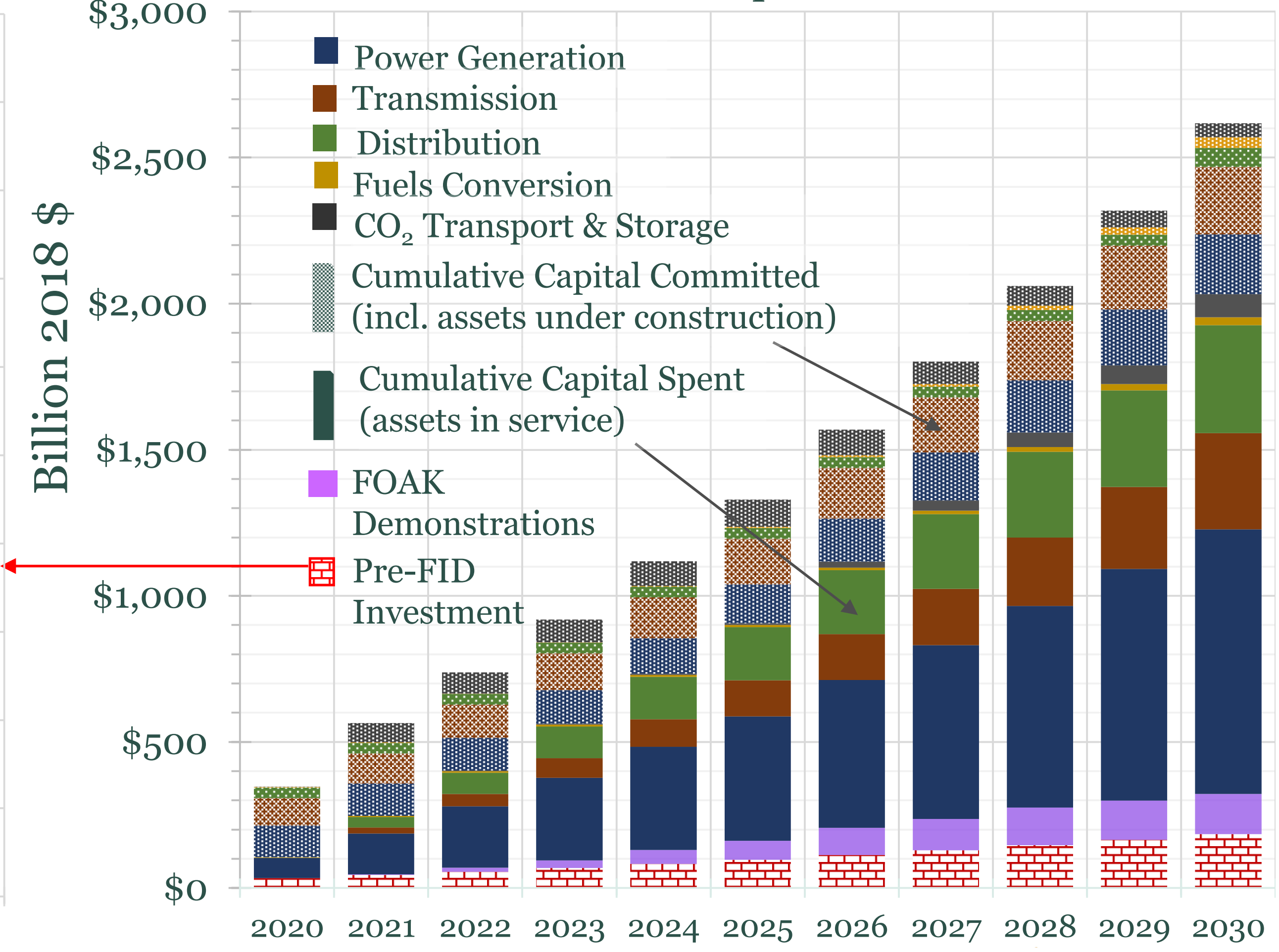
Mobilizing risk capital for development and construction will be a significant challenge for the 2020s (and beyond).

E+

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



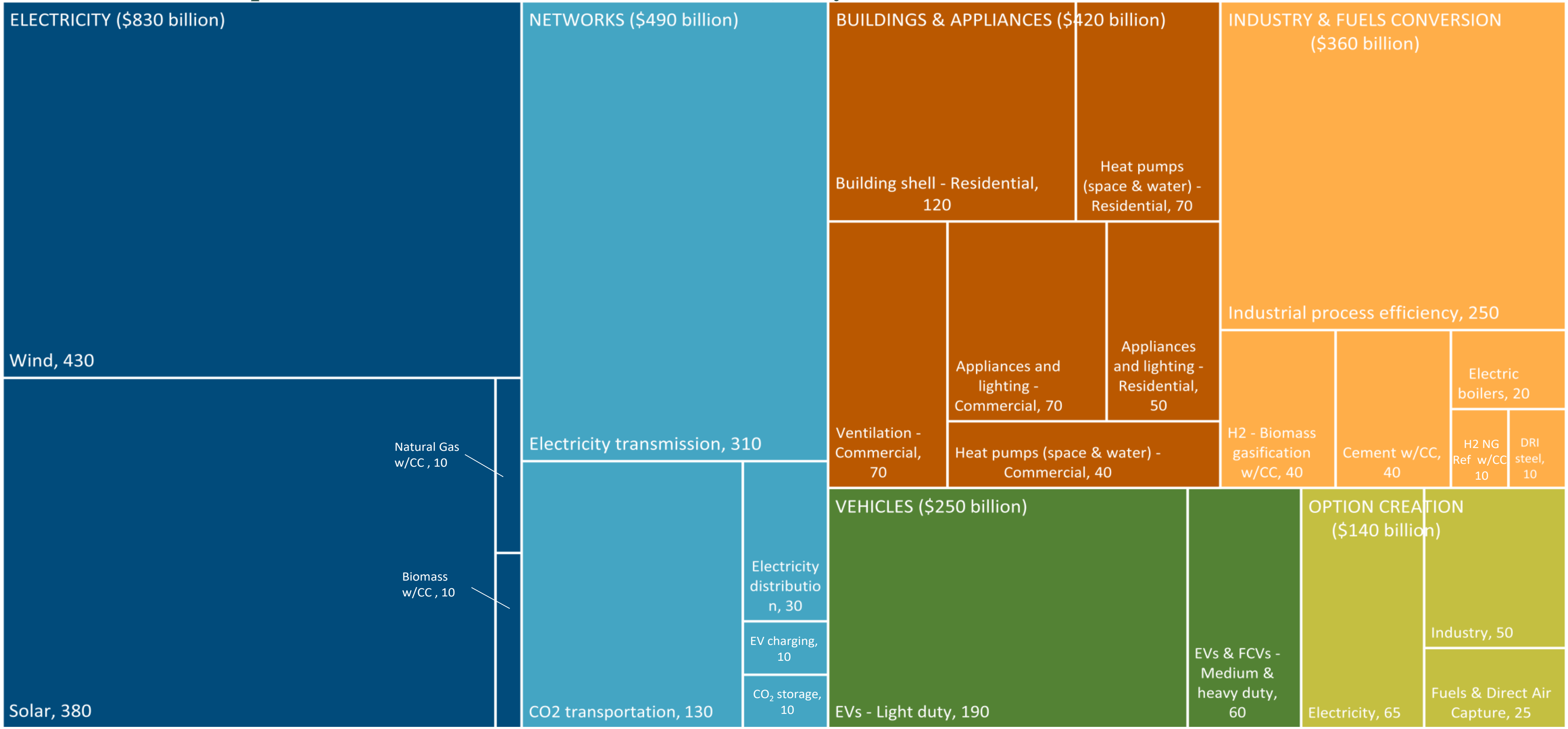
2.6T$ committed to **supply-side** plant & infrastructure in 2020's: $1.8T in service, $0.6T in construction, and $0.2T pre-FID.



Note: Excludes investments in demand-side transport, buildings and industry; fuels distribution systems; biomass crop establishment; and land sink enhancements.

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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Technical annexes provide details on methods, assumptions, and data sources for national-level modeling and downscaled results.

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

Technical annexes available at https://netzeroamerica.princeton.edu/the-report

END OF REPORT