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NET-ZERO AMERICA

POTENTIAL PATHWAYS, INFRASTRUCTURE, AND IMPACTS

FINAL REPORT

October 29, 2021

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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
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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 how much 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 →

Foreword (2/2)

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.

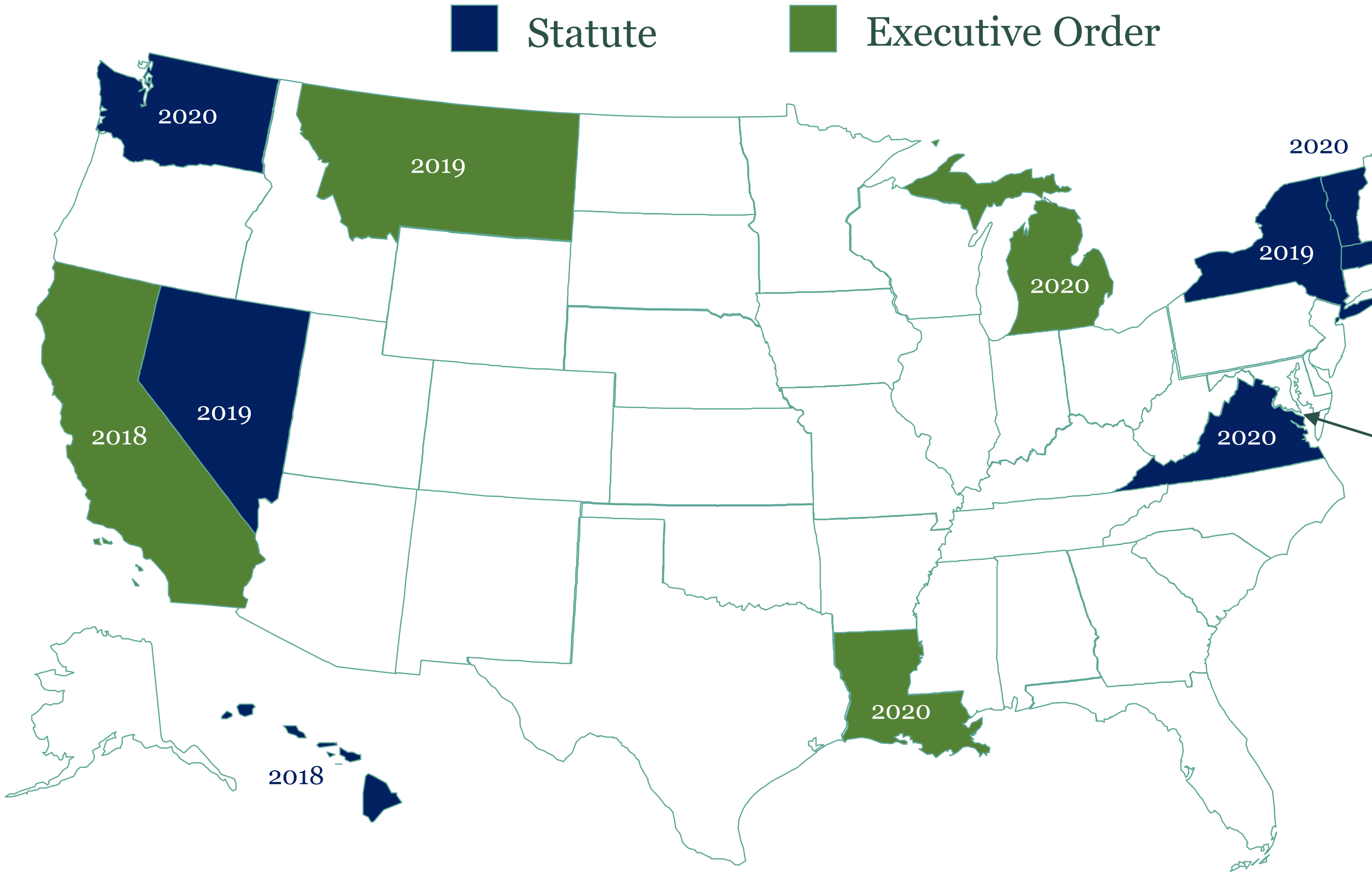
For funding support, the authors thank the Andlinger Center for Energy and the Environment, BP and the Carbon Mitigation Initiative within Princeton's High Meadows Environmental Institute, ExxonMobil, and the University of Queensland.

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, PSEG, Southern California Edison, Southern Company, Duke Energy, DTE Energy, Dominion Energy, nrg, aps, Consumers Energy, Green Mountain Power, Idaho Power, Hawaiian Electric, nationalgrid, Eversource, 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, 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

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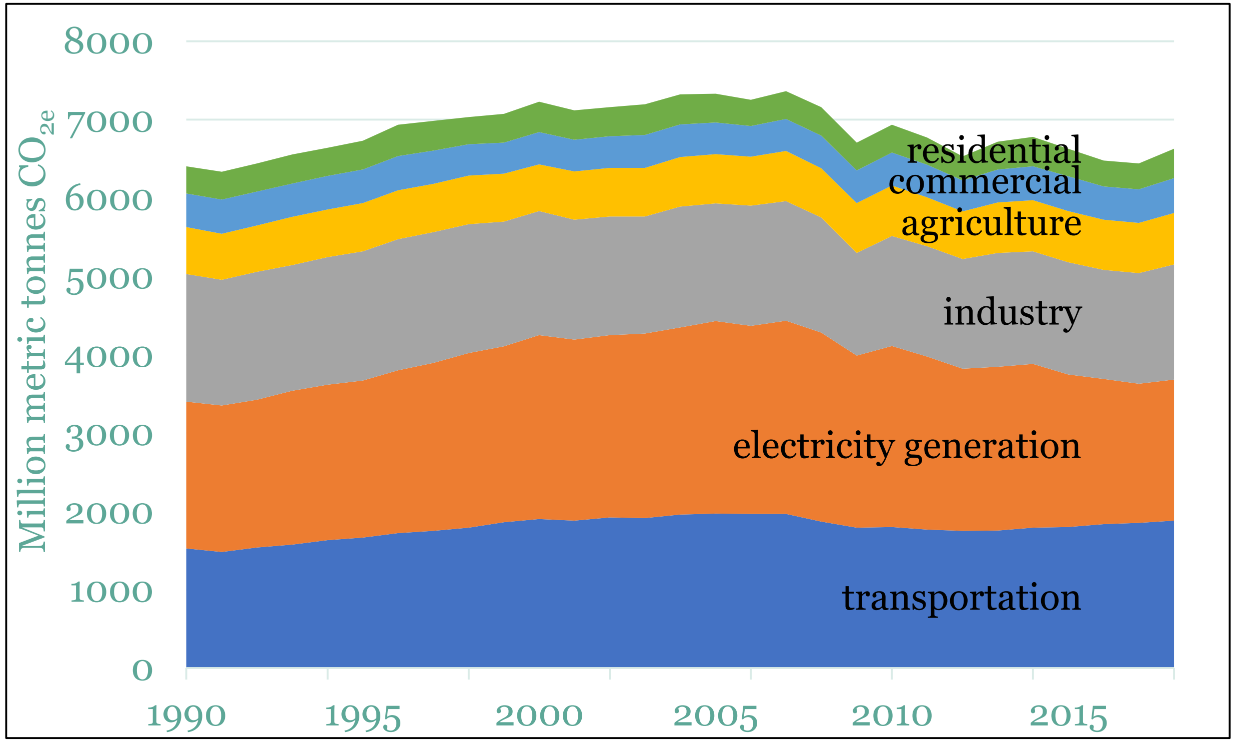
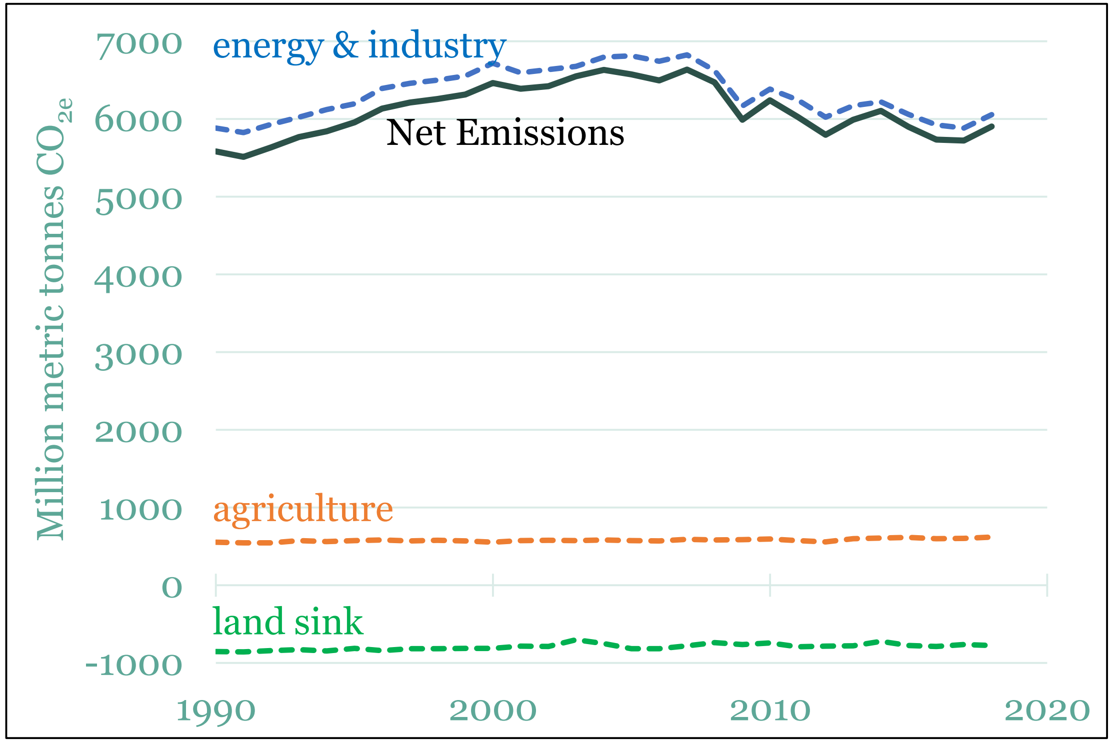
The challenge for the US to reach net-zero emissions: ~ 6 billion tonnes of CO_{2e}/y emissions today (6 $GtCO_{2e}$/y)





EPA GHG Inventory

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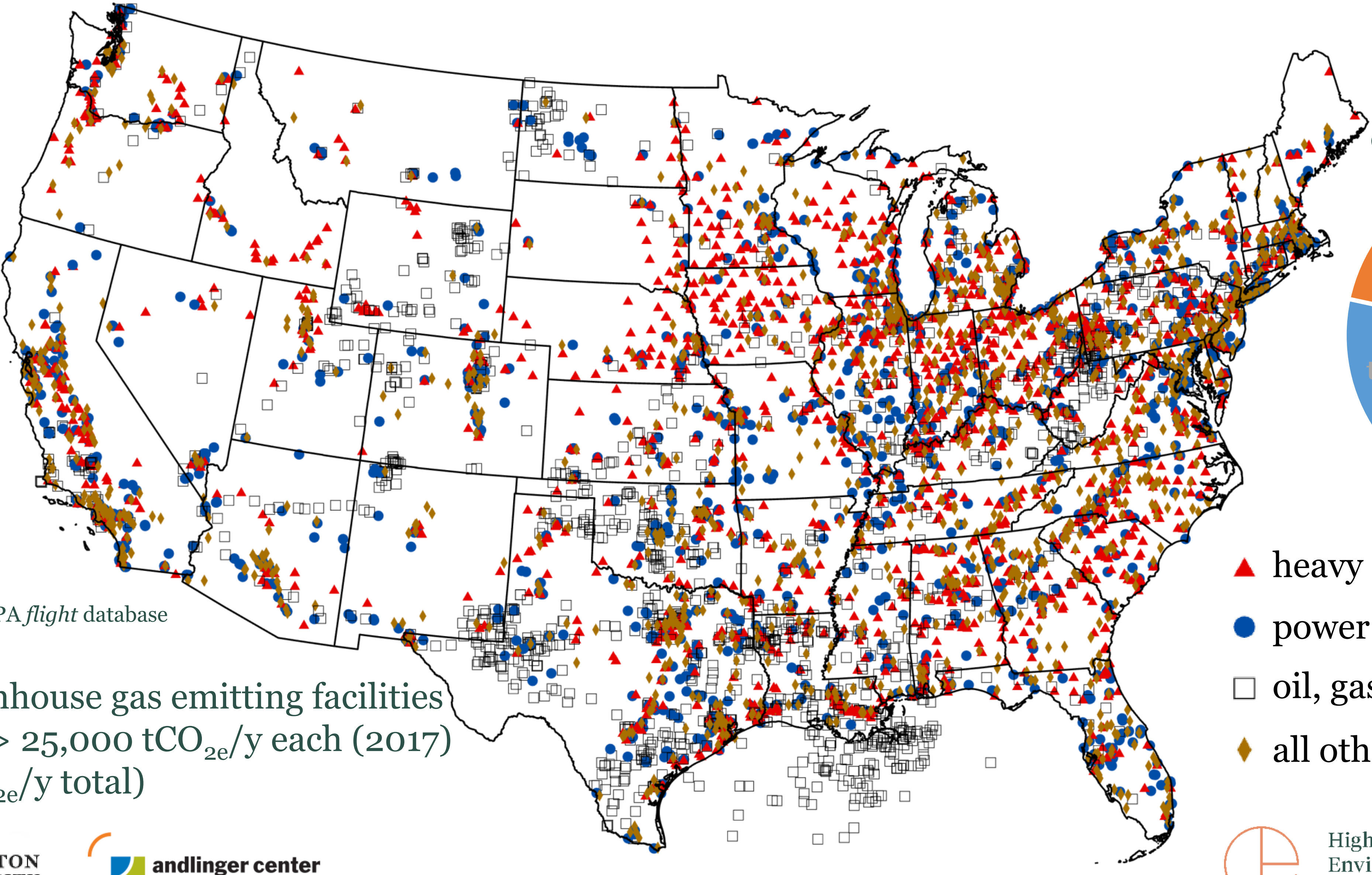
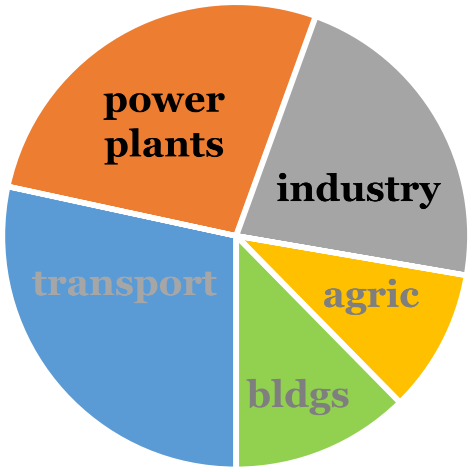
The challenge for the US: Industrial facilities and power plant emission sources are widely dispersed today



EPA *flight* database

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

Economy-wise emissions by sector



- ▲ heavy industries
- ● power plants
- □ oil, gas, coal operations
- ♦ all other industries

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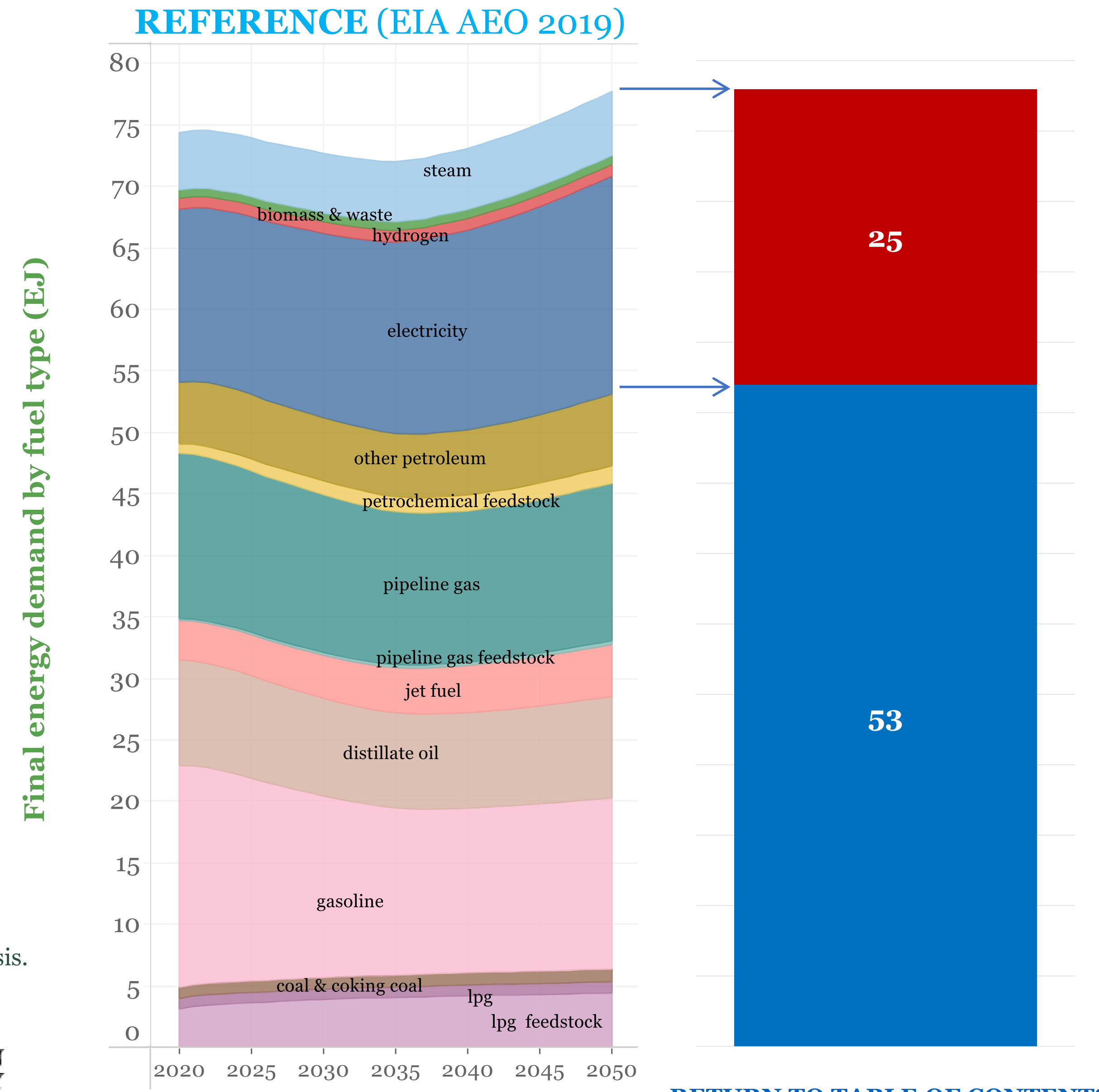
The challenge for the US: 2/3 of final energy today is hydrocarbons



~ 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 → **EnergyPATHWAYS demand-side model** → **RIO supply-side cost-minimization** → **Downscaling analysis**

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**

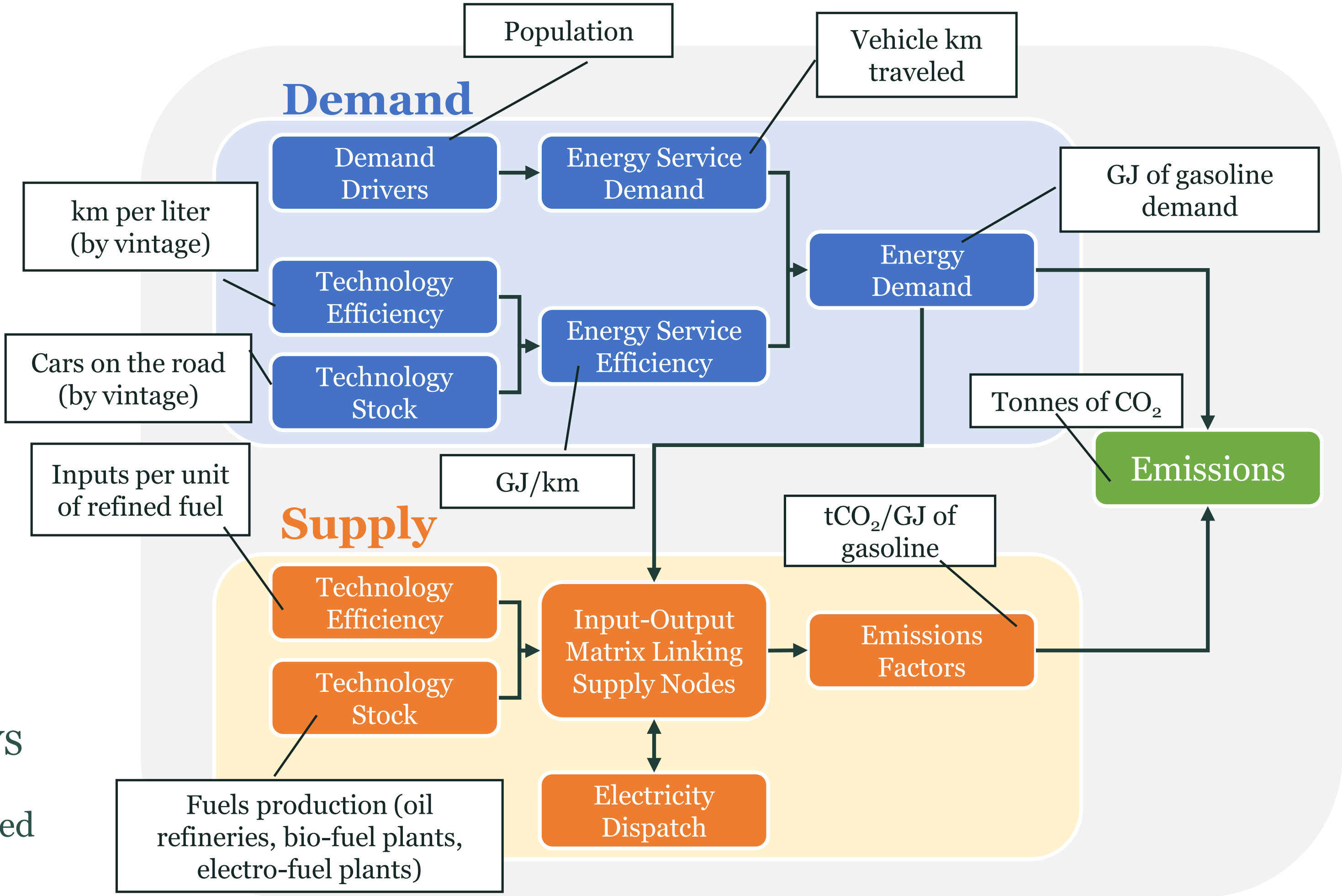
Cost-minimized portfolios of low-carbon technology deployment for electricity generation and balancing, alternative fuel production, and direct air capture.

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

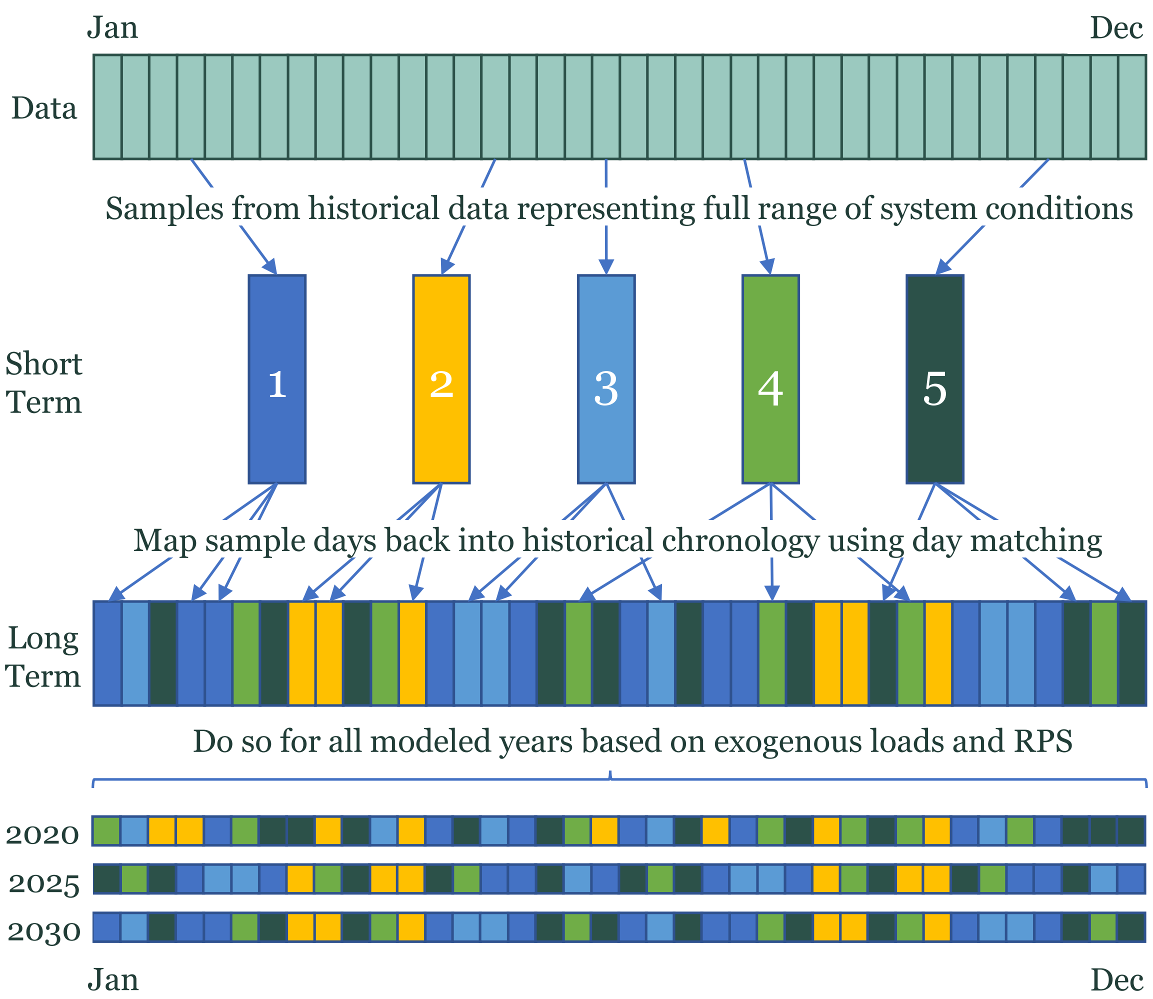
** Evolved Energy Research proprietary.

LIGHT DUTY VEHICLES EXAMPLE

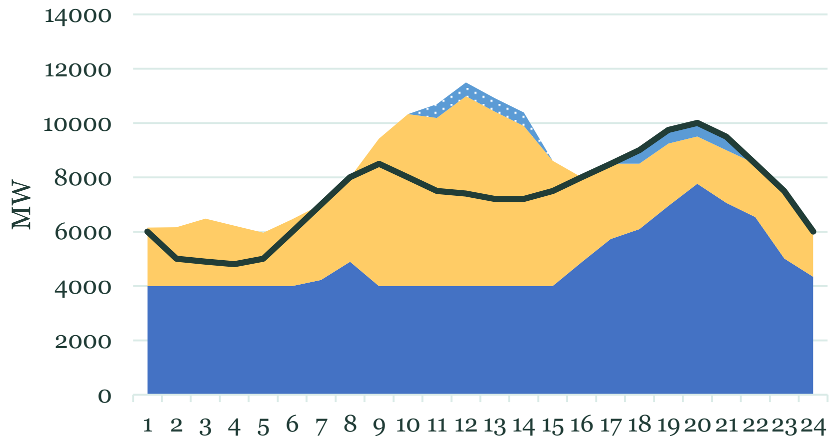


Note: By convention, all fuel values input to EnergyPATHWAYS and RIO are expressed as higher heating values (HHV); all outputs are likewise expressed as HHVs. All fuel values reported in this slide deck are HHVs, unless stated otherwise.

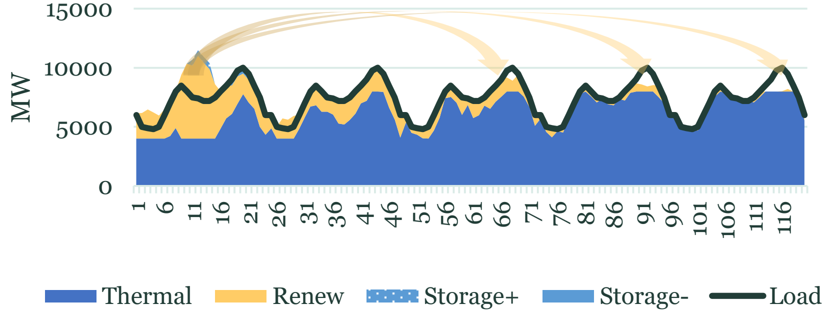
RIO power-sector temporal modeling: Hourly operations for 41 sample days; long-term operations over full chronology

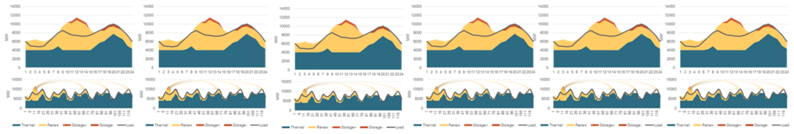


Detailed short term dispatch for every sample day. Dispatch decisions are the same across all days represented by the same sample day.



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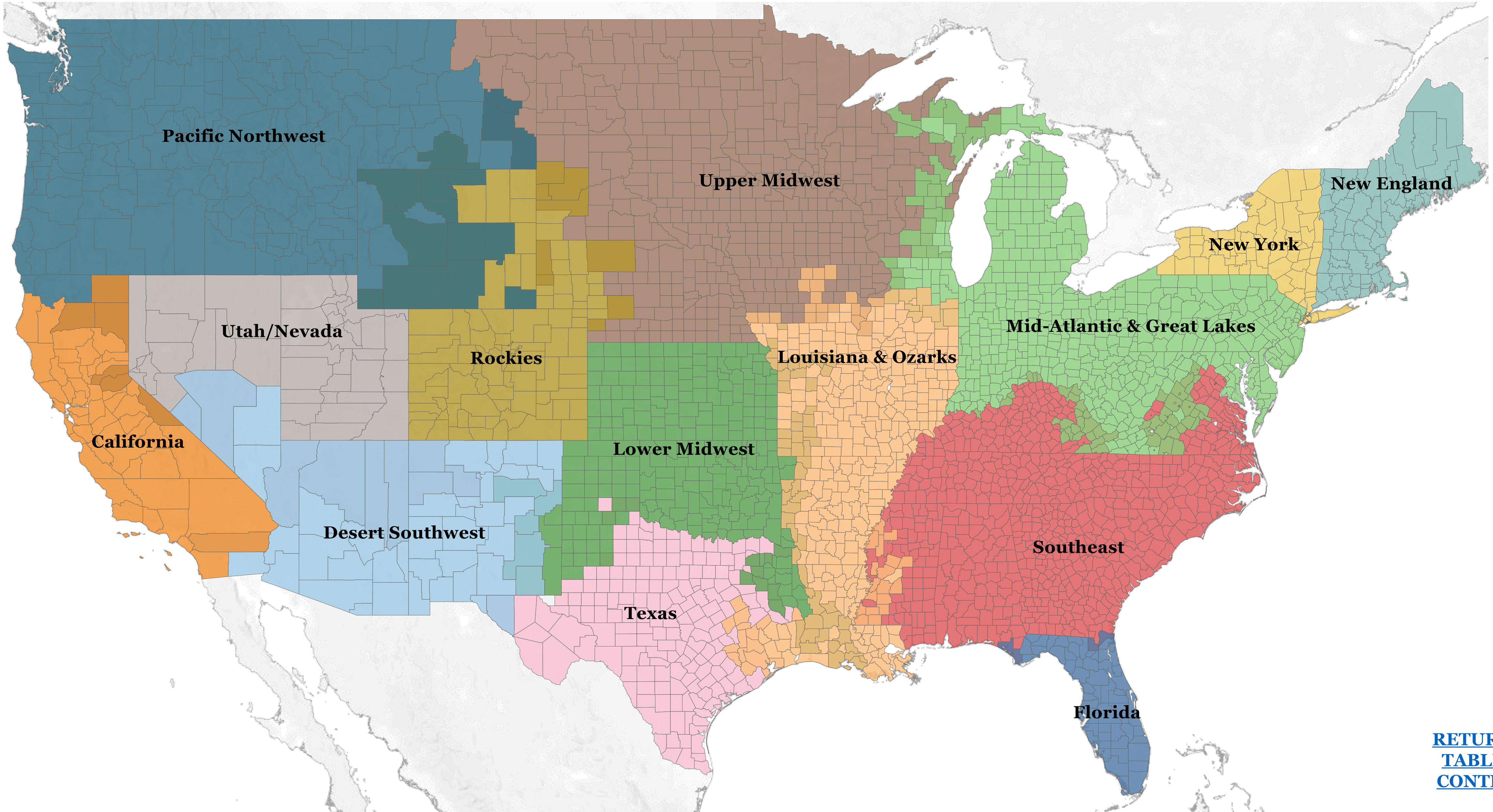
Most model inputs are at state level; outputs are reported for 14 regions (consolidated eGRID regions)



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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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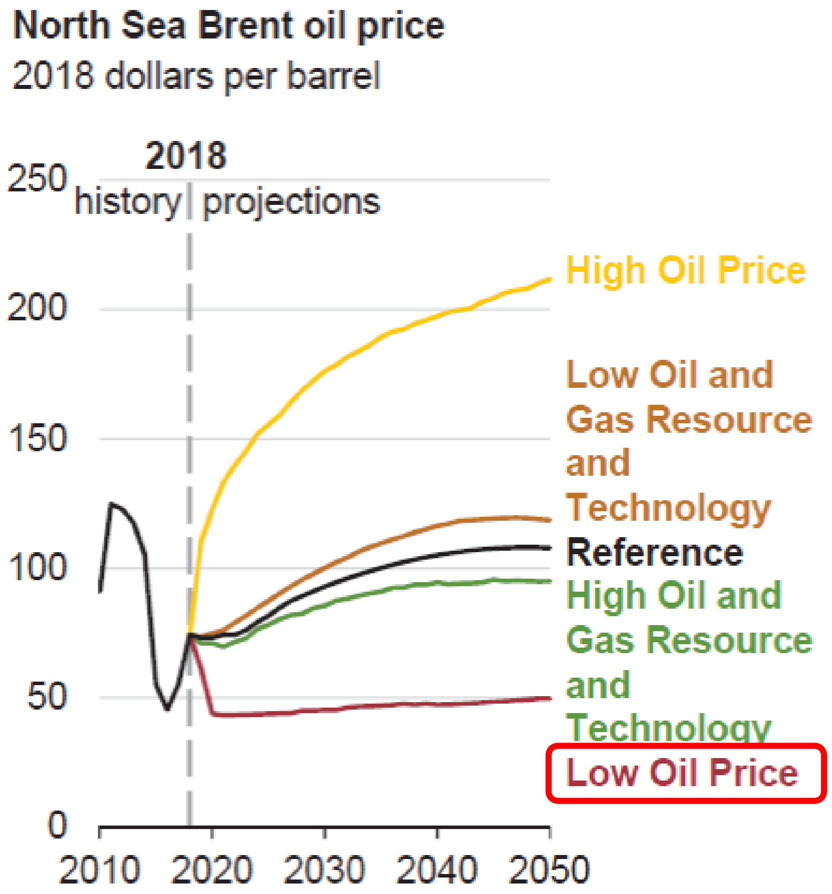
Key assumptions

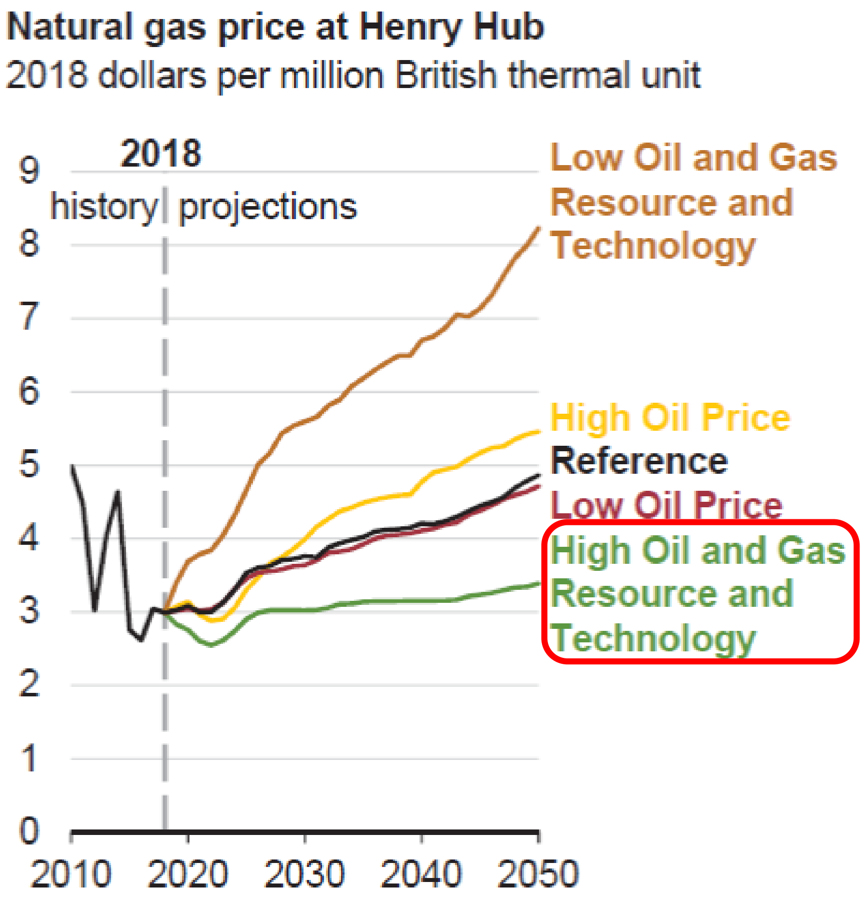
CO_2 emissions	
Land CO_2 in 2050	- 0.85 Gt/y (- 0.7 Gt/y today and declining)
Non-CO_2 in 2050	1 $GtCO_{2e}$/y (25% reduction from today)
Energy/Industry CO_2	- 0.17 GtCO2 in 2050
Technology installed capital costs in 2016$ (some later slides express values in 2018$, assuming 4% escalation from 2016)	
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

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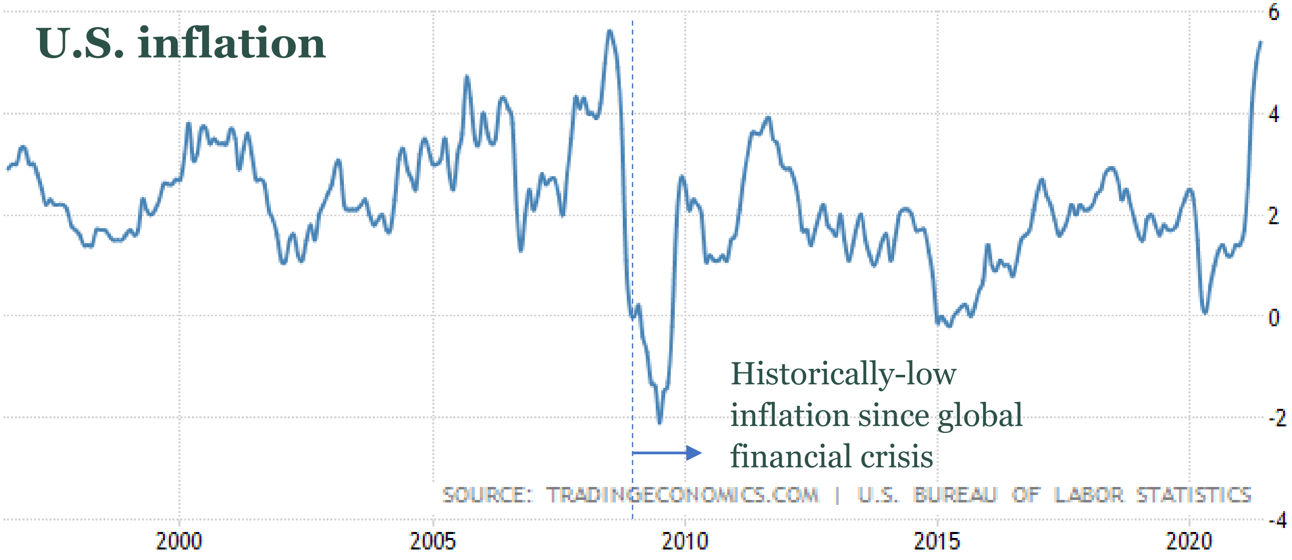
Assumed future inflation rate and cost of capital are consistent with the past decade, but low by historical standards.

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

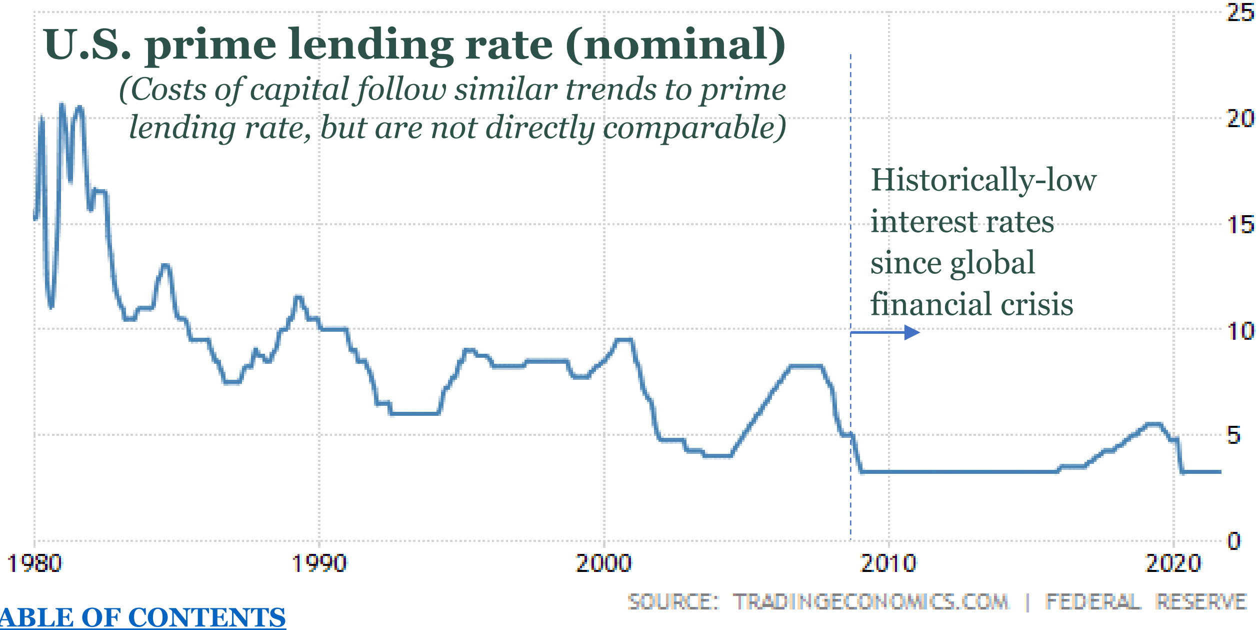
Assumed (weighted-average, real) cost-of-capital for capital investments:

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%



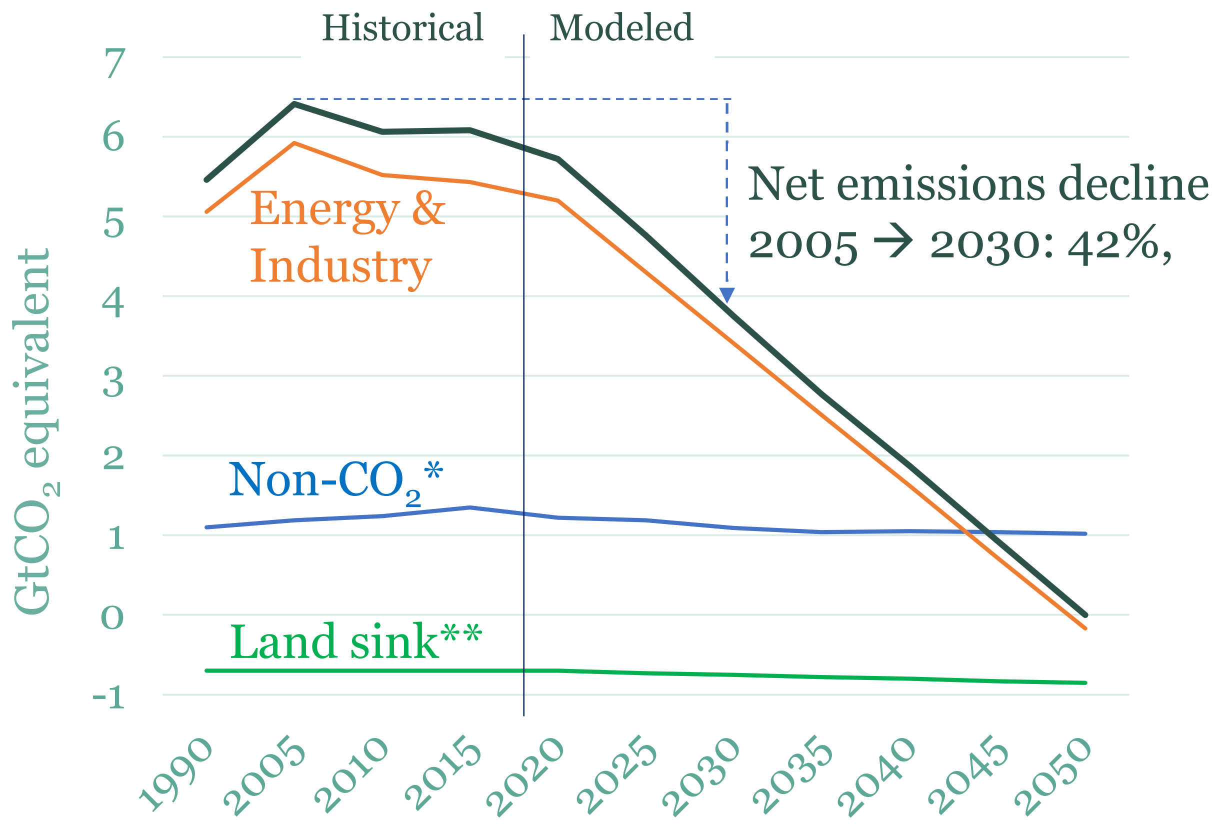
Net-zero emissions by 2050, together with assumed non-CO_2 emissions and land sink set target for energy/industry emissions

	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.

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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*]	

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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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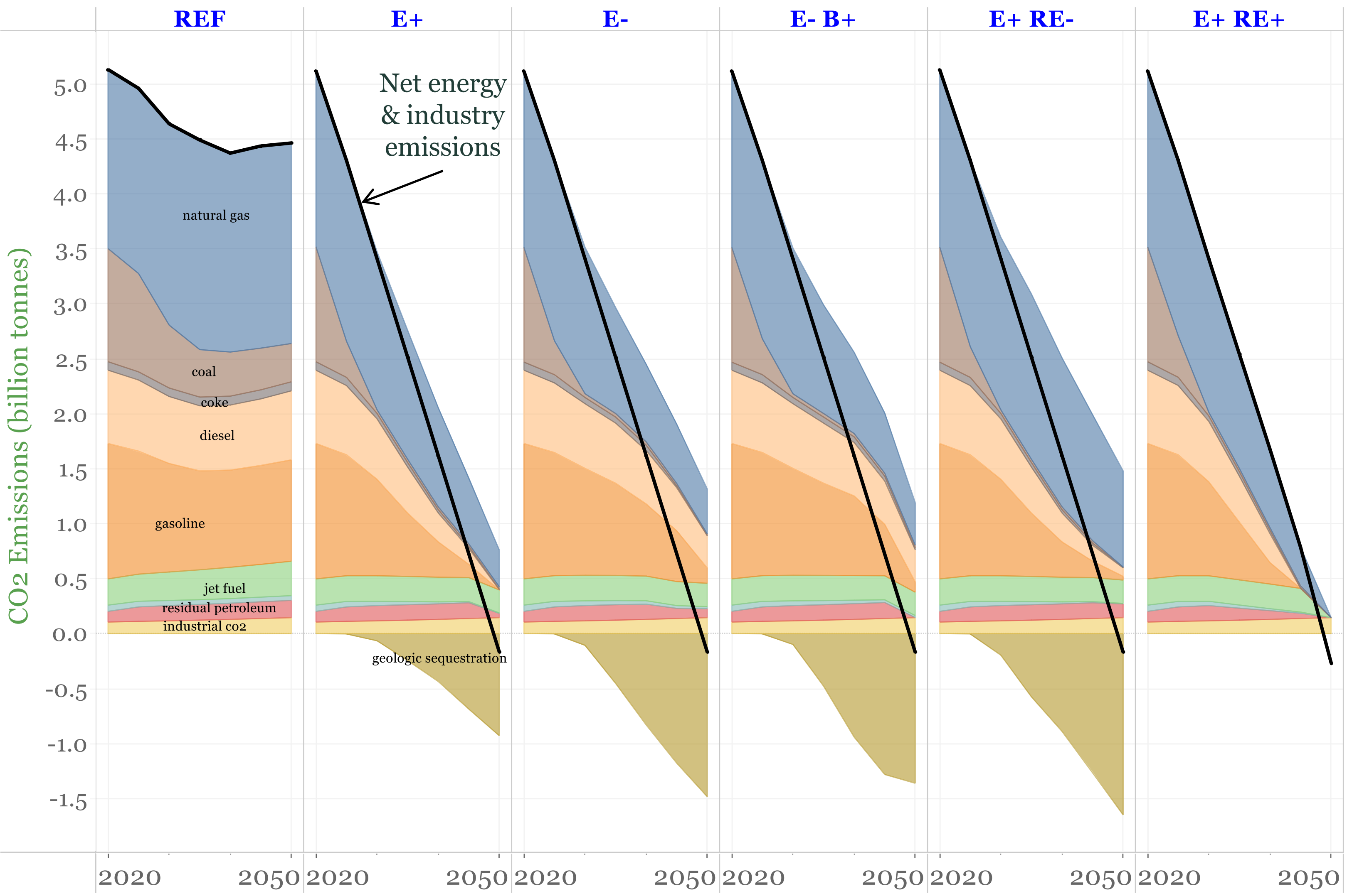
High-level modeling results for net-zero pathways

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.

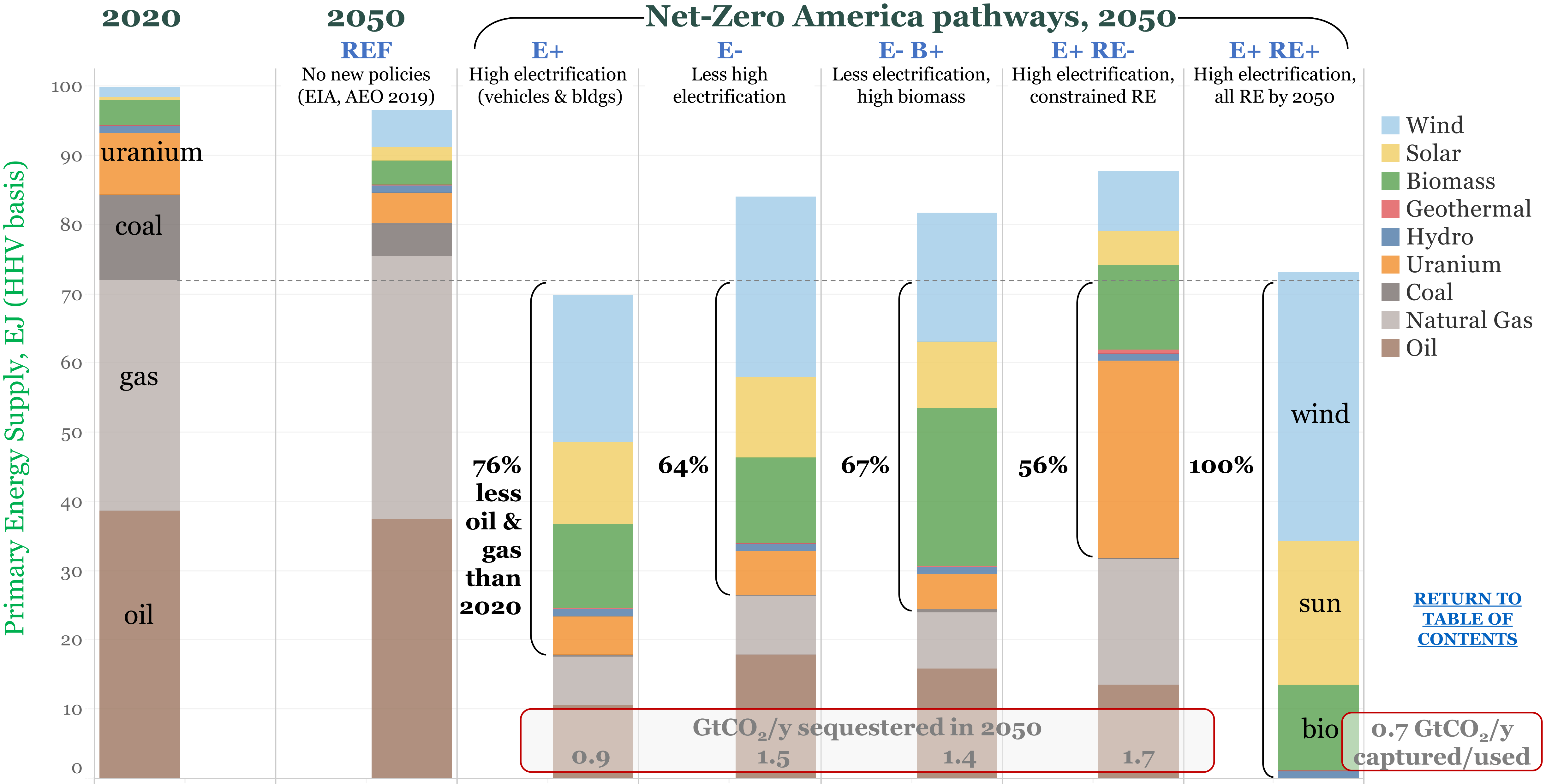
Energy and industrial CO_2 emissions are net negative by 2050 to deliver net-zero emissions for the full economy



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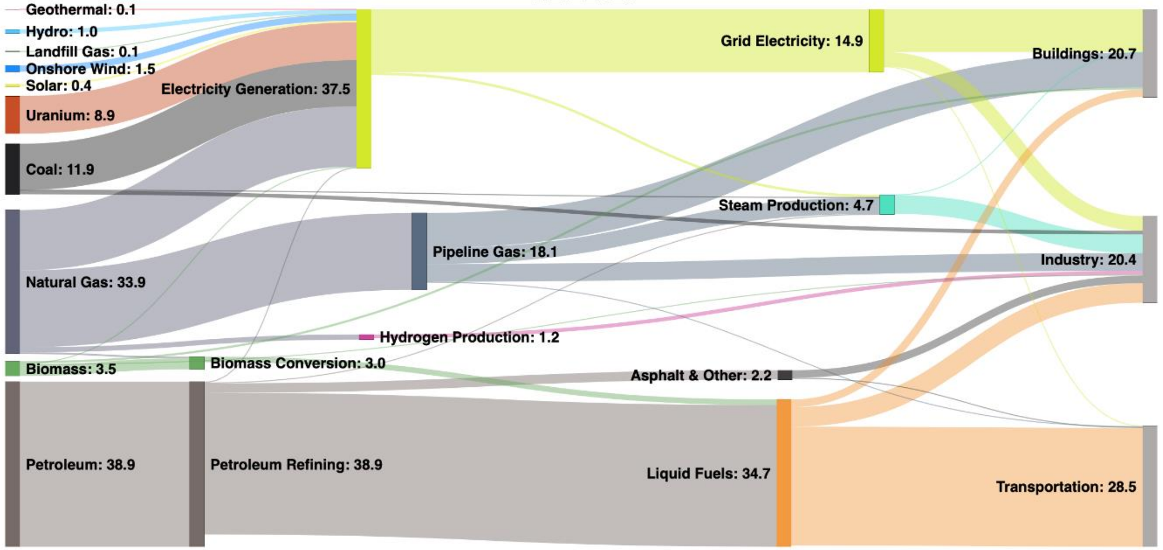
REF primary energy flows (EJ): Relatively little change from 2020 to 2050.

REF 2020



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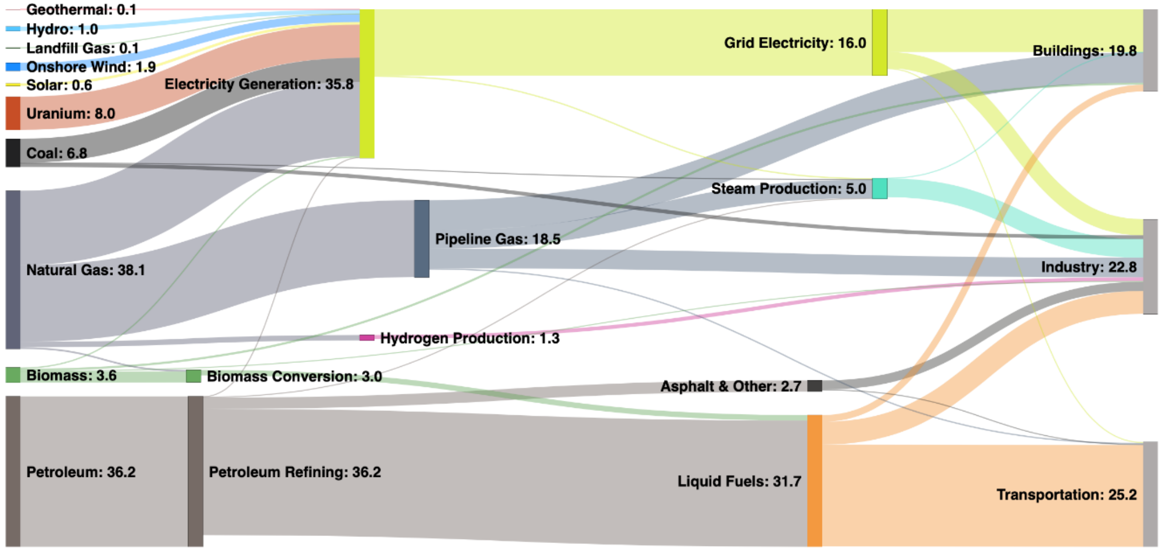

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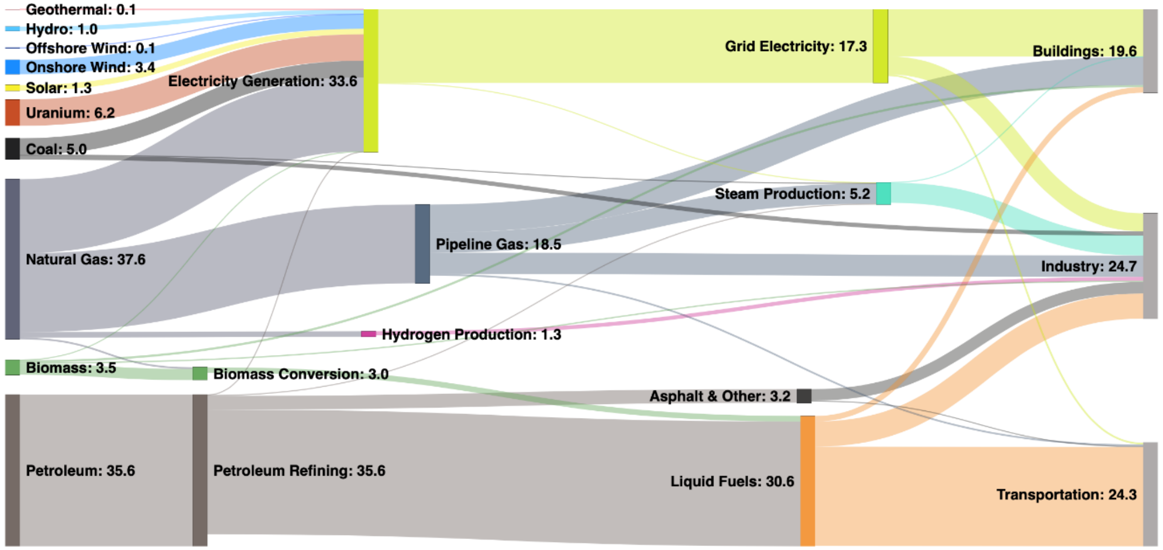

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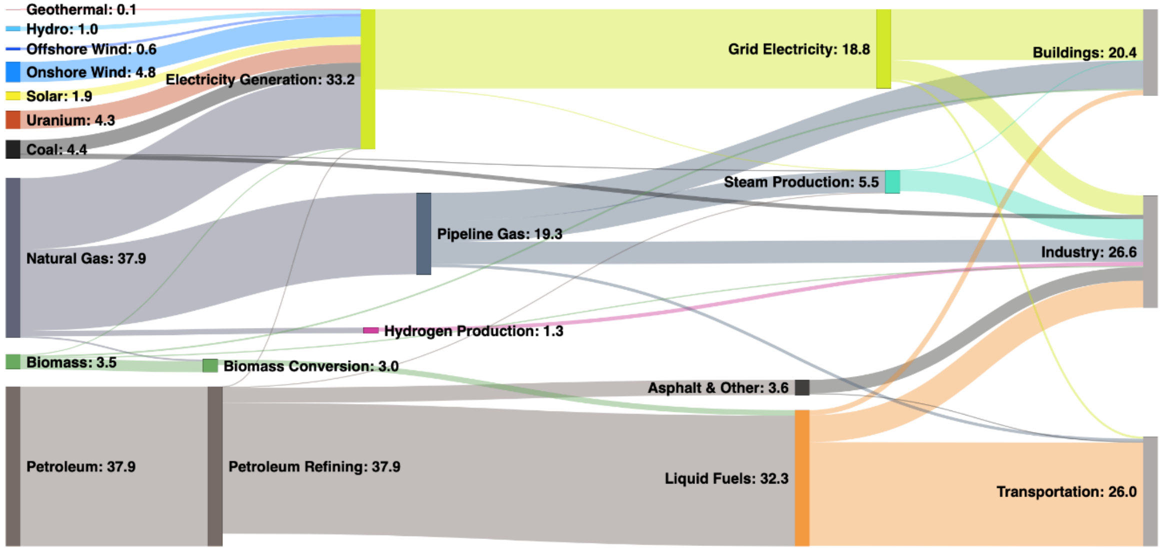

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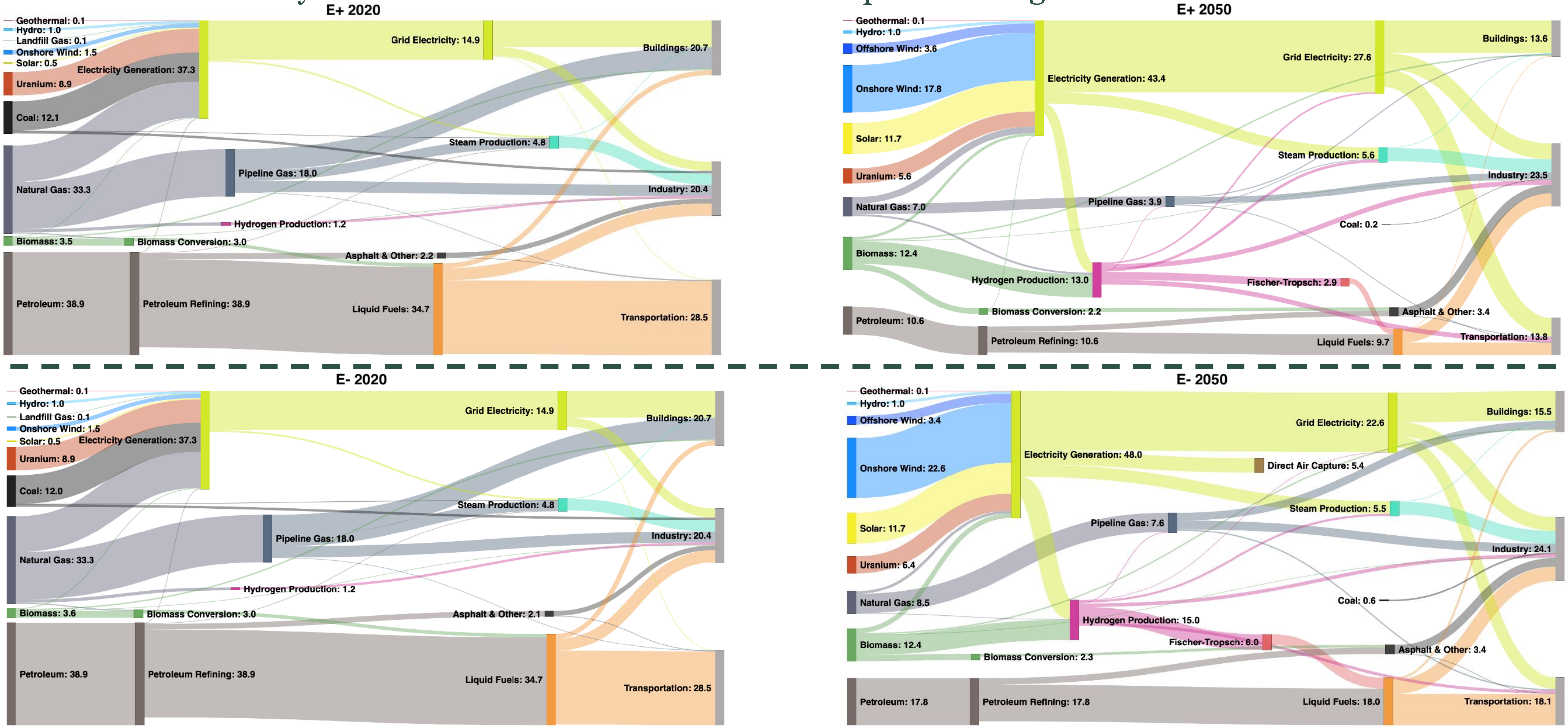
Primary energy flows (EJ) in 2020 & 2050 for E+ and E-. Total energy use declines due to efficiency gains and electrification.

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



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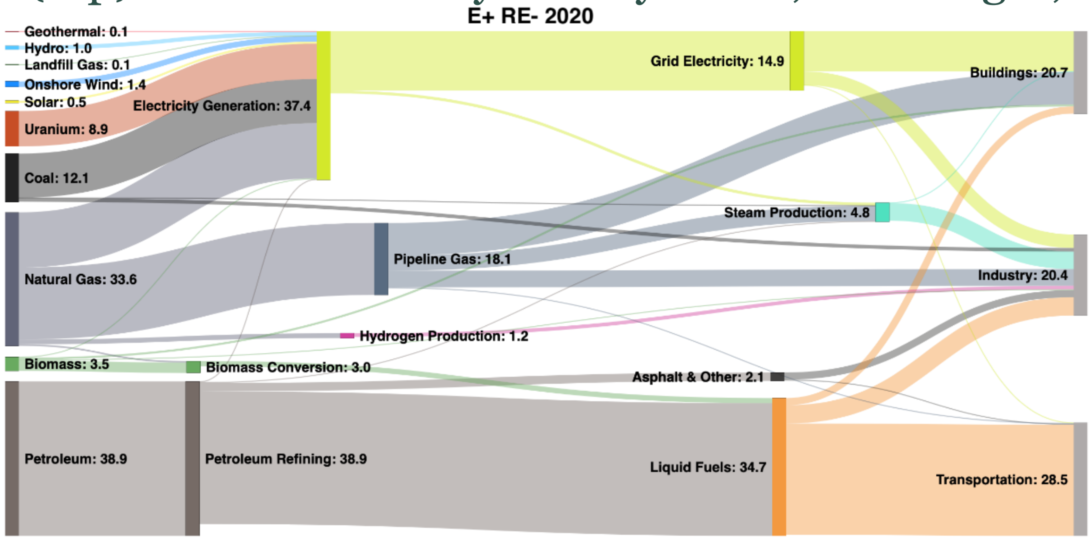
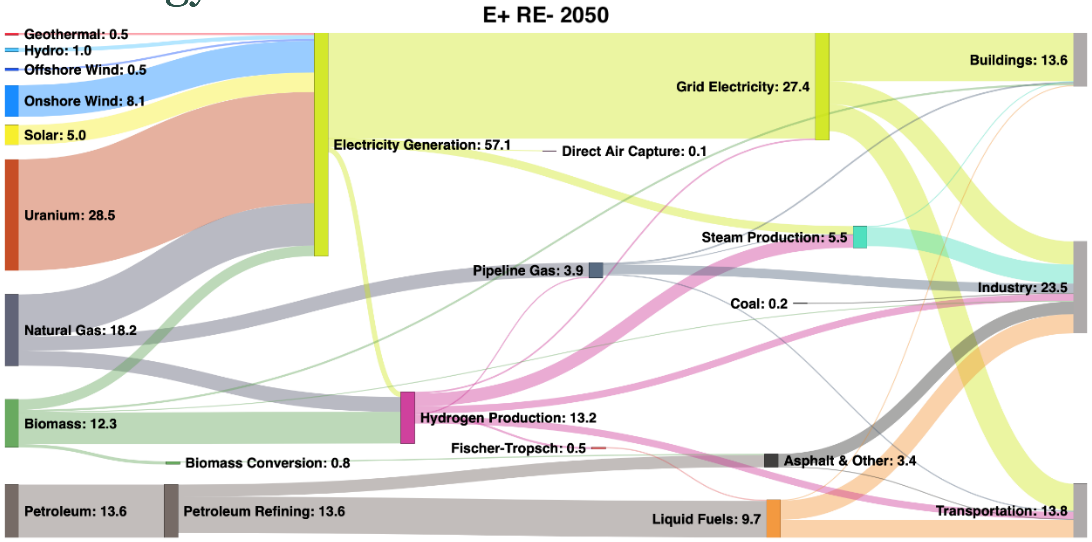
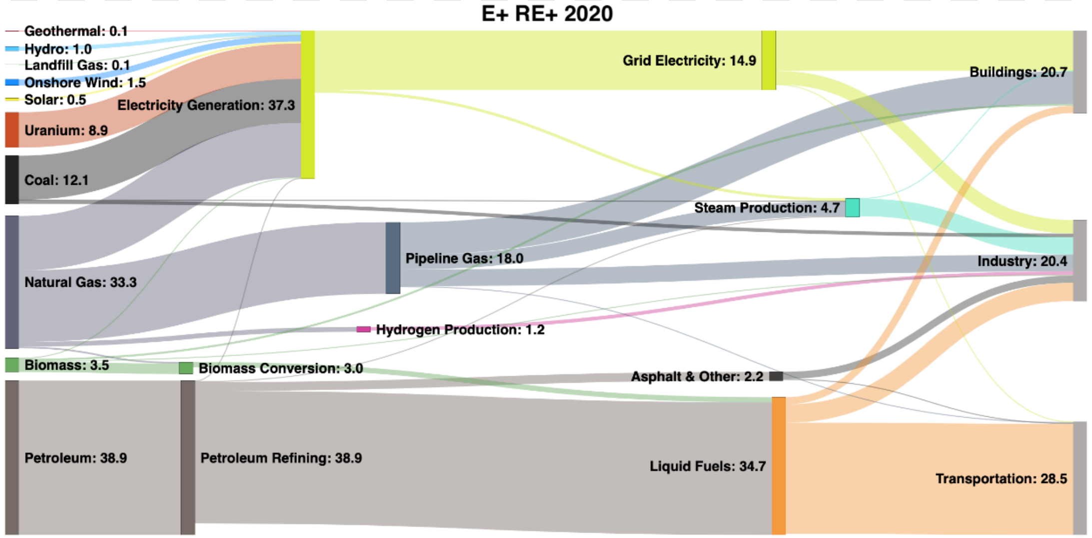
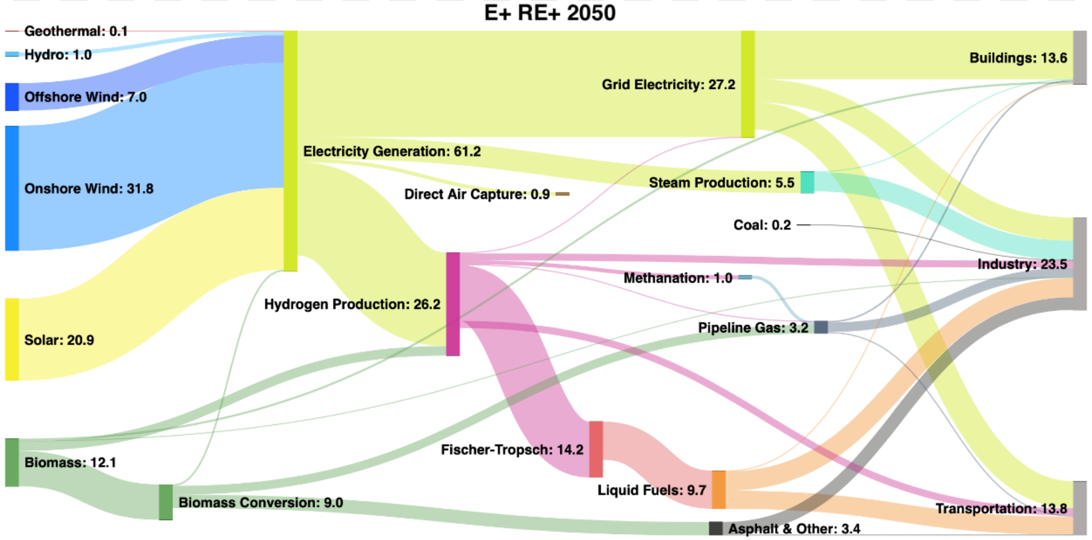
Primary energy flows (EJ) in 2020 & 2050 for E+RE- and E+RE+ highlights large differences in reliance on wind, solar, and nuclear.

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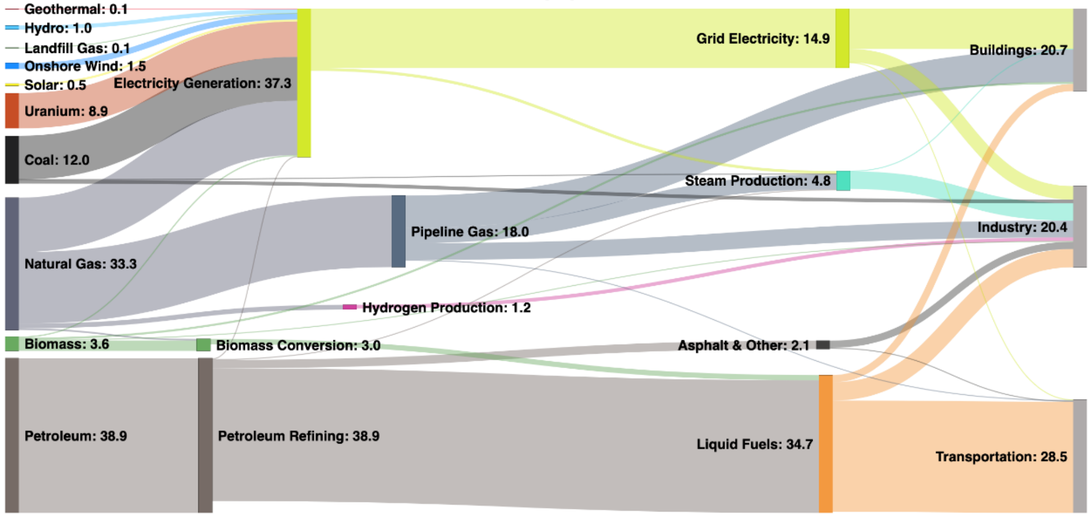
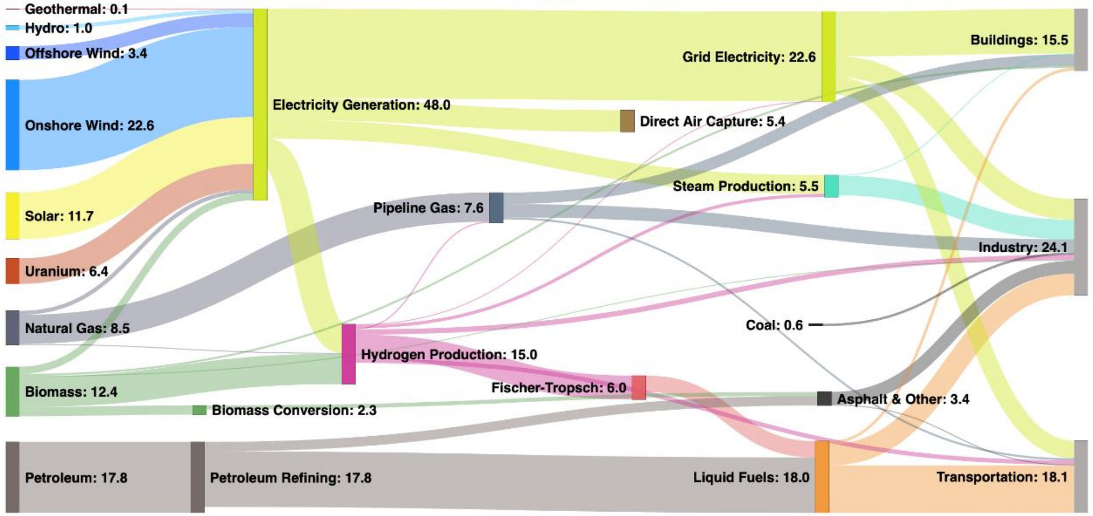
Primary energy flows (EJ) in 2020 & 2050 for E- and E-B+ highlights the impact of biomass resource potential.

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.

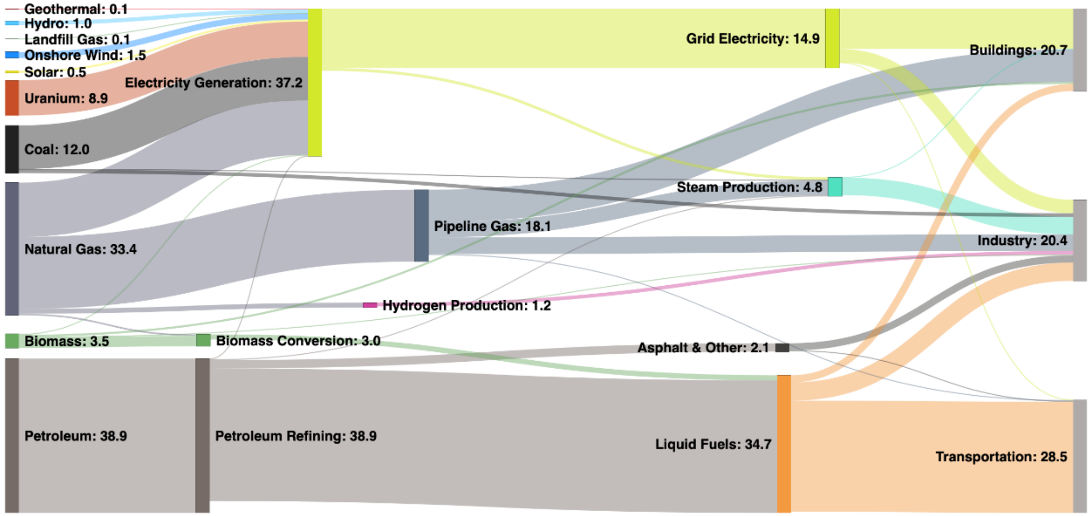
E- 2020



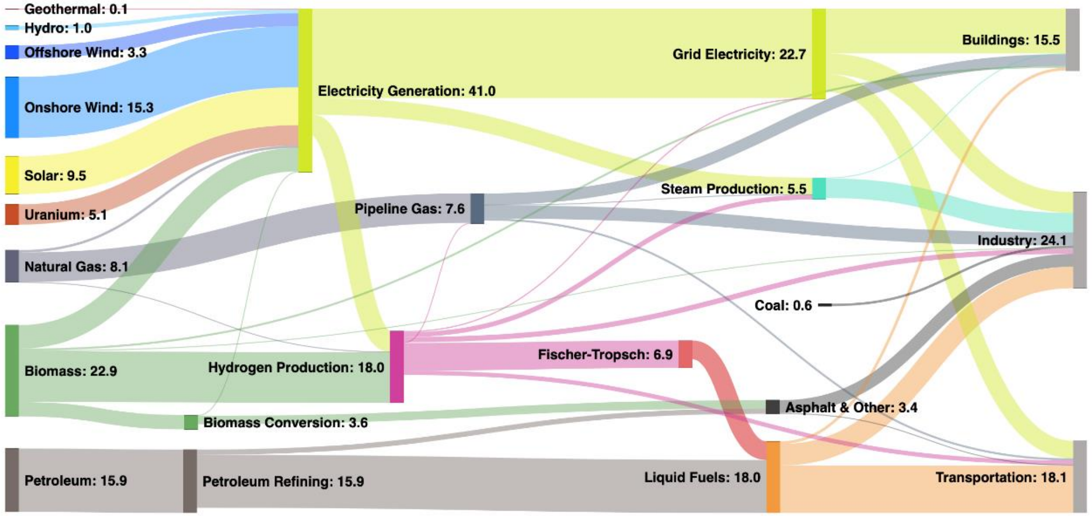
E- 2050



E- B+ 2020



E- B+ 2050



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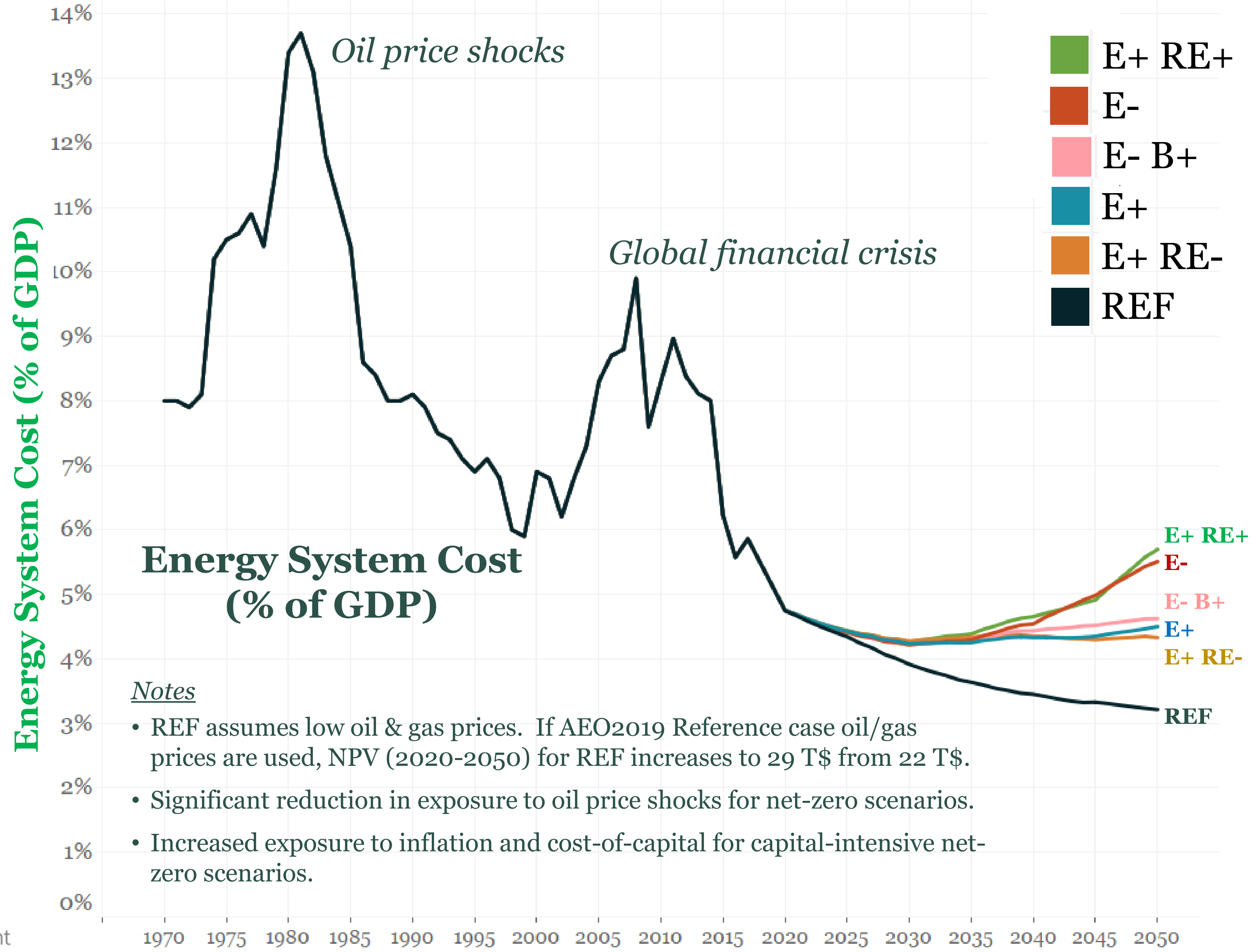
Modeled annualized energy-system costs as % of GDP are comparable to (or less than) in recent prosperous economic times

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



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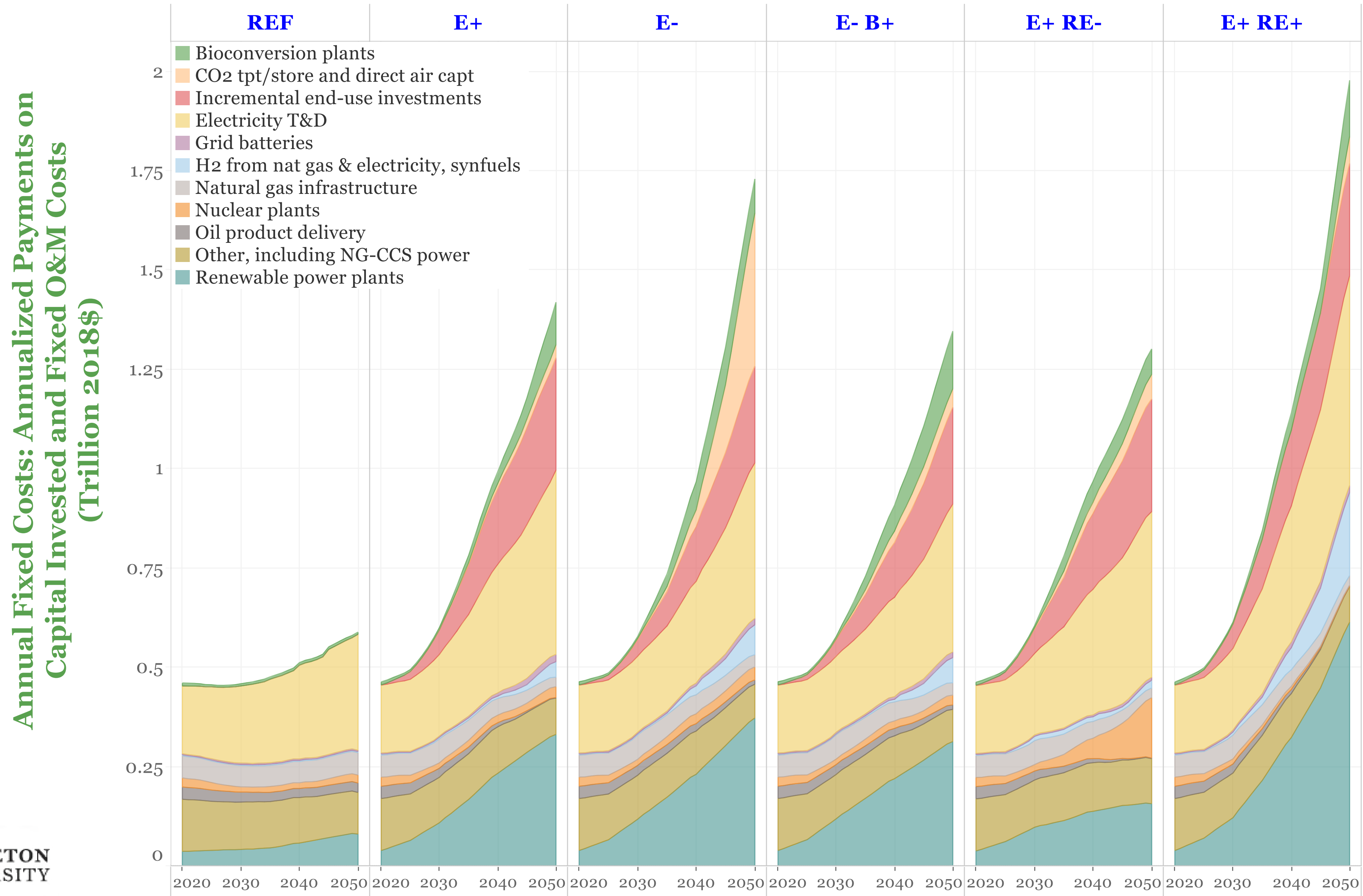
Annual costs shift from fuel costs to fixed costs: annualized capital + fixed O&M payments by 2050 are 2 to 4 times those for REF.



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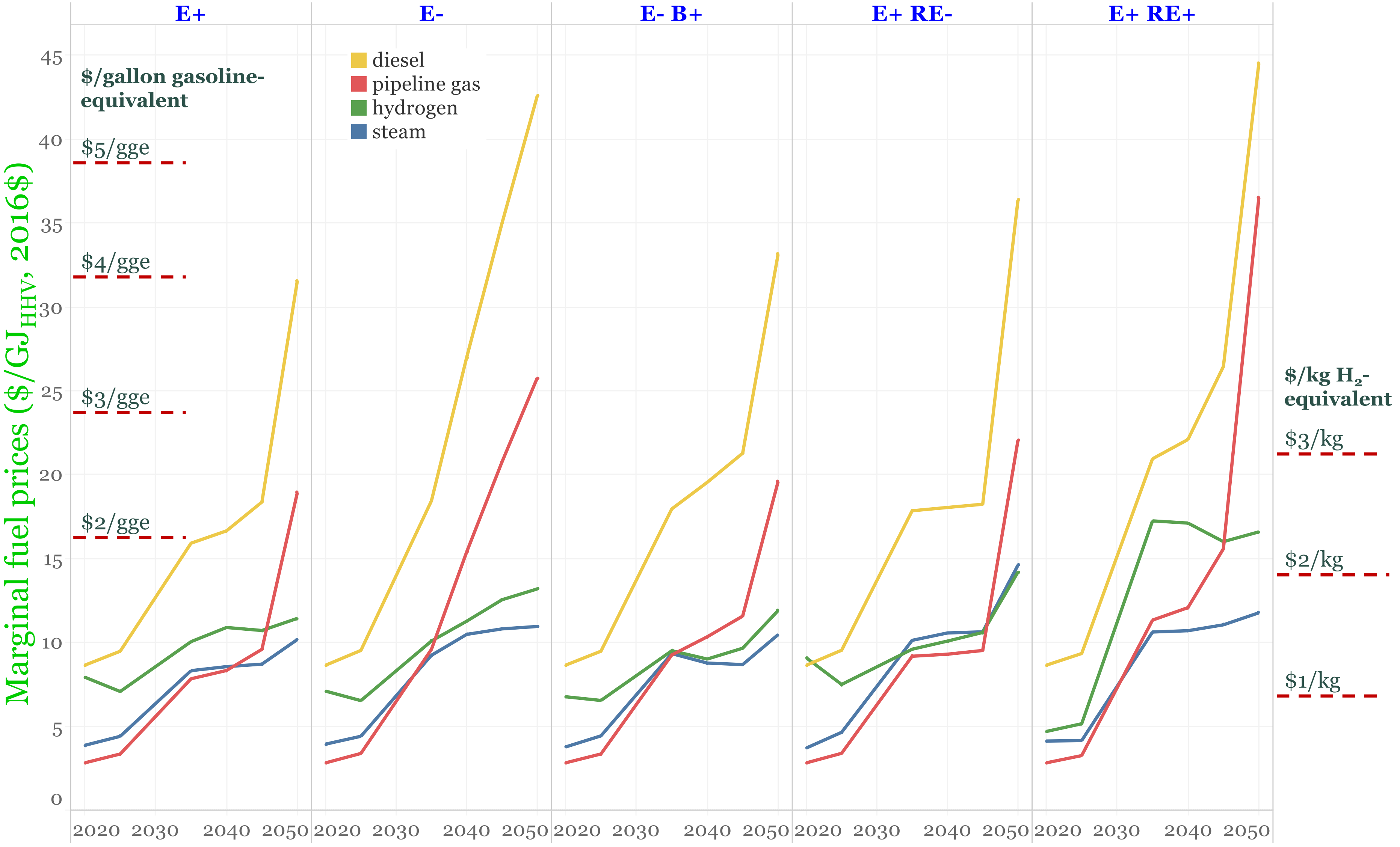
Pillar 1: Improve end-use energy productivity – efficiency and electrification

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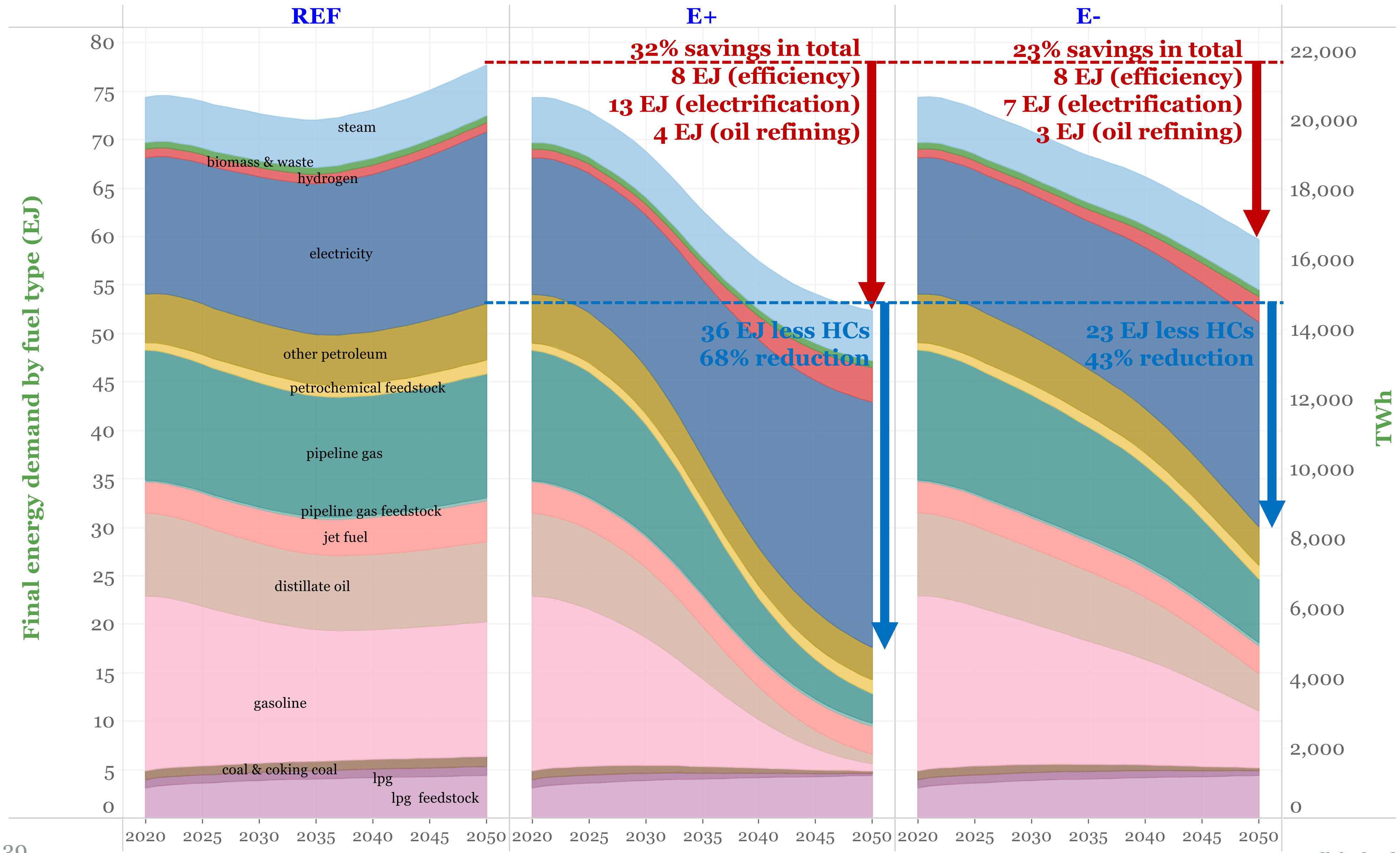
End-use energy productivity improves via same-fuel efficiency gains and via electrification; energy used for oil refining declines.



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		
Battery charge efficiency	5% energy losses		
H_2 to electricity fuel cell efficiency		46% energy losses	
Internal combustion engine efficiency			70% energy losses
Inversion DC/AC	5% energy losses	5% energy losses	
Electric motor efficiency	5% energy losses	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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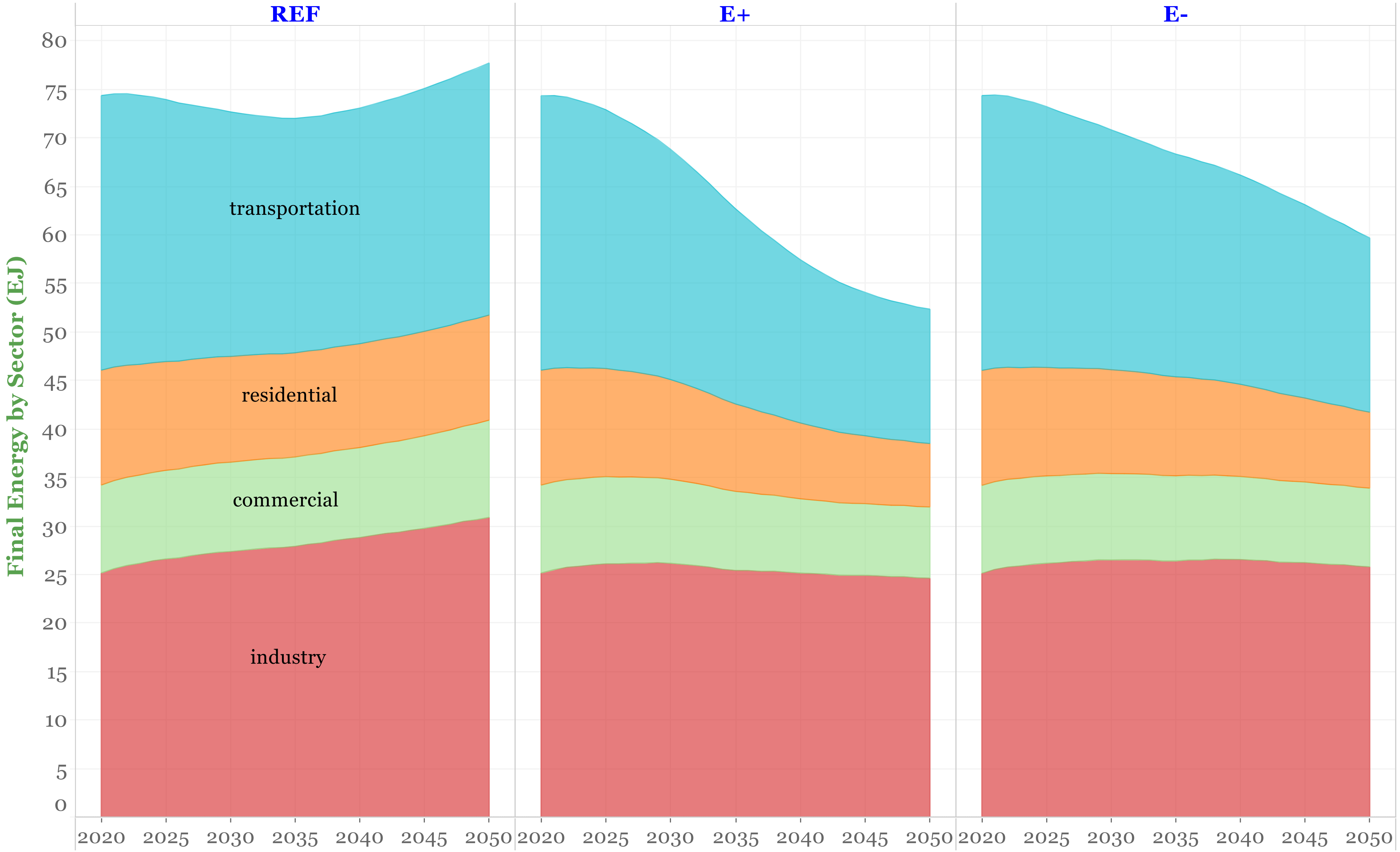
Final-energy demands for transportation decrease dramatically. Other sectors see more modest reductions by 2050.



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.

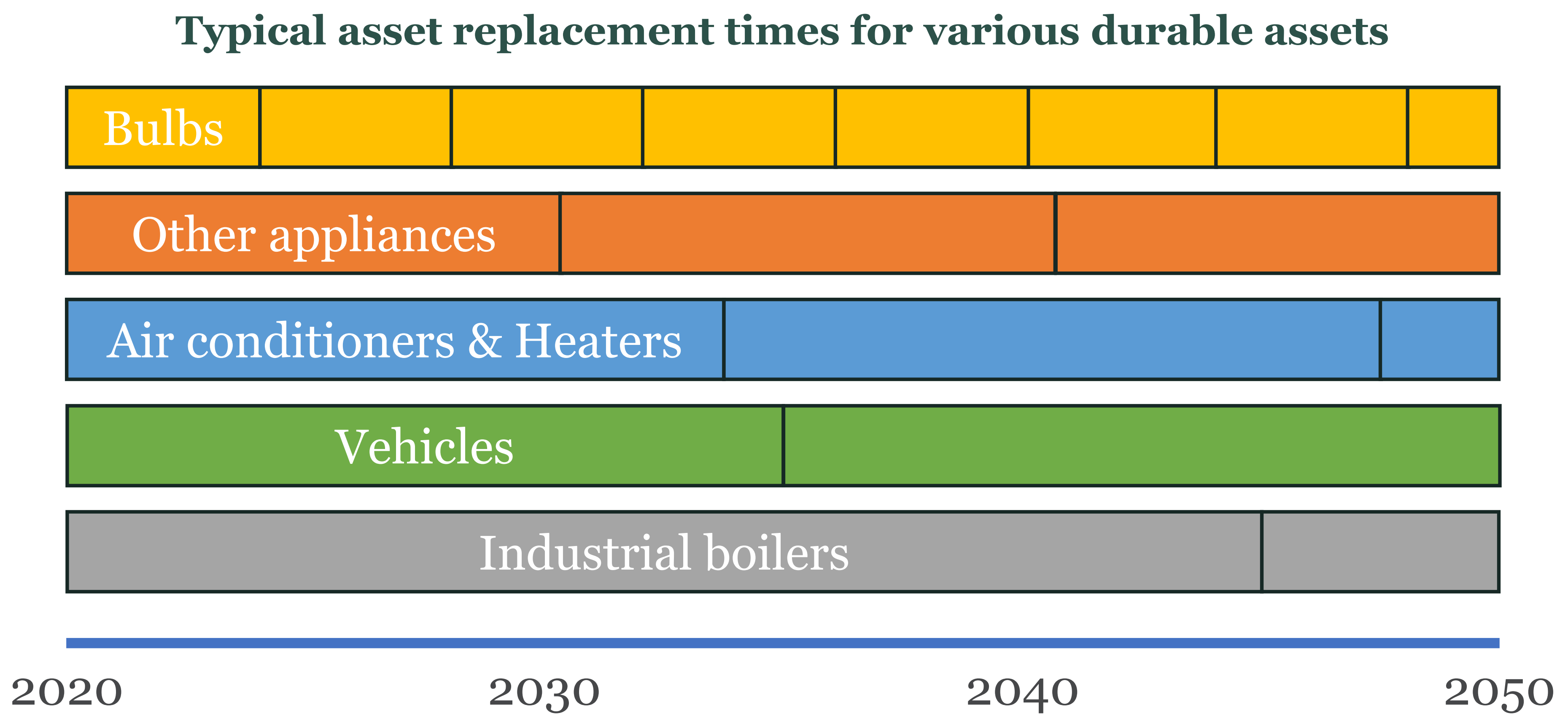

Image credit: Ryan Jones, Evolved Energy Research

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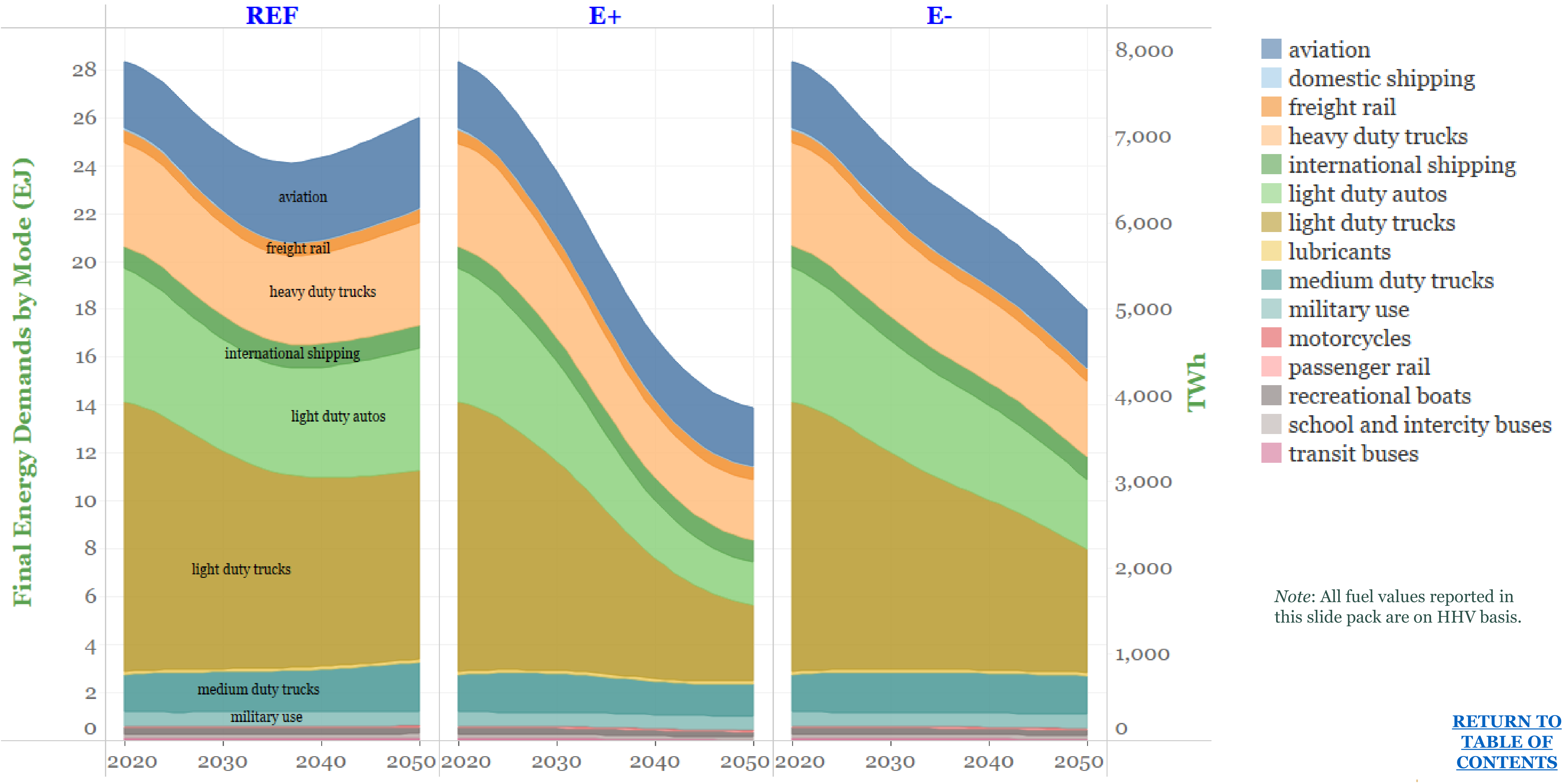
Transportation sector

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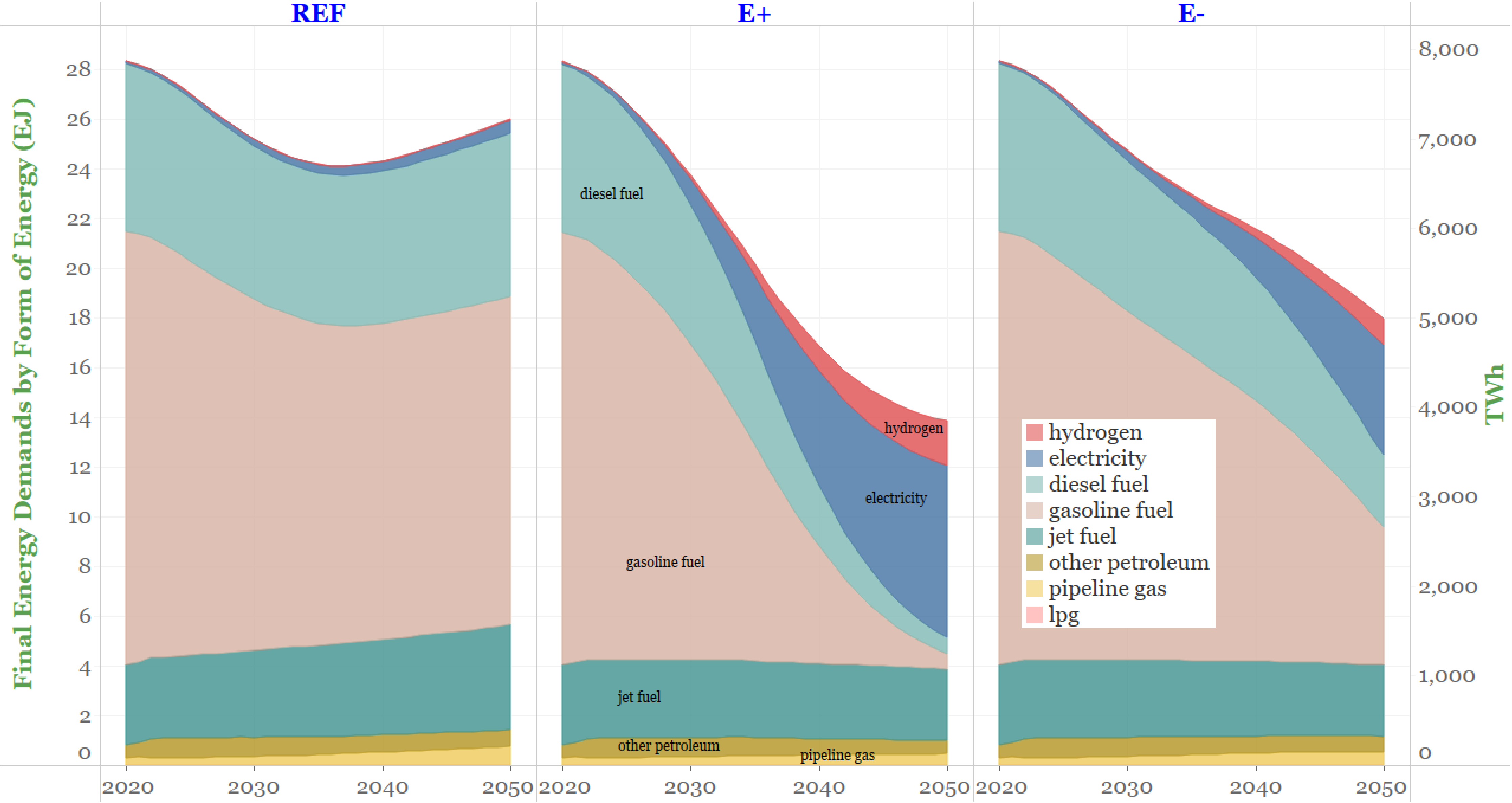
Electricity, jet fuel, and H_2 are predominant transportation fuels in E+ by 2050. Liquid fuels in 2050 are still significant in E-.



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

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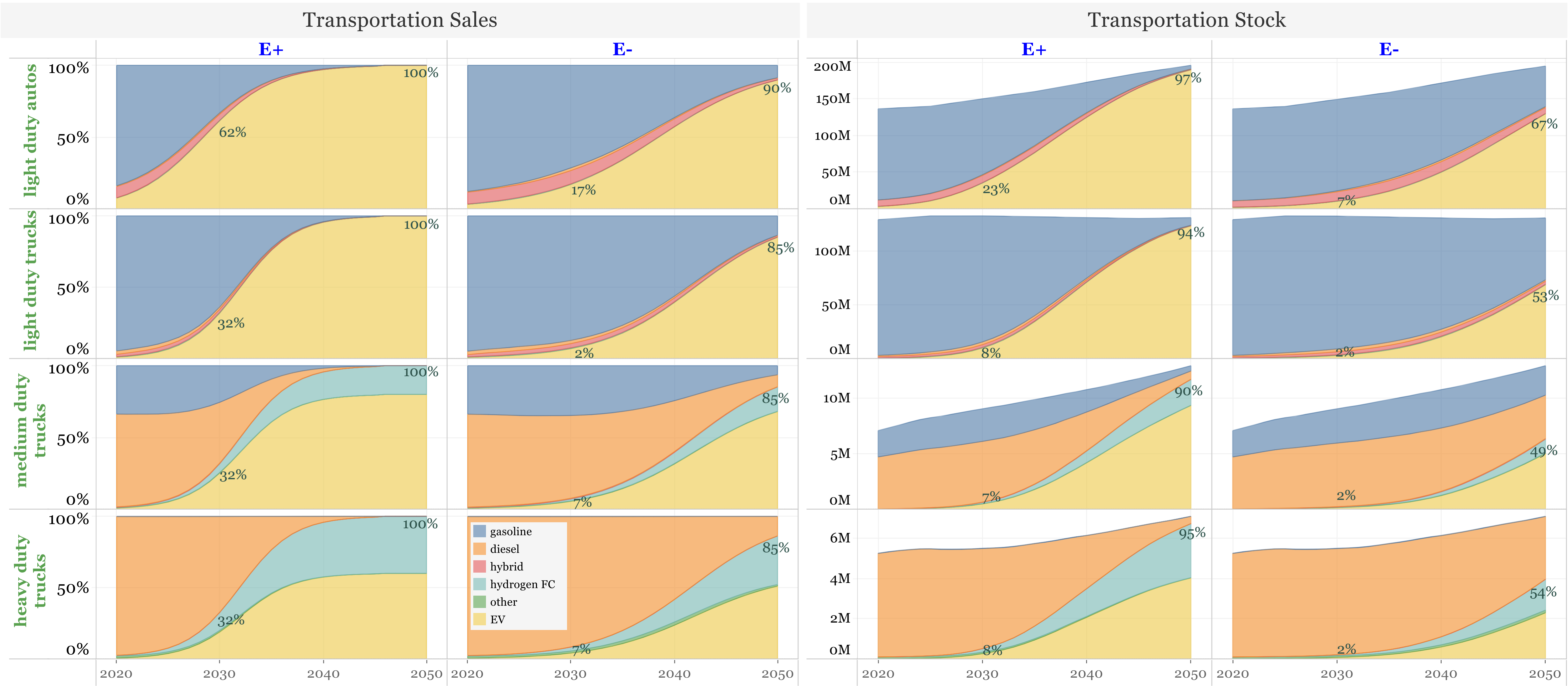
In the 2040s, light duty vehicles sales are 60%-100% EV. Medium & heavy truck sales are 50%-100% electric drivetrain (EV + H_2FCV)



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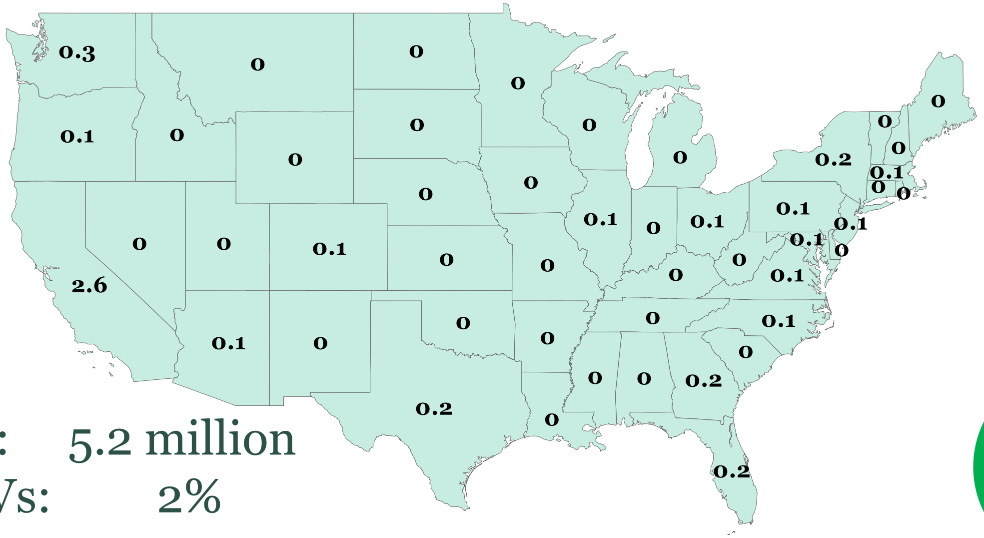
In E+, the stock of EVs grows to 17% of all light-duty vehicles by 2030 and 96% by 2050.

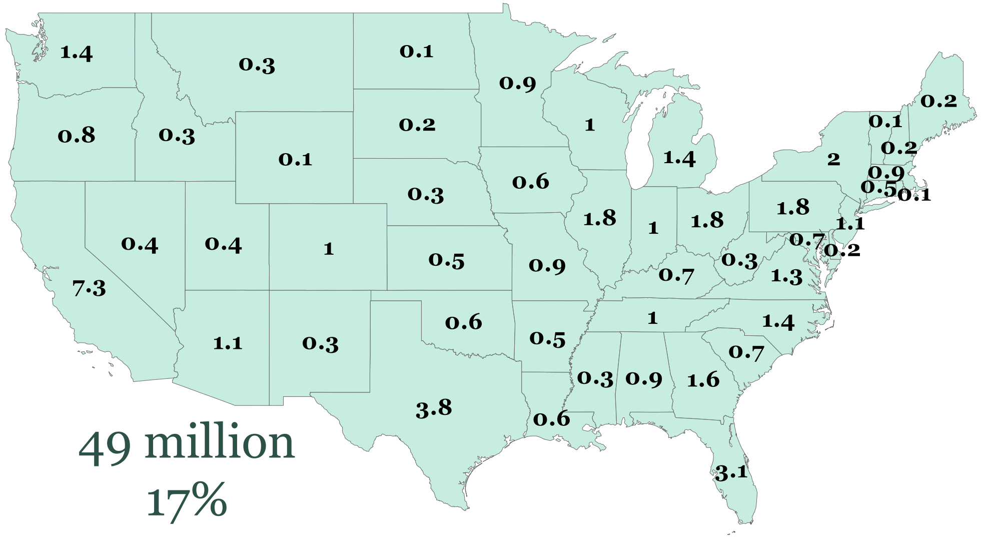
E+

2020



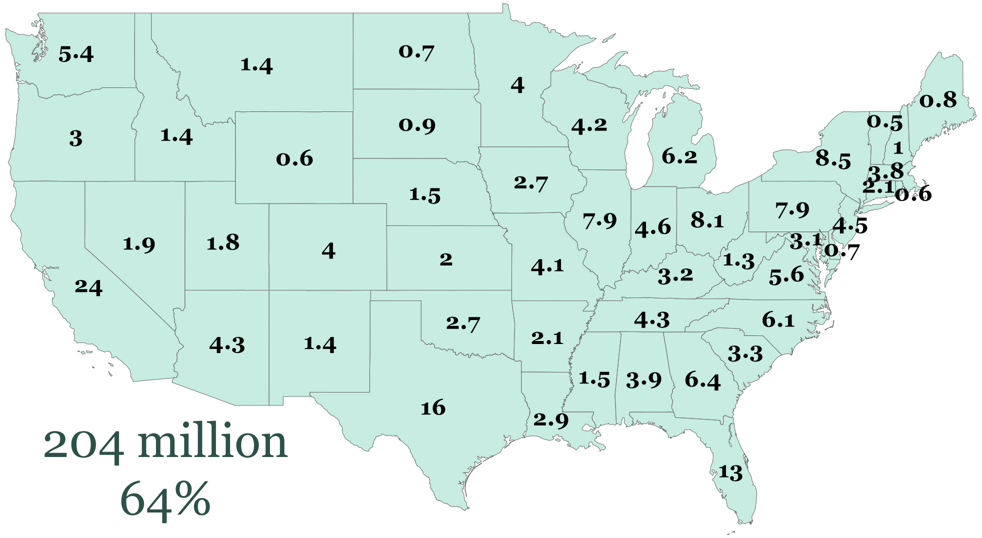
\# of EVs: 5.2 million
% of LDVs: 2%

2030



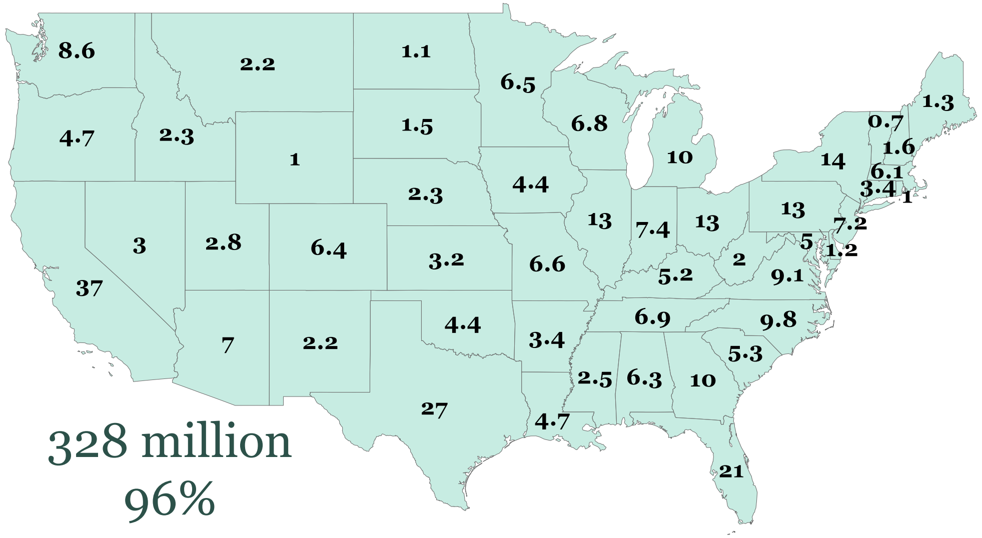
49 million
17%

2040



204 million
64%

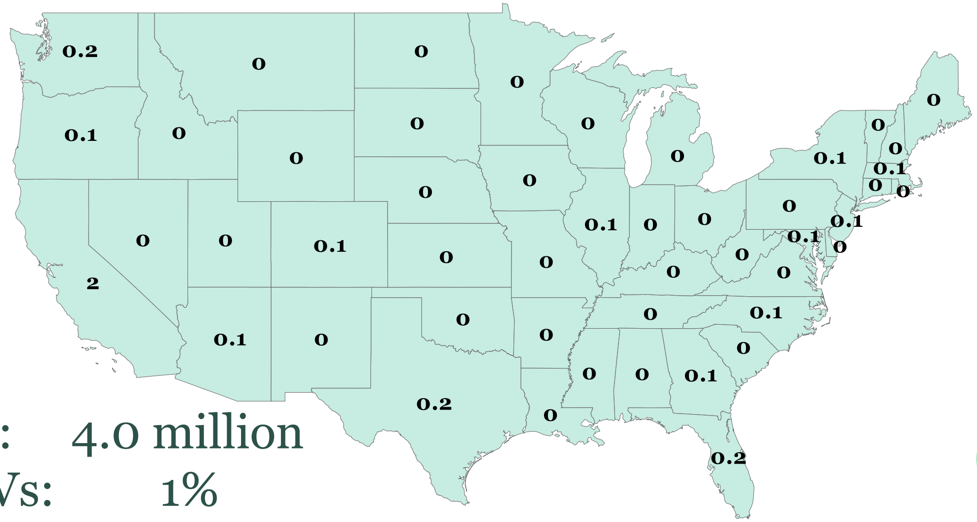
2050



328 million
96%

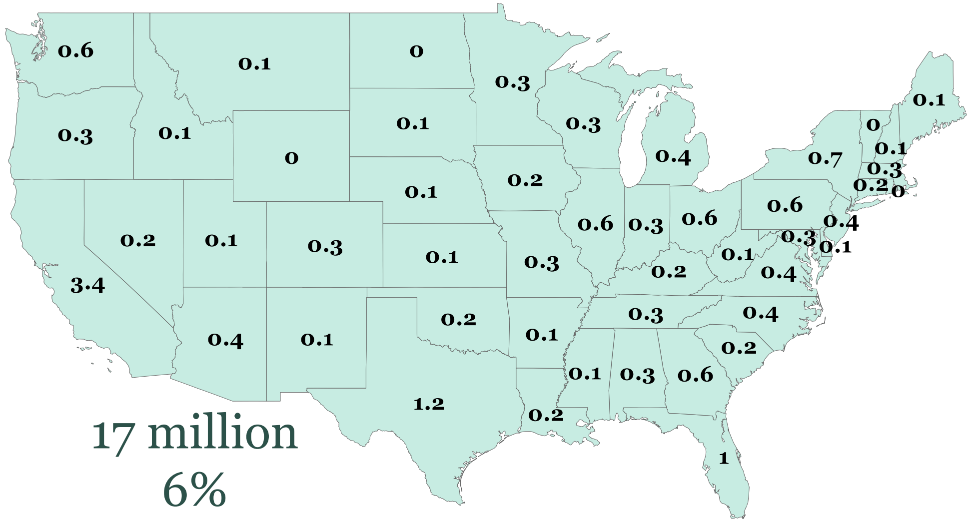
In E-, the stock of EVs grows to 6% of all light-duty vehicles by 2030 and 61% by 2050.

2020



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

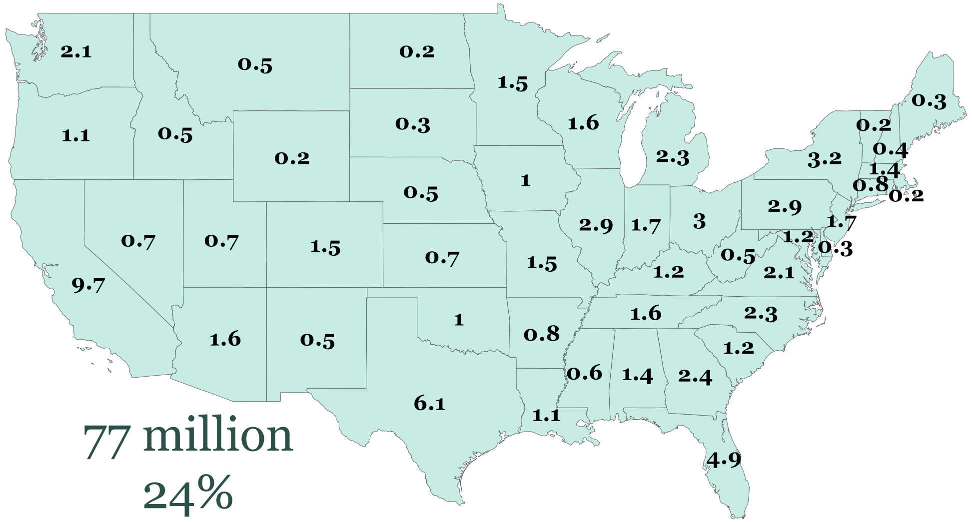
2030



17 million
6%

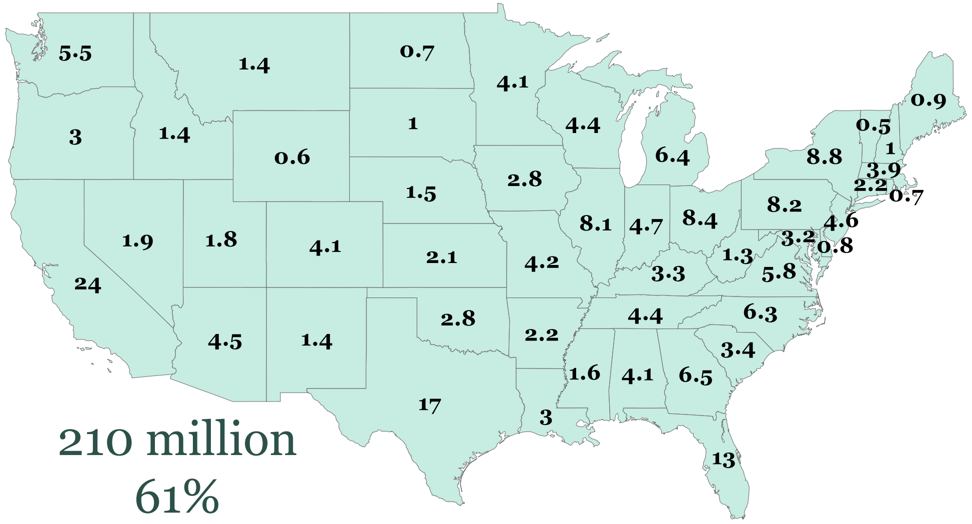
E-

2040



77 million
24%

2050



210 million
61%

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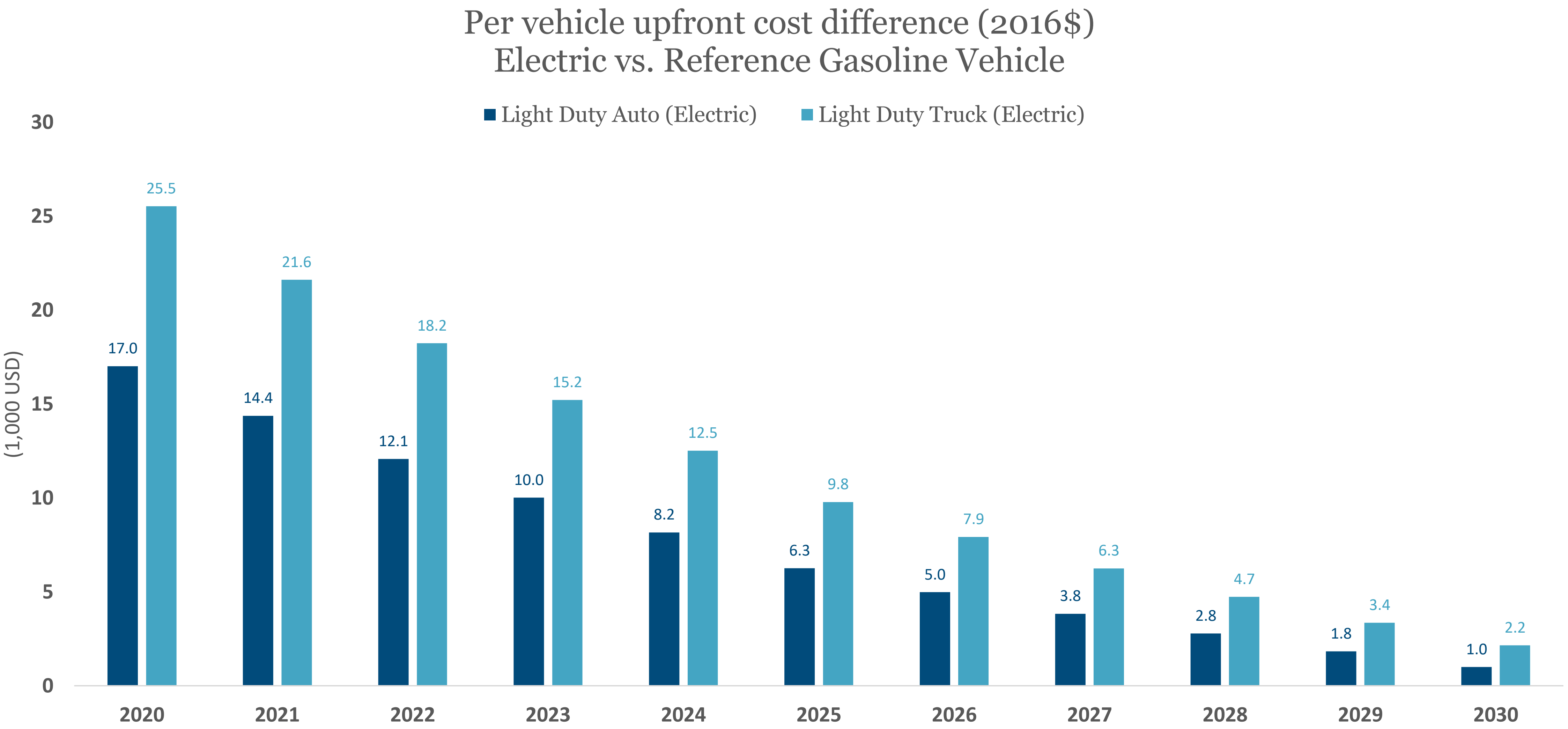
A few states have announced targets for EV registrations in 2025 and/or 2030 that approach E+ levels and generally exceed E- levels.

Green states have announced targets that exceed E- levels.

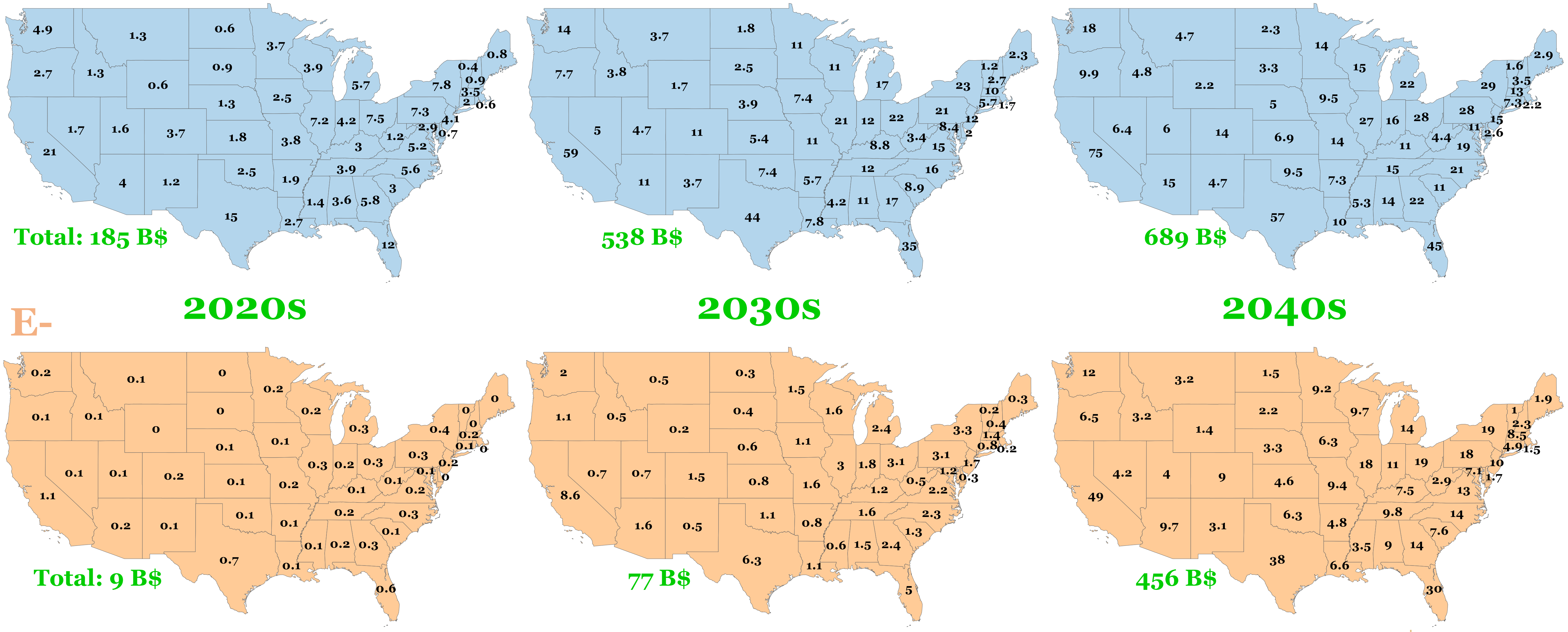
	State targets	E+	E-
	Battery-EVs in the light-duty vehicle fleet (millions)		
California, 2025	1.5	4.9	2.7
California, 2030	5.0	7.3	3.4
Colorado, 2025	0.055	0.542	0.212
Colorado, 2030	0.94	0.97	0.34
Connecticut, 2025	0.15	0.27	0.10
Maine, 2025	0.007	0.10	0.032
Maryland, 2025	0.3	0.41	0.15
Massachusetts, 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



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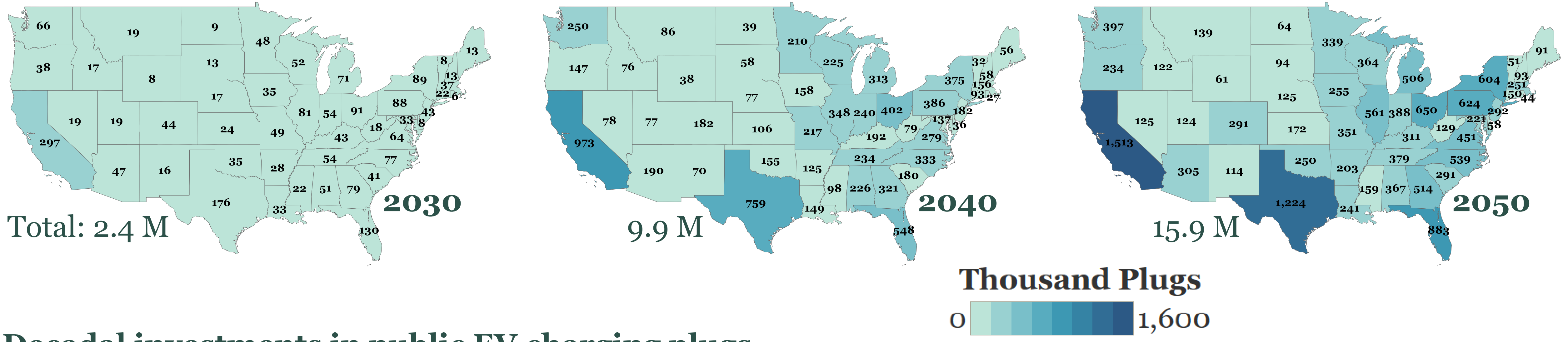
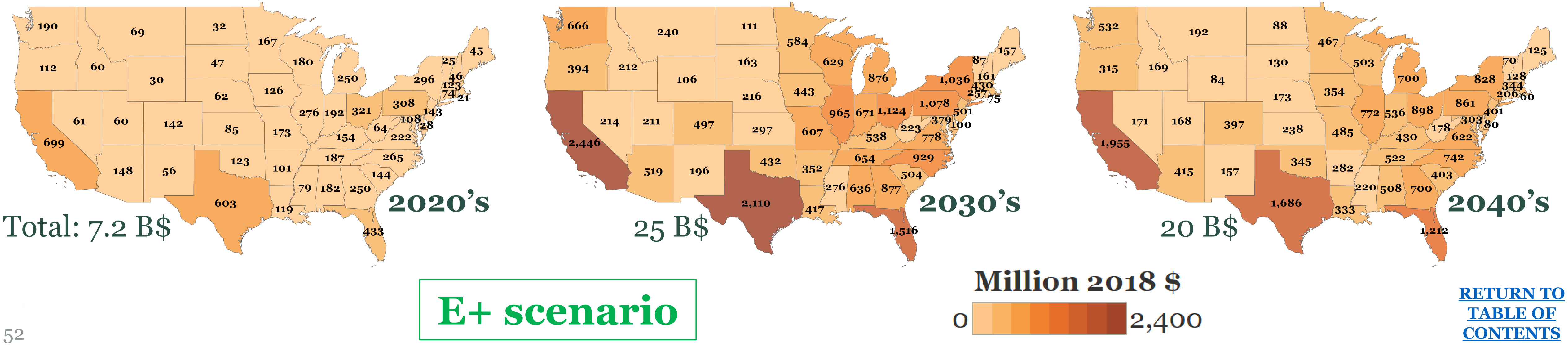
The number of public charging plugs needed to support EV fleets are still modest in 2030 in most states, but grow rapidly after.

Number of public EV charging plugs in operation



Decadal investments in public EV charging plugs



E+ scenario

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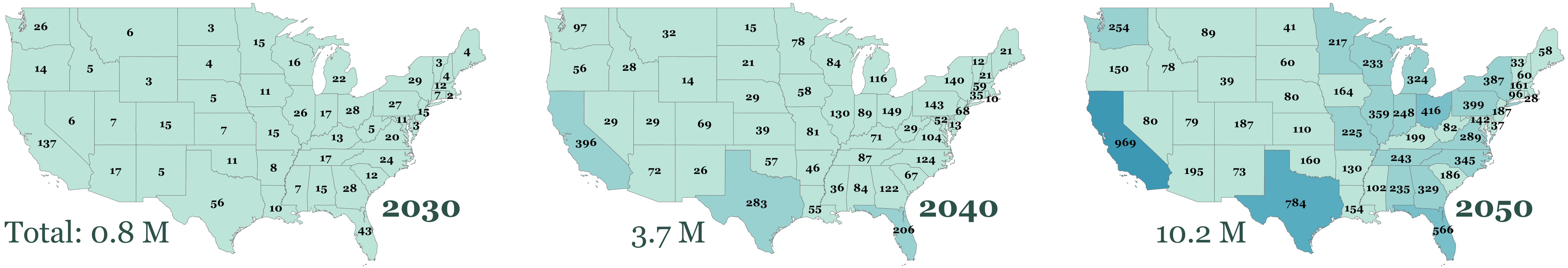
The number of public charging plugs needed to support EV fleets are still modest in 2030 in most states, but grow rapidly after.

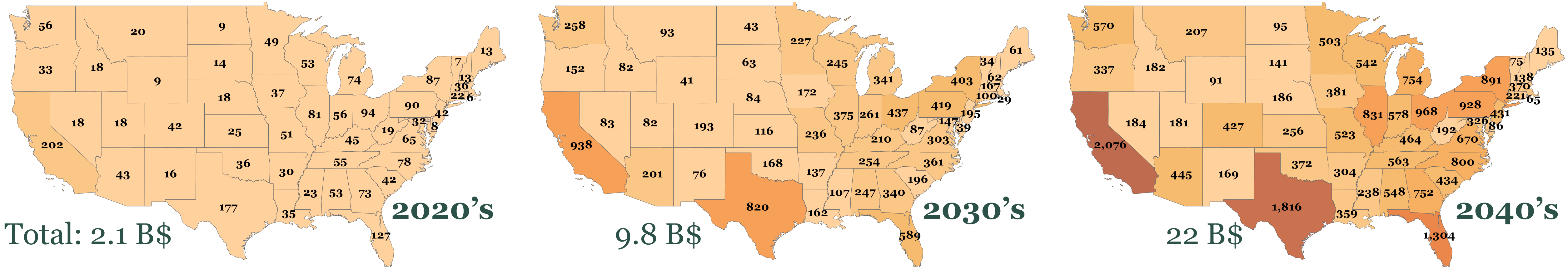
Number of public EV charging plugs in operation



Thousand Plugs

0 – 1,600

Decadal investments in public EV charging plugs



E- scenario

Million 2018 $

0 – 2,400

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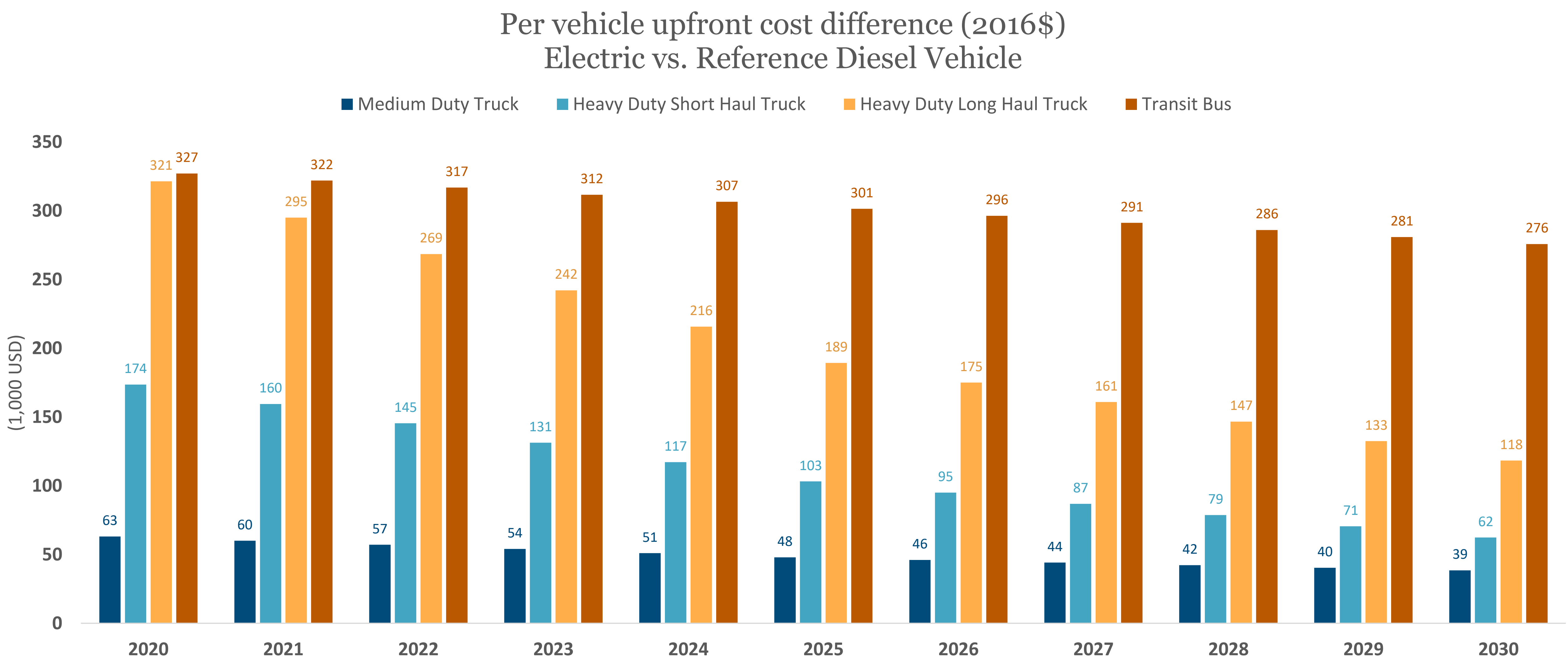
Upfront cost premium for medium and heavy duty electric trucks and transit buses remains significant



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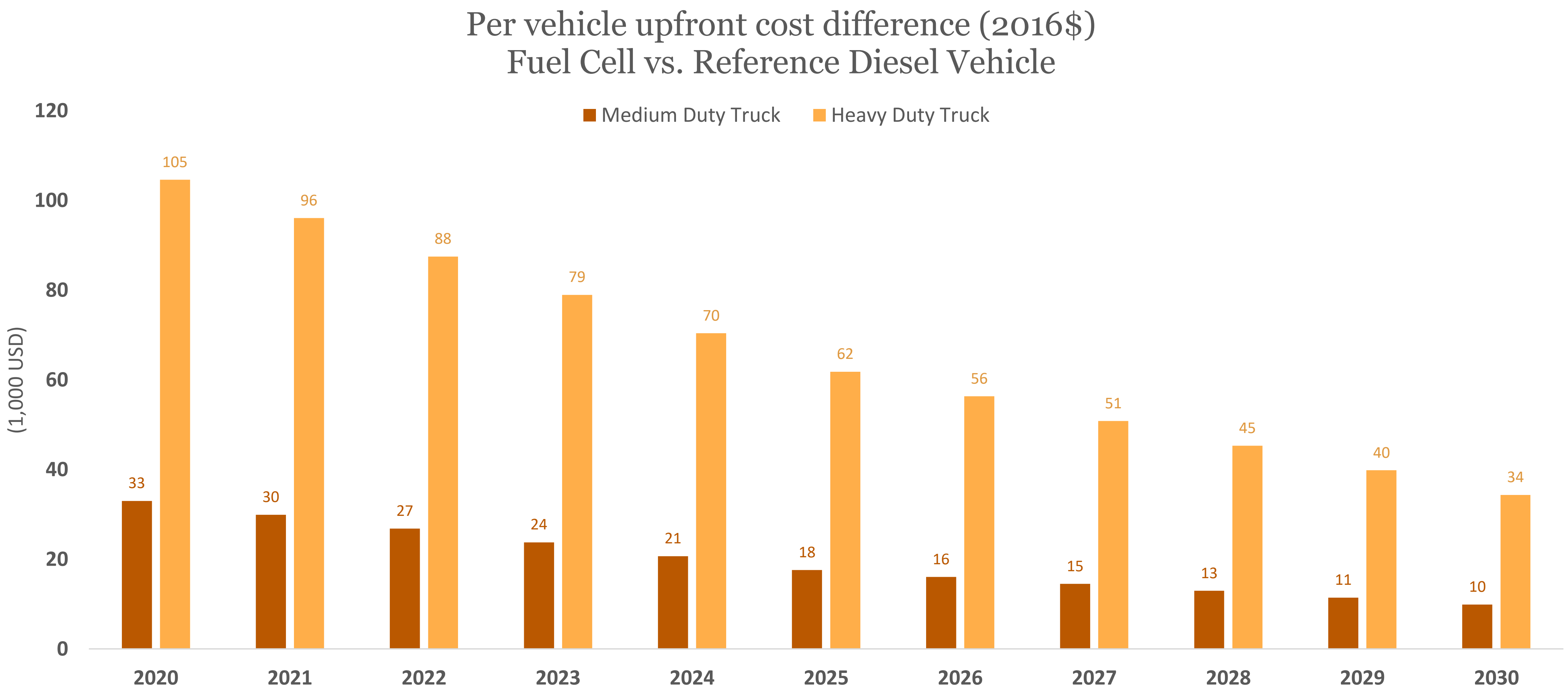
Medium and heavy duty fuel cell vehicles have much lower upfront cost premium than electric but higher fueling costs



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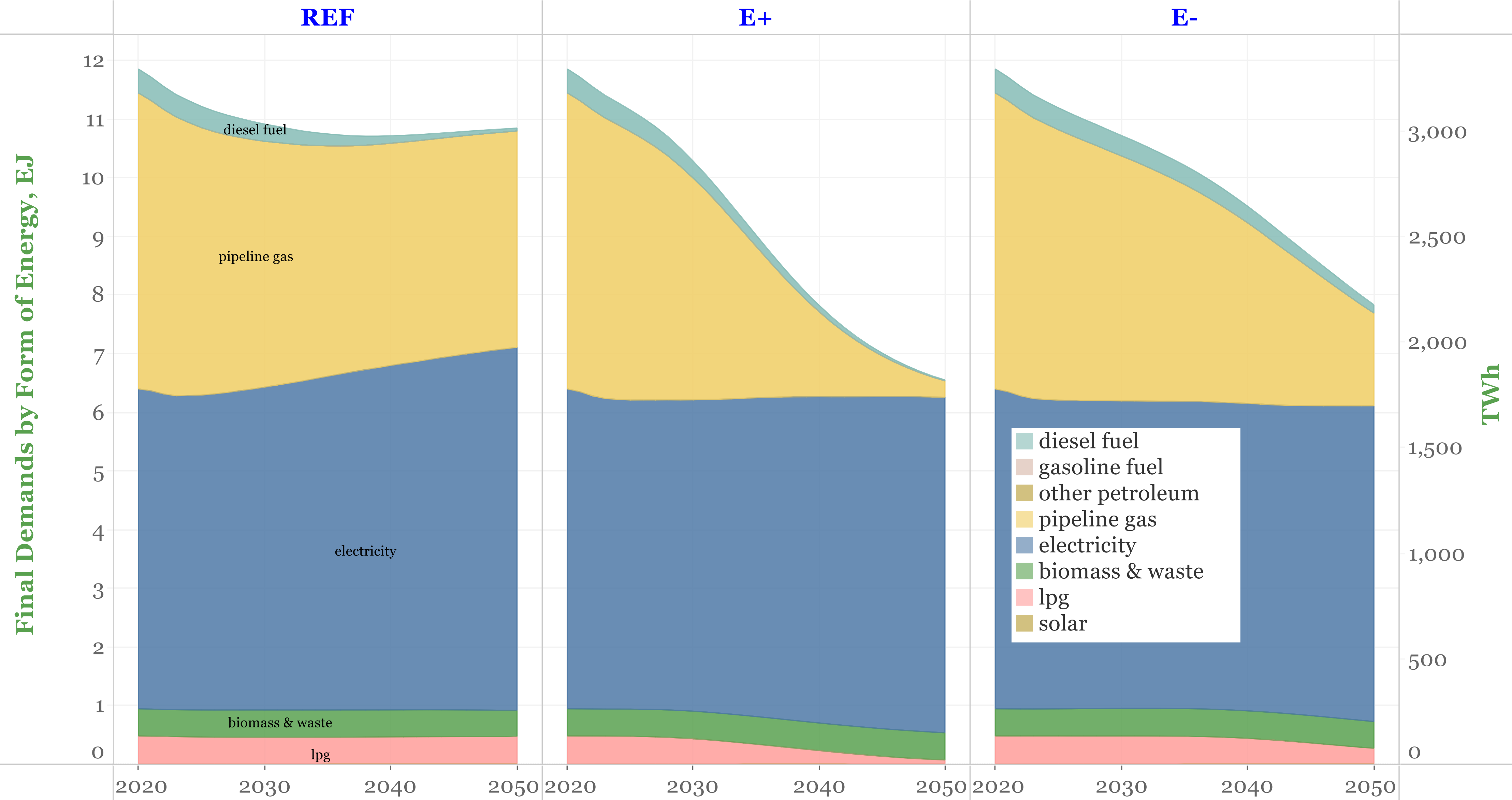
Buildings sector

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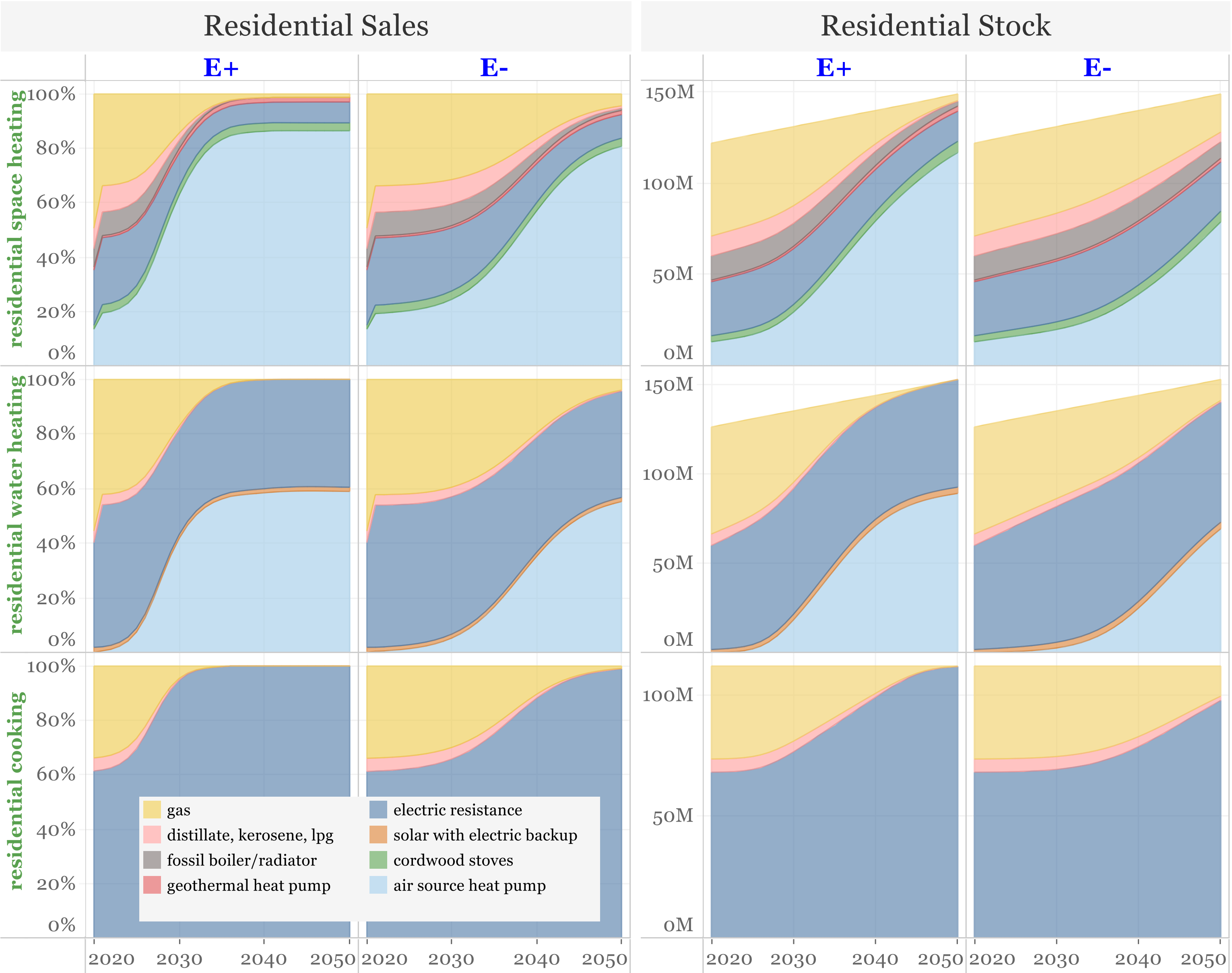
Consumer investment choices shift rapidly to electricity for residential space heating, water heating, and cooking.

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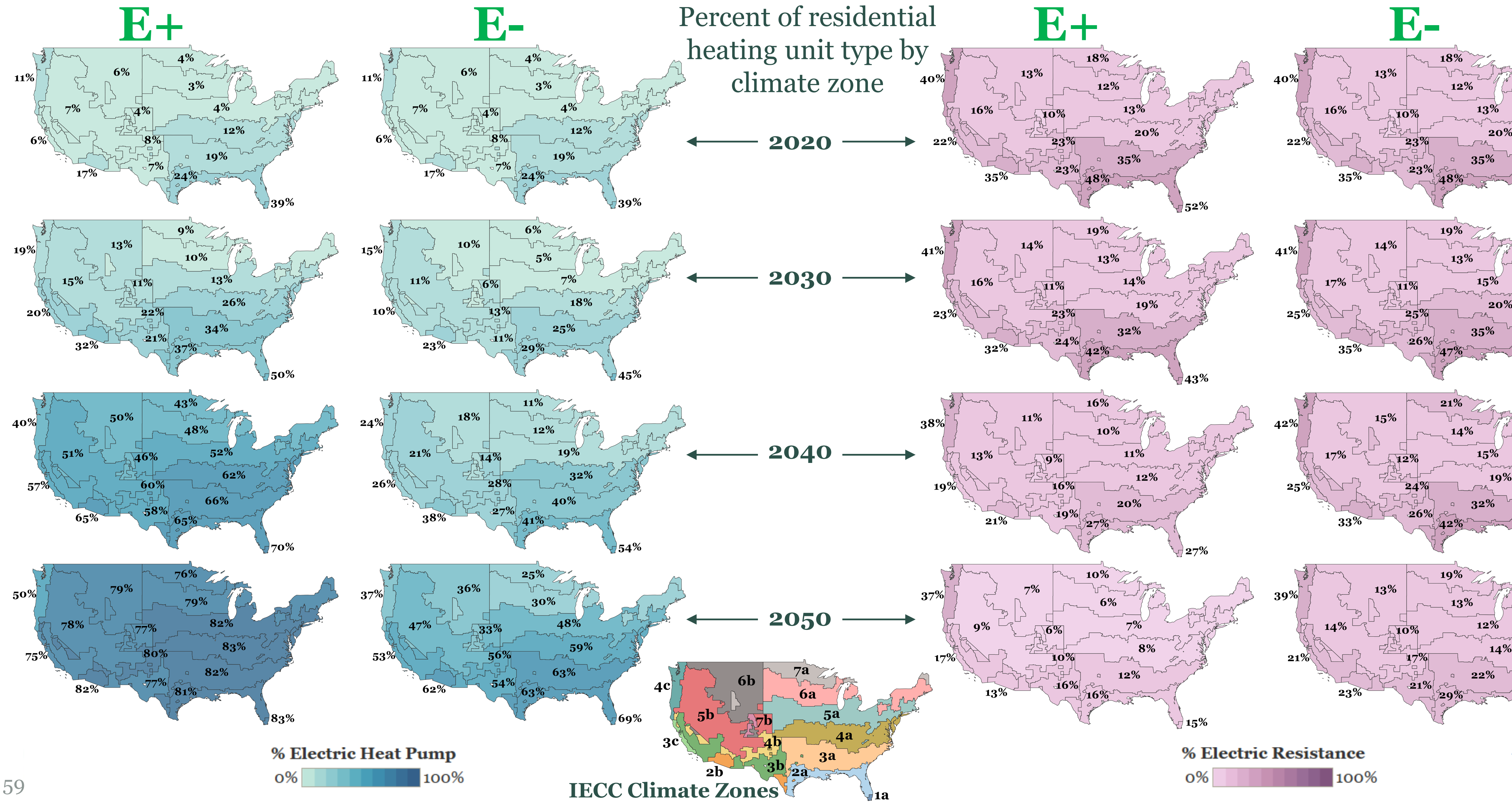
Electric home heating grows significantly, with the fraction adopting heat pumps varying significantly by climate zone.



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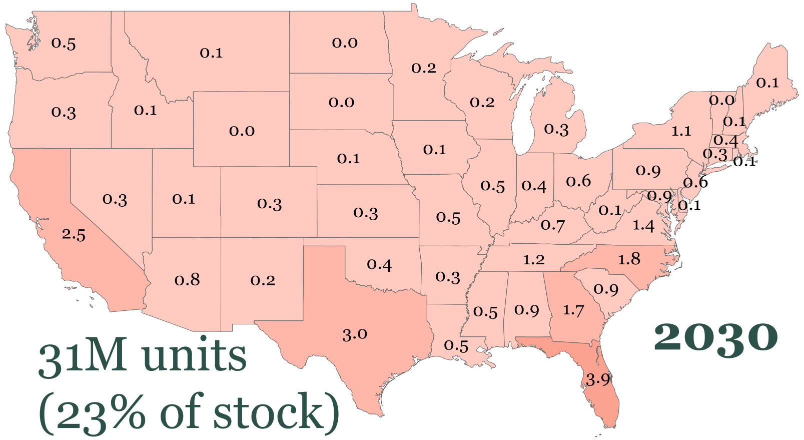
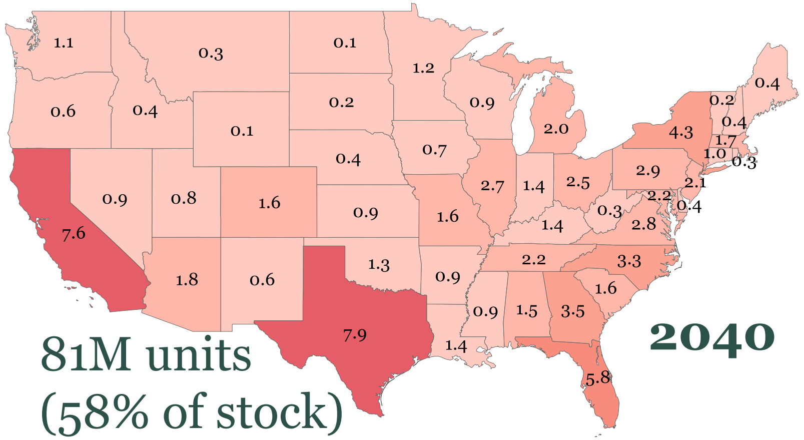
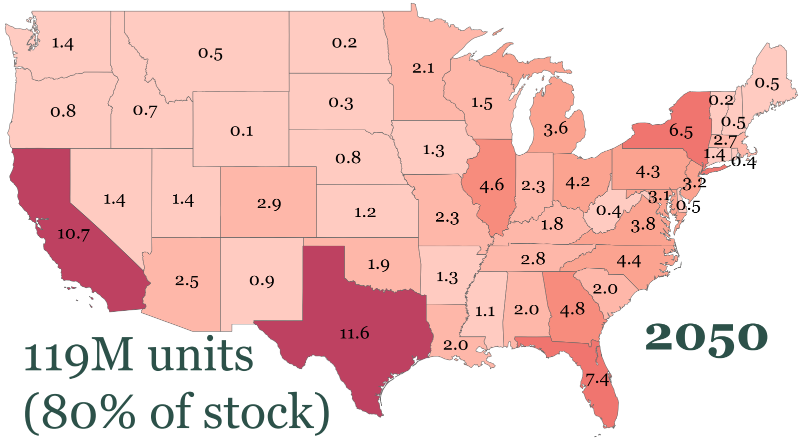
Residential heat pumps grow from ~10% of the space heating stock in 2020 up to 80% (E+) or 54% (E-) by 2050.

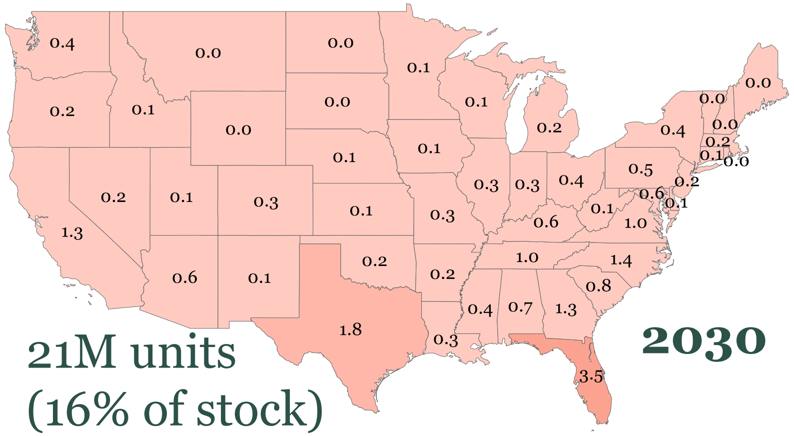
E+

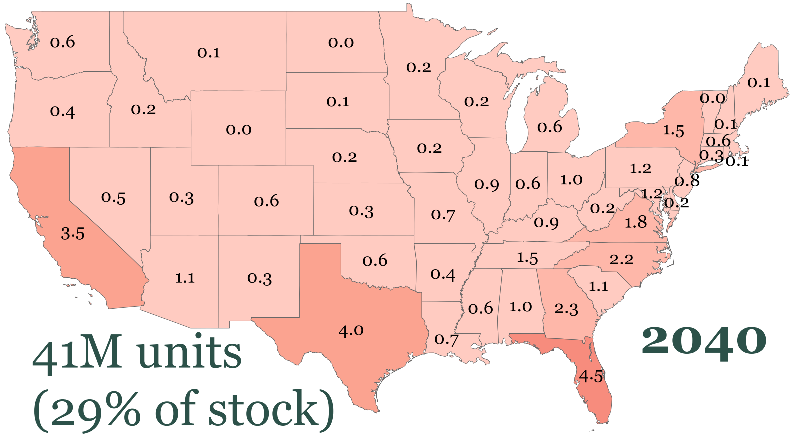


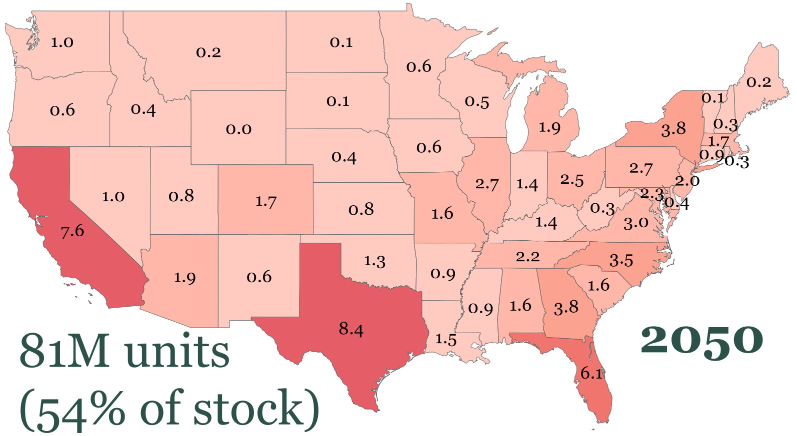




E-







Million Units

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

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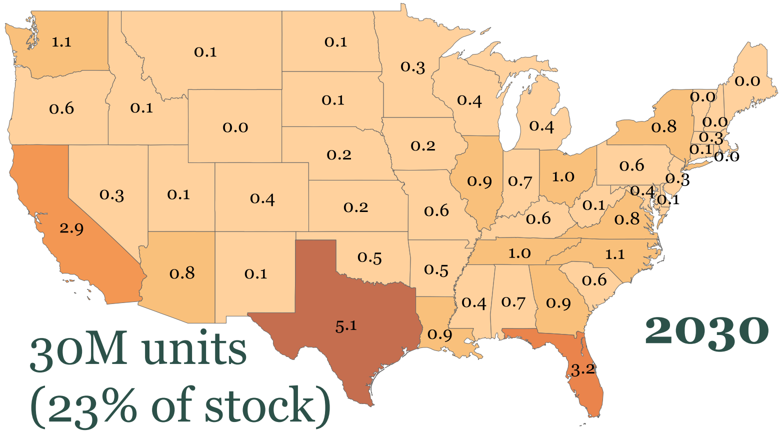
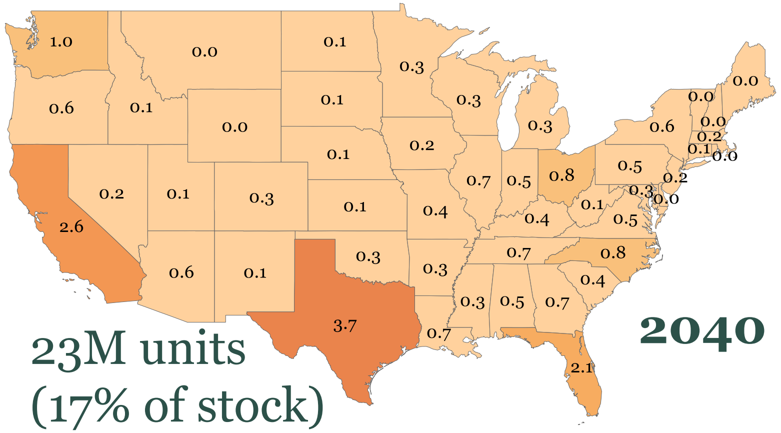
Residential electric resistance units decline from ~25% of the space heating stock in 2020 to 11% (E+) or 18% (E-) by 2050.

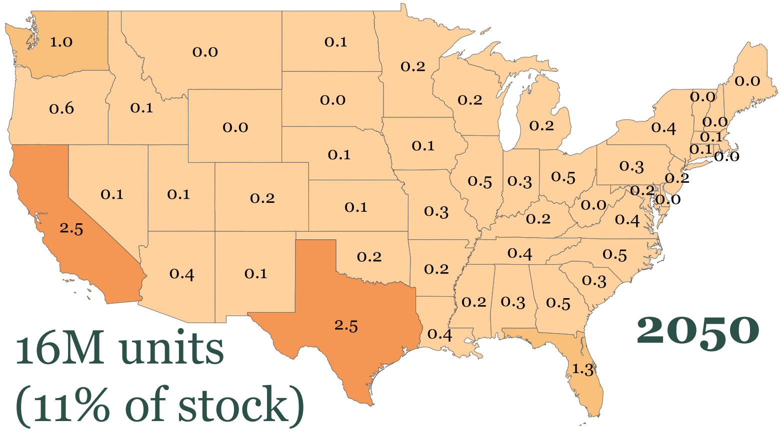
E+



30M units
(23% of stock)

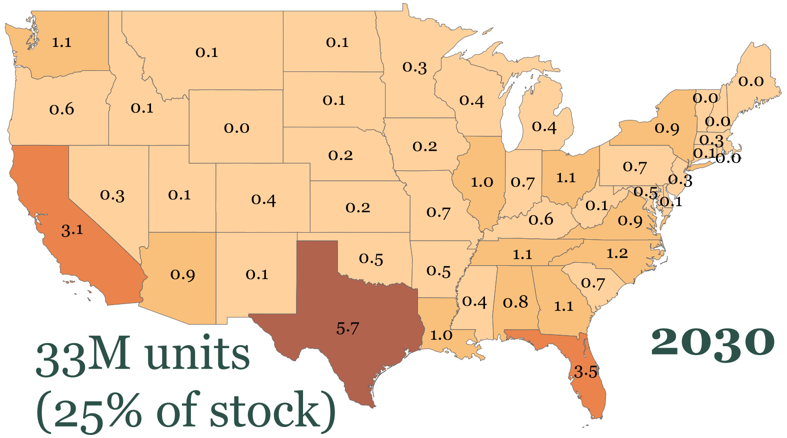


23M units
(17% of stock)

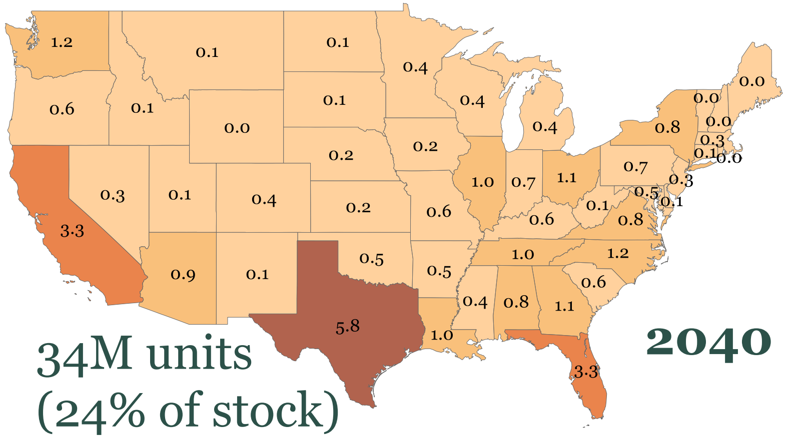


16M units
(11% of stock)

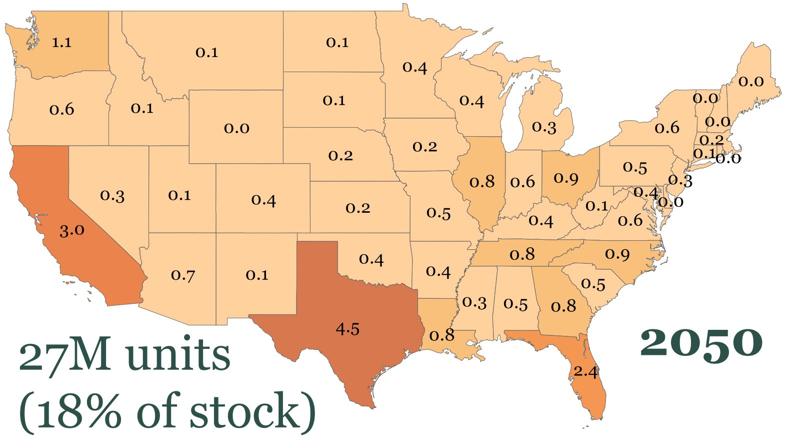
E-



33M units
(25% of stock)



34M units
(24% of stock)



27M units
(18% of stock)

Million Units

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

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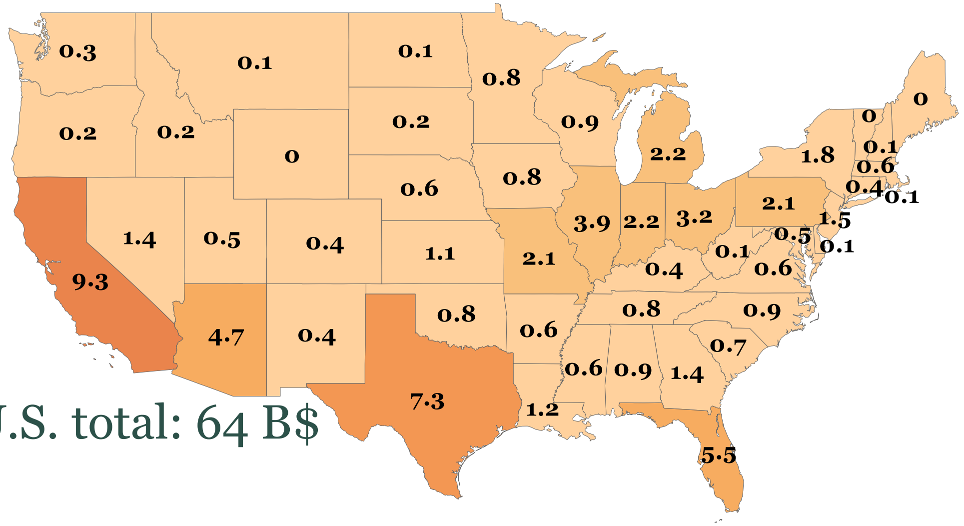
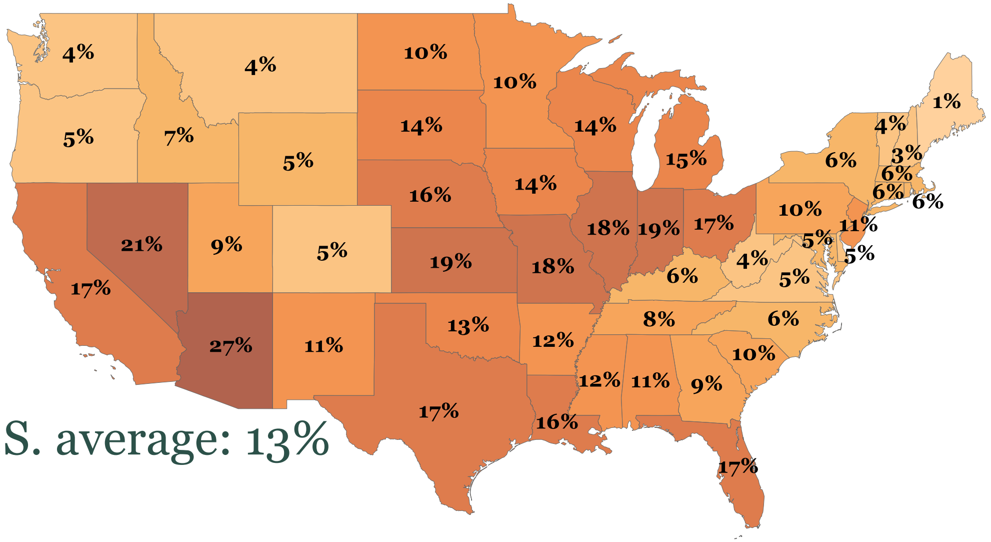
Capital expenditures from 2021-2030 for residential space and water heating are $60B to $70B higher than REF.

E+



U.S. total: 64 B$

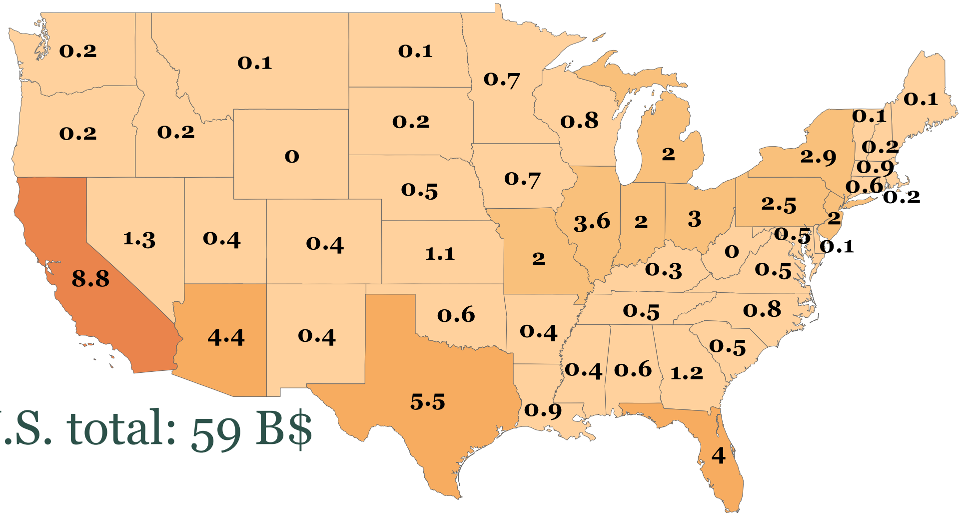


U.S. average: 13%

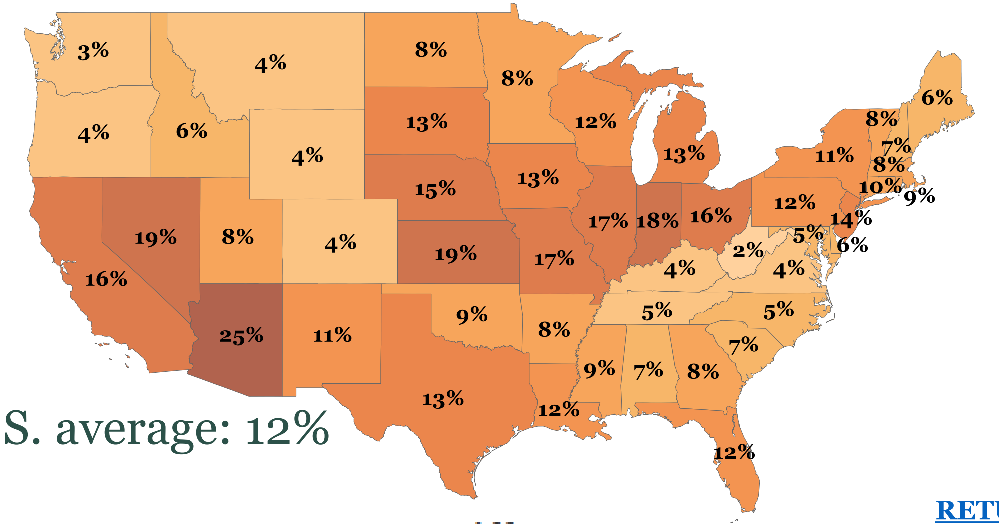
Incremental capital vs. REF

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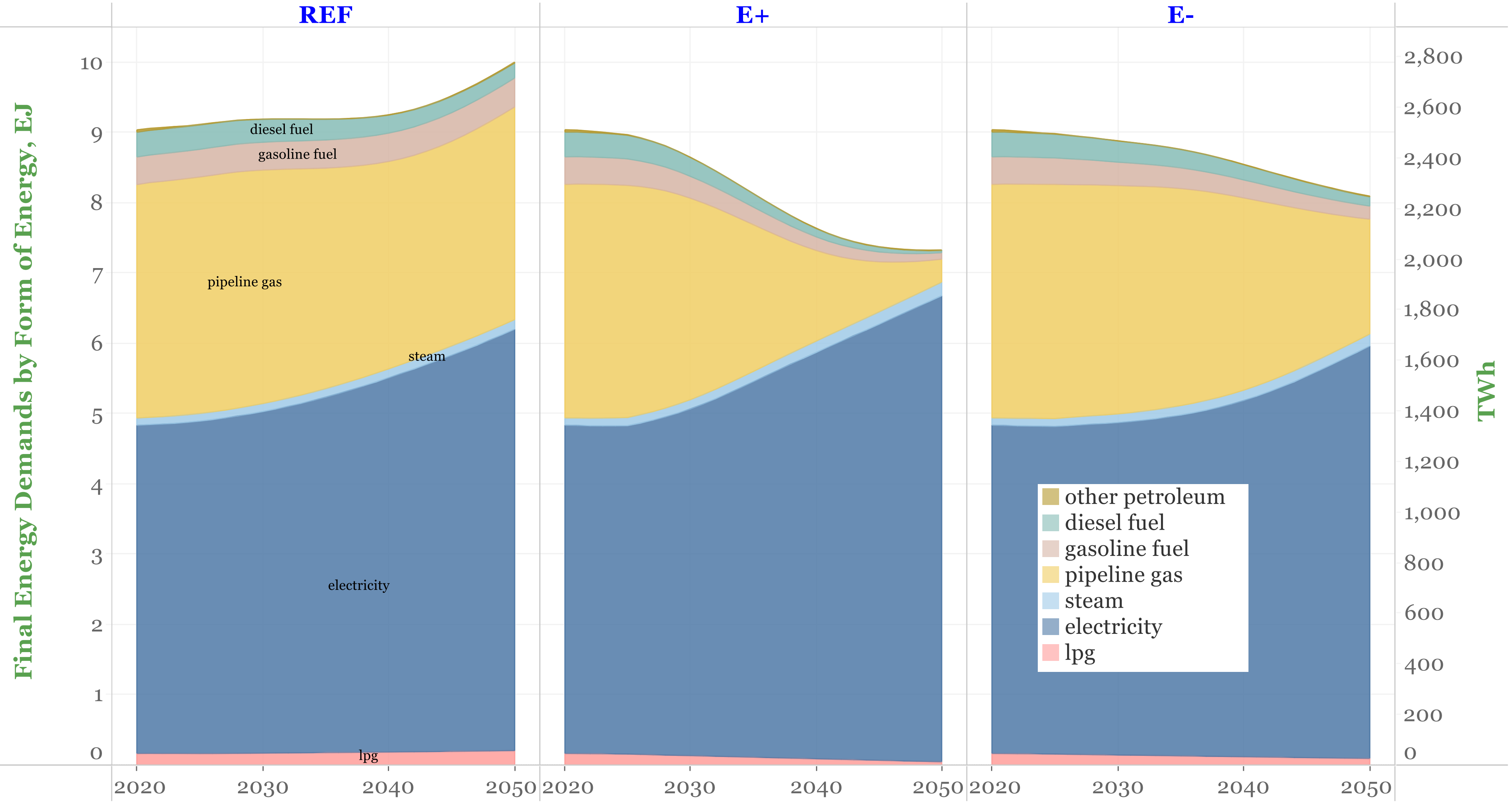
Commercial buildings' final energy use declines, and by 2050 electricity accounts for 90% in E+ and 70% in E-.



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

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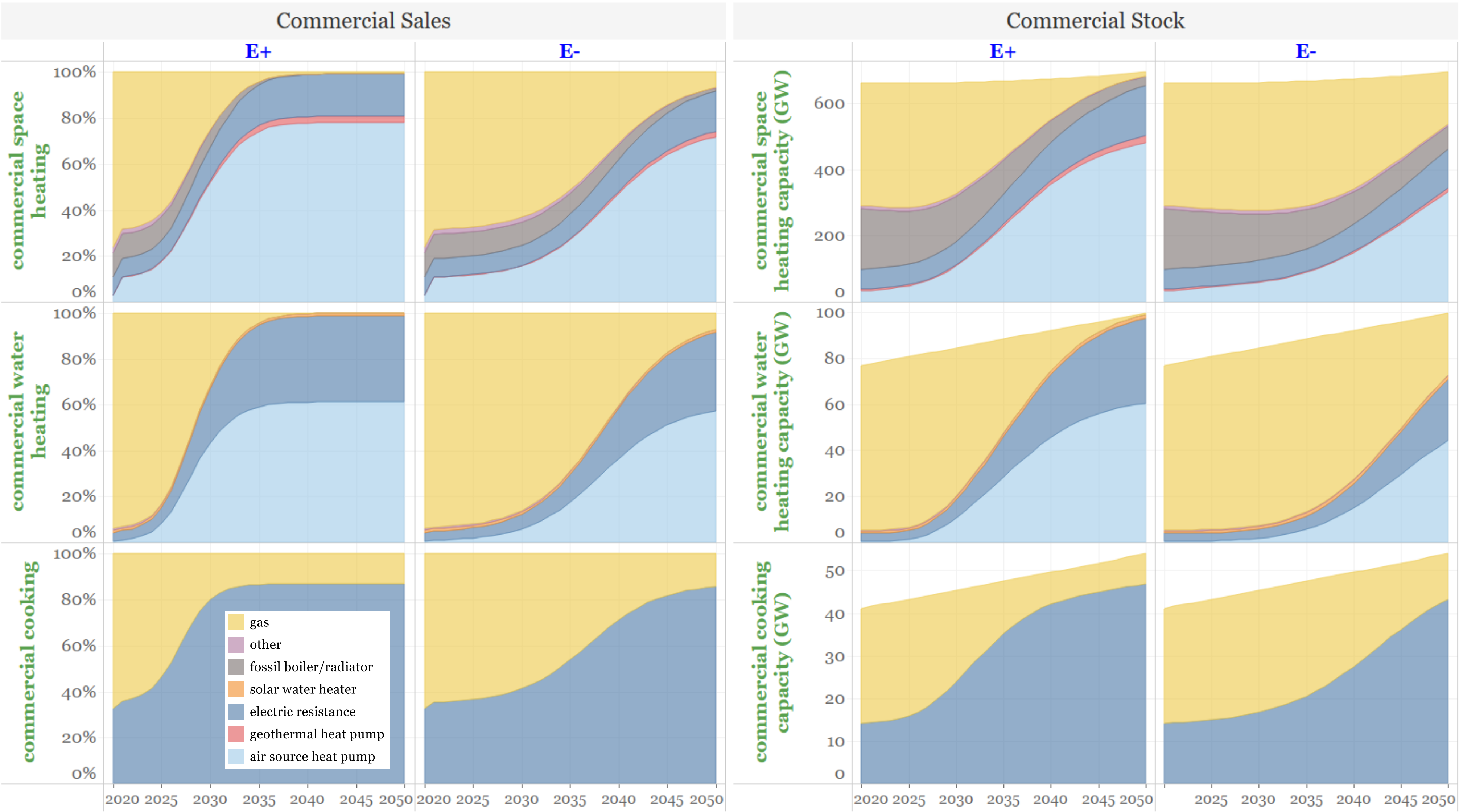
In the commercial sector (as in residential), investment choices shift rapidly to electricity for all energy services.



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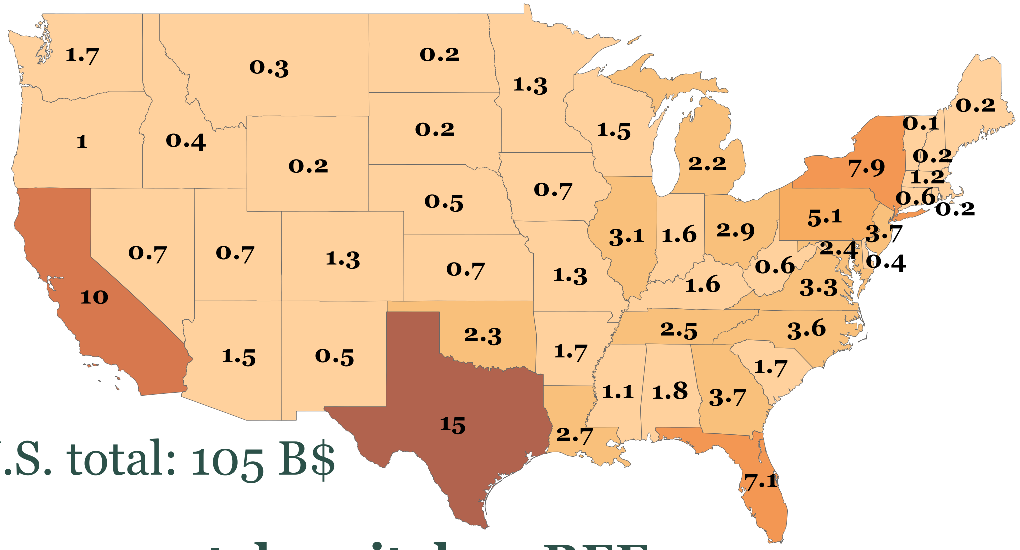
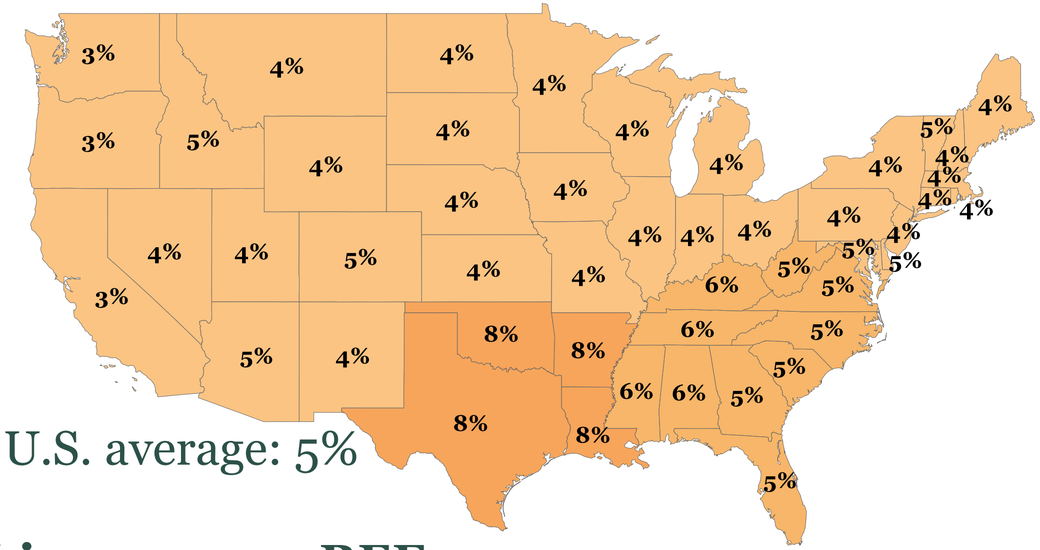
Capital expenditures from 2021-2030 for commercial HVAC and water heating are ~$100B to $110B (5%) higher than REF.

E+



U.S. total: 105 B$

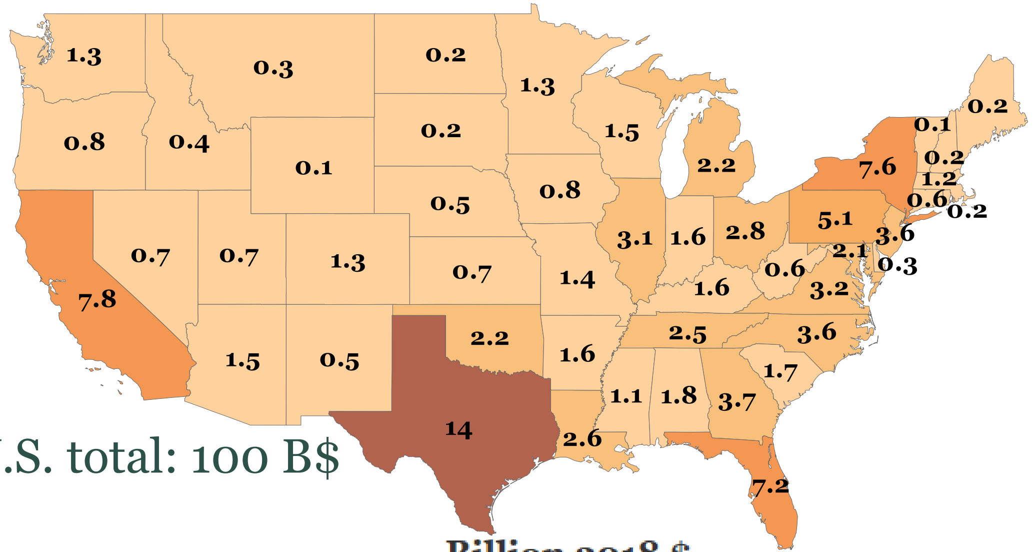


U.S. average: 5%

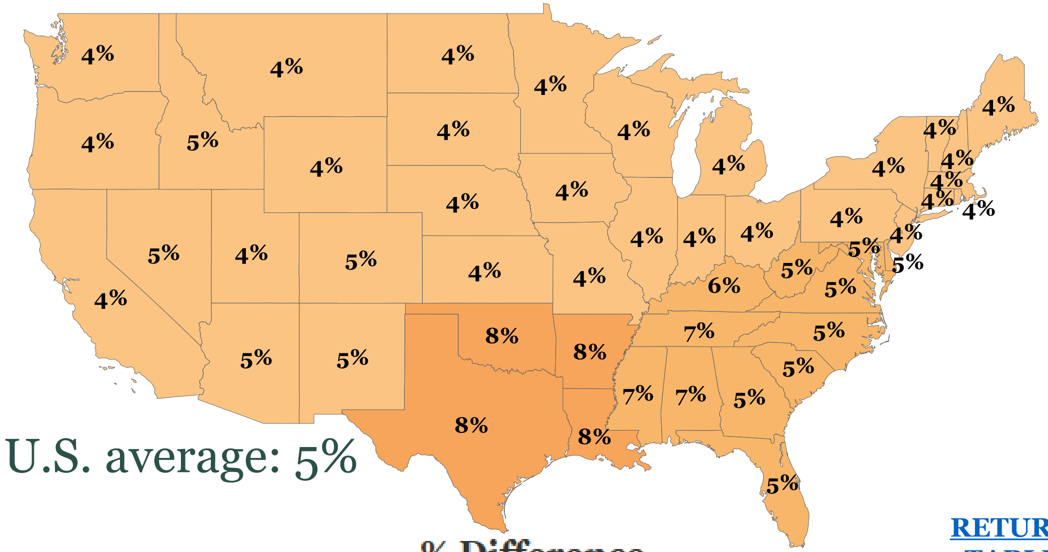
Incremental capital vs. REF

% increase vs. REF

E-



U.S. total: 100 B$



U.S. average: 5%

Billion 2018 $

0 16

% Difference

0% 25%

2021 - 2030

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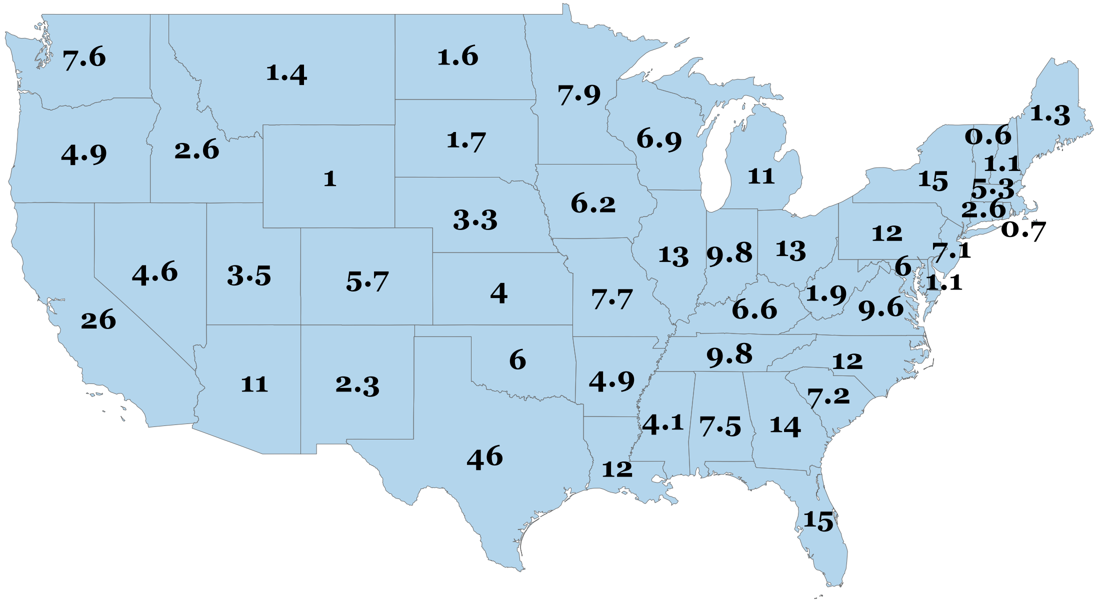
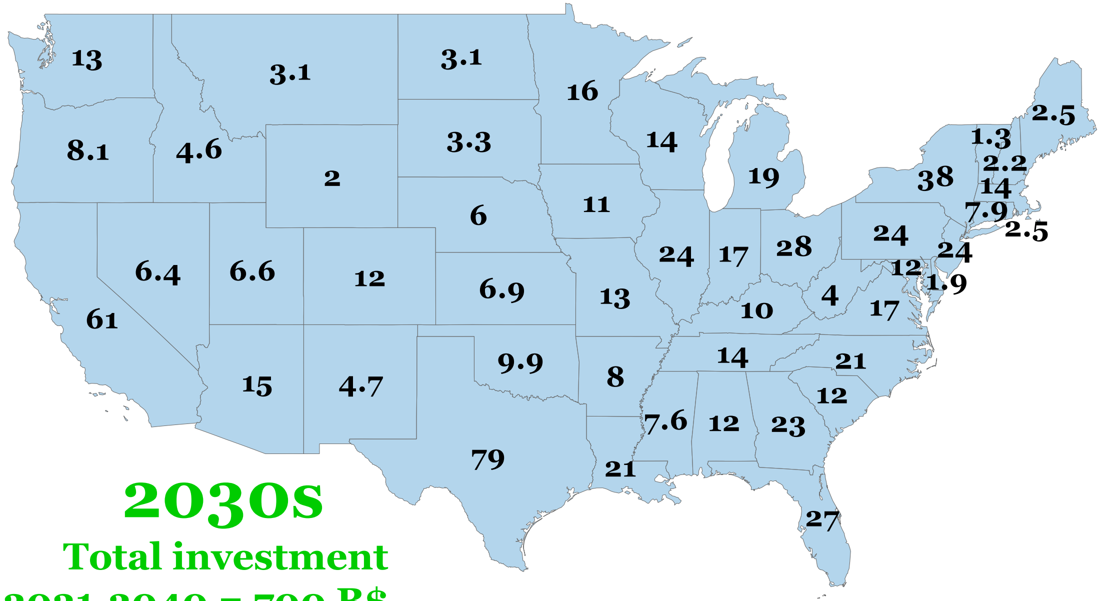
Electricity distribution investments are $370-700B per decade.

E+ scenario

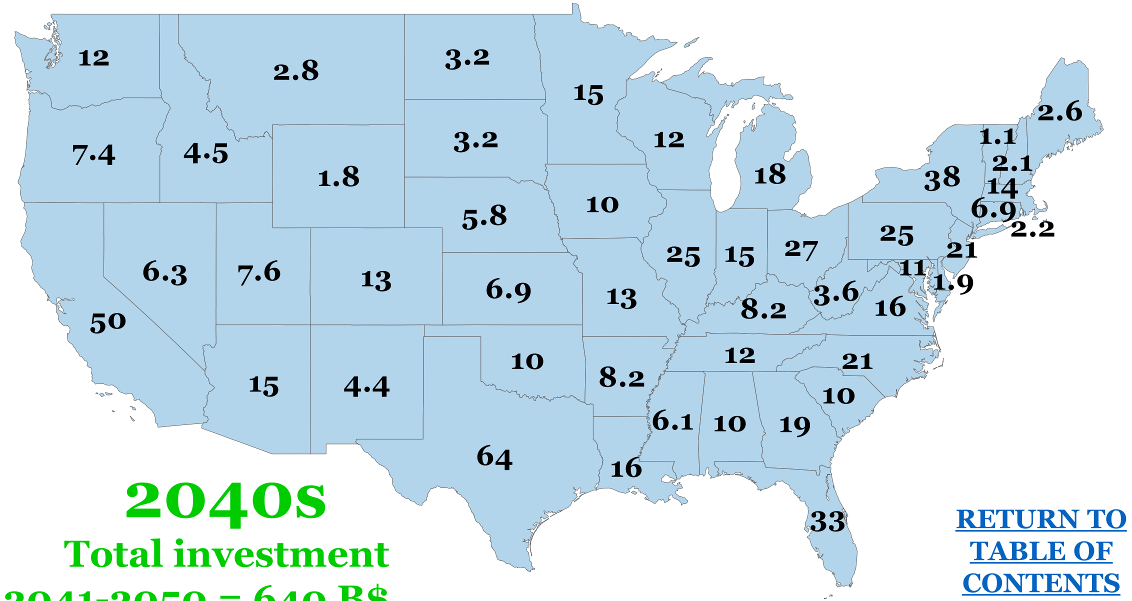
2020s
Total investment
2021-2030 = 370 B$



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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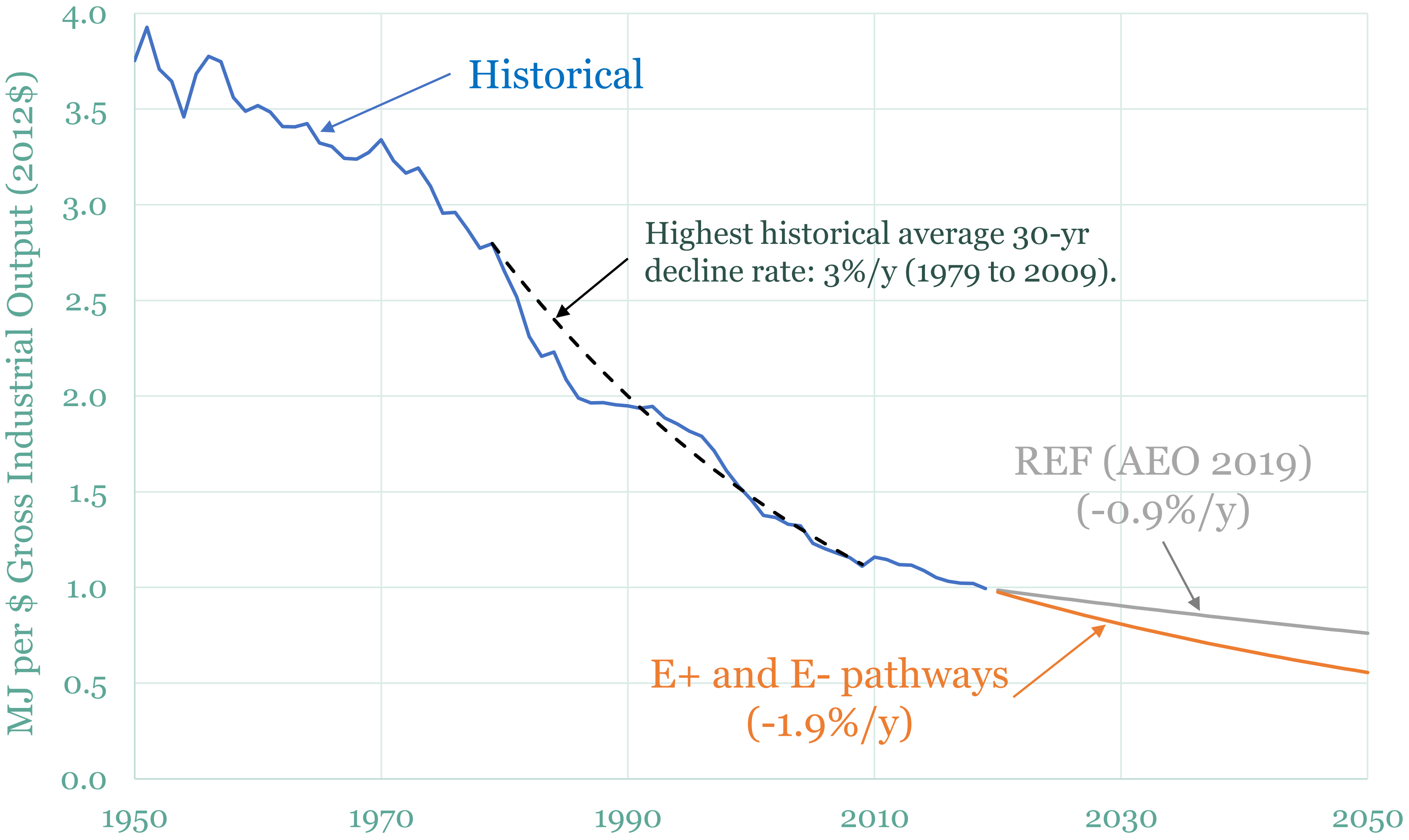
Industrial sector

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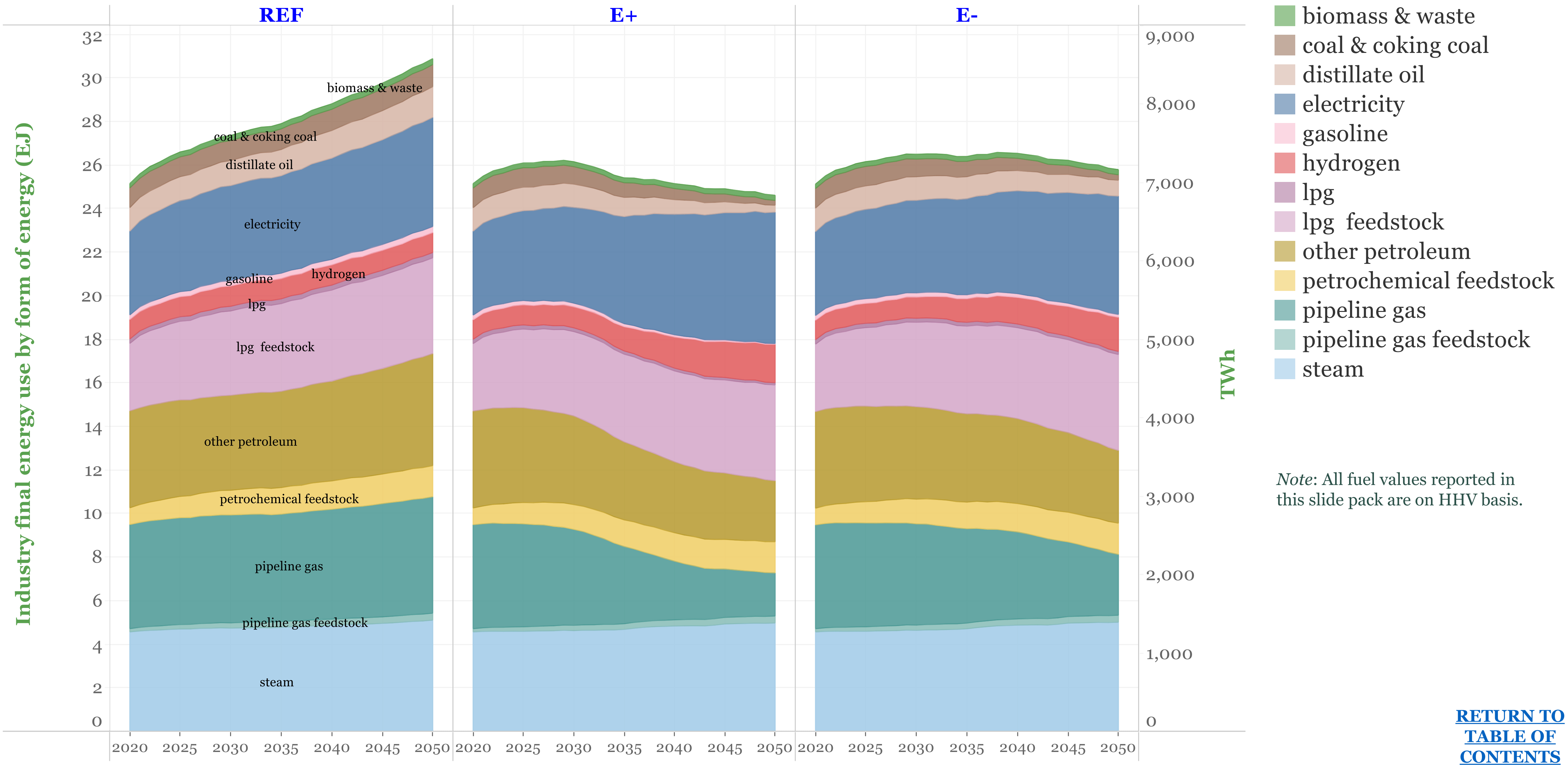
Industrial final energy in 2050 is 15-20% below REF. Roles for electricity and H_2 grow; use of liquids and other gases decline.



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

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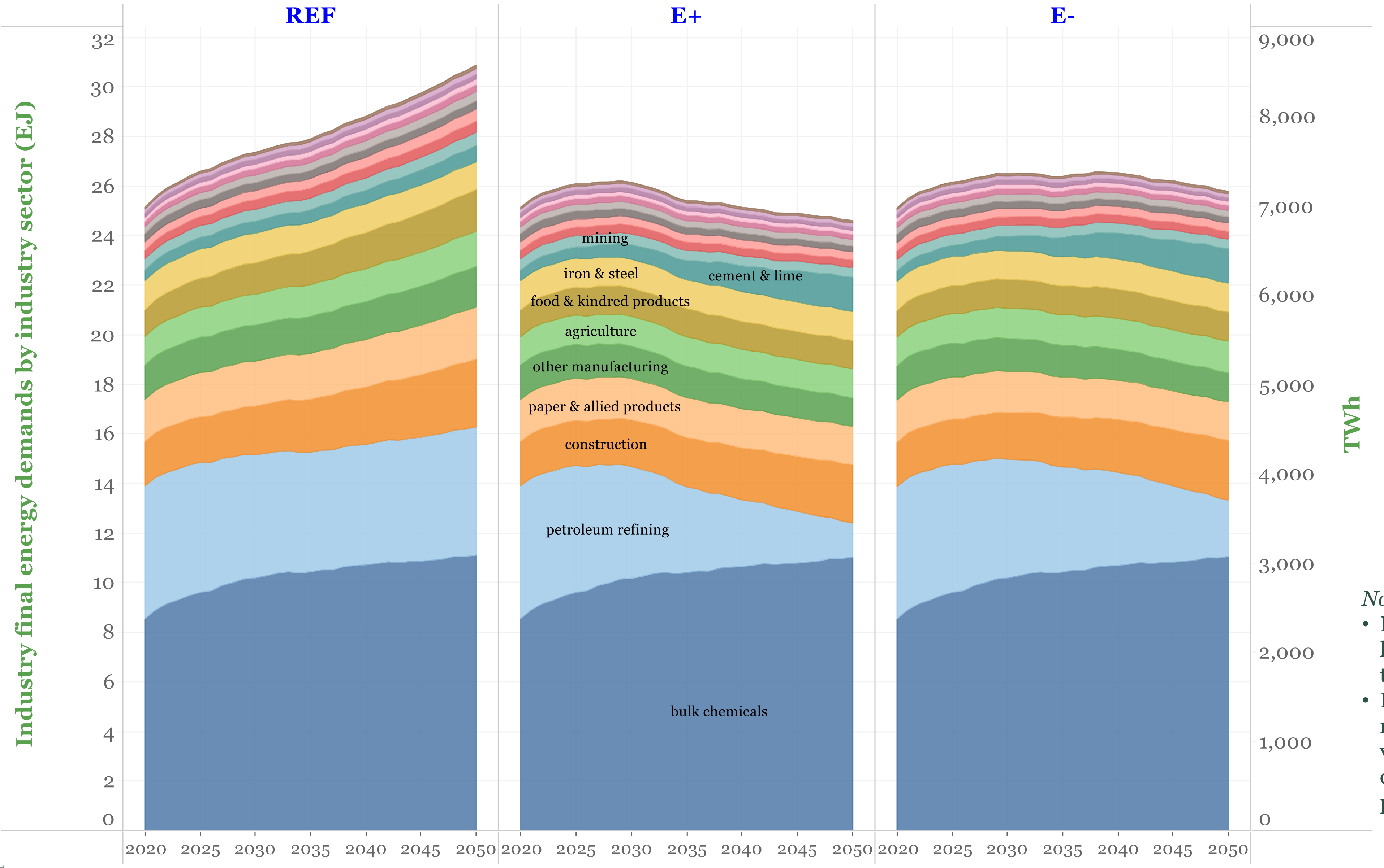
Bulk chemicals remains the largest industrial energy user. Energy use for petroleum refining falls. Cement and lime energy use grows.



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.

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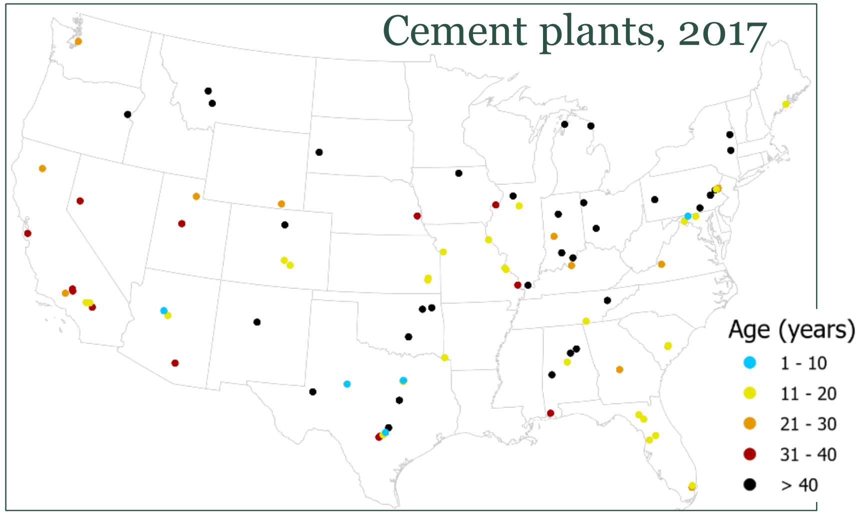
Note: All fuel values reported in this slide pack are on HHV basis.

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:

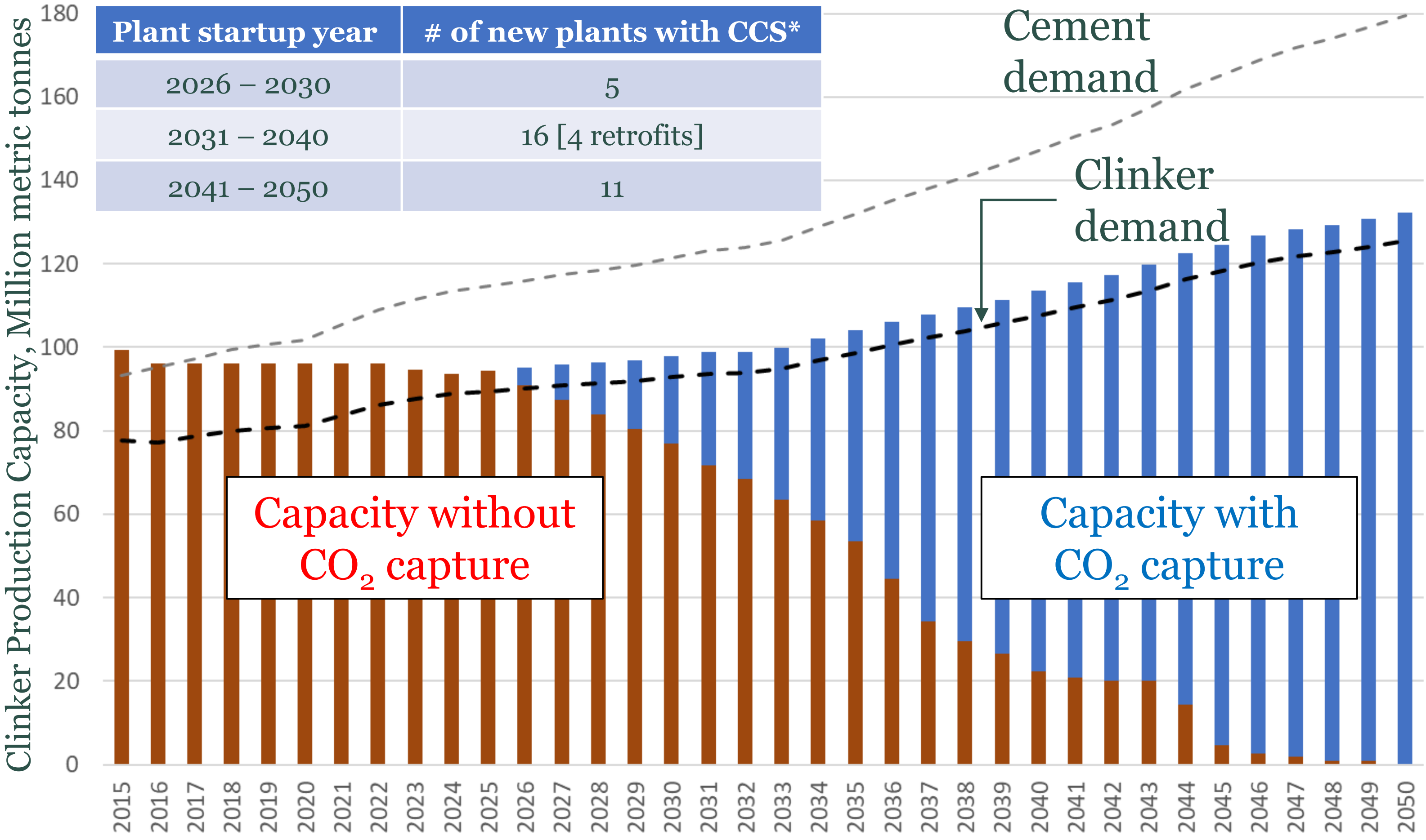
- 92 plants retire when ≥ 35 yrs old.
- 35 world-scale plants with CO_2 capture are built on brownfield sites by 2050, starting in 2020's.

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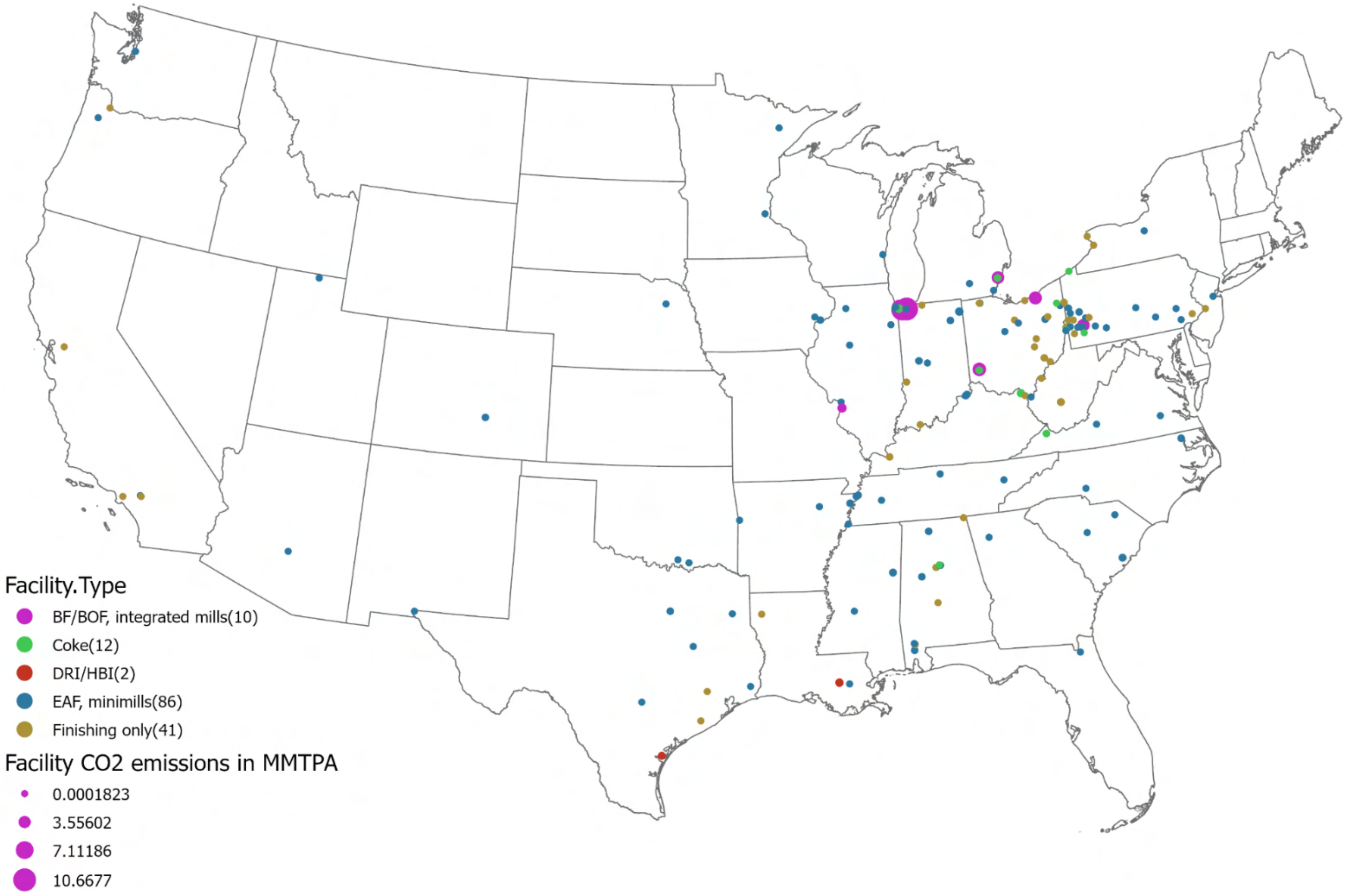
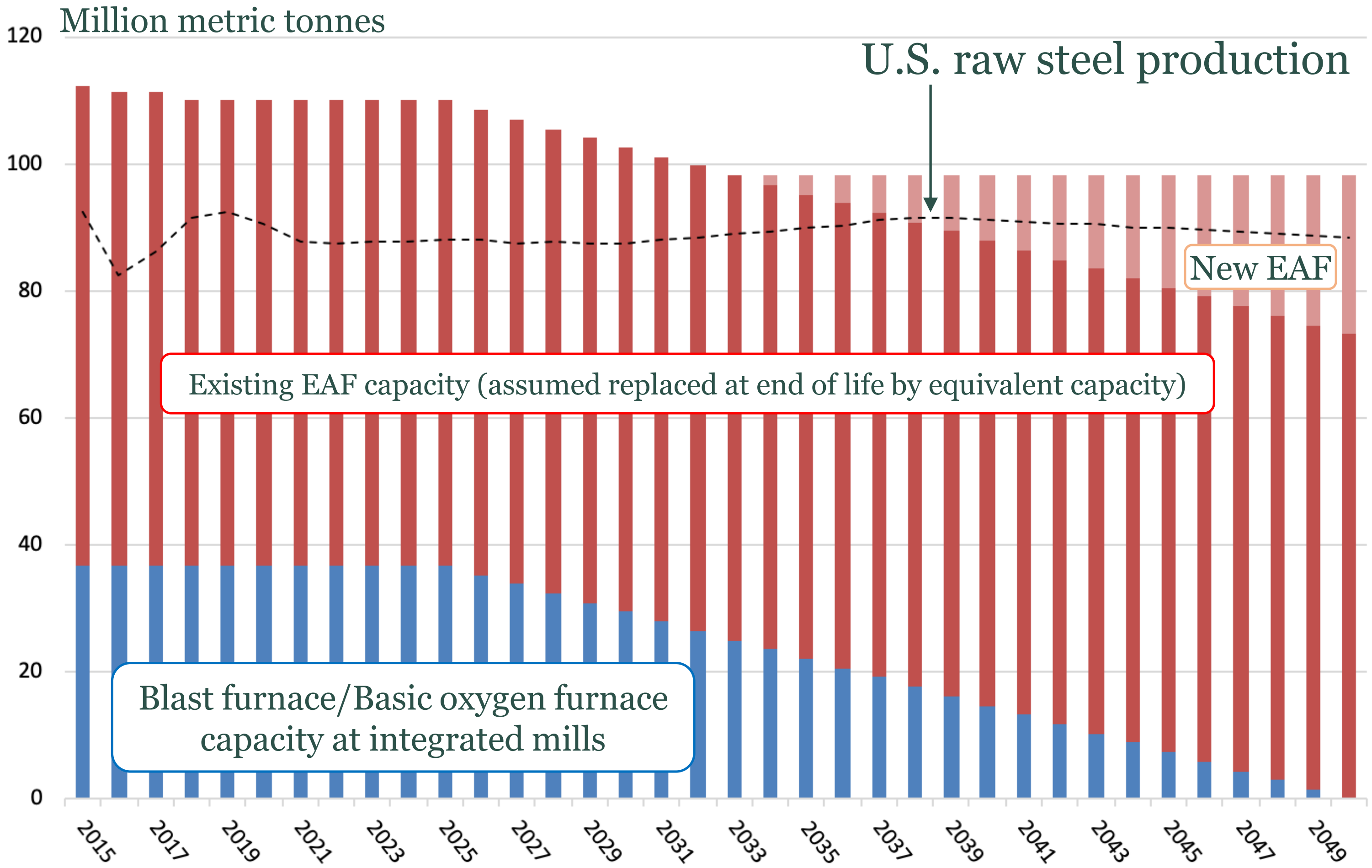
U.S. iron and steel production (~90 million t/y) accounts for 106 million tCO_{2e}/y of emissions today (1.8% of total U.S. emissions).

- 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.



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.

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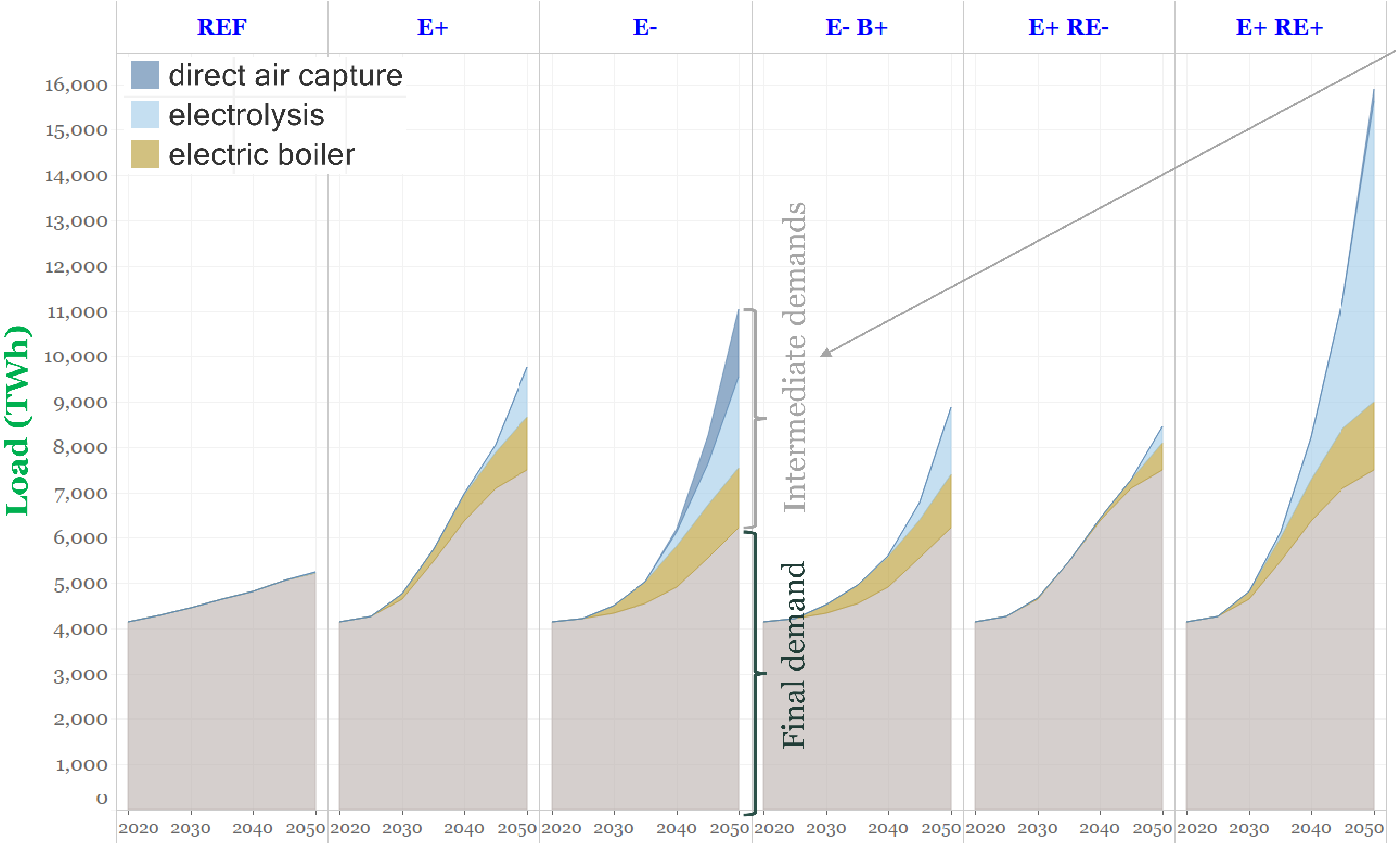
Electricity load grows ~2x – 4x by 2050, including flexible intermediate loads that absorb variable wind and solar generation.



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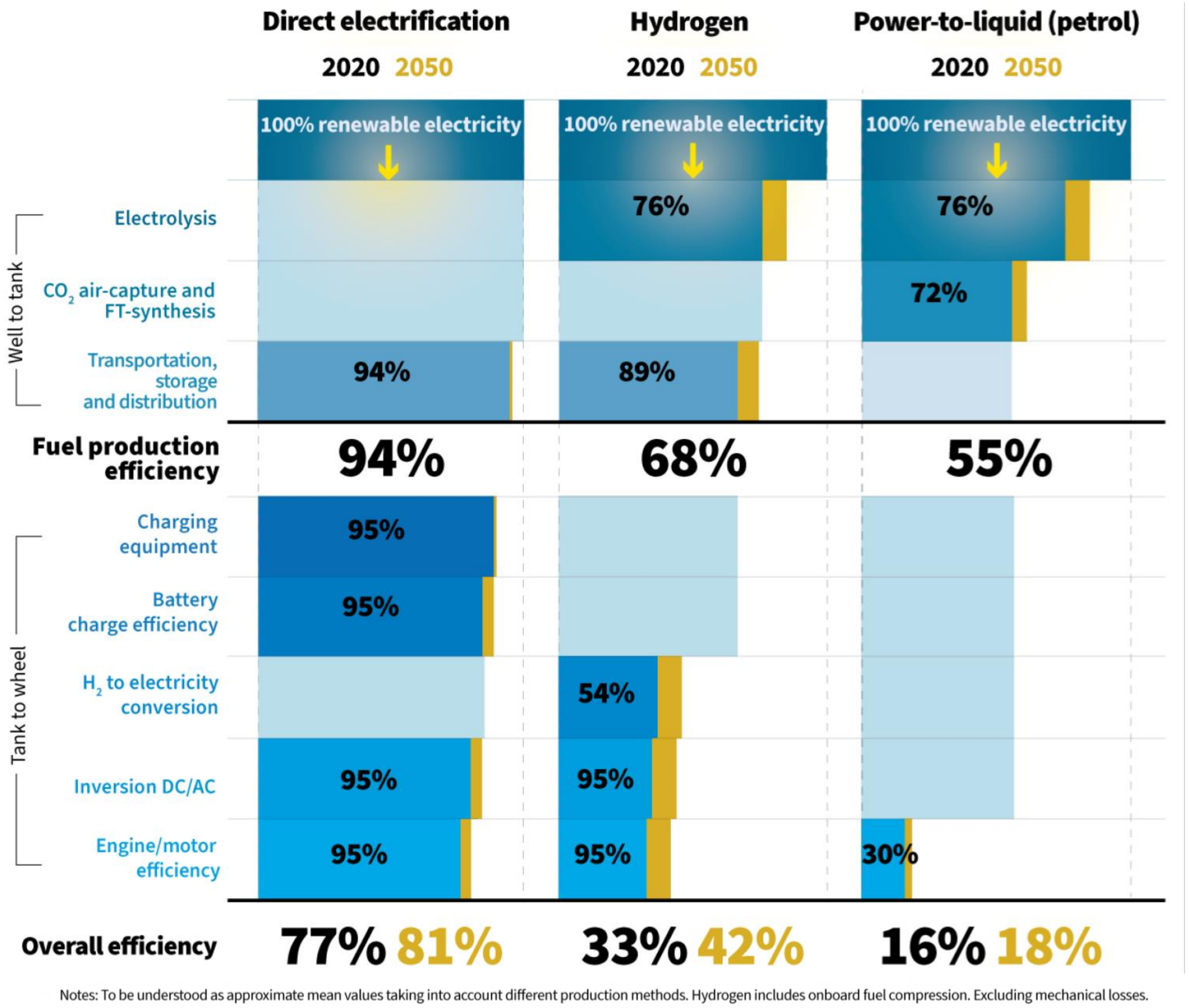
Fueling vehicles with hydrogen or liquids made from electricity requires much more electricity than using it directly in EVs.

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



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

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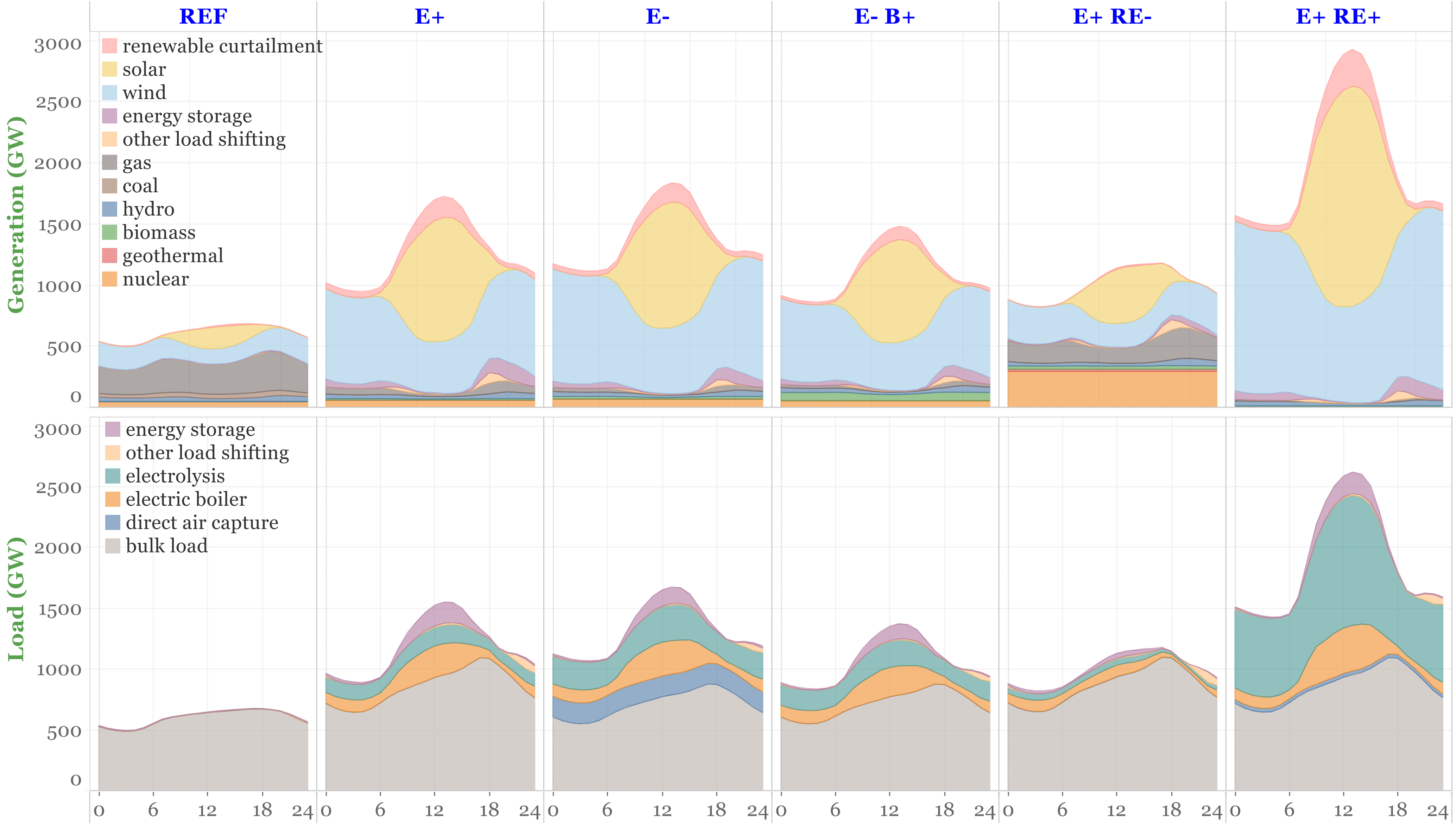
Hourly average grid operations: Short-duration batteries play relatively small roles. Large role for electrolysis in RE+ and E-.



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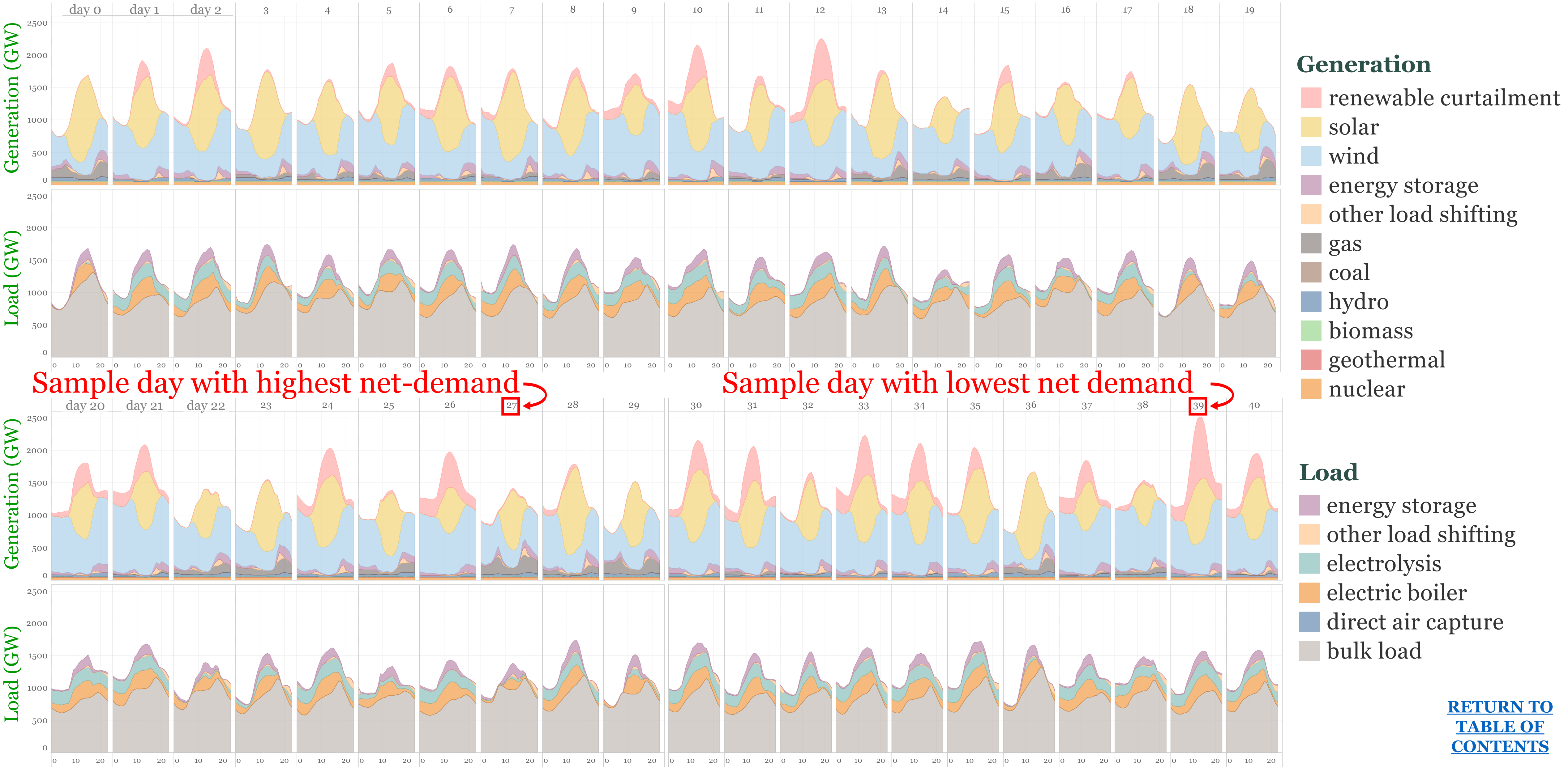
Hourly generation and load profiles in 2050 for each of 41 sample days used to model grid operations, E+ scenario.



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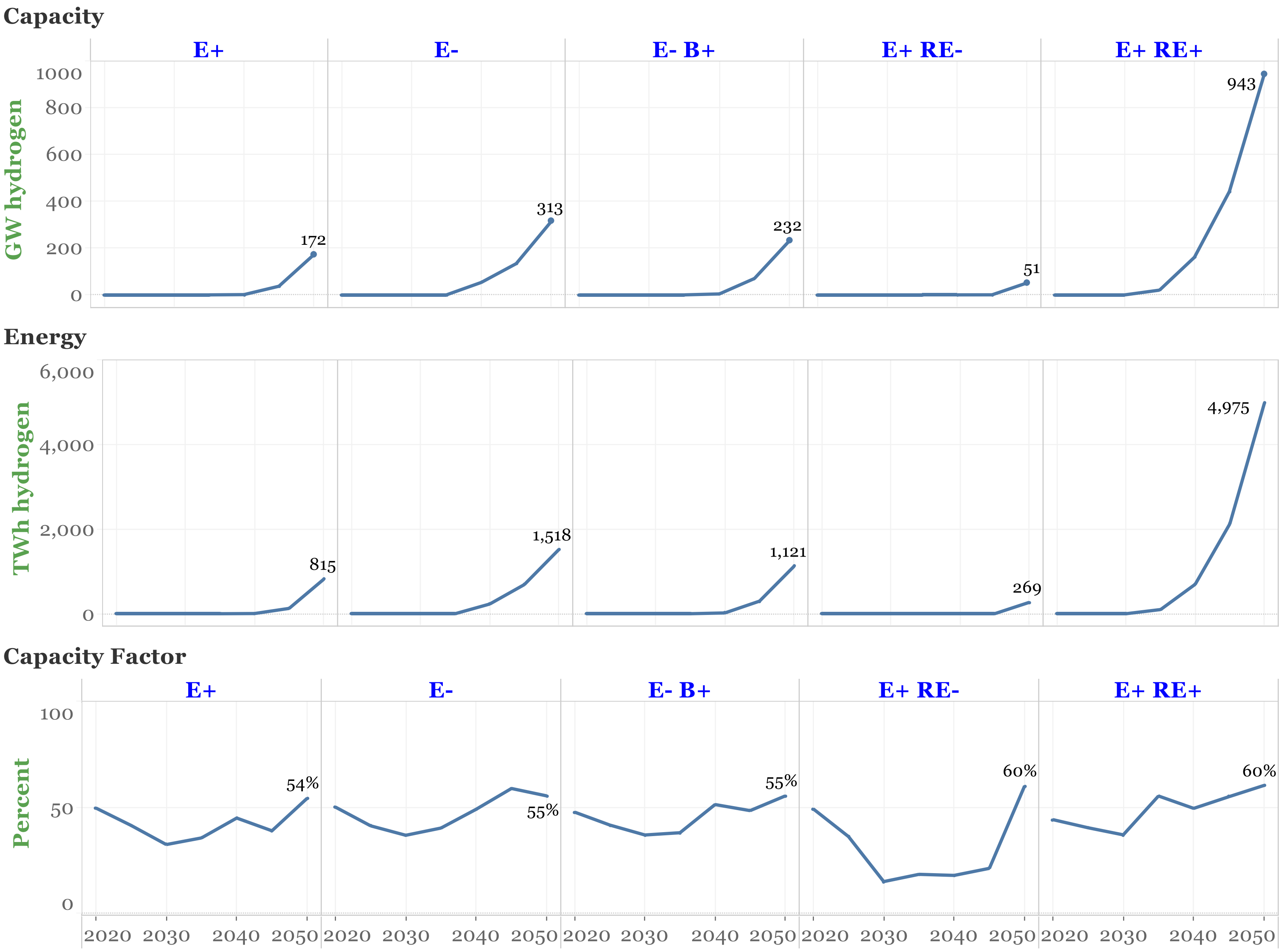
Electrolysis capacity grows primarily in the 2040s in all scenarios, and it grows most significantly in RE+.

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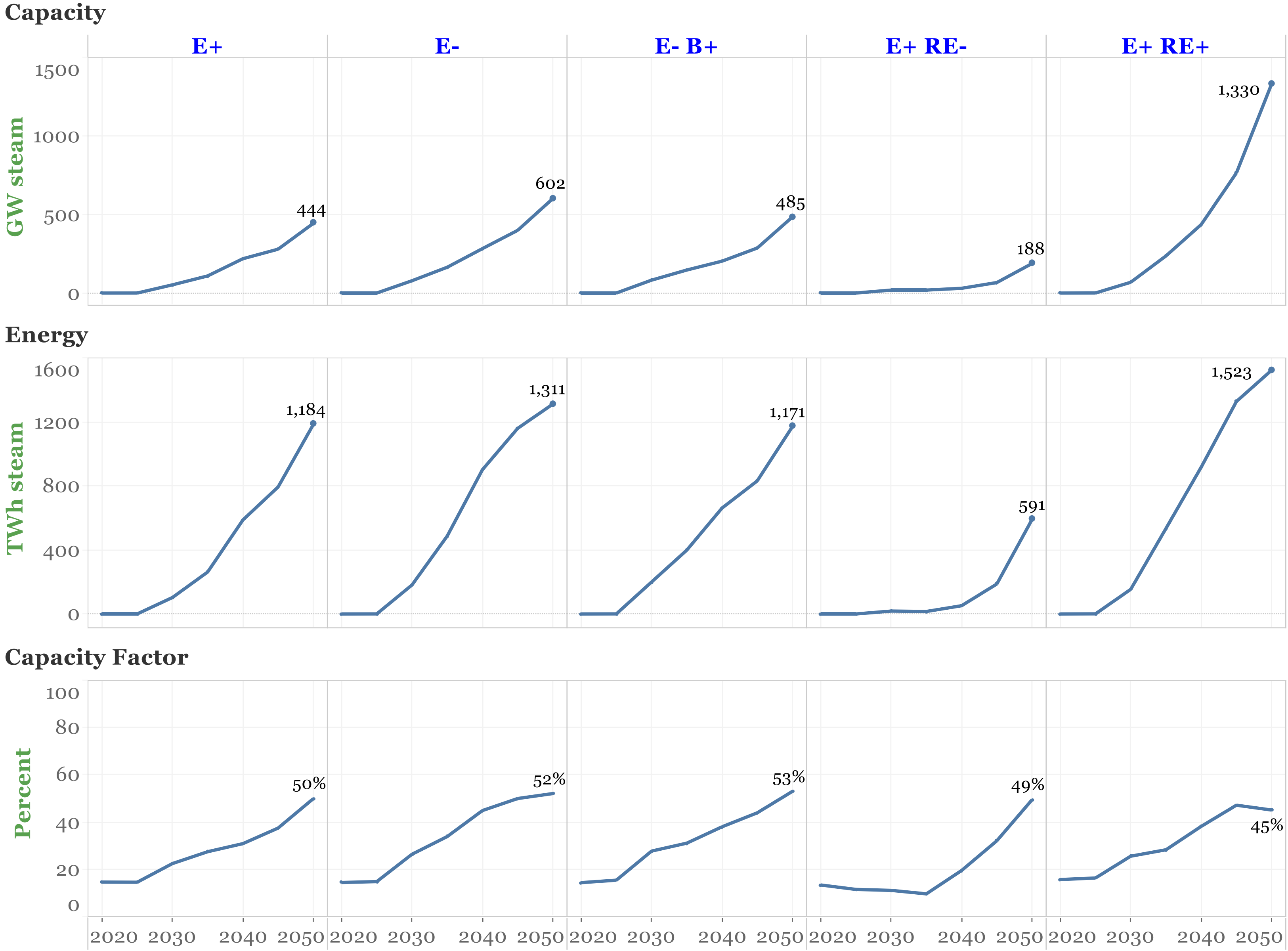
Electric boilers are deployed alongside gas boilers for industrial process heat.

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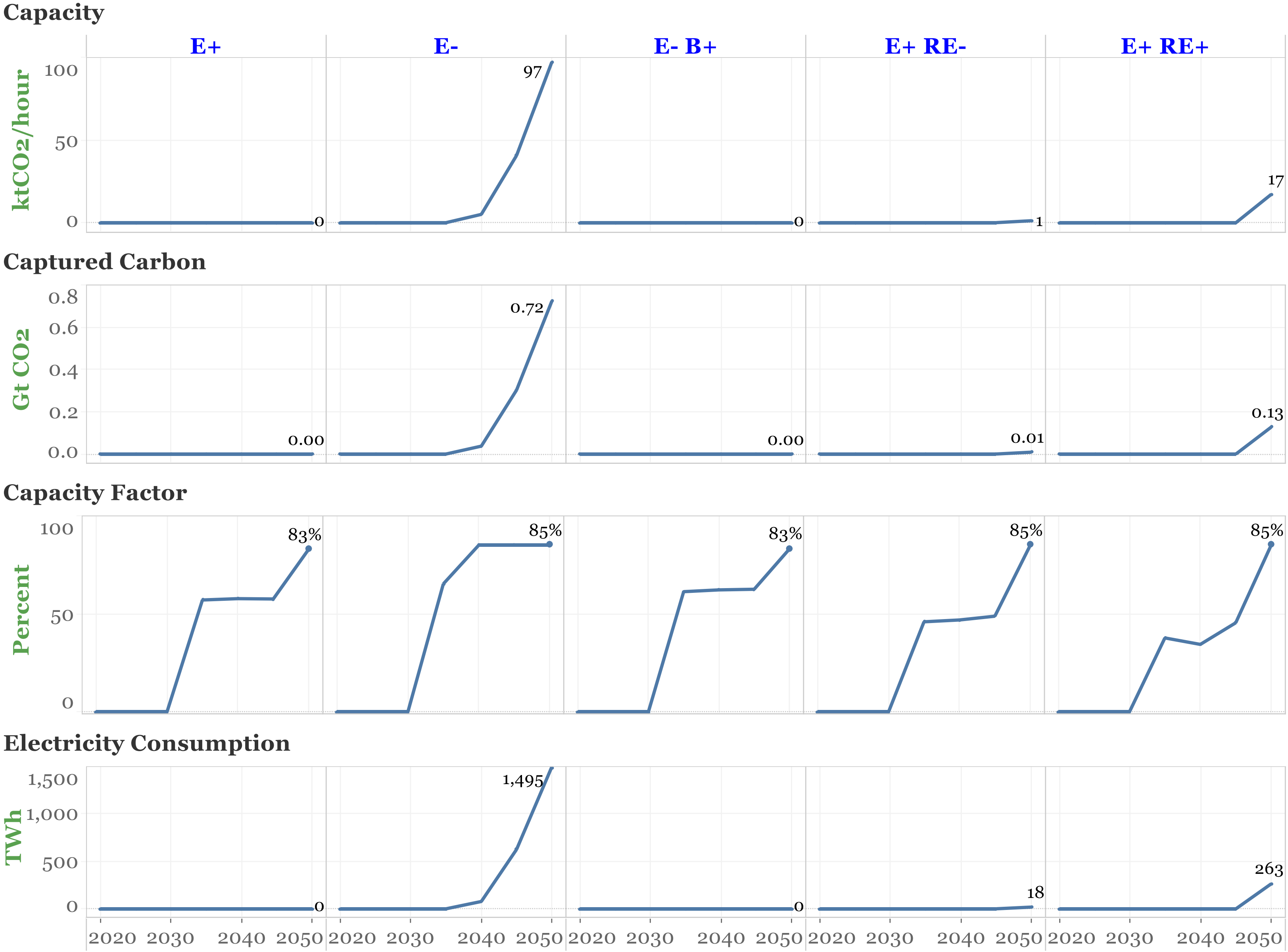
Direct air capture of CO_2 is significant in E- and RE+ scenarios

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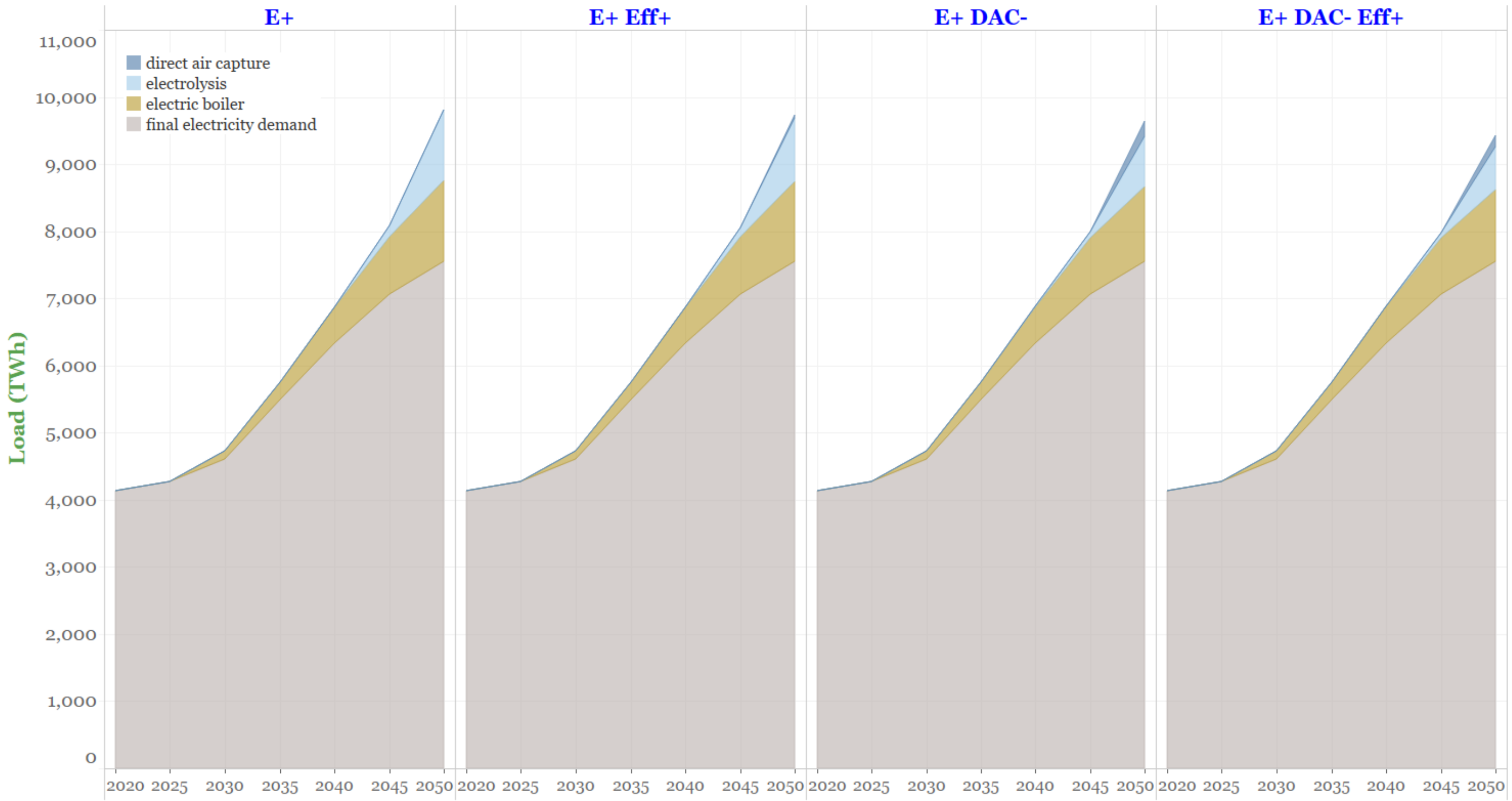
Lower capital cost and/or higher electricity efficiency of direct air capture increases its use slightly in E+ and decreases electrolysis

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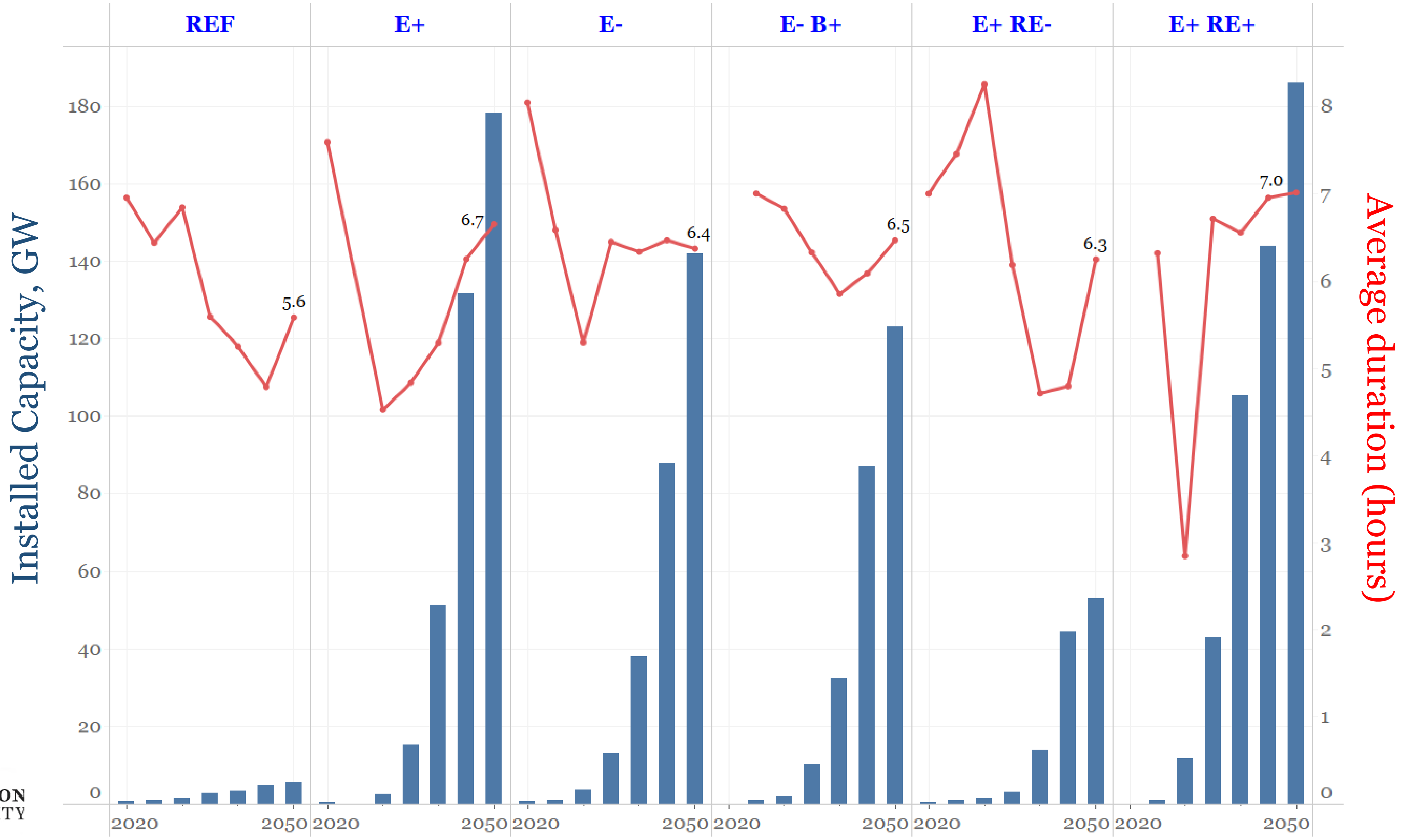
Grid battery capacity grows (mostly after 2030) to handle intra-day flexibility needs (5 to 7 hours storage duration)



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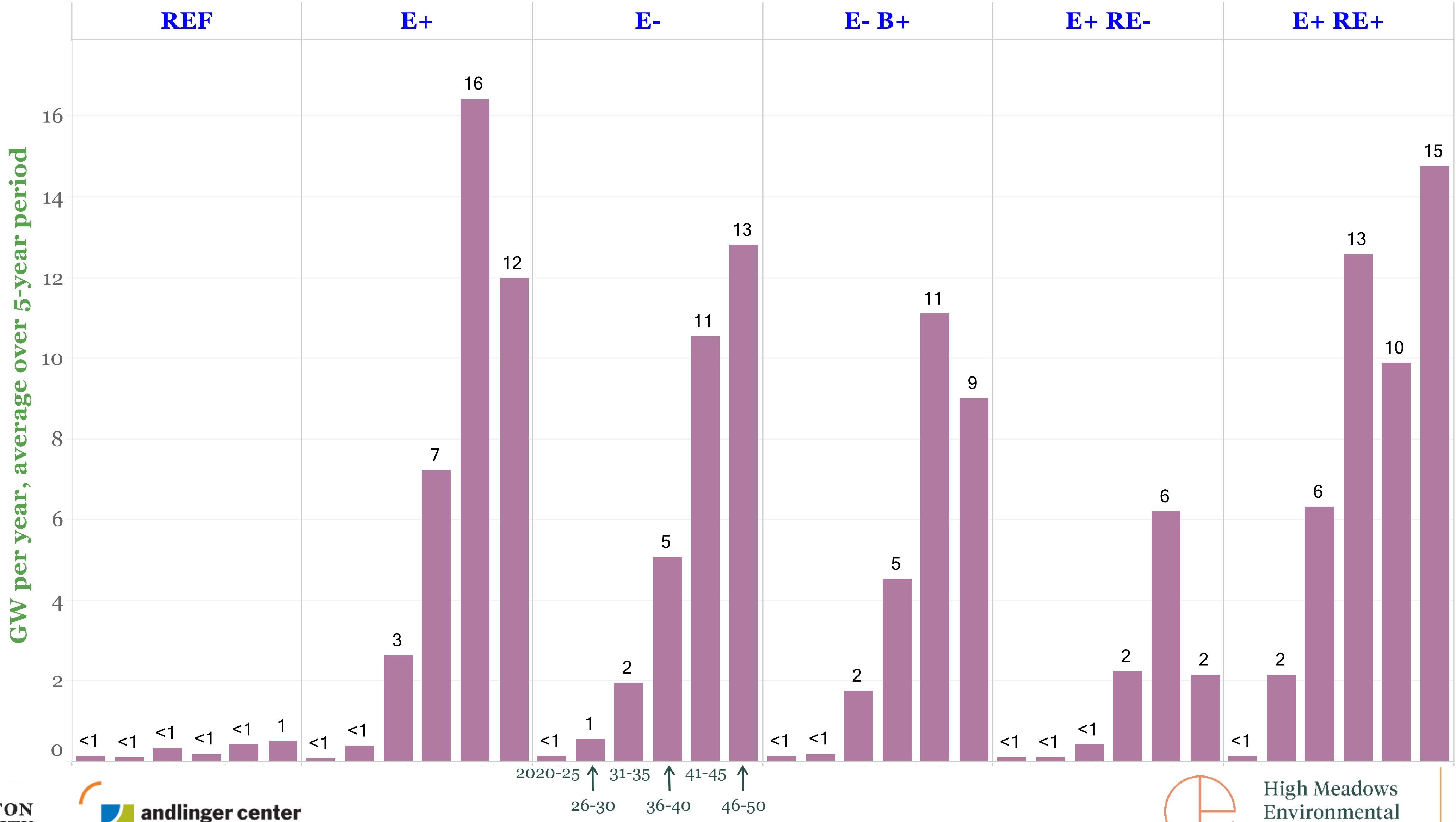
Annual capacity build rates for grid batteries are relatively modest through the 2030s, increasing thereafter.



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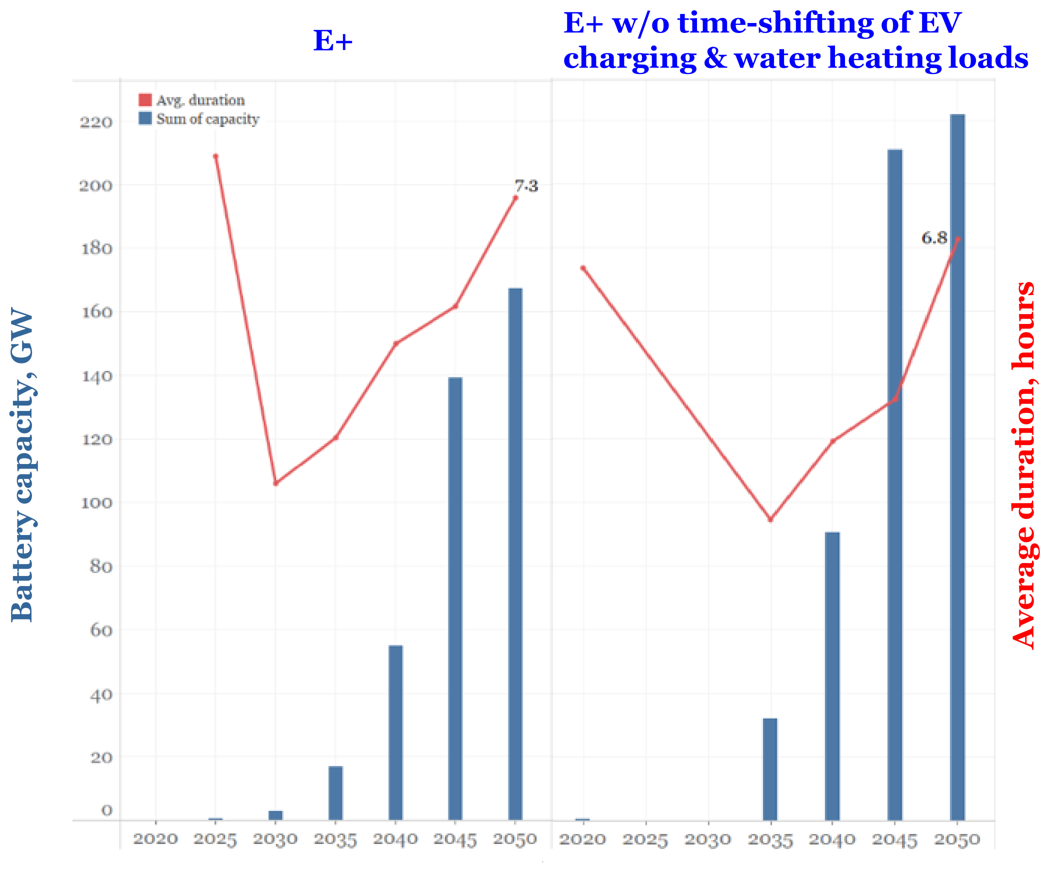
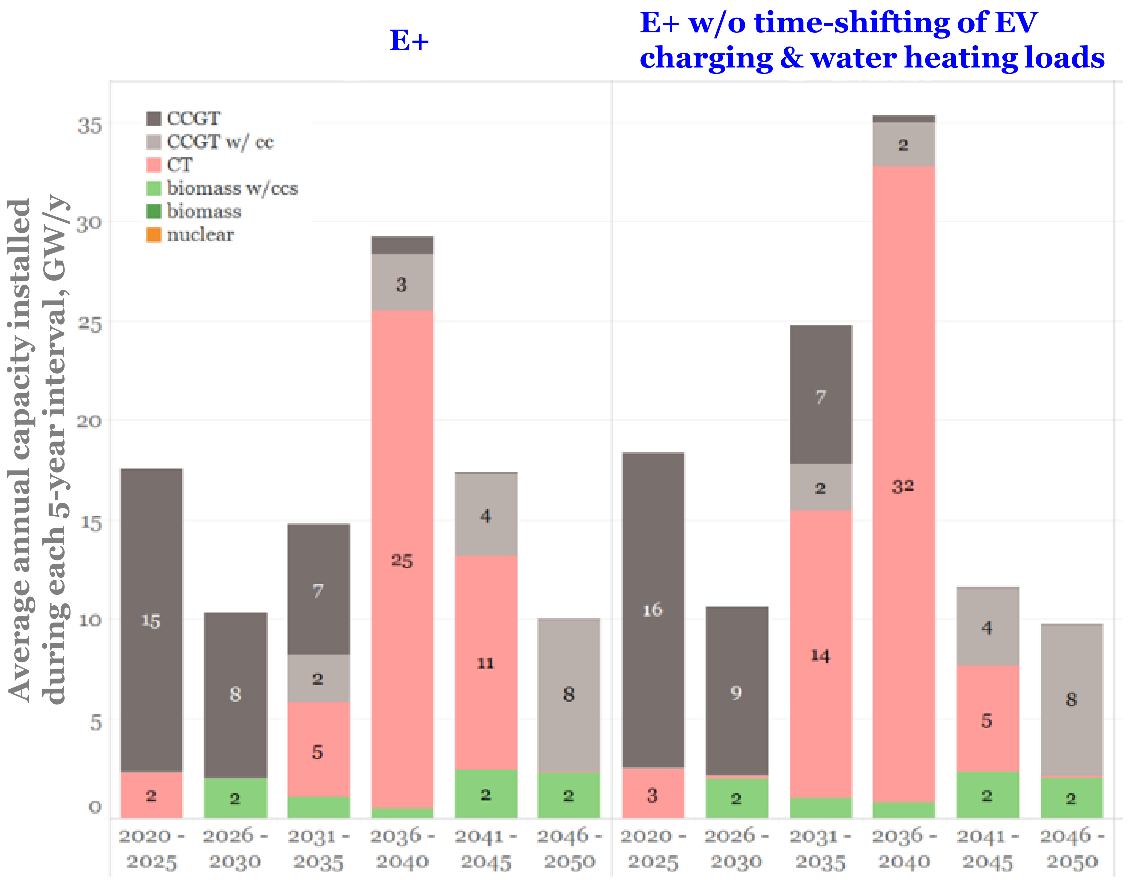
In a sensitivity case w/o time-shiftable EV charging and water heating, capacities of batteries and combustion turbines increase

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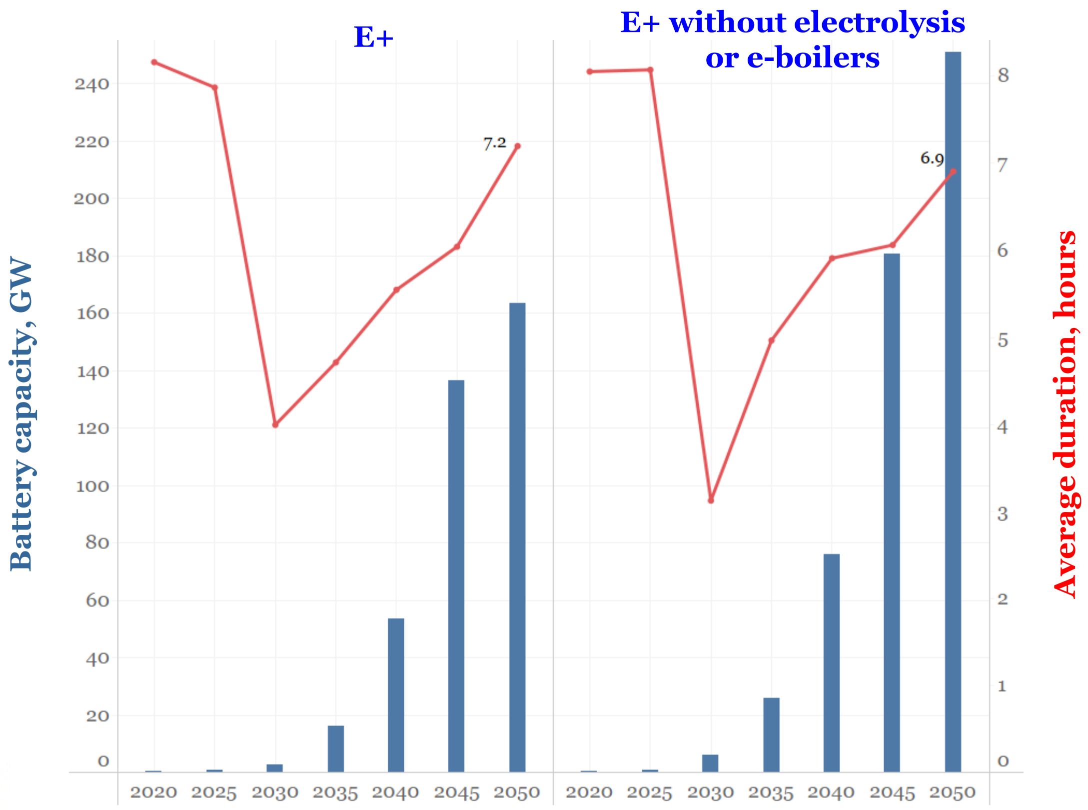
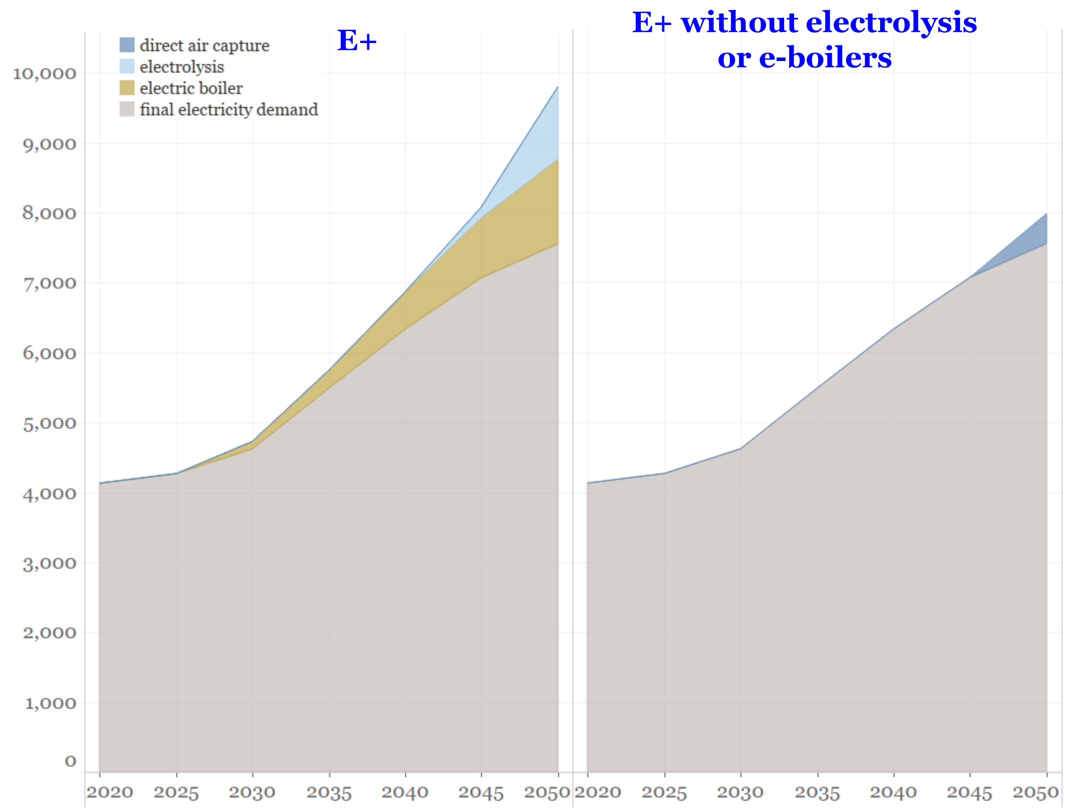
If large intermediate flexible loads are not allowed, battery capacity increases, but there are also other significant impacts

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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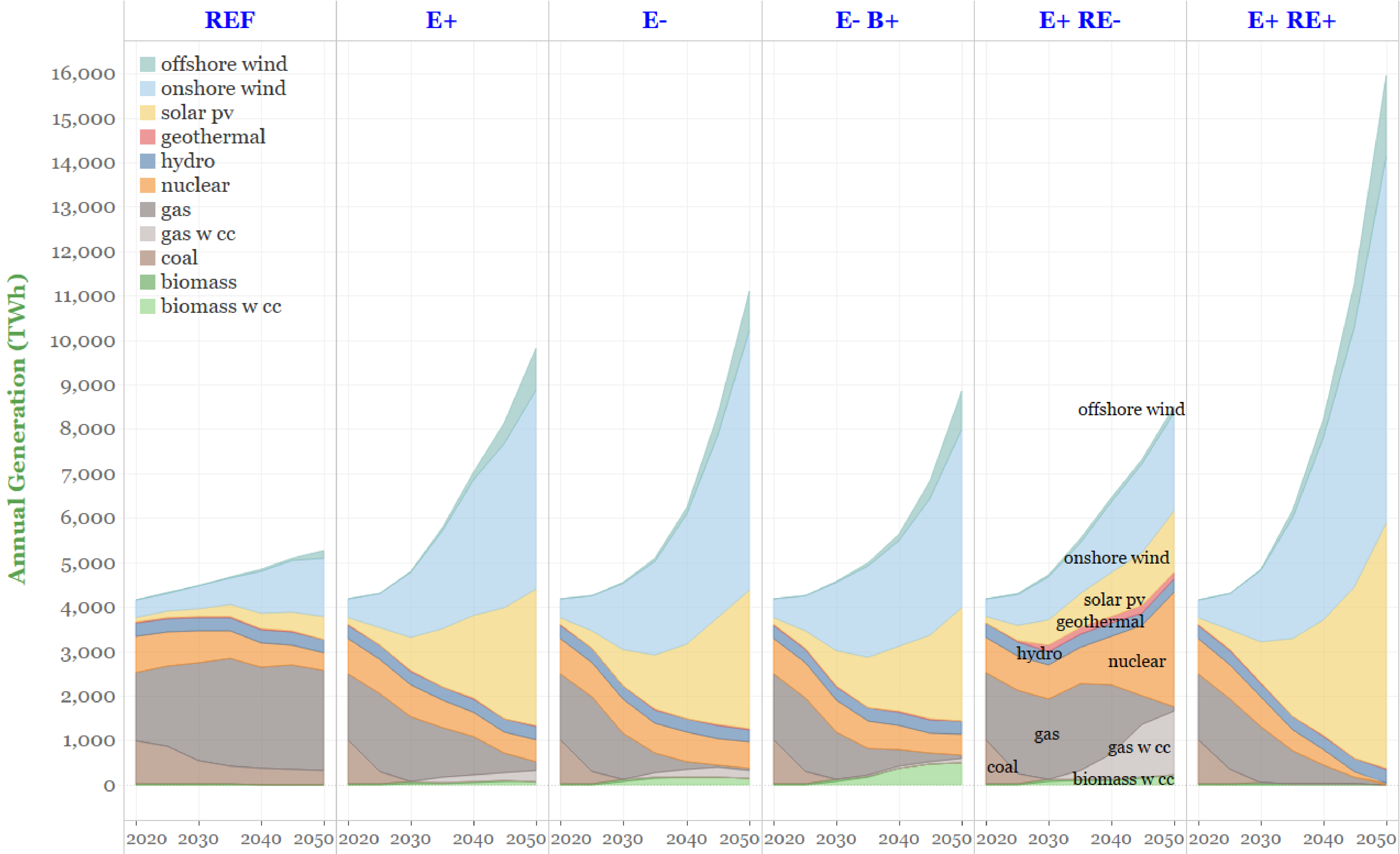
Pillar 2: Clean electricity

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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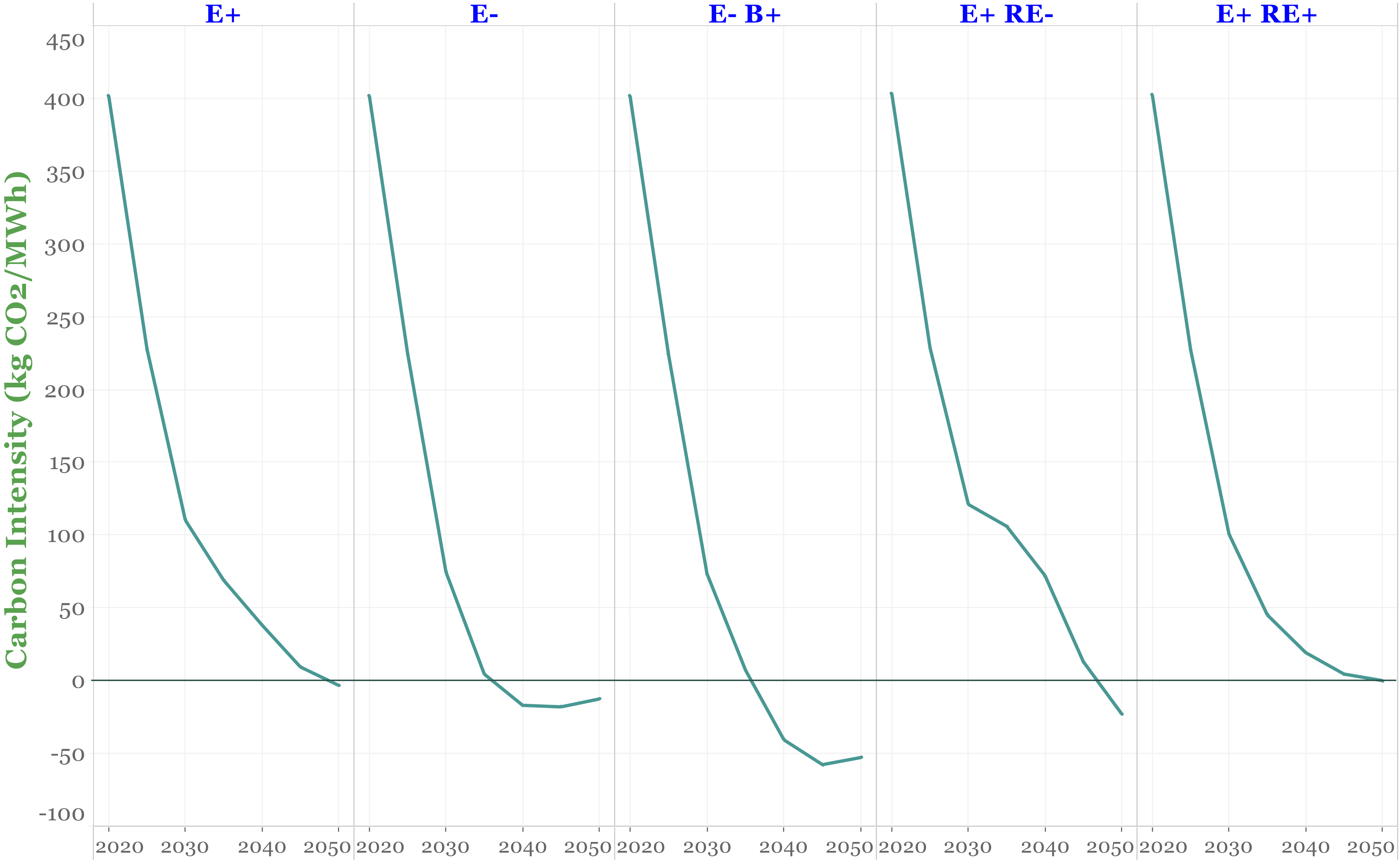
Carbon-intensity of electricity drops rapidly in all cases, reaching net-zero by 2035 in E- and negative values by 2050, except in RE+.



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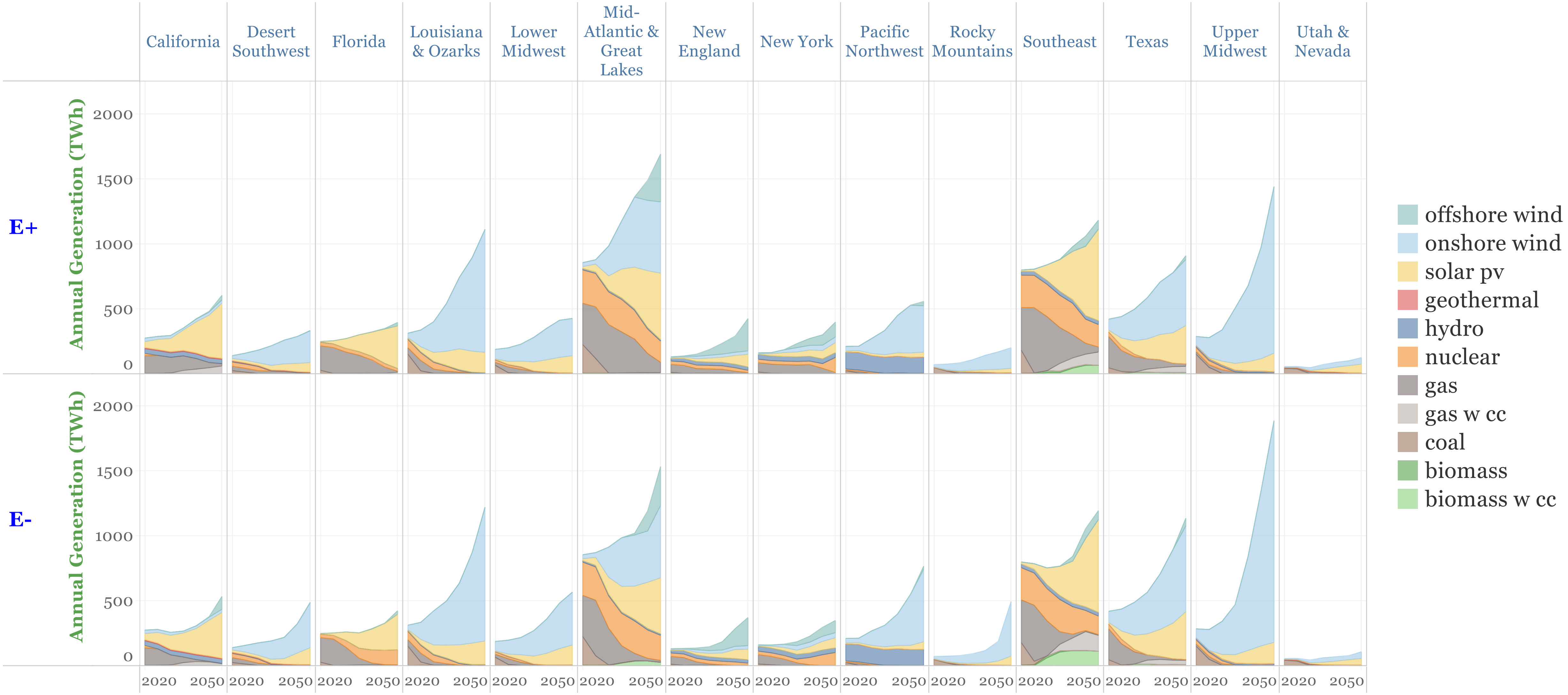
Regional evolution in electricity mix for E+ and E- scenarios.



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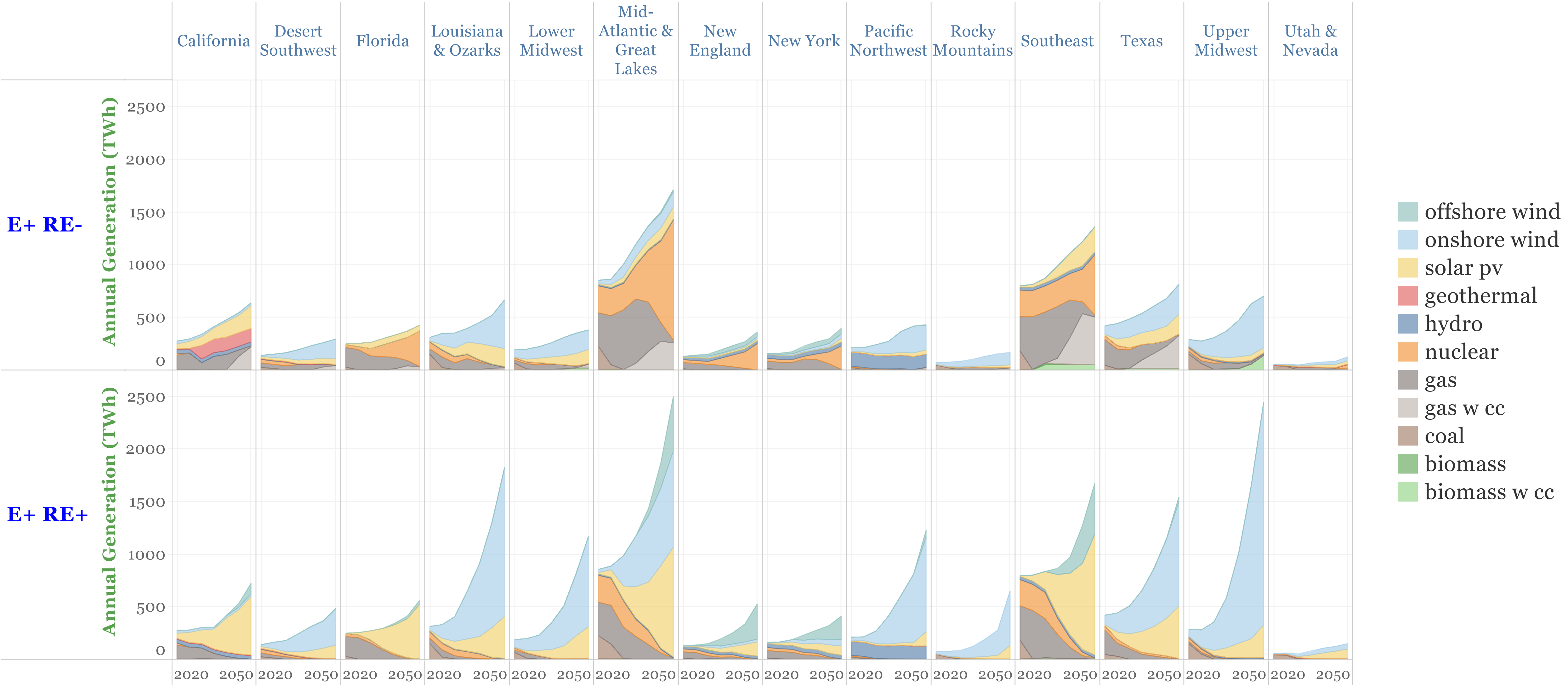
Regional evolution in electricity mix for RE- and RE+ scenarios.



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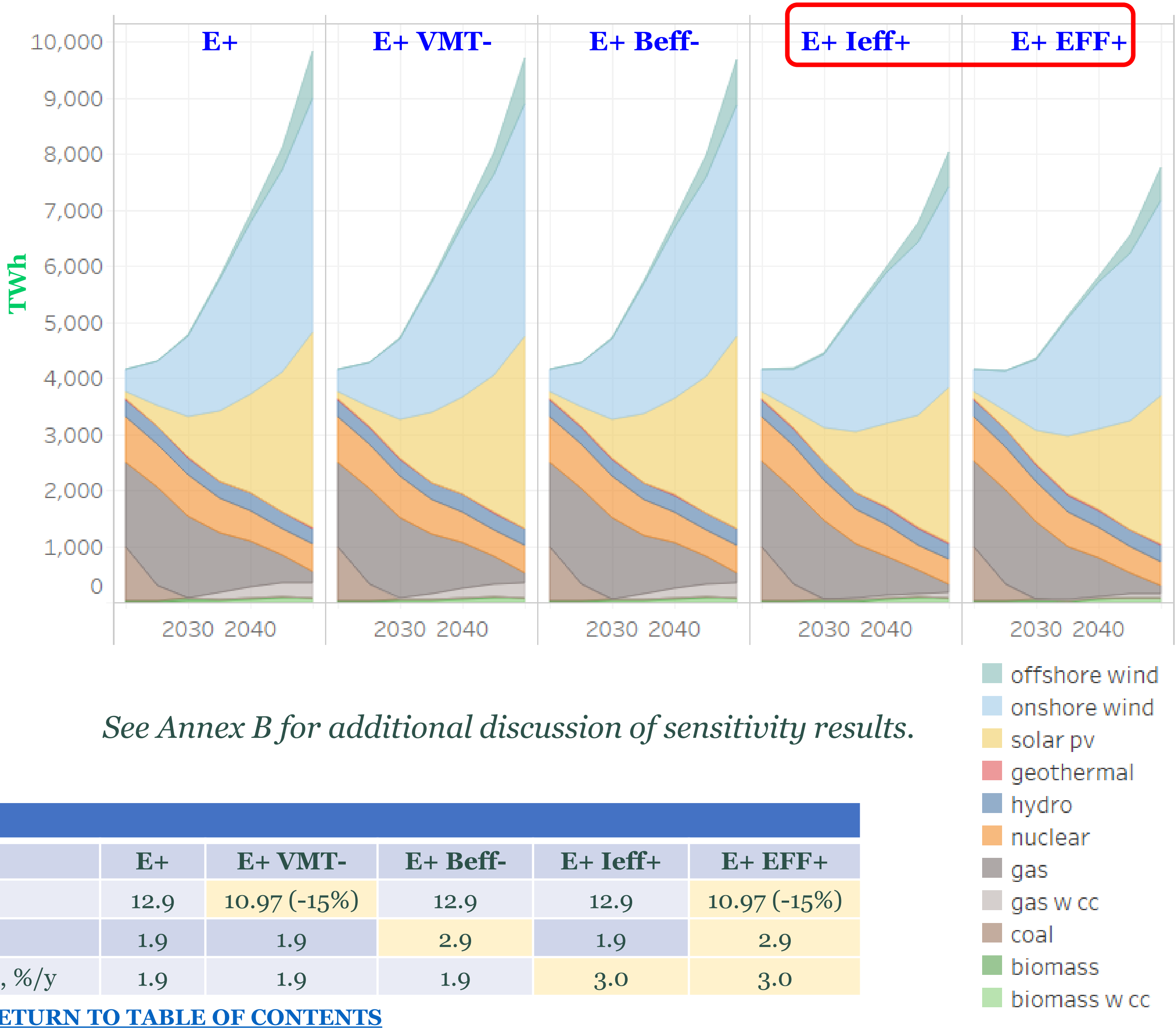
Solar and wind electricity generation in E+ would be reduced with further end-use efficiency improvements, especially in industry

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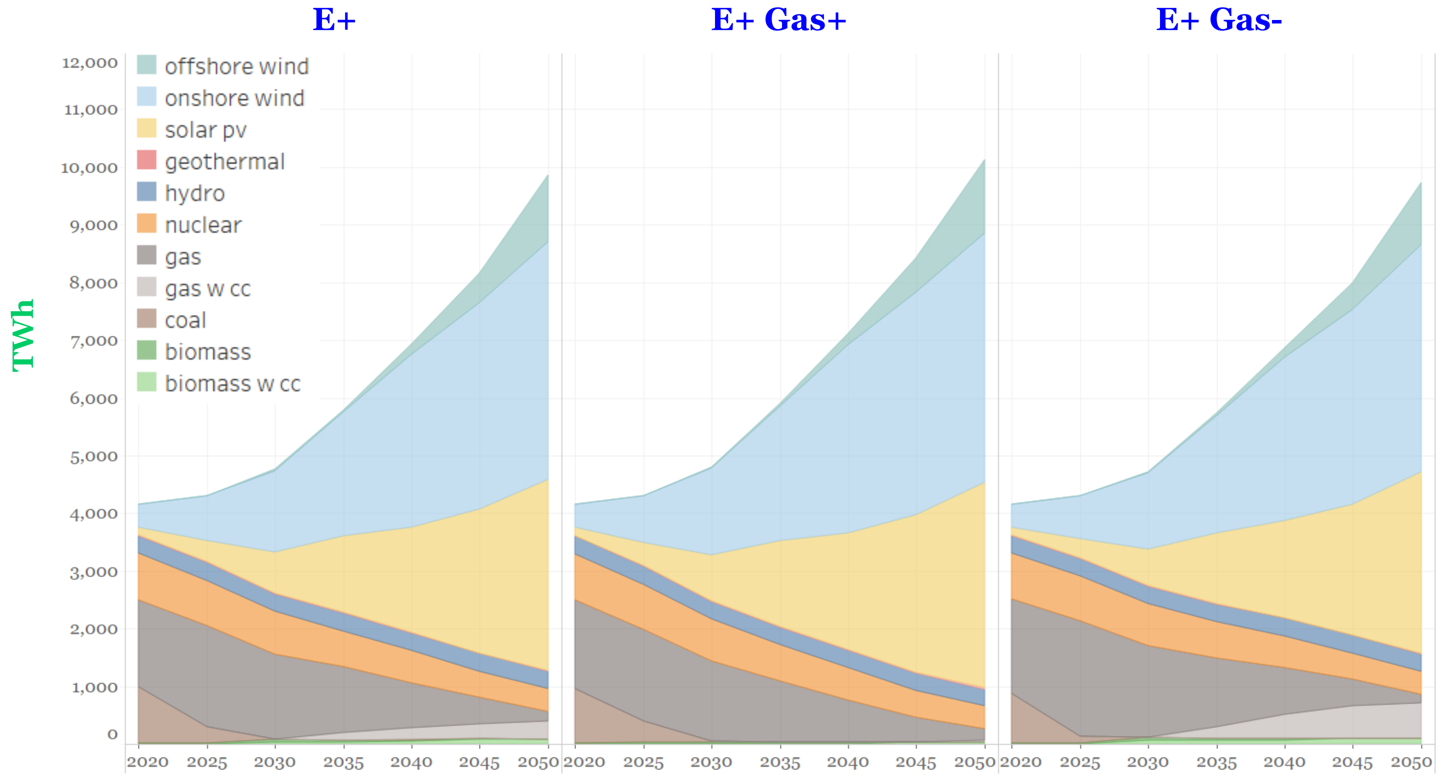
Power generation from natural gas with CO_2 capture plays a larger role if gas prices are lower

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.

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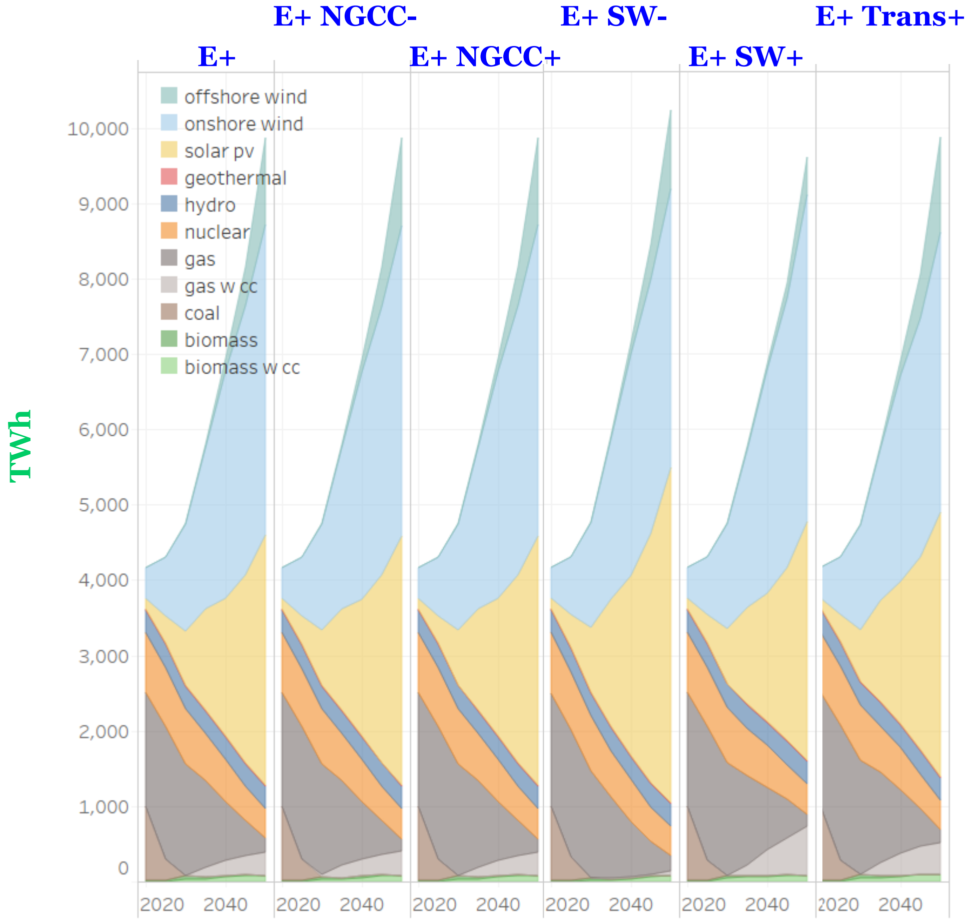
Higher or lower capital costs for solar and wind mostly impact the balance between NGCC w/CC and solar/wind generation

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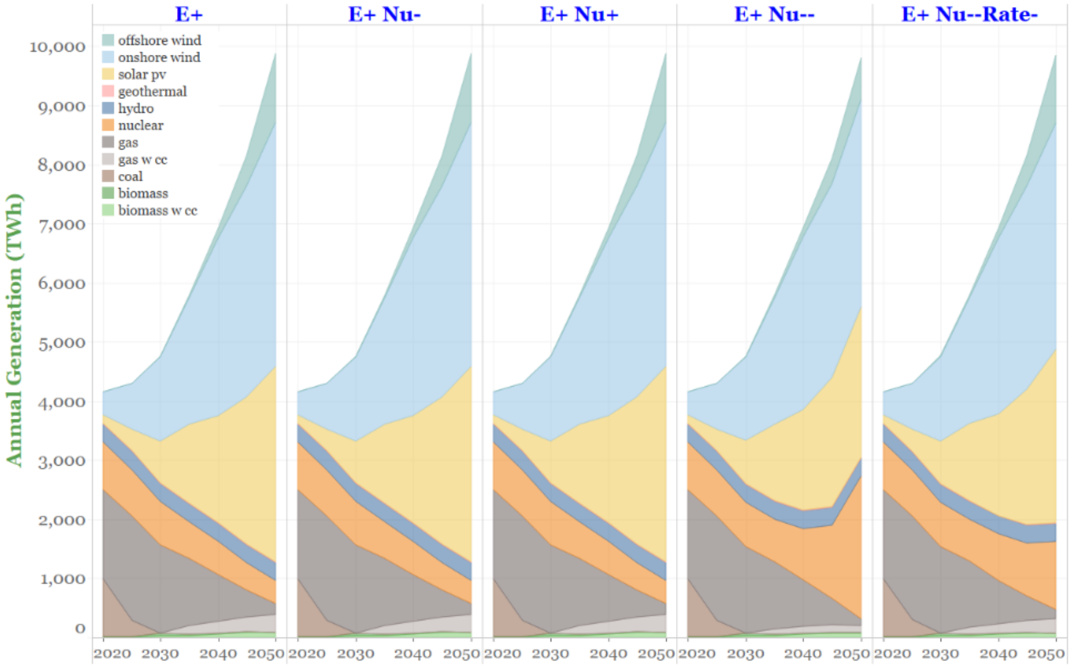
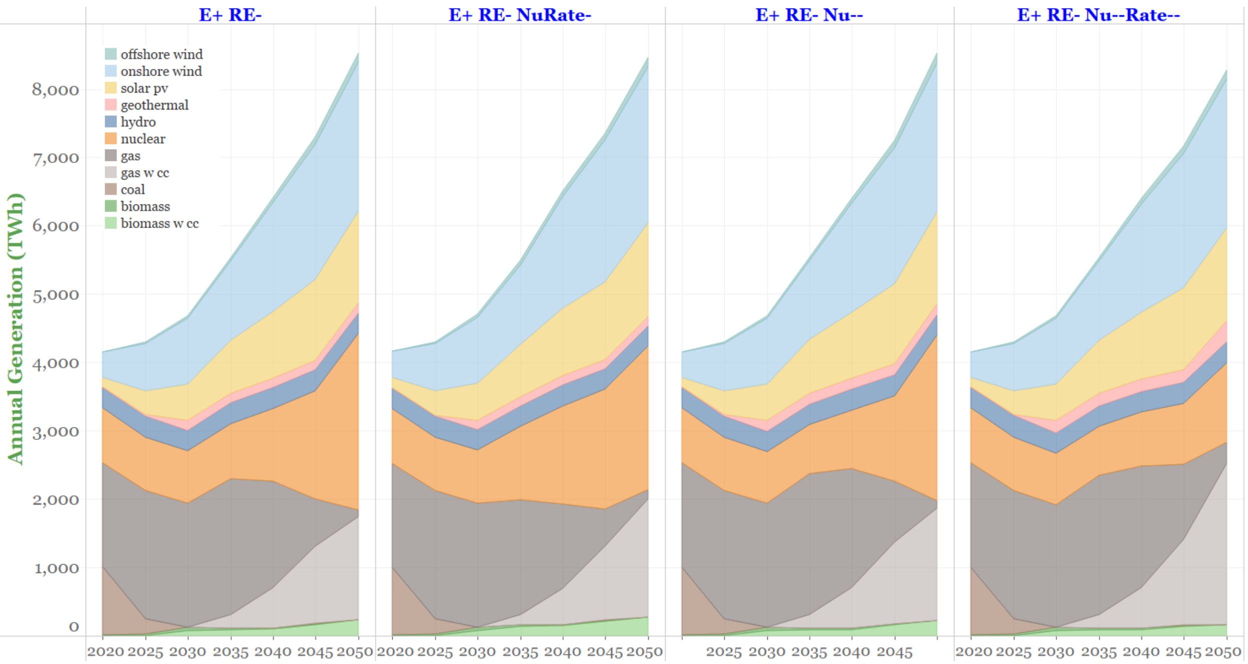
Dramatically reduced capital cost (e.g., for small modular reactors) significantly changes the generating mix in E+, but not E+RE-.

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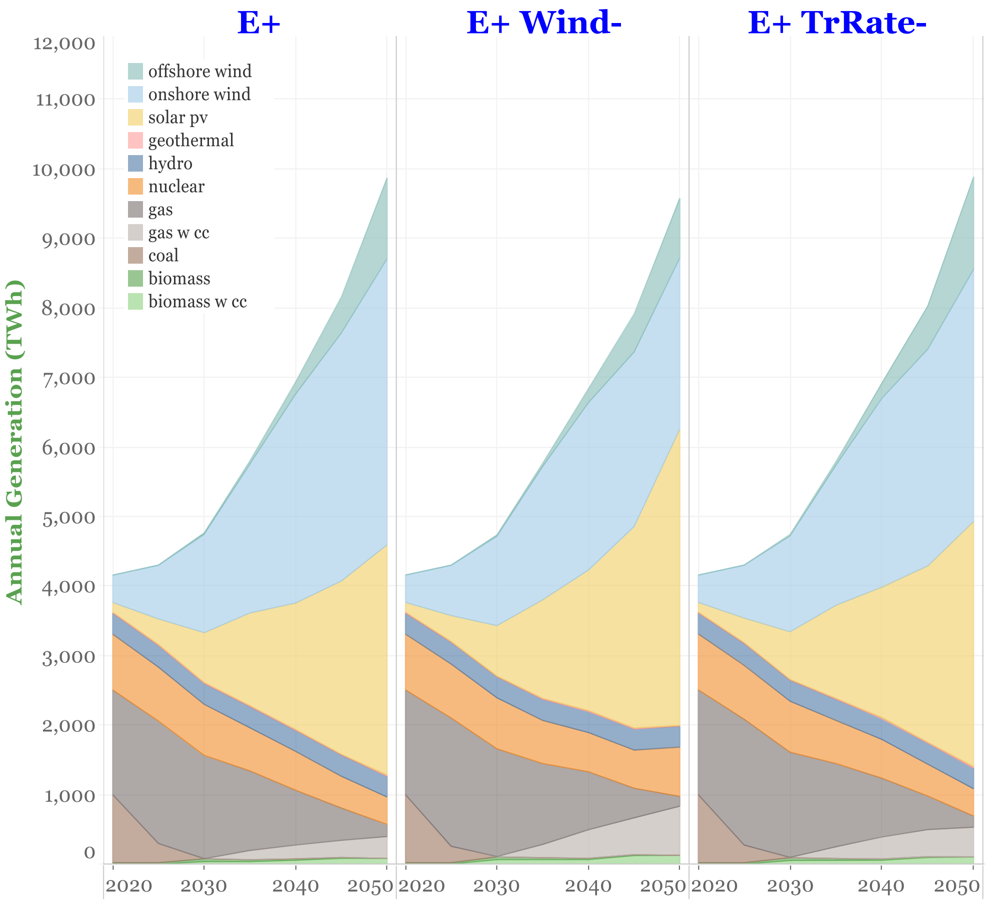
	E+RE-	E+RE- NuRate-	E+RE- Nu--	E+RE- Nu--Rate-
CAPEX 2050, 2016$/KW	5,530	5,530	1,800	1,800
Build rate cap, GW/y	None	10, from 2030	None	0.36 in 2025, 8 in 2050

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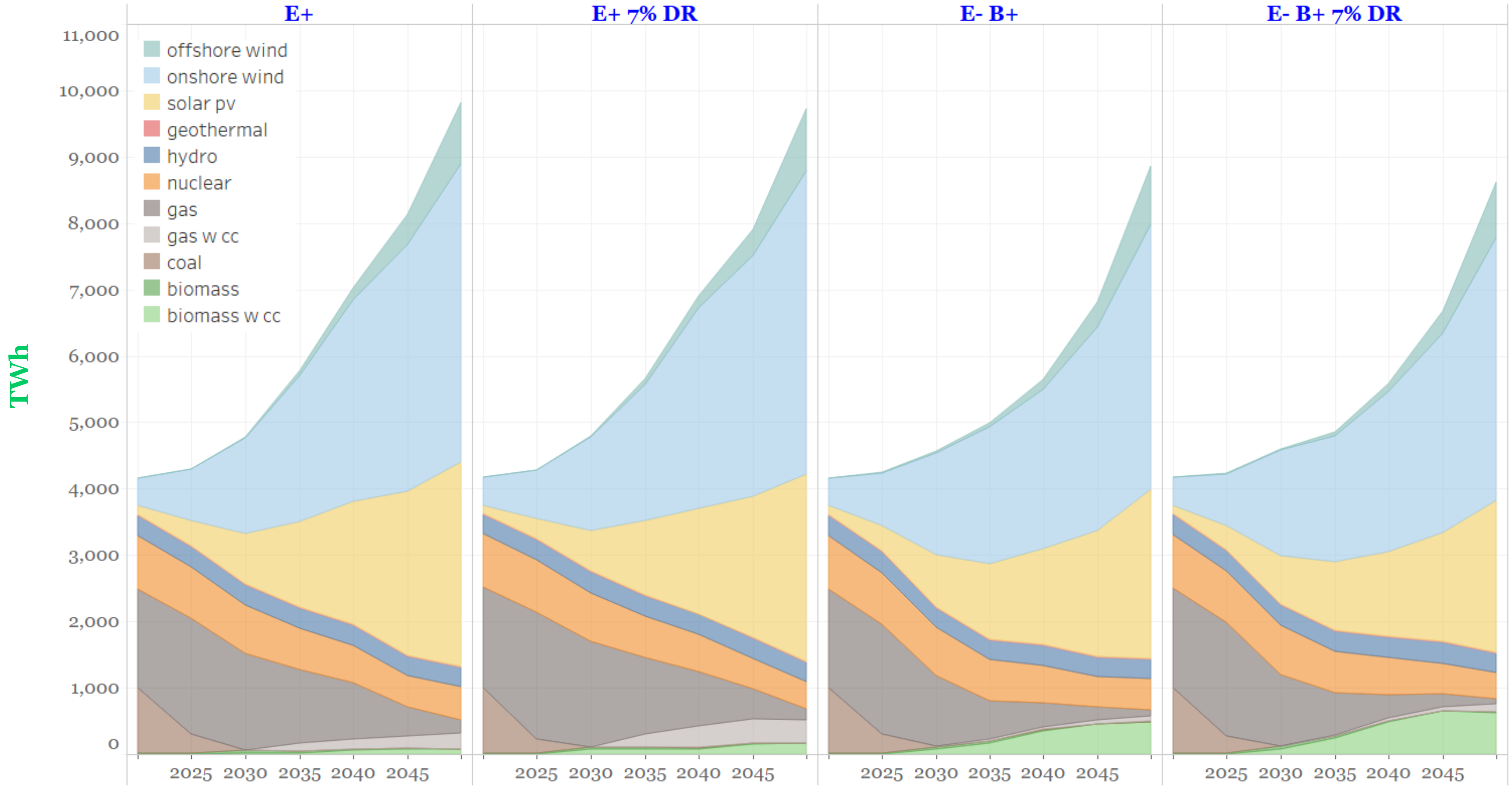
Higher discount rate dramatically reduces the NPV of total energy-system costs, but has no substantial impact on the generating mix

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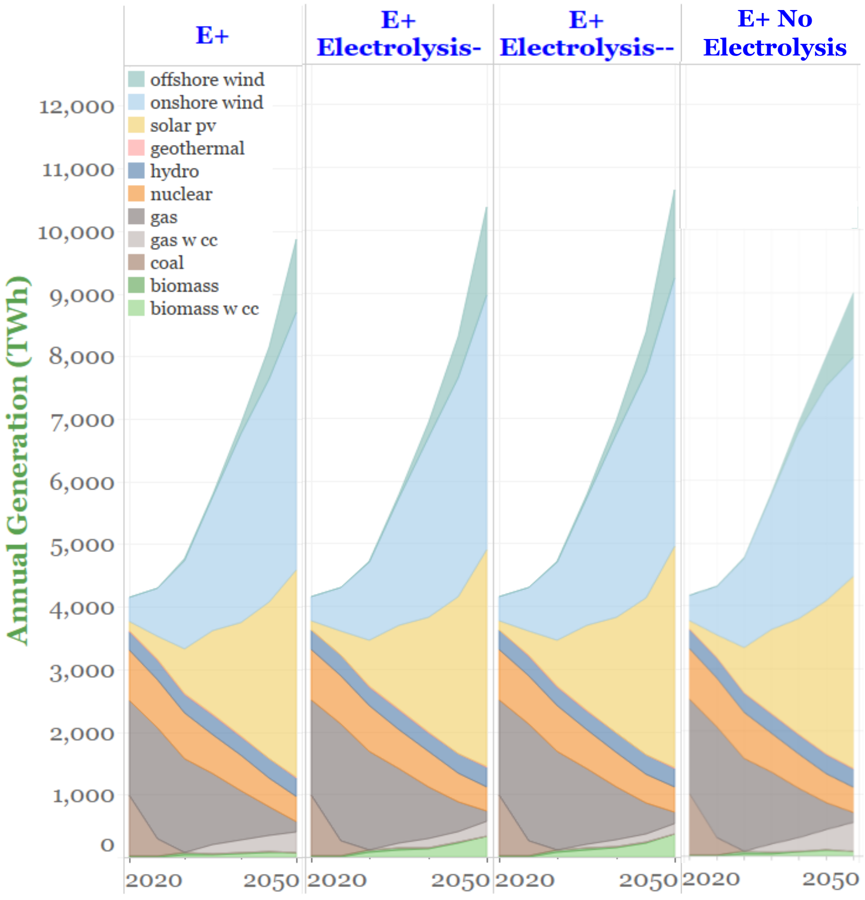
Electrolysis supports wind and solar generation, but the amount generated varies only modestly for a 6x spread in electrolysis cost.

- 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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