Princeton Net-Zero America Project

EVOLVED ENERGY RESEARCH

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Study background and context

- Evolved Energy Research (EER) was retained in 2019 to assist Princeton in creating a low-carbon infrastructure plan for the U.S.
- EER used its in-house energy models EnergyPATHWAYS and RIO to create multiple broad-brush transition strategies using Princeton's inputs.
- The results in this deck are the initial phase of a larger effort to downscale regional results from EER's models to create detailed infrastructure plans and quantify employment, macro-economic, and land-use impacts.

Outline

- Methods and data
- Carbon emissions
- System cost
- Demand-side details
- Electricity details
- Fuels, biomass, & sequestration details

Methods and data

Model coupling for supply-side optimization

EnergyPATHWAYS and RIO

	ENERGY PATHWAYS	RIO
Description	Scenario analysis tool that is used to develop economy-wide energy demand scenarios	Optimization tool to develop portfolios of low-carbon technology deployment for electricity generation and balancing, alternative fuel production, and direct air capture
Application	EnergyPATHWAYS (EP) scenario design produces parameters for RIO's supply-side optimization: • Demand for fuels (electricity, pipeline gas, diesel, etc.) over time • Hourly electricity load shape	RIO returns optimized 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 allocation across fuels

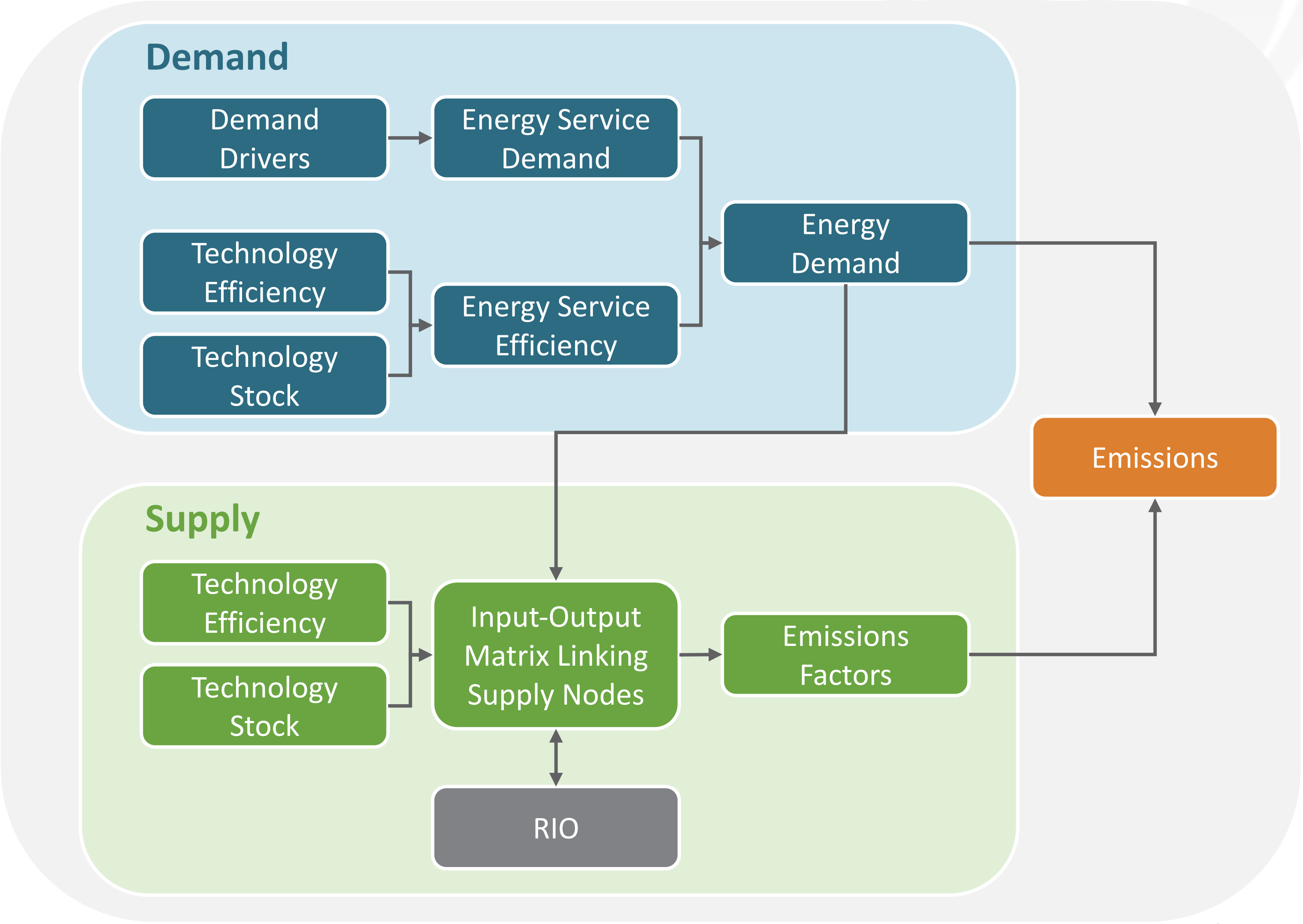
EnergyPATHWAYS overview

Demand- and Supply-side of the Energy System

Broadly speaking, EnergyPATHWAYS can be divided into a demand side and supply side, the former calculating energy demanded by different services, the latter determining how each energy demand is met. Operationally this distinction is important in the model because the demand and supply sides are calculated in sequence.

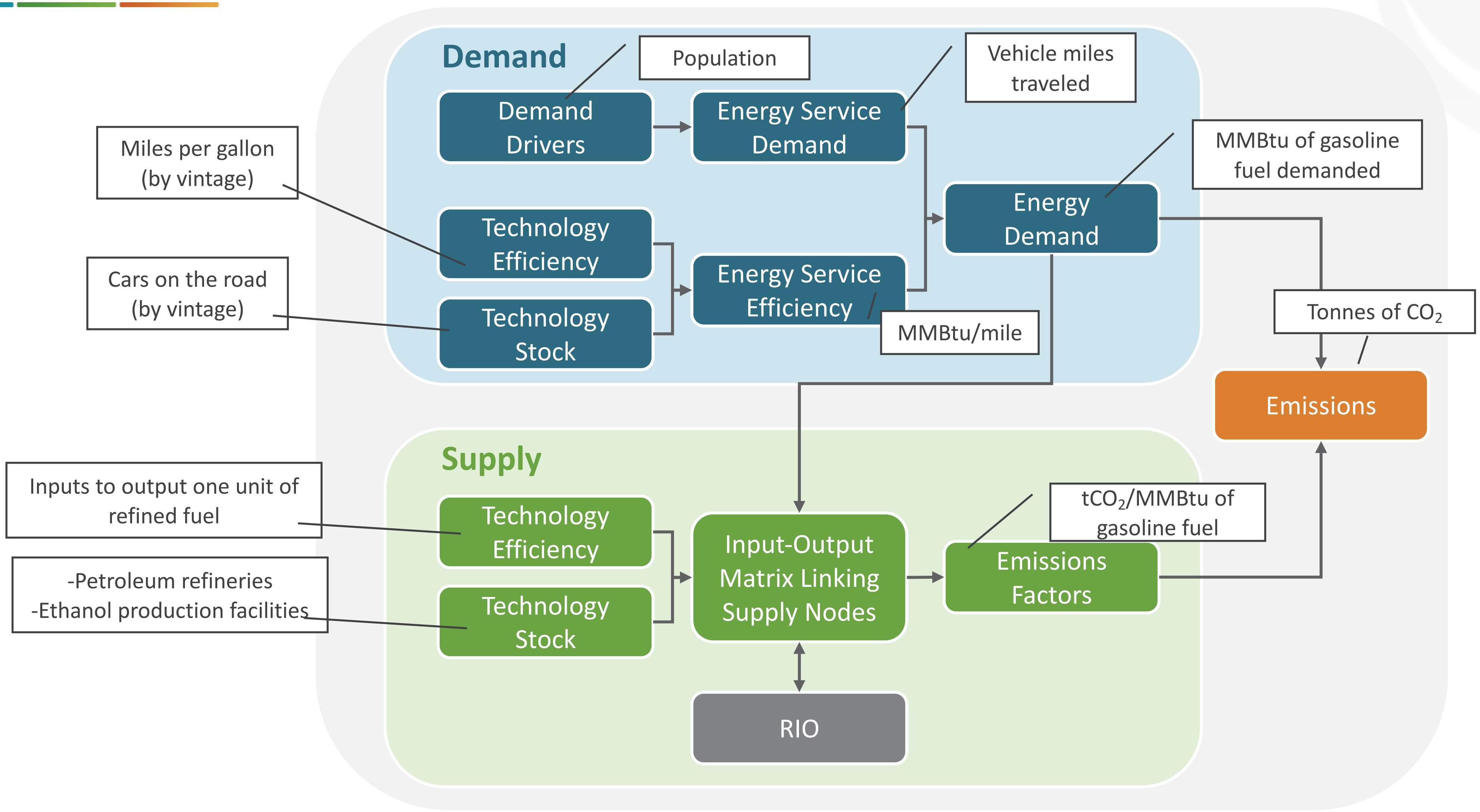
Beginning on the demand side, the model starts with a set of demand drivers. These are variables such as population or the value of industrial shipments and can be thought of as the skeleton upon which the rest of the model calculations depend.

Along with service demand, technology stocks that satisfy each service demand are tracked and projected into the future. The compositions of stocks are tracked by vintage and technology with each combination having a unique service efficiency that also may vary by geography, heat pump efficiency being one example. Total energy demand can be calculated by dividing service demand by service efficiency and summing across each service demand category, referred to in the model as demand subsectors. The fuel type of the final energy demand (e.g. electricity or pipeline gas) will depend on the technologies deployed and will vary by geography, application, and even time-of-year, as is the case with electricity.

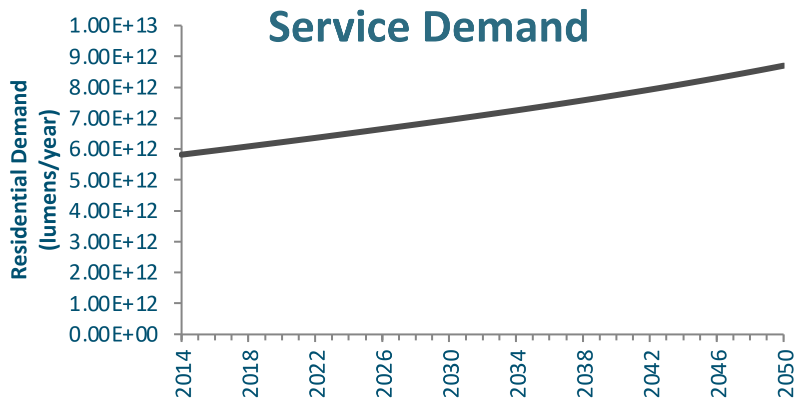


Example Definitions: Light-Duty Automobiles

Demand- and Supply-side of the Energy System



Projecting energy demand from the “bottom-up”



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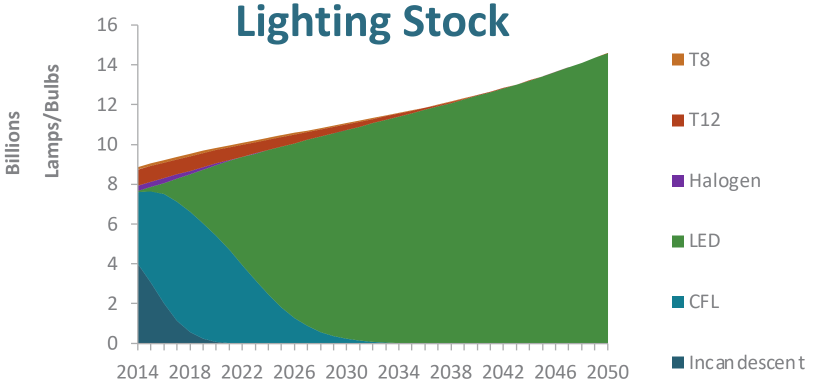

Infrastructure stock rollover model keeps track of “stuff” (i.e., number of light bulbs by type)

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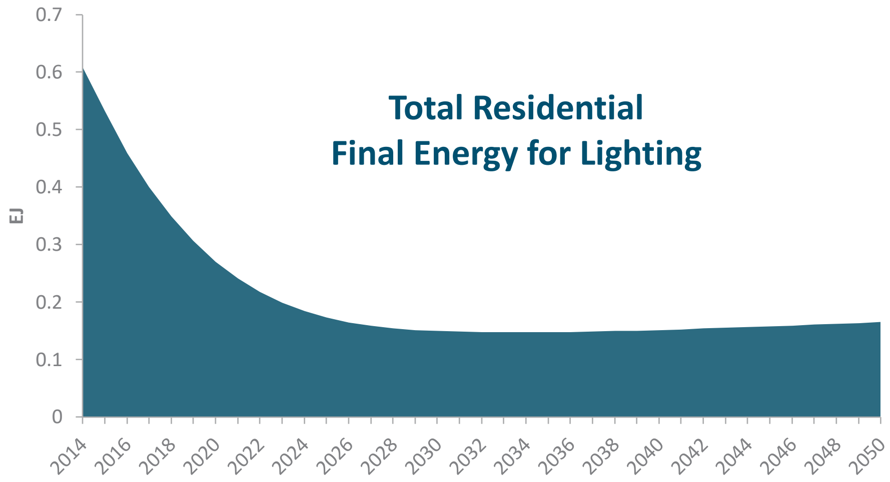

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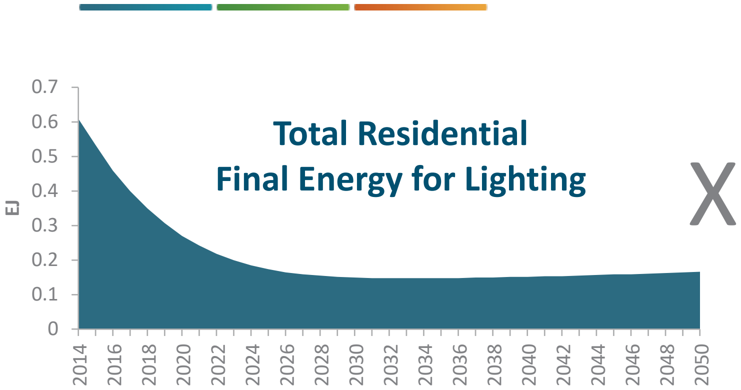
Creating hourly electricity load shapes



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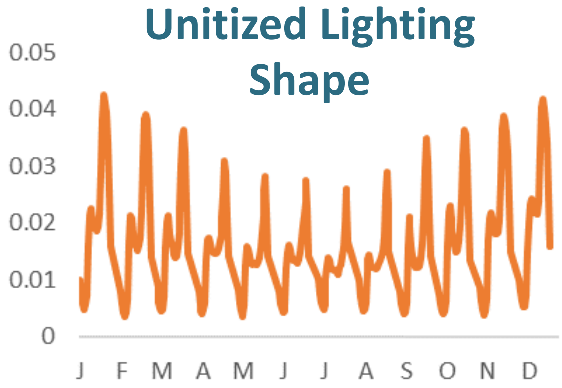

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Projected lighting shape

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Projected EV shape

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Projected heating shape

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Projected dryer shape

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demand subsectors

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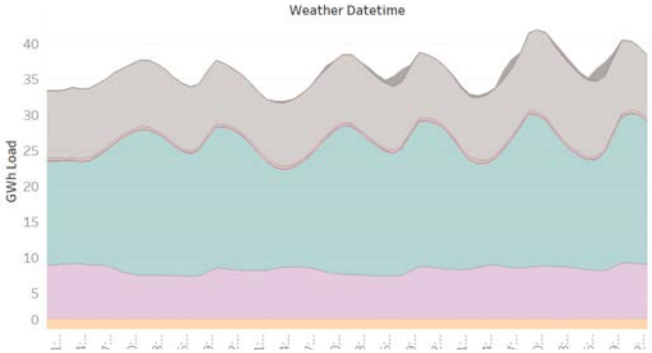
System Load



EnergyPATHWAYS projects future load shapes bottom-up. Annual energy is multiplied by a unitized service demand shape for each subsector and summed across each model region. In the first model year the bottom-up shape is benchmarked against a top-down shape from historical electric utility data. A series of hourly 'reconciliation factors' are created from this comparison that represent both bias and random noise not observed in the (often simulated) end-use data. These reconciliation factors are applied to future years.

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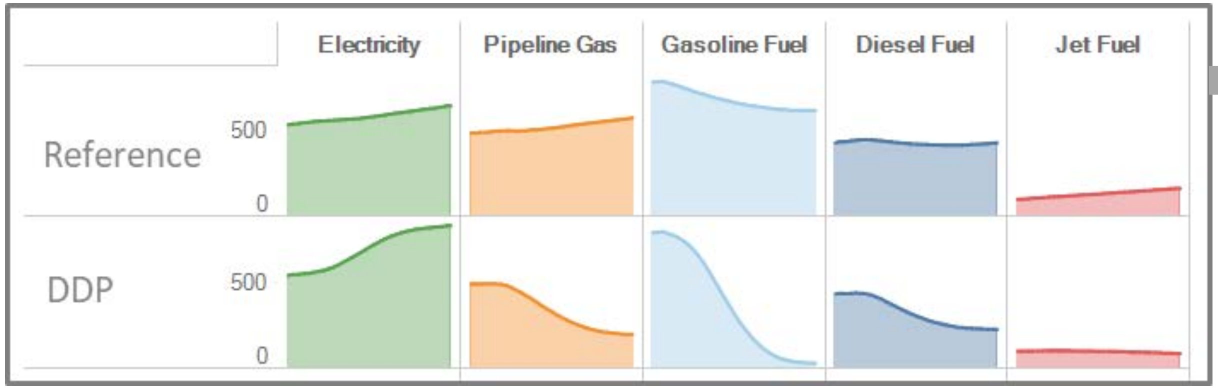
EnergyPATHWAYS Demand-side Outputs Passed to RIO

EnergyPATHWAYS: final energy demand projections



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RIO: case-specific inputs

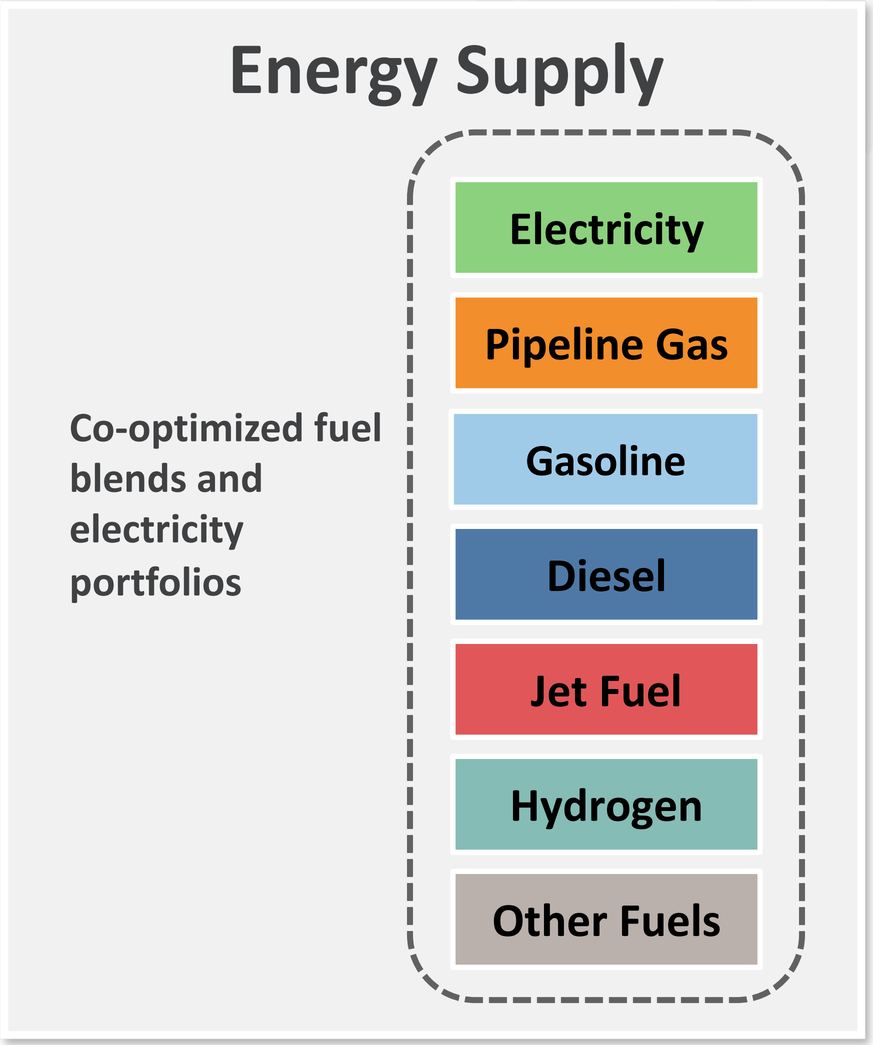
- End-use energy demand
- Biomass supply curve
- System emissions constraints
- RPS or clean energy constraints
- New resource constraints
- Technology and fuel cost projections

RIO: case-specific outputs

- **Electricity sector**
  - Wind/solar build
  - Energy storage capacity/duration
  - Capacity for reliability
  - Curtailment
- Biomass allocation
- Synthetic electric fuel production (H2/SNG)
- Direct air capture deployment
- Residual fossil fuel use

Regional Investment and Operations (RIO)

- RIO is a capacity expansion modeling tool that produces cost-optimal resource portfolios
- Includes electric sector capacity expansion and the optimization of all energy supply options
  - Optimization allows for trade-offs of limited resources across the energy system, such as biomass, to be determined simultaneously
- Model decides the suite of technologies to deploy over time to meet annual emissions and other constraints



RIO distinguishing features

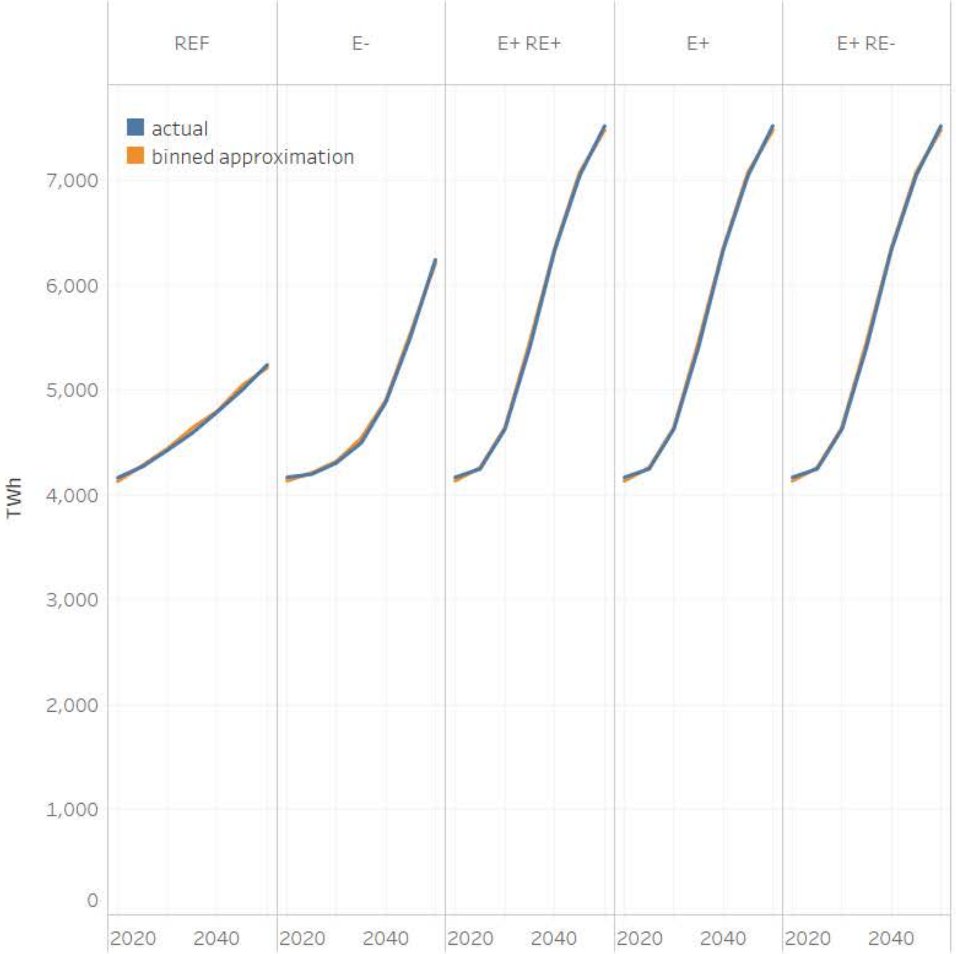
The following features represent methodological advantages of the RIO model over similar tools

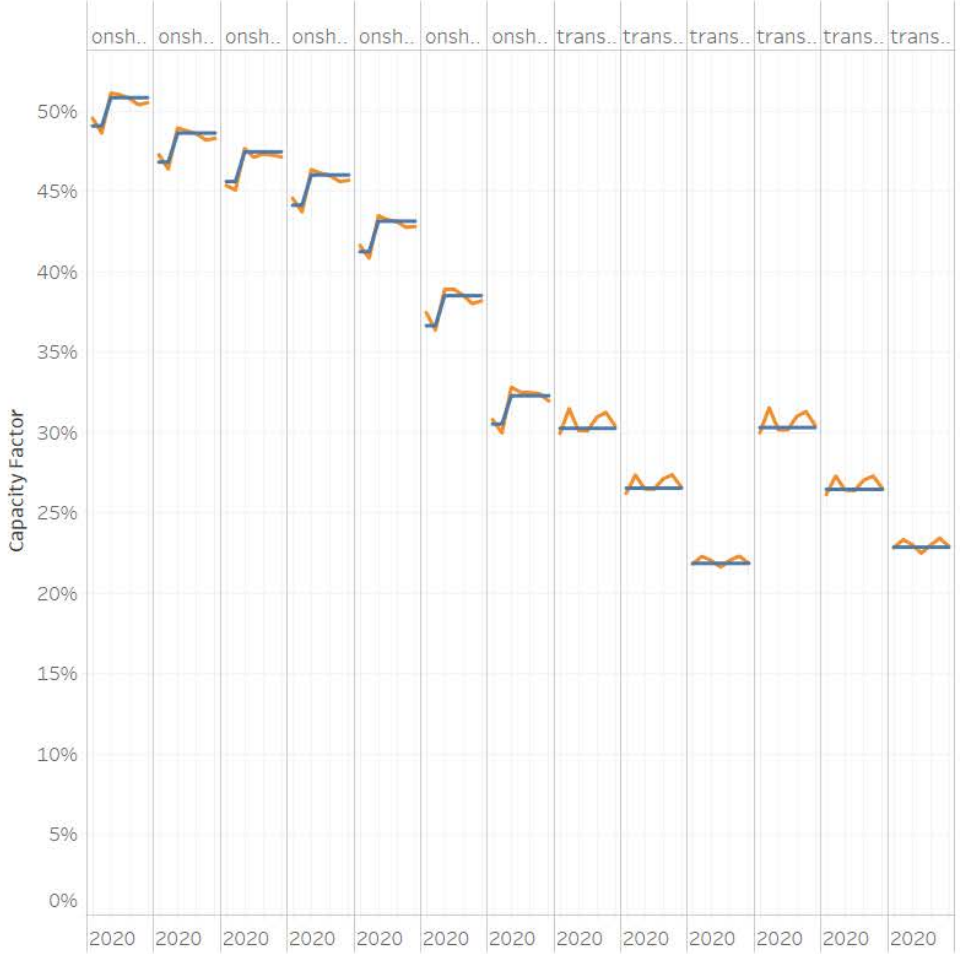
- Simultaneously minimizes cost for electricity transmission, electricity generation, and fuel conversion technologies
  - Optimally allocates biomass & sequestration potential between sectors
- High temporal granularity (984 hours per year) simultaneously modeled with high spatial granularity (16 zones)
  - Hourly operations over 24 hr sample days
  - Evolving load shapes, renewable production profiles, and sampled days between years
- Six annual snapshots between 2020 & 2050 (five-year timestep)
- Long-duration electricity & fuels storage (storage state of charge tracked over 365 days)
- Dynamic electricity reliability constraints that track planning reserve margins across all modeled hours rather than only historical gross-load peaks
- Advanced flexible load algorithms
- Optimal generator retirements and extensions
- Economy wide carbon emission constraints & electricity RPS & CES policies

Day sampling performance

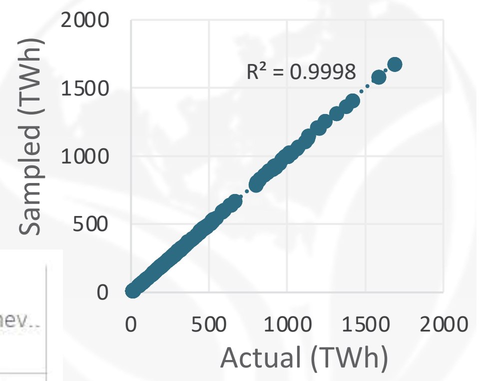
RIO clusters days using several dozen features to determine the subset of days to sample for operations. Examples of features include daily gross load, renewable capacity factors, maximum net load at different renewable fractions, and expected hydro energy.

This sampling is optimized at the start of model runs by changing the weight put on each feature. The figure to the right shows how well the 41 sample days approximate a full year of actual data. The blue are the target inputs that would be matched exactly if a full 365 days were used. The orange is the binned approximation using the 41 sample days. The goal is to have the binned approximation track the actuals while keeping the problem computationally tractable. A pre-processing step iterated through dozens of different feature weights and number of day samples before settling on the selected parameters.

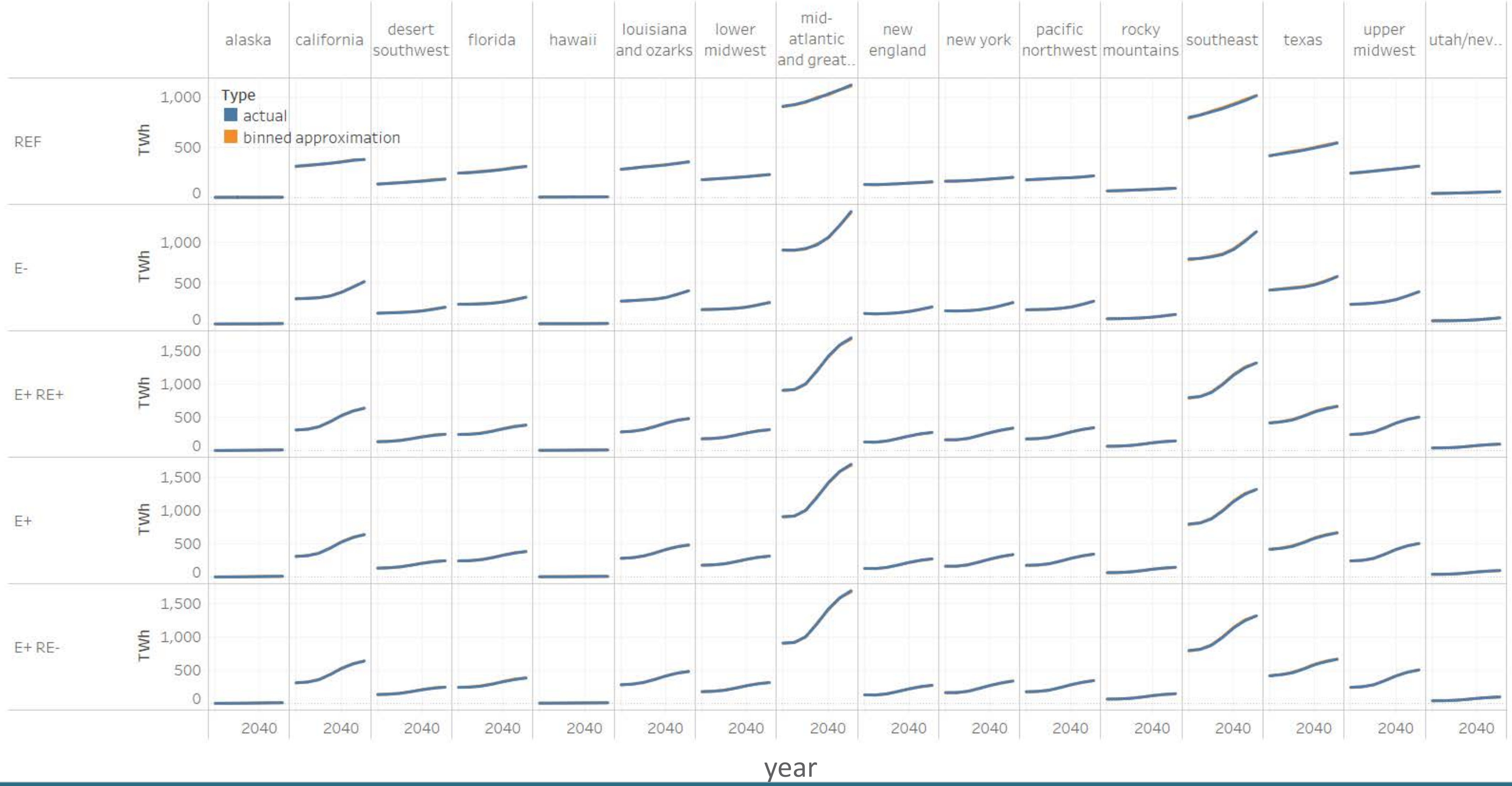




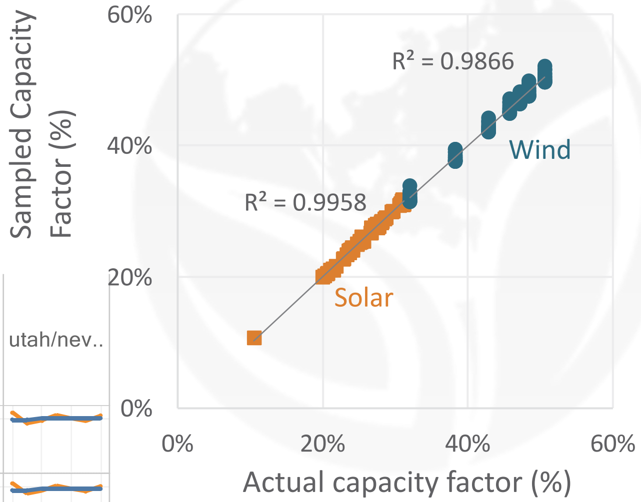
Gross-load sampling performance by region



Scatter plot shows a comparison of actual historical gross annual load on the x-axis against sampled gross load on the y-axis. Each point represents a combination of region, year, and scenario.



Capacity factor sampling performance by region



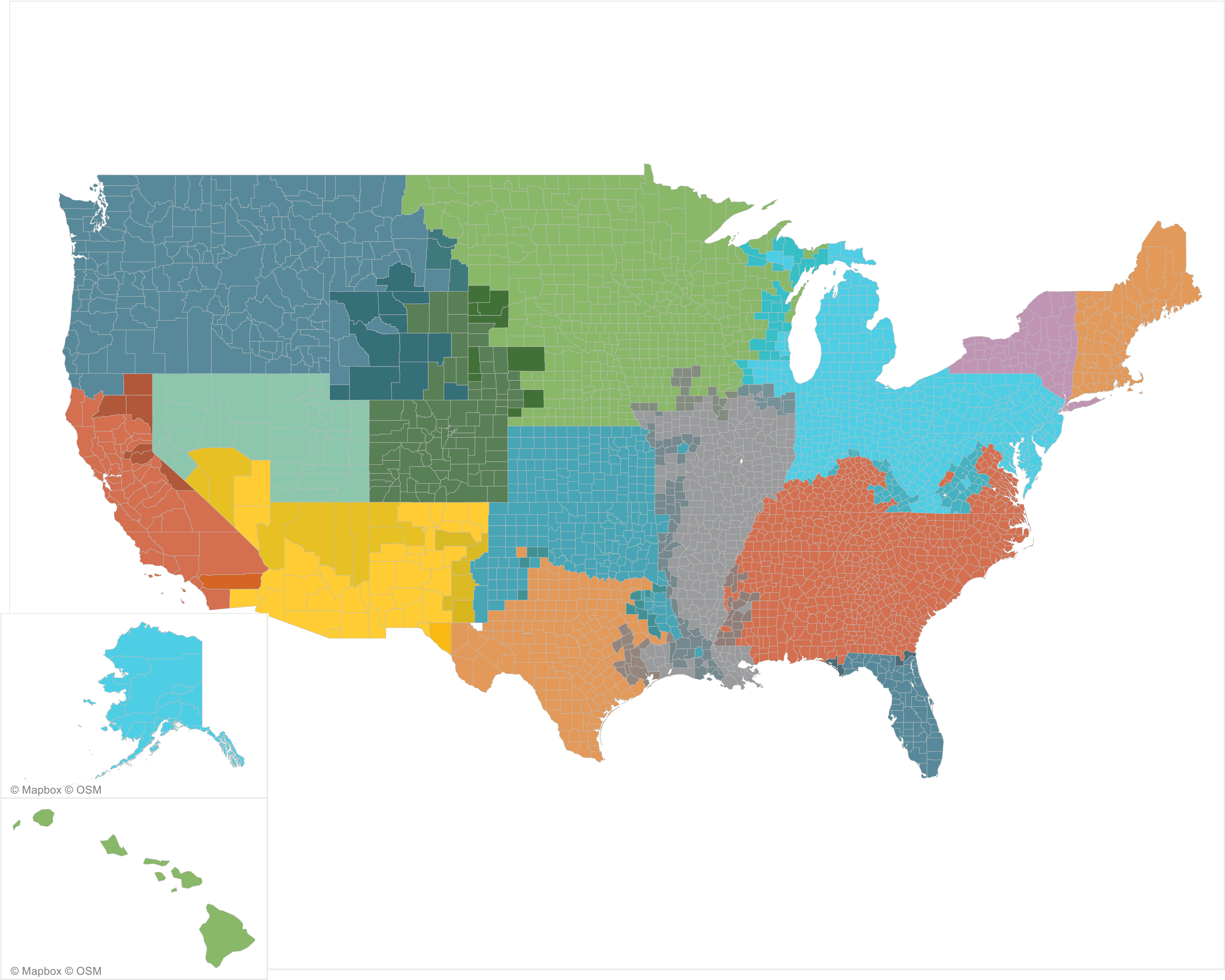
Scatter plot shows a comparison of actual historical capacity factor on the x-axis against sampled capacity factor on the y-axis. Each point represents a combination of region and renewable resource group. The data is averaged over year and vintage.

Generally wind is more difficult to fit that solar as the resource has more day-to-day variability.

Study map

RIO models 16 U.S. regions that represent aggregations of the NEMS Electricity Market Module Regions. The number of regions is a compromise between computational complexity and the spatial resolution deemed necessary to accurately reflect highly carbon constrained power systems. RIO includes electrical transmission constraints between neighboring regions and solves for incremental transmission build simultaneously with generation capacity. The figure to the right maps each of the 16 regions onto U.S. counties. Areas with off-color shading between zones indicate that fractions of the county belong in multiple regions.

EnergyPATHWAYS demand-side is run on a 50-state geography. The electricity profiles for each state get aggregated and mapped to the 16 RIO regions. Cost accounting done in EnergyPATHWAYS, informed by RIO outputs, takes place on the 16 region geography.



RIO decisions variables and outputs

Hours

24 hr * 41 sample days
= 984 hr

Decision Variables	Key Results
Generator Dispatch	Hourly Dispatch
Transmission Flows	Transmission Flows
Operating Reserves	Market Prices
Curtailment	Curtailment
Load Flexibility	

Days

365 days for 1 weather year (2011)

Decision Variables	Key Results
Fuel Energy Balance and Storage	Daily Electricity Balances
Long Duration Electricity Storage	Daily Fuel Balances
Dual Fuel Generator Blends	

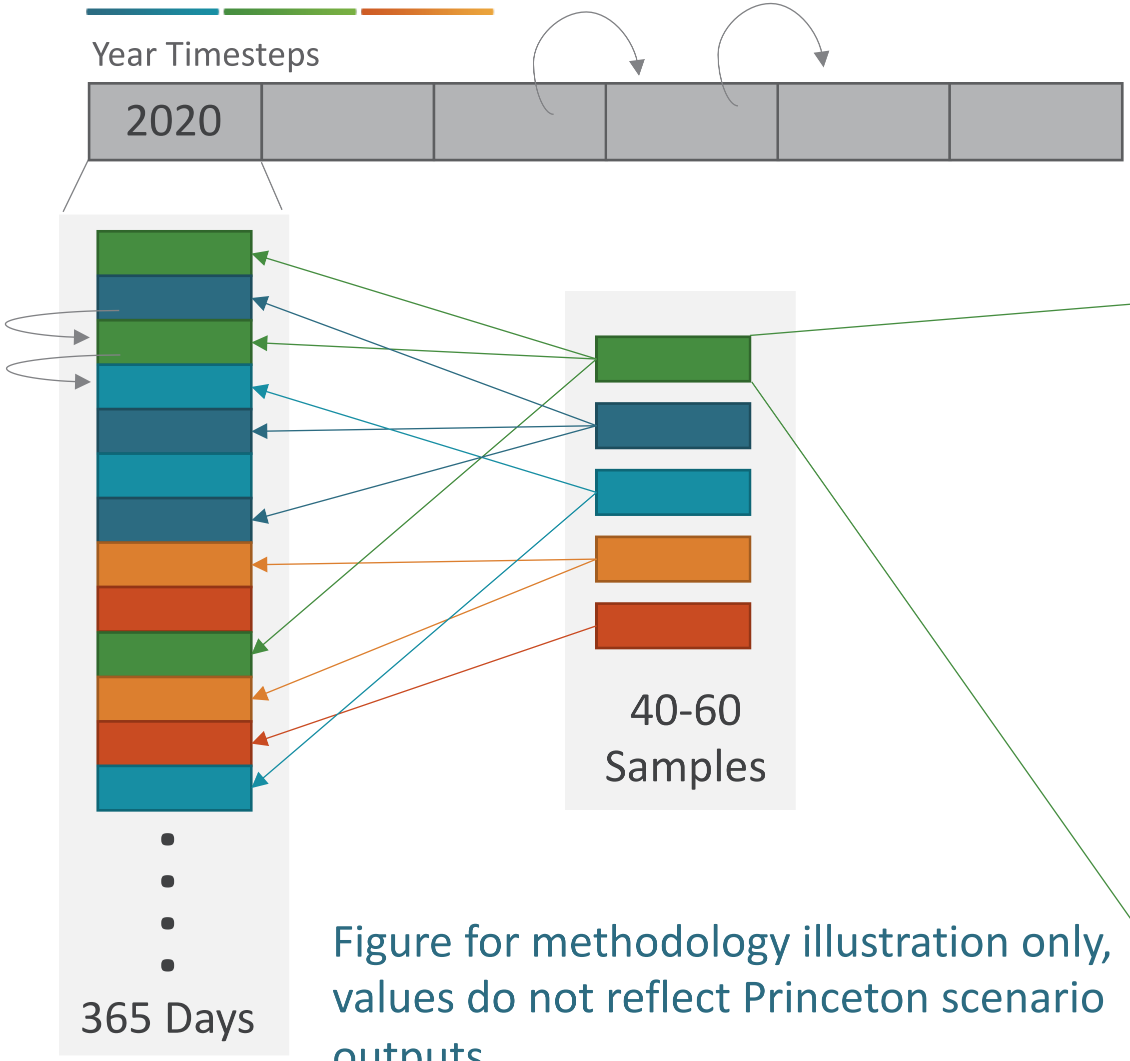
Years

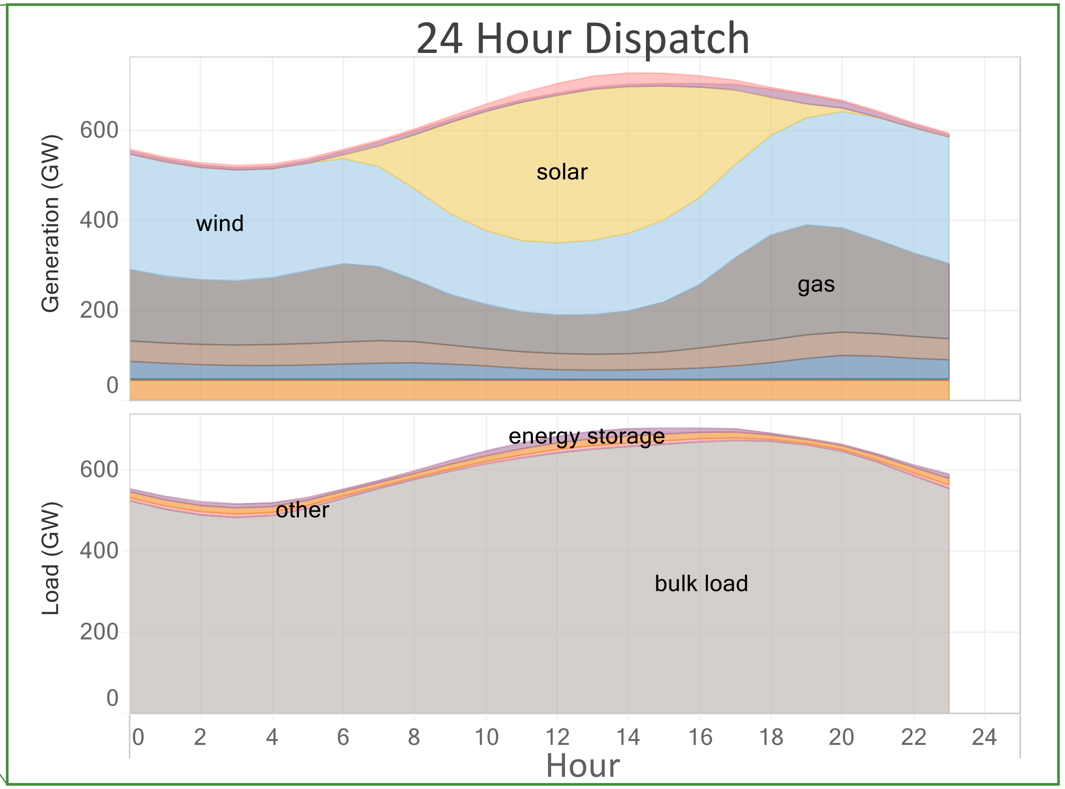
30 yr study / 5 yr timestep
= 6 snapshot years

Decision Variables	Key Results
Emissions from Operations	Total Annual Emissions
RPS Supply and Demand	RPS Composition
Capacity Build, Retirement & Repower	Incremental Build, Retirement, & Repower
	Thermal Capacity Factors
	Annual Average Market Prices
	Marginal Cost of Fuel Supply

RIO considers investments and operations to find the least-cost, reliable system

Operations and investment decisions are co-optimized across the study period to find the optimal portfolio





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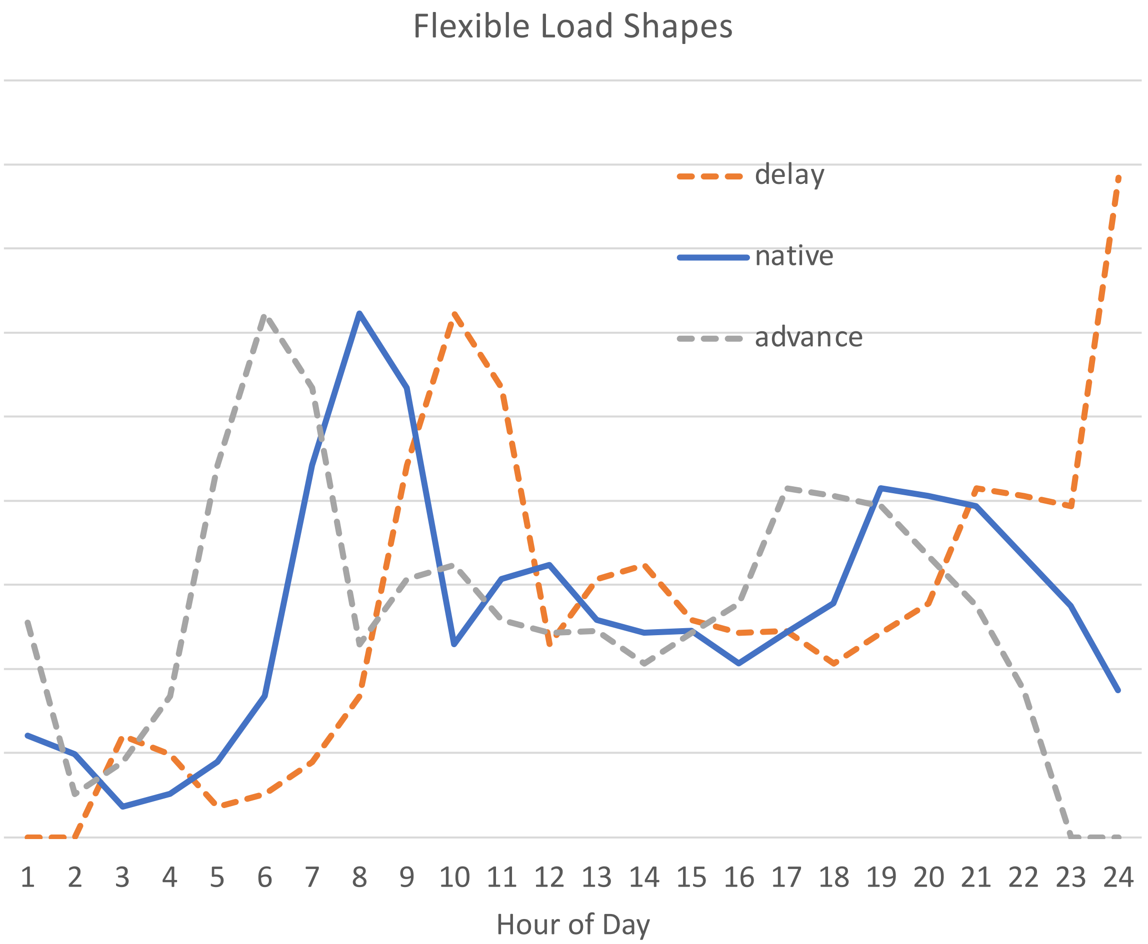
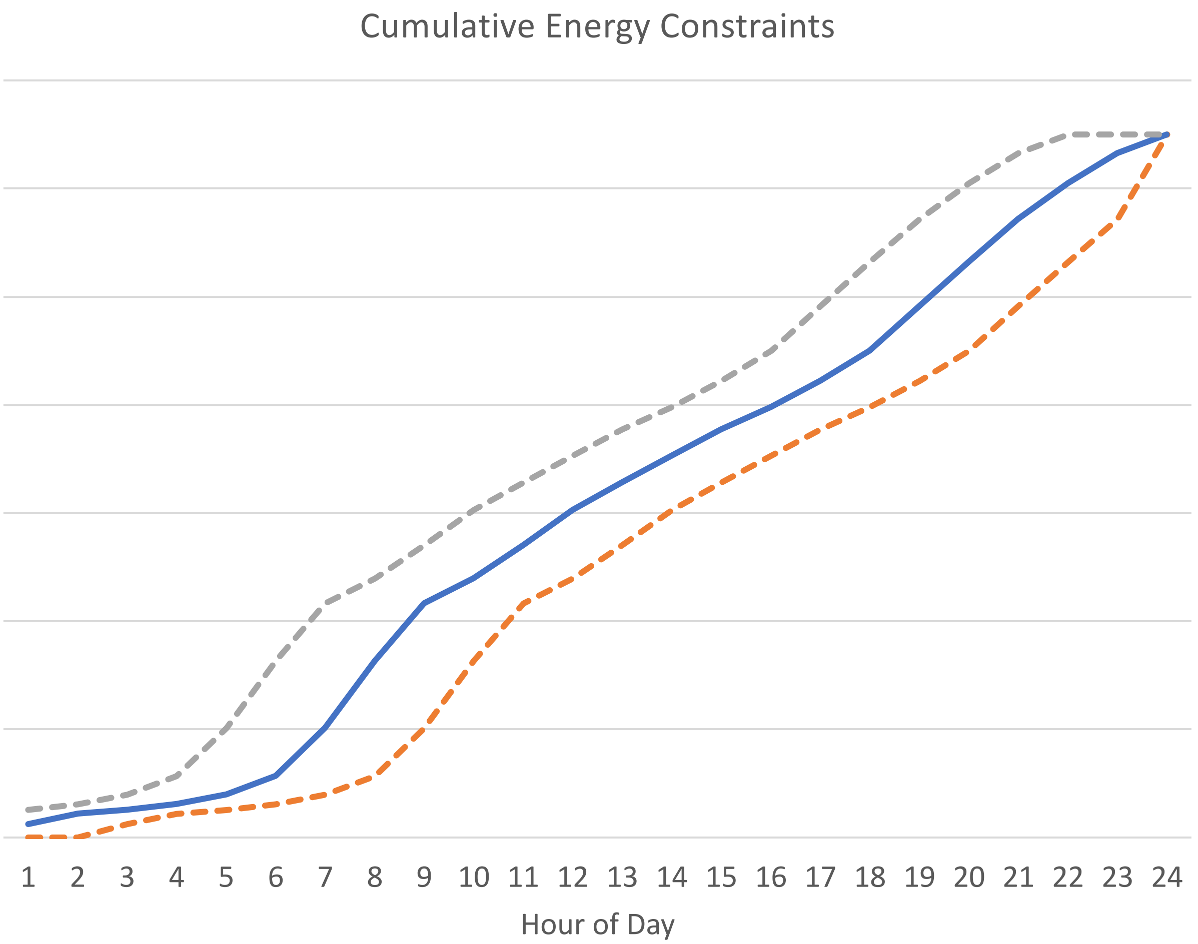
Flexible load operations

A portion of EV charging and water heating in buildings is made flexible and allowed to be scheduled within the electricity dispatch process. Use of flexible load incurs a small penalty in the objective function to avoid trivial use. The flexible load constraints are illustrated below using a profile with building space heating demand. For electric vehicles 50% of load was assumed to be flexible and allowed to delay charging by up to 5 hours. For hot water, 25% of load was assumed flexible and able to shift forward or backward in time by 2 hours. The delay or advance of service demand in time create hourly cumulative energy constraints within RIO. Flexible load can shift between the grey and orange bounds, while respecting maximum and minimum power constraints.





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Scenario differences

Net zero anthropogenic emissions in 2050

	Reference	E+	E+ RE+	E+ RE-	E-
E&I CO_2 Constraint	None	**-0.17 Gt/year**	**-0.17 Gt/year**	**-0.17 Gt/year**	**-0.17 Gt/year**
Land CO_2		-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year
Non-CO_2	~2 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year
Biomass Potential*	12 quads	12 quads	12 quads	12 quads	12 quads
Renewable build constraint across U.S. (solar/wind)	Capped at 10% growth rate	Capped at 10% growth rate	Capped at 10% growth rate	**Capped at current build rates**	Capped at 10% growth rate
Fossil fuel use	Allowed	Allowed	**Zero by 2050**	Allowed	Allowed
Fossil fuel prices	Low	Low	Low	Low	Low
Existing nuclear	50% @ 80-year	50% @ 80-year	**Retire after 60**	50% @ 80-year	50% @ 80-year
New nuclear	Disallowed in CA	Disallowed in CA	**Disallowed in all regions**	Disallowed in CA	Disallowed in CA
CCS supply curve	1.9 Gt/year	1.9 Gt/year	**Disallowed**	**Expanded (3 Gt/yr)**	1.9 Gt/year
Electrification rates	Reference	High	High	High	**20-year sales saturation lag**

* Sensitivities are run for each of these scenarios with 12 quads (base assumption) and 22 quads (high estimate). Results for the base biomass assumption are the primary focus in results presented in this document.

Scenario acronyms

For brevity, all scenarios are assigned a short-hand acronym used in figures and discussion that follow.

The acronym communicates three key features of a scenario by 2050: level of electrification, level of biomass availability, and level of renewable energy contribution to primary energy supply

Electrification level

E+ = high
E- = less high

Renewable Energy

RE- = renewable energy constrained
RE+ = 100% renewable primary energy

Biomass availability

. . . (base) = 12 quads
B+ = high (22 quads)

Acronym	Scenario
REF	Reference
E+	High electrification, 12 quads biomass
E-	Less-high electrification, 12 quads biomass
E+ RE-	E+ and renewables (solar/wind) constrained
E+ RE+	E+ and 100% primary energy from renewables by 2050
E+ B+	E+ and 22 quads (instead of 12) biomass potential by 2050
E- B+	E- and 22 quads (instead of 12) biomass potential by 2050
E+ RE- B+	E+ B+ and renewables (solar/wind) constrained
E+ RE+ B+	E+ B+ and 100% primary energy from renewables by 2050

Scenario similarities

- Societal discount rate 2% real
- Cost of capital assumptions:
  - Demand-side: 3-8% real depending on subsector
  - Nuclear 6% real
  - Offshore wind 5% real
  - All other electricity generation 4% real
  - Fuel conversion technologies 10% real
- Weather-year 2011
- Average hydro year
- 16 U.S. electricity zones
- EnergyPATHWAYS demand-side run with 1-year timestep, RIO optimization run on a 5-year timestep
- Electricity operations sampled with 41 days in each year (984 hours)
- Existing state CES and RPS policies implemented across all scenarios
- A straight-line path to 2050 emissions targets was assumed
- Decarbonizations scenarios assume low fossil fuel prices
  - AEO 2019 low oil price for all petroleum fuels
  - AEO 2019 high technology scenario for natural gas
  - Attempts to reflect the impact that demand-suppression would have on fuel prices
- Energy service demands are identical between scenarios (AEO 2019)
- Allam cycle technologies were not allowed until 2030
- Compound annual growth rate for new build of electricity generation technologies was limited to 10% applied across all zones
- No early retirement of demand-side technologies
- Either economic (early) or end-of life retirement for supply-side assets
- No transmission path was allowed to expand to more than 10x the current transfer capacity

Emissions target is zero anthropogenic emissions in 2050

Gt CO_{2e}

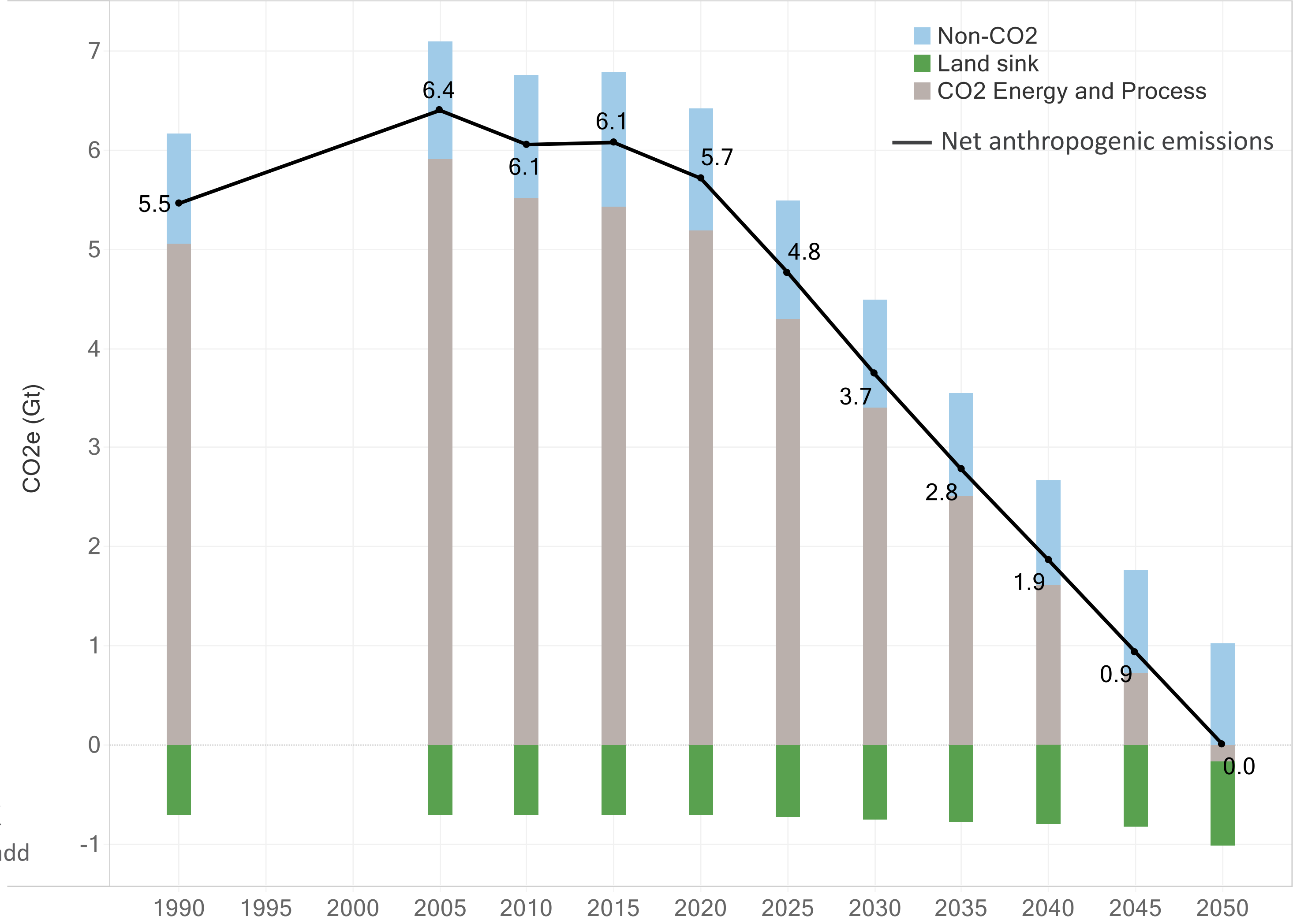
Year	Non-CO_2 [1]	Total Land sink [2]	CO_2 Energy and Process [3]
1990	1.1	-0.7	5.06
2005	1.19	-0.7	5.92
2010	1.24	-0.7	5.52
2015	1.35	-0.7	5.43
2020	1.22	-0.7	**5.2**
2025	1.19	-0.73	**4.3**
2030	1.09	-0.75	**3.41**
2035	1.04	-0.78	**2.51**
2040	1.05	-0.8	**1.62**
2045	1.04	-0.83	**0.72**
2050	1.03	-0.85	**-0.17**

[1] Mid-century strategy benchmark scenario

[2] National academy study on incremental land sink

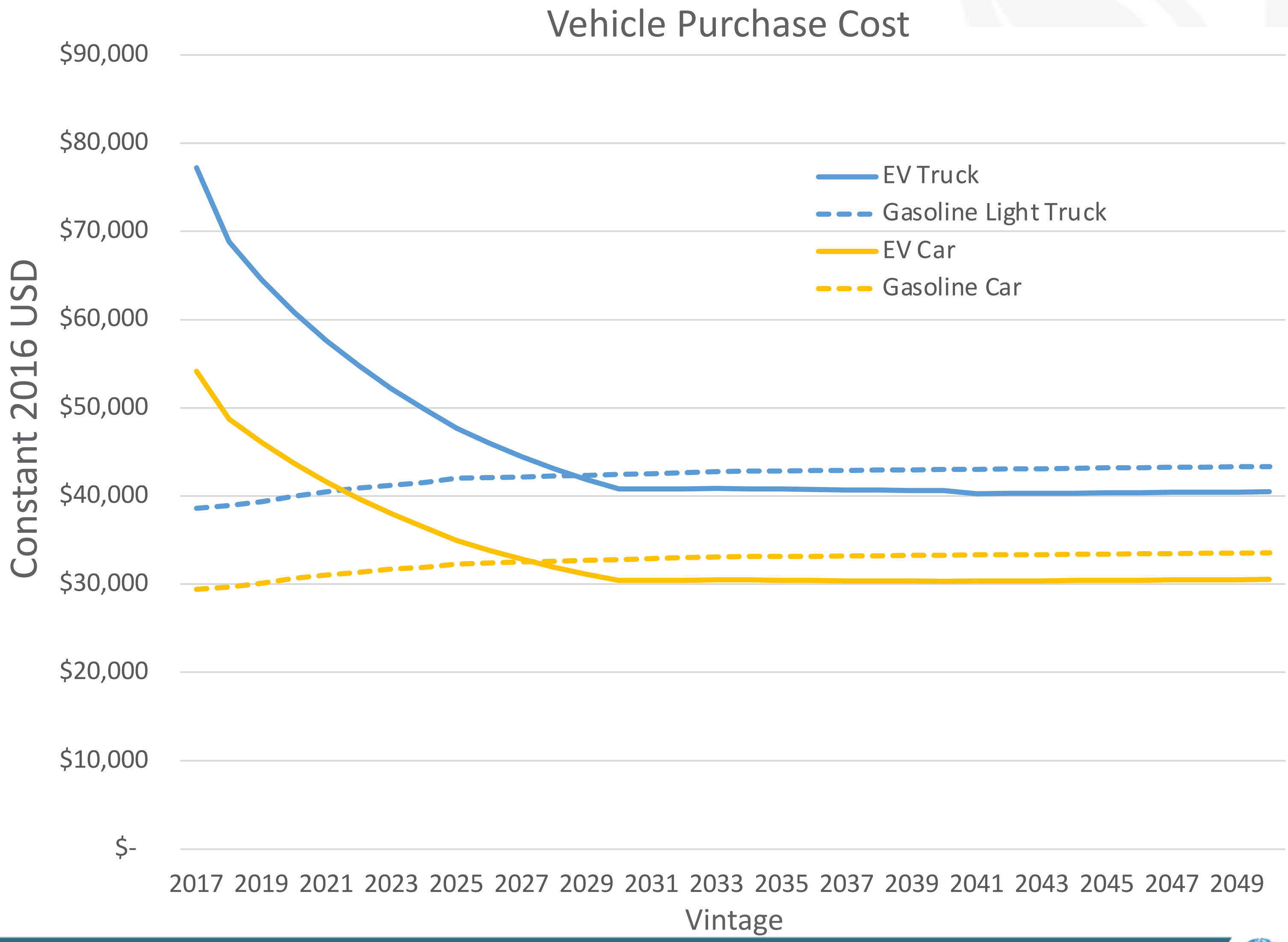
By 2050 existing land sink declines to 300 million tCO2e/y but incremental measures add 550 million tCO2e/y resulting in a total land sink of 850 million tCO2e/y

[3] Modeled in EP & RIO (optimization constraints)



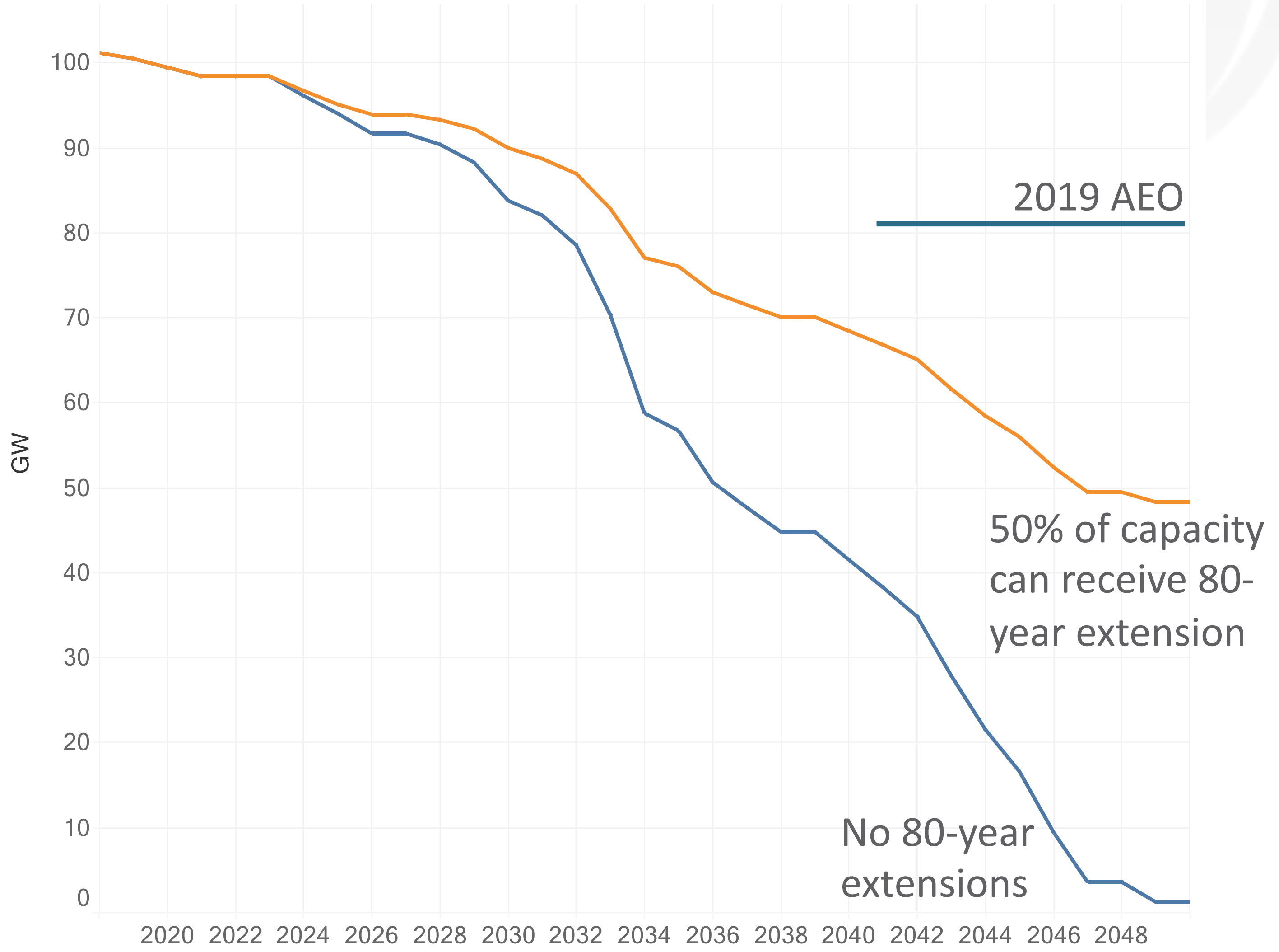
LDV cost

- LDV costs are built bottom-up from Bloomberg and ICCT assumptions, then benchmarked to top-down average vehicle costs
- New battery cost estimates are aggressive ~$70/kWh by 2030 resulting in a capital cost break-even and much lower ownership cost



Nuclear retirement schedules

- Two nuclear scenarios
  - Retire all nuclear after a single 20-year extension (2 GW remain in 2050)
  - Retire 50% of nuclear after a 60-year lifetime and allow the other half to extend to 80 years at a licensing cost of $500/kW
- We have ~49 GW in 2050 under the 50% re-license scenario vs ~80 GW in AEO 2019



Demand-subsectors

- EnergyPATHWAYS database includes 67 subsectors
  - Primary data-sources include AEO 2019 input & output files, RECS, CBECS, MECS, SEDS, NREL
  - 8 industrial process categories, 11 commercial building types, 3 residential building types
  - 363 demand-side technologies with projections of cost (capital, installation, fuel-switching, O&M) and service efficiency
    - **Subsectors highlighted in green** do not have technology representations and capital cost is not tracked within EnergyPATHWAYS

commercial air conditioning
commercial cooking
commercial lighting
commercial other
commercial refrigeration
commercial space heating
commercial ventilation
commercial water heating
district services
office equipment (non-p.c.)
office equipment (p.c.)
aviation
domestic shipping
freight rail
heavy duty trucks
international shipping
light duty autos
light duty trucks
lubricants
medium duty trucks
military use
motorcycles
passenger rail
recreational boats
school and intercity buses
transit buses
residential air conditioning
residential building shell
residential clothes drying
residential clothes washing
residential computers and related
residential cooking
residential dishwashing
residential freezing
residential furnace fans
residential lighting
residential other uses
residential refrigeration
residential secondary heating
residential space heating
residential televisions and related
residential water heating
Cement and Lime CO2 Capture
Cement and Lime Non-Energy CO2
Other Non-Energy CO2
agriculture-crops
agriculture-other
aluminum industry
balance of manufacturing other
bulk chemicals
cement
computer and electronic products
construction
electrical equip., appliances, and components
fabricated metal products
food and kindred products
glass and glass products
iron and steel
machinery
metal and other non-metallic mining
paper and allied products
plastic and rubber products
transportation equipment
wood products
lime

Demand-side technology inputs

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	Air source heat pump (ducted)	Cost: P. Jadun et al. NREL EFS Study Efficiency: NREL building simulations in support of P. Jadun et al.
	Ductless mini-split heat pump	Cost: (J. Dentz et al. EERE 2014) Efficiency: NREL building simulations in support of (P. Jadun et al.)
	Remainder	(Navigant Consulting, 2014)
Residential Water Heating	Heat pump water heater	(P. Jadun et al.)
	Remainder	(Navigant Consulting, 2014)
Residential Remaining Subsectors	All	(Navigant Consulting, 2014)
Commercial Space Heating and Air Conditioning	Air source heat pump	(P. Jadun et al.)
	Remainder	(Navigant Consulting, 2014)
Commercial Water Heating	Heat pump water heater	(P. Jadun et al.)
	Remainder	(Navigant Consulting, 2014)
Commercial Lighting	All	(AEO, 2017)
Commercial Building Shell	All	(AEO, 2017)
Light-duty Vehicles	Battery electric vehicle and plug-in hybrid electric vehicle	Cost: (Bloomberg 2019, ICCT 2019, Jadun et al.) Efficiency: (P. Jadun et al.)
	Remainder	Efficiency: (AEO 2019) Cost: (AEO 2019)
Medium Duty Vehicles	Battery electric	(P. Jadun et al.)
	Hydrogen fuel cell	(E. den Boer et al.)
	Remainder (CNG, diesel, etc.)	(TA Engineering Inc., 2012)
Heavy Duty Vehicles	Battery electric	(P. Jadun et al.)
	Hydrogen fuel cell	(L. Fulton, M. Miller)
	Reference diesel, gasoline and propane	(TA Engineering Inc., 2012)
	Diesel hybrid and liquefied pipeline gas	(TA Engineering Inc., 2012)
Transit Buses	All	(P. Jadun et al., 3)

Load shape sources

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Bulk System Load	initial electricity reconciliation, all subsectors not otherwise given a shape	Emissions and Generation Resource Integrated Database (EGRID) with additional granularity in the western interconnection	hourly, 2012	FERC Form No. 714
Light-Duty Vehicles (LDVs)	all LDVs	United States	month-hour-weekday/weekend average, separated by home vs. work charging	Evolved Energy Research analysis of 2016 National Household Travel Survey
Water Heating (Gas Shape)[a]	residential hot water		month-hour-weekday/weekend average	Northwest Energy Efficiency Alliance Residential Building Stock Assessment Metering Study (Northwest)
Other Appliances	residential TV & computers			
Lighting	residential lighting			
Clothes Washing	residential clothes washing			
Clothes Drying	residential clothes drying			
Dishwashing	residential dish washing			
Residential Refrigeration	residential refrigeration			
Residential Freezing	residential freezing			
Residential Cooking	residential cooking			
Industrial Other	all other industrial loads			California Load Research Data
Agriculture	industry agriculture			
Commercial Cooking	commercial cooking			
Commercial Water Heating	commercial water heating	North American Electric Reliability Corporation (NERC) region		EPRI Load Shape Library 5.0
Commercial Lighting Internal	commercial lighting			
Commercial Refrigeration	commercial refrigeration			

List compiled for NREL EFS study

Load shape sources, continued

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Commercial Ventilation	commercial ventilation			
Commercial Office Equipment	commercial office equipment			
Industrial Machine Drives	machine drives			
Industrial Process Heating	process heating			
electric_furnace_res	electric resistance heating technologies	IECC Climate Zone by state (114 total geographical regions)	hourly, 2012 weather	Evolved Energy Research Regressions trained on NREL building simulations in select U.S. cities for a typical meteorological year and then run on county level HDD and CDD for 2012 from the National Oceanic and Atmospheric Administration (NOAA)
reference_central_ac_res	central air conditioning technologies			
high_efficiency_central_ac_res	high-efficiency central air conditioning technologies			
reference_room_ac_res	room air conditioning technologies			
high_efficiency_room_ac_res	high-efficiency room air conditioning technologies			
reference_heat_pump_heating_res	ASHPs			
high_efficiency_heat_pump_heating_res	high-efficiency ASHPs			
reference_heat_pump_cooling_res	ASHP s			
high_efficiency_heat_pump_cooling_res	high-efficiency ASHPs			
chiller_com	commercial chiller technologies			
dx_ac_com	direct expansion air conditioning technologies			
boiler_com	commercial boiler technologies			
furnace_com	commercial electric furnaces			
Flat shape	MDV and HDV charging	United States	n/a	n/a

[a] natural gas shape is used as a proxy for the service demand shape for electric hot water due to the lack of electric water heater data.

List compiled for NREL EFS study

Supply-side data

Data Category	Data Description	Supply Node	Source
Resource Potential	Binned resource potential (GWh) by state with associated resource performance (capacity factors) and transmission costs to reach load	Transmission – sited Solar PV; Onshore Wind; Offshore Wind; Geothermal	(Eurek et al. 2017)
Resource Potential	Binned resource potential of biomass resources by state with associated costs	Biomass Primary – Herbaceous; Biomass Primary – Wood; Biomass Primary – Waste; Biomass Primary – Corn	(Langholtz, Stokes, and Eaton 2016)
Resource Potential	Binned annual carbon sequestration injection potential by state with associated costs	Carbon Sequestration	Princeton
Resource Potential	Domestic production potential of natural gas	Natural Gas Primary – Domestic	(U.S. Energy Information Administration 2019)
Resource Potential	Domestic production potential of oil	Oil Primary – Domestic	(U.S. Energy Information Administration 2019)
Product Costs	Commodity cost of natural gas at Henry Hub	Natural Gas Primary – Domestic	(U.S. Energy Information Administration 2019)
Product Costs	Undelivered costs of refined fossil products	Refined Fossil Diesel; Refined Fossil Jet Fuel; Refined Fossil Kerosene; Refined Fossil Gasoline; Refined Fossil LPG	(U.S. Energy Information Administration 2019)
Product Costs	Commodity cost of Brent oil	Oil Primary – Domestic; Oil Primary - International	(U.S. Energy Information Administration 2019)
Delivery Infrastructure Costs	AEO transmission and delivery costs by EMM region	Electricity Transmission Grid; Electricity Distribution Grid	(U.S. Energy Information Administration 2019)
Delivery Infrastructure Costs	AEO transmission and delivery costs by census division and sector	Gas Transmission Pipeline; Gas Distribution Pipeline	(U.S. Energy Information Administration 2019)
Delivery Infrastructure	AEO delivery costs by fuel product	Gasoline Delivery; Diesel Delivery; Jet Fuel; LPG Fuel Delivery; Kerosene Delivery	(U.S. Energy Information Administration 2019)

Supply-side data continued

Data Category	Data Description	Supply Node	Source
Technology Cost and Performance	Renewable and conventional electric technology installed cost projections	Nuclear Power Plants; Onshore Wind Power Plants; Offshore Wind Power Plants; Transmission – Sited Solar PV Power Plants; Distribution – Sited Solar PV Power Plants; Rooftop PV Solar Power Plants; Combined – Cycle Gas Turbines; Coal Power Plants; Combined – Cycle Gas Power Plants with CCS; Coal Power Plants with CCS; Gas Combustion Turbines	(National Renewable Energy Laboratory 2019)
Technology Cost and Performance	Renewable and conventional electric technology installed cost projections	BECCS Power Plants	Princeton
Technology Cost and Performance	Electric fuel cost projections including electrolysis and fuel synthesis facilities	Central Hydrogen Grid Electrolysis; Facilities synthesizing diesel, jet fuel, or methane from CO and H2	Princeton
Technology Cost and Performance	Hydrogen Gas Reformation costs with and without carbon capture	H2 Natural Gas Reformation; H2 Natural Gas Reformation w/CCS	Princeton
Technology Cost and Performance	Nth plant Direct air capture costs for sequestration and utilization	Direct Air Capture	Princeton
Technology Cost and Performance	Biomass gasification and H2 production with CO2 capture	Gasification-based BECCS H2 production	Princeton
Technology Cost and Performance	Cost and efficiency of renewable Fischer-Tropsch diesel production.	Biomass Fischer-Tropsch fuels without or with CO2 capture	Princeton
Technology Cost and Performance	Cost and efficiency of industrial boilers	Electric Boilers; Other Boilers	(Capros et al. 2018)
Technology Cost and Performance	Cost and efficiency of other, existing power plant types	Fossil Steam Turbines; Coal Power Plants	(Johnson et al. 2006)

Supply-side technology assumed lifetimes

Name	Lifetime	Book life
advanced nuclear plant	60	40
biomass power plant	50	40
biomass w/ccu allam power plant	50	40
biomass w/ccu power plant	50	40
coal igcc power plant	40	40
coal igcc with ccu power plant	40	40
distribution-sited solar pv power plant	30	20
gas combined cycle ccu oxyfuel	40	40
gas combined cycle power plant	40	40
gas combined cycle power plant with ccu	40	40
gas combustion turbine power plant	40	40
geothermal power plant_1	30	30
landfill gas to electricity power plant	20	20
li-ion	10	10
pulverized coal combined cycle ccu oxyfuel	40	40
pulverized coal power plant	50	40
rooftop solar pv power plant	30	20
offshore wind fixed power plant	30	20
offshore wind floating power plant	30	20
transmission-sited solar pv power plant	30	20
onshore wind power plant	30	20

name	Lifetime	Book life
biomass -> sng w/ccu	25	15
biomass - > sng	25	15
cellulosic ethanol plant	25	15
direct air capture plant for power to fuels	40	15
electric boiler	30	15
corn ethanol plant	25	15
h2 natural gas reformation	25	15
h2 natural gas reformation w/ccu	25	15
industrial coal boiler	25	15
industrial distillate fuel oil boiler	20	15
industrial hydrogen boiler	20	15
industrial lpg boiler	20	15
industrial other petroleum boiler	20	15
industrial petroleum coke boiler	25	15
industrial pipeline gas boiler	20	15
industrial residual fuel oil oil boiler	20	15
BECCS hydrogen production -> hydrogen blend	25	15
ATR w/ccu -> hydrogen blend	25	15
biomass pyrolysis	25	15
central-station hydrogen electrolysis	20	15
power - to - liquids	25	15
power-to-gas methanation	25	15
biomass ft -> diesel w/ccu	25	15
biomass ft -> diesel	25	15

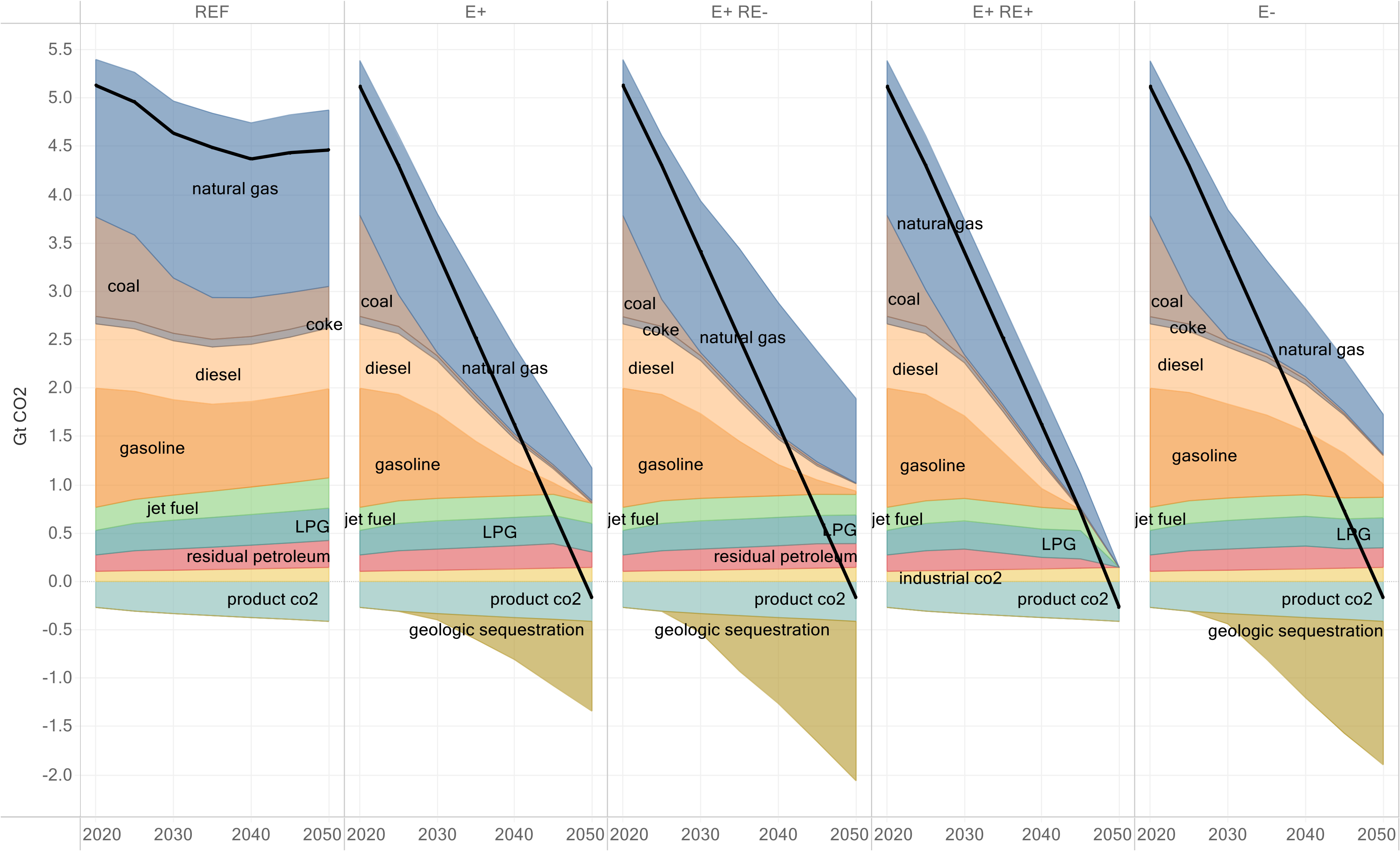
Carbon emissions

Energy and industrial CO_2 emissions by final energy demand

The 2050 E&I CO2 target of -170 MMT was found to be feasible across all scenarios.

All scenarios except for E+ RE+ make significant use of geologic storage to reach this goal. Sequestration of carbon within durable products is an important strategy within all scenarios, particularly the E+ RE+ scenario where geologic storage was disallowed and industrial process emissions must be offset. In this case, the E+ RE+ scenario actually reaches -266 MMT as the zero fossil constraint turned out to be more binding than the economy wide carbon cap.

Reference case emissions gradually decrease until 2040 due to coal retirements and reduced demand for petroleum products before rising slightly in the final decade.



Note: excludes domestic emissions for fossil fuels produced for export.

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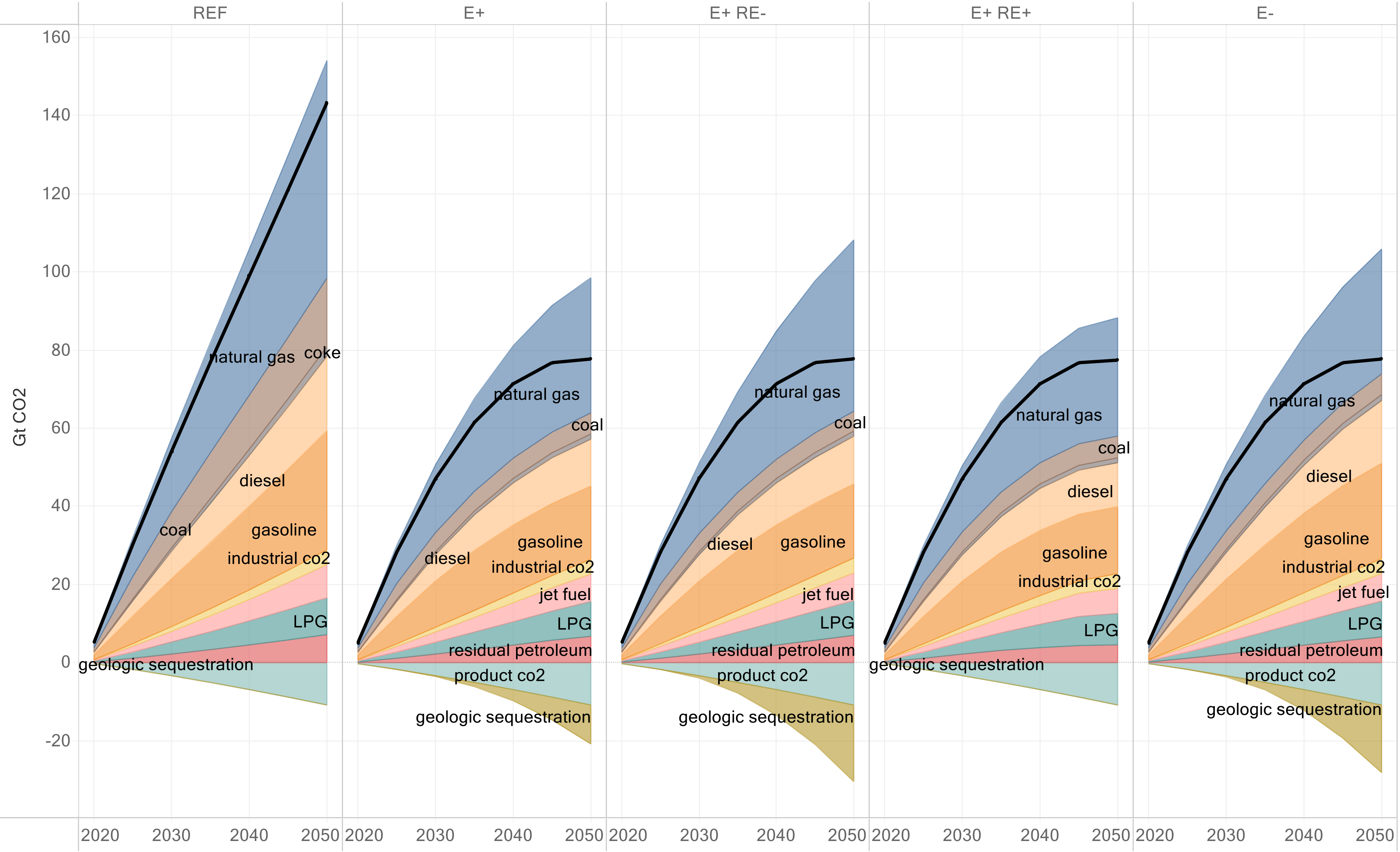
Cumulative energy and industrial CO_2 emissions (domestic consumption)

Cumulative emissions in the REF scenario were 143 Gt from 2020-2050 and 78 Gt in each of the decarbonization scenarios.

Oil products are responsible for most of the cumulative emissions, followed by natural gas, then coal. By 2050 11 Gt CO2 is sequestered in durable products that were produced using non-biogenic carbon [1]. Geologic sequestration is used to offset 10 Gt in the E+ scenario and 20 Gt in the E+ RE- scenario.

[1] Sequestration from lumber and wood products is not included in these estimates.



Note: excludes domestic emissions for fossil fuels produced for export.

System cost

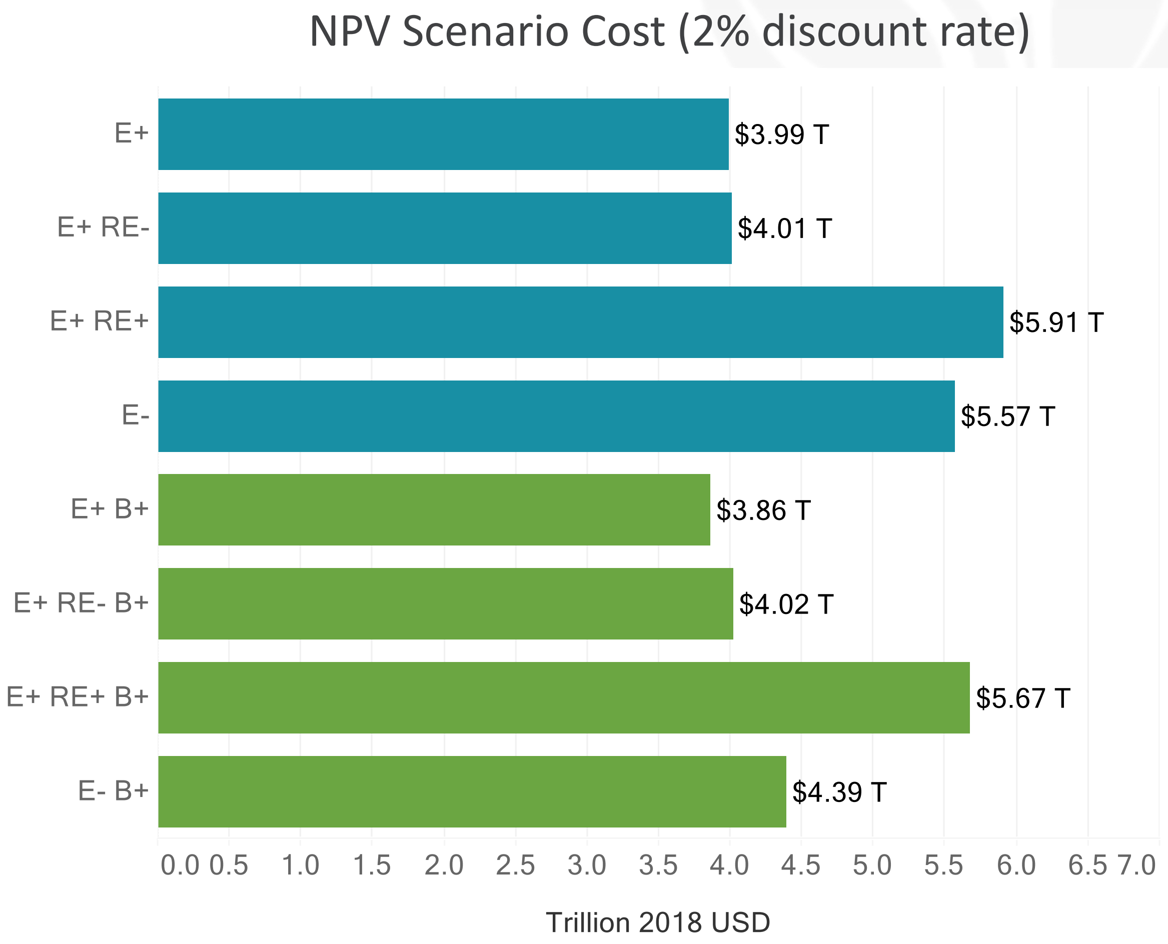
Present value scenario cost

The table shows 2020 present value energy system cost for each decarbonization scenario, found to be 4-6 trillion 2018 USD. This value includes all incremental supply-side energy costs and the cost of demand-side equipment above that in the reference case (e.g. the incremental cost of an electric vehicle is included, but the full cost of the reference vehicle is not). Macroeconomic costs are not included, nor are any benefits from reduced climate damage or air pollution.

The E+ scenario was found to have the lowest present value cost and the E+ RE+ scenario the largest. Each scenario has present value costs that are smaller than the impact of fossil fuel price uncertainty from the 2019 AEO [1]. For comparability, all scenarios are compared to a reference scenario that also has low fossil fuel prices. The lower the fossil fuel price, the more costly each scenario becomes when compared to the counterfactual with reference fossil fuel use. Additional sophistication in the determination of fossil fuel price within the model could allow the fuel price depression that is likely to result from decarbonization to be counted as a benefit.

The E+ RE- and E- scenarios are more sensitive to fossil fuel prices while the E+ and E+ RE+ scenarios are sensitive to the cost of renewables and transmission. The E- scenario is highly sensitive to the cost and availability of biomass.

[1] AEO low fossil fuel prices save 6.5 trillion 2018 USD in the reference case between 2020-2050 compared to reference fuel prices.



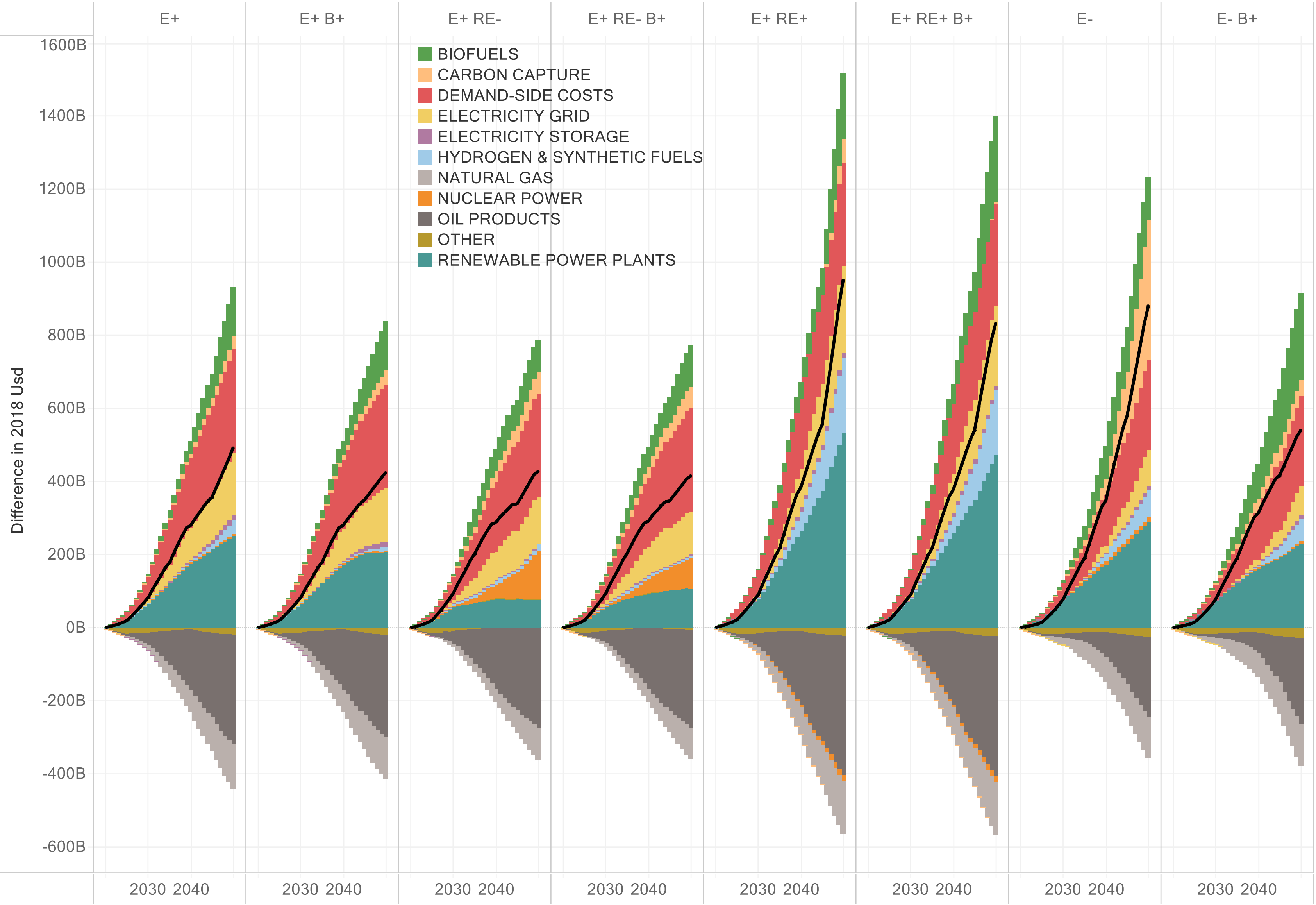
Levelized system cost by component

The stacked area bars show supply-side and demand-side cost components. All costs are presented relative to the REF scenario. Annual levelized net-cost is shown as a black line.

Levelized cost for the E+, E- B+, E+ RE- scenarios were each near 1.2% of 2050 GDP. The E- and E- B+ scenarios are slightly cheaper than the others in the near-term, but more costly post 2035. The E+ scenario is also cheaper before 2040, but post 2040, the E+ RE- scenario has slightly lower annual cost.

The E+ RE+ scenario had 2050 net-costs near double that of the E+ scenario with annual costs increasing significantly during the last decade.

Cost increases come primarily from electricity production & delivery infrastructure, followed by bio- and synthetic-fuel production. Cost savings come from reduced oil and natural gas purchase as well as conventional power plants.



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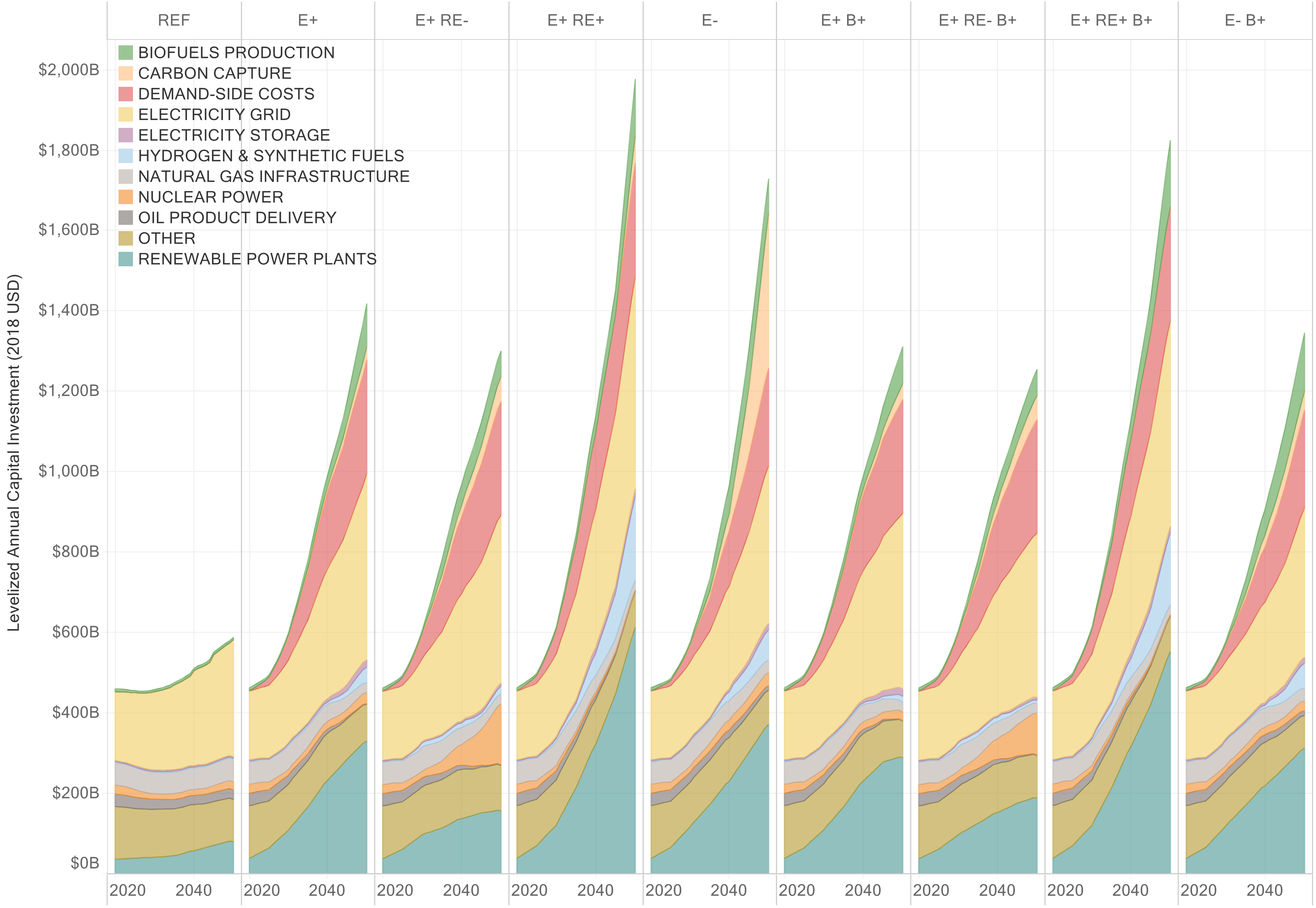
Levelized annual capital investments

Levelized capital investments by year across the energy sector are shown for all scenarios. Scenarios that rely more heavily on renewables in the power system tend to be more capital intensive. By 2050, the E+ RE+ scenario is approaching 2 trillion per year in capital expenditures. The E+ B+, E+ RE- and E+ RE- B+ scenarios have the lowest capital investment at ~1.3 trillion per year.

All scenarios show significant growth in capital deployed vs. the REF scenario (0.6 trillion per year in 2050).

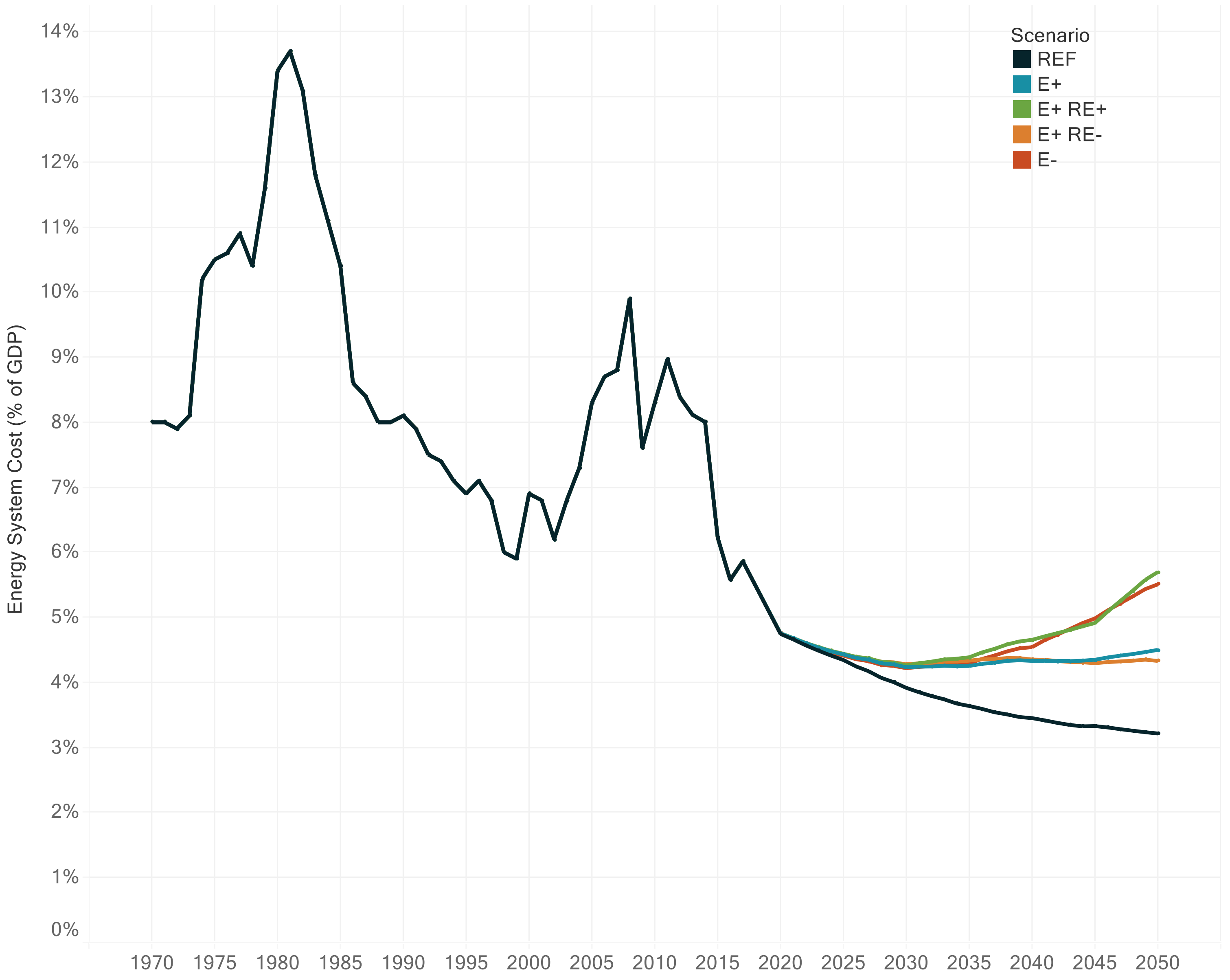


Cost as percent of GDP

Total energy system cost as a percentage of GDP is shown for historical data (1970-2017) and projected for future years 2020-2050. Incremental demand-side cost from decarbonization is included as an energy system cost component

Historical energy system spending as a percent of GDP is highly variable as a function of changes in fuel prices. Reductions in energy intensity of the economy explain the overall downward trend.

Reference scenario energy spending in 2050 with low fossil fuel prices is projected to drop to just over 3% of GDP. Costs across all scenarios are on-par or below historical spending on energy.



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Demand-side details

Demand-side cases

Three demand-side cases form the basis for nine RIO scenarios. High electrification scenarios all have identical final energy demand with both high electrification and high energy efficiency. The less-high electrification scenarios, by contrast, have high energy efficiency, but a 20-year lag in sales saturation of flexible loads. This means that if the sales-share of an electro-technology would have reached 100% by 2040, it instead is on track to reach that point by 2060. In either case, a logistic function (s-curve) adoption shape is followed.

One reason our study did not attempt to solve the demand- and supply-sides of the economy iteratively is that when shooting for a negative energy and industrial (E&I) CO2 target, fewer degrees of freedom on the demand-side exist than would first appear. In most cases, the economics of efficiency and electrification are such that both are already pursued as rapidly as we felt could be technically achieved. The places on the demand-side where actions could feasibly trade-off against one another are primarily in industry and heavy-transport, many of which are active research questions, but are not where the bulk of current emissions reside.

The reference case is based on the 2019 U.S. Annual Energy Outlook with some sales share measures also informed by the NREL Electrification Futures Study reference case. The combination reflects a low level of electrification and incremental efficiency. With a few notable exceptions, most technologies in the reference case are simply replaced by newer versions of themselves.

Scenario Name	Demand-side case
REF	Reference (REF)
E+	High electrification (E+)
E+ B+	High electrification (E+)
E+ RE-	High electrification (E+)
E+ RE- B+	High electrification (E+)
E+ RE+	High electrification (E+)
E+ RE+ B+	High electrification (E+)
E-	Less-high electrification (E-)
E- B+	Less-high electrification (E-)

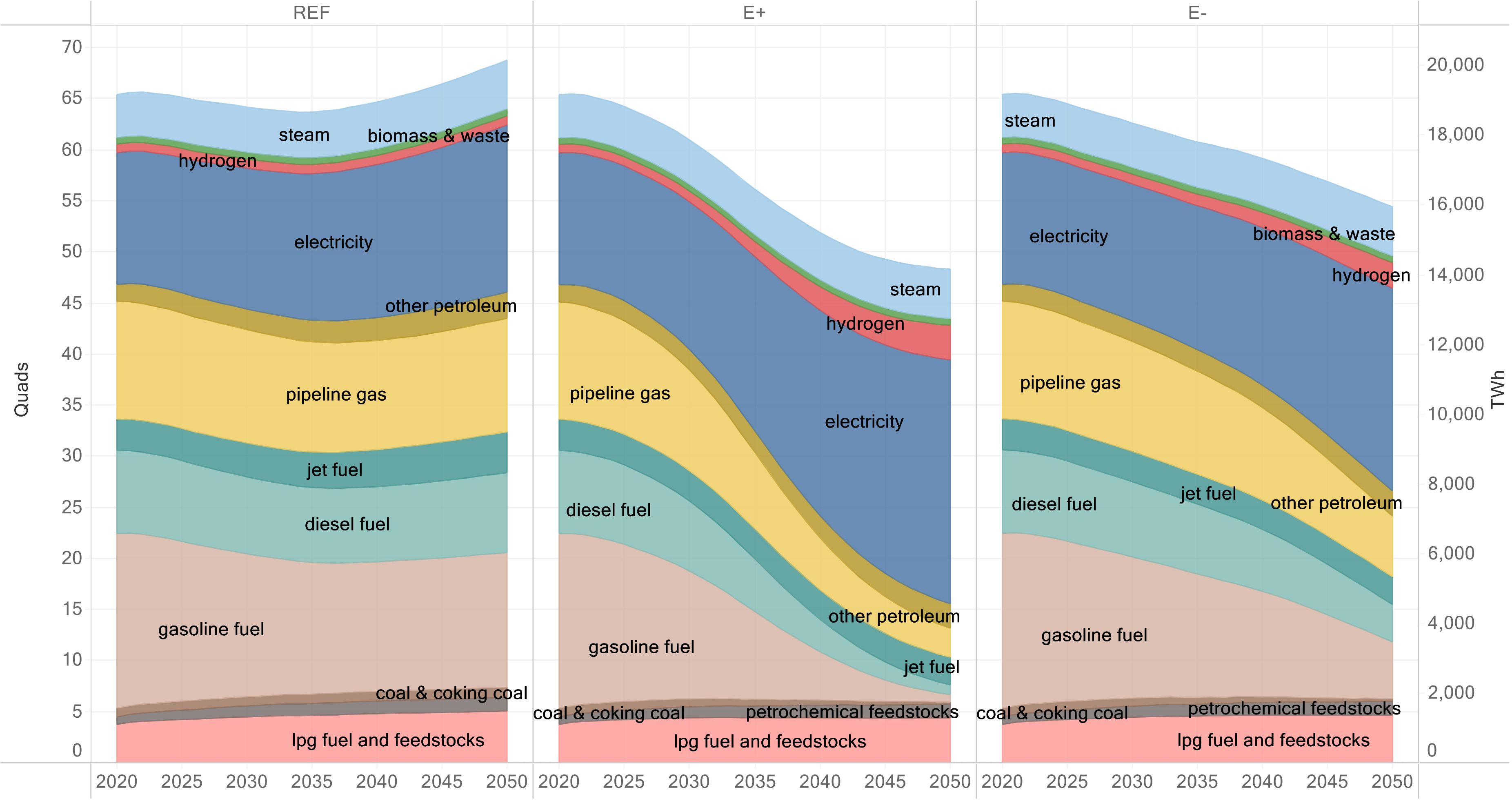
Final energy consumption by final energy grouping

Reference vs. low carbon pathways

Final energy demand in the reference scenario drops until 2035 due to vehicle fuel economy improvements and then starts to increase again over the following 15 years as service demand grows.

By contrast, the high electrification scenario (E+) shows sharp declines in all petroleum fuels and pipeline gas due to electrification of transportation and buildings, and to a lesser extent industry. Electricity grows significantly as a final energy demand, but overall final energy still declines by a quarter due to the higher efficiency of electric vehicles and heat pumps. By 2050 16 quads of residual hydrocarbon fuel demand exists and 32 quads of electricity, hydrogen, and steam demand.

The less-high electrification scenario (E-) shows similar trends to the high electrification scenario, simply less pronounced.



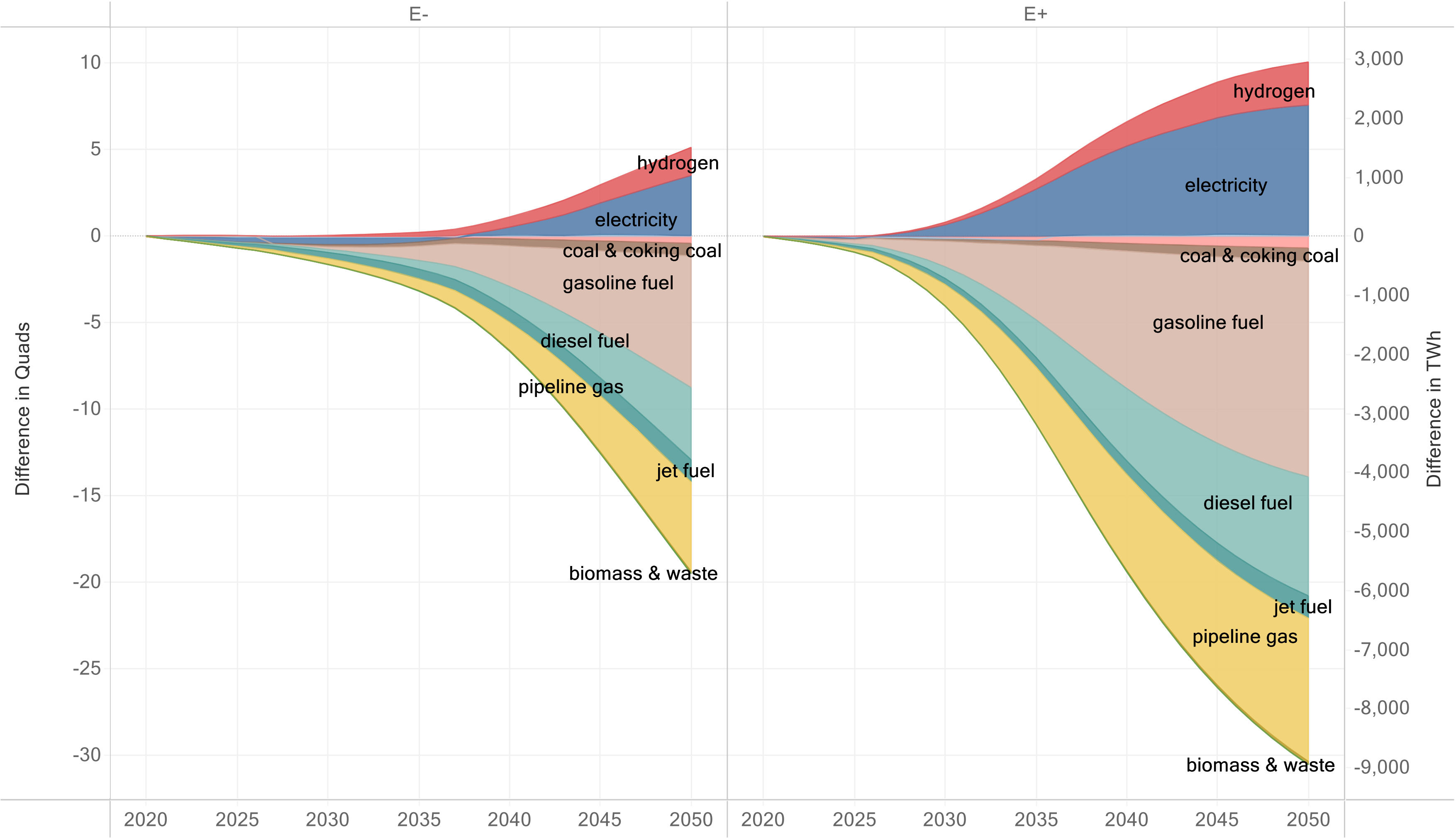
Excludes fossil extraction and refining

Difference in final energy demand compared to reference

Examining the difference in final energy demand from the reference case, the trends become more pronounced. Gasoline and diesel decrease due to adoption of electric and fuel cell vehicles, which are responsible for most of the increase in electricity and hydrogen demand. Pipeline gas decreases due to adoption of heat pumps. LPG (pink) and coal decrease within industry due to a combination of efficiency and fuel switching. Decreases in jet fuel consumption are due to efficiency.

In the E- scenario, electricity consumption is actually below that in the reference case until 2037. This is due to high levels of same-fuel efficiency. Then post 2037, efficiency gains have mostly been achieved and rates of electrification have begun to increase.

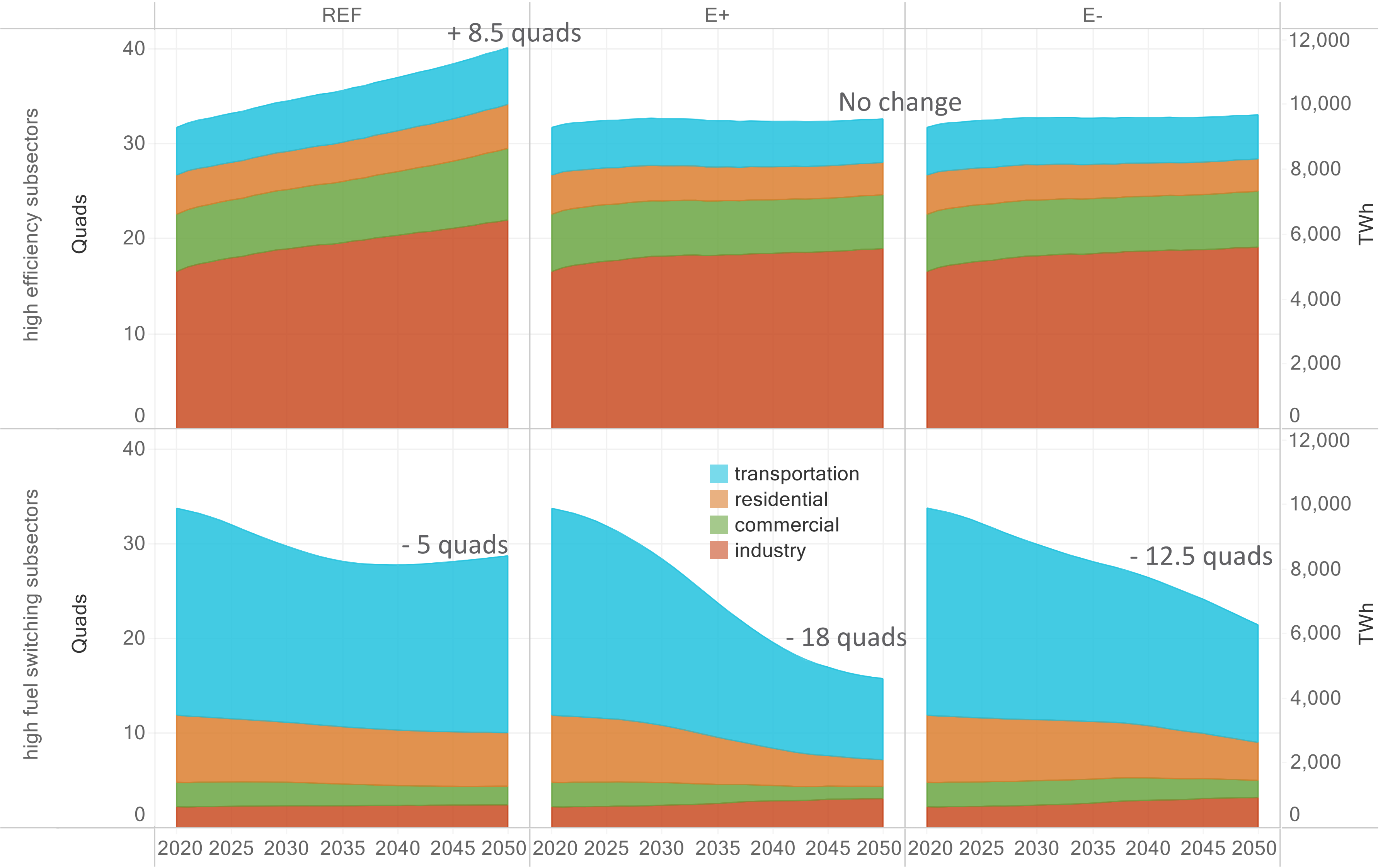
The E+ scenario shows the fastest growth of electricity in the 2030s. After 2045, most electrification measures have been achieved, and the growth of electricity slows.



The role of efficiency vs. fuel switching

Subsectors on the demand-side can be separated into those where the primary mechanism of transformation is higher energy efficiency vs. those where the primary mechanism is fuel switching. Subsectors where energy efficiency plays the largest role is most of industry, non-heat applications in buildings, and most off-road transportation (e.g. aviation). Subsectors where fuel switching plays the largest role are heating applications in buildings, on-road transport, and some industry such as iron and steel or carbon capture on cement.

Both the E+ and E- scenarios receive a 8.5 quad reduction in final energy demand purely from same-fuel energy efficiency measures. The switch to electric vehicles and heat pumps greatly improves service efficiency resulting in even larger reductions in final energy demand.



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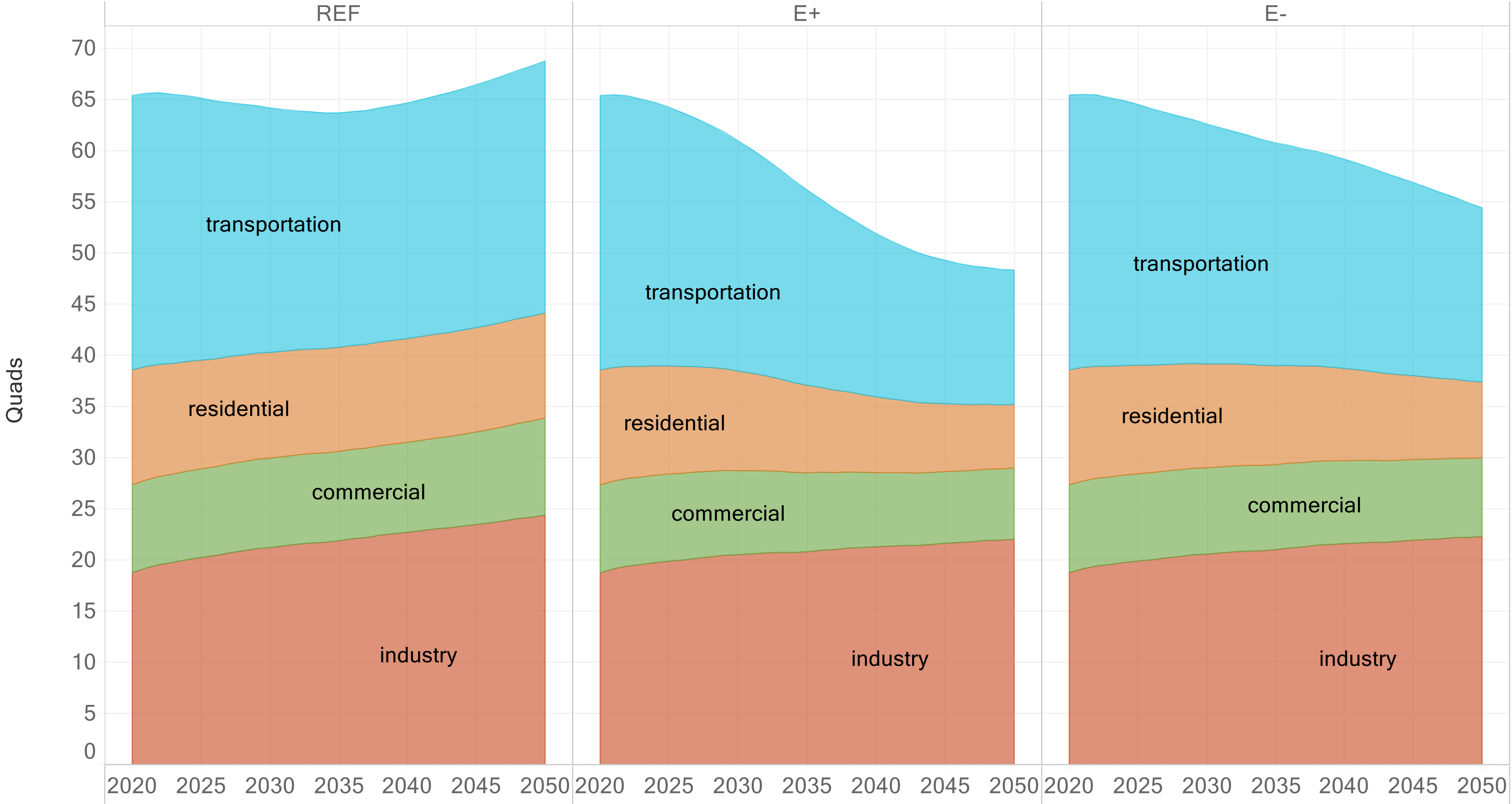
Sector by final energy

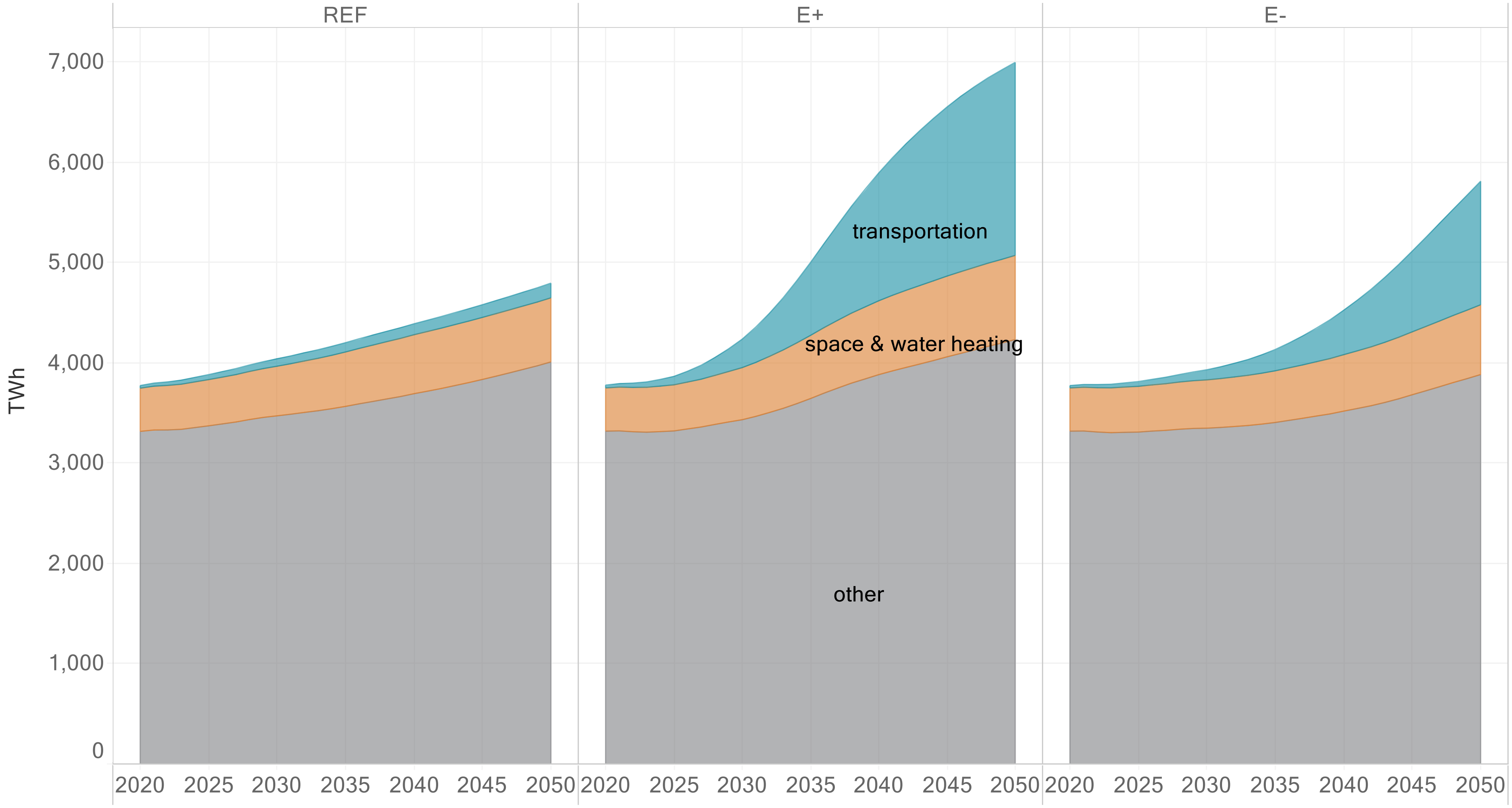
Examining final energy by sector, it's clear that most of the declines in final energy come from transportation, followed by residential buildings. This is from efficiency gains from electric vehicles and heat pumps, respectively. Commercial buildings have much smaller heating loads, so while heat-pump adoption is similarly aggressive, the overall impact on final energy is muted. Final energy to industry decreases some, mostly due to efficiency. Except for in low-temperature process heating where heat pumps can be used, most of the fuel switching measures in industry modeled do not significantly improve end-use efficiency. A large fraction of industrial final energy demand is feedstocks (natural gas, LPG, and petroleum) that make products from plastics to LPG. These feedstocks are difficult to reduce except through improved recycling or conservation, which was not considered in this work.



Electricity for heating and transport

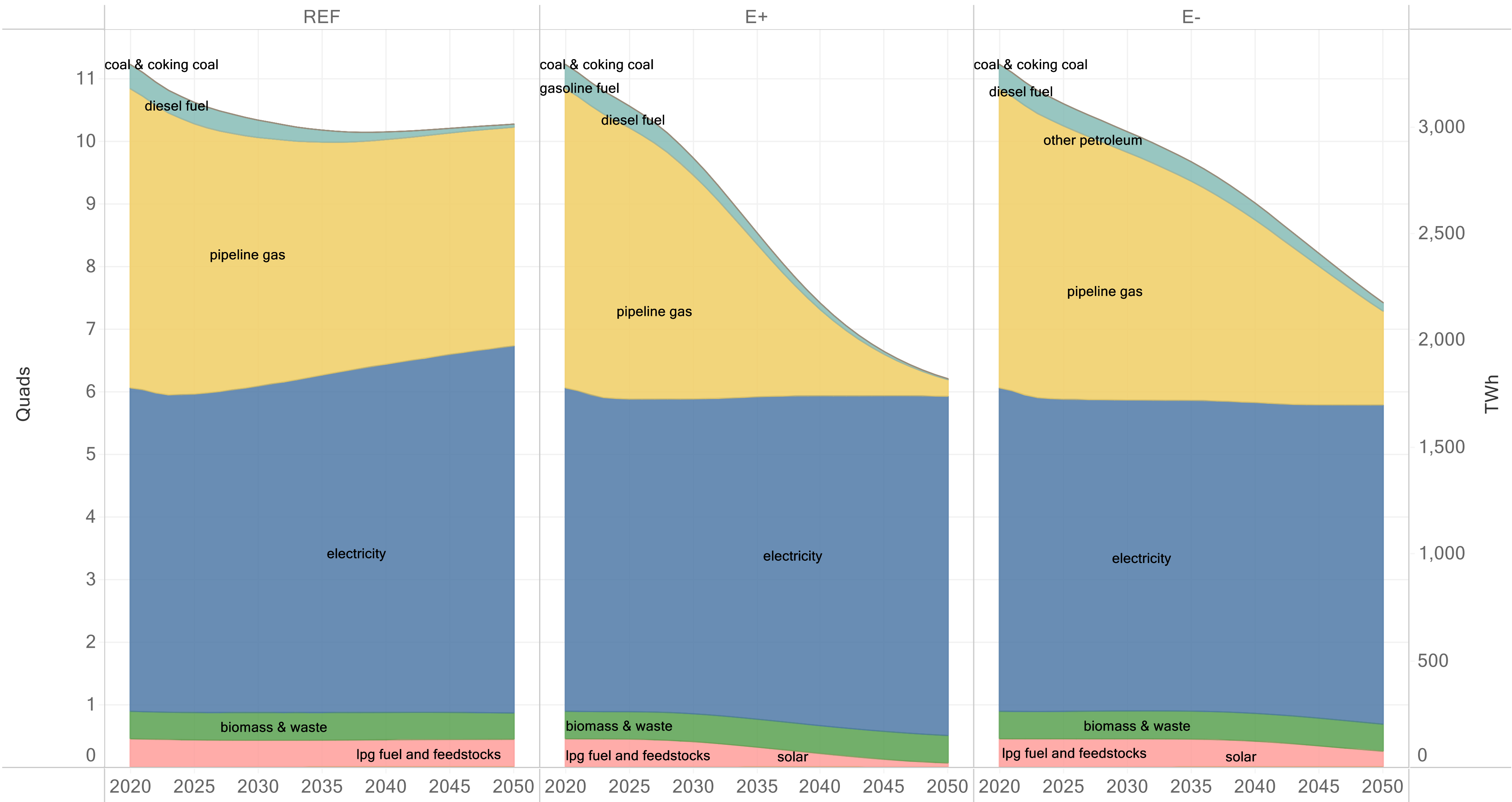
Shown here is electricity final energy demand separated into heating, transportation, and other. Transportation makes up the vast majority of the increase in electricity. Space and water heating is responsible for ~500 TWh today, and most of this is electric resistance in the form of electric furnaces and electric hot water. In the E+ and E- scenarios, these resistance heating technologies are replaced with heat pumps, which save significant amounts of energy. In fact, some regions, such has the southeast, see overall reductions in electricity for heating.

While growth in heating load is not as striking on an annual basis, this load is highly concentrated seasonally (and regionally), which can have a large impact on electricity systems in regions, such as the Northeast.



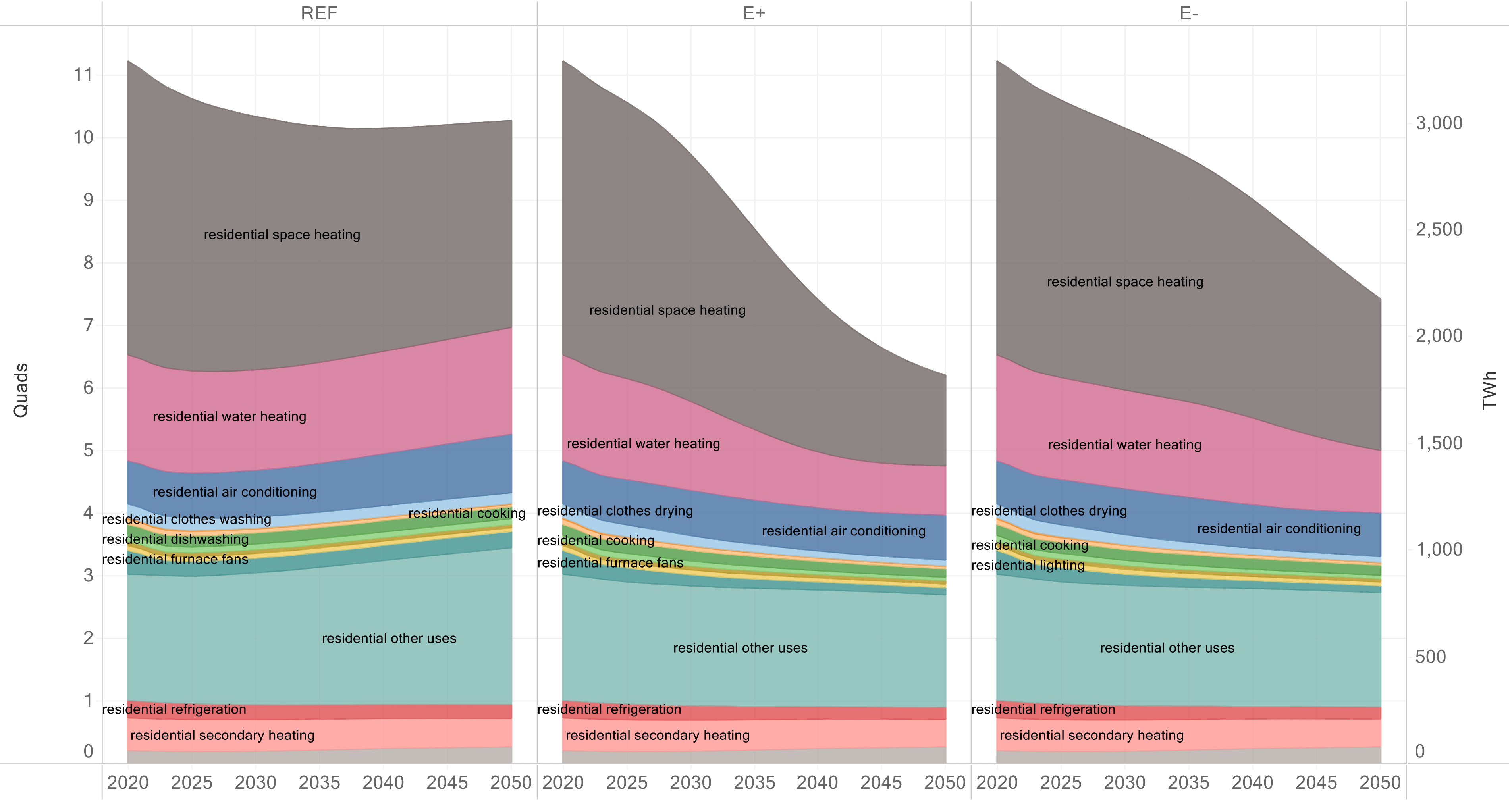
Residential buildings by final energy type

In residential buildings pipeline gas, LPG, and diesel are significantly reduced in the E+ and E- scenarios. Electricity use grows but is lower than in the reference case due to efficiency. Note that this does not include the impact of home vehicle charging, which increases residential building loads significantly.



Residential buildings by subsector

Space heating is the largest consumer of energy in residential buildings today with water heating another significant energy consumer. Building shell improvements combine with heat pump adoption to reduce space heating demand significantly and reduce air conditioning demands. Residential other uses is a category defined within the annual energy outlook that includes a large number of miscellaneous building and plug loads, most of which are electric and are reduced through improvements in energy efficiency.



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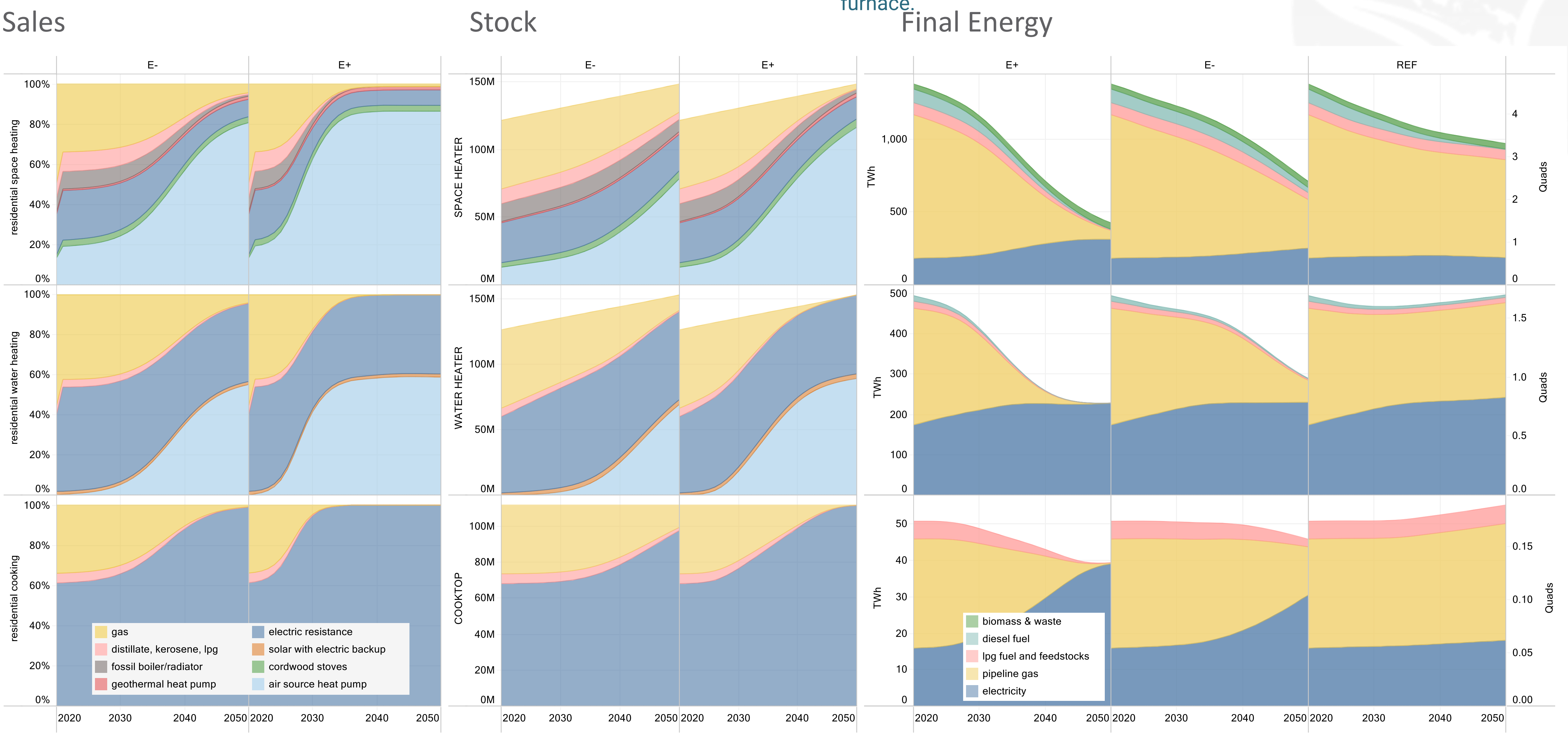
Key residential building subsectors

The following panels show sales shares, stock, and final energy demand for E+ and E- scenarios. Assumptions regarding adoption of different heating technologies vary by climate zone with colder climates less likely to adopt heat pump hot water heaters and slower to adopt a heat pump to replace a natural gas furnace.



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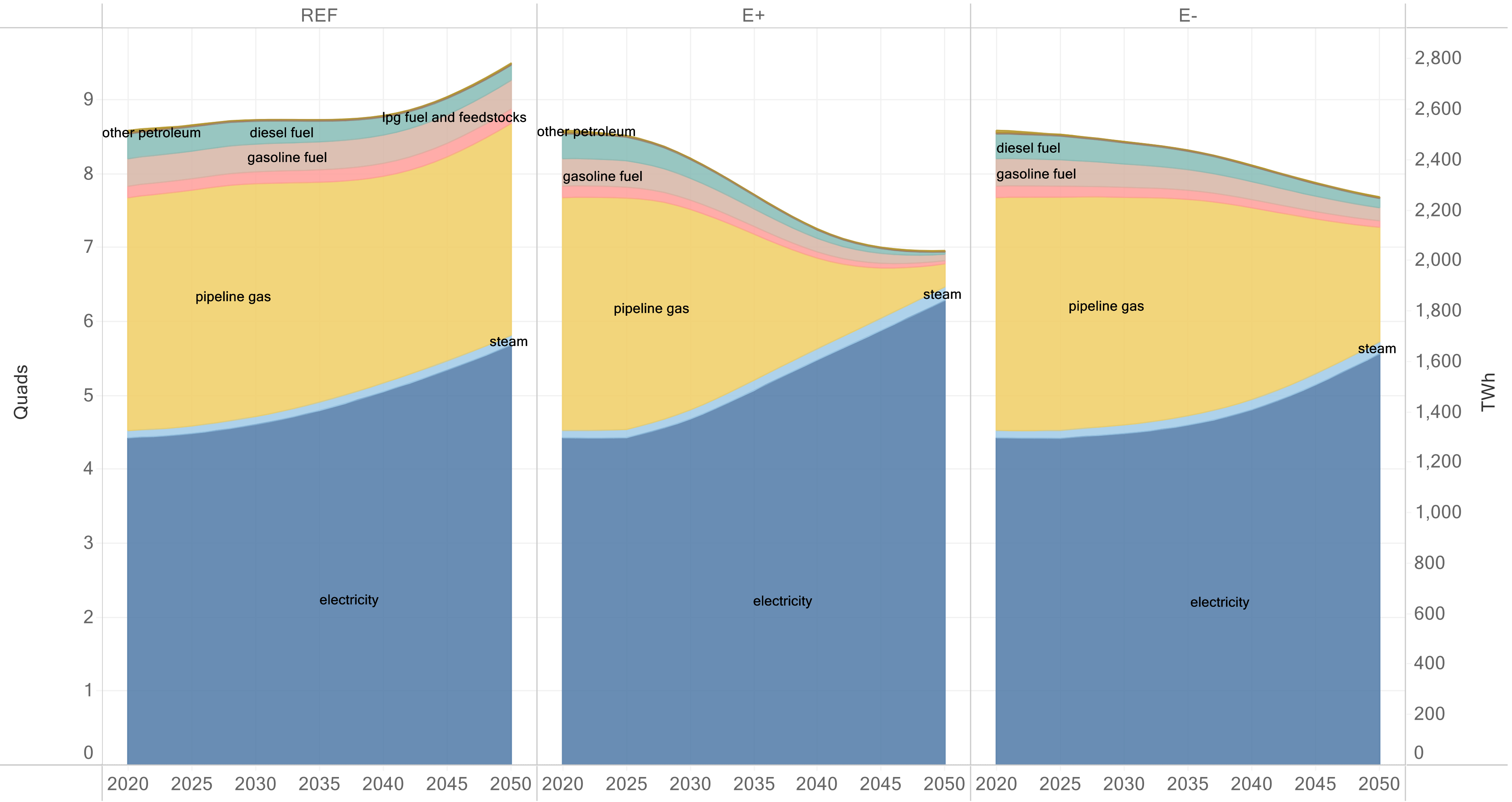
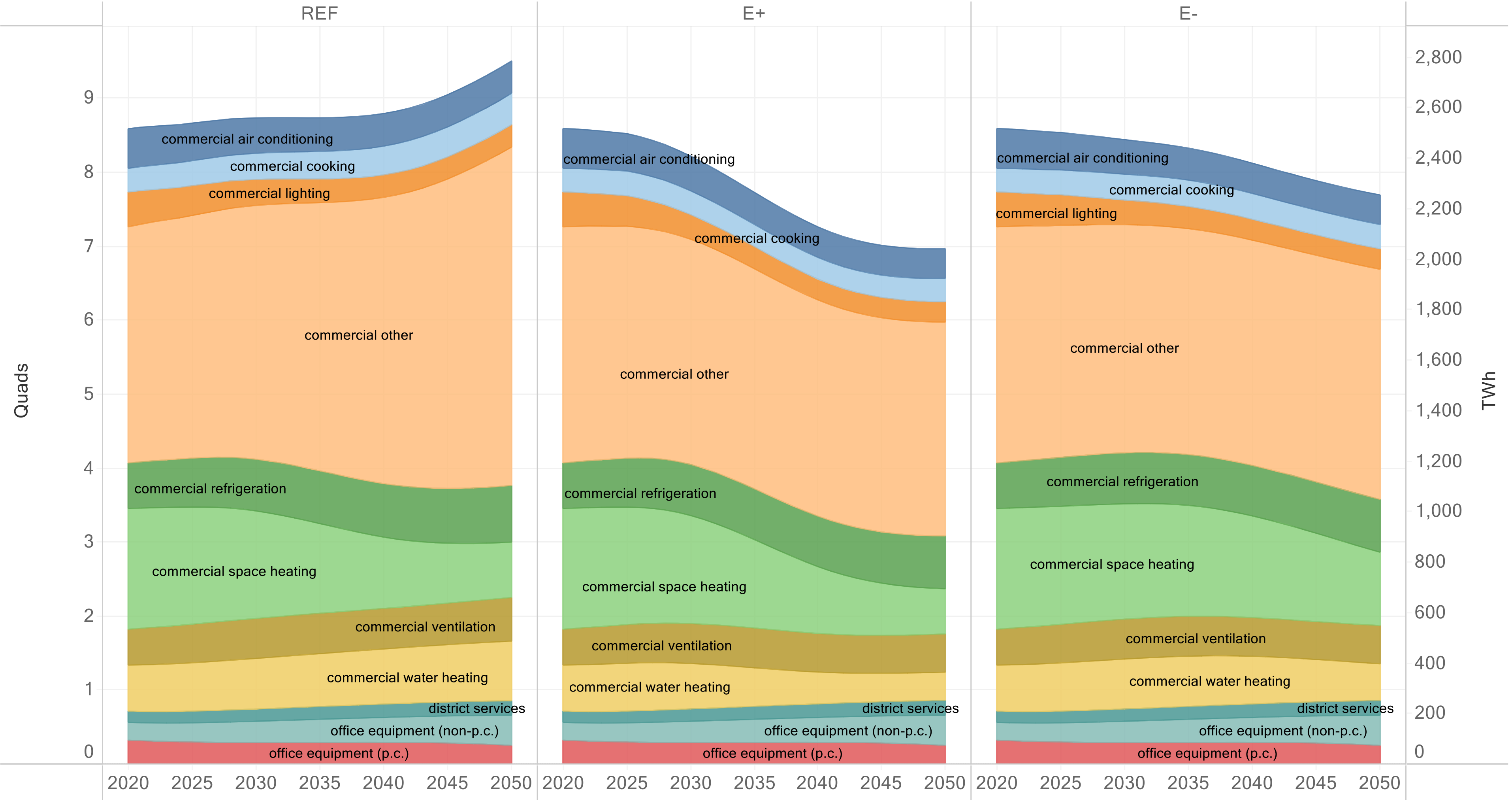
Commercial buildings by final energy type

The actions taken in commercial buildings are similar to those taken in residential buildings, namely adoption of efficient and electric technologies; however, differences in service demand result in slightly different final energy demand patterns.



Commercial buildings by subsector

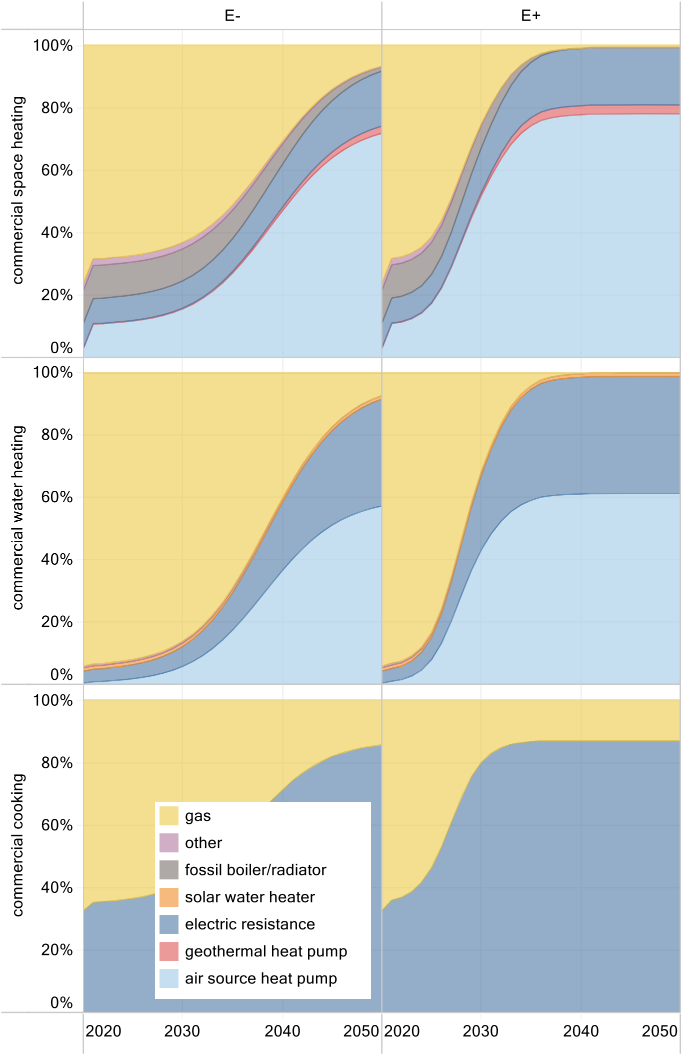
In commercial buildings space heating demand is far lower than in residential buildings. By contrast new subsectors such as refrigeration, ventilation, and electric plug loads are of greater importance and are key areas for efficiency improvements.



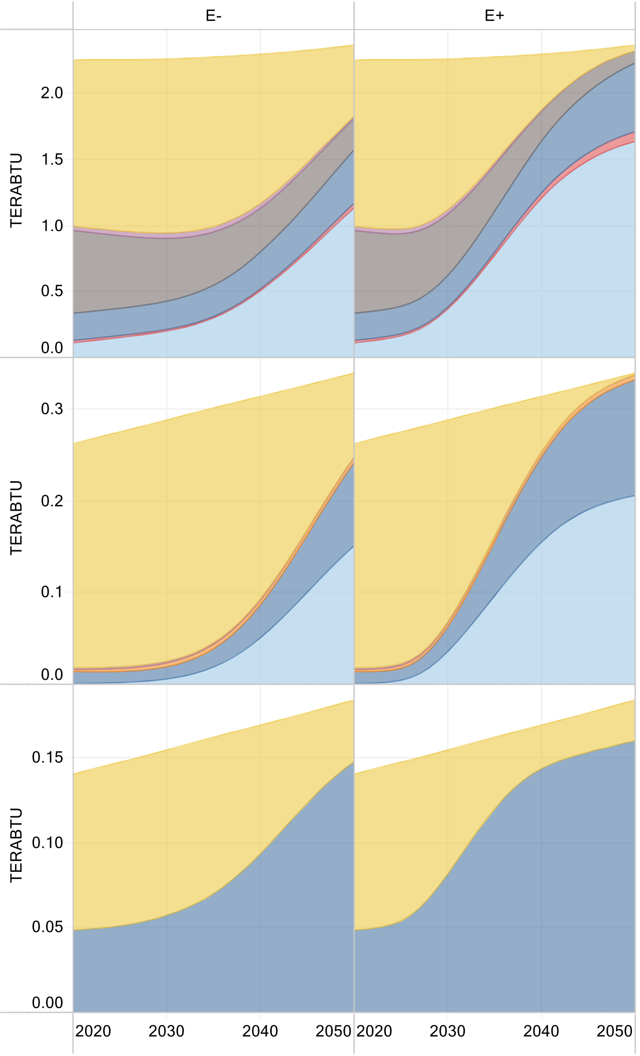
Key commercial building subsectors

Sales, stock, and final energy is shown for commercial space heating, water heating, and cooking.

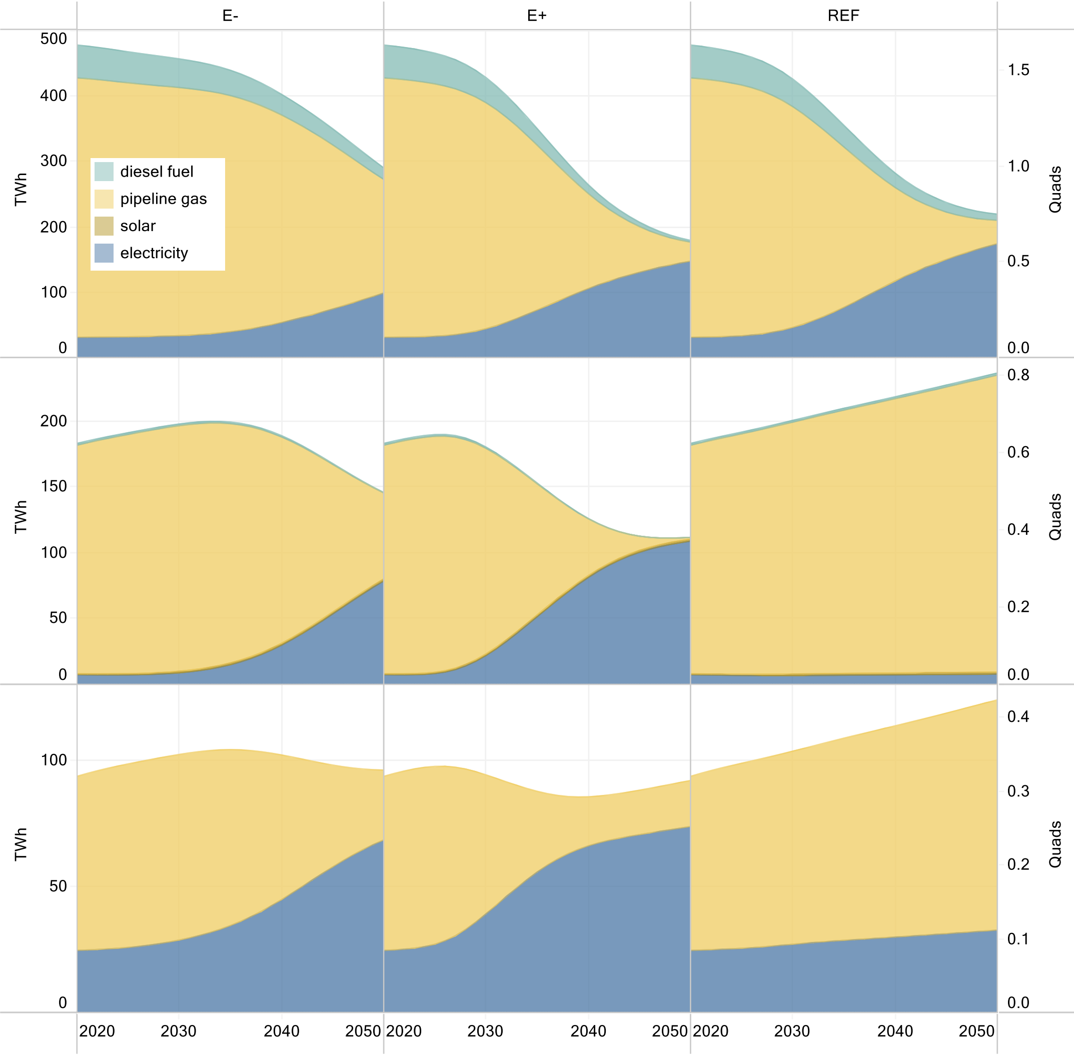
Sales



Stock



Final Energy



Transportation by final energy type

The largest sector today in terms of final energy demand, transportation is where most petroleum fuels are used within the economy. Large declines in fuel use can be seen in the reference case due to CAFE standards. The rapid electrification scenario reduces diesel and gasoline to small fractions of their 2020 highs. The E- scenario shows a more nuanced trend with CAFE mattering in the near term and electrification impacts beginning to be notable after 2035.

We assume battery electric vehicles dominate the transition in the light duty sectors with fuel cell vehicles playing a larger role in medium- and heavy-duty vehicles.

Jet fuel use in the reference case steadily increases through 2050. In the E+ and E- scenarios, assumed efficiency improvements of 1.5% per year result in a flattening and then decline in jet fuel use.

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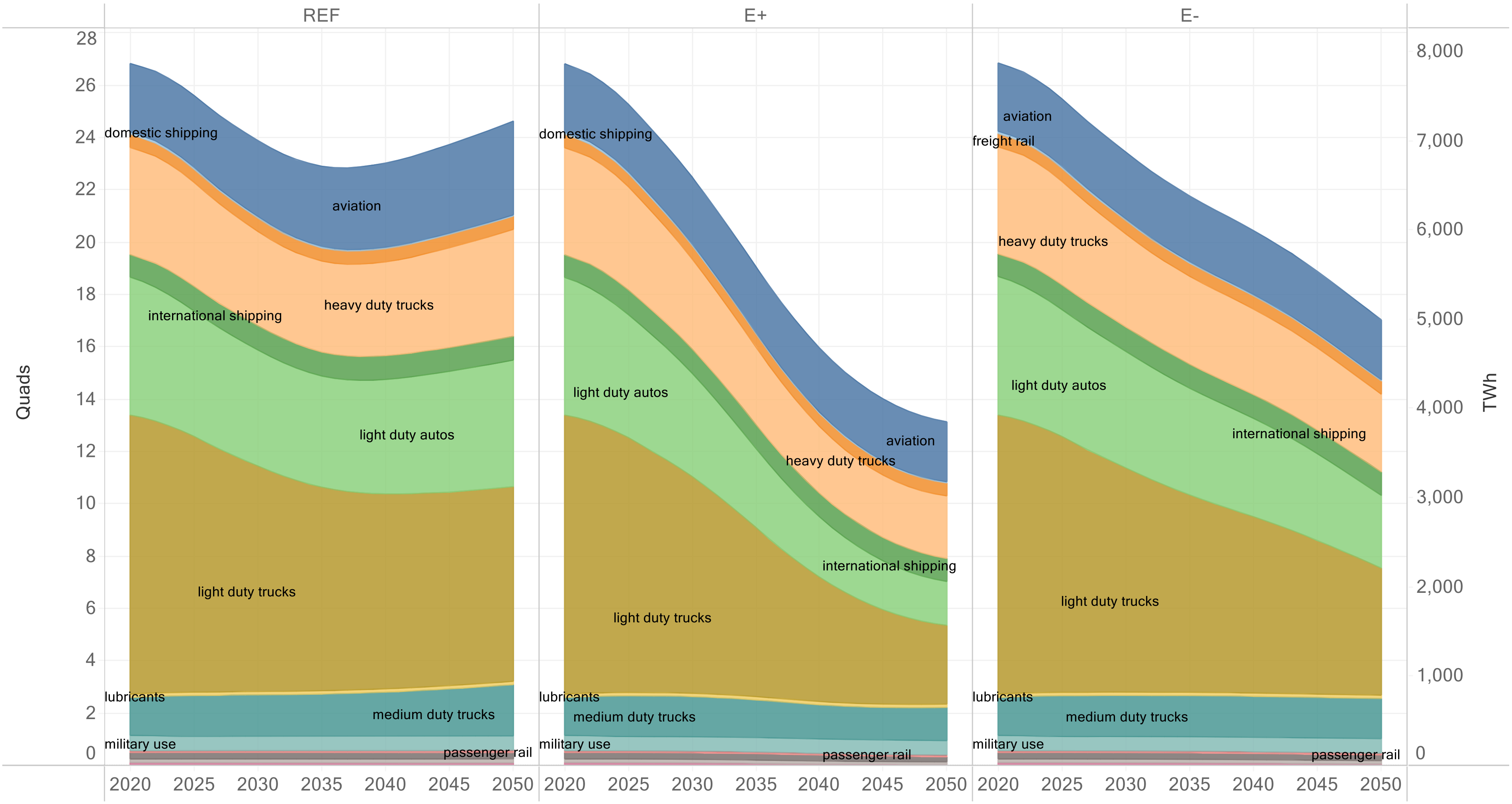
Transportation by subsector

A breakdown of final energy by transportation subsector is shown and highlights the importance of on-road transportation. Aviation, shipping, and military use make up most of the remainder. In our analysis, military use was kept constant between each scenario.

The AEO reference case projects increased use of natural gas in ships. We continue this trend in the E+ and E- scenarios, but also assume a growing fraction of hydrogen as well.



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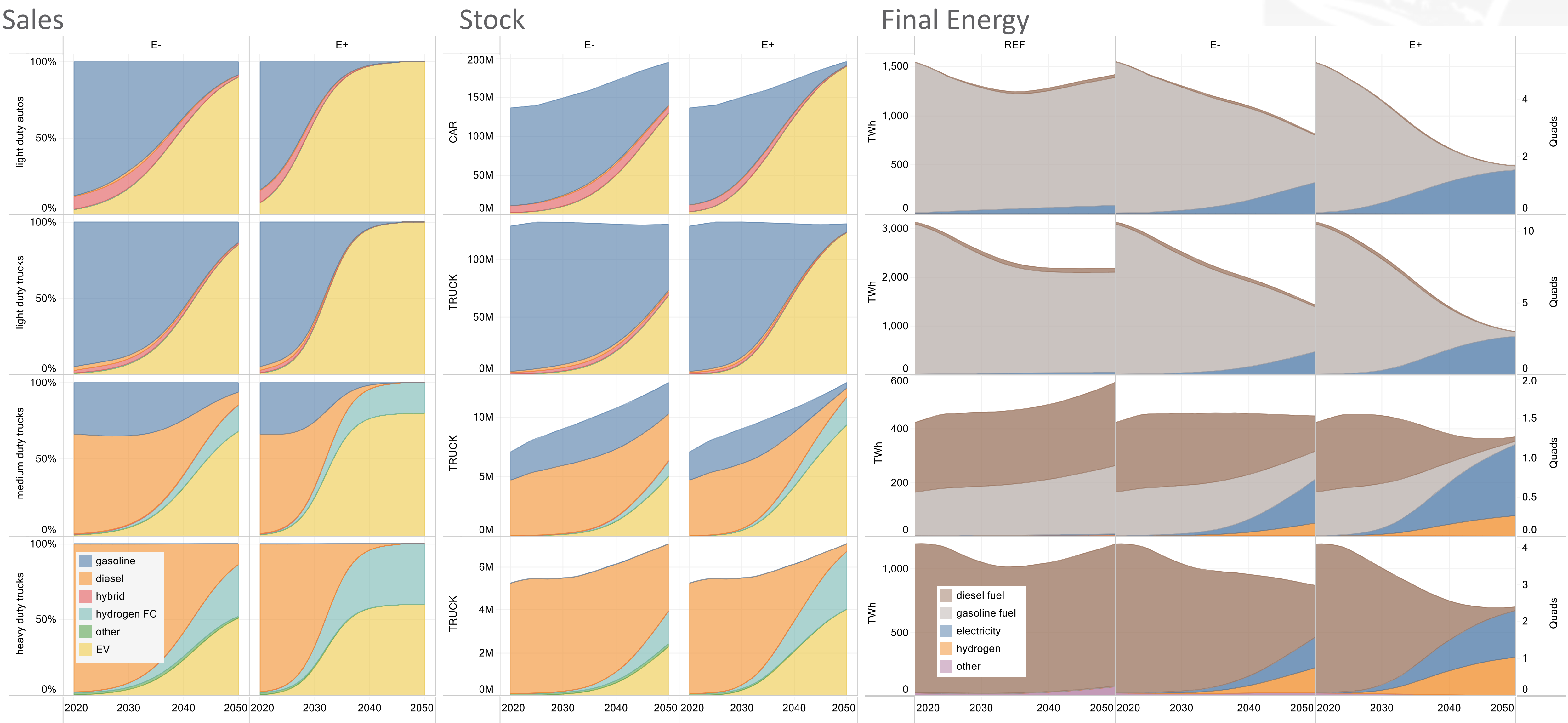
Key transportation subsectors

Sales, stock, and final energy is shown for on-road transportation subsectors light-duty autos, light-duty trucks, medium-duty trucks, and heavy-duty trucks.



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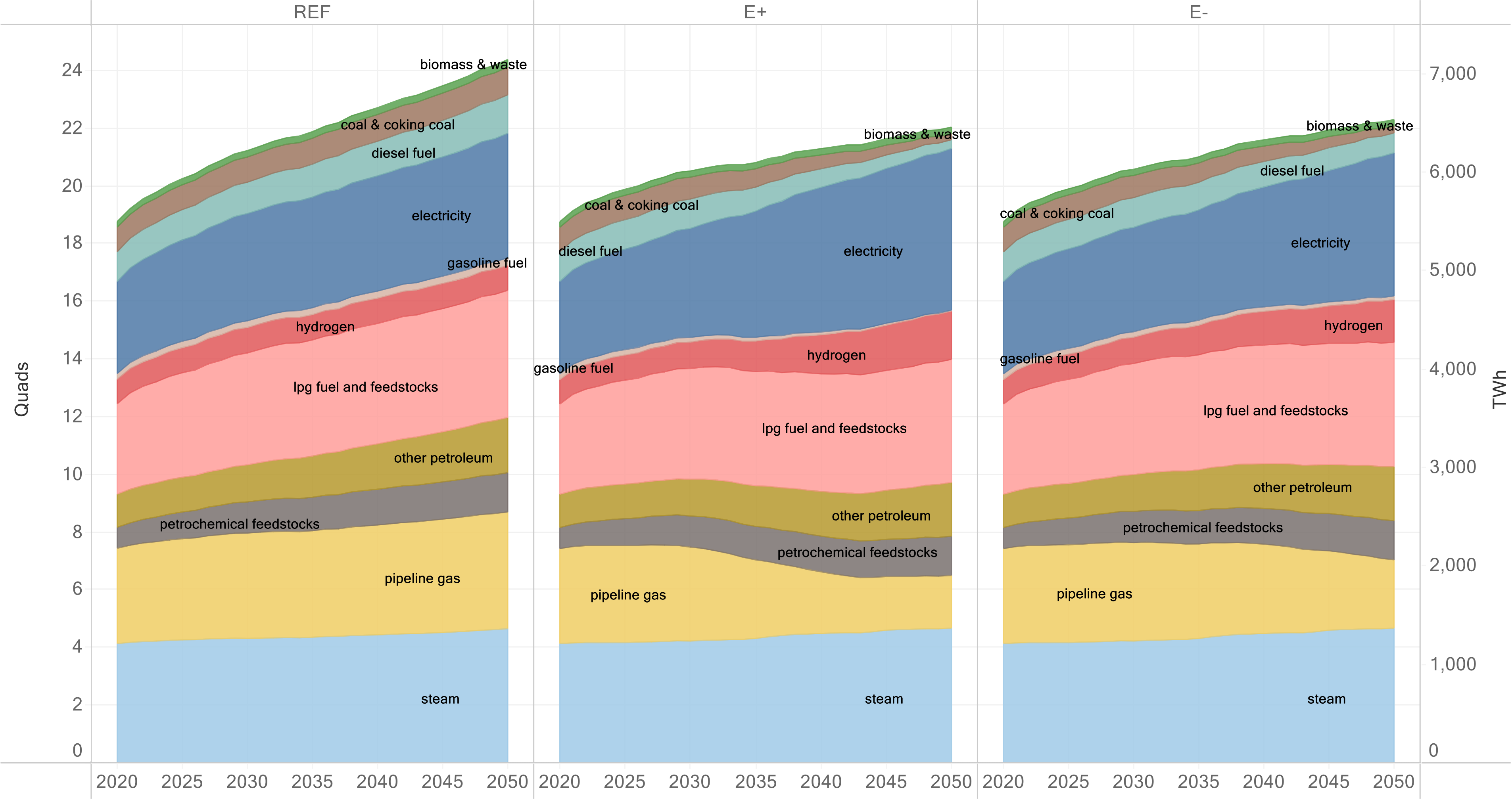
Industry by final energy type

Industry consumes a diverse set of fuel types. To improve our ability to model deep reductions in carbon emissions, several key methodological steps were taken in industry to reflect sequestration and decarbonization opportunities.

1. We decomposed steam from the underlying fuel used to make the steam so that the RIO model could better optimize production of steam using creative strategies, such as dual-fuel electric boilers that complement high wind and solar systems.
2. We decomposed hydrogen demand from overall natural gas feedstock to allow RIO more flexibility on how the hydrogen is supplied.
3. All feedstocks are included in the analysis, not just the fraction that is 'combusted.' This allows an additional pathway for biogenic sequestration in products that is distinct from geologic storage.



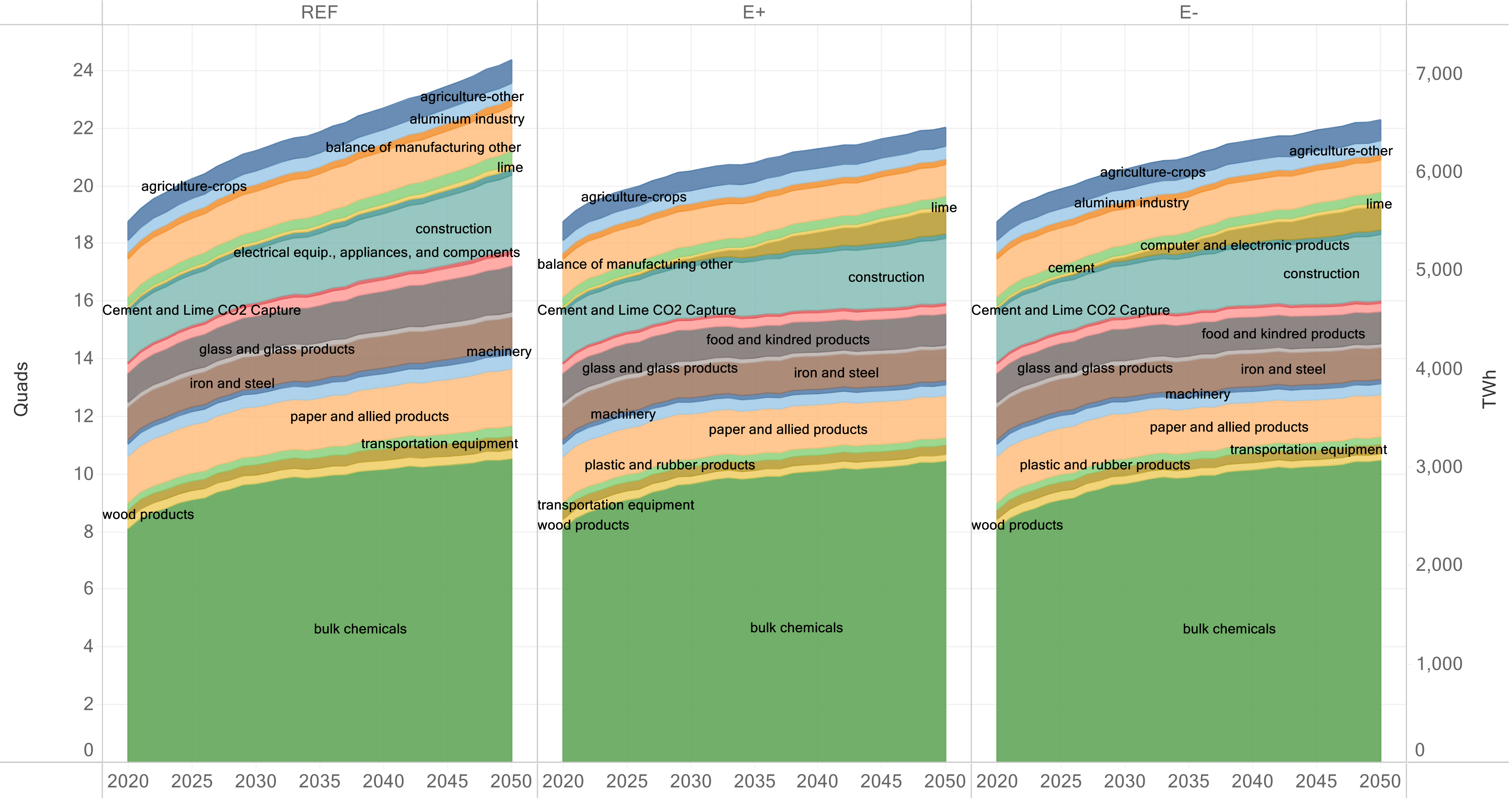
Excludes fossil extraction and refining

Industry by subsector

The bulk chemical subsector is by far the largest final energy demand consumer. From there, paper, iron and steel, food, construction, and agriculture are each of next greatest importance.

In iron and steel we assume adoption of direct reduced iron technologies, which make use of hydrogen rather than hydrocarbons. For cement and lime, we assume carbon capture is deployed and captures both process and energy related emissions. Process heating is a component of many subsectors and we assumed some direct electrification in low temperature applications informed by NREL's Electrification Futures Study.

For most other subsectors the dominant strategy deployed for decarbonization was assumed to be efficiency improvements.



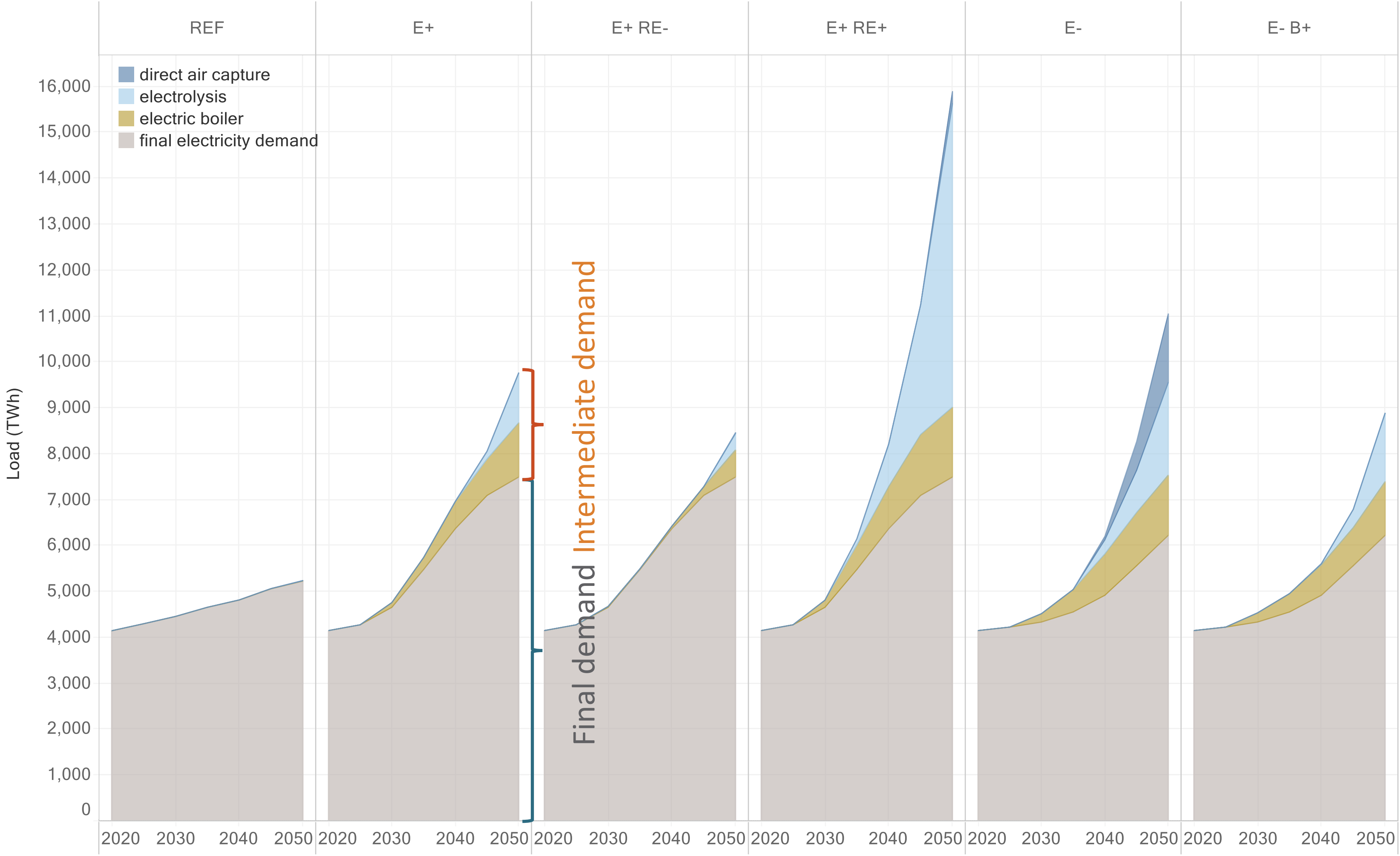
Excludes fossil extraction and refining

Electricity details

Total electricity load including indirect supply-side loads

EnergyPATHWAYS calculates final electricity demand in grey. The direct air capture, electrolysis, and electric boiler loads are all optimized within RIO and change, sometimes dramatically, as a function of additional constraints placed on each scenario. All scenarios aside from reference reach the 2050 emissions target of negative 170 MMT CO2.

At lower amounts of biomass, lower electrification paradoxically leads to higher levels of electricity load due to increased intermediate electricity demands to decarbonize fuels.



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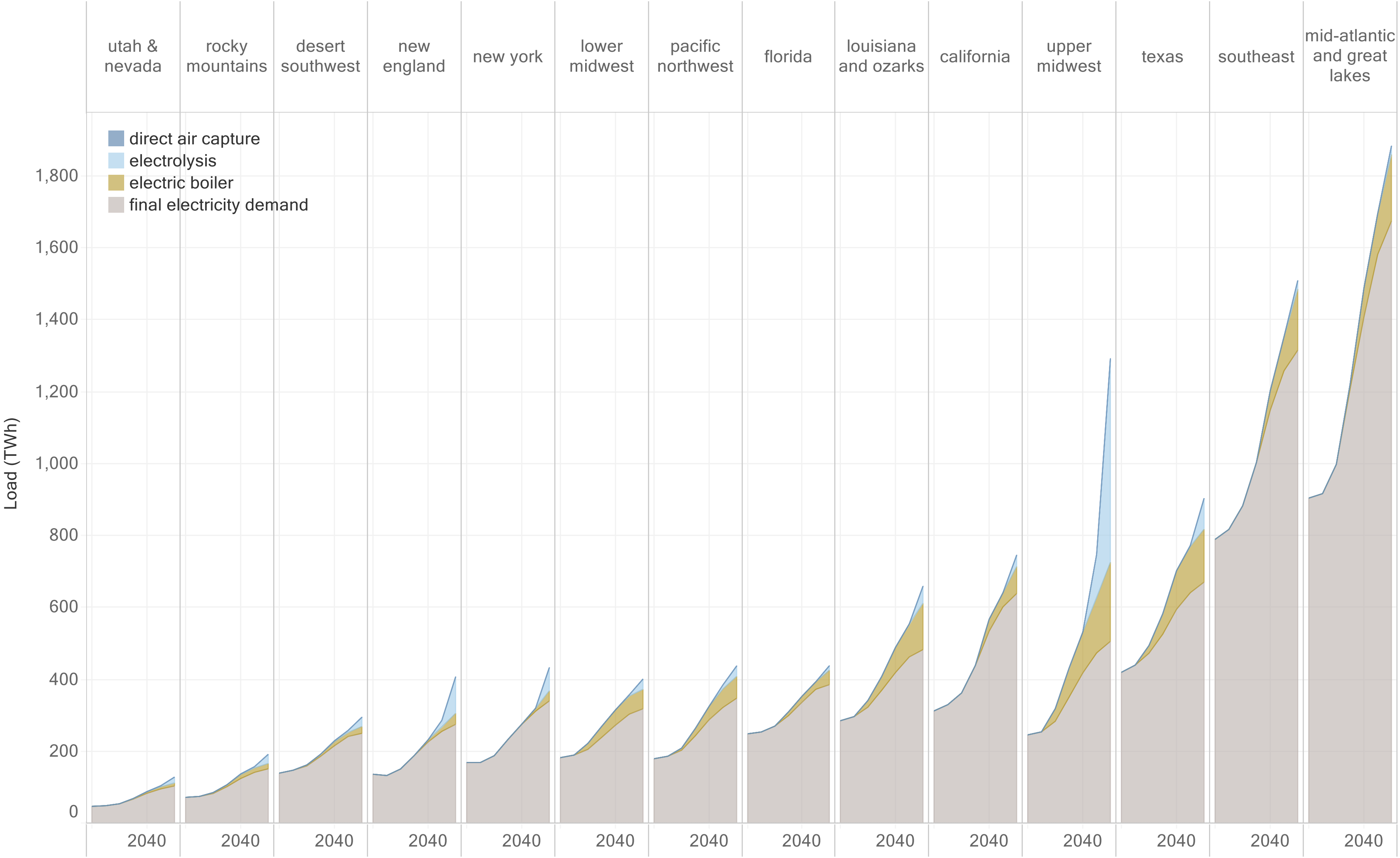
Total electricity load by region for the E+ scenario

Focusing on the E+ scenario, load across regions is shown. The location of electric boilers is dictated, in part, by regional demand for steam and in part the relative economics of generation supply in each region.

The differences in electricity supply economics are more apparent when examining electrolysis for hydrogen production. Hydrogen has two broad uses in these energy systems, either as a direct final energy demand or as an input to other fuels or conversion processes (e.g. Fischer Tropsch). A small amount of electrolysis is apparent in every region for several reasons: (1) every region has final energy demand for hydrogen for trucks and other uses (2) all regions reach relatively high penetrations of renewables, which present opportunities to deploy hydrogen to capture overgeneration.

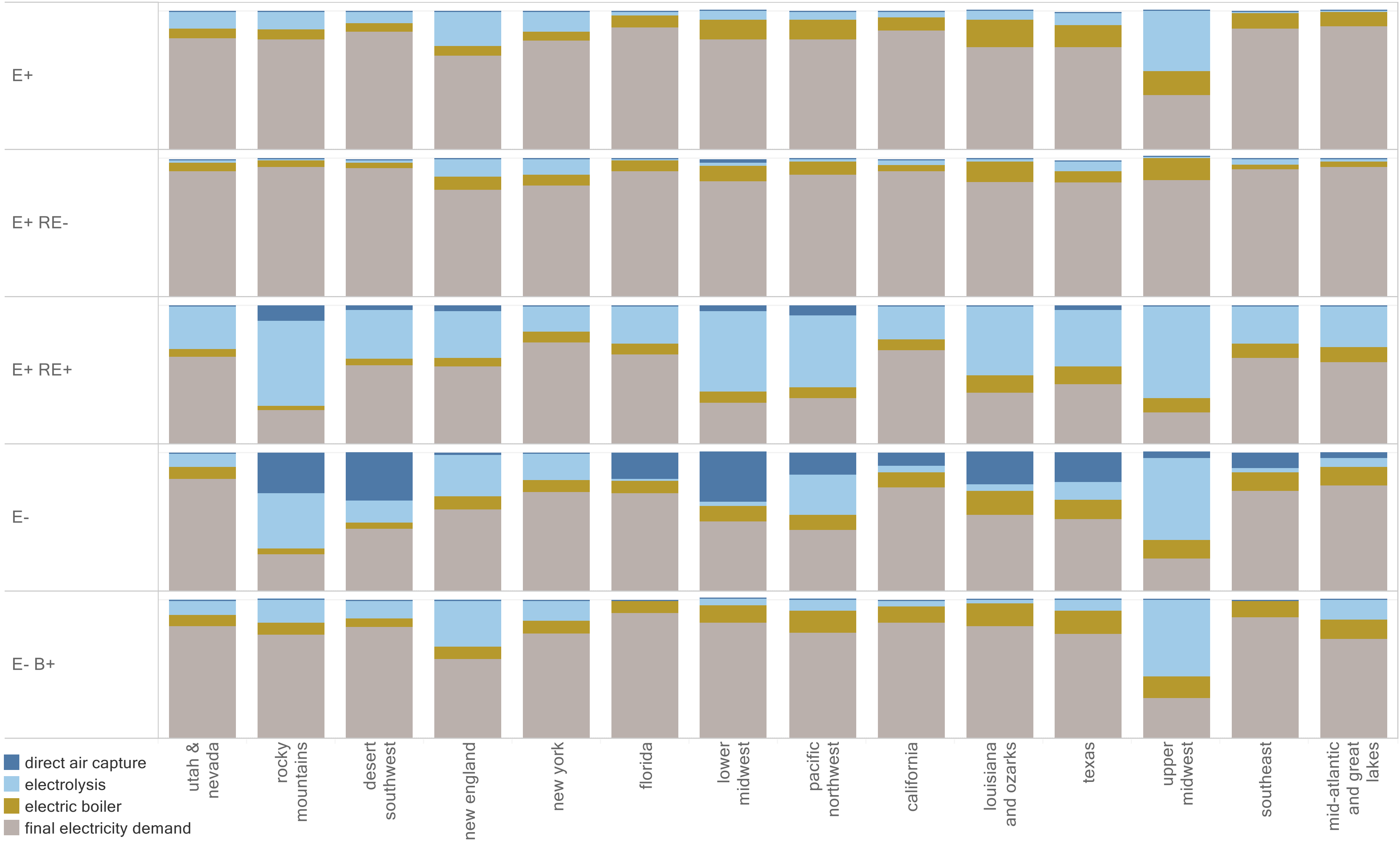
In the E+ scenario hydrogen production becomes significant in the upper Midwest due to excellent wind and sources of CO2 that can be used to synthesize fuels for export to other regions.



2050 Electricity load shares by region and scenario

Looking at the year 2050 across scenarios and regions, an even more complex story emerges. Moving down the rows from the E+ scenario shown on the prior slide, the E+ RE- scenario and E+ RE+ scenario create bookends for use of electrolysis. The E+ RE+ scenario demand for hydrogen is large due to the need to synthesize a large volume of hydrocarbon fuels that are still needed on the demand-side and which biomass alone cannot provide. Contrasting the E+ RE- and E+ RE+ scenarios, another observation is that electric boilers are prioritized over electrolysis, in this case because hydrogen production has more competitive alternative pathways than do boilers.

The E- scenario shows significant direct air capture loads in different regions of the country, either to sequester the carbon or use it for fuels synthesis. In the high biomass sensitivity, this carbon can be sourced biogenically.



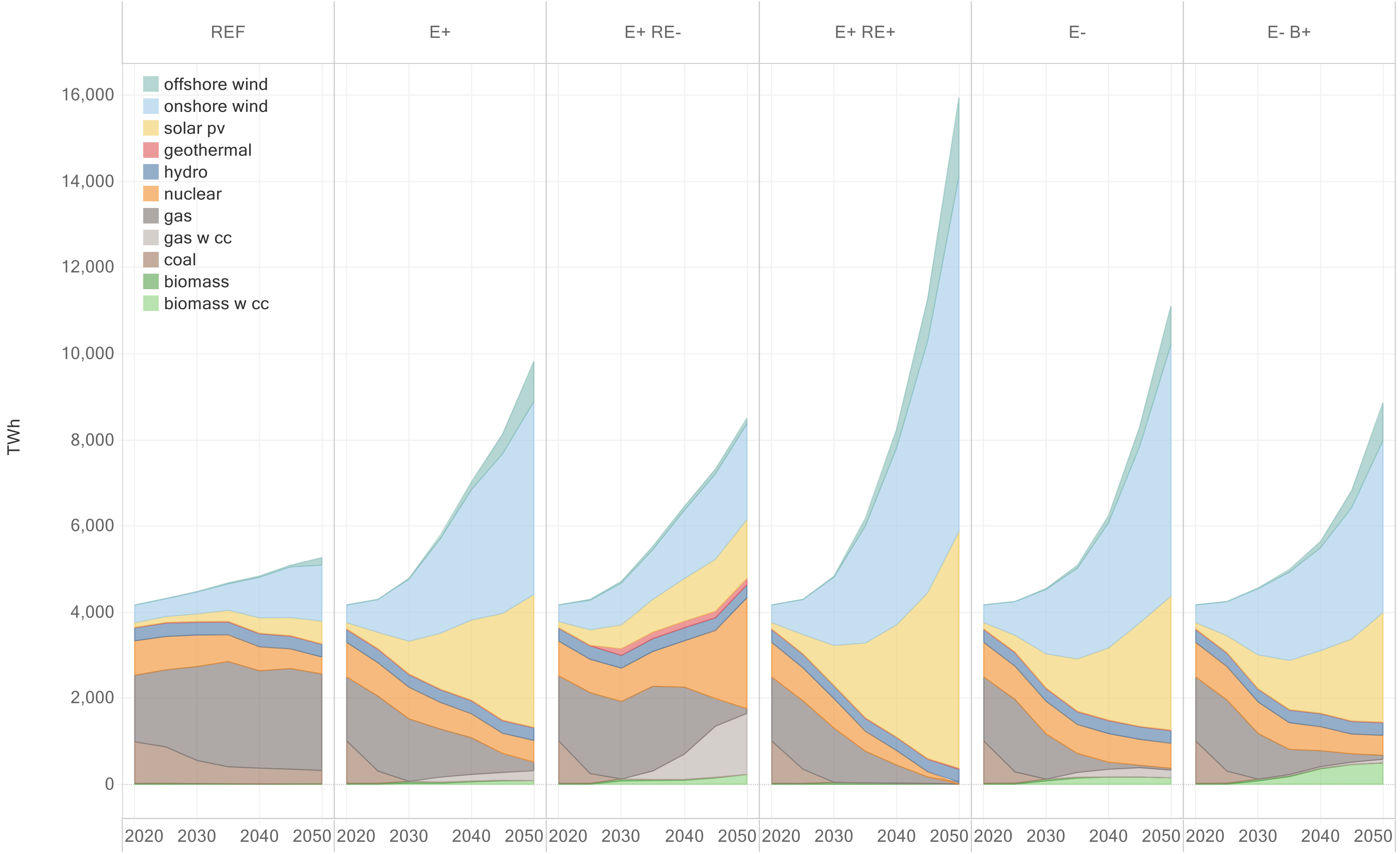
Electricity generation by year

Electricity generation is characterized by high levels of wind and solar in all the deep decarbonization scenarios with the one exception being the E+ RE- scenario where installation rates are constrained to today's level. In this scenario, significant new nuclear and gas with carbon capture (Allam cycle) are necessary.

Coal retirements occur by 2030 for all decarbonization scenarios.

Every scenario except for E+ RE+ shows at least some deployment of new nuclear and technologies with carbon capture; however, most are deployed after 2035 and are not essential components except when renewables are constrained.

The split between wind and solar is roughly 60-40 with wind benefiting from higher capacity factors and generation during nighttime hours and solar benefiting from widespread potential, daytime production, and less day-to-day variability.



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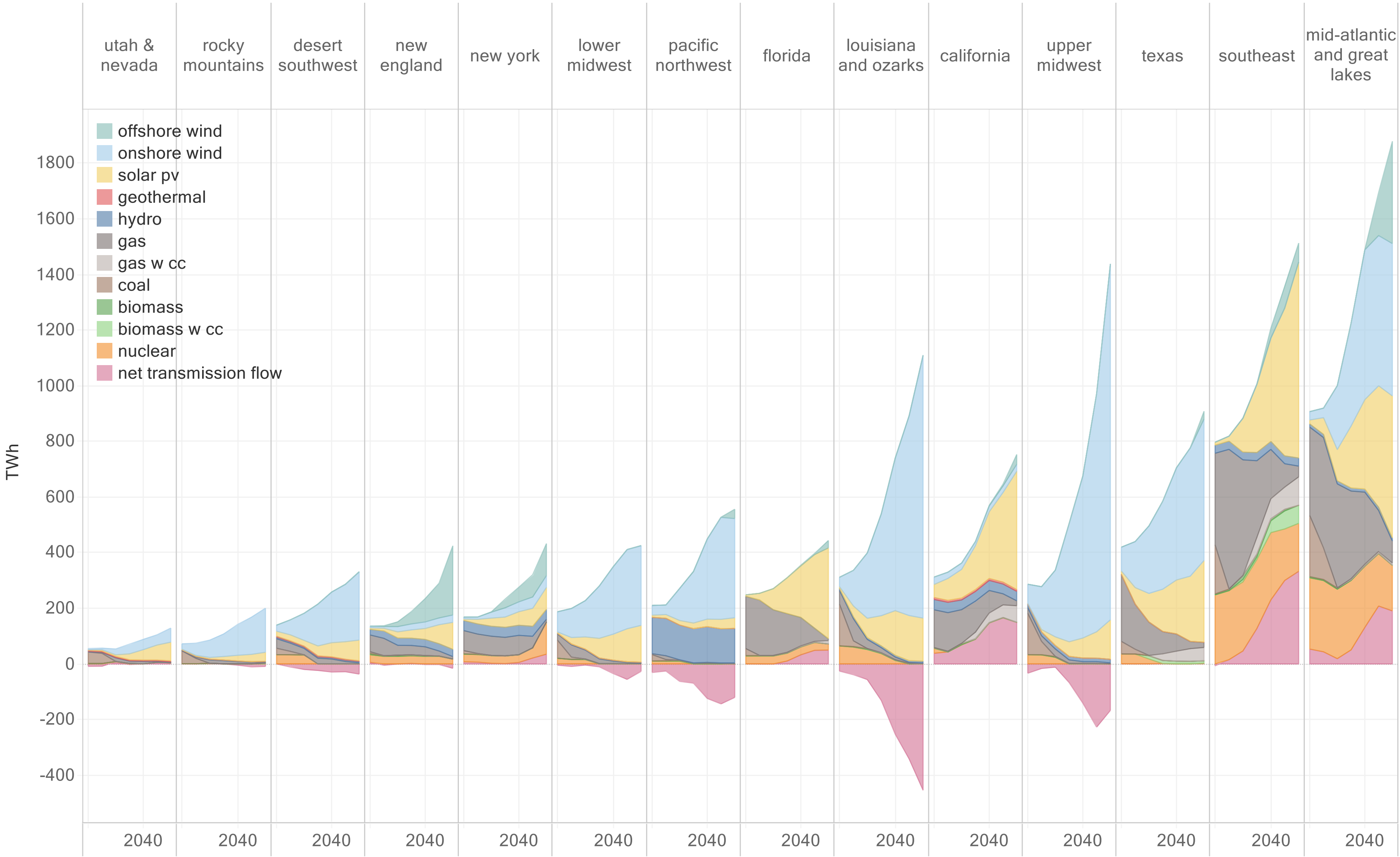
Electricity generation by region in the E+ scenario

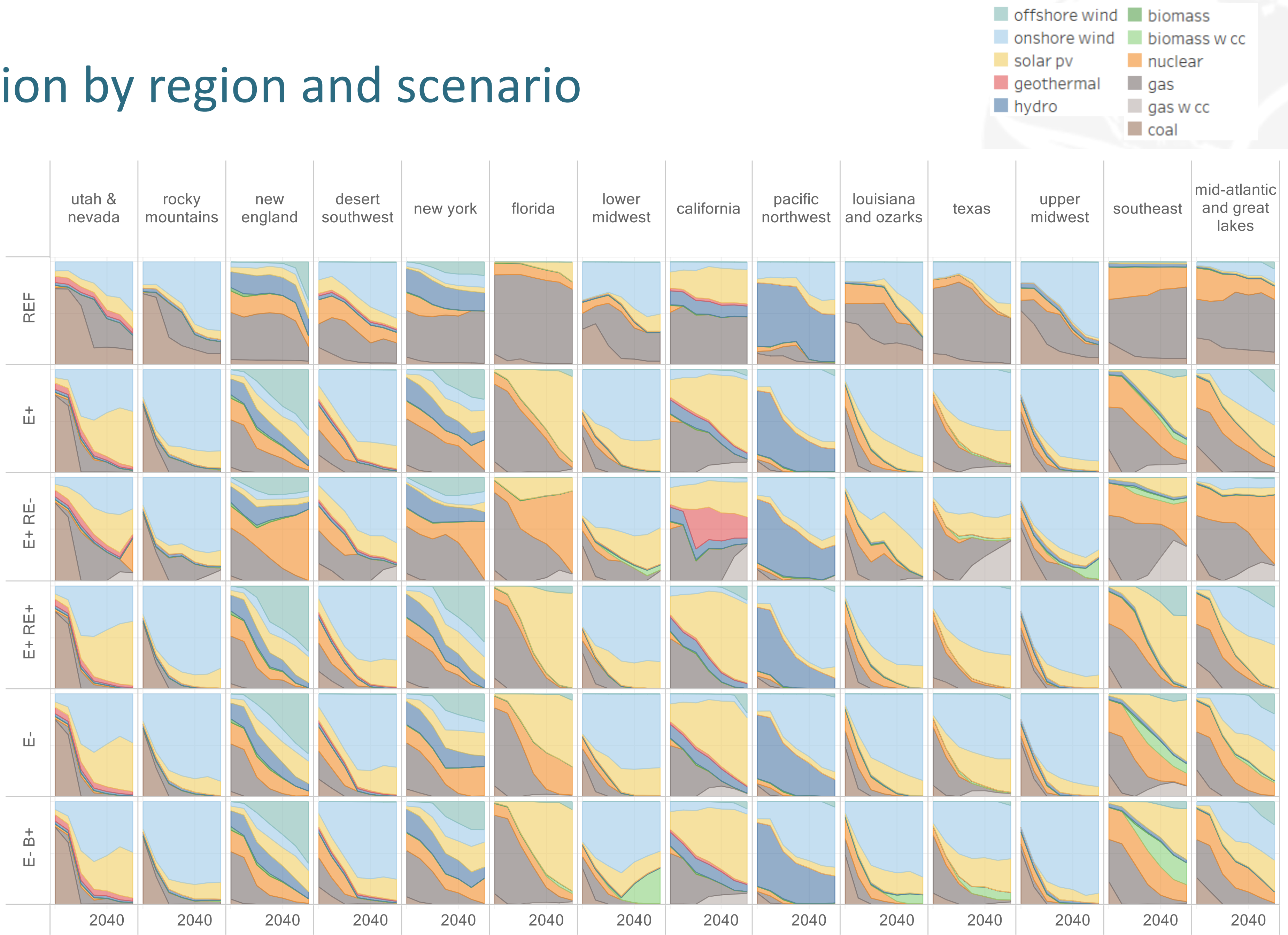
The regional stories are more varied than the national picture first reveals. Locations with good wind resources (e.g. Midwest, Rocky Mountains, Pacific Northwest) meet a significant fraction of annual energy with wind and become either electricity exporters (Louisiana and Ozarks) or synthesized-fuel exporters (Upper Midwest).

Regions with poor wind resources deploy higher amounts of solar, rely more on imports, and are the locations where new nuclear and carbon capture technologies are deployed. Significant energy storage deployment and use of flexible load also occurs in solar heavy regions to shift generation to the night and loads to the day.

Specialization between neighboring regions is facilitated with a significant increase in new inter-regional transmission, particularly in the southeast. Regions like Florida, for instance, may import energy on balance but also spend much of the year exporting solar to wind heavy regions.



Generation fraction by region and scenario



Regional fractions are shown for all regions for each scenario. To just pick out a few of the major differences:

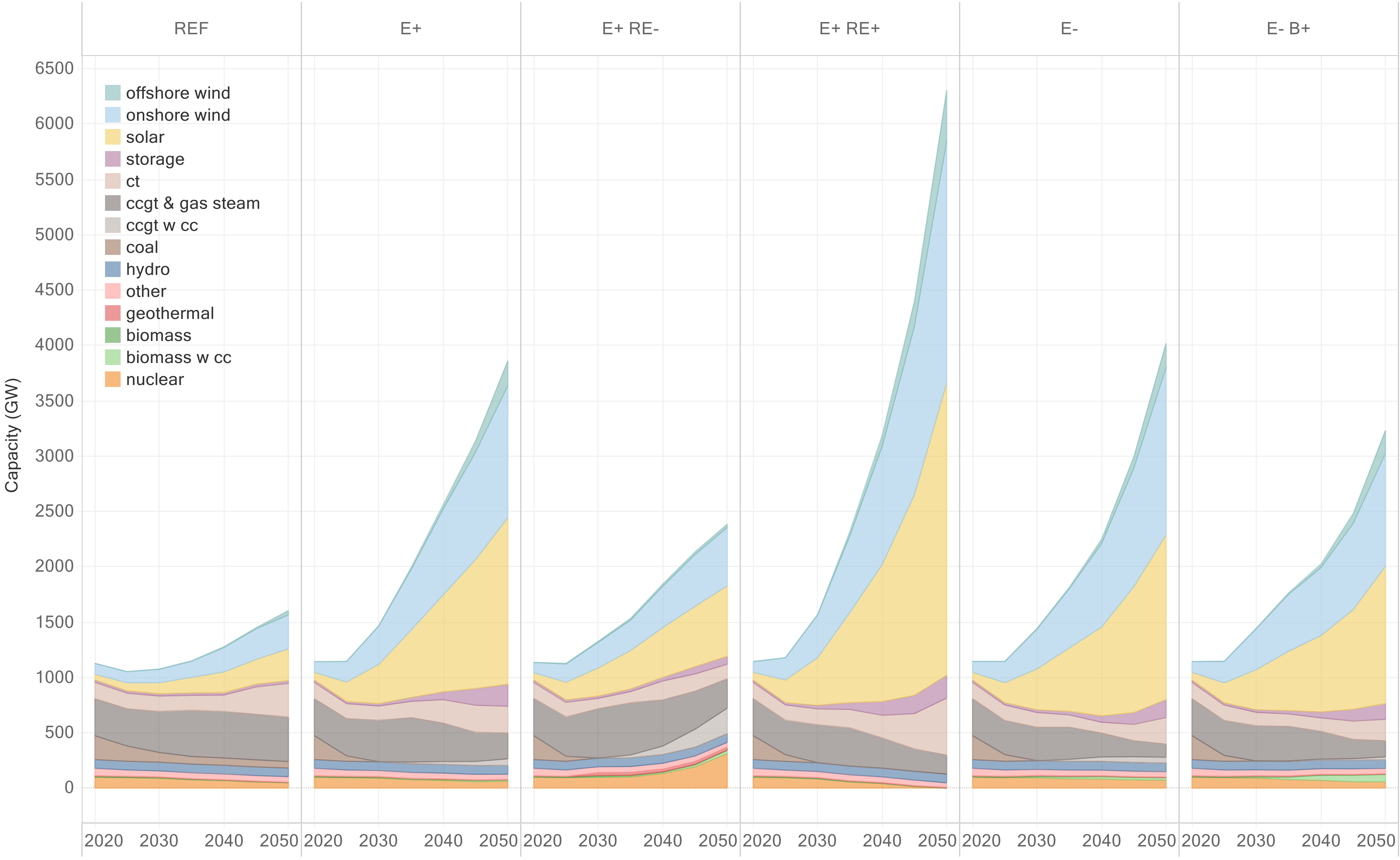
1. New geothermal is deployed only in California and only when annual wind and solar deployment is constrained on a national level.
2. Significant new nuclear in the E+ RE- scenario occurs up and down the east coast
3. BECCS deployment occurs primarily in the Midwest and Southeast where biomass resources are plentiful, but plays a minor role overall.
4. Offshore wind is critical in the Northeast and Mid-Atlantic. Its deployment in the Southeast and West depends on the scenario.
5. Gas with CCS is first deployed in the Southeast, Texas, and California. Regions that have poor wind, have limited interconnections, or disallow nuclear, respectively.

Electricity capacity by year

Electricity capacity tells a different story than annual electricity generation. Approximately two thirds of the renewable capacity build is solar (1,500 GW in the E+ scenario). Exactly how much of this is best deployed on the distribution system vs. the transmission system is not something this study attempted to address.

The dispatchable resources at the bottom of the figure are remarkable in how similar they appear to the reference scenario. This is examined in more detail on a further slide that shows only thermal capacity.

The purple wedge shows energy storage capacity, which becomes significant across each scenario. Energy storage is examined in more detail on the next slide.



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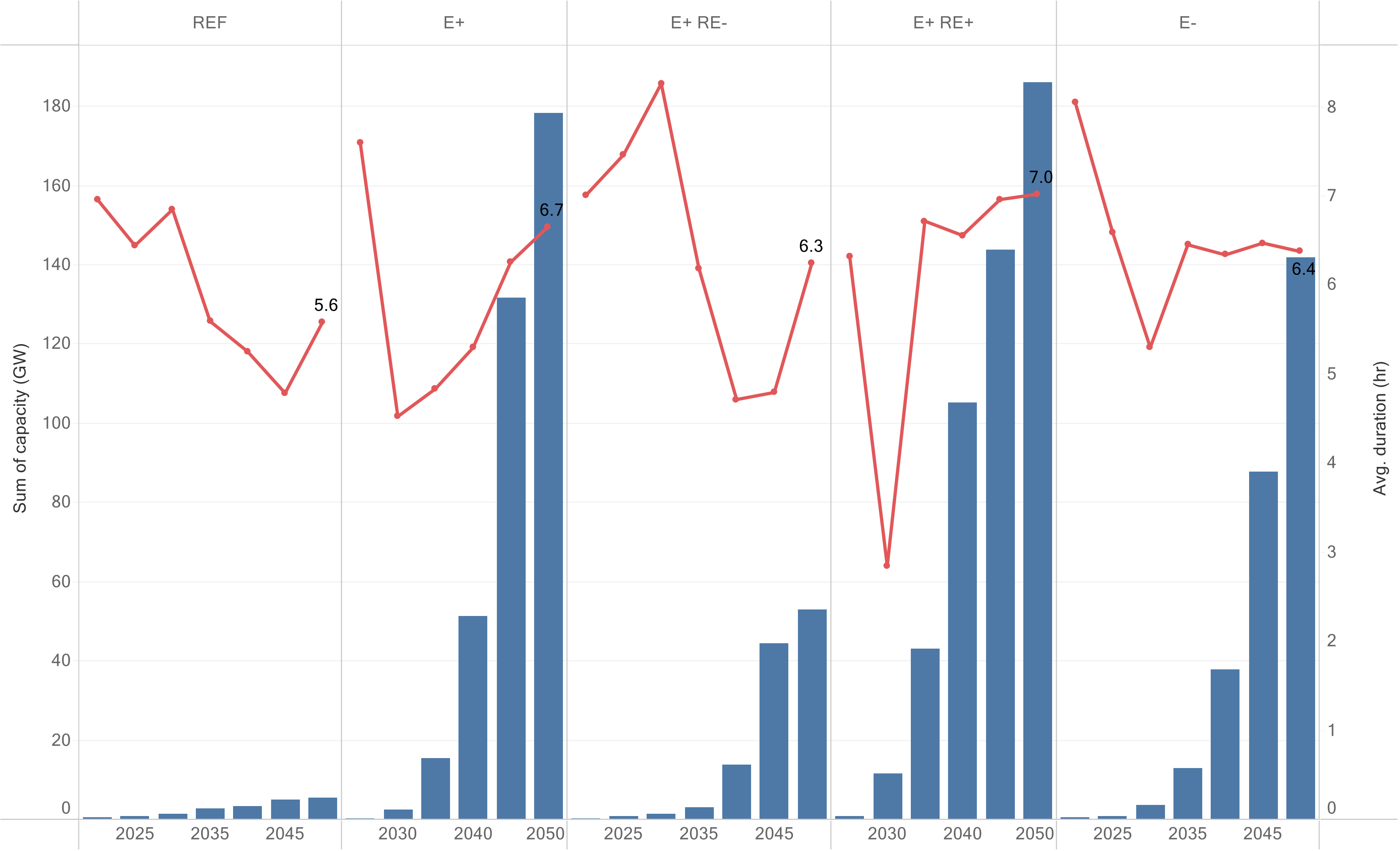
Battery electric storage capacity

Total installed battery energy storage is shown across each scenario along with the average duration in hours. The RIO model solves for the capacity and energy dimensions of energy storage separately. The average storage duration by 2050 is 6-7 hours.

The E+ RE+ scenario builds more storage early due to faster deployment of wind and solar; however, this scenario does not build appreciably more storage than others, because very high electrolysis loads followed by renewable overbuild becomes the dominant balancing strategy.

The amount of energy storage build is extremely sensitive to the amount of flexible end-use load assumed to be available. Turning off all flexible load approximately doubles the amount of storage.



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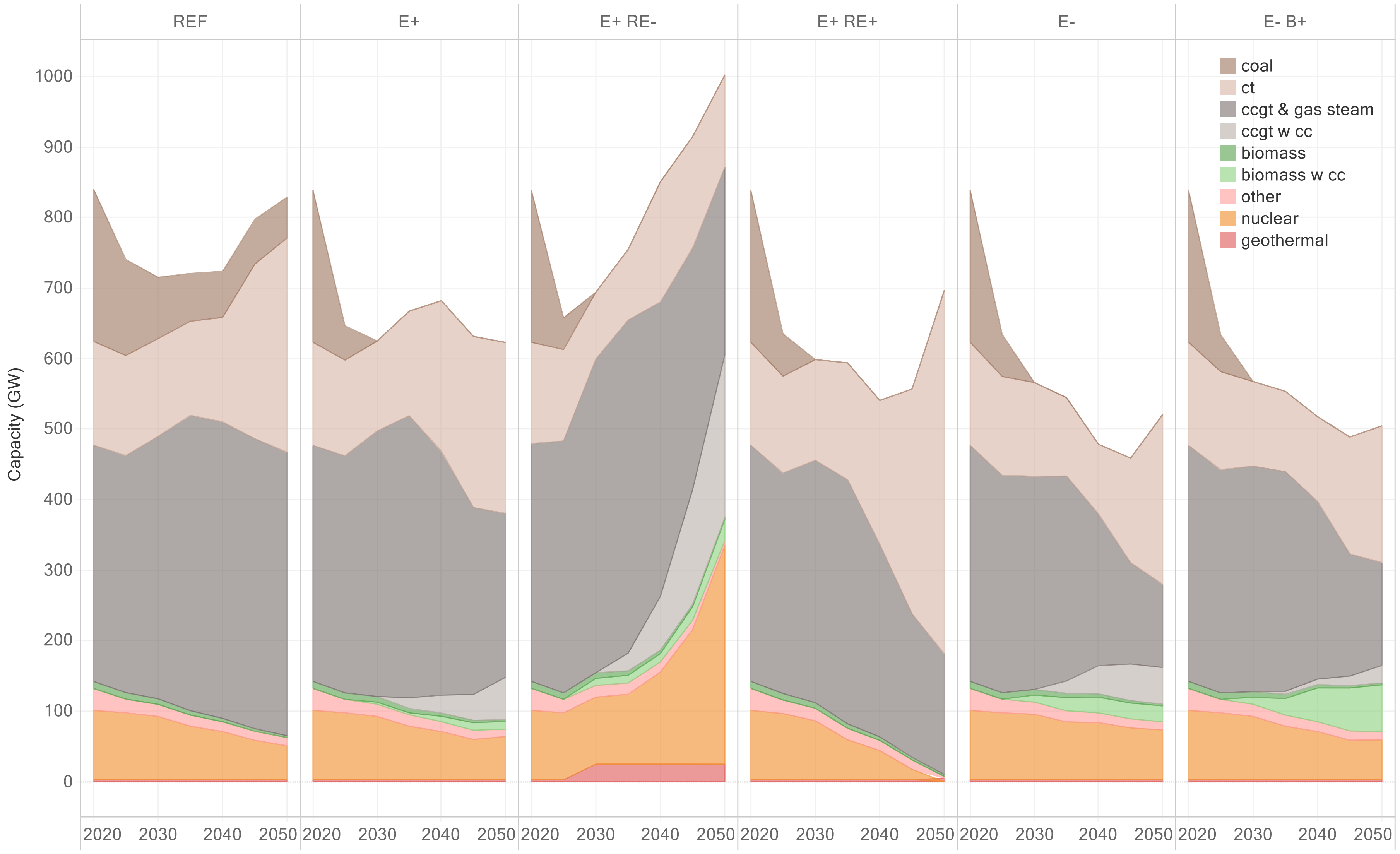
Thermal capacity

The most notable result when looking at thermal capacity is how much gas without carbon capture remains on the system. In each scenario the capacity of CCGTs and CTs are not significantly reduced compared to the reference scenario. These gas power plants play a critical role within high wind and solar energy scenarios by providing a limited amount of sustained peaking capacity, often seasonal, to maintain system reliability. These are reliability events that are highly uneconomic for energy storage to meet either because of how infrequent they are or because of the large number of consecutive hours with an energy deficit.

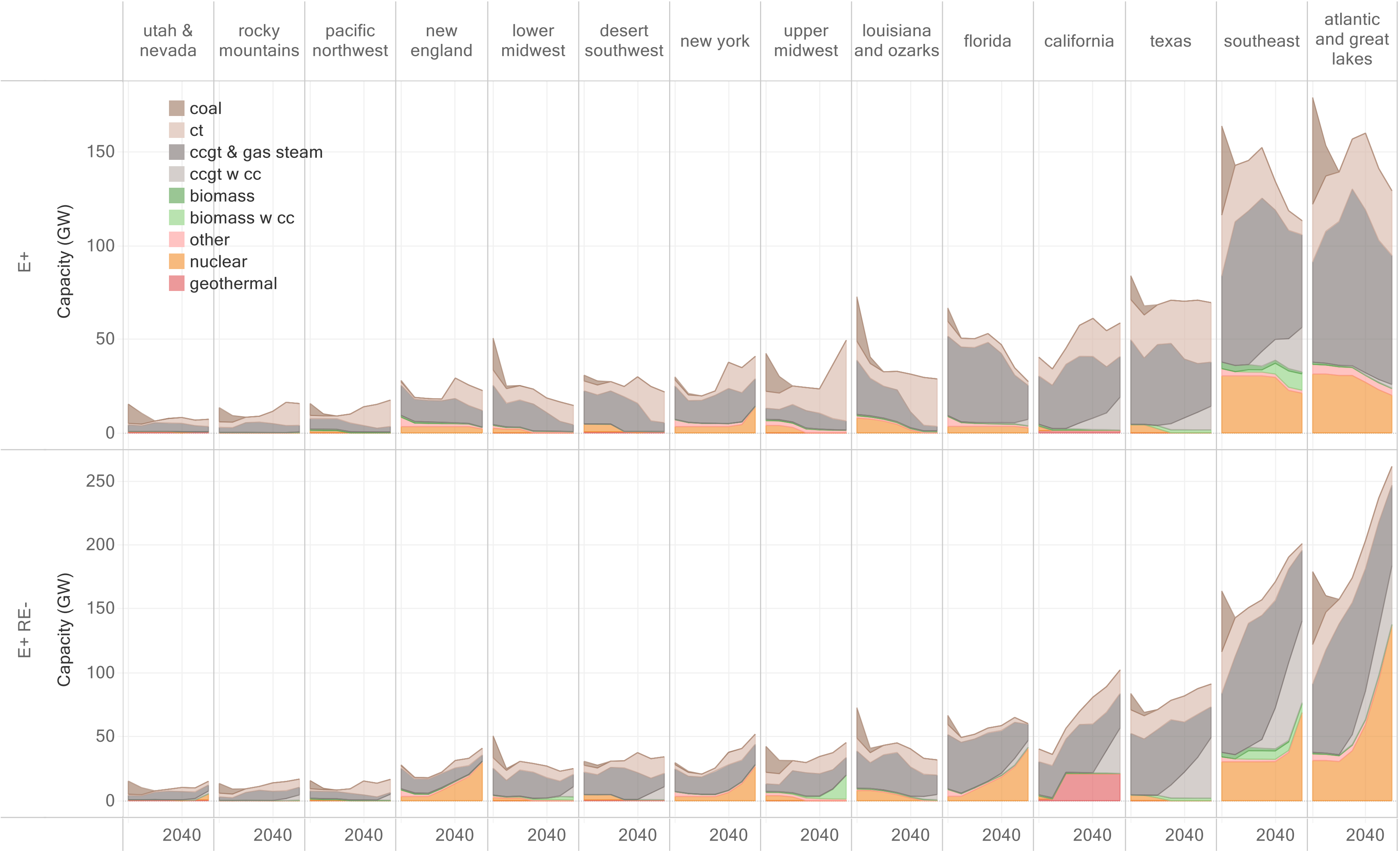
When renewable deployment is unconstrained, putting carbon capture on these gas plants or deploying nuclear is uneconomic because both have very high capital cost and would compete for generation hours with wind and solar. Gas without carbon capture has very high variable cost when accounting for the marginal cost of carbon emissions but remains economic because of the infrequency of dispatch.



Thermal capacity by region for E+ and E+ RE- scenarios

The regional look at thermal capacity shows that gas resources exist in every region to satisfy the reliability criteria in each zone. Areas with better renewable resources are more likely to have thermal resources without carbon capture because good wind and solar together are a reliable indicator of limited run-hours for a thermal power plant.

Coal capacity is retired early in preference for natural gas across all regions. Because the gas is needed as a complement and hedge in high renewable systems, coal retirements do not wait for renewable deployment to replace the lost energy.



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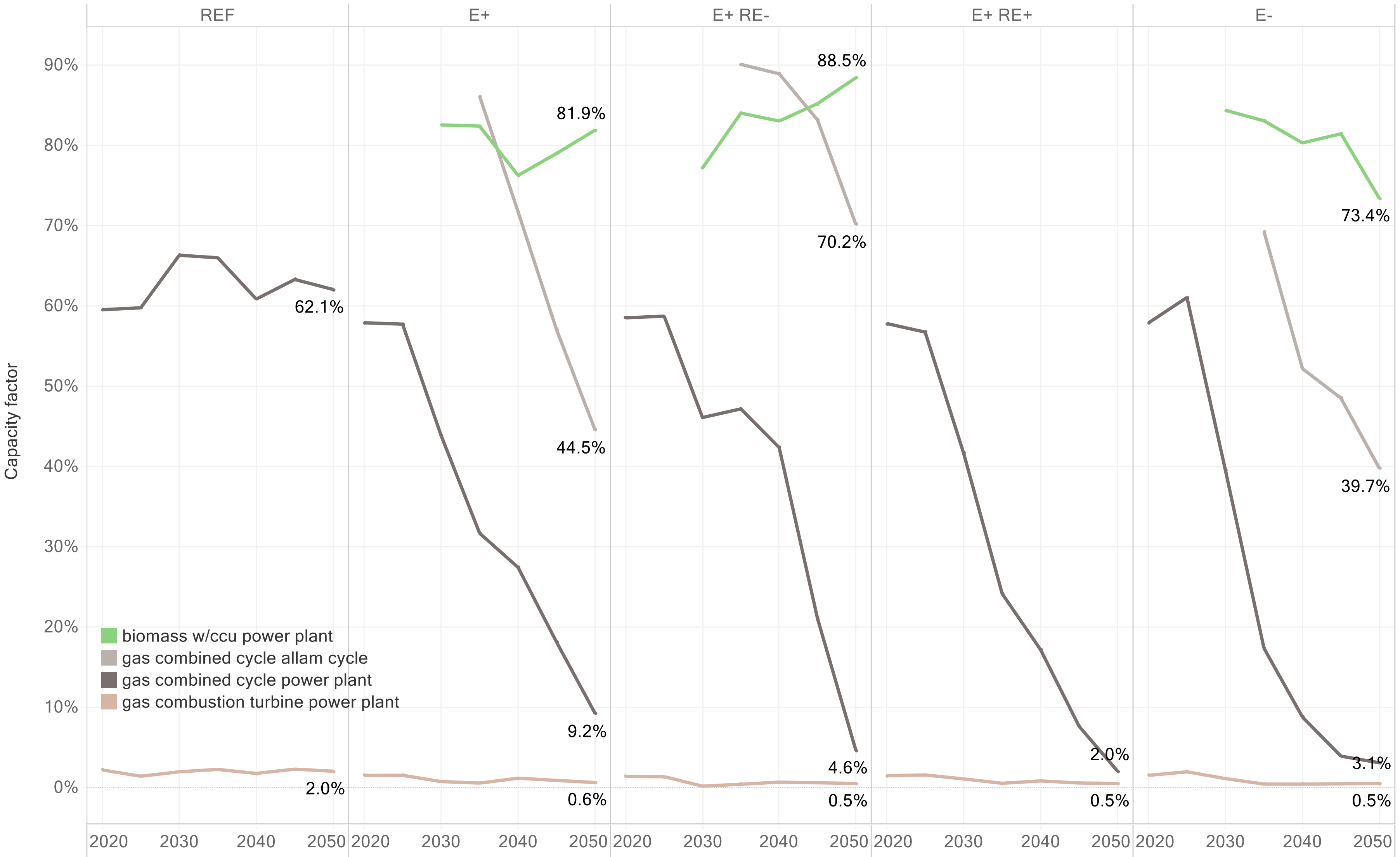
Average thermal capacity factor

In all decarbonization scenarios, all thermal power plants see operating hours reduce as a function of variable costs—including the cost of uncaptured CO_2 emissions. Gas combined cycle plants start with a capacity factor of 55-60% and decrease consistently until reaching a capacity factor of 2-9% in 2050, depending on the scenario. Simple combustion turbines start in the single digits and decline.

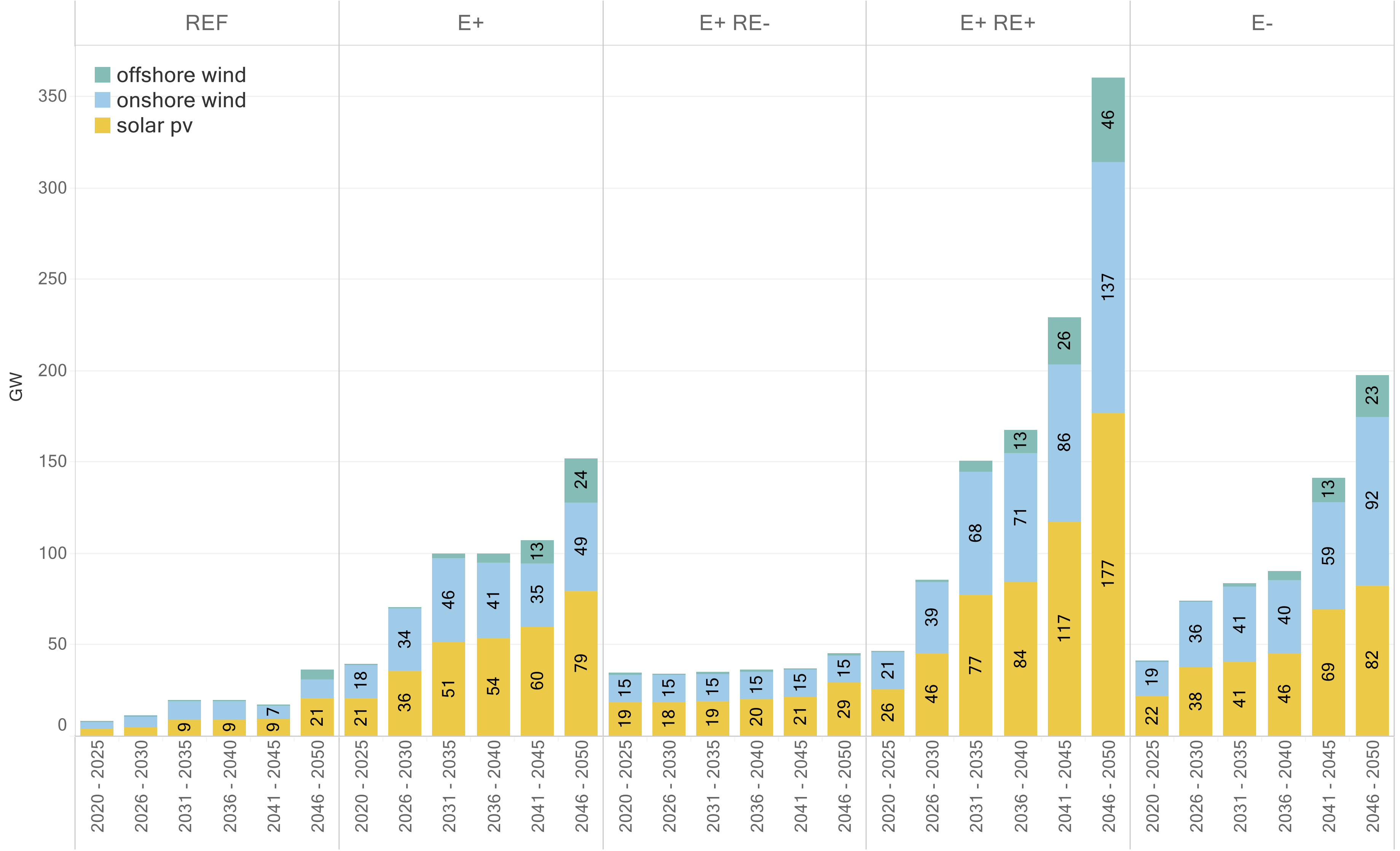
The preference between gas with carbon capture, a combined cycle without carbon capture, and a simple cycle combustion turbine depends on operating hours. The more the plant operates, the more is economic to invest up-front to reduce variable cost, following the logic of a utility screening curve as a method for power plant deployment.



Average annual build (wind & solar)

This figure shows average annual wind and solar build for each five-year period from 2020 through 2050. Build rates in the E+ scenario average 50-60 GW/year for solar and 35-50 GW/year for onshore wind. The fastest build rates are in the E+ RE+ scenario where average annual build of wind and solar reach 183 GW and 177 GW respectively during the five-year period 2046-2050.

The E+ RE- scenario hits its cap on new capacity build in every year with the difference in solar being changes in behind-the-meter solar, which is specified exogenously and kept constant across all scenarios.



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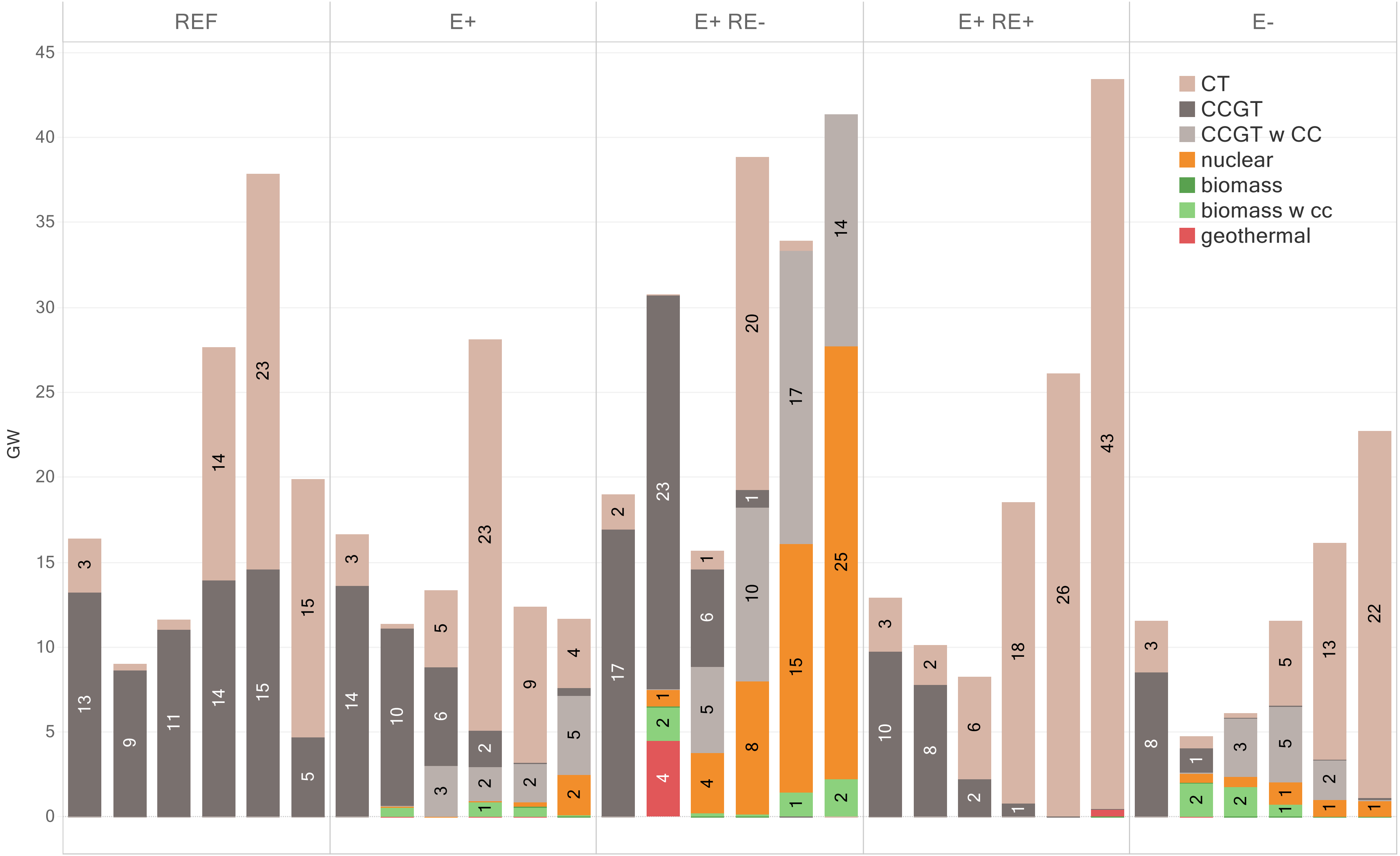
Average annual build (thermal capacity)

In all scenarios except for E+ RE-, thermal power plant build is below historical precedents.

The reference case builds primarily CCGT with some CT capacity post 2035. By contrast E+ RE+ builds CCGTs early, but post 2030 almost all thermal capacity built is CTs.

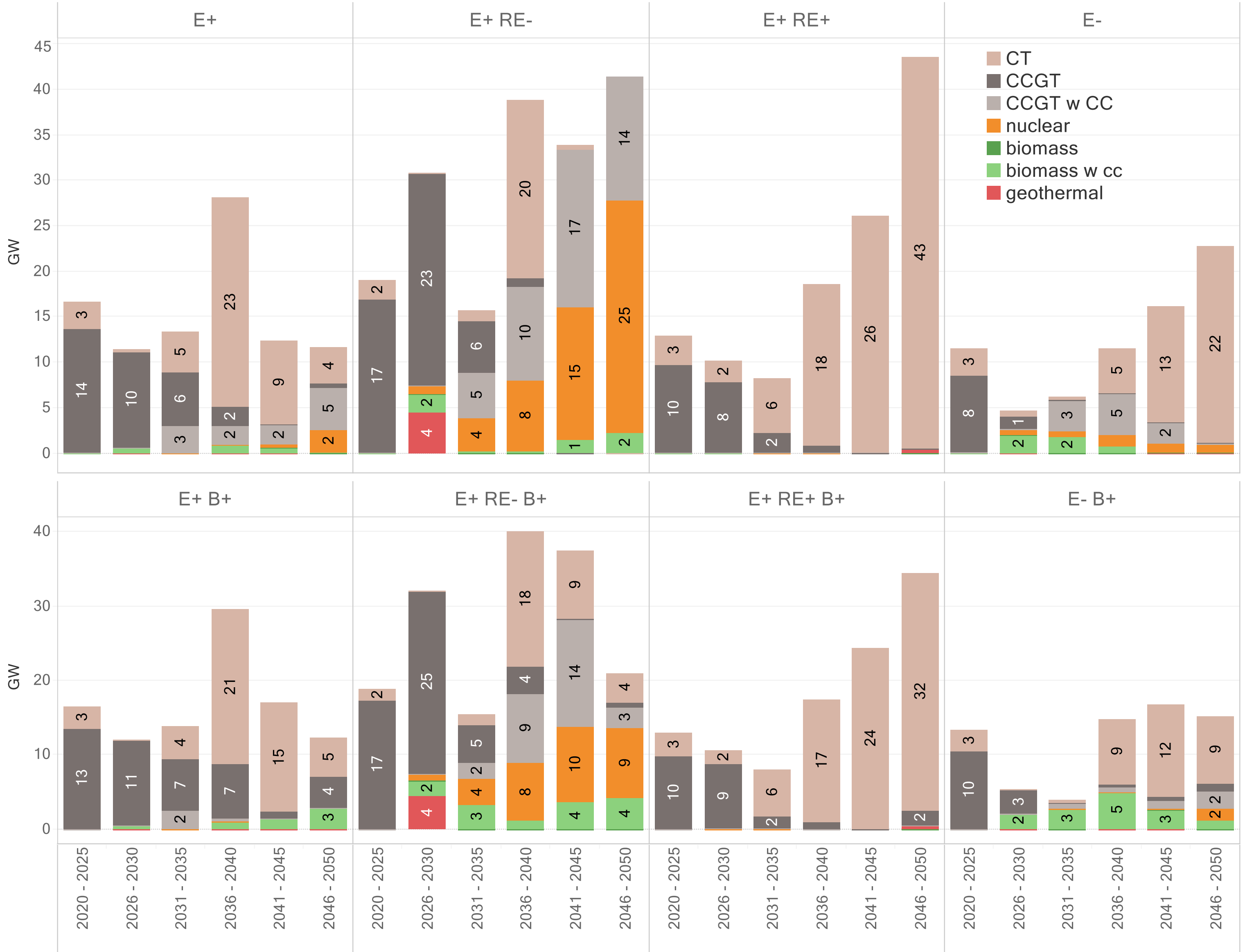
In the E+ RE- scenario average gas with CC build starts at 5 GW per year in 2031 and reaches 17 GW/year leading up to 2045. New nuclear construction starts before 2030 and reaches an average of 25 GW/year by 2050, far surpassing historical build rates for nuclear seen anywhere in the world. These nuclear build rates become necessary to keep up with load growth after capping renewable build and as annual sequestration potential becomes scarce.



Average annual build (thermal) by biomass sensitivity

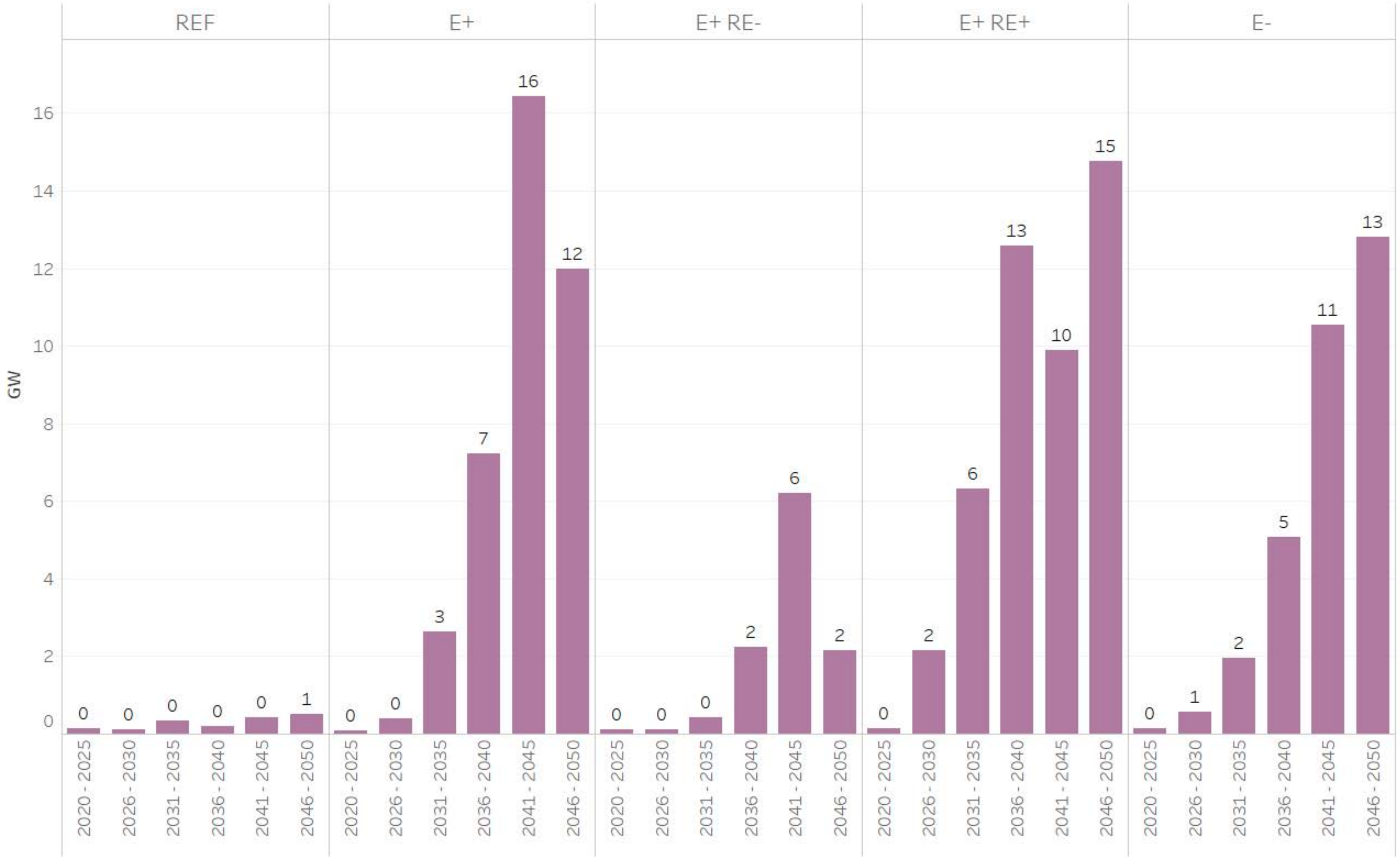
The four decarbonization scenarios are contrasted with and without high biomass.

The build rates for nuclear are far lower under the high biomass sensitivity because the availability of additional biomass alleviates the need for direct air capture and hydrogen electrolysis, reducing electricity loads in 2050. Instead, more BECCS power plants are built and lower amounts of Allam cycle gas plants. Use of limited sequestration potential to store bio-genic carbon provides a negative emissions strategy.



Average annual build (energy storage)

Energy storage build reaches a minimum of 2 GW per year post 2035 in all scenarios. The least amount of storage build is in the E+ RE- case where diurnal mismatches between renewables and load are less severe. The E+ RE+ scenario starts significant energy storage build 5 years sooner than in any other scenario to complement the rapid build-out of renewables.



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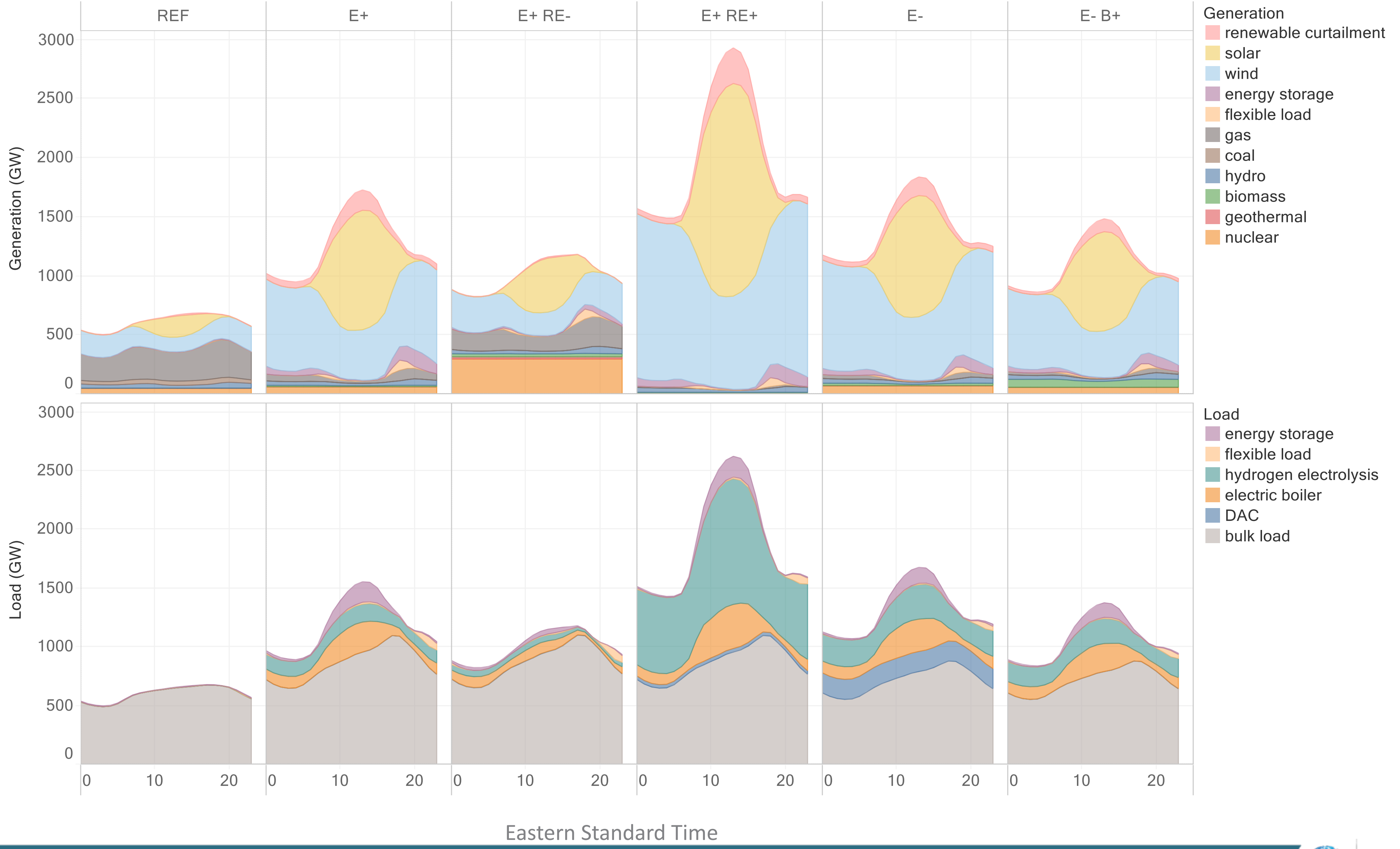
2050 Nation-wide average hourly operations

Average hourly dispatch for loads (bottom) and supply (top) is shown for several scenarios.

Solar and wind complement one another on a diurnal basis. Most curtailment occurs during daytime.

Nuclear is assumed not to dispatch since the turndown of a nuclear plant typically saves very little fuel and shutdown comes with significant cost and additional safety concerns.

Hydrogen electrolysis and electric boilers are used across all hours with heavier use during the daytime to take advantage of solar. Direct air capture is assumed to have very high capital cost and no ability to ramp production on an hourly basis. It therefore operates at very high utilization across the year.

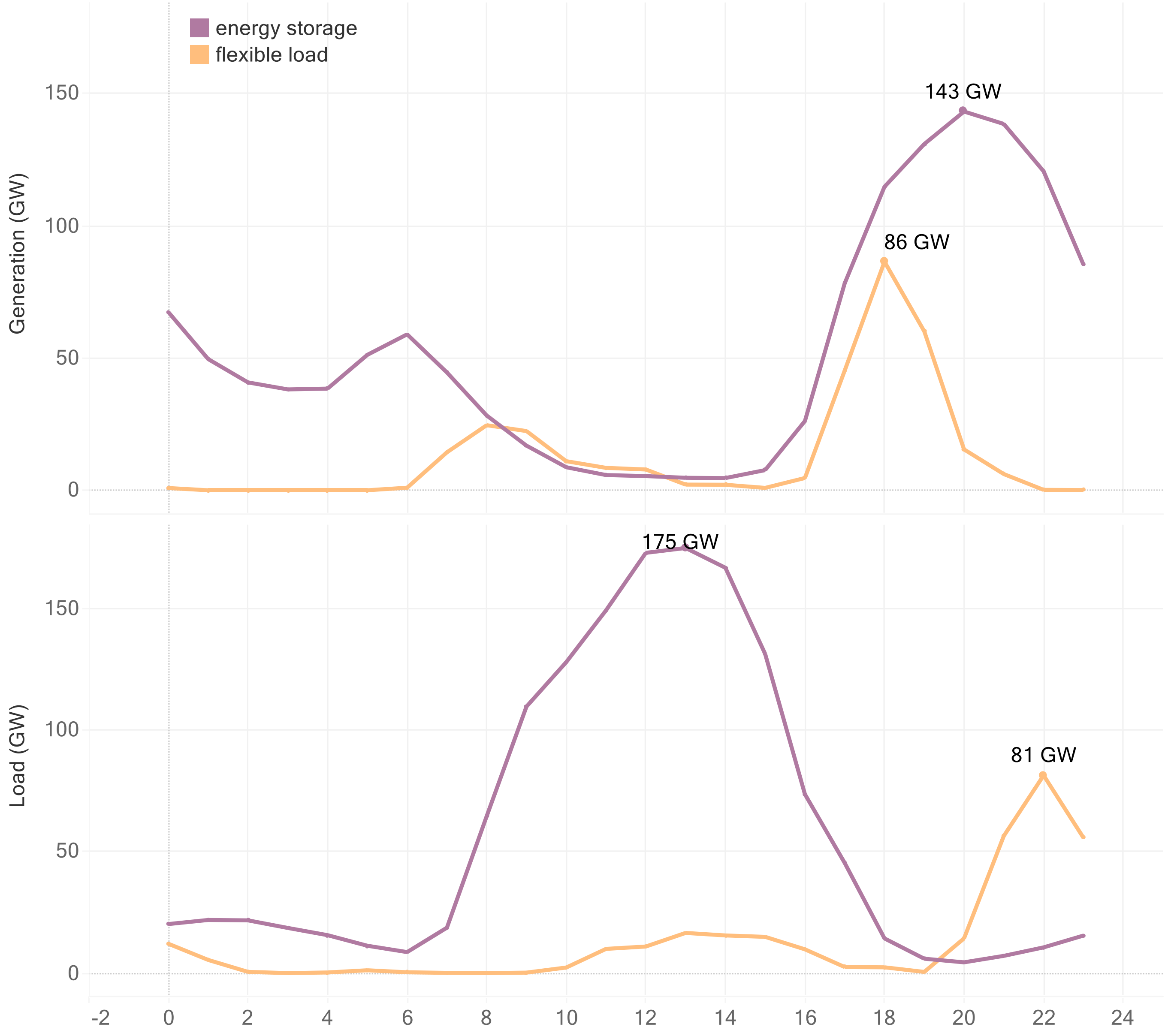


2050 Average storage and flexible load dispatch for the E+ scenario

These figures show average hourly dispatch for flexible load and energy storage in the E+ scenario in 2050. The top figure labeled "Generation" is discharge in the case of energy storage or a reduction in load in the case of flexible load. The bottom figure labeled "Load" shows energy storage charging and increases in load after being reduced at other times of the day. Flexible load is energy neutral in the sense that it reflects load that was shifted but not curtailed.

Energy storage and flexible load are competitors, but their daily use does not show identical patterns. Energy storage primarily charges during daytime and discharges in the evening and to a lesser extent in the morning. In this way, most energy storage nationally is used to shift solar energy. Most of the flexible load modeled represents light duty cars and trucks with flexible at home charging. Its primary pattern is to reduce load in the evening and to shift the energy past the peak. Because a small penalty is applied in every hour for which load is shifted, EV charging is not delayed until early morning hours but is instead charging 2-3 hours after most vehicles are plugged in, once the system can avoid capacity constraints.

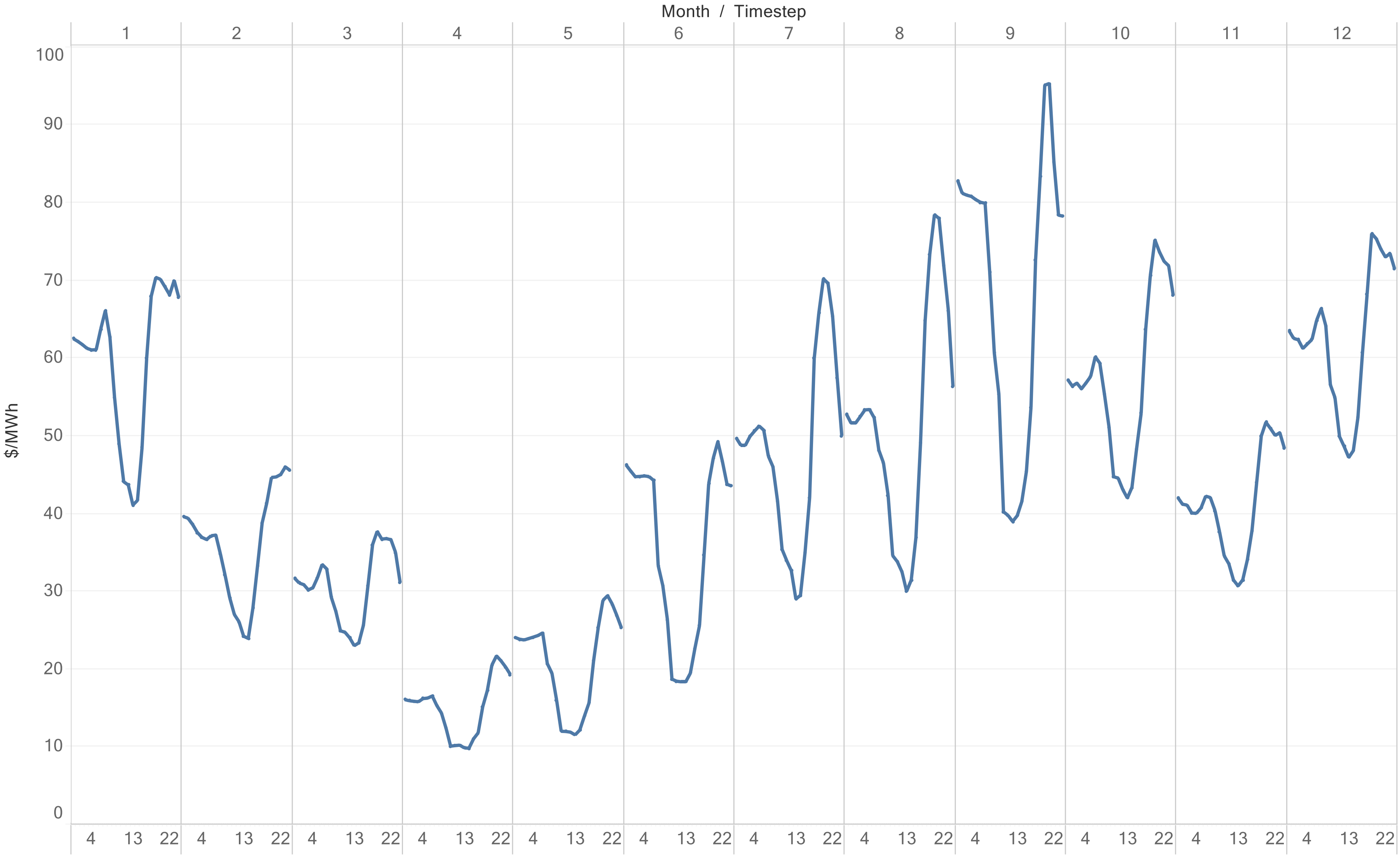
We assume most charging of light-duty vehicles occurs at home and thus the vehicles provide only limited ability to absorb solar during the day as most cars are either away from the home or already charged from the previous day.



2050 Nation-wide average marginal electricity prices for the E+ scenario

These average marginal prices are the shadow price on the energy balance constraint within RIO. Because RIO is a capacity expansion model, the shadow prices reflect both variable energy costs and capacity costs, making this output difficult to compare across all market structures. However, the diurnal and seasonal patterns are still indicative of over- and under-supply of electricity in a high renewables system. The lowest market prices are in the spring when temperatures and load is modest, wind is abundant, solar is waxing towards the summer solstice, and spring runoff for hydro is high. The most constrained hours are in August and September, which are characterized by high load but also low average wind.

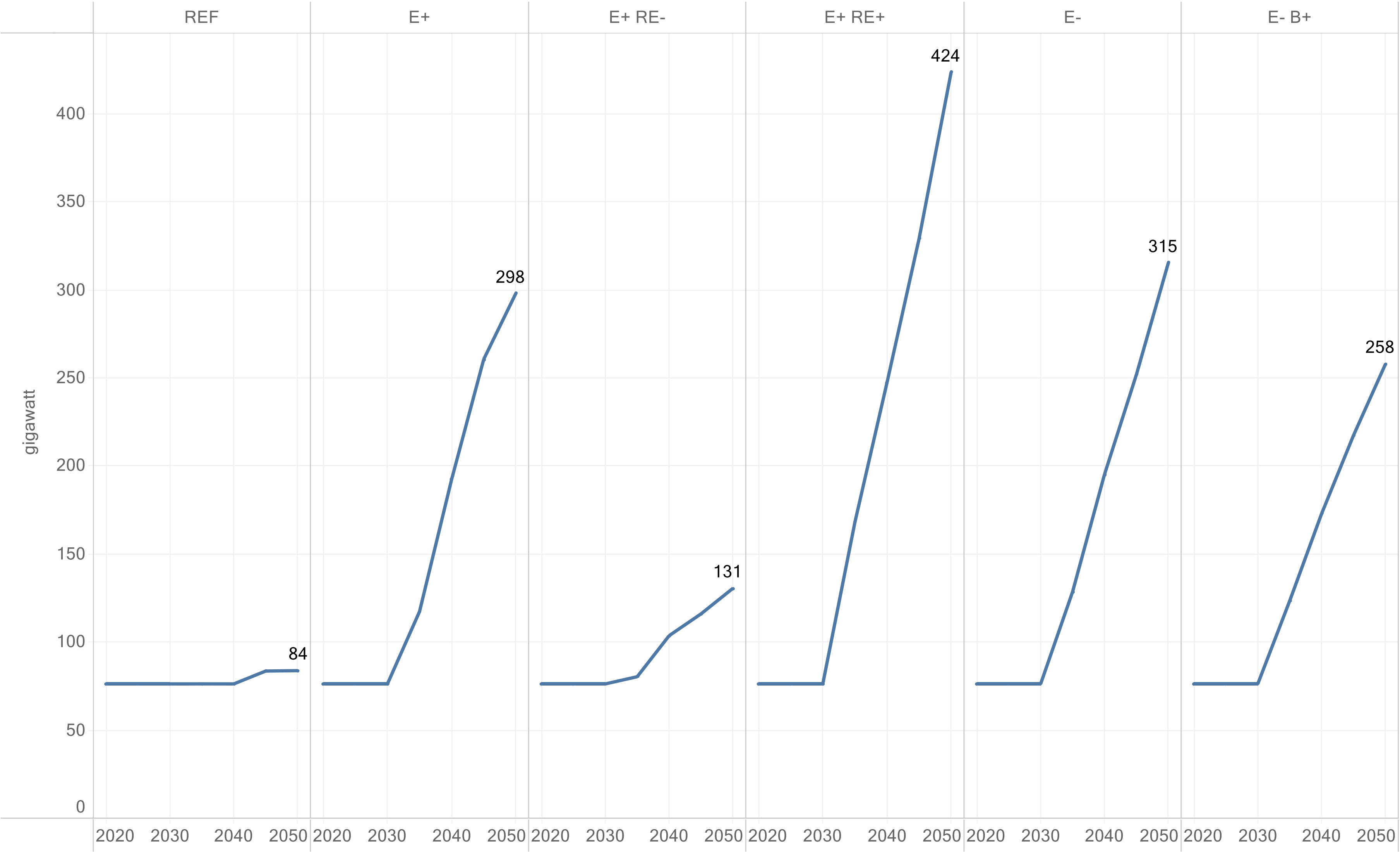
Diurnal patterns are evident that help explain the patterns of energy storage and flexible load dispatch. Shifting load from early evening until daytime is worth, on average, $45/MWh during September.



Sum of inter-regional transmission capacity

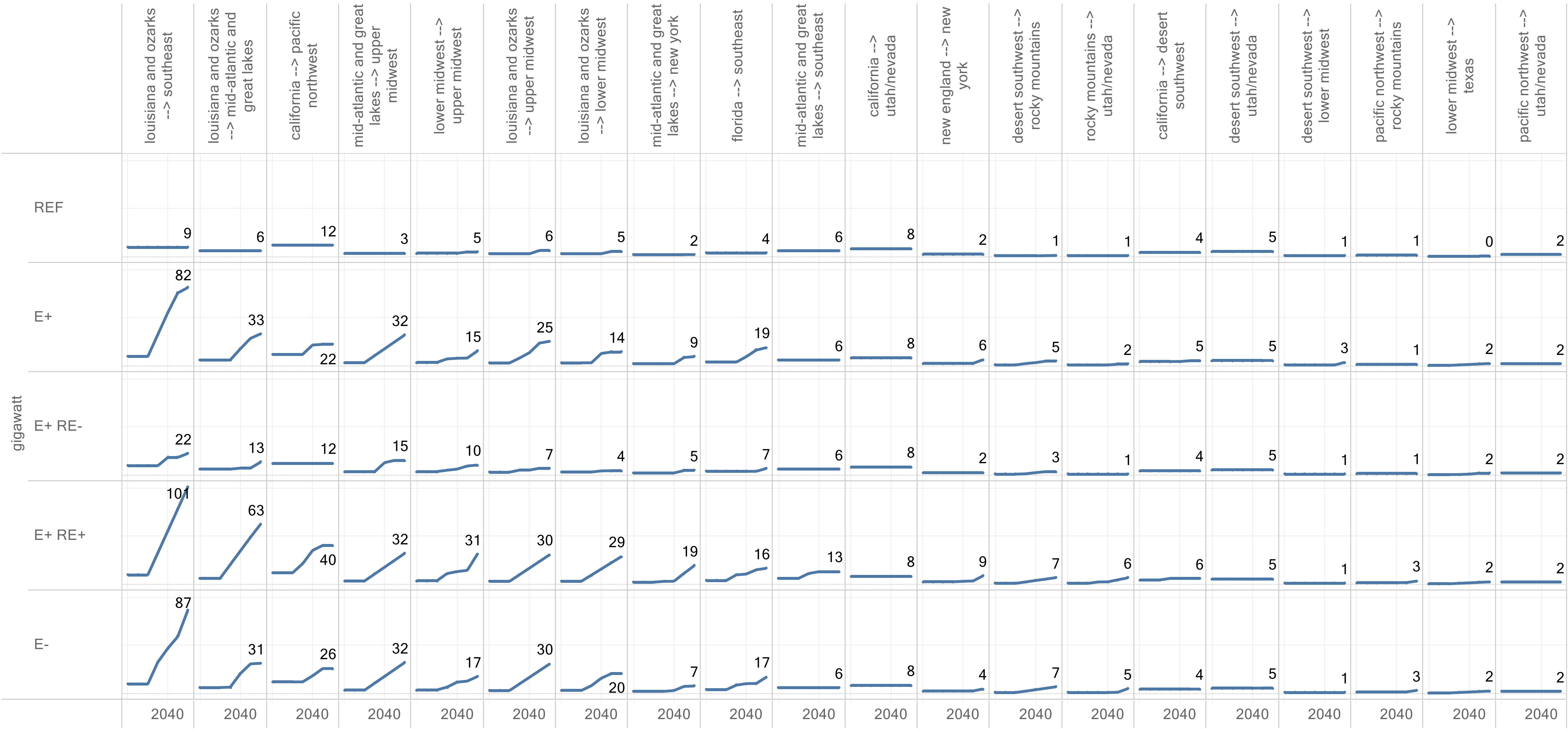
RIO models transmission flows between the 16 regions and transmission expansion to be able to move additional electricity regionally.

The reference scenario shows very modest increase in inter-regional transmission post 2040. By contrast, all deep decarbonization scenarios show significant increases in long distance transmission post 2030. The largest increases in transmission are within the E+ RE+ scenario where a grid supported primarily by wind and solar benefits greatly from optimizing dispatch over a wide geography region.



Transmission build by zone

Shown are the path flow limits on each modeled transmission line across each scenario ordered by the size of the lines. The largest increases in transmission capacity are to connect the Southeast, Florida, and the Mid-Atlantic with wind resources to the west.



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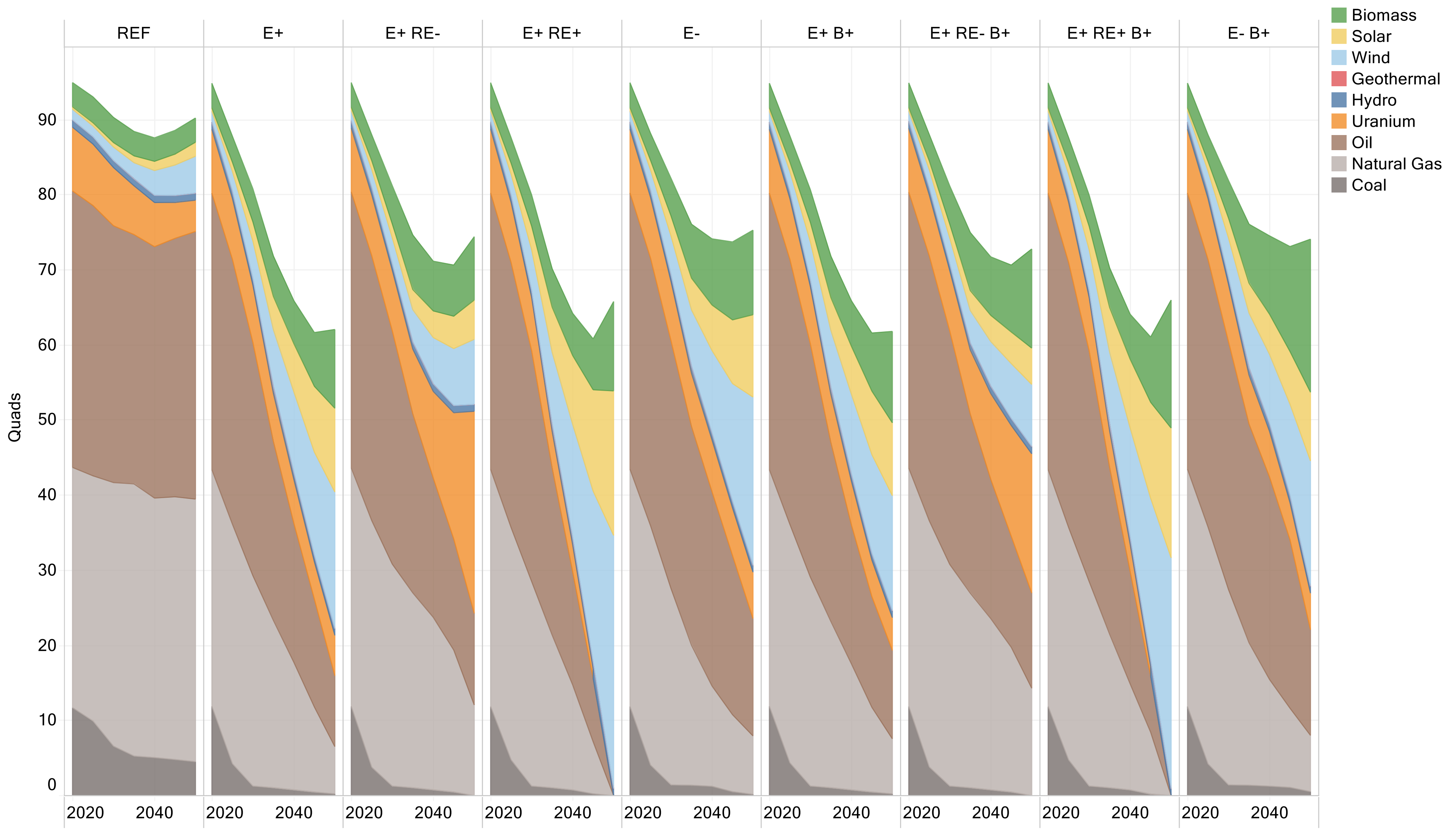
Fuels, biomass, & sequestration details

Primary energy

Primary energy for domestic consumption is shown. Across each decarbonization scenario, primary energy from coal, natural gas, and oil decline significantly. Biomass, solar, and wind all increase, with hydro remaining constant. Nuclear increases or decreases depending on the scenario.

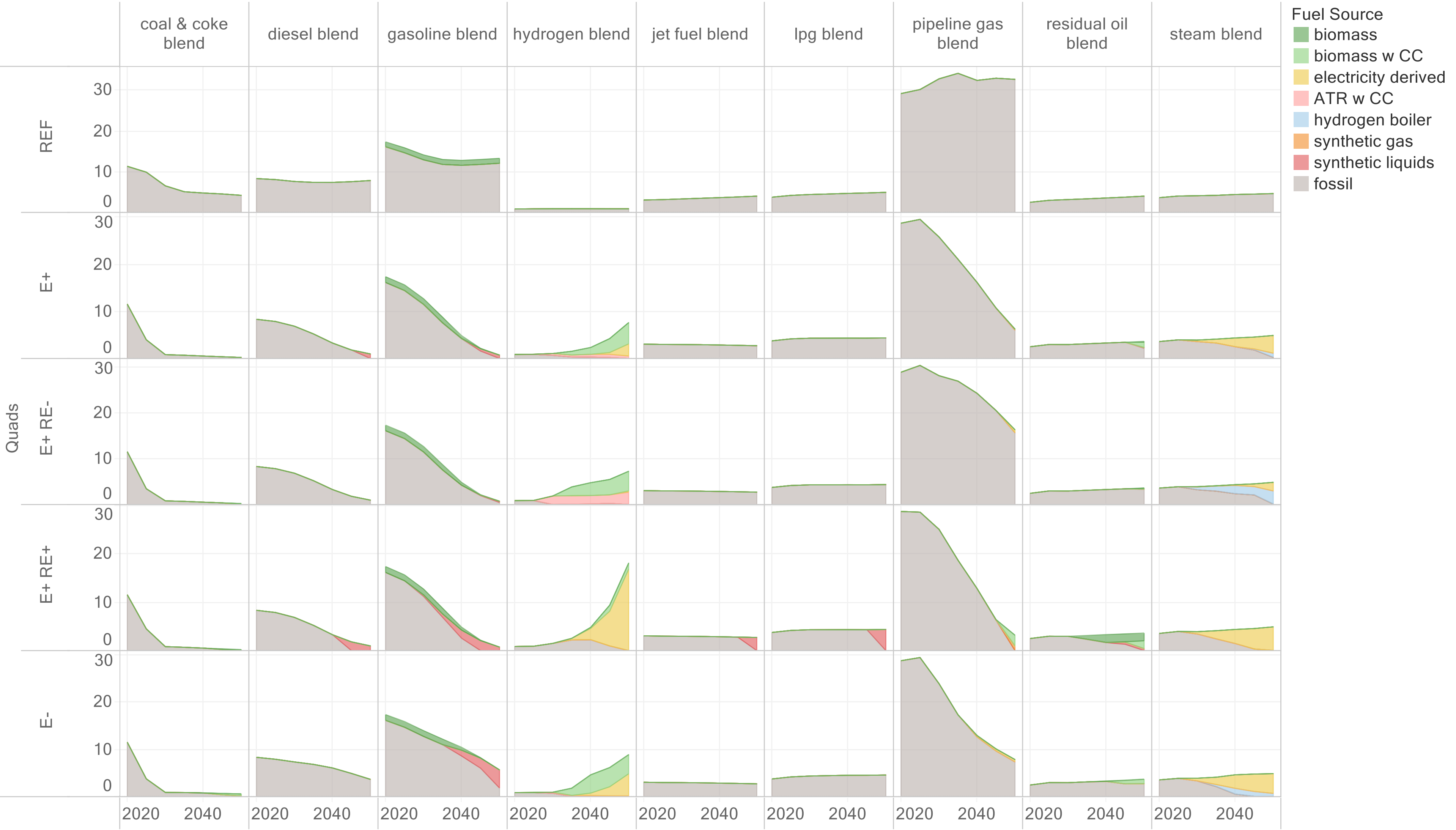


Fuel blends

Note on synthetic liquids & gas: the technologies modeled are Fischer Tropsch and methanation respectively, which themselves draw from the hydrogen blend and captured carbon blends within RIO. The source of hydrogen varies across scenarios, thus the term 'synthetic' can sometimes mean bio-derived and other times electricity derived.

Fuel blends represent categories of delivered energy or final energy demand outside of electricity. The decline in total throughput in most fuel blends is a function of changes that occur on the demand side (e.g. gasoline). Some are supply side decisions (e.g. coal in power plants). Fossil fuel products are represented in grey whereas various drop-in replacement alternatives are shown by different colors.

Noting the magnitude of different fuel blend flows in 2050 is helpful in putting the next slide with fuel blend shares in context.



Fuel blend shares in 2050

Fuel blend shares for 2050 are shown across each scenario with high and low biomass sensitivities.

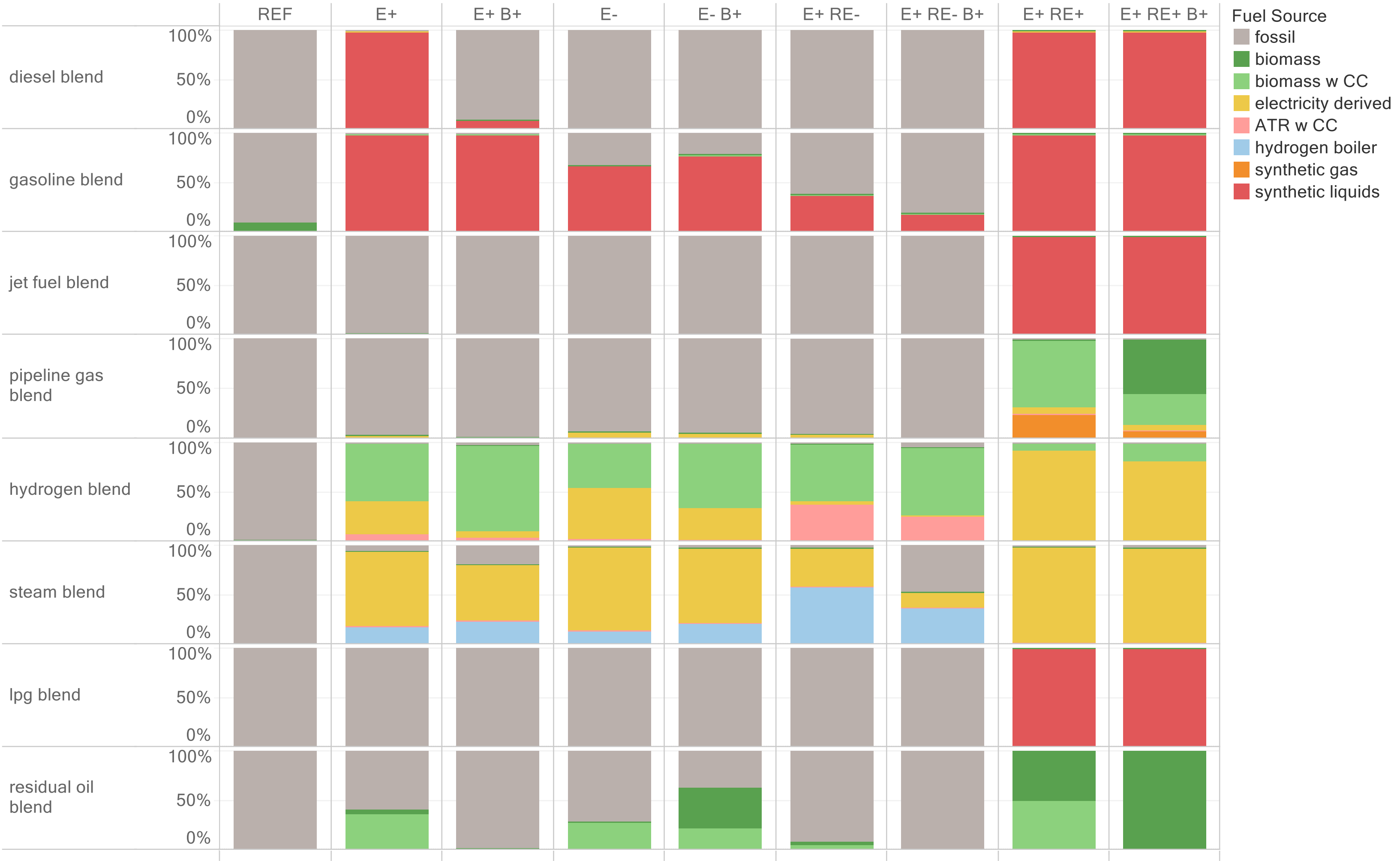
Liquid fuels and LPG either remain fossil at low volumes or are decarbonized using synthetic liquids (Fischer Tropsch). As noted on the prior slide, this term can be a misnomer at times since the hydrogen and carbon used within the Fischer Tropsch frequently comes from biomass.

Pipeline gas is full decarbonized only in the RE+ scenarios. Because natural gas is the cheapest fossil fuel and has the lowest carbon content, it tends to be one of the last blends decarbonized. The electricity derived wedge within the pipeline gas blend represents hydrogen blended directly into the pipeline.

Hydrogen production volumes and shares vary significantly between scenarios. When biomass is abundant and/or renewables plentiful in the electricity system, electrolysis plays a large role. Otherwise direct hydrogen production from biomass with carbon capture (BECCS hydrogen) or autothermal reforming of natural gas with carbon capture (ATR w CC) are deployed.

Production of steam is done with hybrid systems using electricity, direct combustion of hydrogen, or pipeline gas.

Residual oil products are satisfied with pyrolysis.



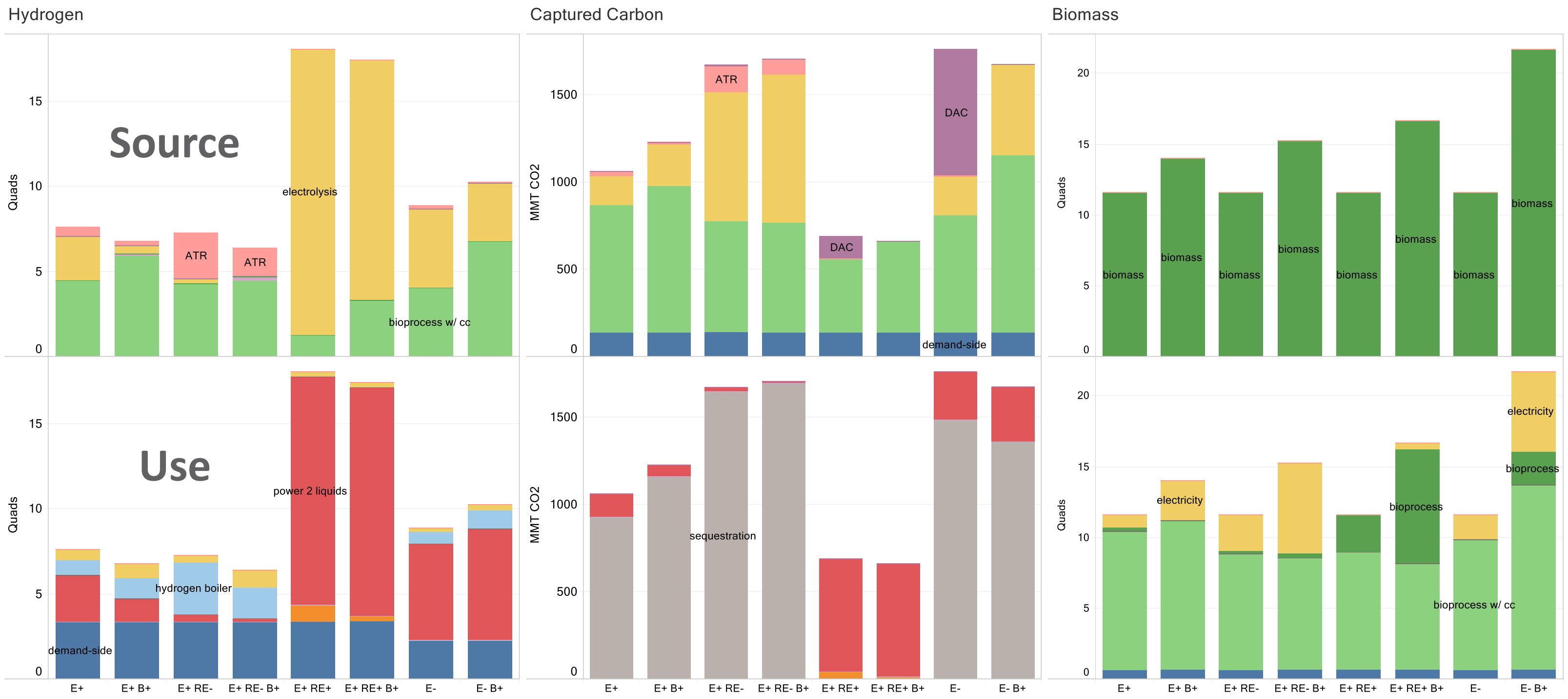
Key fuels in 2050 (full sized figure shown on the next slide)

Hydrogen, captured carbon, and biomass are termed 'key fuels' within a decarbonized energy system as energy flowing within each of these blends tends to interact with all other gaseous and liquid fuels. The top row shows the source for each blend while the bottom shows the use of that blend. Columns describe each scenario and biomass sensitivity.

Hydrogen throughput is highest in the E+ RE+ scenario because it is needed in synthetic liquids processes to replace all remaining liquid fuels. When additional biomass exists, more biomass is used to make hydrogen and less hydrogen comes from electrolysis.

Captured carbon is primarily sourced from bioconversion processes with carbon capture, primarily bio-production of hydrogen. Captured carbon also comes from industrial capture on the demand-side, electricity generation, reformation of gas to make hydrogen, and direct air capture when need for synthesized fuels or carbon offsets are high and biomass supplies low (RE+ and E-). Outside of the E+ RE+ most captured carbon is sequestered where sequestration is disallowed. In E+ RE+ the carbon goes to fuel synthesis.

Biomass mostly goes into fuel conversion processes. When biomass supplies are high, greater volumes of biomass are used in electricity. Carbon capture on biomass processes are also not as critical when biomass supplies are high because the supply of bio-genic carbon is not as tight throughout the economy.

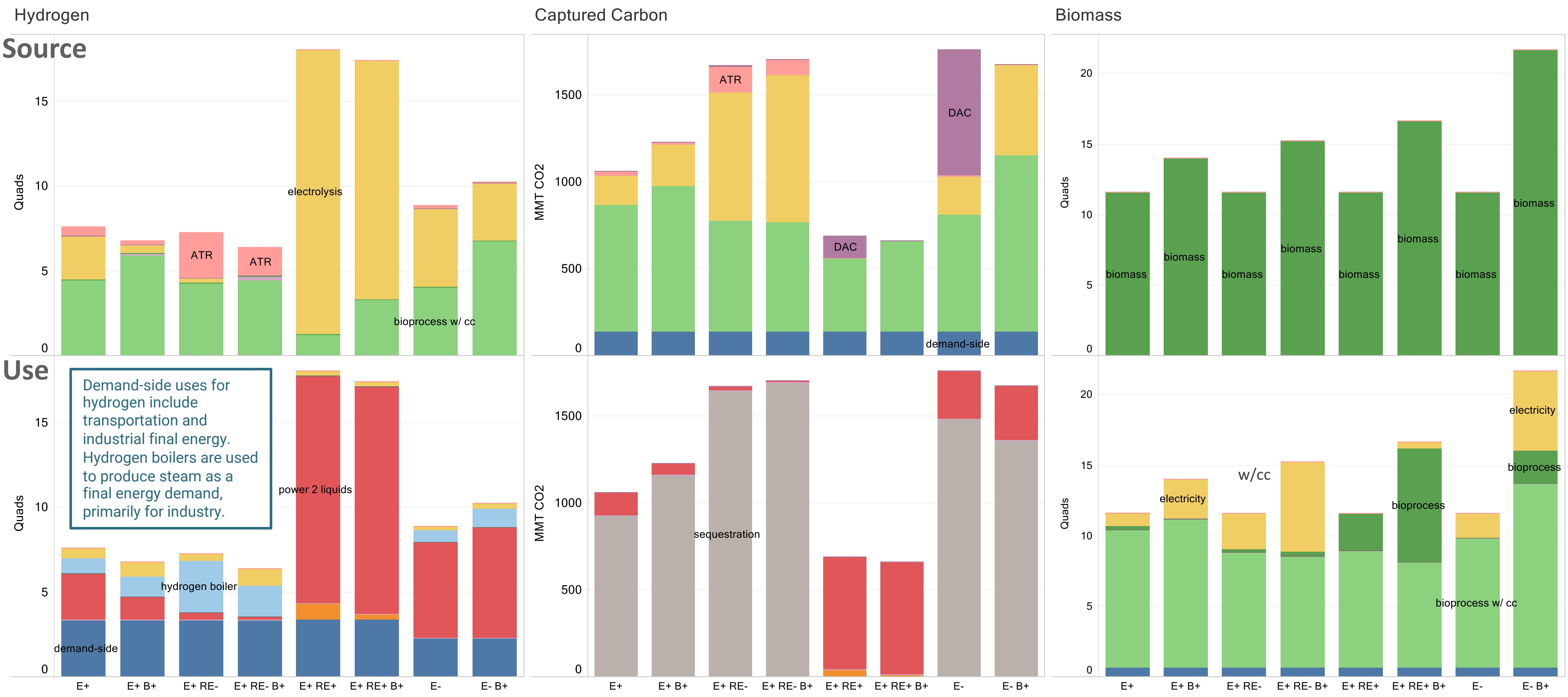


Note on fuel sensitivities: The fuel make-up of each decarbonization scenario is one of the biggest differentiators between scenarios. These outcomes are extremely sensitive to assumptions around fossil fuel prices, sequestration cost, and biomass availability, all of which are uncertain in the timeframes modeled. It is important to note that most deviation between scenarios occur post 2035 with electrification being the most critical near-term strategy. Thus, more time exists for R&D and exploration of each of the different fuel strategies we modeled before committing large amounts of capital to a specific pathway.

Key fuels in 2050

Carbon captured during electricity generation is from both BECCS and CCGTs with CO2 capture.

ATR: Autothermal Reforming
DAC: Direct air capture



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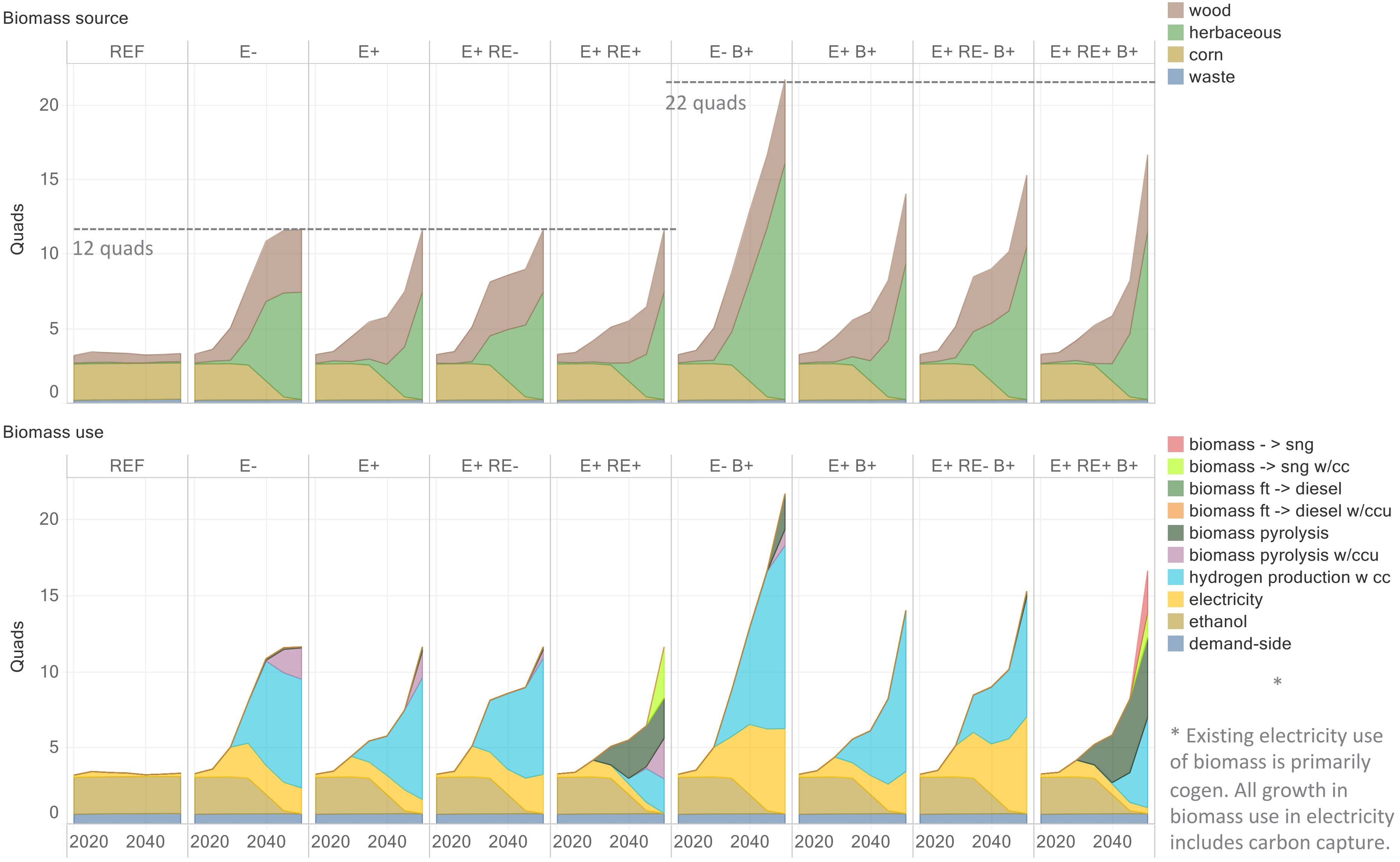
Biomass use

These charts decompose the biomass panel of the 'key fuel' chart in more detail.

All decarbonization scenarios use all the biomass potential within the low biomass sensitivities. The E- B+ scenario also uses all available biomass.

Corn for ethanol plays a diminished role as light duty autos are electrified, but corn volumes are maintained through 2035 and blend percentages gradually increased. Post 2035 land used for corn ethanol is repurposed for herbaceous crops that give better overall yields for dry biomass.

Biomass is primarily used to make hydrogen with carbon capture. It is used in the power system when pathways to negative emissions are vital (electrification delay) renewables are constrained and biomass supplies are high. Use in pyrolysis and other liquid and gaseous processes are highest within the E+ RE+ scenario where fossil alternatives are disallowed.



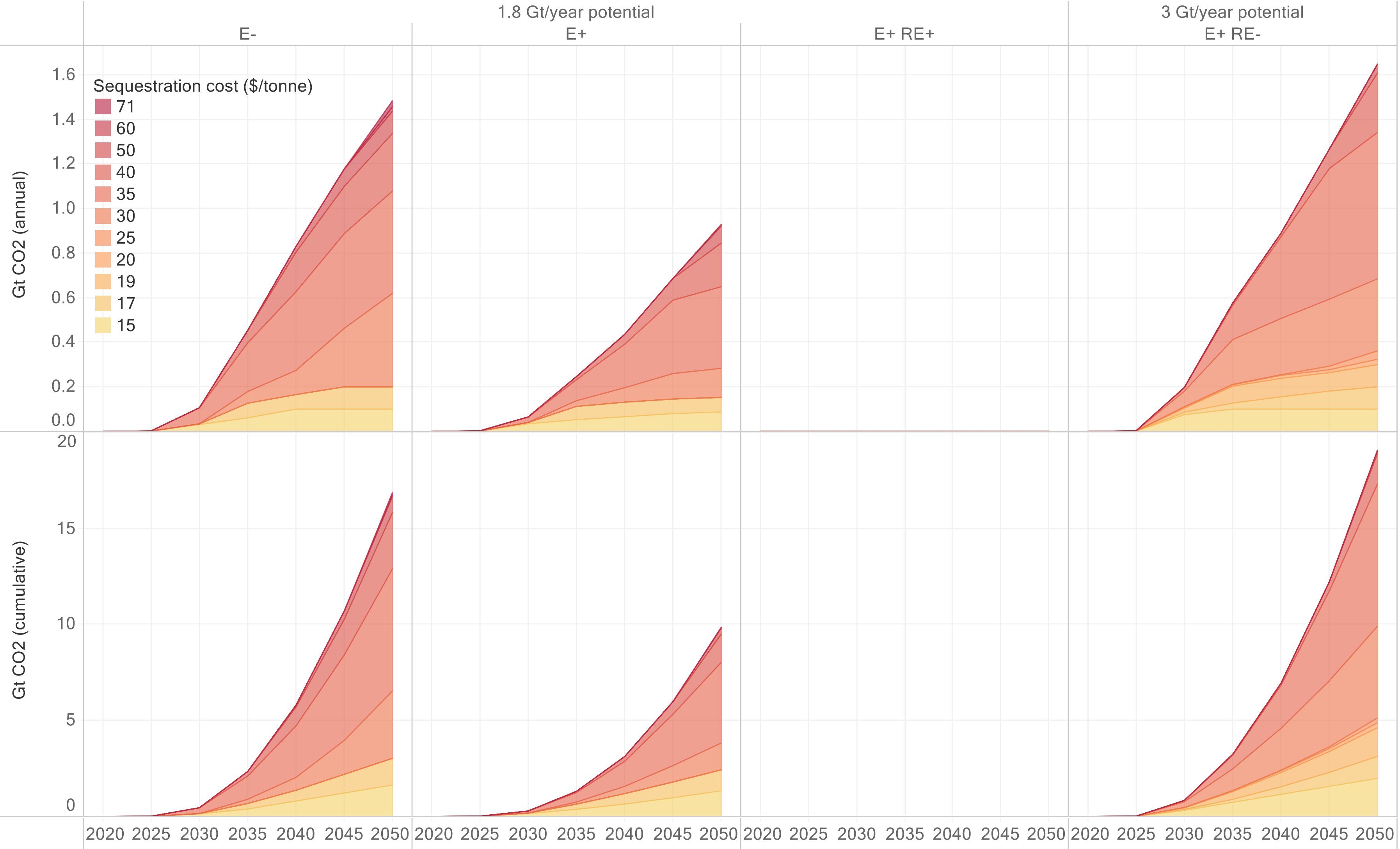
* Existing electricity use of biomass is primarily cogen. All growth in biomass use in electricity includes carbon capture.

Carbon sequestration

The top panel shows annual sequestration decomposed by sequestration cost bin. In the 3 left-most scenarios, the maximum potential storage is 1.8 Gt/y by 2050. In the right-most panel, this cap is raised to 3 Gt/y. Across all 4 scenarios, the average price paid for sequestration is $30/tonne, including transport cost.

All scenarios maximize use of sequestration below $25/tonne with the difference between scenarios emerging from how much of the $35+/tonne sequestration is needed.

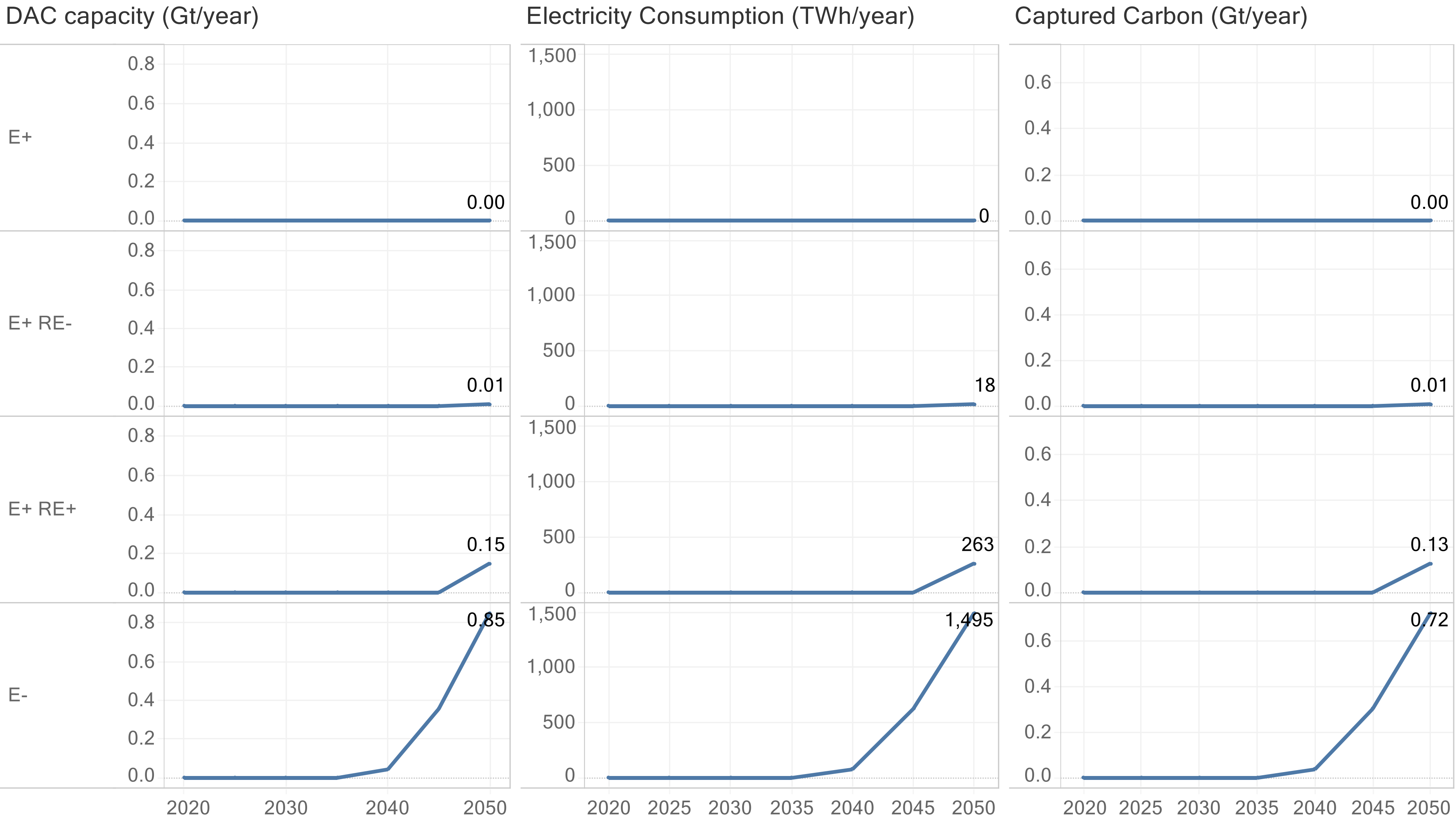
The E+ RE+ scenario includes no geologic sequestration because a modeling input assumption is that it is disallowed in this scenario.



Direct air capture deployment

Direct air capture is needed for the E- and the E+ RE+ scenarios. These results are with the base level of potential biomass availability (12 quads). Results for high biomass availability (22 quads) are not shown, but no scenario in that case requires direct air capture due to the abundant availability of biogenic carbon.

Direct air capture is not modeled as flexible on an hourly basis and due to high capital cost, operates at a very high utilization. It is located either close to geologic storage or in areas with good renewable resources that can supply cheap electricity to operate the DAC plants and provide hydrogen needed to synthesize fuels.



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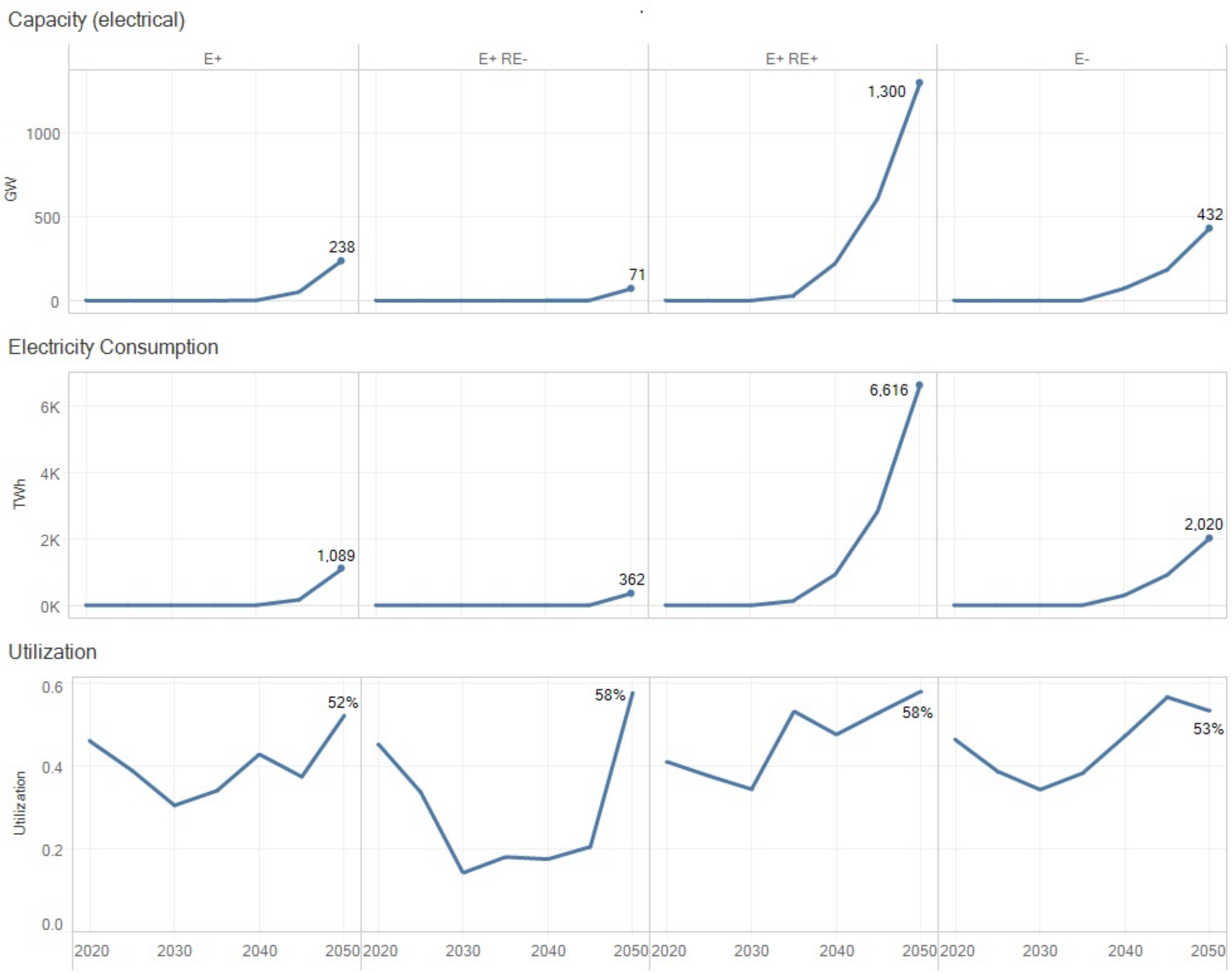
Electrolysis capacity and utilization

Electrolysis is an important source of hydrogen across all scenarios except E+ RE- and is of vital importance within the E+ RE+ scenario, where without it, significantly higher volumes of biomass would otherwise be required.

The utilization (capacity factor) of electrolysis is a function of fixed vs. variable cost. The following factors lead to electrolysis operating at lower utilization—reduced capital cost, lower cost renewables, more constrained transmission, and higher cost batteries.



Shadow price for fuel blends

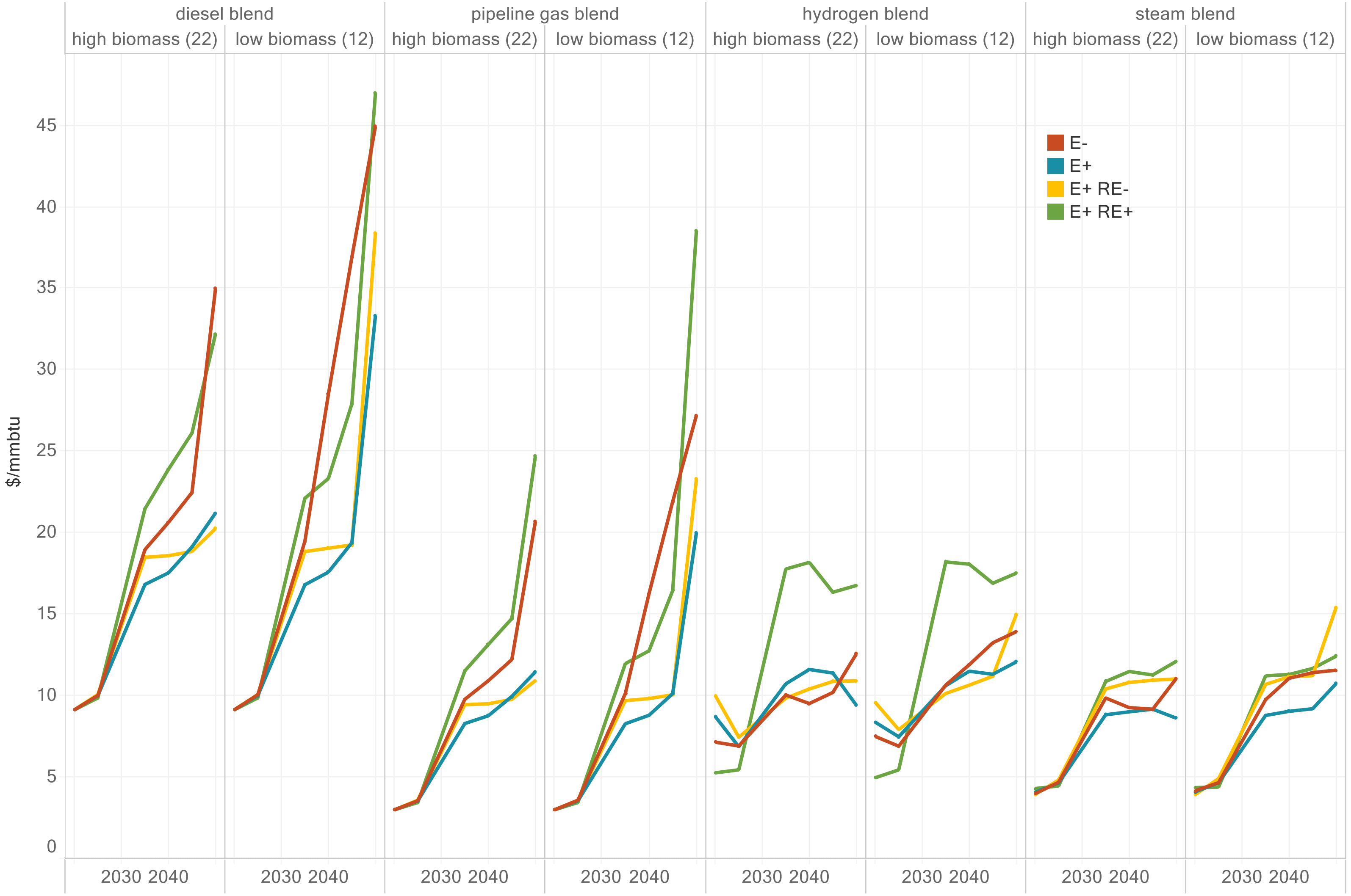
Shown here is the marginal system cost from using one more increment of different fuel blends ($/MMBtu). The base and high biomass availability cases are shown for all scenarios.

The cost in 2020 reflects simply the fossil fuel price as projected in the 2019 Annual Energy Outlook (low fuel price sensitivities). Then, in subsequent years, the price reflects either the cost of producing a zero-carbon drop-in replacement or of offsetting the carbon released from the fossil fuel when burned. Fuels with higher carbon content per unit energy have higher marginal costs.

Supplying any zero-carbon fuel leads to increasing cost with increasing volume. This explains much of the difference between the scenarios in 2050 where the E- and E+ RE+ scenarios both stress the system in different ways.

Biomass availability makes a large difference in 2050 fuel prices, particularly with liquid fuels and pipeline gas.

High marginal system cost for different hydrocarbon fuels is an important motivator for electrification and efficiency on the demand-side.



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