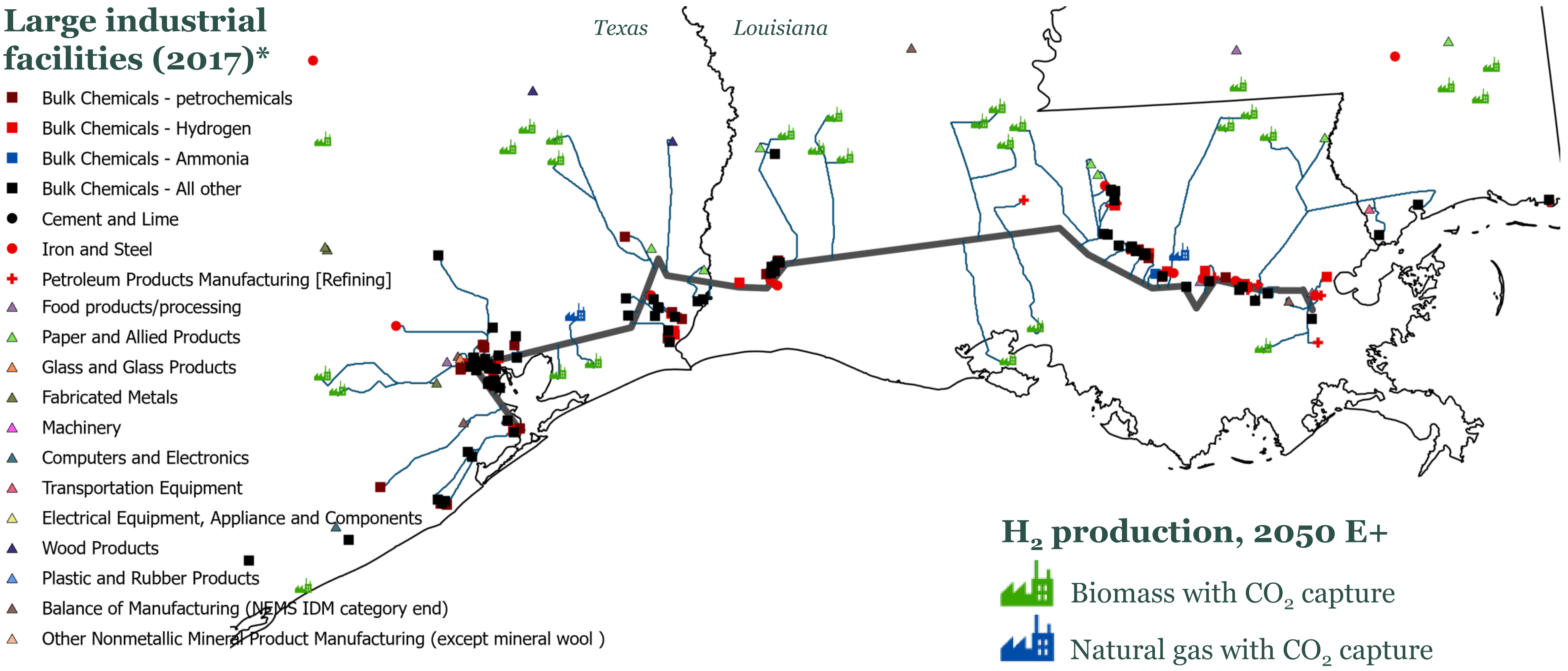
Notional view of 2050 H_2 production and use: Gulf Coast vignette.

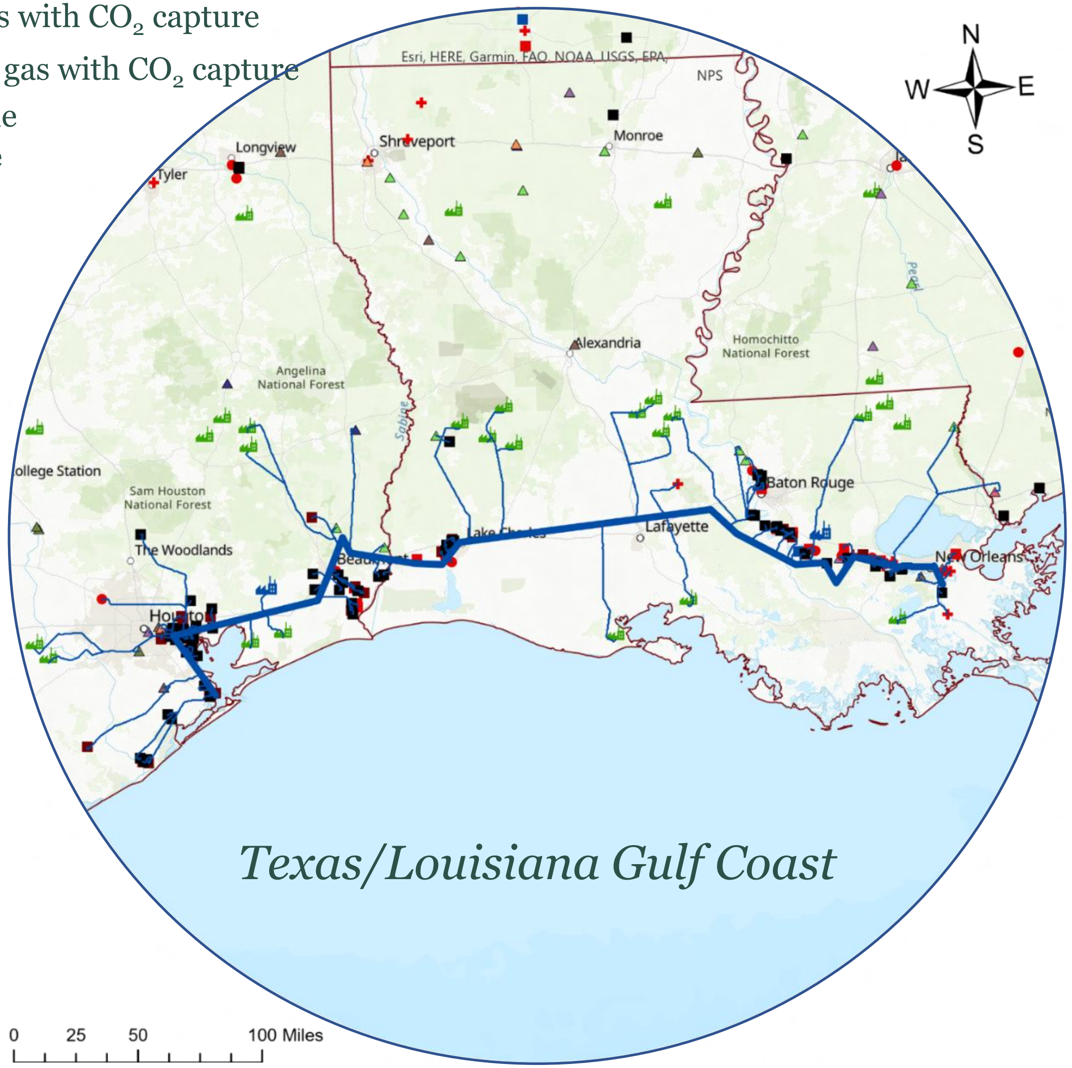


* Source: Environmental Protection Agency, Facility Level Information on GreenHouse gases Tool (FLIGHT) database.

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

2050 H_2 supply system (E+)

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



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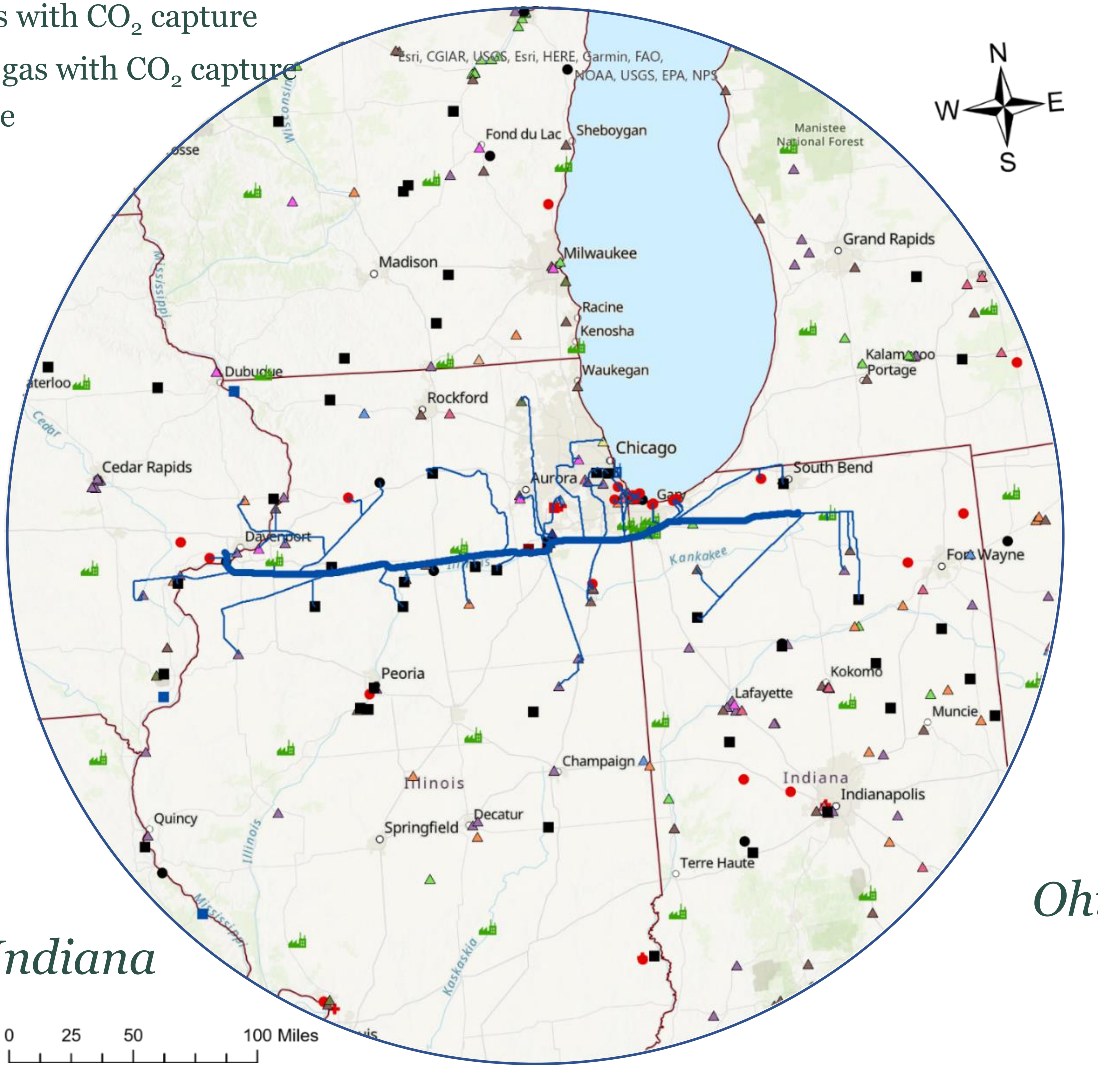
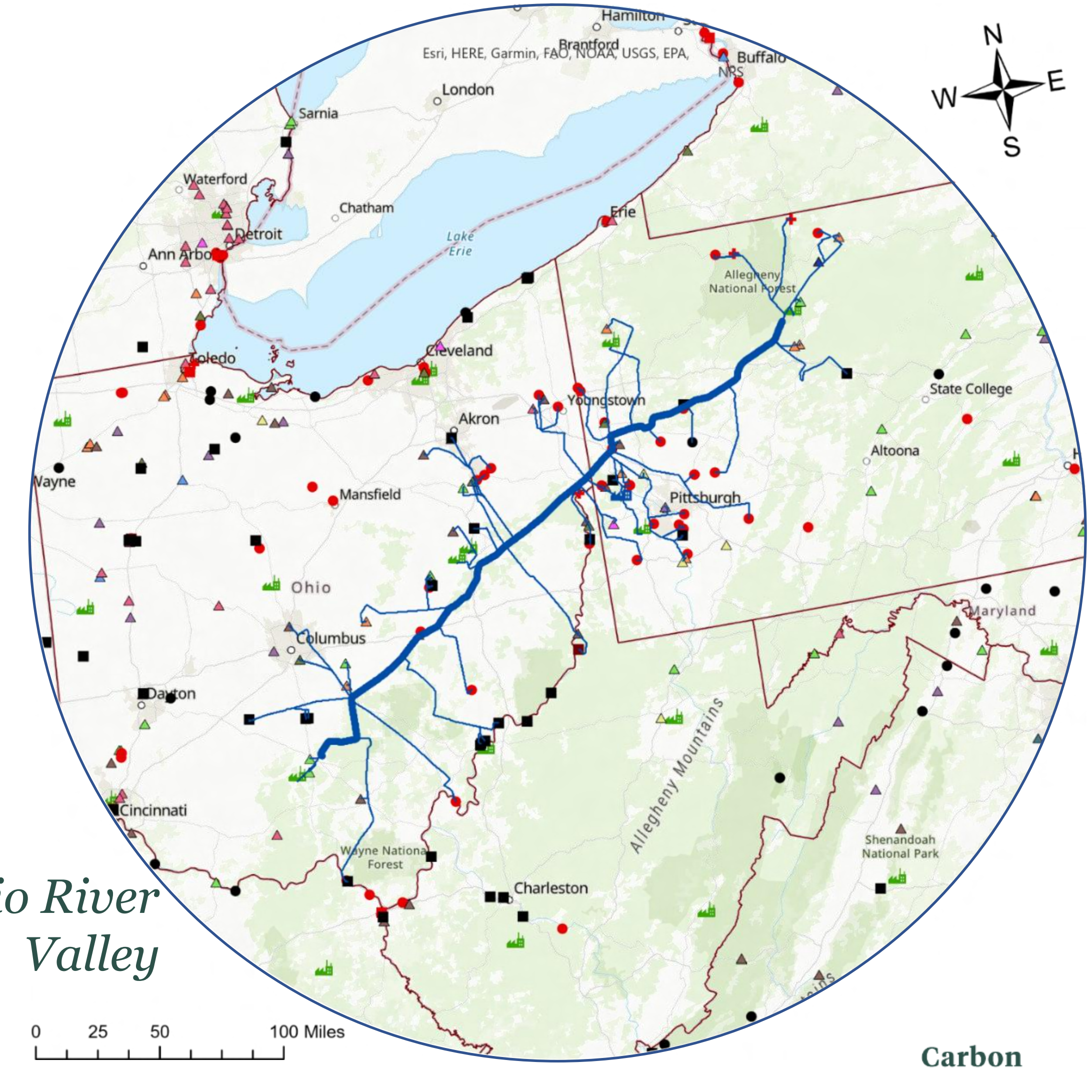
Notional 2050 H_2 production and use clusters: Midwest vignettes.

2050 H_2 supply system (E+)

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



Illinois/Indiana

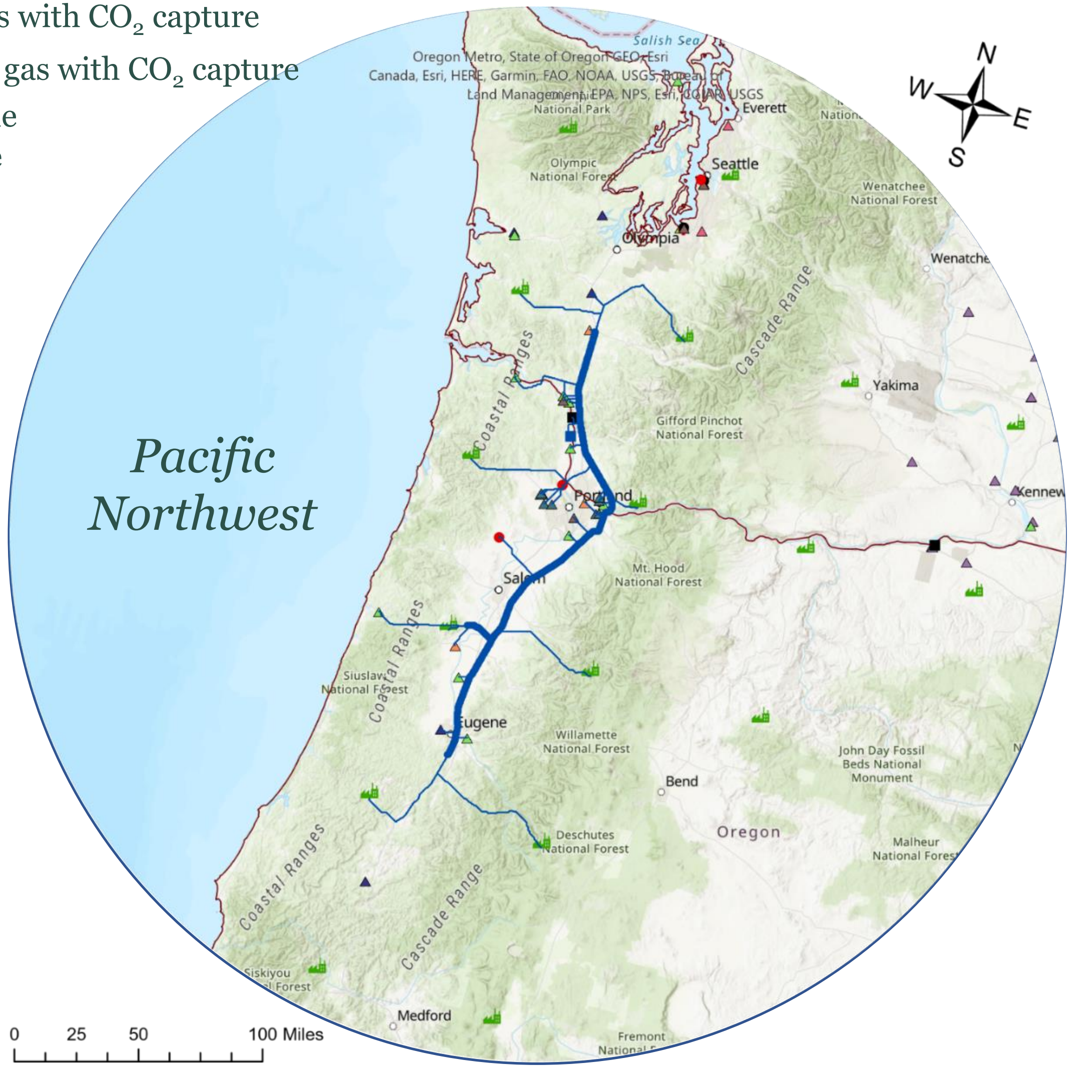


Ohio River Valley

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

2050 H_2 supply system (E+)

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



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Carbon Mitigation Initiative

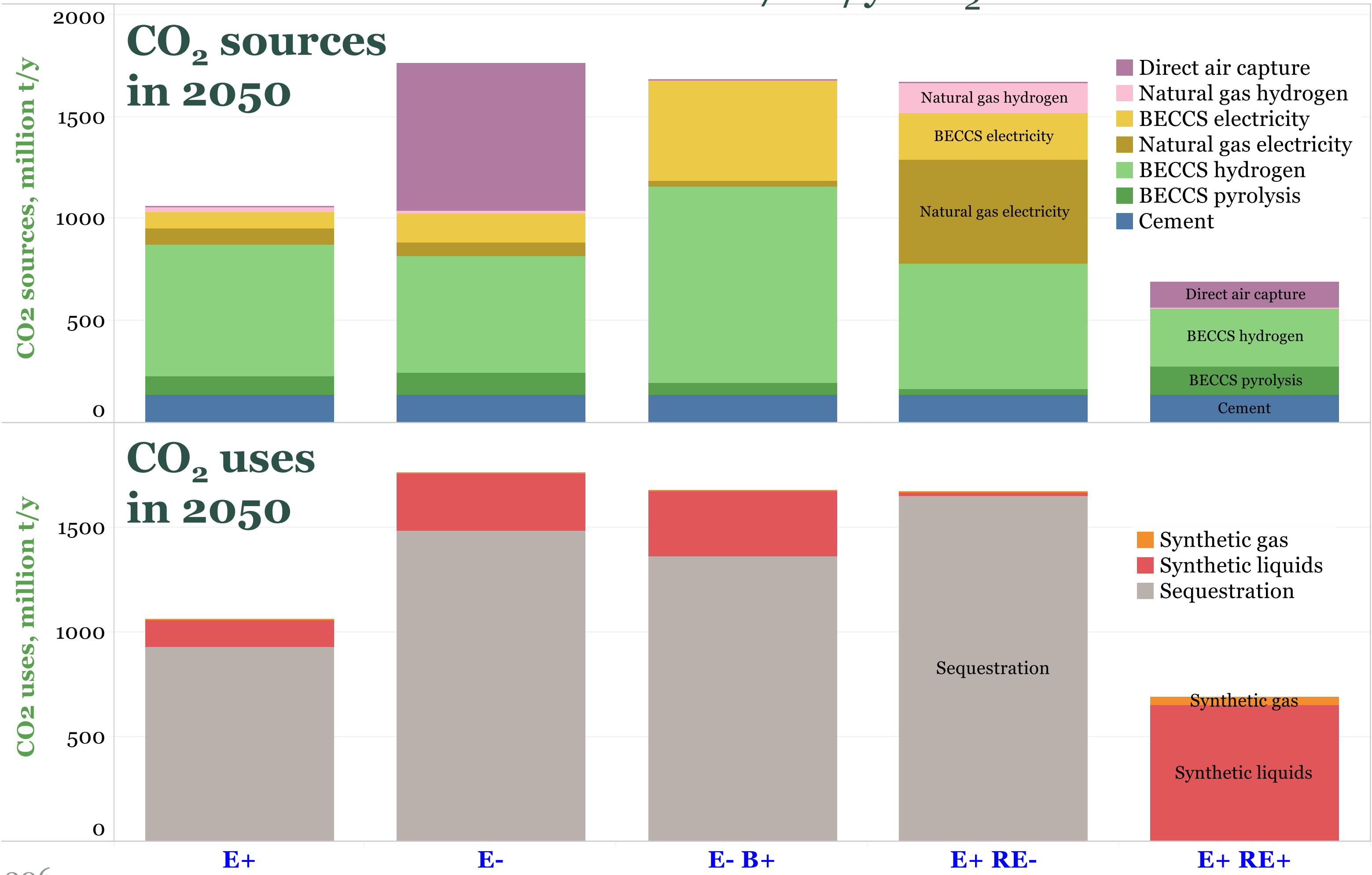
Pillar 4: CO_2 capture, transport, and utilization or geologic storage

Summary of this section

- CO_2 capture is deployed at large scale in all NZA scenarios. Geological storage is deployed at large scale in all NZA scenarios, except E+RE+, where all captured CO_2 is utilized for synthetic fuels.
- CO_2 capture is deployed on cement production, gas- and biomass-fired power generation, natural gas reforming, biomass derived fuels production, and in some cases from direct atmospheric air capture.
- Geological sequestration rates range from almost 1 to 1.7 billion tonnes of CO_2 per annum by 2050, servicing more than a thousand capture facilities distributed across the nation.
- The majority of geologic sequestration takes place in the Texas gulf coast but other basins host sequestration of 10's to more than 100 million tonnes of CO_2 per year.
- An investment of 13 B$ is estimated for stakeholder engagement plus characterization, appraisal and permitting across multiple storage basins and injection sites before 2035 to enable rapid expansion thereafter.
- The CO_2 capture utilization and storage (CCUS) industry is enabled by around 110,000 km of new CO_2 pipeline infrastructure with an estimated capital cost of $170 billion (for E+) to $230 billion (for E-B+).
- Estimated unit costs for CO_2 transport and storage average $17 to $23 per tonne stored depending on the ultimate scale of deployment.
- The scale of CO_2 transport and storage in these scenarios ranges from 1.3 to 2.4 times current US oil production on a volume equivalent basis.
- See Annex I for details around downscaling analysis of CO_2 transport and geologic storage.

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

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



CO_2 sources

Direct air capture

Natural gas hydrogen (autothermal reforming)

BECCS electricity (gasifier-Allam cycle)

Natural gas electricity (Allam cycle)

BECCS hydrogen (gasifier/water gas shift)

BECCS pyrolysis (hydrocatalytic)

Cement via 90% capture (post-combustion).

CO_2 uses

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

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

Sequestration = geological storage

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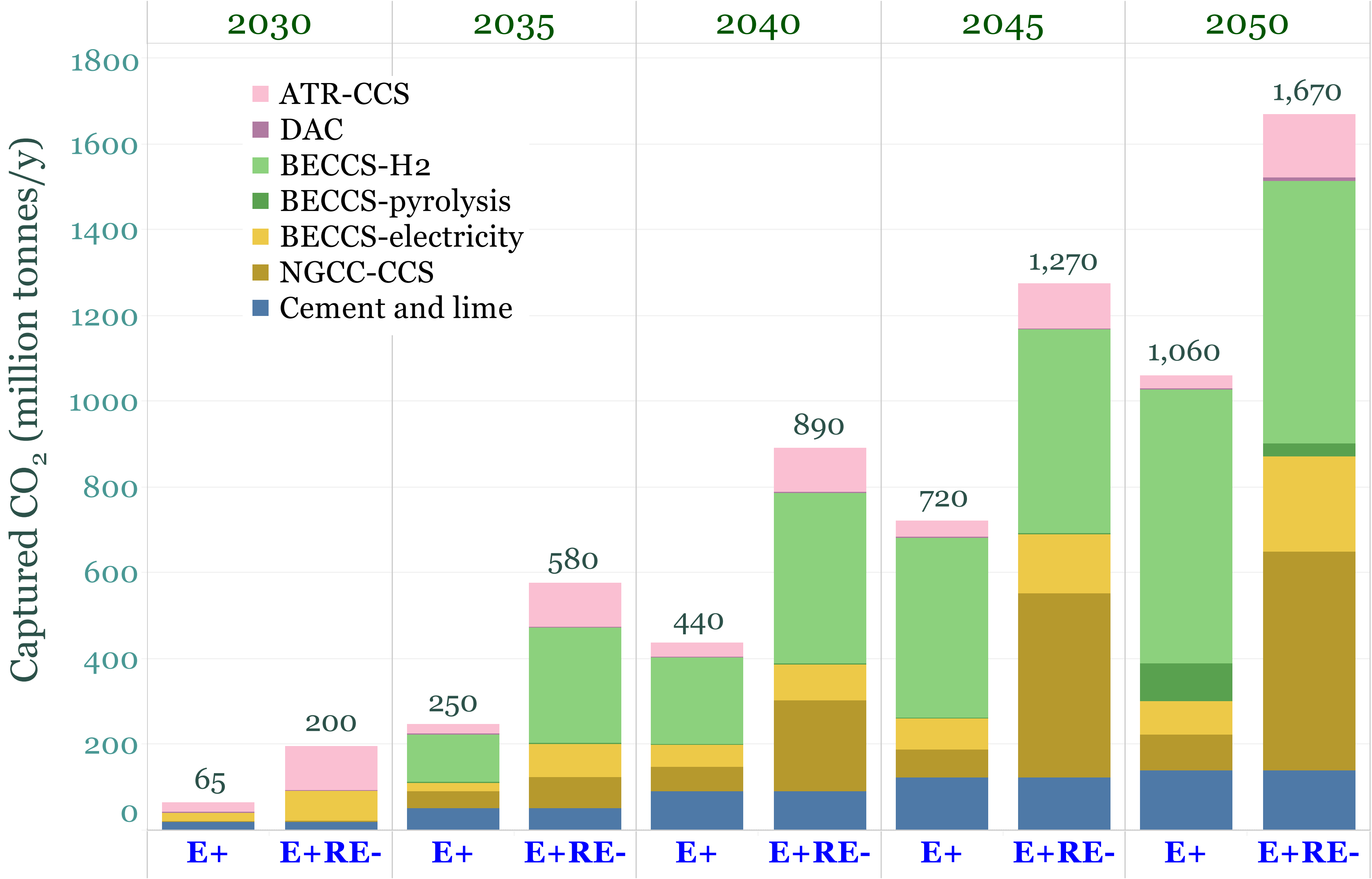
Some capture plants online by 2030, followed by rapid growth in 2030s and 2040s. E+ and E+RE- pathways are shown here.



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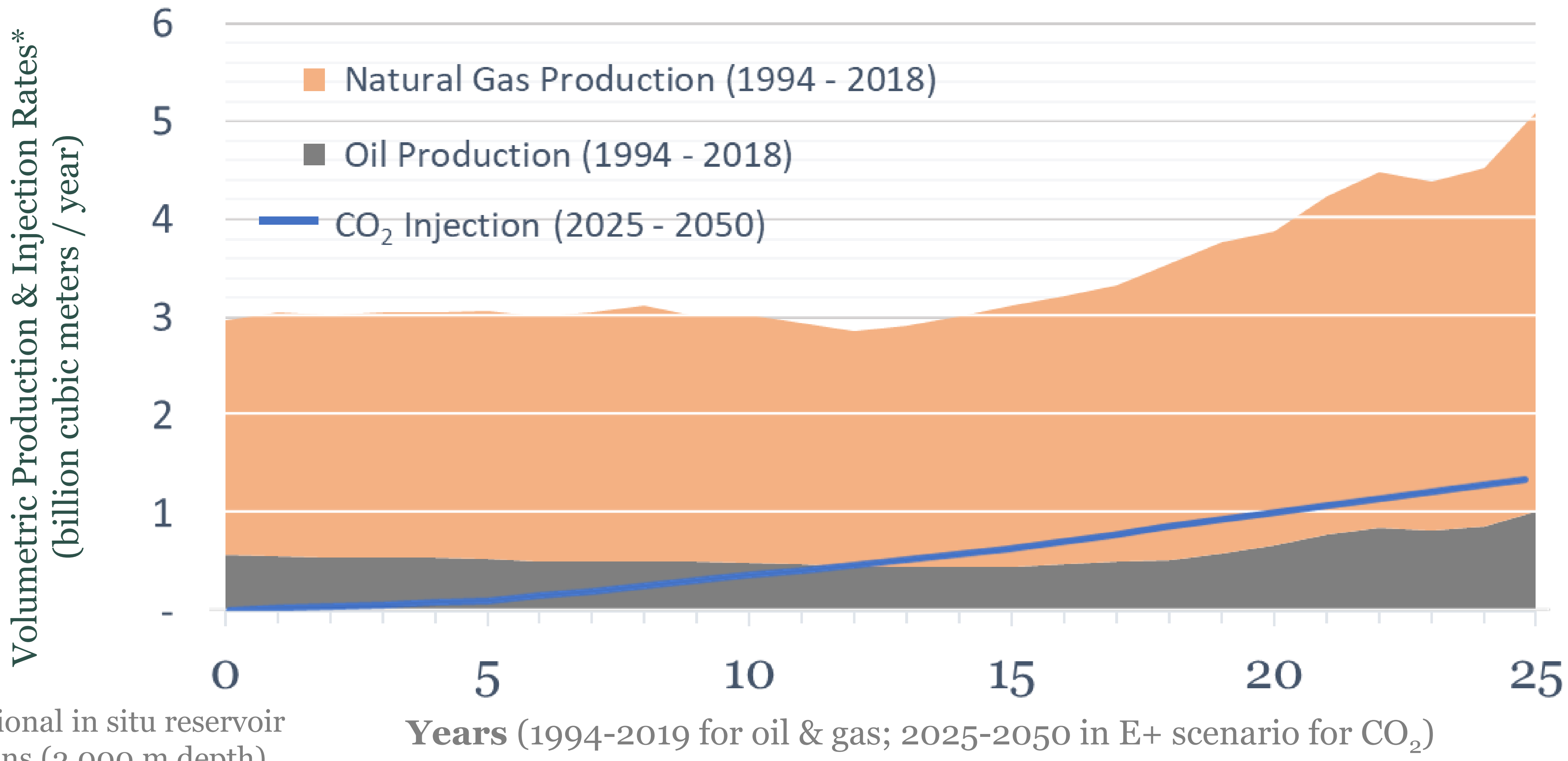
CO_2 injection rates grow from small today to 27% of 2018 oil & gas extraction rates in 2050 (at notional in situ reservoir conditions)



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

Oil & gas production data from BP Statistical review of Energy

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

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

See Annex I for additional details

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

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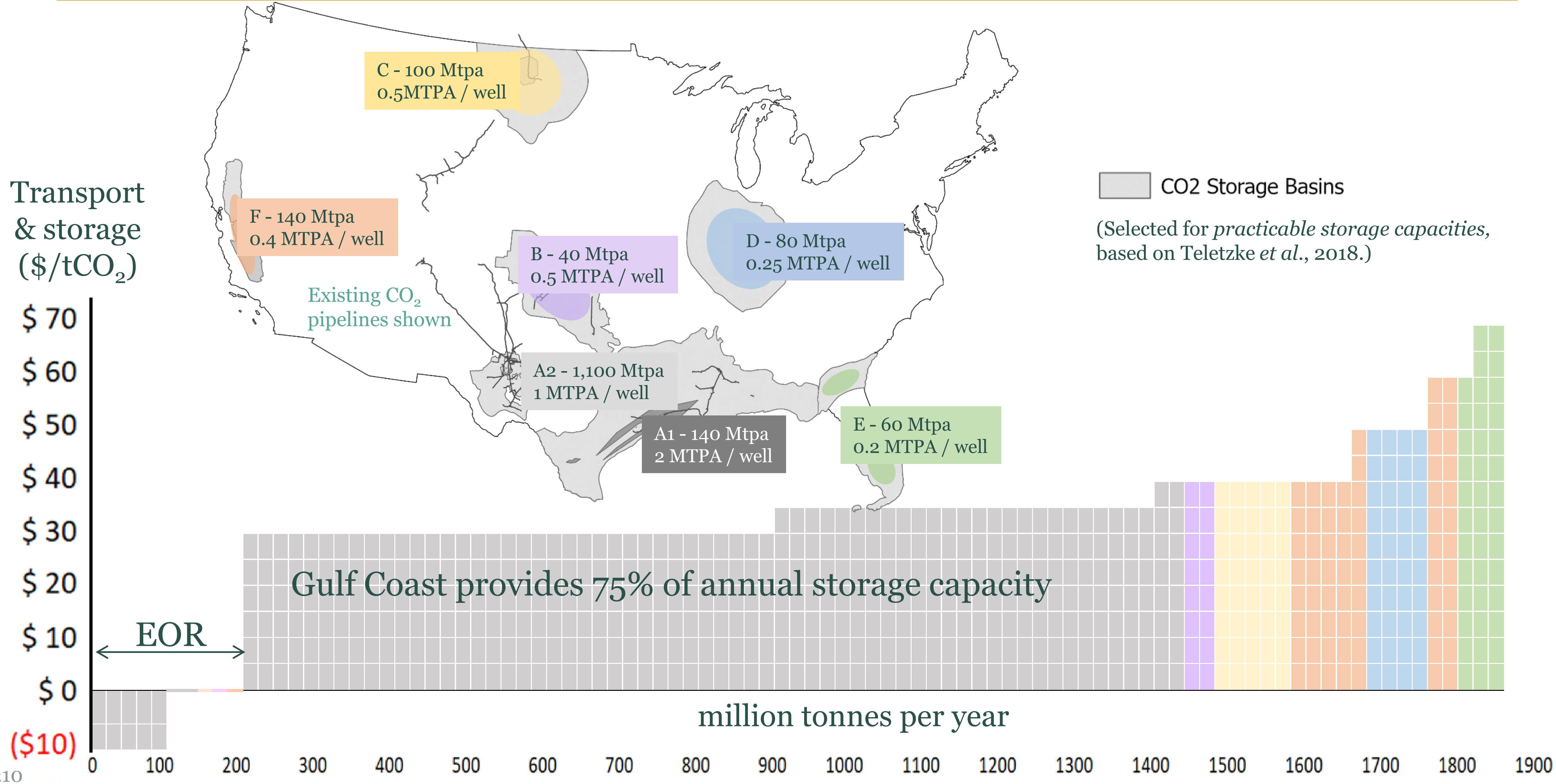
Notional CO_2 storage capacity appraised, permitted and developed in 2050 is up to 1.8 billion t/y, mostly in Gulf Coast



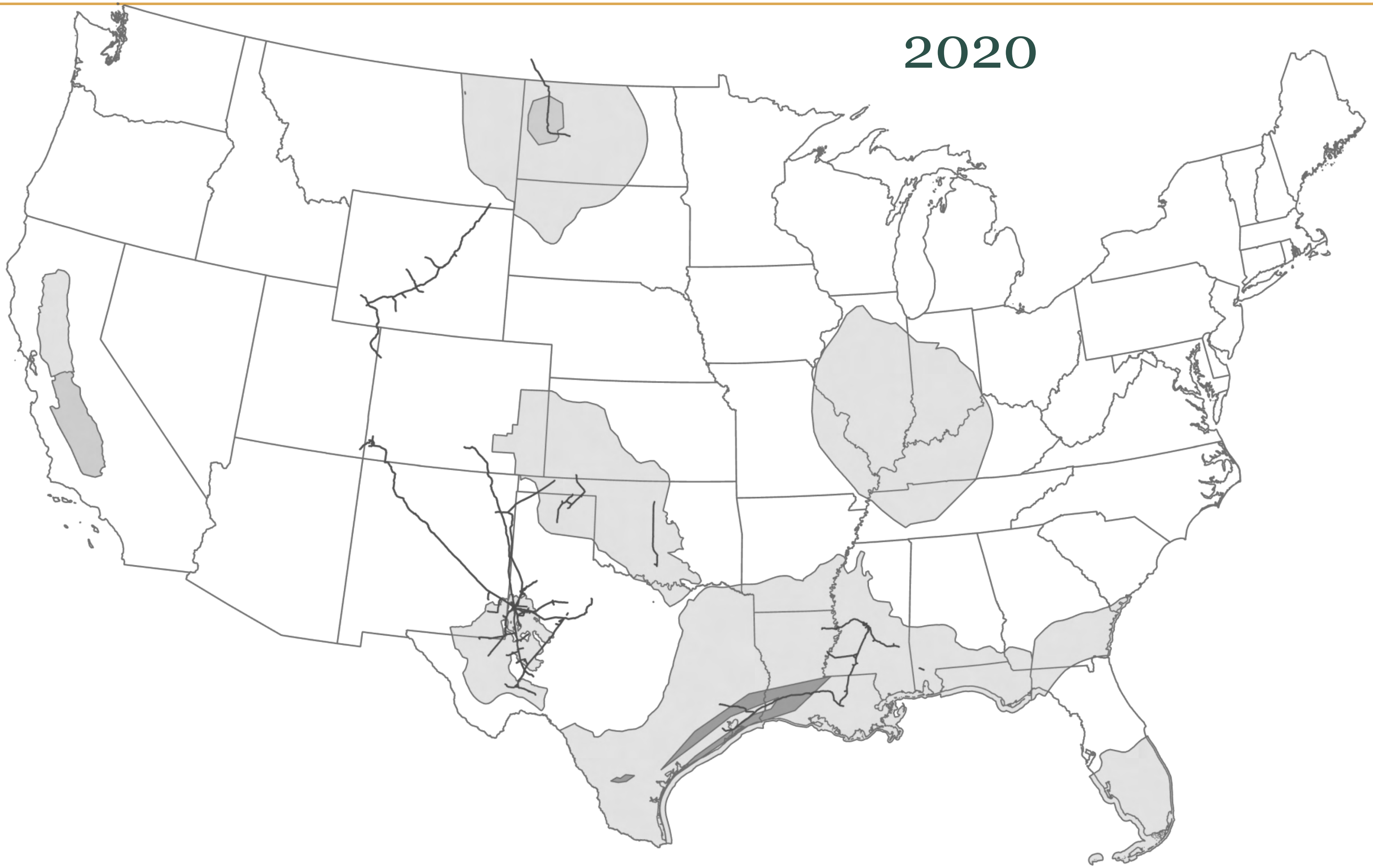
13 B$ invested in stakeholder engagement and characterization, appraisal & permitting pre-2035 enables rapid expansion thereafter.

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

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

Existing CO_2 pipeline network

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

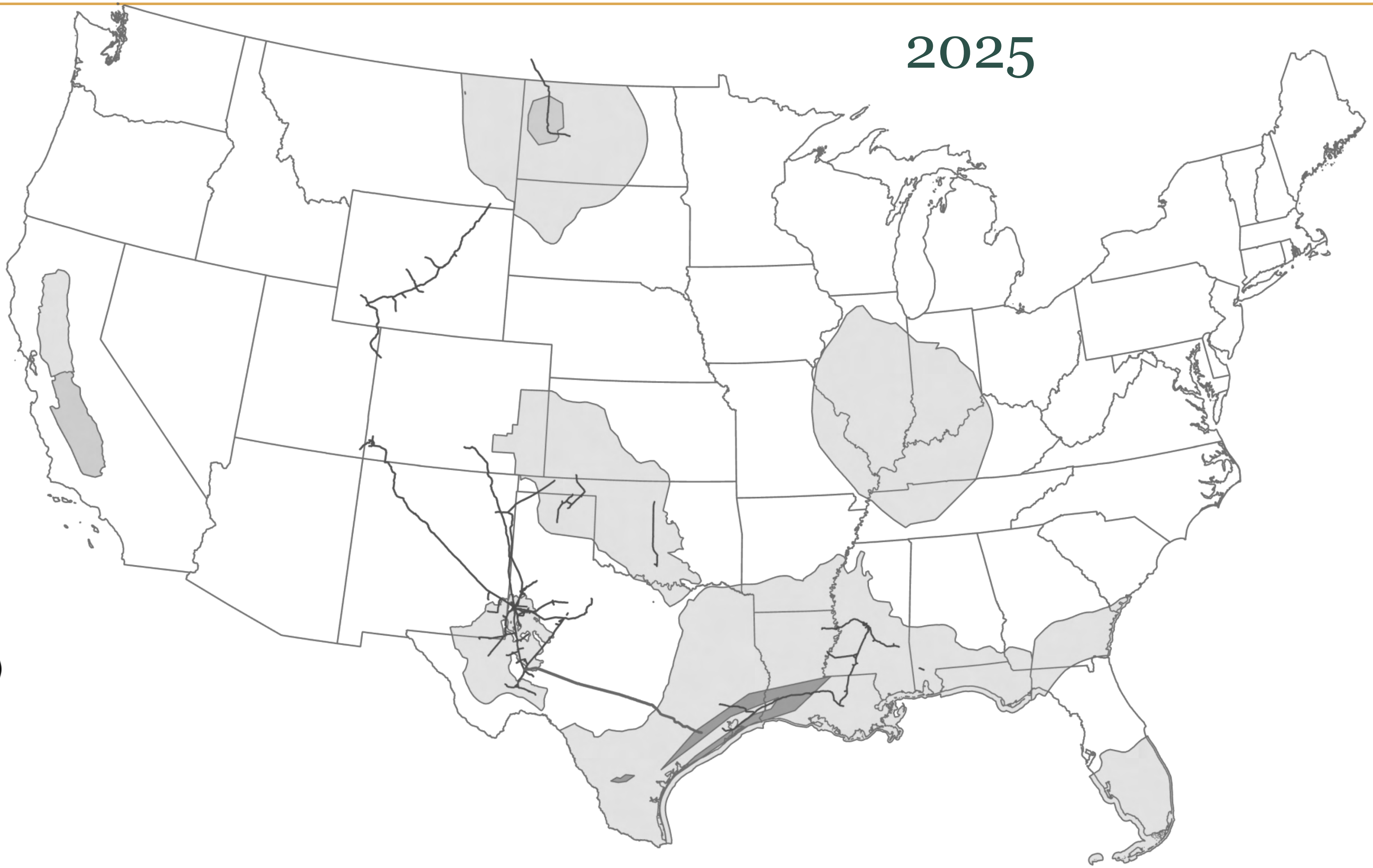


Trunk line construction begins before 2025 with connection between Permian Basin and Gulf Coast

E+ scenario

2025

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



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

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

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

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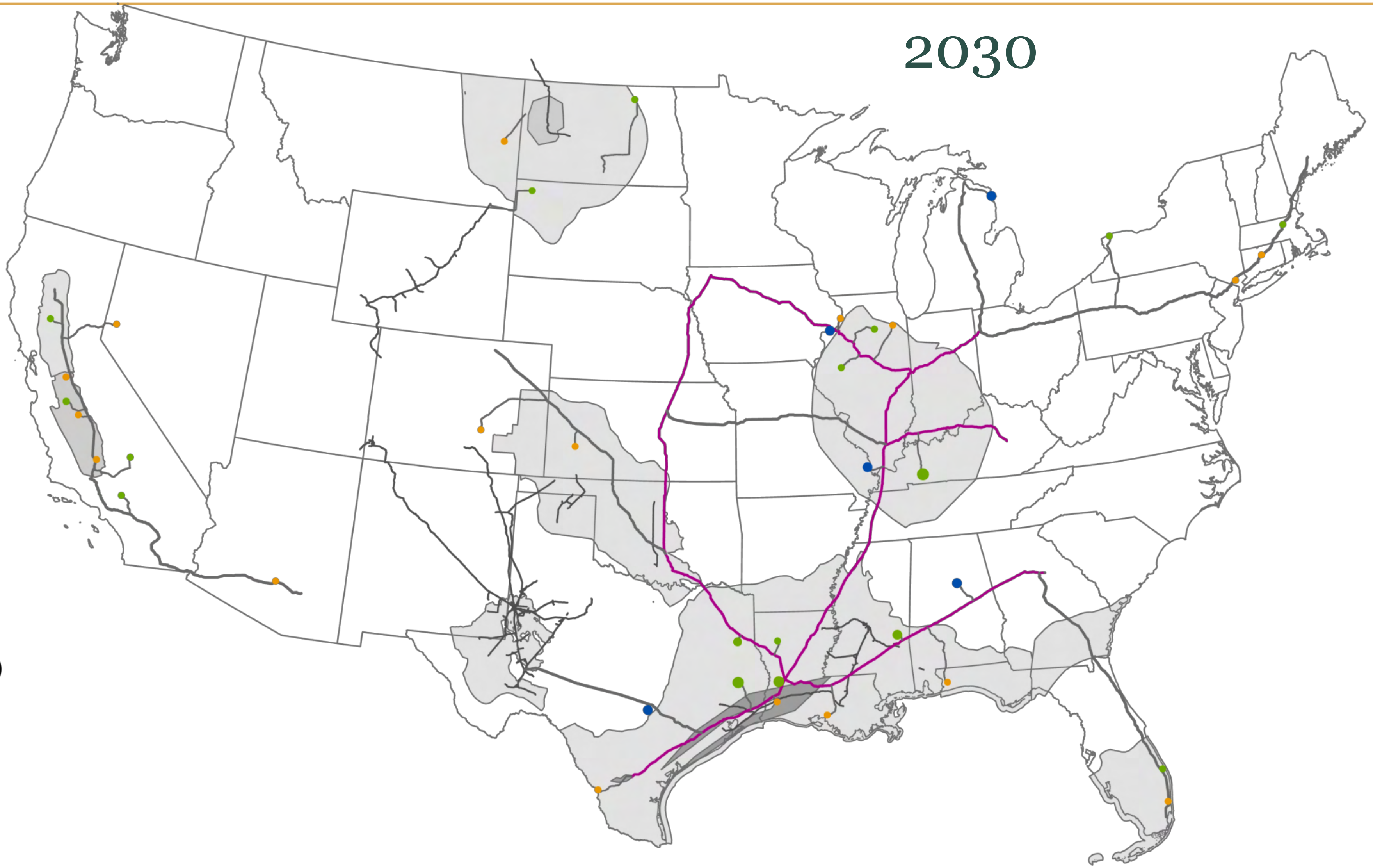
Trunk line build out continues and initial CO_2 capture plants come online, with spur lines connecting to trunk network

E+ scenario

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

2030



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

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

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

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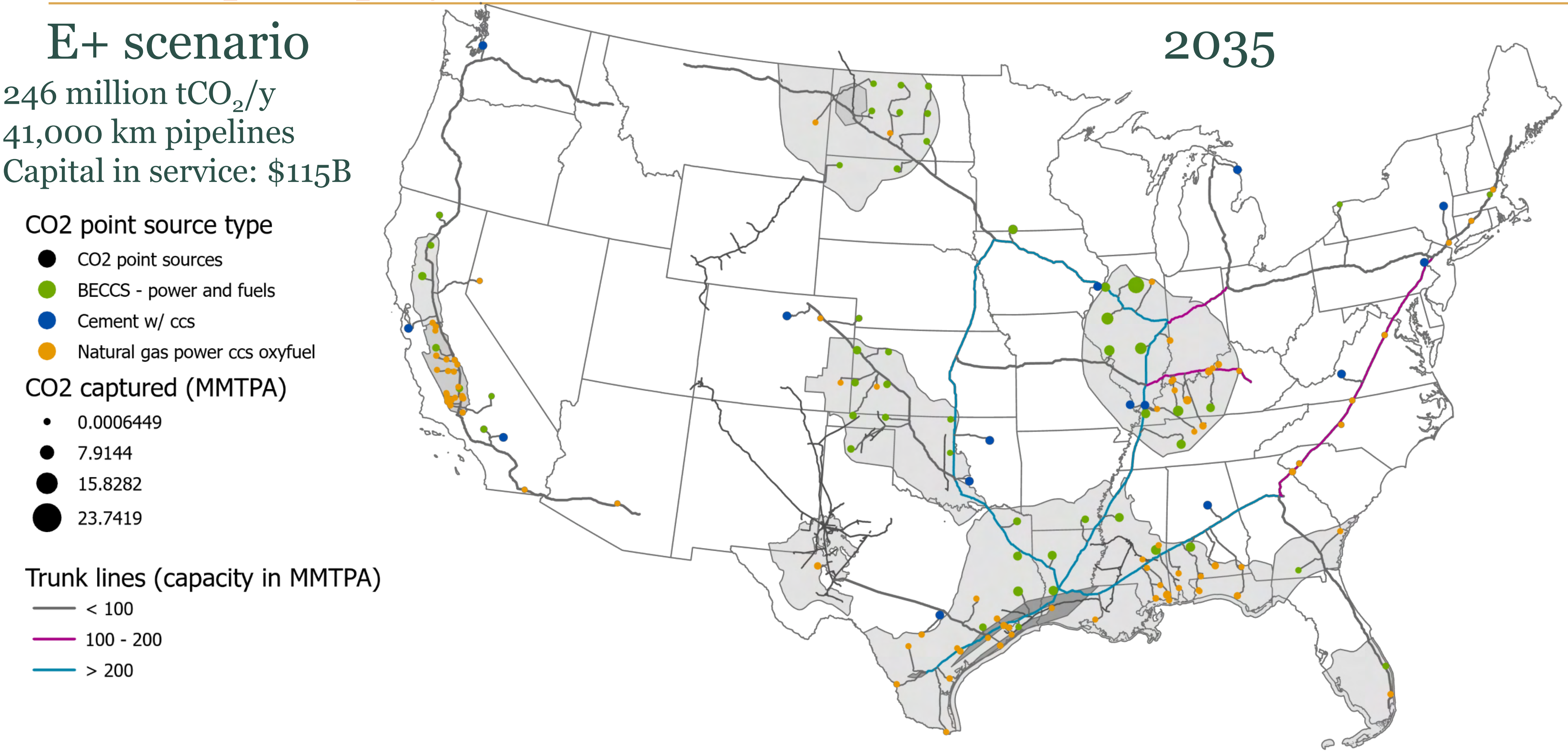
Trunk network routes complete; some sections add parallel lines as more capture projects are built and connected

E+ scenario

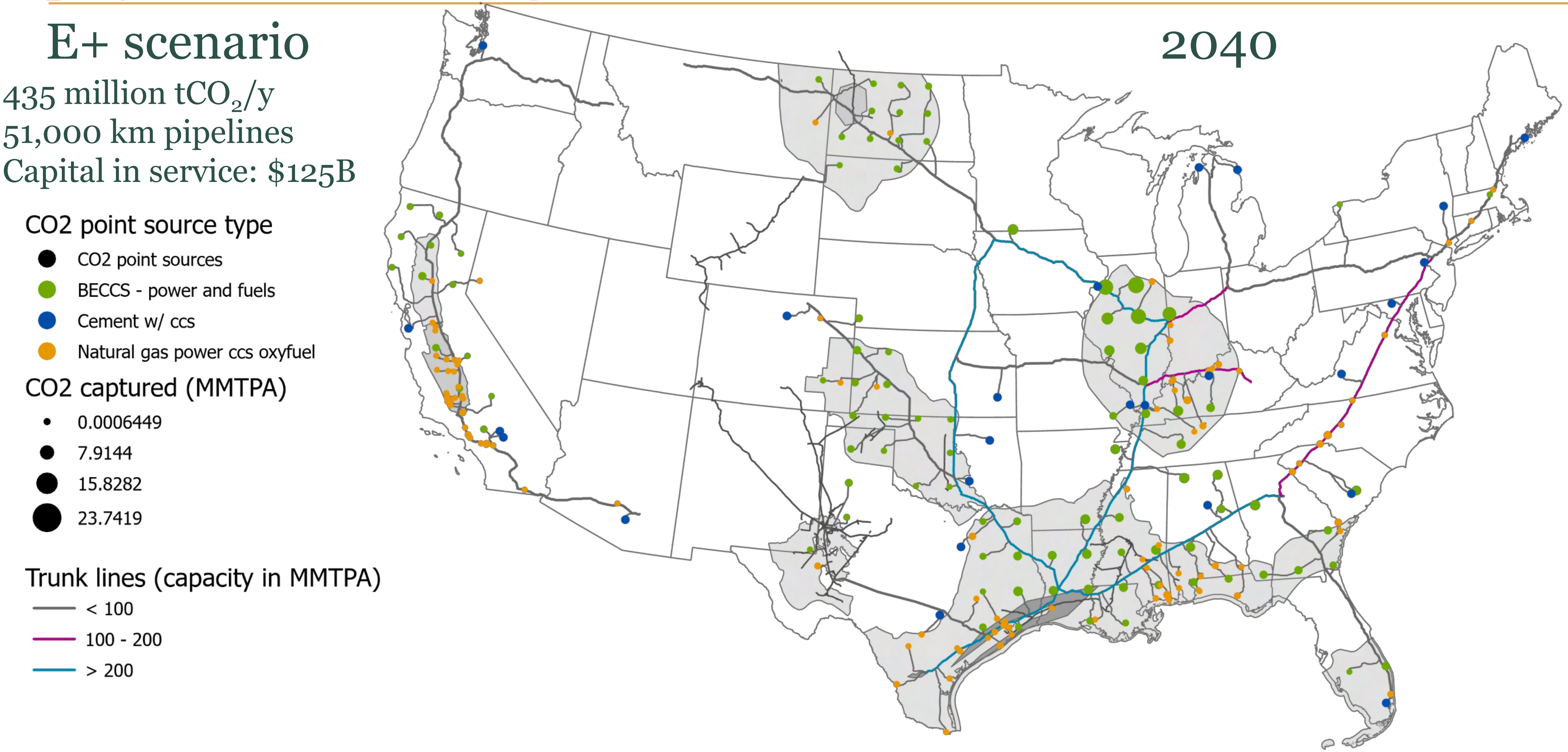
246 million tCO_2/y
41,000 km pipelines
Capital in service: $115B



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

E+ scenario

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



CO_2 capture plants connected to trunk lines grow rapidly

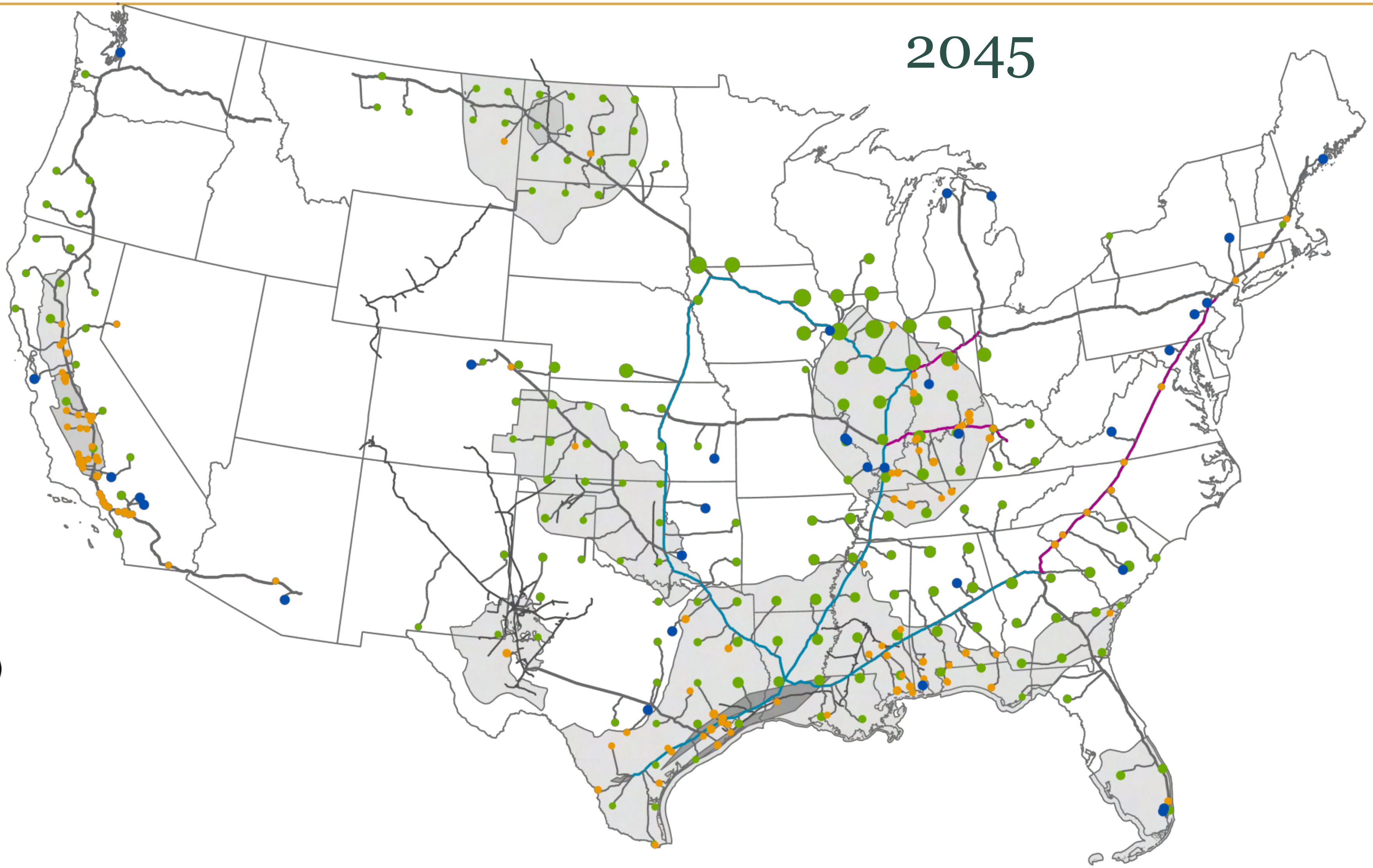
E+ scenario

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

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

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

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



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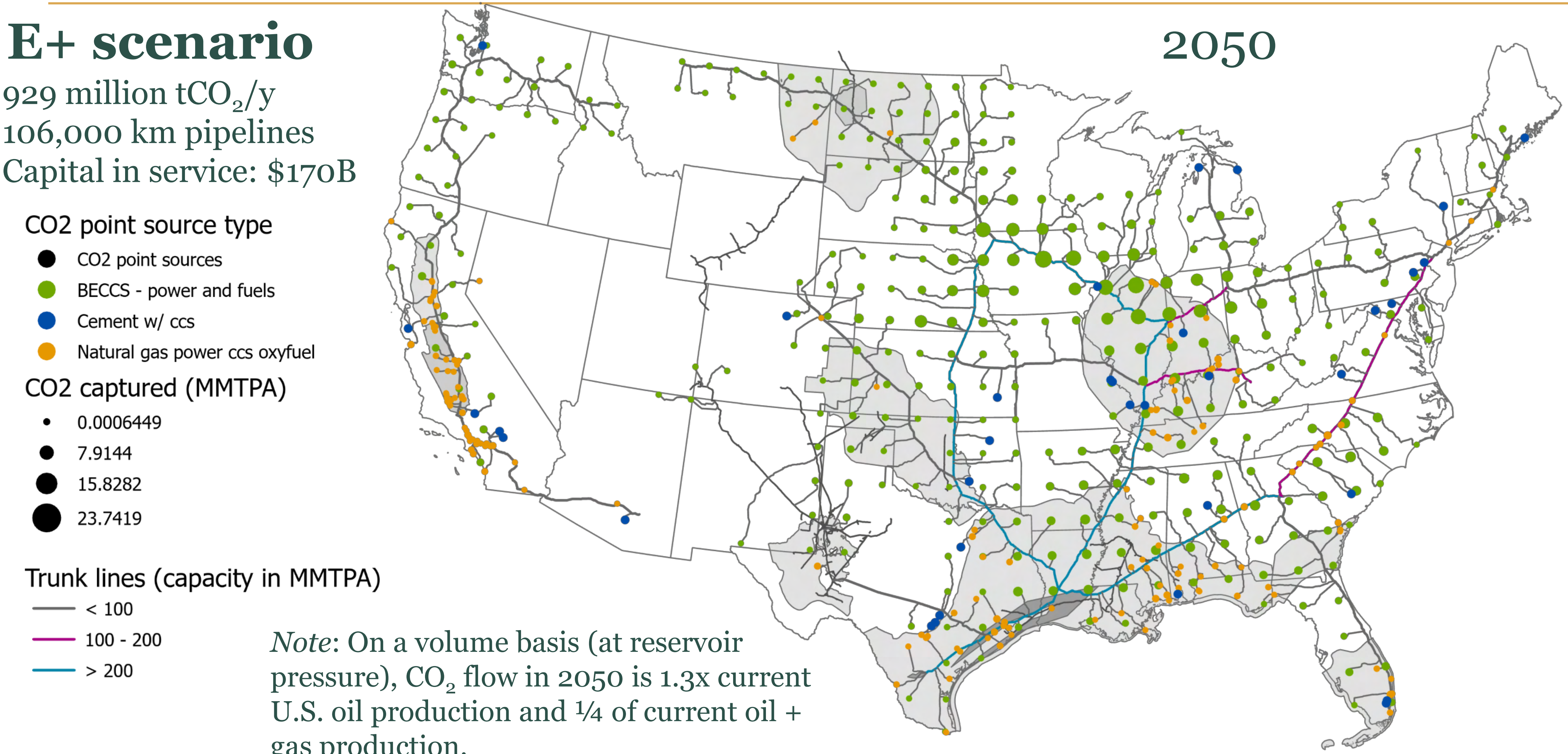
2050 totals: 21,000 km trunk lines + 85,000 km spur lines (equivalent to ~22% of US natural gas transmission pipeline total)

E+ scenario

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



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

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

E-B+ scenario

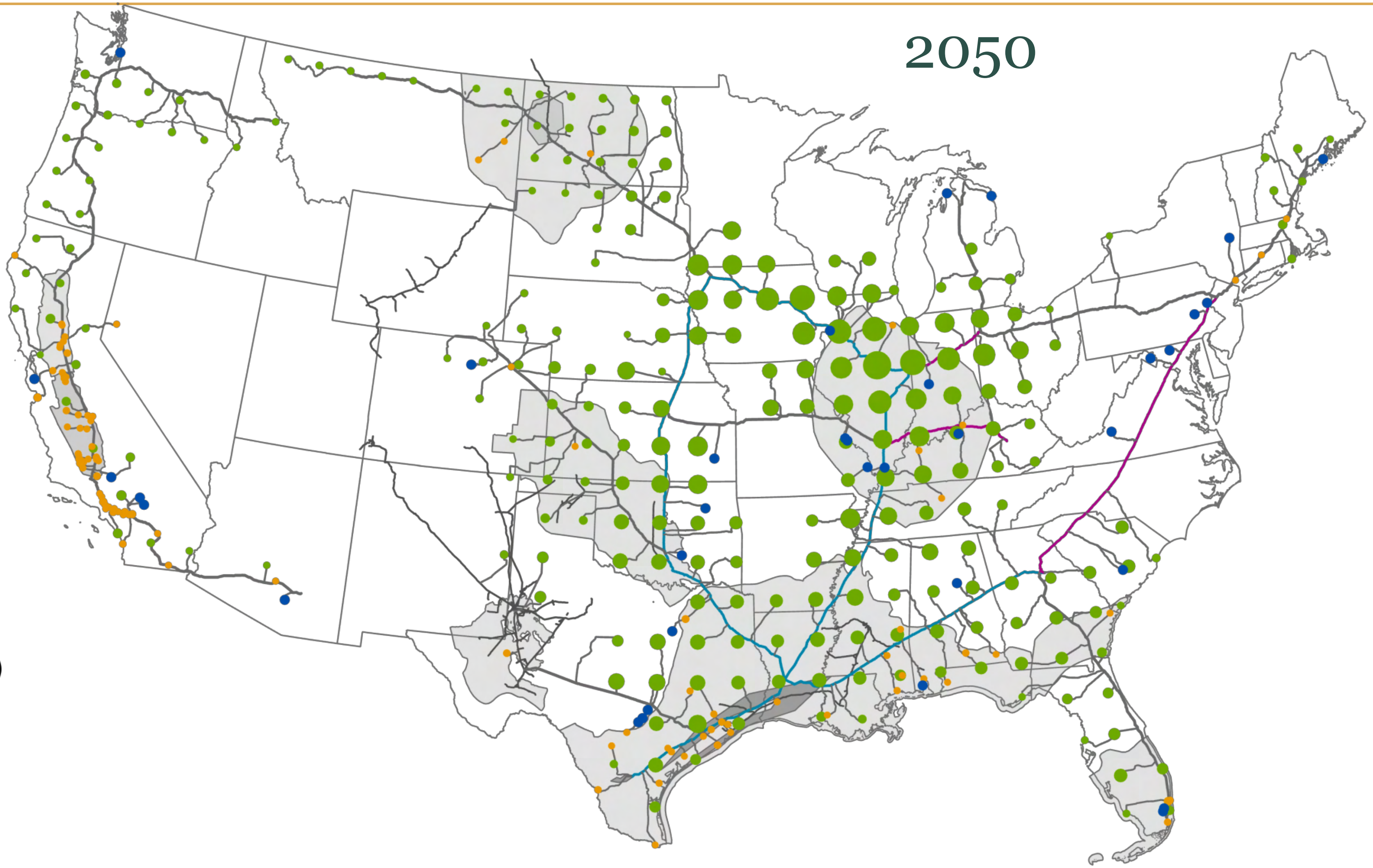
1,361 million tCO_2/y
111,000 km pipelines
Capital in service: $220B

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

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

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

2050



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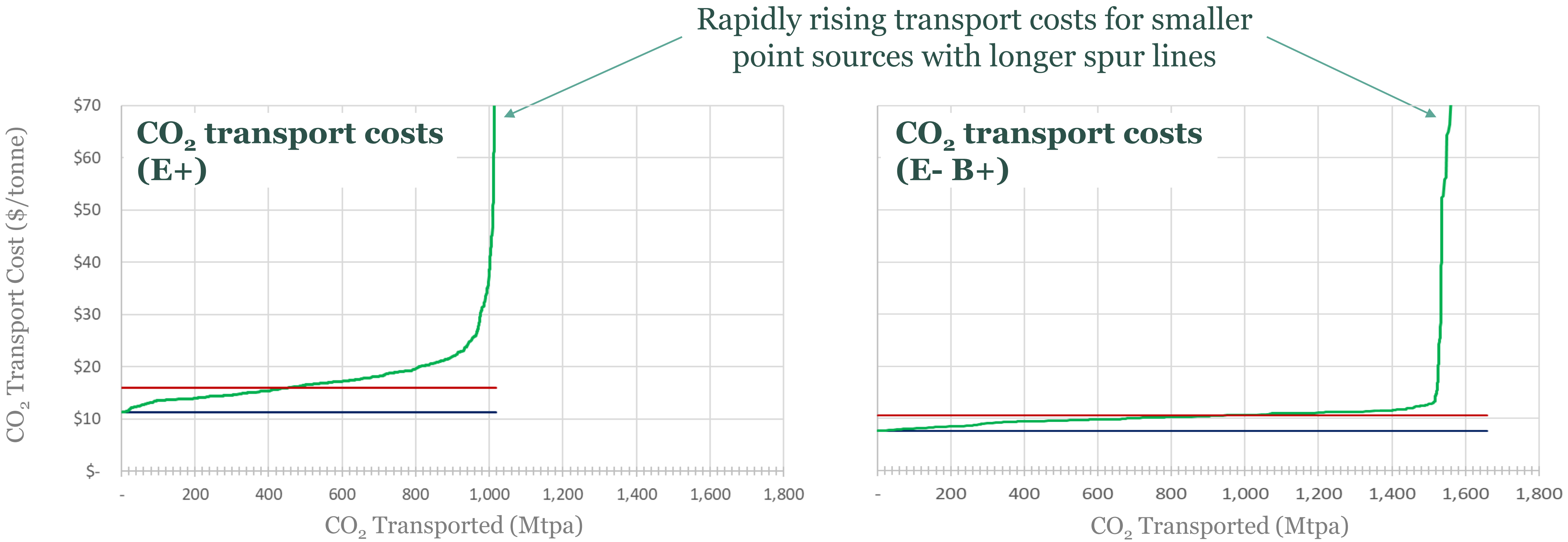
Capital for national CO_2 collection and transport network is \$170 to \$230 billion, or ~ \$11 to \$16/tCO_2 when amortized across all users

Costs (2020$)*	E+	E- B+
Trunk lines		
Total length, km	21,100	25,400
Total installed capital cost, billion 2020$	101	135
National network-access charge, \$/tCO_2 delivered	11.3	7.6
Center-East network-access charge, \$/tCO_2 delivered	11.3	7.4
West network-access charge, \$/tCO_2 delivered	11.6	10.4
Spur lines		
Total length, km	85,800	85,700
Total installed capital cost, billion 2020$	69	88
National network-access charge, \$/tCO_2 delivered	4.6	3.0
Total trunk + spur lines		
National network-access charge, \$/tCO_2 delivered	15.9	10.6

Higher charge for West than for Center-East trunk network

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

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



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

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

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

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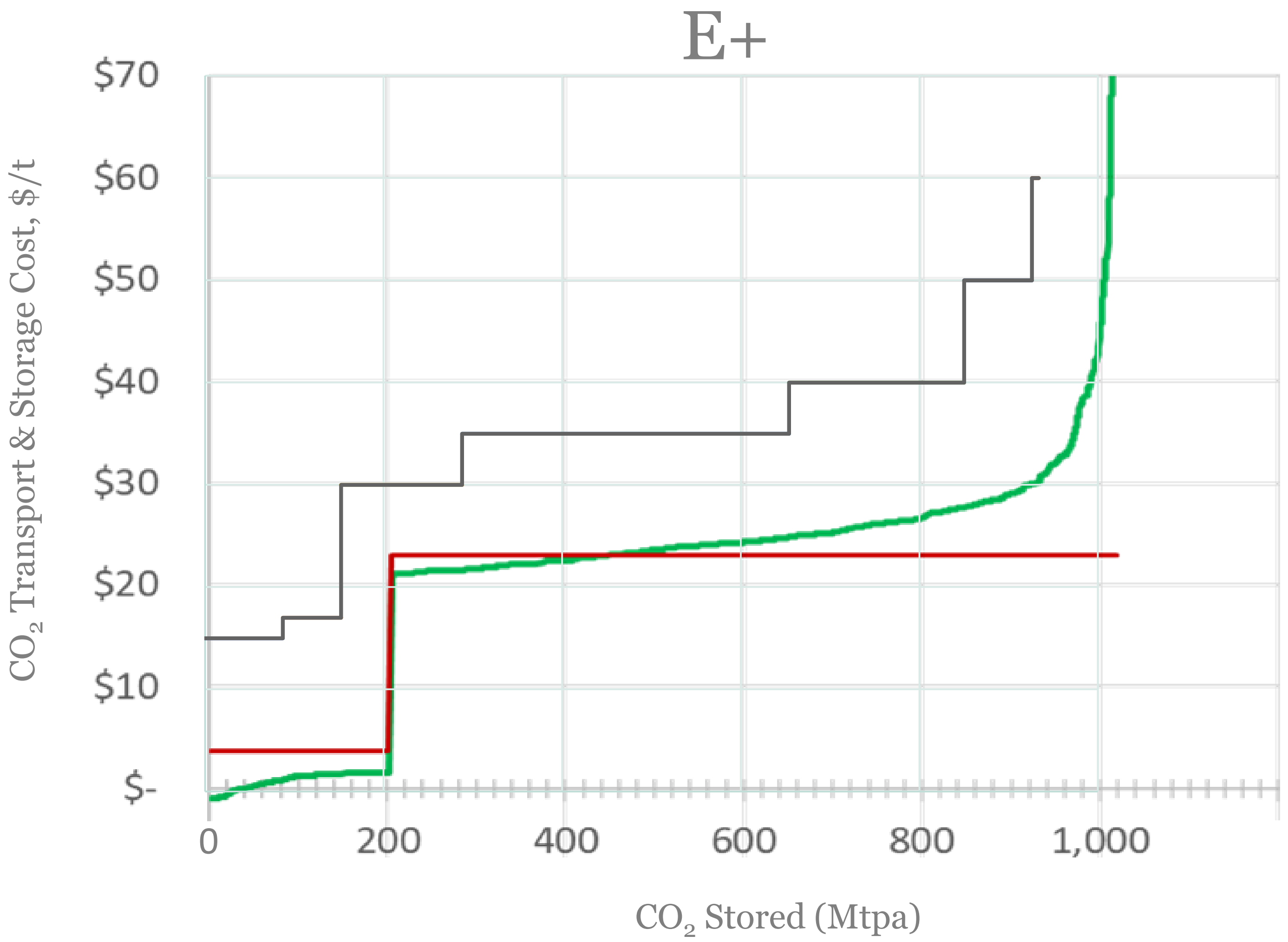
Storage adds $7/t$CO_2$ (DOE low-end estimate) and EOR provides credit of $19/t$CO_2$ (for $50/bbl oil*).



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

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

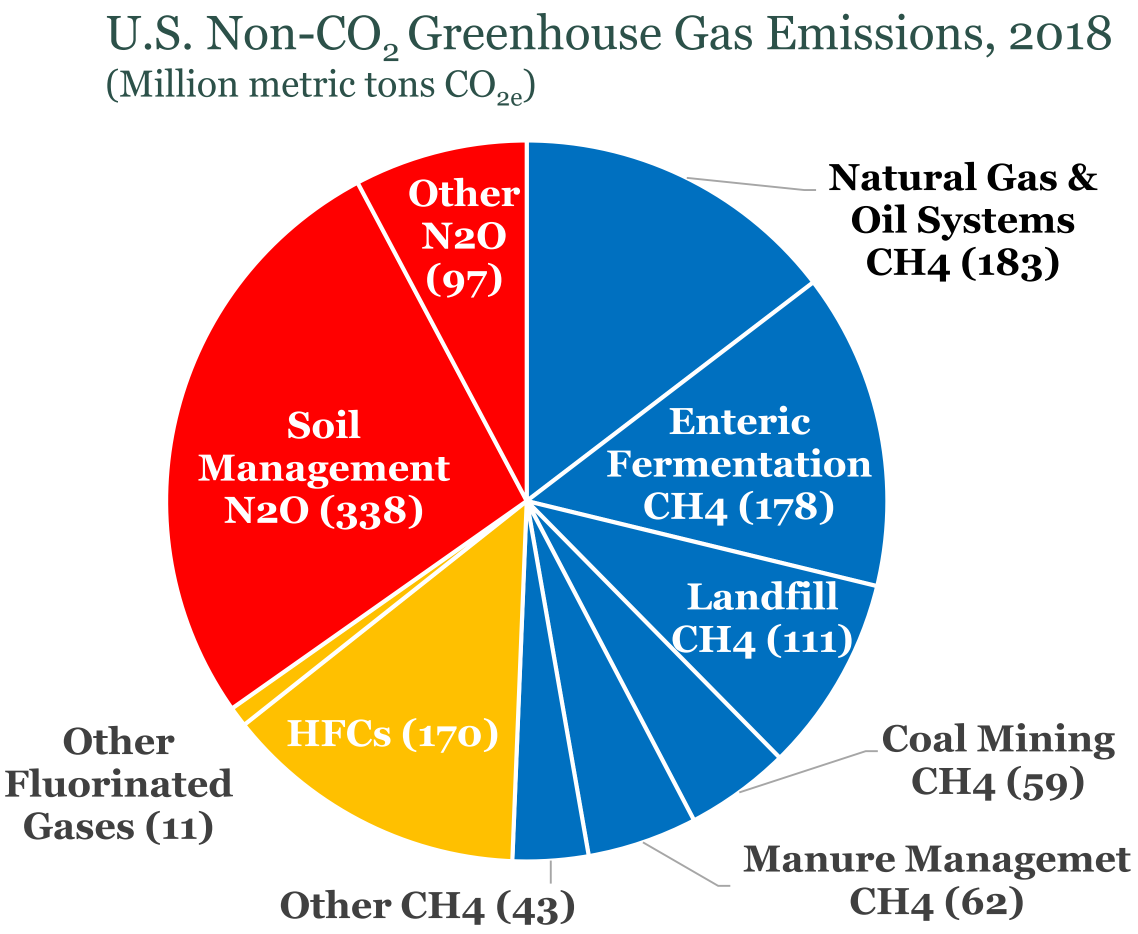
* Rubin, et al. (2015) wrote that "conventional wisdom suggests that the price that EOR projects can afford to pay for CO_2 (in $/1000 standard ft³) is 2% of the oil price in $/bbl."

Pillar 5: Reduced non-CO_2 emissions

Summary of this section

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

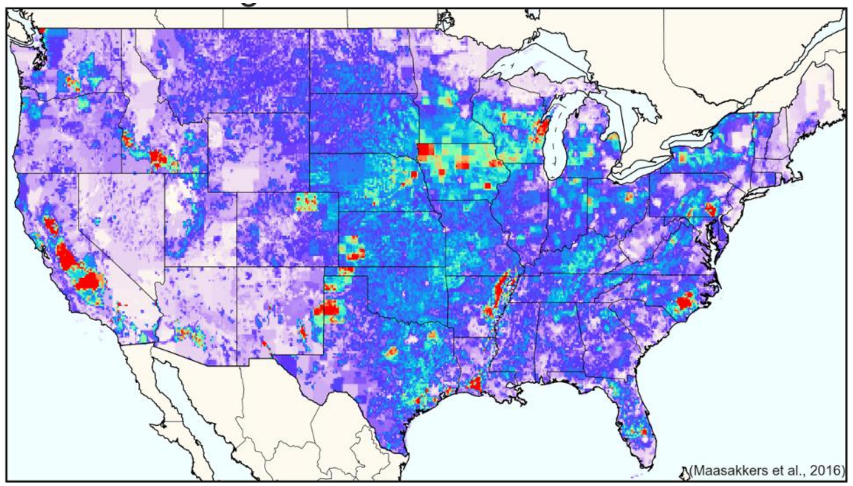
Non-CO_2 emissions today are 1.25 $GtCO_{2e}$/year



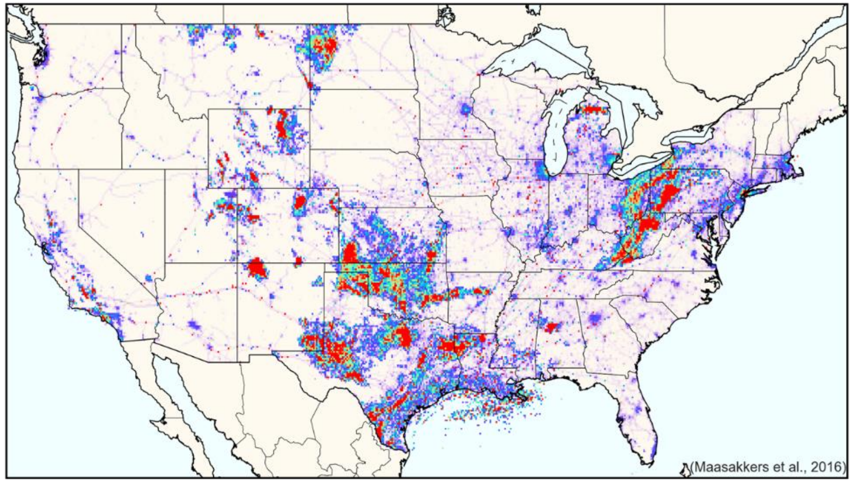
Source: EPA, *2020 GHG Inventory*

Methane emissions follow energy and agricultural production patterns and population densities

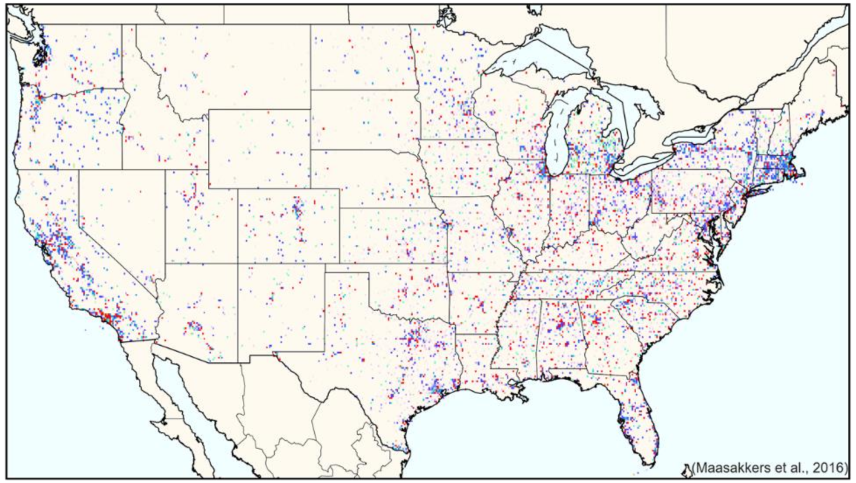
Agricultural emissions are dominated by livestock and dairy production



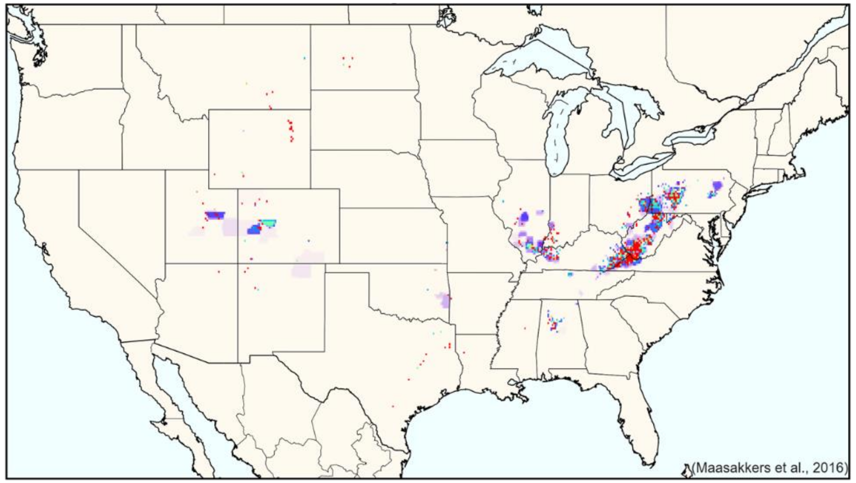
Oil and gas upstream emissions align with production & processing; downstream with pop.



Waste emissions are aligned with population density



Coal upstream emissions are dominated by Appalachian subsurface mining.



Source: EPA

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

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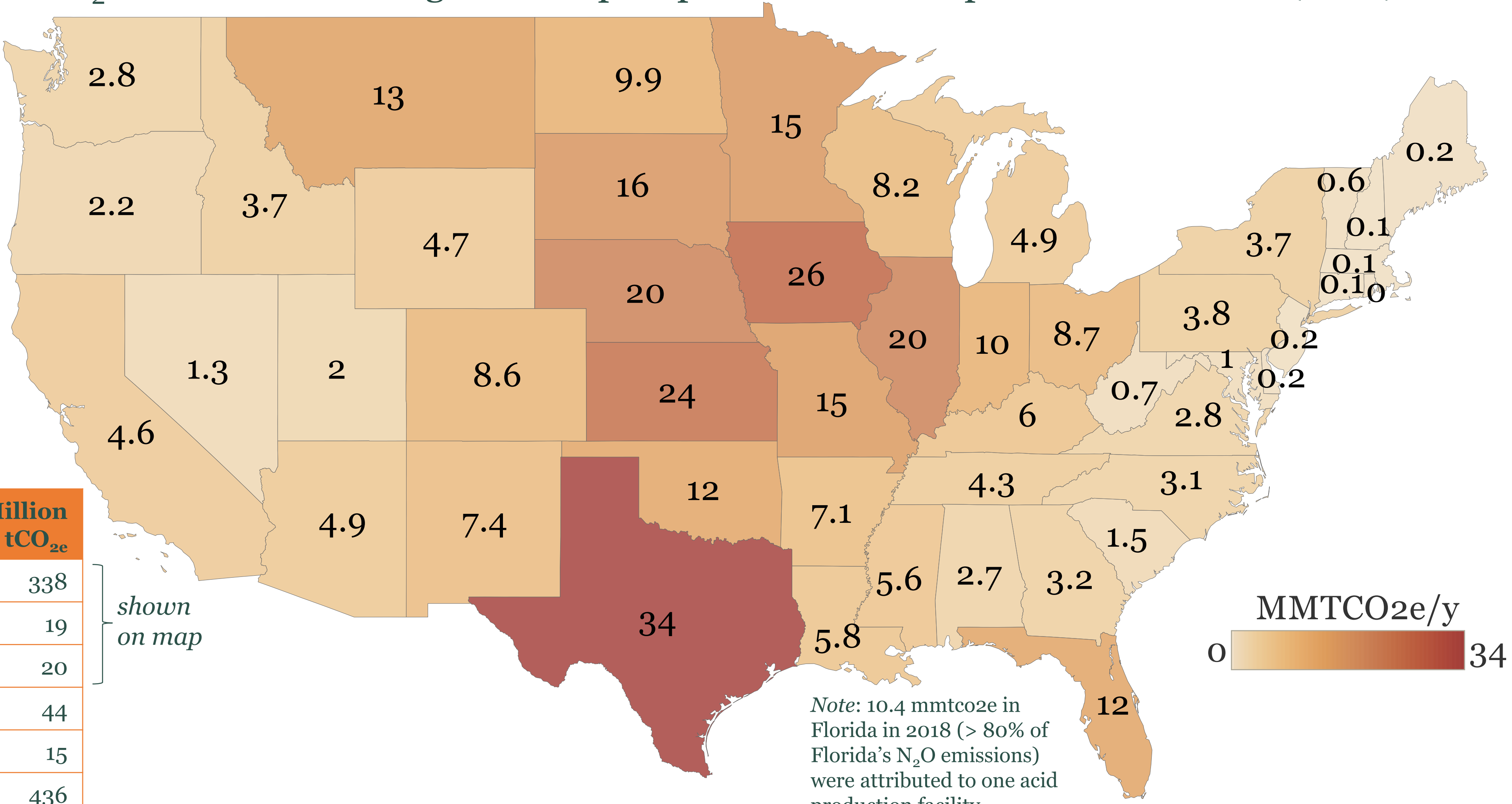
N_2O emissions occur mostly outside of the energy sector and in states with significant agricultural production.

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



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

shown on map

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

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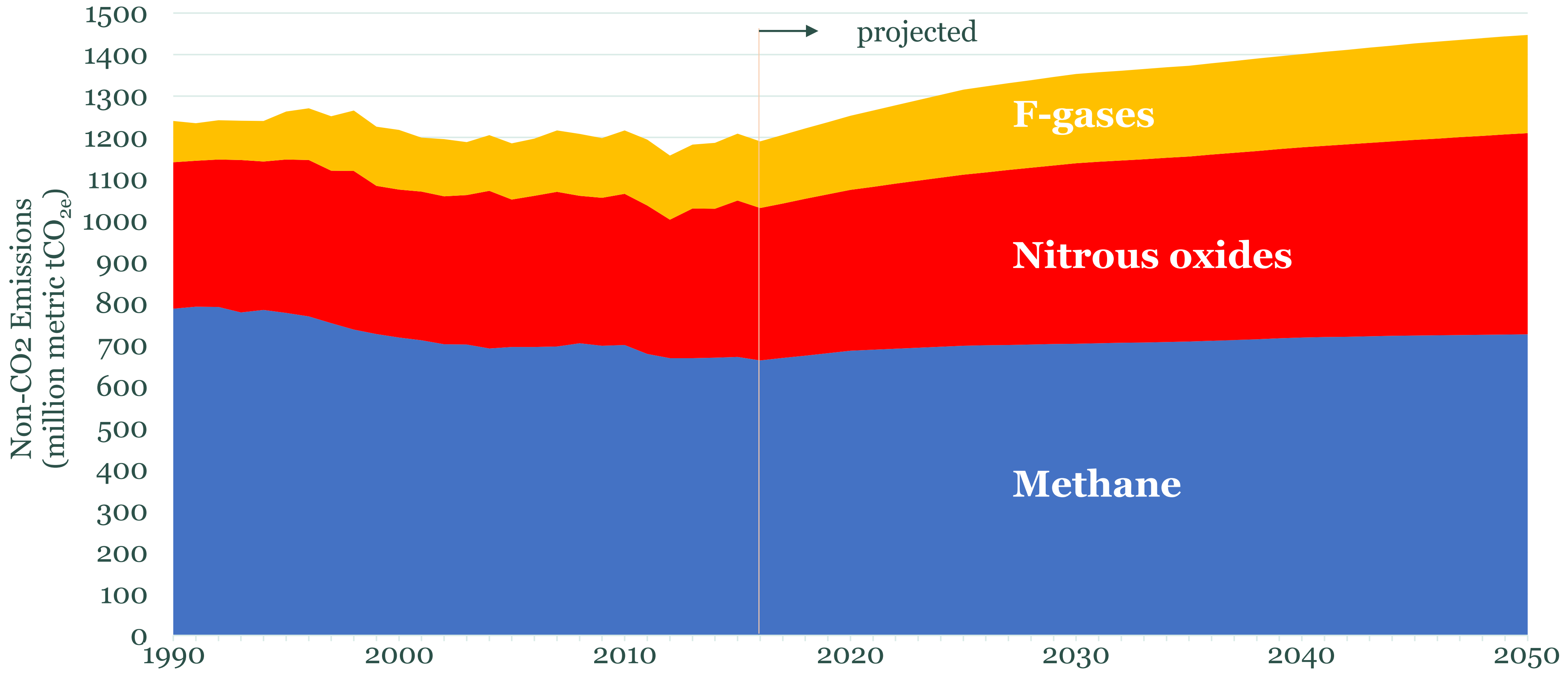
Without mitigation efforts, non-CO_2 emissions grow gradually to 1.45 $GtCO_{2e}$ by 2050, with CH_4 and N_2O contributing most

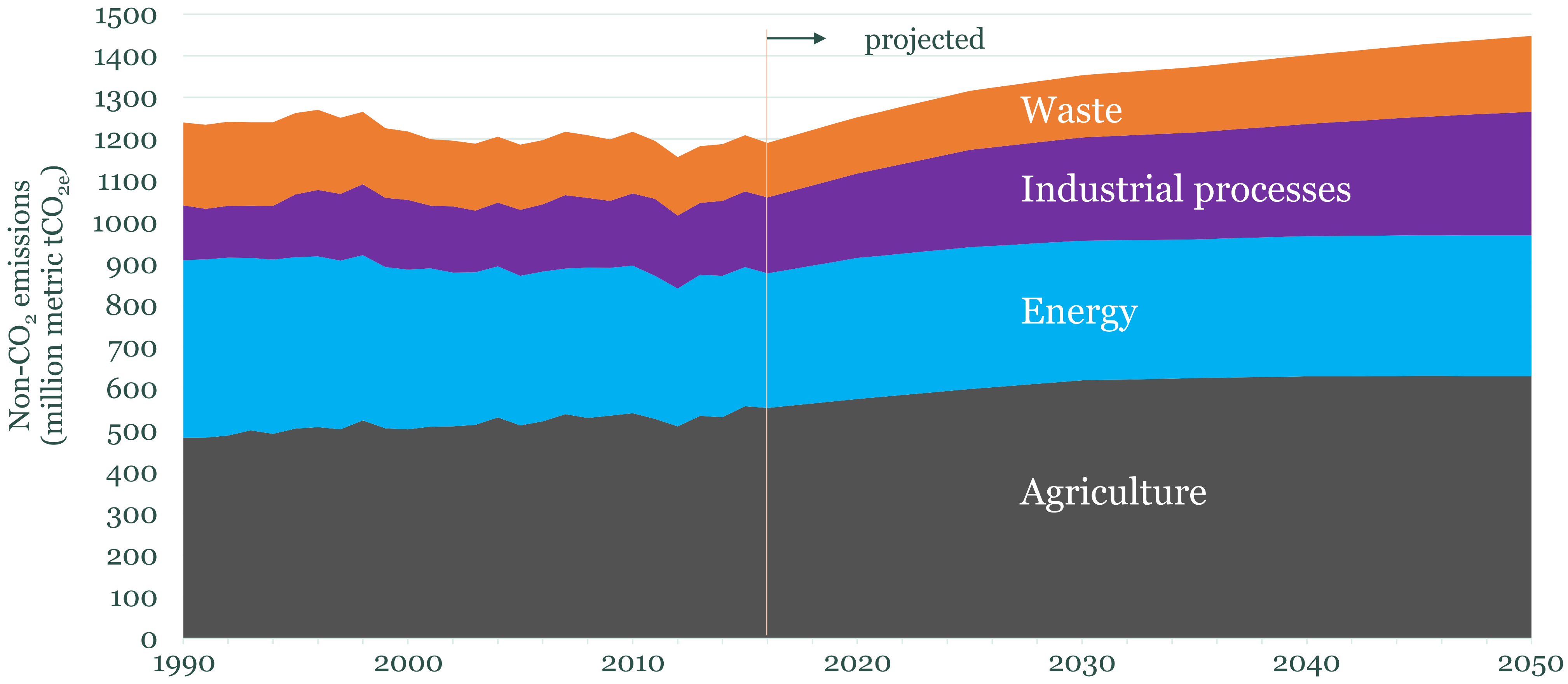
Historical and projected non-CO_2 emissions by gas type under business as usual (BAU)



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

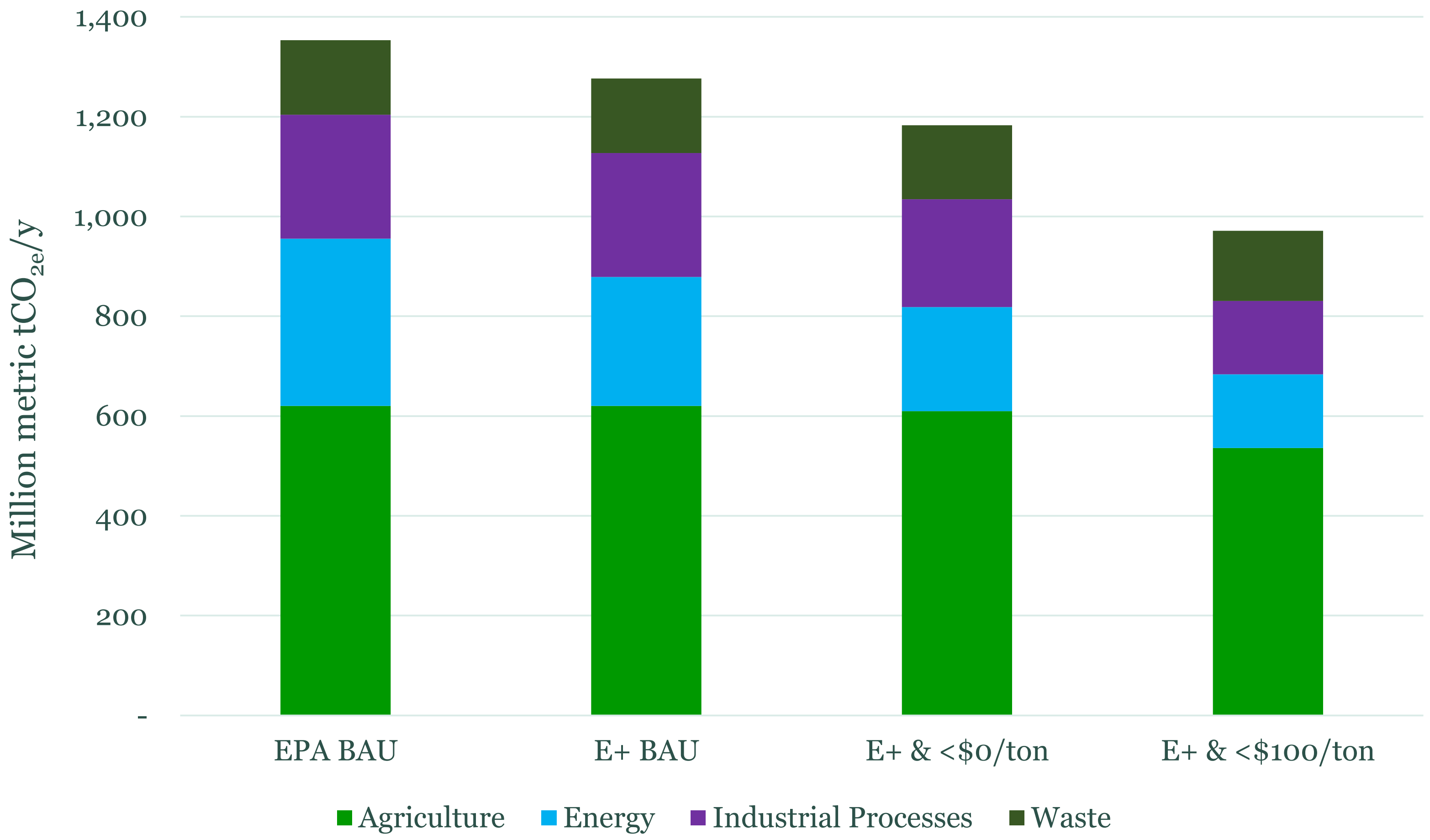
Without mitigation, non-CO_2 emissions grow gradually to 1.45 $GtCO_{2e}$ by 2050, with agriculture and energy remaining dominant

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



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

Mitigation can reduce non-CO_2 emissions substantially by 2030



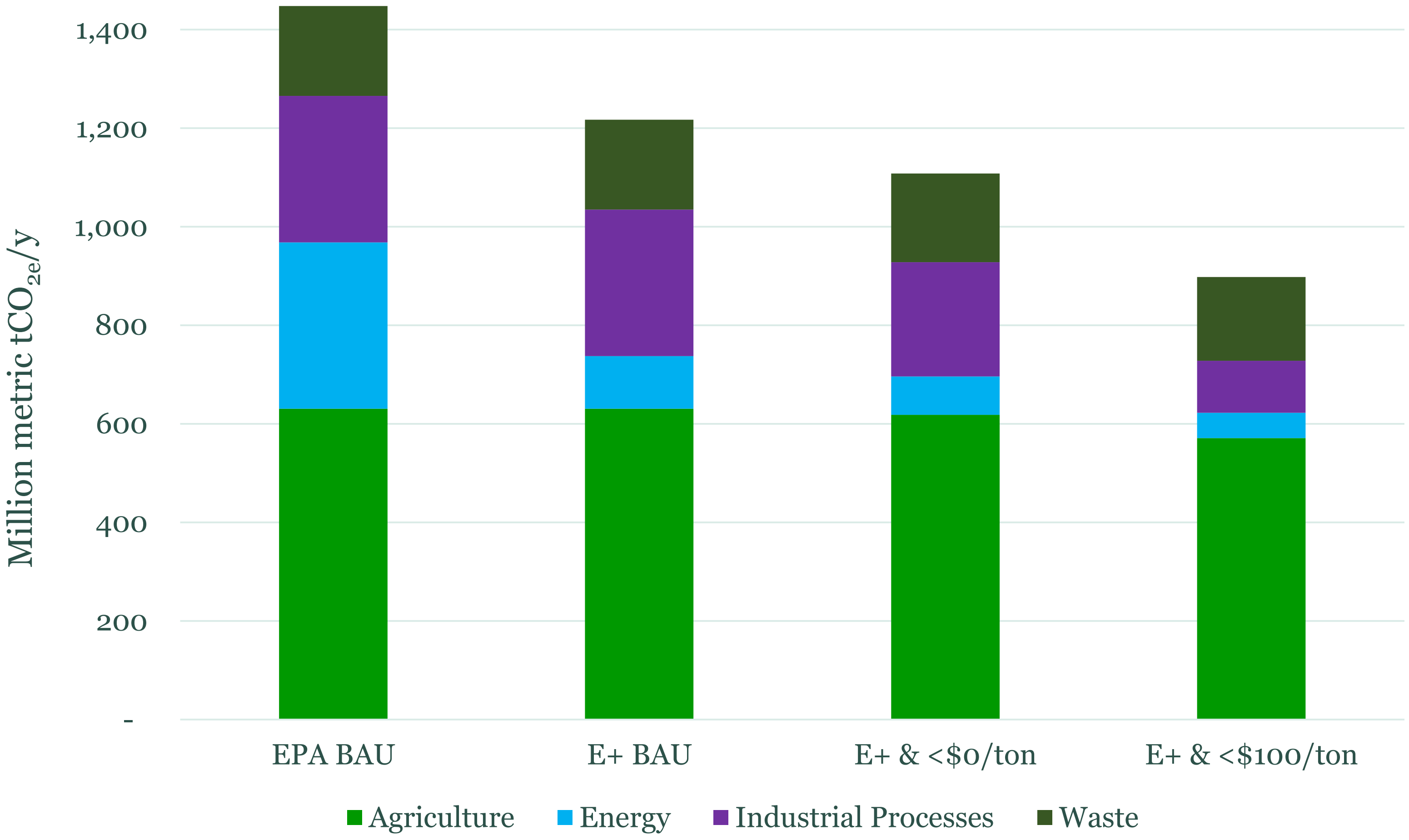
By 2030, EPA projects:

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

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

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

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



By 2050, EPA projects:

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

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

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

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

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

Non-CO_2 Abatement Potential:

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

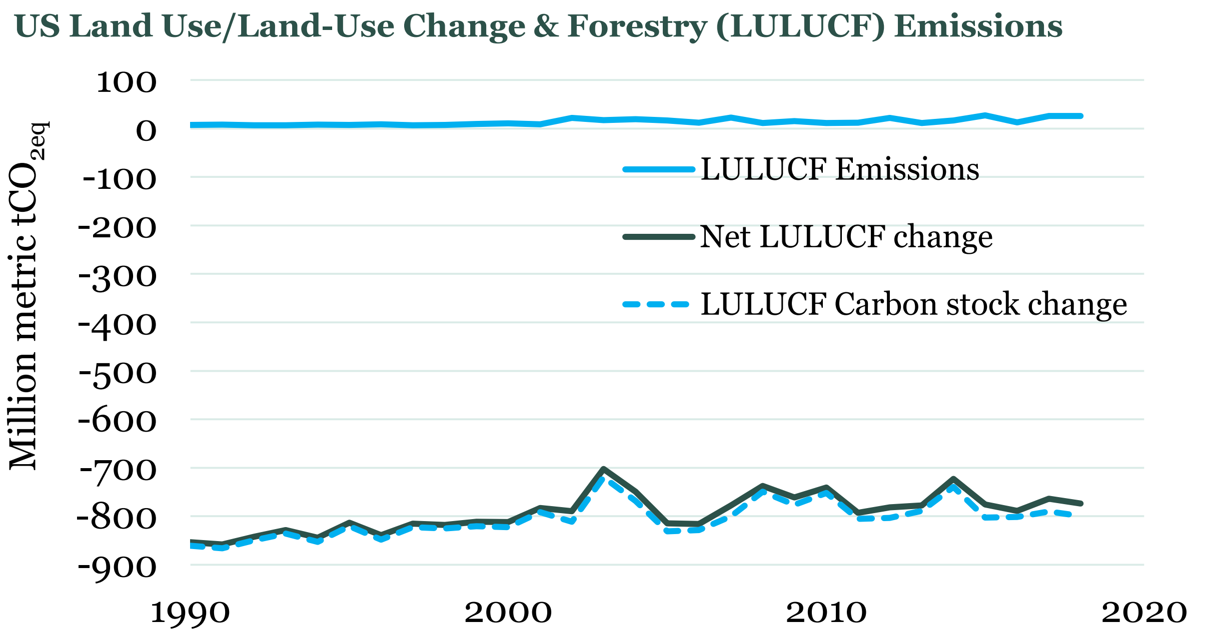
Source: EPA, *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019, but with coal and oil and gas adjustments to reflect E+ scenario: coal abatement is limited to mitigation of abandoned mines and oil/gas abatement is reduced by ~75% to account for lower oil production under E+.

Pillar 6: Enhanced land sinks

Summary of this section

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

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



(EPA, *2020 GHG Emissions Inventory*)

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

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

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

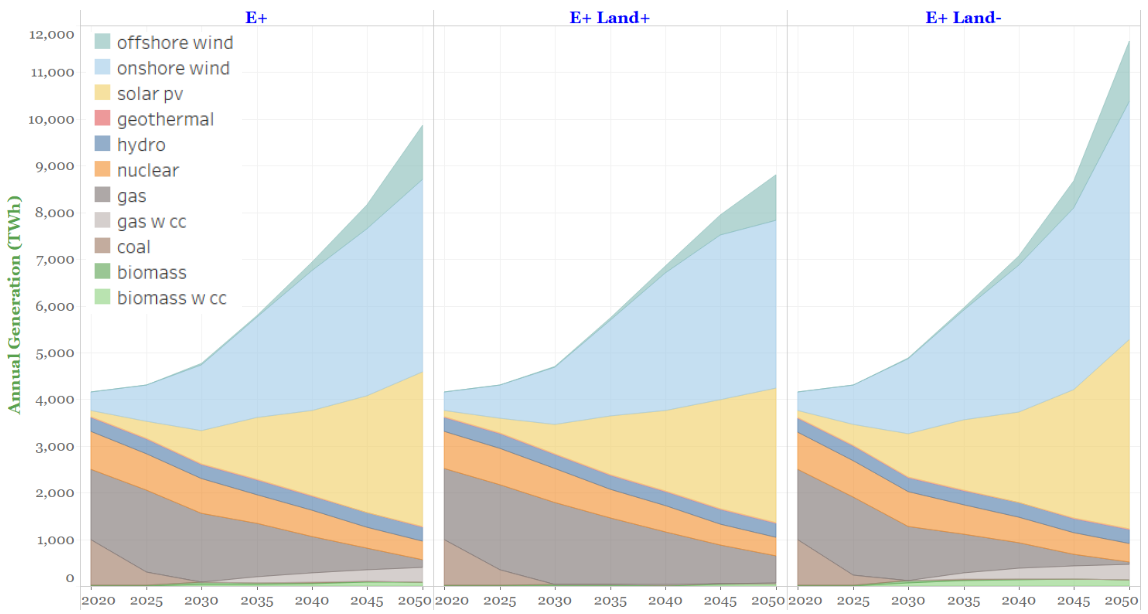
To reach net-zero emissions economy wide in 2050, emissions "allowed" by the energy/industrial system in 2050 depend on the net emissions occurring outside of energy/industry, i.e., land sinks and non-CO_2 emissions. The degree of net land sinks + non-CO_2 emissions that will be achieved is uncertain.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

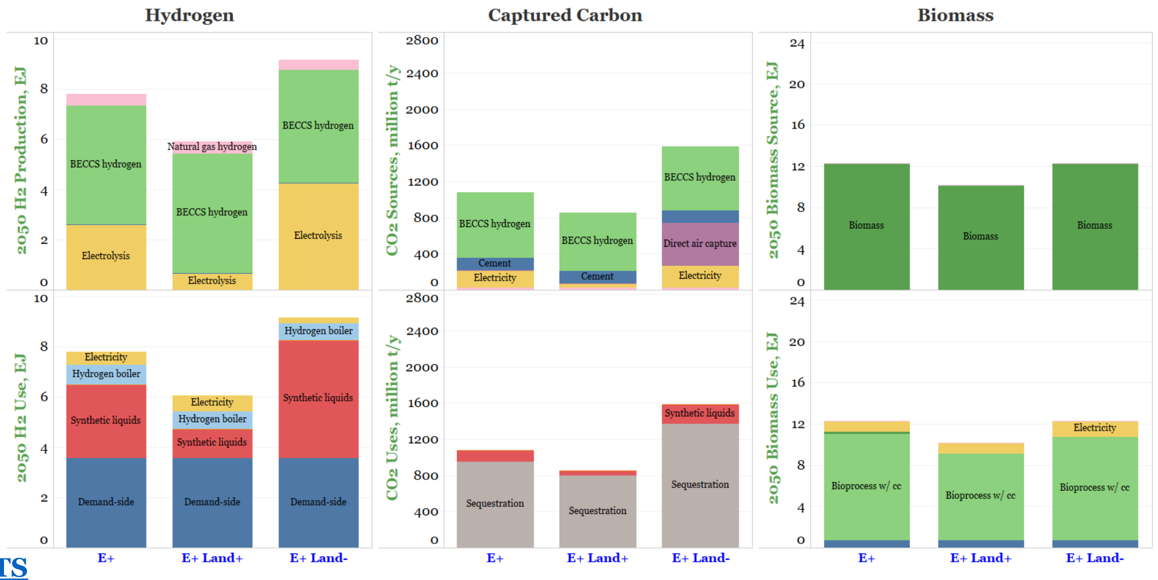
- If the net outside emissions are higher (E+ Land-), electricity generation is much higher by 2050, with most of the increase being solar and wind. Electrolytic H_2 production is also higher, deployment of direct air capture is significant, and about 60% more CO_2 sequestration is required. NPV of the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

See Annex B for additional details.

Input assumptions that vary between cases

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





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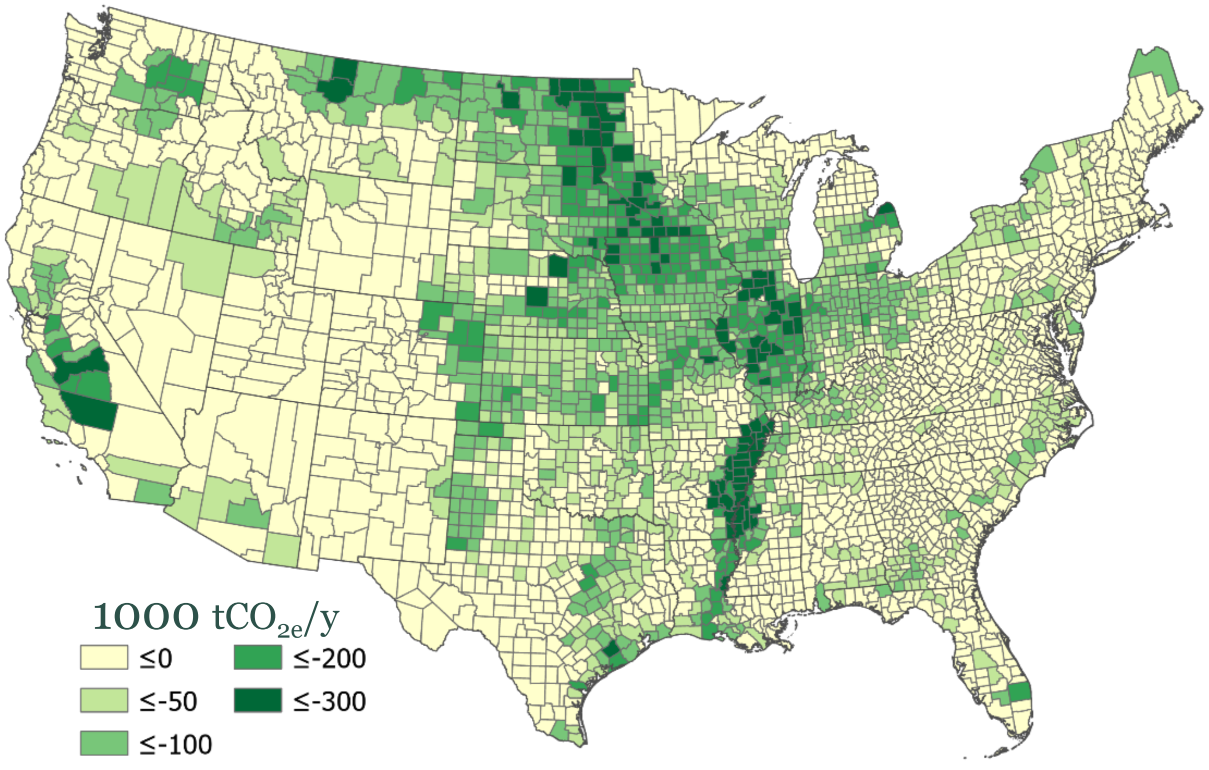
Agricultural measures can yield > 200 million tCO_{2e}/year of additional carbon storage in soils by 2050*

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

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

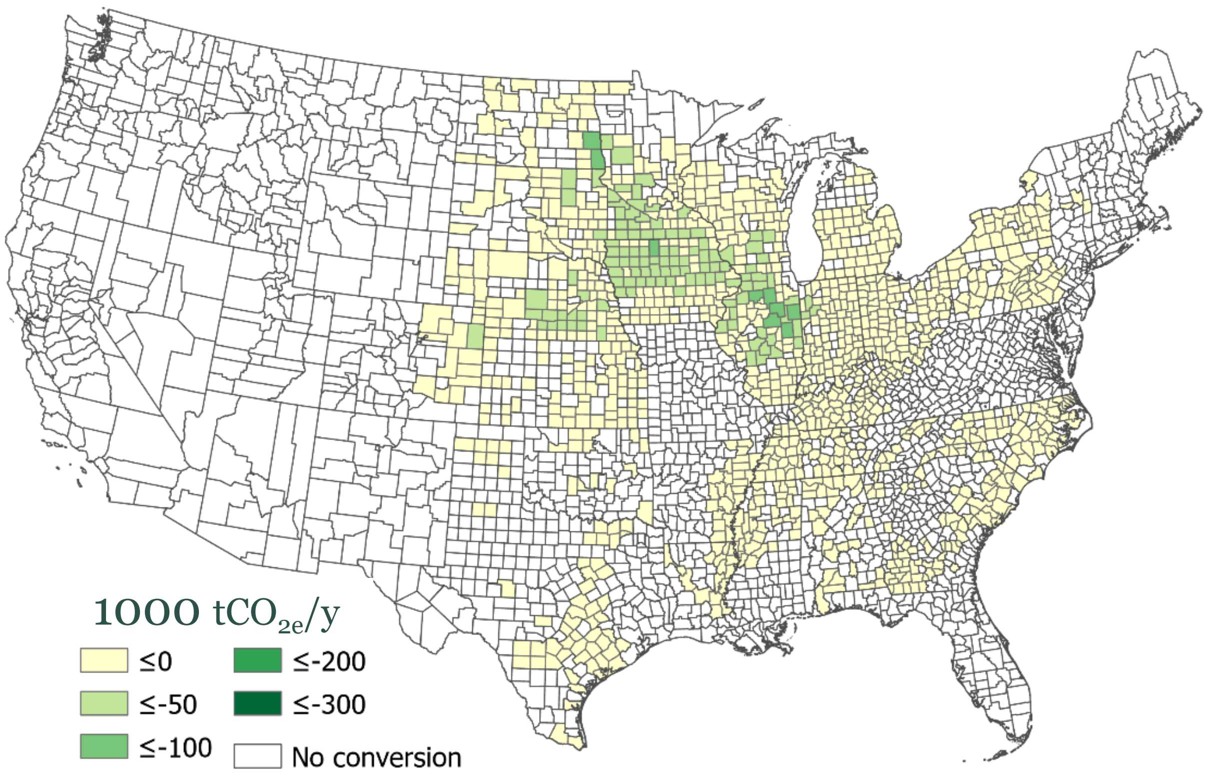
Maximum annual carbon uptake potential on agricultural lands by county; Midwestern states account for >80% of the potential.

Carbon storage across all agricultural lands (160 million ha)



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

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



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

See Swan, et al. (Annex Q).

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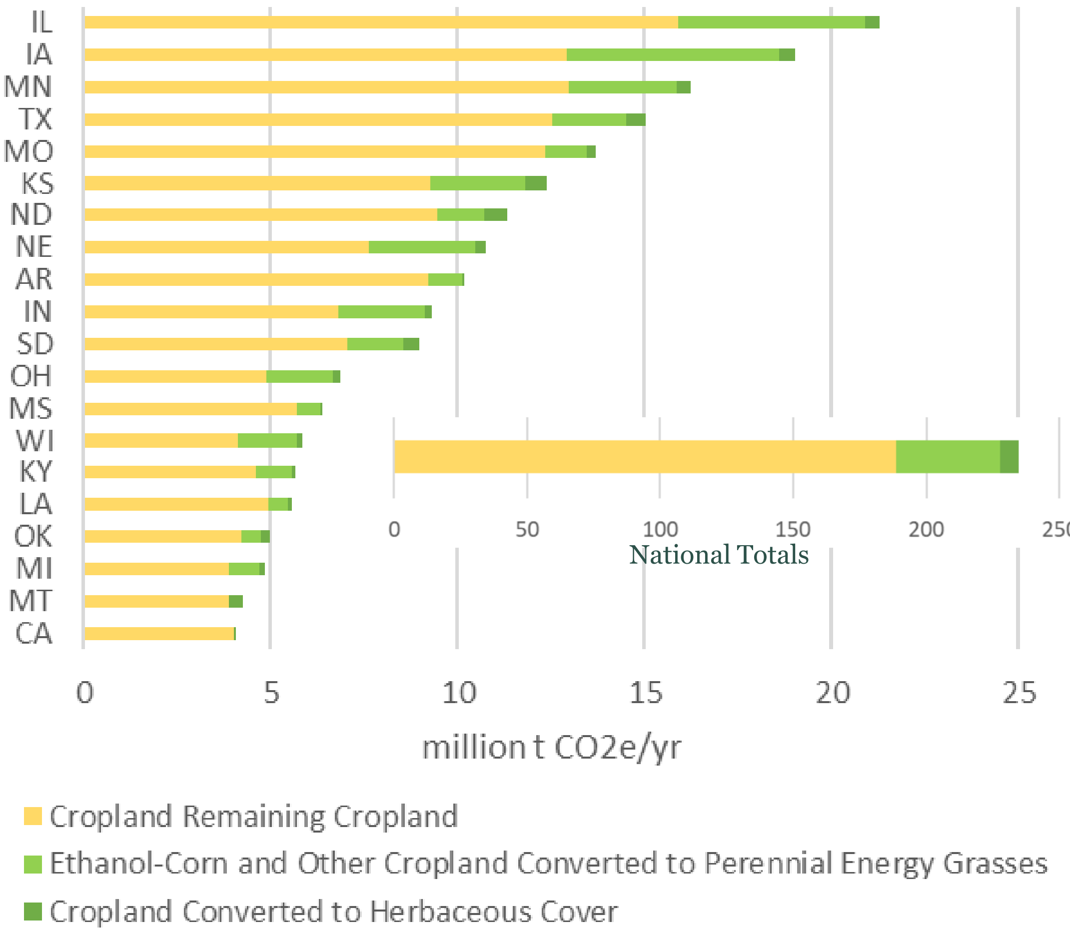
PRINCETON UNIVERSITY
andlinger center for energy+the environment
High Meadows Environmental Institute
Carbon Mitigation Initiative

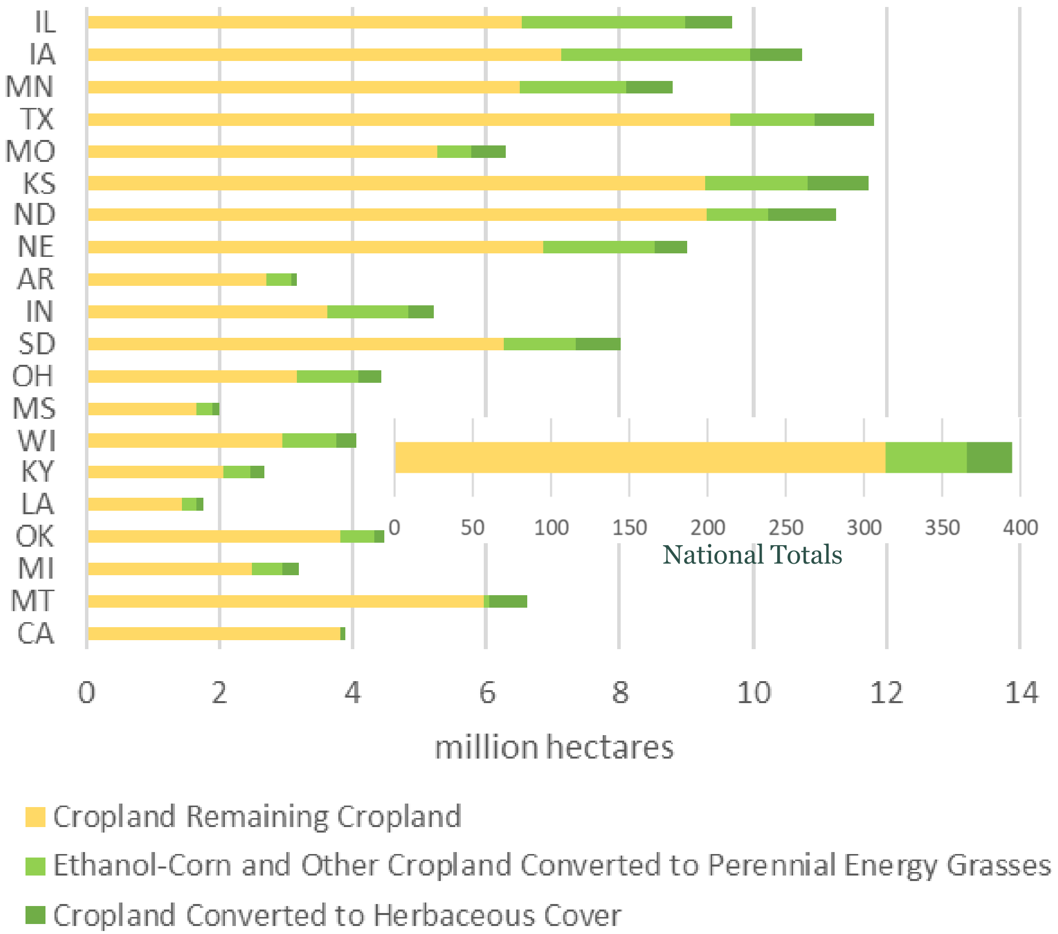
Top 20 states account for > 85% of the carbon storage potential on agricultural lands in 2050 (E+ scenario)

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

Annual C Storage & GHG Emission Reductions



Land area impacted



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

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

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

* See Birdsey, 2020 (Annex P).

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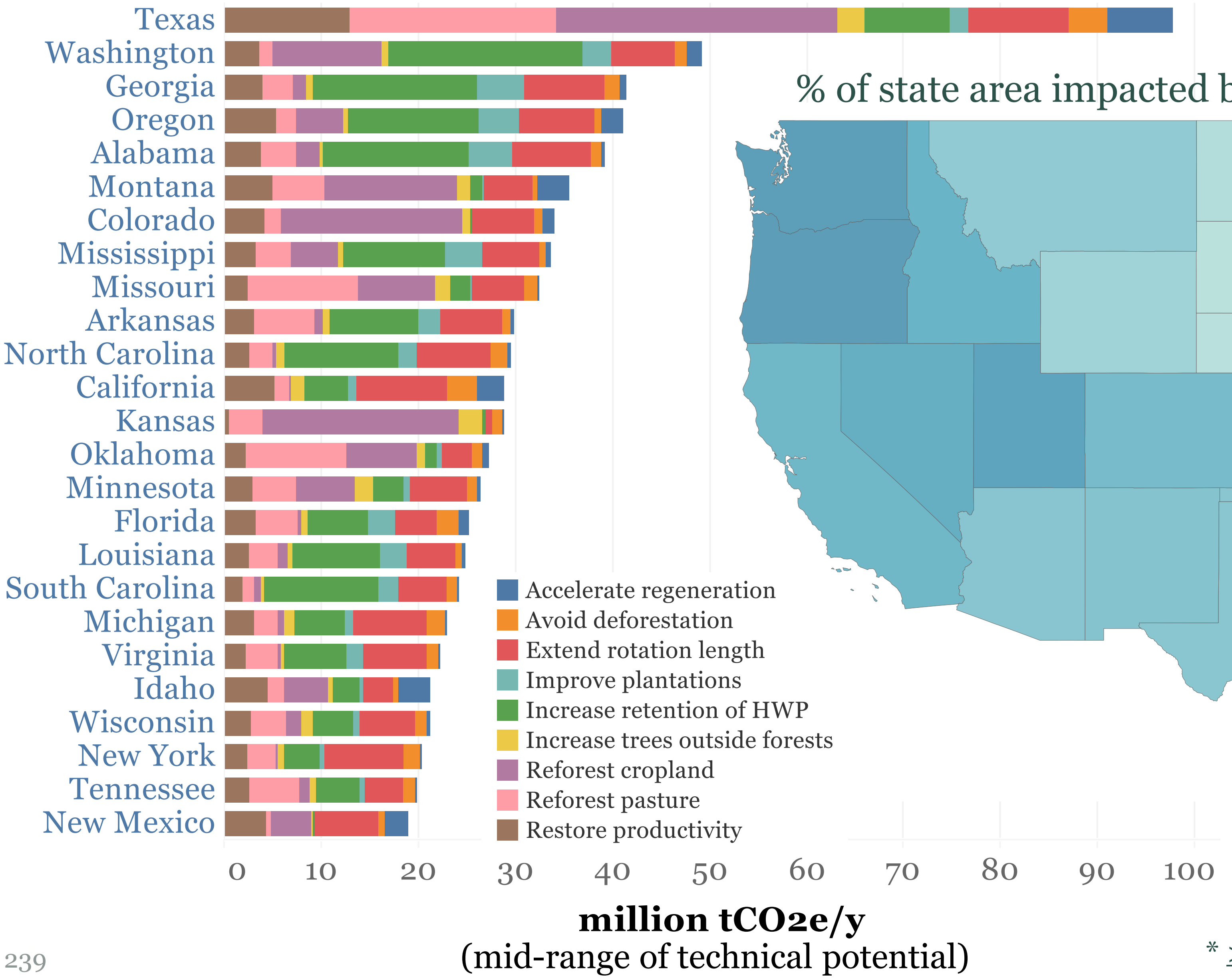
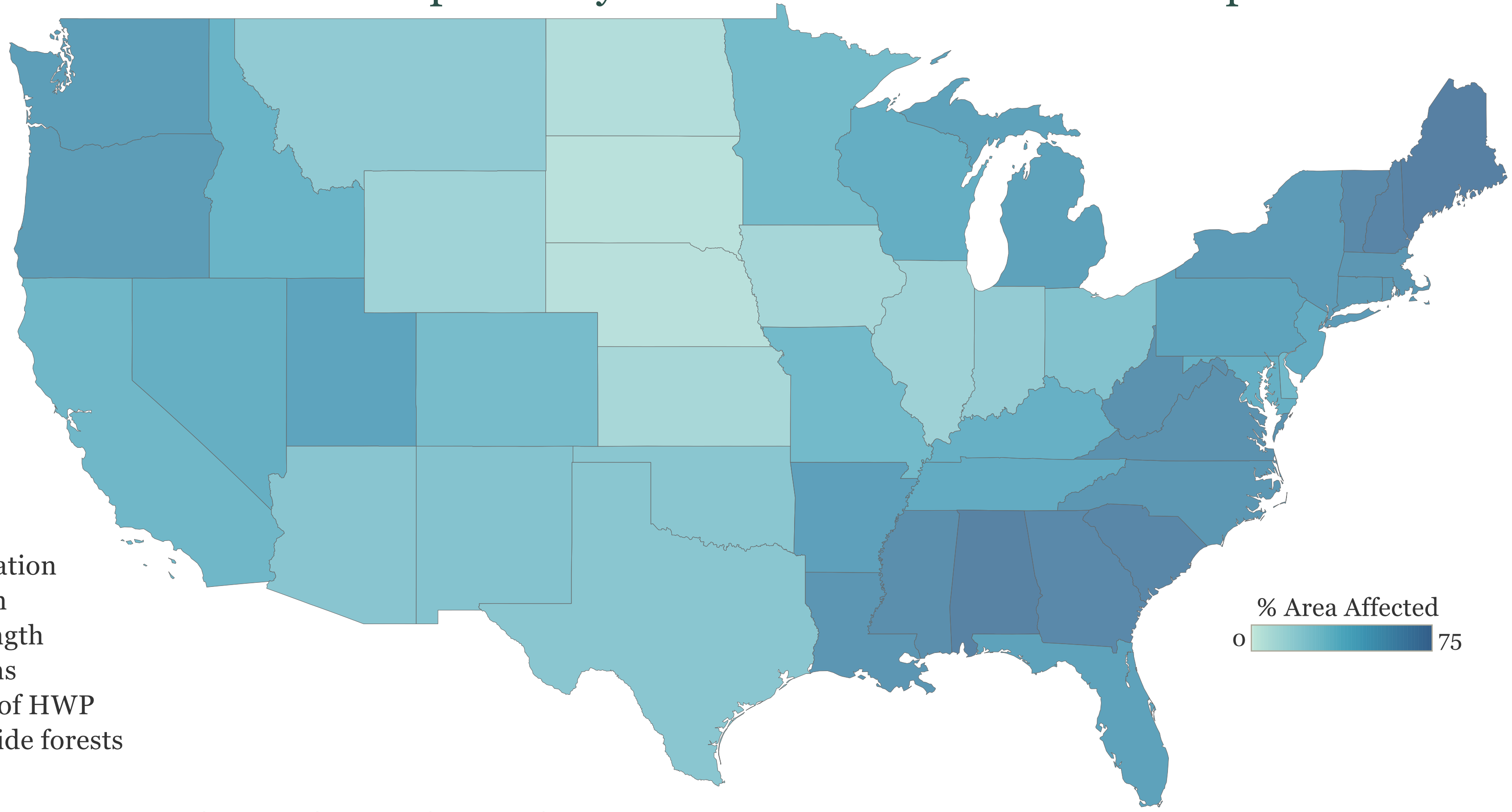
1 $GtCO_{2e}$/yr technical potential for enhanced carbon storage on forest lands (mid-range of estimates)



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



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

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

Summary of goals for the six pillars

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

1. Efficiency & Electrification

Consumer energy investment and use behaviors change

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

Industrial efficiency gains

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

2. Clean Electricity

Wind and solar

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

Nuclear

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

NGCC-CCS

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

Flexible resources

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

3. Zero-Carbon Fuels

Major bioenergy industry

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

H_2 and synfuels industries

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

4. CO_2 capture & storage

Geologic storage of 0.9 – 1.7 $GtCO_2$/y

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

5. Non-CO_2 Emissions

Methane, N_2O, Fluorocarbons

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

6. Enhanced land sinks

Forest management

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

Agricultural practices

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

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Implications of net-zero transitions

Summary of this section

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

Land use

Summary of this section

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

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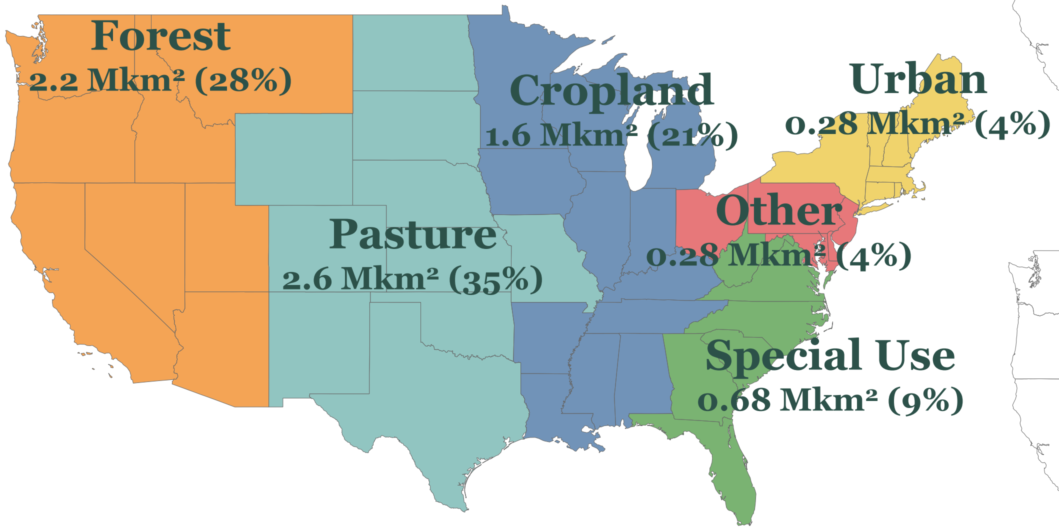
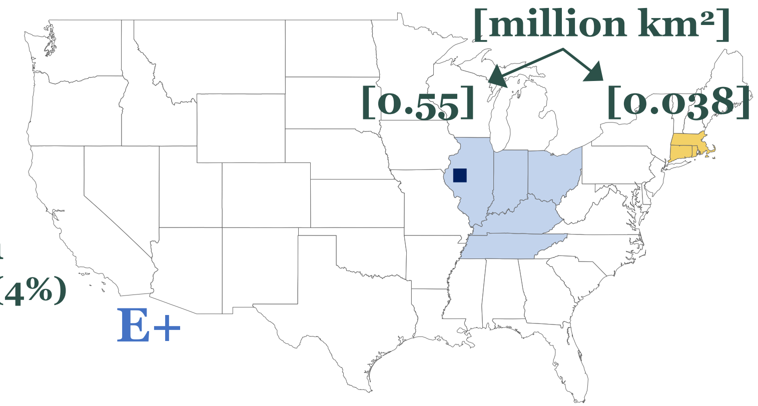
Total land area/visual footprint in 2050 for solar, wind, and biomass across scenarios is 0.25 to 1.1 million km².

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



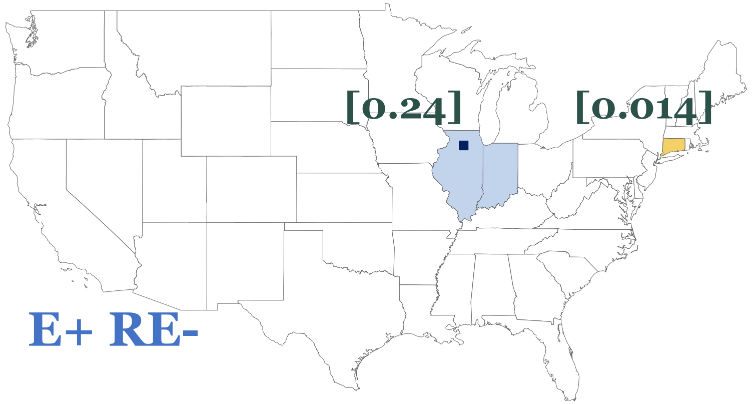
Notes: In these maps, the sum of land areas of colored states is roughly the same as the area nationally of the indicated uses.

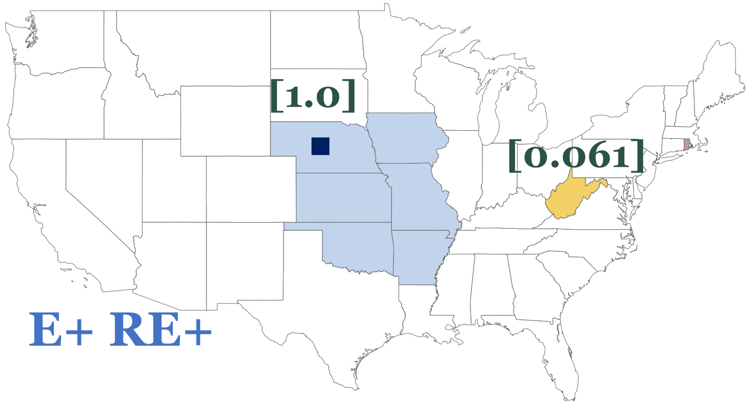


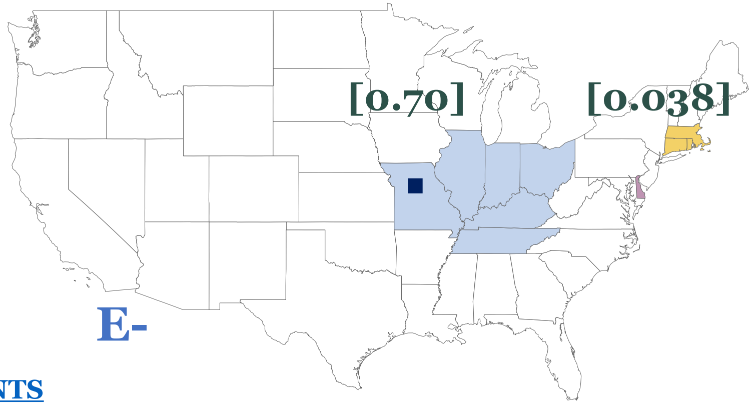
Equivalent land area for

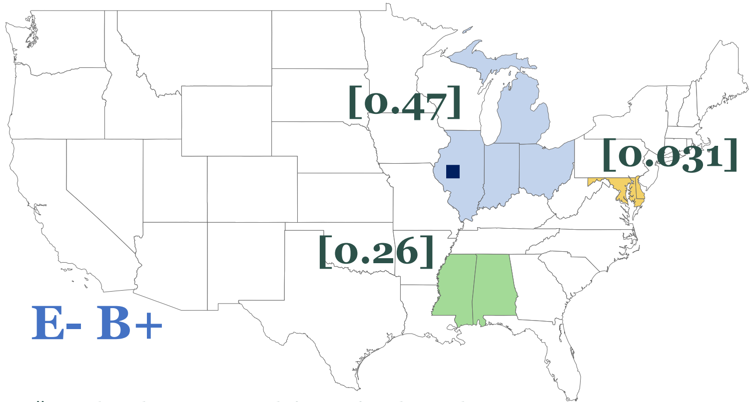
- Solar farms
- Wind farms
- Biomass farms*
- Direct air capture

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









* On lands converted from food production.

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

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

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

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

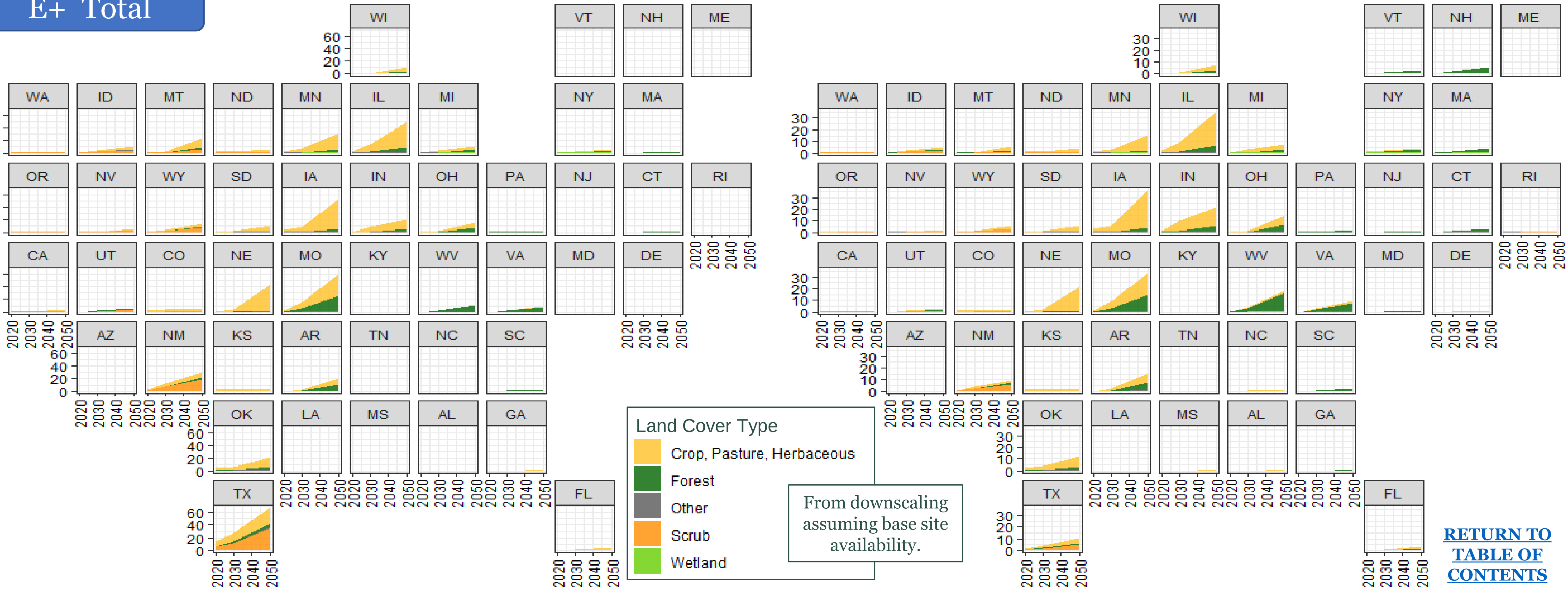
Total area impacted by solar and wind development (1,000 km²)

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

Percent of state land area

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

E+ Total



From downscaling assuming base site availability.

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

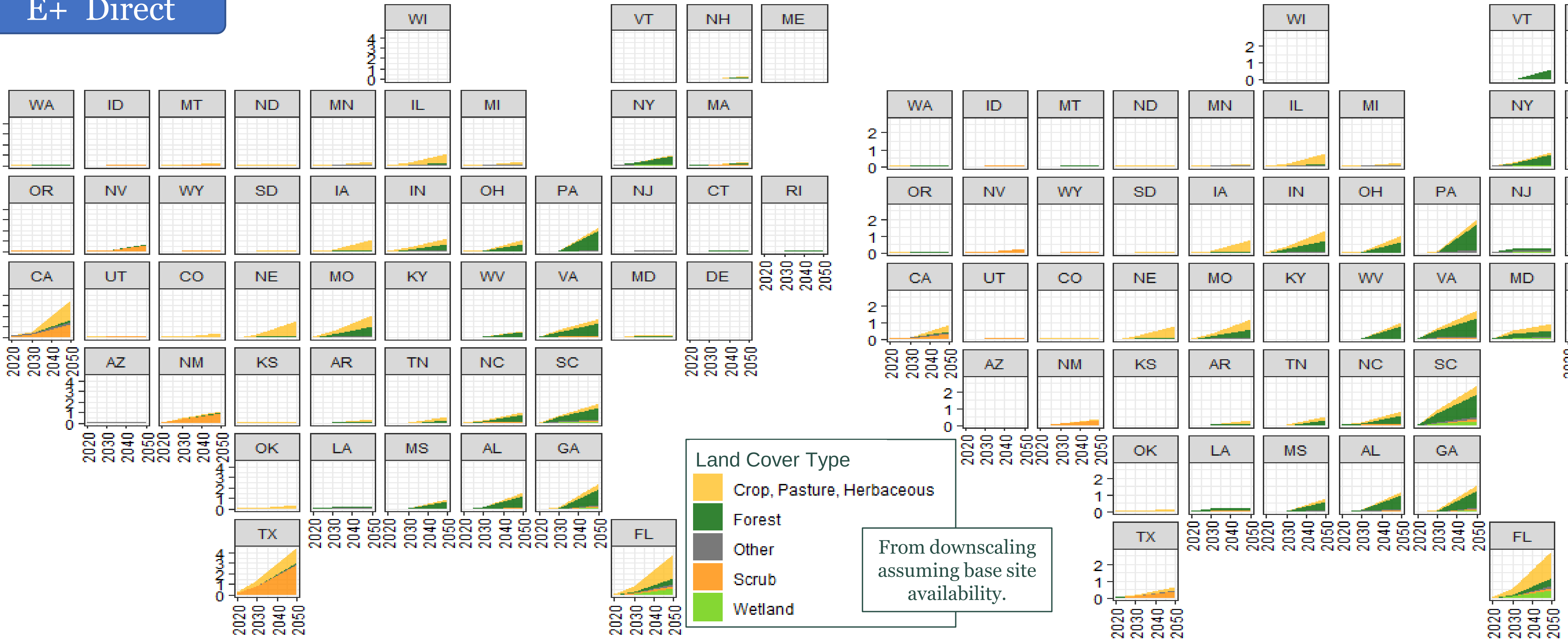
Land area directly impacted by solar and wind development (1,000 km²)

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

Percent of state land area

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

E+ Direct



From downscaling assuming base site availability.

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

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

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

Percent of state land area

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

From downscaling assuming base site availability.

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

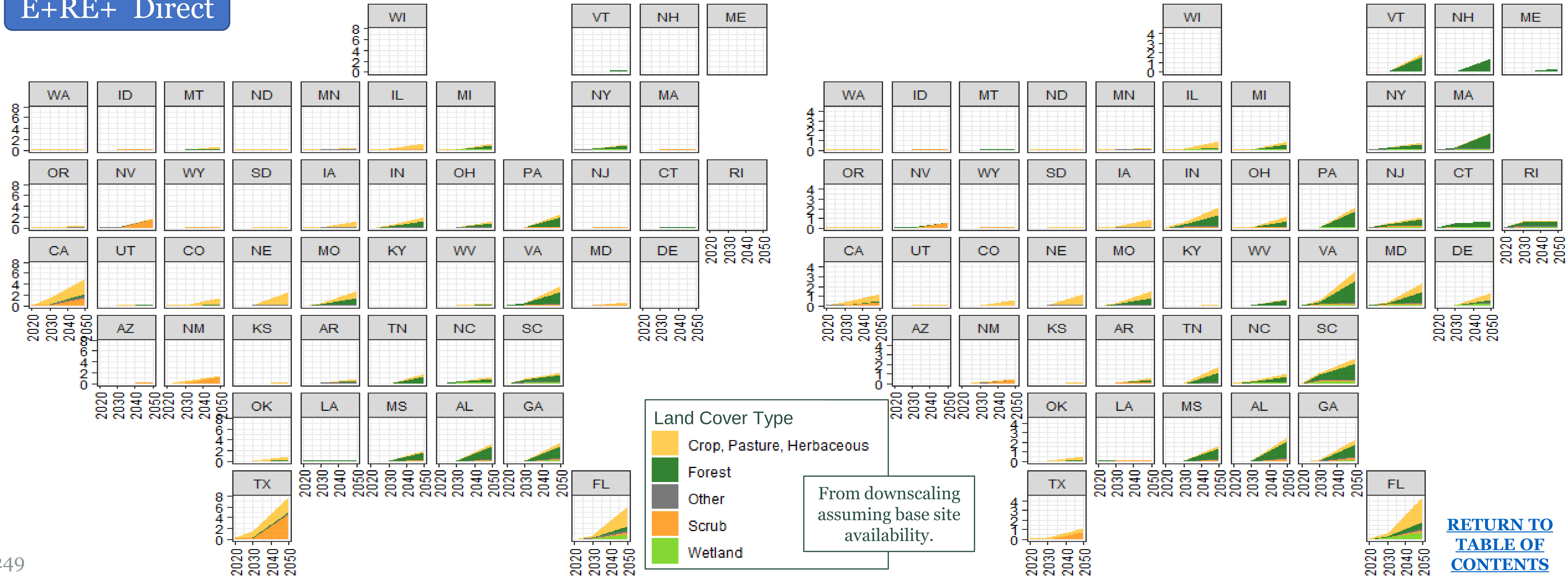
Land area directly impacted by solar and wind development (1,000 km²)

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

Percent of state land area

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

E+RE+ Direct



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

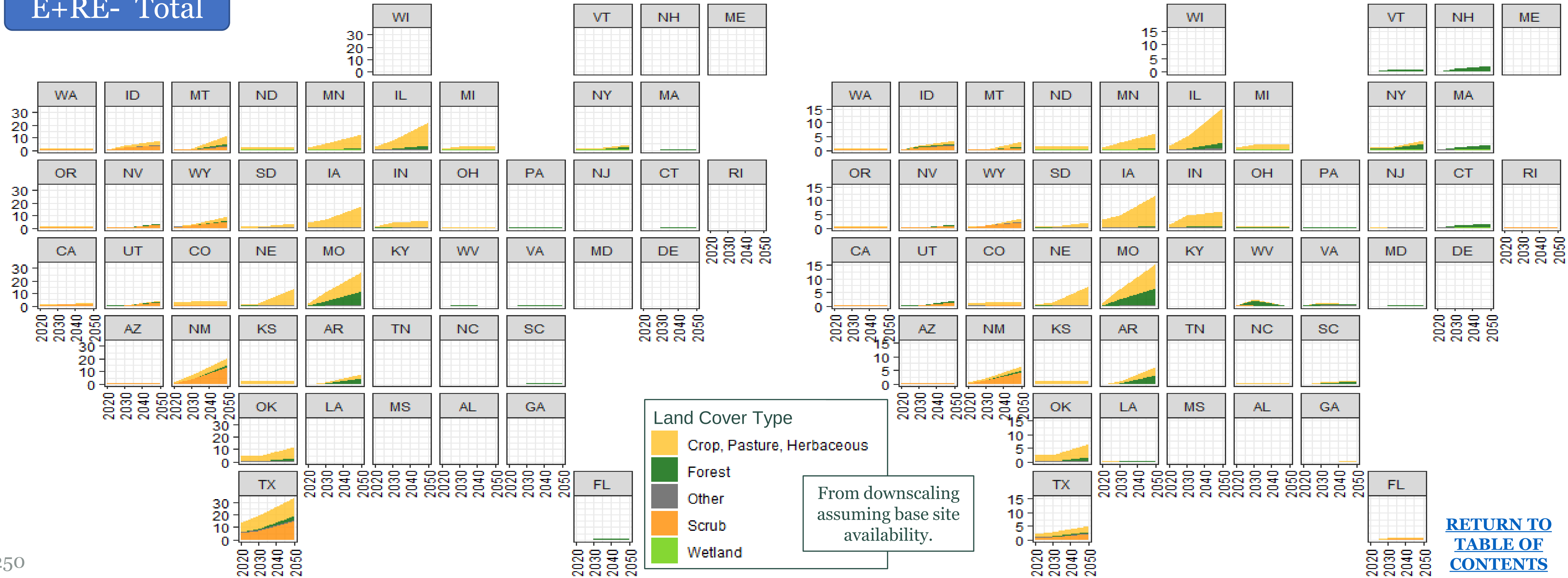
Total area impacted by solar and wind development (1,000 km²)

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

Percent of state land area

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

E+RE- Total



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

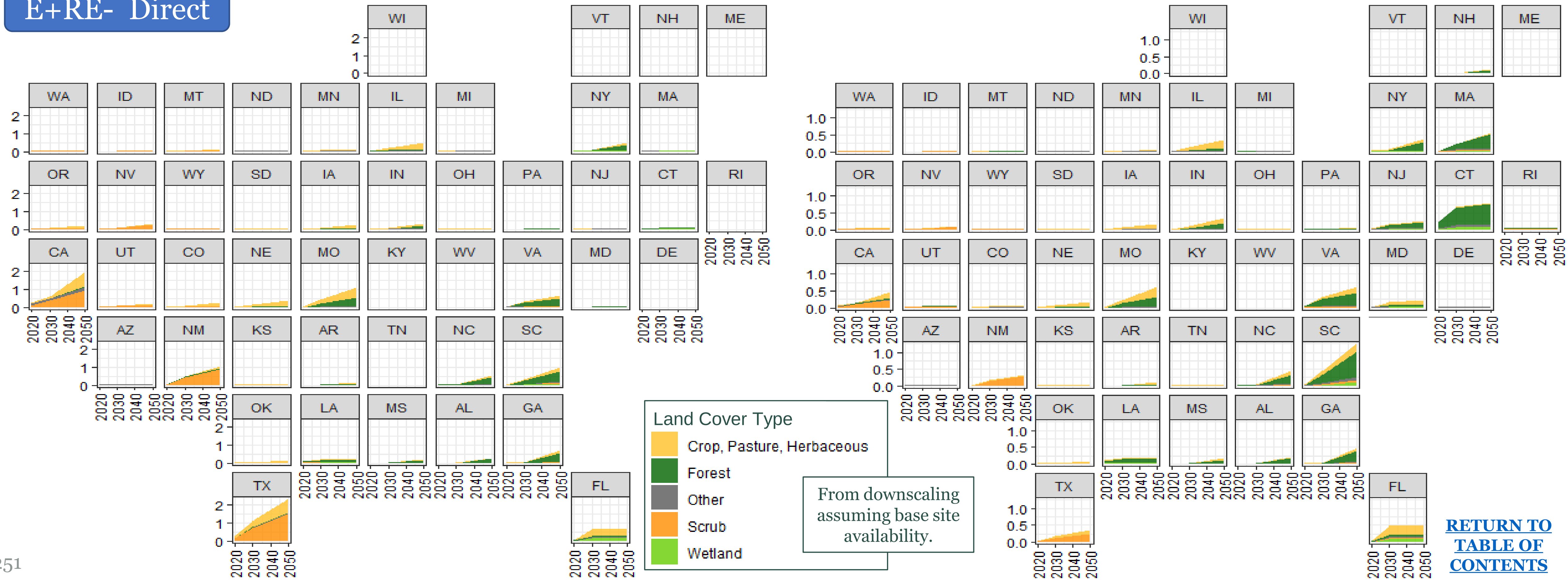
Land area directly impacted by solar and wind development (1,000 km²)

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

Percent of state land area

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

E+RE- Direct



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Capital mobilization

Summary of this section

- Modeled net-zero scenarios are 2 to 4 times more capital intensive than the REF scenario. E+ requires > 2.6 T$ of energy supply-side risk-capital before 2030 and >10 T$ trillion by 2050 (in addition to demand-side capital investments such as vehicles).
- Net-zero scenarios depend critically on timely mobilization of large sums of capital. Capital investments are long-lived, so timing of investments and divestments are critical. The macro-energy systems optimization model used in this study assumes rational and efficient markets that see investors respond instantly to incentives to mobilize capital. In reality, capital is mobilized through a sequence of decisions and activities which require considerable lead times and resources.
- E+ requires on the order of 190 B$ of investment before financial investment decisions (FID) are made on energy-supply projects through 2030 and 600 B$ by 2050. Pre-FID investment typically occurs 2-10 years in advance of when projects come online. Pre-FID costs are fully at-risk, since as there is no guarantee that a given project will proceed past FID to generate value.
- *Risk capital* includes pre-FID capital, as well as all additional capital committed prior to the Commercial Operation Date (COD) of a project. Pre-COD capital is exposed to various development, market, construction and technology performance risks which can impact project cashflows and hence project valuation. These risks can limit the availability, and increase the cost, of investment capital.
- Net-zero scenarios are characterized by a high degree of foresight and seamless integration between sectors; but investors face deep uncertainty around future technology costs and performance, policy priorities of future governments, investment preferences among peers, customers and competitors, and public acceptance of certain technologies.
- Gaps between optimization modeling and the real investment decision making obscure a number of potential challenges to mobilizing risk-capital for project development and construction that must be mitigated through policy mechanisms to meet the 2050 net-zero target.
- Such mechanisms include investment during the 2020's to create *real options* for technologies needed post 2030, including multiple full-scale 'first-N-of-a-kind' projects to de-risk and reduce the cost of less-mature technologies and investment in critical enabling infrastructure (e.g. electricity transmission and CO_2 pipelines) to serve various future supply-side investments.
- See Annex M for details of capital mobilization analysis.

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

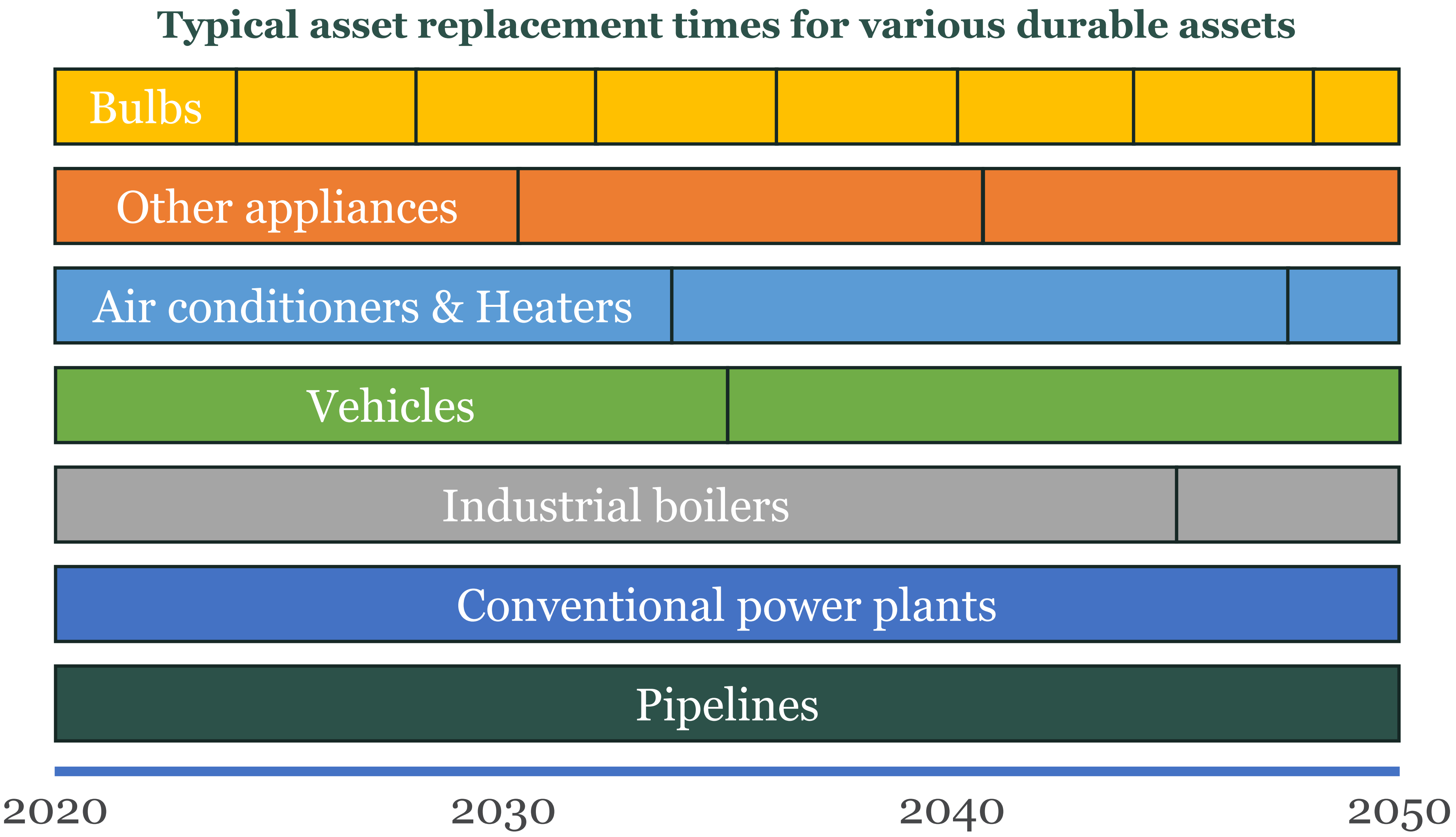

Image credit: Ryan Jones, Evolved Energy Research

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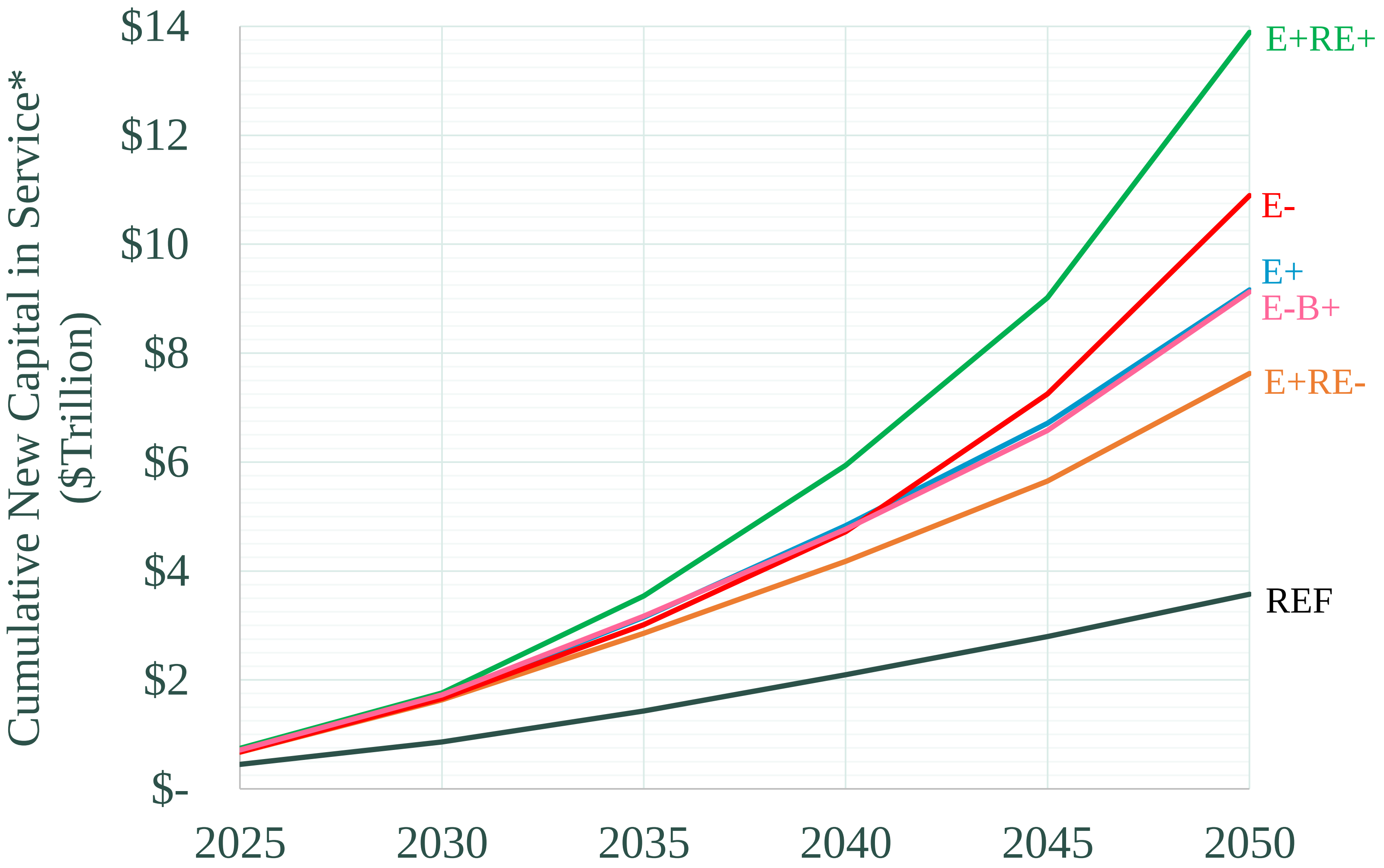
Capital dominates energy system costs in net-zero pathways: Supply-side capital in service by 2050 is 2 to 4 times REF.

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



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

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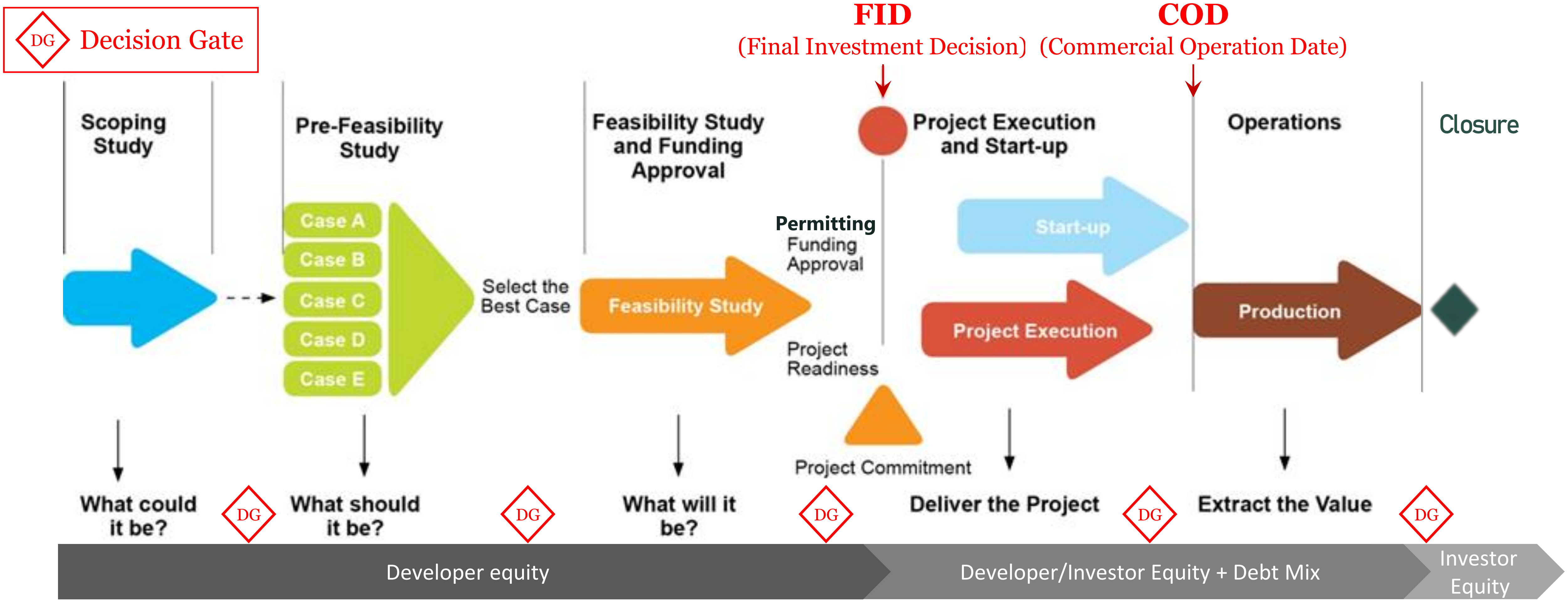
RIO assumes that energy supply assets come online ‘overnight’ as needed to meet demands; but investment lead times are significant

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



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

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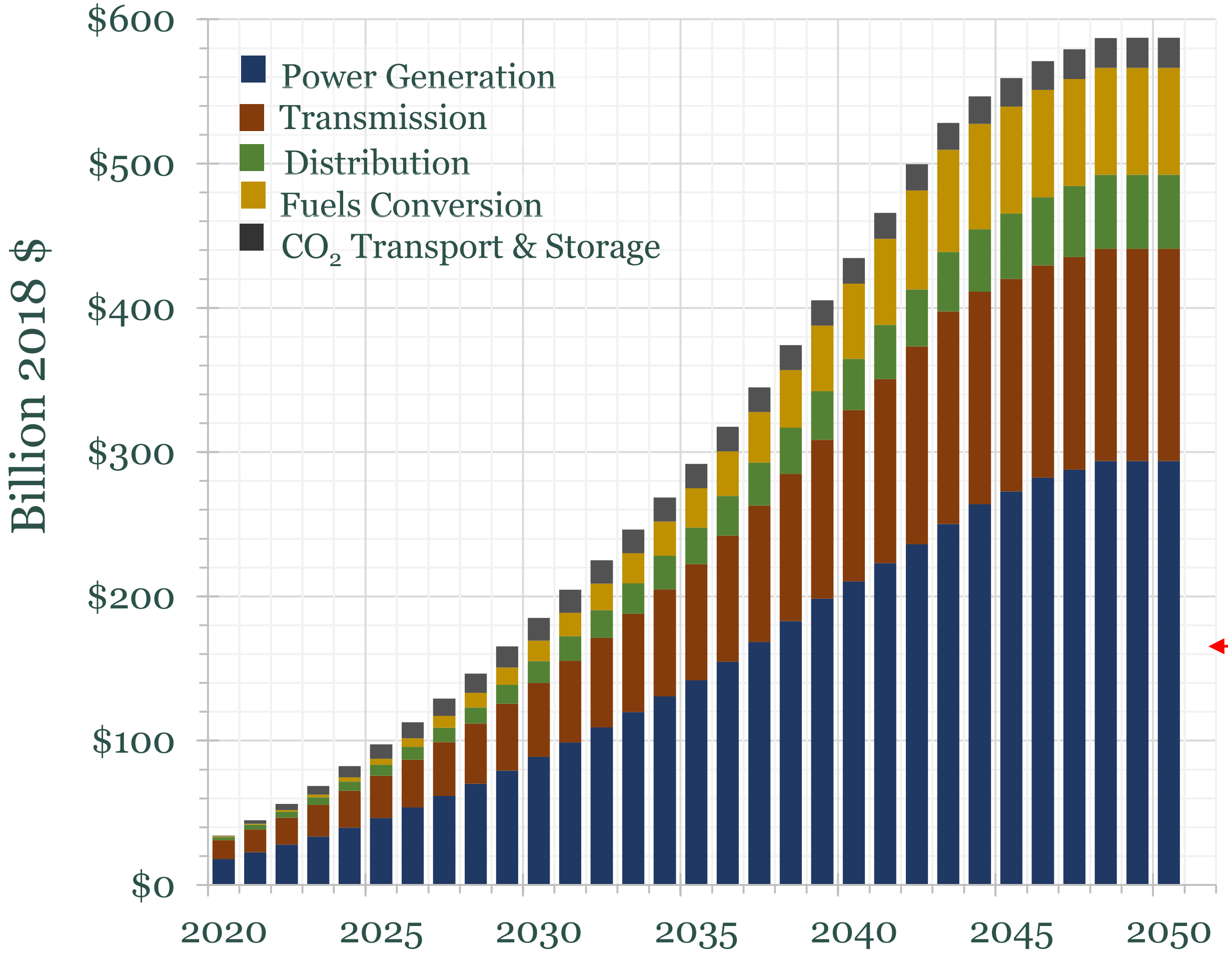
An extensive set of activities must happen before final investment decision (FID)

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

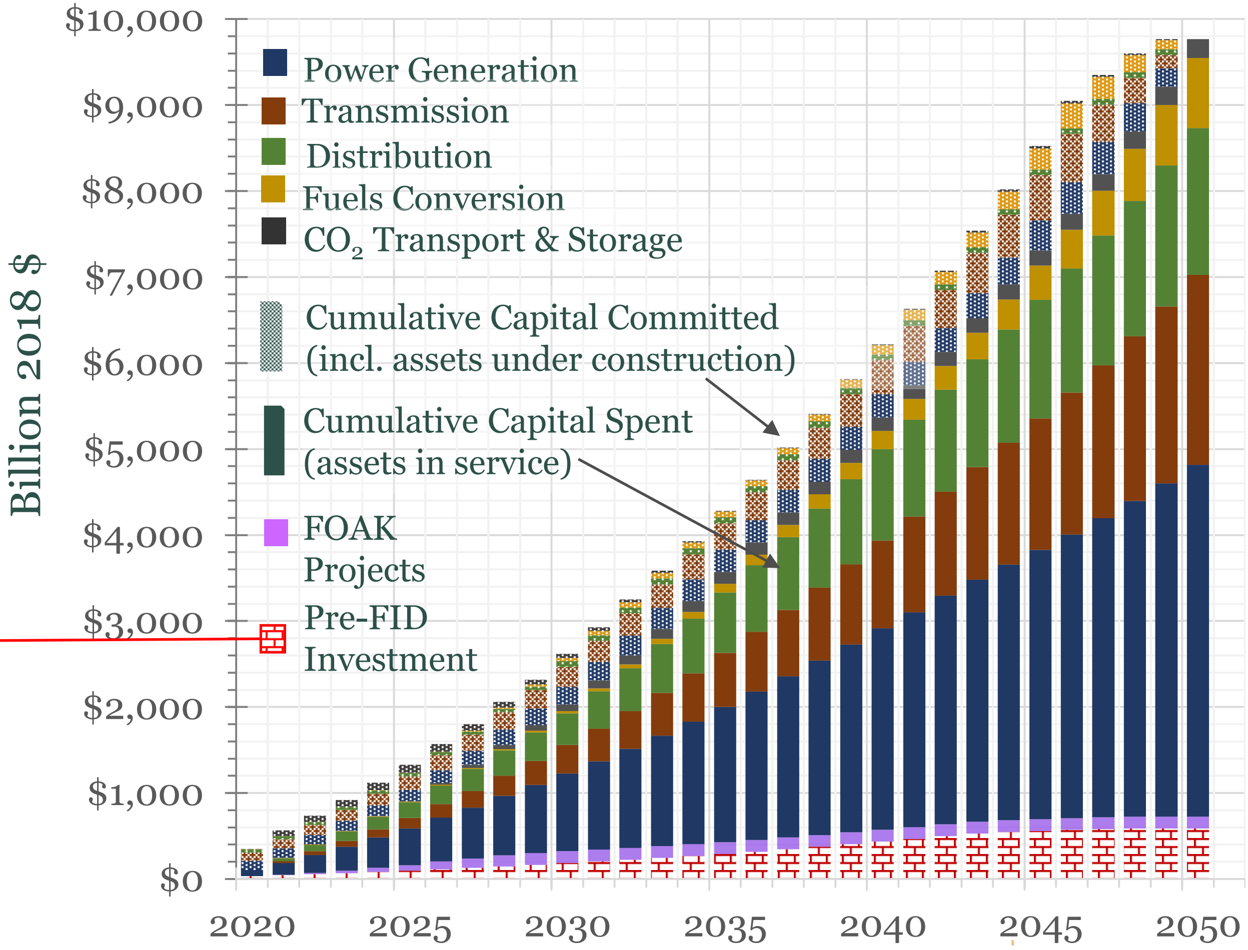
All net-zero scenarios are capital intensive. Mobilizing risk capital for development and construction will be a significant challenge

E+

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



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



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

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

POWER SECTOR

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

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

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

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

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

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

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

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Fossil fuel industries

Summary of this section

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

Thermal coal consumption and production ceases by 2030.

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

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

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

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

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

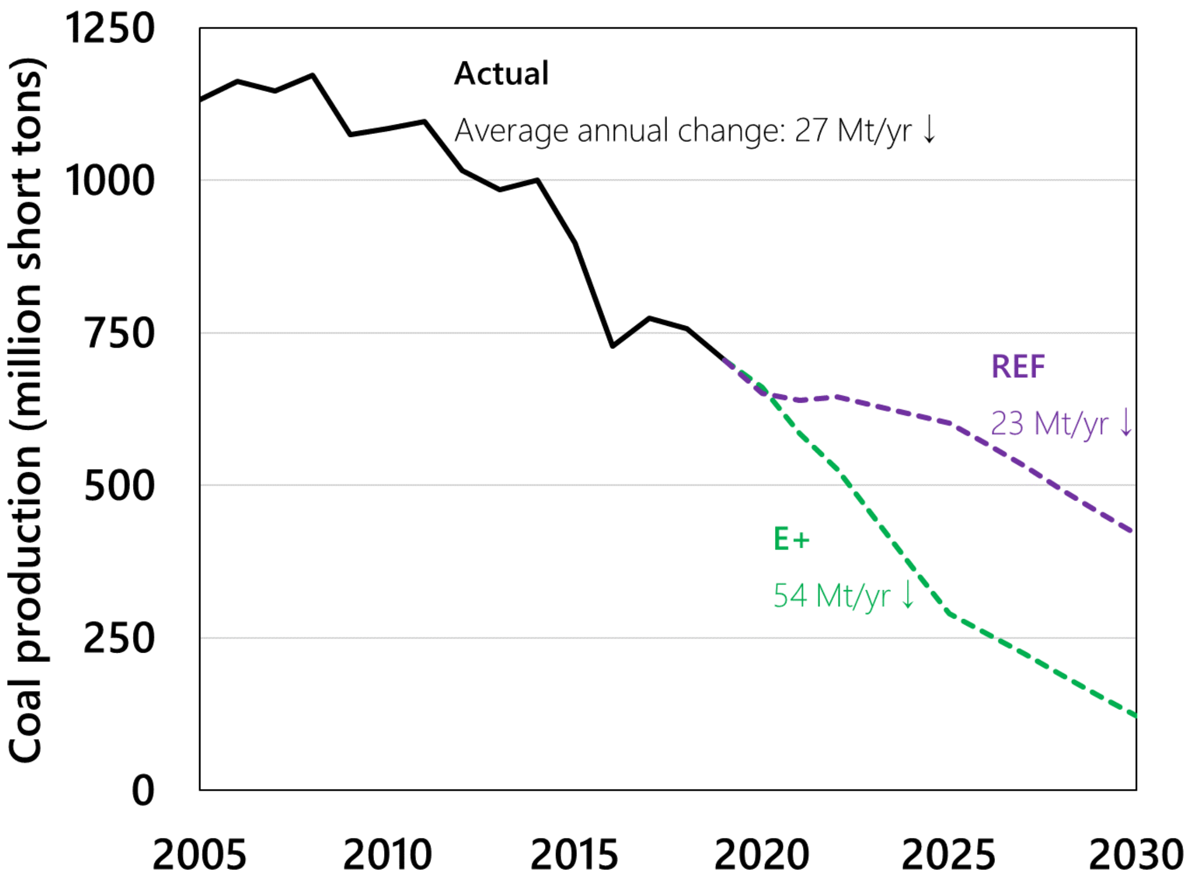
See Annex N for details.

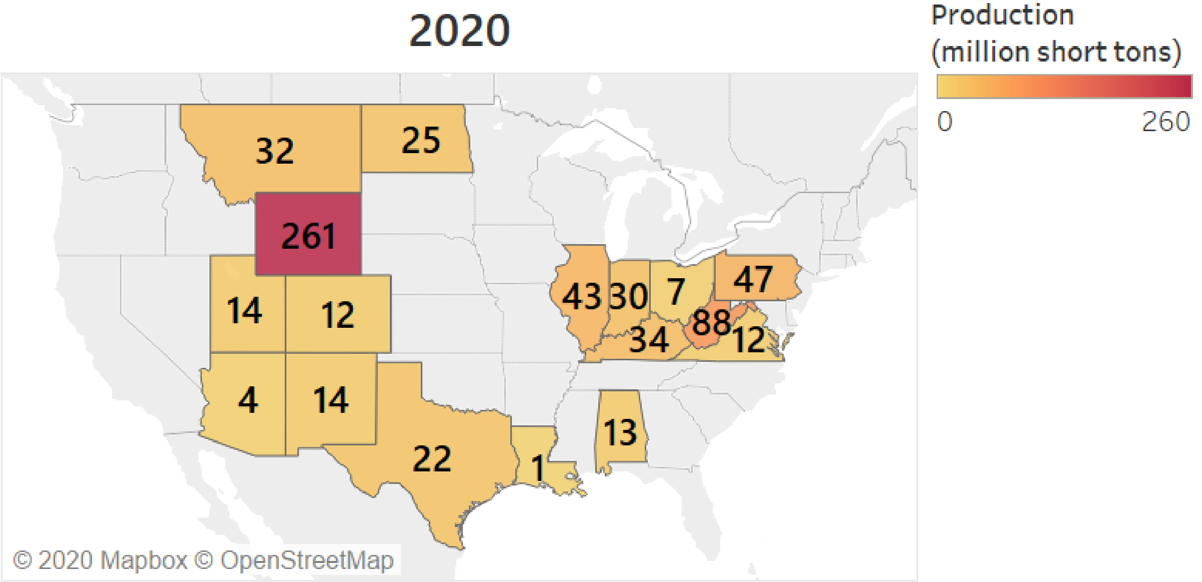
Summary of this section

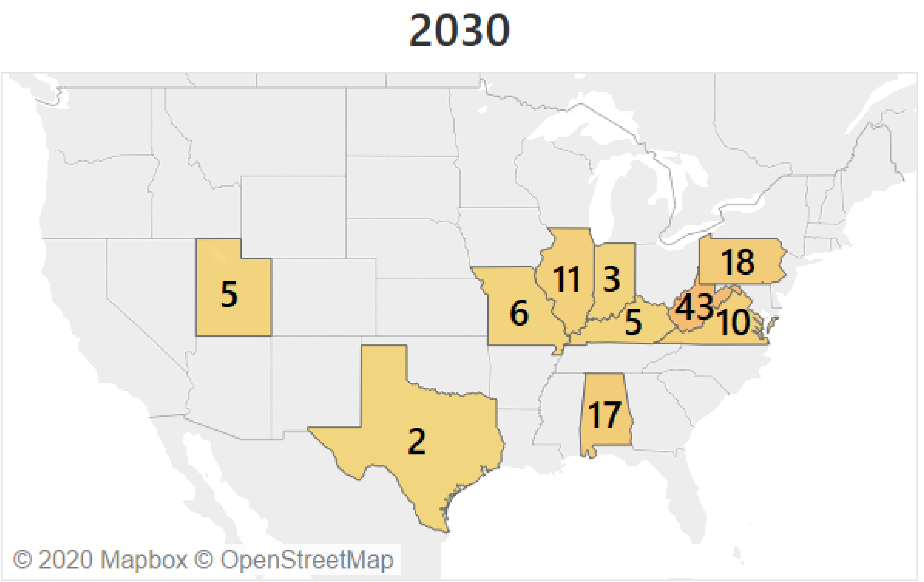
Thermal coal consumption and production ceases by 2030.

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

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







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

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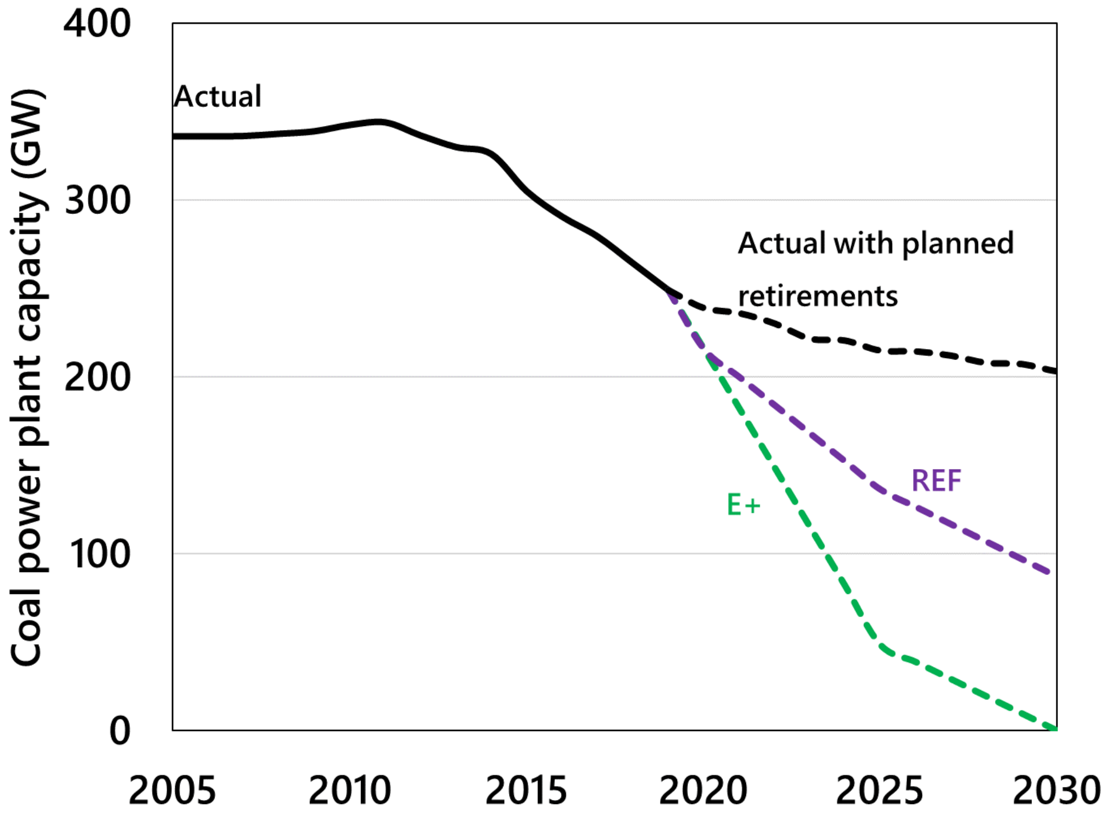
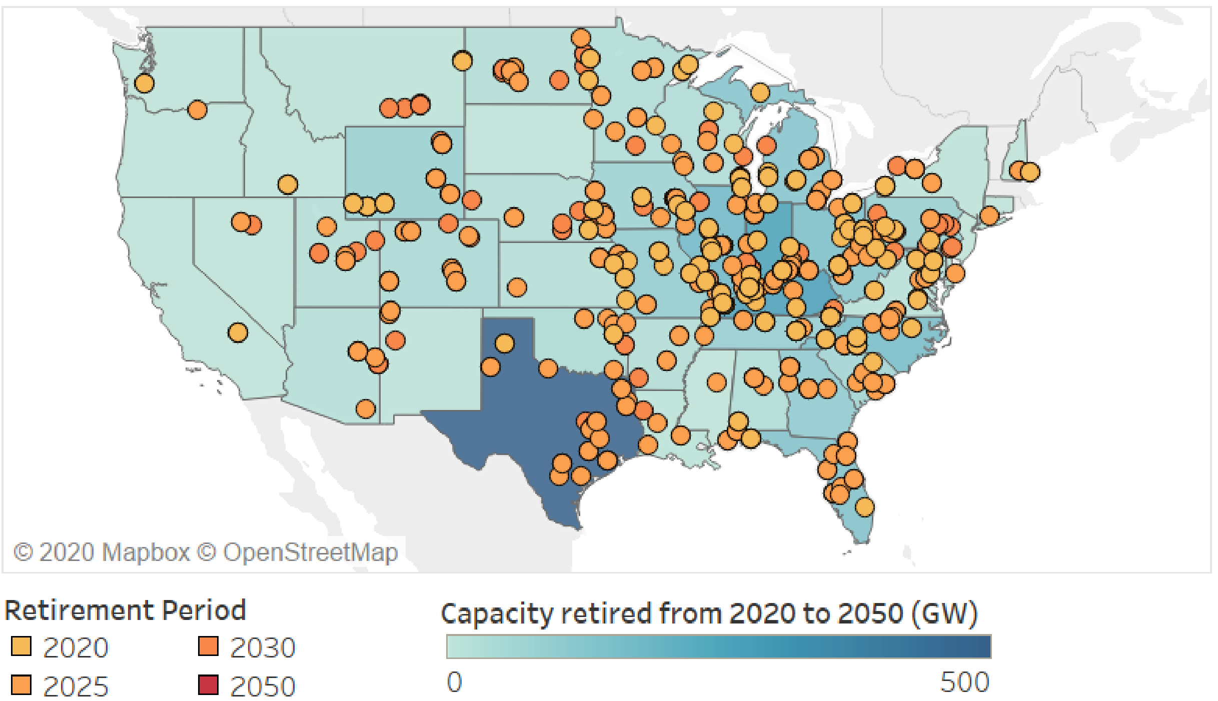
All coal power plants (500+) close by 2030.



Retirement period of coal generators in E+ scenario



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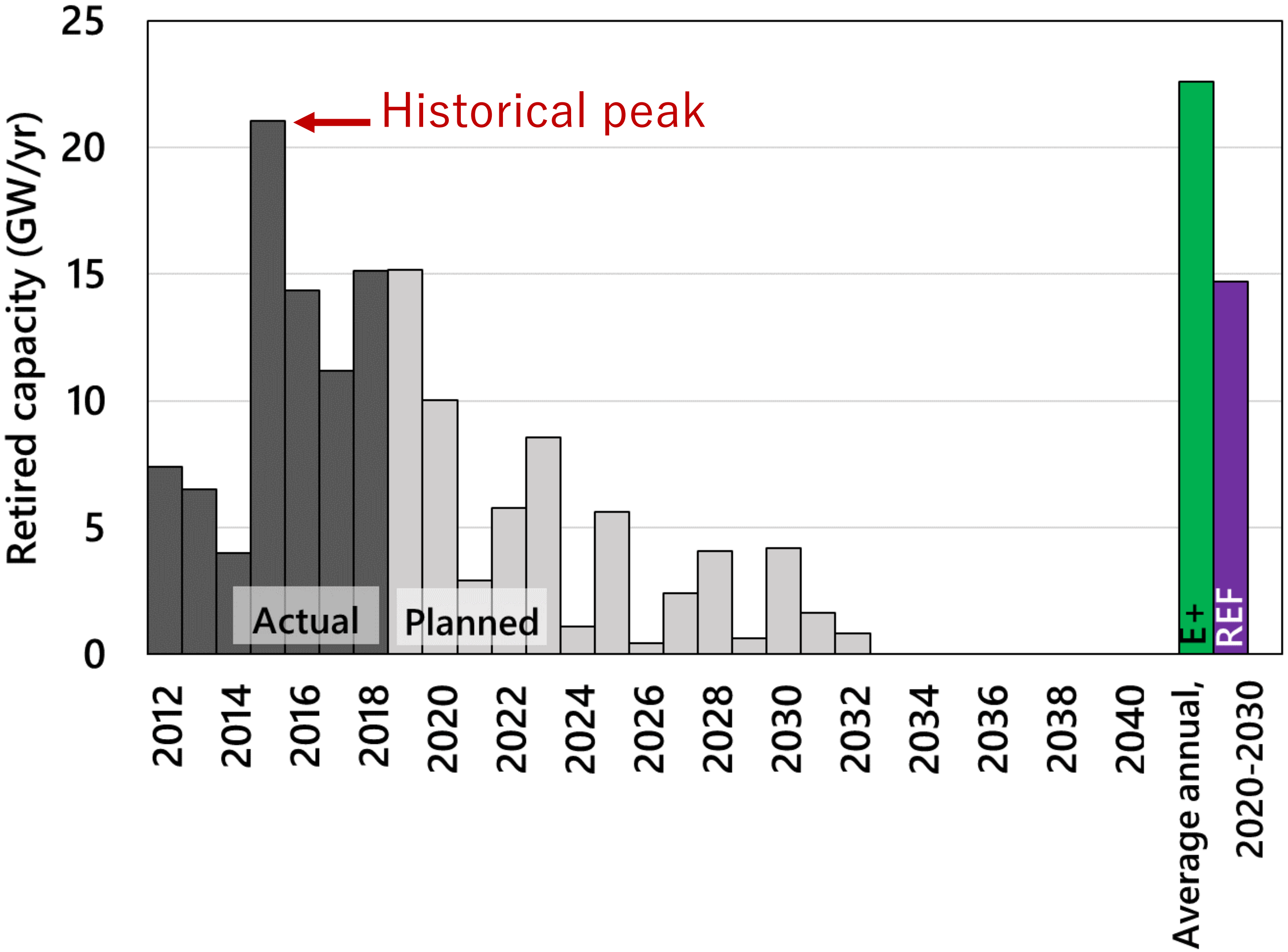
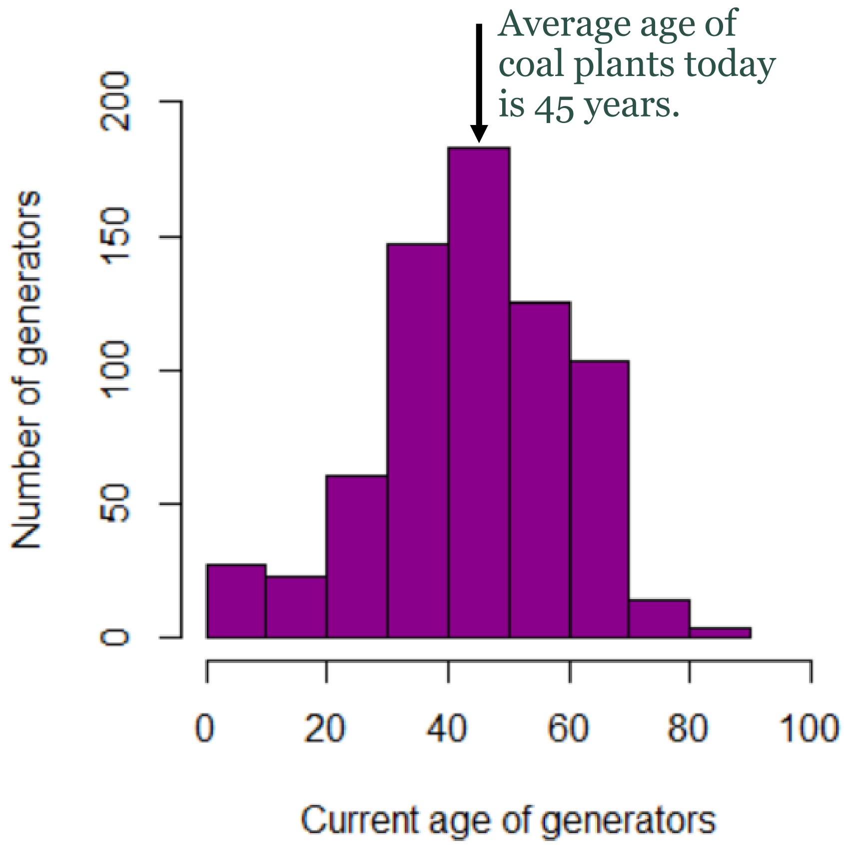
Average annual coal retirements in all net-zero scenarios is close to the historical peak rate observed in 2015.

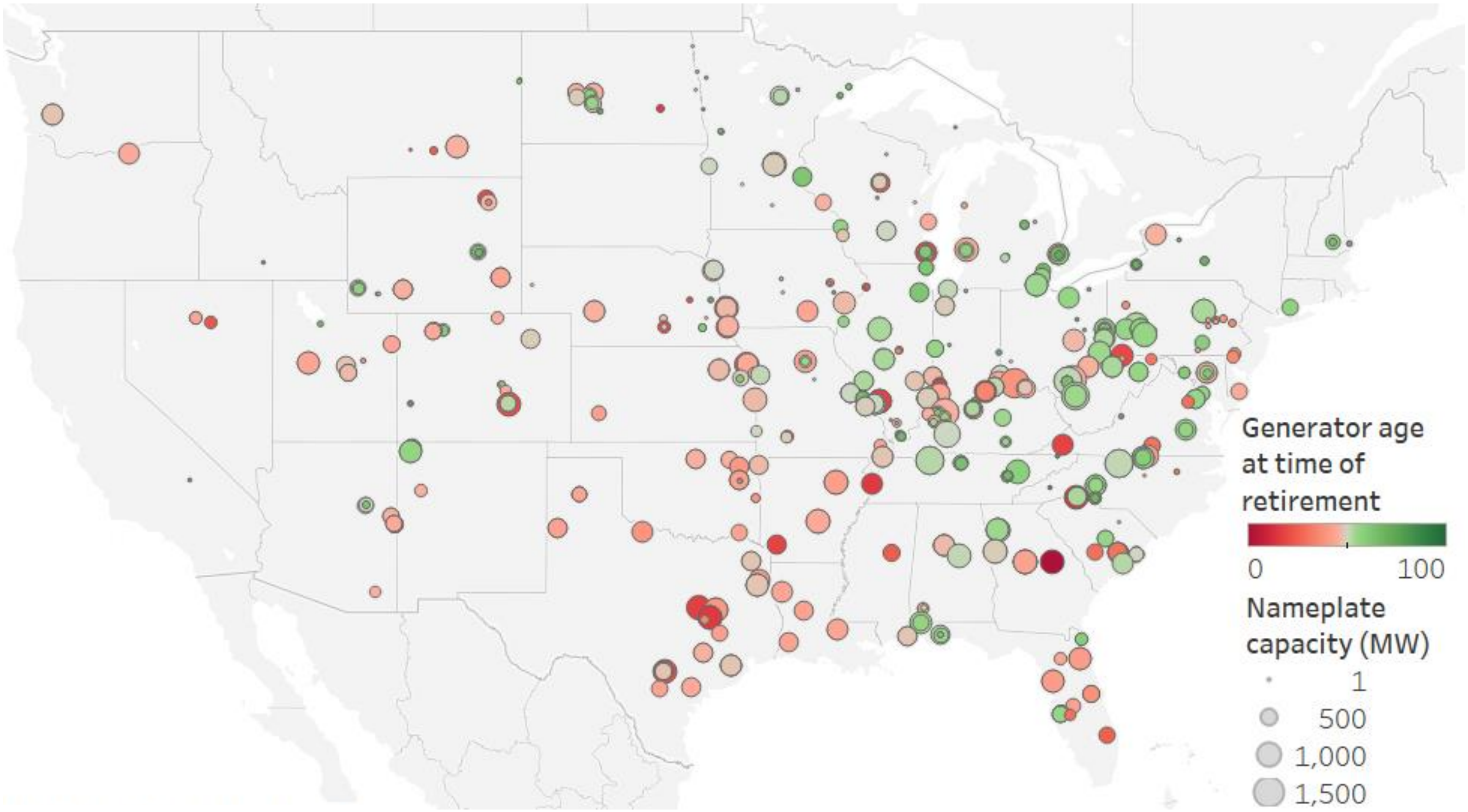


The U.S. coal fleet is old. Half of plants retire 50+ years old in the 2020's. Less than 8% (23 GW) retire before reaching 20 years.



Retirement of coal generators for E+ scenario

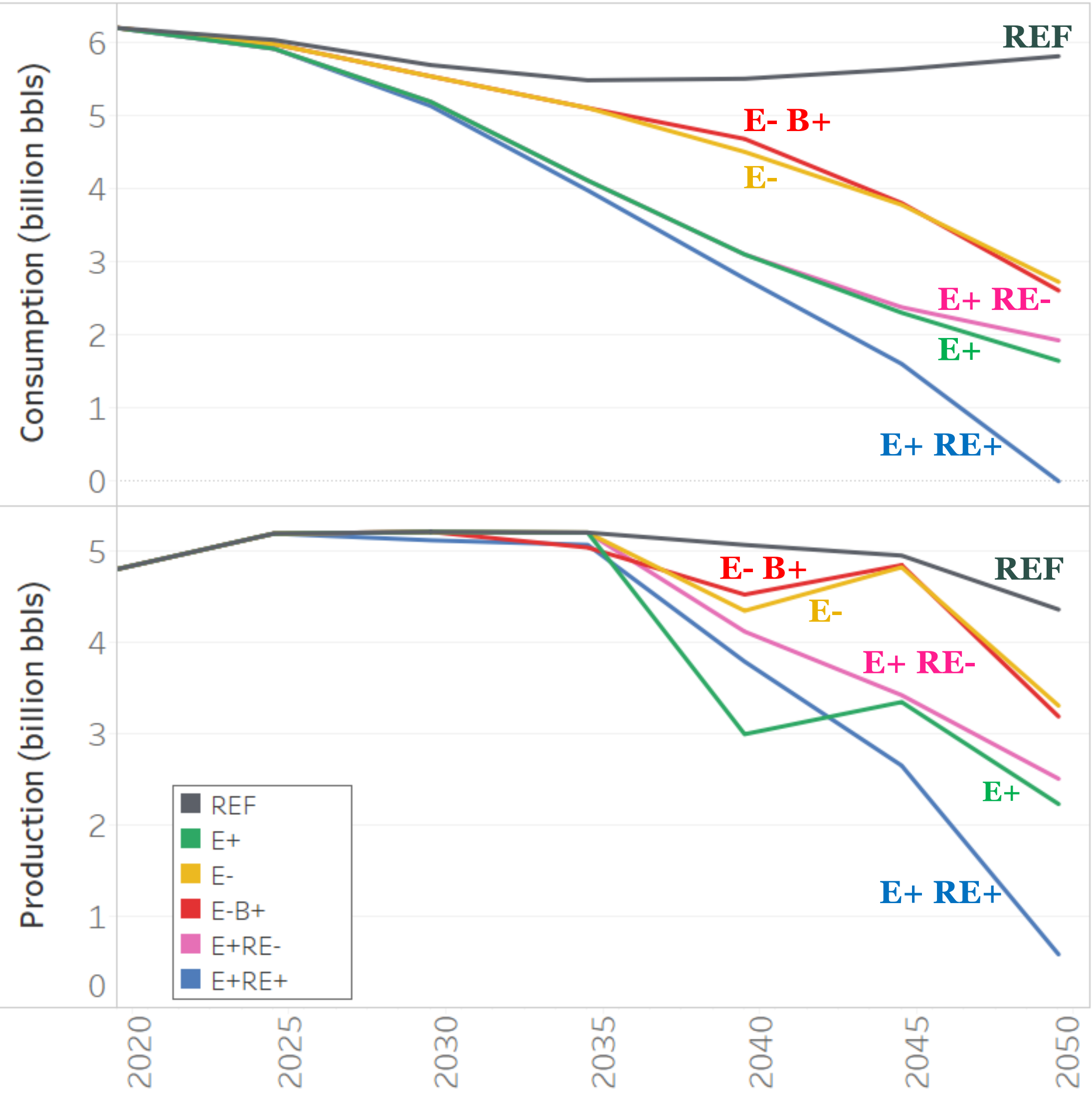
Generators indicated in red retire prior to the typical 50-year lifespan of coal generators, consistent with Grubert (2020).



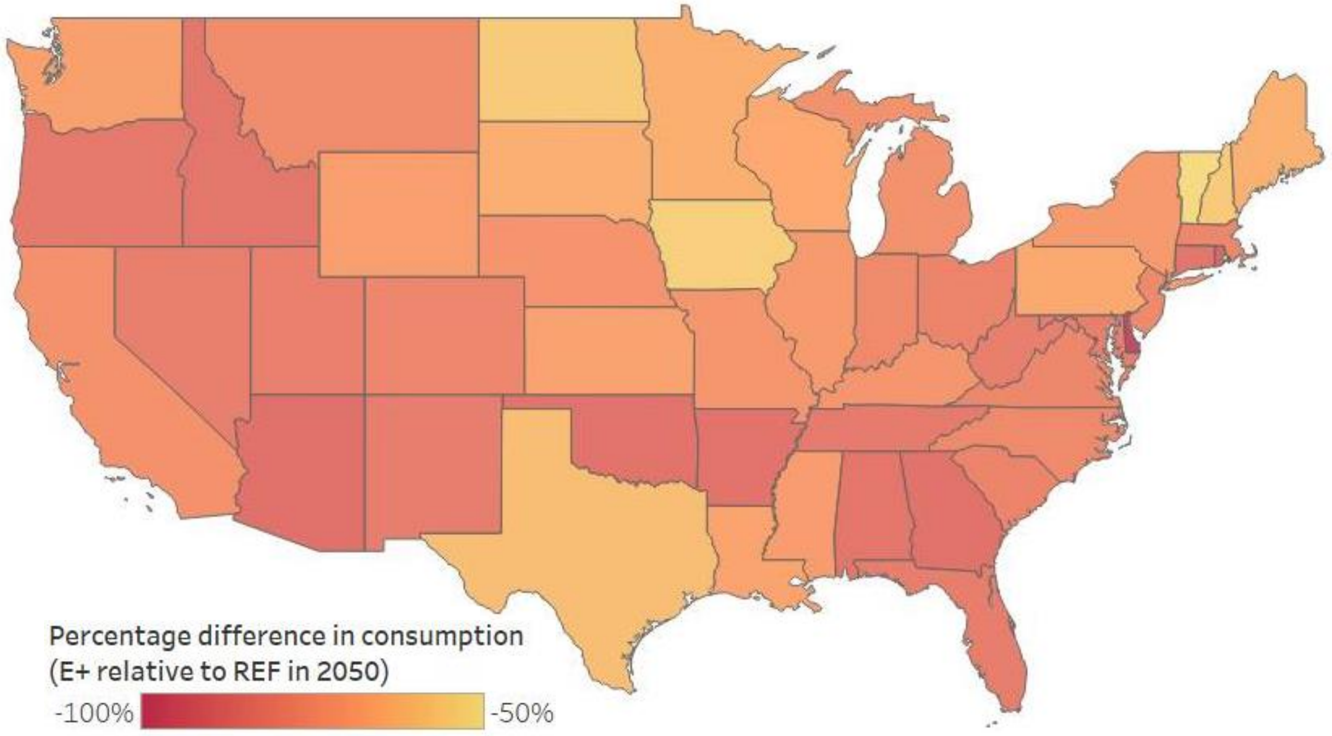
Summary of this section

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

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



Change in oil consumption in E+ case relative to REF



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

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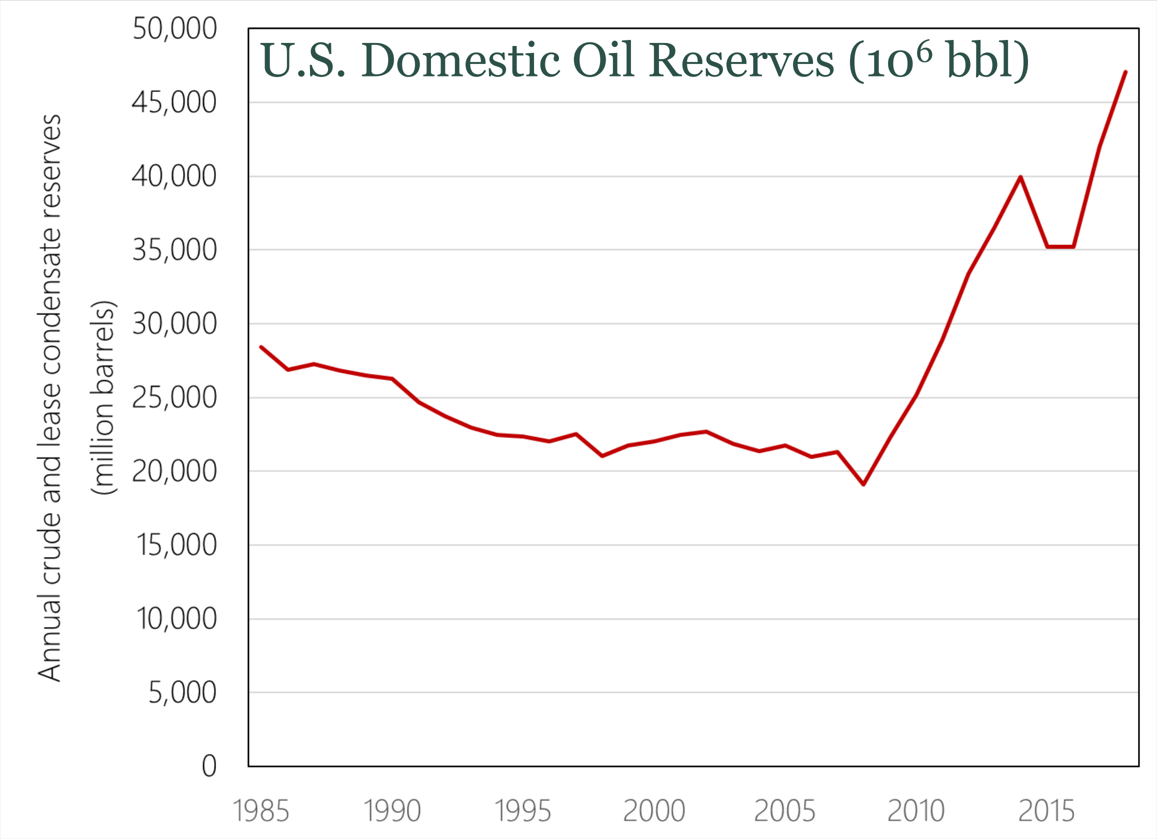
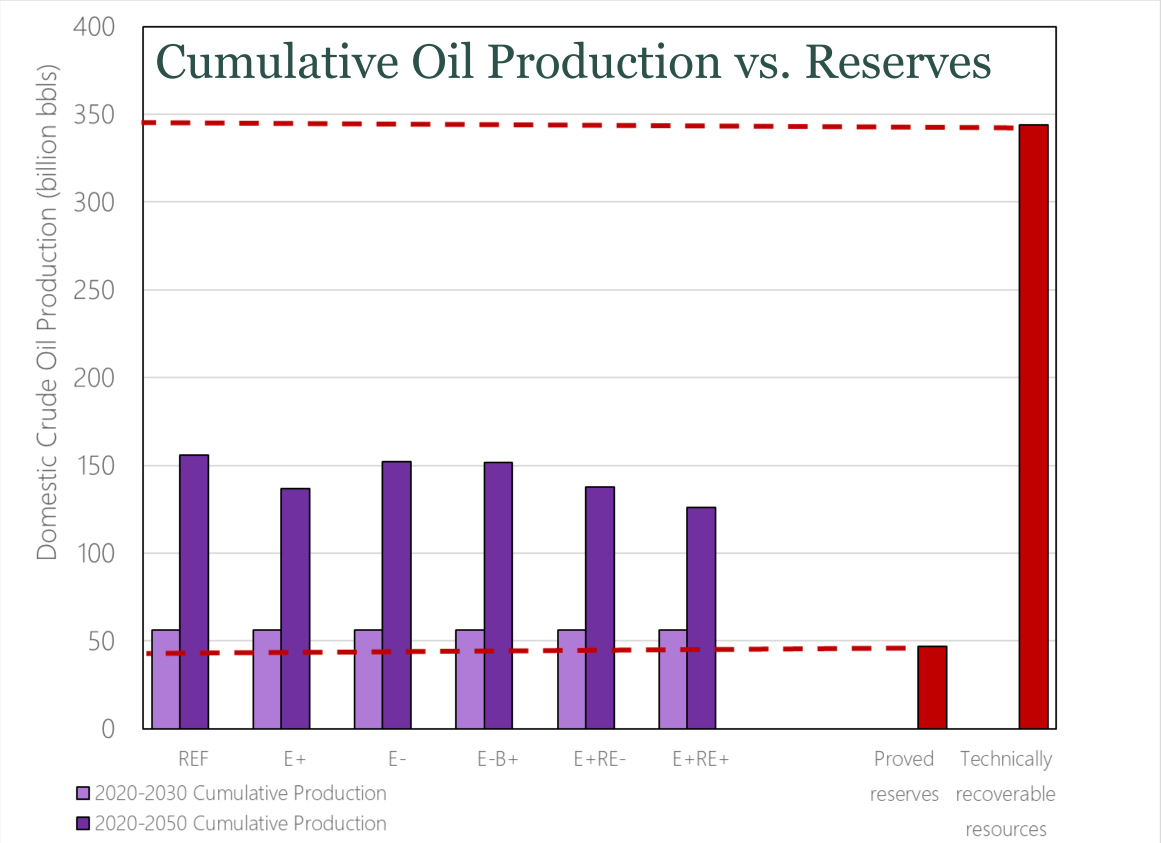
Cumulative oil production through 2030 exceeds current proved reserves, but continued additions could risk stranding assets.





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

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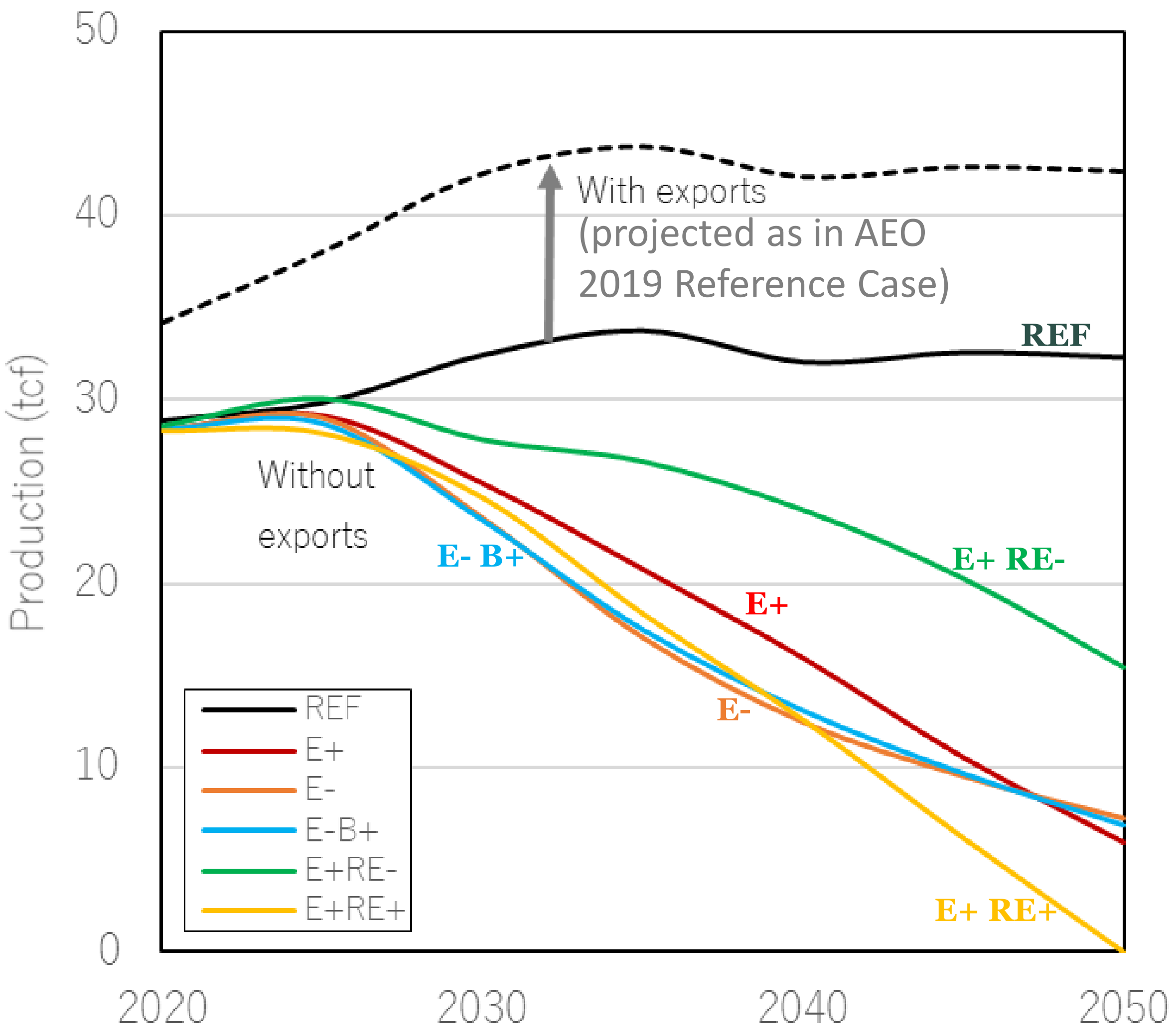
Natural Gas

Summary of this section

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

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

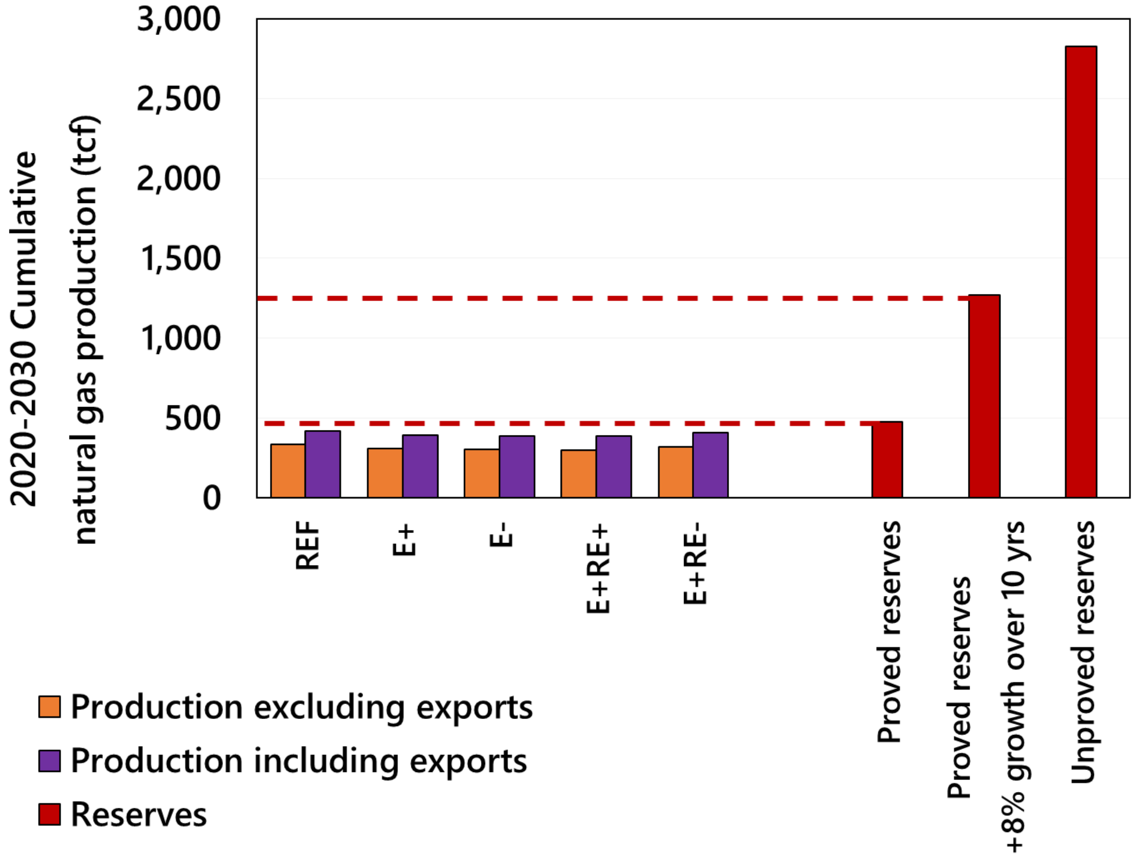


- Over ½ million gas wells close in 2020's; plug and abandonment costs are estimated to be ~$25 billion.

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

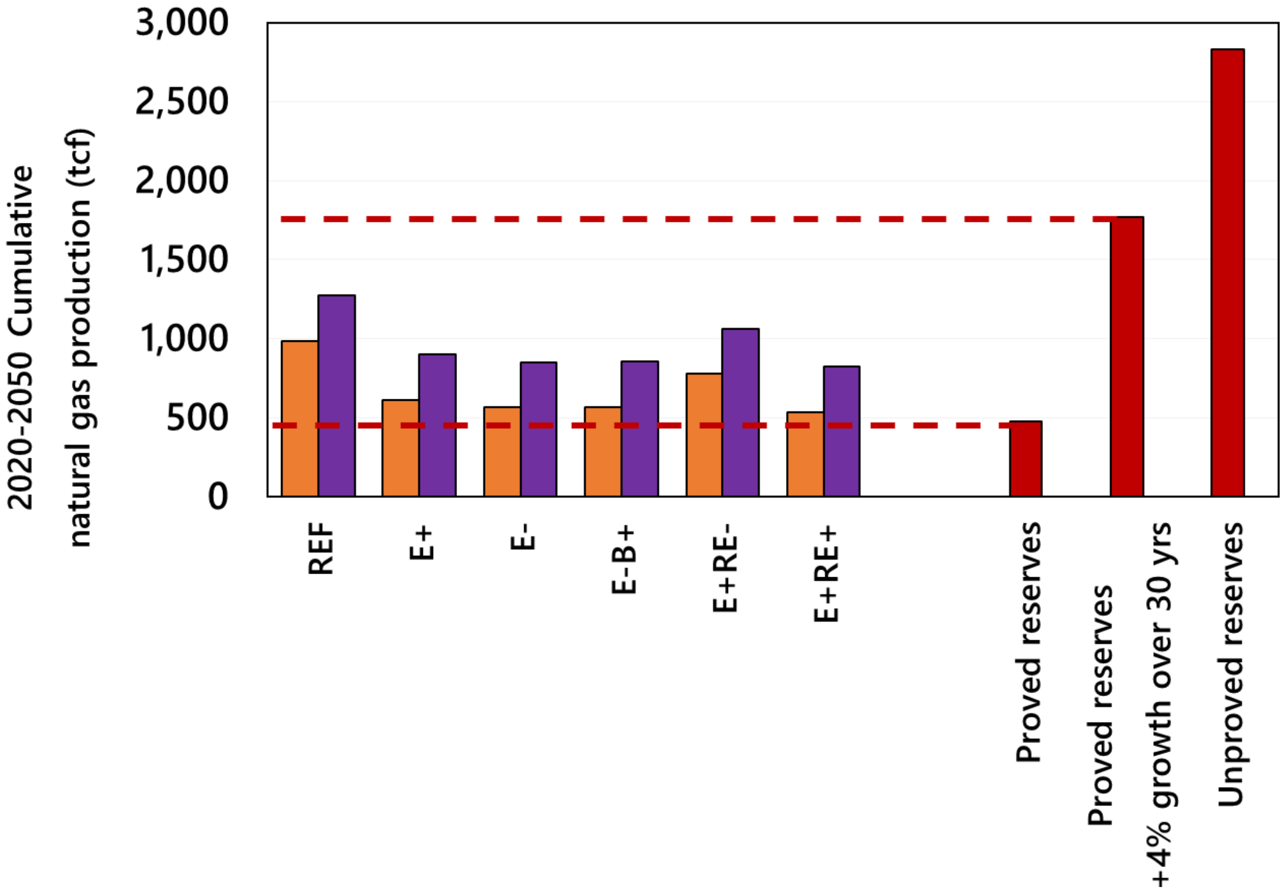
2020-2030 Near-term production and reserves

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



2020-2050 Long-term production and reserves

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



EIA reserves estimates.

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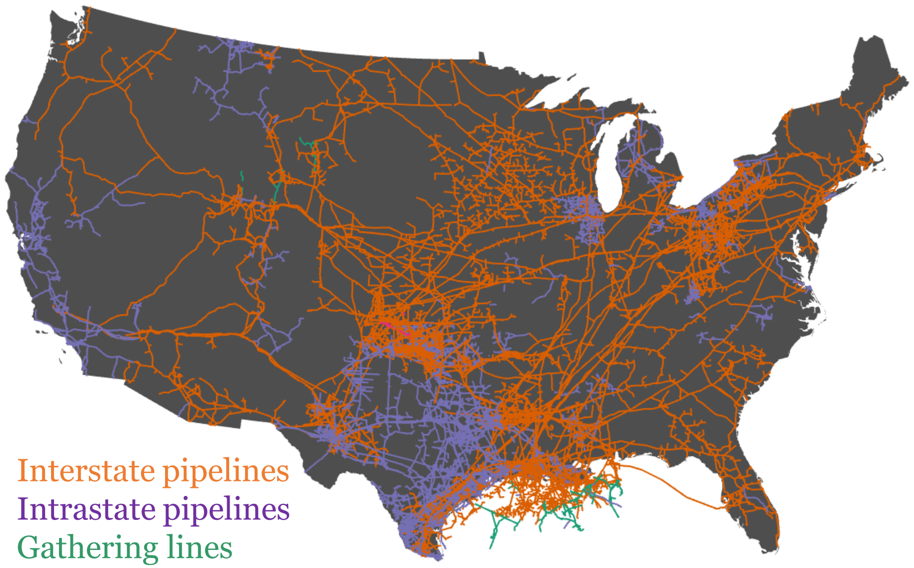
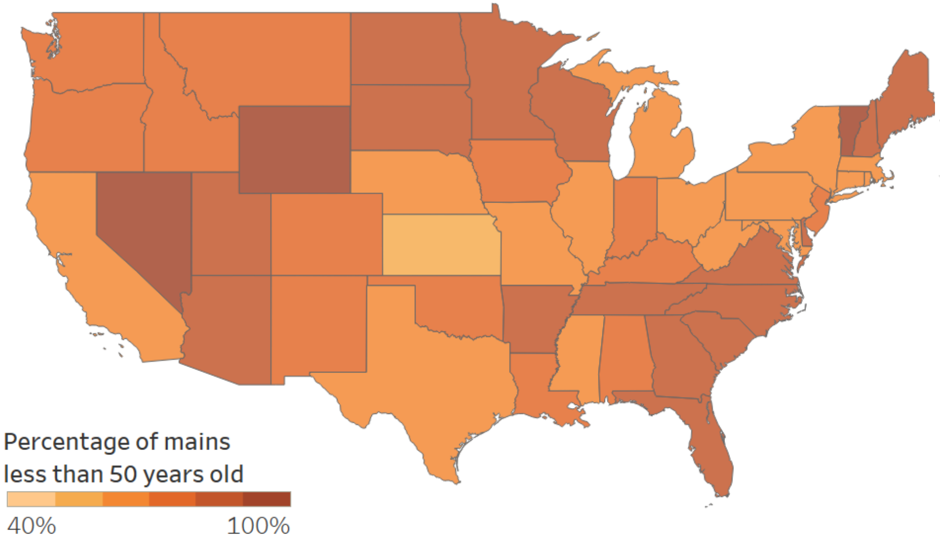
Declines in natural gas consumption will impact gas transmission and distribution infrastructure.



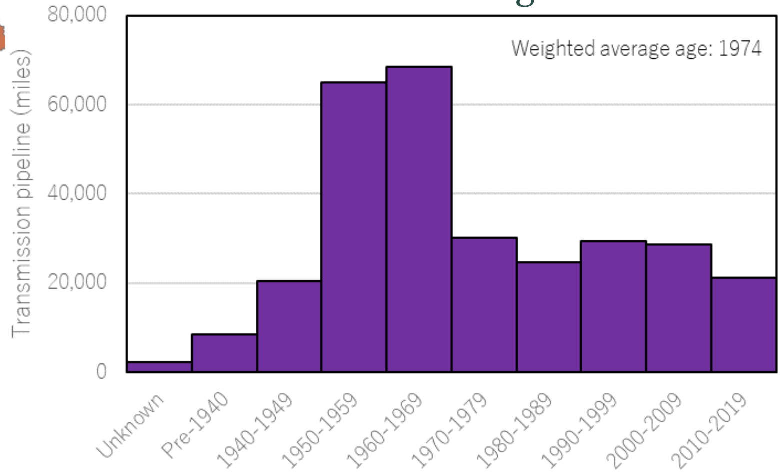
The existing gas pipeline network is vast:

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

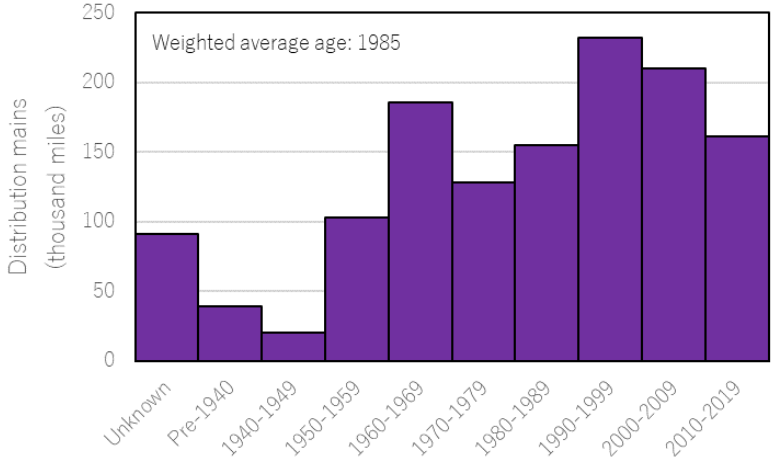
The transmission network is aging, but some distribution system replacements have accompanied the shale gas boom:



Transmission line vintages



Distribution main vintages



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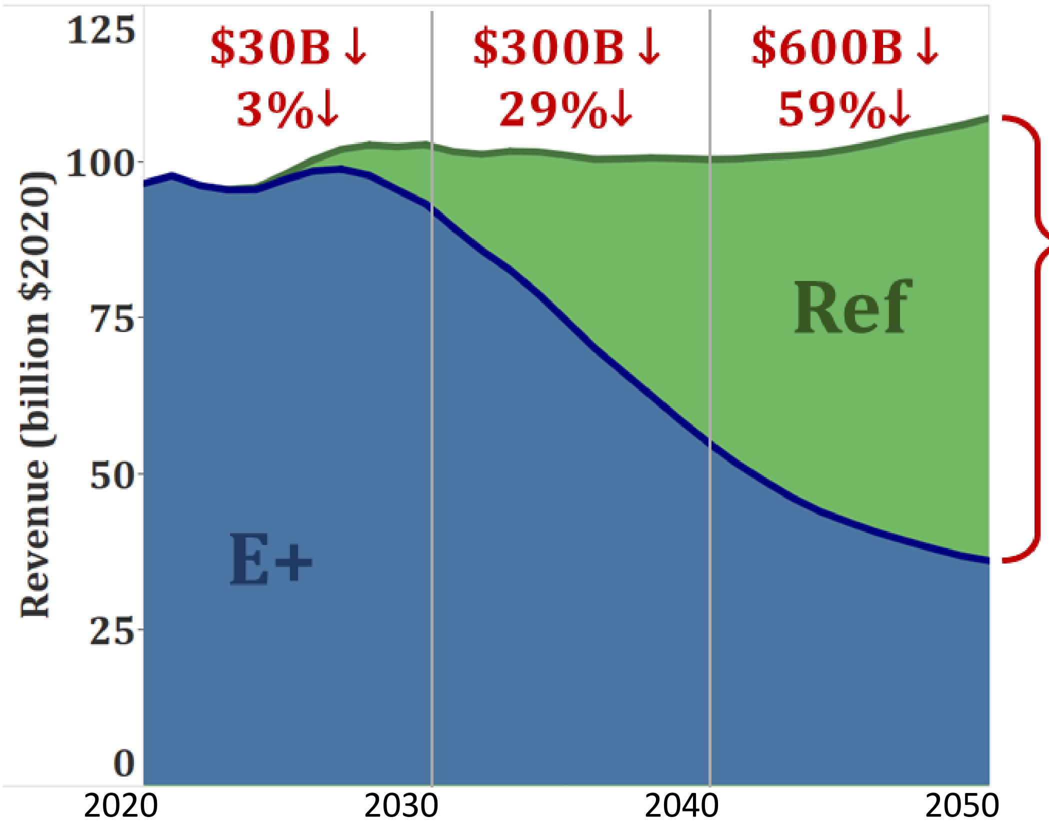
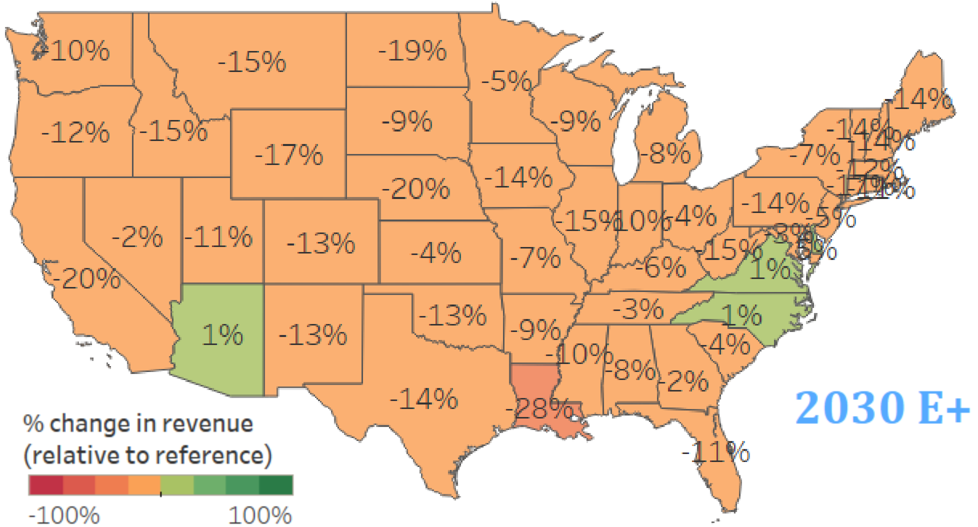
As gas use falls, volumetric revenues will decline, prompting need to review rate design and network asset valuations

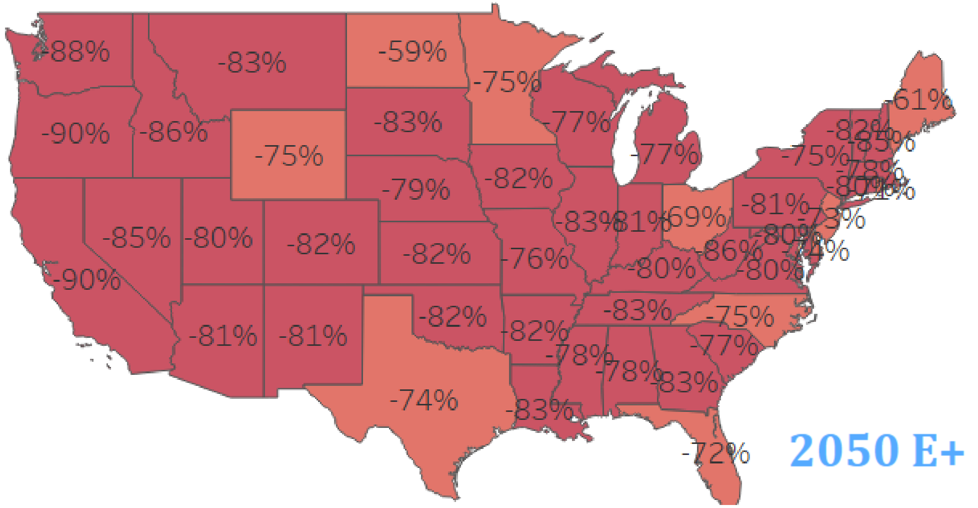
Decline in natural gas market revenue (E+ vs. REF) assuming volumetric rates



Reduced spending, assuming gas prices constant across scenarios

*Revenue includes pass-through commodity cost.





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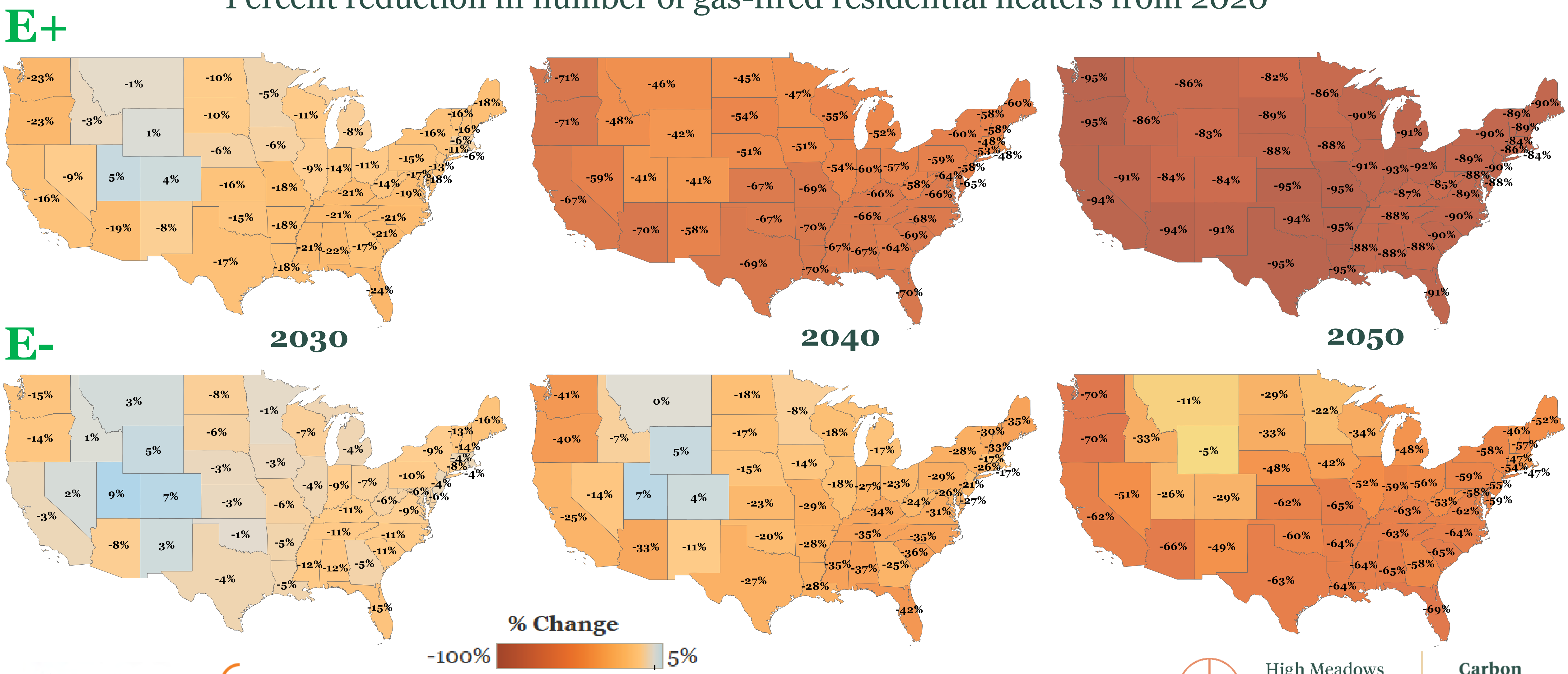
Declining customer base over time will challenge cost recovery and raise equity concerns.

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



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Employment impacts

Summary of this section

- A model was built to assess energy supply-related employment, wages, and workforce development requirements in energy-system transitions. (Energy efficiency, vehicle and appliance related employment is not modeled in this study.)
- To support modeled net-zero transitions, the supply-side energy workforce expands 12-24% in the 2020s across different net-zero scenarios and by 24-152% by 2050. Today ~1.5% of the labor force is directly employed in energy supply-related jobs. By 2050, this grows to 2-4% across different net-zero scenarios.
- Net-zero pathways support ~3 million energy supply-related jobs by 2030, a net increase of 0.3-0.6 million jobs relative to the REF scenario.
- Net job losses in fossil fuel sectors across the transition are more than offset (in aggregate) by increases in low-carbon sectors, especially solar, wind, and electric-grid sectors. Construction comprises an increasing proportion of jobs over time, and mining (i.e., oil, gas, coal upstream activities) comprises a declining portion.
- All employment modeling assumes current domestic content shares persist for major manufactured components.
- This modeling explicitly considers impacts of labor productivity changes on future employment. Changes in productivity have a large influence on modeled employment outcomes and more broadly on the energy transition as whole.
- An annual average of ~$170-180 billion in wages are generated in the 2020s, a net increase of $20-30 billion over the REF scenario. Supply-side energy sector employment generates ~2% of total U.S. wages, rising to as much as 4.5% by mid-century.
- A number of modifiable sociotechnical factors influence the spatial distribution of labor. With assumptions used here, all states see energy-related employment grow as a share of the total state labor force except for a few with very high shares of the current labor force employed in upstream fossil fuel industries (e.g., WY). In some states with high renewable resource quality (e.g., NE, MT, IA), energy industries grow to become dominant employers.
- There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

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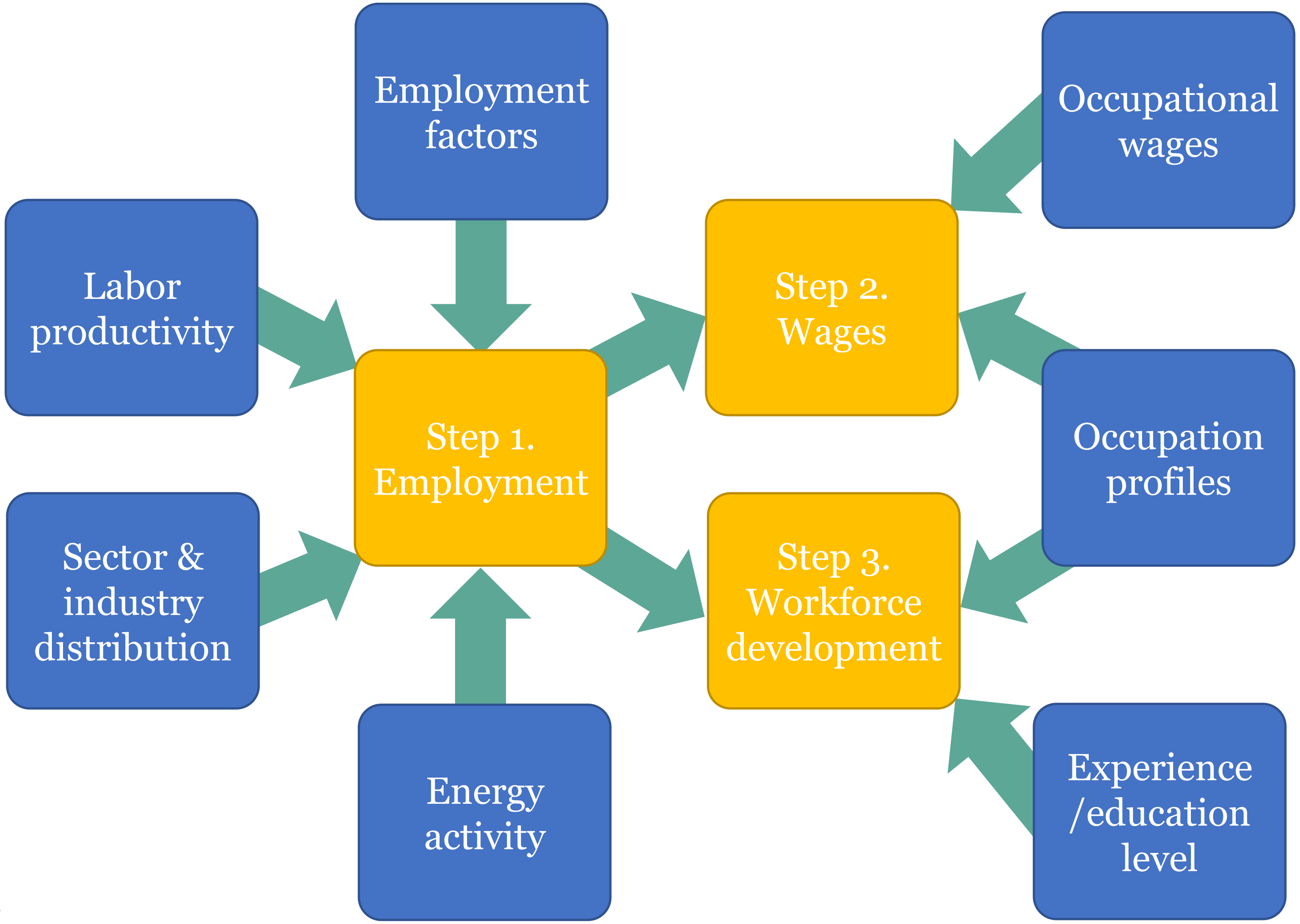
Decarbonization Employment & EneRgy Systems model (DEERS)

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

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

See Annex R for DEERS model details.



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

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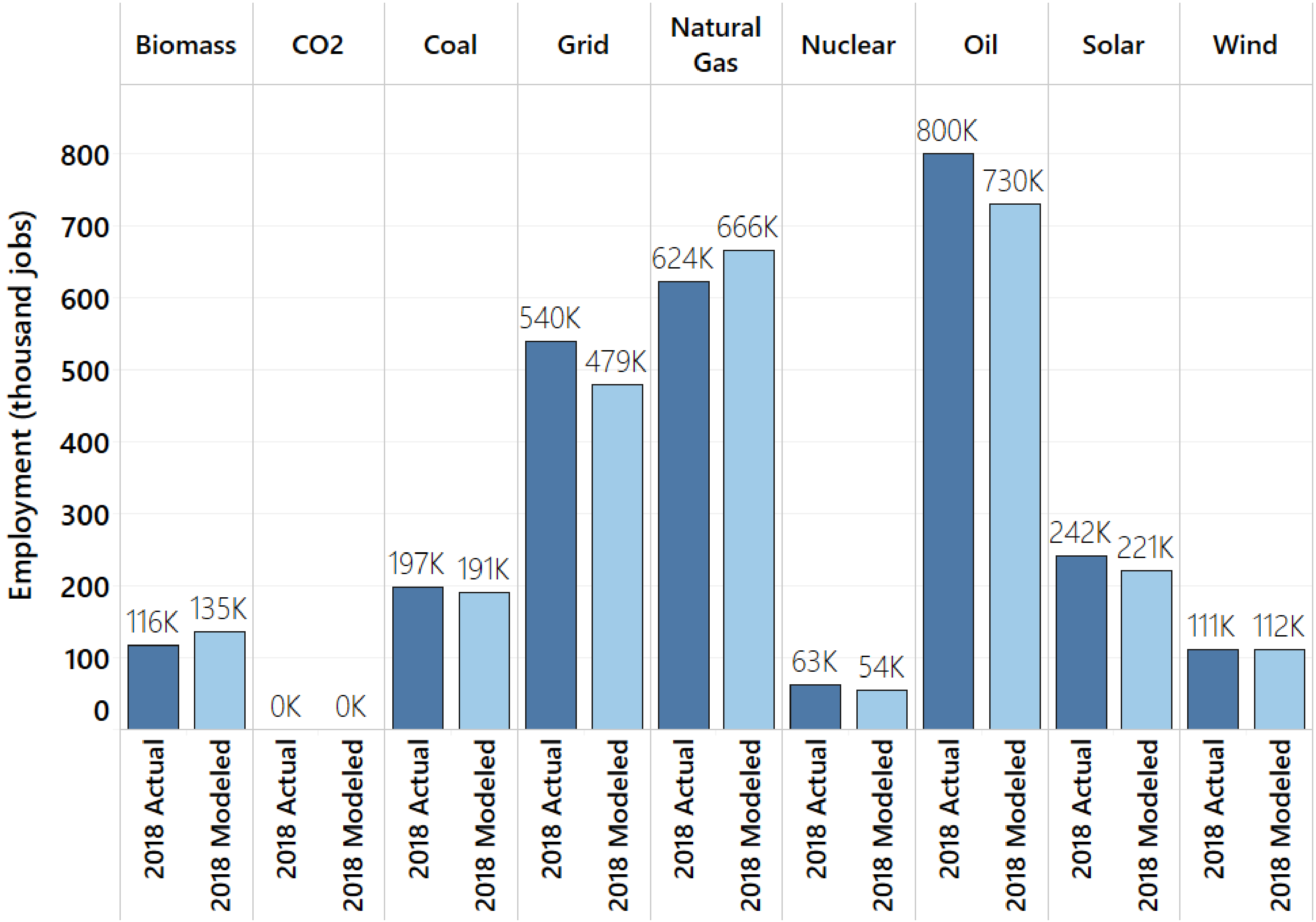
Employment simulated using DEERS (based on actual 2018 activity data) compares well with actual 2018 employment.

Model calibration results



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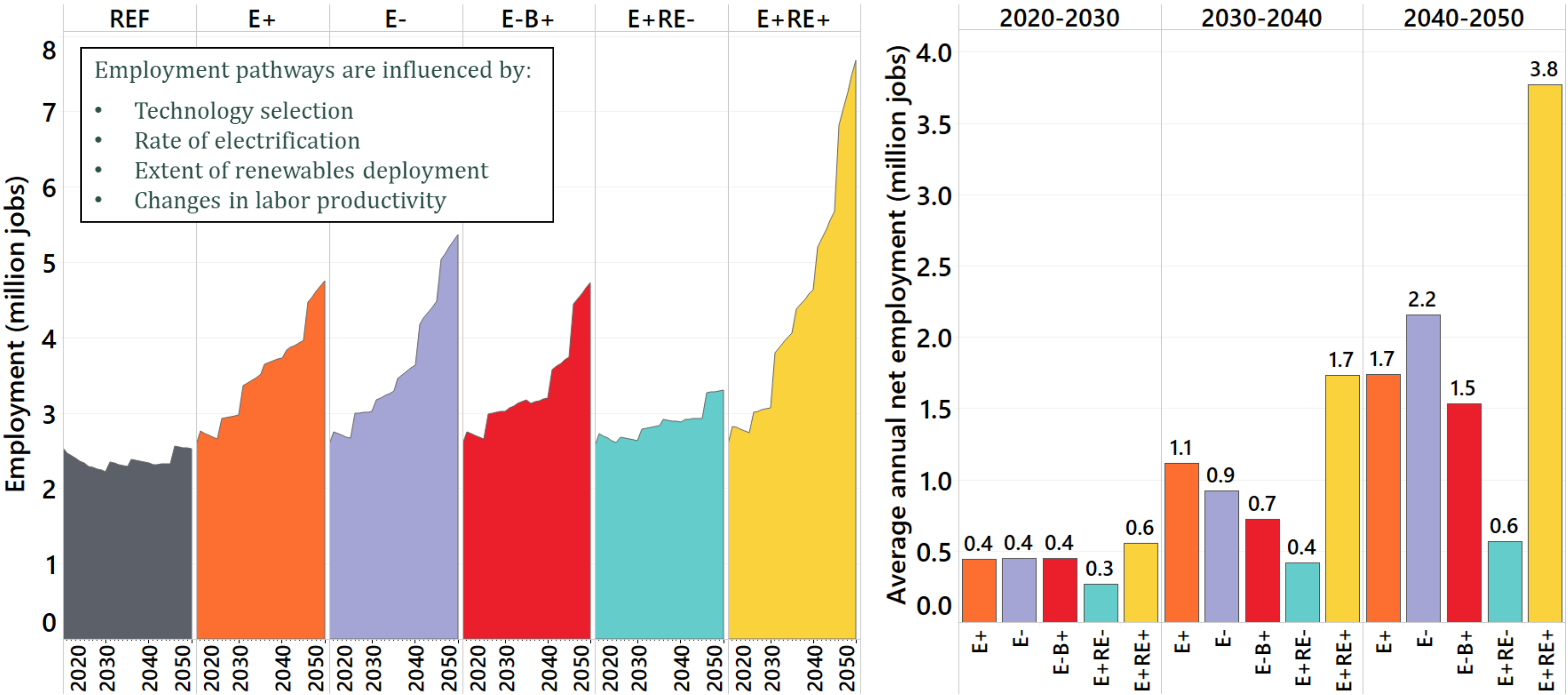
~3 million direct energy supply-related jobs annually in the 2020s in net-zero scenarios, or ~0.5 million more than REF scenario.



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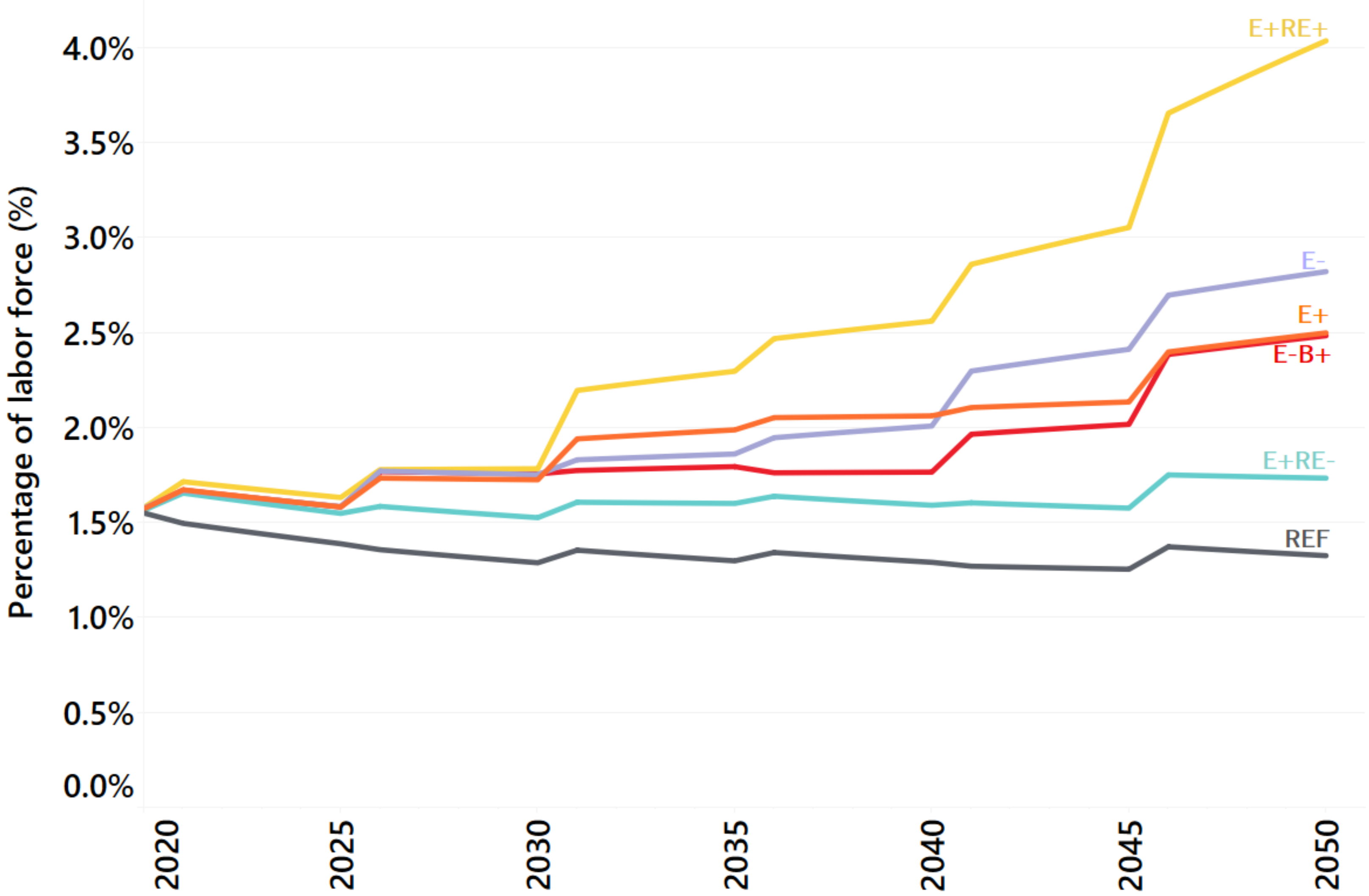
1.5% of the U.S. labor force is directly employed in energy-supply today, increasing to 2-4% by 2050 in net-zero scenarios.



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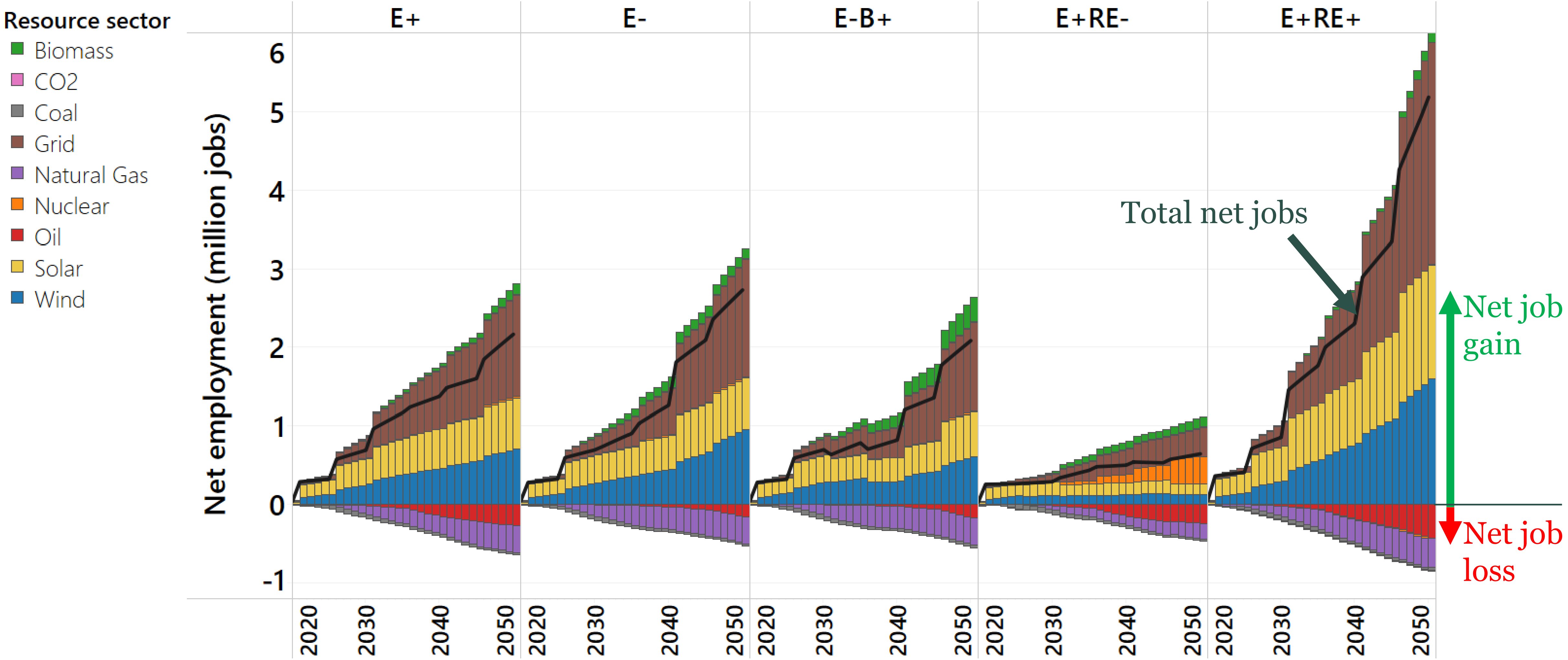
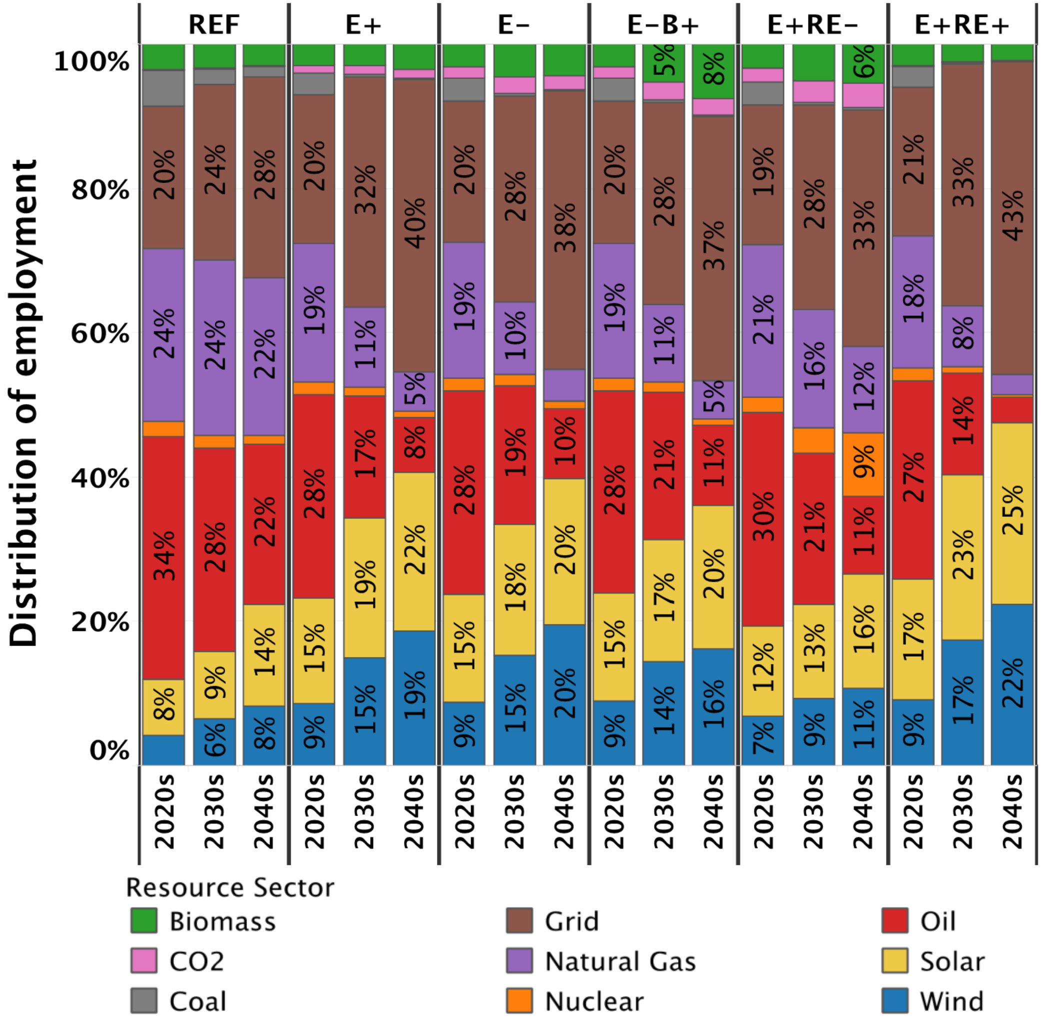
Net job losses in fossil fuel sectors in near- and long-term are more than offset (in aggregate) by increases in low carbon sectors.

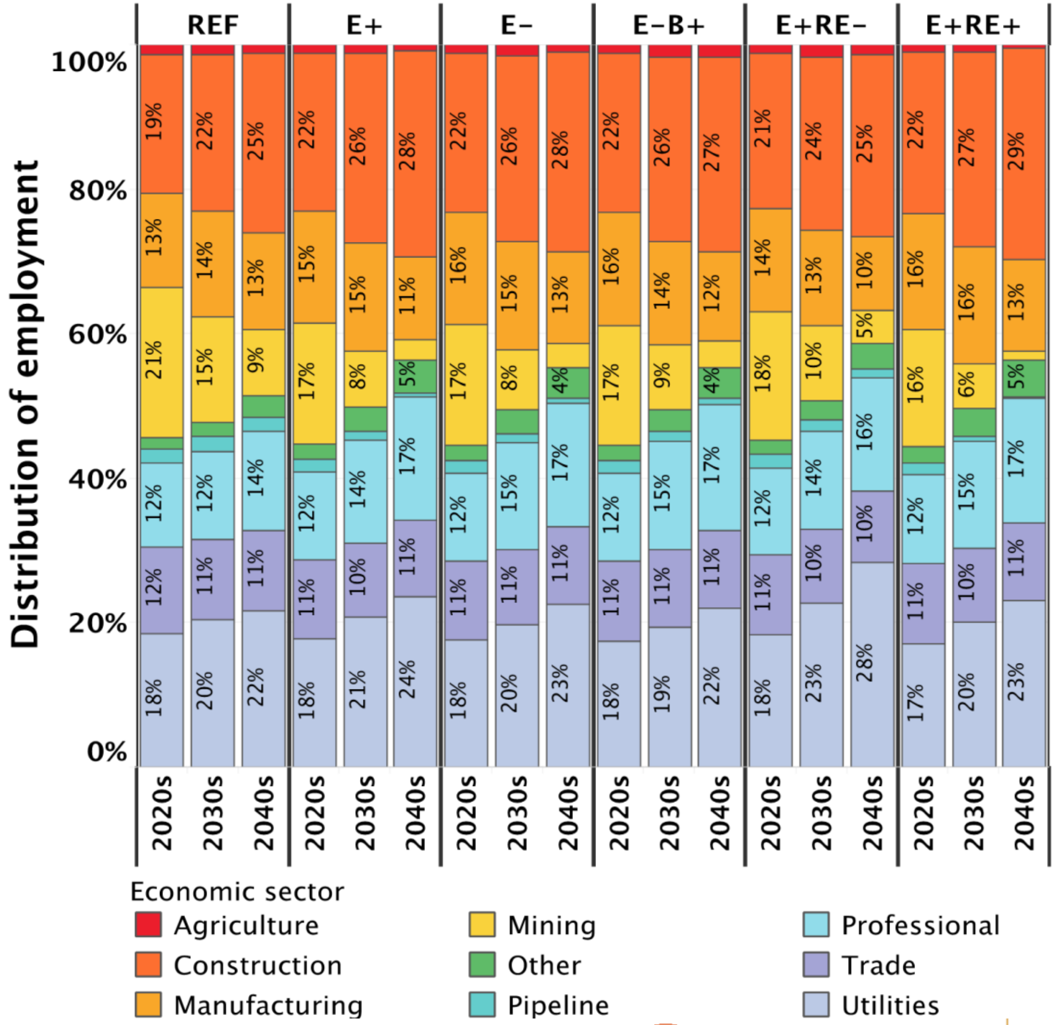


Solar, wind, and grid dominate energy-sector jobs. Construction share increases over time, while mining (upstream fossil) declines.

Distribution of jobs by resource sector



Distribution of jobs by economic sector



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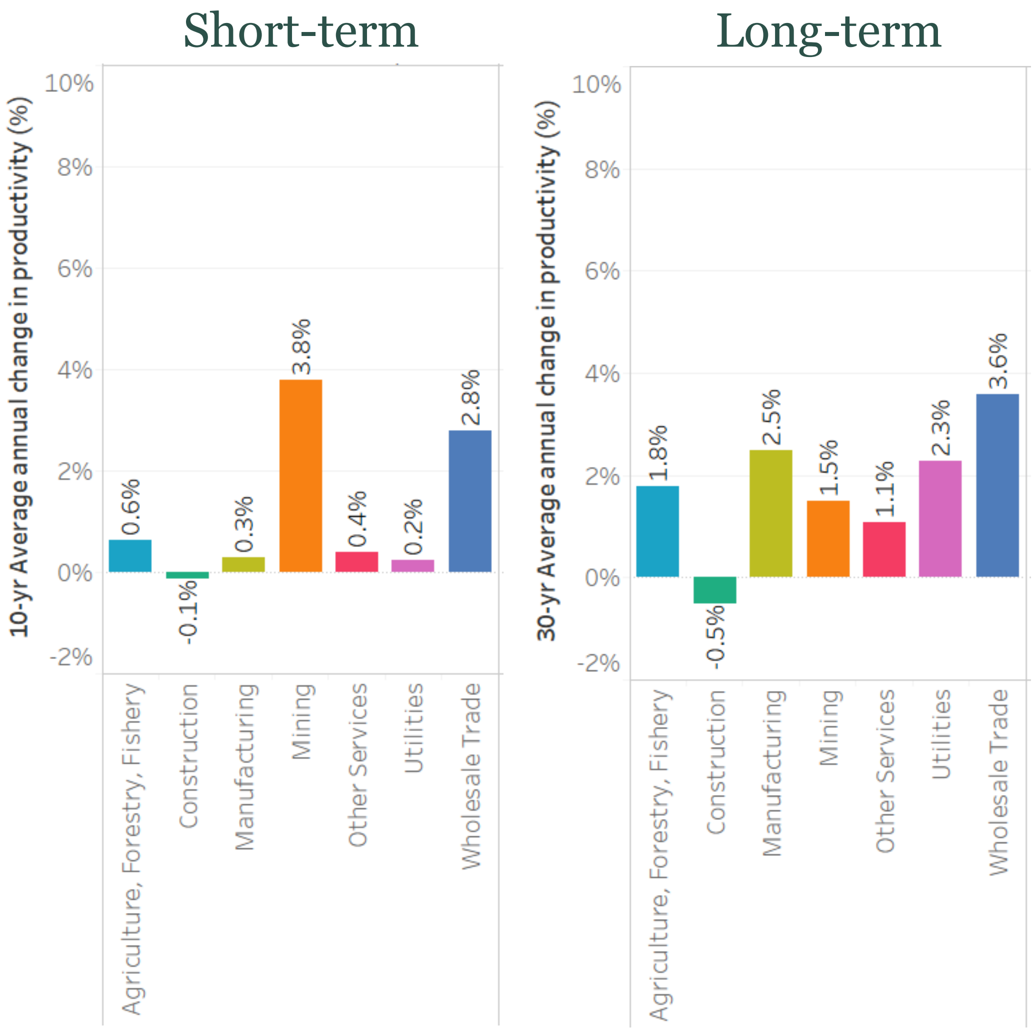
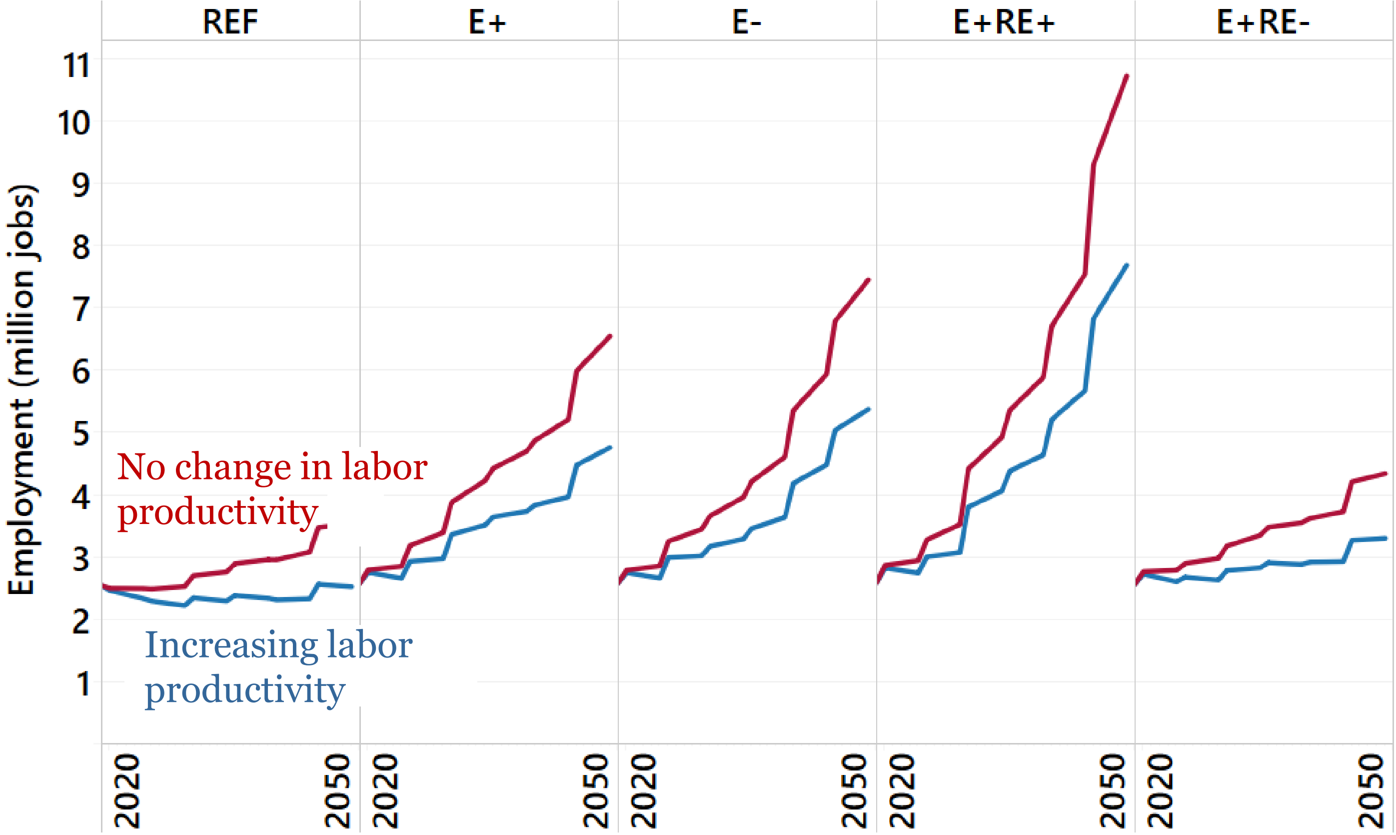
Changes in labor productivity have a large influence on employment outcomes and more broadly the energy transition as whole.

Historical changes in labor productivity

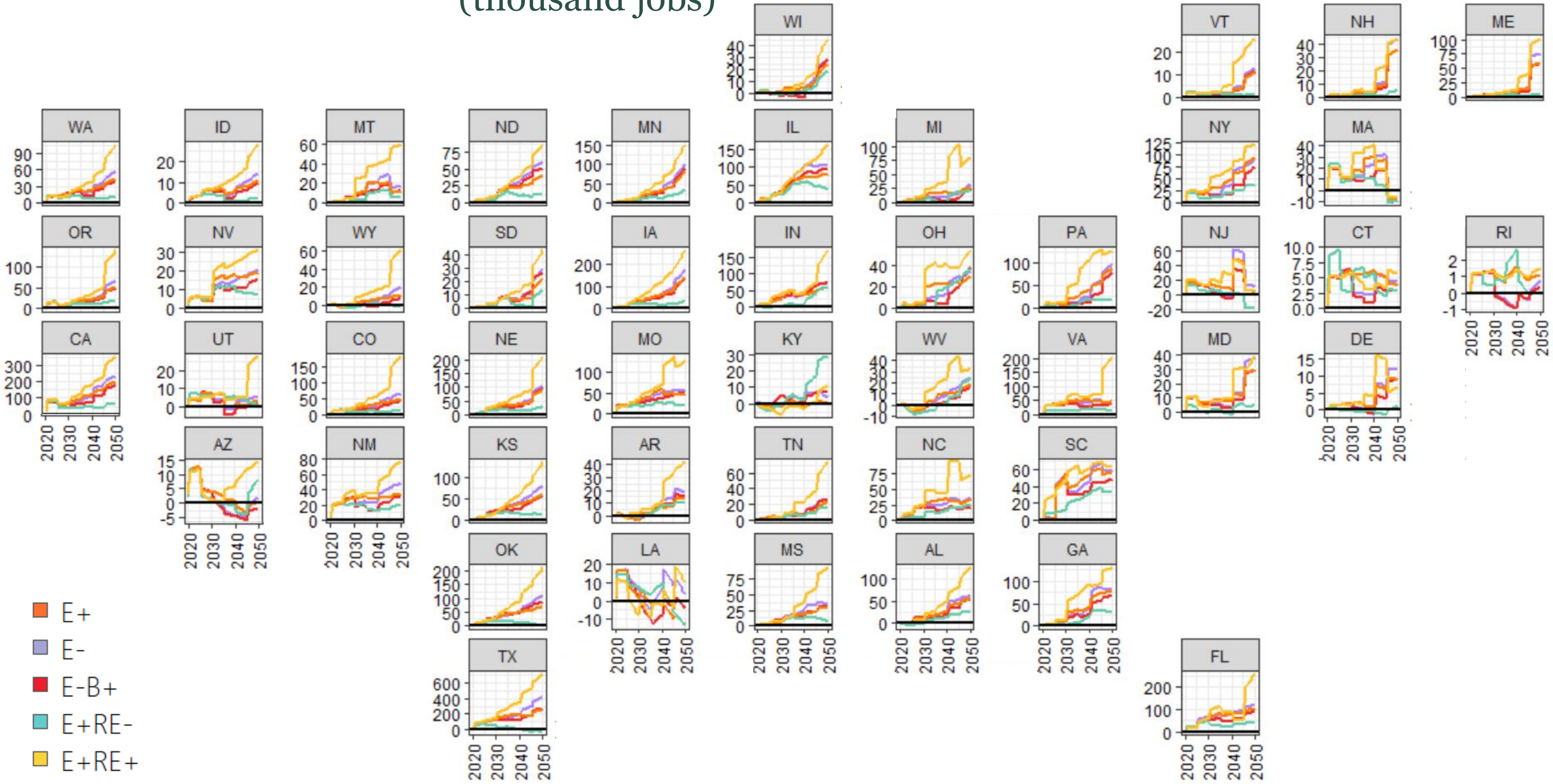




Note: Other employment modeling results shown in this report correspond to the results with increasing labor productivity shown on this slide.

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

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



Modifiable sociotechnical factors that influence the spatial distribution of employment:

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

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

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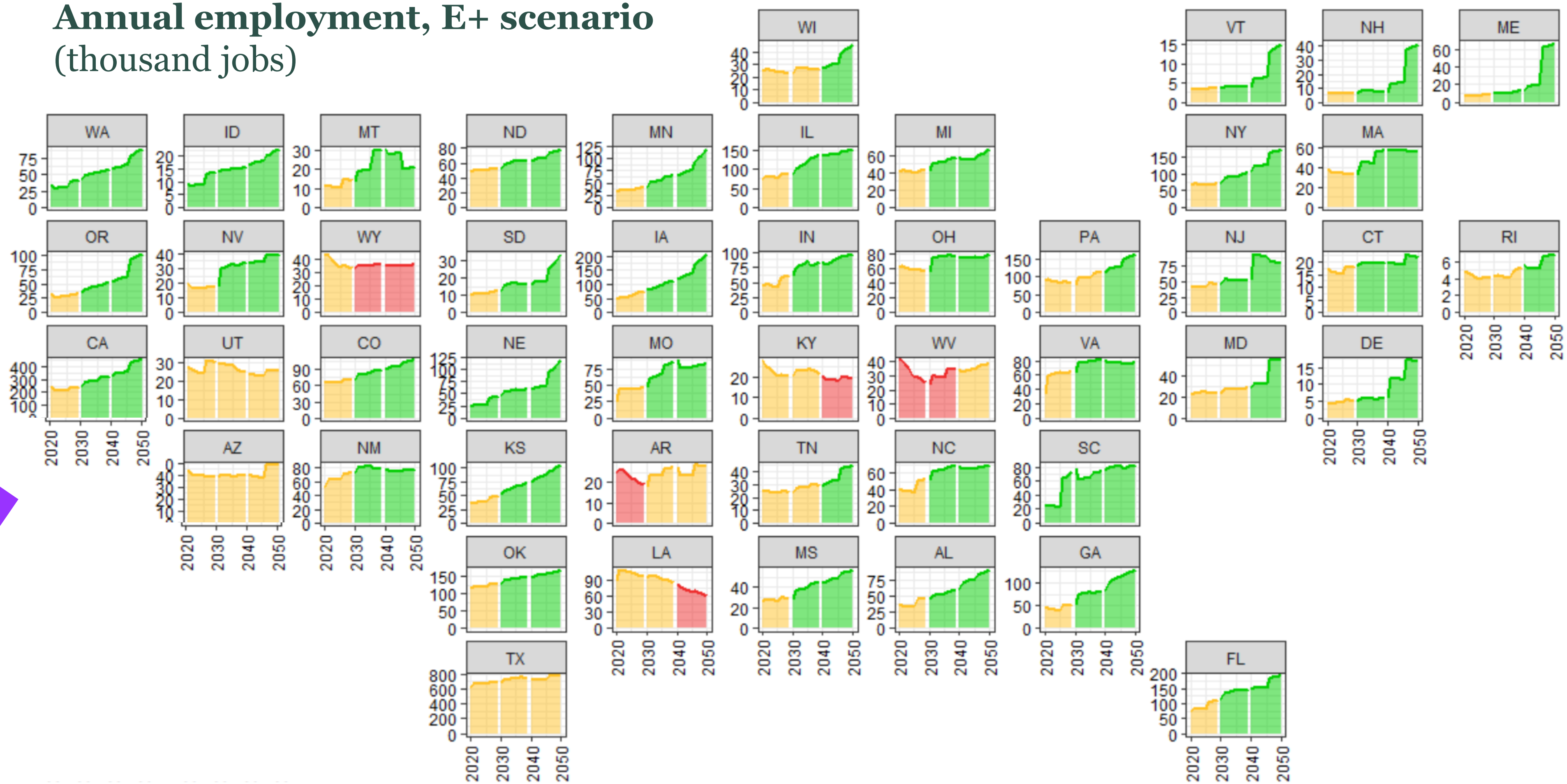
Transitioning to a net-zero energy system has the potential to transform state and local economies.

Annual employment, E+ scenario
(thousand jobs)



Color indicates change in average decadal employment:

> 15% above 2021

within ± 15% of 2021

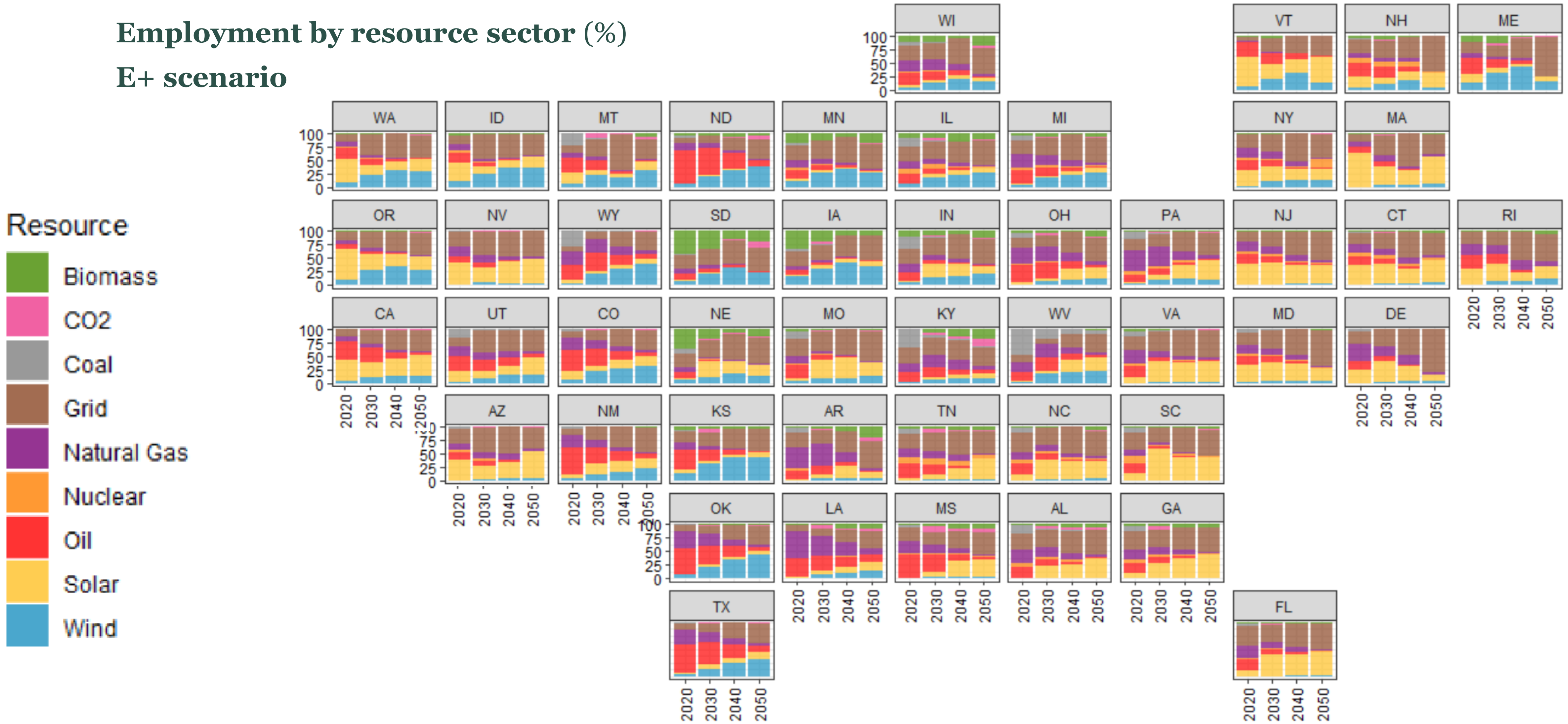
> 15% below 2021

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

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

Employment by resource sector (%)

E+ scenario



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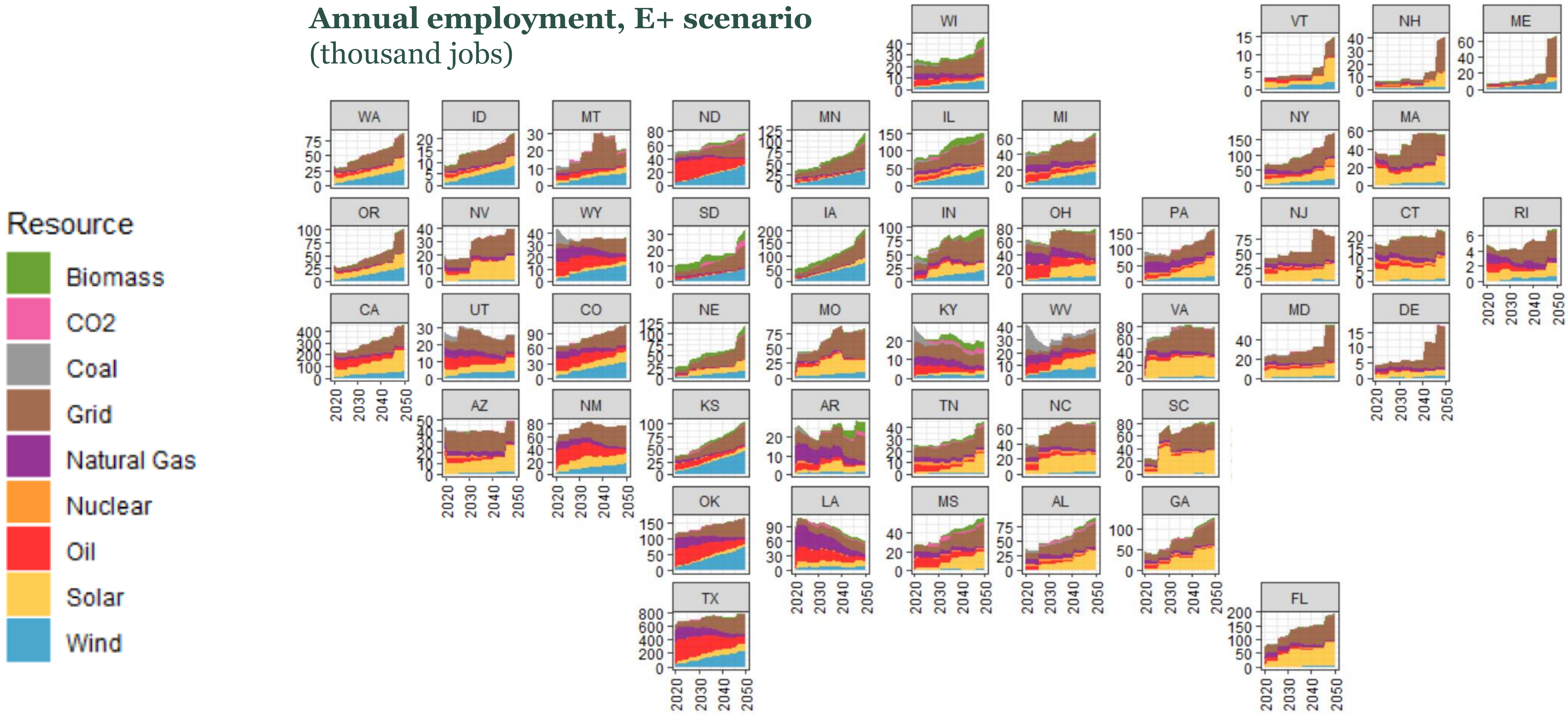
Solar, wind, and grid jobs are increasingly dominant in many states, but regional heterogeneity could be a risk to a just transition



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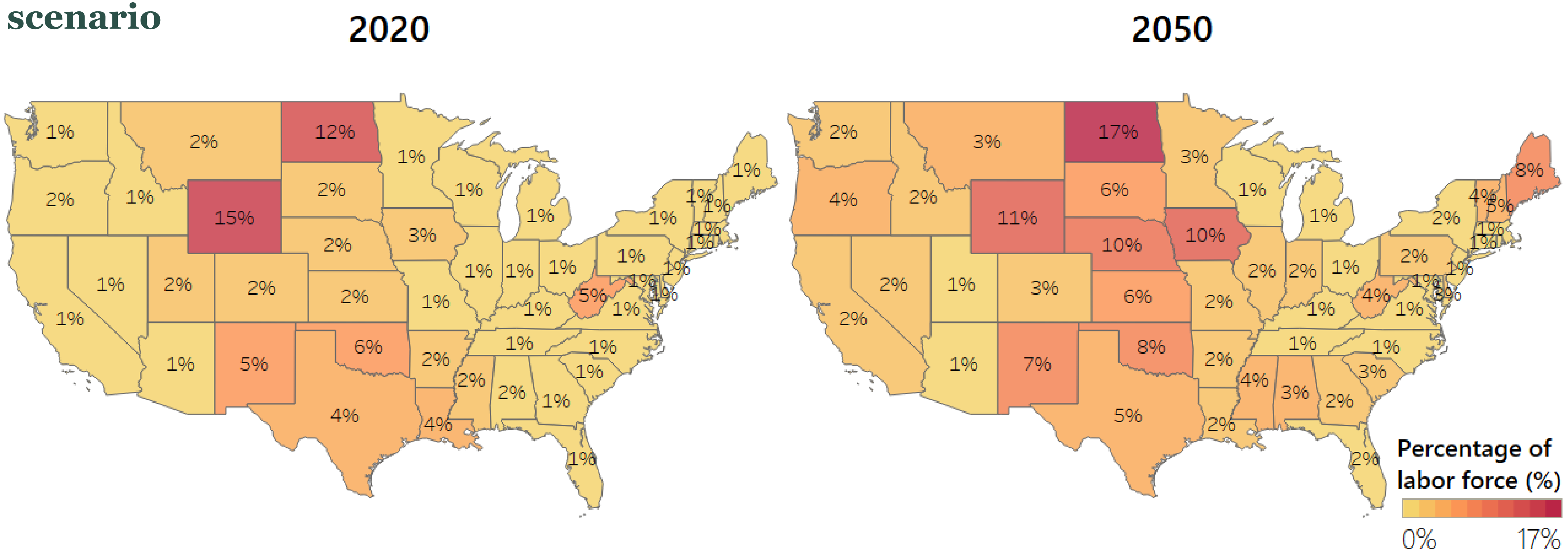
In most states, energy-related employment grows as a share of total employment through the transition to 2050.

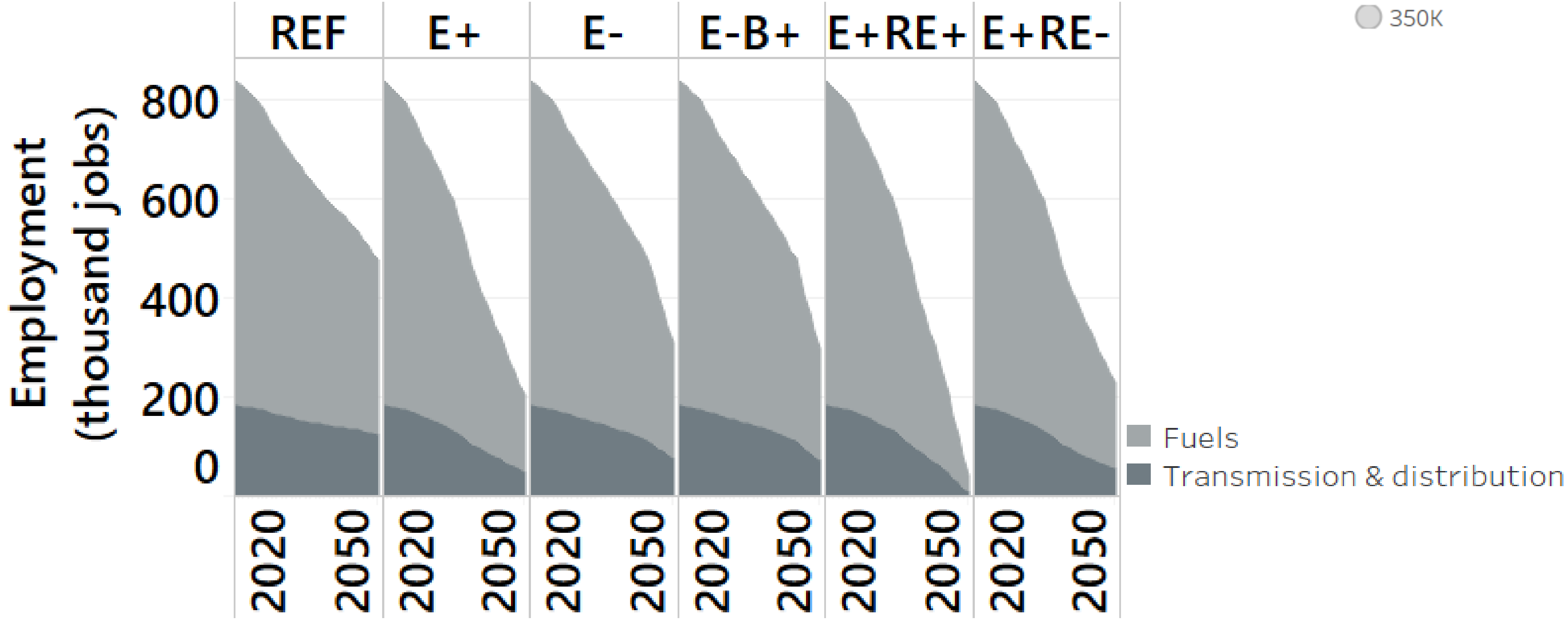
E+ scenario



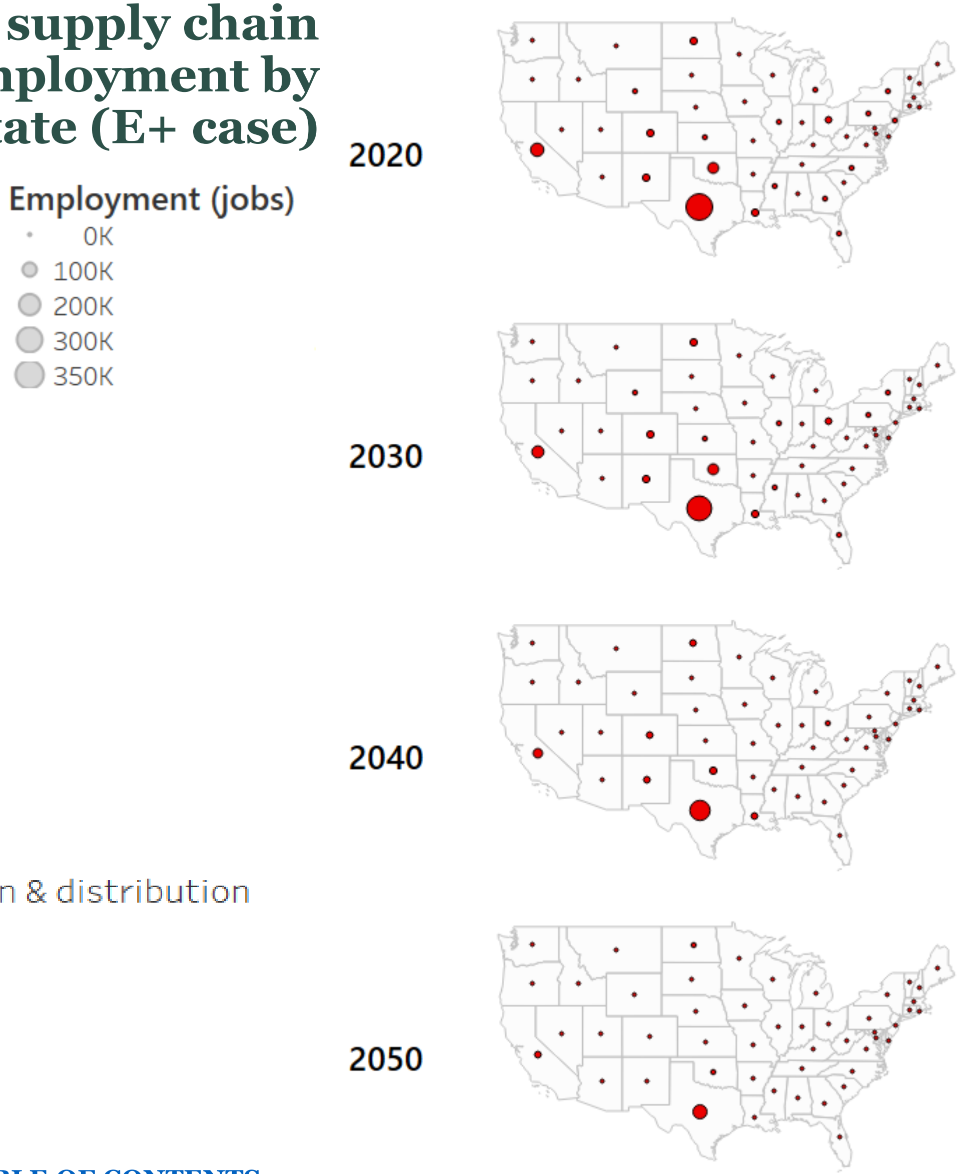
- In a few states with a very high share of the current labor force employed in upstream fossil fuel industries (e.g., WY), energy-related employment decreases as a share of the total employment through the transition.
- In states with high renewable resource quality (e.g., NE, MT, and IA), energy industries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

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

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



Oil supply chain employment by state (E+ case)



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

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

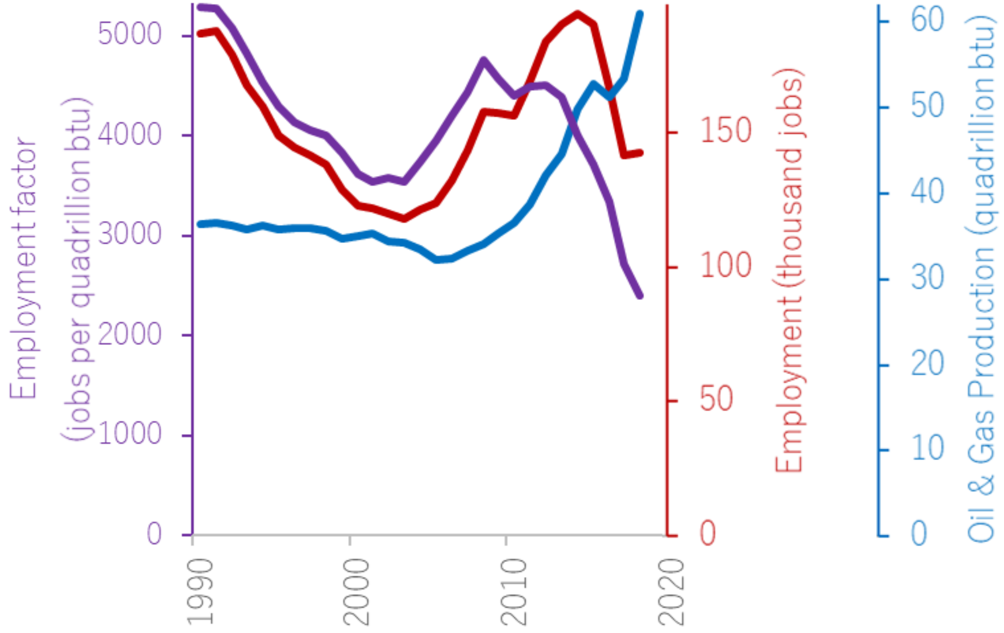
Natural gas sector supports 600,000 jobs associated with production (60%), transmission & distribution (30%), and power generation (10%) in model year 2021.

Source: NPR

Source: theint.net

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

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



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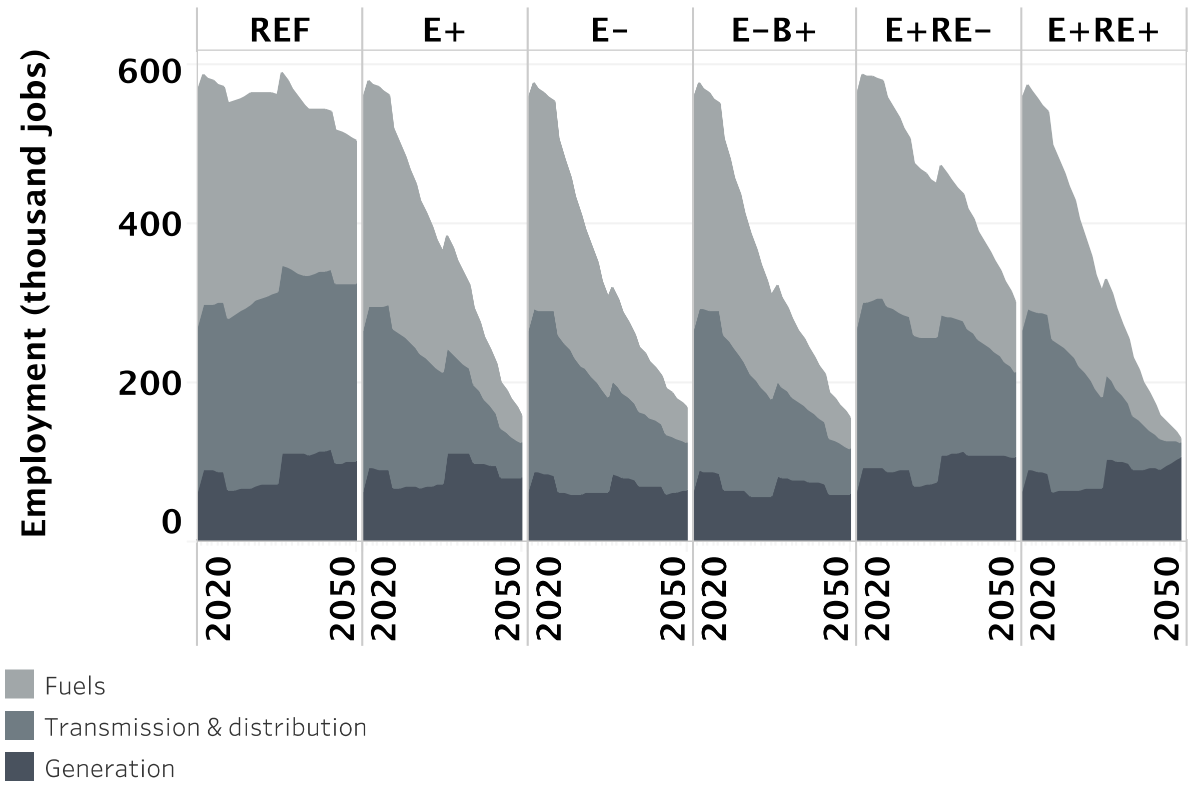
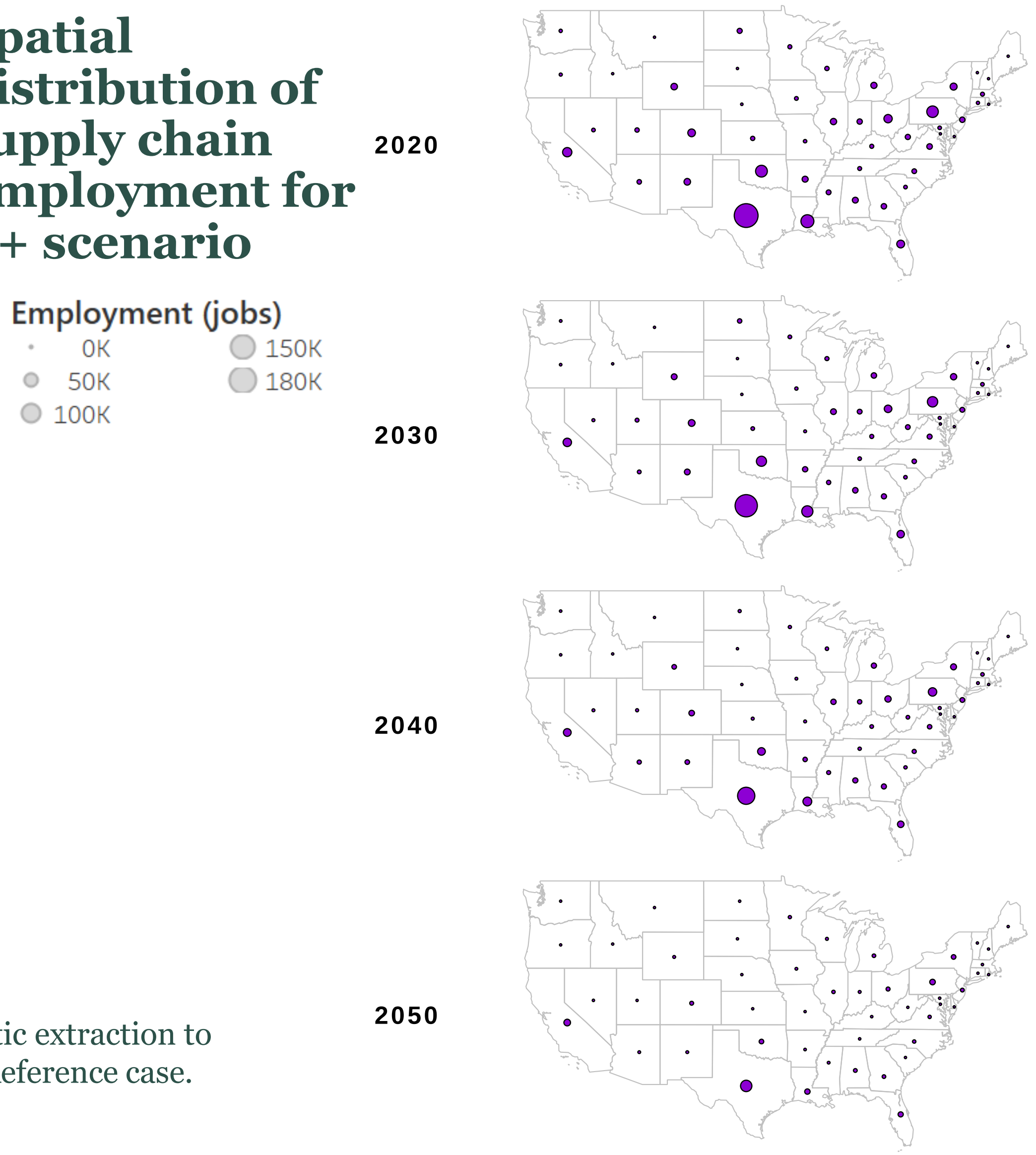
Jobs in natural gas value chain decline to 2050, except for gas power generation. The Appalachian and Permian basins are most affected.

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



Spatial distribution of supply chain employment for E+ scenario



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

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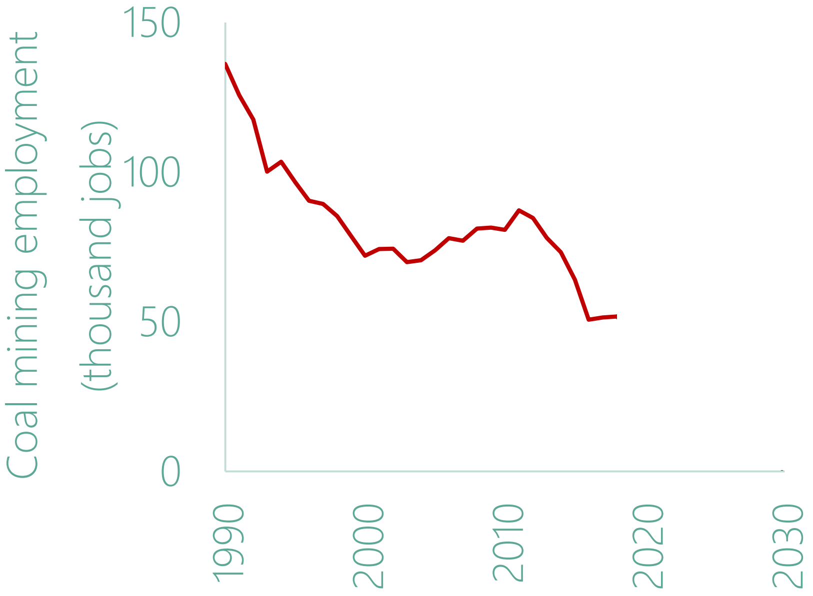
Coal mining jobs have been declining for 3 decades. Phasing out coal has greatest impact on resource-dependent rural labor markets.

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

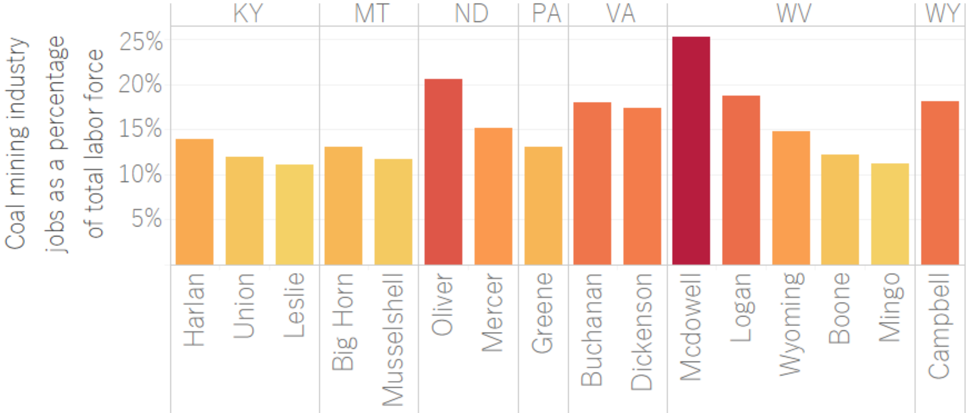
Source: Johnson Group

Source: power-technology.com

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



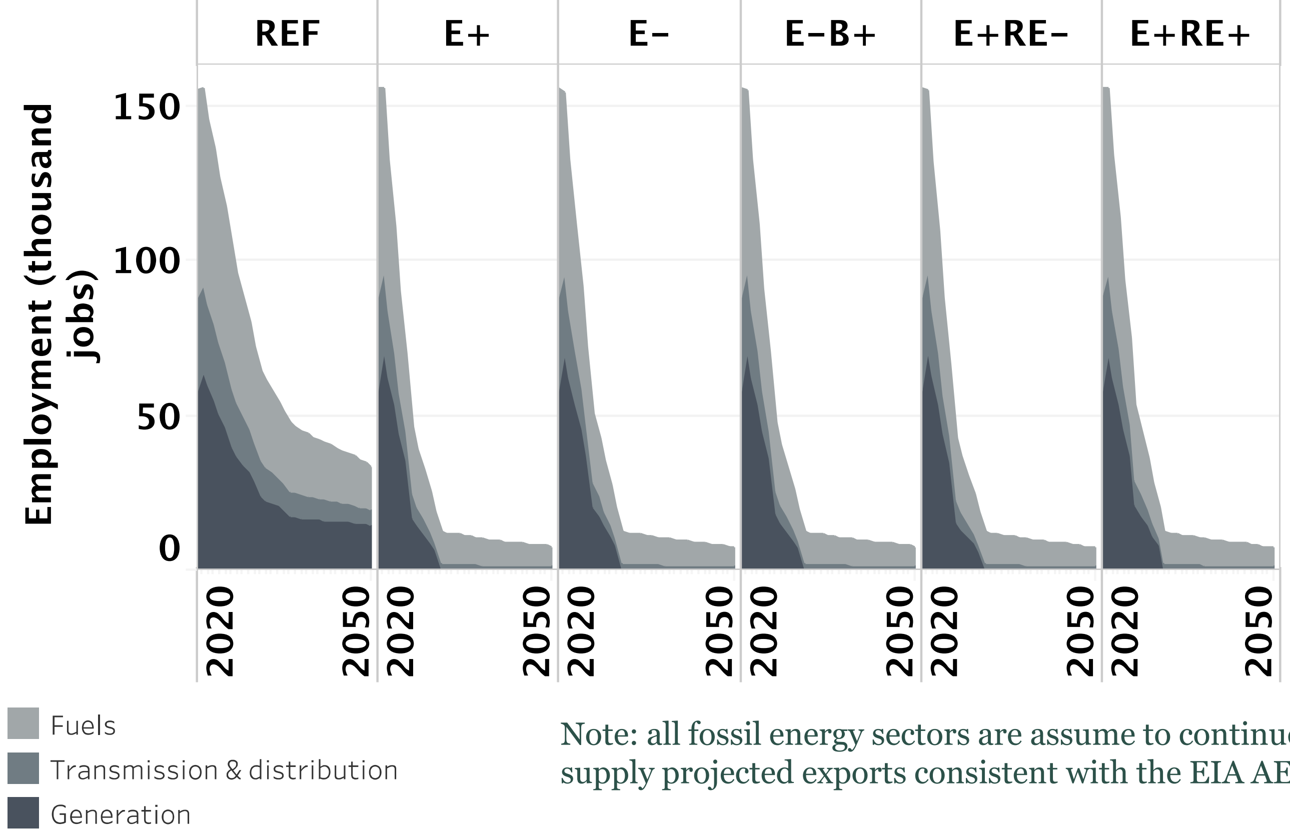
Coal mining industry currently is a major employer in several counties. The coal sector represents 5% or greater of labor force in 35 counties. This includes only jobs within the mining industry, not indirect and induced employment.



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

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

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



Job losses concentrated in mining regions.

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

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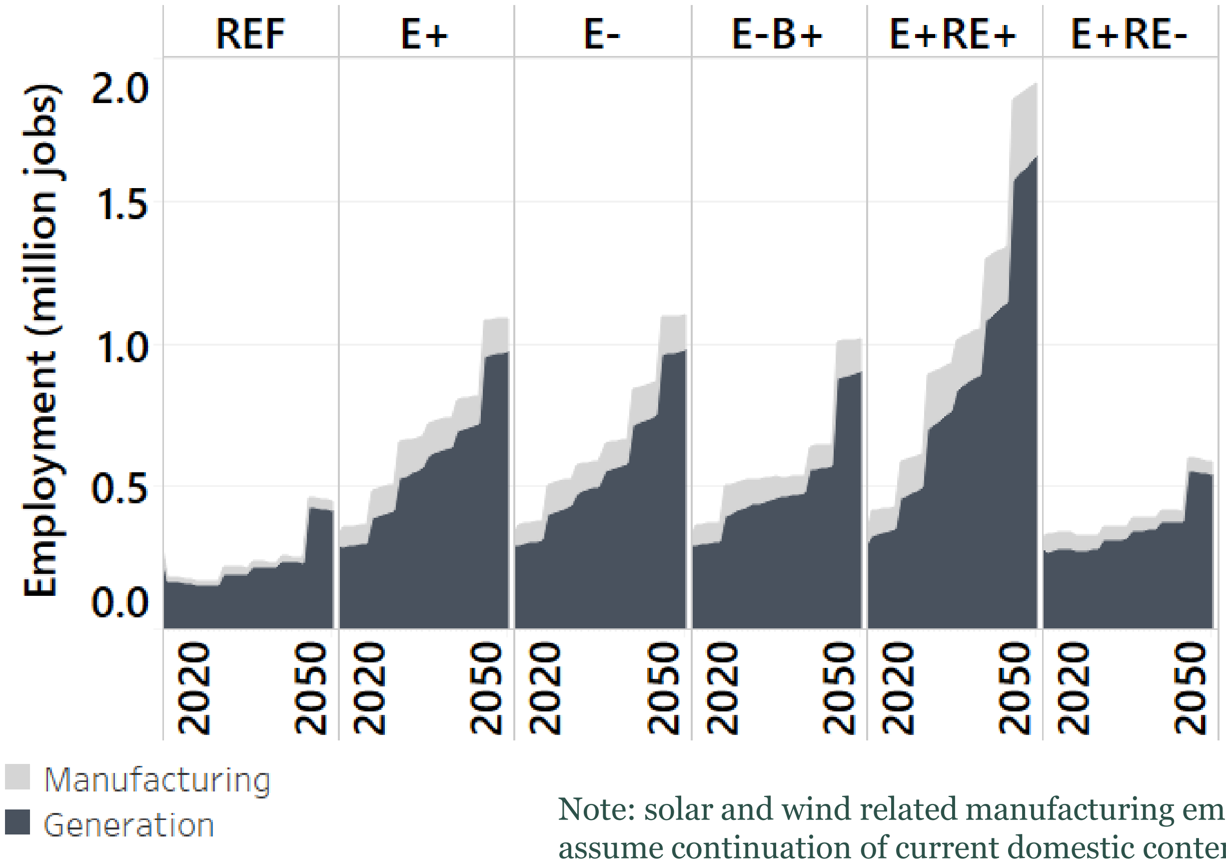
~300,000 solar jobs in model year 2021. In 2030, solar is 2nd or 3rd largest employer, with 80% in generation & 20% in manufacturing.

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



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

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

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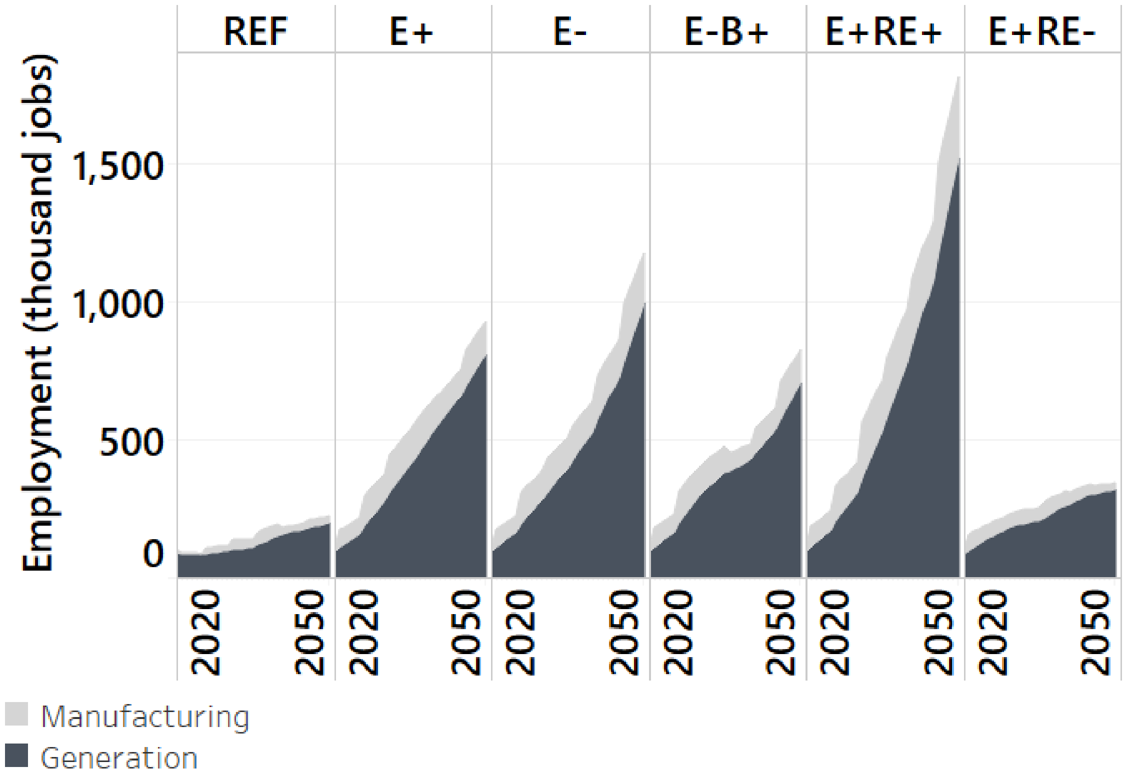
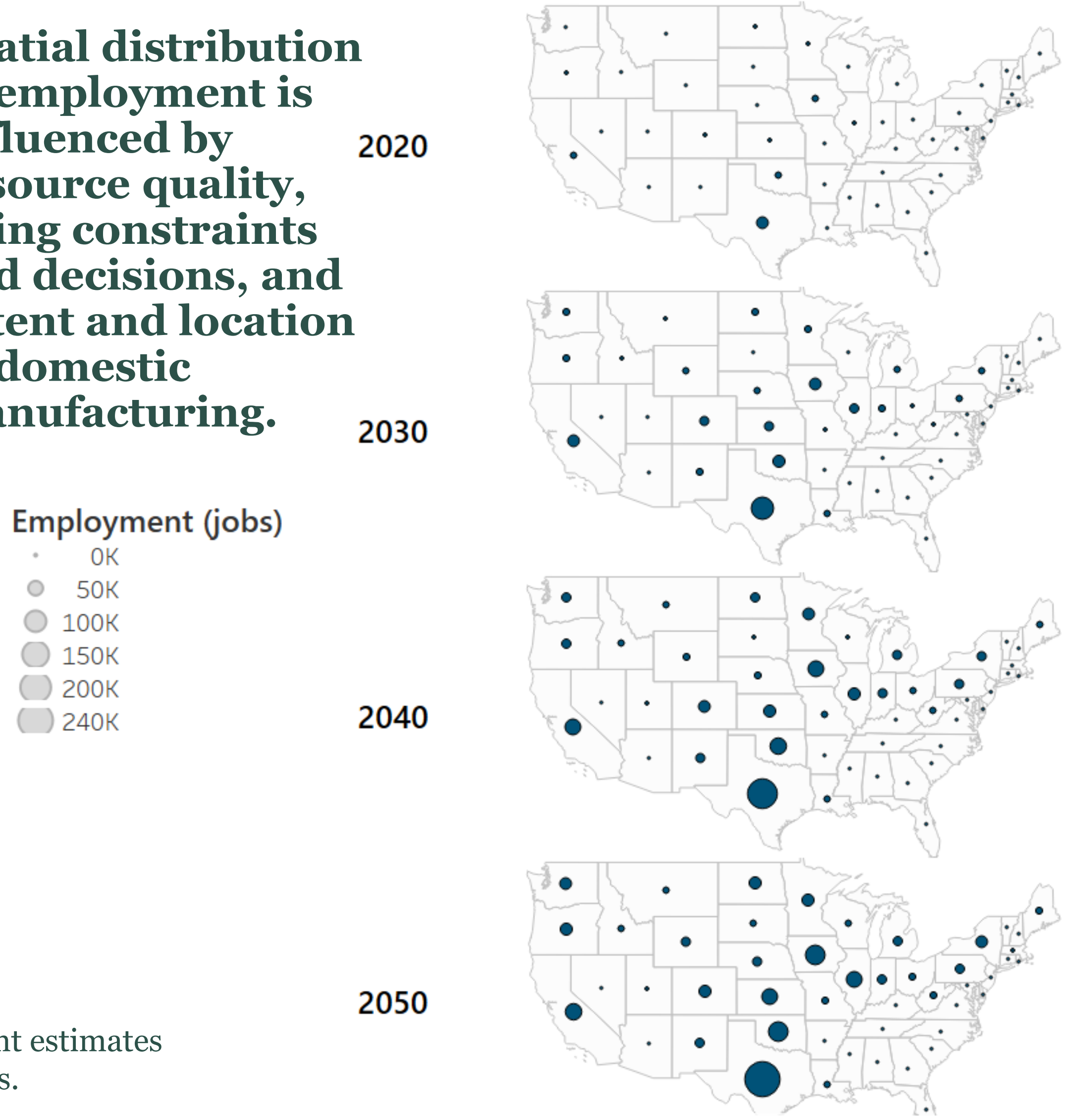
Wind sector employs ~100,000, or <5% of the energy supply-related workforce today but grows to exceed current natural gas employment

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



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



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

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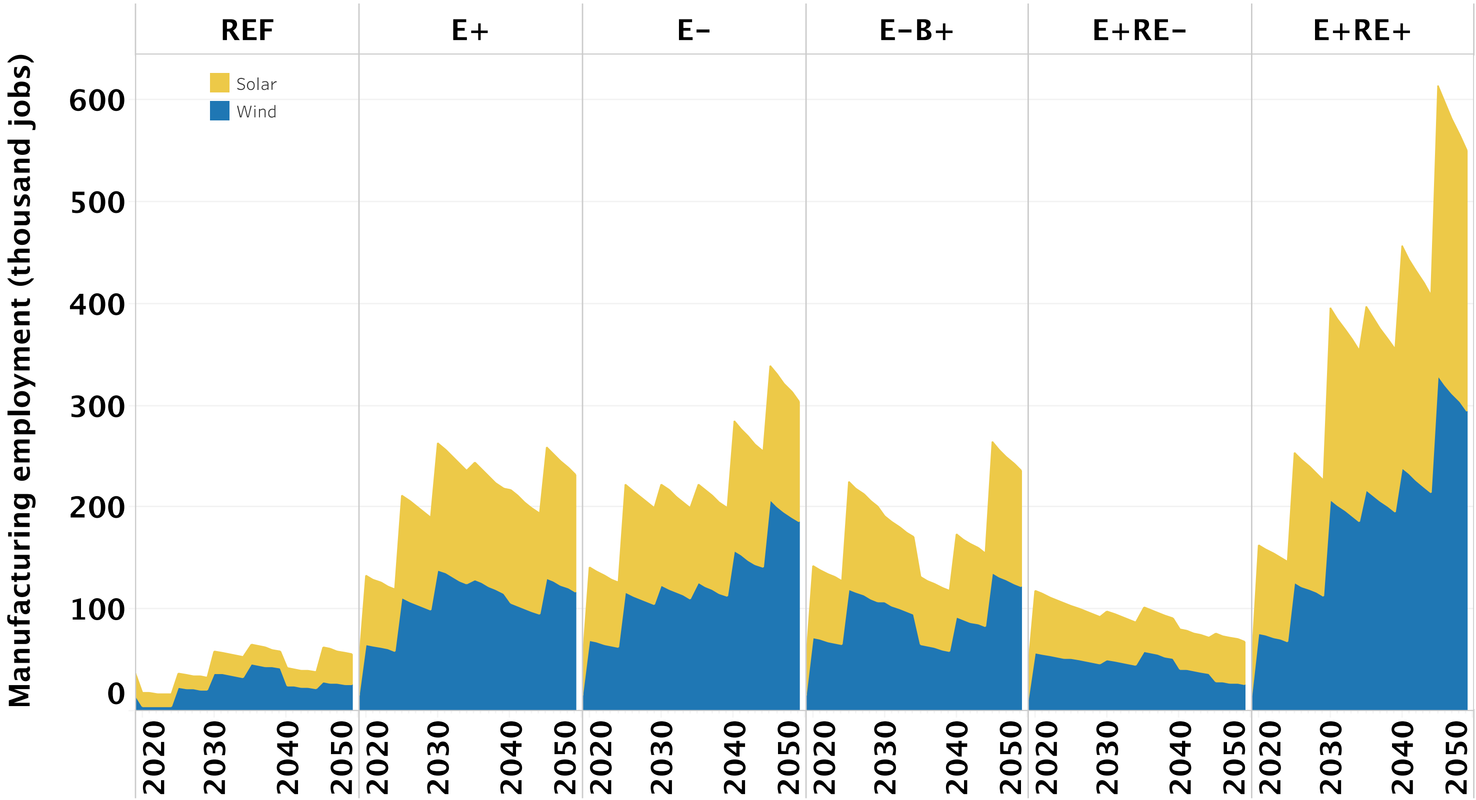
Solar and wind manufacturing offer opportunities to distribute employment benefits across multiple states



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

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

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

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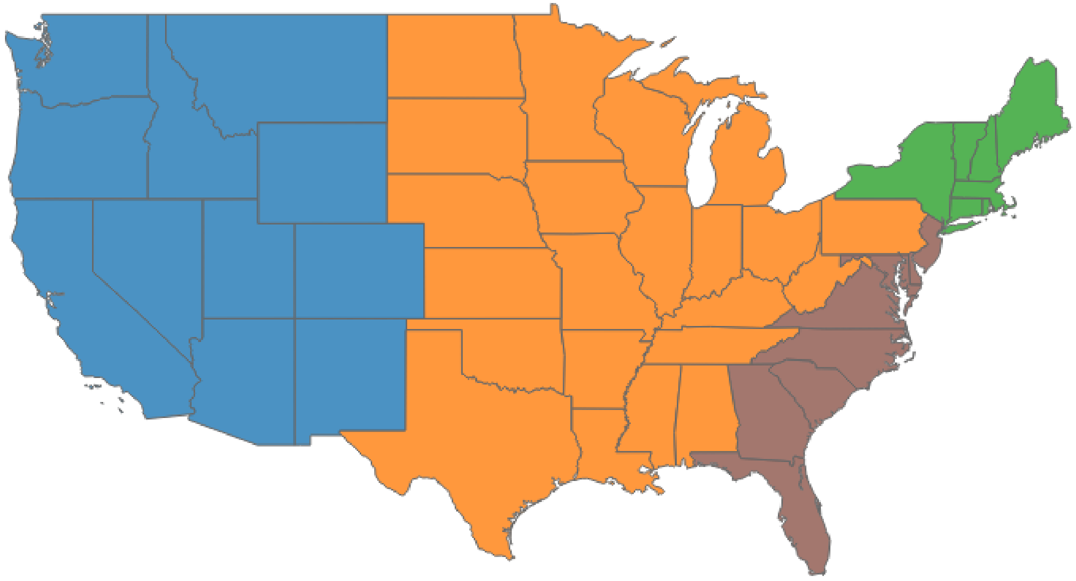
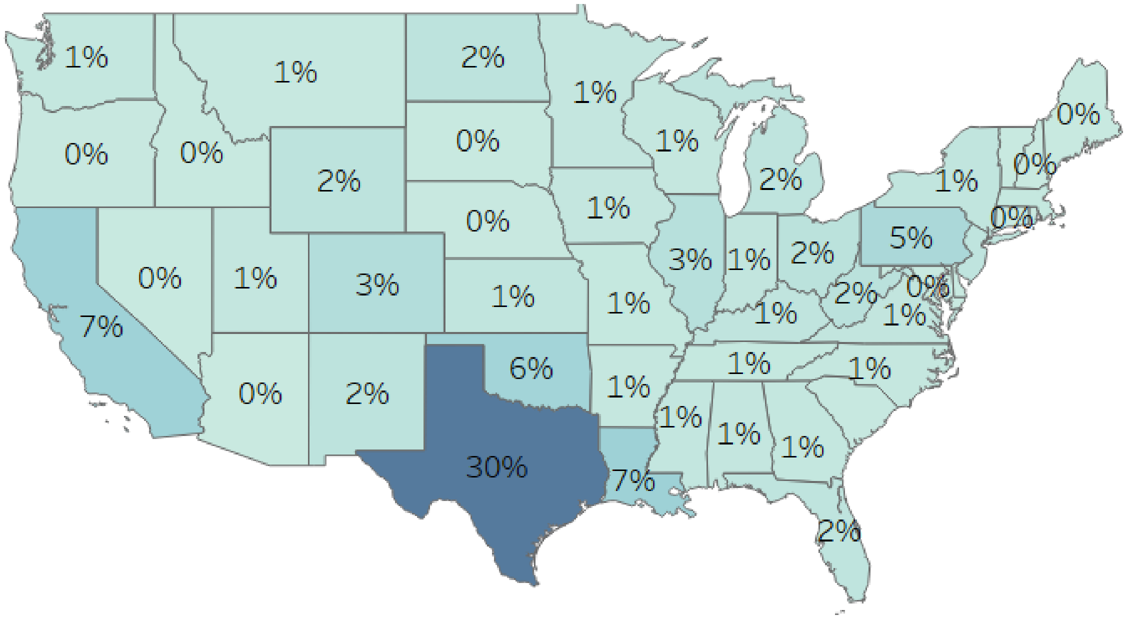
Assumptions for modeling the state-wise distribution of solar and wind manufacturing jobs

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

Logistic regions



2018 distribution of energy labor force



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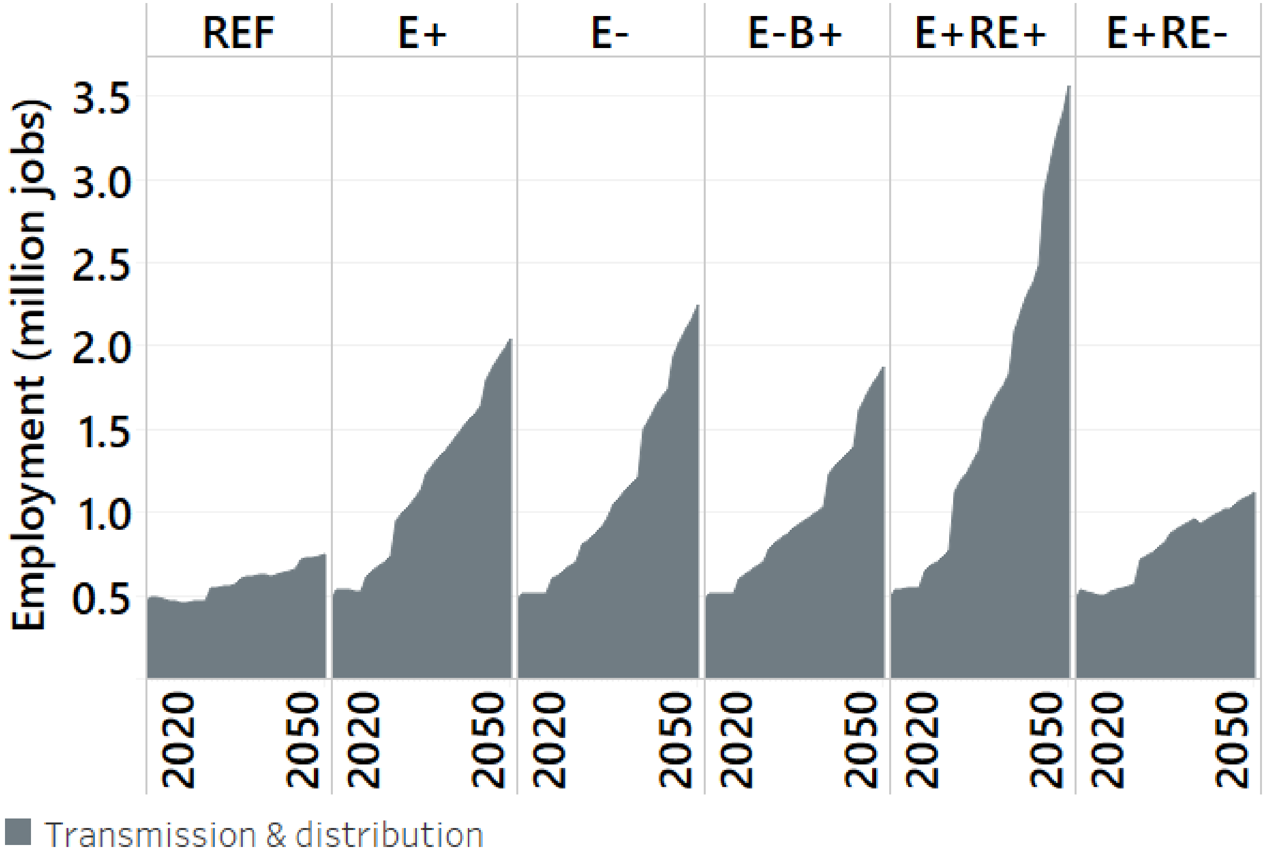
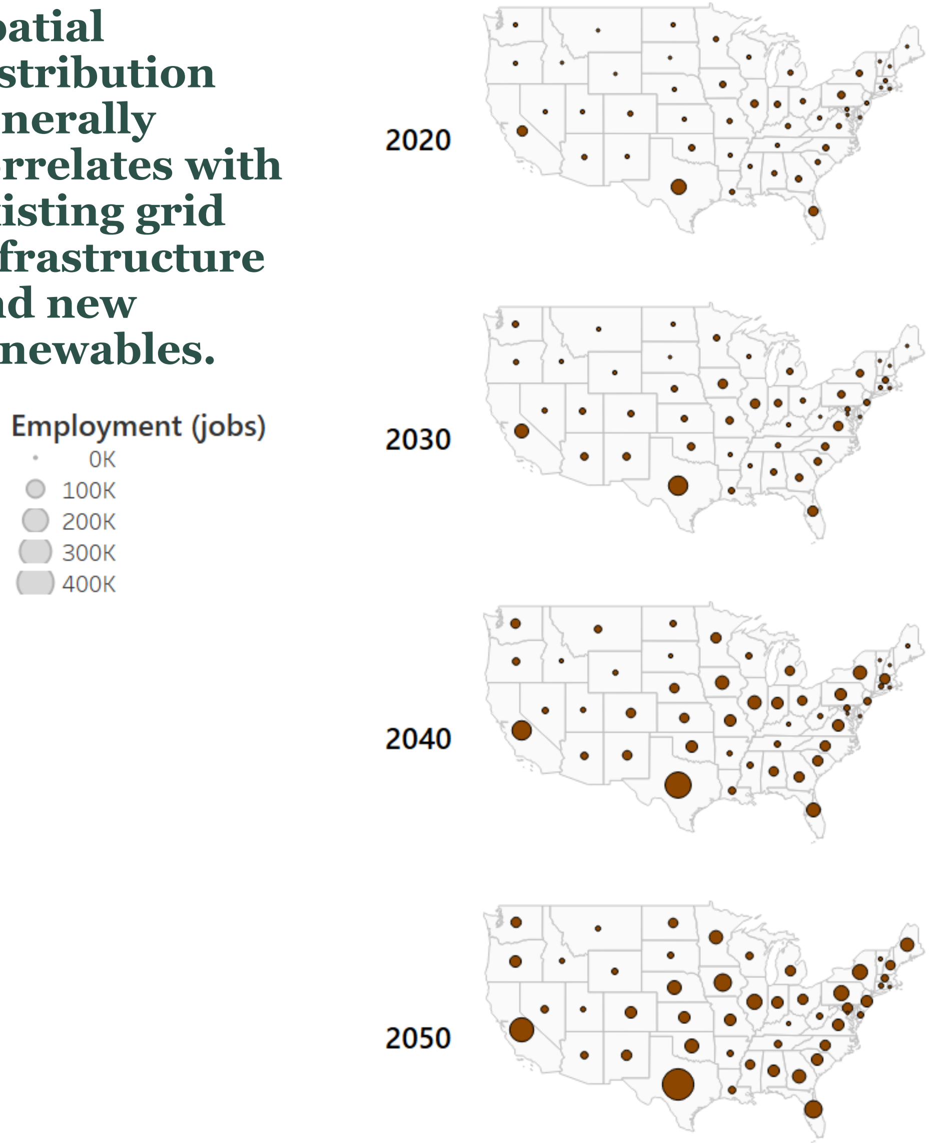
~450k grid-related jobs today represent ~20% of energy supply-related workforce. By 2050, these grow to 35-45%.

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



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



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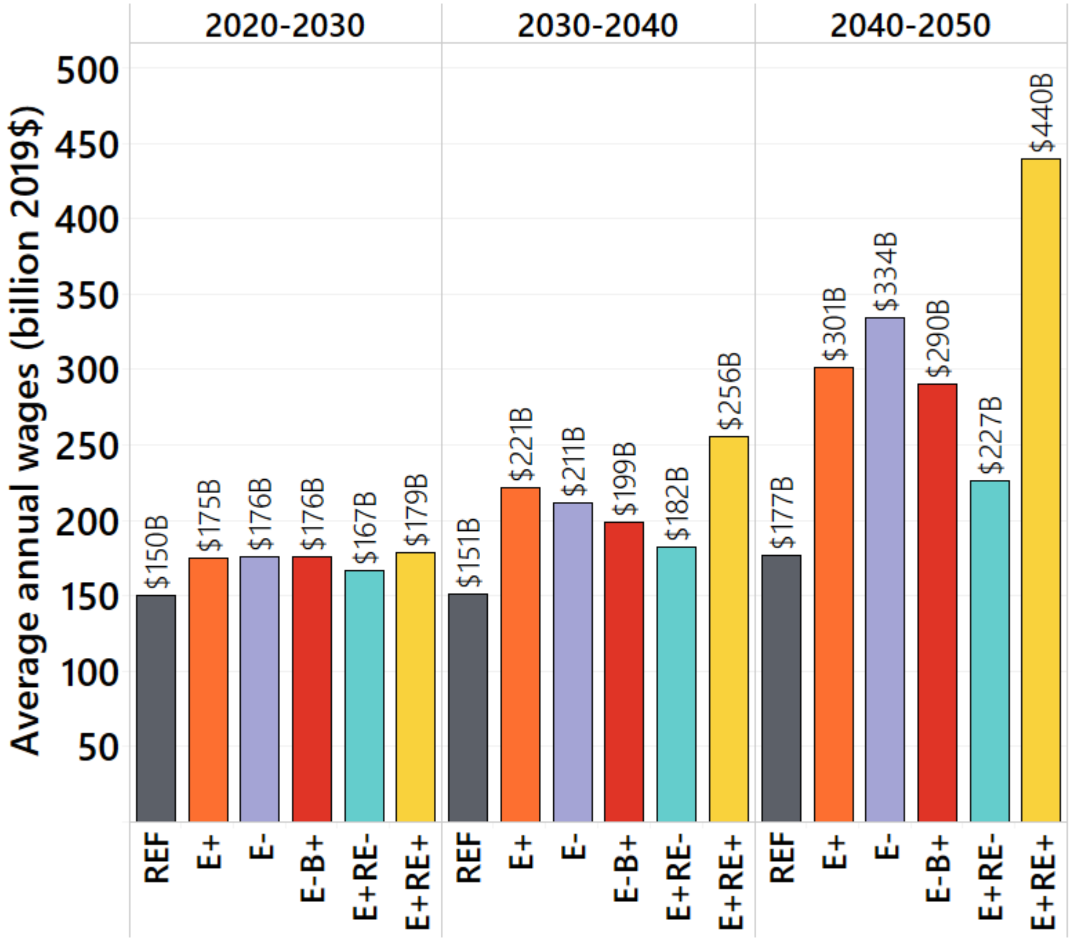
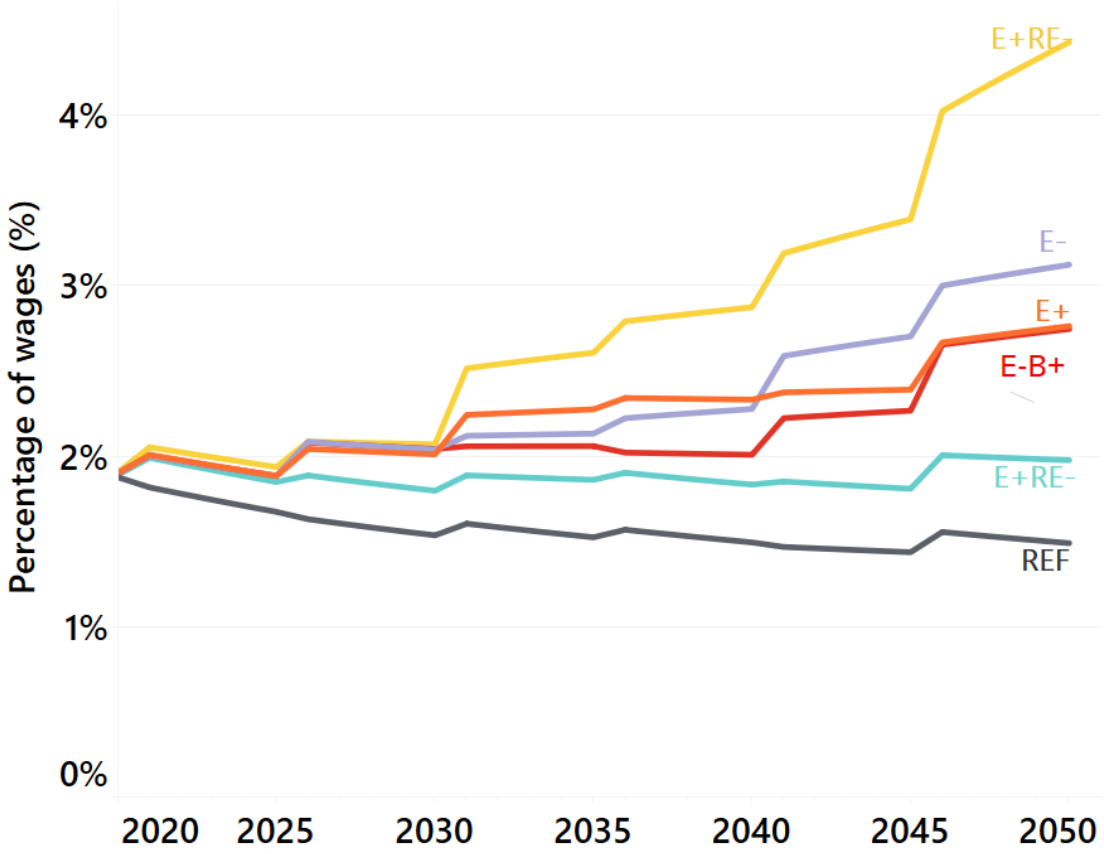
Wages for energy-supply related employment increase through net-zero transitions.

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



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



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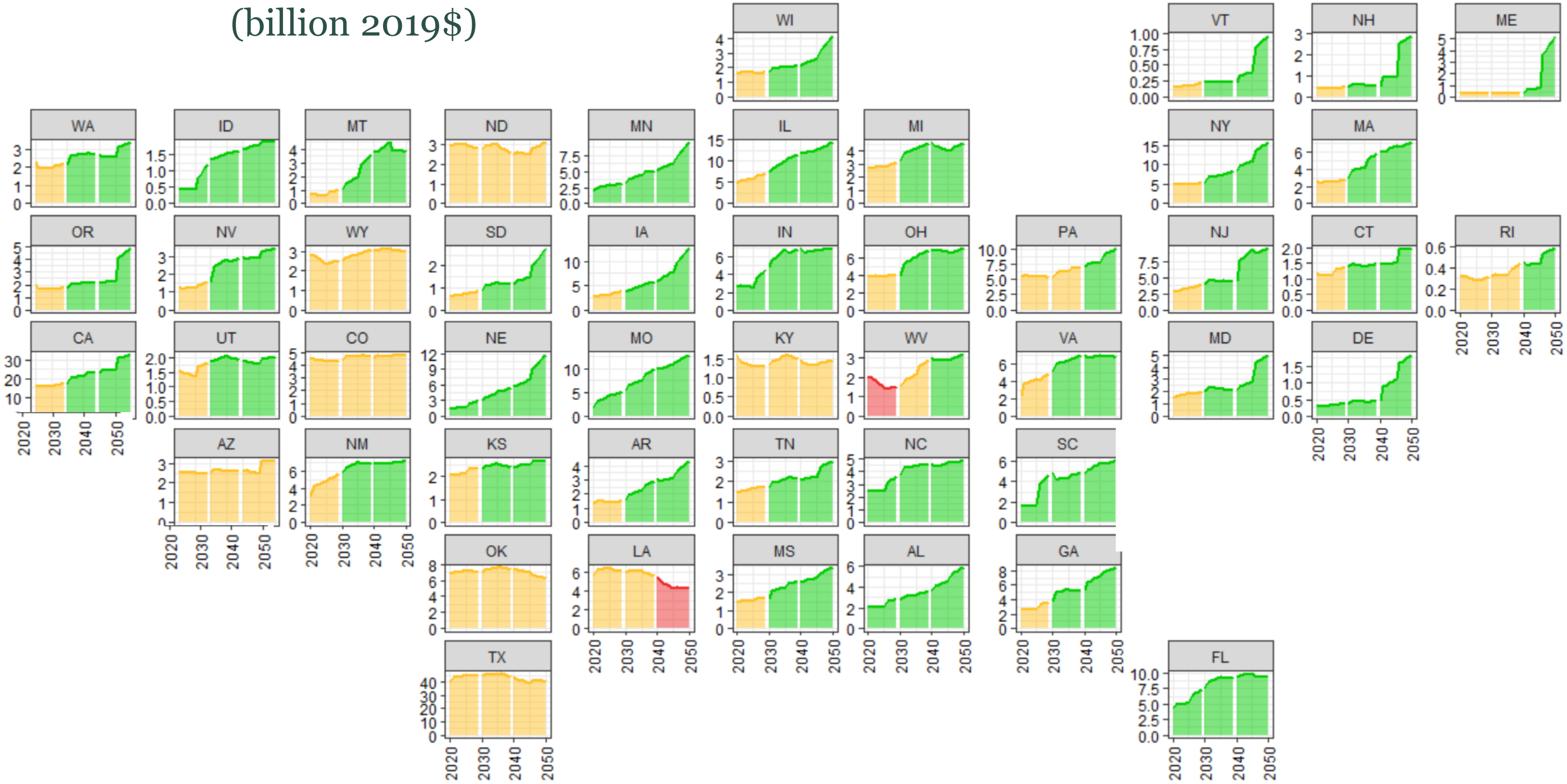
Modifiable socio-technical factors influence spatial distribution of wages. Below is one instantiation of the future.

Annual wages based on downscaled E+ scenario

(billion 2019$)



Modifiable sociotechnical factors that influence the spatial distribution of wages:

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

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

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

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