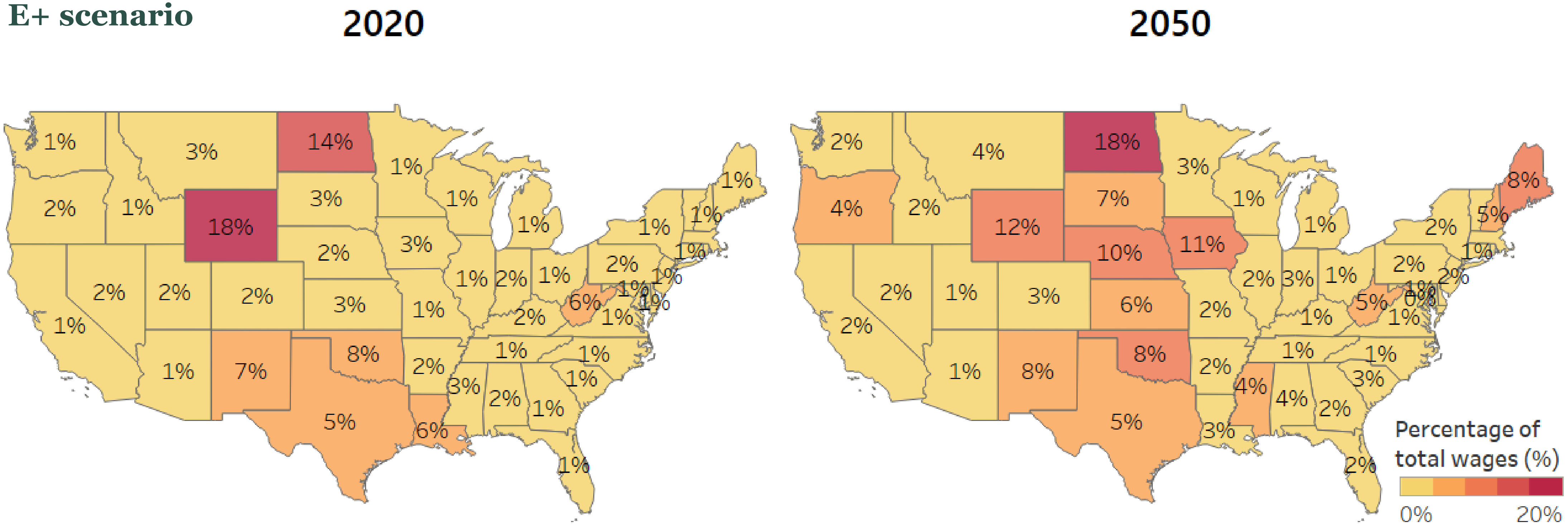
In most states, energy-related wages grow as a share of total wages through the transition period.

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, WV), energy-related employment wages decrease as a share of the total employment wages through the transition.
- In states with high renewable resource quality (e.g., NE, SD, MT, and IA), wages for energy-related employment as a share of total-employment wages grow considerably.

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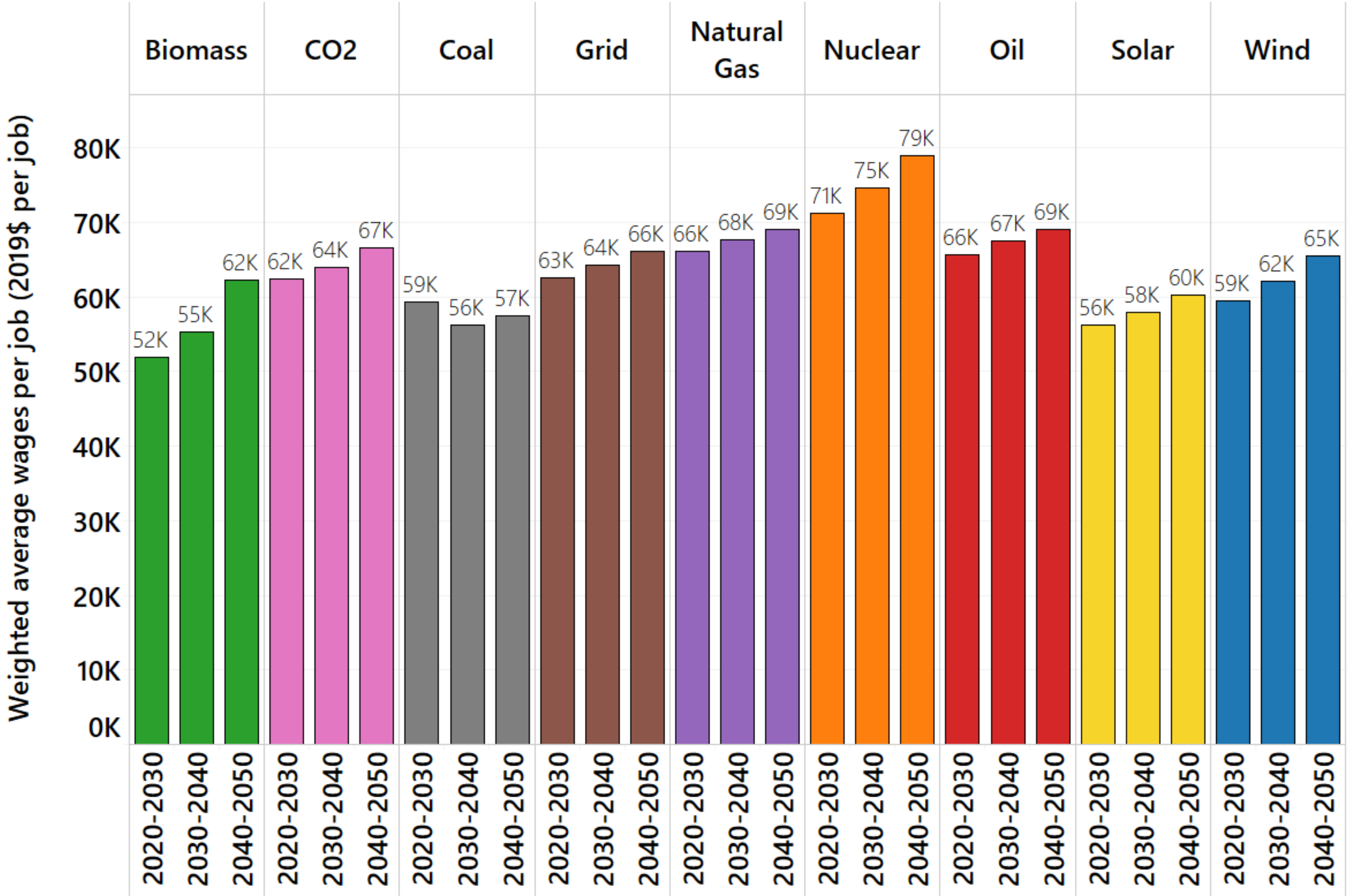
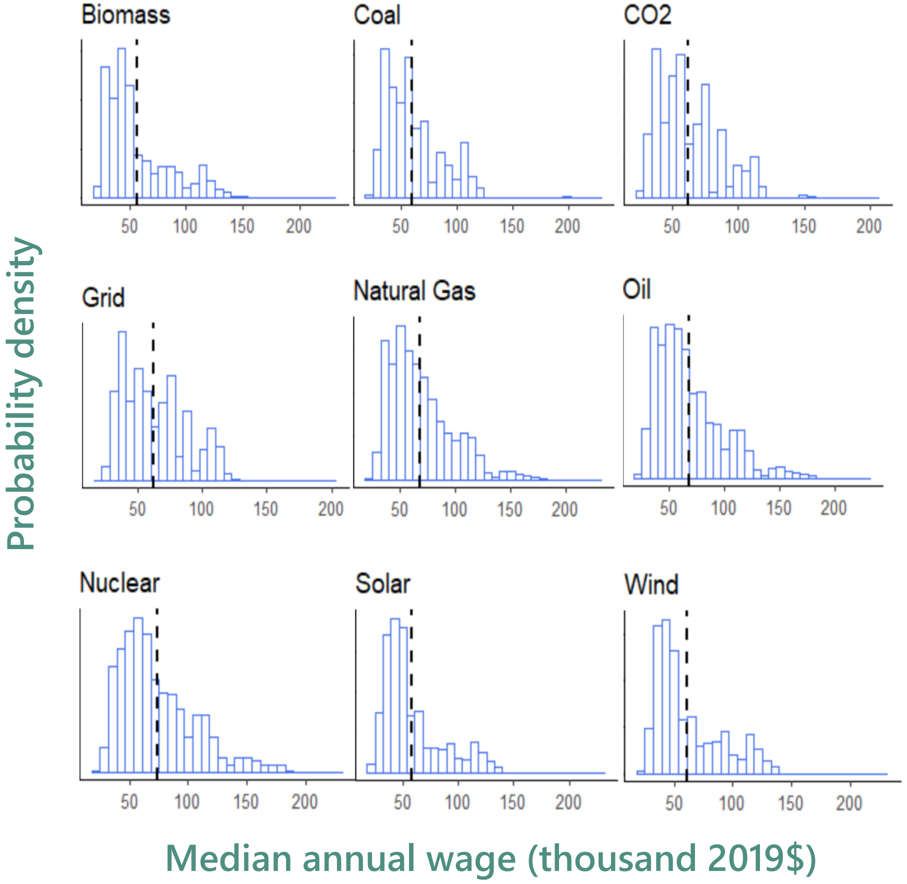
Wages per job for a given resource sector are similar for REF and net-zero scenarios, with some variations between sectors.

E+ scenario



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



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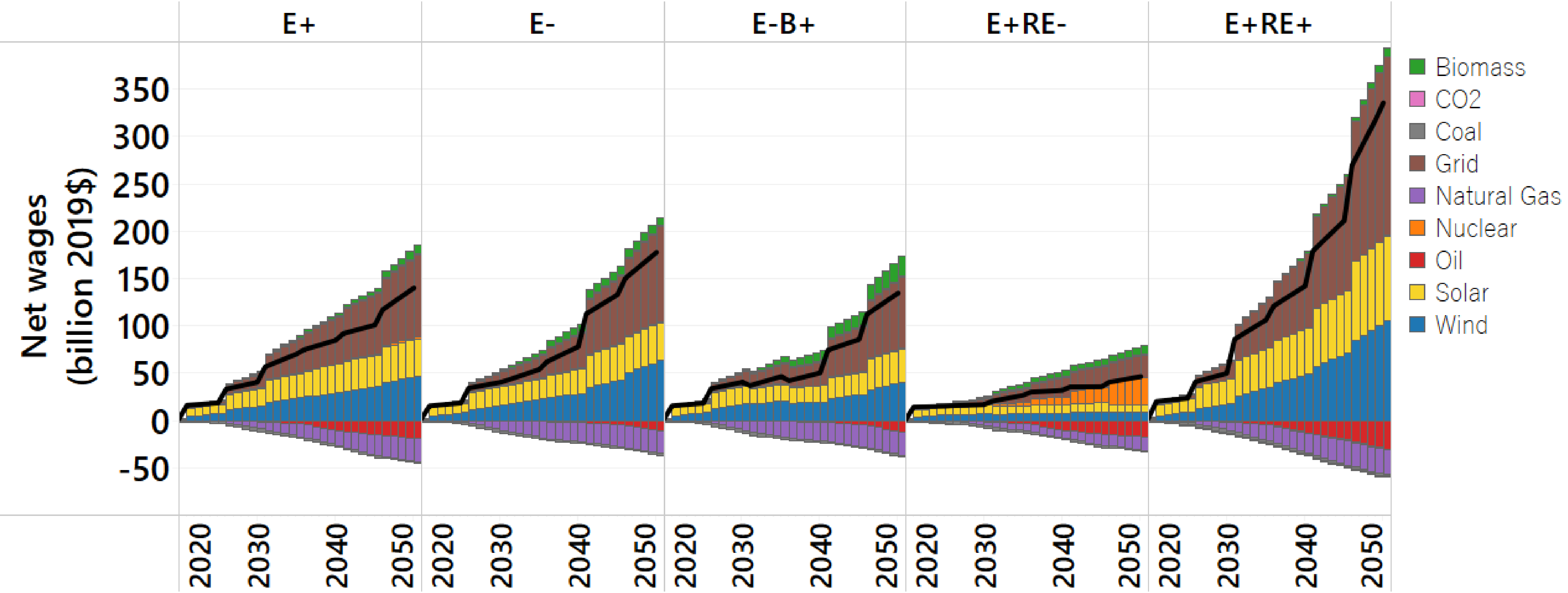
Wages losses in fossil fuel sectors are offset (in aggregate) by added wages in low carbon sectors.

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



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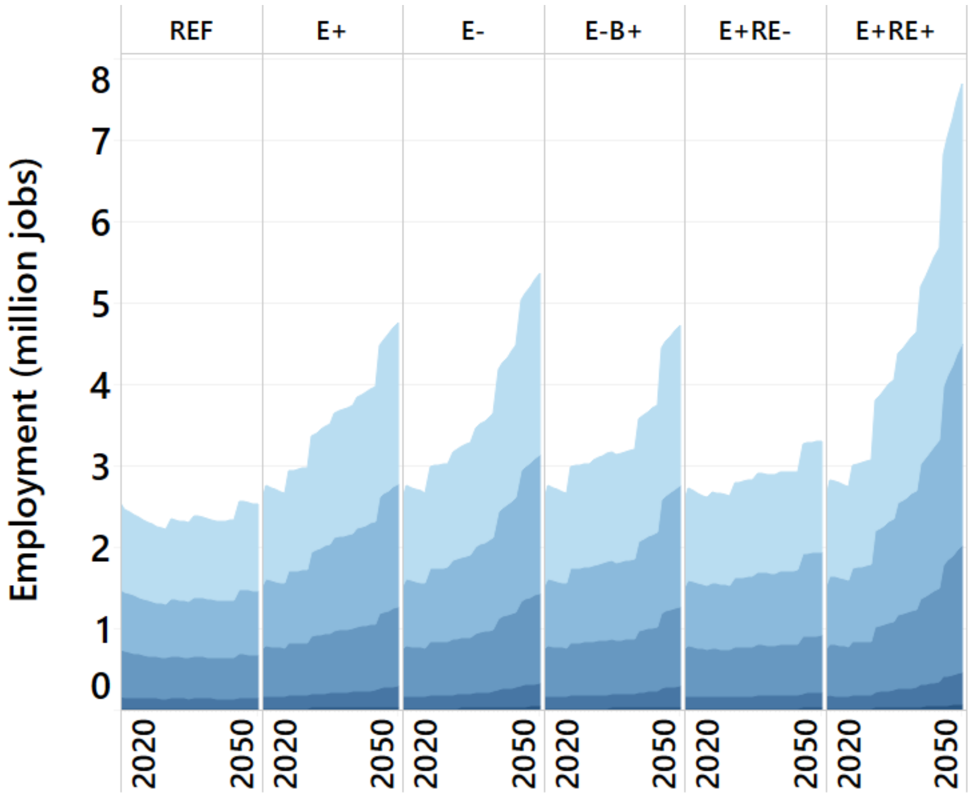
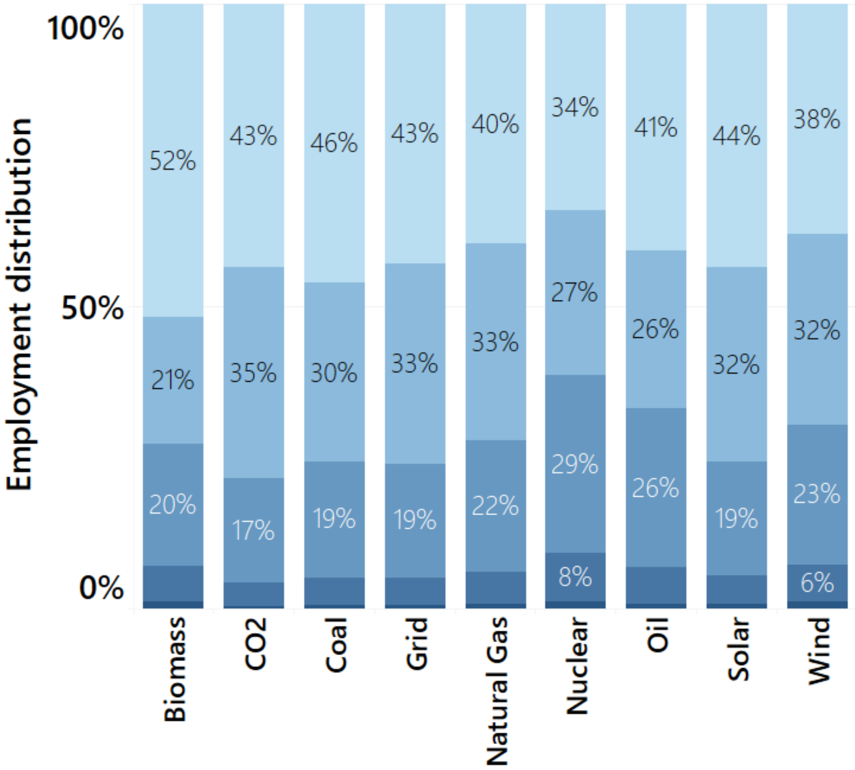
There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

Employment by required level of education



Distribution of employment by required level of education

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



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

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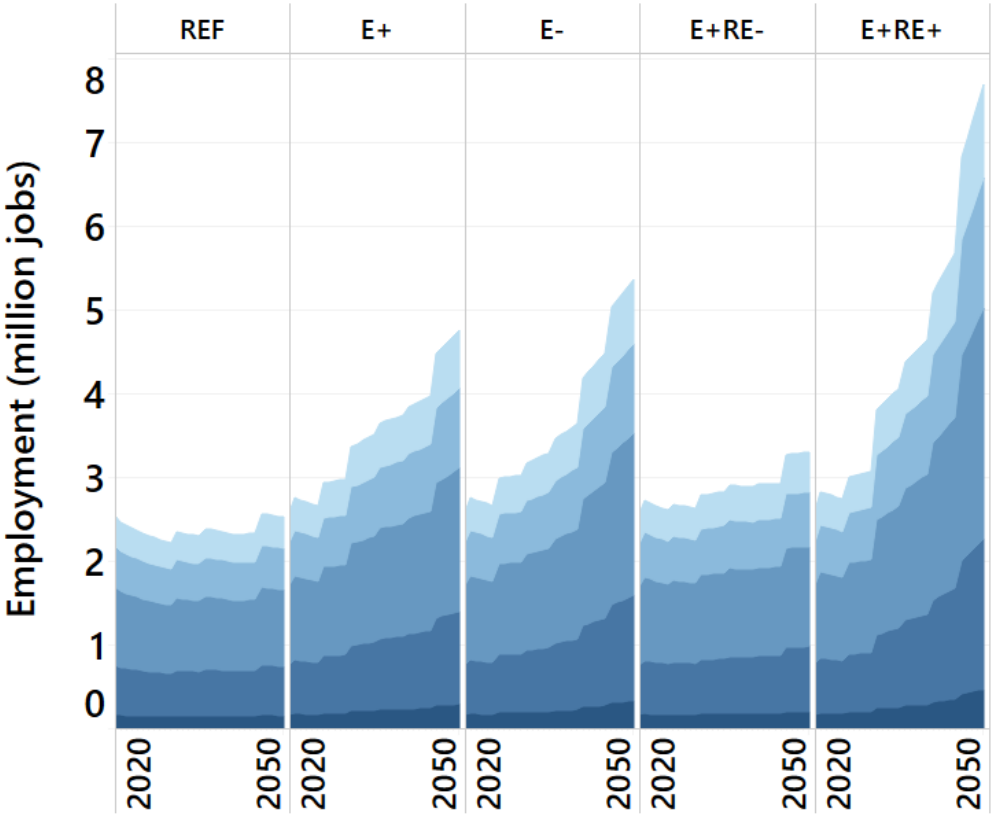
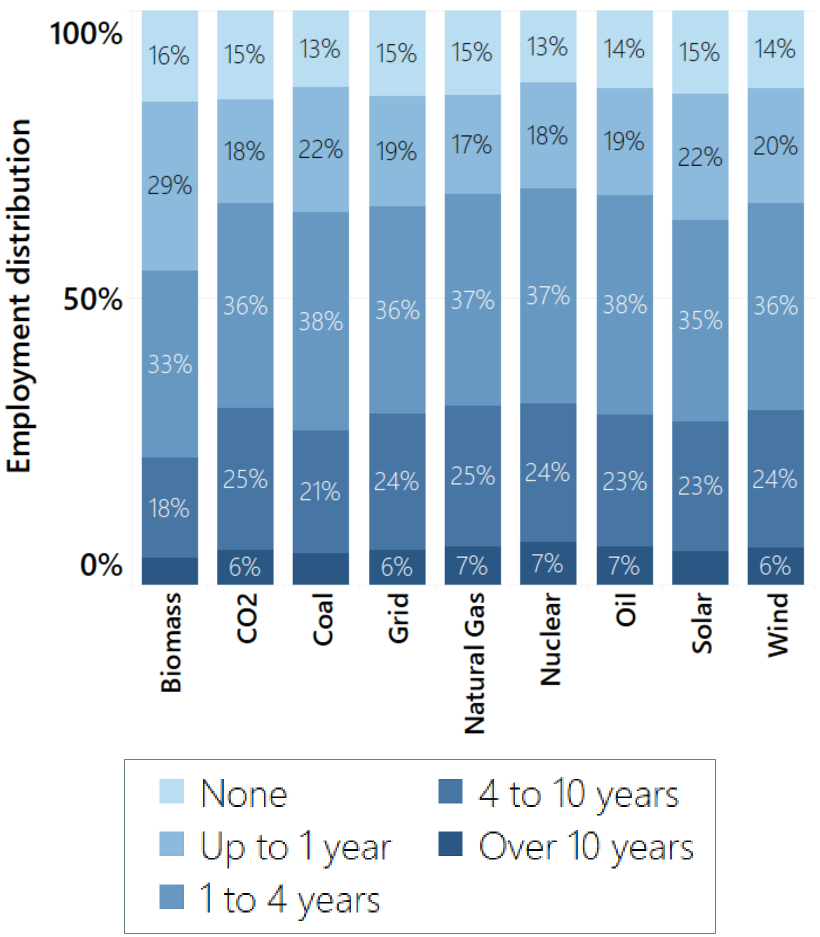
There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.

Employment by required years of experience



Distribution of employment by required years of experience
(results are for E+ scenario aggregated over 30-yr transition period)



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

Considerations for workforce development programs in net-zero transitions

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

Implications of findings on energy-related employment

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

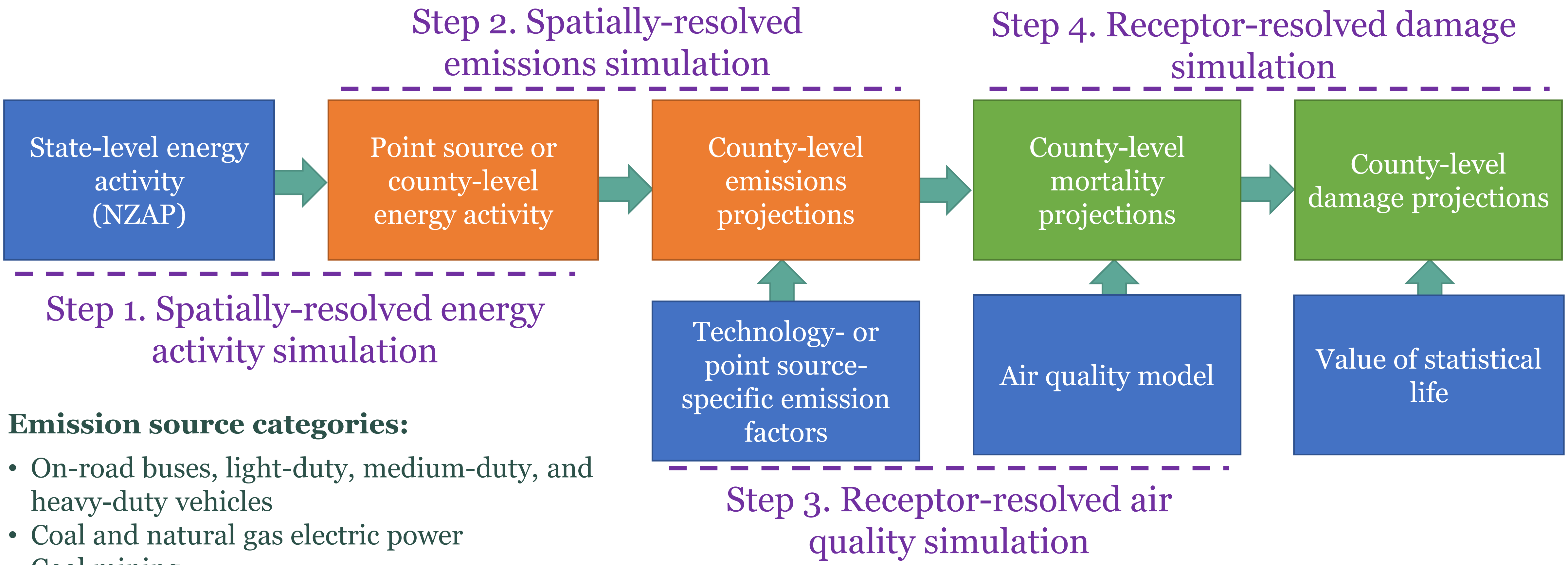
Health impacts related to air quality

Summary of this section

- Historically, there have been persistent and large health impacts from fine particulate matter (PM2.5) exposure associated with air pollutant emissions from carbon-emitting activities.
- PM2.5 exposure disproportionately impacts vulnerable populations, although there is variation in the extent of the disproportionate impacts across different industries.
- Siting decisions, technology selection, air pollutant emissions abatement, and the rate of electrification influence air quality outcomes.
- As a result of changes in coal and natural gas electric power, on-road vehicles, commercial and residential heating and cooling, gas stations, coal mining, and oil and gas production on the path to economy-wide net-zero emissions by 2050, the modeling in this study estimates that
  - Approximately 40,000 to 45,000 premature deaths ($370-410 billion in damages) are avoided in the net-zero scenarios (relative to the REF scenario) in the 2020s. This is on par with estimated increases in energy-related expenditures over the decade.
  - Approximately 260,000 to 410,000 premature deaths ($2.3-3.7 trillion in damages) are avoided from 2020 to 2050.

See Annex S for details of the health impact analysis.

Modeling framework for estimating air pollution and associated health impacts

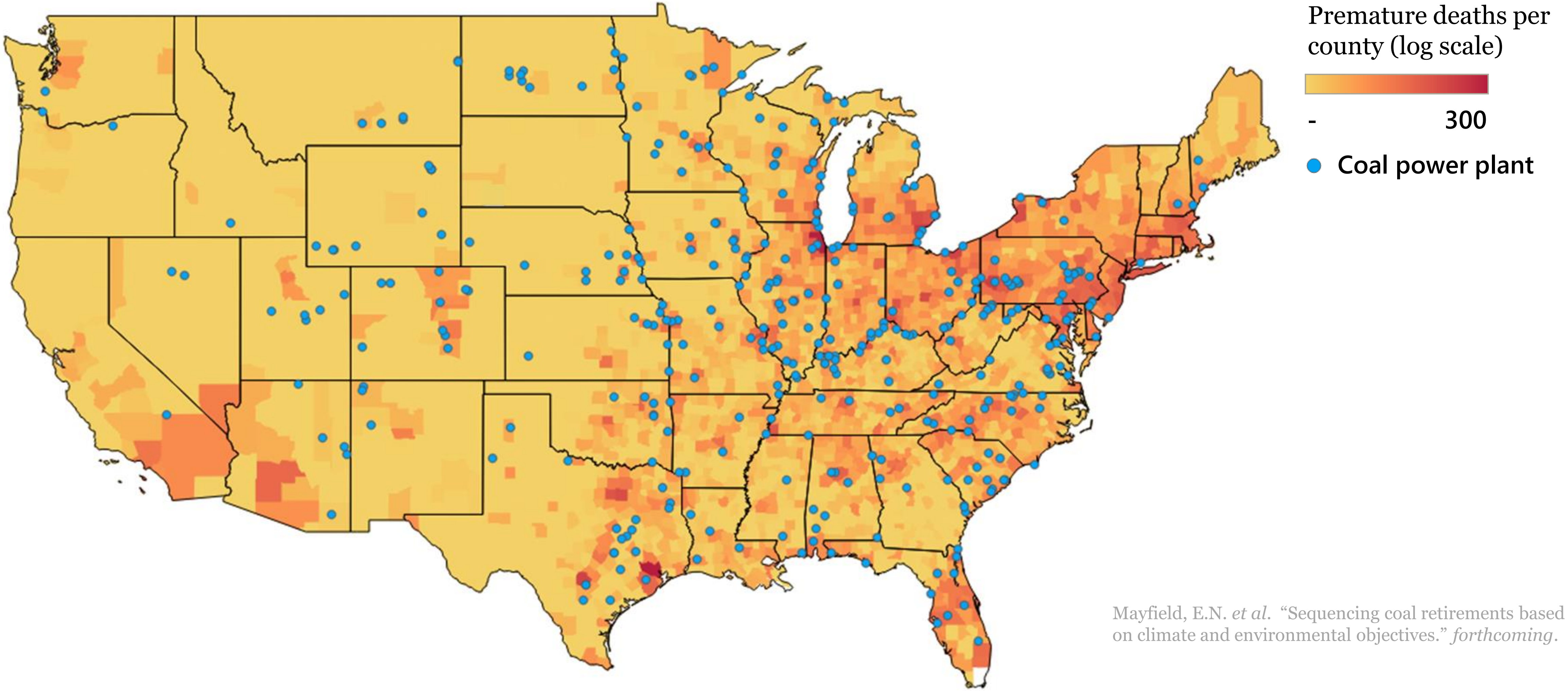


Emission source categories:

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

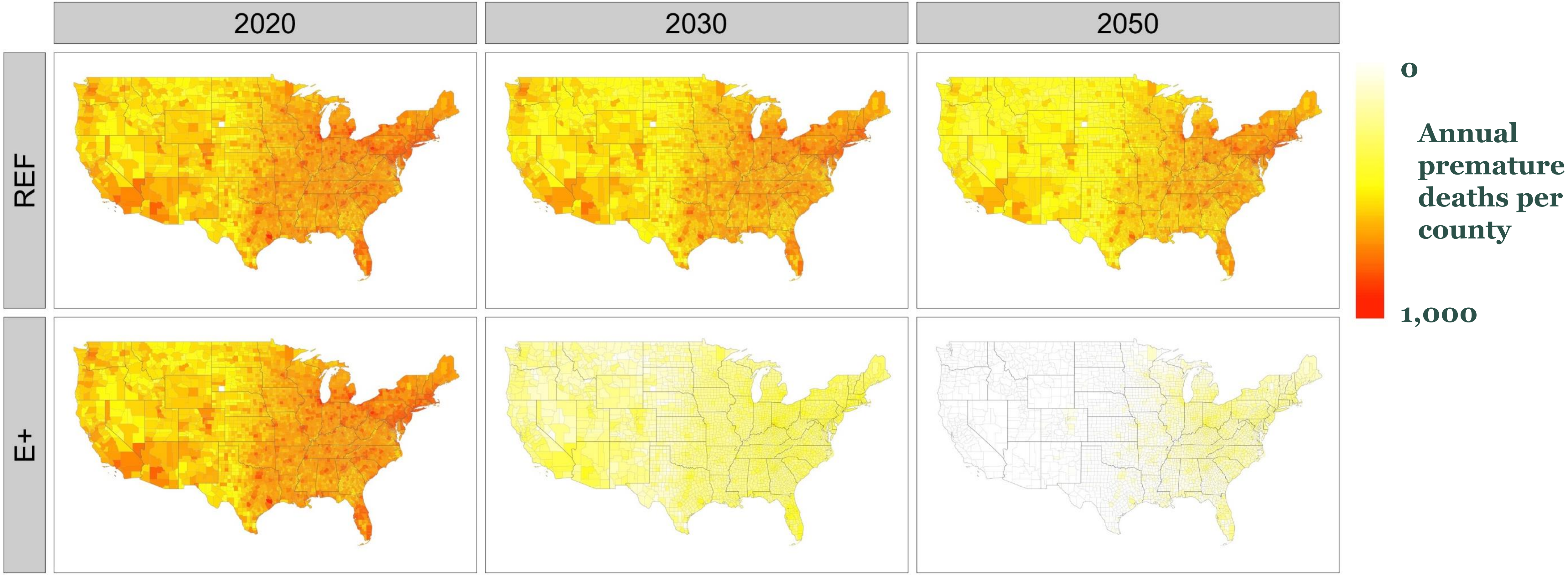
Criteria pollutants: NO_x, $PM_{2.5}$, SO_2, VOC
Air quality model: AP3
Health outcomes: premature mortality and damages
Dose-response relationship: American Cancer Society

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



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

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



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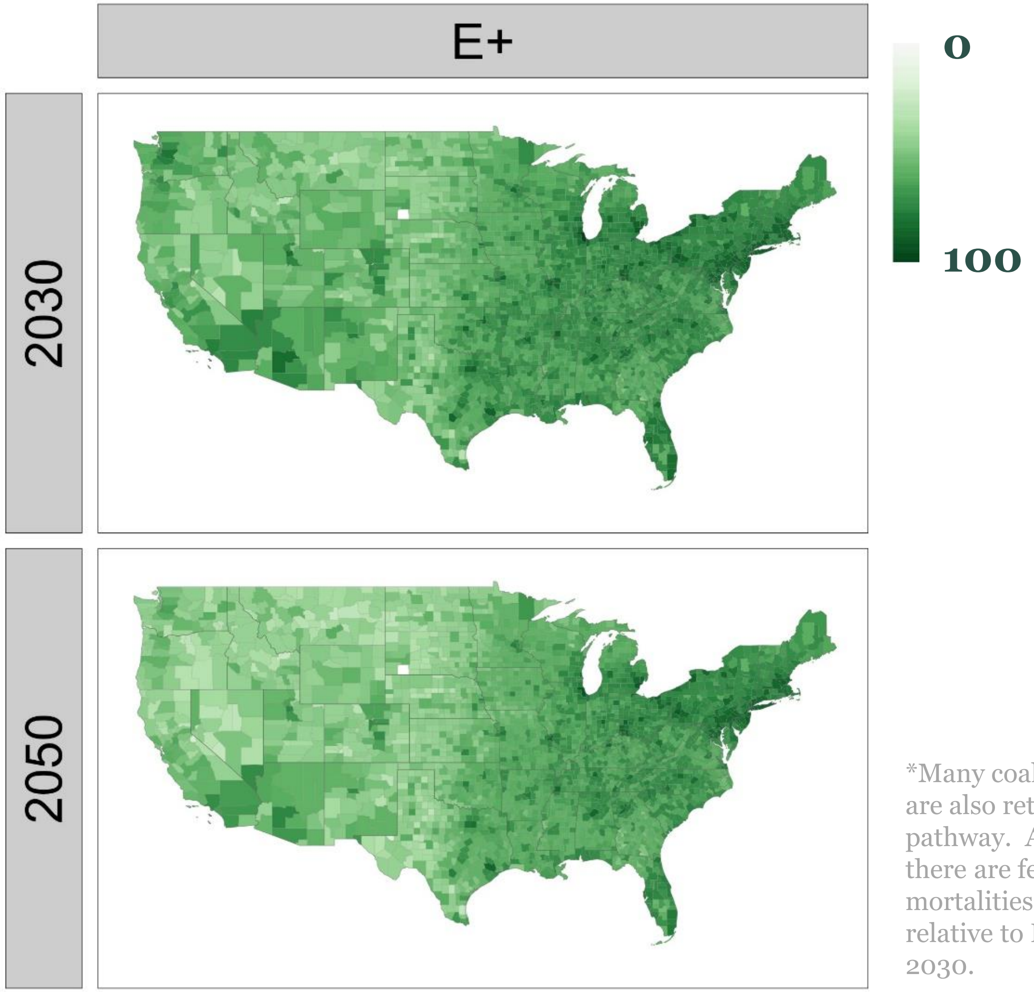
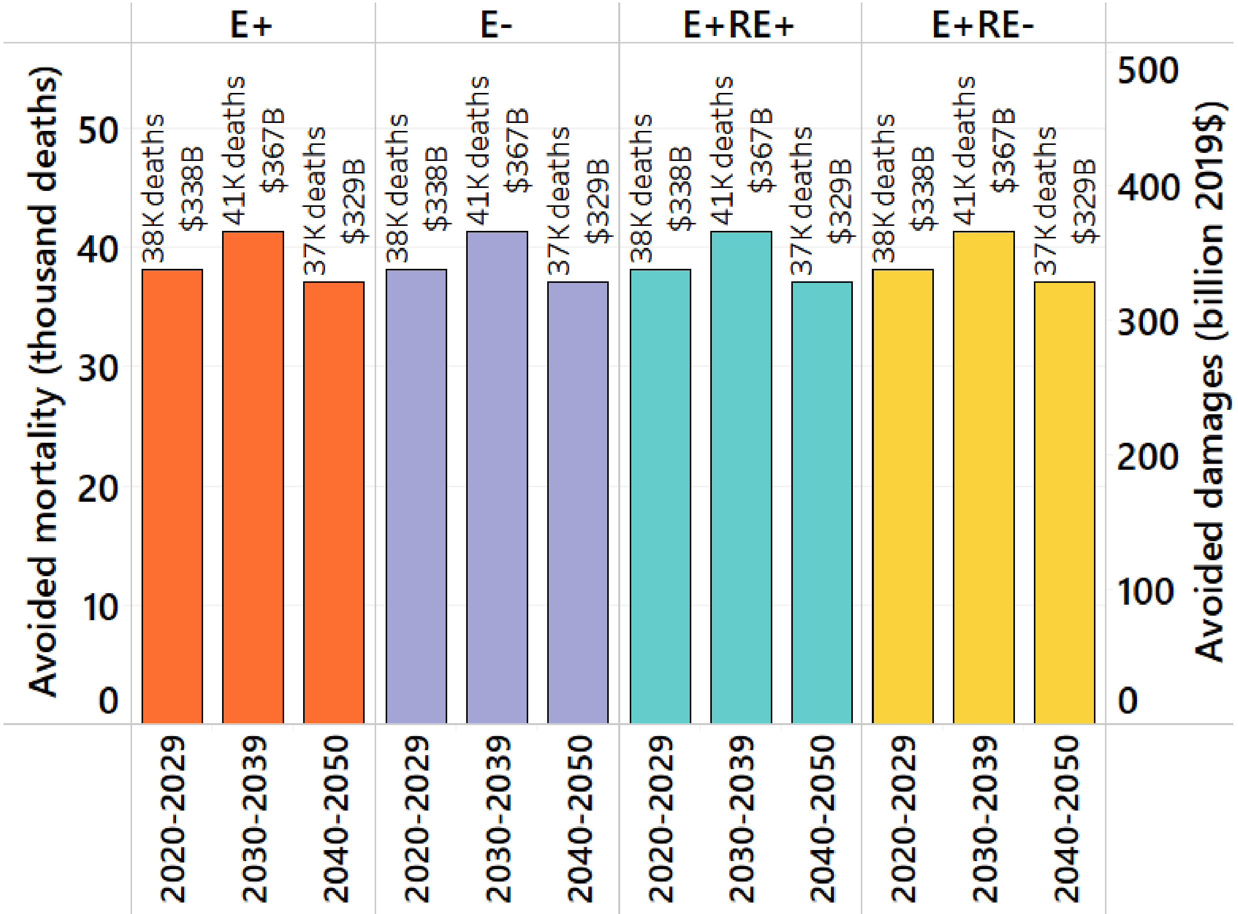
Over 100,000 coal electric power-related air pollution deaths (~1 T$ in damages) are avoided by 2050 with any of the net-zero pathways.

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



Avoided premature mortalities by decade [relative to REF]



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

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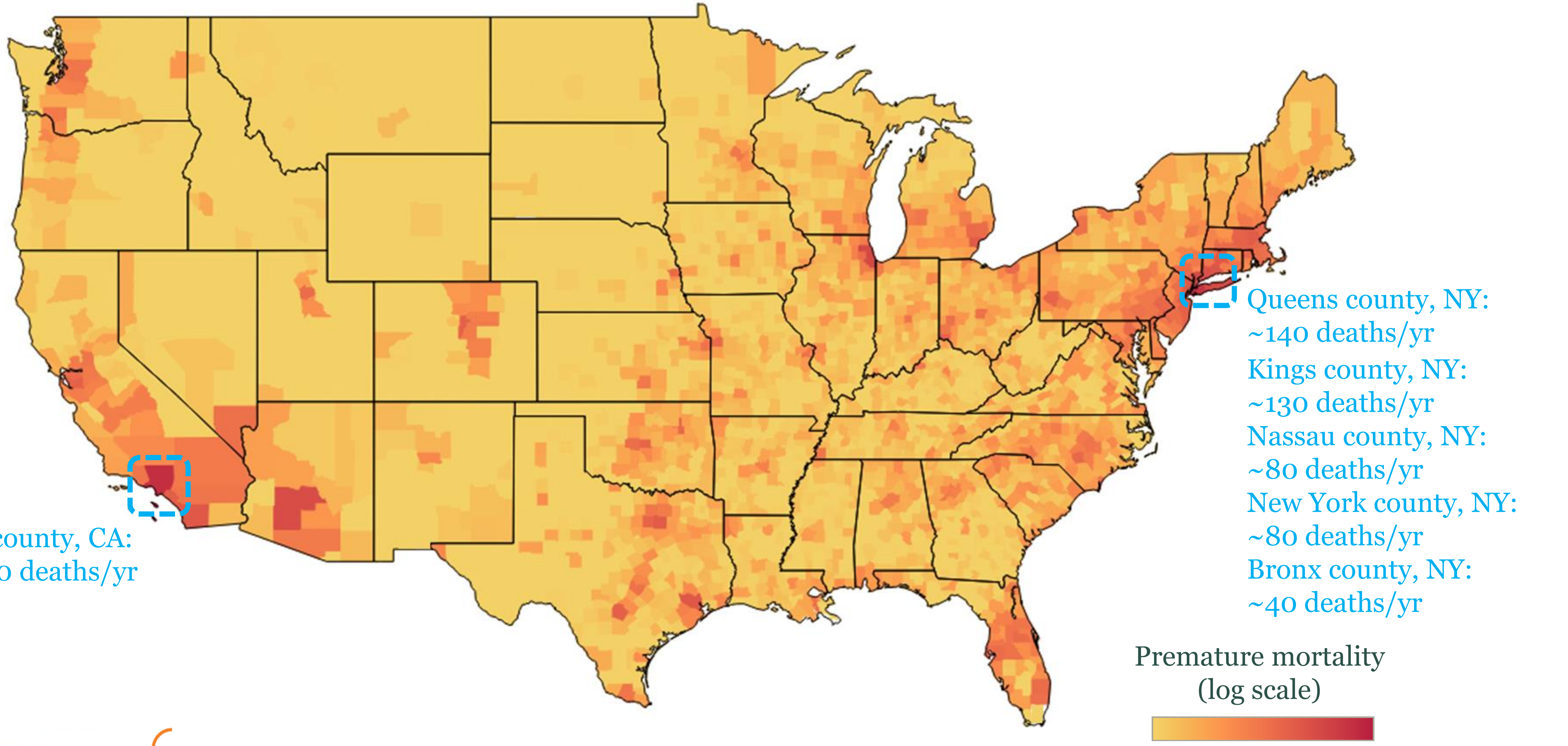
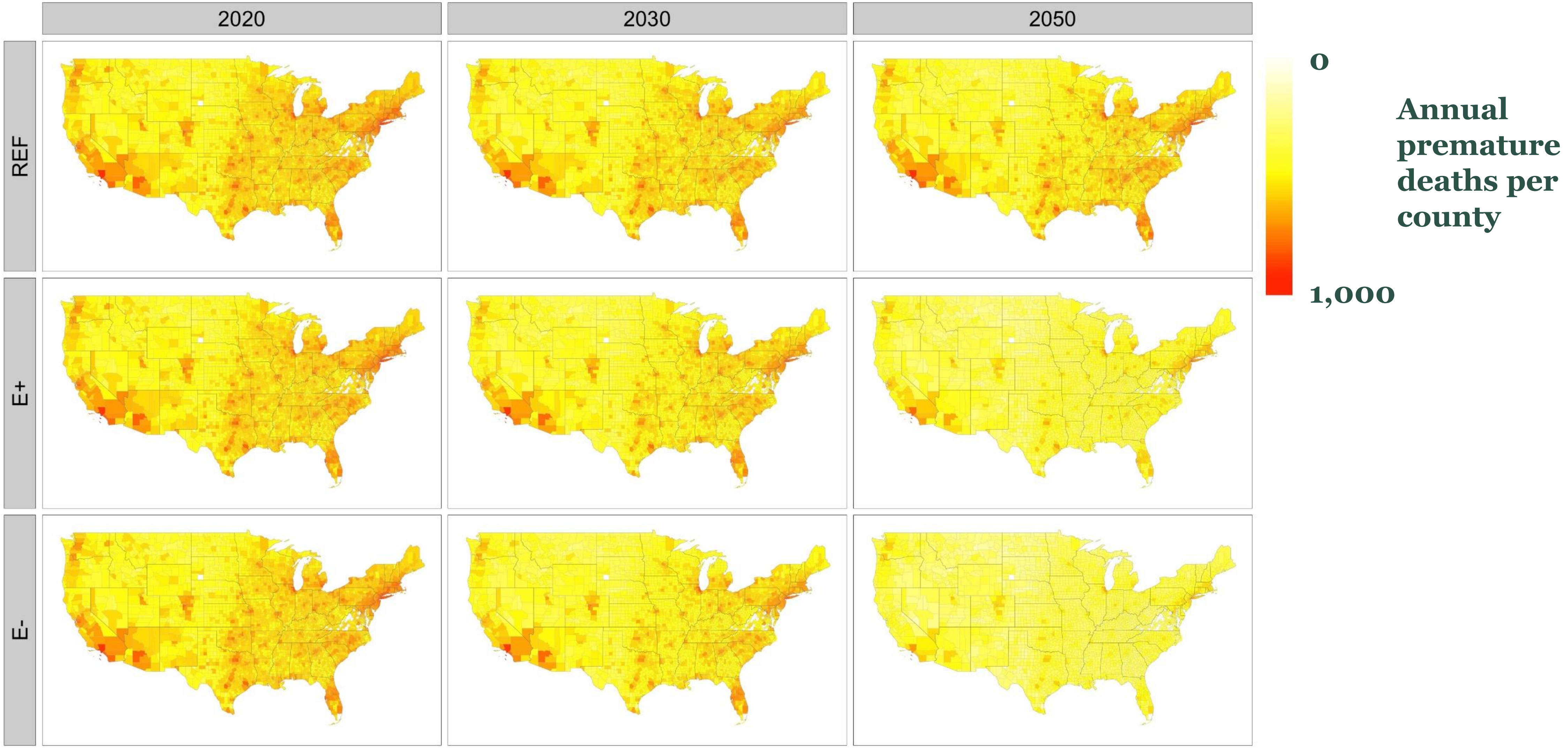
In 2019, ~1,800 premature mortalities ($16B damages) were associated with air pollution from natural gas power plants.



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



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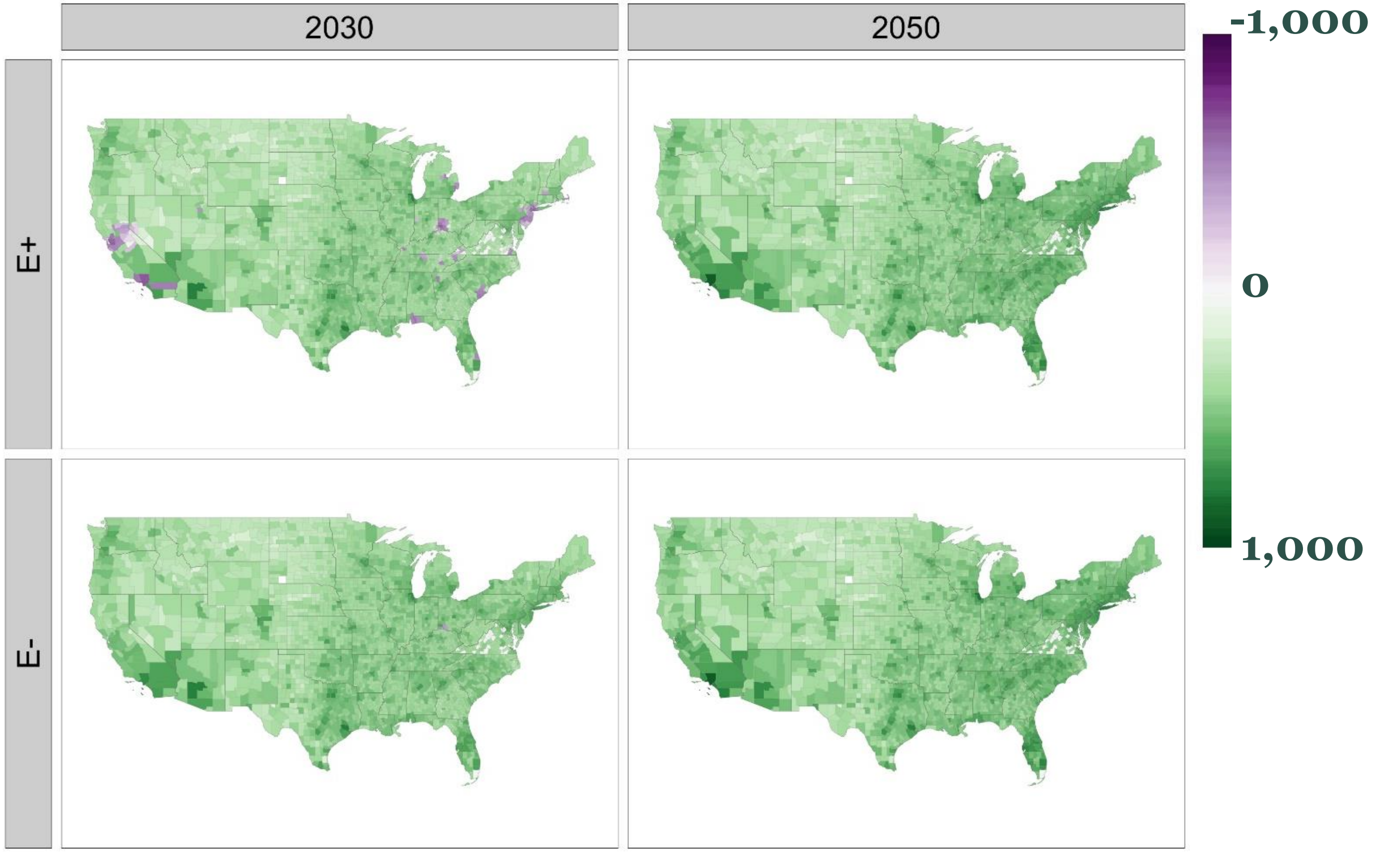
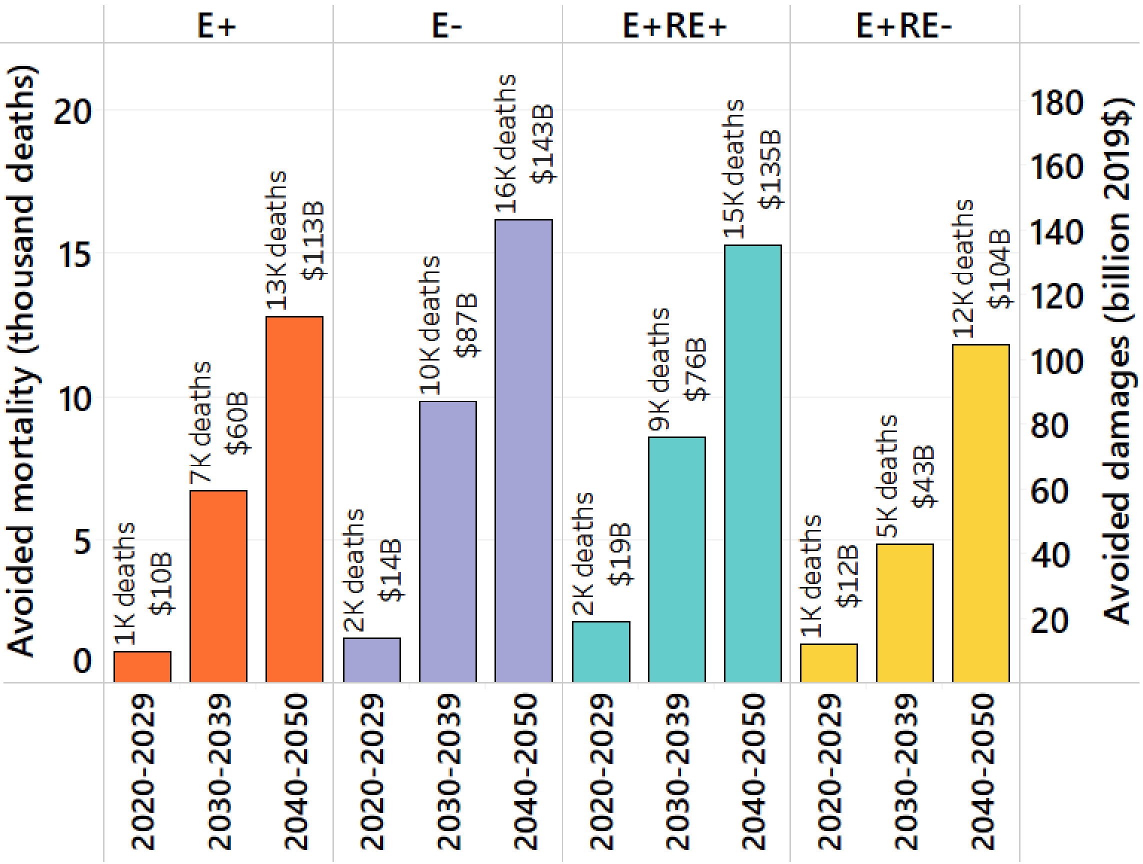
18 – 28k deaths (159 – 244B$ damages) are avoided from 2020 to 2050 by natural gas power plant retirements and conversions.

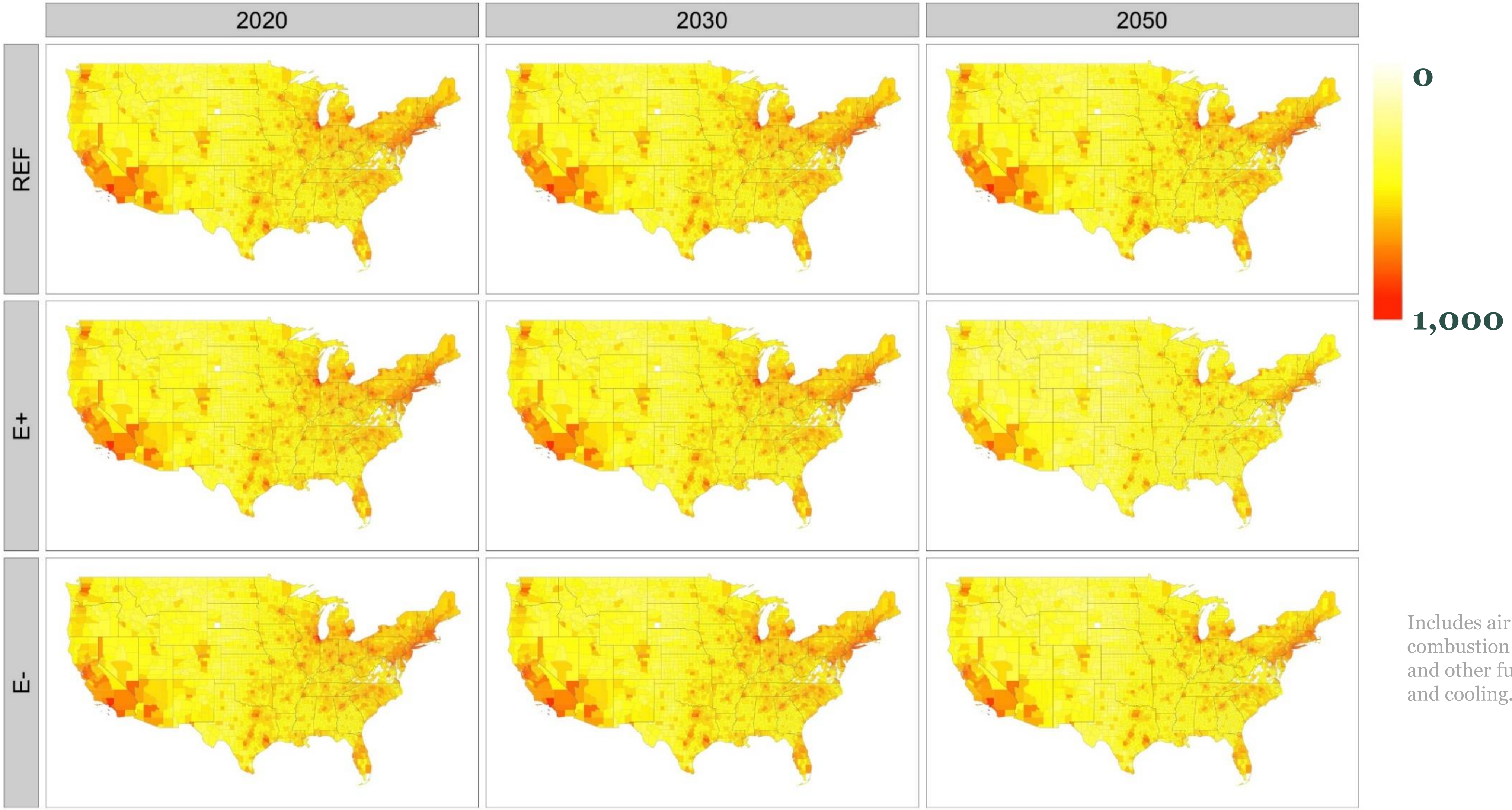
Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



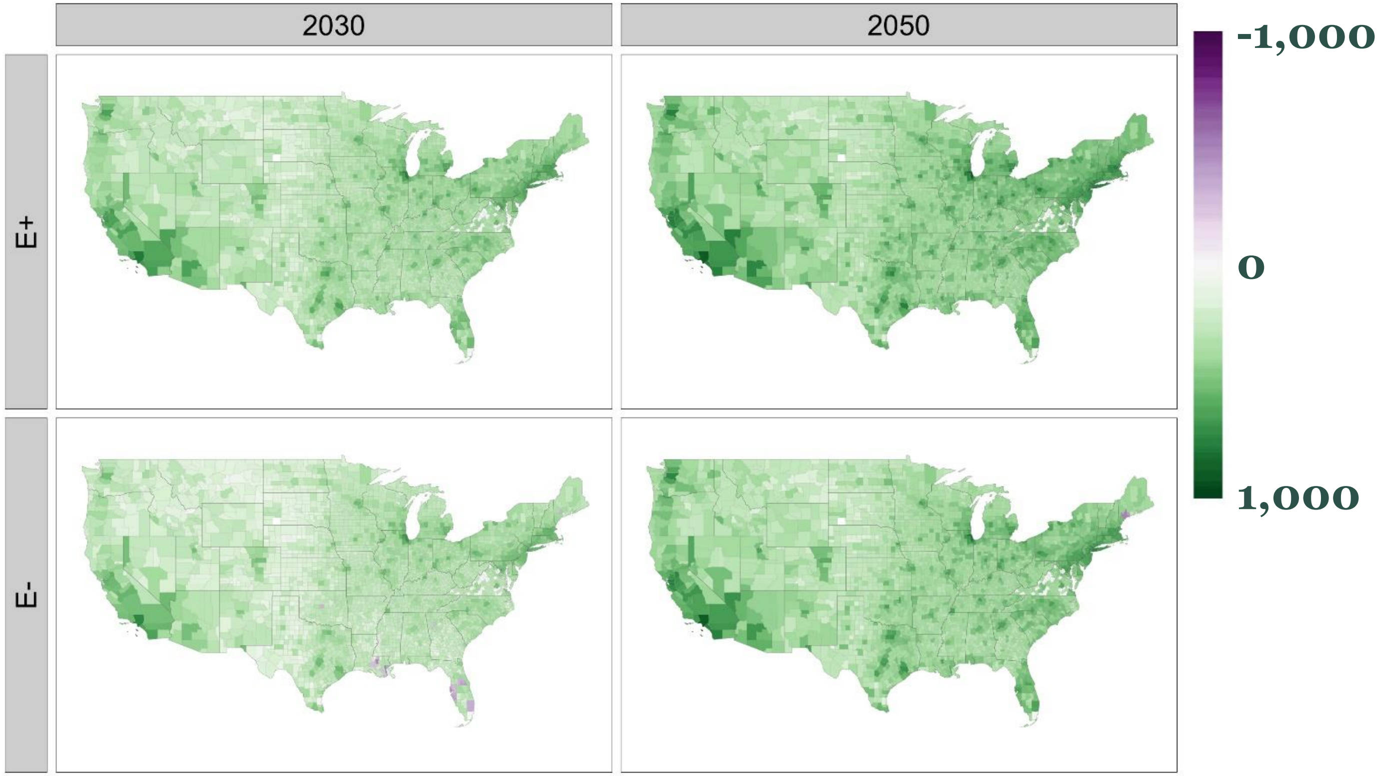
7 – 21k deaths (58 – 183B$ damages) associated with commercial heating & cooling are avoided from 2020 to 2050 by electrification.



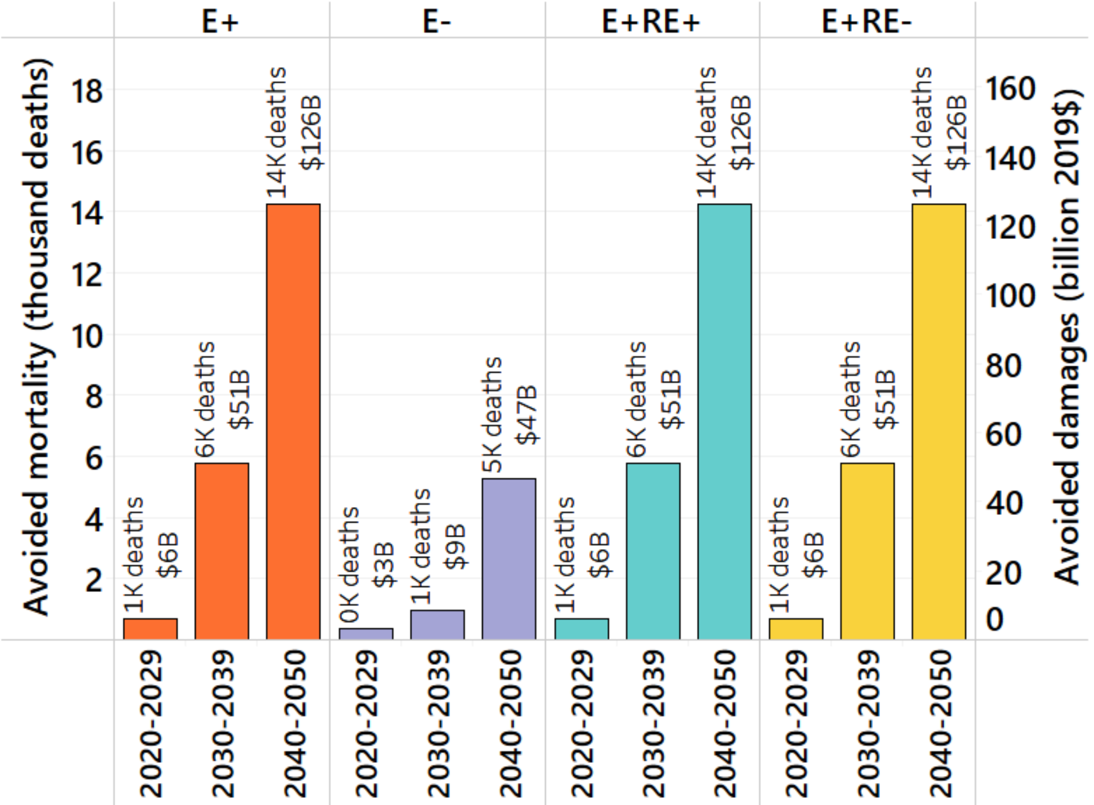
Includes air pollution impacts from combustion of coal, natural gas, oil, and other fuels for commercial heating and cooling.

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

Annual avoided premature deaths per county
[relative to REF]



Avoided premature mortalities by decade
[relative to REF]



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

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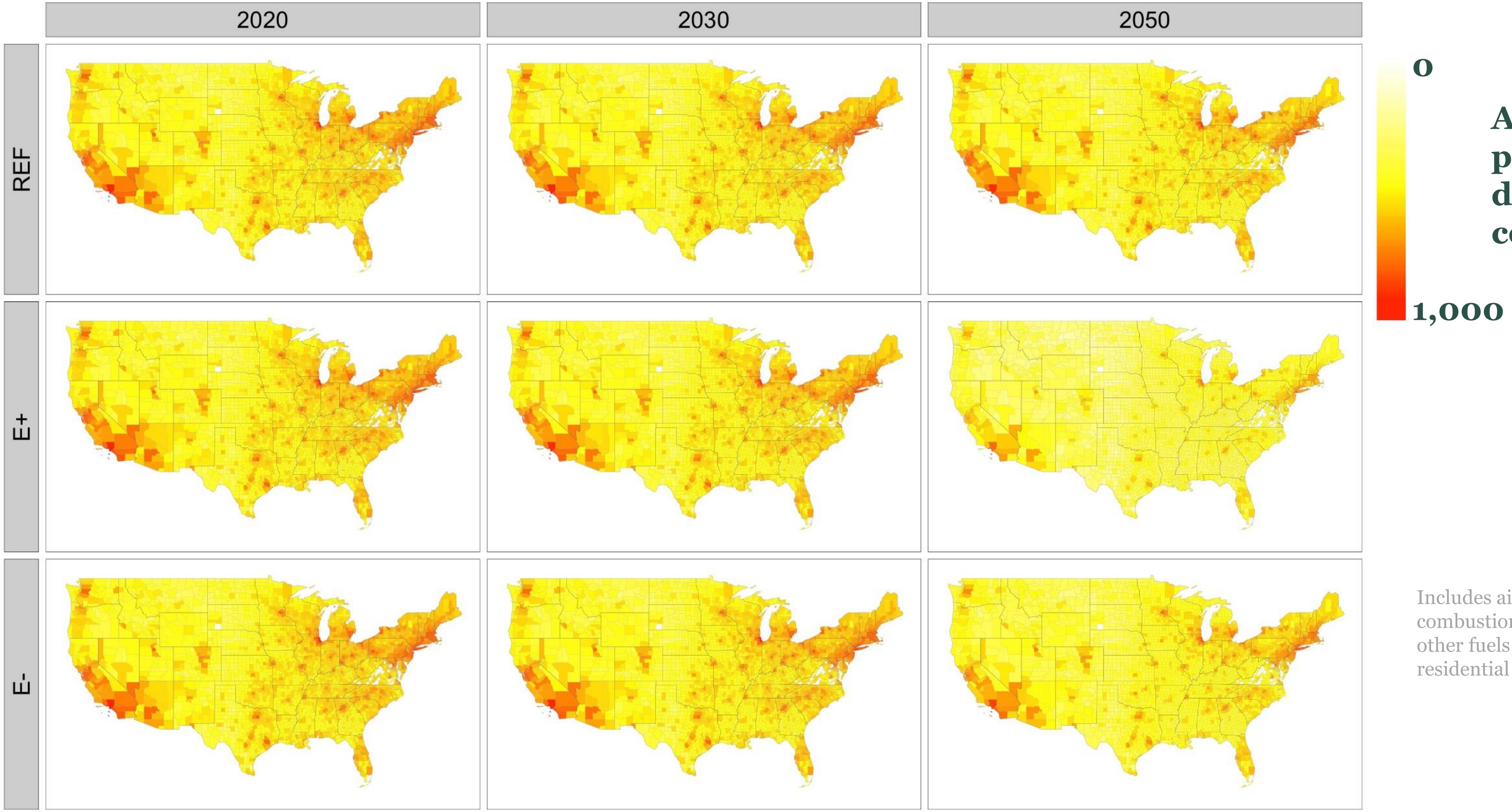
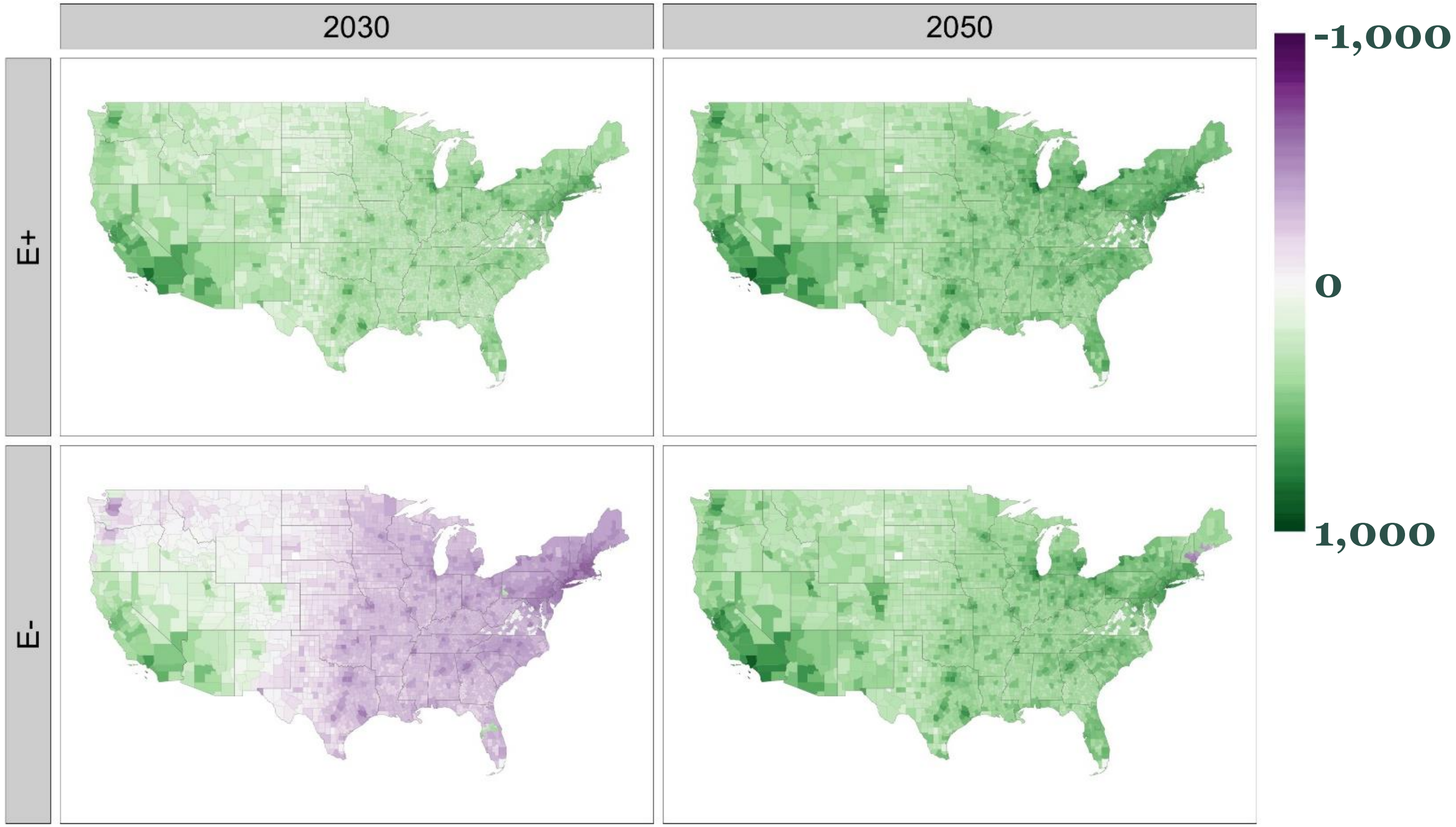
6 – 28k deaths (55 – 246B$) associated with residential heating and cooling are avoided from 2020 to 2050 by electrification.



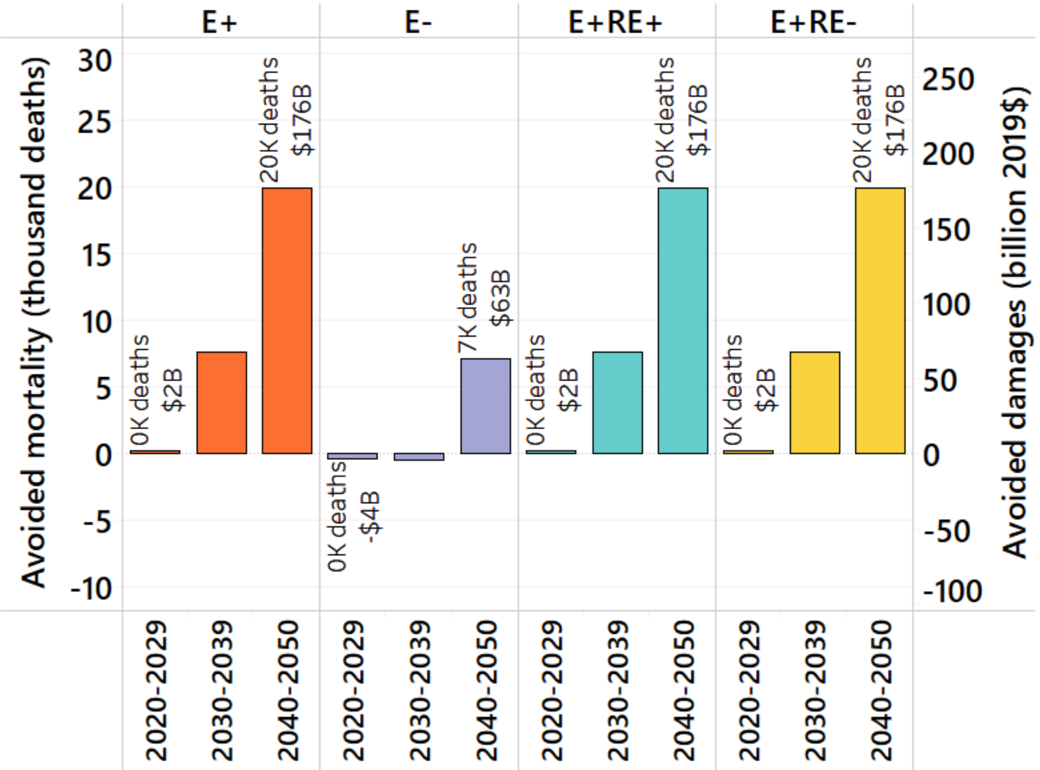
Includes air pollution impacts from combustion of natural gas, oil, and other fuels except wood for residential heating and cooling.

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

Annual avoided premature deaths per county
[relative to REF]

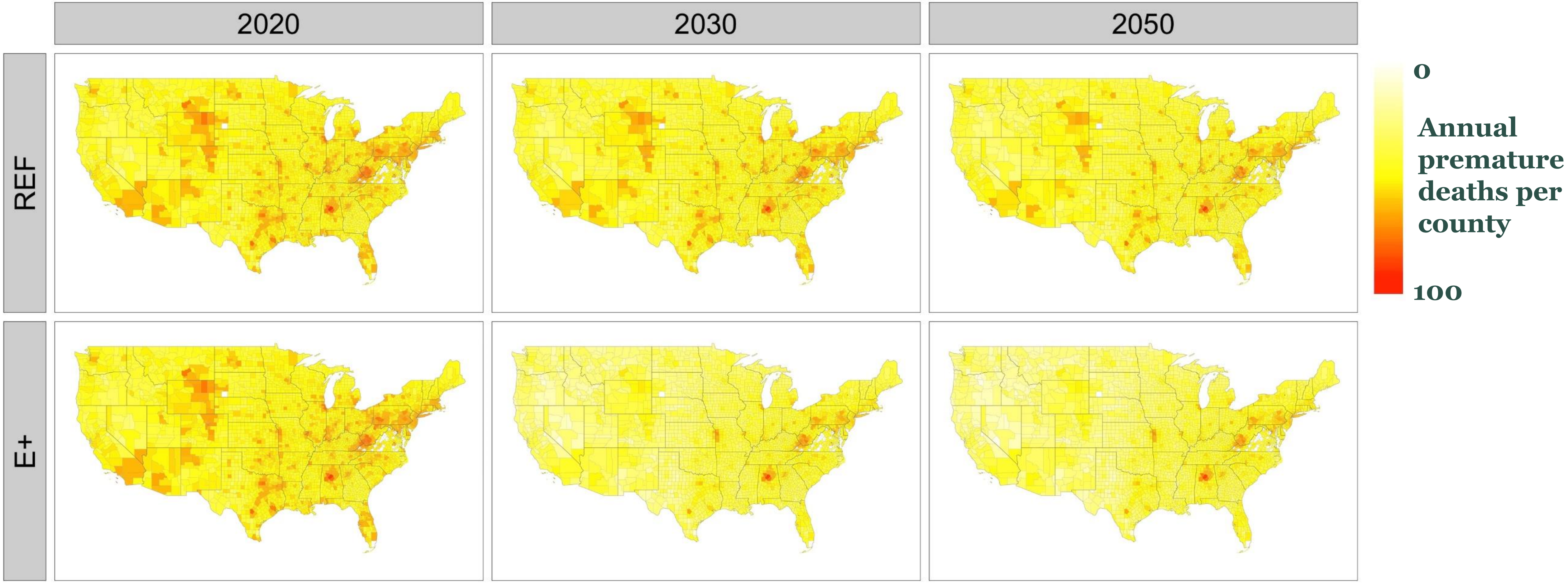


Avoided premature mortalities by decade
[relative to REF]



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

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



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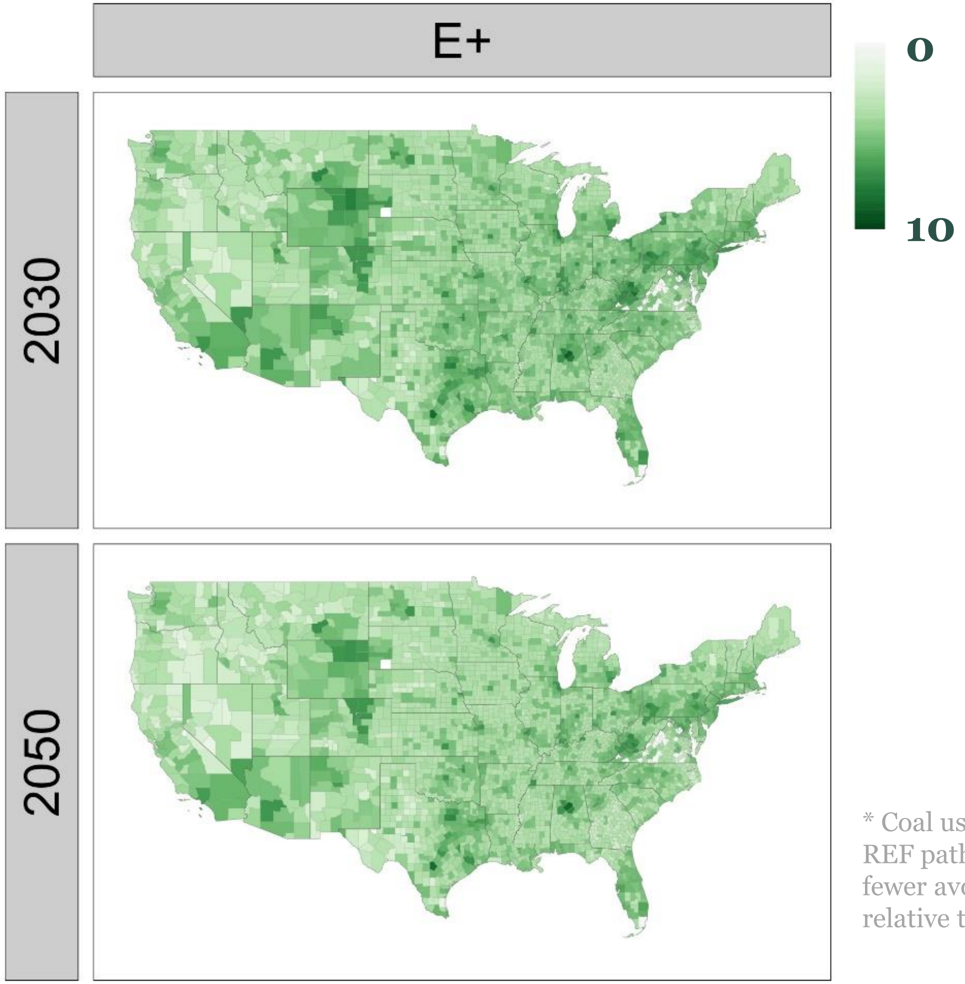
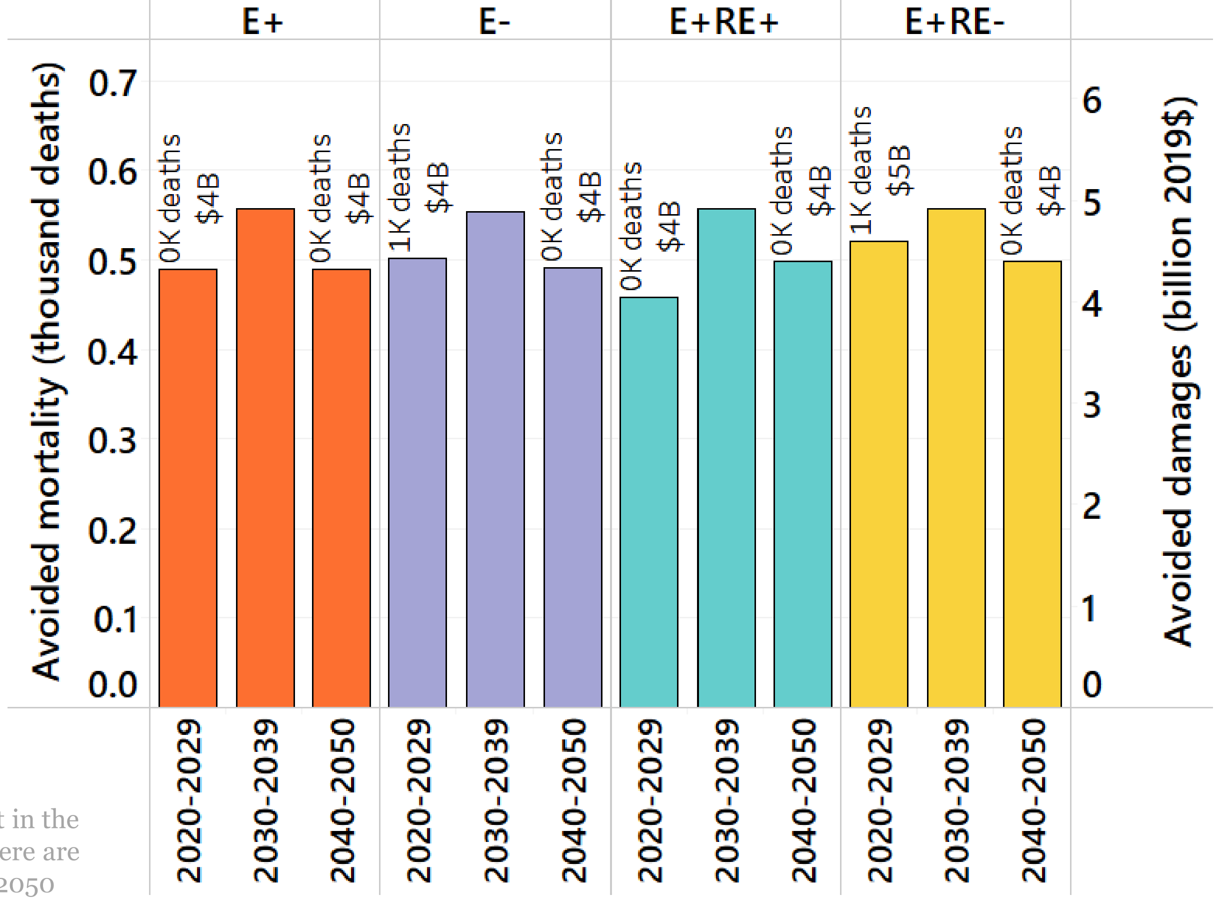
2k deaths ($14B damages) due to air pollution from coal mining are avoided from 2020 to 2050 as a result of reductions in coal use.

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



Avoided premature mortalities by decade [relative to REF]



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

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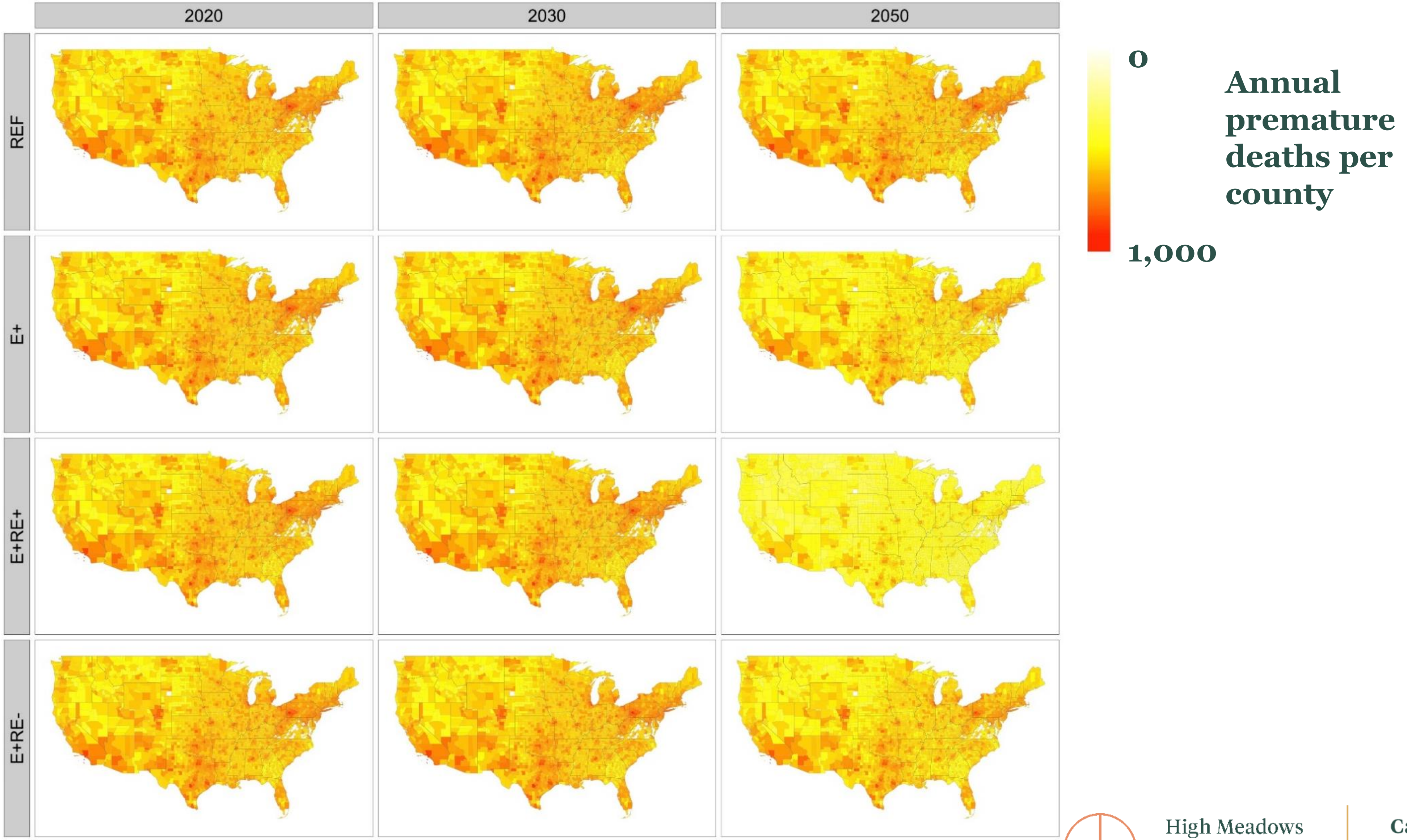
22 – 45k deaths (193 – 395B$ damages) due to emissions from oil and gas production are avoided from 2020 to 2050.



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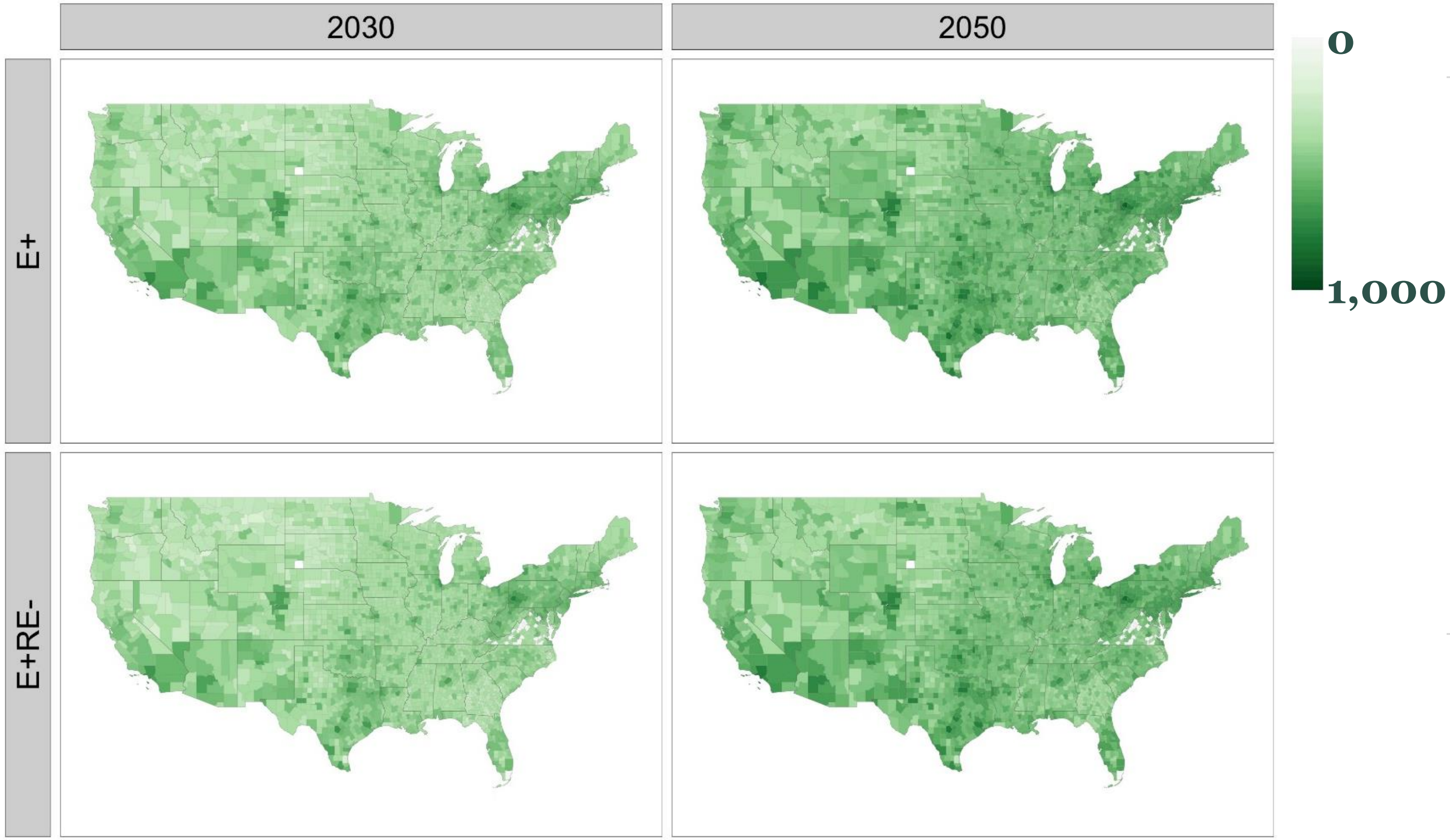
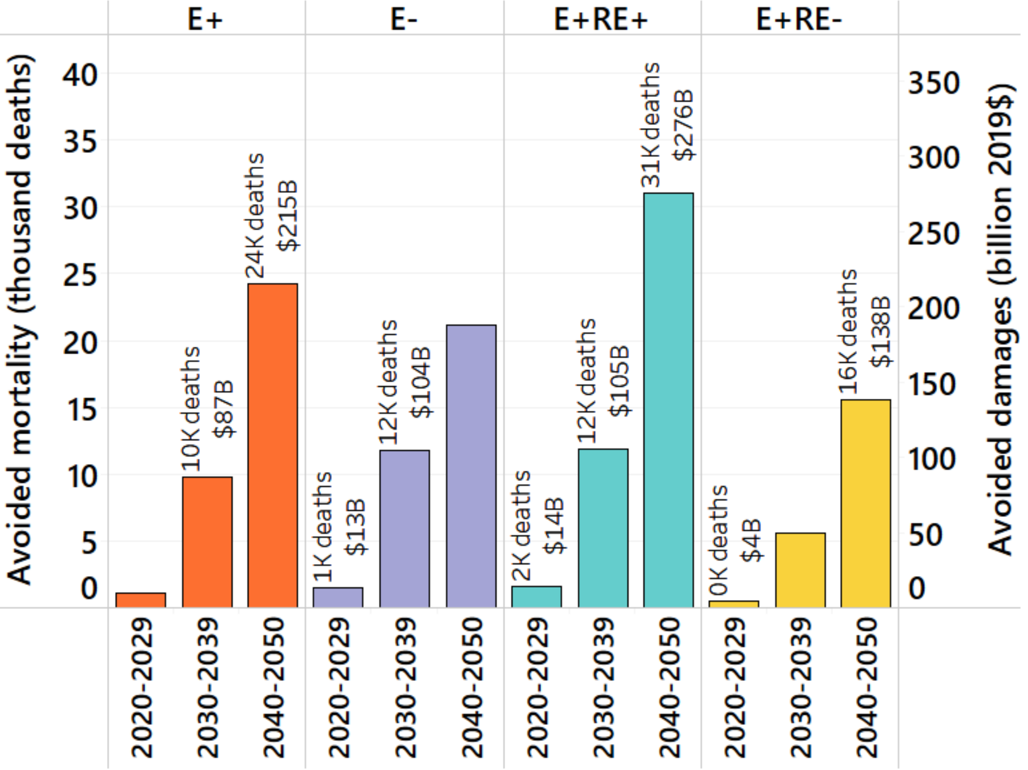
22 – 45k deaths (193 – 395B$ damages) due to emissions from oil and gas production are avoided from 2020 to 2050.

Annual avoided premature deaths per county [relative to REF]



Avoided premature mortalities by decade [relative to REF]



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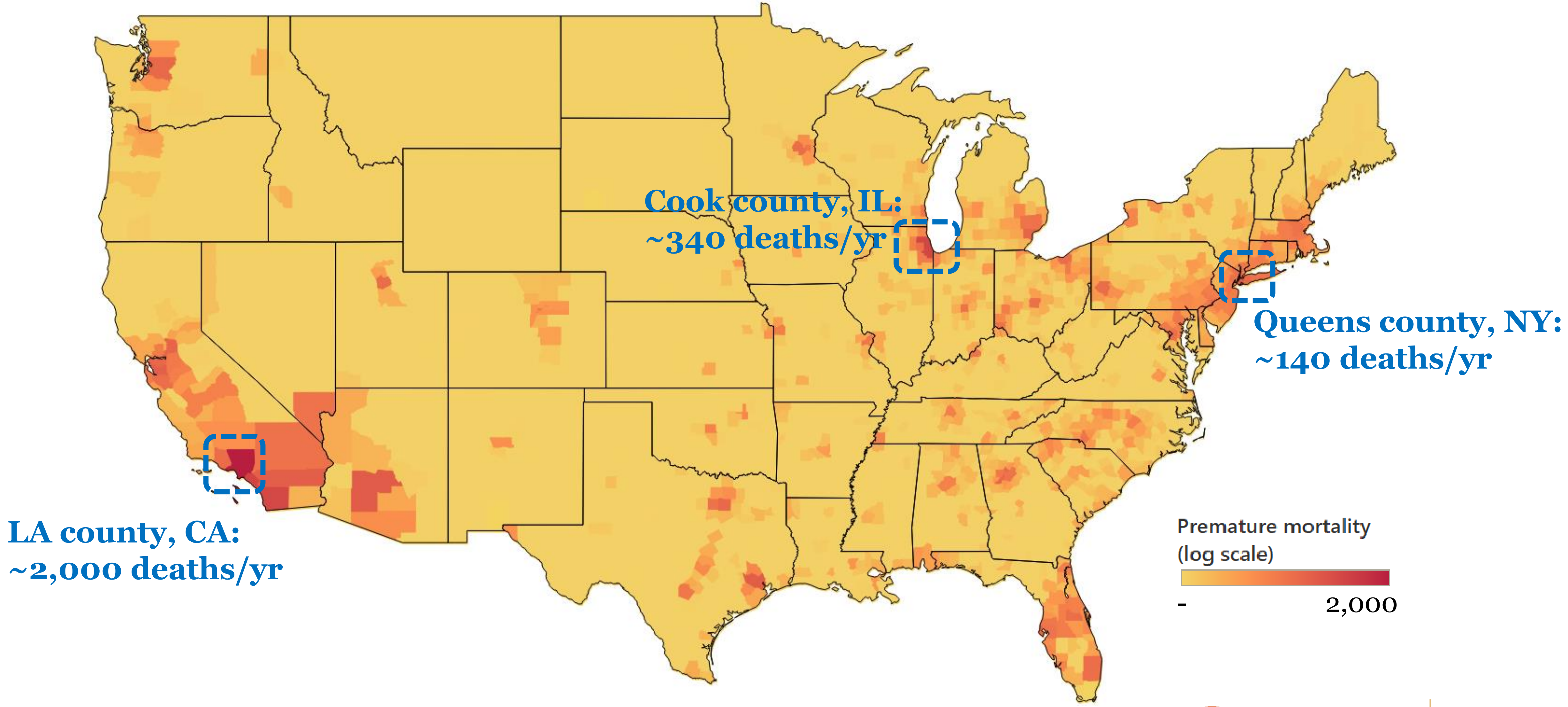
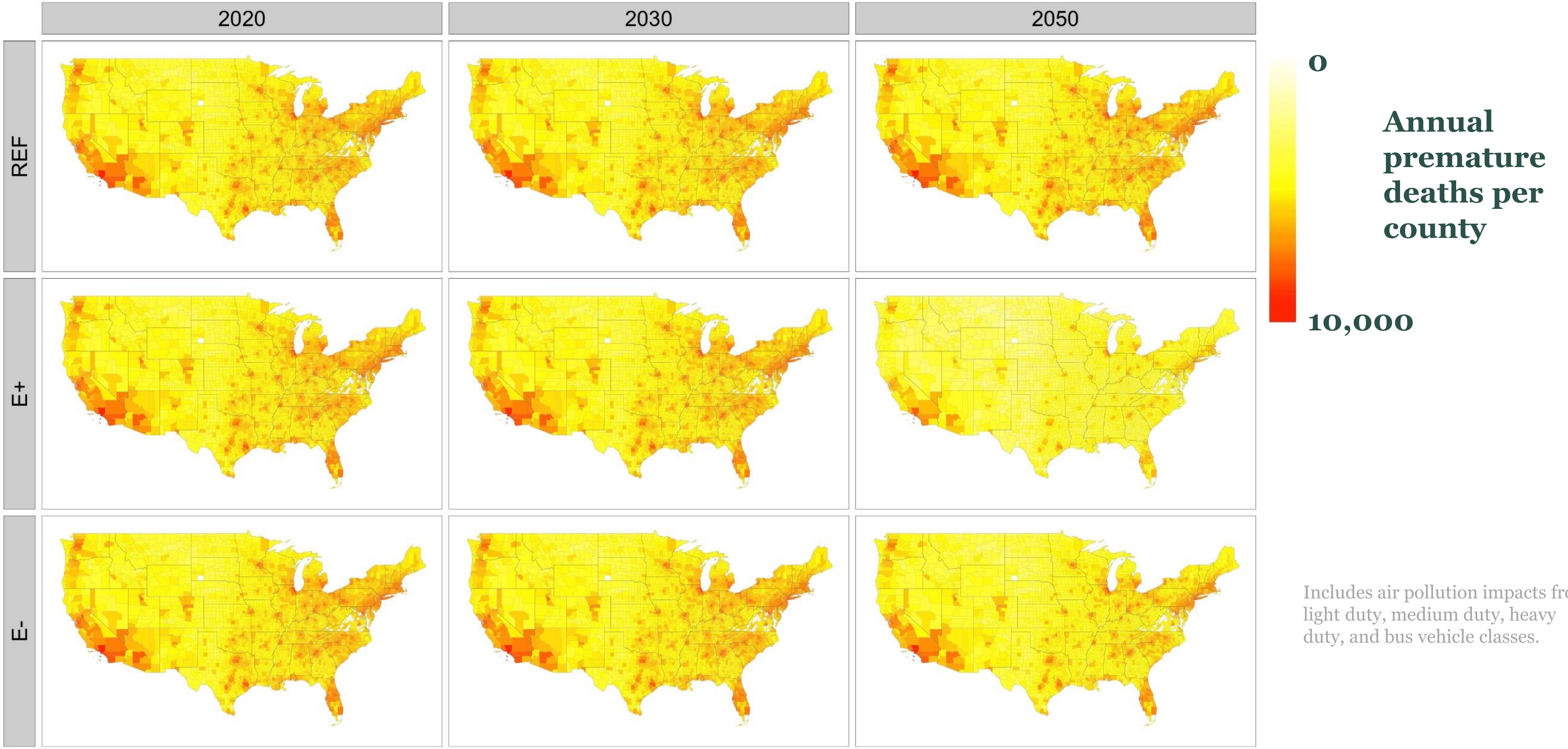
In 2019, ~11,000 premature mortalities (100B$ damages) were associated with emissions from the on-road mobile sources.



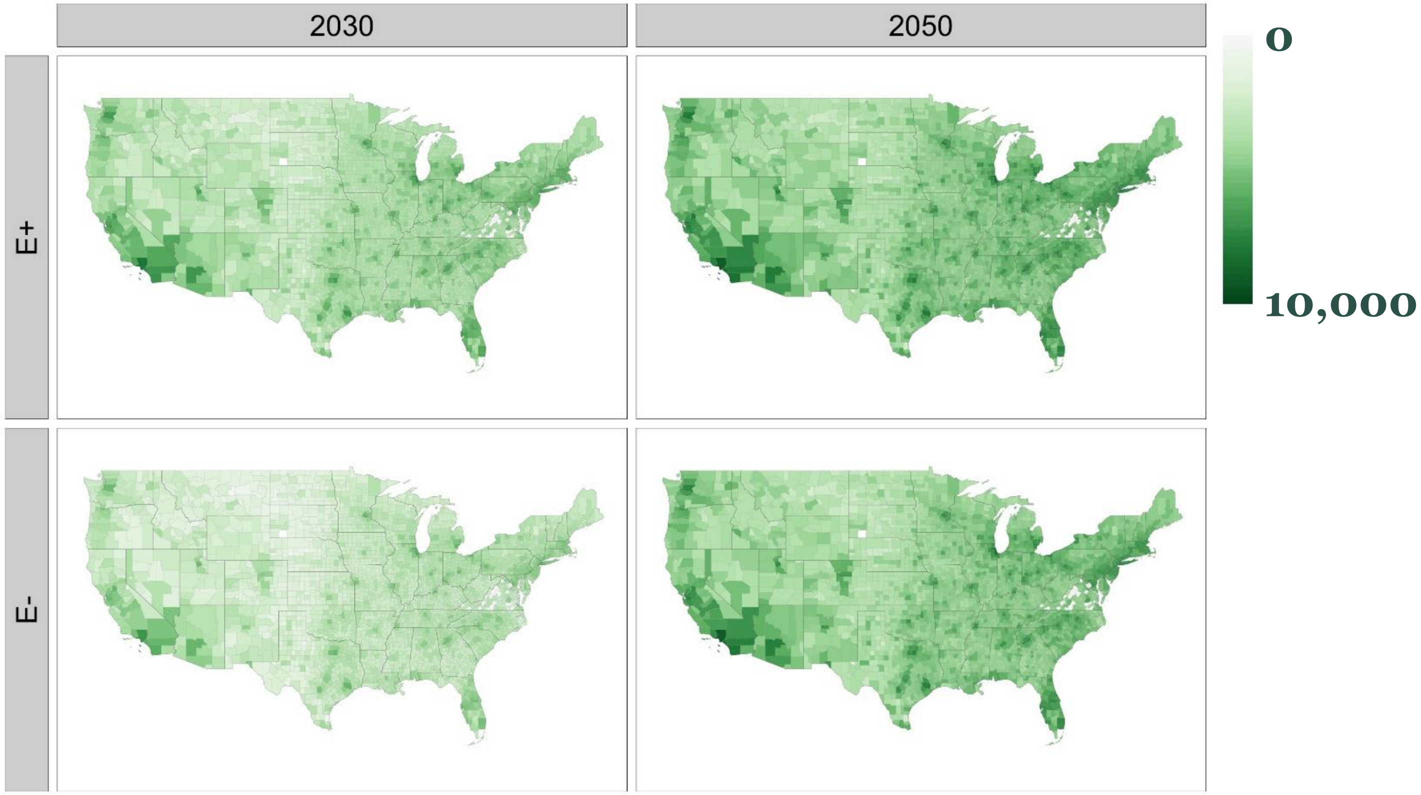
Air pollution benefits from vehicle electrification largely accrue after 2030 and accelerate through to 2050.



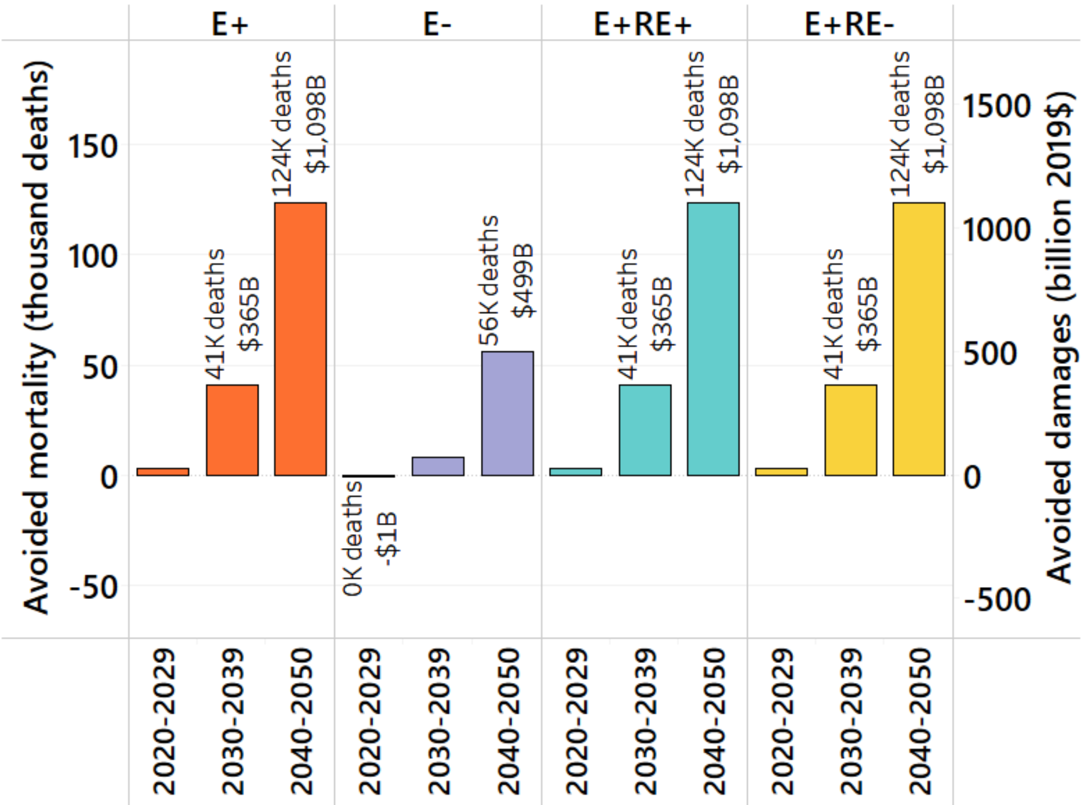
Includes air pollution impacts from light duty, medium duty, heavy duty, and bus vehicle classes.

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

Annual avoided premature deaths per county [relative to REF]

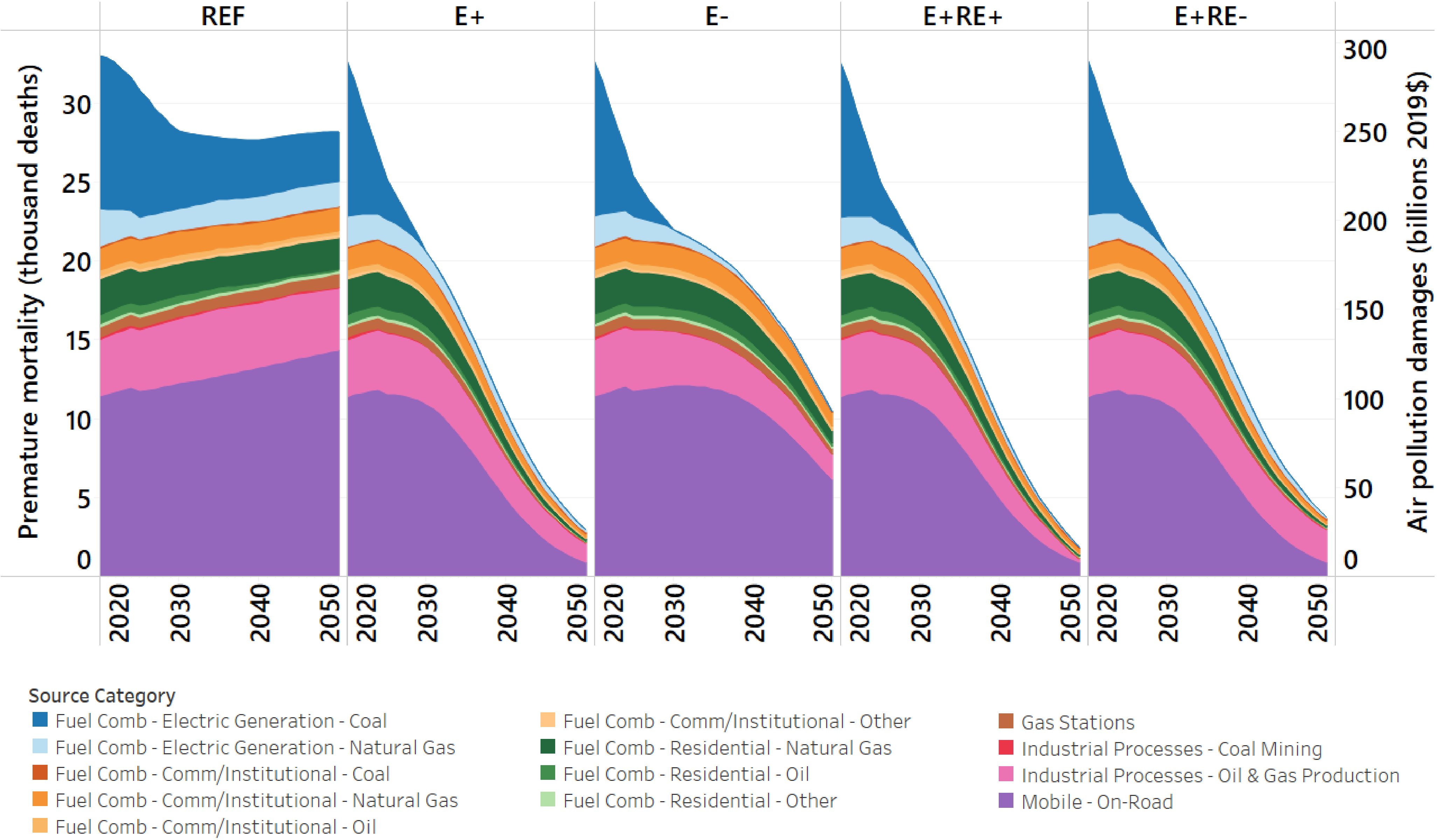


Avoided premature mortalities by decade [relative to REF]



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

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



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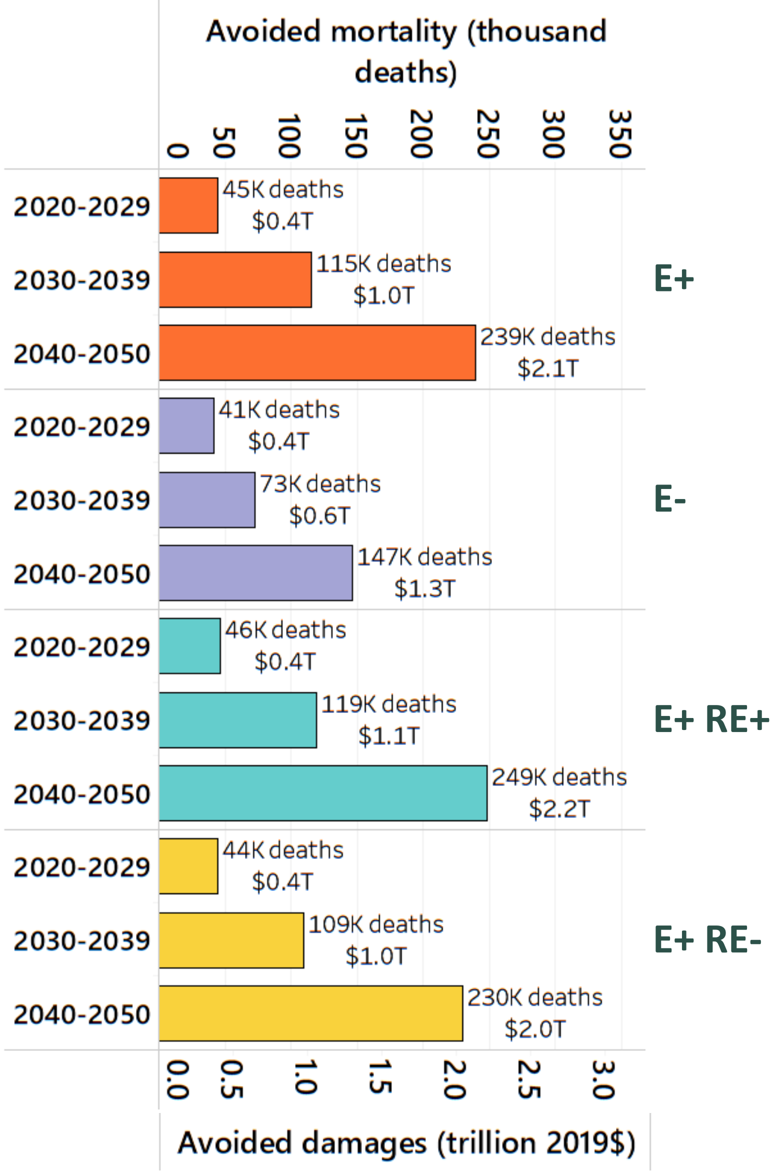
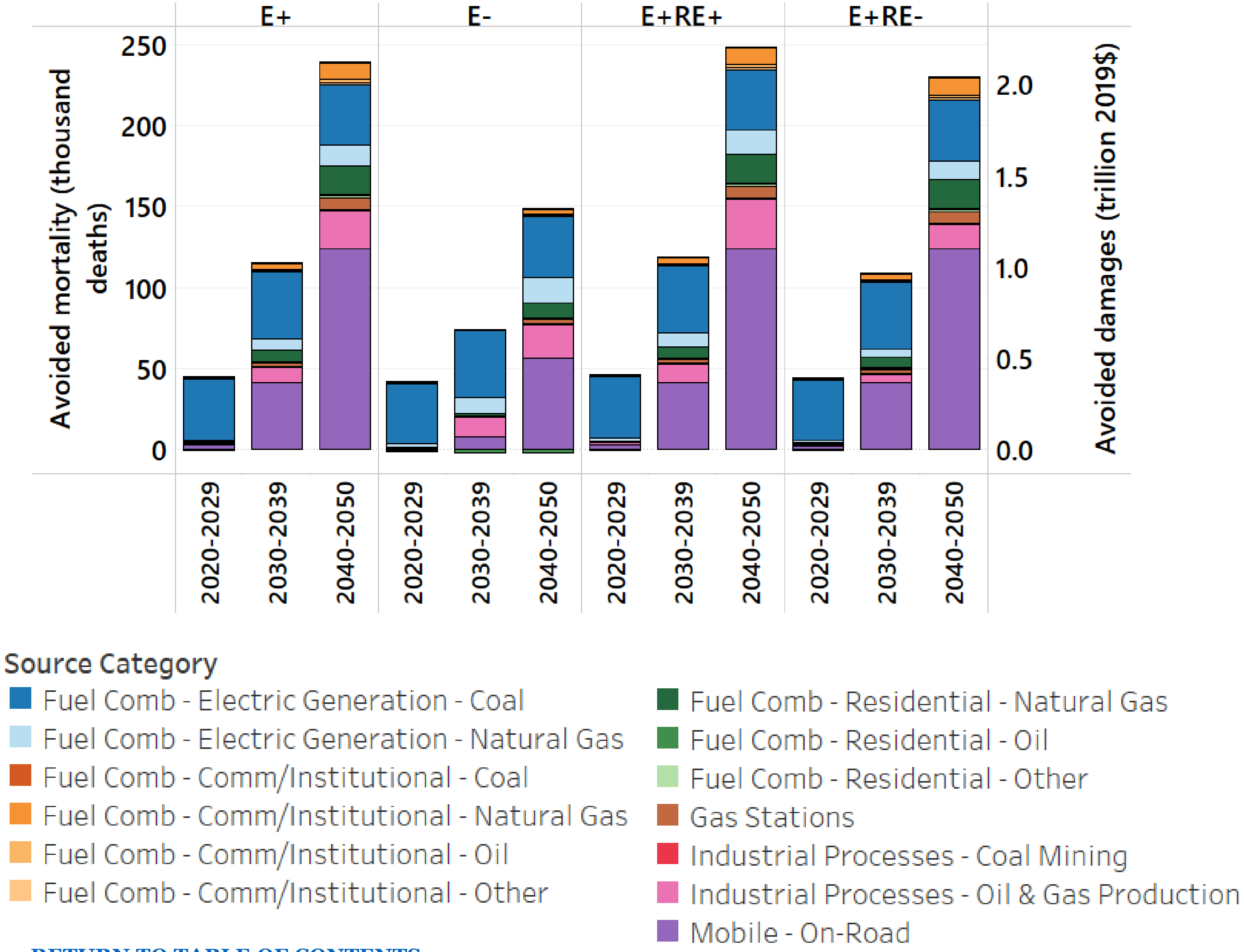
Air quality gains in 2020's are mostly from coal retirements. Vehicle electrification & natural gas transition contribute more after that.





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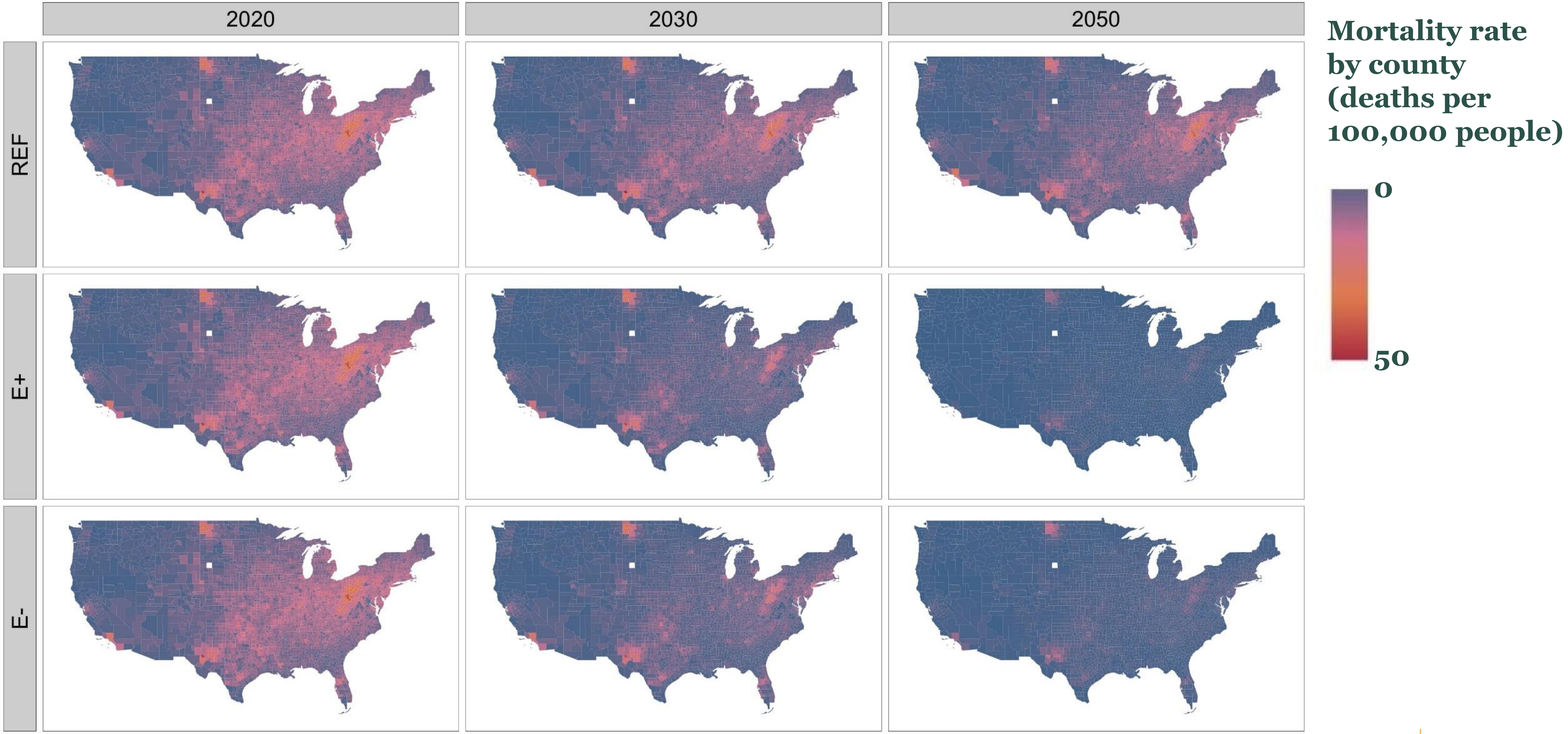
All localities benefit from air pollution reductions in going to net-zero greenhouse gas emissions.



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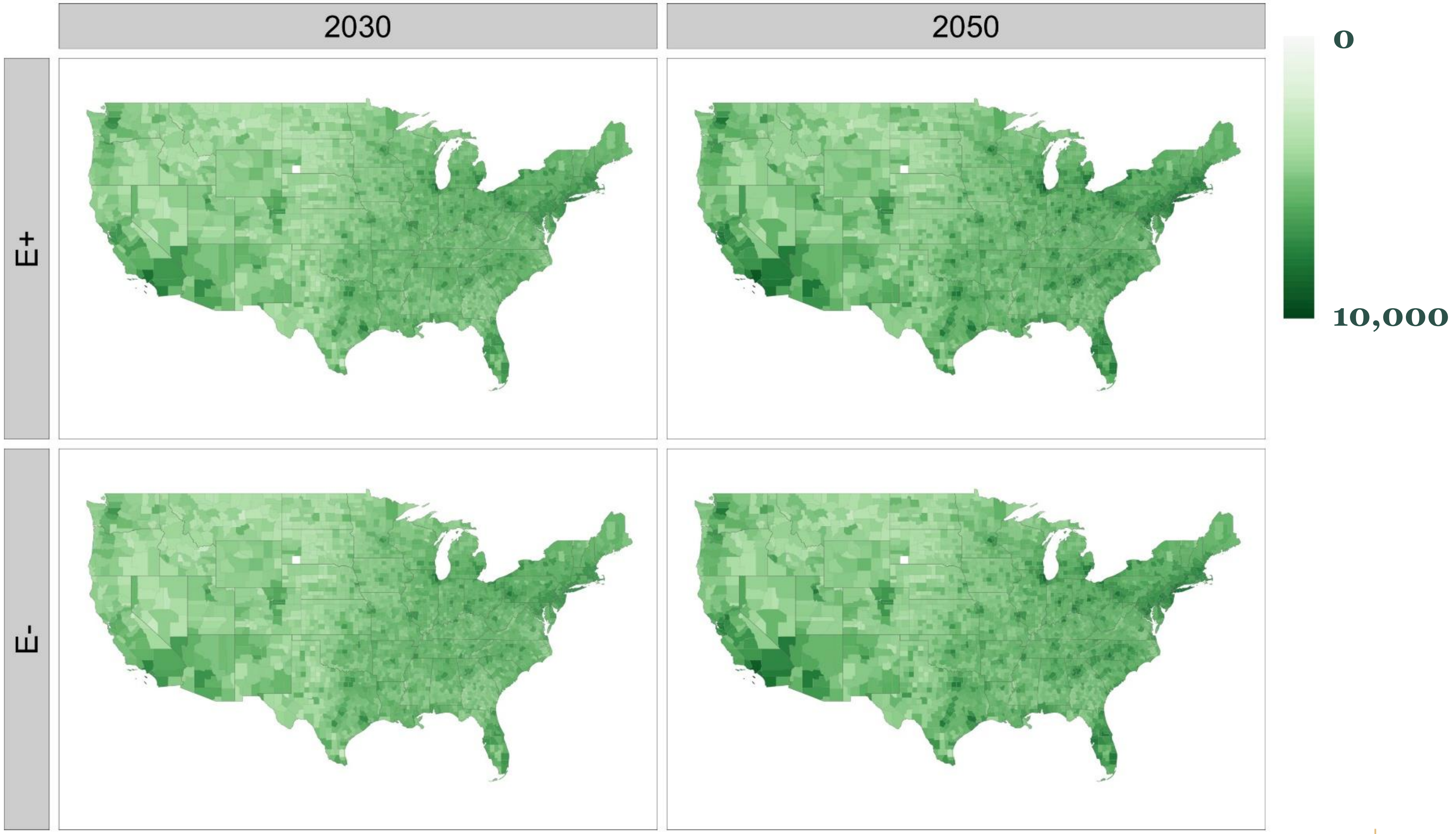
All localities benefit from air pollution reductions in going to net-zero greenhouse gas emissions.

Annual avoided premature deaths per county [relative to REF]



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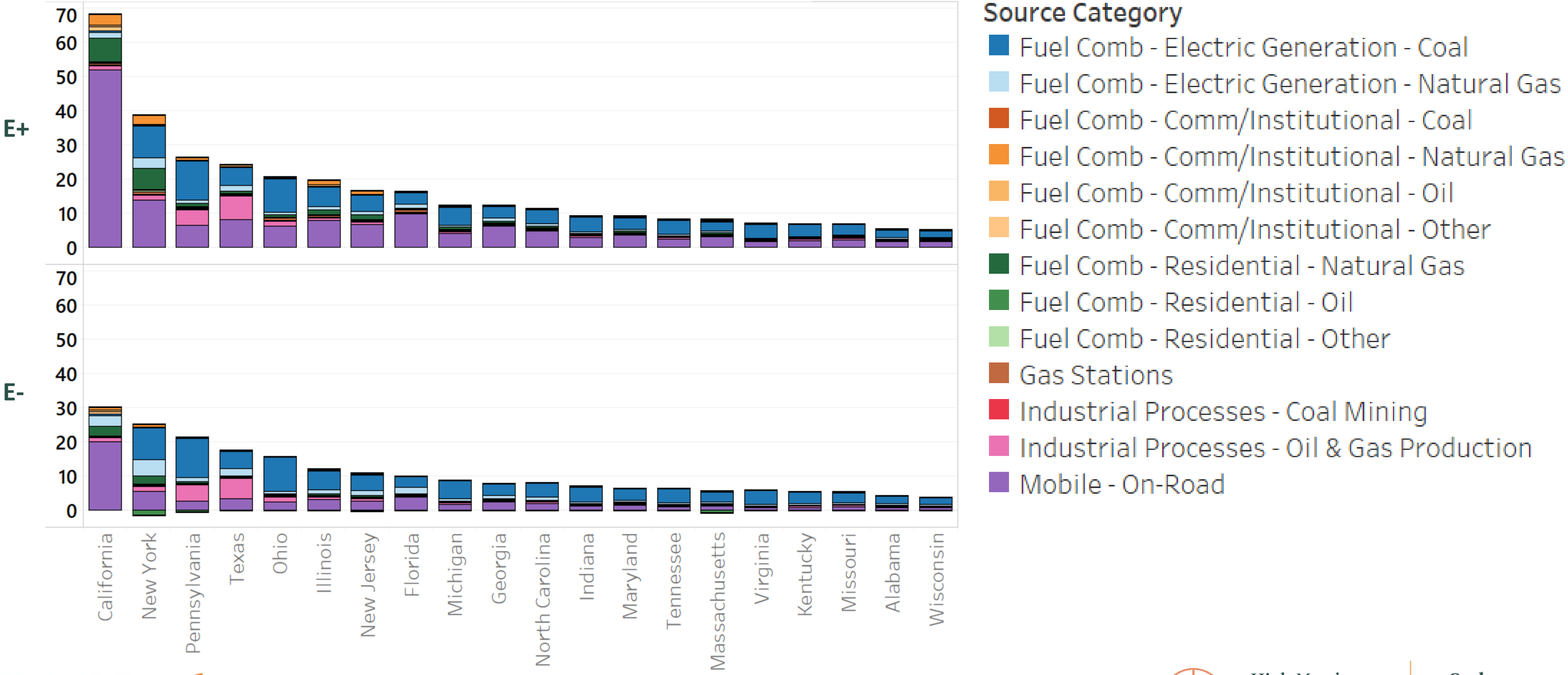
Cumulative air pollution-related health benefits at the state-level are significant in the transition to net-zero.

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



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

Summary of this section

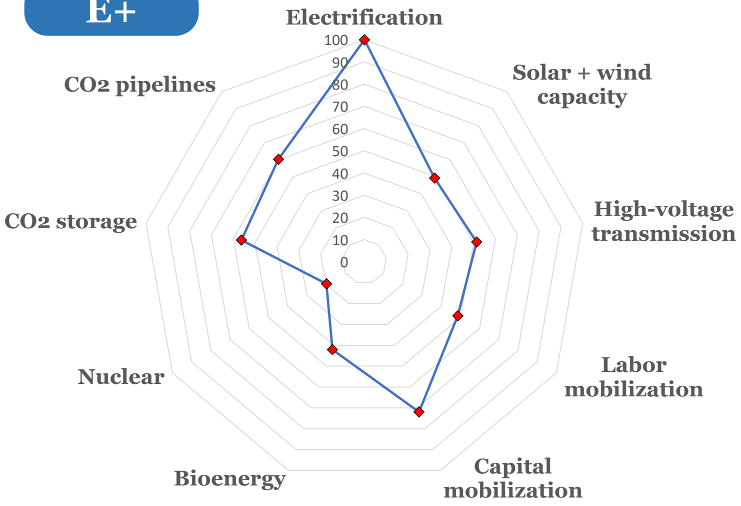
- Each of the five modeling pathways to net-zero emissions by 2050 presents different, but similarly daunting challenges to success.
- A successful transition to net-zero emissions by 2050 implies significant cumulative impacts, both positive and negative, that vary across the different net-zero pathways.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

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

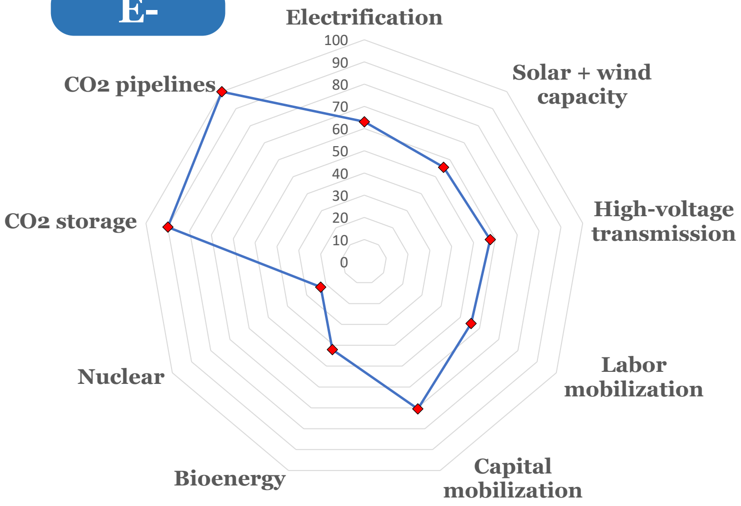
Level of Challenge (ordinal ranking)	
0	Lowest
100	Highest

Challenge	Comparative metric
Electrification	% LDV stock that is EV in 2050
Solar + wind capacity	Capacity in 2050 vs. REF
High-voltage transmission	Cumulative capital invested by 2050
Labor mobilization	Energy workers, 2040s average
Capital mobilization	Cumulative capital vs. REF
Bioenergy	Bioenergy use in 2050 vs. REF.
Nuclear	Operating capacity in 2050
CO_2 storage	Tonnes CO_2 injected in 2050
CO_2 pipelines	Tonnes CO_2 captured in 2050

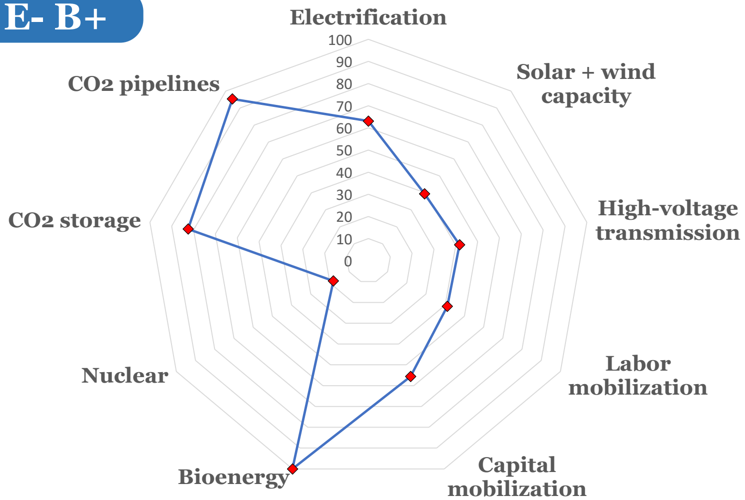
E+



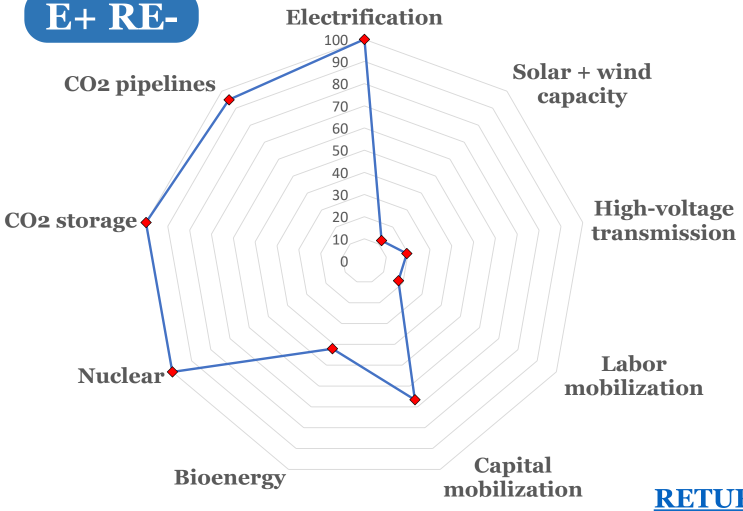
E-



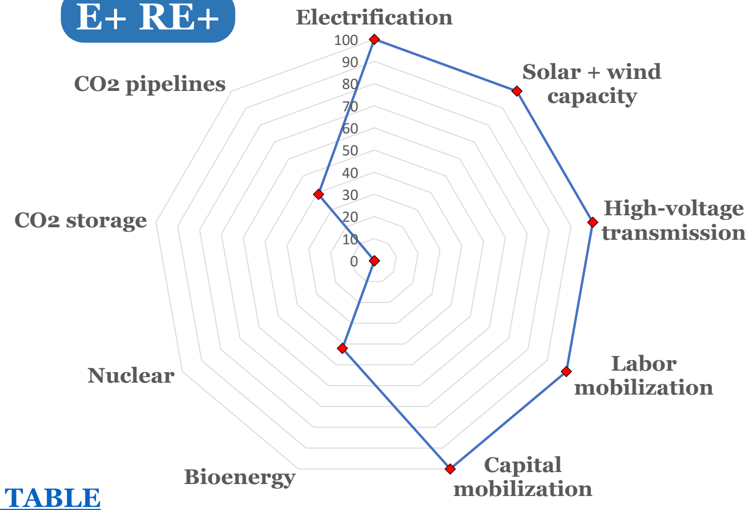
E- B+



E+ RE-



E+ RE+



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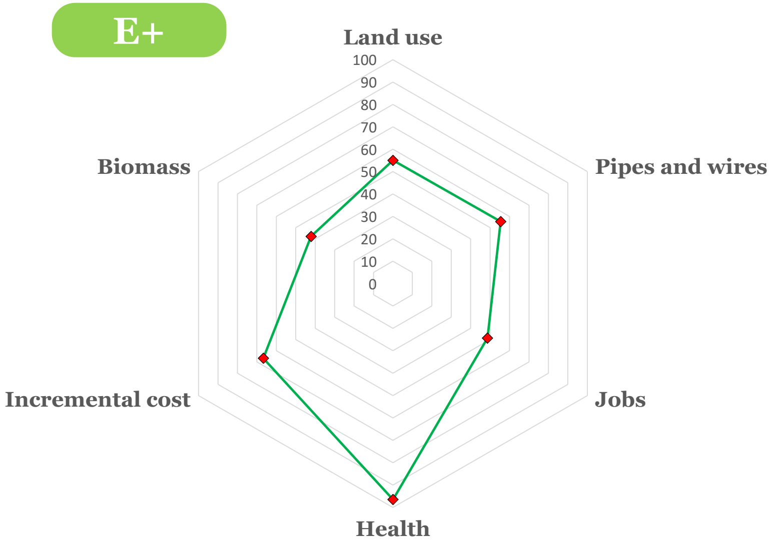
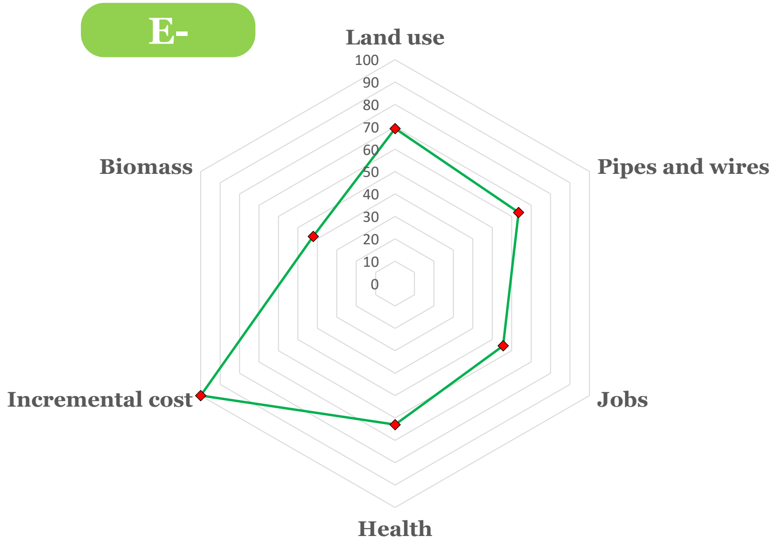
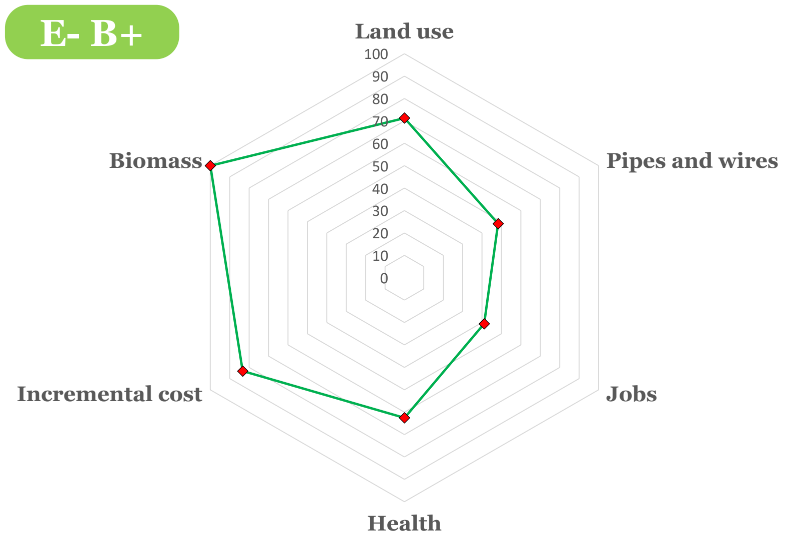
A successful net-zero transition implies cumulative impacts by 2050 (relative to REF) that vary across net-zero pathways

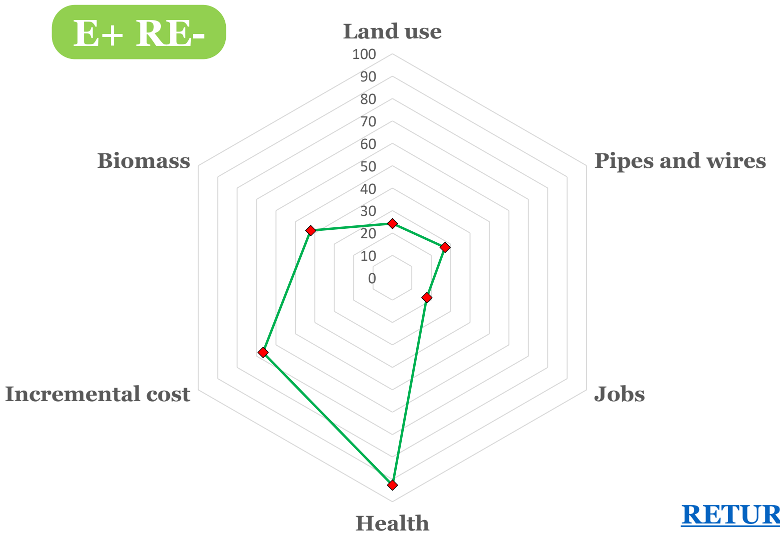
Level of Impact (ordinal ranking)	
0	Lowest
100	Highest

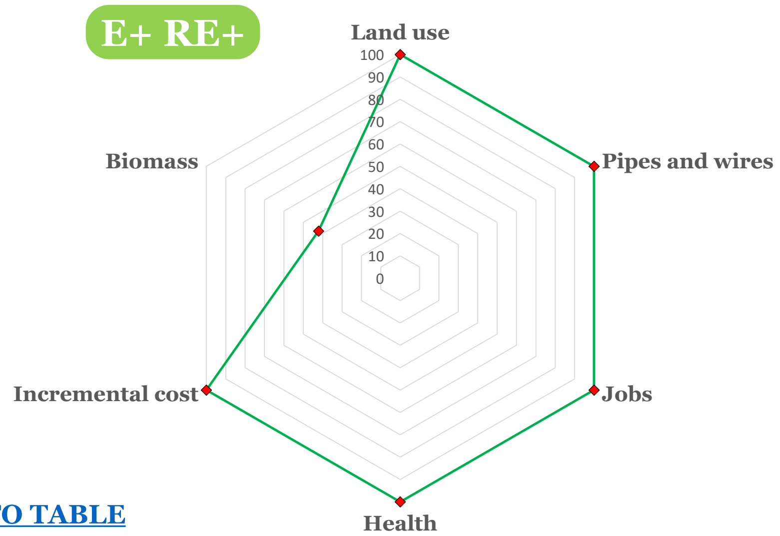
Impact	Comparative metric
Land use	Total km² solar, wind, biomass + DAC, 2050
Pipes & wires	Cumulative capital for HV transmission & CO_2 pipelines, 2020 – 2050
Jobs	Average annual energy jobs in 2040s vs. REF
Health	Cumulative avoided premature deaths, 2020 to 2050.
Cost	NPV of energy-system costs,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











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

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

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

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

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

2. Failure to mobilize capital investments at unprecedented rates

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

3. Failure to gain and sustain social license

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

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

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

A blueprint for action in the 2020s: key priorities

Summary of this section

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

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Carbon Mitigation Initiative

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

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

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

1 Build societal commitment, investment environment, and delivery capabilities

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

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Priorities for the 2020's: Demand-Side

2 Improve end-use energy productivity and efficiency

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

3 Electrify, especially transportation and buildings

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

Priorities for the 2020's: Supply-side

4 Decarbonize and expand electricity

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

5 Prepare for transformation and expansion of bioenergy industry

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

Priorities for the 2020's: Network Infrastructures

6 a. Expand critical electric network infrastructure

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

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

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

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

7 a. Protect and enhance land carbon sinks

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

7 b. Reduce non-CO_2 emissions

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

Priorities for the 2020's: Innovation

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

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

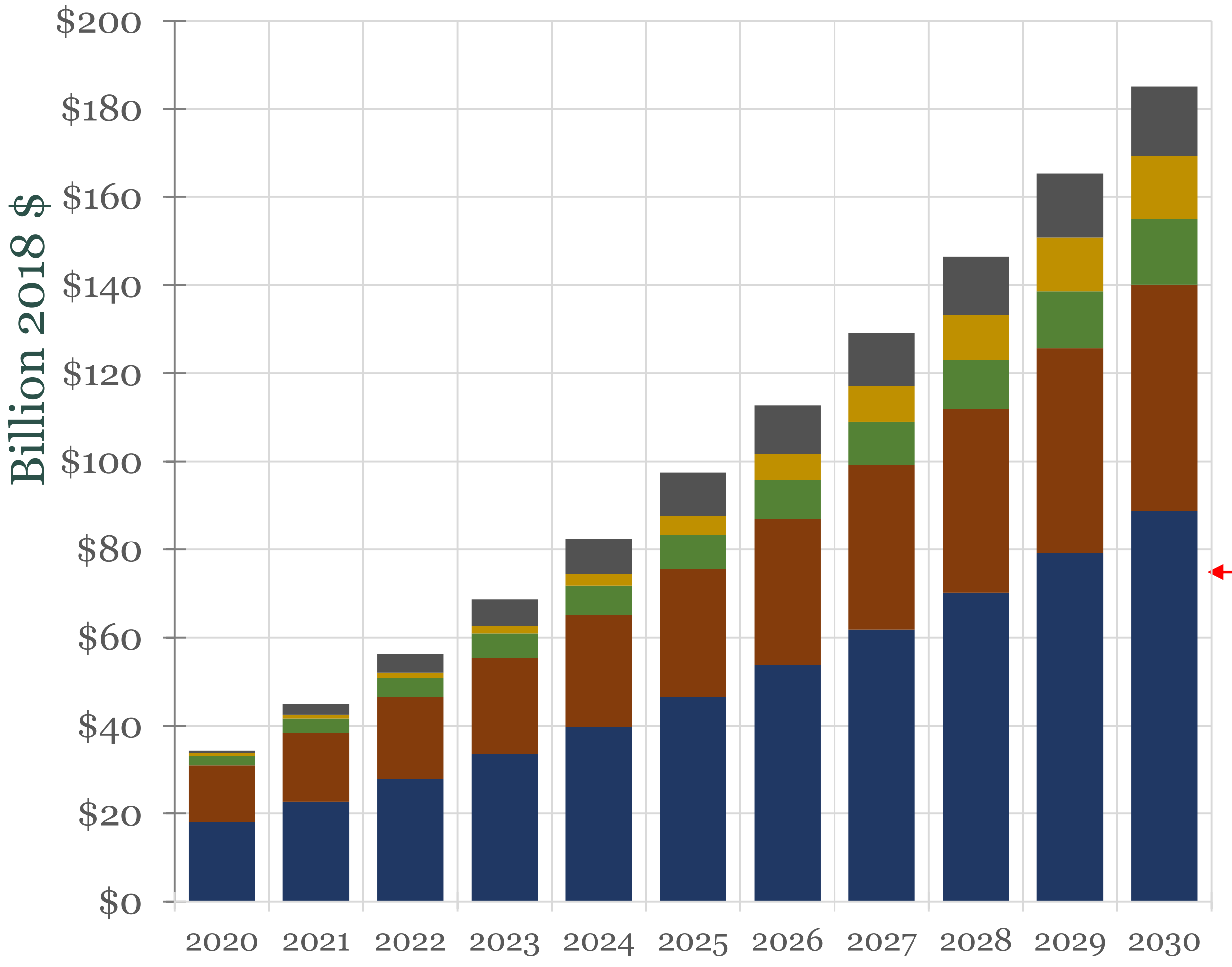
  $140 Billion: Order-of magnitude capital cost estimates for up to 5 first-N-of-a-kind (FOAK) demonstrations for each technology above, including FOAK premiums.
- Technology innovation to reduce siting challenges: Increase investment in research and technology solutions that reduce network infrastructure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

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

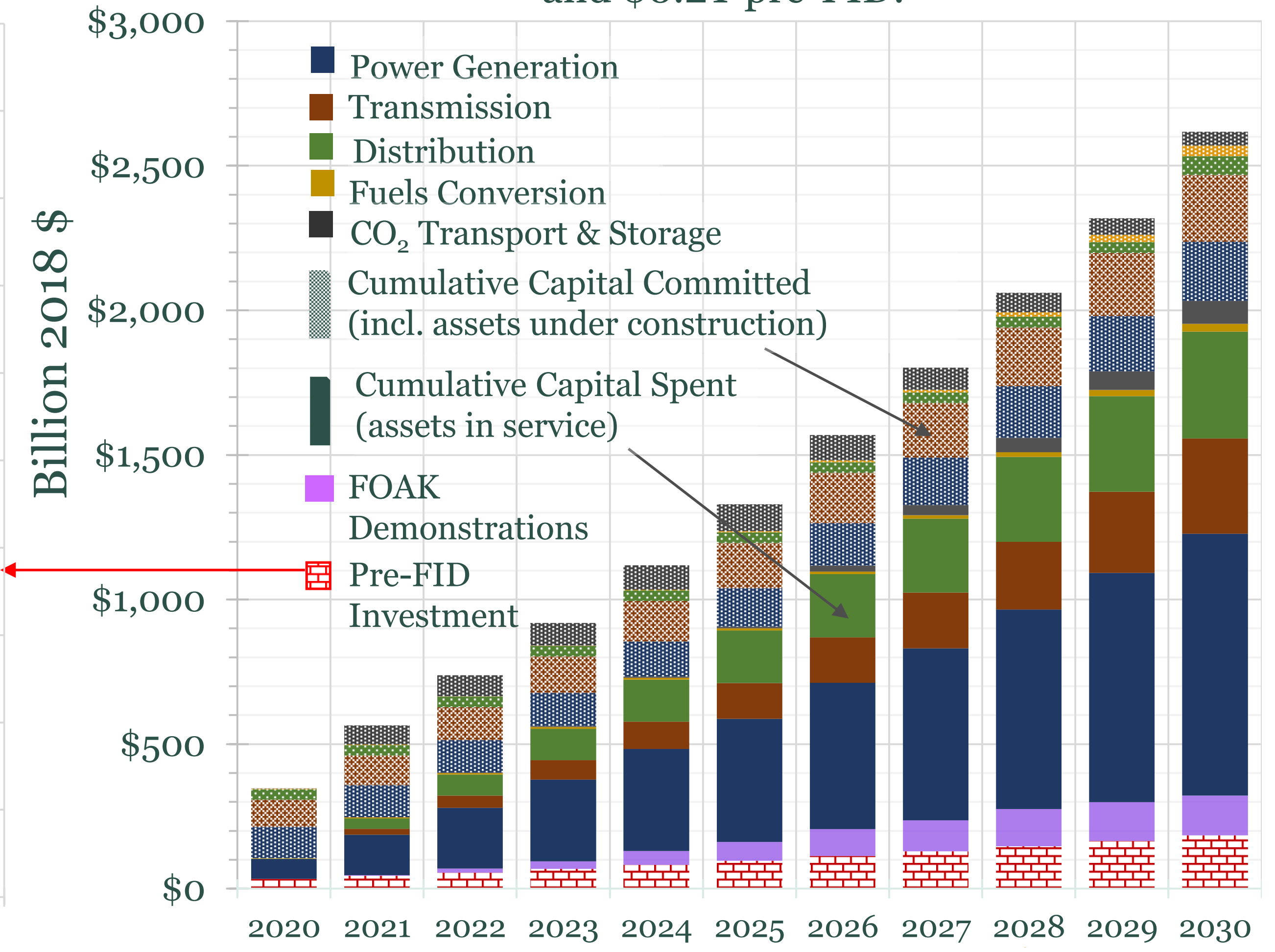
Mobilizing risk capital for development and construction will be a significant challenge for the 2020s (and beyond).

E+

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



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



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

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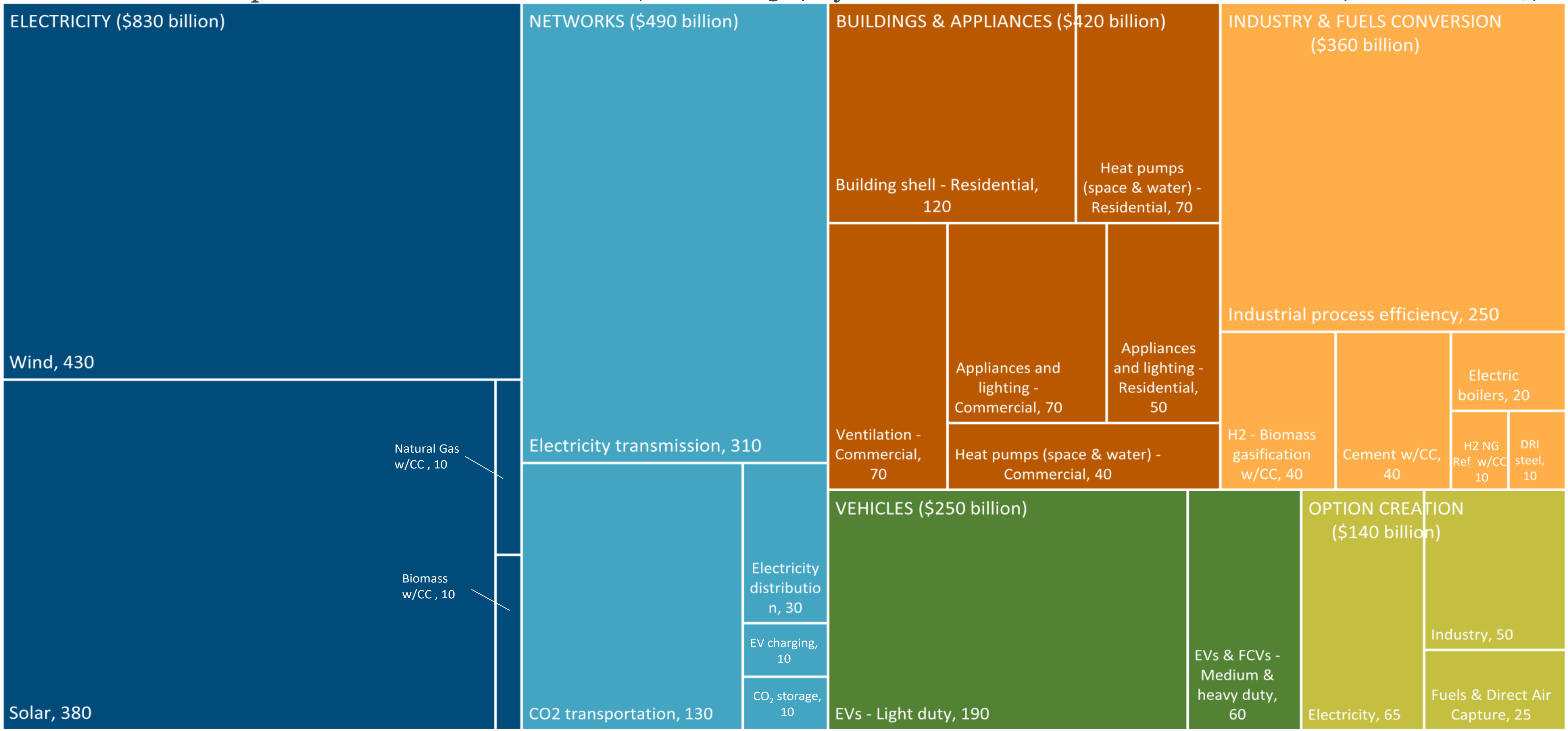
Net-zero path requires **$2.5 T additional capital** in 2020s (vs. REF) across energy supply, buildings, appliances, vehicles, industry.

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



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

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

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

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

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

END OF REPORT