Princeton's Net-Zero America study

Annex E: Thermal Generation Downscaling

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1 Overview

This appendix describes the approach used to downscale thermal (excluding biomass-fired) power plant transitions. Figure 1 is a conceptual model of the downscaling approach. We first simulate the retirement of existing coal, natural gas, and nuclear generators. Then, we perform a multi-attribute geospatial site suitability analysis, assessing the conversion potential of existing thermal sites. Finally, we simulate the conversion of existing sites to new natural gas and nuclear sites.

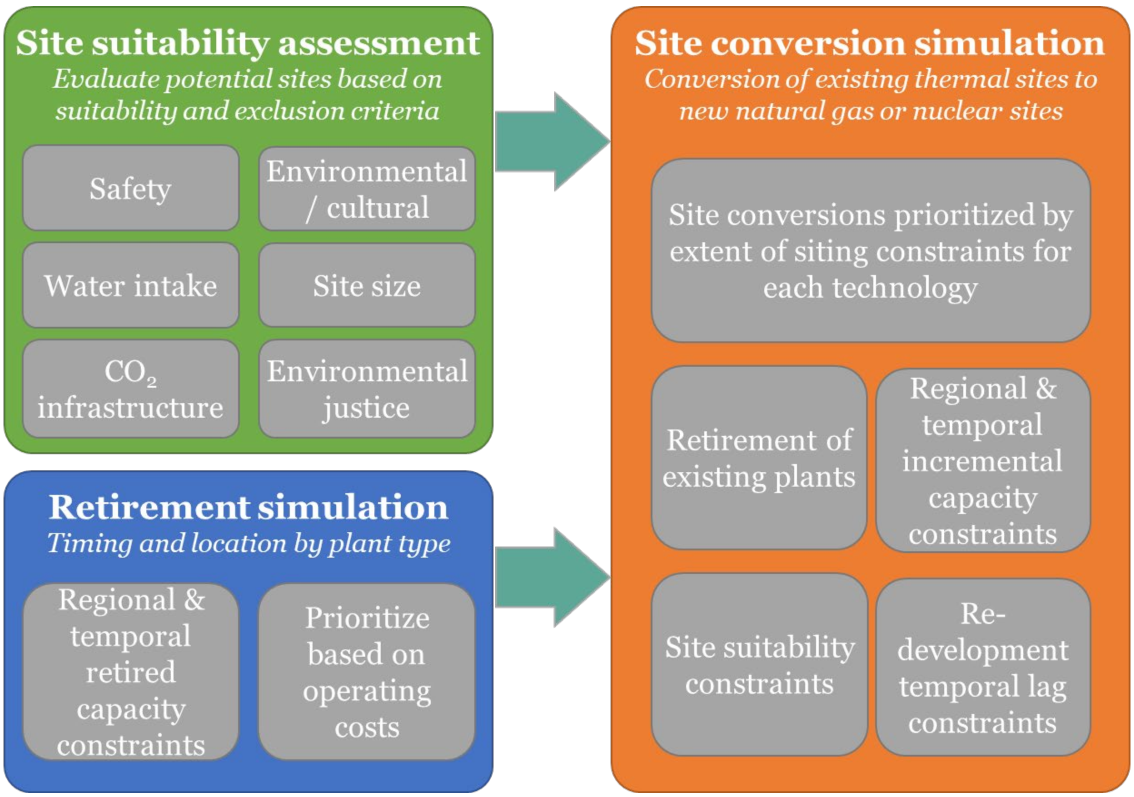

Figure 1. Conceptual model of thermal siting approach.

2 Retirement simulation of coal, natural gas, and nuclear facilities

Thermal generation plant retirements have been significant in recent years, driven by a myriad of market, policy, and plant-specific factors. From 2010 to 2020, coal, natural gas, and nuclear capacity retirements have amounted to 95 GW (28% of 2010 capacity), 56 GW (11% of 2010 capacity), and 8 GW (7% of 2010 capacity), respectively.[1] Empirical evidence shows that retired plants tend to be smaller, older, less efficient, and more polluting than operating plants.[2,3] The strongest predictors of retirements include SO_2 emissions rates for coal generators, planning reserve margins, variations in load growth or contraction, and vintage. The price spread between coal to gas and delivered natural gas prices are also weak predictors of retirement, and factors such as the penetration of renewable energy, recent non-renewable capacity additions, and whether a region hosts an ISO/RTO are not shown to be drivers. Future retirement decisions may be influenced by different factors than in the past, especially in the context of deep decarbonization.

2.1 Method

We simulate the timing, location, and ordering of coal, natural gas, and nuclear generator retirements. We use regional, technology-specific retirement capacity estimates over time from the RIO modeling as constraint sets or goals that align with the reference and net zero (NZ) scenarios. Operating costs are used as a heuristic for sequencing the retirement of coal generators, and vintage is used as a heuristic for natural gas and nuclear generators, although many factors will influence retirements. As an initialization step to align the starting RIO modeling capacity with the existing capacity of actual generators, we model the retirement of several generators in 2020. We then model generator closures over time to meet the regional retirement constraints. We treat generator closures as discrete, and given that the RIO modeling treats capacity as continuous, we assume that generator closures should come close to, but not exceed the regional retirement goals. We further assume planned closures reported by the US EIA and other public announcements will proceed as scheduled, unless there is additional need to retire generators earlier than their planned closure date to meet regional retirement goals.

2.2 Coal retirements

As shown in Figure 2, coal capacity is completely retired by 2030 across all NZ scenarios and retirements follow a similar declining trajectory across all regions. The rate of decline in the NZ scenarios (23 GW/yr), as depicted in Figure 3, is consistent with the peak historical rate of decline in 2015 (21 GW/yr). In the reference scenario, retirement rates are slightly higher than the 2019 AEO Reference case – which assumes that current laws and regulations that affect the energy sector are unchanged throughout the projection period – and much higher than the planned retirements as reported by the EIA and other public notices.[1,4]

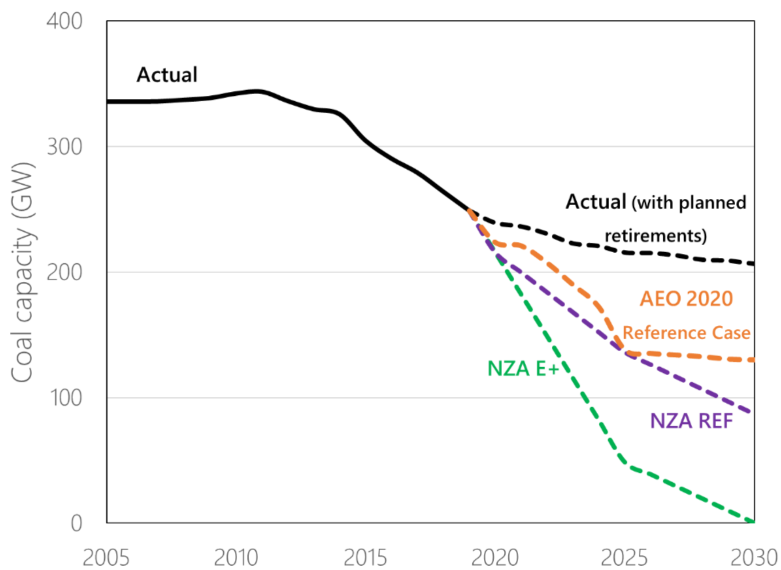

Figure 2. Actual and projected future coal capacity.

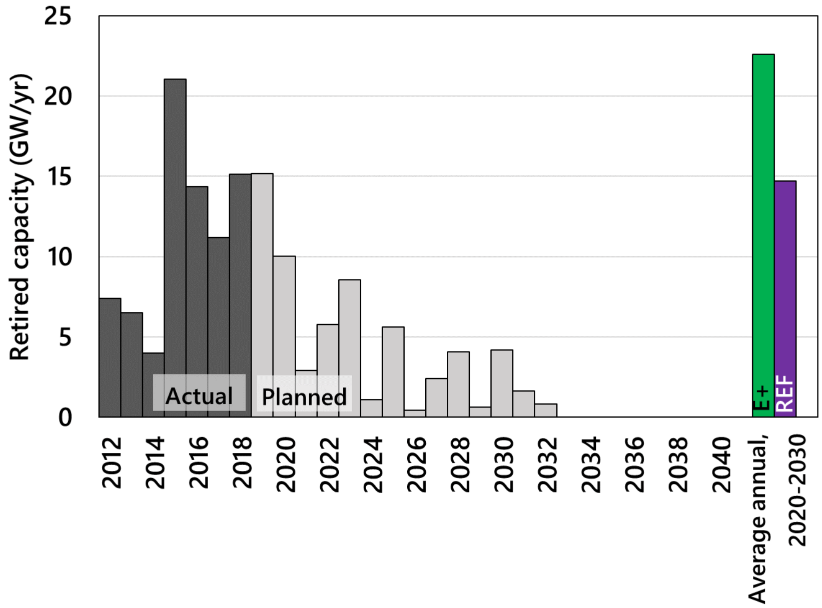

Figure 3. Actual and planned annual coal capacity retirements. Average annual coal capacity retirements from 2020 to 2030.

Figure 4a shows that approximately 500 coal plants and 700 generators, which are distributed across 45 states, retire by 2030 in the NZ scenarios. As depicted in Figure 4b, in some states, such as Texas, Kentucky, and North Carolina, most or all of the coal capacity retires within the first five years. As shown in Figure 5a, the coal fleet is aging with an average vintage of 1975 (as of 2020); this equates to an average age of 45 years old, with a range of 5 to 90 years old. Figure 5b shows age of retirement for each generator, with an average of 50 years old and a range from 10 to 100 years old. Less than 9% of the coal generation fleet (23 GW) will be forced to retire prior to reaching a vintage of 20 years. However, most generators (99%) will retire prior to their technical life of 75 years.

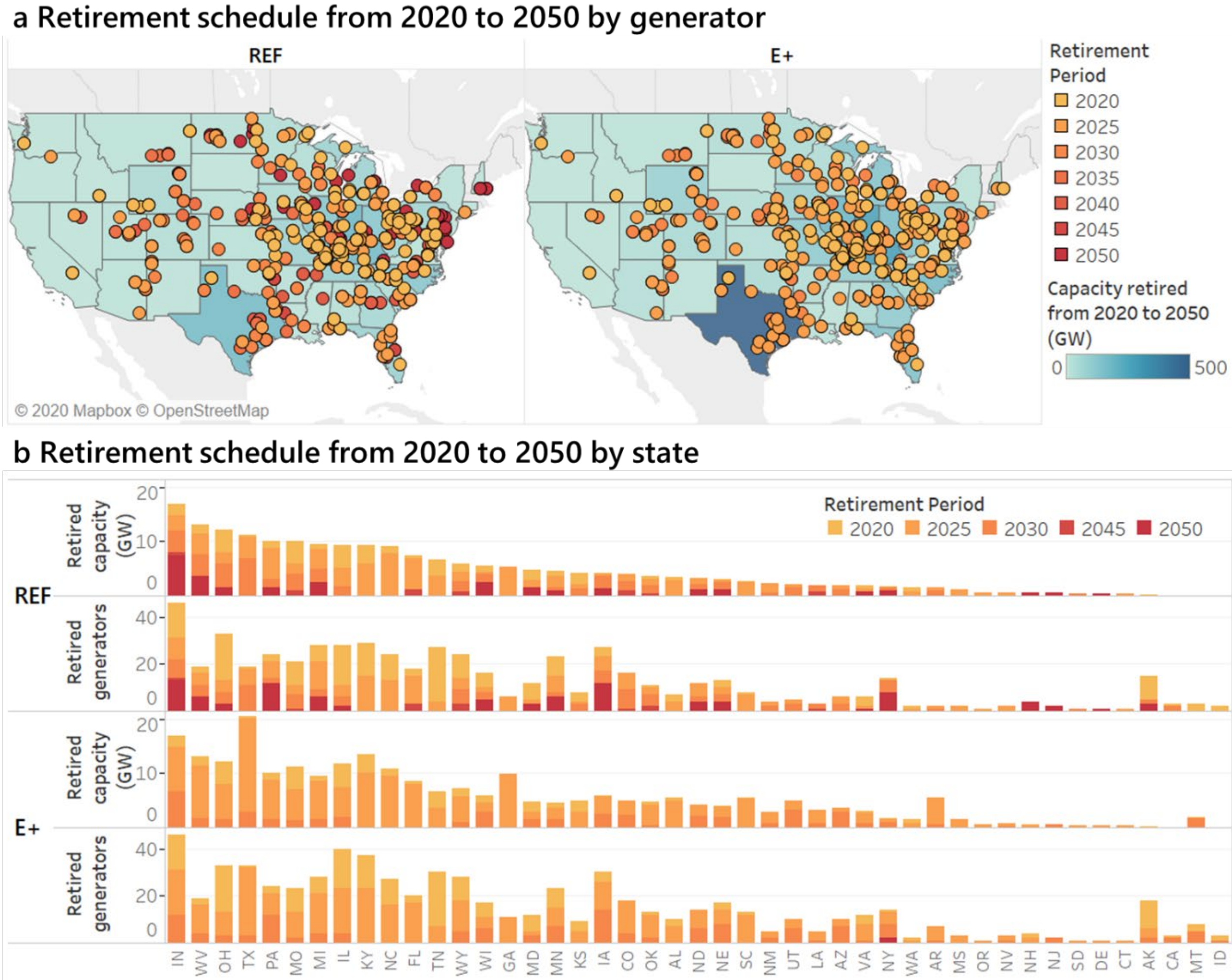

Figure 4. Retirement schedule for coal generators and states from 2020 to 2030.

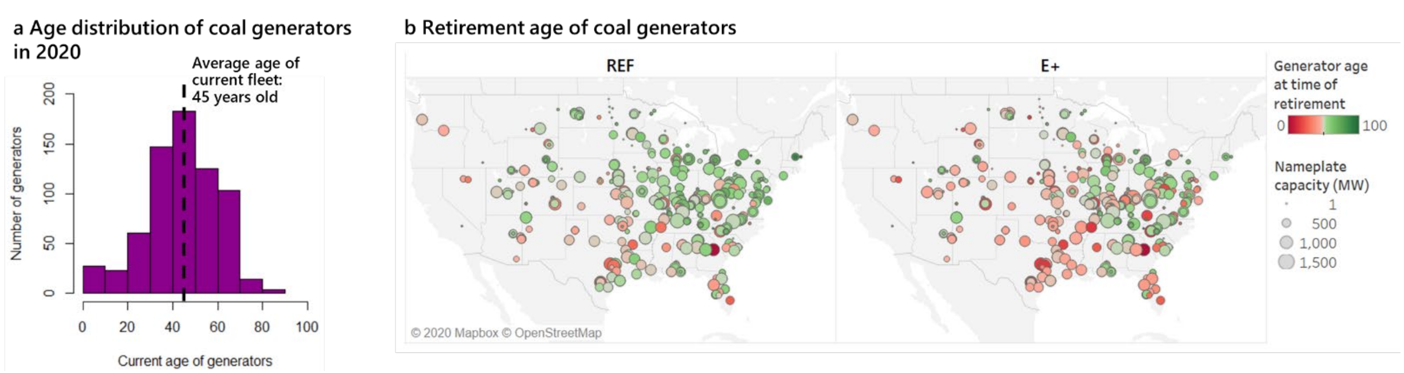

Figure 5. Age distribution of coal generators in 2020, and retirement age of coal generators. Note that E+ is equivalent to all net-zero scenarios with respect to coal retirements.

2.3 Nuclear retirements

Figure 6 and Figure 7 depict the retirement schedule for each nuclear reactor, state, and scenario. The most rapid retirement of nuclear capacity occurs in the E+RE+ scenario, in which 45 reactors (33 GW) are retired by 2030. In all other scenarios, retirements are more gradual with 25 reactors (24 GW) retired by 2030. By 2050, 110 reactors (105 GW) retire across all scenarios.

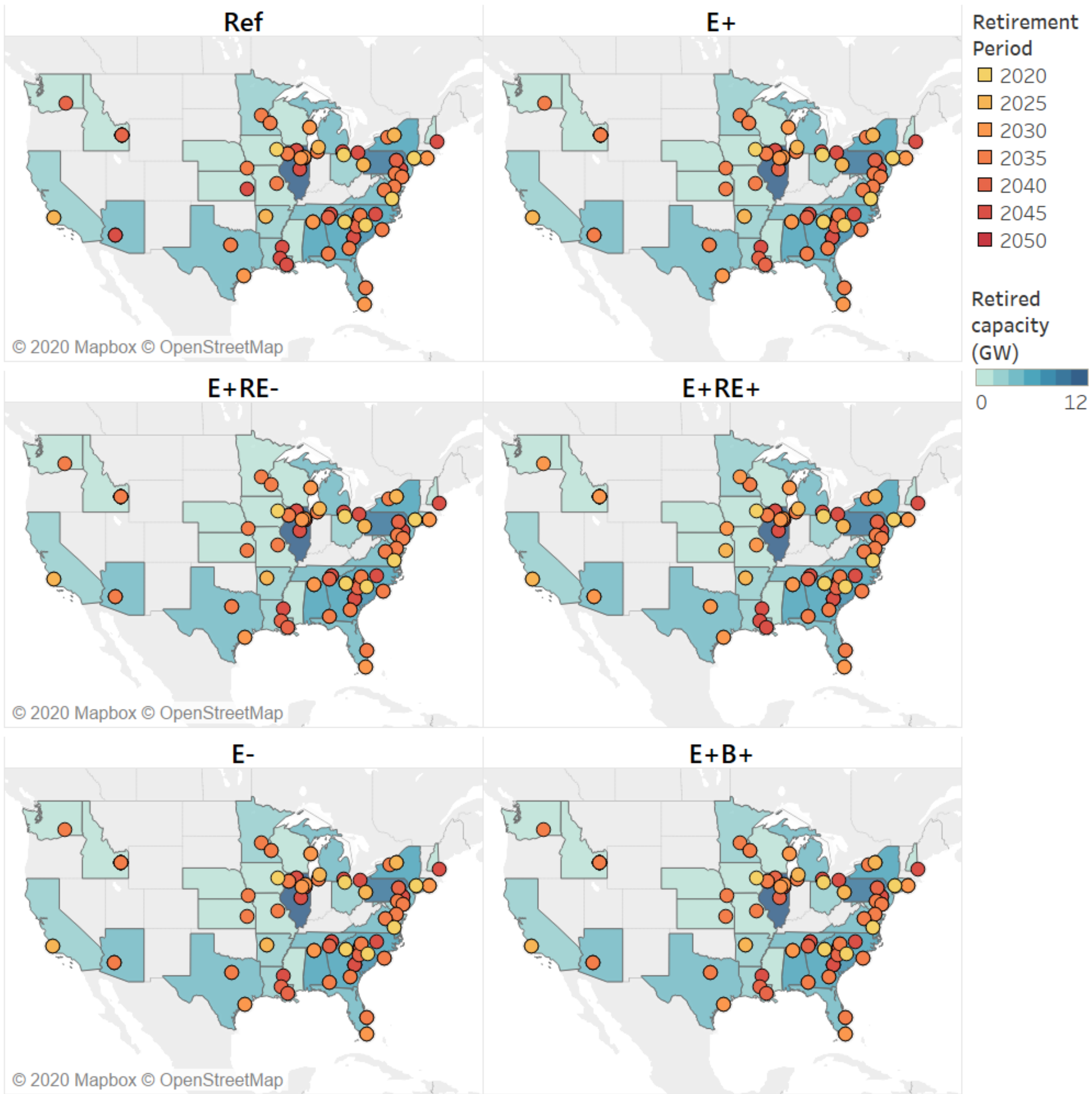

Figure 6. Retirement schedule for nuclear reactors from 2020 to 2050.

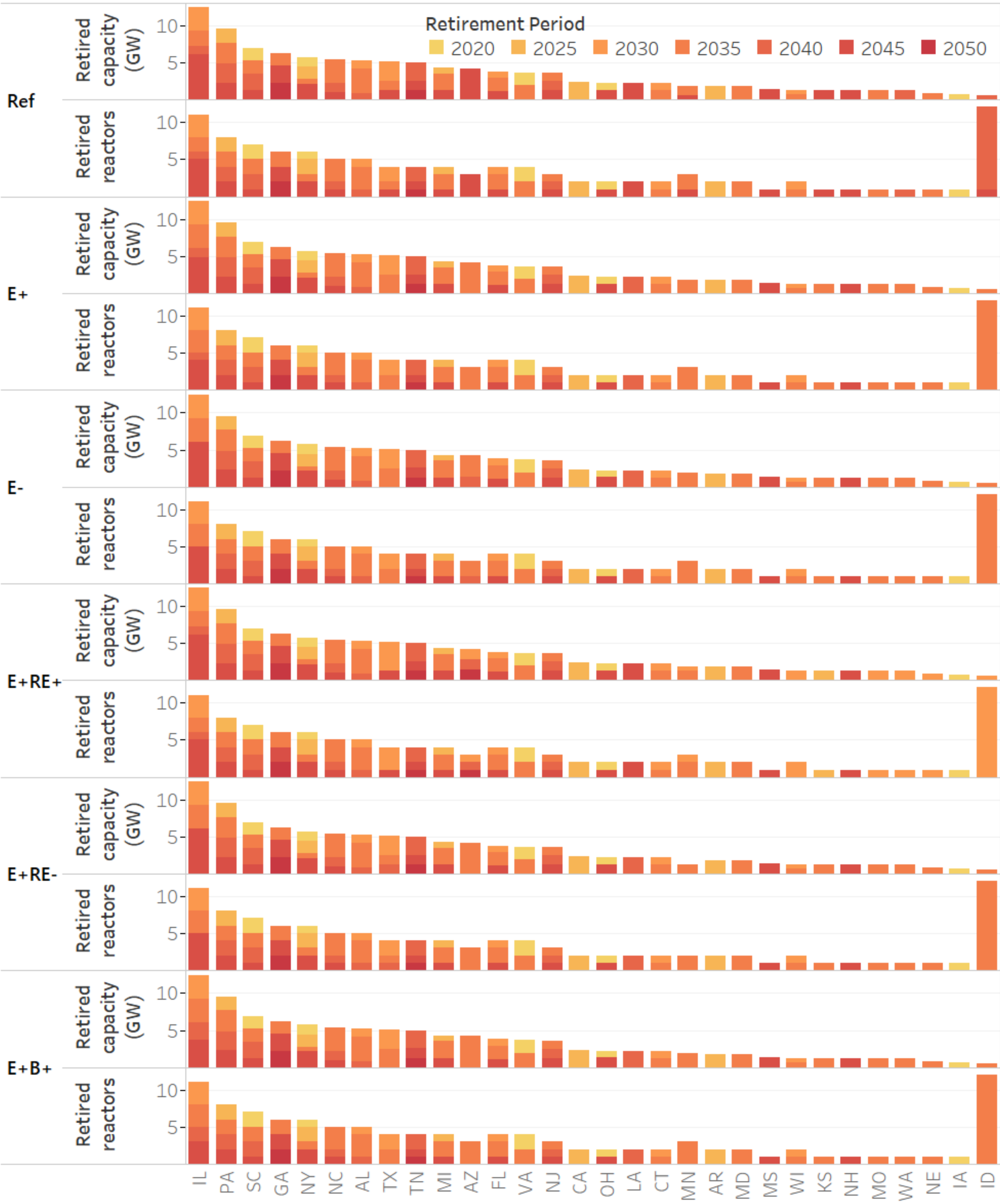

Figure 7. Retirement schedule for nuclear capacity by state.

2.4 Natural gas retirements

Figure 8 and Figure 9 depict the retirement schedule for each natural gas generator, state, and scenario. From 2020 to 2030, natural gas retirements vary considerably across NZ scenarios, with the highest rate observed for E+RE- scenario (224 GW, 3000 generators) and lowest rates observed for the E+RE+ scenario (175 GW, 2600 generators). By 2050, cumulative retirements are consistent across most NZ scenarios (450 GW, 5000 generators), except for the E+RE- scenario (506 GW, 5400 generators).

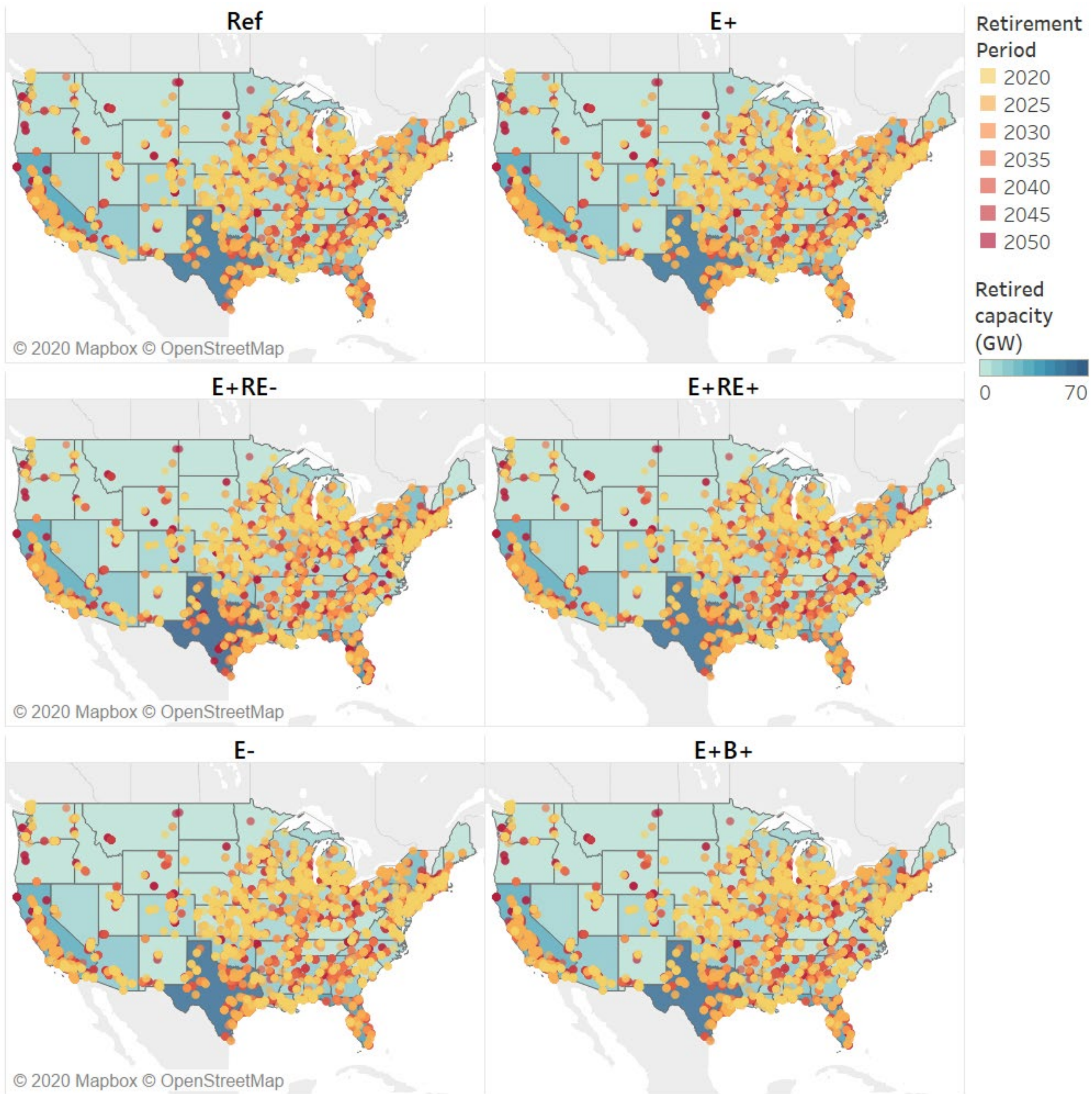

Figure 8. Retirement schedule for natural gas generators from 2020 to 2050.

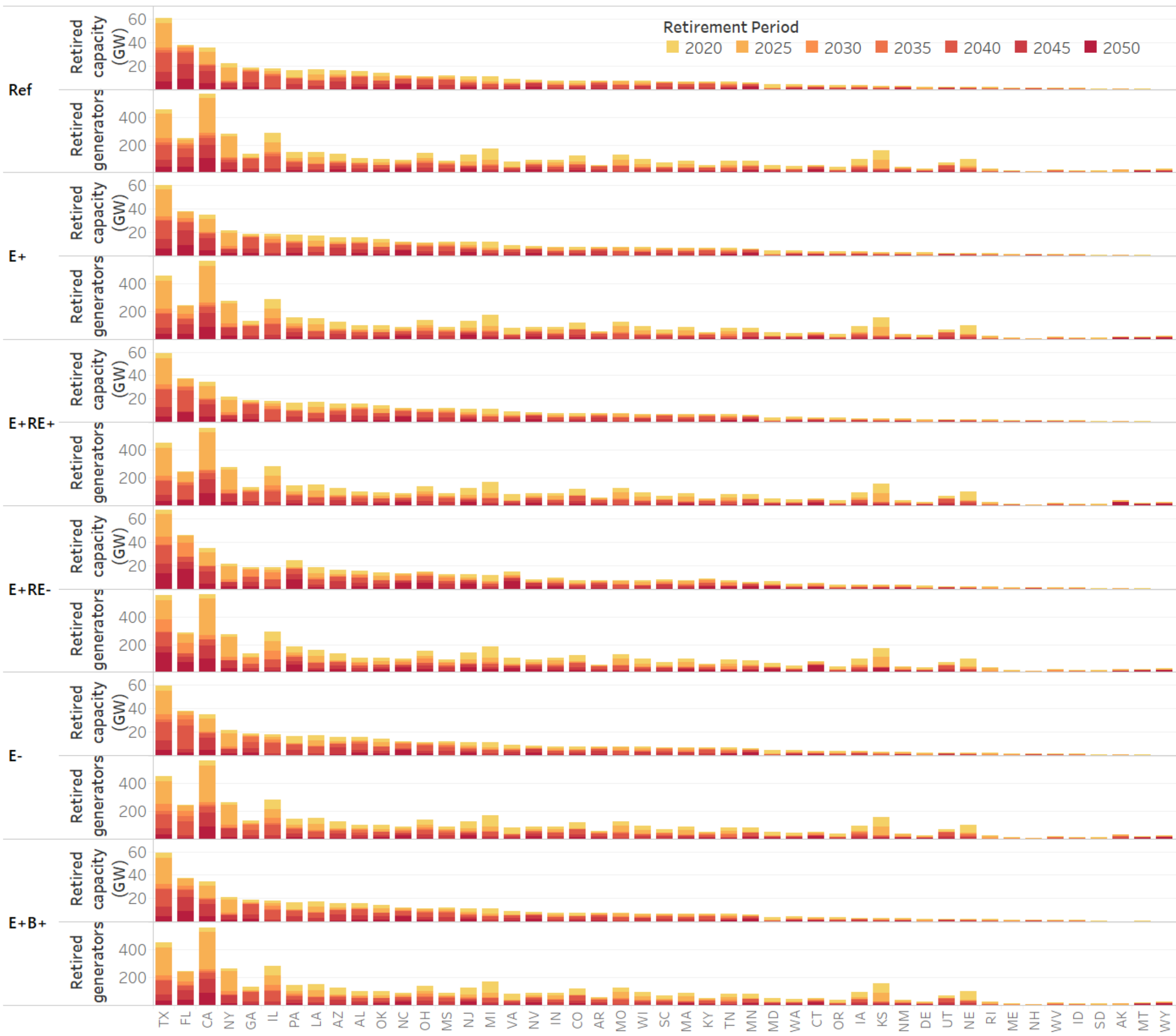

Figure 9. Retirement schedule for natural gas generators by state.

3 Siting new thermal generation capacity

Siting decisions are driven by multiple social, environmental, and technical factors. To assess the conversion potential of 8000+ existing or recently retired thermal generators (as of 2020), a multi-criteria site suitability assessment is performed, considering environmental, cultural, safety, thermal cooling, CO_2 infrastructure, and site size criteria. We model three different site suitability scenarios: 1) unconstrained, 2) moderately constrained (base scenario), and 3) conservatively constrained (conservative scenario) with respect to environmental, cultural, and safety land use criteria. These scenarios vary by power plant type, given differing siting restrictions. In all site suitability scenarios, we constrain the new capacity at each site based on the historical capacity and thermal cooling potential.

3.1 Environmental, cultural, and safety land use

We perform a geospatial analysis, overlaying generator coordinate locations with environmental, cultural, and safety land use shapefiles. Geospatial data are from the U.S. Energy Information Administration, Argonne National Laboratory, and U.S. Census Bureau.[5–7] The 35 environmental & cultural criteria and 12 safety criteria that are listed in and , respectively, are generally based on a Pacific Northwest Laboratory study, and are largely consistent with criteria assessed in the solar and wind siting analysis.[8] Figure 10 shows the environmental & cultural and safety exclusion zones, respectively, for the base and conservative land use scenarios. Figure 11, Figure 12, and Table 3 are results of the overlay analysis.

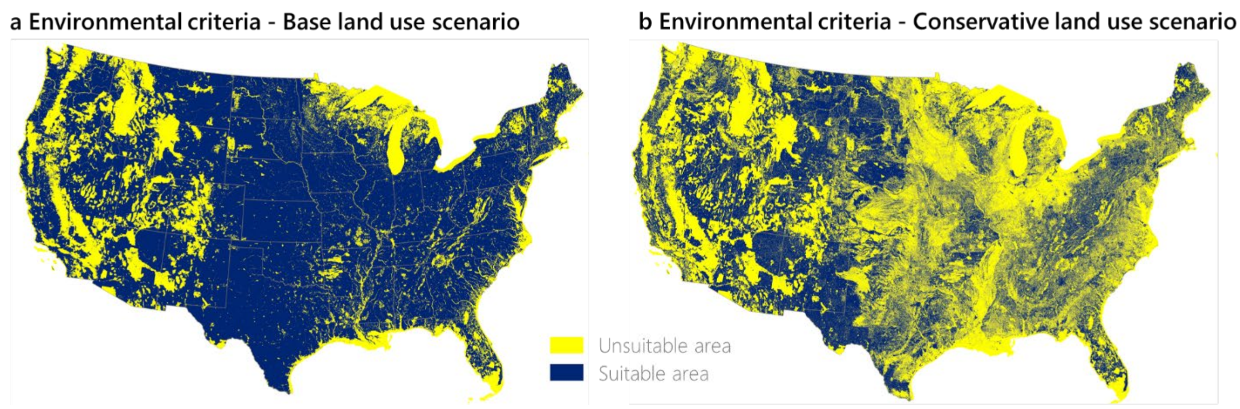

Figure 11. Maps of environmental & cultural criteria by land use scenario.

Table 1. Environmental criteria.

Criteria	Criteria Assumption
Area of Critical Environmental Concern	exclude
Conservation Easements	exclude
Fish and Wildlife Service Areas	exclude
Historic or Cultural Area	exclude
Inventoried Roadless Areas	exclude
Landscape Intactness	exclude where HMI<0.082
Local Conservation Area	exclude
Local Historic or Cultural Area	exclude
Mitigation Land or Bank	exclude
National Conservation Area	exclude
National Forest	exclude
National Historic or Scenic Trail	exclude
National Lakeshore or Seashore	exclude
National Park	exclude
National Recreation Area	exclude
National Scenic, Botanical, Volcanic Area	exclude
National Wildlife Refuge	exclude
Native American Land Area	exclude
Prime Farmland	exclude
Private Conservation	exclude
Private Forest Stewardship	exclude
Private Forest Stewardship Easement	exclude
Research Natural Area	exclude
Special Designation Area	exclude
State Conservation area	exclude
State Historic or Cultural Area	exclude
State Forests	exclude
State Park	exclude
State Wilderness	exclude
Water Bodies and Rivers	exclude
Watershed Protection Area	exclude +250m buffer
Wetlands	exclude
Wild and Scenic Rivers	exclude
Wilderness Area	exclude
Wilderness Study Area	exclude

Table 2. Safety criteria.

Criteria	Criteria Assumption
Active Mines	exclude +1000m buffer
Airports (3 mi buffer)	exclude major airports > 30,000 arrivals and departures per year w/ <3 mi buffer
Airports (10 mi buffer)	exclude major airports > 30,000 arrivals and departures per year w/ <10 mi buffer
Earthquake Risk	exclude >0.3g peak ground acceleration (2% probability in 50 years)
Flood Zones	exclude
Urban Areas	exclude areas with > 50,000 ppl/25 sq mi
Military Installation Areas	exclude +5000m buffer
Military Installation Points	exclude +5000m buffer
Population Density	exclude >500 ppl/sq mi w/ <20 mi buffer
Railways	exclude +250m buffer
Refineries	exclude
Slope	exclude >12% slope

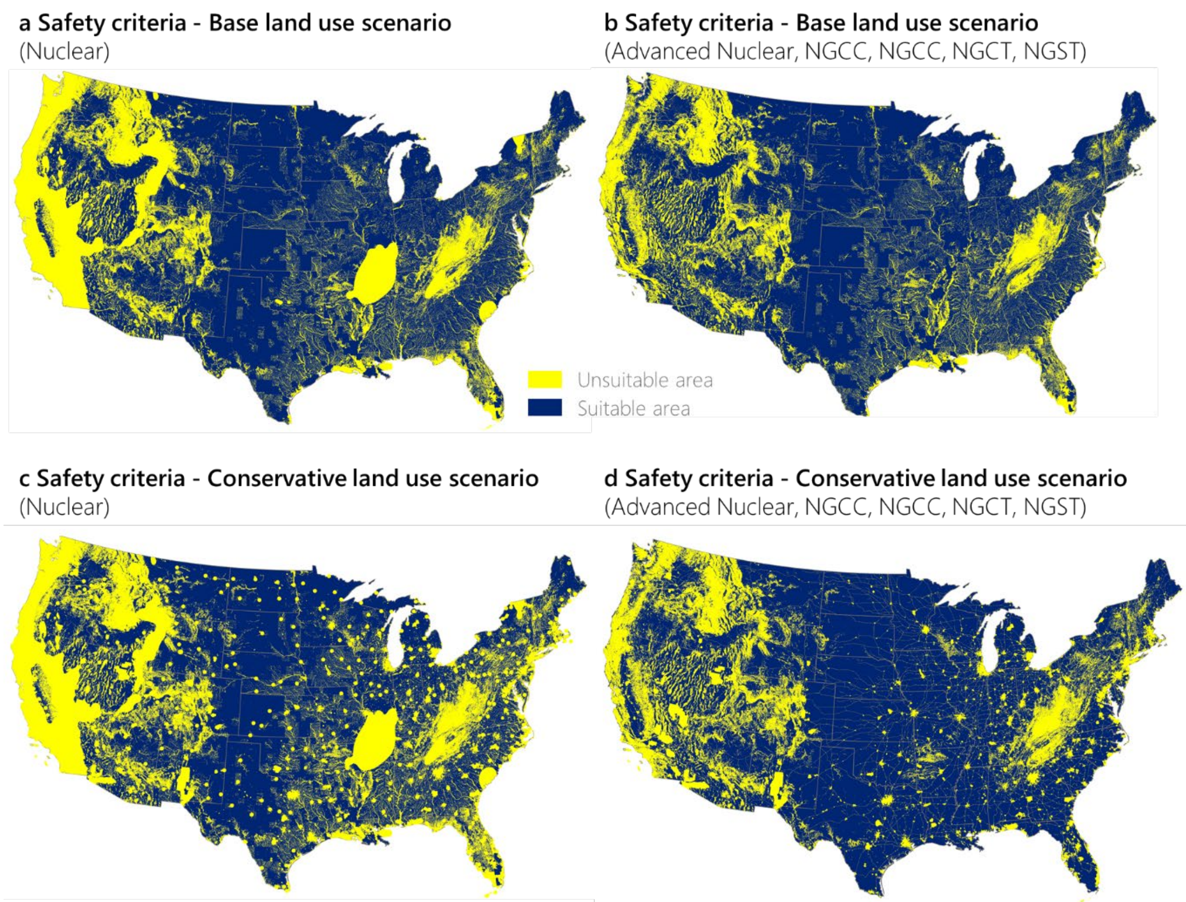

Figure 10. Maps of safety criteria by land use scenario and power plant technology.

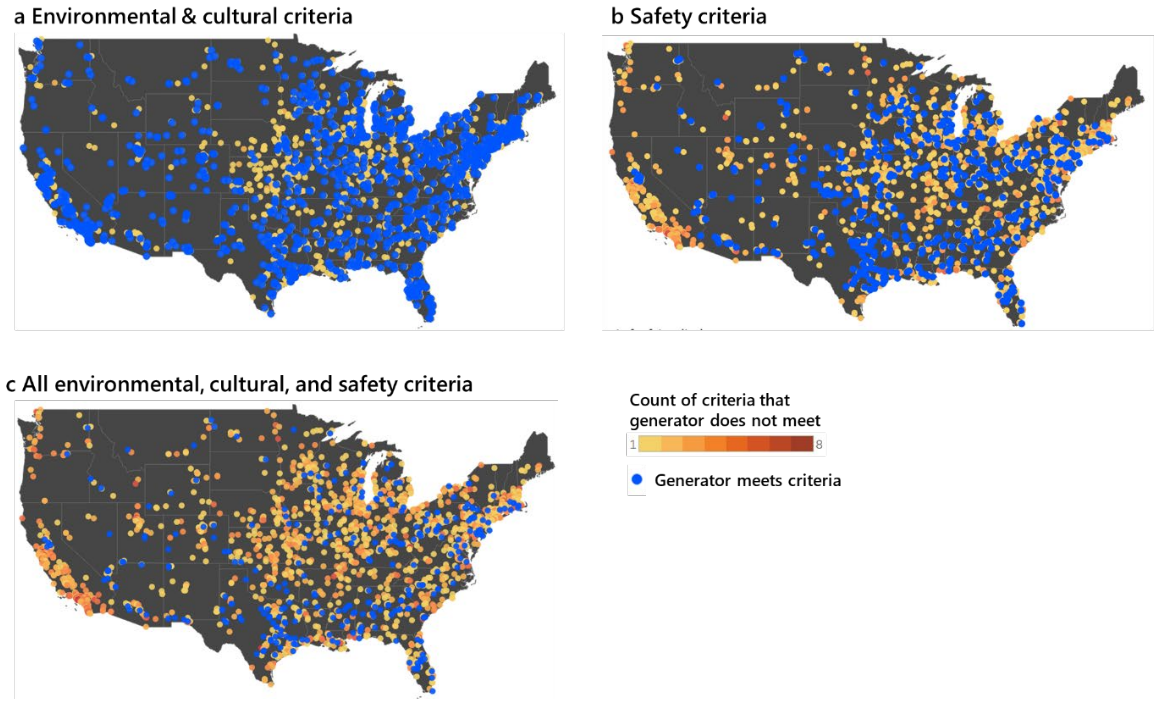

Figure 11. Map of generators indicating whether environmental, cultural, and/or safety criteria are met.

Table 3. Summary of generators meeting environmental, cultural, and/or safety criteria for different land use scenarios.

Technology	Nuclear				Advanced Nuclear			NGCC			NGCC CCS						NGCT	NGST		
Water Use (MGD)	500	600	700	800	200	300	400	0	100	200	0	100	200	300	400	500	0	0	100	200
Base																				
Total Sites	3,639	3,468	3,279	3,200	5,563	5,011	4,686	7,310	6,333	5,563	7,310	6,333	5,563	5,011	4,686	4,467	7,310	7,310	6,333	5,563
Total - Environmental	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357	7,357
Total - Safety	6,257	6,257	6,257	6,257	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002	8,002
Total - Water	4,988	4,750	4,499	4,395	6,149	5,576	5,228	8,061	6,995	6,149	8,061	6,995	6,149	5,576	5,228	4,988	8,061	8,061	6,995	6,149
Percentage of Sites	45%	43%	41%	40%	69%	62%	58%	91%	79%	69%	91%	79%	69%	62%	58%	55%	91%	91%	79%	69%
Percentage - Environmental	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%
Percentage - Safety	78%	78%	78%	78%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
Percentage - Water	62%	59%	56%	55%	76%	69%	65%	100%	87%	76%	100%	87%	76%	69%	65%	62%	100%	100%	87%	76%
Constrained																				
Total Sites	641	610	587	576	1,687	1,495	1,370	1,345	1,174	1,017	1,345	1,166	1,009	903	846	792	1,345	1,345	1,166	1,009
Total - Environmental	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050	5,050
Total - Safety	620	620	620	620	1,693	1,693	1,693	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345	1,345
Total - Water	4,988	4,750	4,499	4,395	6,149	5,576	5,228	8,061	6,995	6,149	8,061	6,995	6,149	5,576	5,228	4,988	8,061	8,061	6,995	6,149
Percentage of Sites	8%	8%	7%	7%	21%	19%	17%	17%	15%	13%	17%	14%	13%	11%	10%	10%	17%	17%	14%	13%
Percentage - Environmental	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%
Percentage - Safety	8%	8%	8%	8%	21%	21%	21%	17%	17%	17%	17%	17%	17%	17%	17%	17%	17%	17%	17%	17%
Percentage - Water	62%	59%	56%	55%	76%	69%	65%	100%	87%	76%	100%	87%	76%	69%	65%	62%	100%	100%	87%	76%

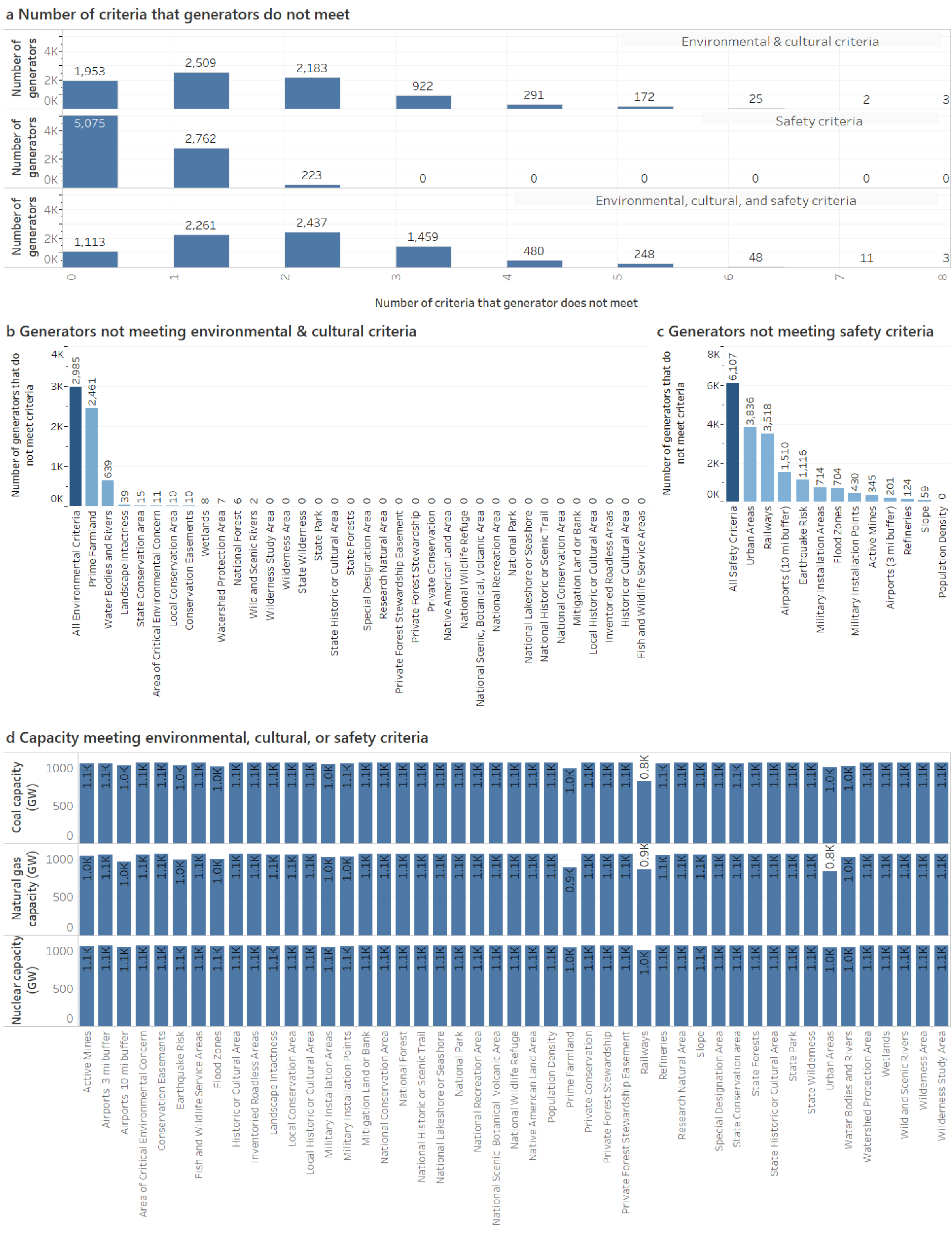

Figure 12. Number of generators not meeting or capacity meeting environmental, cultural, and/or safety criteria.

3.2 Thermal cooling

We assess the potential for new thermal power plants based on the availability of water for thermal cooling. However, we do not consider other limiting factors related to capacity expansion of such water access. We also acknowledge that adoption of dry cooling technologies could alleviate siting restrictions associated with availability of cooling water.

We assume that new capacity must be sited proximate to water sources for cooling, and that new plants employ once-through recirculating cooling technologies, consistent with federal regulations regarding water intake. Withdrawal rates by power plant technology are based on those reported in NREL (2019) and Macknick et al. (2012, 2015), as shown in Table 4.[9–11] We assume that power plant intake flows must be less than or equal to 5% of the mean annual flow rate of the water source in which it withdrawals from in compliance with Clean Water Act regulations.[8] We estimate the maximum power plant capacity associated with different flow rates of proximate water sources ranging from 100 to 1000 million gallons per day (MGD) in increments of 100 MGD, as shown in Table 5.

For each existing thermal site, we perform a geospatial screening analysis to determine the maximum site capacity, given constraints related to the proximity and magnitude of cooling capacity. Using the National Hydrography Dataset (shown in Figure 13), we bin water bodies into to ten flow rate classes, as specified above.[12] We then apply a 20 km buffer to the point locations of power plants and intersect the flow rate class layers to determine the flow rate of proximate water bodies. From there, we can estimate the potential power plant intake flowrates rate and corresponding maximum power plant capacity for each site given thermal cooling constraints. Figure 14 shows the number of generators (out of 8000+ generators) proximate to a water body with a minimum mean annual flow rate.

Table 4. Water withdrawal requirements for difference power plant types.

Technology	Cooling Technology	Withdrawals [gal/MWh]
nuclear	Recirculating	1101
advanced nuclear	Recirculating	1101
gas combined cycle cogen power plant	Recirculating	255
gas combined cycle ipp cogen power plant	Recirculating	255
gas combined cycle power plant	Recirculating	255
gas combined cycle power plant with ccu	Recirculating	506
gas combined cycle ccu oxyfuel	Recirculating	506
gas combustion turbine cogen power plant	NA	0
gas combustion turbine ipp cogen power plant	NA	0
gas combustion turbine power plant	NA	0
gas steam turbine cogen power plant	Recirculating	1203
gas steam turbine ipp cogen power plant	Recirculating	1203
gas steam turbine power plant	Recirculating	1203

Table 5. Maximum generation capacity by technology and flow rate.

Technology	Cooling Technology	Maximum Capacity (MW)										
	Flow Rate (MGD)	0	100	200	300	400	500	600	700	800	900	1000
nuclear	Recirculating	0	189	378	568	757	946	1135	1325	1514	1703	1892
advanced nuclear	Recirculating	0	189	378	568	757	946	1135	1325	1514	1703	1892
gas combined cycle cogen power plant	Recirculating	0	817	1634	2451	3268	4085	4902	5719	6536	7353	8170
gas combined cycle ipp cogen power plant	Recirculating	0	817	1634	2451	3268	4085	4902	5719	6536	7353	8170
gas combined cycle power plant	Recirculating	0	817	1634	2451	3268	4085	4902	5719	6536	7353	8170
gas combined cycle power plant with ccu	Recirculating	0	412	823	1235	1647	2059	2470	2882	3294	3706	4117
gas combined cycle ccu oxyfuel	Recirculating	0	412	823	1235	1647	2059	2470	2882	3294	3706	4117
gas steam turbine cogen power plant	Recirculating	0	173	346	520	693	866	1039	1212	1385	1559	1732
gas steam turbine ipp cogen power plant	Recirculating	0	173	346	520	693	866	1039	1212	1385	1559	1732
gas steam turbine power plant	Recirculating	0	173	346	520	693	866	1039	1212	1385	1559	1732

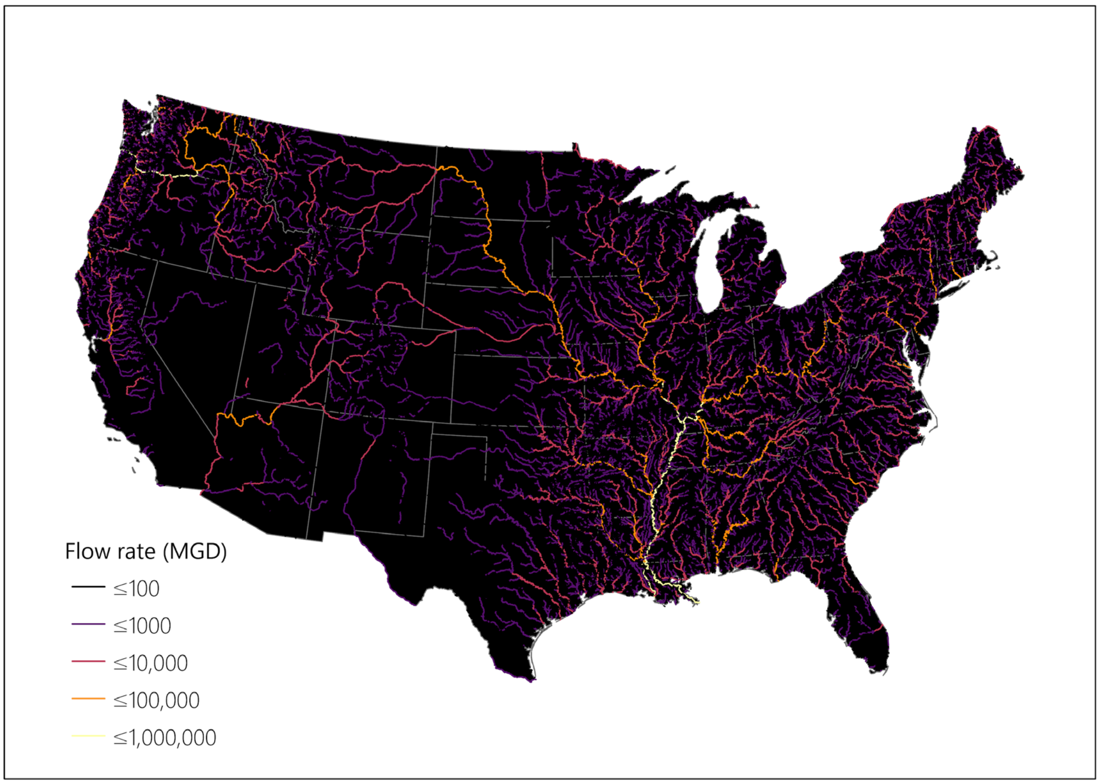

Figure 13. Map of flow rate by water body.

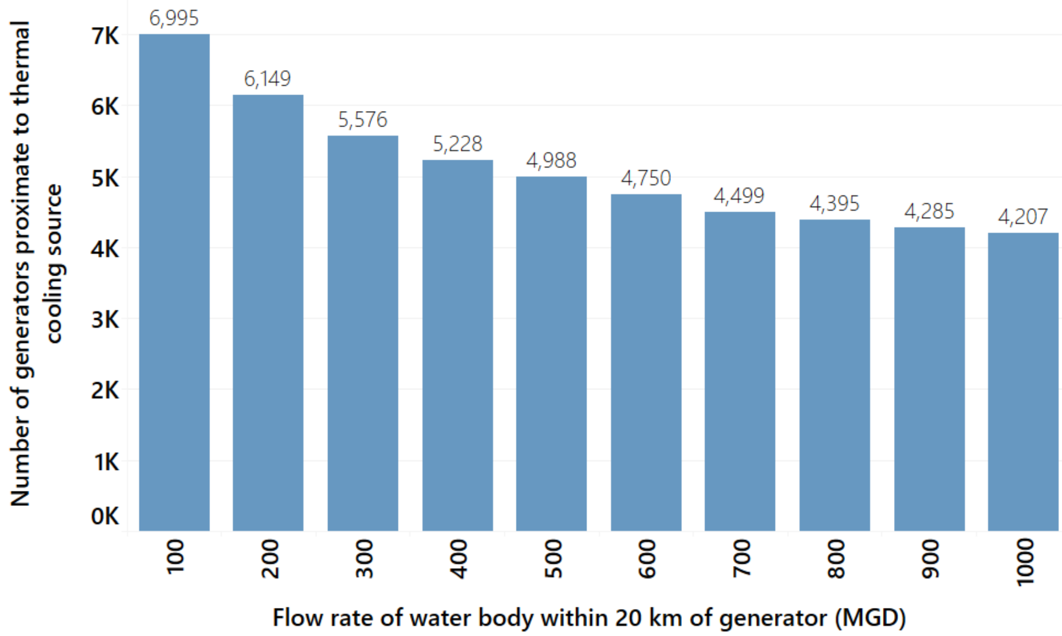

Figure 14. Number of generators within 20 km of a water source with a given flow rate.

3.3 CO_2 infrastructure

We assess the proximity of thermal sites to CO_2 basins and transmission pipeline infrastructure, which partially dictates the conversion potential of existing sites to natural gas combined cycle plant sites (as described in Section 4). Figure 15 shows the location of existing thermal sites relative to CO_2 basins and future CO_2 pipeline infrastructure. The conceptual pipeline infrastructure system (as described in Appendix I) was developed through an iterative process assessing the locations of thermal, industry and bioconversion infrastructure and is based on the E+ scenario, but readily adapts to other scenarios utilizing CCS. For the thermal siting analysis, we use this conceptual design to assess the proximity of sites, which is appropriate for most NZ scenarios, but may not represent an optimal or suitable design for the E+RE- where there is a relatively large buildout of NGCC CCS.

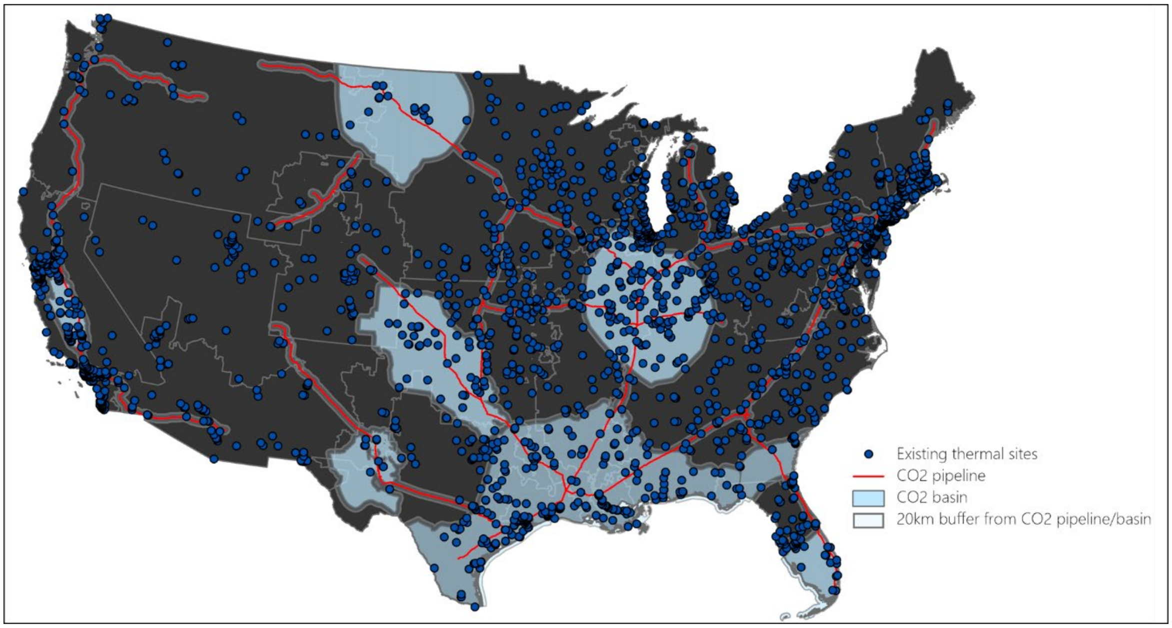

Figure 15. CO_2 basins and future pipeline infrastructure as well as location of existing thermal sites.

3.4 Site size

We assess the maximum capacity of each site. We assume that an individual site cannot be in excess of a given maximum capacity, based on historical levels and future technologies, as shown in Table 6. We further constrain the site size based on thermal constraints. We assume a 1:1 land use conversion ratio across all thermal facilities; while there are differences in the footprint size for each technology and plant size, we assume that they are trivial and obscured by site-level variation in property size.

Table 6. Maximum plant capacity for difference power plant types.

Technology	Maximum Capacity [MW]
nuclear	2000
advanced nuclear	1980
gas combined cycle cogen power plant	3000
gas combined cycle ipp cogen power plant	3000
gas combined cycle power plant	3000
gas combined cycle ccu oxyfuel	3000
gas combined cycle power plant with ccu	3000
gas combustion turbine cogen power plant	4000
gas combustion turbine ipp cogen power plant	4000
gas combustion turbine power plant	4000
gas steam turbine cogen power plant	300
gas steam turbine ipp cogen power plant	300
gas steam turbine power plant	300

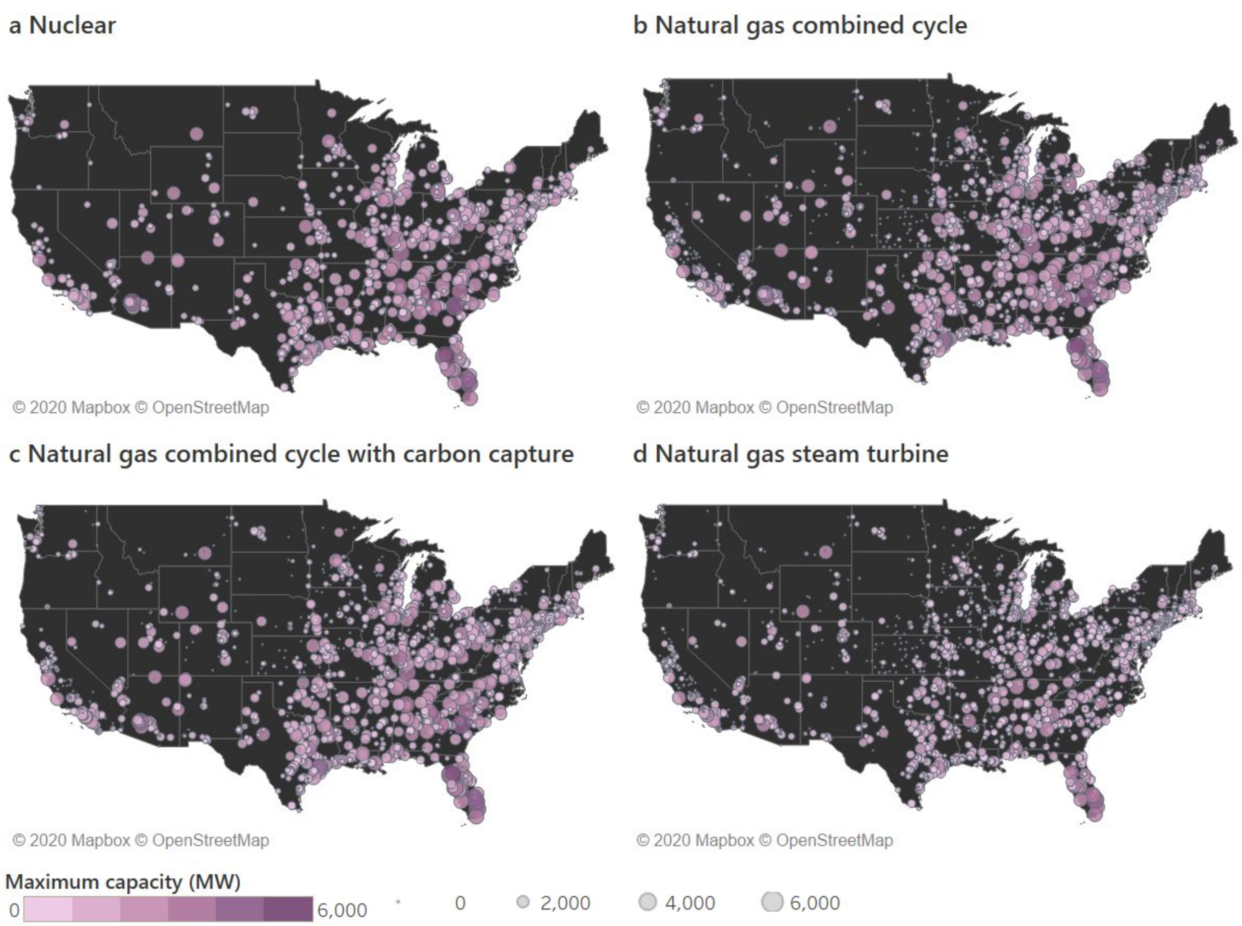

Figure 16. Maximum capacity by site and power plant type.

4 Thermal capacity additions

Thermal capacity, including gas combined cycle, combustion turbines, and new advanced nuclear plants, expands in all Net-Zero America (NZA) scenarios, although there is a large degree of variation. Annual thermal capacity additions based on RIO modeling are shown in Figure 17. New combined cycle and combustion turbine capacity alternatively burns natural gas and synthetic gas, depending on the scenario and year of the transition.

Natural gas-fired and advanced nuclear capacity is added in all scenarios except E+RE+. The most new capacity is added in E+RE- with 465 GW of natural gas combined cycle capacity (approximately half of which has CO_2 capture), 122 GW of combustion turbines, and 265 GW of nuclear by mid-Century. The E+RE+ scenario deploys 490 GW of new combustion turbines which are fired with zero-carbon synthetic gas.

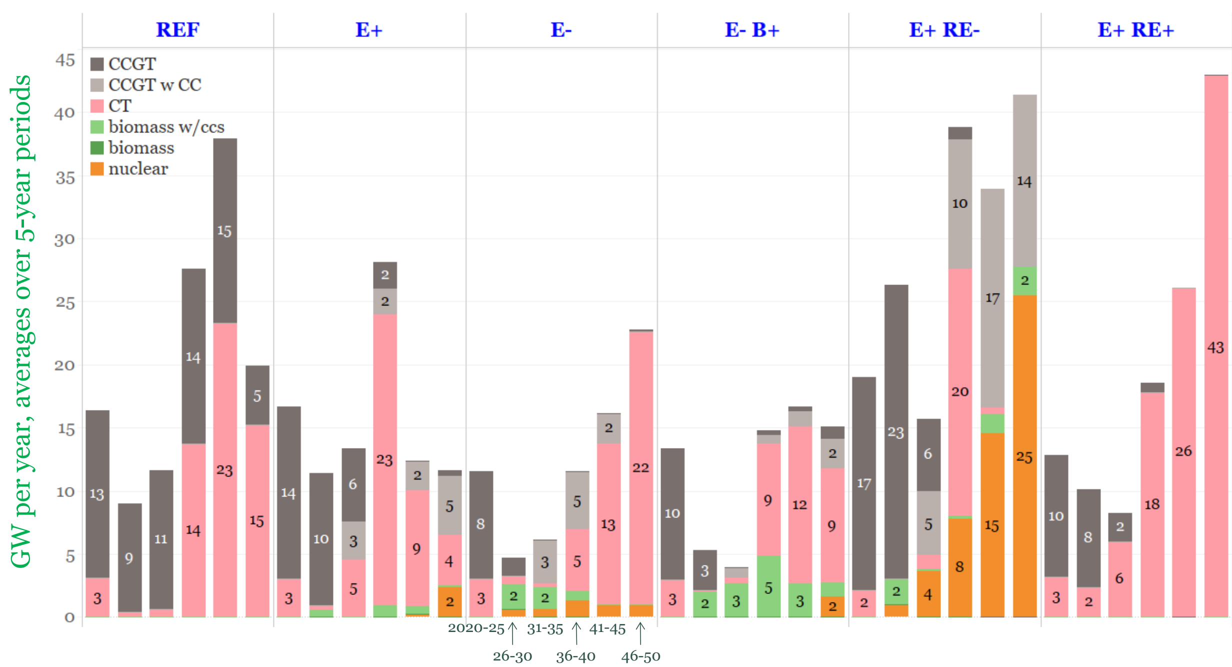

Figure 17. Annual rates of new thermal power plant capacity additions for each scenario.

5 Site conversion simulation

We develop a site conversion algorithm, which selects the timing, location, and magnitude of new natural gas and nuclear capacity on existing or recently closed thermal sites. We use regional, technology-specific capacity estimates over time from the RIO modeling as capacity expansion constraint sets, which align with the reference and net zero scenarios. The conversion algorithm also incorporates the previously described multi-criteria site suitability analysis and retirement simulation. We also assume that there is a five-year lag between when a site is closed and when it has the potential to be converted and operational. As depicted in Table 7, we further assume a conversion ordering, which prioritizes the conversion of existing sites to similar sites (e.g., existing nuclear to advanced nuclear) and the conversion of existing sites that are proximate to future CO_2 transmission and injection sites to natural gas combustion with carbon capture technology. Figure 18 to Figure 23 present results from the conversion modeling.

Table 7. Site conversion prioritization.

Site conversion prioritization
Step 1a: Existing Nuclear → Advanced Nuclear Step 1b: Existing Coal → Advanced Nuclear
Step 2a: Existing Natural Gas → NGCC-CCS (prioritized based on distance to CO_2 infrastructure) Step 2b: Existing Coal → NGCC-CCS (prioritized based on distance to CO_2 infrastructure) Step 2c: Existing Nuclear → NGCC-CCS (prioritized based on distance to CO_2 infrastructure)
Step 3a: Existing Natural Gas → NGCC Step 3b: Existing Coal → NGCC Step 3c: Existing Nuclear → NGCC
Step 4a: Existing Natural Gas → NGCT Step 4b: Existing Coal → NGCT Step 4c: Existing Coal → NGCT

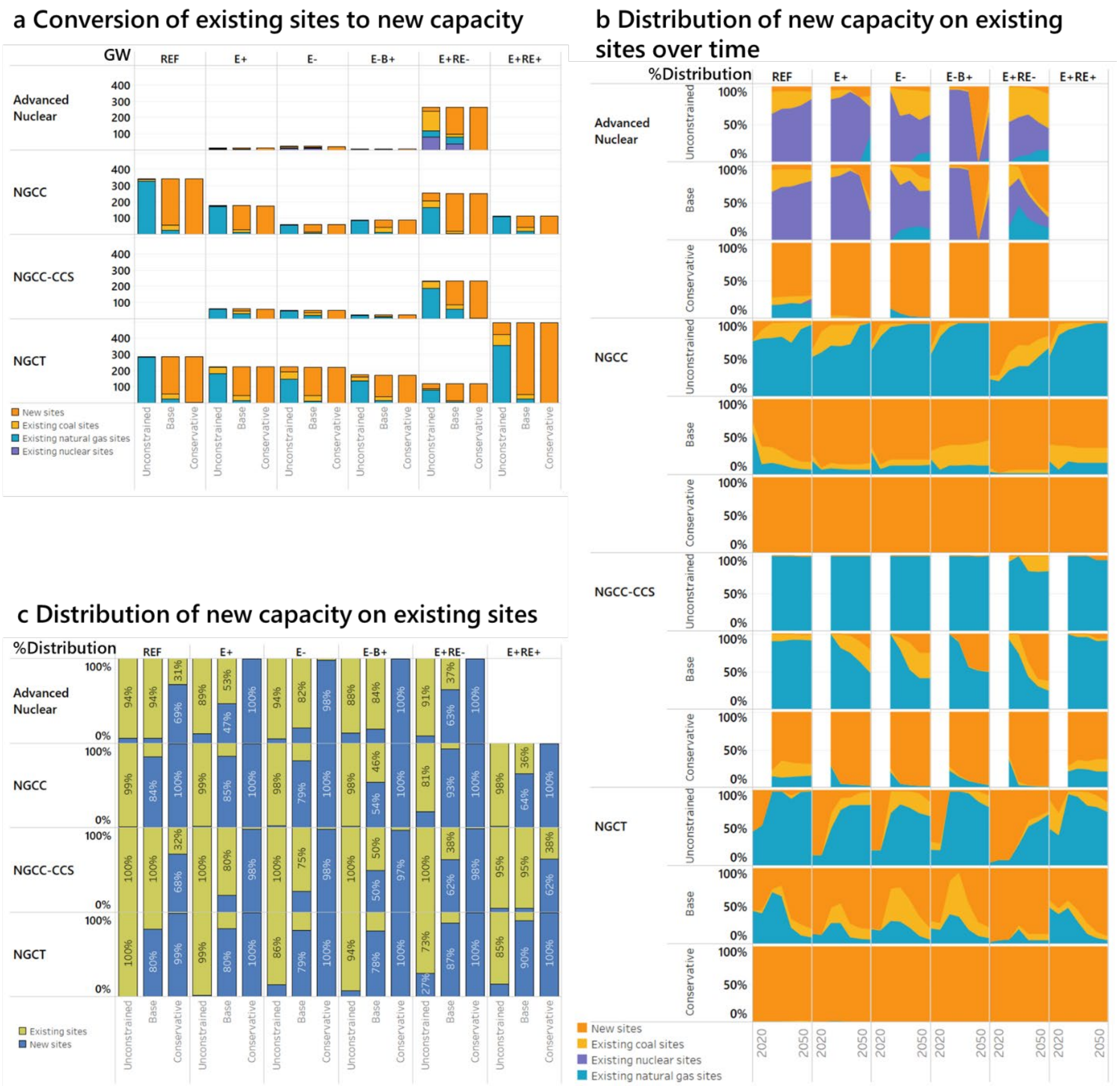

Figure 18. Conversion of existing capacity.

Figure 19. Conversion of existing site by capacity and region.

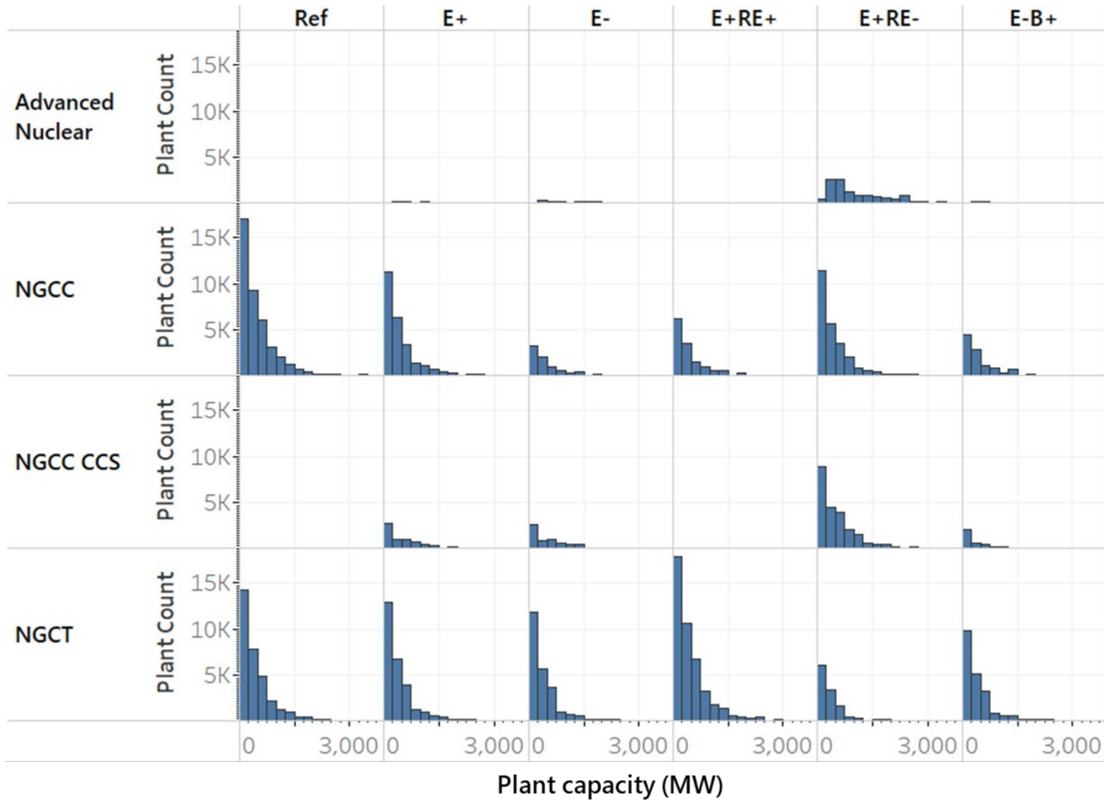

Figure 20. Size distribution of capacity on existing sites.

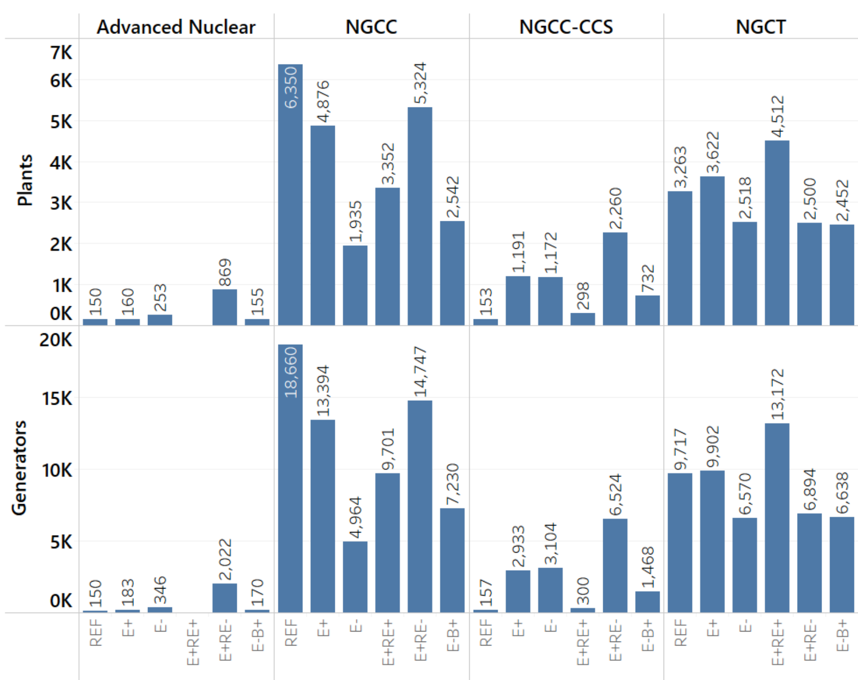

Figure 21. Number of plants and generators on converted sites.

Figure 22. Maps of conversion of existing sites.

Figure 23. Maps of conversion and retirement of existing sites over time.

6 References

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