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Supplementary information

Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide

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Supplementary Information for

Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide

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Supplementary Note 1. Sensitivity analysis

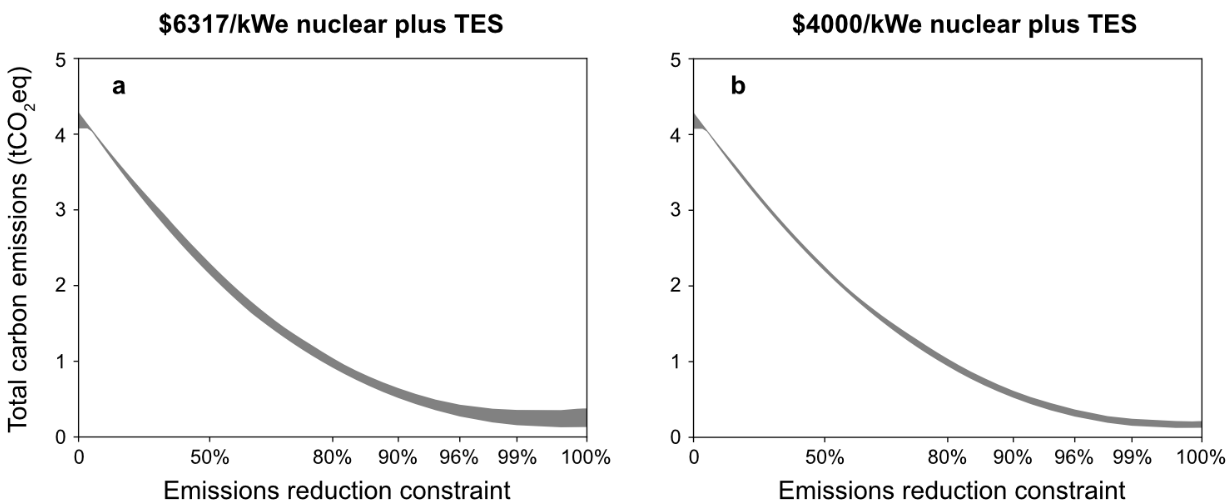
Cost assumptions. In additional to our central cases, which consider nuclear capital cost using the near-current EIA estimates (i.e., $6317/kWe) and $4000/kWe cost levels, we explore additional cost assumptions here. We first conduct simulations, in which nuclear capital cost is specified at $2000/kWe to represent more ambitious cost reduction potential. Compared to $6317/kWe and $4000/kWe nuclear plus TES, reducing the capital costs to $2000/kWe enables nuclear to compete with solar and wind in substantially lower required emission reduction scenarios for data from all 42 regions -- and substantially reduce the use of wind (Supplementary Fig. 21).

In contrast to the $2000/kWe nuclear plus TES case, we also conduct simulations, in which costs of different generation technologies (excluding nuclear) and battery are calculated based on the year-2050 projections from the NREL 2021 Annual Technology Baseline (ATB) report. Compared to EIA cost estimates, the derived fixed cost for solar, wind, and battery are ~ 47%, 32%, and 31% lower, respectively. Our results (Supplementary Fig. 22) show that the $4000/kWe nuclear plus TES remains competitive under deeply decarbonized scenarios in many regions. Innovations and efforts that substantially bring down costs of renewables and storage would further increase the competitiveness of renewables.

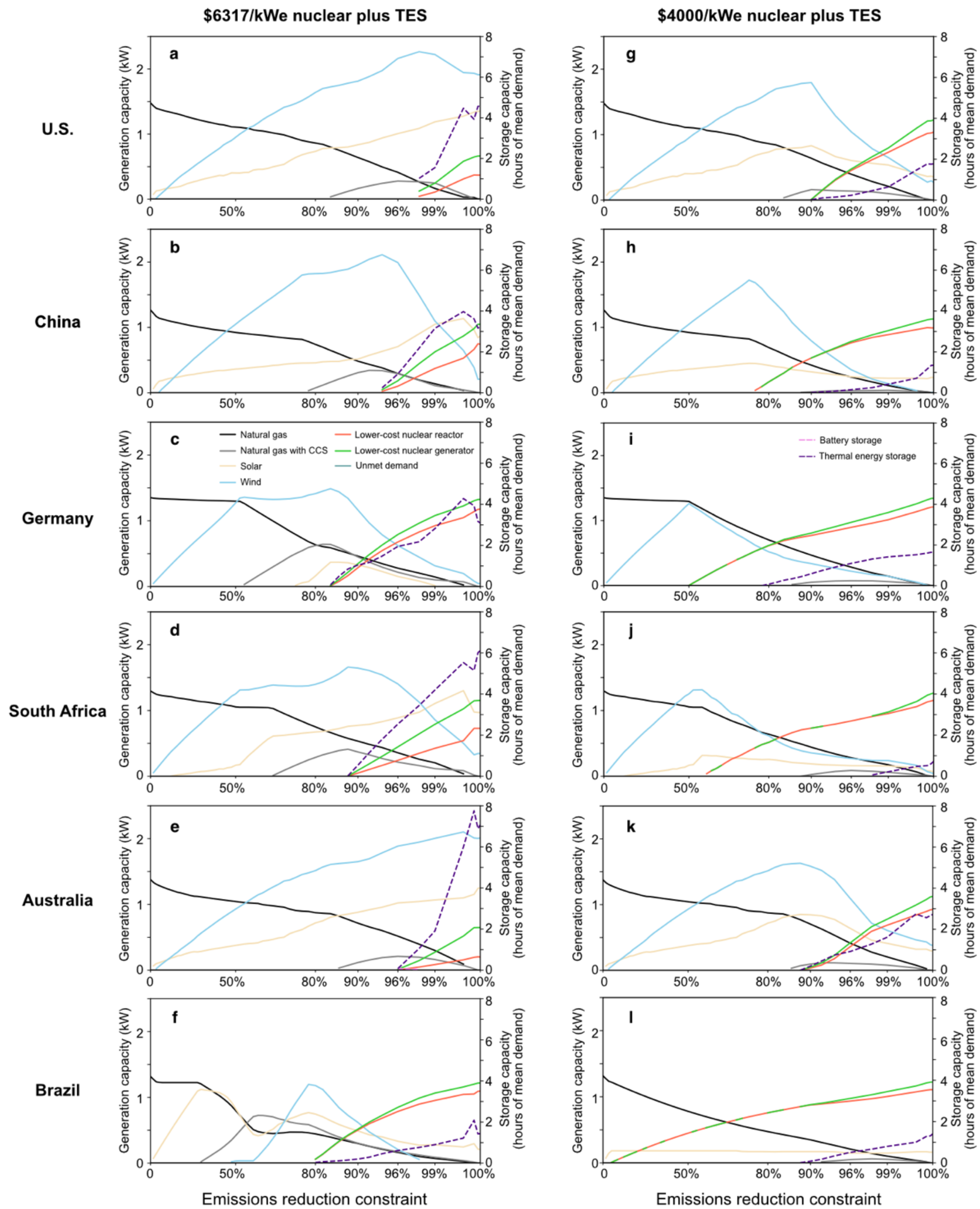
Baseload mode vs. flexible operation. Nuclear technologies considered in our model are flexible, including changing power output over time. Nuclear power plants are commonly operated in a "baseload" mode or have substantially reduced output flexibility. We therefore considered additional cases, in which only electricity generated from solar and wind can be curtailed and nuclear reactor power system component is running at constant output. Our results for six selected countries (Supplementary Figs. 23 and 24) show that including a relatively cheaper thermal energy storage capability can buffer additional electricity generation from nuclear reactor heat sources. As a result, nuclear-with-TES system under both cost assumptions remains as the cost-preferred generation technology-at-the-margin in a substantial range of deeply decarbonized scenarios.

Resistance heater. In addition to our central cases, thermal energy storage could also potentially make use of a resistance heater used to convert free electricity that would otherwise be curtailed into heat that can be stored. Our central cases do not allow conversions from electricity to heat, and we tested this feature by including an effectively free resistance heater with a 100% conversion efficiency (a very small fixed-cost was applied for numerical reasons). For data from six countries used in this analysis, at $4000/kWe nuclear cost, the resistance heating is deployed only within a very narrow range of conditions (Supplementary Fig. 25). This is because the use of resistance heater (even for free) requires overbuilds of solar and wind capacities to provide substantial free electricity to be stored in heat storage, which increases system cost compared to using nuclear-with-TES.

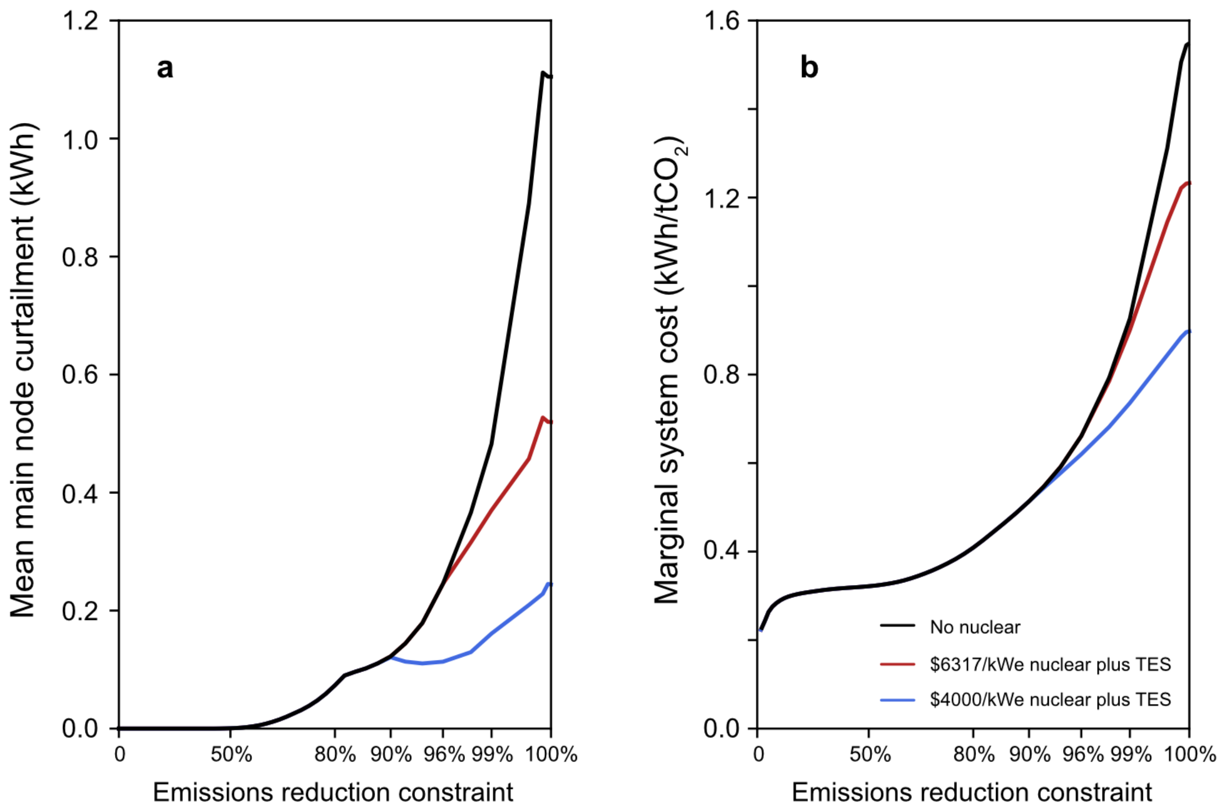
Supplementary Figure 1. Changes in total lifecycle carbon emissions. Results are shown for lifecycle carbon emissions from all generation technologies, during which emissions from natural gas and natural gas with carbon capture and storage (CCS) are gradually removed from the system. Systems with nuclear capital costs at (**a**) near-current EIA level ($6317/kWe) and (**b**) $4000/kWe are compared. Carbon emission assumptions associated with different technologies are based on the fifth IPCC report.



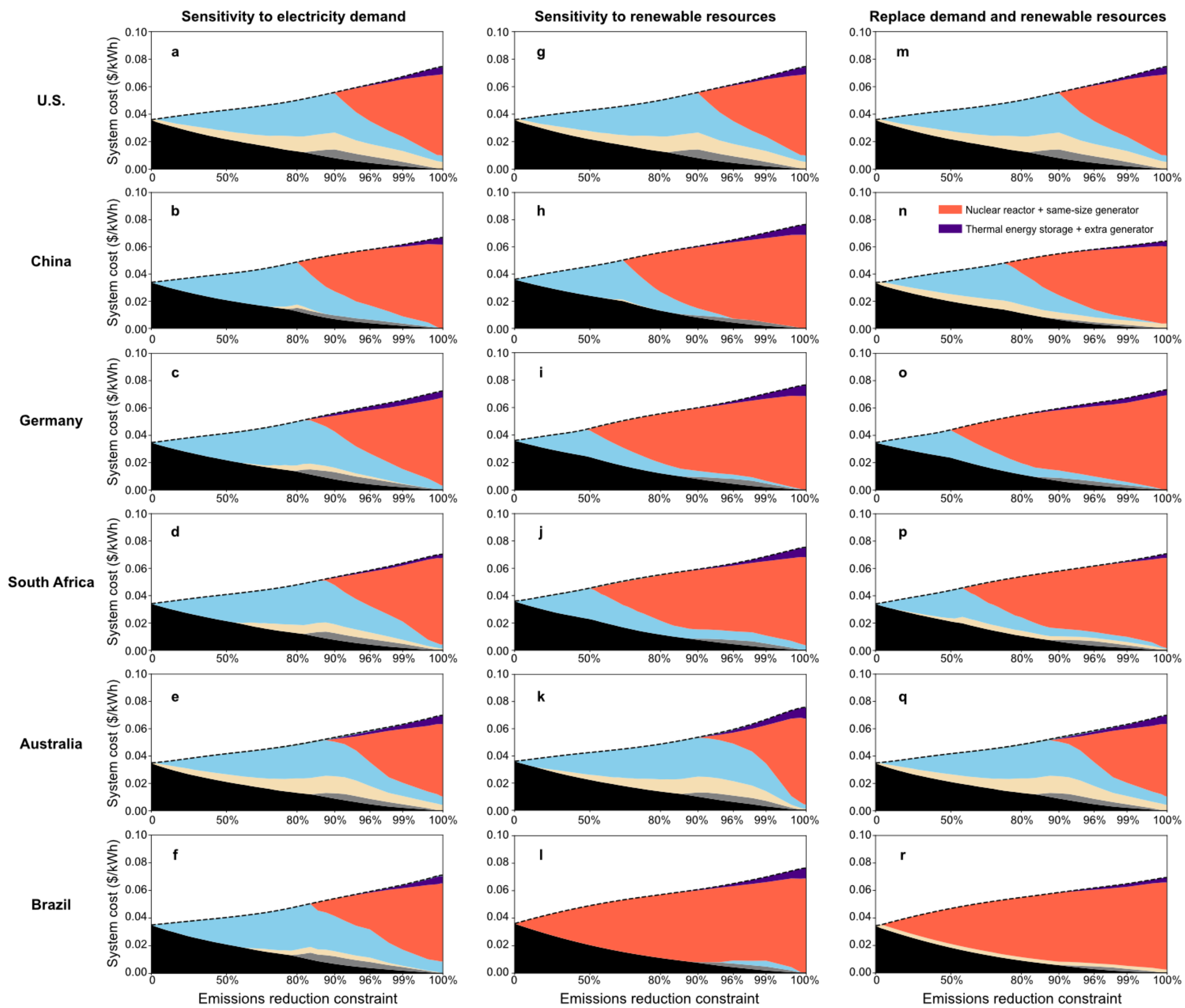
Supplementary Figure 2. Capacity of different technologies from the least-cost optimization. Results under various emission reduction scenarios using 6 selected countries' one-year demand and year-2019 resource data. Systems with nuclear capital costs at (**a** to **f**) near-current EIA level ($6317/kWe) and (**g** to **l**) $4000/kWe are compared. Annual mean demand is normalized to 1 kWh.



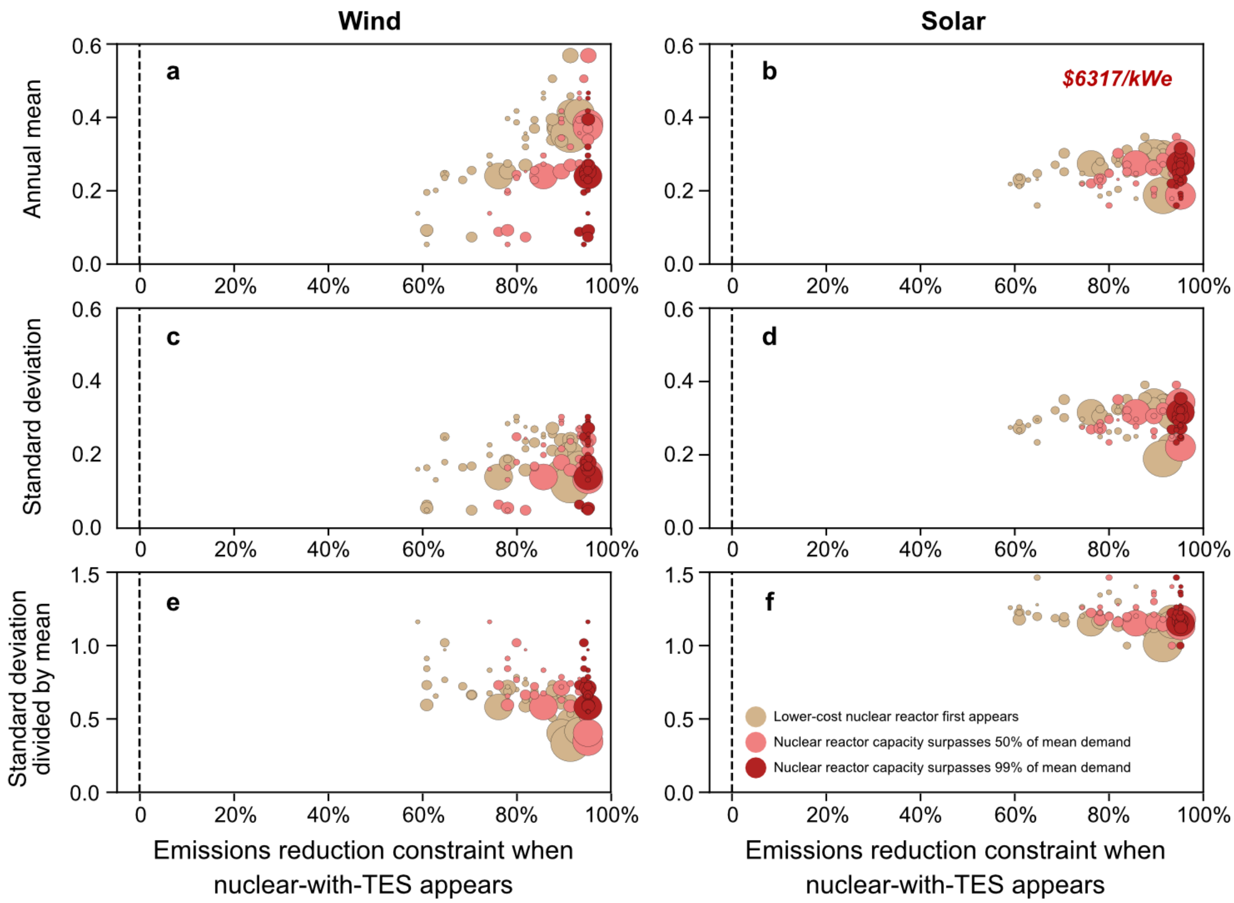
Supplementary Figure 3. Changes in **(a)** average main node curtailment and **(b)** marginal system costs under various emission reduction constraints. Cases with no nuclear, \$6317/kWe nuclear plus TES, and \$4000/kWe nuclear plus TES with the US demand and year-2019 renewable resource profiles are compared. Marginal system cost is calculated using optimized system costs at different emission reduction constraints minus system costs with no emission reduction and then divided by changes in corresponding amounts of allowable carbon emissions.



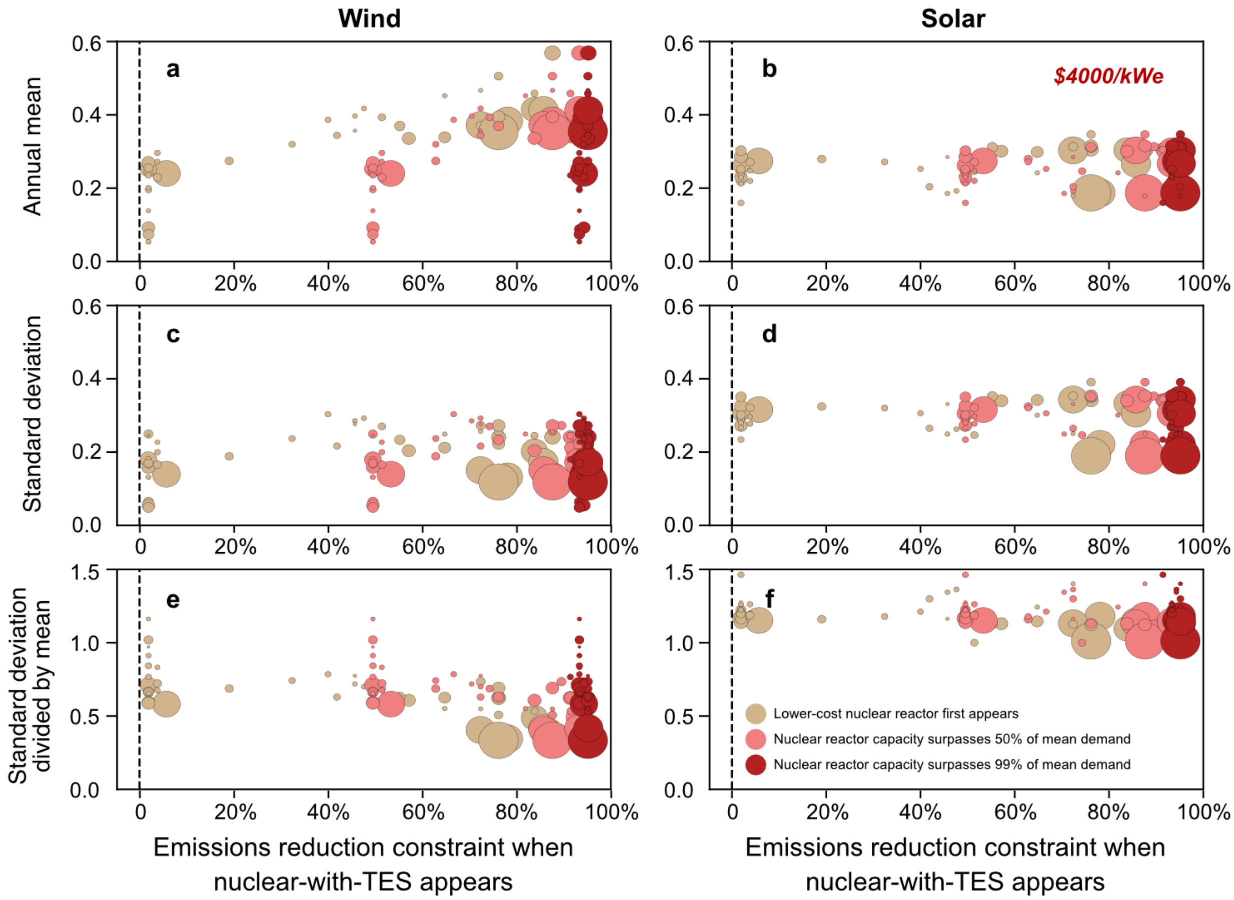
Supplementary Figure 4. Sensitivity analysis to electricity demand and renewable resources. We use the US case as the base case and replace (**a** to **f**) only electricity demand, (**g** to **l**) only renewable profiles, and (**m** to **r**) both demand and renewable profiles derived for other regions. $4000/kWe nuclear plus TES is considered. Changes in optimization results are mostly related to changes in renewable resources.



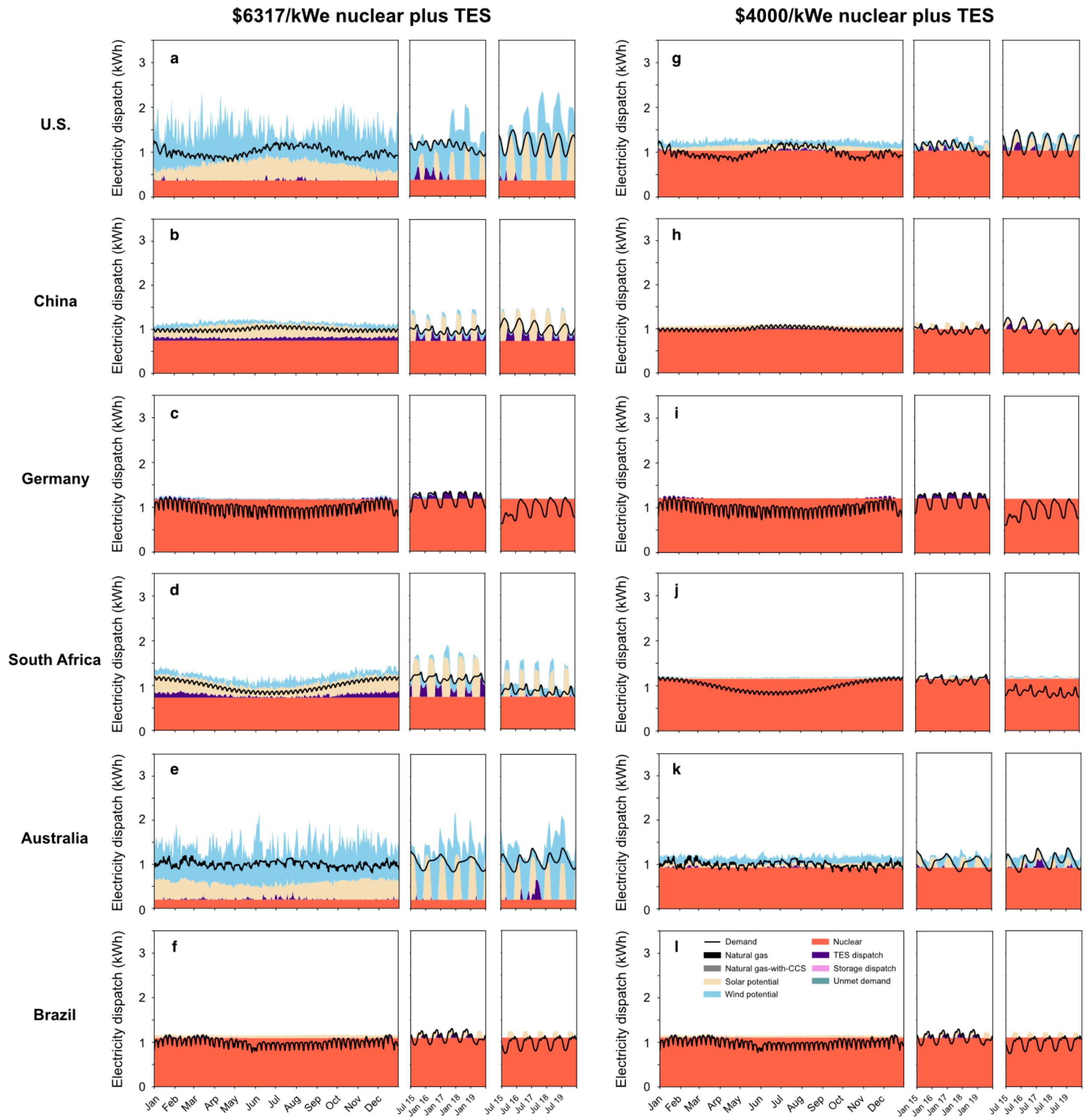
Supplementary Figure 5. Correlations between emission reduction constraint when: (brown) the $6317/kWe nuclear reactor starts playing a role in electricity power systems, (pink) the capacity of EIA cost nuclear reactor reaches 0.5 kW (annual mean demand is normalized to 1 kWh), and (red) the capacity of EIA cost nuclear reactor reaches 0.99 kW and (**a** and **b**) annual mean value, (**c** and **d**) one standard deviation, and (**e** and **f**) the ratio between standard deviation and mean value of solar/wind capacity factors for various countries. Relative sizes of dots represent relative magnitudes of total grid areas for these countries.



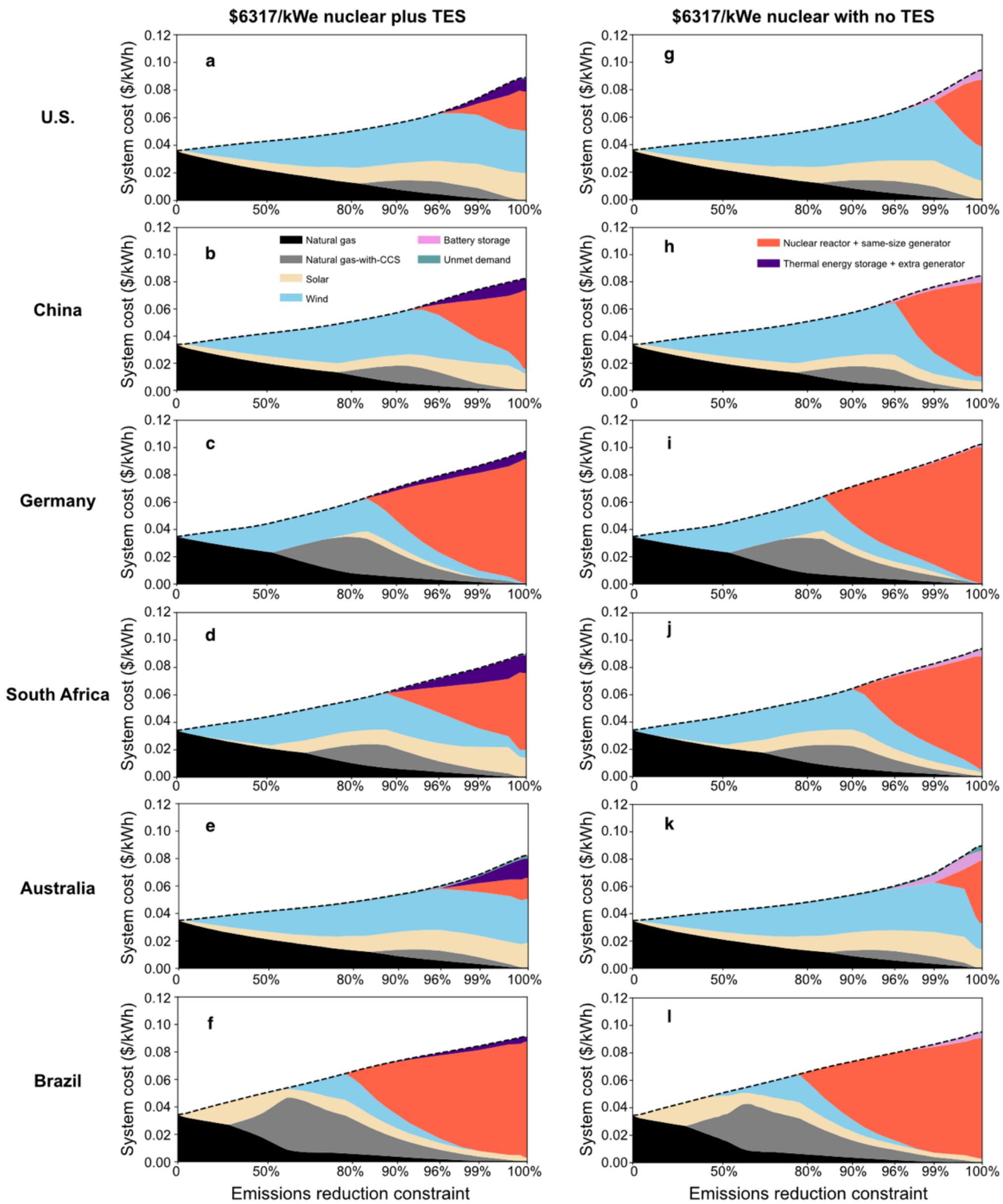
Supplementary Figure 6. Same as Supplementary Fig. 5 but for $4000/kWe nuclear plus TES.



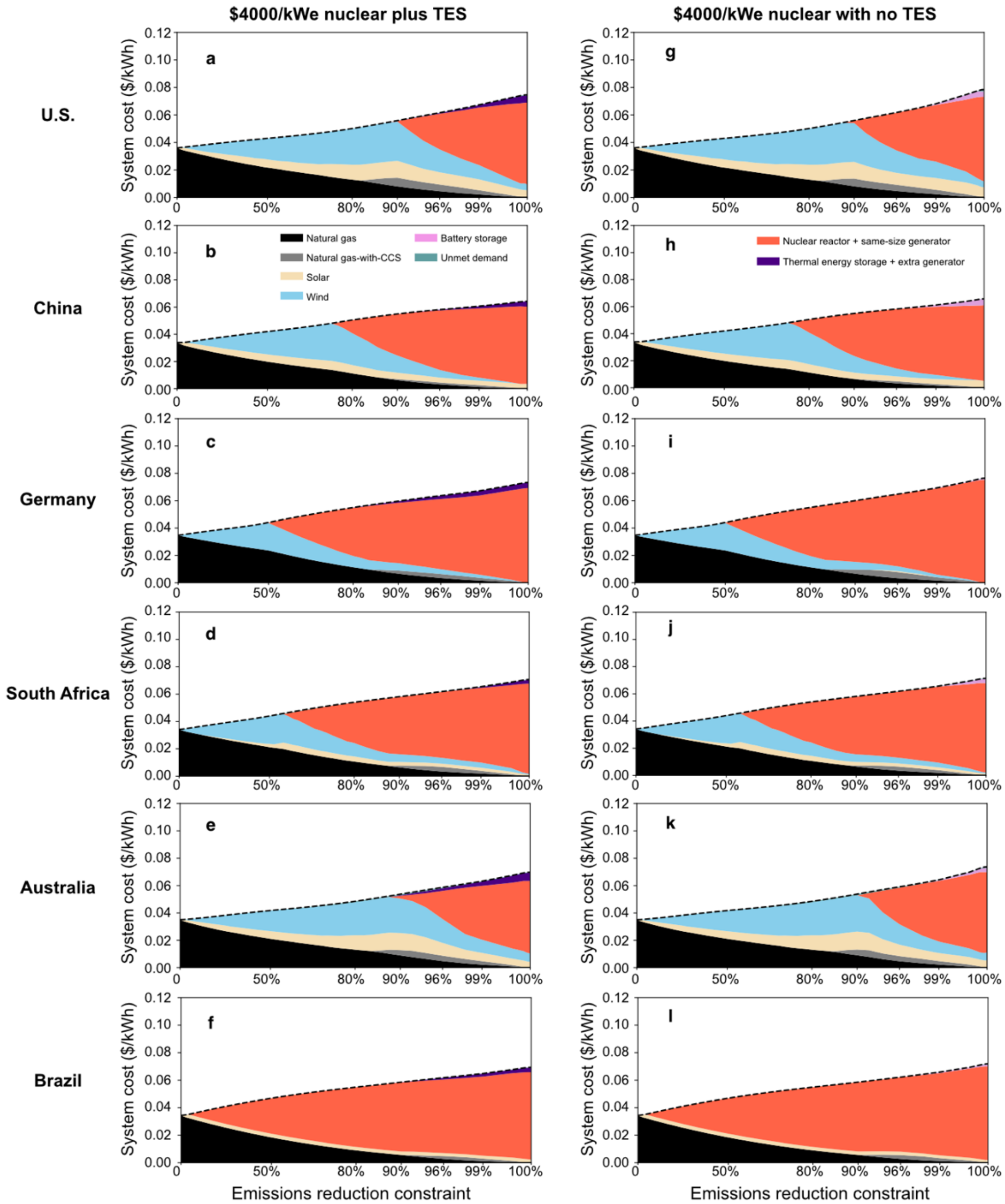
Supplementary Figure 7. Similar as Fig. 4 but for 100% emission reduction scenarios.



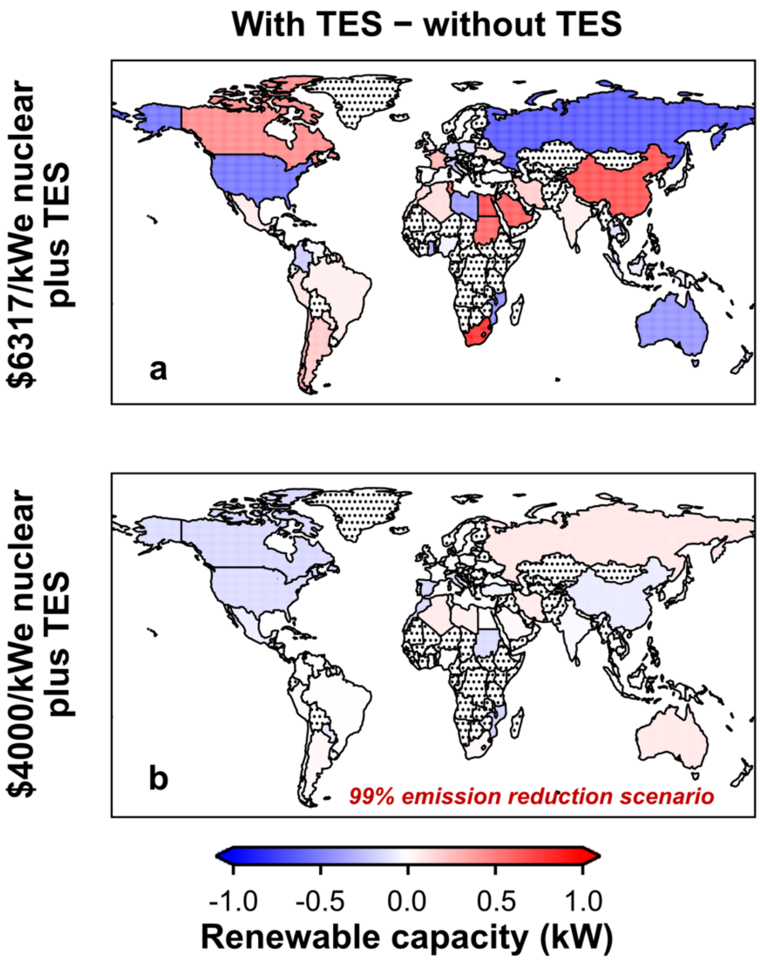
Supplementary Figure 8. Contributions of different technologies to system costs. Results are derived from the least-cost solution and under various emission reduction scenarios using six selected countries' one-year demand and year-2019 resource data. Systems where (**a** to **f**) the TES is attached to the nuclear reactor and (**g** to **l**) cases where TES is removed are compared.



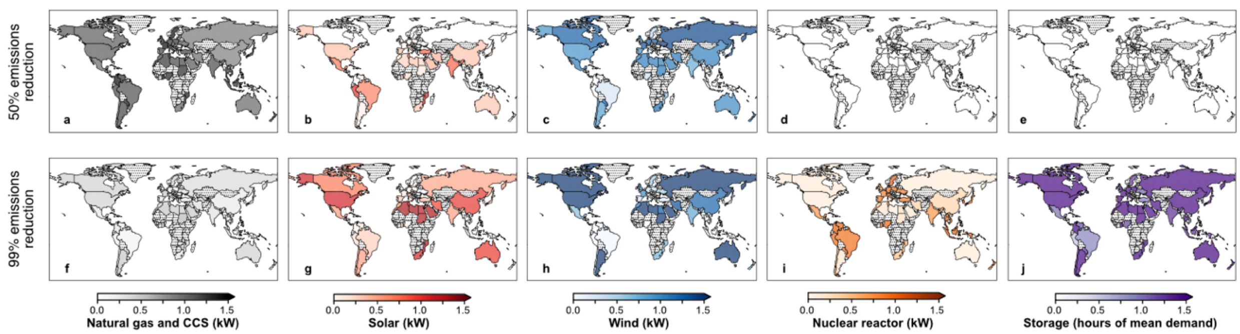
Supplementary Figure 9. Same as Supplementary Fig. 8 but for $4000/kWe nuclear plus TES.



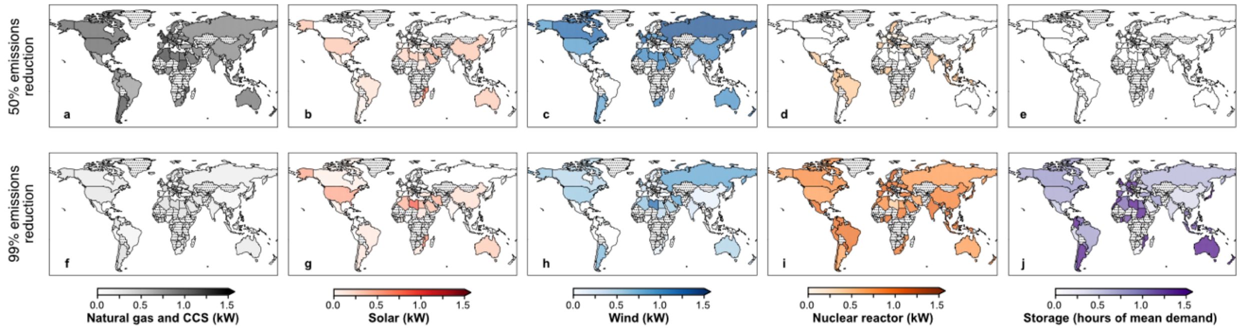
Supplementary Figure 10. Changes in installed solar plus wind capacities between cases with and without TES for (**a**) EIA cost nuclear ($6317/kWe) and (**b**) $4000/kWe nuclear capital costs.



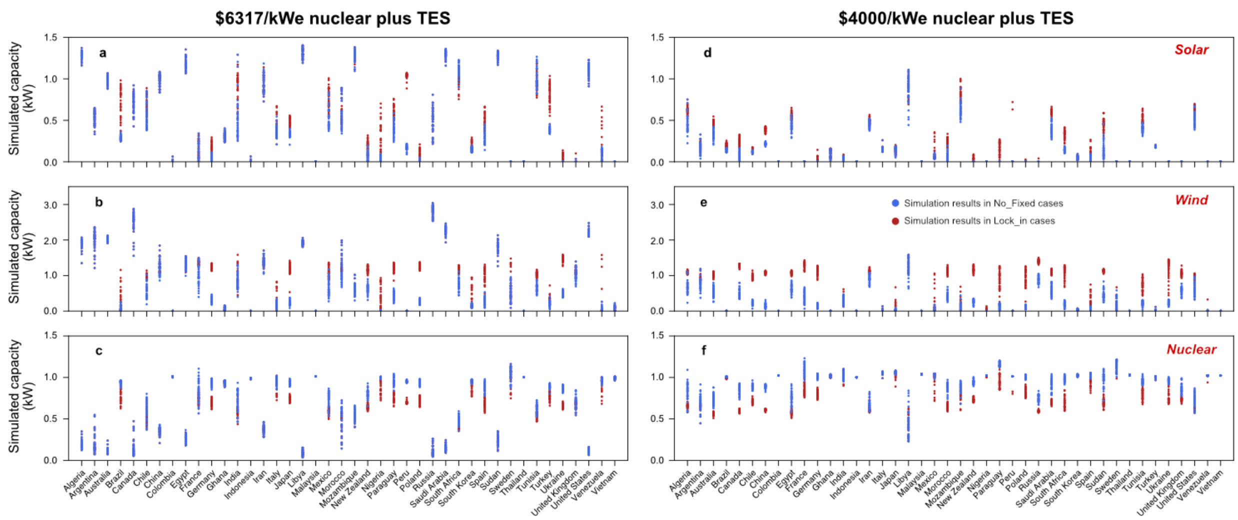
Supplementary Figure 11. Model determined capacities of carbon-emitting technologies (natural gas and natural gas with carbon capture and storage (CCS)), solar, wind, $6317/kWe nuclear reactors, and storages under (**a** to **e**) 50% and (**f** to **j**) 99% emission reduction constraints. All 42 countries with available demands are plotted here and regions with no data are masked with dots. For each country, optimizations are done using one-year demand data in combination with renewable resources from 40 individual year (1980 to 2019). Here we show results averaged across all years.



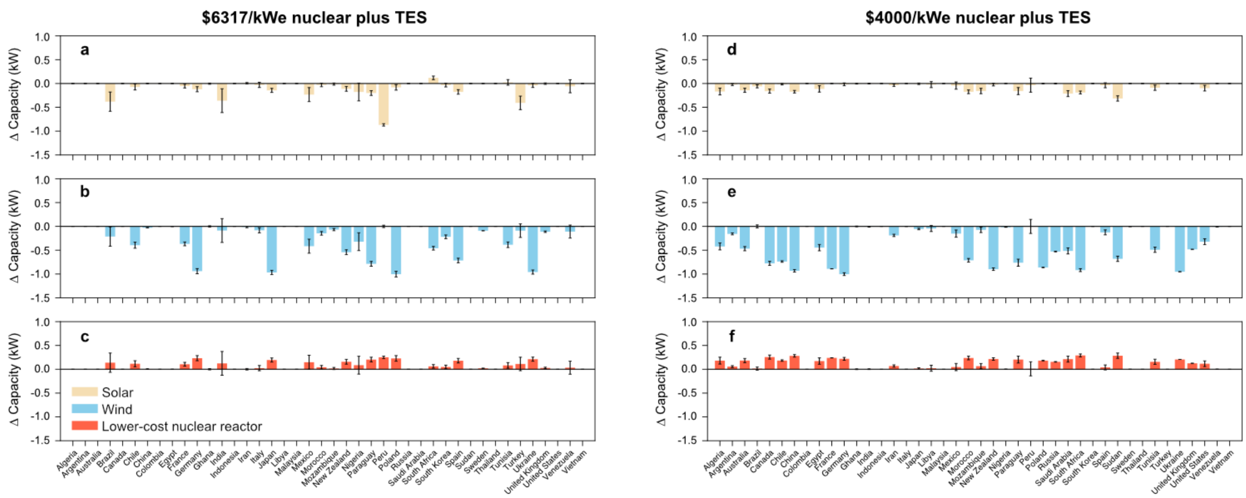
Supplementary Figure 12. Same as Supplementary Fig. 11 but for $4000/kWe nuclear plus TES.



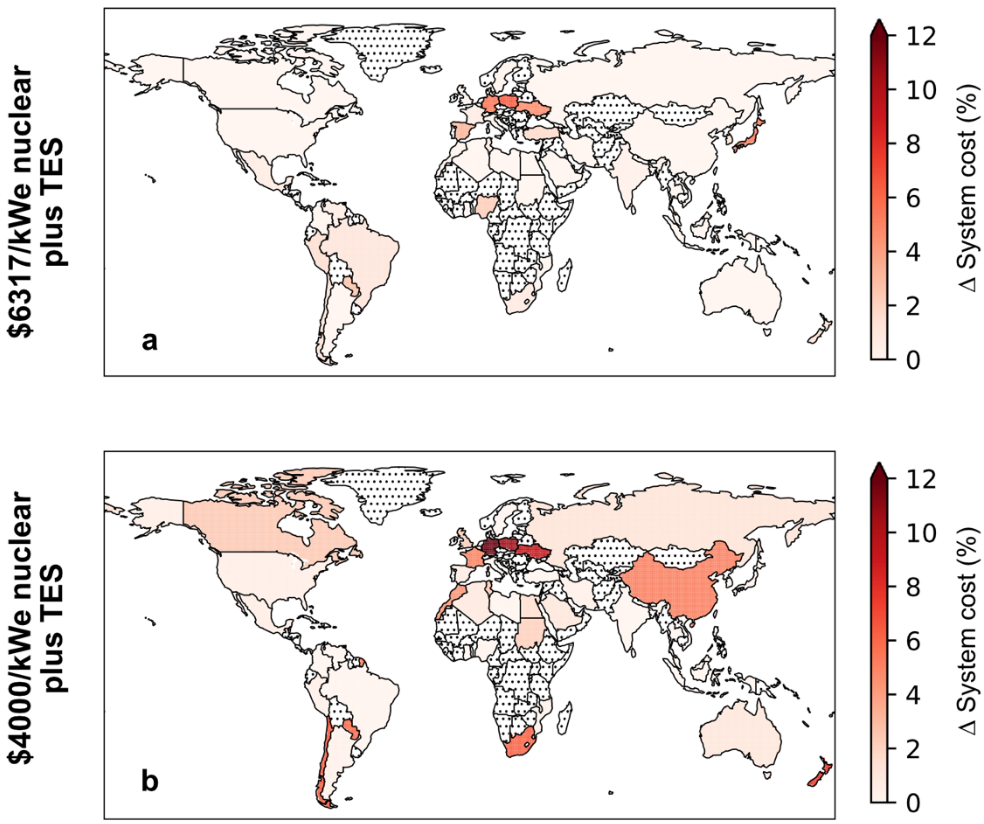
Supplementary Figure 13. Optimized generating capacity (in units of kW; annual mean demand is normalized to 1 kWh) for cases with no pre-existing capacities (**No_Fixed**) and cases with technologies capacity prescribed at the 50% emission reduction constraints (**Lock_In**) for different countries. For **Lock_In**, we first run optimization with an emission reduction constraint at 50%. Then we fix capacities of all technologies except natural gas and natural gas with carbon capture and storage (CCS) and increases emission reduction constraint to 99%. Each dot represents an individual optimization result using one-year demand and 40 individual year historical renewable resource data (1980-2019). Systems with nuclear capital costs at (**a** to **c**) near-current EIA level ($6317/kWe) and (**d** to **f**) $4000/kWe are compared.



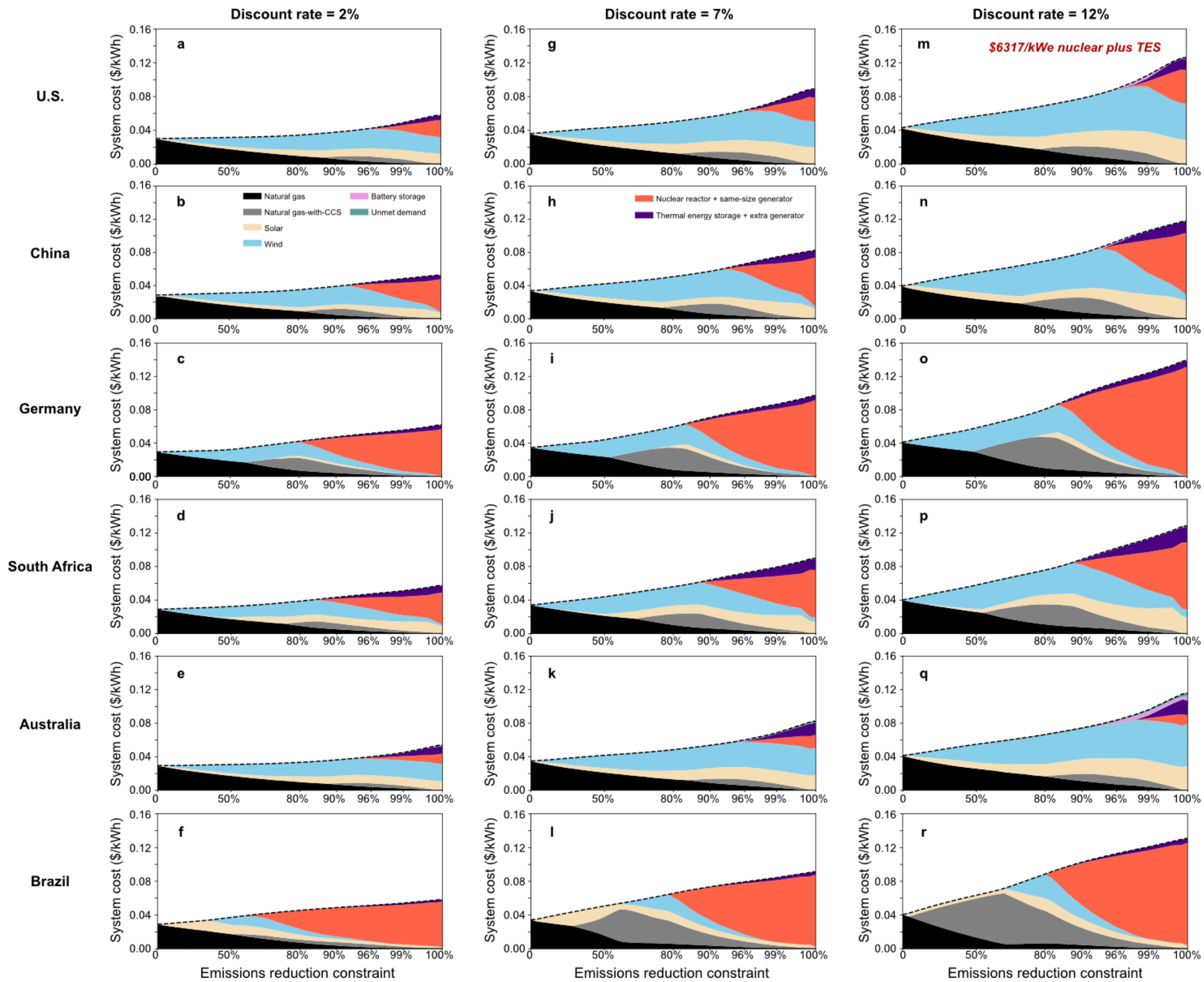
Supplementary Figure 14. Difference of the optimized generating capacity (in units of kW; annual mean demand is normalized to 1 kWh) between cases with no pre-existing capacities (**No_Fixed**) and cases with technologies capacity prescribed at the 50% emission reduction constraints (**Lock_In**) for different countries. Each bar represents the average results of 40 optimization scenarios using different historical renewable resource data and the black line show one standard deviation. Systems with nuclear capital costs at (**a** to **c**) near-current EIA level ($6317/kWe) and (**d** to **f**) $4000/kWe are compared.



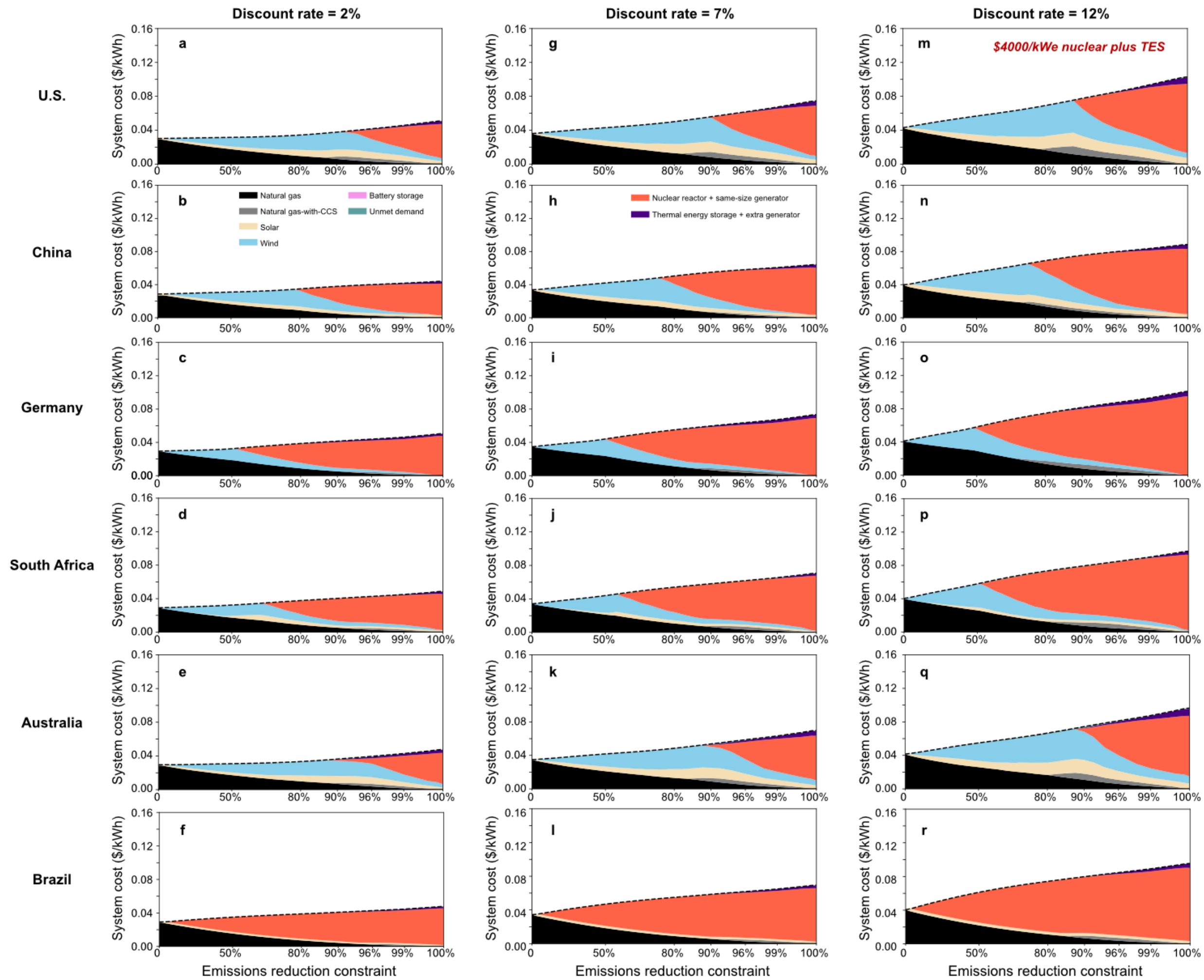
Supplementary Figure 15. Difference of system costs between cases with no pre-existing capacities (**No_Fixed**) and cases with technologies capacity prescribed at the 50% emission reduction constraints (**Lock_In**). Systems with nuclear capital costs at (**a**) near-current EIA level ($6317/kWe) and (**b**) $4000/kWe are compared. Countries with no data are masked with dots. For each region, optimizations are done using one-year demand series combined with renewable resources from 40 individual year (1980 to 2019), and we show results averaged over all years here.



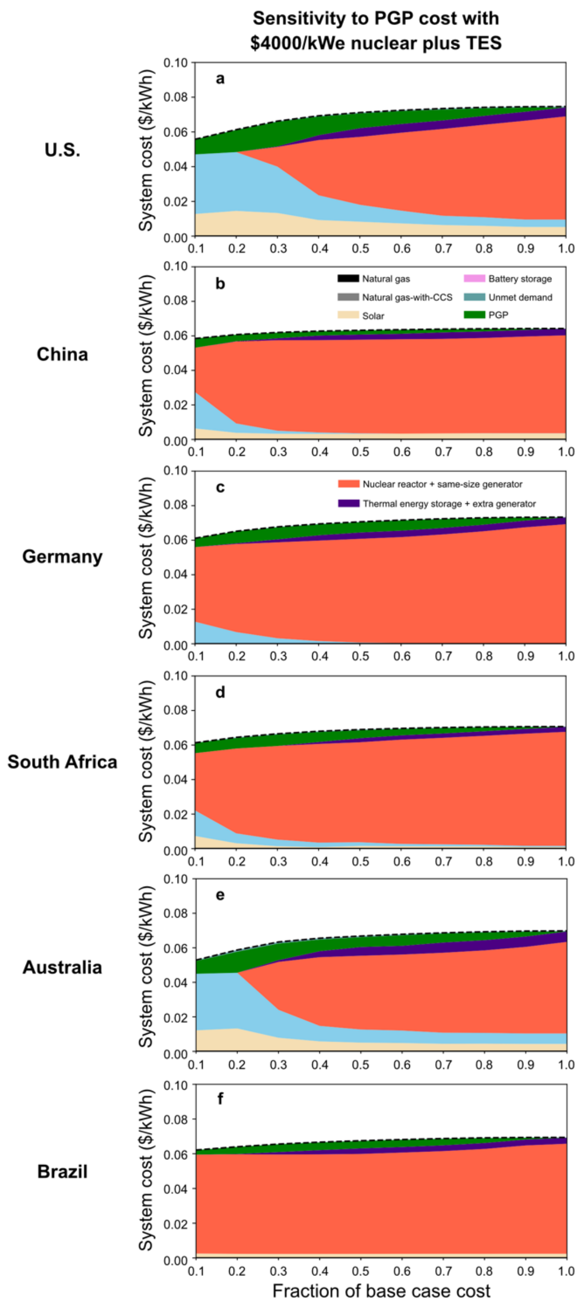
Supplementary Figure 16. Contributions of different technologies to overall system costs derived from the least-cost solution and under various emission reduction scenarios. Scenarios, in which all technologies consider a (**a** to **f**) 2%, (**g** to **l**) 7%, and (**m** to **r**) 12% discount rate are compared using 6 selected countries' demand and resource data. Year-2019 renewable resource data are used with one-year demand.



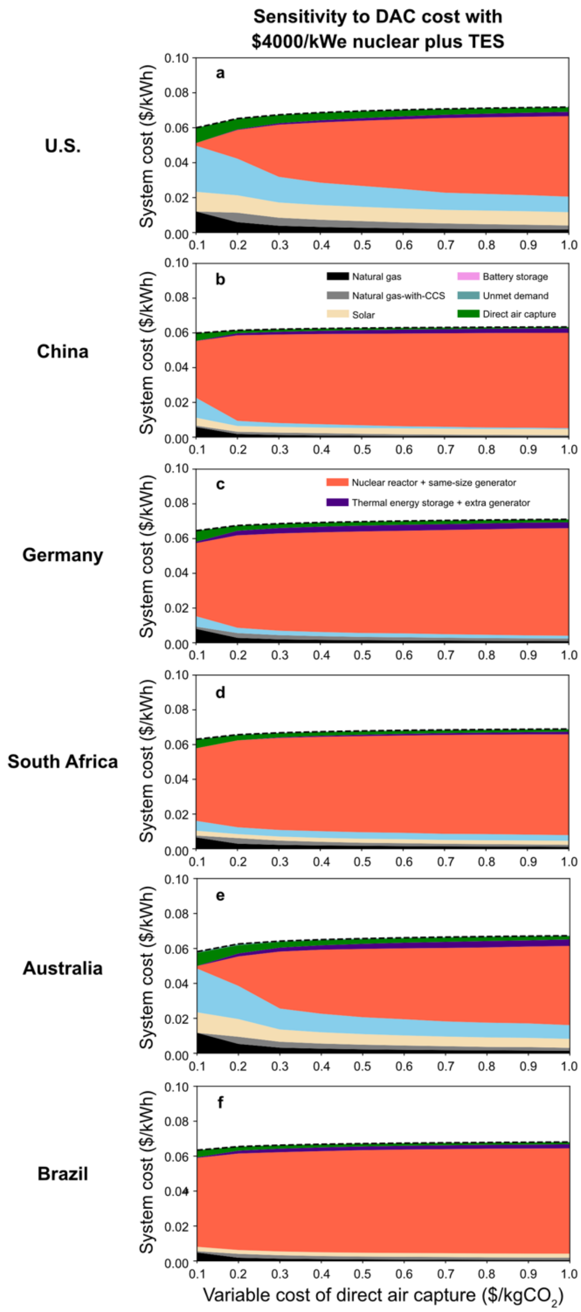
Supplementary Figure 17. Same as Supplementary Fig. 16 but for \$4000/kWe nuclear plus TES.



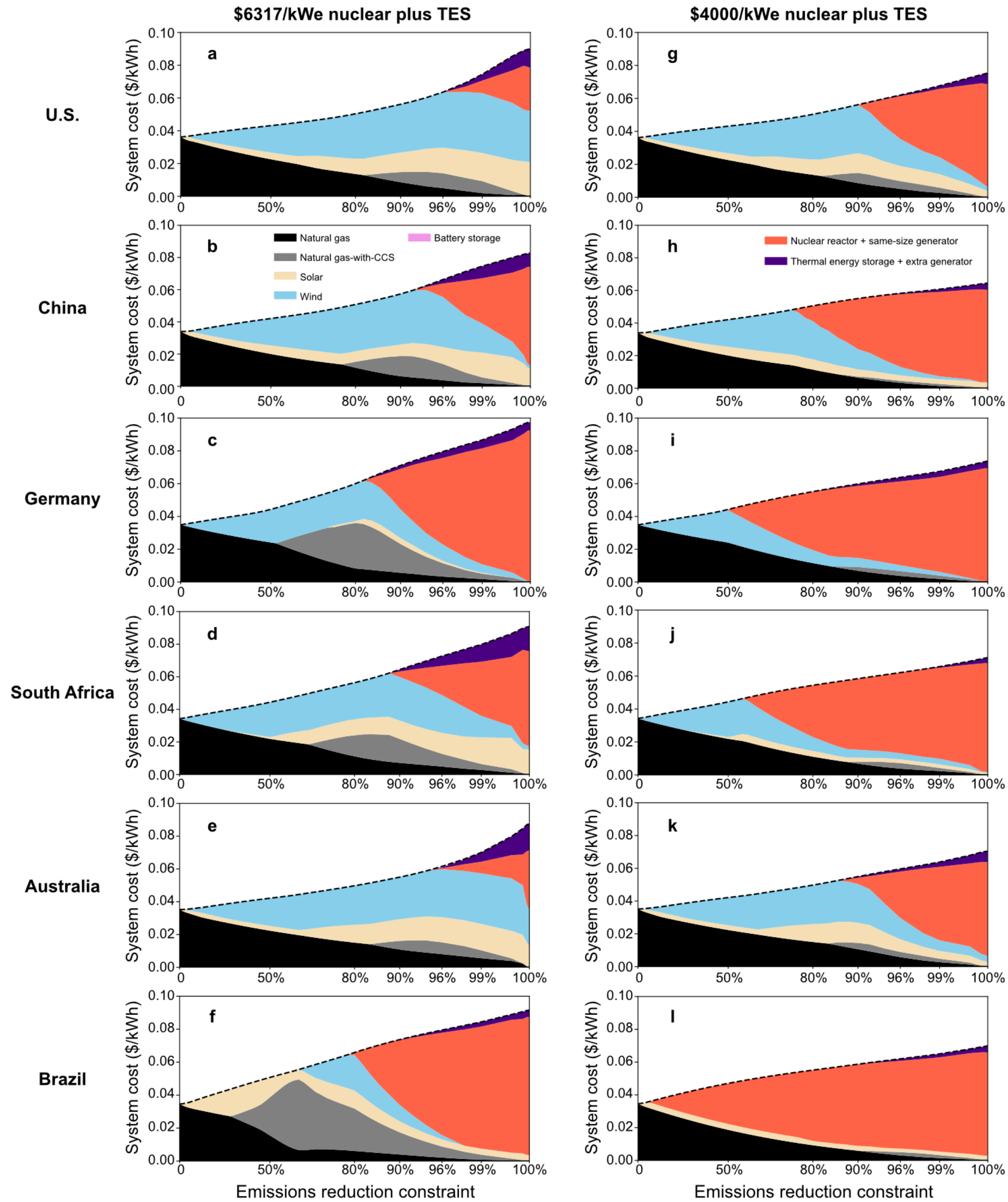
Supplementary Figure 18. Sensitivity analysis of our optimization results with $4000/kWe nuclear plus TES to long-duration storage represented as power-to-gas-to-power (PGP) under different cost levels. The base case represents near-current PGP costs with a fixed cost of $34.61/MWe for the electrolyzer plant, $58.46/MWe for the fuel cell, and $0.0037/MWe for the storage cavern. Year-2019 renewable resource data are used with one-year demand for six selected countries (**a**: U.S., **b:** China, **c:** Germany, **d:** South Africa, **e:** Australia, and **f:** Brazil), and 100% emission reduction scenarios are shown.



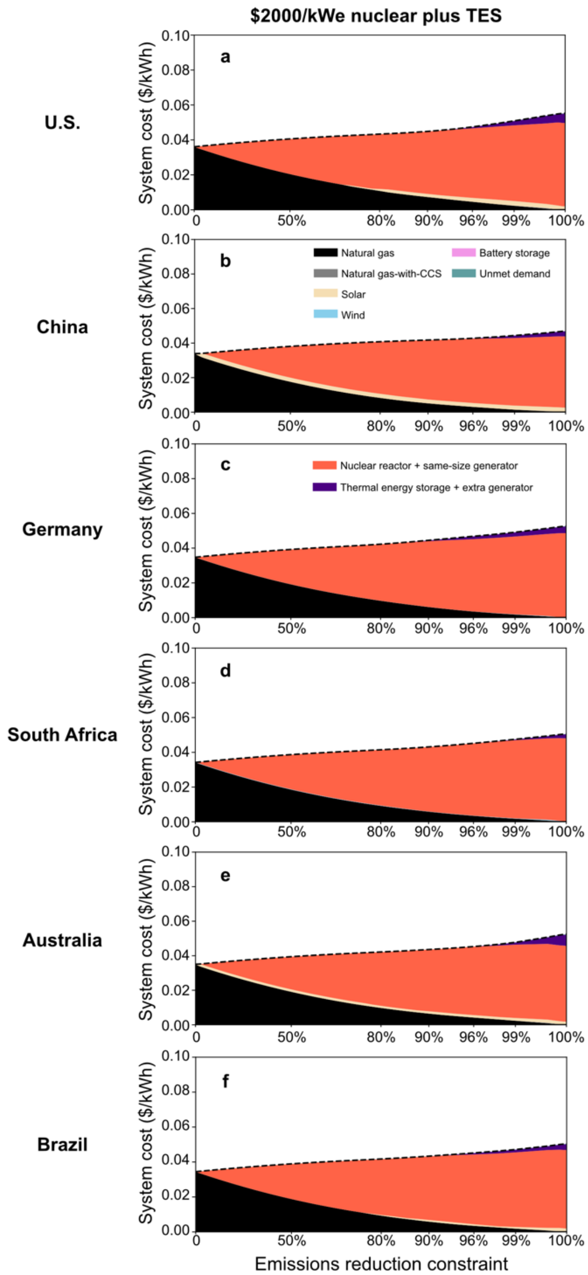
Supplementary Figure 19. Sensitivity analysis of our optimization results with \$4000/kWe nuclear plus TES to direct air capture (DAC), with variable costs varying from \$100/tCO_2 to \$1000/tCO_2. Year-2019 renewable resource data are used with one-year demand for six selected countries (**a**: U.S., **b:** China, **c:** Germany, **d:** South Africa, **e:** Australia, and **f:** Brazil), and 100% emission reduction scenarios are shown.



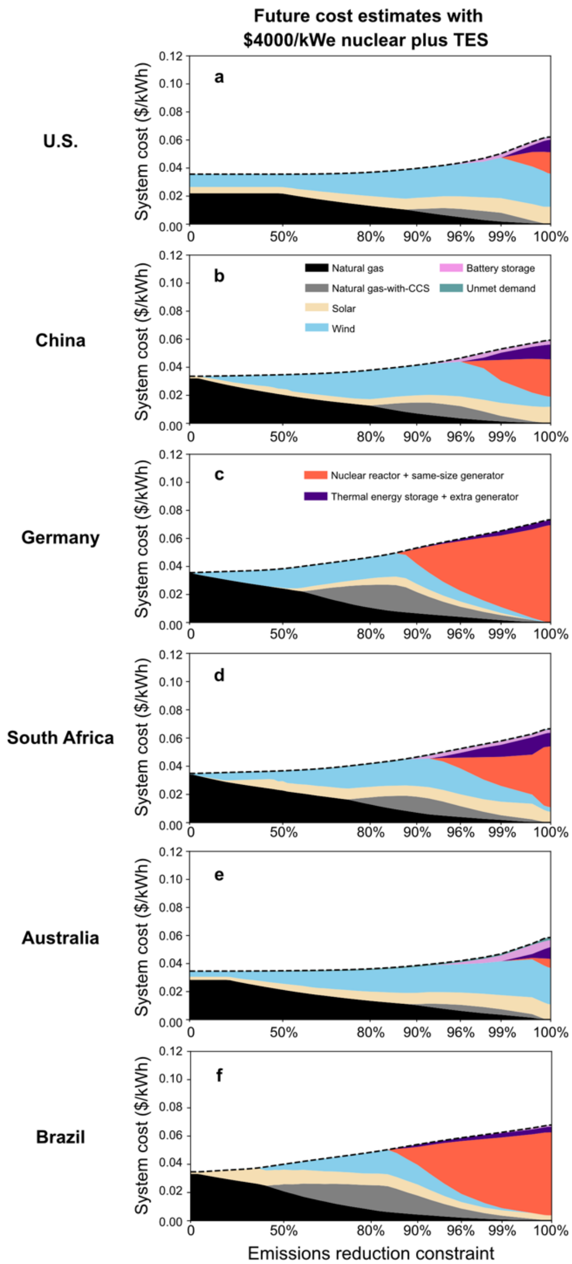
Supplementary Figure 20. Same as Fig. 2, and unmet demand is removed from the system.



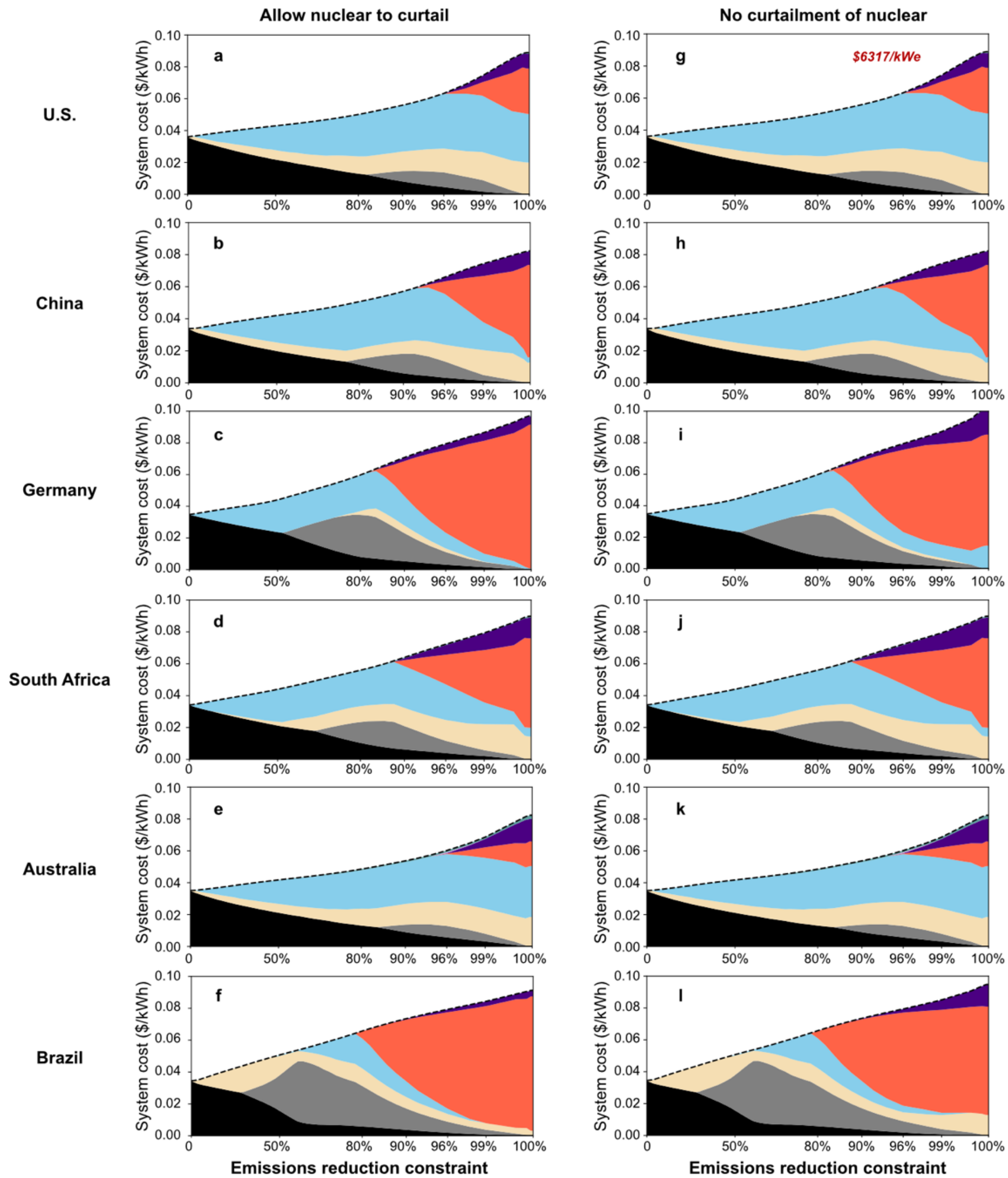
Supplementary Figure 21. Contributions of different technologies to overall system costs derived from the least-cost solution and under various emission reduction scenarios using 6 selected countries' demand and resource data (**a**: U.S., **b:** China, **c:** Germany, **d:** South Africa, **e:** Australia, and **f:** Brazil). $2000/kWe nuclear plus thermal energy storage (TES) is shown. Year-2019 renewable resource data are used in combination with one-year demand.



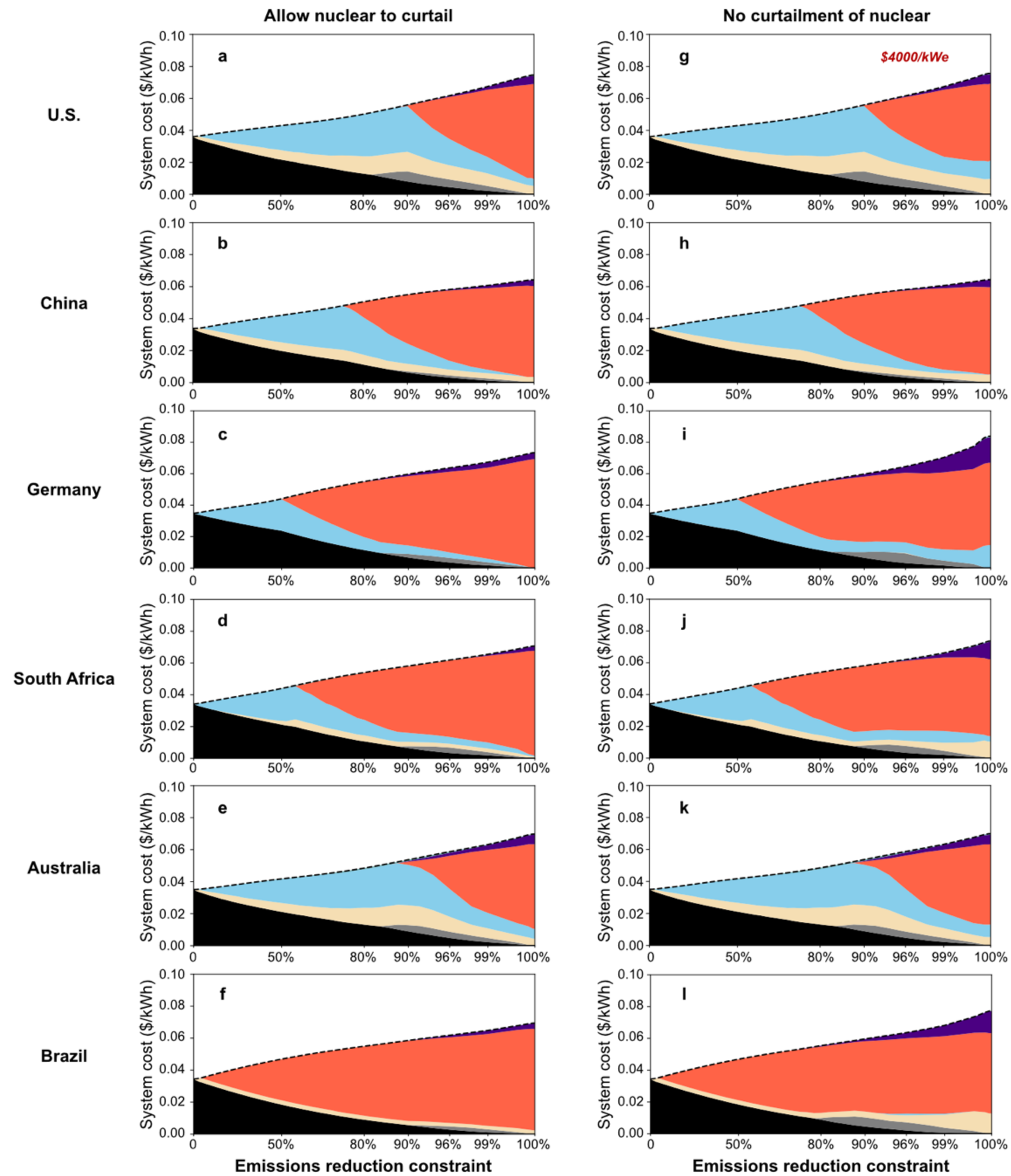
Supplementary Figure 22. Similar to Supplementary Fig. 21 with costs for generation technologies and battery calculated based on the year-2050 projections from the National Renewable Energy Laboratory (NREL) 2021 Annual Technology Baseline (ATB) report. $4000/kWe nuclear plus thermal energy storage (TES) is used.



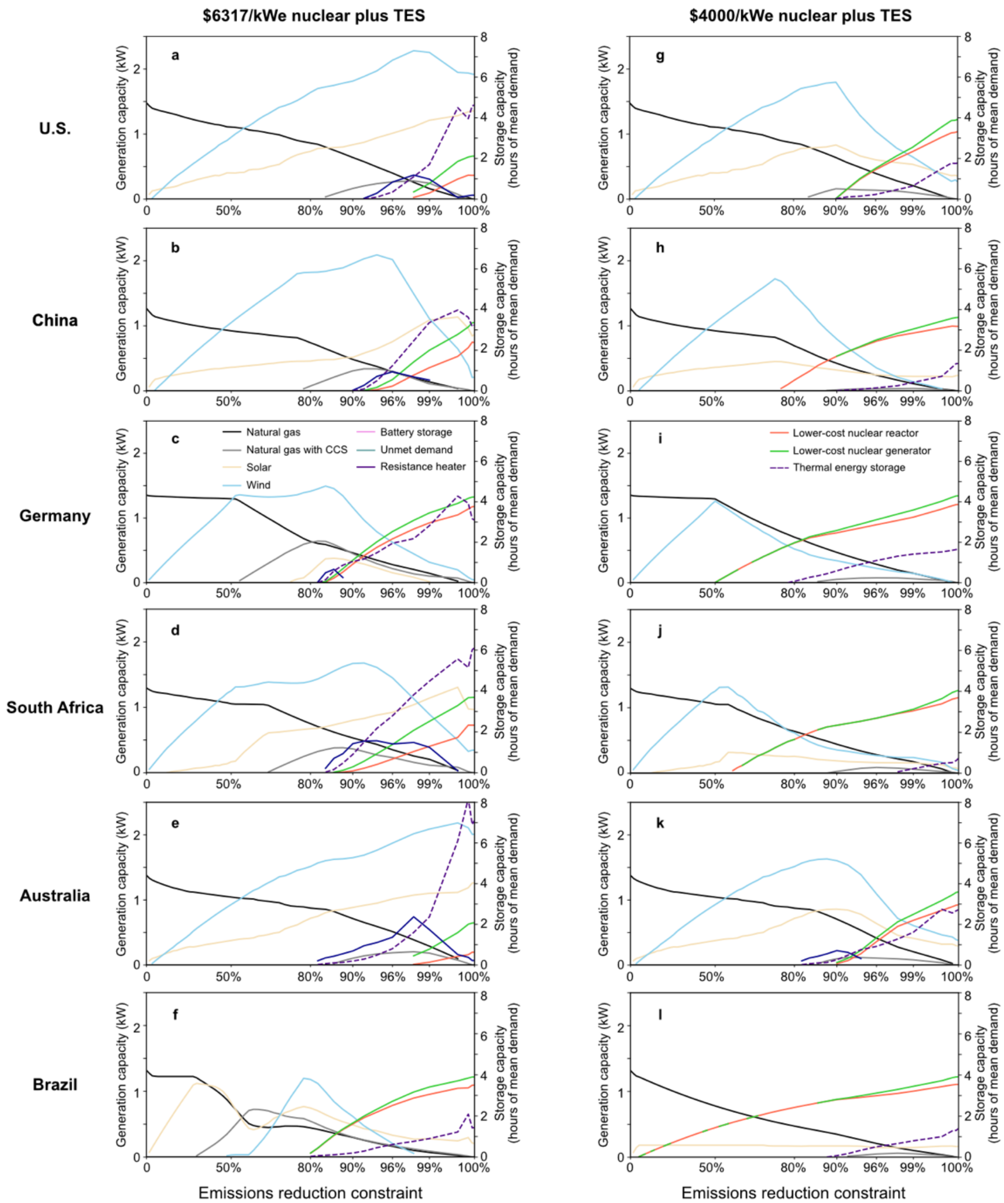
Supplementary Figure 23. Contributions of different technologies to overall system costs derived from the least-cost solution and under various emission reduction scenarios using 6 selected countries' demand and resource data. Scenarios, in which $6317/kWe cost nuclear plus TES is (**a** to **f**) curtailable and (**g** to **l**) non-curtailable are compared.



Supplementary Figure 24. Same as Supplementary Fig. 23 but for $4000/kWe nuclear plus TES.



Supplementary Figure 25. Capacity of different technologies for cases with a cost-effective free resistance heater in the model. Systems with nuclear capital costs at (**a** to **f**) near-current EIA level ($6317/kWe) and (**g** to **l**) $4000/kWe are compared. Resistance heater is rarely used in the system at $4000/kWe costs level and for all six country-level data examined here, which requires substantial free electricity to be stored in heat storage.



Supplementary Table 1. Cost and performance assumptions used for generation and storage technologies in this analysis. All dollar values are represented in year-2019 dollar.

	Natural gas	Natural gas with CCS	Solar	Wind	Higher-cost nuclear	Storage	EIA-cost nuclear reactor plus generator[2]	Nuclear generator	Nuclear reactor	Thermal energy storage[3]
Total overnight capital cost (\$/kW)	954	2569	1331	1319	7227.85	365.77	6317	1854.77	\	74.47
Fixed O&M cost (\$/kW-yr)	12.15	27.48	15.19	26.22	290.57	12.32	121.13	33.66	\	0
Lifetime (year)[1]	30	30	25	25	40	10	40	30	\	30
Hourly fixed costs (\$/MW)[4]	10.16	26.77	14.77	15.91	95.06	7.35	77.08	20.91	20.83	2.23
Variable O&M cost (\$/MWh)	1.86	5.82	\	\	\	\	\	\	\	\
Fuel cost (\$/MWh)	19.11	21.37	\	\	\	\	\	\	\	\
Variable cost (\$/MWh)	20.97	27.19	\	\	\	\	\	\	\	\
Heat to electricity efficiency	\	\	\	\	\	\	\	0.37	\	\
Decay rate (% per hour)	\	\	\	\	\	0.00001	\	\	\	0.00026

[1]Default discount rate = 0.07.

[2]For our base case, we use near-current cost estimates from the Energy Information Administration (EIA) to represent the capital cost of nuclear reactor plus the size-size generator. To separate their individual costs, we use generator cost from the NREL System Advisor Model (SAM) and thus costs of reactor is calculated as difference between total nuclear capital cost and generator cost. When testing different total nuclear capital costs (i.e., EIA cost, \$4000/kWe, and \$2000/kWe), nuclear generator costs keep unchanged, and we vary costs of reactor.

[3]Costs of thermal energy storage (TES) is estimated from the NREL System Advisor Model (SAM) used for concentrated solar power (CSP) plant.

[4]Hourly fixed cost (C_{fixed_cost}) is calculated as

$$C_{fixed\_cost} = C_{capital\_cost} * CRF + C_{O\&M}$$

where $C_{capital\_cost}$ represents the overnight capital cost, $C_{O\&M}$ represents the fixed O&M cost, and CRF represents the capital recovery factor, which is calculated based on discount rate R and lifetime N:

$$CRF = \frac{R * (1 + R)^N}{(1 + R)^N - 1}$$

Supplementary Table 2. Annual mean wind capacities and emission reduction constraints where nuclear reactor first appears in the technology mix.

Country Name	Mean wind capacity factor	Emission reduction when lower-cost nuclear reactor appears at $6317/kWe (%)	Emission reduction when lower-cost nuclear reactor appears at $4000/kWe (%)
Algeria	0.39	94	80
Argentina	0.57	96	92
Australia	0.41	96	88
Brazil	0.24	80	6
Canada	0.38	98	82
Chile	0.51	92	80
China	0.37	94	76
Colombia	0.09	64	2
Egypt	0.37	92	76
France	0.39	88	54
Germany	0.42	84	50
Ghana	0.14	62	2
India	0.25	82	2
Indonesia	0.09	64	2
Iran	0.34	92	68
Italy	0.27	78	4
Japan	0.30	78	4
Libya	0.35	96	80
Malaysia	0.05	64	2
Mexico	0.27	86	2
Morocco	0.46	96	88
Mozambique	0.27	82	20
New Zealand	0.45	90	68
Nigeria	0.24	68	2
Paraguay	0.39	84	42
Peru	0.07	74	2
Poland	0.40	82	48
Russia	0.35	96	80
Saudi Arabia	0.34	94	60
South Africa	0.37	88	58
South Korea	0.25	68	2
Spain	0.32	86	34
Sudan	0.39	92	80
Sweden	0.23	68	2
Thailand	0.20	64	2
Tunisia	0.36	86	48
Turkey	0.23	72	4
Ukraine	0.34	86	44
United Kingdom	0.47	90	76
United States	0.41	98	90
Venezuela	0.26	74	2
Vietnam	0.20	66	2

Supplementary Table 3. Changes in system costs (in units of %) for cases with no thermal energy storage (TES) relative to cases with TES attached to nuclear reactor under 99% and 100% decarbonization scenarios.

Country Name	Changes in system cost at $6317/kWe (%)		Changes in system cost at $4000/kWe (%)	
	100% emission reduction	99% emission reduction	100% emission reduction	99% emission reduction
Algeria	6.25349	4.25256	2.11943	1.42312
Argentina	10.27854	5.06068	4.48213	1.64744
Australia	8.7988	1.40755	5.62447	1.57057
Brazil	4.37065	2.20556	3.6534	1.60881
Canada	3.85518	2.0753	3.91932	1.58361
Chile	5.48098	3.03561	4.34462	1.93844
China	2.57011	2.53742	2.359	0.83021
Colombia	4.67554	2.98398	5.14302	4.01763
Egypt	6.74382	4.94052	2.24749	1.19671
France	2.79561	1.1942	1.90471	0.3659
Germany	5.39402	3.89557	4.23365	3.06155
Ghana	14.54562	9.9073	15.6189	11.63661
India	1.45961	0.80306	1.426	0.55122
Indonesia	3.04914	2.29946	3.66834	3.23396
Iran	5.18422	3.08348	3.53882	1.22762
Italy	7.0962	2.76667	5.28372	3.72769
Japan	8.24914	3.37959	8.14746	3.0885
Libya	4.9417	1.59964	2.3831	1.51476
Malaysia	4.2442	1.89139	3.46178	2.13179
Mexico	1.74404	0.76494	2.50707	0.83705
Morocco	5.87063	4.10887	3.37424	2.31923
Mozambique	13.83759	8.72484	14.16291	10.89044
New Zealand	5.92686	4.07233	4.50059	3.61729
Nigeria	2.69813	2.02038	2.99222	2.40155
Paraguay	2.72933	1.51745	3.05963	1.747
Peru	1.52309	0.74222	1.55832	0.7098
Poland	7.0217	4.22131	4.6654	3.14838
Russia	5.03322	2.80448	2.52115	0.93247
Saudi Arabia	5.31923	3.56374	1.84518	0.24081
South Africa	4.24403	4.33919	1.07471	0.25534
South Korea	2.6183	1.39189	2.43393	0.97379
Spain	5.69643	1.68175	4.69098	2.18041
Sudan	2.71507	3.84598	2.88804	2.22642
Sweden	4.02315	1.62334	3.23699	0.90857
Thailand	4.17274	1.89144	3.70109	2.54516
Tunisia	7.08088	3.28404	2.68593	1.52913
Turkey	4.78777	1.32189	3.89785	1.43083
Ukraine	3.21276	1.64523	2.13731	0.78961
United Kingdom	11.24573	6.17439	7.10691	3.95956
United States	5.89629	1.88898	5.18411	1.14744
Venezuela	3.18773	1.76148	3.44466	2.60604
Vietnam	1.73652	0.83053	1.4433	0.6984

Supplementary Table 4. Model determined storage capacity (battery storage and thermal energy storage, in units of hours of mean demand) for cases with no nuclear, $6317/kWe nuclear plus TES, and $4000/kWe nuclear plus TES nuclear technology under 99% emission reduction scenarios. Year-2019 weather condition data in combination with one-year demand data were used for all simulations across 42 countries examined here.

Country Name	Storage capacity with no nuclear (hours of mean demand)	Storage capacity with $6317/kWe nuclear plus TES (hours of mean demand)	Storage capacity with $4000/kWe nuclear plus TES (hours of mean demand)
Algeria	1.70995	1.31733	1.31733
Argentina	0.51493	1.77271	1.77271
Australia	0.7176	0.70795	0.70795
Brazil	1.26247	0.33348	0.33348
Canada	0.16168	1.90571	1.90571
Chile	1.9559	0.95181	0.95181
China	0.98543	1.17086	1.17086
Colombia	12.70992	0.64788	0.64788
Egypt	2.11148	1.63068	1.63068
France	2.27401	0.55161	0.55161
Germany	3.76932	1.04548	1.04548
Ghana	10.07343	1.25965	1.25965
India	2.067	0.20255	0.20255
Indonesia	11.84453	0.467	0.467
Iran	1.20249	0.94794	0.94794
Italy	7.21168	0.75903	0.75903
Japan	4.28113	0.6585	0.6585
Libya	1.47548	0.87993	0.69111
Malaysia	13.18776	0.57172	0.57172
Mexico	1.32069	0.27594	0.27594
Morocco	1.11186	1.64397	1.64397
Mozambique	2.28386	1.46724	1.46724
New Zealand	1.69918	0.89827	0.89827
Nigeria	8.48079	0.47434	0.47434
Paraguay	3.90062	0.48633	0.48633
Peru	12.80619	0.20782	0.20782
Poland	3.37637	0.94205	0.94205
Russia	0.08508	0.77586	0.77586
Saudi Arabia	0.77161	0.88554	0.88554
South Africa	2.27109	1.55568	1.55568
South Korea	8.81608	0.34633	0.34633
Spain	2.44288	0.60502	0.60502
Sudan	1.73806	1.07739	1.07739
Sweden	2.89055	0.3885	0.3885
Thailand	7.98207	0.6389	0.6389
Tunisia	3.97269	1.52646	1.52646
Turkey	4.18664	0.33443	0.33443
Ukraine	2.0273	0.5496	0.5496
United Kingdom	1.96182	1.97121	1.97121
United States	0.49263	0.57468	0.57468
Venezuela	5.28073	0.43345	0.43345
Vietnam	5.79434	0.19131	0.19131