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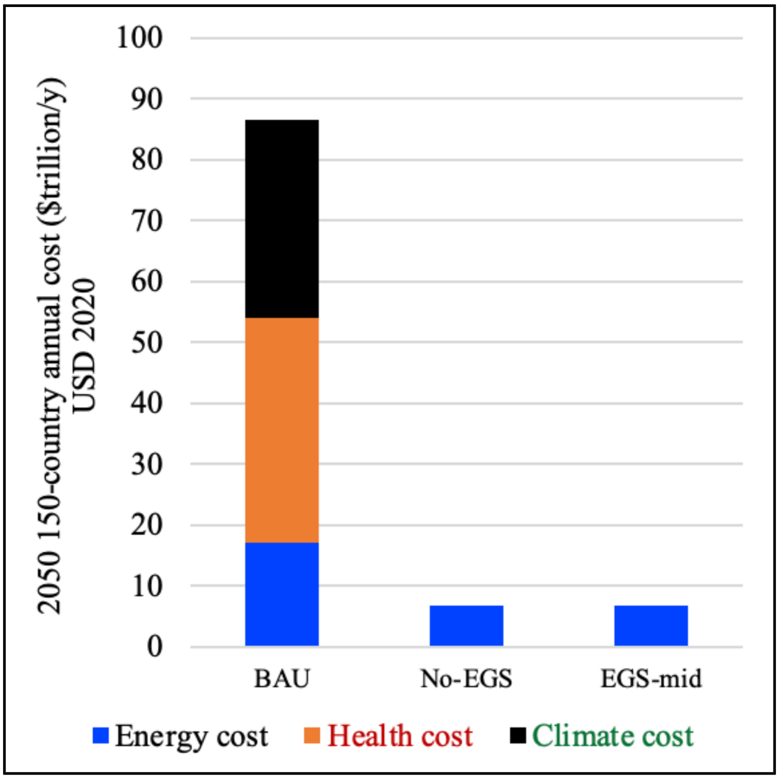
The impact of enhanced geothermal systems on transitioning all energy sectors in 150 countries to 100% clean, renewable energy

Graphical abstract



Highlights

- Impacts modeled of moving 150 countries to 100% WWS with and without EGS electricity
- WWS cost with EGS may be more or less than without EGS, depending on future EGS cost
- WWS with or without EGS reduces private and social costs ~60% and ~90% versus BAU
- EGS reduces land needs, helping small countries most, and storage/generation needs

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In brief

Enhanced geothermal systems (EGSs) are a new clean, renewable electricity- and heat-generating technology. If cost effective, they can help address energy insecurity, air pollution, and climate warming. Here, we find that 100% wind-water-solar (WWS) systems, with or without EGS electricity, reduce annual private and social energy costs by ~60% and ~90%, respectively, versus business-as-usual. WWS energy costs with EGS electricity are uncertain but similar to WWS costs with no EGS. EGS reduces land needs, benefiting small countries the most. Overall, EGS is helpful.

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The impact of enhanced geothermal systems on transitioning all energy sectors in 150 countries to 100% clean, renewable energy

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SCIENCE FOR SOCIETY Enhanced geothermal systems (EGSs) use heat from deep in the Earth to generate electricity and/or district heat and can thus use heat from many more locations than can conventional geothermal heat, which relies on shallow reservoirs. EGSs are clean, so if they are cost effective, they can help address energy insecurity, air pollution, and climate warming. Here, we calculate that, in future low-, mid-, and high-cost-EGS cases, private and social energy costs of 100% wind-water-solar (WWS) systems with EGS used for electricity are, respectively, lower than, similar to, and higher than costs of 100% WWS with no EGS. Regardless, 100% WWS with or without EGS reduces annual private and social energy costs by ~60% and ~90%, respectively, versus a business-as-usual case. With EGS, though, net land requirements decrease, benefiting small countries the most. Thus, EGS is a useful WWS technology that can help reduce air pollution, global warming, and energy insecurity.

SUMMARY

Enhanced geothermal systems (EGSs) involve advanced drilling methods for extracting heat from deep in the Earth to generate clean, renewable electricity and/or district heat. Here, we model transitioning 150 countries to 100% wind-water-solar (WWS) systems across all energy sectors after near-full electrification of all sectors and using conventional geothermal and solar heat for the remaining energy, when EGS electricity is excluded versus included as a WWS technology. In low-, mid-, and high-cost-EGS cases, where EGS provides 10% of electricity supply as baseload, WWS-system private energy and social energy costs, respectively, are lower than, similar to, and higher than costs without EGS. Thus, including baseload electricity appears to have little impact on 100%-WWS-system costs. With EGS, net nameplate capacities, land needs, and jobs decrease. Less land benefits small countries the most. With or without EGS, 100% WWS reduces annual private- and social energy costs ~60% and ~90%, respectively, versus business-as-usual. Thus, EGS helps a world-wide energy transition.

INTRODUCTION

High-temperature heat (120°C–300°C) from within the Earth is needed to generate geothermal electricity[1] and can be used to produce direct heat. Almost all geothermal electricity today is obtained from conventional (hydrothermal) geothermal plants, where the heat is drawn from shallow underground reservoirs of hot rocks, hot water, or steam in the Earth's crust near volcanos, geysers, hot springs, and tectonic plates. Away from such locations, temperatures in the crust naturally increase by 25 (15–40)°C/km of depth.[2] At those temperature gradients, drilling 3–8 km or more and under impermeable rock is usually needed to obtain sufficient heat to generate electricity away from conventional geothermal resources. In some cases, drilling through shallow rock with low permeability or low fluid content can also yield sufficient heat to produce geothermal electricity. In both cases, the wells drilled down to the heat reservoir are called enhanced geothermal systems (EGSs). The reservoirs associated with EGSs contain hot rocks but do not have enough natural fluid or permeability to extract the heat without drilling wells. EGS wells are drilled with hydraulic fracturing techniques borrowed from the oil and fossil gas industries but without the extraction of oil or gas. The heat from EGS wells can be used for electricity generation and/or district heating.

With EGS, two or more wells are drilled—at least one is an injection well for cold fluid to go down and at least one is a production well for hot fluid to rise. The fluid is either degraded water (contaminated groundwater, treated municipal water, industrial process water or wastewater, irrigation return water, storm water runoff, or brackish water) or freshwater,[3] often with ∼1% by weight of chemicals added,[3] just like with hydraulic fracturing. Synthetic chemicals[4] improve the fluid's ability to expand and crack rocks, thus creating permeability through them. The fluid heats as it flows through the cracked rocks. The hot fluid is then pumped through the production well to the surface, where the heat is transferred, in a binary electricity-generating plant, through a heat exchanger to a low-boiling-point organic fluid, which evaporates. The hot organic vapor then generates electricity in an organic Rankine cycle (ORC) turbine. The vapor is then recondensed and reheated to repeat the process. Any leftover waste heat can be piped to nearby district-heating storage, if any, or released into the air.

Prior to 2000, most new geothermal electricity-generating plants were dry steam or flash steam. Since then, most have been binary. In the U.S., for example, 90% of geothermal electricity plants built since 2000 have been binary.[5] An advantage of a binary plant is that it is closed loop, so no carbon dioxide (CO_2) that is dissolved in the fluid pumped up from the production well escapes to the air. Instead, heat from the well fluid is transferred to a secondary fluid. In addition, binary plants need less water than steam-based plants. Because they can operate in lower-temperature reservoirs, binary plants can also be situated in many more places than can steam-based plants. Owing to the high cost of drilling, most future EGS plants will also likely be binary, because EGS wells will be drilled only to depths needed to obtain temperatures usable for a binary plant.[3] Non-binary plants would require deeper, more expensive wells.

Because EGS can be sited in many more locations than can conventional geothermal systems, EGS can tap into an enormous heat reservoir deep in the Earth.[6,7] In theory, sufficient heat can be extracted from deep in the Earth with EGS to satisfy the world's entire energy demand for all purposes upon electrification of most energy and to provide the remaining energy with direct geothermal heat. For example, an estimate from this study of the annual average power demand in 2050 upon electrification or provision of direct heat for all energy across 150 countries, representing 99.64% of world CO_2 emissions, is ∼8,962 GW-delivered (Table 1). This translates to 78,507 TWh/year of annual energy or ∼77% of the estimated worldwide technical potential (102,000 TWh/year) for EGS electricity generation alone from a recent study.[7] However, estimates of long-term EGS resources vary significantly and depend a lot on the rate of heat replenishment.[6]

The U.S. Department of Energy separately estimates that the US has the potential to build ∼40 GW-nameplate of conventional geothermal electricity in 13 states but up to ∼5,500 GW-nameplate of EGS across all 50 states.[9] This is equivalent to ∼4,950 GW-delivered at a 90% capacity factor, which is the expected capacity factor for new geothermal plants.[10] In comparison, the US annual average power demand in 2050 upon electrification of all energy sectors estimated here is ∼945 GW-delivered (Table 1) or only 19% of the EGS potential.

About 25% of all land available worldwide may be suitable (when accounting for temperature at depth and land use restrictions) for EGS electricity generation, but the land available varies by country from 5% to 72%.[7] Less suitable regions for EGS electricity generation (but still suitable for EGS heat for district heating) are in eastern Canada, northern Russia, eastern Europe, and western Africa. More suitable areas for EGS electricity generation include most of North America, all of South America, western Europe, most of Africa, all of Asia, Australia, and New Zealand.[7] EGS can also be installed under the ocean and lakes, which may be useful for some land-constrained coastal cities and countries.

By the end of 2023, the US and the rest of the world had installed 2.67 GW-nameplate and 14.8 GW-nameplate, respectively, of operating conventional geothermal electricity generators.[11] In the US, such geothermal was located in California, Nevada, Oregon, Idaho, Utah, New Mexico, and Hawai'i. In October 2024, the US approved its first major (2 GW-nameplate) EGS-for-electricity plant in Utah, with an expected commercial operation year of 2028.[12]

The future cost per megawatt-hour (MWh) of electricity generation alone (ignoring storage costs) from EGS is still uncertain but likely to be higher than the future cost of solar or onshore wind. For example, estimates of the 2030 and 2035 levelized costs of EGS for electricity generation are \$60–\$70/MWh, and \$45/MWh, respectively.[9] In comparison, the 2023 world average levelized costs of electricity (ignoring storage) from commercial utility photovoltaic (PV), onshore wind, offshore wind, conventional geothermal (since no commercial EGS plant had been built by 2023), and hydro were already \$44, \$33, \$75, \$71, and \$57/MWh, respectively.[13] Levelized costs of solar and wind are expected to decline further due to economies of scale and technological improvements.[14]

Conventional geothermal and EGS electricity produced from binary plants are considered clean, renewable electricity since they emit no air pollutants or greenhouse gases during their operation. Our previous studies have all treated conventional geothermal electricity and heat generators as wind-water-solar (WWS) generators.[15–20] We therefore also treat EGS generators for electricity and heat as WWS generators. WWS is a system consisting of clean, renewable electricity and heat generators, storage devices, electric appliances and machines, and an expanded transmission/distribution system. WWS electricity generators include onshore and offshore wind turbines (wind); tidal and wave devices, conventional and enhanced geothermal electricity-generating plants, and hydroelectricity plants (water); and rooftop/utility solar PV and concentrated solar power (CSP) plants (solar). WWS low-temperature direct heat sources for buildings include geothermal and solar heat. The methods section and Table S2 describe the remaining components of a WWS system.

Previous studies examining the ability to replace 100% of all business-as-usual (BAU) energy with electricity and direct geothermal and solar heat from a 100% WWS system have not included EGS.[15–20] In fact, no previous modeling study that has examined 100% renewable systems (which assumes no nuclear or fossil fuels with carbon capture) has considered EGS.[21]

Some modeling studies, however, have treated EGS in limited scenarios and geographies. In one study, EGS electricity was treated along with renewables and nuclear to examine the cost of US electricity in low-carbon scenarios.[22] The study did not

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Table 1. 2050 demand, cost, and payback-time information for the BAU and base-WWS cases

Region	(a)[a] 2050 BAU annual average end-use demand (GW)	(b)[a] 2050 WWS annual average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[b] WWS mean total capital cost ($tril 2022)	(e)[c] BAU mean private energy cost (¢/kWh-all energy)	(f)[d] WWS mean private energy cost (¢/kWh-all energy)	(g)[e] WWS mean annual all-energy private and social cost = bfH ($bil/year)	(h)[e] BAU mean annual all-energy private cost = aeH ($bil/year)	(i)[f] BAU mean annual BAU health cost ($bil/year)	(j)[g] BAU mean annual climate cost ($bil/year)	(k) BAU mean annual BAU total social cost = h + i + j ($bil/year)	(l) WWS minus BAU private energy cost = (g-h)/h (%)	(m) WWS minus BAU social energy cost = (g-k)/k (%)	(n) Energy cost payback time (year) = d/(h-g)	(o) Social cost payback time (year) = d/(k-g)
Africa-East	229	67.0	−70.7	0.598	8.02	9.85	57.8	161	728	107	995	−64.0	−94.2	5.8	0.64
Africa-North	405	162.2	−60.0	1.006	11.45	7.85	111.6	406	669	719	1,794	−72.5	−93.8	3.4	0.60
Africa-South	265	113.8	−57.1	0.793	9.27	8.41	83.8	215	425	566	1,206	−61.1	−93.0	6.0	0.71
Africa-West	291	92.8	−68.1	1.074	9.64	12.12	98.5	245	1,835	263	2,344	−59.9	−95.8	7.3	0.48
Australia	189.2	84.7	−55.2	0.466	10.24	7.79	57.8	169.7	46.7	345.7	562.1	−66.0	−89.7	4.2	0.92
Canada	418.1	163.3	−60.9	0.794	8.07	7.97	114.1	295.5	56.4	517.5	869.4	−61.4	−86.9	4.4	1.05
Cen. America	332.8	136.8	−58.9	0.949	10.31	8.82	105.7	300.5	495.1	599.9	1,396	−64.8	−92.4	4.9	0.74
Central Asia	410.4	156.8	−61.8	0.967	10.46	7.78	106.9	376.1	1,341	630.7	2,348	−71.6	−95.4	3.6	0.43
China region	5,139	2,625.6	−48.9	15.52	9.65	8.23	1,893	4,345	11,392	9,697	25,435	−56.4	−92.6	6.3	0.66
Cuba	10.0	5.7	−42.8	0.048	11.71	9.65	4.8	10.2	39.5	21.7	71.5	−52.9	−93.2	8.9	0.72
Europe	2,061	872.7	−57.6	5.373	10.20	8.75	669.0	1,841	2,196	2,458	6,494	−63.7	−89.7	4.6	0.92
Haiti region	20.2	8.3	−59.1	0.065	10.77	10.11	7.3	19.1	45.3	34.3	98.7	−61.6	−92.6	5.5	0.71
Iceland	5.11	3.0	−42.2	0.003	7.39	7.15	1.8	3.3	0.4	2.3	6.1	−44.9	−70.0	1.8	0.63
India region	1,997	1,055.8	−47.1	7.102	9.86	8.16	755.1	1,725	9,545	4,053	15,323	−56.2	−95.1	7.3	0.49
Israel	27.2	13.0	−52.0	0.112	11.30	10.34	11.8	26.9	17.8	46.4	91.0	−56.1	−87.0	7.4	1.41
Jamaica	4.89	1.9	−61.5	0.016	11.50	9.96	1.6	4.9	5.3	6.7	17.0	−66.7	−90.3	5.0	1.06
Japan	329.2	174.7	−46.9	1.163	10.50	9.26	141.7	302.8	322.4	577.6	1,203	−53.2	−88.2	7.2	1.10
Madagascar	13.7	3.8	−72.1	0.043	9.70	11.94	4.0	11.6	74.5	5.0	91	−65.7	−95.6	5.6	0.49
Mauritius	4.07	1.5	−62.2	0.011	10.80	9.32	1.3	3.9	3.8	5.1	12.7	−67.4	−90.1	4.3	0.98
Mideast	1,523	698.7	−54.1	4.070	11.43	7.65	468.5	1,525	1,148	2,941	5,614	−69.3	−91.7	3.9	0.79
New Zealand	26.4	14.1	−46.5	0.078	8.02	8.31	10.3	18.5	10.0	33.1	61.6	−44.6	−83.3	9.5	1.53
Philippines	87.9	37.2	−57.7	0.332	10.10	9.89	32.2	77.7	906.0	194.6	1,178	−58.6	−97.3	7.3	0.29
Russia region	748.3	269.9	−63.9	1.390	10.31	7.67	181.3	675.6	1,025	1,444	3,145	−73.2	−94.2	2.8	0.47
South Am-NW	227.7	90.6	−60.2	0.589	8.41	8.59	68.2	167.7	281.6	343	792	−59.3	−91.4	5.9	0.81
South Am-SE	784.0	355.0	−54.7	2.311	8.40	8.71	270.7	576.7	595.1	769	1,941	−53.1	−86.1	7.6	1.38
Southeast Asia	1,207.6	578.5	−52.1	6.391	10.30	11.31	573.2	1,089	2,392	2,110	5,591	−47.4	−89.7	12.4	1.27

(*Continued on next page*)

Table 1. *Continued*

Region	(a)[a] 2050 BAU annual average end-use demand (GW)	(b)[a] 2050 WWS annual average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[b] WWS mean total capital cost ($tril 2022)	(e)[c] BAU mean private energy cost (¢/kWh-all energy)	(f)[d] WWS mean private energy cost (¢/kWh-all energy)	(g)[e] WWS mean annual all-energy private and social cost = bfH ($bil/year)	(h)[e] BAU mean annual all-energy private cost = aeH ($bil/year)	(i)[f] BAU mean annual BAU health cost ($bil/year)	(j)[g] BAU mean annual climate cost ($bil/year)	(k) BAU mean annual BAU total social cost = h + i + j ($bil/year)	(l) WWS minus BAU private energy cost = (g-h)/h (%)	(m) WWS minus BAU social energy cost = (g-k)/k (%)	(n) Energy cost payback time (year) = d/(h-g)	(o) Social cost payback time (year) = d/(k-g)
South Korea	289.3	144.3	−50.1	1.382	10.74	11.06	139.7	272.2	121.2	477.3	870.6	−48.7	−84.0	10.4	1.89
Taiwan	157.0	84.8	−46.0	0.847	10.80	10.91	81.1	148.6	92.2	337.6	578.3	−45.4	−86.0	12.5	1.70
United States	2,356.7	945.4	−59.9	6.546	10.66	8.81	729.9	2,201	1,065	3,200	6,466	−66.8	−88.7	4.5	1.14
All regions	19,560	8,962	−54.2	60.04	10.05	8.64	6,783	17,215	36,875	32,506	86,596	−60.6	−92.2	5.8	0.75

Annual average end-use (a) BAU-case power demand and (b) base-WWS (no-EGS) case power demand; (c) percentage difference between base-WWS case and BAU case demands; (d) mean value of capital cost, averaged between 2022 and 2050, of new WWS energy (USD 2022); mean value of levelized private costs (¢/kWh-all-energy-sectors, averaged between 2022 and 2050) of all (e) BAU and (f) WWS energy; mean value of annual (g) WWS private (equals social) energy cost, (h) BAU private energy cost, (i) BAU health cost, (j) BAU climate cost, (k) BAU total social cost; percentage difference between (l) WWS and BAU private energy cost, (m) and WWS and BAU social energy cost; (n) energy cost payback time; and (o) social cost payback time. Tables S25A and S25B provide the country-specific values for the base-WWS case and EGS cases, respectively. All costs are in USD 2022. Tables S20–S23 give cost parameters. A social discount rate of 2 (1–3)%[8] (Note S9) is used. H = 8,760 h/year.

[a]From Table S4A.

[b]The total capital cost includes the capital cost of new WWS electricity and heat generators; new electricity, heat, cold, and hydrogen storage equipment; hydrogen electrolyzers and compressors; ground- and air-source electric heat pumps for district heating/cooling; and long-distance (HVDC) transmission lines. Capital costs are an average between 2022 and 2050.

[c]This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2022 and 2050.

[d]The WWS cost per unit energy is for all energy, which is almost all electricity (plus some direct heat), averaged between 2022 and 2050.

[e]The annual private cost of WWS or BAU energy equals the cost per unit energy from column (f) or (e), respectively, multiplied by the energy consumed per year, which equals the end-use demand from column (b) or (a), respectively, multiplied by 8,760 h/year.

[f]The 2050 annual BAU health cost equals the number of total air pollution mortalities per year in 2050 from Table S26A, multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy) and by a VOSL calculated for each country, and multipliers for morbidities and non-health, non-climate environmental impacts (see Note S9).

[g]The 2050 annual BAU climate cost equals the 2050 CO_2equiv emissions from Table S26A, multiplied by the mean social cost of carbon in 2050 from Table S26A (USD 2022). See Note S9 for a discussion.

consider electrification of all energy sectors, provision of electricity with 100% WWS, or the impacts of EGS on land needs or jobs.

A second study used a capacity expansion model to study the impact of integrating EGS electricity into the western-US electricity grid, assuming that EGS electricity production could either follow demand flexibly or provide inflexible baseload electricity.[23] The study did not consider electrification of all energy sectors, treated nuclear as a generating source along with WWS technologies, and did not report changes in land needs or jobs.

A third study used a capacity expansion model to simulate the impact on the cost of integrating flexible EGS electricity into California electricity and gas end-use sectors.[24] The study found that including EGS could decrease system nameplate capacity needs and overall energy costs in California. The study did not consider electrification of all energy sectors, provision of all energy with WWS, or changes in land needs or jobs.

This study first compares the modeled costs and benefits, across 150 countries in 2050, of meeting BAU demand with BAU energy sources versus electrifying nearly all BAU energy across all energy sectors and meeting the new demand with 100% WWS energy, ignoring EGS. This is the first time that all 150 countries have been considered, because the International Energy Agency 2022 end-use energy (final consumption) data,[25]—used as a starting point to model 2050 energy in each country here—were previously unavailable.

The study then compares the modeled impacts of using EGS for baseload electricity, together with other WWS electricity- and heat-generating technologies, in regard to meeting demand, social energy cost, storage and generator capacity needs, land needs, and jobs among the 150 countries. Social energy cost is private energy cost plus the health and climate costs of energy. The study does not treat EGS as flexible because geothermal systems have traditionally been designed to provide constant baseload power,[23] and the study already includes flexible hydropower and many backup-electricity-storage options. Whereas, treating EGS as flexible is possible,[23,24] the additional operating cost to a geothermal plant owner of doing so is highly uncertain, and the purpose of this study is to examine the impact of an additional clean, renewable baseload electricity source on WWS system cost. Therefore, this study examines the cost of using EGS for baseload but does not compare the cost of using EGS for baseload versus for peaking.

Although the study includes existing conventional geothermal heat for district heating (Table S9), it does not include EGS heat for district heating, focusing on the potential benefits of using EGS as a WWS baseload electricity source to reduce the need for variable wind and solar. Also, to avoid substantial heat losses and pipeline costs and construction times, EGS heat for district heat should be built primarily where building and heat-demand densities are high,[26] limiting the number of sites where EGS is useful for direct heating. EGS for electricity generation can be built anywhere where a transmission line is nearby or can be connected.

Nevertheless, using EGS for district heat can provide an advantage, not explored here, in locations where it is cost-effective. EGS heat is more efficient when it is used to heat buildings through district heating than when it is used to produce electricity that is then used to power a heat pump to heat such buildings. The thermal efficiency of a binary geothermal plant converting heat to electricity is only ∼10 (5–15)%,[1] whereas a weighted average coefficient of performance of ground- and air-source electric heat pumps is ∼4 (3.2–5.2) (Table S3, footnote). Thus, converting EGS heat to building heat through electric heat pumps (ignoring wire losses) results in ∼60 (22–84)% less heat than by using direct EGS heat (ignoring pipe and other heat losses). However, EGS electricity is used here not only to help heat buildings but also for all other grid-electricity purposes.

This study assumes initially that EGS produces 10% of each country's annual average electricity supply after near-full electrification. Given the uncertainty of future EGS costs, three EGS cost cases (a low-, medium-, and high-cost case) are considered. Sensitivities of overall energy cost to EGS penetrations higher than 10% are then run. Finally, conclusions are drawn about the impact of EGS on an energy transition.

RESULTS

BAU versus base-WWS case results

First, the spreadsheet model used as part of this study indicates that electrifying all BAU energy and then providing the electricity with 100% WWS with no EGS reduce annual average end-use energy demand in 2050, across the 150 countries considered, by an average of 54.2% (from 19.56 to 8.96 TW) among all countries (Figure 1; Tables 1 and S4). Of this, 19.75 percentage points are due to the efficiency advantage of electric over combustion transportation; 4.11 percentage points are due to the efficiency advantage of using WWS electricity instead of combustion for industrial heat; 13.14 percentage points are due to the efficiency advantage of using ground- and air-source electric heat pumps instead of combustion heaters; 10.6 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels and uranium; and 6.57 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Tables S4A and S4B). Table S3 provides estimated WWS versus BAU work-output-to-energy input ratios resulting in the first three reductions. The ratios have uncertainties, but since the resulting energy reductions are so substantial, the uncertainties do not affect the conclusions here. For ammonia and steel manufacturing, energy needs are also reduced to account for different manufacturing processes with WWS[18] (Note S6). Whereas additional energy will be needed to mine for and manufacture a new WWS system between today and 2050, much of this energy would otherwise be used to refurbish (mine for and upgrade) a BAU system. By 2050, when WWS is fully built, the energy needed to refurbish WWS should be similar to that otherwise needed to refurbish BAU, but WWS will require 10.6 percentage points less end-use energy because it eliminates entirely the mining, transporting, and refining of BAU fuels (Tables S4A and S4B).

Whereas WWS reduces all-purpose end-use energy demand by 54.2%, the resulting energy is almost all electricity (with the rest, direct heat), so the world average electricity consumption increases by 85% compared with BAU (Tables S4A and S4B).

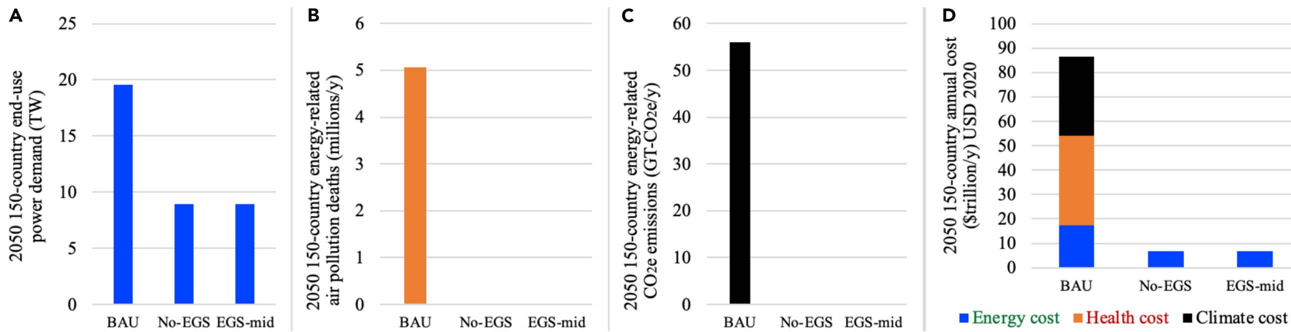

Figure 1. Comparison of main metrics between base-WWS (no-EGS) and EGS cases

(A) 2050 annually averaged end-use demand across 150 countries in the BAU case, the base-WWS case, and mid-cost-EGS (EGS-mid) case. The BAU and no-EGS numbers are from Table 1. Demand in the EGS-mid case is the same as that in the no-EGS case.

(B) Number of 2050 energy-related air pollution mortalities/year across 150 countries in each case. The BAU value is 90% of the value from Table S26A to account for the fact that ~90% of all air pollution deaths are due to energy.[19] 100% WWS eliminates all air pollution mortalities from energy in 2050.

(C) 2050 energy-related CO_2equiv emissions in each case. BAU values are from Table S26A. WWS eliminates CO_2equiv emissions.

(D) 2050 annual social energy cost (USD 2022) across the 150 countries in each case. The BAU and no-EGS numbers are from Table 1; the EGS-mid number is from Table S24.

The LOADMATCH model was run for 3 years (2050–2052) across 29 world regions encompassing 150 countries to match each region's end-use electricity, heat, cold, and hydrogen demand every 30 s (Note S6) with base-WWS-case (no EGS) supply, storage, and demand response. Time-dependent wind and solar production and building heating and cooling demands, used as inputs into LOADMATCH, were previously modeled for the same period with the gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean model (GATOR-GCMOM). LOADMATCH results for the base-WWS case are first compared here with BAU estimates.

The net present value of the capital cost of a transition from BAU to 100% WWS among all 29 regions is estimated as ~60.0 trillion (USD 2022) (Table 1). This value includes the costs of new WWS generators, electricity storage, industrial heat storage in firebricks, district heat and cold storage, hydrogen storage, hydrogen electrolyzers and compressors, ground- and air-source electric heat pumps for generating district heat and cold, and new long-distance HVDC transmission. Such capital costs include the costs of mining, transporting, and refining minerals for and manufacturing the technologies listed. The total capital cost does not include the costs of new electric appliances and machines (e.g., electric heat pumps for individual buildings, electric vehicles, industrial equipment) since it is assumed that their fossil-fuel counterparts will be replaced in any case within 15 years at similar costs.

The annual private cost of energy equals energy use per year multiplied by the system-averaged levelized cost of energy (LCOE). The 2050 mean annual WWS private energy cost among all regions is $6.78 trillion/year (Figure 1; Table 1), which is 60.6% ($10.4 trillion/year) lower than the BAU private energy cost of $17.2 trillion/year (Figure 1; Table 1). Table 1 gives both parameters for the BAU and base-WWS cases by region. Figure 2 also provides the LCOE in the base-WWS case by region. The substantial decrease in the 150-country private energy cost with WWS is due to significant decreases in energy requirements combined with more modest decreases in LCOE. Dividing the 150-country WWS capital cost by the 150-country annual private energy cost savings gives the 2050 base-WWS-case private energy cost payback time of 5.8 years, with a range of 1.8–12.5 years among all regions (Table 1).

With BAU, an estimated 5.6 million/year people may die in 2050 from energy- plus non-energy-related air pollution across the 150 countries, based on an extrapolation of 2019 World Health Organization data[27,28] to 2050 (Table S26A). This number is lower than the 2022 150-country mortality rate of 7.19 million/year due to the assumed use of more and better emission control technologies in 2050 than in 2022. Of all air-pollution-related mortalities, ~90% are estimated to be due to energy.[19] The 150-country 2050 BAU health cost of energy-related mortalities (based on the value of statistical life [VOSL]); associated morbidities; and associated non-health, non-climate environmental damage costs due to energy-related air pollution (Note S9) is estimated here as ~$36.9 trillion/year (Figure 1; Table 1). With 100% WWS, the energy-related air pollution death rate and cost both decrease to zero (Figure 1), because WWS equipment, storage, appliances, and machines emit no energy-related air pollutants. Further, the production of such equipment emits virtually no pollutants since mining and manufacturing will be powered by 100% WWS in 2050.

In 2050, energy-related emissions of CO_2 and other climate-warming pollutants in the 150 countries in the BAU case are estimated to be ~56.1 gigatons-CO_2-equivalent (CO_2equiv)/year (Figure 1; Table S26A). The 2050 climate cost damage of such emissions, based on the 2050 mean social cost of carbon of $580/ton-$CO_2$equiv (Note S9), is ~$32.5 trillion/year (Figure 1; Table 1). The 2050 climate cost damage due to energy-related CO_2equiv emissions with WWS is zero (Figure 1) because WWS eliminates CO_2equiv from energy.

Summing BAU's annual private energy, health, and climate costs yields a 2050 total BAU social cost of $86.6 trillion/year (Figure 1; Table 1). Converting to 100% WWS eliminates the energy-related health and climate costs and reduces the private energy cost to $6.78 trillion/year (Figure 1; Table 1), which equals the WWS social energy cost. Thus, WWS, even without EGS,

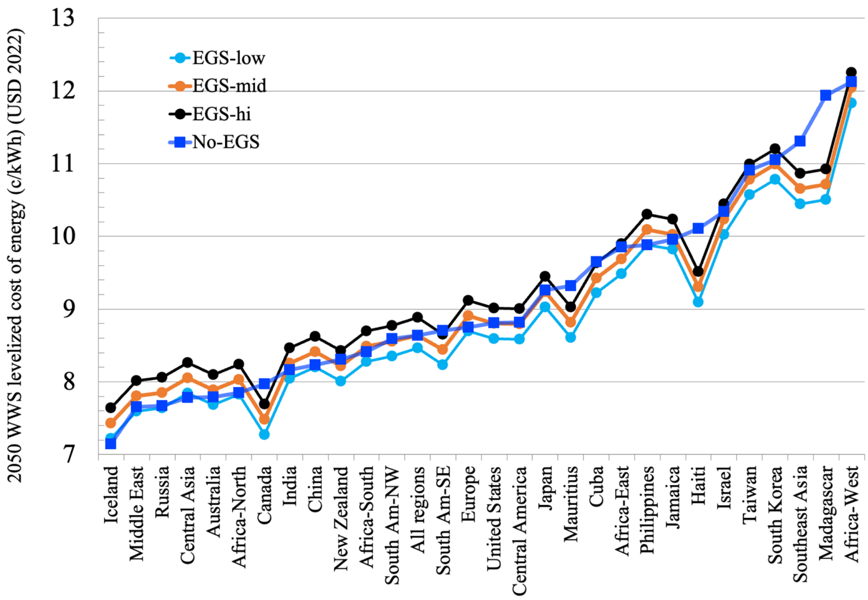

Figure 2. Modeled 2050 system-averaged LCOE in the base-WWS case (no-EGS case) and in the EGS-low-, EGS-mid-, and EGS-hi-cost cases by region and for all regions combined ("all regions")

Table S24 provides the no-EGS-case and EGS-mid-case values.

reduces annual social energy cost by 92.2% ($79.8 trillion/year) in 2050, giving the social cost payback time due to switching of 0.75 years, with a range of 0.29–1.89 years among all regions (Table 1).

Transitioning to 100% WWS without EGS from BAU may also produce 55.4 million new long-term, full-time jobs (22.3 million construction jobs and 33.1 million operations jobs) while costing 27.4 million jobs, resulting in a net increase of 28.0 million long-term, full-time jobs produced among the 150 countries in 2050 (Table S30). Net job gains occur in 24 of 29 regions. Only Africa-East, Africa-North, Africa-West, Canada, and the Russian region experience net job losses. More jobs, not accounted for here, also arise from the need to build more electrical appliances and to improve building energy efficiency.

The new land footprint (defined in Note S10) needed for new WWS generators, in the absence of EGS, is ~0.18% of the 150-country land area (Table S28A), almost all for utility PV and CSP. The only land spacing area needed with WWS is between onshore wind turbines. This spacing area equals ~0.39% of the 150-country land area (Table S28A). New land footprint plus spacing areas for 100% WWS with no EGS thus represents ~0.57% (702,942 km^2) of the 150-country land area (Figure 3), and most of this land is multipurpose spacing. Even the footprint for utility PV that is raised a few meters above farmland (agrivoltaics) can allow crops to grow and can thus also be used for dual purposes.

Results for WWS with versus without EGS electricity

The main hypothesis of this study is that the use of EGS electricity together with other WWS technologies may reduce the cost and land requirements of a transition to 100% clean, renewable energy across all energy sectors. To test this hypothesis, three additional sets of simulations were run with LOADMATCH across the 29 regions encompassing the 150 countries. All such simulations assume that EGS provides 10% of the annual average regional all-purpose energy supply in the form of baseload electricity. Although uncertain, this assumption, in general, appears technically feasible given both the land eligibility and heat available at depth for electricity generation by country throughout the world.[7] Sensitivity tests are then performed for some regions to quantify the impact of different EGS penetrations on cost. Such simulations indicate that the assumption of a 10%, rather than a lower or higher EGS penetration, has no impact on the conclusions of this study.

The capacity factor of EGS for electricity is assumed here to be 90% (Table S12B), based on estimates of geothermal electricity's potential capacity factor.[10] Thus, each individual EGS plant is assumed to run at 100% nameplate capacity for 90% of the hours in a year (e.g., is down for 10% of the hours in a year). However, maintenance downtimes are assumed to be staggered evenly such that the output, when summed among all EGS plants in a region, is 90% of peak output 100% of the time. The resulting nameplate capacity of EGS assumed among all countries is 1.08 TW (Table S10B). This is only 9% of the world technical potential (12 TW) for EGS electricity generation, as estimated by one study.[7]

Three EGS-electricity cases were performed, each with a different assumed 2035 capital cost of EGS: $4,640/kW-el, $9,000/kW-el, and $13,425/kW-el. Table S20 provides additional assumed cost characteristics of EGS and other WWS electricity- and heat-generating technologies. The estimated capital cost of EGS in 2023 was already down to $14,700/kW-el.[9] The EGS capital cost projected by the U.S. Department of Energy for 2030 upon further technology improvements in drilling is $4,700–$5,000/kW-el, and for 2035, it is $3,700/kW-el (resulting in an LCOE of $45/MWh).[9] However, our projected 2035 conventional geothermal electricity middle-value capital cost is $4,640/kW-el (Table S20). Since the EGS capital cost cannot be lower than the conventional geothermal capital cost, we assume the conventional geothermal capital cost in 2035 to be the lower limit for EGS in 2035. We assume the upper limit for EGS to be slightly lower than the 2023 capital cost of EGS. Operation and maintenance costs, decommissioning costs, and plant/reservoir lifetime are assumed to be the same as those of conventional geothermal (Table S20), although this is a simplistic assumption.

Figure 2 compares the system-averaged LCOE for each region in the base-WWS case with those from the three EGS-WWS cases. The figure shows that the mid-cost-EGS case results in similar LCOEs across almost all regions as the base-WWS

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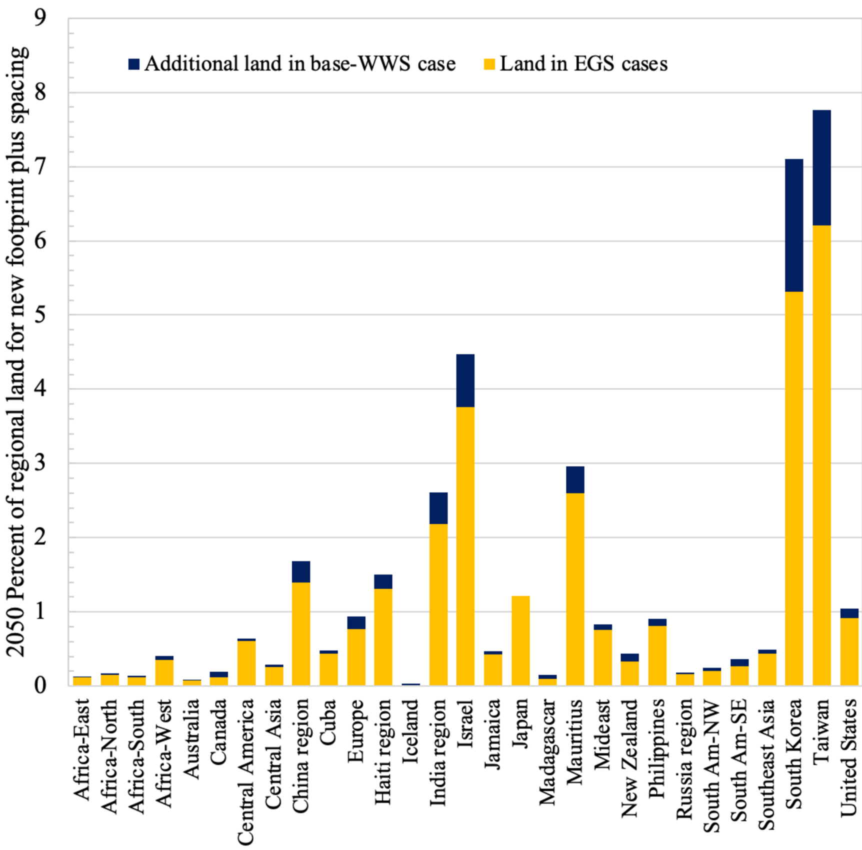

Figure 3. Calculated percent of regional land area for the new footprint plus spacing areas needed in the base-WWS case and the EGS cases (which all use the same amount of land)

Footprint and spacing areas are defined in Note S10. Tables S28A and S28B give the numbers corresponding to this figure.

case. The low- and high-cost-EGS cases result in lower and higher LCOEs, respectively, than does the base-WWS case. Among all regions, the average LCOE (Table S24) in the base-WWS case is 8.64 US cents/kWh, which compares with 8.47, 8.68, and 8.89 cents/kWh in the low-, mid-, and high-cost-EGS cases, respectively, confirming the similarity of system-averaged LCOEs between the mid-cost-EGS case and the "no-EGS" case. Although EGS reduces the nameplate capacities of wind, utility PV, and batteries and their associated costs (discussed next), the higher cost of EGS versus other WWS technologies causes the base-WWS-case system-averaged LCOE to be similar to the mid-cost-EGS-case system-averaged LCOE.

The annual social cost of energy is the sum of the annual private, health, and climate costs of energy. Figure 1D shows that the annual private costs of WWS energy, both without and with EGS (in the mid-cost-EGS case), are ∼60.6% and ∼60.4% less, respectively, than the annual private cost of BAU energy. This is mostly because WWS reduces energy requirements by 54.2% versus BAU (Figure 1A). Figure 1D also shows that the annual social costs of WWS energy, without and with EGS, are ∼92.2% and ∼92.1% less, respectively, than BAU energy, because WWS eliminates energy-related health and climate costs on top of reducing annual energy costs, relative to BAU. Given that energy cost is only a portion of social cost and that the low and high LCOE estimates of EGS differ by only ±2.4% from the mid-cost-EGS estimate, EGS reduces private energy cost by 61.4%–59.5% and social cost by 92.3%–91.9%, relative to BAU, among all EGS cases. Thus, private and social cost differences between BAU and WWS dwarf cost differences between WWS without versus with EGS, regardless of EGS LCOE.

Although the mid-cost-EGS case is similar in annual cost to the base-WWS case, differences arise in land requirements and jobs. Among the 150 countries, the base-WWS case required 0.57% of world land (0.18% for footprint and 0.39% for spacing) for new energy generators (Figure 3; Table S28A); in the mid-cost-EGS case (and all EGS cases), these numbers decrease to 0.48% (0.16% for footprint and 0.32% for spacing) (Figure 3; Table S28B). The reason is that the nameplate capacities of onshore wind and utility PV decrease between the base-WWS case and the EGS cases. Onshore wind nameplate capacity decreases from 10.4 to 8.79 TW, and utility PV nameplate capacity decreases from 19.0 to 16.8 TW (Figure 4; Tables S10A and S10B). Although total EGS nameplate capacity increases from 0 to 1.08 TW (Tables S10A and S10B), the installed power density (MW/km^2) of each EGS plant is much larger than that of a wind farm or utility PV plant (Table S27). The use of EGS also reduces the need for offshore wind nameplate capacity among the 150 countries by 9.5%, from 3.78 to 3.42 TW, and of battery storage (BS) by ∼27.5%, from 8.07 TW/32.28 TWh to 5.85 TW/23.42 TWh (Figure 4; Tables S10A, S10B, and S14). In sum, the use of EGS reduces generator and storage nameplate capacities and land requirements significantly in a 100% WWS world.

Figures S3–S31 show time-series plots over all 3 years and for a 100-day window during all years of energy demand plus losses plus changes in storage matching energy supply, in the base-WWS case and the EGS cases, for each of the 29 regions. No blackout occurs in any region. Figures S3–S31 also show the components of generation in each case (second panel) and a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution (T&D) losses; and changes in storage (electricity, heat, cold, and hydrogen storage) (third panel). With EGS, geothermal generation is notably larger (second panel in each figure), wind and/or solar generation is smaller (second panel), and BS is usually lower (third panel) than in the base-WWS case in each region. The difference in "change in all

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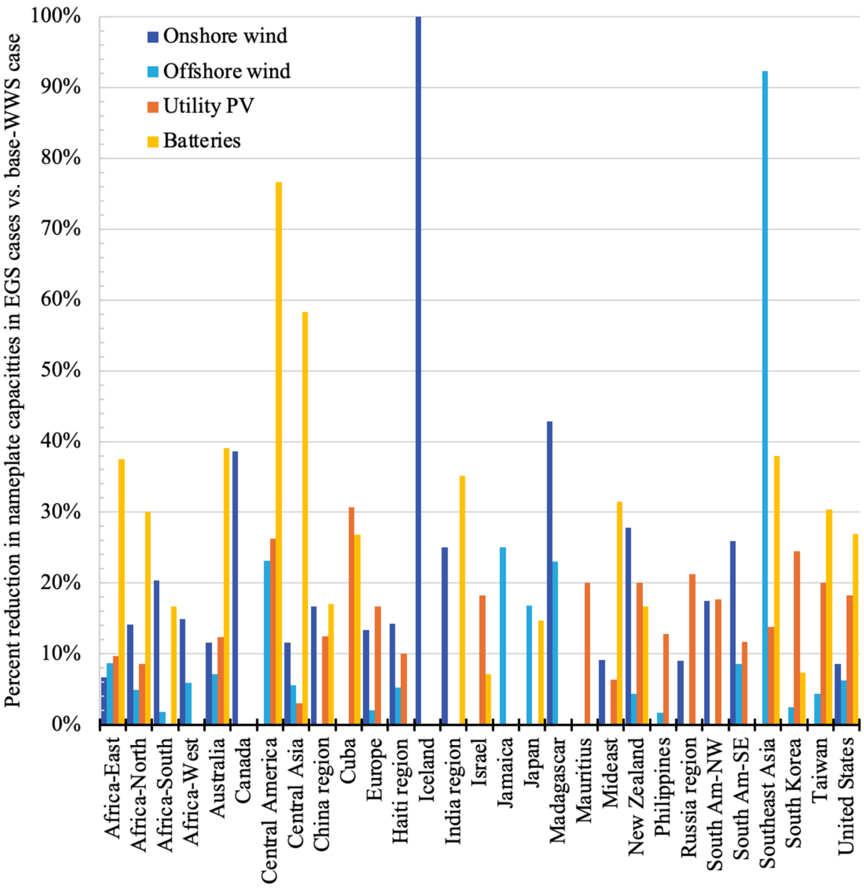

Figure 4. Percent reductions in the modeled nameplate capacities of onshore and offshore wind, utility PV, and batteries by region between the base-WWS case and all three EGS cases (all of which have the same nameplate capacities)

Tables S10A and S10B give the absolute nameplate capacities of onshore and offshore wind and utility PV in the base-WWS case and EGS cases, respectively. Tables S16A and S16B give the same for batteries.

storage" between the base-WWS case and the EGS cases for each region in Figures S3–S31 is the change in BS.

By comparing the change in BS with the change in EGS capacity for each region in Figures S3–S31, one can see that the use of EGS as baseload electricity increases the minimum electricity supply, avoiding the need for batteries to provide that additional supply when other generators are unavailable. For example, in the China region, 315.4 GW of EGS is added (Table S10B). With an annual average capacity factor of 90% (Table S12B), the available EGS supply is ~284 GW. Simultaneously, battery capacity decreases by 160 GW (Table S14). It does not decrease further because batteries are needed for both peaking (GW) and storage (GWh), and in China, the remaining battery capacity is needed for storage.

The decreases in wind, PV, and battery nameplate capacities that occur when EGS is used reduce net job creation among all 150 countries from 28.0 million more long-term, full-time jobs created than lost in the base-WWS case versus BAU to 24.0 million in the EGS cases (Figure 5; Table S30). Although new EGS plants require more jobs per MW-nameplate capacity during construction than new wind, solar, or battery installations do (Table S29), the reduction in nameplate capacities of wind, solar, and batteries (Figure 4) significantly exceeds the increase in nameplate capacity of EGS, resulting in many fewer jobs with EGS.

Figure 6 shows the sensitivity of LCOE to increasing EGS penetration, from 0% to 70% of all electricity supplied after nearly full electrification of Europe and Taiwan, for the mid-cost-EGS case. For Europe, moving from 0% to 10% EGS increases system-averaged LCOE, whereas moving from 10% to 20% EGS decreases LCOE to slightly below that at 0% penetration. However, increasing penetration further, from 20% to 70%, increases LCOE back to above the LCOE at 0% penetration. For Taiwan, increasing EGS from 0% to 30% penetration decreases LCOE but increasing EGS from 30% to 70% increases LCOE, although not to the level at 0% penetration. Thus, both Europe and Taiwan experience minimum LCOEs at EGS penetrations of 20%–30%. In Europe, the minimum LCOE is only 3.3% lower than with no EGS. In Taiwan, it is only 7.2% lower than with no EGS. In the high-cost-EGS case in Europe, the LCOE at 20% EGS penetration is 1.5% higher than at 0% penetration. In the high-cost-EGS case in Taiwan, the LCOE at 30% penetration is only 1.4% lower than at 0% penetration.

The low sensitivity of LCOE to EGS penetration in Figure 6 supports the contention that the selection of 10% EGS penetration for the main scenario here does not affect the conclusion that geothermal is a cost-effective WWS technology. A penetration of 5%, for example, results in little cost difference versus 10% penetration. Since geothermal electricity is treated as baseload electricity here, the results illustrate how EGS may obviate the need for nuclear, another baseload electricity source. Many have suggested that nuclear is needed to keep costs low due to the greater need for storage with WWS. However, Figure 6 illustrates that WWS costs without baseload EGS electricity are similar to, and sometimes less than, those with baseload EGS electricity. The results here also suggest that the use of a baseload electricity source (EGS) may have little impact on the cost of an all-sector 100% WWS system, as discussed next.

DISCUSSION

Results here suggest that EGS electricity can contribute to a 100% clean, renewable energy transition across all energy sectors throughout the world. Whereas future costs of using EGS are uncertain, the mid-cost-EGS case (100% WWS including 10%

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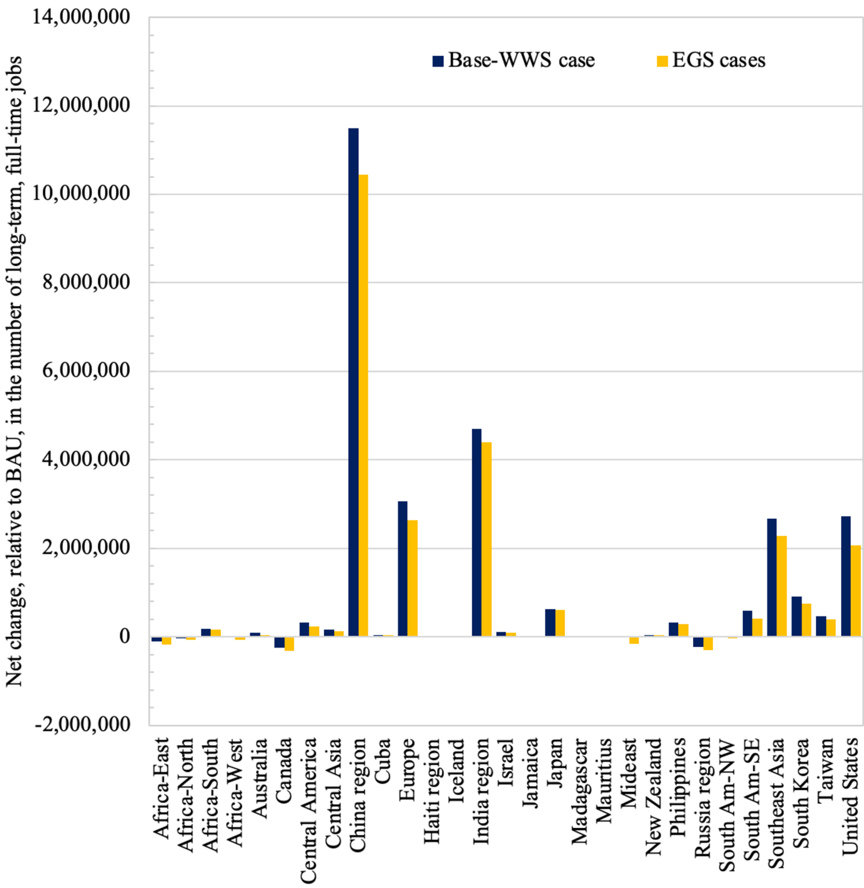

Figure 5. Estimated net change, relative to the BAU case, in long-term, full-time construction plus operation jobs produced, minus jobs lost in each the base-WWS case and all three EGS cases (which all of which have the same number of job changes)

Table S30 provides numerical values and separates job creation versus loss.

EGS for electricity) here results in a cost similar to that of using 100% WWS without EGS (Figures 1 and 2). Moreover, annual private and social energy costs in all EGS cost cases are much lower than in the BAU case. Even in the high-cost-EGS case, annual private and social energy costs are ~59.5% and 91.9% lower, respectively, than in the BAU case. The main benefits of WWS with EGS over WWS with no EGS are the significant reductions in nameplate capacities of wind, solar, and batteries and in the land needed. On the other hand, using EGS may decrease the numbers of long-term, full-time jobs needed for a transition.

Some argue that increasing the supply of intermittent WWS from 20% to 80% of demand may not raise energy costs very much, but that increasing WWS from 80% to 100% of demand may increase costs significantly. If that is true, and if EGS is treated as baseload electricity (as done here) like a conventional nuclear reactor, then 100% WWS without EGS should be much more expensive than WWS with EGS. However, that result was not found here. Figure 2, for example, shows that 100% WWS with 0% EGS (no-EGS case) is, in fact, less expensive than 100% WWS with 10% EGS ("EGS-mid" case) in 12 out of 29 regions. Averaged over all regions, the cost difference between the two cases is 0.0%, with a range from 3.9% lower to 10.3% higher with no EGS versus with 10% EGS. Figure 6 further shows that in Europe, for example, 0% EGS is less expensive than 10% EGS, more expensive than 20% EGS, and less expensive than 40% EGS, indicating no trend. Thus, a rapid increase in cost with intermittent WWS increasing from 80% to 100% penetration is not found here. Some reasons this study does not see rapidly rising costs as WWS approaches 100% may be that this study includes sector coupling, demand response, many flexible loads, hydrogen production, heat and cold production, and other factors not treated in other studies examining this issue.

The argument that costs increase exponentially with increasing intermittent WWS above 80% also appears to be overstated. A National Renewable Energy Laboratory study,[29] for example, examined WWS penetrations of 0%, 80%, 90%, 95%, 97%, 99%, and 100% in the US without sector coupling, flexible loads, demand response, hydrogen production, or all-electric heat or cold production. Table S10 of that study indicates that the system electricity cost, averaged among all 23 scenarios, increased from $33/MWh with 80% WWS to only $39/MWh with 100% WWS, thus by only 19%, with a range of 1.4%–38% among scenarios. Such an increase may be nonlinear but is not exponential. Further, the $39/MWh average system cost with 100% WWS is lower than the cost of new fossil gas in the US in 2025, $48–109/MWh,[30] again indicating that 100% WWS can be low cost.

Potential concerns with EGS include the slight increase in the risk of earthquakes and the potential for contaminating groundwater if chemicals are mixed in the water used for cracking rock. In addition, a risk always exists that the wells drilled do not produce as much heat, thus geothermal electricity, as anticipated.

Whereas risks of earthquakes from EGS exist, they are much smaller overall than those from hydraulic fracturing for fossil gas. The reason is the much larger number of wells drilled every year for fossil gas (up to 50,000 per year in central North America alone)[31] than will be needed for EGS. For example, the present study examines the buildout of 1.08 TW of EGS across 150 countries (114 GW in the US) (Table S10B). If each electricity-generating plant is 100 MW in nameplate capacity and each plant requires two wells, the number of wells required among the 150 countries is 21,600 (with 2,280 in the US). These wells are needed once every 45 years (Table S20), so they represent only 0.96% (worldwide) and 0.10% (US) of the number of fossil gas wells needed during 45 years in central North America alone.

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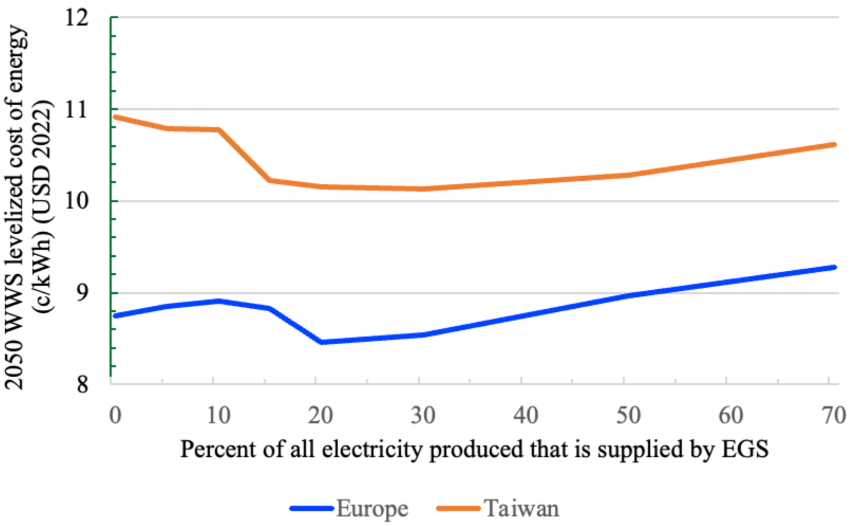

Figure 6. Modeled 2050 system-averaged LCOE as a function of percent of all electricity produced that is supplied by EGS after near-full electrification of all energy sectors in Europe and Taiwan in the mid-cost-EGS case

Zero percent penetration is the base-WWS case here. Here, 10% penetration is the mid-cost-EGS case.

Thus, the earthquake risk of EGS should be much smaller than that of hydraulic fracking. Nevertheless, siting EGS facilities away from tectonic activity can minimize the potential of a small EGS-related earthquake triggering a larger one.

The risk of groundwater contamination from chemicals used with EGS should similarly be much smaller than with fossil gas drilling owing to the fewer number of wells drilled with EGS, particularly since drilling with EGS is deeper than it is with hydraulic fracking, so the chemicals are injected deeper with EGS. Regardless, regular monitoring of near-surface groundwater near EGS wells would help to alleviate concerns of contamination.

In addition, the risk of a well not being re-supplied with heat fast enough[6] or not meeting its expected production will likely decline as technologies for siting EGS improve and the cost of drilling deeper declines.

Similarly, the use of degraded water with EGS could cause a buildup of minerals and organics on surfaces deep in the well, reducing heat transfer to the fluid over time. If this issue occurs, one remedy may be to filter the water ahead of its use.

An advantage of EGS is that it is a low-land-requirement WWS option. This is especially important in countries that have limited land area available for utility PV and onshore wind and/or have limited offshore wind resources. Several small countries or territories, including Gibraltar, Singapore, South Korea, Taiwan, and Hong Kong may require the use of offshore solar PV or large amounts of offshore wind to go to 100% WWS across all energy sectors in the absence of EGS. Using EGS electricity allows these countries to reduce their land and offshore requirements substantially at similar cost to a no-EGS system. For example, the overall land requirements for South Korea and Taiwan, the two most land-constrained regions examined, decreased from 7.10% and 7.76%, respectively, of country land area required for total footprint plus spacing of WWS with no EGS (and ignoring the potential for offshore solar and more offshore wind), down to 5.31% and 6.21%, respectively, of land area required for WWS with EGS (Tables S28A and S28B).

Another advantage of EGS is its ability to provide constant electricity for long periods. This allows it to avoid creating sudden, unplanned high voltage/current swings on the grid, thereby reducing the need for battery backup, which is necessary for intermittent generators.

EGS electricity and heat may benefit small-scale off-grid energy systems as well as large-scale grids. Off-grid communities far from transmission grids require time-varying electricity and heat. New off-grid data centers require relatively constant electricity but often have trouble connecting to the grid in a timely manner because of long interconnection queues. EGS plus solar, wind, batteries, and/or green hydrogen production and fuel cells can potentially provide constant year-round electricity for datacenters and load-matching electricity and heat for off-grid communities.

An uncertainty of this study is the extent to which bottlenecks in the buildout, by 2050, of a 100% WWS system, with or without EGS, may occur. Bottlenecks may arise because of limited availability of critical minerals, supply chain constraints, or lack of financing.[32,33] This study does not assume that these bottlenecks will not occur. Instead, it examines whether countries can obtain a stable grid at low cost in 2050 if a buildout is successful because bottlenecks have been overcome. Therefore, the study does not examine the country-by-country potential for bottlenecks. Nevertheless, some discussion on the availability of materials needed for a transition is warranted.

Several raw materials needed for a buildout include precious metals (e.g., lithium, rare-earth elements, and cobalt), industrial metals (e.g., aluminum, chromium, copper, and manganese), and iron ore. In 2021, the annual mass of precious metals mined worldwide was ~1.5 million tons, that of industrial metals was ~182 million tons, and that of iron ore was ~2.6 billion tons.[34] This compares with ~15 billion tons of coal, oil, and gas mined per year. Thus, fossil fuels, iron ore, industrial metals, and precious metals represented ~84.4%, 14.6%, 1.02%, and 0.008% of mined material, respectively.

The mass of mined precious metals, in particular, was only ~1/10,000th that of mined fossil fuels. Replacing the 1.475 billion vehicles in the world today (1.1 billion passenger cars and 375 million trucks and buses) with lithium-based battery-electric vehicles would require ~46.7 million tons of lithium (70 kWh per passenger vehicle and 900 kWh per truck or bus multiplied by 4.35 kg-LMFP [lithium-manganese-iron-phosphate] material in batteries per kWh and 0.0259 kg-Li per kg-LMFP). However, that lithium stays in a vehicle during the 15- to 25-year life of the vehicle. At the end of a vehicle's life, recycling of the vehicle's lithium for another battery or reusing the battery for stationary electricity storage[35] can significantly reduce the future need for lithium mining.[36] Thus, during 100 years of vehicle use, less than 100 million tons of lithium may be needed for vehicle batteries. This is only ~0.0067% of the fossil-fuel mass that would otherwise be mined for all purposes during the same 100 years if a transition to 100% WWS did not occur. Thus, a transition to WWS should reduce overall mining by a factor of 15,000. However, a transition may still be slowed by bottlenecks. Future work is warranted to examine this issue in more detail.

In sum, EGS has an enormous electricity-generating potential throughout the world. This study finds that EGS electricity, when used with other WWS technologies upon near-full electrification of all energy sectors, can help to address air pollution, global warming, and energy insecurity problems in every country examined but particularly in countries with limited land resources. The use of EGS electricity reduces wind, solar, and battery generation capacity needs and land requirements versus no EGS. EGS also reduces the number of jobs versus no EGS. The future capital cost and penetration of EGS are still uncertain; thus, it is difficult to determine if WWS with EGS will result in a slightly lower or slightly higher overall levelized energy cost than WWS without EGS. EGS appears to achieve a minimum system-averaged cost when its penetration reaches 20%–30% of electricity supply after nearly full electrification. However, the cost difference between systems with EGS and without EGS are small, even accounting for the uncertainties in EGS cost. Thus, using EGS as a baseload electricity source appears to have little impact on the cost of an all-sector 100% WWS system.

Importantly, though, because electrification plus the use of WWS with or without EGS reduces end-use energy requirements so significantly versus BAU, WWS with or without EGS electricity reduces annual private and social energy costs significantly (by ~60% and 90%, respectively) versus BAU. Thus, EGS is another WWS technology that can help address air pollution, global warming, and energy insecurity. Because EGS can be used as a baseload electricity source, it also obviates the need for nuclear electricity.

METHODS

Table S2 summarizes the components of the WWS system modeled here. WWS electricity generators were previously defined. WWS electricity storage technologies include conventional hydropower storage (CHS), pumped hydropower storage (PHS), CSP storage (CSPS), BS, and green hydrogen storage (GHS). Industrial-process heat for industry is stored in firebricks. Low-temperature heat for buildings is stored in water tanks, soil, and water pits. Cold is stored in water tanks and ice. WWS electricity running through electrolyzers produces green hydrogen, which is stored for grid and non-grid purposes (steel and ammonia manufacturing and extra long-distance transport).

In individual buildings, ground- and air-source electric heat pumps provide heat and cold for air and heat for showers, dishwashers, clothes washers, and clothes dryers. Electric induction cooktops replace gas stoves. Large ground- and air-source electric heat pumps provide heat and cold for district heating and cooling systems and low-temperature heat for industry. Electric arc furnaces, induction furnaces, resistance furnaces and boilers, electron beam heaters, and dielectric heaters provide high- and medium-temperature heat for industry. Firebricks heated by direct resistance heating replace most industrial heating technologies to provide all-temperature heat for industry.[20]

Transport relies on battery-electric vehicles for all but very-long-distance trucks, airplanes, ships, and trains, which are propelled by hydrogen-fuel-cell electricity. WWS also assumes energy efficiency improvements (more efficient appliances, machines, and insulation) and reduced energy use (e.g., improved public transit; increased biking, telecommuting) beyond those with BAU.

The work is carried out with three types of models: (1) a spreadsheet model[30] (Note S2) that feeds its output into (2) GATOR-GCMOM, a global weather-climate-air pollution model (Note S3), which in turn supplies its output into (3) LOADMATCH[15–20] (Notes S4–S7), a model that matches demand with supply, storage, and demand response (methods).

The modeling scenarios here build on previous WWS studies for 149 countries[19,20] by extending them to 150 countries (adding Guyana) and using newer (2022) International Energy Agency (IEA) energy data.[25] In 2023, the 150 countries were responsible for 99.64% of world fossil-fuel CO_2 emissions (Table S26A). For LOADMATCH, the 150 countries are combined into 29 regions (Table S1), including 13 multi-country regions and 16 individual countries or pairs of countries. A region is either a group of countries close to one another, which are likely to share an electrical grid; an individual island country; or an individual large country. Grid analyses are performed with LOADMATCH in each region, both with EGS excluded and included. The models are described briefly next.

Spreadsheet model

The spreadsheet model[37] first projects IEA[25] total final consumption, also called energy consumption in end-use sectors or end-use energy demand, from 2022 to 2050 in a BAU case. Consumption is projected for each of seven fuel types (oil, natural gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat) in each of six end-use energy sectors (residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other), for each of the 150 countries (Note S2). The projections assume moderate economic growth, population growth, energy consumption growth, modest energy policy changes that vary by world region, use of some renewable energy, modest energy efficiency measures, and reductions in energy use. Based on this calculation, the BAU annual average total final consumption, averaged among all 150 countries, increases from 13.3 TW in 2022 to 19.6 TW in 2050 or by 47.0% (Tables S4A and S4B).

The spreadsheet model then estimates the 2050 reduction in BAU energy demand due to converting each fuel type in each end-use sector in each country to electricity, electrolytic hydrogen, low-temperature heat, or high-temperature heat and providing the electricity, hydrogen, and heat with WWS technologies (Note S2). The reductions in end-use energy demand are calculated using conversion factors (Table S3) that vary by fuel type within each energy sector. The factors assume the use of vehicles, equipment, and machines running primarily on electricity (Note S2). Overall, ~97% of the technologies needed for a transition are commercial currently. Those that are not commercial are primarily long-distance aircraft and ships, which are proposed to be powered by hydrogen fuel cells,[8] and some industrial processes.

The spreadsheet model is then used to estimate nameplate capacities of WWS electricity and heat generators that can meet the annual average WWS demand in each country (Table S8; Note S2). Tables S4A and S4B provide 2022 end-use demands, end-use demands projected to 2050 in a BAU case, and 2050 end-use demands with WWS, converted from BAU, for each energy sector in each country.

GATOR-GCMOM

2050 nameplate capacities from the spreadsheet model for each WWS electricity and heat generator in each country are then used as inputs into GATOR-GCMOM, which is a global air pollution-weather-climate model (Note S3). The model has participated in 14 model inter-comparisons, and its results have been compared with data in 34 studies.[17] It is used here to predict meteorological data and building heating and cooling requirements at a 30-s time resolution, a 2° by 2.5° horizontal space resolution, and a 30-m vertical resolution (in the bottom 1 km) globally, from 2050 to 2052. Outputs include continuous (at 30-s resolution) onshore and offshore wind electricity supply at 100-m hub heights, rooftop solar PV electricity supply, utility PV electricity supply, CSP electricity supply, solar heat supply, building cooling demand, and building heating demand in each of 150 countries.

GATOR-GCMOM is initialized under 2050 astronomical and climate conditions. Initial greenhouse gas levels in the model are presumed to be those projected from the present to 2050 in a BAU case. The model accounts for competition among wind turbines for available kinetic energy in all three spatial dimensions (Note S3). It also calculates changes in air temperature due to (1) wind turbine extraction of kinetic energy, (2) PV extraction of solar radiation, (3) CSP extraction of solar radiation, and (4) extraction of solar radiation by solar thermal devices (Note S3). Time- and space-dependent wave electricity output from GATOR-GCMOM is calculated proportionally to co-located offshore wind output. GATOR-GCMOM calculates building cooling and heating demands by comparing modeled outdoor temperatures over time in each near-surface model grid cell within each country with an assumed comfort temperature for buildings while accounting for building characteristics (Note S3). GATOR-GCMOM output is fed offline into LOADMATCH.

LOADMATCH

LOADMATCH (Notes S4–S7) simulates the matching of electricity, high-temperature heat, low-temperature heat, cold, and hydrogen demand with supply and storage over time. LOADMATCH is a "trial-and-error" simulation model. It works by running multiple simulations for each region, one at a time. Each simulation advances one time step at a time, just as the real world does, for any number of years. The main constraints are that electricity, low- and high-temperature heat, cold, and hydrogen demands plus losses, adjusted by demand response, must each meet corresponding WWS supplies and storage every 30-s time step of a simulation. Thus, the model conserves energy exactly each time step. The simulation stops if a demand is not met during a time step. Inputs of either the nameplate capacity of one or more generators (Tables S8 and S10); the peak charge rate, peak discharge rate, or peak energy capacity of a storage device (Tables S8 and S14); or characteristics of demand response are then adjusted one at a time after examining what caused the demand mismatch (hence the description trial-and-error model). Another simulation is then run from the beginning. New simulations (usually less than 10) are run until demand is met during each time step of the entire simulation. After demand is met once, another 4–20 simulations are generally performed with further adjusted inputs based on user intuition and experience to generate a set of solutions that match demand during every time step. From the set, the lowest-cost solution is then selected. Because LOADMATCH does not permit load loss at any time, it is designed to exceed the utility industry standard of load loss once every 10 years.

LOADMATCH is not an optimization model, so it does not find the lowest-cost solution. Instead, it produces a set of low-cost solutions from which the lowest levelized-cost solution is selected. Its advantage is that it treats many more processes while taking orders of magnitude less computer time at a much shorter time step than an optimization model. For example, the simulations here required only 1 min each to solve 3 years of simulation with a 30-s time step (~3.2 million time steps total) on a single computer processor (Note S4). In comparison, no optimization model to date has run for 3 years at a 30-s resolution and with the number of parameters treated here. The reason is that the computer time of an optimization code increases quadratically with the number of variables (the number of time steps multiplied by the number of parameters) simulated,[38] which is why optimization codes generally (but not always) use 1 h or more time steps and solve far fewer parameters than treated here. In addition, the present study involves many nonlinear relationships. A trial-and-error model does not seek the lowest-cost solution, so it has no problem with such relationships, but an optimization model must be nonconvex to solve these relationships. A nonconvex model is extremely difficult to converge in any reasonable computer time with the number of variables treated here. Therefore, it may be fair to say this study could not have been performed with an optimization model.

Whereas different users of LOADMATCH may obtain slightly different low-cost solutions from one another, all such solutions will have zero load loss. The more simulations that each user runs, each with a slightly different set of inputs, the more the lowest-cost solutions among all users will converge. By documenting their adjustments, users can help others obtain solutions for the same dataset faster.

Table S2 summarizes the processes in LOADMATCH. Note S4 describes many of the model's inputs. Several of these inputs are first estimates of nameplate capacities from the spreadsheet model, and some other inputs are 30-s-resolution outputs from GATOR-GCMOM. LOADMATCH treats several electricity storage options: CHS, PHS, CSPS, BS, and GHS (Table S2). Table S14 provides the maximum charge rates, discharge rates, storage capacities, and storage times for each technology. Table S8 summarizes the peak discharge rates of all generators and electricity and thermal storage options among all 150 countries. Grid stability is obtained in eight ways (Note S8).

Note S6 discusses the time-dependent demand profiles, maximum storage sizes, and flexible and inflexible demand treatments in LOADMATCH. Note S7 describes the model's order of operation, including how it treats excess generation over demand and excess demand over generation. Note S7 also provides details of how LOADMATCH treats demand response. Once LOADMATCH simulations are complete, energy costs, health costs, climate costs, and job numbers between WWS and BAU (Notes S9 and S11) and new land requirements (Note S10) are calculated.

Whereas T&D line costs and energy losses are accounted for, this study assumes transmission lines are perfectly sized and interconnected within each region simulated so no grid congestion occurs. Since grid stability at low cost can be obtained even when countries[39] or states[40] are either islanded or interconnected, the assumption of such a transmission system should not impact the conclusions here. The study assumes a social discount rate of 2 (1–3)% given that this is a social cost analysis (Note S9), and a survey of experts suggests that this is the appropriate rate and range for such an analysis.[41]

RESOURCE AVAILABILITY

Lead contact

The lead contact for this project is Mark Z. Jacobson (jacobson@stanford.edu).

Materials availability

No materials were used for this study.

Data and code availability

All data supporting the findings of this study are presented in the paper and its supplemental information and in the spreadsheet model.[37] The LOADMATCH source code used, which was modified for the present application, is available at https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/25-10-31-LOADMATCH.pdf.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.Z.J.; methodology, M.Z.J.; investigation, M.Z.J.; software, M.Z.J.; writing – original draft, M.Z.J.; and writing – review and editing, M.Z.J., D.J.S., Y.F.F., A.M., and G.C.D.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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REFERENCES

1. Zarrouk, S.J., and Moon, H. (2014). Efficiency of geothermal power plants: A worldwide review. Geothermics *51*, 142–153. https://doi.org/10.1016/j.geothermics.2013.11.001.
2. Kolawole, F., and Evenick, J.C. (2023). Global distribution of geothermal gradients in sedimentary basins. Geosci. Front. *14*, 101685. https://doi.org/10.1016/j.gsf.2023.101685.
3. Fervo Energy (2025). Geothermal mythbusting: Water use and impacts. https://fervoenergy.com/geothermal-mythbusting-water-use-and-impacts/.
4. Jung, H.B., Carroll, K.C., Kabilan, S., Heldebrant, D.J., Hoyt, D., Zhong, L., Varga, T., Stephens, S., Adams, L., Bonneville, A., et al. (2015). Stimuli-responsive/rheoreversible hydraulic fracturing fluids as a greener alternative to support geothermal and fossil energy production. Green Chem. *17*, 2799–2812. https://doi.org/10.1039/C4GC01917B.
5. U.S. Energy Information Administration (2020). Most U.S. utility-scale geothermal power plants built since 2000 are binary-cycle plants. https://www.eia.gov/todayinenergy/detail.php?id=44576.
6. Aghahosseini, A., and Breyer, C. (2020). From hot rock to useful energy: A global estimate of enhanced geothermal systems potential. Appl. Energy *279*, 115769. https://doi.org/10.1016/j.apenergy.2020.115769.
7. Franzmann, D., Heinrichs, H., and Stolten, D. (2025). Global geothermal electricity potentials: A technical, economic, and thermal renewability assessment. Renew. Energy *250*, 123199. https://doi.org/10.1016/j.renene.2025.123199.
8. Katalenich, S.M., and Jacobson, M.Z. (2022). Toward battery electric and hydrogen fuel cell military vehicles for land, air, and sea. Energy *254*, 124355. https://doi.org/10.1016/j.energy.2022.124355.
9. U.S. Department of Energy (2024). Pathways to commercial liftoff: Next-generation geothermal power. https://cdn.catf.us/wp-content/uploads/2025/06/09154348/doe-liftoff-nextgen-geothermal.pdf.
10. U.S. Department of Energy (2025). Geothermal FAQs. https://www.energy.gov/eere/geothermal/geothermal-faqs.
11. International Renewable Energy Agency (2024). Renewable capacity statistics 2023. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_RE_Capacity_Statistics_2024.pdf.
12. DiGangi, D. (2024). Interior approves 2-GW Fervo Energy geothermal project in Utah. Utility Dive. https://www.utilitydive.com/news/interior-geothermal-fervo-energy-categorical-exclusion-nepa/730413/.
13. International; Renewable; Energy Agency (2024). Renewable power generation costs in 2023 (International Renewable Energy Agency). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf.
14. Abdullah, A.J. (2024). The global competitiveness of renewable LCOE (Levelized Cost of Electricity) is on the rise. https://www.woodmac.com/news/opinion/the-global-competitiveness-of-renewable-lcoe-levelised-cost-of-electricity-is-on-the-rise/.
15. Jacobson, M.Z., Delucchi, M.A., Cameron, M.A., and Mathiesen, B.V. (2018). Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew. Energy *123*, 236–248. https://doi.org/10.1016/j.renene.2018.02.009.
16. Jacobson, M.Z., Delucchi, M.A., Cameron, M.A., Coughlin, S.J., Hay, C.A., Manogaran, I.P., Shu, Y., and von Krauland, A.-K. (2019). Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. One Earth *1*, 449–463. https://doi.org/10.1016/j.oneear.2019.12.003.
17. Jacobson, M.Z., von Krauland, A.-K., Coughlin, S.J., Dukas, E., Nelson, A.J.H., Palmer, F.C., and Rasmussen, K.R. (2022). Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. Energy Environ. Sci. *15*, 3343–3359. https://doi.org/10.1039/D2EE00722C.
18. Jacobson, M.Z., von Krauland, A.-K., Song, K., and Krull, A.N. (2023). Impacts of green hydrogen for steel, ammonia, and long-distance transport

on the cost of meeting electricity, heat, cold, and hydrogen demand in 145 countries running on 100% wind-water-solar. Smart Energy *11*, 100106. https://doi.org/10.1016/j.segy.2023.100106.

19. Jacobson, M.Z., Fu, D., Sambor, D.J., and Mühlbauer, A. (2025). Energy, health, and climate costs of carbon-capture and direct-air-capture versus 100%-wind-water-solar climate policies in 149 countries. Environ. Sci. Technol. *59*, 3034–3045. https://doi.org/10.1021/acs.est.4c10686.
20. Jacobson, M.Z., Sambor, D.J., Fan, Y.F., and Mühlbauer, A. (2024). Effects of firebricks for industrial process heat on the cost of matching all-sector energy demand with 100% wind-water-solar supply in 149 countries. PNAS Nexus *3*, pgae274. https://doi.org/10.1093/pnasnexus/pgae274.
21. Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A.S., Aghahosseini, A., Gulagi, A., Solomon, A.A., Keiner, D., Lopez, G., et al. (2022). On the history and future of 100% renewable energy systems research. IEEE Access *10*, 78176–78218. https://doi.org/10.1109/ACCESS.2022.3193402.
22. Denholm, P. (2022). Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. Technical Report No. NREL/TP6A40-81644 (National Renewable Energy Laboratory).
23. Ricks, W., Voller, K., Galban, G., Norbeck, J.H., and Jenkins, J.D. (2025). The role of flexible geothermal power in decarbonized electricity systems. Nat. Energy *10*, 28–40. https://doi.org/10.1038/s41560-023-01437-y.
24. Aljubran, M.J., Saad, D.M., Sodwatana, M., Brandt, A.R., and Horne, R.N. (2025). The value of enhanced geothermal systems for the energy transition in California. Sustainable Energy Fuels *9*, 1317–1337. https://doi.org/10.1039/D4SE01520G.
25. International Energy Agency (2025). Energy Statistics Data Browser (OECD Publishing). https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser.
26. Rismanchi, B. (2017). District energy network (DEN), current global status and future development. Renew. Sustain. Energy Rev. *75*, 571–579. https://doi.org/10.1016/j.rser.2016.11.025.
27. World Health Organization. (2022). Household air pollution attributable deaths. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/household-air-pollution-attributable-deaths.
28. World Health Organization (2022). Ambient air pollution attributable deaths. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/ambient-air-pollution-attributable-deaths.
29. Cole, W.J., Greer, D., Denholm, P., Frazier, A.W., Machen, S., Mai, T., Vincent, N., and Baldwin, S.F. (2021). Quantifying the challenge of reaching a 100% renewable energy power system for the United States. Joule *5*, 1732–1748. https://doi.org/10.1016/j.joule.2021.05.011.
30. Lazard (2025). Levelized cost of energy +. https://www.lazard.com/media/5tlbhyla/lazards-lcoeplus-june-2025-_vf.pdf.
31. Allred, B.W., Smith, W.K., Twidwell, D., Haggerty, J.H., Running, S.W., Naugle, D.E., and Fuhlendorf, S.D. (2015). Sustainability. Ecosystem services lost to oil and gas in North America. Science *348*, 401–402. https://doi.org/10.1126/science.aaa4785.
32. Jones, E.C., Jr. (2024). Lithium supply chain optimization: A global analysis of critical minerals for batteries. Energies *17*, 2685. https://doi.org/10.3390/en17112685.
33. Yao, B., Jeong, H., Mehrtash, M., Allan, B., Ockerman, D., and Dvorkin, Y. (2025). Understanding supply chain constraints for the US clean energy transition. Clean Energy *1*, 9. https://doi.org/10.1038/s44406-025-00009-1.
34. Bhutada, G., and Smith, M. All the metals we mined in 2021: Visualized. Visual Capitalist. https://www.visualcapitalist.com/all-the-metals-we-mined-in-2021-visualized.
35. Wesselkämper, J., Hendrickson, T.P., Lux, S., and von Delft, S. (2025). Recycling or second use? Supply potentials and climate effects of end-of-life electric vehicle batteries. Environ. Sci. Technol. *59*, 15751–15765. https://doi.org/10.1021/acs.est.5c01823.
36. Busch, P., Chen, Y., Ogbonna, P., and Kendall, A. (2025). Effects of demand and recycling on the when and where of lithium extraction. Nat. Sustain. *8*, 773–783. https://doi.org/10.1038/s41893-025-01561-5.
37. Jacobson, M.Z., and Delucchi, M.A. (2025). Spreadsheets for 150-country WWS study. http://web.stanford.edu/group/efmh/jacobson/Articles/I/150Country/150-Countries.xlsx.
38. Frew, B.A., and Jacobson, M.Z. (2016). Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model. Energy *117*, 198–213. https://doi.org/10.1016/j.energy.2016.10.074.
39. Jacobson, M.Z. (2021). The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected. Renew. Energy *179*, 1065–1075. https://doi.org/10.1016/j.renene.2021.07.115.
40. Jacobson, M.Z., von Krauland, A.-K., Coughlin, S.J., Palmer, F.C., and Smith, M.M. (2022). Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage. Renew. Energy *184*, 430–442. https://doi.org/10.1016/j.renene.2021.11.067.
41. Drupp, M.A., Freeman, M.C., Groom, B., and Nesje, F. (2018). Discounting disentangled. Am. Econ. J.: Econ. Policy *10*, 109–134. https://doi.org/10.1257/pol.20160240.

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Supplemental information

The impact of enhanced geothermal systems

on transitioning all energy sectors

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This Supplemental Information file (pages S1-S146) contains additional discussion of the models used, additional results in the business-as-usual (BAU) case, the base wind-water-solar (WWS) case (without enhanced geothermal systems, EGS), and the EGS cases (Notes S1-S13). It also contains five additional figures (Figures S1-S33) and 30 additional tables (Tables S1-S30), and additional references.

Supplemental Notes

Note S1. Summary

In this study, we model several cases of the matching, every 30 seconds from 2050 to 2052, of all-purpose electricity and heat demand (load) with supply, storage, losses, and demand response after all 2050 business-as-usual (BAU) energy in 150 countries has been hypothetically transitioned to electricity and heat provided by 100% wind-water-solar (WWS) sources. In one case (base-WWS case), enhanced geothermal systems (EGS) for electricity production are excluded in each country. In the other cases (EGS cases), EGS for electricity are included, along with other WWS technologies, in each country. Three EGS-electricity cases are considered, each with a different capital cost of EGS. To simulate matching demand, the 150 countries are grouped into 29 grid regions. Each region is either a group of countries close to each other that are likely to share an electrical grid, an individual island country, or an individual large country.

All results provide here are shown for 2050-2052. However, 2050-2052 results are derived assuming a transition between 2022 and 2050. Figure S1 provides two of many possible transition timelines that provide the same end results in 2050: one with an 80% transition by 2030 and 100% by 2050; the second with an 80% transition by 2030 and 100% by 2035. Whereas both timelines help to minimize air pollution deaths, global warming, and energy insecurity while reducing annual costs and creating jobs, the second does so faster.

In this study, green hydrogen (produced from WWS electricity) is produced, stored, and used for three non-grid purposes: steel and ammonia manufacturing and long-distance transport of aircraft, ships, trains, and heavy-duty trucks. Green hydrogen is also produced, stored, and used for grid electricity backup. The storage of green hydrogen for grid electricity and non-grid purposes is referred to here as green hydrogen storage (GHS). Hydrogen for GHS is stored as a compressed gas. The exception is that hydrogen stored onboard aircraft and some ships is stored as a liquid[S1]. Conventional hydropower storage (CHS), pumped hydroelectric storage (PHS), concentrated solar power (CSP) storage (CSPS), and battery storage (BS) also provide grid electricity storage here. Low-temperature heat for district heating is stored in water tanks, soil (borehole storage), and water pits. High-temperature industrial process heat is stored in firebricks[S2]. Low-temperature water heat for buildings is stored in small water tanks. CSP heat produced is store in a phase-change material.

Conventional geothermal and solar provide direct heat in the model. Table S9 provides the existing nameplate capacities of conventional geothermal and solar heat generators by region. These capacities are assumed to stay constant, for simplicity, between the present and 2050 (Tables S10a,b). Cold is stored in water tanks and ice. Hydrogen is stored in storage tanks. Transportation is electrified with battery-electric and, for long-distance, heavy transport, hydrogen-fuel-cell-electric vehicles[S1]. Buildings are electrified with a combination of ground- and air-source electric heat pumps for air and water heating, air conditioning, clothes washing and drying, and dishwashing and electric induction cooktops for cooking. District heating and cooling are used to heat and cool some cities (Note S7). Medium to high-temperature (150-2,000 ^{o}C) industrial process heat is obtained with electric arc furnaces; electric induction furnaces; electric resistance furnaces, kilns, and boilers; electric crackers; electron beam heaters; dielectric heaters; and firebricks. Low-temperature (<150 ^{o}C) heat is obtained from ground- and air-source electric heat pumps.

Table S1 lists the 29 regions and the 150 countries treated. The regions include a mix of 13 multi-country regions (East Africa, North Africa, South Africa, West Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, Northwest South America, Southeast South America, and Southeast Asia) and 16 individual countries or pairs of countries (Australia, Canada, Cuba, Haiti-Dominican Republic, Israel, Iceland, Jamaica, Japan, Madagascar, Mauritius, New Zealand, the Philippines, Russia-Georgia, South Korea, Taiwan, and the United States).

Note S2. Methodology

This note summarizes the overall methodology used in this study. It then describes the first step, which is to use a spreadsheet model to develop year-2050 roadmaps to transition each of 150 countries to 100% WWS among all energy sectors in order to meet annual average demand.

The general steps in performing the overall analysis are as follows:

(1) project business-as-usual (BAU) end-use energy demand (also known as final consumption) from 2022 to 2050 for each of seven fuel types in each of six energy-use sectors, for each of 150 countries;
(2) estimate the 2050 reduction in demand due to electrifying or providing direct heat for each fuel type in each energy sector in each country and providing that electricity and heat with WWS;
(3) during step (2), replace BAU steel and ammonia manufacturing with green-hydrogen steel and ammonia manufacturing and replace BAU long-distance transport vehicles with green-hydrogen fuel cell-electric vehicles;
(4) perform resource analyses then estimate mixes of wind-water-solar (WWS) electricity and heat generators required to meet the aggregate demand in each country in the annual average. Do this for a WWS case with no EGS electricity (base-WWS case) and three WWS cases with EGS electricity (EGS cases), each assuming a different capital cost of EGS electricity.
(5) use a prognostic global weather-climate-air pollution model (GATOR-GCMOM), which accounts for competition among wind turbines for available kinetic energy, to estimate wind and solar radiation fields and building heat and cold demands every 30 s for three years in each country;
(6) group the 150 countries into 29 world regions and use a model (LOADMATCH) to match variable electricity, high-temperature heat, low-temperature heat, cold, and hydrogen demand with variable supply, storage (electricity, high-temperature heat, low-temperature heat, cold, and hydrogen storage), and demand response in each region every 30 s, from 2050 to 2052;
(7) evaluate energy, health, and climate costs in the BAU case, in the base-WWS case (WWS with no EGS electricity), and in the three EGS cases (WWS with EGS electricity, with different capital costs of EGS in each case);

(8) calculate land area requirements in base-WWS case and EGS cases; and
(9) calculate changes in jobs numbers between the BAU and base-WWS case and between the BAU and EGS cases.

Thus, three types of models are used for this study: a spreadsheet model (Steps 1-4), a 3-D global weather-climate-air pollution model (Step 5), and a model that matches electricity, high-temperature heat, low-temperature heat, cold, and hydrogen demand with supply, storage, and demand response assuming perfect grid interconnection (Steps 6-9). The rest of this note describes the spreadsheet model[S3]. Note S3 describes GATOR-GCMOM. Notes S4-S7 describe LOADMATCH.

We start with 2022 business-as-usual (BAU) end-use energy consumption (also called final consumption) data for each country from IEA[S4]. End-use energy is energy directly used by a consumer. It is the energy embodied in electricity, fossil gas, gasoline, diesel, kerosene, and jet fuel that people use directly, including to extract and transport fuels themselves. It equals primary energy minus the energy lost in converting primary energy to end-use energy, including the energy lost during transmission and distribution. Primary energy is the energy naturally embodied in chemical bonds in raw fuels, such as coal, oil, fossil gas, biomass, uranium, or renewable (e.g., hydroelectric, solar, wind) electricity, before the fuel has been subjected to any conversion process.

For each country, end-use energy data are available for each of seven energy categories (oil, fossil gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat) in each of six energy sectors (residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other).

These data are projected for each fuel type in each sector in each country from 2022 to 2040 using "BAU reference scenario" projections from EIA[S5] for each of 16 world regions. This is extended to 2075 using a ten-year moving linear extrapolation. The reference scenario is one of moderate economic growth and accounts for policies, population growth, economic and energy growth, the growth of some renewable energy, modest energy efficiency measures, and reductions in energy use. EIA refers to their reference scenario as their BAU scenario. The 2050 BAU end-use energy for each fuel type in each energy sector in each of 150 countries is then set equal to the corresponding 2022 end-use energy value for the fuel type and sector from IEA[S4] multiplied by the EIA 2050-to-2022 energy consumption ratio, available after the extrapolation, for the same fuel type and sector of the world region containing the country.

The 2050 BAU end-use energy for each fuel type in each sector and country is then converted to 2050 WWS electricity and heat using the conversion factors in Table S3.

For example, air and water heat from fossil-fuel burning, wood burning, and waste heat are converted to heat from ground- and air-source electric heat pumps running on WWS electricity. Building cooling is also provided by such heat pumps powered by WWS electricity. Existing solar and conventional geothermal direct heat are retained without change. Fossil gas clothes washers, clothes dryers, and dishwashers are converted to electric heat-pump versions; fossil-fuel and bioenergy stoves are converted to electric induction stoves. As such, there is no need for any energy carrier, aside from electricity, in a building. Buildings also use more efficient electric appliances, LED lights, and better insulation.

Liquid-fuel (mostly gasoline, ethanol, diesel, bunker fuel, and jet fuel) and fossil-gas vehicles are transitioned to battery-electric (BE) vehicles and some hydrogen-fuel-cell-electric (HFC) vehicles, where the hydrogen is produced with WWS electricity (green hydrogen). BE vehicles are assumed to dominate short- and long-distance light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance (<1,000 km) heavy-duty trucks, trains (except when powered by electric rails or overhead wires), ferries, speedboats, and ships. Batteries also power short-haul (<3 h) aircraft flights. HFC vehicles make up all long-distance ships, trains, and trucks; medium- and long-distance aircraft; and long-distance military vehicles[S1]. Gasoline lawnmowers, leaf blowers, and chainsaws are converted to electric equivalents.

Mid- and high-temperature industrial processes are electrified with electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, and firebricks. Low-temperature heat for industry is provided with ground- and air-source electric heat pumps and firebricks. Firebricks are assumed to store up to 90% of the process heat needed for all industry[S6]. Thus, firebrick heat can supply up to ~46.7% of all industrial annual average power needed for heat in 2050 upon electrification of all energy sectors across the 150 countries (2,269 GW of industrial process heat demand subject to firebrick storage from Table S7 divided by 4,862 GW of total industrial demand from Table S6). It also represents 25.3% of all-sector annual average power (2,269 GW divided by 8,962 GW from Table S6).

Green hydrogen for steel and ammonia manufacturing replaces fossil and bioenergy fuels for these processes[S7]. Table S5 summaries the annual hydrogen production by year for these processes, as well as for long-distance transport. All electricity for industry comes from WWS sources.

In each country, a mix of WWS resources is estimated in the spreadsheet to meet the all-sector annual average end-use energy demand after electrification. The mix is determined after a WWS resource analysis is performed for each country and after the technical potential of each WWS resource in each country is estimated. Ref. S8 provides the methodology for the resource analysis performed here for each country.

Next, a first estimate of the nameplate capacities of a mix of WWS generators needed to meet annual average all-purpose end-use energy demand in each country is calculated iteratively in the spreadsheet[S3]. The penetration of each WWS electricity generator in each country is limited by the following constraints: (1) each generator type cannot produce more electricity in the country than the technical potential allows; (2) the land area taken up among all WWS land-based generators should be no more than a few percent of the land area of the country of interest; (3) the area of installed rooftop photovoltaics (PV) in each country must be less than the respective rooftop area suitable for PV; (4) the nameplate capacity of hydropower is the same as in 2023; and (6) wind and solar, which are complementary in nature, are used in roughly equal proportions where feasible.

Country-specific nameplate capacities from the spreadsheet model are then used as inputs into the global weather-climate-air-pollution model, GATOR-GCMOM (Note S3), as described next.

Note S3. Description of GATOR-GCMOM and its Calculations

This note briefly summarizes the GATOR-GCMOM model and the main processes that it treats. GATOR-GCMOM is a three-dimension Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model[S9-S12]. It simulates weather, climate, and air pollution on the global, regional, and urban scales. The main processes treated are as follows:

Gas processes (emissions, gas photochemistry, gas transport, gas-to-particle conversion, gas-cloud interactions, and removal).

Aerosol processes (size- and composition-resolved emissions, homogeneous nucleation, coagulation, condensation, dissolution, equilibrium and non-equilibrium chemistry, aerosol-cloud interactions, and aerosol removal).

Cloud processes (size- and composition-resolved aerosol particle activation into cloud drops, drop freezing; collision-coalescence with cloud particles and aerosol particles, condensation/evaporation, dissolution, ice crystal formation, graupel formation, lightning formation, convection, precipitation, and drop breakup).

Transport processes (horizontal and vertical advective and diffusive transport of individual gas, size- and composition-resolved aerosol particles, and size- and composition-resolved hydrometeor particles).

Radiative processes (spectral solar and thermal infrared radiation transfer; heating rates that affect temperatures; actinic fluxes that affect photolysis coefficients; radiation transfer through gases, aerosols, clouds, snow, sea ice, and ocean water).

Meteorological processes (winds, temperatures, pressures, humidity, size- and composition-resolved clouds).

Surface processes (dry deposition of gases, sedimentation of aerosol and hydrometeor particles, dissolution of gases and particles into the oceans and surface water, soil moisture and energy balance, evapotranspiration, sea ice and snow formation and impacts; radiative transfer through snow, sea ice, and ocean water).

Ocean processes (2-D ocean transport and 3-D ocean diffusion and chemistry, phytoplankton affecting optical properties and emissions, radiative transfer through the ocean).

GATOR-GCMOM simulates feedback among all these processes, in particular among meteorology, solar and thermal-infrared radiation, gases, aerosol particles, cloud particles, oceans, sea ice, snow, soil, and vegetation. Model predictions have been compared with data in 34 peer-reviewed studies. The model has also taken part in 14 model inter-comparisons[S13].

The model is run here at 2- by 2.5-degree horizontal resolution and with 68 sigma-pressure-coordinate layers in the vertical, from the ground to 0.219 hPa (~60 km), with 15 layers in the bottom 0.95 km. Of these layers, the bottom five above the ground are at 30-m resolution; the next seven are at 50-m resolution, one is at 100-m resolution, and the last two are at 200-m resolution. Vertical resolution from 1 to 21 km is 500 m.

Country-specific inputs into GATOR-GCMOM from the spreadsheet model include the projected 2050 nameplate capacities of onshore and offshore wind turbines, rooftop and utility PV panels, CSP plants, and solar thermal heat plants needed to meet 2050 annual average demand.

Onshore wind turbines are placed in windy areas in each country in GATOR-GCMOM. Offshore turbines are placed in coastal water in each country that has a coastline. The wind turbine blades in the model cross five vertical model layers. Spatially-varying model-predicted wind speeds are used to calculate wind power output from each turbine every 30 s. This calculation accounts for the reduction in the wind's kinetic energy and speed due to the competition among wind turbines for limited available kinetic energy[S11].

Rooftop solar PV panels, utility PV panels, CSP plants, and solar thermal plants are also placed by country in GATOR-GCMOM. Rooftop PV is placed in urban areas. Utility PV, CSP, and solar thermal are placed in southern parts of each country in the Northern Hemisphere and northern parts of each country in the Southern Hemisphere.

The model calculates the temperature-dependence of PV output[S12] and the reduction in sunlight to buildings and the ground due to the conversion of radiation to electricity by solar devices[S12,S13]. It also accounts for (1) changes in air and ground temperature due to power extraction by solar PV panels, CSP plants, solar thermal equipment, and wind turbines and subsequent electricity use[S12,S13]; (2) impacts of time-dependent gas, aerosol, and cloud concentrations on solar radiation and wind fields[S14]; (3) radiation to rooftop PV panels at a fixed optimal tilt[S12]; and (4) radiation to utility PV panels, half of which are at an optimal tilt and the other half of which track the sun with single-axis horizontal tracking[S12].

Finally, GATOR-GCMOM calculates building cooling and heating demands in each country every 30 s. The model predicts the ambient air temperature in each of multiple surface grid cells in each country and compares it with an ideal building interior temperature, set to 294.261 K (70°F). It then calculates how much heating or cooling energy is needed every 30 s to maintain the interior temperature among all buildings in the grid cell (assuming an average *U*-value and surface area for buildings and a given number of buildings in each grid cell)[S15]. The time series demands among all grid cells in a country are then summed to obtain a countrywide demand time series for the country, which is then output for use in LOADMATCH.

Note S4. Description of and Processes in the LOADMATCH Model
This note discusses the LOADMATCH model[S2,S7,S13,S15-S22] and its main processes. LOADMATCH is a trial-and-error simulation model written in Fortran. Its goal is to match time-dependent electricity, high-temperature heat, low-temperature heat, cold, and hydrogen demand with supply, storage, and demand response with zero loss of load at any time. It works by running multiple simulations for each grid region (Table S2), one at a time. Each simulation marches forward one timestep at a time, just as the real world does, for any number of years for which sufficient input data are available. In past studies, the model has been run for 1 to 6 years[S16], but there is no technical or computational limit preventing the model from running for hundreds or thousands of years, given sufficient input data. In the present study, the time step used is 30 s, and the simulation period is three years for each region.

The WWS supply and building heating and cooling loads used in LOADMATCH vary every 30 s of every year, because they are predicted over time with GATOR-GCMOM, which includes prognostic weather prediction. The simulations, which are for 2050-2052, also account for future climate and weather, including the impacts of more greenhouse gases and an astronomically-accurate future Earth orbit around the sun. As such, grid reliability is determined based both on interannual variability of demand and supply and future weather conditions. This differs from many modeling studies that use the same demand and supply data each year and past data rather than future data affected by climate change.

Simulations longer than three years could result in slightly different cost results than found here given that weather will continue to vary after three years, sometimes in extreme ways. However, in a previous study of the U.S.[S15], results from six years of simulation were compared with results from two, and overall annual energy and social costs ($/year), as well as levelized costs of energy ($/kWh), were similar. In the present study, annual and levelized costs between all three years of simulation and the first year of simulation are also similar. Also, the use of three years of output for calculating costs, even though equipment lifetimes are much longer than three years (Tables S20-S22) and equipment degrades over time, should not bias results much because all WWS simulations (with and without EGS electricity) are calculated consistently over the same three-year period. Further, the enormous annual energy and social cost differences between BAU and WWS (with or without EGS) (Tables S25a,b) cannot come close to being made up by additional maintenance costs of WWS equipment over a period longer than three years.

The main constraints are that electricity, high-temperature heat, low-temperature heat, cold, and hydrogen demands plus losses, adjusted by demand response, must each meet corresponding WWS supplies and storage every 30-s timestep of a simulation. All five parameters are conserved and their balances tracked (Tables S19a,b). Some low-temperature heat here is provided by direct geothermal and solar heat, whereas the rest is provided by ground- and air-source electric heat pumps. All high-temperature heat, cold, and hydrogen are produced by electric technologies. If a demand is not met during any timestep, the simulation stops. Inputs (either the nameplate capacity of one or more generators; the peak charge rate, peak discharge rate, or peak capacity of storage; or characteristics of demand response) are then adjusted one at a time based on an examination of what caused the demand mismatch (thus, LOADMATCH is a “trial-and-error” model). Another simulation is then run from the beginning. New simulations are run until demand is met every time step of the simulation period. After demand is met once, additional simulations are performed with further-adjusted inputs based on user intuition and experience to generate a set of solutions that match demand every timestep. The lowest-cost solution (based on the levelized cost of all-energy) in this set is then selected.

Unlike with an optimization model, which solves among all timesteps simultaneously, a trial-and-error model does not know what the weather (thus wind, wave, and solar output and building heating and cooling demands) will be during the next timestep. Because a trial-and-error model is non-iterative, it requires only one minute on a single processor for a 3-year simulation when the time step is 30 s. This is 1/10,000th to 1/1,500,000th the computer time of an optimization model for the same number of timesteps and parameters, regardless of computer architecture. The disadvantage of a trial-and-error model compared with an optimization model is that the former does not determine the least cost solution out of all possible solutions. Instead, it produces a set of viable solutions, from which the lowest-cost solution is selected.

Table S2 summarizes dozens of the processes treated in LOADMATCH. Model inputs are as follows:

(1) time-dependent electricity generation from onshore and offshore wind turbines, residential and commercial rooftop PV systems, utility PV plants, CSP plants, and wave devices in each region of interest, all predicted by GATOR-GCMOM, with nameplate capacities from the spreadsheet model (Section S3);
(2) time-dependent heat from solar thermal devices, predicted by GATOR-GCMOM;
(3) time-dependent building heat and cold demands, predicted by GATOR-GCMOM;
(4) baseload (constant) geothermal electricity and heat and tidal electricity generation, with magnitudes determined in the spreadsheet model;
(5) baseload and peaking hydropower electricity generation (Note S5) limited to 2023 annual hydropower generation and nameplate capacity (thus no hydropower growth);
(6) specifications of hot-water and chilled-water sensible-heat thermal energy storage (HW-STES and CW-STES) (peak charge rate, peak discharge rate, peak storage capacity, losses into storage, and losses out of storage) (Tables S14, S22);
(7) specifications of underground thermal energy storage (UTES) (Tables S14, S22);
(8) specifications of ice storage (ICE) (Tables S14, S22);
(9) specifications of industrial-process heat storage in firebricks (Tables S14, S22);
(10) specifications of electricity storage in PHS, CSPS, BS, and GHS (Tables S14, S22);
(11) specifications of hydrogen electrolyzer, rectifier, compressor, and storage tank sizes for non-grid versus grid applications, and the quantity of hydrogen needed for steel and ammonia manufacturing, long-distance transport, and grid electricity backup (Tables S5, S21, S23);

(12) specifications of ground- and air-source electric heat pumps for district heating (aside from district heat provided by direct geothermal and solar heat) and for heating individual buildings (Table S22);
(13) specifications of a demand response system (Note S6);
(14) specifications of losses along short- and long-distance transmission and distribution lines and district heating pipelines (Tables S15, S20);
(15) assumed or data-derived time-dependent electricity, heat, cold, and hydrogen demand profiles (Note S6); and
(16) specifications of scheduled and unscheduled maintenance downtimes for generators, storage, and transmission (Table S20).

From model results, differences in energy, health, and climate costs and job creation and loss between BAU and WWS are estimated. Land requirements of WWS are also calculated. The cost calculation requires specifications of WWS electricity and heat generator costs (Tables S20, S24); the costs of electricity storage, cold storage, low-temperature heat storage, high-temperature-heat (process) storage, and hydrogen storage (Tables S22, S21); the costs of hydrogen electrolyzers, rectifiers, compressors, dispensers, cooling equipment, and fuel cells (Table S21); transmission and distribution costs (Table S20); air pollution costs (Tables S25a,b); and climate costs (Tables S25a,b). Details of the cost calculations are provided in the footnotes to the tables cited. Changes in job numbers (Table S30) require specifications of job data for generators, storage, hydrogen, and transmission/distribution (Table S29). Land requirements (Tables S28a,b) require specification of the installed power density of different types of land-based generators (Table S27).

LOADMATCH is used here to match time-dependent (30-s resolution) electricity, high-temperature-heat, low-temperature-heat, cold, and hydrogen demands and losses with supply, storage, and demand response for three years, from 2050 to 2052. Note S5 summarizes the treatment of hydropower in the model. Note S6 discusses thermal and electricity demand profiles, maximum storage sizes, flexible and inflexible demands, and the treatment of demand response in the model. Note S7 discusses the order of operation in the model. Whereas GATOR-GCMOM provides time-dependent wind, solar, and wave electricity supplies and solar heat supplies for LOADMATCH, conventional and enhanced geothermal electricity and heat supplies and tidal electricity supplies are assumed to be constant throughout the year. The assumption of constant tidal energy is a simplification but not unreasonable given that tidal is proposed to power only 0.015% of the 150-country demand in this study (Tables S13a,b). In addition, tidal power output varies sinusoidally, with four peaks and four valleys per day, but the annual-average output difference between the peaks and the valleys is only ~25% of the average output, although tidal power output also varies seasonally[S23]. Hydropower is used for baseload, load-following, and peaking electricity (Note S5).

Transmission in LOADMATCH is assumed to be perfectly interconnected. However, transmission and distribution costs and losses are accounted for (Table S20). The regions simulated here (Table S1) cover different spatial scales, from 11 relatively small regions (Cuba, Haiti-Dominican Republic, Iceland, Israel, Jamaica, Japan, Madagascar, Mauritius, New Zealand, Philippines, South Korea, and Taiwan) to the continental scale. Long-distance transmission costs increase when countries are interconnected versus isolated. For the smallest individual countries or pairs of countries (Cuba, Haiti-Dominican Republic, Iceland, Israel, Jamaica, Madagascar, Mauritius, South Korea, and Taiwan), no long-distance transmission is assumed because the distance across such entities is less than a typical HVDC transmission line length (1,000-2,000 km). For New Zealand, 15% of all non-rooftop PV and non-curtailed electricity consumed is assumed to be subject to long-distance transmission. For Central America, Japan, and the Philippines, 20% is assumed to be subject to long-distance transmission. For all other countries and regions, 30% is assumed to be subject to long-distance transmission (Table S15). Ref. S18 evaluated the difference in cost when countries in several grid regions in Europe were isolated versus interconnected. The study found that interconnecting reduces aggregate annual energy costs, but whether isolated or interconnected, all countries can match all energy demand with supply and storage at low cost.

Note S5. Treatment of Hydropower for Both Baseload and Peaking

The annual hydropower output (TWh/y) in 2050 in each country is limited to the 2023 output in the country. This annual hydropower energy output is assumed to be exactly replenished each year by rainfall and runoff. The 2050 peak discharge rate (nameplate capacity) of hydropower in each country is also limited by the country's 2023 nameplate capacity. The nameplate capacity of hydropower is the peak discharge rate of its generators.

Ref. S21 solved a set of six equations and six unknowns to treat hydropower in each grid region in LOADMATCH for both baseload and peaking simultaneously. The six unknowns are the maximum storage capacity (TWh), total nameplate capacity (TW), and recharge rate (TW), of each baseload and peaking hydropower. These unknowns are solved considering three known quantities - the maximum storage capacity (TWh), total nameplate capacity (TW) and total recharge rate (TW) of baseload plus peaking hydropower in each region. The maximum storage capacity for 2050 equals the 2020 storage capacity by region, from IEA[S24], redistributed into the regions used here with the technique described in Ref. S21. The total hydropower nameplate capacity for 2050 is assumed to be the 2023 nameplate capacity of hydropower. The 2050 total recharge rate is assumed to equal the 2023 estimated hydropower output (TWh/y) divided by the number of hours per year. Table S14 provides values for all three known parameters as well as the resulting values for the unknown parameters for each region.

The six equations solved are as follows: (1) the sum of the maximum energy storage capacities (TWh) of baseload hydropower and peaking hydropower in each region must equal the overall maximum energy storage capacity among all hydropower reservoirs in a region; (2) the sum of the instantaneous average charge rates (TW) of baseload hydropower and of peaking hydropower in all reservoirs in the region equals the average charge rate, summed among all reservoirs in the region; (3) the sum of the maximum discharge rates (nameplate capacities) (TW) of generators assigned to baseload hydropower and peaking hydropower equals the total nameplate capacity of all generators among all hydropower plants in the region; (4) the maximum discharge rate (TW) of baseload hydropower in each region must equal the instantaneous average charge rate of baseload hydropower in the region; (5) the nameplate capacity of baseload hydropower multiplied by the hours of baseload storage at that nameplate capacity equals the maximum storage capacity of baseload power; and (6) the maximum energy storage capacity (TWh) of peaking hydropower equals the instantaneous average charge rate of peaking power (TW) multiplied by 8,760 h per year. In other words, the peaking portion of the reservoir must be filled fully once per year. Ref. S21 provides the solution implemented here to obtain the results shown in Table S14 for each region.

In sum, whereas baseload power is produced and discharged continuously in the model every 30 s, peaking power is also produced every 30 s but discharged only when needed. Whereas Table S14 gives hydropower's maximum energy storage capacity available for baseload and peaking, hydropower's output from baseload storage or peaking storage during a time step is limited by the smallest among three factors: the actual energy currently available in storage for baseload or peaking, the hydropower maximum discharge rate (nameplate capacity) for peaking or baseload multiplied by the time step, and (in the case of peaking) the energy needed during the time step to keep the grid stable.

Note S6. Time-Dependent Thermal/Electricity Demand Profiles in LOADMATCH

This note discusses the development of time-dependent demand profiles at 30-s time resolution for use in LOADMATCH. Demand profiles are developed starting with 2050 annual average WWS energy demand values for each sector in each country from Table S4a. These demands are separated into (1) electricity demands for cooling and refrigeration; (2) electricity and direct heat demands for low-temperature heating; (3) electricity demands for industrial process heat; (4) electricity demands for producing, compressing, and storing hydrogen to run hydrogen fuel cell-electric vehicles with or to manufacture steel and ammonia with; and (5) all other electricity demands, as described in Section S1.3.3 of Ref. S13 and updated in Ref. S15 and Ref. S2.

Each of these demands is then divided further into flexible and inflexible demands. Inflexible demands are demands that are not flexible, thus must be met immediately. Flexible demands include electricity and direct heat demands that can be used to fill cold and low-temperature heat storage (district heat storage or building water tank storage), electricity demands either used immediately or stored in firebricks, electricity demands used to produce and compress hydrogen (since all hydrogen can be stored), and remaining electricity and direct heat demands subject to demand response (Table S7). Table S15 gives the fraction of building heating and cooling demands subject to district heating and cooling in each region.

Demands subject to demand response can be shifted forward in time one time step at a time, but by no more than eight hours, until the demands are met. Demands subject to cold/low-temperature heat storage can be met with such storage or with electricity, either currently available or stored. Demands for industrial process heat can be met either with current electricity or with heat stored in firebricks. Inflexible demands must be met immediately with electricity that is currently available or stored.

To summarize, total annual-average cooling and low-temperature heating demands consist of flexible demands subject to storage, flexible demands subject to demand response, and inflexible demands. Such annual-average cooling and low-temperature heating demands for each country are converted to time-dependent cooling and low-temperature heating demands using the time-dependent cooling and low-temperature heating demand output from GATOR-GCMOM for each country (Note S3). In LOADMATCH, the cooling and low-temperature heating demand time series from GATOR-GCMOM are summed for each time step over all countries in each region to obtain regional time series. The annual average of each regional time series is then found. Each regional time series, from 2050 to 2052, is then scaled by the ratio of the annual-average cooling or low-temperature heating demand subject to storage required for a 100% WWS region in 2050 from Table S7 to the annual-average cooling or heating demand from the GATOR-GCMOM time series, just calculated. This gives time-dependent 2050-2052 cooling and heating demands for each region that, when averaged over time, exactly match the estimated 2050 annual-average demands from Table S7.

In this study, as in Ref. S7, a portion of the total industrial process energy demand is removed from the IEA[S4] database due to the use of an electrolyzer instead of a steam reformer to produce hydrogen for ammonia manufacturing. Another portion is eliminated due to the use of direct hydrogen reduction instead of coke reduction during the purification of iron ore to iron since the former requires a much lower temperature than the latter.

Remaining industrial process energy demand consists of inflexible process heat demand, flexible process heat demand subject to demand response or firebrick storage, and industrial hydrogen demand. Inflexible industrial process heat demand is assumed to comprise 10% of total industrial process energy demand[S2]. The inflexible industrial process heat demand is then assumed to vary each hour with the same profile as the overall electricity demand in the country of the demand and must be met immediately with either current electricity or stored electricity.

Industrial process heat demand subject to demand response or firebrick storage consists of total industrial process demand minus inflexible industrial process demand and minus industrial process hydrogen demand. This demand subject to demand response or firebrick storage is assumed to be constant every hour of every day. It is met first with firebrick storage. If firebrick storage is empty, half the remaining demand is made inflexible and must be met immediately with current electricity or electricity storage. The other half is made flexible so can either be met immediately with current electricity or electricity storage or can be shifted forward by up to eight hours with demand response.

Industrial hydrogen demand (for steel and ammonia manufacturing) is assumed to be constant each hour of each day. It is met first from hydrogen storage. If no hydrogen is available, the remaining load becomes inflexible and must be met with current electricity or with electricity storage.

All annual average 2050-2052 inflexible electricity demands (in the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors) in each region are converted to time-dependent 2050-2052 inflexible electricity demands for the region by projecting contemporary time-dependent electricity demand data for the region forward to 2050-2052. Contemporary hourly demand data for European countries are for 2014[S25]. Those for almost all remaining countries are for 2030[S26]. Since demand profiles for Sudan, Zimbabwe, and Equatorial Guinea do not exist from either of these datasets, their profiles are assumed to be the same as those of a nearby country, but with the magnitude each hour scaled so that the resulting annual average inflexible demand reflects that of each original country.

The 2050-2052 inflexible demand time-series for each country is then obtained by multiplying the 2014 or 2030 time-series electricity demand, respectively, for the country by the ratio of the annual average 2050 inflexible demand for the region the country resides in (Table S7) to the annual average 2014 or 2030 inflexible demand profile summed among all countries in the region.

All remaining demands, which include flexible low-temperature heat and cold demands for residential, commercial, and industrial buildings; other flexible demands for buildings; flexible electricity demands for battery-electric vehicles, flexible electricity demands for hydrogen used in hydrogen fuel cell-electric vehicles, electricity demands for industrial process heat subject to storage (as discussed), and electricity for hydrogen for steel and ammonia manufacturing, are distributed evenly during the year.

For vehicles, this assumption is roughly justified by the fact that, between 2016-2019 in the U.S., the minimum and maximum monthly U.S. gasoline supplies were 7.76% and 8.73%, respectively, of the annual supply[S27], with the highest consumption during the summer and the lowest during the winter. Both gasoline vehicle (GV) and battery-electric vehicle (BEV) ranges drop with lower temperature, with BEV ranges dropping more. For example, gasoline-vehicle fuel mileage is about 15-24% lower at 20°F (-6.67°C) than at 77°F (25°C)[S28], whereas BEV range is ~40% lower between those two temperatures[S29]. Since gasoline consumption is greater during summer than winter, this implies that the summer minus winter difference in BEV electricity consumption will be less than the summer minus winter difference in gasoline consumption, justifying a relatively even spread during the year of electricity consumption with BEVs.

Fifteen percent of electricity demands for vehicles is assumed to be inflexible, and 85% is assumed to be flexible and subject to demand response. The flexible demands can be shifted forward in time if necessary or pulled from storage whenever electricity storage is sufficient available. The demand for producing and compressing hydrogen for fuel cell vehicles comprises 32.9% of the total transportation demand among the 150 countries [Table S5, Column (f) divided by Table S6, Column (e)]. The rest of the transportation demand (67.1%) is for powering battery-electric vehicles. The demand for producing and compressing hydrogen for steel and ammonia manufacturing comprises 12.2% of the total industrial demand [Table S5, Column (e) divided by Table S6, Column (d)]. The demand for producing and compressing hydrogen for both transportation and industry comprises 11.5% of the all-purpose demand [Table S5, Column (g) divided by Table S6, Column (a)]. All these demands are flexible, so hydrogen can be produced whenever excess electricity is available. The hydrogen can then be stored and used as needed. Of all transportation demands, 85% are flexible. This includes 100% of electricity demands for hydrogen production and compression for hydrogen fuel cell vehicles (32.9% of transportation electricity demands) and 77.6% of electricity demands for battery-electric vehicles (67.1% of transportation electricity demands).

Once time-dependent demand profiles are developed, maximum electricity, high-temperature heat, low-temperature heat, cold, and hydrogen storage sizes and times are estimated (Tables S14, S17).

Note S7. Order of Operation in LOADMATCH

In this note, the order of operations in LOADMATCH, including how the model treats excess generation over demand and excess demand over generation, is summarized. The first situation discussed is one in which the current (instantaneous) supply of WWS electricity or heat exceeds the current electricity or heat demand. The total demand, whether for electricity or heat, consists of flexible and inflexible demands. Whereas flexible demand may be shifted forward in time with demand response, inflexible demand must be met immediately. If WWS instantaneous electricity or heat supply exceeds the instantaneous inflexible electricity or heat demand, then the supply is used to satisfy that demand. The excess WWS is then used to satisfy as much current flexible electricity or heat demand as possible. If any excess electricity exists after inflexible and current flexible demands are met, the excess electricity is used to fill electricity storage, produce hydrogen, fill industrial process heat storage, fill low-temperature heat storage, or fill cold storage.

Excess WWS electricity is used first to charge battery storage. If battery storage is full, remaining electricity is next used to produce hydrogen that can later be used to re-generate electricity in a fuel cell or for non-grid purposes. If either hydrogen storage is full or the excess power available exceeds the electrolyzer plus compressor nameplate capacity for grid plus non-grid hydrogen, the remaining electricity is used to fill pumped hydropower storage, then industrial process heat storage in firebricks, then cold water storage, then ice storage, then hot water tank storage, and then underground thermal energy storage, respectively. Any residual after that is curtailed.

Another source of excess electricity is excess CSP heat. Excess CSP high-temperature heat is first put into CSP thermal energy storage (CSPS). If CSPS is full, remaining high-temperature CSP heat is used to produce electricity immediately. That electricity, if not needed for current demand, is then used to fill storage in the same order as with excess electricity just discussed, starting with filling battery storage. Hydropower dam storage is filled naturally with rainfall and runoff as described in Note S5.

Low-temperature district heat and cold storage for buildings is filled primarily by using excess electricity to power ground- and air-source electric heat pumps to move heat or cold from the air, water, or ground, respectively, to a thermal storage medium. If any excess direct geothermal or solar heat exists after it is used to satisfy inflexible and flexible heat demands, the remainder is also used to fill either district heat storage (water tank and underground heat storage) or building water tank heat storage.

High-temperature industrial process heat for storage in firebricks is produced from excess electricity with resistance heaters connected to the firebricks or direct resistance heating of the firebricks themselves[S2].

Non-grid and grid hydrogen storage are filled by using electricity in an electrolyzer (after a rectifier converts AC to DC electricity for use in the rectifier) to produce hydrogen and in a compressor to compress the hydrogen, which is then moved to a storage tank.

If any excess direct geothermal or solar heat exists after it is used to satisfy inflexible and flexible low-temperature heat demands, the remainder is used to fill either district heat storage (water tank and underground heat storage) or building water tank heat storage.

The second situation is one in which current demand exceeds WWS electricity or heat supply. When current inflexible plus flexible electricity demand exceeds the current WWS electricity supply from the grid, the first step is to use electricity storage (CSPS, BS, GHS, PHS, and CHS, in that order) to fill in the gap in supply. The electricity is used to supply the inflexible demand first, followed by the flexible demand.

If electricity storage becomes depleted and flexible demand persists, demand response is used to shift the flexible demand to a future time step.

If the inflexible plus flexible low-temperature heat demand subject to storage exceeds immediate WWS heat supply, then centrally-stored heat (in district heating water tanks and underground soil and water pits) is used to satisfy district heat demands subject to storage, and distributed heat storage (in hot water tanks) is used to satisfy individual building water heat demands. If stored heat becomes exhausted, then any remaining low-temperature air or water heat demand becomes either an inflexible demand (85%), which must be met immediately with electricity, or a flexible demand (15%), which can either be met with electricity or shifted forward to the next time step with demand response, up to the maximum number of demand response hours (eight or less). After that, the demand becomes inflexible.

Similarly, if the inflexible plus flexible cold demand subject to storage exceeds cold storage (in ice or water), excess cold demand becomes either an inflexible demand (85%), which must be met immediately with electricity, or a flexible demand (15%), which can be met with electricity or shifted forward in time with demand response. If a demand shifted forward is not met after the maximum number of demand response hours, it is turned into an inflexible demand.

If the industrial process heat demand subject to firebrick storage exceeds the heat stored in firebricks, then the excess becomes either an inflexible demand (50%), which must be met immediately with electricity, or a flexible demand (50%), which can be met with current electricity or shifted forward in time with demand response. If a demand shifted forward is not met after the maximum number of demand response hours, it is turned into an inflexible demand.

Finally, if the current non-grid hydrogen demand depletes non-grid hydrogen storage, the remaining non-grid hydrogen demand becomes an inflexible electricity demand that must be met immediately with current electricity.

In any of the cases above, if electricity is not available to meet the remaining inflexible demand, the simulation stops and must be restarted after increasing nameplate capacities of generation and/or storage.

Because the model does not permit load loss at any time, it is designed to exceed the utility industry standard of load loss once every 10 years.

Note S8. Methods of Matching Meeting Grid Demand in the Model

LOADMATCH matches demand for grid electricity, high-temperature heat, low-temperature heat, cold, and hydrogen with supply, storage, and demand response continuously over multiple years in each region. It employs at least eight methods in helping match demand. These are described next.

S8.1. Electrifying non-Electricity Sectors

Electrifying, to the extent possible, all non-electricity sectors, then providing the electricity with WWS reduces 2050 BAU end-use demand across all 150 countries considered here by an average of 54.2% among all regions (Tables 1 and S4a). Of this, 37.0 percentage points are due to the efficiency of using WWS electricity over combustion; 10.6 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels and uranium; and 6.57 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Tables S4a,b). Of the 37.0% reduction due to the efficiency of WWS electricity, 19.75 percentage points are due to the efficiency advantage of WWS transportation, 4.11 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.14 percentage points are due to the efficiency advantage of using electric heat pumps instead of combustion heaters. These three reductions are calculated from the BAU versus WWS work-output-to-energy-input ratios given in Table S3 for each energy sector and fuel type. Whereas additional energy will be needed to mine for and manufacture a new WWS system between today and 2050, much of this energy would be used otherwise to refurbish a BAU system. By 2050, when WWS is fully built, the energy needed to refurbish WWS should by similar to that otherwise needed to refurbish BAU, but WWS will require 10.6 percentage point less end-use energy because it eliminates entirely the mining, transporting, and refining of BAU fuels (Tables S4a,b).

Whereas all-purpose energy demand declines by 54.2% with WWS, the energy is almost all electricity (with the rest, direct heat), so the world-average electricity consumption increases by 85% compared with BAU (Tables S4a,b). Reducing overall energy demand by more than half helps WWS electricity and heat supplies match demand continuously. Increasing electricity demand also creates new opportunities to create new flexible demands that can be met by demand response (such as electric vehicle charging) or by storage (such as hydrogen use in steel and ammonia factories).

S8.2. Over-generating Electricity

Based on the simulations performed here, averaged among all regions and energy-generating technologies, about 16.4% more nameplate capacity of generators is needed to meet continuous demand than to meet annual average demand in the base case (Table S8). In the EGS cases, the overgeneration decreases to 8.2% (Table S8). Overgeneration helps to keep the grid stable by providing extra electricity that can be stored directly or converted to and stored as heat, cold, or hydrogen.

S8.3. Storing Excess Electricity

The electricity storage options in LOADMATCH include CHS, PHS, CSPS, BS, and GHS. BS assumes four-hour batteries with the measured efficiency of a 2021 lithium-ion Tesla Powerpack and a projected 2035 cost per kWh of lithium-ion batteries given in Table S22. Although batteries store electricity for only four hours at their peak discharge rate, longer storage times are obtained by concatenating batteries in series[S20]. For example, concatenating 100 4-h batteries, each with a peak discharge rate of 10 kW, allows for either 400 hours of storage at a peak discharge rate of 10 kW or 4 h of storage at a peak discharge rate of 1,000 kW, or anything in between. Thus, batteries with longer than 4-h storage are never "necessary" for keeping the grid stable. However, BS is most cost optimal if both its maximum discharge rate and its maximum storage capacity are reached (see Note S12.2 for an analysis).

GHS includes hydrogen gas production via electrolysis and compression with WWS electricity, hydrogen storage, and use of fuel cells to convert stored hydrogen back to grid electricity (Tables S14, S17, S21). Combining GHS with BS reduces the cost of grid stability in many regions versus BS alone[S21]. Non-grid green hydrogen here is produced, compressed, and stored for steel and ammonia manufacturing and long-distance transport[S7]. Table S5 summarizes the 2050 quantity of hydrogen needed by country and region for each non-grid use. For the present study, the same rectifiers, electrolyzers, compressors, and storage tanks are used for non-grid hydrogen as for GHS. Sharing hydrogen production and storage for both grid and non-grid purposes reduces costs in more regions, due to economies of scale, than separating the production and storage of hydrogen between grid and non-grid uses[S7]. Hydrogen is not piped or shipped in the model. Electricity is transmitted and electrolytic hydrogen is produced and stored at steel and ammonia factories and long-distance transport hubs (e.g., airports, docks, train stations, major truck stops, and military bases), minimizing the need for hydrogen piping or shipping. Fuel cells for GHS then produce grid electricity from the communally-stored hydrogen at the non-grid hydrogen storage locations.

Conventional hydropower's total nameplate capacity, energy storage capacity, and annual recharge rate are allocated between peaking and baseload power while conserving several properties by solving a set of six equations and six unknowns (Note S5). Conventional hydropower's total nameplate capacity, reservoir energy capacity, and recharge rate in each country are limited to ~2023 values (Table S14). The total conventional hydropower storage capacity in all hydropower reservoirs among the 150 countries examined is ~1,588 TWh (Table S14), which is close to the reported worldwide storage capacity[S24]. For comparison, the total battery storage capacity among the 150 countries is 32.28 TWh (Table S14). Thus, the storage capacity of existing CHS is 49.2 times that of batteries needed. However, batteries needed in 2050 also have a peak discharge rate of 8.07 TW, whereas CHS has a peak discharge rate in 2023 of 1.26 TW (Table S14). Thus, BS is used mostly for peaking, whereas CHS is used mostly for energy storage in this study.

S8.4. Using Excess Electricity for Heat and Cold Storage

Total end-use demand in this study is split into flexible and inflexible demands (Note S6 and Table S7). Inflexible demands are demands that must be met immediately. Flexible demands are (a) demands for electricity and heat that are used to fill high-temperature heat storage for industry, low-temperature district-heat storage or building water-tank storage, and district cold storage, (b) demands for electricity used to produce and compress hydrogen (since all hydrogen can be stored), and (c) remaining electricity and direct heat demands subject to demand-response. Table S7 provides the distribution of inflexible and flexible demands by regions. The table indicates that, among all regions, 40.2% of all demand is inflexible and 59.8% are flexible. Of the flexible demand, 1.95% is cold demand subject to storage, 10.7% is low-temperature heat demand subject to storage, 42.4% is high-temperature heat demand subject to storage, 19.3% is demand for non-grid hydrogen, and 25.7% is demand subject to DR. Table S14 provides the maximum storage capacities and maximum discharge rates of cold storage in water tanks (CS-STES) and ice (ICE) and low-temperature heat storage in water tanks (HW-STES), low-temperature heat storage in soil and water pits (UTES-heat; UTES-elect), and high-temperature heat storage in firebricks.

S8.5. Using Excess Electricity for Non-Grid Hydrogen Storage

Hydrogen is used here for both non-grid purposes (steel and ammonia manufacturing and long-distance transport) and grid purposes (GHS). Storage tanks for grid and non-grid purposes are assumed communal in the present study. Ref. S7 provides cases where such storage is separated as well. Tables S5 and S7 provide the annual electricity demand and hydrogen quantities needed to supply enough hydrogen to meet all non-grid hydrogen purposes. Using excess electricity to fill hydrogen storage, even with low electrolyzer and compressor use factors (0.2-0.65) thus high electrolyzer and compressor nameplate capacities, helps to keep the grid stable at lower cost than continuously producing hydrogen at a higher use factor (thus lower electrolyzer and compressor nameplate capacity). One reason is, a lower use factor reduces the overgeneration of WWS electricity production needed to produce hydrogen, thus reduces generator nameplate capacities needed[S7].

S8.6. Using Demand Response Management

Demand response helps to reduce current demand by shifting demand forward in 30-s increments, but by no more than eight hours, until the demand is met. In a case of 145 countries/24 regions, only two regions needed eight hours of load shifting for demands subject to demand response[S20]. Five regions needed no hours; six regions needed two hours; nine regions needed four hours; and two regions needed six hours. Thus, the maximum load shifting may be less necessary than the eight hours allowed here.

S8.7. Interconnecting Distant and Complementary WWS Resources

Although the wind is variable in nature, that variability decreases when wind energy is aggregated over large geographical regions[S30]. Thus, interconnecting 19 geographically-dispersed wind farms over an 850-km x 850-km region may eliminate the number of zero-power hours during a year compared with one wind farm within that region[S30]. What is more, because solar and wind are complementary in nature (when the wind is not blowing, the sun is often shining during the day and vice versa) for meteorological reasons[S15], interconnecting wind and solar on the grid reduces variability of either one independently.

S8.8. Importing/Exporting Electricity and Heat

Finally, interconnecting geographically-dispersed WWS generation and storage over long distances, including across political boundaries, can help to lower the cost of matching demand with supply[18,19]. In this study, 13 regions are multi-country regions and two regions are 2-country regions (Table S1). Large regions have more diversity of weather and WWS resources, improving the ability of a combination of wind electricity, hydroelectricity, and solar PV electricity, in particular, to provide a regular electricity supply. Small regions may also be lucky in having a diversity of resources and weather patterns or may just have an abundance of a particular resource. On the one hand, the region calculated with the highest cost per unit energy here (Table 1) (the Haiti region) is small, with little hydropower resource, poor wind resource, but a good solar resource. On the other hand, Iceland, which is also small, has substantial hydropower, wind, and geothermal resources but little solar. Due to the ability of Iceland to use CHS as backup and to capture its fast winds, its energy cost is low (Table 1). The Haiti region, on the other hand, needs significant overgeneration and GHS backup to keep its energy cost under control. Europe maintains a low energy cost because it can import electricity from either northern-European countries (where wind and hydropower resources are high) or from southern European countries (where solar resources are high).

Note S9. Calculations of Energy, Air Pollution, and Climate Costs

Once LOADMATCH simulations are complete, the resulting energy costs, health costs, climate costs, and total social costs (energy plus health plus climate costs) between WWS and BAU are estimated. All costs are evaluated with a social discount rate of 2 (1-3)%[S31], since the analysis here is a social cost analysis. Social cost analyses must use a social discount rate, even for the private-market-cost portion of the total social cost, because all costs in a social cost analysis must be treated from the perspective of society, not from the perspective of an individual or firm in the market.

The social cost of an investment is the investment's direct cost plus its externality costs (health costs, non-health-environmental costs, and climate costs in this case). A social discount rate is used when the costs and benefits of a project occur at different times and over more than one generation. Such projects are called intergenerational projects. By contrast, the private discount rate is the interest rate that banks charge builders and consumers for taking out loans. Such loans may be used to pay for the construction of a power plant or to build a house. The private discount rate is also the opportunity cost of capital. In other words, it is the rate of return that can be obtained by investing capital in a market. Private discount rates are appropriate only for relatively short-term public projects that dollar-for-dollar crowd out private investment[S32,S33].

Social discount rates are smaller than private discount rates, because society, as a whole, cares more about the welfare of distant future generations than does the average consumer or investor, who is generally concerned with near-term impacts during his or her lifetime. As a result, social discount rates appropriately weigh the present value of future impacts higher than do private discount rates. The (incorrect) use of a relatively high private discount rate in the evaluation of long-term climate-change mitigation would undervalue future social benefits and thus bias present-day investments away from efforts that provide long-term benefits to society. In order to properly evaluate long-term costs and benefits from the perspective of society, the social discount rate must be used.

Moore et al.[S32] reviewed accepted methods of estimating social discount rates and concluded (p. 809), "…no matter which method one chooses, the estimates for the social discount rate vary…between 0 and 3.5 percent for projects with intergenerational impacts." Drupp et al.[S31] surveyed 197 experts and similarly found that 92% of them believe the social discount rate should be between 1% and 3%. Three-quarters found 2% acceptable. Thus, here, we adopt 2 (1-3)% as the social discount rate (Table S14).

BAU air pollution health cost estimates (Table S25a) are based on the projected number of all air pollution deaths per year in 2050 by country provided in Table S26a (with a description of the calculation in Footnote 1 of the table) multiplied by the fraction of such deaths that are due to energy-related emissions (0.9)[S13], a 2050 value of statistical life (VOSL) for each country, a cost factor for morbidity (1.15), and a cost factor for non-health and non-climate environmental impacts (1.1)[S13].

With BAU, an estimated 5.6 million people die per year in 2050 from energy- plus non-energy-related air pollution across the 150 countries (Table S26a). Most deaths are in the India region (1.63 million/y), followed by the China region (1.17 million/y), West Africa (510,000/y), Southeast Asia (387,000/y), East Africa (353,000/y), Central Asia (292,000/y), and Europe (217,000/y). About 90% of these premature deaths are estimated to be due to energy generation and use[S22].

The 2050 value of statistical life (VOSL) (millions of dollars per person) by country was updated from Ref. S13 to USD 2022. Results are shown in the spreadsheet for each country[S3]. The mean VOSL in 2050 among all countries is $5.75 (4.94-7.66) million/person (USD 2022). The mean total cost of each life after accounting for associated morbidities and non-health environmental impacts is $7.27 (5.44-10.53) million/person. In the U.S., the 2050 VOSL and total cost are $12.1 million/person and $15.3 million/person (USD 2022). This is conservative relative to DOT[S34], who estimate the 2022 VOSL in the U.S. of $12.5 million/person.

The 2050 BAU health cost of energy-related deaths (based on the value of statistical life), associated morbidities, and associated non-health, non-climate environmental damage due to energy-related air pollution in the BAU case is estimated to be ~$32.5 trillion/y (Table S25a). Energy-related air pollution deaths due to WWS are assumed to equal zero since

100% WWS results in zero emissions associated with energy, even during the mining and manufacturing of WWS equipment.

2050 energy-related emissions of carbon dioxide and other climate-warming pollutants in the BAU case are estimated to be 56.1 gigatonnes (GT)-CO_2-equivalent (CO_2e)/y across 150 countries (Table S26a). The highest emission rates are in the China region (16.7 GT/y), India region (7.0 GT/y), United States (5.5 GT/y), Mideast (5.1 GT/y), Europe (4.2 GT/y), Southeast Asia (3.6 GT/y), and the Russia region (2.5 GT/y).

BAU climate costs are estimated based on the mean social cost of carbon (SCC) in each country and region (Table S26a) multiplied by the estimated energy-related CO_2-equivalent emissions in 2050 (Table S26a). The mean social cost of carbon in 2050 in each country is calculated as $580 ($327-$1,234)/tonne-$CO_2$e[S3] and is an update from Ref. S13 to USD 2022. The 2050 estimate assumes 2010 values of $250 ($125-$600)/tonne-$CO_2$e and growth factors of 1.5 (1.8-1.2)% per year between 2010 and 2050 and a multiplier of 1.226 to obtain values in USD 2022. The 2010 SCC is estimated as follows. Ref. S35 suggest that the 2014 lower bound of the SCC should be at least $125 per tonne-$CO_2$e. Ref. S36 concludes that incorporating the effect of climate change on the rate of economic growth can increase the SCC to between $200 and $1,000 per tonne-$CO_2$e. Ref. S37 similarly finds that accounting for the long-term effects of temperature rise on economic productivity results in climate change damage estimates that are 2.5 to 100 times higher than those from earlier studies. Nevertheless, we limit the upper limit of the 2010 SCC to $600/tonne-$CO_2$e.

Note S10. Calculation of Land Requirements

Footprint is the physical area on the top surface of soil or water needed for each energy device[S38]. It does not include the area of underground structures. Spacing is the area between some devices, such as wind turbines, wave devices, and tidal turbines, needed to minimize interference of the wake of one turbine with downwind turbines. Spacing area can be used for multiple purposes, including rangeland, ranching land, industrial land (e.g., installing solar PV panels), open space, or open water. Table S27 provides estimated footprint and spacing areas per MW of nameplate capacity of WWS electricity and heat generating technologies considered here.

Applying the footprint and spacing areas per MW nameplate capacity from Table S27 to the new nameplate capacities needed to provide grid stability (obtained by subtracting the existing nameplate capacities in Table S9 from the existing plus new nameplate capacities in Tables S10a,b) gives the total new land footprint and spacing areas required for each country and region, as shown in Tables S28a,b.

New land footprint arises only for solar PV plants, CSP plants, onshore wind turbines, geothermal plants, and solar thermal plants. Offshore wind, wave, and tidal generators are in water, so they don't take up new land, and rooftop PV does not take up new land. The footprint area of a wind turbine is relatively trivial (primarily the area of the tower and of exposed cement above the ground surface).

Note S11. Calculation of Employment Changes

Table S29 provides estimated numbers of long-term full-time construction and operation jobs per MW of new nameplate capacity or per kilometer of new transmission line for several electricity-generating and storage technologies and for transmission and distribution expansion. The total number of jobs produced in a region equals the new nameplate capacity of each electricity generator or storage device or the number of kilometers of new transmission/distribution lines multiplied by the respective number of jobs per MW or per kilometer from Table S29.

The number of jobs per MW was derived for the United States primarily from the Jobs and Economic Development Impact (JEDI) models[S39]. These models estimate the number of construction and operation jobs plus earnings due to building an electric power generator or transmission line. The models treat direct jobs, indirect jobs, and induced jobs.

Direct jobs are jobs for project development, onsite construction, onsite operation, and onsite maintenance of the electricity generating facility. Indirect jobs are revenue and supply chain jobs. They include jobs associated with construction material and component suppliers; analysts and attorneys who assess project feasibility and negotiate agreements; banks financing the project; all equipment manufacturers; and manufacturers of blades and replacement parts. The number of indirect manufacturing jobs is included in the number of construction jobs. Induced jobs result from the reinvestment and spending of earnings from direct and indirect jobs. They include jobs resulting from increased business at local restaurants, hotels, and retail stores, and for childcare providers, for example. Changes in jobs due to changes in energy prices are not included. Energy price changes may trigger changes in factor allocations among capital, energy input, and labor that result in changes in the number of jobs.

Specific output from the JEDI models for each new electric power generator includes temporary construction jobs, permanent operation jobs, and earnings, all per unit nameplate capacity. A temporary construction job is defined as a full-time equivalent job required for building infrastructure for one year. A full-time equivalent (FTE) job is a job that provides 2,080 hours per year of work. Permanent operation jobs are full-time jobs that last as long as the energy facility lasts and that are needed to manage, operate, and maintain an energy generation facility. In a 100% WWS system, permanent jobs are effectively indefinite because, once a plant is decommissioned, another one must be built to replace it. The new plant requires additional construction and operation jobs.

The number of temporary construction jobs is converted to a number of permanent construction jobs as follows. One permanent construction job is defined as the number of consecutive one-year construction jobs for L years to replace $1/L$ of the total nameplate capacity of an energy device every year, all divided by L years, where L is the average facility life. In other words, suppose 40 GW of nameplate capacity of an energy technology must be installed over 40 years, which is also the lifetime of the technology. Also, suppose the installation of 1 MW creates 40 one-year construction jobs (direct, indirect, and induced jobs). In that case, 1 GW of wind is installed each year and 40,000 one-year construction jobs are required each year. Thus, over 40 years, 1.6 million one-year jobs are required. This is equivalent to 40,000 40-year jobs. After the technology life of 40 years, 40,000 more 1-year jobs are needed continuously each year in the future. As such, the 40,000 construction jobs are permanent jobs.

Jobs losses due to a transition to WWS include losses in the mining, transport, processing, and use of fossil fuels, biofuels, bioenergy, and uranium. Jobs will also be lost in the BAU electricity generation industry and in the manufacturing of appliances that use combustion fuels. In addition, when comparing the number of jobs in a BAU versus WWS system, jobs are lost due to *not* constructing BAU electricity generation plants, petroleum refineries, and oil and gas pipelines.

Note S12. Summary of Energy, Storage, Cost, Land, and Employment Results

S12.1. Energy Demand and Generation Results

Table S4a provides the 2022 annual average end-use BAU demand, the projected 2050 annual average end-use BAU demand, and the 2050 annual average end-use WWS demand by energy sector and country from the spreadsheet analysis done in this study. Table S4b and Figure S2 provide the end-use demand by region.

Table S4a indicates that transitioning from BAU to 100% WWS in 2050 in 150 countries reduces the 2050 annual average end-use power demand by an average of 54.2%, from 19.6 TW to 9.0 TW. Of the total 150-country reduction, 37.0 percentage points are due to the efficiency of using WWS electricity over combustion; 10.6 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels; and 6.57 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Table S4a). Of the 37.0% reduction due to the efficiency advantage of WWS electricity, 19.75 percentage points are due to the efficiency advantage of WWS transportation, 4.11 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.14 percentage points are due to the efficiency advantage of using electric heat pumps instead of combustion heaters. Whereas all-purpose energy demand declines by 54.2%, the energy is almost all electricity (with some direct heat), causing world-average electricity consumption to increase by ~85% compared with BAU (Table S4a).

Table S5 summarizes the hydrogen amounts needed for steel production, ammonia production, and for long-distance transport (all non-grid hydrogen applications) by country and region. It also estimates the energy needed to produce the hydrogen for each application. Table S6 summarizes the 2050 annual average end-use WWS demand by sector for each of the 29 regions, also from the spreadsheet analysis. Table S7 provides a breakdown of the 2050 annual average end-use demand by inflexible versus flexible demand. Flexible demand is divided into cold demand subject to storage, low-temperature heat demand subject to storage, industrial heat demand subject to firebrick storage, demand for non-grid hydrogen, and all other flexible demands, which are subject to demand response. It also summarizes the amounts of non-grid hydrogen needed by region.

Figures S3-S31 show time-series plots of LOADMATCH final results for each of the 29 regions. The figures show hourly matching of all-purpose end-use demand with supply, changes in storage, and losses exactly every 30 s, during a 100-day period of the three-year simulations (2050 to 2052). No failure occurs during any time step in any region at any time during the three years. Thus, WWS avoided blackouts by ensuring that generation, storage, losses, and demand response met demand every 30 s for multiple years, each with different meteorological conditions.

Table S9 provides the existing 2023 nameplate capacities of each electricity and heat generator by country. Table S10a and b provide the final nameplate capacities for each generator in each region, as determined by LOADMATCH, in the Base-WWS case and the EGS cases, respectively.

Table S11 gives the ratio of the final nameplate capacities needed to meet continuous demand in LOADMATCH to the initial estimated nameplate capacities needed to meet annual average demand, as determined from the spreadsheet analysis used to estimate such demands[S3]. The ratios are referred to as capacity adjustment factors (CAFs). Overall, ~16.4% more overall generator nameplate capacity is needed, summed over all 150 countries, to meet continuous 2050 demand than to meet annually averaged 2050 demand (Table S8). The difference is due to oversizing generation in order to meet continuous demand. Storage is also needed to meet continuous demand (Tables S14-S16).

Tables S12a and b give the regional-average modeled capacity factor (CF) of each generator over the three-year base and EGS simulations, respectively. Tables S13a and b give the percent of all electricity plus heat consumed plus losses that is produced from each WWS energy generator, averaged over the respective three-year simulations.

S12.2. Storage Results

Table S14 provides storage maximum charge rates, discharge rates and capacities. The total battery storage (BS) capacity among all 150 countries is 23.42 TWh (Table S14). For comparison, the total conventional hydropower (CH) storage capacity in reservoirs in the 150 countries is 1,588 TWh, close to the estimated worldwide storage capacity[S24]. Thus, the storage capacity of CHS already existing in the world is 67.8 times the storage capacity of batteries needed for these plans. However, BS needed in 2050 has a peak discharge rate of 5.85 TW, whereas CHS has a peak discharge rate of 1.26 TW, all of which already exists. Thus, BS in this study is used more for peaking, whereas CHS is used more for energy storage.

World hydropower output in 2020 was 4,370 TWh/y[S40]. Thus, hydropower consumed (cycled) 2.75 times its 2023 storage capacity (1,588 TWh). In the present study, the 150-country hydropower output in 2050 was 4,754 TWh/y (Table S19); thus, hydropower cycled 3.0 times per year. By contrast, the number of battery cycles needed per year in 2050 varied from 0 to 194, with 23 regions needing 100 cycles or less per year (Table S16). Table S16 also provides BS capacities and maximum charge and discharge rates for all regions.

Although batteries store electricity here for only four hours at their peak discharge rate, longer storage can be obtained by concatenating batteries in series. In other words, if 8-h storage is needed, then two 4-h batteries can be depleted sequentially. Having a low number of hours of storage (e.g., four hours) maximizes the flexibility of batteries both to meet peaks in power demand (GW) and to store electrical energy for long periods (GWh). For example, suppose 100 batteries, each with 4-h storage and a peak discharge rate of 10 kW, are concatenated. This allows for either 400 hours of storage at a peak discharge rate of 10 kW or 4 h of storage at a peak discharge rate of 1,000 kW, or anything in between. Thus, batteries with longer than 4-h storage are not "necessary" for keeping the grid stable. However, BS is most cost optimal if both its maximum discharge rate and its maximum storage capacity are reached.

If BS is used mostly for its storage capacity (rather than its peak discharge ability), BS is expensive, relative to green hydrogen storage (GHS), due to the high cost per kWh of BS. On the other hand, if BS is used primarily for peaking, then BS is inexpensive, relative to GHS, because of its low cost per kW compared with GHS. Because GHS has a lower cost per kWh of storage capacity but a higher cost per kW of peak discharge than does BS, combining GHS with BS reduces the cost of grid stability in locations where the ratio of the maximum storage capacity (TWh) needed to maximum discharge rate (TW) needed (R_{ideal}) is high[S21]. R_{ideal} is the same as the maximum number of hours of storage needed at the maximum discharge rate.

R_{ideal} is the maximum number of hours of storage ever needed at the maximum discharge rate that actually occurs during a simulation. If this ratio exceeds four hours (the number of hours of battery storage at the peak discharge rate assumed for all simulations), then the battery peak discharge rate used is greater than that actually needed, so the peak discharge rate (TW) used can be decreased without any impact on the results, if the original storage capacity (TWh) is maintained by increasing the number of hours of storage at the new peak discharge rate. Using both GHS and batteries versus using batteries alone reduces both the value of R_{ideal} and the cost of grid stability[S21]. Using GHS together with BS reduces the need to use batteries for storage capacity while maintaining their use for peaking.

Here, both BS and GHS are used in 18 of 29 regions; BS alone is used in 5 regions (eastern Africa, Australia, Central America, Cuba, and Jamaica), GHS alone is used in 1 region (Haiti-Dominican Republic), and no BS or GHS is used in 5 regions (Canada, Iceland, Russia region, northwest South America, and southeast South America) (Table S14). In the regions with no BS or GHS, electricity storage is supplied by either CHS alone (Iceland); CHS and PHS (Canada and Russia region); or CHS, PHS, and CSPS (northwest and southeast South America). Thus, in three regions, no storage aside from CHS and/or PHS is needed.

Among the regions all BS storage times are 4 h, but an analysis of R_{ideal} (Table S16a) suggests that batteries with storage times of 4 h to 23.7 h would ensure batteries both fill their maximum storage capacity and discharge at their maximum rate at least once during a simulation. The upper limit of R_{ideal} would be higher without the inclusion of GHS[21].

Thus, batteries with longer than 4-h storage are not necessary for keeping the grid stable. However, storage times of greater than four hours and up to 23.7 h (in the base-WWS case), while not needed, can be advantageous for a region. Batteries with storage times longer than ~23.7 h are never needed nor advantageous in the present study (Table S16a).

S12.3. Cost Results

The net present value of the capital cost to transition all 150 countries while keeping the grid stable is \$60.0 trillion (USD 2022) in the base-WWS case and \$64.9 trillion in the mid-cost-EGS case, with new electricity generators comprising \$45.9 trillion and \$51.4 trillion, respectively, of this (Table S24, Figure S2). The remaining capital costs are for new (1) storage: electricity storage in batteries, PHS, CSPS, and GHS; firebrick storage for industrial heat; hot and cold water storage and ice storage for district heat and cold, and non-grid GHS; (2) hydrogen electrolyzers and compressors; (3) ground- and air-source electric heat pumps for generating district heat and cold; and (4) long-distance HVDC transmission. Capital costs for generators, storage, and equipment include the costs of mining, transporting, and refining minerals for and manufacturing these technologies. The total capital cost does not include the capital costs of new electric appliances and machines (e.g., ground- and air-source electric heat pumps for individual buildings, electric vehicles, industrial equipment) since it is assumed that their fossil-fuel counterparts will be replaced in any case within 15 years at similar cost. Table S24 provides a dissection of the levelized cost of energy (LCOE) for each region. A few more components of levelized cost appear than of capital cost because it is assumed simplistically that the nameplate capacities and outputs of some generators (conventional hydropower turbines, direct geothermal heat generators, and direct solar heat generators) stay constant from the present through 2050, so no new generators are added; however, the existing generators still incur an annual cost of electricity, included in Table S24.

Among all 150 countries, the 2050 annual social cost (Note S9) for BAU energy, without a conversion to WWS, is calculated here as \$86.6 trillion/y, which consists of a 2050 private energy cost (\$17.2 trillion/y), health cost (\$36.9 trillion/y), and climate cost (\$32.5 trillion/y) (Table S25a). To determine the BAU private energy-cost total across all energy sectors (rather than just in the electricity sector), we assume that the BAU private energy cost per unit-all-energy equals the BAU private energy cost per unit-electricity. This assumption is needed since BAU costs in non-electricity sectors are not readily available whereas those in the electricity sector are. Because annual WWS social (and private) costs are an order of magnitude lower than are corresponding BAU costs, this assumption should make no difference in the conclusions drawn here.

Thus, switching all countries to 100% WWS in the base-WWS case reduces both social and private energy costs to \$6.78 trillion/y, or by 92.2% and 60.6%, respectively (Table S25a). The significant decrease in private energy cost between BAU and WWS occurs because WWS reduces energy demand by 54.2% and the cost per unit energy by ~14.0% (Table S25a). The decrease in social energy cost occurs because WWS eliminates energy-related health and climate costs in addition to reducing energy needs and costs.

The WWS capital cost divided by the difference between the BAU and WWS annual private and social energy costs (Table S25a) is the payback time due to the WWS private and social cost savings, respectively. The base-WWS-case 150-country payback time due to annual private energy cost savings is a mean of 5.8 years. That due to social cost savings is 0.75 years. The capital cost is paid back through energy sales rather than subsidies.

Among all world regions, the average base-WWS-case LCOE, between 2022 and 2050, that results in a stable grid, is 8.64 ¢/kWh (USD 2022) (Tables S24 and S25). Averaged among all regions, this cost is dominated by the costs of electricity generation (4.01 ¢/kWh), electricity distribution (2.38 ¢/kWh), short-distance transmission (1.05 ¢/kWh), non-grid green hydrogen production/compression/storage (0.60 ¢/kWh), long-distance transmission (0.17 ¢/kWh), battery storage (0.15 ¢/kWh), geothermal plus solar heat generation (0.082 ¢/kWh), underground heat storage (0.078 ¢/kWh), grid hydrogen production, storage, and use with fuel cells (0.077 ¢/kWh), electric heat pumps for district heating (0.055 ¢/kWh), CSPS and pumped hydro storage (0.006 ¢/kWh), hot water storage (0.005 ¢/kWh), and cold water and ice storage (0.002 ¢/kWh) (Table S24).

S12.4. New Land Area Requirements

The total new land area for footprint (before removing the fossil-fuel infrastructure) required with 100% WWS in the base-WWS case is about 0.18% of the 150-country land area (Table S28, Figures S32 and S33), almost all for utility PV. WWS has no footprint associated with mining fuels to run the equipment, but both WWS and BAU energy infrastructures require one-time mining for raw materials for new plus repaired equipment construction.

The only spacing area over land needed in a 100% WWS world is between onshore wind turbines. The spacing area for onshore wind to power the 150 countries is about 0.39% of the 150-country land area (Table S28, Figures S32 and S33).

Together, the new land footprint plus spacing areas for 100% WWS across all energy sectors represents 0.57% of the 150-country land area, and most of this land area is multi-purpose spacing land. Iceland has the lowest footprint plus spacing area as a percent of regional land area (0.04%); Taiwan has the greatest (7.8%), dominated by footprint (Table S28, Figures S32 and S33). It is possible to reduce footprint area in several ways: by using more offshore wind and behind-the-meter rooftop PV and less utility PV or putting some utility PV offshore.

S12.5. Employment Change Results

Table S30 estimates the number of permanent, full-time jobs created and lost due to a transition in each country to 100% WWS by 2050. The job creation accounts for new direct, indirect, and induced jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including HVDC transmission) industries (Note S11). It also accounts for the building of electric heat pumps to supply district heating and cooling. However, it does not account for changes in jobs in the production of electric appliances, vehicles, and machines or in increasing building energy efficiency. Construction jobs are for new WWS devices only. Operation jobs are for new and existing devices.

The job losses in Table S30 are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, biofuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke, are retained. For transportation sectors, the jobs lost are those due to transporting fossil fuels (e.g., through truck, train, barge, ship, or pipeline); the jobs not lost are those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion appliances, including automobiles, ships, or industrial machines.

Table S30 indicates that transitioning to 100% WWS may produce 55.4 million new long-term, full-time jobs in the base-WWS case and 51.3 million jobs in the EGS cases. In both cases, 25.3 million jobs may be lost from the current-fuel industries, for net increases of 28.0 million and 24.0 million, respectively, long-term, full-time jobs produced among the 150 countries. In the base-WWS case, net job gains occur in 24 out of 29 regions, although not all countries within each region gain jobs. Only the regions of eastern Africa, northern Africa, western Africa, Canada, and the Russia region experience net job losses in the base-WWS case. In the EGS cases, Madagascar, the Mideast, and northwestern South America also experience net job losses.

Locations with fewer net job gains or net job losses are usually locations with a substantial fossil-fuel industry. More jobs, not accounted for here, may arise from the need to build more electrical appliances and to improve building energy efficiency.

S12.6. Energy Conservation and Grid Stability

LOADMATCH exactly conserves energy over the three-year simulations for every region. For example, “End-use demand plus losses” for “All regions” in Table S18 equals 11,803 GW averaged over the simulations, and this exactly equals “Supply plus changes in storage.” Of that total, 8,962 GW is “annual average end-use demand,” which is the exact total, within roundoff error, shown in Table S4 for “All Countries.” The rest of the total is the sum of transmission and distribution losses (772.5 GW), losses going in and out of storage (263.1 GW), and curtailment losses (1,805 GW). Thus, curtailment losses are 15.3% of total supply plus changes in storage.

Note S13. Some Hurdles to Overcome

What are some of the hurdles to a transition? A major hurdle is the competition among different ideas for solving the problems. Energy industries that do not benefit from a transition to WWS include the fossil-fuel industry, bioenergy industry, and nuclear industry. These industries have large shares in the current energy economy and would like to maintain their shares.

Other hurdles include up-front financing, zoning difficulties in expanding transmission lines, NIMBYism (not-in-my-backyard-ism) against new energy projects, social anxiety stemming from eliminating combustion vehicles and appliances, and lining up manufacturing capabilities rapidly. Also, a transition is difficult in countries engaged in conflict and countries in poverty. On the flip side, 97% of the technologies needed for a WWS transition are available commercially. The main technologies not yet included are long-distance aircraft and ships and some industrial-process technologies. However, it is expected that solutions for those technologies will be available by 2027-2035.

Supplemental Tables

Table S1. The 29 world grid regions and the 150 countries within those regions treated in this study.

Region	Country(ies) Within Each Region
Africa-East (8)	Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, Uganda
Africa-North (6)	Algeria, Egypt, Libya, Morocco, Niger, Tunisia
Africa-South (8)	Angola, Botswana, Eswatini, Mozambique, Namibia, South Africa, Zambia, Zimbabwe
Africa-West (11)	Benin, Cameroon, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Equatorial Guinea, Gabon, Ghana, Nigeria, Senegal, Togo
Australia (1)	Australia
Canada (1)	Canada
Central America (7)	Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
Central Asia (6)	Kazakhstan, Kyrgyz Republic, Pakistan, Tajikistan, Turkmenistan, Uzbekistan
China region (4)	China, Hong Kong, Democratic People's Republic of Korea, Mongolia
Cuba (1)	Cuba
Europe (40)	Albania, Austria, Belarus, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Gibraltar, Greece, Hungary, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Moldova Republic, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
Haiti region (2)	Dominican Republic, Haiti
Iceland (1)	Iceland
India region (4)	Bangladesh, India, Nepal, Sri Lanka
Israel (1)	Israel
Jamaica (1)	Jamaica
Japan (1)	Japan
Madagascar (1)	Madagascar
Mauritius (1)	Mauritius
Mideast (15)	Armenia, Azerbaijan, Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Türkiye, United Arab Emirates, Yemen
New Zealand (1)	New Zealand
Philippines (1)	Philippines
Russia region (2)	Georgia, Russia
South America-NW (9)	Bolivia, Colombia, Curacao, Ecuador, Guyana, Peru, Suriname, Trinidad and Tobago, Venezuela
South America-SE (5)	Argentina, Brazil, Chile, Paraguay, Uruguay
Southeast Asia (9)	Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Singapore, Thailand, Vietnam
South Korea (1)	Korea, Republic of
Taiwan (1)	Taiwan
United States (1)	United States

Numbers in parentheses are the number of countries in each region. Guyana was added since the last evaluation, which was for 149 countries.

Table S2. Primary processes treated within the LOADMATCH model, as well as some inputs into and some outputs from the model.

WWS electricity and heat generation
Onshore and offshore wind electricity Utility photovoltaic (PV) electricity Residential, commercial/government rooftop PV electricity Concentrated solar power (CSP) electricity Conventional geothermal electricity Enhanced geothermal systems (EGS) electricity Tidal and wave electricity Conventional geothermal heat Solar heat
WWS storage for grid electricity
Existing hydropower reservoirs with water turbines (no uprating turbines) Hydropower used separately for peaking and baseload Pumped hydropower storage with water turbines Concentrated solar power storage with steam turbines Batteries Green hydrogen storage with fuel cells
WWS heat and cold storage
Low-temperature heat storage in water tanks, soil, and water pits Cold storage in water tanks and ice Industrial process heat storage for industry in firebricks
WWS hydrogen production, storage, and use
Green hydrogen production by electrolysis using WWS electricity Hydrogen compression Hydrogen storage Separate or combined electrolysis, compression, and storage for grid versus non-grid hydrogen Hydrogen for steel and ammonia manufacturing in industry Hydrogen fuel cell-electric long-distance aircraft, ships, trains, trucks, military vehicles Hydrogen fuel cells for grid electricity
WWS appliances and machines
Battery-electricity vehicles for all but long-distance (where hydrogen fuel cell vehicles used) Battery-electric construction machines and agricultural equipment Ground- and air-source electric heat pumps for building cooling and air/water heating Ground- and air-source electric heat pumps for district heating and cooling Ground- and air-source electric heat pumps for low-temperature industrial heat Ground- and air-source electric heat pump clothes washers and dryers and dishwashers Electric lawn mowers, leaf blowers, induction cooktops Electric arc, resistance, and induction furnaces for mid- and high-temperature industrial heat
WWS electricity and heat grids
Assumes perfect transmission interconnections AC, HVAC, and HVDC transmission line lengths calculated Transmission and distribution line losses calculated District heating/cooling and distributed heating/cooling treated Losses of electricity and heat in and out of storage calculated Losses of electricity and heat due to curtailment and generator downtime calculated
Costs, jobs, and land use outputs from LOADMATCH
Costs of all generation, all storage, short- and long-distance transmission/distribution Costs of hydrogen rectifiers, electrolyzers, compressors, storage, dispensing, cooling, fuel cells Avoided cost of air pollution damage Avoided cost of climate damage Changes in job numbers for new generators, storage, transmission Land footprint and spacing requirements for new electricity and heat generators
GATOR-GCMOM output used as input into LOADMATCH
Onshore and offshore wind, roof PV, utility PV, CSP, solar heat, wave supply Heat and cold demands in buildings Wind supply accounts for array losses due to competition among turbines for kinetic energy Wind and solar supplies account for air temperature changes due to wind and solar devices

*Process added as part of this study.

Table S3. Factors to multiply BAU end-use energy consumption by in each of six energy sectors to obtain equivalent WWS end-use energy consumption in the base-WWS and EGS cases. The factors are the ratios of BAU work-output/energy-input to WWS work-output/energy-input, provided by fuel and sector.

	Residential		Comm./Govt.		Industrial		Transportation		Ag-for-fish		Military-other	
Fuel	Elec: fuel ratio	Extra effic-iency	Elec: fuel ratio	Extra effic-iency	Elec: fuel ratio	Extra effic-iency	Elec: fuel ratio	Extra effic-iency	Elec: fuel ratio	Extra effic-iency	Elec: fuel ratio	Extra effic-iency
Oil	0.2[a]	0.84	0.2[a]	0.95	0.78[e]	0.98	.21/.40[f]	0.96	0.21	0.96	0.21	0.96
Fossil gas	0.2[a]	0.81	0.2[a]	1	0.78[e]	0.98	.21/.40[g]	0.88	0.2	0.91	0.2	0.91
Coal	0.2[a]	1	0.2[a]	1	0.78[e]	0.97	--	--	0.2	--	0.2	--
Electricity	1[b]	0.77	1[b]	0.78	1[b]	0.92	1[b]	1	1	0.78	1	0.78
Heat for sale	0.25[c]	1.0	0.25[c]	1	0.25[c]	1	--	--	0.25	1	0.25	1
WWS heat	1[d]	1	1[d]	1	1[d]	1	--	--	1	1	1	1
Biofuels/waste	0.2[a]	0.87	0.2[a]	1	0.78[e]	1	0.21/[h]	0.96	0.2	0.93	0.2	0.93

Residential demands include electricity and heat consumed by households, excluding transportation.

Comm./Govt. demands include electricity and heat consumed by commercial and public buildings, excluding transportation.

Industrial demands include energy consumed by all industries, including iron, steel, and cement; chemicals and petrochemicals; non-ferrous metals; non-metallic minerals; transport equipment; machinery; mining (excluding fuels, which are treated under transport); food and tobacco; paper, pulp, and print; wood and wood products; construction; and textile and leather.

Transportation demands include energy consumed during any type of transport by road, rail, domestic and international aviation and navigation, or by pipeline, and by agricultural and industrial use of highways. For pipelines, the energy required is for the support and operation of the pipelines. The transportation category excludes fuel used for agricultural machines, fuel for fishing vessels, and fuel delivered to international ships, since those are included under the agriculture/forestry/fishing category.

Agriculture-forestry-fishing demands include energy consumed by users classified as agriculture, hunting, forestry, or fishing. For agriculture and forestry, it includes consumption of energy for traction (excluding agricultural highway use), electricity, or heating in those industries. For fishing, it includes energy for inland, coastal, and deep-sea fishing, including fuels delivered to ships of all flags that have refueled in the country (including international fishing) and energy used by the fishing industry.

Military-other demands include fuel used by the military for all mobile consumption (ships, aircraft, tanks, on-road, and non-road transport) and stationary consumption (forward operating bases, home bases), regardless of whether the fuel is used by the country or another country.

Elec:fuel ratio (electricity-to-fuel ratio) is the ratio of the energy input of end-use WWS electricity to energy input of BAU fuel needed for the same work output. For example, a value of 0.5 means that the WWS device consumed half the end-use energy as did the BAU device to perform the same work.

Extra efficiency is the effect of the additional efficiency and energy reduction measures in the WWS system beyond those in the BAU system. It assumes moderate economic growth. For example, in the case of fossil gas, oil, and biofuels for residential air and water heating, it is the additional efficiency due to better insulation of pipes and weatherizing homes. For residential electricity, it is due to more efficient light bulbs and appliances. In the industrial sector, it is due to faster implementation of more energy efficient technologies than in a reference case. The improvements are calculated as the product of (a) the ratio of energy use, by fuel and energy sector, of the EIA's *high efficiency all scenarios* (HEAS) case and their *reference* case[5] and (b) additional estimates of slight efficiency improvements beyond those in the HEAS case[S13].

Oil includes end-use energy embodied in oil products, including refinery gas, ethane, liquefied petroleum gas, motor gasoline (excluding biofuels), aviation gasoline, gasoline-type jet fuel, kerosene-type jet fuel, other kerosene, gas oil, diesel oil, fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes, petroleum coke, and other oil products. Does not include oil used to generate electricity.

Fossil gas includes end-use energy embodied in fossil gas. Does not include fossil gas used to generate electricity.

Coal includes end-use energy embodied in hard coal, brown coal, anthracite, coking coal, other bituminous coal, sub-bituminous coal, lignite, patent fuel, coke oven coke, gas coke, coal tar, brown coal briquettes, gas works gas, coke oven gas, blast furnace gas, other recovered gases, peat, and peat products. Does not include coal used to generate electricity.

Electricity includes end-use energy embodied in electricity produced by any source.

Heat for sale is end-use energy embodied in any heat produced for sale. This includes mostly waste heat from the combustion of fossil fuels, but it also includes some heat produced by electric heat pumps and boilers.

WWS heat is end-use energy in the heat produced from geothermal heat reservoirs and solar hot water heaters.

Biofuels and waste include end-use energy for heat and transportation from solid biomass, liquid biofuels, biogas, biogasoline, biodiesel, bio jet kerosene, charcoal, industrial waste, and municipal waste.

[a]The ratio 0.2 assumes electric heat pumps (mean coefficient of performance, COP, of 4, with a range of 3.2 to 5.2 (3.2-4.5 for air-source heat pumps and 4.2-5.2 for ground-source heat pumps[S41] replace oil, gas, coal, biofuel, and waste combustion heaters (COP=0.803) for low temperature air and water heating in buildings. The ratio is calculated by dividing the COP of BAU heaters by that of heat pumps. The mean heat pump COP of 4 assumes 60% of heat pumps are air-source at the low end of the range (COP=3.2) and 40% are ground source (or water source) at the high end of the range (COP=5.2). The COP of combustion heaters assumes 98% have a COP of 0.8 and 2% have a COP of 0.95.

[b]Since *electricity* is already end-use energy, there is no reduction in end-use energy (only in primary energy) from using WWS technologies to produce electricity.

[c]Since *heat for sale* is low-temperature heat, it will be replaced by heat from electric heat pumps (mean COP=4, with a range of 3.2 to 5.2) giving an electricity-to-fuel ratio of 0.25 (=1/4). Heat for sale is also low-temperature heat in the industrial sector, so it is replaced in that sector with heat pumps as well.

[d]Since *WWS heat* is already from WWS resources, there is no reduction in end-use or primary energy upon a transition to 100% WWS for this source.

[e]The ratio 0.78 for industrial heat processes assumes a mixture of electric resistance furnaces, arc furnaces, induction furnaces, and dielectric heaters replace oil, gas, coal, biofuels, and waste combustion heaters for mid- and high-temperature heating processes (above 150 ^{o}C). It also assumes that ground- and air-source heat pumps replace those fuels for low-temperature heating processes (below 150 ^{o}C). The electricity-to-fuel ratio for mid- and high-temperature replacement is 0.88 (=0.854/0.97), where 0.854 is the mean COP for fossil gas, coal, or oil boilers and 0.97 is that for electric resistance furnaces. The COP for fossil fuel boilers assumes 80% have a COP of 0.8 and 20% have a COP of 107%, which can occur because some industrial boilers recapture waste heat and latent heat of condensation, and the COP is based on the lower heating value. The electricity-to-fuel ratio for heat pumps replacing low-temperature industrial heat processes is 0.21 (=0.854/4), where 0.854 was just defined and 4 is the mean COP of a heat pump. It is assumed that 15% of industrial heat will be with heat pumps (electricity-to-fuel ratio of 0.21) and 85% with mid- and high-temperature replacements (0.88), giving a mean replacement ratio of 0.78. The industrial sector electricity-to-fuel ratio and extra efficiency measure factors are applied only after industrial sector BAU energy used for mining and processing fossil fuels, biofuels, bioenergy, and uranium (industry "own use") has been removed from each fuel sector. The amount of industry own use is given in IEA[S4] for each country. The ratio and factors are also applied only after the change in energy between BAU and WWS during steel manufacturing due to purifying iron using green hydrogen in a shaft furnace instead of purifying iron from coke in a blast furnace is accounted for (Table S5,), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen is accounted for (Table S5).

[f]The electricity-to-fuel ratio for a battery-electric (BE) vehicle is 0.21; that for a hydrogen fuel cell (HFC) vehicle is 0.40. The ratio for BE vehicles is calculated assuming 85% of vehicles have a ratio of 0.19 and 15% have a ratio of 0.31. The 0.19 ratio is calculated as the ratio of the low tank-to-wheel efficiency of internal combustion engine (ICE) vehicles (0.17) to the high plug-to-wheel efficiency of a BE vehicle (0.89). The 0.31 value is calculated as the high efficiency of an ICE vehicle (0.2) divided by the low efficiency of a BE vehicle (0.64). The 0.40 ratio for HFC vehicles is calculated assuming 85% of vehicles have a ratio of 0.365 and 15% have a ratio of 0.578. The 0.365 value is the low tank-to-wheel efficiency of an ICE vehicle (0.17) divided by the high efficiency of an HFC vehicle (0.466). The 0.578 value is the high efficiency of an ICE vehicle (0.20) divided by the low efficiency of an HFC vehicle (0.346). 2% of BAU energy in the form of *oil* in the *transportation* sector is used to transport fossil fuels, biofuels, bioenergy, and uranium. That BAU energy is eliminated in a 100% WWS world. Of the remaining 2050 end-use fuel from oil used for transportation, a worldwide average of 75.3% is replaced with battery electricity, and 24.7% is replaced with electrolytic hydrogen (Table S5). The percent replaced by battery electricity is multiplied by the electricity-to-fuel ratio for BE vehicles to determine the WWS electricity used for BE transportation replacing oil and the percent replaced by electrolytic hydrogen is multiplied by the electricity-to-fuel ratio for HFC transportation replacing oil.

[g]About 80% of *fossil gas* energy in the transportation sector is used to transport fossil fuels, biofuels, bioenergy, and uranium (e.g., through pipelines or other means). That BAU energy is eliminated in a 100% WWS world. Of the remainder, 95% is assumed to be electrified with BE vehicles and 5% is assumed to be electrified with HFC vehicles.

[h]It is assumed that 100% of *biofuels and waste* currently used in transportation will be electrified in 2050 thus will have the electricity-to-fuel ratio of a BE vehicle.

Table S4a.i. Annual-average end-use demand (total final consumption) and its components in 2022 by country. First row of each country: 2022 annually averaged end-use demand (GW) and percentage of the demand by sector. Second row: projected 2050 annually averaged end-use BAU demand (GW) and percentage of the total demand by sector. Third row: estimated 2050 total end-use demand (GW) and percentage of total demand by sector if 100% of end-use delivered BAU demand in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU demand due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity demand (=all energy demand) in the 2050 base-WWS case to the electricity demand in the 2050 BAU base. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases. Column (k) shows that all energy decreases. All results in this table for the base-WWS case are the same as for the EGS cases.

Country	Case	(a) Total annual average end-use demand (GW)	(b) Resi-den-tial % of total	(c) Com-merc ial % of total	(d) Indu s-try % of total	(e) Tran s-port % of total	(f) Ag-for-fish % of total	(g) Mil-itary-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to elim-inating up-stream	(j) % change end-use demand with WWS due to effic-iency be-yond BAU	(k) Overall % change in end-use demand with WWS	(l) WWS: BAU elec-tric-ity dem-and
Albania	BAU 2022	2.8	24.9	10.2	24.3	35.3	5.37	0					
	BAU 2050	3.8	29.3	12.1	20.9	33.3	4.24	0					
	WWS 2050	1.8	36.7	15.3	28.5	17.2	2.31	0	-38.31	-4.09	-9.39	-51.8	1.3
Algeria	BAU 2022	63	29.6	1.5	30	33.7	0.7	4.57					
	BAU 2050	129.2	23.5	1.4	25.5	44.9	0.64	4.19					
	WWS 2050	43.5	22	2.3	43.6	25.6	1.26	5.24	-42.92	-15.84	-7.58	-66.34	2.26
Angola	BAU 2022	17.7	58.6	4.8	12.2	24.3	0.04	0.07					
	BAU 2050	27.1	49.7	4.4	14.2	31.6	0.04	0.08					
	WWS 2050	8.7	44.8	2.6	28.4	24.2	0.03	0.05	-55.83	-3.26	-8.66	-67.75	2.34
Argentina	BAU 2022	84.1	23.9	6.7	30.4	32.7	6.29	0					
	BAU 2050	131.9	22.5	6.3	28.3	37.8	5.07	0					
	WWS 2050	46.8	22.3	11	43.5	20.1	3.1	0	-42.07	-14.96	-7.45	-64.47	2.03
Armenia	BAU 2022	4	33	3.5	15.5	32.8	3.38	11.84					
	BAU 2050	5.6	34.6	3.4	12.8	37	2.71	9.5					
	WWS 2050	1.8	34.8	4.2	28.7	15.3	2.28	14.68	-43.7	-13.94	-9.95	-67.59	1.55
Australia	BAU 2022	125.9	12	7.7	43.1	34.5	2.62	0.03					
	BAU 2050	189.2	11.7	10.4	45.1	30.6	2.18	0.02					
	WWS 2050	84.7	14.6	16.6	50.3	17.3	1.22	0.01	-32.3	-16.65	-6.3	-55.25	1.54
Austria	BAU 2022	36	23.5	8.6	35.6	30.4	1.89	0					
	BAU 2050	42.9	23.5	9	33.8	32	1.64	0					
	WWS 2050	19.8	19.3	11.1	45.7	22.7	1.17	0	-38.11	-9.1	-6.65	-53.87	1.7
Azerbaijan	BAU 2022	15.9	34	8.5	22.6	29.6	5.28	0					
	BAU 2050	21.6	36.7	10.3	20.6	28.1	4.27	0					
	WWS 2050	7.4	30.1	16.9	28.8	19.6	4.57	0	-49.27	-6.94	-9.44	-65.65	1.63
Bahrain	BAU 2022	9.9	11.2	7.8	56	25	0.07	0					
	BAU 2050	17	13.5	8.6	54.7	23.1	0.07	0					
	WWS 2050	9.8	17.5	11.5	62.2	8.7	0.09	0	-21.26	-14.18	-7.27	-42.71	1.31
Bangladesh	BAU 2022	43.8	43.6	2.6	32.7	16.1	4.54	0.45					
	BAU 2050	78.1	36.5	3	33	22.8	4.24	0.44					
	WWS 2050	37.6	29.3	4.5	53.4	9.9	2.28	0.69	-36.54	-6.29	-9.04	-51.87	1.66
Belarus	BAU 2022	24.3	30.1	9	34.6	19.7	6.61	0					
	BAU 2050	32.5	32	10.7	32.2	19.8	5.4	0					
	WWS 2050	11.4	27.5	16.4	37.9	13.8	4.35	0	-47.41	-11.75	-5.86	-65.02	1.76
Belgium	BAU 2022	55.9	16.8	9.4	29.4	42.4	1.93	0.09					
	BAU 2050	63.9	16.3	10	29.3	42.5	1.77	0.08					
	WWS 2050	26.4	12.6	12.9	45.2	28.2	1.13	0.05	-44.63	-7.59	-6.57	-58.79	2.02
Benin	BAU 2022	5.4	45.8	10.6	5.4	37.7	0.49	0					
	BAU 2050	8.9	34.7	13.1	6	45.6	0.56	0					
	WWS 2050	2.3	26.5	15.5	18.5	38.7	0.76	0	-66.97	-0.85	-6.77	-74.6	5.75
Bolivia	BAU 2022	11	13.4	3.2	25.9	52.7	4.46	0.29					
	BAU 2050	17.7	10	3	22.6	60.6	3.57	0.25					
	WWS 2050	5.7	12.8	6.2	42.8	33.8	3.85	0.6	-45.68	-16.26	-5.96	-67.9	3.12
Bosnia and Herzegovina	BAU 2022	6.2	39.6	8.8	21.4	29.1	1.16	0					
	BAU 2050	8.4	41.3	10.5	19.6	27.6	0.91	0					
	WWS 2050	3.4	37.8	15.4	28.7	17.5	0.6	0	-42.95	-7.15	-8.8	-58.9	1.44
Botswana	BAU 2022	2.7	40.3	4.4	15	38.4	1.29	0.64					
	BAU 2050	4.7	32.6	5.7	15.5	44	1.38	0.71					
	WWS 2050	1.7	27.8	10.8	31.2	26.8	2	1.47	-52.43	-1.84	-8.27	-62.54	1.86
Brazil	BAU 2022	342.2	11.2	5.2	41.5	37	5.07	0					
	BAU 2050	565.1	9.5	5.1	40.8	39.8	4.83	0					
	WWS 2050	263.5	11.5	8.1	57.9	18.9	3.59	0	-37.68	-10.07	-5.63	-53.37	2.15
Brunei	BAU 2022	3	6.9	6.8	66.4	19.9	0	0					
	BAU 2050	5.1	7.5	8.7	59.7	24.1	0	0					
	WWS 2050	1.5	17.2	22.4	42.2	18.2	0	0	-31.5	-33.51	-4.82	-69.84	1.36
Bulgaria	BAU 2022	14.8	19.1	10.7	34.7	33.6	1.74	0.1					
	BAU 2050	20.5	22.7	13	30.9	31.9	1.36	0.08					
	WWS 2050	9.2	27.6	18.5	35.3	17.6	0.83	0.03	-36.65	-11.1	-7.53	-55.29	1.31
Cambodia	BAU 2022	9.9	27.1	6.1	33.2	30.6	2.97	0					
	BAU 2050	17.4	21.4	6.8	32.4	36.6	2.8	0					
	WWS 2050	8.2	16.2	9.5	54	19.1	1.18	0	-44.93	-1.09	-6.69	-52.71	2.61
Cameroon	BAU 2022	11.5	63.1	14.8	6.1	14.3	0.07	1.6					
	BAU 2050	17.5	52.2	19.5	7.5	18.7	0.09	1.96					
	WWS 2050	4.8	39.5	16.4	23.3	16.3	0.25	4.29	-64.07	-0.61	-8.11	-72.78	2.54
Canada	BAU 2022	310.9	14.1	11.6	44.1	27	3.23	0.02					
	BAU 2050	418.1	13	11.7	46.2	26.1	2.96	0.02					
	WWS 2050	163.3	16.1	17.9	45.3	18.6	2.08	0.03	-32.2	-22.79	-5.94	-60.93	1.48

Chile	BAU 2022	40.7	16.1	6.2	38.4	36.7	2.22	0.38					
	BAU 2050	65.8	14.9	9.2	38.6	34.5	2.23	0.39					
	WWS 2050	34.2	12.3	10.3	57.3	17.6	1.98	0.55	-37.48	-3.44	-7.02	-47.94	1.76
China	BAU 2022	3,091.70	16	4.2	59.9	14.4	2.04	3.45					
	BAU 2050	5,055.80	17.9	4.5	55.5	17.9	1.49	2.81					
	WWS 2050	2,586.50	17	5.5	64.7	8.1	1.22	3.52	-30.48	-12.27	-6.09	-48.84	1.71
Colombia	BAU 2022	45.1	22.9	5.8	25	43.4	1.28	1.63					
	BAU 2050	67.7	21	5.9	24.3	46.3	1.08	1.37					
	WWS 2050	26.3	26.5	10.3	35.5	26.2	0.83	0.72	-45.24	-8.76	-7.22	-61.22	1.79
Congo	BAU 2022	2.8	58.4	14.3	6	21.3	0	0					
	BAU 2050	4.5	48.1	18.7	6.6	26.6	0	0					
	WWS 2050	1.3	41.5	24	12.2	22.3	0	0	-60.32	-2.4	-8.48	-71.2	2.03
Congo, DR	BAU 2022	34.4	87.3	0.4	4.3	6.4	1.01	0.61					
	BAU 2050	46.1	81.2	0.7	6.2	9.5	1.51	0.87					
	WWS 2050	11.1	62	2.4	21.8	9.8	1.18	2.83	-65.29	-0.25	-10.46	-76	3.81
Costa Rica	BAU 2022	5.4	13	10	21.5	53.1	2.33	0					
	BAU 2050	8	12.9	10.8	18.8	55.5	2.06	0					
	WWS 2050	3.5	18.8	17.2	32.8	29.3	1.85	0	-46.52	-1.48	-7.47	-55.47	1.79
Côte d'Ivoire	BAU 2022	13.7	54.4	7	10.9	26.3	1.39	0.01					
	BAU 2050	21.9	44.6	8.8	12.3	32.8	1.57	0.01					
	WWS 2050	6.9	37.5	9	26.9	25.1	1.46	0.03	-58.23	-2.09	-8.06	-68.38	2.66
Croatia	BAU 2022	9.8	30.9	11	21.5	33.1	3.56	0					
	BAU 2050	13.3	32.9	13.8	19.3	31.2	2.81	0					
	WWS 2050	5.5	30.7	20.9	26.9	19.8	1.62	0	-44	-6.21	-8.7	-58.91	1.56
Cuba	BAU 2022	7.2	20.3	5	51.3	14.2	1.97	7.25					
	BAU 2050	10	21.1	6	48.3	16.3	1.81	6.6					
	WWS 2050	5.7	22.7	7.8	57.6	8.6	0.91	2.29	-30.08	-5.49	-7.22	-42.79	2.02
Curacao	BAU 2022	3.3	3.1	0.8	6.9	89.3	0	0					
	BAU 2050	5	2.3	0.9	5.8	91	0	0					
	WWS 2050	1.5	3.5	2.2	15.2	79.2	0	0	-63.79	-1.76	-4.48	-70.04	10.67
Cyprus	BAU 2022	2.8	16.3	11.7	13	56.3	2.1	0.61					
	BAU 2050	3.8	17.8	15.5	11	53.5	1.69	0.49					
	WWS 2050	1.7	26.6	24.9	17.8	28.7	1.47	0.47	-45.39	-2.04	-8.26	-55.69	1.59
Czech Republic	BAU 2022	34.8	26.1	10.9	33.5	27.1	2.32	0.1					
	BAU 2050	41.5	26.1	11.5	32.5	27.8	2.02	0.09					
	WWS 2050	17.3	20.2	15.1	44	19.2	1.4	0.04	-41.81	-9.67	-6.74	-58.22	1.6
Denmark	BAU 2022	19.6	25.1	12.9	21.9	35.3	4.6	0.18					
	BAU 2050	23	25.4	13.6	22.1	34.6	4.12	0.16					
	WWS 2050	9	23.5	19	28.8	25	3.46	0.08	-46.84	-7.84	-6.34	-61.02	1.63
Dominican Republic	BAU 2022	10.8	19.3	6.5	28.9	43.1	2.24	0					
	BAU 2050	15.3	16.2	7.3	27.1	47.4	2.12	0					
	WWS 2050	7	16.2	11.2	45.1	24.9	2.62	0	-44.46	-2.7	-7.23	-54.38	1.96
Ecuador	BAU 2022	19.9	12.4	5.7	20.9	53.6	1.04	6.29					
	BAU 2050	28.5	10.1	6.2	19.7	57.6	0.92	5.57					
	WWS 2050	10.6	13.3	11	34.6	36.9	0.49	3.67	-51.99	-4.8	-6.14	-62.93	2.11
Egypt	BAU 2022	86.3	19.2	5.8	42.3	30	2.5	0.14					
	BAU 2050	171.6	17.8	7.1	36.5	36.2	2.33	0.13					
	WWS 2050	78.5	22	12	46.9	16.6	2.43	0.06	-31.56	-15.36	-7.36	-54.28	1.71
El Salvador	BAU 2022	4.3	17.9	4.5	28.1	48.3	0	1.21					
	BAU 2050	6	14.9	5.3	25.8	52.7	0	1.19					
	WWS 2050	2.7	16	8.9	44.9	28.1	0	2.07	-46.75	-1.64	-6.98	-55.37	2.15
Equatorial Guinea	BAU 2022	1.7	12.9	2.9	71.1	13	0	0.15					
	BAU 2050	3.1	11.4	3.2	70.4	14.8	0	0.17					
	WWS 2050	1.4	10.8	4	77.4	7.6	0	0.28	-29.42	-20.03	-3.98	-53.42	4.42
Eritrea	BAU 2022	0.9	77.6	5.1	2.1	15	0.15	0					
	BAU 2050	1.3	69	7.2	2.7	20.9	0.18	0					
	WWS 2050	0.3	59.6	10	8	22.2	0.15	0	-65.21	-0.66	-9.69	-75.56	3.39
Estonia	BAU 2022	4.3	29.4	13.9	16.4	37.3	2.99	0					
	BAU 2050	5.7	27.5	14	15.1	41	2.41	0					
	WWS 2050	1.9	26.4	25.3	22.1	24.2	2.04	0	-46.74	-12.76	-7.34	-66.85	1.32
Eswatini, Kingdom of	BAU 2022	1.4	33.2	1.2	36.7	27.2	1.62	0					
	BAU 2050	2.5	25.8	1.6	40.4	30.4	1.74	0					
	WWS 2050	1.2	15.6	2.5	65	14.3	2.61	0	-43.34	-0.64	-6.19	-50.17	3.14
Ethiopia	BAU 2022	52.5	84.1	1.5	4.9	8.6	0.44	0.44					
	BAU 2050	71.8	77.4	2.3	6.5	12.6	0.58	0.58					
	WWS 2050	17.5	61.1	4.1	20.7	13	0.48	0.48	-65.27	-0.24	-10.05	-75.57	5.77
Finland	BAU 2022	32.8	20	11.7	45.5	19	2.95	0.77					
	BAU 2050	37.9	21.6	13	42.7	19.3	2.64	0.7					
	WWS 2050	19.8	19	14.4	53.9	10.9	1.46	0.28	-34.76	-6.53	-6.5	-47.78	1.58
France	BAU 2022	190.4	23.6	13.8	23.6	35.2	3.27	0.53					
	BAU 2050	227.9	24.2	15.3	22.4	34.8	2.86	0.46					
	WWS 2050	102.3	24.1	20.6	30.6	22.6	1.84	0.3	-40.76	-5.88	-8.47	-55.1	1.37
Gabon	BAU 2022	6.2	26	0.8	67.8	5.1	0.09	0.06					
	BAU 2050	11.2	19.5	1	73.7	5.7	0.09	0.07					
	WWS 2050	6.9	8.7	1.1	87.8	2.3	0.09	0.04	-30.69	-4.08	-3.37	-38.14	10.6
Georgia	BAU 2022	6.8	30.9	10.8	18.5	34	0.59	5.11					
	BAU 2050	9.5	31.9	13	15	35.6	0.47	4.07					
	WWS 2050	3.7	24.2	20.3	31	15.8	0.48	8.26	-42.29	-9.05	-10.22	-61.56	1.52
Germany	BAU 2022	283.6	26.1	11.8	31.6	28.7	1.75	0.03					
	BAU 2050	331.9	25.5	12.4	30.8	29.7	1.54	0.03					
	WWS 2050	140.8	20.3	14.8	44.4	19.5	0.98	0.01	-42.05	-8.08	-7.44	-57.56	1.69
Ghana	BAU 2022	12	36.1	4.1	19.6	39.2	1.03	0					
	BAU 2050	21.4	29.8	5.2	20.4	43.6	1.04	0					
	WWS 2050	8.7	27	8	39.2	25.3	0.56	0	-49.74	-1.81	-7.78	-59.32	1.86
Gibraltar	BAU 2022	6.3	0.1	0.1	0.1	99.6	0	0.15					
	BAU 2050	7	0.2	0.1	0.1	99.5	0	0.15					

	WWS 2050	1.7	0.6	0.4	0.2	98.4	0	0.46	-68.12	-2.97	-4.22	-75.32	54.2
Greece	BAU 2022	26.5	21.1	8.8	21.3	46	1.43	1.34					
	BAU 2050	31.4	21	11.2	22.2	43.2	1.29	1.19					
	WWS 2050	12.4	25.2	20.6	24.6	27.1	1.95	0.6	-42.8	-10.03	-7.59	-60.43	1.53
Guatemala	BAU 2022	18.8	58.3	3.3	10.7	27.7	0	0					
	BAU 2050	22.6	49.3	3.8	11.6	35.3	0	0					
	WWS 2050	6.7	36.2	7.3	28.9	27.6	0	0	-60.43	-1.49	-8.43	-70.35	3.16
Guyana	BAU 2022	1.1	10.5	2.6	37.8	45.6	3.61	0					
	BAU 2050	1.6	9.2	2.7	34.5	50.4	3.26	0					
	WWS 2050	0.7	10.1	3.4	58.3	26.7	1.43	0	-47.74	-1.19	-5.21	-54.14	4.07
Haiti	BAU 2022	4.5	75.7	1.6	8.5	14.2	0	0					
	BAU 2050	5	69.1	1.5	9.7	19.7	0	0					
	WWS 2050	1.3	52.1	1.4	28.4	18.2	0	0	-64.01	-0.43	-9.3	-73.74	7.74
Honduras	BAU 2022	5.9	37.5	7.6	18.4	35.9	0.58	0					
	BAU 2050	7.8	31.2	8.1	18.1	42	0.56	0					
	WWS 2050	3	25.1	11.8	37.3	25.5	0.29	0	-52.26	-1.08	-7.87	-61.2	2.12
Hong Kong	BAU 2022	20.3	9.7	18.3	3.2	68.7	0.02	0					
	BAU 2050	42.2	8.8	18.6	2.6	70	0.02	0					
	WWS 2050	16.6	14.6	35.2	3.7	46.5	0.02	0	-50.4	-2	-8.22	-60.62	1.41
Hungary	BAU 2022	25.6	30	9.8	28.4	28.5	3.1	0.19					
	BAU 2050	30	30.5	10	27.7	28.9	2.78	0.17					
	WWS 2050	12.3	22.7	12.6	41.6	20.6	2.28	0.13	-44.57	-6.7	-7.75	-59.02	1.73
Iceland	BAU 2022	4.6	13.8	14.8	41.1	20.3	9.43	0.49					
	BAU 2050	5.1	14.3	15.7	40.6	20.2	8.76	0.47					
	WWS 2050	3	9.1	14.4	60.9	9.5	5.83	0.25	-33.5	-2.16	-6.48	-42.14	1.12
India	BAU 2022	892.2	25	3.4	47	17.6	4.75	2.23					
	BAU 2050	1,866.90	18.3	3.1	47.3	24.6	4.43	2.16					
	WWS 2050	997.2	13.9	2.9	65.7	11	4.76	1.8	-34.41	-5.91	-6.26	-46.58	2.54
Indonesia	BAU 2022	219.6	13.6	4.2	46.6	34.6	0.59	0.4					
	BAU 2050	403.5	10.9	4.8	43.9	39.5	0.54	0.36					
	WWS 2050	207.1	11.8	7	63	17.7	0.34	0.14	-38.51	-4.32	-5.85	-48.68	2.53
Iran	BAU 2022	304.8	28.3	5.6	38.7	22.5	4.7	0.2					
	BAU 2050	494.4	25.1	5	41.3	23.3	5.05	0.21					
	WWS 2050	209.5	17	5.4	61.4	10.9	4.78	0.39	-39.09	-11.2	-7.34	-57.62	2.92
Iraq	BAU 2022	43.6	18.5	3.4	33.4	43.1	0.26	1.27					
	BAU 2050	69.6	17.1	4.1	34	43.1	0.28	1.37					
	WWS 2050	27.4	24.7	8.1	38.5	25.5	0.56	2.62	-41.44	-12.85	-6.39	-60.68	1.98
Ireland	BAU 2022	16.2	21.6	15.1	19.5	41.2	2.68	0					
	BAU 2050	18.6	20.3	18.5	18.6	40.1	2.46	0					
	WWS 2050	8.2	17.7	27.6	29.7	23.4	1.55	0	-43.82	-3.29	-8.61	-55.72	1.56
Israel	BAU 2022	22.6	15	11.5	21.1	45.4	1.22	5.87					
	BAU 2050	27.1	16.8	14.9	20.9	41.1	1.11	5.21					
	WWS 2050	13	27	23.3	23	19.8	1.8	5.16	-36	-7.28	-8.72	-52	1.24
Italy	BAU 2022	161.3	24.1	11.7	27	34.6	2.56	0.15					
	BAU 2050	197.9	23.2	12.6	25.6	36.2	2.2	0.13					
	WWS 2050	79.6	17.9	19.2	37.1	24.1	1.74	0.07	-41.95	-10.01	-7.84	-59.79	1.59
Jamaica	BAU 2022	3.4	9.4	8.8	23.9	57.8	0.08	0					
	BAU 2050	4.9	7.9	7.4	22.4	62.2	0.07	0					
	WWS 2050	1.9	10.2	5.9	45.4	38.4	0.04	0	-54.65	-1.74	-5.17	-61.56	3.35
Japan	BAU 2022	343.4	16.1	17.5	35.8	28.6	1.85	0.21					
	BAU 2050	329.2	16.6	18.7	33.4	29.8	1.38	0.18					
	WWS 2050	174.7	16.4	20.1	46.9	15.9	0.63	0.07	-30.8	-8.25	-7.88	-46.92	1.5
Jordan	BAU 2022	8.9	24.6	7.7	16.6	44.3	3.46	3.41					
	BAU 2050	14.4	23.9	7.5	17.8	43.6	3.7	3.43					
	WWS 2050	6.9	32	10.1	28.7	21.6	6.06	1.44	-41.74	-1.89	-8.69	-52.32	1.48
Kazakhstan	BAU 2022	65.9	28	11.2	40.7	17.7	2.17	0.17					
	BAU 2050	85.3	27.2	12.7	40.3	17.9	1.83	0.15					
	WWS 2050	30.6	21.1	17.2	47.2	12.7	1.59	0.11	-42.45	-16.15	-5.59	-64.19	1.68
Kenya	BAU 2022	22.9	63.5	2.1	9.8	24.2	0.28	0.16					
	BAU 2050	34.7	53.2	2.4	12.1	31.8	0.34	0.19					
	WWS 2050	10.3	37.5	3.8	32.7	25.7	0.23	0.13	-61.2	-0.63	-8.51	-70.35	3.92
Korea, DPR	BAU 2022	18.4	11.1	3.2	62.1	9.3	1.88	12.52					
	BAU 2050	30.2	7.9	2.3	65.9	8.8	1.99	13.15					
	WWS 2050	18.3	4.5	1.5	83.5	4.3	0.9	5.23	-32.46	-3.15	-3.82	-39.43	3.86
Korea, Republic of	BAU 2022	217.3	12.9	12.4	41	31.5	1.58	0.61					
	BAU 2050	289.3	11.5	14.2	42.3	30.1	1.48	0.5					
	WWS 2050	144.3	9	19.3	55.1	14.6	1.76	0.2	-32.96	-9.95	-7.22	-50.13	1.44
Kosovo	BAU 2022	2.1	35.9	10.7	23.1	28	2.39	0					
	BAU 2050	2.9	41.8	12.1	18.8	25.5	1.83	0					
	WWS 2050	1.5	46.9	14.3	24.2	13.2	1.44	0	-35.23	-3.81	-10.79	-49.83	1.13
Kuwait	BAU 2022	37.1	10.7	5.3	55.9	27.6	0.47	0					
	BAU 2050	62.8	12.8	6	54.6	26	0.48	0					
	WWS 2050	27.9	21.3	10.5	53.7	13.7	0.84	0	-29.65	-20.21	-5.79	-55.65	1.67
Kyrgyzstan	BAU 2022	4.7	64.9	9.6	11	13.6	0.54	0.43					
	BAU 2050	6.3	66.9	9.8	9.5	13.1	0.45	0.36					
	WWS 2050	3	69.6	9	13.8	6.4	0.67	0.49	-37.92	-1.28	-12.21	-51.42	1.05
Lao PDR	BAU 2022	4.7	36.2	11.4	28.2	23.9	0.25	0					
	BAU 2050	7.8	30.2	9.4	29.6	30.6	0.27	0					
	WWS 2050	3.8	20.4	9.2	52.6	17.4	0.43	0	-43.26	-0.55	-8.08	-51.89	1.55
Latvia	BAU 2022	5.5	26.7	13.7	23.9	30.6	4.82	0.17					
	BAU 2050	7.2	28.2	16.2	21.3	30.2	3.98	0.14					
	WWS 2050	2.9	21.7	20.2	35.9	19.6	2.45	0.07	-50.49	-2.69	-6.48	-59.65	2.16
Lebanon	BAU 2022	4.4	13.4	2.3	8.3	73.1	0	2.94					
	BAU 2050	6.9	11.8	2.5	9	73.6	0	3.04					
	WWS 2050	2.3	18.4	6.3	22.2	47.7	0	5.47	-59.45	-1.37	-6.13	-66.95	2.65
Libya	BAU 2022	14.7	17.5	2	16.2	56.9	1.32	5.99					

	BAU 2050	28.8	18.4	2.5	14.1	57.9	1.29	5.85					
	WWS 2050	11.4	30.9	4.9	18.9	31.2	2.55	11.55	-47	-5.62	-7.89	-60.51	1.51
Lithuania	BAU 2022	8.2	23.8	10	26.1	37.8	2.05	0.16					
	BAU 2050	11.1	25.3	11.9	24.6	36.4	1.67	0.13					
	WWS 2050	4.6	21.9	15.9	38.7	22.3	1.09	0.06	-41.99	-10.34	-6.3	-58.63	2.02
Luxembourg	BAU 2022	4.9	12.1	12.2	15.5	59.4	0.75	0					
	BAU 2050	5.5	12.1	12.7	15.2	59.3	0.71	0					
	WWS 2050	2.1	9.9	16.5	31.1	42.1	0.49	0	-53.37	-2.07	-6.56	-62	2.01
Macedonia, North	BAU 2022	2.5	26.3	9.5	22.4	40.9	0.9	0					
	BAU 2050	3.5	31.6	11.5	18.4	37.8	0.71	0					
	WWS 2050	1.7	37.3	15.2	26.6	20.2	0.66	0	-39.18	-2.97	-9.43	-51.58	1.3
Madagascar	BAU 2022	8.6	55.3	25.3	9.2	8.3	0.05	1.95					
	BAU 2050	13.7	43.9	32.1	11.2	10.4	0.06	2.27					
	WWS 2050	3.8	30.9	24.1	31.9	9.5	0.16	3.37	-65.53	-0.21	-6.38	-72.11	6.07
Malaysia	BAU 2022	83	6.8	7.2	51.4	32.8	1.79	0					
	BAU 2050	154.8	6.5	8.1	46.8	37	1.59	0					
	WWS 2050	71.1	9.8	13	57.7	18.7	0.77	0	-35.26	-13.3	-5.5	-54.06	1.87
Malta	BAU 2022	3.8	3.6	4.2	2.8	88.5	0.67	0.07					
	BAU 2050	5	5.2	5.8	2.4	86	0.54	0.06					
	WWS 2050	1.6	12.2	13.1	6	68.1	0.4	0.15	-61.29	-1.77	-5.79	-68.86	2.72
Mauritius	BAU 2022	2.1	9.7	6.8	12.3	70.6	0.26	0.32					
	BAU 2050	4.1	9.2	7.6	11.5	71.2	0.24	0.31					
	WWS 2050	1.5	15.4	14	24.5	45.1	0.32	0.55	-53.97	-1.54	-6.68	-62.2	1.98
Mexico	BAU 2022	172.3	14.9	2.7	39.9	38	3.26	1.17					
	BAU 2050	268	14.4	4	40.6	36.4	3.34	1.31					
	WWS 2050	113.9	16.6	5.1	53.5	19.4	2.94	2.4	-38.53	-12.93	-6.05	-57.51	1.61
Moldova, Republic of	BAU 2022	3.7	39.4	9.5	16.8	28.6	5.02	0.75					
	BAU 2050	4.9	41	11.5	14.7	28.1	4.06	0.65					
	WWS 2050	1.8	34.8	17	26.3	18.8	2.66	0.37	-51.07	-2.27	-8.97	-62.31	1.69
Mongolia	BAU 2022	6.4	20.7	10.2	34.7	21.9	2.12	10.35					
	BAU 2050	10.8	17	7.7	35.3	27.1	2.11	10.83					
	WWS 2050	4.2	15.8	4.9	53.4	16	1.31	8.51	-52.38	-4.54	-3.73	-60.65	2.28
Montenegro	BAU 2022	1	31.9	14	13	40.4	0.64	0					
	BAU 2050	1.5	35.8	17.4	10.1	36.1	0.48	0					
	WWS 2050	0.7	39.8	25.4	14.8	19.7	0.32	0	-39.5	-1.72	-10.91	-52.13	1.2
Morocco	BAU 2022	22.3	26.8	8.4	18.4	39	7.51	0					
	BAU 2050	40	20.3	9.7	19	43.4	7.67	0					
	WWS 2050	17.3	21	10.5	35.8	26.3	6.44	0	-48.19	-0.88	-7.61	-56.68	1.88
Mozambique	BAU 2022	11.6	60.7	2.7	19.4	16.6	0.18	0.37					
	BAU 2050	17.8	50.3	3.7	23.4	22	0.21	0.45					
	WWS 2050	6.3	29.7	3.7	50.9	15.3	0.12	0.23	-53.54	-2.97	-8.25	-64.76	2.12
Myanmar	BAU 2022	25.7	56.7	3.8	12.2	22.4	0.29	4.58					
	BAU 2050	40.6	46	5.3	12.7	30.8	0.3	4.91					
	WWS 2050	12.2	32.4	13.2	24.2	23	0.2	7	-56.23	-5.1	-8.52	-69.85	2.48
Namibia	BAU 2022	2.1	8.3	22.4	14.7	46.4	5.79	2.43					
	BAU 2050	4	9.3	19	14.7	48.9	5.68	2.45					
	WWS 2050	1.6	15	12.8	31	30.2	6.77	4.26	-52.48	-0.91	-6.59	-59.98	1.85
Nepal	BAU 2022	20.3	61.5	5	21.2	11.1	1.03	0.23					
	BAU 2050	29.5	53.4	4.1	25	16	1.19	0.28					
	WWS 2050	11	30.9	4.4	52.4	10.8	0.98	0.58	-54.24	-0.32	-8.1	-62.66	5.17
Netherlands	BAU 2022	78.8	14	10.2	31	39.6	5.12	0.14					
	BAU 2050	92.7	14	11.2	31	39	4.57	0.13					
	WWS 2050	36.8	11.8	16.3	41.7	26.1	4.03	0.06	-43.41	-10.41	-6.46	-60.27	1.97
New Zealand	BAU 2022	17.7	11.5	9.9	31.1	41.9	5.17	0.36					
	BAU 2050	26.4	11.9	12	34.4	36.3	4.98	0.43					
	WWS 2050	14.1	14.5	15.4	49	16.5	4.05	0.63	-35.89	-3.08	-7.55	-46.52	1.63
Nicaragua	BAU 2022	3.7	41.8	11.1	15.4	29	2.34	0.39					
	BAU 2050	4.8	34.7	11.4	16.1	35.1	2.32	0.42					
	WWS 2050	1.6	27.3	14.7	29.8	25.2	1.99	0.98	-54.5	-3.97	-7.89	-66.36	2.02
Niger	BAU 2022	5.1	77.4	3.4	4.1	15.1	0.05	0					
	BAU 2050	7.2	69	4.7	5	21.2	0.07	0					
	WWS 2050	1.8	58	7.4	13.3	21.1	0.14	0	-65.01	-1.17	-9.56	-75.75	4.28
Nigeria	BAU 2022	83.5	39.5	5.6	20.5	34.1	0.01	0.32					
	BAU 2050	140.7	30.5	6.9	21.9	40.3	0.01	0.35					
	WWS 2050	44	23.8	7.3	41.2	27.4	0.01	0.22	-56.81	-5.91	-6.01	-68.73	4.88
Norway	BAU 2022	33.7	15.1	11.2	47.9	23.2	2.43	0.11					
	BAU 2050	44.5	15.7	12.4	46.1	23.8	1.96	0.09					
	WWS 2050	20.7	22.6	18.4	40.5	16.8	1.64	0.04	-23.65	-22.39	-7.35	-53.39	1.04
Oman	BAU 2022	39.7	5.5	28.3	39	24.2	0.15	2.87					
	BAU 2050	62.4	6.9	23.6	41.6	24.7	0.17	3.01					
	WWS 2050	25	12.4	18.2	53.8	13.8	0.32	1.49	-41.48	-14.42	-4.04	-59.94	2.93
Pakistan	BAU 2022	115.7	45	3	27.5	23.1	1.11	0.34					
	BAU 2050	194.9	37	3	29	29.5	1.16	0.33					
	WWS 2050	81.9	25.7	4	52.5	15.5	2.13	0.16	-47.43	-2.54	-8.03	-57.99	2.9
Panama	BAU 2022	10.4	7.9	7.4	9.3	75.4	0.01	0					
	BAU 2050	15.7	6.8	8.1	7.9	77.1	0.01	0					
	WWS 2050	5.4	10.7	18.1	17.7	53.5	0.01	0	-57.76	-1.6	-6.24	-65.6	2.49
Paraguay	BAU 2022	8.4	25.7	8.1	25.7	36.5	0	3.95					
	BAU 2050	11.7	22.8	9.6	23.4	40.6	0	3.6					
	WWS 2050	5.4	22	15.6	39.7	21.1	0	1.55	-44.68	-1.09	-7.71	-53.48	1.95
Peru	BAU 2022	31.8	18.2	5.9	32.2	42.6	1.05	0					
	BAU 2050	47.1	14	5.7	30.7	48.6	0.94	0					
	WWS 2050	19.1	12.6	8.2	51.8	26.1	1.25	0	-42.87	-10.29	-6.32	-59.48	2.09
Philippines	BAU 2022	49.5	27.6	11.9	22.7	36.7	1.02	0					
	BAU 2050	87.9	22.6	11.5	21.6	43.3	0.99	0					
	WWS 2050	37.2	22.8	14.8	36.1	24.9	1.33	0	-46.48	-3.37	-7.82	-57.67	1.64

Table S4a.ii. 2022 annual-average end-use demand and its components by country. First row of each country: 2022 annually averaged end-use demand (GW) and percentage of the demand by sector. Second row: projected 2050 annually averaged end-use BAU demand (GW) and percentage of the total demand by sector. Third row: estimated 2050 total end-use demand (GW) and percentage of total demand by sector if 100% of end-use delivered BAU demand in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU demand due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity demand (=all energy demand) in the 2050 base-WWS case to the electricity demand in the 2050 BAU base. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases. Column (k) shows that all energy decreases. All results in this table for the base-WWS case are the same Continuation of Table S4a.i.

Country	Case	(a) Total annual average end-use demand (GW)	(b) Resi-den-tial % of total	(c) Com-merc ial % of total	(d) Indu s-try % of total	(e) Tran s-port % of total	(f) Ag-for-fish % of total	(g) Mil-itary-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to elim-inating up-stream	(j) % change end-use demand with WWS due to effic-iency be-yond BAU	(k) Over-all % change in end-use demand with WWS	(l) WWS: BAU elec-tric-ity dem-and
Poland	BAU 2022	104	25.9	10.4	27.4	32.1	4.21	0					
	BAU 2050	121.1	25.2	11.7	27.7	31.6	3.76	0					
	WWS 2050	47.3	18.5	18.1	38.8	22.4	2.19	0	-45.26	-9.34	-6.32	-60.92	1.71
Portugal	BAU 2022	24.5	14.4	10	30.4	42.4	2.61	0.19					
	BAU 2050	28.9	15.4	12.4	29.1	40.6	2.34	0.17					
	WWS 2050	13.1	16.6	19.1	39	23.6	1.61	0.08	-39.99	-7.58	-7.15	-54.73	1.62
Qatar	BAU 2022	44.4	6.3	2.4	71.6	18.6	0	1.18					
	BAU 2050	73.5	8	2.8	70.1	17.9	0	1.24					
	WWS 2050	31.3	14	5.1	68.2	10.5	0	2.27	-22.66	-30.64	-4.16	-57.46	2.71
Romania	BAU 2022	34.1	30.6	7.4	28.9	29.4	2.16	1.48					
	BAU 2050	44.8	32.5	8.8	26.7	28.9	1.78	1.2					
	WWS 2050	17	26.2	11.9	40.2	19.8	1.16	0.63	-46.95	-7.57	-7.58	-62.1	1.85
Russia	BAU 2022	686.3	27.3	7.7	40.8	22.2	2.05	0					
	BAU 2050	738.8	26.7	8	38.1	25.6	1.59	0					
	WWS 2050	266.2	22.9	10.9	51.2	13.7	1.44	0	-40.07	-17.69	-6.2	-63.96	1.75
Rwanda	BAU 2022	4.5	79.6	3	7.7	9.3	0	0.45					
	BAU 2050	6.2	71.3	4.2	10.5	13.3	0	0.63					
	WWS 2050	1.6	49.3	7.6	30.5	12.2	0	0.45	-63.65	-0.5	-9.52	-73.67	6.79
Saudi Arabia	BAU 2022	183	10.3	7.8	43.7	37.8	0.32	0.03					
	BAU 2050	312.4	12.3	8.8	43.2	35.4	0.32	0.03					
	WWS 2050	160.7	17.5	13.3	51.8	16.9	0.49	0.04	-33.14	-8.79	-6.63	-48.56	2.02
Senegal	BAU 2022	5.6	34.9	3.2	15.5	45.2	0.57	0.71					
	BAU 2050	10	27.9	4.2	16	50.6	0.61	0.76					
	WWS 2050	3.9	25.4	8.1	31.5	32.3	1.21	1.51	-51.48	-1.36	-7.83	-60.67	2.19
Serbia	BAU 2022	14	32.5	9.5	29.8	26.8	1.4	0					
	BAU 2050	19.2	36	10.9	26.8	25.2	1.12	0					
	WWS 2050	8.3	37.7	13.5	32.6	15.4	0.83	0	-39.95	-8.77	-8.28	-57.01	1.29
Singapore	BAU 2022	90.7	1.1	3.2	14.2	81.5	0	0.03					
	BAU 2050	185.7	1.1	3.3	11.6	84	0	0.03					
	WWS 2050	59.5	2.5	7.6	23.5	66.4	0	0.05	-59.82	-3.54	-4.58	-67.95	4.18
Slovak Republic	BAU 2022	15	23.2	11.2	40.4	24.1	1.11	0					
	BAU 2050	17.8	23.3	11.5	39.8	24.4	0.97	0					
	WWS 2050	8.1	16.3	13.4	53.9	15.8	0.61	0	-35.46	-12.72	-6.54	-54.72	1.87
Slovenia	BAU 2022	6.4	20.4	8.6	26.8	41.3	1.53	1.39					
	BAU 2050	7.5	21.5	10.1	25.3	40.4	1.38	1.28					
	WWS 2050	3.4	19.1	14.1	39.6	24.7	0.74	1.67	-43.04	-3.59	-7.56	-54.19	1.56
South Africa	BAU 2022	95.2	11	6.1	52.4	26.6	2.76	1.18					
	BAU 2050	175.2	10.9	7.3	49	28.9	2.73	1.18					
	WWS 2050	81	14.1	10.1	57.3	15.6	1.93	0.96	-33.53	-14.58	-5.67	-53.78	1.61
South Sudan	BAU 2022	1	29.4	1.8	12.9	51.5	4.44	0					
	BAU 2050	1.7	22.9	1.9	11.8	58.7	4.62	0					
	WWS 2050	0.4	24.5	2.3	12	56.2	5.1	0	-59.27	-8.04	-5.9	-73.21	3.35
Spain	BAU 2022	129.2	14.4	9.6	27.3	45.5	2.95	0.21					
	BAU 2050	154.4	14.8	11.1	27.3	44.1	2.6	0.18					
	WWS 2050	63.1	17.9	17.3	34.2	28.6	1.87	0.15	-41.21	-11.09	-6.83	-59.14	1.6
Sri Lanka	BAU 2022	12.9	27.8	5.3	28.9	37.7	0	0.29					
	BAU 2050	22.8	21.6	5.7	27.8	44.6	0	0.27					
	WWS 2050	10	17.2	8.8	49.6	24.3	0	0.12	-48.36	-1.31	-6.44	-56.1	2.81
Sudan	BAU 2022	18.5	45.2	13.8	8.9	30	1.31	0.78					
	BAU 2050	31.7	36.7	16.1	9.9	35.1	1.43	0.85					
	WWS 2050	10.2	34.2	12.6	22.9	26.6	2.29	1.39	-59.28	-1.14	-7.28	-67.7	2.71
Suriname	BAU 2022	1	12.9	3.6	17.2	46	20.13	0.25					
	BAU 2050	1.5	12.4	3.6	16.4	49.6	17.78	0.25					
	WWS 2050	0.6	19.8	5.6	33	31.6	9.52	0.51	-53.28	-2.86	-6.46	-62.6	1.71
Sweden	BAU 2022	45.9	20.4	12.2	38.6	26.9	1.93	0					
	BAU 2050	54.8	21.7	14	35.4	27.3	1.66	0					
	WWS 2050	29.6	21.1	16.5	44.4	17	0.99	0	-32.42	-6.61	-7.03	-46.05	1.4
Switzerland	BAU 2022	24.2	25.3	15.8	20.8	36.5	0.62	1					
	BAU 2050	29.1	24.6	16.8	19.2	38	0.54	0.87					
	WWS 2050	13.7	23	19.5	27.8	28.7	0.73	0.36	-40.64	-3.67	-8.47	-52.78	1.3
Syria	BAU 2022	7.2	22.3	4.5	30.6	35.7	3.07	3.77					
	BAU 2050	11.5	21.1	4.4	31.6	35.8	3.14	4					
	WWS 2050	5.3	26.3	5.4	42.9	19.2	1.35	4.89	-38.9	-6.87	-7.74	-53.51	1.47
Taiwan	BAU 2022	84.9	9.9	8.3	53.6	26.1	1.2	0.9					
	BAU 2050	157	9.6	8.6	49.8	30	1.1	0.85					
	WWS 2050	84.8	11.8	10.5	62.1	13.8	0.86	0.97	-31.16	-8.16	-6.7	-46.02	1.41

Tajikistan	BAU 2022	4.4	26.2	7.2	23.1	24.1	5.76	13.56					
	BAU 2050	6	31.5	10.4	19.8	22.8	4.74	10.62					
	WWS 2050	3.2	36.2	15	27.5	10.3	6.88	3.95	-33.99	-2.24	-10.02	-46.25	1.12
Tanzania	BAU 2022	30.3	65.1	0.9	11	15.1	5.84	2.12					
	BAU 2050	45.9	54.1	1.5	14	19.9	7.72	2.81					
	WWS 2050	13.6	36.4	3.8	36.7	16.2	4.98	1.86	-61.47	-0.44	-8.5	-70.42	6.43
Thailand	BAU 2022	116.4	9.8	5.5	45.8	35.7	2.48	0.81					
	BAU 2050	219.1	8.5	6	41.4	41.2	2.18	0.76					
	WWS 2050	106.3	10.2	8.8	58.8	20.1	0.94	1.22	-38.1	-7.65	-5.72	-51.47	2.38
Togo	BAU 2022	3.3	64.4	10.3	4.6	20.7	0	0					
	BAU 2050	5.1	54.4	13.3	5.6	26.8	0	0					
	WWS 2050	1.4	47.8	12.6	16.6	23	0	0	-63.78	-0.53	-8.5	-72.81	2.96
Trinidad and Tobago	BAU 2022	6.8	7.3	1.7	71.2	19.8	0	0					
	BAU 2050	10.1	7.2	1.9	70.4	20.5	0	0					
	WWS 2050	7.3	5.6	2	85.9	6.6	0	0	12.22	-34.44	-5.22	-27.44	4.72
Tunisia	BAU 2022	12	25.9	8.2	26.9	33.1	5.89	0					
	BAU 2050	28.5	16.2	6.8	20.5	51.9	4.54	0					
	WWS 2050	9.8	19.8	12	42.7	21	4.53	0	-38.8	-19.12	-7.53	-65.45	2
Türkiye	BAU 2022	157.7	21	12.1	33.4	29.3	4.25	0					
	BAU 2050	181.7	21.6	12.9	32.6	29.1	3.86	0					
	WWS 2050	84.1	18.2	15.2	46.6	16.4	3.58	0	-39.34	-6.9	-7.49	-53.73	1.83
Turkmenistan	BAU 2022	40	1.4	33.9	33	13.9	1.38	16.39					
	BAU 2050	51.4	1.8	34.2	31.9	17.1	1.21	13.83					
	WWS 2050	16.1	3.7	21.8	54.1	7.9	2.99	9.43	-50.64	-14.9	-3.03	-68.56	5.06
Uganda	BAU 2022	23	60.5	8.4	22.3	7.8	1.01	0					
	BAU 2050	35.4	49.1	11	28.7	10.1	1.19	0					
	WWS 2050	12.9	24.7	6.6	61.6	6.4	0.65	0	-56.6	-0.25	-6.67	-63.52	12.63
Ukraine	BAU 2022	44.5	33.8	11	28.7	3.1	3.91	19.47					
	BAU 2050	59.2	38.3	12.4	26.5	4.2	3.2	15.53					
	WWS 2050	31.3	27.2	11.2	51.5	2.2	1.94	5.88	-29.12	-9.35	-8.62	-47.09	1.82
United Arab Emirates	BAU 2022	106.3	4.7	7.5	40.9	46.2	0.39	0.24					
	BAU 2050	184.2	5.8	8.4	42.6	42.5	0.39	0.23					
	WWS 2050	97.6	8.3	12.2	59.9	18.7	0.58	0.29	-38.77	-2.47	-5.77	-47.02	2.97
United Kingdom	BAU 2022	172.7	24.3	9.9	23.7	37.9	1.13	2.99					
	BAU 2050	202.9	24.2	11	24.2	36.9	1.01	2.69					
	WWS 2050	78.8	22.1	16.5	32.3	26.9	0.87	1.28	-44.43	-8.84	-7.89	-61.15	1.63
United States	BAU 2022	2,140.70	17.1	13.4	26.3	40.8	1.31	1.16					
	BAU 2050	2,356.70	15.7	14.9	29.3	37.7	1.31	1.15					
	WWS 2050	945.4	19.7	19.4	37.7	19.7	1.21	2.24	-40.48	-12.31	-7.09	-59.88	1.58
Uruguay	BAU 2022	6.9	16.3	6.5	43.2	30.6	3.41	0					
	BAU 2050	9.5	15.6	7.4	39.8	34	3.13	0					
	WWS 2050	4.9	16.2	10.1	56.1	15.8	1.7	0	-38.13	-3.76	-6.35	-48.24	2.24
Uzbekistan	BAU 2022	47.4	36	8.5	30.9	20.2	2.48	1.97					
	BAU 2050	66.6	36.5	8.6	26.9	24.5	1.97	1.59					
	WWS 2050	21.9	30.2	9.8	46.9	8.3	3.52	1.37	-41.68	-16.89	-8.48	-67.05	2.1
Venezuela	BAU 2022	32.6	10.2	6.8	61.3	21.6	0.13	0					
	BAU 2050	48.6	9.9	7.2	60.5	22.4	0.12	0					
	WWS 2050	19	13.3	12.8	61.1	12.6	0.24	0	-31.24	-24.92	-4.79	-60.95	2.15
Vietnam	BAU 2022	94.9	14.1	4.1	54.9	21.9	5.02	0					
	BAU 2050	173.4	13.2	4.6	52.3	25.2	4.61	0					
	WWS 2050	108.6	13.6	5.2	68.9	9.9	2.36	0	-29.43	-1.14	-6.79	-37.36	2.01
Yemen	BAU 2022	3.5	36.3	4.3	16.7	38.4	2.23	2.12					
	BAU 2050	5	29.3	4.1	19	42.9	2.55	2.18					
	WWS 2050	1.8	32.9	4.7	31	28.8	1.43	1.15	-52.07	-4.77	-7.62	-64.46	2.6
Zambia	BAU 2022	14.2	65.6	2.8	20.1	8.1	2.35	1.01					
	BAU 2050	21.6	56.4	3.9	24.8	10.6	3.04	1.2					
	WWS 2050	8.4	34.9	4.1	51.5	6.8	1.92	0.71	-51.7	-0.49	-8.99	-61.18	2.4
Zimbabwe	BAU 2022	7.7	50	6.8	19.7	14.8	8.55	0.16					
	BAU 2050	12.4	41.3	7.3	22.6	18.3	10.41	0.18					
	WWS 2050	4.8	28.2	8	45.9	11.3	6.43	0.25	-51.73	-1.18	-8.5	-61.4	2.21
All Countries	**BAU 2022**	**13,307.7**	**20**	**8**	**40.3**	**27.8**	**2.29**	**1.54**					
	BAU 2050	**19,559.6**	**18.8**	**7.9**	**40.7**	**29.1**	**2.11**	**1.44**					
	WWS 2050	**8,961.9**	**17.4**	**9.9**	**54.2**	**14.9**	**1.88**	**1.74**	**-37.03**	**-10.58**	**-6.57**	**-54.18**	**1.85**

2022 BAU values are from IEA[S4]. These values are projected to 2050 using EIA's "reference scenario" projections[S5], as described in the text. The EIA projections account for policies, population growth, modest economic and energy growth, some modest renewable energy additions, and modest energy efficiency measures and reduced energy use in each sector. The transportation demand includes, among other demands, energy produced in each country for aircraft and shipping. 2050 WWS values are estimated from 2050 BAU values assuming electrification of end-uses and effects of additional energy-efficiency measures beyond those in the BAU case, using the factors from Table S3. In the case of the industrial sector, the factors are applied after accounting for the change in energy between BAU and WWS during steel manufacturing due to purifying iron using green hydrogen in a shaft furnace instead of purifying it using coke in a blast furnace (Table S5), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen (Table S5). Multiply annual average demand (GW) by 8,760 hours per year to obtain annual energy per year (GWh/y) consumed. In 2022 and 2050, 23.11% and 22.99%, respectively, of the 150-country total BAU demand was for electricity

Table S4b. Annual-average end-use demand (total final consumption) and its components in 2022 by regions. These values are the sum or average of values from Table S4a.i., by region See caption of Table S4a.i for more details.

Country	Case	(a) Total annual average end-use demand (GW)	(b) Residential % of total	(c) Commercial % of total	(d) Industry % of total	(e) Transport % of total	(f) Ag-for-fish % of total	(g) Military-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to eliminating upstream	(j) % change end-use demand with WWS due to efficiency beyond BAU	(k) Overall % change in end-use demand with WWS	(l) WWS:BAU electricity demand
Africa-East	BAU 2022	153.6	68.5	4.05	10.0	15.0	1.68	0.70					
	BAU 2050	228.7	58.4	5.49	12.9	20.1	2.20	0.91					
	WWS 2050	66.8	40.8	5.87	34.2	16.7	1.68	0.75	-61.6	-0.5	-8.6	-70.8	5.14
Africa-North	BAU 2022	203.4	25.0	4.56	32.1	33.9	2.55	1.91					
	BAU 2050	405.3	20.7	5.15	28.0	42.1	2.36	1.81					
	WWS 2050	162.3	22.8	8.69	42.2	21.4	2.65	2.24	-39.0	-13.4	-7.5	-60.0	1.86
Africa-South	BAU 2022	152.6	28.0	5.57	39.2	23.7	2.51	0.92					
	BAU 2050	265.3	23.1	6.58	39.3	27.3	2.68	0.97					
	WWS 2050	113.7	19.7	8.61	53.1	15.8	1.95	0.85	-40.2	-10.3	-6.6	-57.1	1.75
Africa-West	BAU 2022	180.1	51.1	5.3	16.7	26.1	0.41	0.39					
	BAU 2050	290.4	41.0	6.8	19.0	32.2	0.49	0.46					
	WWS 2050	92.7	29.9	7.4	39.0	22.5	0.40	0.74	-51.3	-3.7	-6.5	-68.1	4.02
Australia	BAU 2022	125.9	12	7.7	43.1	34.5	2.62	0.03					
	BAU 2050	189.2	11.7	10.4	45.1	30.6	2.18	0.02					
	WWS 2050	84.7	14.6	16.6	50.3	17.3	1.22	0.01	-32.3	-16.65	-6.3	-55.25	1.54
Canada	BAU 2022	310.9	14.1	11.6	44.1	27	3.23	0.02					
	BAU 2050	418.1	13	11.7	46.2	26.1	2.96	0.02					
	WWS 2050	163.3	16.1	17.9	45.3	18.6	2.08	0.03	-32.2	-22.79	-5.94	-60.93	1.48
Central America	BAU 2022	220.8	19.3	3.46	34.3	39.2	2.66	0.94					
	BAU 2050	332.9	17.1	4.57	35.4	39.1	2.79	1.08					
	WWS 2050	136.8	17.7	6.36	49.6	21.8	2.53	2.05	-41.8	-10.7	-6.3	-58.9	1.70
Central Asia	BAU 2022	278.1	33.2	10.5	31.7	19.9	1.70	3.10					
	BAU 2050	410.5	30.9	10.0	30.9	24.4	1.48	2.34					
	WWS 2050	156.7	24.2	9.54	49.6	12.9	2.38	1.36	-45.5	-9.2	-7.1	-61.8	2.38
China region	BAU 2022	3,136.8	15.9	4.30	59.5	14.7	2.03	3.49					
	BAU 2050	5,139.0	17.8	4.61	55.1	18.3	1.48	2.86					
	WWS 2050	2,625.6	16.9	5.66	64.4	8.3	1.21	3.52	-30.7	-12.1	-6.1	-48.9	1.72
Cuba	BAU 2022	7.2	20.3	5	51.3	14.2	1.97	7.25					
	BAU 2050	10	21.1	6	48.3	16.3	1.81	6.6					
	WWS 2050	5.7	22.7	7.8	57.6	8.6	0.91	2.29	-30.08	-5.49	-7.22	-42.79	2.02
Europe	BAU 2022	1,712.7	23.1	11.1	28.6	33.7	2.59	1.01					
	BAU 2050	2,060.4	23.5	12.2	27.7	33.5	2.26	0.89					
	WWS 2050	872.6	20.9	16.7	38.3	22.0	1.60	0.43	-11.6	-2.6	-2.2	-57.6	5.50
Haiti region	BAU 2022	15.3	35.9	5.06	22.9	34.6	1.58	0.00					
	BAU 2050	20.3	29.2	5.87	22.8	40.6	1.60	0.00					
	WWS 2050	8.3	21.8	9.67	42.5	23.9	2.21	0.00	-49.3	-2.1	-7.7	-59.1	2.22
Iceland	BAU 2022	4.6	13.8	14.8	41.1	20.3	9.43	0.49					
	BAU 2050	5.1	14.3	15.7	40.6	20.2	8.76	0.47					
	WWS 2050	3	9.1	14.4	60.9	9.5	5.83	0.25	-33.5	-2.16	-6.48	-42.14	1.12
India region	BAU 2022	969.2	26.6	3.42	45.6	17.7	4.60	2.08					
	BAU 2050	1997.3	19.6	3.14	46.2	24.6	4.32	2.04					
	WWS 2050	1055.8	14.7	3.03	65.0	11.1	4.59	1.73	-34.9	-5.8	-6.4	-47.1	2.51
Israel	BAU 2022	22.6	15	11.5	21.1	45.4	1.22	5.87					
	BAU 2050	27.1	16.8	14.9	20.9	41.1	1.11	5.21					
	WWS 2050	13	27	23.3	23	19.8	1.8	5.16	-36	-7.28	-8.72	-52	1.24
Jamaica	BAU 2022	3.4	9.4	8.8	23.9	57.8	0.08	0					
	BAU 2050	4.9	7.9	7.4	22.4	62.2	0.07	0					

	WWS 2050	1.9	10.2	5.9	45.4	38.4	0.04	0	-54.65	-1.74	-5.17	-61.56	3.35
Japan	BAU 2022	343.4	16.1	17.5	35.8	28.6	1.85	0.21					
	BAU 2050	329.2	16.6	18.7	33.4	29.8	1.38	0.18					
	WWS 2050	174.7	16.4	20.1	46.9	15.9	0.63	0.07	-30.8	-8.25	-7.88	-46.92	1.5
Madagascar	BAU 2022	8.6	55.3	25.3	9.2	8.3	0.05	1.95					
	BAU 2050	13.7	43.9	32.1	11.2	10.4	0.06	2.27					
	WWS 2050	3.8	30.9	24.1	31.9	9.5	0.16	3.37	-65.53	-0.21	-6.38	-72.11	6.07
Mauritius	BAU 2022	2.1	9.7	6.8	12.3	70.6	0.26	0.32					
	BAU 2050	4.1	9.2	7.6	11.5	71.2	0.24	0.31					
	WWS 2050	1.5	15.4	14	24.5	45.1	0.32	0.55	-53.97	-1.54	-6.68	-62.2	1.98
Mideast	BAU 2022	970.4	17.9	8.00	40.3	30.9	2.47	0.45					
	BAU 2050	1,523.0	17.3	7.90	41.7	30.3	2.39	0.47					
	WWS 2050	698.8	16.7	10.4	54.9	15.2	2.25	0.53	-20.9	-5.9	-3.7	-54.1	3.49
New Zealand	BAU 2022	17.7	11.5	9.9	31.1	41.9	5.17	0.36					
	BAU 2050	26.4	11.9	12	34.4	36.3	4.98	0.43					
	WWS 2050	14.1	14.5	15.4	49	16.5	4.05	0.63	-35.89	-3.08	-7.55	-46.52	1.63
Philippines	BAU 2022	49.5	27.6	11.9	22.7	36.7	1.02	0					
	BAU 2050	87.9	22.6	11.5	21.6	43.3	0.99	0					
	WWS 2050	37.2	22.8	14.8	36.1	24.9	1.33	0	-46.48	-3.37	-7.82	-57.67	1.64
Russia region	BAU 2022	693.1	27.3	7.73	40.6	22.3	2.04	0.05					
	BAU 2050	748.3	26.8	8.06	37.8	25.7	1.58	0.05					
	WWS 2050	269.9	22.9	11.0	50.9	13.7	1.43	0.11	-40.1	-17.6	-6.3	-63.9	1.75
South America -NW	BAU 2022	152.6	15.88	5.51	35.5	40.6	1.24	1.32					
	BAU 2050	227.8	13.80	5.62	34.3	44.1	1.07	1.13					
	WWS 2050	90.8	16.18	9.32	48.5	24.4	0.93	0.68	-40.6	-13.5	-6.1	-60.1	2.18
South America -SE	BAU 2022	482.3	14.2	5.6	39.1	36.1	4.93	0.10					
	BAU 2050	784.0	12.4	5.7	38.2	39.0	4.56	0.09					
	WWS 2050	354.8	13.2	8.8	55.6	18.9	3.29	0.08	-38.5	-10.1	-6.1	-54.7	2.09
Southeast Asia	BAU 2022	647.9	12.4	4.7	42.1	38.6	1.67	0.47					
	BAU 2050	1,207.4	10.2	5.3	38.8	43.8	1.49	0.43					
	WWS 2050	578.3	11.2	8.0	57.6	21.9	0.86	0.43	-40.7	-5.6	-5.8	-52.1	2.37
South Korea	BAU 2022	217.3	12.9	12.4	41	31.5	1.58	0.61					
	BAU 2050	289.3	11.5	14.2	42.3	30.1	1.48	0.5					
	WWS 2050	144.3	9	19.3	55.1	14.6	1.76	0.2	-32.96	-9.95	-7.22	-50.13	1.44
Taiwan	BAU 2022	84.9	9.9	8.3	53.6	26.1	1.2	0.9					
	BAU 2050	157	9.6	8.6	49.8	30	1.1	0.85					
	WWS 2050	84.8	11.8	10.5	62.1	13.8	0.86	0.97	-31.16	-8.16	-6.7	-46.02	1.41
United States	BAU 2022	2,140.70	17.1	13.4	26.3	40.8	1.31	1.16					
	BAU 2050	2,356.70	15.7	14.9	29.3	37.7	1.31	1.15					
	WWS 2050	945.4	19.7	19.4	37.7	19.7	1.21	2.24	-40.48	-12.31	-7.09	-59.88	1.58
All Regions	**BAU 2022**	**13,307.7**	**20**	**8**	**40.3**	**27.8**	**2.29**	**1.54**					
	BAU 2050	**19,559.6**	**18.8**	**7.9**	**40.7**	**29.1**	**2.11**	**1.44**					
	WWS 2050	**8,961.9**	**17.4**	**9.9**	**54.2**	**14.9**	**1.88**	**1.74**	**-37.03**	**-10.58**	**-6.57**	**-54.18**	**1.85**

Table S5. 2050 mass of hydrogen and electricity to product that hydrogen needed per year in the base-WWS and EGS cases. Results are shown for (a) steel manufacturing, (b) ammonia manufacturing, (c) long-distance hydrogen fuel cell-electric vehicles, (d) the sum of all of these by country and world region, (e) power needed to produce and compress hydrogen for steel plus ammonia manufacturing, (f) power needed to produce and compress hydrogen for transportation, and (g) power needed to produce and compress hydrogen for steel and ammonia manufacturing and transportation.

Region or country	(a) 2050 Tg-H_2/y needed to purify iron by hydrogen direct reduction	(b) 2050 Tg-H_2/y needed to make NH_3	(c) 2050 Tg-H_2/y needed for HFC vehicles	(d) 2050 Total Tg-H_2/y produced for steel, NH_3, & transport = a+b+c	(e) 2050 Power needed to produce & compress H_2 for steel & NH_3 (GW)	(f) 2050 power needed to produce & compress H_2 for transport (GW)	(g) 2050 power needed to produce & compress H_2 for steel, NH_3, & transport (GW) = e+f
Africa-East	**0**	**0**	**0.858**	**0.858**	**0**	**4.611**	**4.611**
Eritrea	0	0	0.007	0.007	0	0.037	0.037
Ethiopia	0	0	0.196	0.196	0	1.052	1.052
Kenya	0	0	0.188	0.188	0	1.012	1.012
Rwanda	0	0	0.015	0.015	0	0.079	0.079
South Sudan	0	0	0.023	0.023	0	0.126	0.126
Sudan	0	0	0.215	0.215	0	1.158	1.158
Tanzania	0	0	0.165	0.165	0	0.885	0.885
Uganda	0	0	0.049	0.049	0	0.262	0.262
Africa-North	**0.535**	**1.387**	**2.621**	**4.543**	**10.333**	**14.091**	**24.425**
Algeria	0.184	0.475	0.857	1.517	3.544	4.610	8.154
Egypt	0.302	0.907	1.035	2.244	6.499	5.568	12.066
Libya	0.049	0.005	0.115	0.169	0.291	0.616	0.907
Morocco	0	0	0.432	0.432	0	2.322	2.322
Niger	0	0	0.027	0.027	0	0.147	0.147
Tunisia	0	0	0.154	0.154	0	0.829	0.829
Africa-South	**0.168**	**0.098**	**1.320**	**1.586**	**1.430**	**7.099**	**8.529**
Angola	0	0	0.171	0.171	0	0.921	0.921
Botswana	0	0	0.026	0.026	0	0.140	0.140
Eswatini	0	0	0.012	0.012	0	0.063	0.063
Mozambique	0	0	0.083	0.083	0	0.444	0.444
Namibia	0	0	0.040	0.040	0	0.214	0.214
South Africa	0.168	0.097	0.905	1.170	1.425	4.867	6.292
Zambia	0	0	0.045	0.045	0	0.244	0.244
Zimbabwe	0	0.001	0.038	0.039	0.005	0.207	0.211
Africa-West	**0.000**	**0.153**	**1.000**	**1.153**	**0.824**	**5.378**	**6.202**
Benin	0	0	0.032	0.032	0	0.171	0.171
Cameroon	0	0	0.052	0.052	0	0.281	0.281
Congo	0	0	0.021	0.021	0	0.114	0.114
Congo, DR	0	0	0.089	0.089	0	0.479	0.479
Côte d'Ivoire	0	0	0.131	0.131	0	0.702	0.702
Equatorial Guin.	0	0	0.007	0.007	0	0.040	0.040
Gabon	0	0	0.013	0.013	0	0.069	0.069
Ghana	0	0	0.146	0.146	0	0.783	0.783
Nigeria	0	0.153	0.377	0.530	0.824	2.030	2.854
Senegal	0	0	0.111	0.111	0	0.599	0.599
Togo	0	0	0.020	0.020	0	0.109	0.109
Australia	**0.206**	**0.345**	**1.036**	**1.587**	**2.964**	**5.572**	**8.535**
Canada	**0.422**	**0.841**	**1.257**	**2.520**	**6.792**	**6.761**	**13.553**
Central America	**0.460**	**0.024**	**1.530**	**2.014**	**2.605**	**8.227**	**10.832**
Costa Rica	0	0	0.069	0.069	0	0.370	0.370
El Salvador	0	0	0.052	0.052	0	0.281	0.281
Guatemala	0	0	0.114	0.114	0	0.615	0.615
Honduras	0	0	0.051	0.051	0	0.276	0.276
Mexico	0.46	0.024	1.018	1.502	2.605	5.473	8.077
Nicaragua	0	0	0.030	0.030	0	0.163	0.163

Panama	0	0	0.195	0.195	0	1.049	1.049
Central Asia	**0.168**	**1.130**	**1.187**	**2.485**	**6.985**	**6.381**	**13.366**
Kazakhstan	0.168	0.039	0.218	0.425	1.112	1.174	2.285
Kyrgyz Republic	0	0	0.012	0.012	0	0.067	0.067
Pakistan	0	0.712	0.750	1.462	3.831	4.031	7.862
Tajikistan	0	0	0.025	0.025	0	0.135	0.135
Turkmenistan	0	0.142	0.089	0.231	0.766	0.479	1.245
Uzbekistan	0	0.237	0.092	0.329	1.277	0.495	1.772
China region	**47.049**	**8.420**	**10.443**	**65.912**	**298.239**	**56.148**	**354.388**
China	47.035	8.42	9.790	65.245	298.167	52.637	350.803
Hong Kong	0	0	0.589	0.589	0	3.166	3.166
Korea, DPR	0.014	0	0.021	0.035	0.073	0.113	0.186
Mongolia	0	0	0.043	0.043	0	0.232	0.232
Cuba	**0**	**0**	**0.040**	**0.040**	**0.000**	**0.215**	**0.215**
Europe	**5.826**	**3.688**	**12.618**	**22.132**	**51.161**	**67.846**	**119.007**
Albania	0	0	0.025	0.025	0	0.135	0.135
Austria	0.33	0.091	0.247	0.668	2.264	1.329	3.592
Belarus	0	0.165	0.111	0.276	0.886	0.599	1.485
Belgium	0.227	0.184	0.550	0.961	2.210	2.960	5.169
Bosnia-Herzeg.	0.04	0	0.057	0.097	0.215	0.305	0.521
Bulgaria	0	0.05	0.134	0.184	0.267	0.719	0.986
Croatia	0	0.08	0.092	0.172	0.430	0.494	0.923
Cyprus	0	0	0.034	0.034	0	0.183	0.183
Czech Rep.	0.211	0.02	0.200	0.431	1.243	1.078	2.321
Denmark	0	0	0.145	0.145	0	0.778	0.778
Estonia	0	0.004	0.035	0.039	0.022	0.188	0.210
Finland	0.135	0.017	0.127	0.279	0.818	0.682	1.501
France	0.514	0.177	1.526	2.217	3.720	8.206	11.926
Germany	1.419	0.503	1.605	3.527	10.333	8.627	18.960
Gibraltar	0	0	0.139	0.139	0.000	0.748	0.748
Greece	0	0.022	0.261	0.283	0.116	1.402	1.518
Hungary	0.032	0.093	0.149	0.274	0.674	0.801	1.475
Ireland	0	0	0.163	0.163	0	0.876	0.876
Italy	0.211	0.134	1.225	1.570	1.855	6.585	8.440
Kosovo	0	0	0.019	0.019	0	0.101	0.101
Latvia	0	0	0.053	0.053	0	0.283	0.283
Lithuania	0	0.182	0.091	0.273	0.979	0.489	1.468
Luxembourg	0	0	0.066	0.066	0	0.356	0.356
Macedonia, N.	0	0	0.033	0.033	0	0.175	0.175
Malta	0	0	0.085	0.085	0	0.458	0.458
Moldova	0	0	0.029	0.029	0	0.157	0.157
Montenegro	0	0	0.013	0.013	0	0.072	0.072
Netherlands	0.319	0.453	0.554	1.326	4.156	2.978	7.134
Norway	0.004	0.071	0.185	0.260	0.406	0.996	1.402
Poland	0.195	0.488	0.745	1.428	3.674	4.003	7.677
Portugal	0	0	0.250	0.250	0	1.342	1.342
Romania	0.114	0.101	0.270	0.485	1.157	1.453	2.610
Serbia	0.06	0	0.110	0.170	0.322	0.594	0.916
Slovakia	0.168	0.077	0.080	0.325	1.315	0.430	1.745
Slovenia	0	0	0.060	0.060	0	0.324	0.324
Spain	0.217	0.091	1.450	1.758	1.652	7.796	9.448
Sweden	0.168	0	0.205	0.373	0.903	1.101	2.004
Switzerland	0	0.002	0.170	0.172	0.012	0.913	0.925
Ukraine	1.148	0.497	0.001	1.646	8.847	0.007	8.853
United Kingdom	0.314	0.186	1.325	1.825	2.687	7.124	9.811
Haiti region	**0**	**0**	**0.142**	**0.142**	**0**	**0.765**	**0.765**
Dominican Rep.	0	0	0.124	0.124	0	0.669	0.669
Haiti	0	0	0.018	0.018	0	0.095	0.095
Iceland	**0**	**0**	**0.022**	**0.022**	**0**	**0.119**	**0.119**
India region	**6.314**	**2.815**	**8.839**	**17.968**	**49.085**	**47.528**	**96.613**
Bangladesh	0	0.181	0.286	0.467	0.975	1.540	2.515
India	6.314	2.634	8.279	17.227	48.110	44.513	92.624

Nepal	0	0	0.100	0.100	0	0.539	0.539
Sri Lanka	0	0	0.174	0.174	0	0.935	0.935
Israel	**0**	**0**	**0.155**	**0.155**	0	**0.835**	**0.835**
Jamaica	**0**	**0**	**0.050**	**0.050**	0	**0.268**	**0.268**
Japan	**3.807**	**0.139**	**1.507**	**5.453**	**21.214**	**8.105**	**29.319**
Madagascar	**0**	**0**	**0.032**	**0.032**	0	**0.172**	**0.172**
Mauritius	**0**	**0**	**0.049**	**0.049**	0	**0.264**	**0.264**
Mideast	**3.064**	**3.177**	**7.567**	**13.808**	**33.568**	**40.686**	**74.254**
Armenia	0	0	0.014	0.014	0	0.078	0.078
Azerbaijan	0	0	0.091	0.091	0	0.492	0.492
Bahrain	0.076	0.082	0.030	0.188	0.850	0.160	1.009
Iran	1.76	0.777	1.438	3.975	13.641	7.731	21.372
Iraq	0	0.019	0.433	0.452	0.104	2.326	2.430
Jordan	0	0	0.101	0.101	0	0.542	0.542
Kuwait	0	0	0.243	0.243	0	1.306	1.306
Lebanon	0	0	0.037	0.037	0	0.200	0.200
Oman	0.092	0.374	0.182	0.648	2.503	0.979	3.482
Qatar	0.043	0.712	0.274	1.029	4.064	1.472	5.536
Saudi Arabia	0.33	0.928	2.197	3.455	6.768	11.815	18.583
Syria	0	0.004	0.086	0.090	0.023	0.463	0.486
Türkiye	0.563	0.08	1.238	1.881	3.457	6.658	10.116
UAE	0.2	0.201	1.166	1.567	2.157	6.269	8.426
Yemen	0	0	0.036	0.036	0	0.196	0.196
New Zealand	**0.038**	**0.027**	**0.164**	**0.229**	**0.349**	**0.882**	**1.231**
Philippines	**0**	**0**	**0.692**	**0.692**	**0**	**3.719**	**3.719**
Russia region	**3.325**	**3.525**	**2.001**	**8.851**	**36.828**	**10.758**	**47.587**
Georgia	0	0.043	0.029	0.072	0.232	0.156	0.388
Russia	3.325	3.482	1.972	8.779	36.596	10.602	47.198
South Am-NW	**0.106**	**0.942**	**1.414**	**2.462**	**5.640**	**7.605**	**13.245**
Bolivia	0	0	0.123	0.123	0	0.661	0.661
Colombia	0.009	0	0.347	0.356	0.048	1.865	1.913
Curacao	0	0	0.115	0.115	0	0.618	0.618
Ecuador	0	0	0.271	0.271	0	1.459	1.459
Guyana	0	0	0.015	0.015	0	0.080	0.080
Peru	0	0.002	0.410	0.412	0.013	2.206	2.218
Suriname	0	0	0.012	0.012	0	0.066	0.066
Trinidad/Tobago	0.081	0.899	0.030	1.010	5.272	0.162	5.434
Venezuela	0.016	0.041	0.091	0.148	0.308	0.488	0.796
South Am-SE	**1.773**	**0.164**	**4.401**	**6.338**	**10.413**	**23.663**	**34.077**
Argentina	0.19	0.138	0.651	0.979	1.762	3.502	5.264
Brazil	1.543	0.026	3.164	4.733	8.437	17.012	25.449
Chile	0.038	0	0.443	0.481	0.204	2.384	2.588
Paraguay	0.002	0	0.085	0.087	0.010	0.456	0.467
Uruguay	0	0	0.057	0.057	0	0.309	0.309
Southeast Asia	**0.731**	**1.803**	**8.681**	**11.215**	**13.623**	**46.677**	**60.300**
Brunei	0	0	0.016	0.016	0	0.085	0.085
Cambodia	0	0	0.128	0.128	0	0.688	0.688
Indonesia	0.162	1.274	2.084	3.520	7.722	11.203	18.925
Lao PDR	0	0	0.051	0.051	0	0.276	0.276
Malaysia	0.038	0.281	0.777	1.096	1.713	4.180	5.892
Myanmar	0	0	0.196	0.196	0	1.056	1.056
Singapore	0	0	2.919	2.919	0	15.697	15.697
Thailand	0	0	1.737	1.737	0	9.342	9.342
Vietnam	0.531	0.248	0.772	1.551	4.188	4.150	8.338
South Korea	**2.513**	**0**	**1.663**	**4.176**	**13.509**	**8.942**	**22.451**
Taiwan	**0.823**	**0**	**0.625**	**1.448**	**4.426**	**3.362**	**7.788**
United States	**1.392**	**3.023**	**9.576**	**13.991**	**23.734**	**51.489**	**75.223**
All regions	**78.72**	**31.70**	**81.49**	**191.91**	**593.72**	**438.17**	**1031.89**

Same methodology as in Ref. S7. Column (e) = Columns (a) plus (b), all multiplied by 47.1 TWh/Tg-H_2 and divided by 8,760 hours per year; Column (f) = Column (c) multiplied by 47.1 TWh/Tg-H_2 and divided by 8,760 hours per year.

Table S6. 2050 annual average end-use electricity plus heat demand (GW) by sector and region after energy in all sectors has been converted to WWS. Instantaneous demands can be higher or lower than annual average demands. Values for each region are derived from Tables S4a. Values are the same for both the base-WWS case and the EGS cases.

Region	(a) Total	(b) Resi-dential	(c) Com-mercial	(d) Industrial	(e) Transport	(f) Agricul-ture-fores-try-fishing	(g) Military-other
Africa-East	66.95	27.32	3.95	22.86	11.19	1.12	0.50
Africa-North	162.22	36.93	14.13	68.51	34.71	4.31	3.63
Africa-South	113.80	22.41	9.77	60.48	17.96	2.22	0.96
Africa-West	92.76	27.76	6.87	36.19	20.89	0.37	0.69
Australia	84.65	12.34	14.05	42.57	14.65	1.04	0.009
Canada	163.32	26.35	29.16	73.94	30.43	3.40	0.051
Central America	136.83	24.20	8.73	67.82	29.81	3.46	2.80
Central Asia	156.78	38.03	14.94	77.77	20.19	3.72	2.13
China region	2,625.6	444.0	149.1	1,690.8	217.4	31.78	92.48
Cuba	5.71	1.30	0.45	3.29	0.49	0.052	0.13
Europe	872.65	182.12	146.23	334.56	192.01	13.95	3.79
Haiti region	8.28	1.81	0.80	3.52	1.97	0.18	0
Iceland	2.96	0.27	0.43	1.80	0.28	0.17	0.008
India region	1,055.83	154.73	31.97	685.80	116.67	48.39	18.27
Israel	13.03	3.52	3.03	3.00	2.58	0.24	0.67
Jamaica	1.88	0.19	0.11	0.85	0.72	0.001	0
Japan	174.71	28.61	35.11	81.94	27.83	1.11	0.12
Madagascar	3.81	1.18	0.92	1.22	0.36	0.006	0.13
Mauritius	1.54	0.24	0.22	0.38	0.69	0.005	0.008
Mideast	698.73	116.59	72.43	383.81	106.44	15.73	3.74
New Zealand	14.10	2.04	2.17	6.91	2.32	0.57	0.089
Philippines	37.19	8.47	5.51	13.44	9.27	0.49	0
Russia region	269.91	61.78	29.65	137.35	36.97	3.85	0.30
South Am-NW	90.64	14.66	8.43	44.00	22.09	0.84	0.62
South Am-SE	354.96	47.00	31.46	197.48	67.09	11.66	0.27
Southeast Asia	578.51	64.91	46.36	332.88	126.94	4.95	2.47
South Korea	144.29	13.03	27.89	79.44	21.10	2.54	0.29
Taiwan	84.77	9.97	8.93	52.64	11.70	0.73	0.82
United States	945.42	185.79	183.88	356.56	186.55	11.43	21.22
Total 2050	**8,961.8**	**1,557.5**	**886.7**	**4,861.8**	**1,331.4**	**168.3**	**156.2**

Sector values in each region are obtained by multiplying the total WWS 2050 value for each country by the percentage of the total in each sector, given in Table S4a, and summing the result over all countries in a region.

Table S7. Annual average WWS all-sector inflexible and flexible demands (GW) for 2050 by region in the base and EGS cases. "Total demand" is the sum of columns (b) and (c). "Flexible demand" is the sum of columns (d)-(h). DR is demand-response. "Hight-temp industrial heat demand subject to firebrick storage" is demand for industrial heat that can be met by heat stored in firebricks that was produced by electric-resistance heating. "Demand for non-grid H_2" accounts for the production, compression, storage, and leakage of hydrogen. Annual average demands are distributed in time at 30-s resolution, as described in Note S6. Instantaneous demands, either flexible or inflexible, can be much higher or lower than annual average demands. Column (i) shows the annual hydrogen mass production rate needed for steel and ammonia manufacturing and long-distance transport (shown by country in Table S5) in each region, estimated as the H_2 demand multiplied by 8,760 h/y and divided by 47.01 kWh/kg-H_2. Table S17 shows hydrogen production for grid electricity. Table S1 defines the regions. Note S6 describes the meaning of each category. Values are the same for both the base-WWS case and the EGS cases.

				Flexible demands					
Region	(a) Total end-use demand (GW) =b+c	(b) Inflexible demand (GW)	(c) Flexible demand (GW) =d+e+f +g+h	(d) Cold demand subject to storage (GW)	(e) Low-temperature heat demand subject to storage (GW)	(f) Industrial process heat demand subject to fire-brick storage (GW)	(g) Demand subject to DR	(h) Demand for non-grid H_2 (GW)	(i) Non-grid H_2 needed (Tg-H_2/y)
Africa-East	67.0	26.0	41.0	0.5	9.3	17.20	9.3	4.61	0.86
Africa-North	162.2	66.9	95.3	1.86	7.20	33.38	28.4	24.42	4.54
Africa-South	113.8	54.7	59.1	2.24	4.49	25.95	17.9	8.53	1.59
Africa-West	92.8	31.8	60.9	0.73	10.00	26.40	17.6	6.20	1.15
Australia	84.7	39.0	45.7	0.35	2.70	20.91	13.2	8.54	1.59
Canada	163.3	73.3	90.0	0.66	9.10	35.79	30.9	13.56	2.52
Central America	136.8	56.4	80.4	1.31	4.93	35.43	27.9	10.83	2.01
Central Asia	156.8	73.6	83.2	0.29	7.21	38.02	24.3	13.36	2.49
China region	2,625.6	1,010.1	1,615.6	37.9	194.7	671.0	357.5	354.45	65.93
Cuba	5.7	2.4	3.3	0.24	0.31	1.85	0.7	0.21	0.04
Europe	872.7	342.2	530.4	12.2	114.9	132.6	151.7	119.00	22.13
Haiti region	8.3	3.6	4.6	0.08	0.33	1.97	1.5	0.76	0.14
Iceland	3.0	0.9	2.1	0.04	0.52	1.17	0.3	0.12	0.02
India region	1,055.8	396.1	659.7	12.0	38.2	386.0	126.9	96.64	17.97
Israel	13.0	6.6	6.4	0.17	0.82	1.68	2.9	0.84	0.16
Jamaica	1.9	0.7	1.2	0.00	0.03	0.48	0.4	0.27	0.05
Japan	174.7	86.0	88.7	0.33	6.74	22.59	29.7	29.32	5.45
Madagascar	3.8	1.9	1.9	0.14	0.27	0.78	0.5	0.17	0.03
Mauritius	1.5	0.5	1.0	0.06	0.07	0.24	0.4	0.26	0.05
Mideast	698.7	289.3	409.4	3.04	22.7	211.3	98.1	74.26	13.81
New Zealand	14.1	6.7	7.4	0.01	0.37	3.53	2.2	1.23	0.23
Philippines	37.2	14.8	22.4	1.60	2.85	7.78	6.5	3.72	0.69
Russia region	269.9	90.9	179.0	3.52	40.64	52.29	35.0	47.59	8.85
South Am-NW	90.6	36.3	54.4	1.63	3.25	19.03	17.2	13.24	2.46
South Am-SE	355.0	145.0	209.9	5.00	9.44	105.12	56.3	34.08	6.34
Southeast Asia	578.5	216.6	361.9	8.16	18.38	179.01	96.0	60.30	11.22
South Korea	144.3	66.4	77.9	0.48	6.31	28.67	20.0	22.46	4.18
Taiwan	84.8	33.6	51.2	1.13	3.73	26.03	12.5	7.79	1.45
United States	945.4	433.8	511.6	8.62	53.45	182.6	191.7	75.23	13.99
Total	**8,961.8**	**3,606**	**5,355.7**	**104.3**	**572.9**	**2,269**	**1,378**	**1,032**	**191.9**

Table S8. Contemporary and 2050 nameplate capacities of WWS technologies in the base-WWS case and EGS cases. a) Nameplate capacities of WWS electricity and heat generators already installed among 150 countries as of 2023 (except that solar thermal heat is for 2020 and geothermal heat is for 2019). (b) Nameplate capacities by WWS generator needed to meet 2050 annual average all-purpose end-use demand plus transmission/distribution/maintenance losses, plus storage losses, plus curtailment losses for 150 countries grouped into 29 world regions in both the base-WWS case and EGS cases (before EGS added). (c) Nameplate capacities needed to meet continuous all-purpose end-use demand and (d) average (among all countries) percent of 2050 end-use demand plus losses that is supplied by the final nameplate capacity of each technology, in the base-WWS case. (e) and (f) Same as (c) and (d), except in the EGS cases.

			Base-WWS case		EGS cases	
WWS Technology	(a) 2023 name-plate capacity already installed (GW)	(b) 2050 initial existing plus new nameplate capacity to meet annual average demand plus losses (GW)	(c) 2050 final existing plus new nameplate capacity to meet continuous demand plus losses (GW)	(d) Percent of 2050 WWS demand plus losses supplied by each generator	(e) 2050 final existing plus new nameplate capacity to meet continuous demand plus losses (GW)	(f) Percent of 2050 WWS demand plus losses supplied by each generator
Onshore wind	943.9	6,764	10,453	33.19	8,789	28.54
Offshore wind	72.7	3,132	3,783	11.53	3,419	10.88
Res. roof PV	174.7	7,085	4,009	6.25	4,009	6.36
Com/gov roof PV	415.6	6,998	5,711	8.91	5,711	9.07
Utility PV plant	818.6	13,240	19,003	33.63	16,783	30.3
CSP plant	6.88	8.3	5.3	0.03	5.3	0.035
Conventional geo elec.	14.8	193.7	193.7	0.99	193.7	1.003
Enhanced geothermal elec.	0	0	0	0	1,077	8.22
Hydroelectricity	1,262	1,262	1,262	4.52	1,262	4.62
Wave electricity	0.0006	21.5	21.5	0.029	21.5	0.03
Tidal electricity	0.527	7.48	7.48	0.015	7.48	0.015
Solar heat	490.9	490.9	490.9	0.416	490.9	0.423
Geothermal heat	107.7	107.7	107.7	0.485	107.7	0.494
Total generators	**4,308**	**39,311**	**45,047**	**100**	**41,875**	**100**
PHS	142.3	--	568	--	568	--
CSPS	6.88	--	5.3	--	5.3	--
Batteries	55.7	--	8,070	--	5,854	--
Grid H_2	0	--	1,450	--	1,450	--
Total non-hydro elec. storage	**204.9**	**--**	**10,093**	**--**	**7,877**	**--**
CW-STES	--	--	42	--	42	--
ICE	--	--	63	--	63	--
HW-STES	--	--	2,238	--	2,238	--
UTES	--	--	2,215	--	2,215	--
Firebricks	--	--	2,269	--	2,269	--
Total hot and cold storage	**--**	**--**	**6,827**	**--**	**6,827**	**--**

All values are summed over 150 countries in 29 regions, except values in Columns (d) and (f) are simulation-averaged outputs by energy generator determined by summing outputs over all countries and dividing by total energy output among all generators and countries. Table S13 gives values in Column (d) by region. "Annual average demand plus losses" is all-purpose end-use energy demand plus losses per year divided by 8,760 hours per year. "Initial" nameplate capacities (meeting annual average demand) are nameplate capacities at the start of a LOADMATCH simulation. "Final" nameplate capacities are those needed to match demand plus losses after LOADMATCH simulations. Tables S10a and b give final nameplate capacities of electricity and heat generators by country/region. Table S9 gives nameplate capacities of electricity and heat generators already installed by country/region in 2023. Tables S11a and b give the capacity adjustment factors that result in the differences between Columns (b) and (c) and between Columns (b) and (e), respectively. The nameplate capacities of non-hydro-electricity storage and hot and cold storage are from Table S14. The total nameplate capacity of conventional hydropower is already included in the present table as an electricity generator; Table S14 gives its breakdown for baseload and peaking power. PHS=pumped hydropower storage; CSPS=storage associated with concentrated solar power; Batteries=battery storage (BS) for grid backup; Grid H_2 is green hydrogen storage (GSH) for grid backup; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; UTES=Underground thermal energy storage in soil or water pits; and firebricks are bricks used to store low- to high-temperature heat for industrial processes. This study assumes that all thermal-energy storage needed in 2050 will be built from scratch so assumes no existing storage in 2023 although some hot and cold storage already exists. The study also assumes that all battery storage, CSPS, and grid H2 storage will be built from scratch but that 2023 existing PHS will still exist in 2023.

Table S9. Existing nameplate capacity (GW) by WWS generator in each region. All data are for 2023, except for solar heat and geothermal data, which are for 2020 and 2019, respectively.

Region or country	On-shore wind	Off-shore wind	Resi-dential roof PV	Com /gov roof PV	Utility PV	CSP	Trad-itional geo-ther-mal elec-tricity	Enh-anced geo-ther-mal elec-tricity	Hydro	Wave	Tidal	Solar heat	Geo-therm-al heat	Total
Africa-East	0.76	0	0.094	0.22	0.44	0	0.991	0	8.98	0	0	0	0.0207	**11.51**
Africa-North	4.00	0	0.40	0.96	1.90	0.585	0	0	4.33	0	0	1.43	0.171	**13.78**
Africa-South	3.45	0	0.80	1.89	3.73	0.5	0	0	11.33	0	0	1.85	0.0023	**23.55**
Africa-West	0.16	0	0.093	0.22	0.44	0	0	0	10.04	0.0004	0	0.0217	0.0007	**10.97**
Australia	11.33	0	4.18	9.94	19.57	0.003	0	0	8.44	0	0	6.78	0.0944	**60.32**
Canada	16.99	0	0.71	1.70	3.34	0	0.006	0	83.31	0	0.021	0.938	1.83	**108.85**
Central America	8.65	0	1.58	3.77	7.43	0.017	1.74	0	20.74	0	0	3.58	0.166	**47.68**
Central Asia	3.29	0	0.35	0.83	1.63	0	0	0	24.93	0	0	0	0.0029	**31.02**
China region	404.76	37.29	75.61	179.88	354.27	0.57	0.026	0	375.5	0	0.006	364	40.63	**1,832**
Cuba	0.066	0	0.035	0.08	0.16	0	0	0	0.072	0	0	0	0	**0.42**
Europe	224.72	32.37	35.44	84.31	166.04	2.321	0.881	0	194.7	0.0001	0.241	40.31	31.64	**812.92**
Haiti region	0.42	0	0.134	0.32	0.63	0	0	0	0.702	0	0	0	0	**2.20**
Iceland	0.00	0	0.001	0.0021	0.0041	0	0.756	0	2.11	0	0	0	2.37	**5.25**
India region	45.01	0	9.25	22.01	43.35	0.343	0	0	52.08	0	0	11.48	0.361	**183.88**
Israel	0.32	0	0.53	1.26	2.49	0.242	0	0	0.006	0	0	3.449	0.082	**8.38**
Jamaica	0.10	0	0.014	0.0324	0.0639	0	0	0	0.03	0	0	0	0	**0.24**
Japan	5.08	0.154	10.80	25.69	50.59	0	0.428	0	28.22	0	0	2.404	2.57	**125.92**
Madagascar	0	0	0.0073	0.0174	0.0343	0	0	0	0.193	0	0	0	0.0028	**0.25**
Mauritius	0.011	0	0.013	0.0319	0.0628	0	0	0	0.061	0	0	0.093	0	**0.27**
Mideast	13.32	0	3.11	7.41	14.58	0.703	1.69	0	49.45	0	0	19.82	3.78	**113.87**
New Zealand	1.06	0	0.05	0.11	0.22	0	1.05	0	5.68	0	0	0.112	0.518	**8.79**
Philippines	0.44	0	0.21	0.49	0.97	0	1.95	0	3.09	0	0	0	0.0017	**7.16**
Russia region	2.54	0	0.28	0.66	1.29	0	0.074	0	54.02	0	0.003	0.019	0.502	**59.38**
South Am-NW	1.02	0	0.16	0.37	0.73	0	0	0	41.64	0	0	0	0.0299	**43.94**
South Am-SE	38.87	0	5.89	14.02	27.61	0.108	0.083	0	138.1	0.0001	0	13.65	0.591	**238.93**
Southeast Asia	6.48	1.104	3.01	7.16	14.10	0.005	2.42	0	53.56	0	0	0.11	0.154	**88.10**
South Korea	2.03	0.136	3.35	7.98	15.71	0	0	0	1.805	0	0.256	1.353	1.49	**34.12**
Taiwan	1.11	1.569	1.54	3.66	7.21	0	0.007	0	2.104	0	0	1.271	0.0001	**18.47**
United States	147.98	0.041	17.08	40.63	80.02	1.48	2.67	0	86.66	0	0	18.185	20.71	**415.46**
All regions	**943.95**	**72.66**	**174.7**	**415.6**	**818.6**	**6.88**	**14.78**	**0**	**1,262**	**0.0006**	**0.53**	**490.9**	**107.7**	**4,308**

Onshore and offshore wind, solar PV, CSP, conventional geothermal electricity, hydroelectricity, and wave electricity are from IRENA[S42]. Due to a lack of data, existing solar PV is assumed to be split 20% residential rooftop PV, 20% commercial/govt. rooftop PV, and 60% utility PV. Solar thermal values are for 2020 and from Weiss and Spork-Dur[S43]. Tidal values are from various sources. Geothermal heat values are for 2019 and from Lund and Toth[S44].

Table S10a. Base-WWS-case final 2050-2052 total (existing plus new) nameplate capacities (GW) by generator needed in each region to supply 100% of all end-use demand plus losses continuously with WWS across all energy sectors in the region (as determined by LOADMATCH). A nameplate capacity equals the maximum possible instantaneous discharge rate of a generator. The nameplate capacity of each generator in each region multiplied by the mean capacity factor for the generator in the region (from Table S12a) gives the simulation-averaged power output from the generator in the region in Table S13a.

Region or country	On-shore wind	Off-shore wind	Resi-dential roof PV	Com /gov roof PV	Utility PV	CSP	Trad-itional geo-ther-mal elec-tricity	Enh-anced geo-ther-mal elec-tricity	Hydro	Wave	Tidal	Solar heat	Geoth ermal heat	Total
Africa-East	96.1	9.2	52.4	65.1	163.9	0.00	4.081	0	8.98	0.094	0.065	0.000	0.021	**399.9**
Africa-North	198	34.8	106.3	159.9	186	0.00	0.001	0	4.33	0.218	0.136	1.43	0.17	**690.7**
Africa-South	118	26.8	90.4	105.0	166	0.10	0.090	0	11.33	0.158	0.072	1.85	0.00	**519.2**
Africa-West	369	15.3	91.8	129.4	201	0.01	0	0	10.04	0.385	0.100	0.02	0.00	**816.9**
Australia	112	12.5	43.7	62.4	146	0.00	0.400	0	8.44	0.131	0.176	6.78	0.09	**392.6**
Canada	342	35.5	11.9	48.4	69	0.00	5.000	0	83.31	0.222	0.281	0.94	1.83	**598.9**
Central America	265	52.3	62.7	89.5	209	0.00	13.391	0	20.74	0.518	0.142	3.58	0.17	**717.0**
Central Asia	225	19.7	107.7	153.4	198	0.00	0	0	24.93	0.346	0.021	0.00	0.00	**729.1**
China region	2,791	877.2	1,353	1,010	5,717	1.76	1.860	0	375.5	8.445	2.057	364.00	40.63	**12,543**
Cuba	7	1.6	3.9	7.8	13	0.00	0	0	0.07	0.008	0.013	0.00	0.00	**33.1**
Europe	937	245.5	284.5	492.9	1,540	0.18	76.658	0	194.7	1.272	0.880	40.31	31.64	**3,845**
Haiti region	21	1.9	2.9	8.3	10	0.00	0.680	0	0.70	0.000	0.018	0.00	0.00	**45.5**
Iceland	1	0.0	0.0	0.0	0	0.00	1.139	0	2.11	0.002	0.002	0.00	2.37	**6.3**
India region	1,119	106.4	99.6	1,472	2,672	2.21	10.00	0	52.08	4.126	0.810	11.48	0.36	**5,551**
Israel	3	3.5	1.1	14.2	71	0.02	0	0	0.01	0.000	0.009	3.45	0.08	**96.3**
Jamaica	0	1.2	1.6	2.7	3	0.00	0	0	0.03	0.000	0.005	0.00	0.00	**9.0**
Japan	11	255.2	22.7	15.3	390	0.00	1.460	0	28.22	0.614	0.349	2.40	2.57	**729.5**
Madagascar	14	1.3	2.7	3.8	15	0.00	0	0	0.19	0.014	0.008	0.00	0.00	**37.1**
Mauritius	0	1.1	0.4	0.3	5	0.00	0	0	0.06	0.003	0.003	0.09	0.00	**6.6**
Mideast	747	134.6	304.2	319.2	1,279	0.42	14.559	0	49.45	0.107	0.255	19.82	3.78	**2,872**
New Zealand	18	4.6	5.2	7.4	25	0.00	0.704	0	5.68	0.017	0.025	0.11	0.52	**67.2**
Philippines	13	11.7	18.3	42.9	171	0.00	2.256	0	3.09	0.138	0.078	0.00	0.00	**261.6**
Russia region	518	7.6	35.6	76.1	258	0.00	0.500	0	54.02	0.514	0.354	0.02	0.50	**951.4**
South Am-NW	211	10.9	32.2	42.8	147	0.00	4.770	0	41.64	0.206	0.147	0.00	0.03	**490.6**
South Am-SE	858	60.3	211.5	302.1	358	0.04	2.640	0	138.1	0.905	0.332	13.65	0.59	**1,946**
Southeast Asia	56	1,0956	643.2	572.6	1,432	0.00	13.360	0	53.56	1.126	0.462	0.11	0.15	**3,868**
South Korea	2	174.9	69.1	117.1	581	0.00	0	0	1.81	0.000	0.308	1.35	1.49	**949.5**
Taiwan	3	82.1	34.8	73.7	219	0.00	33.640	0	2.10	0.283	0.027	1.27	0.00	**450.1**
United States	1,398	499.9	315.9	315.9	2,760	0.56	6.520	0	86.66	1.656	0.350	18.19	20.71	**5,424**
All regions	**10,453**	**3,783**	**4,009**	**5,711**	**19,003**	**5.3**	**193.71**	**0**	**1,262**	**21.51**	**7.48**	**490.9**	**107.7**	**45,047**

Table S10b. All EGS-cases final 2050-2052 total (existing plus new) modeled nameplate capacities (GW) by generator needed in each region to supply 100% of all end-use demand plus losses continuously with WWS across all energy sectors in the region. The nameplate capacity of each generator in each region multiplied by the mean capacity factor for the generator in the region (from Table S12b) gives the simulation-averaged power output from the generator in the region in Table S13b.

Region or country	On-shore wind	Off-shore wind	Resi-dential roof PV	Com /gov roof PV	Utility PV	CSP	Trad-itional geo-ther-mal elec-tricity	Enh-anced geo-ther-mal elect-ricity	Hydro	Wave	Tidal	Solar heat	Geoth ermal heat	Total
Africa-East	89.7	8.4	52.4	65.1	148.0	0.00	4.081	8.043	8.98	0.094	0.065	0.000	0.021	**384.9**
Africa-North	170	33.1	106.3	159.9	170	0.00	0.001	19.49	4.33	0.218	0.136	1.43	0.17	**664.3**
Africa-South	94	26.3	90.4	105.0	166	0.10	0.090	13.67	11.33	0.158	0.072	1.85	0.00	**508.7**
Africa-West	314	14.4	91.8	129.4	201	0.01	0	11.14	10.04	0.385	0.100	0.02	0.00	**772.4**
Australia	99	11.6	43.7	62.4	128	0.00	0.400	10.17	8.44	0.131	0.176	6.78	0.09	**370.8**
Canada	210	35.5	11.9	48.4	69	0.00	5.000	19.62	83.31	0.222	0.281	0.94	1.83	**485.6**
Central America	265	40.2	62.7	89.5	154	0.00	13.391	16.44	20.74	0.518	0.142	3.58	0.17	**666.1**
Central Asia	199	18.6	107.7	153.4	192	0.00	0	18.83	24.93	0.346	0.021	0.00	0.00	**714.1**
China region	2,326	877.2	1,353	1,010	5,002	1.76	1.860	315.39	375.52	8.445	2.057	364.00	40.63	**11,678**
Cuba	7	1.6	3.9	7.8	9	0.00	0	0.69	0.07	0.008	0.013	0.00	0.00	**30.6**
Europe	812	240.6	284.5	492.9	1,283	0.18	76.658	104.82	194.66	1.272	0.880	40.31	31.64	**3,564**
Haiti region	18	1.8	2.9	8.3	9	0.00	0.680	0.99	0.70	0.000	0.018	0.00	0.00	**42.8**
Iceland	0	0.0	0.0	0.0	0	0.00	1.139	0.35	2.11	0.002	0.002	0.00	2.37	**6.0**
India region	839	106.4	99.6	1,472	2,672	2.21	10.00	126.83	52.08	4.126	0.810	11.48	0.36	**5,398**
Israel	3	3.5	1.1	14.2	58	0.02	0	1.57	0.01	0.000	0.009	3.45	0.08	**85.1**
Jamaica	0	0.9	1.6	2.7	3	0.00	0	0.23	0.03	0.000	0.005	0.00	0.00	**8.7**
Japan	11	212.3	22.7	15.3	390	0.00	1.460	20.99	28.22	0.614	0.349	2.40	2.57	**707.6**
Madagascar	8	1.0	2.7	3.8	15	0.00	0	0.46	0.19	0.014	0.008	0.00	0.00	**30.8**
Mauritius	0	1.1	0.4	0.3	4	0.00	0	0.18	0.06	0.003	0.003	0.09	0.00	**6.2**
Mideast	679	134.6	304.2	319.2	1,198	0.42	14.559	83.93	49.45	0.107	0.255	19.82	3.78	**2,807**
New Zealand	13	4.4	5.2	7.4	20	0.00	0.704	1.69	5.68	0.017	0.025	0.11	0.52	**58.9**
Philippines	13	11.5	18.3	42.9	149	0.00	2.256	4.47	3.09	0.138	0.078	0.00	0.00	**244.0**
Russia region	471	7.6	35.6	76.1	203	0.00	0.500	32.42	54.02	0.514	0.354	0.02	0.50	**881.9**
South Am-NW	174	10.9	32.2	42.8	121	0.00	4.770	10.89	41.64	0.206	0.147	0.00	0.03	**438.0**
South Am-SE	635	55.1	211.5	302.1	316	0.04	2.640	42.64	138.11	0.905	0.332	13.65	0.59	**1,718**
Southeast Asia	56	843.0	643.2	572.6	1,234	0.00	13.360	69.49	53.56	1.126	0.462	0.11	0.15	**3,487**
South Korea	2	170.5	69.1	117.1	439	0.00	0	17.33	1.81	0.000	0.308	1.35	1.49	**819.7**
Taiwan	3	78.5	34.8	73.7	175	0.00	33.640	10.18	2.10	0.283	0.027	1.27	0.00	**412.4**
United States	1,278	468.4	315.9	315.9	2,256	0.56	6.520	113.56	86.66	1.656	0.350	18.19	20.71	**4,882**
All regions	**8,789**	**3,419**	**4,009**	**5,711**	**16,783**	**5.3**	**193.71**	**1,077**	**1,262**	**21.51**	**7.48**	**490.9**	**107.7**	**41,875**

Table S11a. Base-WWS-case LOADMATCH capacity adjustment factors (CAFs). CAFs show the ratio of the final nameplate capacity of a generator to meet demand continuously, after running LOADMATCH, to the pre-LOADMATCH initial nameplate capacity estimated to meet demand in the annual average. Thus, a CAF less than 1.0 means that the LOADMATCH-stabilized grid meeting continuous demand requires less than the nameplate capacity needed to meet annual average demand (which is our initial, pre-LOADMATCH nameplate-capacity assumption).

Region	(a) Onshore wind CAF	(b) Off-shore wind CAF	(c) Utility PV CAF	(g) Res. Roof PV CAF	(h) Com./Gov Roof PV CAF	(i) CSP turbine factor	(j) Solar heat CAF
Africa-East	1.5	1	0.9	1	1.55	0	0
Africa-North	1.4	1	0.95	1	1.05	0	1
Africa-South	1.25	1	1	1	1.2	1	1
Africa-West	2.7	0.83	0.9	1	1	1	1
Australia	1.7	0.7	0.69	0.69	1.71	0	1
Canada	2.32	1	0.2	0.65	0.5	0	1
Central America	1.4	1.3	0.7	0.7	1.63	0	1
Central Asia	1.98	0.9	0.85	0.85	0.9	0.5	0
China region	1.8	1	0.55	0.55	1.6	0.5	1
Cuba	1	1	1	1.39	2.2	0	0
Europe	1.5	1	0.68	0.9	1.2	0.5	1
Haiti region	3.1	1	0.5	1	1.2	1	0
Iceland	0.34	0	0	0	0	0	0
India region	1.2	0.6	0.1	1.3	1.6	1.6	1
Israel	1.2	0.88	0.1	2.3	2.5	1	1
Jamaica	0.75	1.8	0.8	1	1.08	0.1	0
Japan	0.2	2.5	0.2	0.2	1	0	1
Madagascar	2.38	1.4	1	1	3.95	1	0
Mauritius	1	2.03	0.2	0.2	1.71	0.4	1
Mideast	1.87	0.8	0.7	0.75	0.95	0.5	1
New Zealand	2	2	0.6	0.6	1.9	0.3	1
Philippines	1	0.9	0.55	0.9	3.5	0.8	0
Russia region	1.76	0.53	0.23	0.32	0.8	0	1
South Am-NW	1.26	0.72	0.6	0.6	1.38	0.1	0
South Am-SE	1.35	0.8	1	1	1.1	0.1	1
Southeast Asia	0.2	1.95	1	1	1.45	0	1
South Korea	0.1	2	0.9	2.4	1.14	0	1
Taiwan	0.44	1.6	0.7	3	1	0	1
United States	1.75	0.95	0.45	0.45	2.3	0.5	1

All generators not on this list have a CAF=1. Table S10a provides final nameplate capacities in the base-WWS case accounting for the CAFs. The initial estimated nameplate capacity of each generator in each country or region equals the final nameplate capacity divided by the CAF of the generator in the region that the country resides or in the region itself, respectively. The CAFs are also used to adjust the time-dependent wind and solar supplies provided from GATOR-GCMOM to LOADMATCH. Such supplies are calculated based on the initial nameplate capacities fed into LOADMATCH. The supplies from GATOR-GCMOM must be multiplied by the CAFs to be consistent with the new nameplate capacities used in LOADMATCH. Table S1 lists the countries in each region.

Table S11b. All EGS-cases LOADMATCH capacity adjustment factors (CAFs). CAFs show the ratio of the final nameplate capacity of a generator to meet demand continuously, after running LOADMATCH, to the pre-LOADMATCH initial nameplate capacity estimated to meet demand in the annual average. Thus, a CAF less than 1.0 means that the LOADMATCH-stabilized grid meeting continuous demand requires less than the nameplate capacity needed to meet annual average demand (which is our initial, pre-LOADMATCH nameplate-capacity assumption).

Region	(a) Onshore wind CAF	(b) Off-shore wind CAF	(c) Utility PV CAF	(g) Res. Roof PV CAF	(h) Com./Gov Roof PV CAF	(i) CSP turbine factor	(j) Solar heat CAF
Africa-East	1.4	0.91	0.9	1	1.4	0	0
Africa-North	1.2	0.95	0.95	1	0.96	0	1
Africa-South	1	0.98	1	1	1.2	1	1
Africa-West	2.3	0.78	0.9	1	1	1	1
Australia	1.5	0.65	0.69	0.69	1.5	0	1
Canada	1.42	1	0.2	0.65	0.5	0	1
Central America	1.4	1	0.7	0.7	1.2	0	1
Central Asia	1.75	0.85	0.85	0.85	0.87	0.5	0
China region	1.5	1	0.55	0.55	1.4	0.5	1
Cuba	1	1	1	1.39	1.65	0	0
Europe	1.3	0.98	0.68	0.9	1	0.5	1
Haiti region	2.69	0.94	0.5	1	1.1	1	0
Iceland	0.03	0	0	0	0	0	0
India region	0.9	0.6	0.1	1.3	1.6	1.6	1
Israel	1.2	0.88	0.1	2.3	2.05	1	1
Jamaica	0.71	1.3	0.8	1	1	0.1	0
Japan	0.2	2.08	0.2	0.2	1	0	1
Madagascar	1.31	1	1	1	3.9	1	0
Mauritius	0.92	2.03	0.2	0.2	1.5	0.4	1
Mideast	1.7	0.8	0.7	0.75	0.89	0.5	1
New Zealand	1.5	1.89	0.6	0.6	1.5	0.3	1
Philippines	1	0.89	0.55	0.9	3.05	0.8	0
Russia region	1.6	0.53	0.23	0.32	0.63	0	1
South Am-NW	1.04	0.72	0.6	0.6	1.13	0.1	0
South Am-SE	1	0.73	1	1	0.97	0.1	1
Southeast Asia	0.2	1.5	1	1	1.25	0	1
South Korea	0.1	1.95	0.9	2.4	0.86	0	1
Taiwan	0.37	1.53	0.7	3	0.8	0	1
United States	1.6	0.89	0.45	0.45	1.88	0.5	1

All generators not on this list have a CAF=1. Table S10b provides final nameplate capacities in the base-WWS case accounting for the CAFs. The initial estimated nameplate capacity of each generator in each country or region equals the final nameplate capacity divided by the CAF of the generator in the region that the country resides or in the region itself, respectively. The CAFs are also used to adjust the time-dependent wind and solar supplies provided from GATOR-GCMOM to LOADMATCH. Such supplies are calculated based on the initial nameplate capacities fed into LOADMATCH. The supplies from GATOR-GCMOM must be multiplied by the CAFs to be consistent with the new nameplate capacities used in LOADMATCH. Table S1 lists the countries in each region.

Table S12a. Base-WWS-case simulation-averaged 2050-2052 capacity factors (percentage of nameplate capacity produced as electricity before transmission, distribution, maintenance, storage, or curtailment losses) by region. The mean capacity factors in this table equal the simulation-averaged power output supplied by each generator in each region from Table S13a divided by the final nameplate capacity of each generator in each region from Table S10a.

Region	Onshore wind	Off-shore wind	Roof PV	Utility PV	CSP with storage	Trad-itional geo-thermal elec-tricity	Enh-anced geo-ther-mal elec-tricity	Hydro	Wave	Tidal	Solar heat	Geo-thermal heat
Africa-East	0.343	0.383	0.193	0.212	0	0.672	0	0.335	0.127	0.225	0	0.54
Africa-North	0.526	0.446	0.213	0.246	0	0.865	0	0.36	0.149	0.222	0.113	0.54
Africa-South	0.346	0.503	0.203	0.232	0.821	0.835	0	0.352	0.324	0.236	0.113	0.54
Africa-West	0.185	0.224	0.17	0.177	0.544	0	0	0.332	0.124	0.217	0.098	0.54
Australia	0.391	0.505	0.185	0.238	0	0.904	0	0.475	0.332	0.247	0.102	0.54
Canada	0.485	0.555	0.167	0.184	0	0.862	0	0.318	0.297	0.235	0.091	0.54
Central America	0.251	0.328	0.21	0.241	0	0.528	0	0.388	0.127	0.225	0.116	0.54
Central Asia	0.501	0.49	0.184	0.214	0.803	0	0	0.324	0.121	0.216	0	0.54
China region	0.439	0.437	0.185	0.217	0.735	0.896	0	0.496	0.139	0.244	0.102	0.54
Cuba	0.293	0.359	0.216	0.25	0	0	0	0.397	0.374	0.229	0	0
Europe	0.443	0.562	0.161	0.183	0.776	0.58	0	0.425	0.192	0.24	0.088	0.54
Haiti region	0.337	0.477	0.222	0.251	0	0.532	0	0.404	0	0.231	0	0
Iceland	0.493	0	0	0	0	0.925	0	0.559	0	0.26	0	0.54
India region	0.321	0.394	0.187	0.225	0.794	0.857	0	0.445	0.133	0.233	0.105	0.54
Israel	0.387	0.343	0.218	0.252	0.914	0	0	0.504	0	0.252	0.121	0.54
Jamaica	0.299	0.489	0.228	0.263	0	0	0	0.36	0	0.203	0	0
Japan	0.378	0.468	0.161	0.183	0	0.909	0	0.478	0.141	0.249	0.088	0.54
Madagascar	0.242	0.381	0.198	0.229	0	0	0	0.376	0.147	0.252	0	0.541
Mauritius	0.499	0.531	0.201	0.224	0	0	0	0.484	0.337	0.265	0.112	0
Mideast	0.471	0.417	0.203	0.226	0.809	0.798	0	0.453	0.136	0.235	0.108	0.54
New Zealand	0.483	0.562	0.173	0.199	0	0.885	0	0.466	0.355	0.243	0.095	0.54
Philippines	0.28	0.385	0.219	0.247	0	0.858	0	0.451	0.133	0.234	0	0.54
Russia region	0.48	0.603	0.151	0.185	0	0.863	0	0.344	0.256	0.236	0.083	0.54
South Am-NW	0.132	0.412	0.201	0.226	0.814	0.571	0	0.471	0.166	0.232	0	0.54
South Am-SE	0.188	0.444	0.205	0.224	0.788	0.872	0	0.458	0.148	0.238	0.114	0.54
Southeast Asia	0.11	0.22	0.187	0.203	0	0.878	0	0.432	0.18	0.234	0.109	0.54
South Korea	0.325	0.464	0.161	0.165	0	0	0	0.485	0	0.251	0.088	0.54
Taiwan	0.287	0.389	0.183	0.203	0	0.269	0	0.489	0.144	0.255	0.101	0.54
United States	0.371	0.307	0.192	0.212	0.849	0.891	0	0.275	0.294	0.244	0.102	0.54
Average	0.381	0.366	0.187	0.212	0.782	0.61	0	0.43	0.162	0.239	0.102	0.54

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). Capacity factors are determined before transmission, distribution, maintenance, storage, or curtailment losses, which are summarized for each region in Tables S18 and S19. T&D loss rates are given in Table S20. A zero indicates no installation of the technology. Roof PV panels are fixed-tilt at the optimal tilt angle of the country they reside in; utility PV panels are half fixed optimal tilt and half single-axis horizontal tracking[12].

Table S12b. All EGS-cases simulation-averaged 2050-2052 capacity factors (percentage of nameplate capacity produced as electricity before transmission, distribution, maintenance, storage, or curtailment losses) by region. The mean capacity factors in this table equal the simulation-averaged power output supplied by each generator in each region from Table S13b divided by the final nameplate capacity of each generator in each region from Table S10b.

Region	Onshore wind	Off-shore wind	Roo PV	Utility PV	CSP with storage	Trad-itional geo-thermal elec-tricity	Enh-anced geo-ther-mal elec-tricity	Hydro	Wave	Tidal	Solar heat	Geo-thermal heat
Africa-East	0.343	0.383	0.193	0.212	0	0.672	0.9	0.335	0.127	0.225	0	0.54
Africa-North	0.526	0.446	0.213	0.246	0	0.865	0.9	0.362	0.149	0.222	0.113	0.54
Africa-South	0.346	0.503	0.203	0.232	0.821	0.835	0.9	0.351	0.324	0.236	0.113	0.54
Africa-West	0.185	0.224	0.17	0.177	0.544	0	0.9	0.333	0.124	0.217	0.098	0.54
Australia	0.391	0.505	0.185	0.238	0	0.904	0.9	0.476	0.332	0.247	0.102	0.54
Canada	0.485	0.555	0.167	0.184	0	0.862	0.9	0.354	0.297	0.235	0.091	0.54
Central America	0.251	0.328	0.21	0.241	0	0.528	0.9	0.395	0.127	0.225	0.116	0.54
Central Asia	0.501	0.49	0.184	0.214	0.803	0	0.9	0.325	0.121	0.216	0	0.54
China region	0.439	0.437	0.185	0.217	0.735	0.896	0.9	0.496	0.139	0.244	0.102	0.54
Cuba	0.293	0.359	0.216	0.25	0	0	0.9	0.397	0.374	0.229	0	0
Europe	0.443	0.562	0.161	0.183	0.776	0.58	0.9	0.419	0.192	0.24	0.088	0.54
Haiti region	0.337	0.477	0.222	0.251	0	0.532	0.9	0.402	0	0.231	0	0
Iceland	0.493	0	0	0	0	0.925	0.9	0.558	0	0.26	0	0.54
India region	0.321	0.394	0.187	0.225	0.794	0.857	0.9	0.445	0.133	0.233	0.105	0.54
Israel	0.387	0.343	0.218	0.252	0.914	0	0.9	0.504	0	0.252	0.121	0.54
Jamaica	0.299	0.489	0.228	0.263	0	0	0.9	0.36	0	0.203	0	0
Japan	0.378	0.468	0.161	0.183	0	0.909	0.9	0.478	0.141	0.249	0.088	0.54
Madagascar	0.242	0.381	0.198	0.229	0	0	0.9	0.376	0.147	0.252	0	0.541
Mauritius	0.499	0.531	0.201	0.224	0	0	0.9	0.483	0.337	0.265	0.112	0
Mideast	0.471	0.417	0.203	0.226	0.809	0.798	0.9	0.453	0.136	0.235	0.108	0.54
New Zealand	0.483	0.562	0.173	0.199	0	0.885	0.9	0.467	0.355	0.243	0.095	0.54
Philippines	0.28	0.385	0.219	0.247	0	0.858	0.9	0.451	0.133	0.234	0	0.54
Russia region	0.48	0.603	0.151	0.185	0	0.863	0.9	0.344	0.256	0.236	0.083	0.54
South Am-NW	0.132	0.412	0.201	0.226	0.814	0.571	0.9	0.468	0.166	0.232	0	0.54
South Am-SE	0.188	0.444	0.205	0.224	0.788	0.872	0.9	0.453	0.148	0.238	0.114	0.54
Southeast Asia	0.11	0.22	0.187	0.203	0	0.878	0.9	0.438	0.18	0.234	0.109	0.54
South Korea	0.325	0.464	0.161	0.165	0	0	0.9	0.484	0	0.251	0.088	0.54
Taiwan	0.287	0.389	0.183	0.203	0	0.269	0.9	0.488	0.144	0.255	0.101	0.54
United States	0.371	0.307	0.192	0.212	0.849	0.891	0.9	0.275	0.294	0.244	0.102	0.54
Average	0.383	0.375	0.187	0.213	0.782	0.61	0.9	0.431	0.162	0.239	0.102	0.541

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). Capacity factors are determined before transmission, distribution, maintenance, storage, or curtailment losses, which are summarized for each region in Tables S18 and S19. T&D loss rates are given in Table S20. A zero indicates no installation of the technology. Roof PV panels are fixed-tilt at the optimal tilt angle of the country they reside in; utility PV panels are half fixed optimal tilt and half single-axis horizontal tracking.

Table S13a. Base-WWS-case LOADMATCH 2050-2052 simulation-averaged all-sector projected WWS end-use power supplied by region and percentage of such supply met by each generator. Power supplied equals power consumed plus power lost during transmission, distribution, maintenance, and curtailment. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/simulation) divided by the number of hours of simulation. The percentages for each region add to 100%. Multiply each percentage by the 2050 total supply to obtain the GW supply by each generator. Divide the GW supply from each generator by its capacity factor (Table S12a) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table S10a). The 2050 total WWS supply is also obtained from Column (f) of Table S18a.

Region	Annual average total WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with stor-age (%)	Trad-itional geo-therm-al elec-tricity (%)	Enh-anced geo-thermal elec-tricity (%)	Hydro (%)	Wave (%)	Tidal (%)	Solar heat (%)	Geo-ther-mal heat (%)
Africa-East	99.8	33.04	3.54	22.73	34.89	0	2.748	0	3.016	0.012	0.015	0	0.011
Africa-North	223.7	46.50	6.95	25.32	20.40	0	0.0004	0	0.698	0.015	0.014	0.072	0.041
Africa-South	136.7	29.82	9.87	29.04	28.04	0.062	0.055	0	2.917	0.037	0.012	0.153	0.001
Africa-West	148.4	46.02	2.31	25.39	23.98	0.002	0	0	2.248	0.032	0.015	0.001	0
Australia	109.7	40.11	5.76	17.84	31.55	0	0.330	0	3.657	0.040	0.040	0.628	0.047
Canada	240.7	69.06	8.19	4.17	5.27	0	1.790	0	11.004	0.028	0.028	0.036	0.411
Central America	181.9	36.55	9.43	17.57	27.81	0	3.887	0	4.427	0.036	0.018	0.229	0.049
Central Asia	220.8	51.03	4.37	21.75	19.17	0.001	0	0	3.660	0.019	0.002	0	0.001
China region	3,538	34.61	10.84	12.39	35.10	0.037	0.047	0	5.264	0.033	0.014	1.049	0.621
Cuba	8.37	24.86	6.92	30.24	37.56	0	0	0	0.341	0.036	0.036	0	0
Europe	1,109	37.46	12.44	11.25	25.46	0.013	4.008	0	7.456	0.022	0.019	0.322	1.542
Haiti region	13.6	51.02	6.64	18.42	19.13	0	2.666	0	2.089	0	0.030	0	0
Iceland	3.87	9.02	0	0	0	0	27.25	0	30.55	0	0.014	0	33.17
India region	1,334	26.97	3.14	22.09	45.13	0.132	0.642	0	1.736	0.041	0.014	0.091	0.015
Israel	24.1	4.95	4.92	13.94	74.19	0.059	0	0	0.013	0	0.009	1.733	0.185
Jamaica	2.51	4.25	23.16	39.30	32.82	0	0	0	0.430	0	0.039	0	0
Japan	217.5	1.88	54.91	2.81	32.77	0	0.610	0	6.204	0.040	0.040	0.097	0.639
Madagascar	8.69	38.12	5.91	14.94	40.13	0	0	0	0.835	0.024	0.024	0	0.018
Mauritius	1.83	2.72	31.58	6.92	56.50	0	0	0	1.613	0.047	0.047	0.568	0
Mideast	862	40.85	6.52	14.66	33.49	0.039	1.349	0	2.601	0.002	0.007	0.248	0.237
New Zealand	22.0	39.49	11.84	9.93	22.50	0	2.831	0	12.04	0.027	0.027	0.048	1.273
Philippines	66.8	5.28	6.73	20.03	62.92	0	2.897	0	2.085	0.028	0.028	0	0.001
Russia region	337.4	73.77	1.35	5.00	14.09	0	0.128	0	5.510	0.039	0.025	0.001	0.080
South Am-NW	103.0	26.88	4.38	14.65	32.34	0.002	2.643	0	19.03	0.033	0.033	0	0.016
South Am-SE	440.7	36.54	6.08	23.84	18.19	0.007	0.523	0	14.34	0.030	0.018	0.352	0.073
Southeast Asia	800.5	0.76	30.15	28.39	36.30	0	1.465	0	2.891	0.025	0.014	0.002	0.010
South Korea	209.2	0.33	38.77	14.28	45.72	0	0	0	0.419	0	0.037	0.057	0.385
Taiwan	107.4	0.88	29.70	18.46	41.41	0	8.44	0	0.958	0.038	0.006	0.119	0
United States	1,423	36.44	10.80	8.53	41.16	0.033	0.408	0	1.671	0.034	0.006	0.130	0.787
All regions	**11,994**	**33.19**	**11.53**	**15.16**	**33.63**	**0.035**	**0.986**	**0**	**4.522**	**0.029**	**0.015**	**0.416**	**0.485**

Table S13b. All EGS-cases LOADMATCH 2050-2052 simulation-averaged all-sector projected WWS end-use power supplied by region and percentage of such supply met by each generator. Power supplied equals power consumed plus power lost during transmission, distribution, maintenance, and curtailment. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/simulation) divided by the number of hours of simulation. The percentages for each region add to 100%. Multiply each percentage by the 2050 total supply to obtain the GW supply by each generator. Divide the GW supply from each generator by its capacity factor (Table S12b) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table S10b). The 2050 total WWS supply is also obtained from Column (f) of Table S18b.

Region	Annual average total WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with stor-age (%)	Trad-itional geo-therm-al elec-tricity (%)	Enh-anced geo-thermal elec-tricity (%)	Hydro (%)	Wave (%)	Tidal (%)	Solar heat (%)	Geo-ther-mal heat (%)
Africa-East	101.1	30.43	3.18	22.43	31.09	0	2.711	7.159	2.976	0.012	0.014	0	0.011
Africa-North	221.7	40.21	6.66	25.55	18.82	0	0.0004	7.911	0.707	0.015	0.014	0.073	0.042
Africa-South	140.6	23.20	9.41	28.24	27.26	0.061	0.053	8.750	2.830	0.036	0.012	0.149	0.001
Africa-West	148.1	39.28	2.18	25.44	24.02	0.002	0	6.769	2.254	0.032	0.015	0.001	0
Australia	109.0	35.62	5.38	17.96	27.86	0	0.332	8.398	3.684	0.040	0.040	0.632	0.047
Canada	196.8	51.68	10.02	5.10	6.45	0	2.189	8.970	14.977	0.034	0.034	0.044	0.503
Central America	179.5	37.03	7.35	17.80	20.74	0	3.938	8.241	4.565	0.037	0.018	0.232	0.050
Central Asia	222.8	44.71	4.09	21.56	18.37	0.001	0	7.609	3.638	0.019	0.002	0	0.001
China region	3,462	29.47	11.07	12.66	31.38	0.037	0.048	8.198	5.382	0.034	0.015	1.071	0.634
Cuba	8.20	25.38	7.06	30.87	28.75	0	0	7.525	0.349	0.037	0.037	0	0
Europe	1,097	32.82	12.33	11.37	21.45	0.013	4.052	8.599	7.439	0.022	0.019	0.325	1.559
Haiti region	13.3	45.25	6.38	18.83	17.92	0	2.725	6.736	2.125	0	0.031	0	0
Iceland	3.87	0.80	0	0	0	0	27.25	8.26	30.52	0	0.014	0	33.17
India region	1,358	19.86	3.09	21.70	44.32	0.129	0.631	8.406	1.707	0.040	0.014	0.089	0.014
Israel	22.3	5.36	5.32	15.07	65.77	0.064	0	6.329	0.014	0	0.010	1.873	0.200
Jamaica	2.49	4.07	16.89	39.69	30.69	0	0	8.176	0.434	0	0.039	0	0
Japan	216.3	1.89	45.93	2.83	32.95	0	0.614	8.732	6.237	0.040	0.040	0.098	0.642
Madagascar	7.42	24.57	4.94	17.50	46.39	0	0	5.552	0.977	0.028	0.028	0	0.021
Mauritius	1.87	2.46	30.99	6.79	48.63	0	0	8.911	1.577	0.046	0.046	0.557	0
Mideast	887	36.08	6.33	14.24	30.48	0.038	1.311	8.516	2.527	0.002	0.007	0.241	0.230
New Zealand	20.2	32.30	12.20	10.83	19.37	0	3.087	7.558	13.16	0.030	0.030	0.053	1.388
Philippines	65.4	5.40	6.80	20.47	56.04	0	2.960	6.146	2.131	0.028	0.028	0	0.001
Russia region	333.9	67.78	1.37	5.05	11.22	0	0.129	8.740	5.566	0.039	0.025	0.001	0.081
South Am-NW	101.8	22.44	4.43	14.82	26.78	0.002	2.674	9.622	19.15	0.034	0.033	0	0.016
South Am-SE	424.8	28.08	5.75	24.74	16.64	0.008	0.542	9.034	14.71	0.032	0.019	0.365	0.075
Southeast Asia	767.6	0.80	24.18	29.60	32.63	0	1.528	8.148	3.053	0.026	0.014	0.002	0.011
South Korea	199.3	0.35	39.68	14.99	36.21	0	0	7.828	0.438	0	0.039	0.060	0.404
Taiwan	106.1	0.75	28.74	18.68	33.52	0	8.54	8.639	0.968	0.038	0.006	0.121	0
United States	1,365	34.76	10.55	8.89	35.10	0.035	0.426	7.490	1.748	0.036	0.006	0.136	0.821
All regions	**11,783**	**28.54**	**10.88**	**15.43**	**30.31**	**0.035**	**1.003**	**8.222**	**4.618**	**0.030**	**0.015**	**0.423**	**0.494**

Table S14.i. Final modeled storage peak charge rates, peak discharge, peak capacities, and other statistics. Aggregate (among all countries in each region) of the maximum instantaneous charge rates, maximum instantaneous discharge rates, maximum energy storage capacities, hours of storage at the maximum discharge rate, and storage capacity factor, of the different types of electricity storage technologies treated here, in the base-WWS case and all three EGS cases, for each region. Total hydropower values are split into baseload and peaking hydropower values, as described in Note S5. The maximum storage capacities are either of electricity (for the electricity storage options), or of thermal energy (for the hot and cold storage options). The storage capacity factor is the energy discharged from the storage medium over the entire simulation divided by the product of the maximum discharge rate and the number of hours of simulation. See footnote of Table S14.iii. for more details.

	Africa-East (base)					Africa-East (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	4.0	4.0	0.06	14.0	0.004	4.0	4.0	0.06	14.0	0.008
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	320	320	1.28	4.0	0.93	200	200	0.80	4.0	1.21
Hydropower	4.0	9.0	34.9	3,883	31.00	4.0	9.0	34.9	3,883	31.00
Base	3.0	3.0	26.0	8,640	92.50	3.0	3.0	26.0	8,640	92.50
Peaking	1.0	6.0	8.9	1,486	0.004	1.0	6.0	8.9	1,486	0.008
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.22	0.22	0.003	14.0	42.80	0.22	0.22	0.003	14.0	50.68
ICE	0.32	0.32	0.005	14.0	42.80	0.32	0.32	0.005	14.0	50.68
HW-STES	59.7	74.7	0.15	2.0	7.62	59.7	74.7	0.15	2.0	7.81
UTES-heat	0.02	74.67	16.1	216.0	4.56	0.02	74.67	16.1	216.0	4.51
UTES-elec.	59.7	--	--	--	--	59.7	--	--	--	--
Firebricks	60.21	17.20	0.258	15.0	97.39	60.21	17.20	0.258	15.0	98.36
	Africa-North (base)					**Africa-North (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	5.6	5.6	0.08	14.0	0.41	5.6	5.6	0.08	14.0	0.41
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0.
Batteries	130	130	0.52	4.0	1.88	91	91	0.36	4.0	2.03
Hydropower	2.1	4.3	17.9	4,133	33.32	2.1	4.3	17.9	4,133	33.48
Base	1.5	1.5	13.4	8,640	92.50	1.5	1.5	13.4	8,640	92.50
Peaking	0.5	2.8	4.6	1,634	0.52	0.5	2.8	4.6	1,634	0.76
Grid H_2	15.0	15.0	0	0	0.23	9.0	9.0	0	0	0.33
CW-STES	0.74	0.74	0.010	14.0	24.63	0.74	0.74	0.010	14.0	24.90
ICE	1.12	1.12	0.016	14.0	24.63	1.12	1.12	0.016	14.0	24.90
HW-STES	25.4	28.2	0.06	2.0	12.87	25.4	28.2	0.06	2.0	12.16
UTES-heat	1.60	28.24	0.7	24.0	1.30	1.60	28.24	0.7	24.0	1.25
UTES-elec.	2.8	--	--	--	--	2.8	--	--	--	--
Firebricks	116.8	33.38	0.501	15.0	93.30	116.8	33.38	0.501	15.0	93.95
	Africa-South (base)					**Africa-South (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	13.6	13.6	0.19	14.0	0.17	13.6	13.6	0.19	14.0	0.07
CSP-elec.	0.1	0.1	--	--	--	0.1	0.1	--	--	--
CSPS	0.2	--	0.00	22.6	25.59	0.2	--	0	22.6	24.21
Batteries	240	240	0.96	4.0	4.71	200	200	0.80	4.0	4.06
Hydropower	5.3	11.3	46.1	4,065	32.56	5.3	11.3	46.1	4,065	32.50
Base	4.0	4.0	34.3	8,640	92.50	4.0	4.0	34.3	8,640	92.50
Peaking	1.3	7.4	11.7	1,593	0.17	1.3	7.4	11.7	1,593	0.07
Grid H_2	29.0	29.0	0	0	0.08	29.0	29.0	0	0	0.03
CW-STES	0.89	0.89	0.013	14.0	19.83	0.89	0.89	0.013	14.0	23.68
ICE	1.34	1.34	0.019	14.0	19.83	1.34	1.34	0.019	14.0	23.68
HW-STES	37.7	41.9	0.08	2.0	5.49	37.7	41.9	0.08	2.0	5.81
UTES-heat	1.85	41.90	9.1	216.0	4.34	1.85	41.90	9.1	216.0	4.34
UTES-elec.	37.7	--	--	--	--	37.7	--	--	--	--
Firebricks	90.82	25.95	0.389	15.0	77.80	90.82	25.95	0.389	15.0	88.50
	Africa-West (base)					**Africa-West EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	4.0	4.0	0.06	14.0	0.040	4.0	4.0	0.06	14.0	0.080
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	22.5	6.84	0	--	0	22.5	6.01
Batteries	400	400	1.60	4.0	0.46	400	400	1.60	4.0	0.43
Hydropower	4.5	10.0	38.6	3,848	30.75	4.5	10.0	38.6	3,848	30.77
Base	3.3	3.3	28.8	8,640	92.50	3.3	3.3	28.8	8,640	92.50

Peaking	1.1	6.7	9.8	1,465	0.04	1.1	6.7	9.8	1,465	0.08
Grid H_2	25.0	25.0	0	0	0.02	25.0	25.0	0	0	0.03
CW-STES	0.29	0.29	0.004	14.0	41.49	0.29	0.29	0.004	14.0	40.63
ICE	0.44	0.44	0.006	14.0	41.49	0.44	0.44	0.006	14.0	40.63
HW-STES	31.9	31.9	0.06	2.0	17.00	31.9	31.9	0.06	2.0	16.13
UTES-heat	0.02	31.92	4.6	144.0	11.71	0.02	31.92	4.6	144.0	11.60
UTES-elec.	28.7	--	--	--	--	28.7	--	--	--	--
Firebricks	92.41	26.40	0.396	15.0	97.50	92.41	26.40	0.396	15.0	97.03
	Australia (base)					**Australia (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	8.8	8.8	0.124	14.0	0.04	8.8	8.8	0.124	14.0	0.11
CSP-elec.	0	0	--	--	--	0	0.00	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	110	110	0.44	4.0	2.05	67	67	0.27	4.0	2.17
Hydropower	4.24	8.44	7.8	919	43.97	4.24	8.44	7.8	919	44.01
Base	4.01	4.01	5.8	1,440	92.50	4.01	4.01	5.8	1,440	92.50
Peaking	0.23	4.43	2.0	448	0.04	0.23	4.43	2.0	448	0.11
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.138	0.138	0.0019	14.0	23.48	0.138	0.138	0.0019	14.0	24.22
ICE	0.207	0.207	0.0029	14.0	23.48	0.207	0.207	0.0029	14.0	24.22
HW-STES	0.83	8.33	0.017	2.0	3.88	0.83	8.33	0.017	2.0	3.91
UTES-heat	6.87	8.33	0.200	24.0	2.38	6.87	8.33	0.200	24.0	2.37
UTES-elec.	0.83	--	--	--		0.83	--	--	--	
Firebricks	73.17	20.91	0.314	15.0	97.58	73.17	20.91	0.314	15.0	98.99
	Canada (base)					**Canada (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	0.8	0.8	0.011	14.0	5.99	0.8	0.8	0.011	14.0	6.53
CSP-elec.	0	0	--	--		0	0	--	--	
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	39.86	83.31	188.3	2,260	29.41	39.86	83.31	188.3	2,260	32.74
Base	21.98	21.98	31.6	1,440	92.50	21.98	21.98	31.6	1,440	92.50
Peaking	17.88	61.33	156.7	2,555	6.81	17.88	61.33	156.7	2,555	11.33
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.263	0.263	0.0037	14.0	11.52	0.263	0.263	0.0037	14.0	8.75
ICE	0.394	0.394	0.0055	14.0	11.52	0.394	0.394	0.0055	14.0	8.75
HW-STES	2.22	22.15	0.044	2.0	5.76	2.22	22.15	0.044	2.0	4.90
UTES-heat	0.00	0.00	0	0.0	0.00	0.00	0.00	0	0.0	0.00
UTES-elec.	0.00	--	--	--		0.00	--	--	--	
Firebricks	125.3	35.79	0.537	15.0	89.37	125.3	35.79	0.537	15.0	82.94
	Central America (base)					**Central America (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	6.02	6.02	0.084	14.0	0.33	6.02	6.02	0.084	14.0	2.88
CSP-elec.	0	0	--	--		0.00	0.00	--	--	
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	120	120	0.48	4.0	2.94	28	28	0.11	4.0	4.98
Hydropower	9.54	20.74	25.0	1,204	35.92	9.54	20.74	25.0	1,204	36.55
Base	8.01	8.01	11.5	1,440	92.50	8.01	8.01	11.5	1,440	92.50
Peaking	1.53	12.73	13.4	1,056	0.33	1.53	12.73	13.4	1,056	1.36
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.526	0.526	0.0074	14.0	31.67	0.526	0.526	0.0074	14.0	33.35
ICE	0.79	0.79	0.0110	14.0	31.67	0.79	0.79	0.0110	14.0	33.35
HW-STES	3.34	33.40	0.067	2.0	3.26	3.34	33.40	0.067	2.0	3.56
UTES-heat	3.75	33.40	0.801	24.0	1.96	3.75	33.40	0.801	24.0	2.14
UTES-elec.	3.34	--	--	--	--	3.34	--	--	--	--
Firebricks	124.0	35.43	0.531	15.0	97.35	124.0	35.43	0.531	15.0	99.86
	Central Asia (base)					**Central Asia (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	12.0	12.0	0.168	14.0	0.73	12.0	12.0	0.168	14.0	0.89
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	23.3	4.44	0	--	0	23.3	3.68
Batteries	24	24	0.10	4.0	3.93	10	10	0.04	4.0	4.09
Hydropower	11.30	24.93	40.5	1,623	29.99	11.30	24.93	40.5	1,623	30.08
Base	7.99	7.99	11.5	1,440	92.50	7.99	7.99	11.5	1,440	92.50
Peaking	3.31	16.94	29.0	1,710	0.49	3.31	16.94	29.0	1,710	0.62
Grid H_2	21.0	21.0	0	0	1.00	21.0	21.0	0	0	1.22
CW-STES	0.115	0.115	0.0016	14.0	26.14	0.115	0.115	0.0016	14.0	26.69
ICE	0.173	0.173	0.0024	14.0	26.14	0.173	0.173	0.0024	14.0	26.69

HW-STES	34.73	34.73	0.278	8.0	16.28	34.73	34.73	0.278	8.0	16.14
UTES-heat	0.0029	34.73	5.834	168.0	3.19	0.0029	34.73	5.834	168.0	3.24
UTES-elec.	10.42	--	--	--	--	10.42	--	--	--	--
Firebricks	133.1	38.02	0.570	15.0	98.71	133.1	38.02	0.570	15.0	98.86
	China region (base)					**China region (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	178.3	178.3	2.496	14.0	0.23	178.3	178.3	2.496	14.0	0.34
CSP-elec.	1.8	1.8	--	--	--	1.8	1.8	--	--	--
CSPS	2.8	--	0.040	22.6	4.23	2.8	--	0.040	22.6	3.16
Batteries	940	940	3.76	4.0	1.35	780	780	3.12	4.0	1.12
Hydropower	186.6	375.5	274	729	45.87	186.6	375.5	274	729	45.90
Base	186.0	186.0	268	1,440	92.50	186.0	186.0	268	1,440	92.50
Peaking	0.7	189.6	6	31.4	0.13	0.7	189.6	6	31.4	0.19
Grid H_2	440.0	440.0	0	0	0.23	440.0	440.0	0	0	0.39
CW-STES	15.17	15.17	0.2123	14.0	17.59	15.17	15.17	0.2123	14.0	17.64
ICE	22.75	22.75	0.3185	14.0	17.59	22.75	22.75	0.3185	14.0	17.64
HW-STES	677.4	677.4	2.032	3.0	11.79	677.4	677.4	2.032	3.0	11.21
UTES-heat	404.6	677.4	211.3	312.0	9.72	404.6	677.4	211.3	312.0	9.35
UTES-elec.	677.4	--	--	--	--	677.4	--	--	--	--
Firebricks	2348.6	671.0	10.065	15.0	97.95	2348.6	671.0	10.065	15.0	97.24
	Cuba (base)					**Cuba (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	3.00	3.00	0.042	14.0	0	3.00	3.00	0.042	14.0	0.07
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0.0	0	0	--	0	0	0.00
Batteries	41	41	0.164	4.0	1.63	30	30	0.120	4.0	1.64
Hydropower	0.034	0.072	0.089	1,238	36.72	0.034	0.072	0.089	1,238	36.74
Base	0.029	0.029	0.041	1,439	92.50	0.029	0.029	0.041	1,439	92.50
Peaking	0.006	0.043	0.048	1,105	0.0030	0.006	0.043	0.048	1,105	0.0510
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.097	0.097	0.0014	14.0	28.38	0.097	0.097	0.0014	14.0	30.28
ICE	0.146	0.146	0.0020	14.0	28.38	0.146	0.146	0.0020	14.0	30.28
HW-STES	1.16	1.16	0.009	8.0	17.53	1.16	1.16	0.009	8.0	18.21
UTES-heat	0.00	1.16	0.028	24.0	2.77	0.00	1.16	0.028	24.0	2.79
UTES-elec.	0.47	--	--	--	--	0.47	--	--	--	--
Firebricks	6.46	1.85	0.028	15.0	88.75	6.46	1.85	0.028	15.0	89.91
	Europe (base)					**Europe (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	101.1	101.1	1.41	14.0	3.33	101.1	101.1	1.41	14.0	1.43
CSP-elec.	0.18	0.18	--	--	--	0.18	0.18	--	--	--
CSPS	0.30	--	0.004	22.6	11.06	0.30	--	0.004	22.6	9.31
Batteries	1	1	0.004	4.0	8.39	1	1	0.004	4.0	7.71
Hydropower	95.32	194.7	247.9	1,274	39.30	95.32	194.7	247.9	1,274	38.79
Base	80.20	80.2	115.5	1,440	92.50	80.20	80.2	115.5	1,440	92.50
Peaking	15.12	114.5	132.4	1,157	2.02	15.12	114.5	132.4	1,157	1.15
Grid H_2	160.0	160.0	0	0	5.98	160.0	160.0	0	0	4.33
CW-STES	4.87	4.87	0.0681	14.0	9.62	4.87	4.87	0.0681	14.0	10.69
ICE	7.30	7.30	0.1022	14.0	9.62	7.30	7.30	0.1022	14.0	10.69
HW-STES	279.4	279.4	0.559	2.0	13.68	279.4	279.4	0.559	2.0	13.75
UTES-heat	71.94	279.4	201.186	720.0	3.56	71.94	279.4	167.655	600.0	3.35
UTES-elec.	27.9	--	--	--	--	27.9	--	--	--	--
Firebricks	464.1	132.6	1.989	15.0	73.07	464.1	132.6	1.989	15.0	71.93
	Haiti region (base)					**Haiti region (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	2.00	2.00	0.028	14.0	0.87	2.00	2.00	0.028	14.0	0.55
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.05	0	--	0	0	0.05
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	0.335	0.702	0.88	1,249	37.35	0.335	0.702	0.88	1,249	37.18
Base	0.281	0.281	0.40	1,440	92.50	0.281	0.281	0.40	1,440	92.50
Peaking	0.054	0.421	0.47	1,122	0.492	0.054	0.421	0.47	1,122	0.207
Grid H_2	4.0	4.0	0	0	3.69	4.0	4.0	0	0	2.95
CW-STES	0.034	0.034	0.00047	14.0	40.29	0.034	0.034	0.00047	14.0	40.84
ICE	0.051	0.051	0.00071	14.0	40.29	0.051	0.051	0.00071	14.0	40.84
HW-STES	0	1	0		0	0	1	0		0
UTES-heat	0	0.61	0.015	24.0	2.99	0	0.61	0.015	24.0	3.02
UTES-elec.	0.06	--	--	--	--	0.06	--	--	--	--
Firebricks	6.90	1.97	0.030	15.0	94.62	6.90	1.97	0.030	15.0	95.47

Table S14.ii. Final modeled storage peak charge rates, peak discharge, peak capacities, and other statistics. Continuation of Table S14.i. See caption of Table S14.i and footnote of Table S14.iii. for more details.

	Iceland (base)					Iceland (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	0	0	0	0	0	0	0	0	0	0
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	1.09	2.11	2.8	1,337	51.71	1.09	2.11	2.8	1,337	51.64
Base	0.77	0.77	0.1	120	92.50	0.77	0.77	0.1	120	92.50
Peaking	0.31	1.34	2.7	2,040	28.12	0.31	1.34	2.7	2,040	28.02
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.016	0.016	0.00022	14.0	0	0.016	0.016	0.00022	14.0	0
ICE	0.024	0.024	0.00033	14.0	0	0.024	0.024	0.00033	14.0	0
HW-STES	0.10	0.97	0.0010	1.0	0	0.10	0.97	0.0010	1.0	0
UTES-heat	0	0	0	0	0	0	0	0	0	0
UTES-elec.	0	--	--	--		0	--	--	--	
Firebricks	4.09	1.17	0.018	15.0	0.25	4.09	1.17	0.018	15.0	0.09
	India region (base)					**India region (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	25.8	25.8	0.361	14.0	0.08	25.8	25.8	0.361	14.0	0.13
CSP-elec.	2.21	2.21	--	--	--	2.21	2.21	--	--	--
CSPS	3.6	--	0.050	22.6	21.33	3.6	--	0.050	22.6	20.38
Batteries	1,850	1,850	7.40	4.0	3.25	1,200	1,200	4.80	4.0	3.85
Hydropower	24.44	52.08	44.8	859	41.13	24.44	52.08	44.8	859	41.18
Base	23.13	23.13	33.3	1,440	92.50	23.13	23.13	33.3	1,440	92.50
Peaking	1.31	28.95	11.4	395	0.08	1.31	28.95	11.4	395	0.16
Grid H_2	230.0	230.0	0	0	0.04	230.0	230.0	0	0	0.07
CW-STES	4.79	4.79	0.0671	14.0	21.05	4.79	4.79	0.0671	14.0	22.51
ICE	7.19	7.19	0.1006	14.0	21.05	7.19	7.19	0.1006	14.0	22.51
HW-STES	339.6	339.6	0.679	2.0	6.10	339.6	339.6	0.679	2.0	6.05
UTES-heat	11.84	339.6	81.50	240.0	4.70	11.84	339.6	81.50	240.0	4.72
UTES-elec.	339.6	--	--	--	--	339.6	--	--	--	--
Firebricks	1351.1	386.0	5.790	15.0	93.73	1351.1	386.0	5.790	15.0	96.55
	Israel (base)					**Israel (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	1.1	1.1	0.015	14.0	0.01	1.1	1.1	0.015	14.0	0.00
CSP-elec.	0.016	0.016	--	--	--	0.016	0.016	--	--	--
CSPS	0.03	--	0.0004	22.6	31.17	0.03	--	0.0004	22.6	31.11
Batteries	98	98	0.392	4.0	3.83	91	91	0.364	4.0	3.40
Hydropower	0.0030	0.0060	0.0021	342.5	46.67	0.0030	0.0060	0.0021	342.5	46.67
Base	0.0030	0.0030	0.0021	685.0	92.50	0.0030	0.0030	0.0021	685.0	92.50
Peaking	0	0.0030	0	0	0	0	0.0030	0	0	0
Grid H_2	6.0	6.0	0	0	0.00	6.0	6.0	0	0	0.00
CW-STES	0.068	0.068	0.0010	14.0	16.89	0.068	0.068	0.0010	14.0	16.96
ICE	0.102	0.102	0.0014	14.0	16.89	0.102	0.102	0.0014	14.0	16.96
HW-STES	3.09	3.09	0.025	8.0	9.28	3.09	3.09	0.025	8.0	9.19
UTES-heat	3.53	3.09	1.853	600.0	7.73	3.53	3.09	1.853	600.0	7.65
UTES-elec.	2.16	--	--	--	--	2.16	--	--	--	--
Firebricks	5.88	1.68	0.025	15.0	78.58	5.88	1.68	0.025	15.0	78.40
	Jamaica (base)					**Jamaica (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	0.10	0.10	0.0014	14.0	0	0.10	0.10	0.0014	14.0	0
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.04	0	--	0	0.0	0.04
Batteries	13	13	0.0500	4.0	2.18	13	13	0.0500	4.0	2.02
Hydropower	0.013	0.03	0.0337	1,122	33.30	0.013	0.03	0.0337	1,122	33.29
Base	0.011	0.01	0.0155	1,439	92.50	0.011	0.01	0.0155	1,439	92.50
Peaking	0.002	0.02	0.0181	944	0	0.002	0.02	0.0181	944	0
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0	0	0		0	0	0	0		0
ICE	0	0	0		0	0	0	0		0
HW-STES	0.79	0.98	0.0059	6.0	2.61	0.79	0.98	0.0059	6.0	2.60
UTES-heat	0	0.98	0.0707	72.0	0.64	0	0.98	0.0471	48.0	0.60
UTES-elec.	0.10	--	--	--	--	0.10	--	--	--	--
Firebricks	1.68	0.48	0.0072	15.0	86.52	1.68	0.48	0.0072	15.0	87.16

Storage technology	Japan (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Japan (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	76.4	76.4	1.07	14.0	0.27	76.4	76.4	1.07	14.0	0.19
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0.0	0
Batteries	170	170	0.68	4.0	3.60	145	145	0.58	4.0	3.63
Hydropower	14.24	28.22	26.1	924	44.23	14.24	28.22	26.1	924	44.23
Base	13.48	13.48	19.4	1,440	92.50	13.48	13.48	19.4	1,440	92.50
Peaking	0.76	14.73	6.7	453	0.07	0.76	14.73	6.7	453	0.05
Grid H_2	39.0	39.0	0	0	0.53	39.0	39.0	0	0	0.56
CW-STES	0.132	0.132	0.0018	14.0	8.82	0.132	0.132	0.0018	14.0	9.57
ICE	0.197	0.197	0.0028	14.0	8.82	0.197	0.197	0.0028	14.0	9.57
HW-STES	2.03	20.33	0.041	2.0	2.01	2.03	20.33	0.041	2.0	1.84
UTES-heat	4.97	20.33	2.440	120.0	3.29	4.97	20.33	2.440	120.0	3.07
UTES-elec.	4.07	--	--	--	--	4.07	--	--	--	--
Firebricks	79.07	22.59	0.339	15.0	63.67	79.07	22.59	0.339	15.0	64.08
Storage technology	Madagascar (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Madagascar (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	0.40	0.40	0.006	14.0	0.08	0.40	0.40	0.006	14.0	0.05
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.05	0	--	0	0.0	0.05
Batteries	10	10	0.04	4.0	2.71	10	10	0.04	4.0	3.68
Hydropower	0.097	0.19	0.84	4,351	34.79	0.097	0.19	0.84	4,351	34.77
Base	0.073	0.073	0.63	8,638	92.50	0.073	0.073	0.63	8,638	92.50
Peaking	0.024	0.121	0.21	1,773	0.08	0.024	0.121	0.21	1,773	0.05
Grid H_2	2.10	2.10	0	0	0.04	2.10	2.10	0	0	0.03
CW-STES	0.055	0.055	0.0008	14.0	39.15	0.055	0.055	0.0008	14.0	33.69
ICE	0.082	0.082	0.0012	14.0	39.15	0.082	0.082	0.0012	14.0	33.69
HW-STES	0.25	2.48	0.005	2.0	4.09	0.25	2.48	0.005	2.0	3.21
UTES-heat	0.00	2.48	0.059	24.0	2.26	0.00	2.48	0.059	24.0	1.83
UTES-elec.	0.25	--	--	--	--	0.25	--	--	--	--
Firebricks	2.71	0.78	0.0116	15.0	95.43	2.71	0.78	0.0116	15.0	94.00
Storage technology	Mauritius (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Mauritius (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	0.10	0.10	0.0014	14.0	0.50	0.10	0.10	0.0014	14.0	0.22
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.05	0	--	0	0.0	0.05
Batteries	3.6	3.6	0.0144	4.0	6.78	3.6	3.6	0.0144	4.0	5.45
Hydropower	0.031	0.061	0.057	931	44.81	0.031	0.061	0.057	931	44.64
Base	0.029	0.029	0.042	1,438	92.50	0.029	0.029	0.042	1,438	92.50
Peaking	0.002	0.032	0.015	460	0.54	0.002	0.032	0.015	460	0.21
Grid H_2	0.7	0.7	0	0	0.32	0.7	0.7	0	0	0.15
CW-STES	0.025	0.025	0.00035	14.0	13.49	0.025	0.025	0.00035	14.0	14.67
ICE	0.038	0.038	0.00053	14.0	13.49	0.038	0.038	0.00053	14.0	14.67
HW-STES	0.077	0.773	0.0015	2.0	1.29	0.077	0.773	0.0015	2.0	1.41
UTES-heat	0.093	0.773	1.0944	1416.1	4.46	0.093	0.773	0.0185	24.0	0.97
UTES-elec.	0.077	--	--	--	--	0.077	--	--	--	--
Firebricks	0.84	0.24	0.0036	15.0	57.18	0.84	0.24	0.0036	15.0	60.15
Storage technology	Mideast (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Mideast (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	4.5	4.5	0.063	14.0	0.38	4.5	4.5	0.063	14.0	0.34
CSP-elec.	0.42	0.42	--	--	--	0.42	0.42	--	--	--
CSPS	0.67	--	0.009	22.6	10.31	0.67	--	0.009	22.6	5.50
Batteries	730	730	2.92	4.0	2.14	500	500	2.00	4.0	1.16
Hydropower	22.42	49.45	15.2	307.8	41.93	22.42	49.45	15.2	307.8	41.93
Base	22.42	22.42	15.2	679.0	92.50	22.42	22.42	15.2	679.0	92.50
Peaking	0	27.04	0	0	0	0	27.04	0	0	0
Grid H_2	50.0	50.0	0	0	0.293	50.0	50.0	0	0	0.277
CW-STES	1.22	1.22	0.0170	14.0	19.96	1.22	1.22	0.0170	14.0	21.63
ICE	1.83	1.83	0.0256	14.0	19.96	1.83	1.83	0.0256	14.0	21.63
HW-STES	70.59	78.43	0.157	2.0	7.98	70.59	78.43	0.157	2.0	9.29
UTES-heat	23.60	78.43	75.292	960.0	14.25	23.60	78.43	62.116	792.0	13.61
UTES-elec.	78.4	--	--	--	--	78.4	--	--	--	--
Firebricks	739.7	211.3	3.170	15.0	90.27	739.7	211.3	3.170	15.0	95.47

Storage technology	New Zealand (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	New Zealand (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	2.0	2.0	0.028	14.0	0.12	2.0	2.0	0.028	14.0	0.14
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.04	0	--	0	0	0.04
Batteries	30	30	0	4	1	25	25	0	4	1
Hydropower	2.79	5.68	5.1	900	43.12	2.79	5.68	5.1	900	43.22
Base	2.64	2.64	3.8	1,440	92.50	2.64	2.64	3.8	1,440	92.50
Peaking	0.15	3.04	1.3	430	0.20	0.15	3.04	1.3	430	0.38
Grid H_2	0.5	0.5	0	0	0.04	0.5	0.5	0	0	0.07
CW-STES	0.0035	0.0035	0.00005	14.0	14.87	0.0035	0.0035	0.00005	14.0	14.43
ICE	0.01	0.01	0.0001	14.0	14.87	0.01	0.01	0.0001	14.0	14.43
HW-STES	0.08	0.80	0.002	2.0	4.42	0.08	0.80	0.002	2.0	3.96
UTES-heat	0.63	0.80	0.019	24.0	2.93	0.63	0.80	0.019	24.0	2.65
UTES-elec.	0.08	--	--	--	--	0.08	--	--	--	--
Firebricks	12.35	3.53	0.053	15.0	94.64	12.35	3.53	0.053	15.0	94.18

Storage technology	Philippines (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Philippines (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	2.6	2.6	0.036	14.0	0	2.6	2.6	0.036	14.0	0
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0.05	0	--	0	0	0.05
Batteries	190	190	0.760	4.0	2.74	190	190	0.760	4.0	1.93
Hydropower	1.47	3.09	2.7	873	41.74	1.47	3.09	2.7	873	41.74
Base	1.39	1.39	2.0	1,440	92.50	1.39	1.39	2.0	1,440	92.50
Peaking	0.08	1.70	0.7	407	0.002	0.08	1.70	0.7	407	0.002
Grid H_2	6.0	6.0	0	0	0	6.0	6.0	0	0	0
CW-STES	0.64	0.64	0.0090	14.0	31.75	0.64	0.64	0.0090	14.0	33.26
ICE	0.96	0.96	0.0135	14.0	31.75	0.96	0.96	0.0135	14.0	33.26
HW-STES	8.52	21.29	0.170	8.0	10.01	8.52	21.29	0.170	8.0	10.23
UTES-heat	0.00	21.29	4.599	9.0	3.32	0.00	21.29	4.599	9.0	3.14
UTES-elec.	4.26	--	--	--	--	4.26	--	--	--	--
Firebricks	27.22	7.78	0.117	15.0	97.03	27.22	7.78	0.117	15.0	97.86

Storage technology	Russia region (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Russia region (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	10.7	10.7	0.150	14.0	0.79	10.7	10.7	0.150	14.0	0.30
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	26.01	54.02	93.2	1,725	31.84	26.01	54.02	93.2	1,725	31.83
Base	18.40	18.40	26.5	1,440	92.50	18.40	18.40	26.5	1,440	92.50
Peaking	7.61	35.62	66.7	1,872	0.50	7.61	35.62	66.7	1,872	0.48
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	1.41	1.41	0.0197	14.0	21.20	1.41	1.41	0.0197	14.0	23.00
ICE	2.11	2.11	0.0295	14.0	21.20	2.11	2.11	0.0295	14.0	23.00
HW-STES	99.51	99.51	0.199	2.0	36.97	99.51	99.51	0.199	2.0	37.16
UTES-heat	0.52	99.51	35.82	360.0	2.38	0.52	99.51	35.82	360.0	2.01
UTES-elec.	9.95	--	--	--	--	9.95	--	--	--	--
Firebricks	183.0	52.29	0.784	15.0	99.46	183.0	52.29	0.784	15.0	99.38

Storage technology	South America-NW (base) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	South America-NW (EGS) Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	8.0	8.0	0.112	14.0	27.60	8.0	8.0	0.112	14.0	24.36
CSP-elec.	0.0028	0.0028	--	--	--	0.0028	0.0028	--	--	--
CSPS	0.0045	--	0.00006	22.5	22.72	0.0045	--	0.00006	22.5	21.29
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	18.96	41.64	49.6	1,192	43.55	18.96	41.64	49.6	1,192	43.33
Base	15.91	15.91	22.9	1,440	92.50	15.91	15.91	22.9	1,440	92.50
Peaking	3.05	25.72	26.7	1,039	13.26	3.05	25.72	26.7	1,039	12.91
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	0.65	0.65	0.0091	14.0	29.80	0.65	0.65	0.0091	14.0	28.09
ICE	0.98	0.98	0.0137	14.0	29.80	0.98	0.98	0.0137	14.0	28.09
HW-STES	8.12	20.29	0.162	8.0	10.60	8.12	20.29	0.162	8.0	9.99
UTES-heat	0.03	20.29	1.461	72.0	1.51	0.03	20.29	0.974	48.0	1.25
UTES-elec.	2.03	--	--	--	--	2.03	--	--	--	--
Firebricks	66.61	19.03	0.285	15.0	99.90	66.61	19.03	0.285	15.0	99.66

Table S14.iii. Final modeled storage peak charge rates, peak discharge, peak capacities, and other statistics. Continuation of Table S14.ii. See caption of Table S14.i. for more details.

	South America-SE (base)					South America-SE (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	11.4	11.4	0.160	14.0	17.81	11.4	11.4	0.160	14.0	17.32
CSP-elec.	0.04	0.04	--	--	--	0.04	0.04	--	--	--
CSPS	0.07	--	0.001	22.6	11.98	0.07	--	0.001	22.6	11.99
Batteries	0	0	0	0	0	0	0	0	0	0
Hydropower	66.96	138.11	175.2	1,269	42.33	66.96	138.11	175.2	1,269	41.86
Base	56.19	56.19	80.9	1,440	92.50	56.19	56.19	80.9	1,440	92.50
Peaking	10.77	81.92	94.3	1,151	7.92	10.77	81.92	94.3	1,151	7.12
Grid H_2	0	0	0	0	0	0	0	0	0	0
CW-STES	2.00	2.00	0.0280	14.0	29.91	2.00	2.00	0.0280	14.0	28.04
ICE	3.00	3.00	0.0420	14.0	29.91	3.00	3.00	0.0420	14.0	28.04
HW-STES	4.90	49.05	0.049	1.0	2.75	4.90	49.05	0.049	1.0	2.52
UTES-heat	14.24	49.05	1.177	24.0	1.64	14.24	49.05	1.177	24.0	1.49
UTES-elec.	4.90	--	--	--	--	4.90	--	--	--	--
Firebricks	367.9	105.1	1.577	15.0	100.00	367.9	105.1	1.577	15.0	99.82
	Southeast Asia (base)					Southeast Asia (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	2.0	2.0	0.027	14.0	0.07	2.0	2.0	0.027	14.0	0.90
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	1,000	1,000	4.00	4.0	4.96	620	620	2.48	4.0	6.49
Hydropower	24.43	53.56	44.7	835	39.97	24.43	53.56	44.7	835	40.48
Base	23.12	23.12	33.3	1,440	92.50	23.12	23.12	33.3	1,440	92.50
Peaking	1.31	30.44	11.4	376	0.07	1.31	30.44	11.4	376	0.97
Grid H_2	150.0	150.0	0	0	0.03	150.0	150.0	0	0	0.46
CW-STES	3.26	3.26	0.0457	14.0	26.83	3.26	3.26	0.0457	14.0	24.10
ICE	4.90	4.90	0.0686	14.0	26.83	4.90	4.90	0.0686	14.0	24.10
HW-STES	127.4	141.5	0.283	2.0	9.26	127.4	141.5	0.283	2.0	8.32
UTES-heat	0.264	141.5	6.793	48.0	3.09	0.264	141.5	3.397	24.0	2.74
UTES-elec.	56.6	--	--	--	--	56.6	--	--	--	--
Firebricks	626.6	179.0	2.685	15.0	89.90	626.6	179.0	2.685	15.0	89.23
	South Korea (base)					South Korea (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	16.5	16.5	0.23	14.0	0.43	16.5	16.5	0.23	14.0	0.16
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	270	270	1.08	4.0	5.22	250	250	1.00	4.0	4.22
Hydropower	0.92	1.81	1.688	935	44.87	0.92	1.81	1.688	935	44.74
Base	0.87	0.87	1.256	1,440	92.50	0.87	0.87	1.256	1,440	92.50
Peaking	0.05	0.93	0.432	463	0.30	0.05	0.93	0.432	463	0.05
Grid H_2	100.0	100.0	0	0	0.87	100.0	100.0	0	0	0.72
CW-STES	0.192	0.192	0.0027	14.0	12.50	0.192	0.192	0.0027	14.0	13.44
ICE	0.288	0.288	0.0040	14.0	12.50	0.288	0.288	0.0040	14.0	13.44
HW-STES	22.93	22.93	0.046	2.0	8.06	22.93	22.93	0.046	2.0	7.91
UTES-heat	2.84	22.93	8.254	360.0	6.59	2.84	22.93	7.704	336.0	6.26
UTES-elec.	9.17	--	--	--	--	9.17	--	--	--	--
Firebricks	100.35	28.67	0.430	15.0	74.94	100.35	28.67	0.430	15.0	73.86
	Taiwan (base)					Taiwan (EGS)				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	9.1	9.1	0.127	14.0	0.29	9.1	9.1	0.127	14.0	0.20
CSP-elec.	0	0	--	--	--	0	0	--	--	--
CSPS	0	--	0	0	0	0	--	0	0	0
Batteries	230	230	0.92	4.0	4.58	160	160	0.64	4.0	4.89
Hydropower	1.08	2.10	1.983	942	45.22	1.08	2.10	1.983	942	45.16
Base	1.02	1.02	1.476	1,440	92.50	1.02	1.02	1.476	1,440	92.50
Peaking	0.06	1.08	0.507	470	0.30	0.06	1.08	0.507	470	0.20
Grid H_2	48.0	48.0	0	0	0.46	48.0	48.0	0	0	0.62
CW-STES	0.45	0.45	0.0063	14.0	11.39	0.45	0.45	0.0063	14.0	11.29
ICE	0.68	0.68	0.0095	14.0	11.39	0.68	0.68	0.0095	14.0	11.29
HW-STES	7.41	24.70	0.049	2.0	4.03	7.41	24.70	0.049	2.0	4.18
UTES-heat	1.27	24.70	9.485	384.0	3.20	1.27	24.70	1.186	48.0	2.28
UTES-elec.	4.94	--	--	--	--	4.94	--	--	--	--
Firebricks	91.12	26.03	0.391	15.0	68.08	91.12	26.03	0.391	15.0	70.22
	United States (base)					United States (EGS)				

Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	58.6	58.6	0.82	14.0	0.18	58.6	58.6	0.82	14.0	0.25
CSP-elec.	0.56	0.56	--	--	--	0.56	0.56	--	--	--
CSPS	0.90	--	0.013	22.6	11.01	0.90	--	0.013	22.6	9.07
Batteries	1,150	1,150	4.60	4.0	3.09	840	840	3.36	4.0	2.89
Hydropower	42.91	86.66	202.7	2,339	25.39	42.91	86.66	202.7	2,339	25.47
Base	23.66	23.66	34.1	1,440	92.50	23.66	23.66	34.1	1,440	92.50
Peaking	19.25	63.00	168.6	2,676	0.19	19.25	63.00	168.6	2,676	0.30
Grid H_2	130.0	130.0	0	0	0.07	130.0	130.0	0	0	0.11
CW-STES	3.45	3.45	0.0483	14.0	19.29	3.45	3.45	0.0483	14.0	19.30
ICE	5.17	5.17	0.0724	14.0	19.29	5.17	5.17	0.0724	14.0	19.30
HW-STES	177.8	177.8	0.356	2.0	16.55	177.8	177.8	0.356	2.0	16.81
UTES-heat	38.90	177.8	51.20	288.0	8.09	38.90	177.8	51.20	288.0	7.79
UTES-elec.	160.0	--	--	--	--	160.0	--	--	--	--
Firebricks	639.1	182.6	2.739	15.0	96.59	639.1	182.6	2.739	15.0	96.80
	All regions (base)					**All regions (EGS)**				
Storage technology	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Storage hrs at max discharge rate	Storage capacity factor (%)
PHS	568	568	7.96	14.0	1.54	568	568	7.96	14.0	1.20
CSP-elec.	5.3	5.3	--	--	--	5.3	5.3	--	--	--
CSPS	8.5	--	0.12	22.6	13.36	8.5	--	0.12	22.6	11.94
Batteries	8,070	8,070	32.28	4.0	2.98	5,854	5,854	23.42	4.0	2.98
Hydropower	611	1,262	1,588	1,259	39.76	611	1,262	1,588	1,259	39.89
Base	523	523	822	1,570	92.50	523	523	822	1,570	92.50
Peaking	88	738	767	1,038	2.38	88	738	767	1,038	2.60
Grid H_2	1,456	1,456	0	0	0.87	1,450	1,450	0	0	0.79
CW-STES	42	42	0.58	14.0	19.71	42	42	0.58	14.0	19.96
ICE	63	63	0.88	14.0	19.71	63	63	0.88	14.0	19.96
HW-STES	2,027	2,238	5.59	2.5	11.58	2,027	2,238	5.59	2.5	11.40
UTES-heat	593	2,215	731.0	330.0	6.34	593	2,215	670.4	302.6	6.09
UTES-elec.	1,526	--	--	--	--	1,526	--	--	--	--
Firebricks	7,941	2,269	34.03	15.0	92.95	7,941	2,269	34.03	15.0	93.70

PHS=pumped hydropower storage; CSP=concentrated solar power; Batteries=battery storage (BS) for grid backup; Grid H_2 is green hydrogen storage (GSH) for grid backup; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; UTES=Underground thermal energy storage in soil or water pits; and firebricks are bricks used to store low- to high-temperature heat for industrial processes. The maximum storage capacity equals the maximum discharge rate multiplied by the number of hours of storage at that rate.

CSP-elec. is the production of electricity from CSP regardless of whether CSP storage exists. Heat captured in a working fluid by a CSP solar collector can be either used immediately to produce electricity by evaporating water and running it through a steam turbine connected to a generator, stored in a phase-change material, or both. The maximum discharge rate of electricity from CSP generators is the summed nameplate capacity of the generators. The maximum charge rate of such electricity generators is limited to the maximum discharge rate.

CSPS is storage associated with CSP. The storage material is a phase-change material. CSPS is discharged for electricity production at the maximum discharge rate of CSP-elec. Thus, the maximum energy storage capacity of CSPS equals the maximum electricity discharge rate of CSP-elec. multiplied by the maximum number of hours of storage at full discharge. The maximum charge rate of CSP phase-change material storage is set to 1.612 multiplied by the maximum electricity discharge rate, which allows more energy to be collected than discharged directly as electricity. Thus, since the high temperature working fluid in the CSP plant can be used to produce electricity and charge storage at the same time, the maximum overall electricity production plus storage charge rate of energy is 2.612 multiplied by the maximum discharge rate. This ratio is also the ratio of the mirror size with storage versus without storage. This ratio can be up to 3.2 in existing CSP plants (footnote to Table S20). The maximum number of hours of storage at full discharge is 22.6 hours, or 1.612 multiplied by the 14 hours required for CSP storage to charge when charging at its maximum rate.

Hydropower's maximum discharge rate (GW) in 2050 is its 2023 nameplate capacity, and its annual energy output (TWh/y) in 2050 is close to that in 2023 in every region. Water released from a dam during hydropower production is replenished naturally with rainfall and runoff. Hydropower reservoirs contain water for energy and non-energy purposes. About 50-60% of the water in a reservoir is generally used for energy[24]. The hydropower storage capacity available for energy in all reservoirs worldwide is estimated as ~1,470 TWh, broken down as follows: North America: 370 TWh; China: 250 TWh; Latin America: 245 TWh; Europe: 215 TWh; Eurasia: 130 TWh; Africa: 125 TWh; Asia Pacific: 120 TWh; Middle East: 15 TWh (Ref. S24-Figure 4.8). The maximum hydropower storage capacity (TWh) in each country here is estimated by multiplying these regional storage capacities by the ratio of the 2023 estimated hydroelectric energy output of the country to that of the region the country falls in. The maximum storage capacity in each region is then calculated simply by summing the maximum storage capacities among all countries in the region. The maximum storage capacity and the total nameplate capacity of hydropower generators in each region are then distributed between baseload and peaking power uses by solving a set of six equations and six unknowns: (1) the sum of the maximum energy storage capacities (TWh) for baseload and peaking power equals the total maximum energy storage capacity of all reservoirs in each region, as just determined; (2) the sum of the instantaneous average charge rates (TW) of power for baseload and peaking power equals the total average charge rate of the reservoir, which equals the annual average hydropower power output (TW) of the reservoir in 2023 (which equals the 2023 energy output in TWh/y divided by 8,760 hours per year); (3) the sum of the maximum discharge rates (TW) for each baseload and peaking power equals the total nameplate capacity of all hydropower generators in the region; (4) the maximum discharge rate (TW) of baseload power from generators equals the instantaneous average charge rate of baseload power; (5) the maximum energy storage capacity (TWh) for peaking power equals the instantaneous average charge rate of peaking power (TW) multiplied by 8,760 hours per year (in other words, the peaking portion of the reservoir must be filled once per year); and (6) the maximum energy storage capacity (TWh) for baseload power equals the instantaneous average charge rate of baseload power (TWh multiplied by a designated number of hours of storage of baseload energy. Since the maximum discharge rate of baseload hydropower is assumed to equal its instantaneous average charge rate, there should be no need for baseload storage. However, in reality, discharged water for baseload power is not replenished immediately. As such, sufficient storage capacity is assigned to baseload hydropower so that, if full, baseload can supply 60 days (1,440 hours) straight of hydroelectricity without any replenishment. For Iceland and South America, 5 and 15 days, respectively, are assumed instead of 60 days. In sum, whereas baseload power is produced and discharged continuously in the model every 30 s, peaking power is also produced every 30 s but discharged only when needed due to a lack of other WWS resources available. Whereas the present table gives hydropower's maximum energy storage capacity available for each baseload and storage, hydropower's output from baseload or peaking storage during a time step is limited by the smallest among three factors: the actual energy currently available in storage for baseload or peaking, the maximum hydro discharge rate for peaking or baseload multiplied by the time step, and (in the case of peaking) the energy needed during the time step to keep the grid stable. In addition, energy in the peaking portion of reservoirs is limited by the maximum storage capacity in that portion. Thus, if peaking energy is not used fast enough, it cannot accumulate due to rainfall and runoff to more than the maximum capacity.

The CW-STES peak discharge rate is set equal to 40% of the annual average cold demand (for air conditioning and refrigeration) subject to storage, which is given in Table S7 for each region. The ICE storage discharge rate is set to 60% of the same annual average cold demand subject to storage. The peak charge rate is set equal to the peak discharge rate. Ground- and air-source heat pumps are used to produce both cold water and ice. Table S22 (footnotes) provides the cost of the heat pumps per kW-electricity consumed to charge storage.

The HW-STES peak discharge rate is set equal to the maximum instantaneous heat demand subject to storage during any 30-second period of the simulation. The values have been converted to electricity assuming the heat needed for storage is produced by heat pumps (with a coefficient of performance of 4) running on electricity. Table S22 (footnotes) provides the cost of the heat pumps per kW-electricity consumed to charge storage. Because peak discharge rates are based on maximum rather than the annual average demands, they are higher than the annual average low-temperature heat demands subject to storage in Table S7. The peak charge rate is set equal to the peak discharge rate.

UTES heat stored in soil (borehole storage) or water pits (water pit storage) can be charged with either solar or geothermal heat or excess electricity running an electric heat pump with a coefficient of performance of 4. The maximum charge rate of heat (converted to equivalent electricity) to UTES storage (UTES-heat) is set to the nameplate capacity of solar thermal collectors plus that of geothermal heat, all divided by the coefficient of performance of a heat pump (=4). When no solar thermal collectors or geothermal heat is used, the maximum charge rate for UTES-heat is zero, and UTES is charged only with excess grid electricity running heat pumps. The maximum charge rate of UTES storage using excess grid electricity (UTES-elec.) is set equal to the maximum instantaneous heat demand subject to storage during any 30-second period of the two-year simulation. The maximum UTES heat discharge rate is set equal to the maximum instantaneous heat demand subject to storage. The maximum charge rate, discharge rate, and capacity of UTES storage are all in units of equivalent electricity that would give heat at a coefficient of performance of 4. Table S22 (footnotes) provides the cost of the heat pumps per kW-electricity consumed to charge storage with electricity.

Grid H_2. The storage capacity and storage duration of green hydrogen storage (GHS) for grid electricity storage are set to zero in this table because hydrogen production and storage for grid and non-grid purposes are merged in this study. In such a case, the storage time depends on the discharge rate of both grid and non-grid hydrogen. Table S17 provides the storage time of grid hydrogen as if it is the only hydrogen stored and discharged and the storage time of non-grid hydrogen as if it is the only hydrogen stored and discharged.

Firebricks are modeled after the RHB300 heat battery of from Rondo[6]. Each battery has a peak charge rate of 70 MW-AC-electricity, peak discharge rate of 20 MW-thermal, energy storage capacity of 300 MWh-thermal, storage time at the peak discharge rate of 15 h, round-trip efficiency of 98%, land a heat loss rate from storage of 1% per day. The cost is estimated by Rondo to be 1/10th that of battery electricity per kWh storage. The RHB300 provides heat output as hot air, nominally from 80ºC to 1,100ºC. This range is extended to 1,800ºC assuming low-cost direct resistance heating of firebricks[S45,S46].

Table S15. Long-distance transmission and district heating/cooling assumptions in the model. (a) and (c) HVDC line length needed in each region; (b) and (d) HVDC line capacity needed in each region; (e) fraction of non-roof PV and non-curtailed energy use that is subject to HVDC transmission in each region; and (f) the fraction of building heating and cooling demand that is subject to district heating and cooling in each region in the base-WWS case and EGS cases.

	Base-WWS case		EGS case		Base and EGS cases	
Region	(a) HVDC line length (km)	(b) HVDC line capacity (MW)	(c) HVDC line length (km)	(d) HVDC line capacity (MW)	(e) Fraction of non-roof PV/non-curtailed electricity subject to HVDC	(f) Fraction of building heating/ cooling subject to district heating/ cooling
Africa-East	2,563	31,974	2,529	32,057	0.3	0.1
Africa-North	2,770	70,409	2,795	70,353	0.3	0.1
Africa-South	3,178	49,857	3,091	49,850	0.3	0.1
Africa-West	2,386	40,780	2,391	40,708	0.3	0.1
Australia	2,947	41,492	2,967	41,522	0.3	0.1
Canada	2,592	102,197	3,169	100,142	0.3	0.2
Central America	2,874	46,166	2,911	46,198	0.2	0.1
Central Asia	2,712	73,481	2,688	73,650	0.3	0.01
China region	2,835	1,446,445	2,896	1,442,851	0.3	0.3
Cuba	0	0	0	0	0	0.2
Europe	3,005	495,990	3,038	491,828	0.3	0.5
Haiti region	0	0	0	0	0	0.05
Iceland	0	0	0	0	0	0.92
India region	3,024	501,814	2,970	502,247	0.3	0.1
Israel	0	0	0	0	0	0.2
Jamaica	0	0	0	0	0	0
Japan	3,068	73,764	3,085	73,677	0.2	0.1
Madagascar	0	0	0	0	0	0.1
Mauritius	0	0	0	0	0	0.2
Mideast	3,097	378,294	3,009	379,472	0.3	0.05
New Zealand	2,449	3,928	2,670	3,889	0.15	0.05
Philippines	2,125	11,398	2,172	11,303	0.2	0.2
Russia region	3,055	171,545	3,088	171,353	0.3	0.5
South Am-NW	3,361	49,743	3,399	49,663	0.3	0.1
South Am-SE	3,076	165,027	3,192	164,342	0.3	0.1
Southeast Asia	2,760	241,841	2,878	240,795	0.3	0.1
South Korea	0	0	0	0	0	0.15
Taiwan	0	0	0	0	0	0.15
United States	2,537	557,677	2,646	554,461	0.3	0.2
All regions	**56,413**	**4,553,820**	**57,584**	**4,540,358**		

The capital cost of HVDC transmission is the product of Columns (a), (b) or (c), (d) and $400/MW-km[8].

Table S16a. Modeled base-WWS-case battery-storage characteristics. (a) Battery maximum charge and discharge rate (nameplate capacity); (b) battery storage capacity (batteries are all 4-hour batteries); (c) battery full charge and discharge cycles per year; (d) maximum battery discharge rate actually occurring during any time interval of each simulation; and (e) R_{ideal}, the number of hours of battery storage actually needed for each simulation, which equals the ratio of the battery storage capacity to the peak actual discharge rate during a simulation. The battery peak discharge rate during a simulation is always less than or equal to the battery nameplate capacity (maximum possible discharge rate) from column (a).

Region	(a) Battery max charge and dis-charge rate (GW)	(b) Battery capacity (TWh)	(c) Battery full cycles/year	(d) Battery peak actual discharge rate during simulation (TW)	(e) R_{ideal}=Ratio of battery storage capacity (TWh) to battery peak actual discharge rate (TW) during simulation (hours) = b / d
Africa-East	320	1.28	21.5	0.147	8.7
Africa-North	130	0.52	43.5	0.110	4.7
Africa-South	240	0.96	109.1	0.098	9.8
Africa-West	400	1.6	10.6	0.109	14.7
Australia	110	0.44	47.5	0.057	7.8
Canada	0	0	0	0	0.0
Central America	120	0.48	68.2	0.084	5.7
Central Asia	24	0.096	91.0	0.024	4.0
China region	940	3.76	31.3	0.940	4.0
Cuba	41	0.164	37.7	0.007	23.7
Europe	1	0.004	194.3	0.001	4.0
Haiti region	0	0	0	0	0.0
Iceland	0	0	0	0	0.0
India region	1,850	7.4	75.2	0.909	8.1
Israel	98	0.392	88.6	0.017	23.7
Jamaica	12.5	0.05	50.5	0.004	11.3
Japan	170	0.68	83.3	0.132	5.2
Madagascar	10	0.04	62.7	0.005	8.7
Mauritius	3.6	0.0144	157.0	0.001	10.0
Mideast	730	2.92	49.7	0.438	6.7
New Zealand	30.0	0.12	19.4	0.014	8.6
Philippines	190	0.76	63.5	0.070	10.8
Russia region	0	0	0	0	0
South Am-NW	0	0	0	0	0
South Am-SE	0	0	0	0	0
Southeast Asia	1,000	4	115.0	0.461	8.7
South Korea	270	1.08	121.0	0.147	7.4
Taiwan	230	0.92	106.2	0.083	11.0
United States	1,150	4.6	71.5	0.680	6.8
All regions	**8,070**	**32.28**		**4.538**	**7.1**

Table S16b. Modeled EGS-cases battery-storage characteristics. (a) Battery maximum charge and discharge rate (nameplate capacity); (b) battery storage capacity (batteries are all 4-hour batteries); (c) battery full charge and discharge cycles per year; (d) maximum battery discharge rate actually occurring during any time interval of each simulation; and (e) R_{ideal}, the number of hours of battery storage actually needed for each simulation, which equals the ratio of the battery storage capacity to the peak actual discharge rate during a simulation. The battery peak discharge rate during a simulation is always less than or equal to the battery nameplate capacity (maximum possible discharge rate) from column (a).

Region	(a) Battery max charge and dis-charge rate (GW)	(b) Battery capacity (TWh)	(c) Battery full cycles/year	(d) Battery peak actual discharge rate during simulation (TW)	(e) R_{ideal}=Ratio of battery storage capacity (TWh) to battery peak actual discharge rate (TW) during simulation (hours) = b / d
Africa-East	200	0.8	27.9	0.126	6.4
Africa-North	91	0.364	47.0	0.077	4.7
Africa-South	200	0.8	94.0	0.092	8.7
Africa-West	400	1.6	9.9	0.105	15.2
Australia	67	0.268	50.1	0.051	5.2
Canada	0	0	0	0	0
Central America	28	0.112	115.5	0.028	4.0
Central Asia	10	0.04	94.8	0.010	4.0
China region	780	3.12	25.9	0.780	4.0
Cuba	30	0.12	37.9	0.006	18.9
Europe	1	0.004	178.7	0.001	4.0
Haiti region	0	0	0	0	0
Iceland	0	0	0	0	0
India region	1,200	4.8	89.1	0.918	5.2
Israel	91	0.364	78.7	0.015	23.9
Jamaica	12.5	0.05	46.9	0.004	11.7
Japan	145	0.58	84.0	0.122	4.8
Madagascar	10	0.04	85.2	0.005	7.3
Mauritius	3.6	0.0144	126.1	0.002	9.4
Mideast	500	2	26.8	0.384	5.2
New Zealand	25.0	0.1	18.1	0.013	7.6
Philippines	190	0.76	44.6	0.056	13.6
Russia region	0	0	0	0	0
South Am-NW	0	0	0	0	0
South Am-SE	0	0	0	0	0
Southeast Asia	620	2.48	150.2	0.410	6.1
South Korea	250	1	97.8	0.133	7.5
Taiwan	160	0.64	113.3	0.075	8.5
United States	840	3.36	67.0	0.604	5.6
All regions	**5,854**	**23.42**		**4.017**	**5.8**

Table S17a. Modeled hydrogen system characteristics in the base-WWS case. (a) Annual hydrogen production for non-grid purposes; (b) annual hydrogen production for grid purposes; (c) electrolyzer plus compressor nameplate capacity (electrolyzers make up 88.03% of the total); (d) electrolyzer and compressor use factor, averaged over simulation; (e) storage time of hydrogen in communal storage tank if non-grid hydrogen is the only hydrogen stored and discharged (at the same rate as non-grid hydrogen production) in the storage tank; (f) size of communal hydrogen storage tank; (g) nameplate capacity of fuel cells used for producing grid electricity; (h) fuel cell use factor; (i) hours of electricity storage in the communal hydrogen storage tank as if grid hydrogen is the only hydrogen stored and discharge (at the peak discharge rate of the fuel cells); and (j) usable (non-waste) electricity storage capacity in the communal hydrogen storage tank if hydrogen were used only for electricity.

	Non-grid plus grid hydrogen						Grid hydrogen			
Region	(a) Non-grid H_2 produced ($Tg-H_2/y$)	(b) Grid H_2 produced ($Tg-H_2/y$)	(c) Electrolyzer plus compressor nameplate capacity (GW)	(d) Use factor of electrolyzer and compressor (frac)	(e) Grid plus non-grid H_2 storage times (days) = 365 days * f/a	(f) H_2 tank size (Tg)	(g) Fuel cell for grid electricity nameplate capacity (GW)	(h) Use factor of fuel cell (frac)	(i) Hours of electricity storage in H_2 tank if H_2 used only for electricity= j*1000/g	(j) Electricity storage capacity in H_2 tank if H_2 were used only for electricity (TWh)
Africa-East	0.86	0	30.7	0.15	1	0.0024	0	0	0	0.05
Africa-North	4.54	0.03	162.8	0.15	4	0.0498	15	0.0052	70	1.05
Africa-South	1.59	0.022	56.9	0.15	14	0.0608	29	0.0018	44	1.28
Africa-West	1.15	0.004	41.4	0.15	7	0.0221	25	0.00035	19	0.47
Australia	1.59	0	56.90	0.15	2	0.0087	0	0	0	0.18
Canada	2.52	0	90.37	0.15	50	0	0	0	0	7
Central America	2.01	0	72.20	0.15	22	0.1214	0	0	0	2.56
Central Asia	2.49	0.20	89.09	0.16	6	0.0409	21	0.022	41	0.86
China region	65.93	0.96	2,363	0.15	5	0.9031	440	0.005	43	19.1
Cuba	0.04	0	1.43	0.15	1	0.0001	0	0	0	0.002
Europe	22.13	8.90	793.3	0.21	31	1.8798	160	0.134	248	39.7
Haiti region	0.14	0.14	5.10	0.29	102	0.0397	4	0.083	210	0.84
Iceland	0.022	0	0.12	1.00	0	0	0	0	0	0
India region	17.97	0.08	644.3	0.15	10	0.4924	230	0.0008	45	10.4
Israel	0.16	0.0002	6.00	0.14	22	0.0094	6	0.00008	33	0.20
Jamaica	0.050	0	1.79	0.15	18	0.0025	0	0	0	0.052
Japan	5.45	0.19	195.5	0.16	16	0.2390	39	0.012	129	5.05
Madagascar	0.032	0.0007	2.1	0.08	10	0.0009	2	0.0008	9	0.019
Mauritius	0.049	0.0021	1.76	0.16	19	0.0026	1	0.007	77	0.05
Mideast region	13.81	0.14	495.1	0.15	9	0.3406	50	0.007	144	7.19
New Zealand	0.23	0.00019	8.21	0.15	3	0.0019	1	0.0009	79	0.040
Philippines	0.69	0.00005	24.79	0.15	5	0.0095	6	0.00002	33	0.20
Russia	8.85	0	260.6	0.18	18	0.4365	0	0	0	9.22
South Am-NW	2.46	0	88.3	0.15	1	0.0068	0	0	0	0.14
South Am-SE	6.34	0	227.2	0.15	10	0.1737	0	0	0	3.67
Southeast Asia	11.22	0.05	402.0	0.15	4	0.1229	150	0.0008	17	2.60
South Korea	4.18	0.81	149.7	0.18	41	0.4691	100	0.0194	99	9.91
Taiwan	1.45	0.21	51.93	0.17	79	0.3136	48	0.0103	138	6.62
United States	13.99	0.09	501.6	0.15	3	0.1150	130	0.0016	19	2.4
All regions	**191.94**	**11.80**	**6,824**	**0.161**		**6.210**	**1,456**	**0.0195**	**90**	**131.2**

*Usable electricity storage capacity equals hydrogen tank storage capacity from Column (f) multiplied by the higher heating value of hydrogen (39.39 kWh/kg-H_2) and by 0.536 (Table S21), which equals the product of the fuel cell efficiency (0.65), the latent heat loss efficiency (0.846), and the DC to AC conversion efficiency (0.975). When a region has no hydrogen storage but has electrolyzers and compressors, the hydrogen is being produced on demand by electricity, so no storage is required.

Table S17b. Modeled hydrogen system characteristics in the EGS cases. (a) Annual hydrogen production for non-grid purposes; (b) annual hydrogen production for grid purposes; (c) electrolyzer plus compressor nameplate capacity (electrolyzers make up 88.03% of the total); (d) electrolyzer and compressor use factor, averaged over simulation; (e) storage time of hydrogen in communal storage tank if non-grid hydrogen is the only hydrogen stored and discharged (at the same rate as non-grid hydrogen production) in the storage tank; (f) size of communal hydrogen storage tank; (g) nameplate capacity of fuel cells used for producing grid electricity; (h) fuel cell use factor; (i) hours of electricity storage in the communal hydrogen storage tank as if grid hydrogen is the only hydrogen stored and discharge (at the peak discharge rate of the fuel cells); and (j) usable (non-waste) electricity storage capacity in the communal hydrogen storage tank if hydrogen were used only for electricity.

	Non-grid plus grid hydrogen						Grid hydrogen			
Region	(a) Non-grid H_2 produced (Tg-H_2/y)	(b) Grid H_2 produced (Tg-H_2/y)	(c) Electrolyzer plus compressor nameplate capacity (GW)	(d) Use factor of electrolyzer and compressor (frac)	(e) Grid plus non-grid H_2 storage times (days) = 365 days *f/a	(f) H_2 tank size (Tg)	(g) Fuel cell for grid electricity nameplate capacity (GW)	(h) Use factor of fuel cell (frac)	(i) Hours of electricity storage in H_2 tank if H_2 used only for electricity= j*1000/g	(j) Electricity storage capacity in H_2 tank if H_2 were used only for electricity (TWh)
Africa-East	0.86	0	30.7	0.15	1	0.0024	0	0	0	0.05
Africa-North	4.54	0.03	162.8	0.15	4	0.0498	9	0.0074	117	1.05
Africa-South	1.59	0.009	56.9	0.15	4	0.0174	29	0.0008	13	0.37
Africa-West	1.15	0.007	41.4	0.15	7	0.0221	25	0.0007	19	0.47
Australia	1.59	0.000	56.90	0.15	2	0.0087	0	0	0	0.18
Canada	2.52	0	90.37	0.15	30	0	0	0	0	4
Central America	2.01	0	72.20	0.15	22	0.1214	0	0	0	2.56
Central Asia	2.49	0.24	89.09	0.16	6	0.0409	21	0.0274	41	0.86
China region	65.93	1.60	2,363	0.15	5	0.9031	440	0.0087	43	19.1
Cuba	0.04	0	1.43	0.15	1	0.0001	0	0	0	0.002
Europe	22.13	6.44	793.3	0.19	31	1.8798	160	0.0968	248	39.7
Haiti region	0.14	0.11	5.10	0.27	40	0.0156	4	0.0659	82	0.33
Iceland	0.022	0	0.12	1.00	0	0	0	0	0	0
India region	17.97	0.16	644.3	0.15	10	0.4924	230	0.0016	45	10.4
Israel	0.16	0.0000	6.00	0.14	20	0.0085	6	0	30	0.18
Jamaica	0.050	0	1.79	0.15	18	0.0025	0	0	0	0.052
Japan	5.45	0.20	195.5	0.16	16	0.2390	39	0.0125	129	5.05
Madagascar	0.032	0.0006	2.1	0.08	10	0.0009	2	0.0007	9	0.019
Mauritius	0.049	0.0010	1.76	0.15	16	0.0022	1	0.0034	65	0.05
Mideast region	13.81	0.13	495.1	0.15	4	0.1514	50	0.0062	64	3.20
New Zealand	0.23	0.00030	8.21	0.15	3	0.0019	1	0.0015	79	0.040
Philippines	0.69	0.00005	24.79	0.15	5	0.0095	6	0.00002	33	0.20
Russia	8.85	0	234.8	0.20	18	0.4365	0	0	0	9.22
South Am-NW	2.46	0	88.3	0.15	1	0.0068	0	0	0	0.14
South Am-SE	6.34	0	227.2	0.15	4	0.0695	0	0	0	1.47
Southeast Asia	11.22	0.64	402.0	0.16	4	0.1229	150	0.0102	17	2.60
South Korea	4.18	0.67	149.7	0.17	41	0.4691	100	0.0162	99	9.91
Taiwan	1.45	0.28	51.93	0.18	79	0.3136	48	0.0140	138	6.62
United States	13.99	0.13	501.6	0.15	3	0.1150	130	0.0025	19	2.4
All regions	**191.94**	**10.65**	**6,798**	**0.16**		**5.710**	**1,450**	**0.0176**	**83**	**120.6**

*Usable electricity storage capacity equals hydrogen tank storage capacity from Column (f) multiplied by the higher heating value of hydrogen (39.39 kWh/kg-H_2) and by 0.536 (Table S21), which equals the product of the fuel cell efficiency (0.65), the latent heat loss efficiency (0.846), and the DC to AC conversion efficiency (0.975). When a region has no hydrogen storage but has electrolyzers and compressors, the hydrogen is being produced on demand by electricity, so no storage is required.

Table S18a. Verification of energy conservation in LOATMATCH by region in the base-WWS case. Budget of simulation-averaged end-use power demand met, energy lost, WWS energy supplied, and changes in storage, during the three-year (26,291.4875 hour) simulations for each region and summed for all regions. All units are GW averaged over the simulation and are derived from the data in Table S19a by dividing values from that table in units of TWh per simulation by the number of hours of simulation. TD&M losses are transmission, distribution, and maintenance losses. Wind turbine array losses are already accounted for in the "WWS supply before losses" numbers," since wind supply values come from GATOR-GCMOM, which accounts for such losses.

Region	(a) Annual average end-use demand (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Curtail-ment losses (GW)	**(e) End-use demand+ losses =a+b+c+d (GW)**	(f) WWS supply before losses (GW)	(g) Changes in storage (GW)	**(h) Supply +chan-ges in storage =f+g (GW)**
Africa-East	66.95	6.12	4.55	22.47	**100.1**	99.8	0.321	**100.1**
Africa-North	162.22	13.37	2.28	45.88	**223.8**	223.7	0.029	**223.8**
Africa-South	113.80	7.87	3.87	11.20	**136.7**	136.8	-0.033	**136.7**
Africa-West	92.76	8.87	4.93	42.07	**148.6**	148.5	0.166	**148.6**
Australia	84.65	7.02	1.01	17.02	**109.7**	109.7	-0.003	**109.7**
Canada	163.32	17.44	1.12	58.74	**240.6**	240.7	-0.062	**240.6**
Central America	136.83	11.70	2.09	31.27	**181.9**	181.9	0.004	**181.9**
Central Asia	156.78	13.68	3.65	46.98	**221.1**	220.8	0.257	**221.1**
China region	2,625.6	237.39	87.84	593.84	**3,544.6**	3,538.1	6.515	**3,544.6**
Cuba	5.71	0.48	0.20	1.99	**8.38**	8.4	0.003	**8.38**
Europe	872.68	75.55	43.25	125.35	**1,116.8**	1,109.3	7.521	**1,116.8**
Haiti region	8.28	0.87	0.48	3.95	**13.57**	13.58	-0.006	**13.57**
Iceland	2.91	0.29	0.00	0.67	**3.87**	3.87	0.000	**3.87**
India region	1,055.8	82.30	32.83	163.92	**1,334.9**	1,333.8	1.062	**1,334.9**
Israel	13.03	1.58	0.71	8.77	**24.10**	24.07	0.030	**24.10**
Jamaica	1.88	0.13	0.05	0.45	**2.51**	2.51	0.002	**2.51**
Japan	174.71	15.94	2.28	24.62	**217.54**	217.50	0.041	**217.54**
Madagascar	3.81	0.57	0.13	4.18	**8.69**	8.69	0.000	**8.69**
Mauritius	1.54	0.13	0.06	0.15	**1.87**	1.83	0.037	**1.87**
Mideast	698.74	56.96	16.51	91.46	**863.7**	861.9	1.809	**863.7**
New Zealand	14.10	1.52	0.14	6.24	**22.00**	22.0	0.000	**22.00**
Philippines	37.19	4.21	1.85	23.71	**66.96**	66.9	0.106	**66.96**
Russia region	269.90	24.30	11.05	31.77	**337.02**	337.4	-0.430	**337.02**
South Am-NW	90.64	6.82	1.78	3.78	**103.03**	103.0	0.002	**103.03**
South Am-SE	354.96	26.68	4.32	54.79	**440.75**	440.7	0.001	**440.75**
Southeast Asia	578.51	46.41	16.29	159.72	**800.93**	800.7	0.231	**800.93**
South Korea	144.28	13.89	6.07	46.07	**210.31**	209.2	1.081	**210.31**
Taiwan	84.77	6.86	3.01	13.07	**107.71**	107.4	0.333	**107.71**
United States	945.42	99.41	26.53	352.23	**1,423.6**	1,423.7	-0.146	**1,423.6**
All regions	8,961.8	788.4	278.9	1,986.4	**12,015**	11,996	18.871	**12,015**

Table S18b. Verification of energy conservation in LOATMATCH by region in the EGS cases. Budget of simulation-averaged end-use power demand met, energy lost, WWS energy supplied, and changes in storage, during the three-year (26,291.4875 hour) simulations for each region and summed for all regions. All units are GW averaged over the simulation and are derived from the data in Table S19b by dividing values from that table in units of TWh per simulation by the number of hours of simulation. TD&M losses are transmission, distribution, and maintenance losses. Wind turbine array losses are already accounted for in the "WWS supply before losses" numbers," since wind supply values come from GATOR-GCMOM, which accounts for such losses.

Region	(a) Annual average end-use demand (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Curtail-ment losses (GW)	**(e) End-use demand+ losses =a+b+c+d (GW)**	(f) WWS supply before losses (GW)	(g) Changes in storage (GW)	**(h) Supply +changes in storage =f+g (GW)**
Africa-East	66.95	6.22	4.51	23.74	**101.4**	101.1	0.298	**101.4**
Africa-North	162.22	13.22	2.15	44.16	**221.8**	221.7	0.034	**221.8**
Africa-South	113.80	8.16	3.56	15.09	**140.6**	140.6	-0.026	**140.6**
Africa-West	92.76	8.85	4.84	41.90	**148.3**	148.2	0.171	**148.3**
Australia	84.65	6.97	0.93	16.43	**109.0**	109.0	-0.002	**109.0**
Canada	163.32	14.16	1.01	18.34	**196.8**	196.9	-0.038	**196.8**
Central America	136.83	11.53	1.98	29.19	**179.5**	179.5	0.005	**179.5**
Central Asia	156.78	13.83	3.73	48.70	**223.0**	222.8	0.260	**223.0**
China region	2,625.6	231.74	86.22	526.47	**3,470.0**	3,462.8	7.227	**3,470.0**
Cuba	5.71	0.46	0.18	1.85	**8.21**	8.2	0.003	**8.21**
Europe	872.68	74.65	35.43	121.04	**1,103.8**	1,097.3	6.483	**1,103.8**
Haiti region	8.28	0.85	0.40	3.76	**13.28**	13.28	-0.002	**13.28**
Iceland	2.91	0.29	0.00	0.67	**3.87**	3.87	0.000	**3.87**
India region	1,055.8	84.12	31.76	187.47	**1,359.2**	1,358.1	1.109	**1,359.2**
Israel	13.03	1.45	0.63	7.18	**22.29**	22.26	0.030	**22.29**
Jamaica	1.88	0.13	0.05	0.43	**2.49**	2.49	0.002	**2.49**
Japan	174.71	15.85	2.15	23.67	**216.37**	216.32	0.047	**216.37**
Madagascar	3.81	0.48	0.12	3.01	**7.42**	7.42	0.000	**7.42**
Mauritius	1.54	0.13	0.04	0.16	**1.87**	1.87	0.001	**1.87**
Mideast	698.74	58.86	15.60	115.29	**888.5**	887.2	1.326	**888.5**
New Zealand	14.10	1.38	0.13	4.56	**20.17**	20.2	0.001	**20.17**
Philippines	37.19	4.10	1.66	22.56	**65.51**	65.4	0.093	**65.51**
Russia region	269.90	24.03	10.80	28.73	**333.45**	333.9	-0.430	**333.45**
South Am-NW	90.64	6.73	1.65	2.83	**101.85**	101.9	-0.004	**101.85**
South Am-SE	354.96	25.49	4.19	40.31	**424.95**	424.8	0.110	**424.95**
Southeast Asia	578.51	43.94	16.23	129.23	**767.90**	767.7	0.155	**767.90**
South Korea	144.28	13.15	5.18	37.67	**200.29**	199.3	0.983	**200.29**
Taiwan	84.77	6.76	2.85	11.75	**106.14**	106.1	0.030	**106.14**
United States	945.42	94.99	25.10	299.07	**1,364.6**	1,364.8	-0.225	**1,364.6**
All regions	8,961.8	772.5	263.1	1,805.2	**11,803**	11,785	17.641	**11,803**

Table S19a.i. Detailed base-WWS-case verification of LOADMATCH energy conservation by region. Budgets of total end-use energy demand met, energy lost, WWS energy supplied, and changes in storage, during the 26,291.4875-h (3 y) simulation, by region, and summed over all regions. Units are TWh over the simulation. Divide by hours of simulation to obtain simulation-averaged power values.

	Africa-East	Africa-North	Africa-South	Africa-East	Australia
A1. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for electricity inflexible demand	700	1,887	1,560	873	1,075
Electricity for electricity, heat, cold storage + DR	939	1,735	1,208	1,402	926
Electricity for H_2 direct use + H_2 storage	121	642	224	163	224
A2. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for direct use, electricity storage, + H_2	1,074	3,324	2,337	1,513	1,660
Low-T heat demand met by heat storage	239	111	113	241	27
Cold demand met by cold storage	6.05	12.04	11.66	8.00	2.13
Hi-T heat demand met by firebrick storage	440.48	818.91	530.80	676.79	536.35
A3. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for direct use, electricity storage, DR	929	2,507	1,909	1,299	1,371
Electricity for H_2 direct use + H_2 storage	121	642	224	163	224
Electricity + heat for heat subject to storage	244	189	118	263	71
Electricity for cold demand subject to storage	14.14	48.87	58.80	19.29	9.07
Hi-T heat from electricity + firebrick storage	452.29	877.68	682.23	694.16	549.65
B. Total losses	**871**	**1,618**	**603**	**1,469**	**659**
Transmission, distribution, downtime losses	161	352	207	233	185
Losses CSP storage	0.00	0.00	0.01	0.00	0
Losses PHS storage	0.00	0.15	0.16	0.01	0.0273
Losses battery storage	9	8	35	6	7.0
Losses grid H_2 storage	0	3	2	0	0
Losses CW-STES + ICE storage	1	2	2	1	0.4
Losses HW-STES storage	31	20	12	29	1.7
Losses UTES storage	68	7	38	76	4.1
Losses firebrick storage	11	20	13	17	13
Losses from curtailment	591	1,206	294	1,106	448
Net end-use demand plus losses (A1 + B)	***2,632***	***5,883***	***3,595***	***3,908***	***2,884***
C. Total WWS supply before T&D losses	**2,623**	**5,882**	**3,596**	**3,904**	**2,884**
Onshore + offshore wind electricity	960	3,144	1,427	1,887	1,323
Rooftop + utility PV+ CSP electricity	1,512	2,689	2,054	1,927	1,425
Hydropower electricity	79.1	41.0	104.9	87.7	105.5
Wave electricity	0.31	0.86	1.34	1.26	1.14
Geothermal electricity	72.0756	0.0227	1.9754	0	9.5047
Tidal electricity	0.3809	0.793	0.4462	0.5685	1.1426
Solar heat	0	4.2466	5.49	0.0561	18.1176
Geothermal heat	0.2942	2.4231	0.0327	0.01	1.3416
D. Net taken from (+) or added to (-) storage	**8.4269**	**0.7699**	**-0.8612**	**4.3627**	**-0.0658**
CSP storage	0	0	0.0004	0	0
PHS storage	-0.0056	-0.0079	-0.019	-0.0056	-0.0309
Battery storage	-0.1194	-0.052	0.1054	0.0496	-0.11
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0068	-0.0021	0.0282	0.0092	0.0036
HW-STES storage	0.0817	0.0508	-0.0071	0.0575	-0.004
UTES storage	8.3242	0.6099	-0.9051	4.1373	-0.05
Firebrick storage	0.041	0.3224	0.1592	0.1848	0.0219
Non-grid H_2 storage	0.0983	-0.1512	-0.2233	-0.0701	0.1036
Energy supplied plus taken from storage (C+D)	***2,632***	***5,883***	***3,595***	***3,908***	***2,884***

	Canada	Central America	Central Asia	China region	Cuba
A1. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for electricity inflexible demand	2,145	1,578	1,956	27,678	72
Electricity for electricity, heat, cold storage + DR	1,792	1,735	1,815	32,034	73
Electricity for H_2 direct use + H_2 storage	356	285	351	9,319	6
A2. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for direct use, electricity storage, + H_2	3,393	2,624	2,955	46,742	99
Low-T heat demand met by heat storage	58	56	178	4,832	6
Cold demand met by cold storage	1.99	10.95	1.98	175.37	1.82
Hi-T heat demand met by firebrick storage	841.02	906.70	986.81	17,280.97	43.06
A3. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for direct use, electricity storage, DR	2,740	2,217	2,574	35,953	82
Electricity for H_2 direct use + H_2 storage	356	285	351	9,319	6

Electricity + heat for heat subject to storage	239	130	190	5,119	8
Electricity for cold demand subject to storage	17.26	34.56	7.56	996.89	6.40
Hi-T heat from electricity + firebrick storage	941.05	931.38	999.71	17,642.13	48.51
B. Total losses	**2,032**	**1,185**	**1,691**	**24,164**	**70**
Transmission, distribution, downtime losses	459	308	360	6,241	13
Losses CSP storage	0.00	0.00	0.00	0.03	0.00
Losses PHS storage	0.3096	0.1308	0.5606	2.7073	0.0012
Losses battery storage	0.00	10.9	2.9	39	2.06
Losses grid H_2 storage	0	0	15	75	0
Losses CW-STES + ICE storage	0.36	2.0	0.4	32	0.33
Losses HW-STES storage	7	5.9	30.4	430	1.10
Losses UTES storage	0	13.3	21.3	1,304	0.66
Losses firebrick storage	22	23	25	427	1
Losses from curtailment	1,544	822	1,235	15,613	52
Net end-use demand plus losses (A1 + B)	***6,326***	***4,782***	***5,813***	***93,194***	***220***
C. Total WWS supply before T&D losses	**6,328**	**4,782**	**5,806**	**93,023**	**220**
Onshore + offshore wind electricity	4,889	2,198	3,216	42,270	70
Rooftop + utility PV+ CSP electricity	598	2,170	2,376	44,215	149
Hydropower electricity	696.5	211.7	212.5	4,896.4	0.8
Wave electricity	1.74	1.73	1.10	30.88	0.08
Geothermal electricity	113.2666	185.8964	0	43.8315	0
Tidal electricity	1.740	0.839	0.117	13.214	0.080
Solar heat	2.2511	10.9574	0	975.7811	0
Geothermal heat	26.0254	2.3516	0.0416	577.4566	0
D. Net taken from (+) or added to (-) storage	**-1.6426**	**0.0981**	**6.7561**	**171.3008**	**0.0855**
CSP storage	0	0	0	-0.004	0
PHS storage	-0.0011	-0.0084	0.1028	-0.2496	-0.0042
Battery storage	0	-0.048	0.0864	-0.376	0.0235
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	-0.0009	-0.0018	0.0003	-0.0359	0.0031
HW-STES storage	0.0399	0.0601	0.25	1.829	0.0084
UTES storage	0	0.7213	4.7752	166.7861	0.0251
Firebrick storage	-0.0537	-0.0531	0.5133	7.568	0.0249
Non-grid H_2 storage	-1.6267	-0.5718	1.028	-4.2167	0.0046
Energy supplied plus taken from storage (C+D)	***6,326***	***4,782***	***5,813***	***93,194***	***220***

	Europe	Haiti region	Iceland	India region	Israel
A1. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for electricity inflexible demand	10,814.0	105	38	10,949	184
Electricity for electricity, heat, cold storage + DR	9,001.4	92	36	14,269	137
Electricity for H_2 direct use + H_2 storage	3,128.7	20	3	2,541	22
A2. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for direct use, electricity storage, + H_2	18,639.0	167	63	17,183	288
Low-T heat demand met by heat storage	1,727.3	0	14	997	19
Cold demand met by cold storage	30.77	0.90	0.00	66.30	0.75
Hi-T heat demand met by firebrick storage	2,547.10	49.03	0.08	9,512.81	34.69
A3. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for direct use, electricity storage, DR	12,988.1	135	29	13,749	251
Electricity for H_2 direct use + H_2 storage	3,128.7	20	3	2,541	22
Electricity + heat for heat subject to storage	3,021.4	9	14	1,005	21
Electricity for cold demand subject to storage	319.87	2.22	0.00	314.98	4.46
Hi-T heat from electricity + firebrick storage	3,486.07	51.82	30.71	10,149.16	44.15
B. Total losses	**6,419**	**139**	**25**	**7,337**	**291**
Transmission, distribution, downtime losses	1,986.33	23	8	2,164	42
Losses CSP storage	0.0087	0.00	0.00	0.20	0.00
Losses PHS storage	22	0.1144	0.0000	0.1339	0.00
Losses battery storage	0	0.0	0.00	185	12
Losses grid H_2 storage	696	11	0	6	0
Losses CW-STES + ICE storage	6	0.2	0.00	11.98	0.14
Losses HW-STES storage	206	0.0	0.00	111.39	2
Losses UTES storage	145	0.4	0.00	321.60	5
Losses firebrick storage	63	1	0	227	1
Losses from curtailment	3,295.6	103.7	17.5	4,310	230
Net end-use demand plus losses (A1 + B)	***29,363.1***	***356.7***	***101.7***	***35,096***	***634***
C. Total WWS supply before T&D losses	**29,165.4**	**357**	**102**	**35,068**	**633**
Onshore + offshore wind electricity	14,554.2	206	9	10,558	62

Rooftop + utility PV+ CSP electricity	10,712.4	134	0	23,619	558
Hydropower electricity	2,174.5	7.5	31.1	608.9	0
Wave electricity	6.42	0.00	0.00	14.42	0
Geothermal electricity	1168.85	9.5132	27.7013	225.26	0
Tidal electricity	5.551	0.108	0.014	4.97	0.057
Solar heat	93.8819	0	0	32	10.9716
Geothermal heat	449.6054	0	33.7242	5	1.171
D. Net taken from (+) or added to (-) storage	**197.7312**	**-0.1633**	**0.0083**	**27.9171**	**0.7798**
CSP storage	0.0021	0	0	0.0226	0.0003
PHS storage	1.0877	-0.0028	0	-0.018	-0.0015
Battery storage	0.0031	0	0	0.5409	0.0508
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.1533	0.0011	0	0.0087	-0.0001
HW-STES storage	0.503	0	-0.0005	1	0.0222
UTES storage	181.0677	0.0132	0	23.7181	0.6936
Firebrick storage	1.79	0.0016	0.0088	4.2085	0.0227
Non-grid H_2 storage	13.1245	-0.1763	0	-1.2088	-0.0083
Energy supplied plus taken from storage (C+D)	***29,363.1***	***356.7***	***101.7***	***35,096***	***634***

	Jamaica	Japan	Mada-gascar	Mauritius	Mideast
A1. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for electricity inflexible demand	18	2,473	55	16	7,986
Electricity for electricity, heat, cold storage + DR	24	1,349	41	17	8,433
Electricity for H_2 direct use + H_2 storage	7	771	5	7	1,952
A2. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for direct use, electricity storage, + H_2	38	4,151	75	35	12,808
Low-T heat demand met by heat storage	1	63	4	1	531
Cold demand met by cold storage	0.00	0.76	1.41	0.22	15.98
Hi-T heat demand met by firebrick storage	10.89	378.15	19.45	3.63	5,015.43
A3. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for direct use, electricity storage, DR	29	3,043	65	24	10,186
Electricity for H_2 direct use + H_2 storage	7	771	5	7	1,952
Electricity + heat for heat subject to storage	1	177	7	2	596
Electricity for cold demand subject to storage	0.00	8.65	3.61	1.66	80.04
Hi-T heat from electricity + firebrick storage	12.59	593.97	20.38	6.34	5,556.22
B. Total losses	**17**	**1,126**	**128**	**9**	**4,336**
Transmission, distribution, downtime losses	3	419	15	3	1,498
Losses CSP storage	0.00	0.00	0.00	0.00	0.02
Losses PHS storage	0.00	1.37	0.00	0.00	0.11
Losses battery storage	1	19	1	1	48
Losses grid H_2 storage	0	15	0	0	11
Losses CW-STES + ICE storage	0.00	0.14	0.25	0.04	2.88
Losses HW-STES storage	0	2	1	0	34
Losses UTES storage	0	13	1	0	217
Losses firebrick storage	0	9	0	0	122
Losses from curtailment	12	647	110	4	2,405
Net end-use demand plus losses (A1 + B)	***66***	***5,719***	***228***	***49***	***22,707***
C. Total WWS supply before T&D losses	**66**	**5,718**	**228**	**48**	**22,660**
Onshore + offshore wind electricity	18	3,247	101	17	10,734
Rooftop + utility PV+ CSP electricity	48	2,035	126	31	10,919
Hydropower electricity	0	355	2	1	589
Wave electricity	0	2	0	0	0
Geothermal electricity	0	34.8924	0	0	305.6606
Tidal electricity	0.026	2.280	0.054	0.023	1.578
Solar heat	0	5.5701	0	0.2736	56.0975
Geothermal heat	0	36.5304	0.04	0	53.6542
D. Net taken from (+) or added to (-) storage	**0.043**	**1.0719**	**-0.0006**	**0.9816**	**47.5734**
CSP storage	0	0	0	0	0.0058
PHS storage	-0.0001	-0.1069	-0.0006	-0.0001	-0.0063
Battery storage	0.019	-0.068	0.0017	0.0027	0.8776
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0	-0.0003	0.0017	0.0008	0.0384
HW-STES storage	0.0053	0.0366	-0.0004	0.0014	0.1412
UTES storage	0.0091	2.1961	-0.0059	0.9849	42.5184
Firebrick storage	0.0065	0.1241	0.0056	0.0017	2.853
Non-grid H_2 storage	0.0033	-1.1097	-0.0027	-0.0098	1.1454
Energy supplied plus taken from storage (C+D)	***66***	***5,719***	***228***	***49***	***22,707***

Table S19a.ii. Detailed base-WWS-case verification of LOADMATCH energy conservation by region. Continuation of Table S19a.i. See caption of Table S19a.i. for more details.

	New Zealand	Philippines	Russia region	South Am-NW	South Am-SE
A1. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for electricity inflexible demand	181	416	2,482	997	4,023
Electricity for electricity, heat, cold storage + DR	158	464	3,363	1,038	4,414
Electricity for H_2 direct use + H_2 storage	32	98	1,251	348	896
A2. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for direct use, electricity storage, + H_2	275	691	4,673	1,805	6,435
Low-T heat demand met by heat storage	8	75	1,036	65	94
Cold demand met by cold storage	0.03	13.37	19.60	12.77	39.32
Hi-T heat demand met by firebrick storage	87.77	198.39	1,367.37	499.88	2,763.69
A3. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for direct use, electricity storage, DR	236	558	3,309	1,406	5,293
Electricity for H_2 direct use + H_2 storage	32	98	1,251	348	896
Electricity + heat for heat subject to storage	10	75	1,069	86	248
Electricity for cold demand subject to storage	0.23	42.11	92.44	42.85	131.48
Hi-T heat from electricity + firebrick storage	92.74	204.46	1,374.82	500.38	2,763.71
B. Total losses	**208**	**783**	**1,765**	**326**	**2,256**
Transmission, distribution, downtime losses	40	111	639	179	701
Losses CSP storage	0.00	0.00	0.00	0.00	0.00
Losses PHS storage	0.02	0.00	0.56	14.51	13.35
Losses battery storage	1	16	0	0	0
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	0.01	2.41	3.54	2.30	7.10
Losses HW-STES storage	0	11	198	12	7
Losses UTES storage	0	14	52	6	17
Losses firebrick storage	2	5	36	12	69
Losses from curtailment	164	623	835	99	1,441
Net end-use demand plus losses (A1 + B)	***578***	***1,760***	***8,861***	***2,709***	***11,588***
C. Total WWS supply before T&D losses	**578**	**1,758**	**8,872**	**2,709**	**11,588**
Onshore + offshore wind electricity	297	211	6,665	846	4,938
Rooftop + utility PV+ CSP electricity	188	1,458	1,694	1,273	4,872
Hydropower electricity	70	37	489	515	1,662
Wave electricity	0	0	3	1	4
Geothermal electricity	16.3689	50.9117	11.3466	71.5924	60.5528
Tidal electricity	0.156	0.483	2.200	0.895	2.081
Solar heat	0.2785	0	0.0413	0	40.7929
Geothermal heat	7.3616	0.0237	7.1371	0.425	8.3968
D. Net taken from (+) or added to (-) storage	**0.0095**	**2.79**	**-11.3077**	**0.0409**	**0.0363**
CSP storage	0	0	0	0	0
PHS storage	-0.0028	-0.0018	-0.0376	-0.0091	0.0044
Battery storage	-0.012	0.4381	0	0	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0001	0.0213	-0.0123	0.0202	0.063
HW-STES storage	-0.0002	0.1618	-0.0498	0.0204	-0.0049
UTES storage	-0.0019	2.0505	-8.956	0.0301	-0.1177
Firebrick storage	0.0312	0.1108	-0.1961	-0.013	0.1132
Non-grid H_2 storage	-0.0049	0.0093	-2.0559	-0.0077	-0.0217
Energy supplied plus taken from storage (C+D)	***578***	***1,760***	***8,861***	***2,709***	***11,588***

	Southeast Asia	South Korea	Taiwan	United States	All regions
A1. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for electricity inflexible demand	6,085	1,898	1,056	11,647	100,947
Electricity for electricity, heat, cold storage + DR	7,540	1,305	968	11,231	107,538
Electricity for H_2 direct use + H_2 storage	1,585	590	205	1,978	27,133
A2. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for direct use, electricity storage, + H_2	10,459	3,119	1,710	18,777	167,112
Low-T heat demand met by heat storage	462	108	50	1,399	12,516
Cold demand met by cold storage	57.57	1.58	3.38	43.70	540
Hi-T heat demand met by firebrick storage	4,231.25	564.91	466.00	4,636.65	55,449
A3. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for direct use, electricity storage, DR	8,220	2,271	1,212	16,446	131,029
Electricity for H_2 direct use + H_2 storage	1,585	590	205	1,978	27,133
Electricity + heat for heat subject to storage	483	166	98	1,405	15,063
Electricity for cold demand subject to storage	214.57	12.61	29.64	226.60	2,741
Hi-T heat from electricity + firebrick storage	4,706.55	753.79	684.47	4,800.61	59,652

B. Total losses	**5,848**	**1,736**	**603**	**12,572**	**80,284**
Transmission, distribution, downtime losses	1,220	365	180	2,614	20,728
Losses CSP storage	0.00	0.00	0.00	0.03	0
Losses PHS storage	0.01	0.45	0.18	0.71	58
Losses battery storage	153	43	32	109	741
Losses grid H_2 storage	4	63	16	7	923
Losses CW-STES + ICE storage	10.39	0.28	0.61	7.90	98
Losses HW-STES storage	71	10	5	158	1,396
Losses UTES storage	88	29	13	298	2,752
Losses firebrick storage	102	14	11	116	1,365
Losses from curtailment	4,199	1,211	344	9,261	52,224
Net end-use demand plus losses (A1 + B)	***21,058***	***5,529***	***2,832***	***37,428***	***315,902***
C. Total WWS supply before T&D losses	**21,052**	**5,501**	**2,823**	**37,432**	**315,406**
Onshore + offshore wind electricity	6,507	2,151	863	17,681	141,049
Rooftop + utility PV+ CSP electricity	13,617	3,301	1,690	18,615	154,005
Hydropower electricity	608	23	27	625	14,261
Wave electricity	5	0	1	13	92
Geothermal electricity	308.349	0	238.1099	152.826	3,109
Tidal electricity	2.842	2.038	0.179	2.243	47
Solar heat	0.3166	3.126	3.3711	48.674	1,312
Geothermal heat	2.1889	21.1719	0.0014	294.3594	1,531
D. Net taken from (+) or added to (-) storage	**6.0629**	**28.4223**	**8.768**	**-3.8396**	**496**
CSP storage	0	0	0	-0.0013	0.0259
PHS storage	-0.0014	0.1686	-0.0064	-0.082	0.7538
Battery storage	-0.2	0.6585	0.5238	-0.46	1.9357
Grid H_2 storage	0	0	0	0	0.0000
CW-STES+ICE storage	0.096	0.0018	0.0114	-0.0121	0.4035
HW-STES storage	0.2689	0.0413	0.0469	-0.0356	4.1691
UTES storage	6.4536	7.4289	9.0107	-2.4331	449.0843
Firebrick storage	0.0245	0.3871	0.371	-0.2739	18.3060
Non-grid H_2 storage	-0.5789	19.7361	-1.1894	-0.5417	21.4775
Energy supplied plus taken from storage (C+D)	***21,058***	***5,529***	***2,832***	***37,428***	***315,902***

End-use demands in A1, A2, A3 should be identical. Transmission/distribution/maintenance loss rates are given in Table S20. Round-trip storage efficiencies are given in Table S22. Electricity production is curtailed when it exceeds the sum of electricity demand, cold storage capacity, heat storage capacity, and H_2 storage capacity.

Onshore and offshore wind turbines in GATOR-GCMOM, used to calculate wind power output for use in LOADMATCH, are assumed to be Senvion 5 MW turbines with 126-m diameter blades, 100 m hub heights, a cut-in wind speed of 3.5 m/s, and a cut-out wind speed of 30 m/s.

Rooftop PV panels in GATOR-GCMOM were modeled as fixed-tilt panels at the optimal tilt angle of the country they resided in; utility PV panels were modeled as half fixed optimal tilt and half single-axis horizontal tracking. All panels were assumed to have a nameplate capacity of 390 W and a panel area of 1.629668 m^2, which gives a 2050 panel efficiency (Watts of power output per Watt of solar radiation incident on the panel) of 23.9%, which is an increase from the 2015 value of 20.1%.

Each CSP plant before storage is assumed to have the mirror and land characteristics of the Ivanpah solar plant, which has 646,457 m^2 of mirrors and 2.17 km^2 of land per 100 MW nameplate capacity and a CSP efficiency (fraction of incident solar radiation that is converted to electricity) of 15.796%, calculated as the product of the reflection efficiency of 55% and the steam plant efficiency of 28.72%. The efficiency of the CSP hot fluid collection (energy in fluid divided by incident radiation) is 34%.

Table S19b.i. Detailed EGS-cases verification of LOADMATCH energy conservation by region. Budgets of total end-use energy demand met, energy lost, WWS energy supplied, and changes in storage, during the 26,291.4875-h (3 y) simulation, by region, and summed over all regions. Units are TWh over the simulation. Divide by hours of simulation to obtain simulation-averaged power values. See footnote of Table S19.a.ii. for more details.

	Africa-East	Africa-North	Africa-South	Africa-East	Australia
A1. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for electricity inflexible demand	694	1,889	1,518	882	1,071
Electricity for electricity, heat, cold storage + DR	945	1,734	1,250	1,394	930
Electricity for H_2 direct use + H_2 storage	121	642	224	163	224
A2. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for direct use, electricity storage, + H_2	1,066	3,323	2,258	1,525	1,652
Low-T heat demand met by heat storage	242	105	116	233	27
Cold demand met by cold storage	7.17	12.17	13.92	7.84	2.20
Hi-T heat demand met by firebrick storage	444.86	824.59	603.79	673.52	544.11
A3. Total end use demand	**1,760**	**4,265**	**2,992**	**2,439**	**2,226**
Electricity for direct use, electricity storage, DR	929	2,507	1,909	1,299	1,371
Electricity for H_2 direct use + H_2 storage	121	642	224	163	224
Electricity + heat for heat subject to storage	244	189	118	263	71
Electricity for cold demand subject to storage	14.14	48.87	58.80	19.29	9.07
Hi-T heat from electricity + firebrick storage	452.29	877.68	682.23	694.16	549.65
B. Total losses	**906**	**1,565**	**705**	**1,461**	**640**
Transmission, distribution, downtime losses	164	348	214	233	183
Losses CSP storage	0.00	0.00	0.01	0.00	0
Losses PHS storage	0.00	0.15	0.06	0.02	0.0701
Losses battery storage	7	6	25	5	4.5
Losses grid H_2 storage	0	2	1	1	0
Losses CW-STES + ICE storage	1	2	3	1	0.4
Losses HW-STES storage	31	18	13	28	1.8
Losses UTES storage	67	7	38	75	4.1
Losses firebrick storage	12	21	14	17	14
Losses from curtailment	624	1,161	397	1,102	432
Net end-use demand plus losses (A1 + B)	***2,667***	***5,830***	***3,697***	***3,900***	***2,865***
C. Total WWS supply before T&D losses	**2,659**	**5,829**	**3,697**	**3,896**	**2,865**
Onshore + offshore wind electricity	893	2,732	1,206	1,615	1,175
Rooftop + utility PV+ CSP electricity	1,423	2,586	2,054	1,927	1,313
Hydropower electricity	79.1	41.2	104.7	87.8	105.6
Wave electricity	0.31	0.86	1.34	1.26	1.14
Geothermal electricity	262.386	461.1101	325.4318	263.6425	250.1216
Tidal electricity	0.3809	0.793	0.4462	0.5685	1.1426
Solar heat	0	4.2466	5.49	0.0561	18.1176
Geothermal heat	0.2942	2.4231	0.0327	0.01	1.3416
D. Net taken from (+) or added to (-) storage	**7.8345**	**0.9008**	**-0.6794**	**4.4972**	**-0.064**
CSP storage	0	0	0.0004	0	0
PHS storage	-0.0056	-0.0079	-0.019	-0.0056	-0.0309
Battery storage	-0.0723	-0.0364	0.0854	0.0871	-0.067
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0068	-0.002	0.0282	0.0092	0.0036
HW-STES storage	0.0752	0.0508	-0.0071	0.0575	-0.0037
UTES storage	7.7219	0.6099	-0.9051	4.1373	-0.05
Firebrick storage	0.0089	0.4221	0.1583	0.2819	0.0057
Non-grid H_2 storage	0.0996	-0.1358	-0.0206	-0.0702	0.0781
Energy supplied plus taken from storage (C+D)	***2,667***	***5,830***	***3,697***	***3,900***	***2,865***

	Canada	Central America	Central Asia	China region	Cuba
A1. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for electricity inflexible demand	2,180	1,562	1,956	27,885	71
Electricity for electricity, heat, cold storage + DR	1,757	1,750	1,815	31,826	74
Electricity for H_2 direct use + H_2 storage	356	285	351	9,319	6
A2. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for direct use, electricity storage, + H_2	3,459	2,595	2,955	47,038	98
Low-T heat demand met by heat storage	53	60	177	4,662	6
Cold demand met by cold storage	1.51	11.53	2.02	175.88	1.94
Hi-T heat demand met by firebrick storage	780.46	930.04	988.28	17,154.68	43.62
A3. Total end use demand	**4,294**	**3,597**	**4,122**	**69,030**	**150**
Electricity for direct use, electricity storage, DR	2,740	2,217	2,574	35,953	82
Electricity for H_2 direct use + H_2 storage	356	285	351	9,319	6

Electricity + heat for heat subject to storage	239	130	190	5,119	8
Electricity for cold demand subject to storage	17.26	34.56	7.56	996.89	6.40
Hi-T heat from electricity + firebrick storage	941.05	931.38	999.71	17,642.13	48.51
B. Total losses	**881**	**1,123**	**1,742**	**22,201**	**66**
Transmission, distribution, downtime losses	372	303	363	6,093	12
Losses CSP storage	0.00	0.00	0.00	0.02	0.00
Losses PHS storage	0.3373	1.1401	0.6951	4.0088	0.0142
Losses battery storage	0.00	4.3	1.3	27	1.51
Losses grid H_2 storage	0	0	19	125	0
Losses CW-STES + ICE storage	0.27	2.1	0.4	32	0.35
Losses HW-STES storage	6	6.4	30.2	409	1.14
Losses UTES storage	0	14.5	21.5	1,245	0.66
Losses firebrick storage	20	24	25	425	1
Losses from curtailment	482	768	1,280	13,842	49
Net end-use demand plus losses (A1 + B)	***5,175***	***4,720***	***5,864***	***91,232***	***216***
C. Total WWS supply before T&D losses	**5,176**	**4,720**	**5,857**	**91,042**	**216**
Onshore + offshore wind electricity	3,193	2,094	2,858	36,905	70
Rooftop + utility PV+ CSP electricity	598	1,819	2,339	40,133	129
Hydropower electricity	775.3	215.4	213.1	4,899.5	0.8
Wave electricity	1.74	1.73	1.10	30.88	0.08
Geothermal electricity	577.4776	574.8087	445.6251	7506.7285	16.2268
Tidal electricity	1.740	0.839	0.117	13.214	0.080
Solar heat	2.2511	10.9574	0	975.7811	0
Geothermal heat	26.0254	2.3516	0.0416	577.4566	0
D. Net taken from (+) or added to (-) storage	**-0.9885**	**0.1349**	**6.8244**	**190.0004**	**0.0749**
CSP storage	0	0	0	-0.004	0
PHS storage	-0.0011	-0.0084	0.0817	-0.2496	-0.0042
Battery storage	0	-0.0112	0.036	-0.312	0.0129
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	-0.0009	-0.0018	0.0003	-0.0359	0.0031
HW-STES storage	0.0399	0.0601	0.25	1.829	0.0084
UTES storage	0	0.7213	5.098	186.0187	0.0251
Firebrick storage	-0.0537	-0.0531	0.5133	7.0077	0.0249
Non-grid H_2 storage	-0.9726	-0.5718	0.8449	-4.2534	0.0046
Energy supplied plus taken from storage (C+D)	***5,175***	***4,720***	***5,864***	***91,232***	***216***

	Europe	Haiti region	Iceland	India region	Israel
A1. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for electricity inflexible demand	10,839.6	105	38	10,804	184
Electricity for electricity, heat, cold storage + DR	8,975.8	92	36	14,414	136
Electricity for H_2 direct use + H_2 storage	3,128.7	20	3	2,541	22
A2. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for direct use, electricity storage, + H_2	18,685.4	167	63	16,894	289
Low-T heat demand met by heat storage	1,717.0	0	14	995	19
Cold demand met by cold storage	34.20	0.91	0.00	70.90	0.76
Hi-T heat demand met by firebrick storage	2,507.55	49.47	0.03	9,798.97	34.61
A3. Total end use demand	**22,944.1**	**218**	**77**	**27,759**	**343**
Electricity for direct use, electricity storage, DR	12,988.1	135	29	13,749	251
Electricity for H_2 direct use + H_2 storage	3,128.7	20	3	2,541	22
Electricity + heat for heat subject to storage	3,021.4	9	14	1,005	21
Electricity for cold demand subject to storage	319.87	2.22	0.00	314.98	4.46
Hi-T heat from electricity + firebrick storage	3,486.07	51.82	30.71	10,149.16	44.15
B. Total losses	**6,076**	**132**	**25**	**7,976**	**244**
Transmission, distribution, downtime losses	1,962.68	22	8	2,212	38
Losses CSP storage	0.0073	0.00	0.00	0.19	0.00
Losses PHS storage	9	0.0732	0.0000	0.2217	0.00
Losses battery storage	0	0.0	0.00	142	10
Losses grid H_2 storage	503	9	0	12	0
Losses CW-STES + ICE storage	6	0.2	0.00	12.81	0.14
Losses HW-STES storage	207	0.0	0.00	110.64	2
Losses UTES storage	143	0.4	0.00	322.70	5
Losses firebrick storage	63	1	0	234	1
Losses from curtailment	3,182.2	98.9	17.5	4,929	189
Net end-use demand plus losses (A1 + B)	***29,020.5***	***349.1***	***101.7***	***35,735***	***586***
C. Total WWS supply before T&D losses	**28,850.0**	**349**	**102**	**35,706**	**585**
Onshore + offshore wind electricity	13,025.0	180	1	8,194	62
Rooftop + utility PV+ CSP electricity	9,474.4	128	0	23,619	474
Hydropower electricity	2,146.0	7.4	31.0	609.5	0
Wave electricity	6.42	0.00	0.00	14.42	0
Geothermal electricity	3649.22	33.0306	36.0975	3226.26	37.0383

Tidal electricity	5.551	0.108	0.014	4.97	0.057
Solar heat	93.8819	0	0	32	10.9716
Geothermal heat	449.6054	0	33.7242	5	1.171
D. Net taken from (+) or added to (-) storage	**170.4482**	**-0.052**	**0.0083**	**29.1464**	**0.7952**
CSP storage	0.0018	0	0	0.0217	0.0003
PHS storage	1.0688	-0.0028	0	-0.018	-0.0015
Battery storage	0.0018	0	0	0.5119	0.0488
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.1533	0.0011	0	0.0087	0
HW-STES storage	0.503	0	-0.0005	1	0.0222
UTES storage	150.8897	0.0132	0	24.9815	0.6935
Firebrick storage	1.79	0.0011	0.0088	4.2085	0.0227
Non-grid H_2 storage	16.0399	-0.0646	0	-1.2131	0.0092
Energy supplied plus taken from storage (C+D)	***29,020.5***	***349.1***	***101.7***	***35,735***	***586***

	Jamaica	Japan	Mada-gascar	Mauritius	Mideast
A1. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for electricity inflexible demand	18	2,474	56	17	7,829
Electricity for electricity, heat, cold storage + DR	24	1,349	40	17	8,590
Electricity for H_2 direct use + H_2 storage	7	771	5	7	1,952
A2. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for direct use, electricity storage, + H_2	38	4,151	77	36	12,504
Low-T heat demand met by heat storage	1	61	3	1	545
Cold demand met by cold storage	0.00	0.83	1.21	0.24	17.31
Hi-T heat demand met by firebrick storage	10.97	380.64	19.16	3.81	5,304.74
A3. Total end use demand	**49**	**4,593**	**100**	**40**	**18,371**
Electricity for direct use, electricity storage, DR	29	3,043	65	24	10,186
Electricity for H_2 direct use + H_2 storage	7	771	5	7	1,952
Electricity + heat for heat subject to storage	1	177	7	2	596
Electricity for cold demand subject to storage	0.00	8.65	3.61	1.66	80.04
Hi-T heat from electricity + firebrick storage	12.59	593.97	20.38	6.34	5,556.22
B. Total losses	**16**	**1,095**	**95**	**9**	**4,989**
Transmission, distribution, downtime losses	3	417	13	3	1,548
Losses CSP storage	0.00	0.00	0.00	0.00	0.01
Losses PHS storage	0.00	0.99	0.00	0.00	0.10
Losses battery storage	1	16	1	1	18
Losses grid H_2 storage	0	16	0	0	10
Losses CW-STES + ICE storage	0.00	0.15	0.22	0.04	3.13
Losses HW-STES storage	0	2	0	0	39
Losses UTES storage	0	12	1	0	209
Losses firebrick storage	0	9	0	0	131
Losses from curtailment	11	622	79	4	3,031
Net end-use demand plus losses (A1 + B)	***65***	***5,689***	***195***	***49***	***23,360***
C. Total WWS supply before T&D losses	**65**	**5,687**	**195**	**49**	**23,325**
Onshore + offshore wind electricity	14	2,720	58	16	9,893
Rooftop + utility PV+ CSP electricity	46	2,035	125	27	10,439
Hydropower electricity	0	355	2	1	589
Wave electricity	0	2	0	0	0
Geothermal electricity	5.3436	531.4774	10.8321	4.3743	2291.691
Tidal electricity	0.026	2.280	0.054	0.023	1.578
Solar heat	0	5.5701	0	0.2736	56.0975
Geothermal heat	0	36.5304	0.04	0	53.6542
D. Net taken from (+) or added to (-) storage	**0.0483**	**1.2296**	**0.0049**	**0.0139**	**34.8608**
CSP storage	0	0	0	0	-0.0009
PHS storage	-0.0001	-0.1069	-0.0006	-0.0001	-0.0063
Battery storage	0.0193	-0.058	0.0069	0.0014	-0.2
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0	0	0.0017	0.0008	-0.0024
HW-STES storage	0.0053	0.0366	-0.0004	0.0014	0.1412
UTES storage	0.012	2.1961	-0.0059	0.0167	34.1091
Firebrick storage	0.0065	0.2384	0.0059	0.0017	1.5331
Non-grid H_2 storage	0.0053	-1.0765	-0.0027	-0.0079	-0.7129
Energy supplied plus taken from storage (C+D)	***65***	***5,689***	***195***	***49***	***23,360***

Table S19b.ii. More detailed verification of LOADMATCH energy conservation by region in the EGS cases. Continuation of Table S19b.i. See caption of Table S19b.i. and footnote of Table S19.a.ii. for more details.

	New Zealand	Philippines	Russia region	South Am-NW	South Am-SE
A1. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for electricity inflexible demand	181	415	2,485	1,002	4,031
Electricity for electricity, heat, cold storage + DR	157	465	3,360	1,033	4,405
Electricity for H_2 direct use + H_2 storage	32	98	1,251	348	896
A2. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for direct use, electricity storage, + H_2	276	689	4,677	1,812	6,447
Low-T heat demand met by heat storage	8	75	1,031	60	89
Cold demand met by cold storage	0.03	14.01	21.26	12.04	36.87
Hi-T heat demand met by firebrick storage	87.35	200.07	1,366.33	498.66	2,758.59
A3. Total end use demand	**371**	**978**	**7,096**	**2,383**	**9,332**
Electricity for direct use, electricity storage, DR	236	558	3,309	1,406	5,293
Electricity for H_2 direct use + H_2 storage	32	98	1,251	348	896
Electricity + heat for heat subject to storage	10	75	1,069	86	248
Electricity for cold demand subject to storage	0.23	42.11	92.44	42.85	131.48
Hi-T heat from electricity + firebrick storage	92.74	204.46	1,374.82	500.38	2,763.71
B. Total losses	**160**	**745**	**1,671**	**295**	**1,840**
Transmission, distribution, downtime losses	36	108	632	177	670
Losses CSP storage	0.00	0.00	0.00	0.00	0.00
Losses PHS storage	0.02	0.00	0.22	12.81	12.98
Losses battery storage	1	11	0	0	0
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	0.01	2.53	3.84	2.17	6.65
Losses HW-STES storage	0	12	199	11	7
Losses UTES storage	0	13	44	5	15
Losses firebrick storage	2	5	36	12	69
Losses from curtailment	120	593	755	74	1,060
Net end-use demand plus losses (A1 + B)	***530***	***1,722***	***8,767***	***2,678***	***11,173***
C. Total WWS supply before T&D losses	**530**	**1,720**	**8,778**	**2,678**	**11,170**
Onshore + offshore wind electricity	236	210	6,070	719	3,779
Rooftop + utility PV+ CSP electricity	160	1,316	1,428	1,114	4,623
Hydropower electricity	70	37	489	513	1,643
Wave electricity	0	0	3	1	4
Geothermal electricity	56.4457	156.6091	778.4981	329.2234	1069.4553
Tidal electricity	0.156	0.483	2.200	0.895	2.081
Solar heat	0.2785	0	0.0413	0	40.7929
Geothermal heat	7.3616	0.0237	7.1371	0.425	8.3968
D. Net taken from (+) or added to (-) storage	**0.016**	**2.4357**	**-11.3077**	**-0.0935**	**2.9016**
CSP storage	0	0	0	0	0
PHS storage	-0.0028	-0.0018	-0.0376	-0.011	0.04
Battery storage	-0.01	0.3829	0	0	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0001	0.0213	-0.0123	0.0201	0.063
HW-STES storage	-0.0002	0.1618	-0.0498	0.0204	-0.0049
UTES storage	-0.0019	1.7514	-8.956	-0.0974	-0.1177
Firebrick storage	0.0336	0.1108	-0.1961	-0.0161	0.1263
Non-grid H_2 storage	-0.0029	0.0093	-2.0559	-0.0095	2.7948
Energy supplied plus taken from storage (C+D)	***530***	***1,722***	***8,767***	***2,678***	***11,173***

	Southeast Asia	South Korea	Taiwan	United States	All regions
A1. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for electricity inflexible demand	6,146	1,905	1,053	11,644	100,935
Electricity for electricity, heat, cold storage + DR	7,478	1,298	971	11,235	107,550
Electricity for H_2 direct use + H_2 storage	1,585	590	205	1,978	27,133
A2. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for direct use, electricity storage, + H_2	10,545	3,130	1,700	18,768	166,915
Low-T heat demand met by heat storage	414	105	45	1,397	12,263
Cold demand met by cold storage	51.70	1.69	3.35	43.73	547
Hi-T heat demand met by firebrick storage	4,199.47	556.78	480.63	4,646.81	55,893
A3. Total end use demand	**15,210**	**3,793**	**2,229**	**24,857**	**235,618**
Electricity for direct use, electricity storage, DR	8,220	2,271	1,212	16,446	131,029
Electricity for H_2 direct use + H_2 storage	1,585	590	205	1,978	27,133
Electricity + heat for heat subject to storage	483	166	98	1,405	15,063
Electricity for cold demand subject to storage	214.57	12.61	29.64	226.60	2,741

Hi-T heat from electricity + firebrick storage	4,706.55	753.79	684.47	4,800.61	59,652
B. Total losses	**4,979**	**1,472**	**562**	**11,020**	**74,690**
Transmission, distribution, downtime losses	1,155	346	178	2,497	20,311
Losses CSP storage	0.00	0.00	0.00	0.02	0
Losses PHS storage	0.12	0.16	0.12	0.95	45
Losses battery storage	124	33	24	75	538
Losses grid H_2 storage	50	53	22	10	832
Losses CW-STES + ICE storage	9.33	0.31	0.60	7.90	99
Losses HW-STES storage	63	10	6	161	1,374
Losses UTES storage	79	27	11	288	2,649
Losses firebrick storage	101	14	12	117	1,380
Losses from curtailment	3,398	990	309	7,863	47,462
Net end-use demand plus losses (A1 + B)	***20,189***	***5,266***	***2,790***	***35,877***	***310,308***
C. Total WWS supply before T&D losses	**20,185**	**5,240**	**2,790**	**35,883**	**309,844**
Onshore + offshore wind electricity	5,043	2,098	823	16,257	122,138
Rooftop + utility PV+ CSP electricity	12,563	2,683	1,456	15,801	141,835
Hydropower electricity	616	23	27	627	14,308
Wave electricity	5	0	1	13	92
Geothermal electricity	1952.66	410.1131	479.065	2840.018	28,581
Tidal electricity	2.842	2.038	0.179	2.243	47
Solar heat	0.3166	3.126	3.3711	48.674	1,312
Geothermal heat	2.1889	21.1719	0.0014	294.3594	1,531
D. Net taken from (+) or added to (-) storage	**4.0871**	**25.8448**	**0.7992**	**-5.9074**	**464**
CSP storage	0	0	0	-0.0013	0.0180
PHS storage	-0.0014	0.0712	-0.0064	-0.082	0.6501
Battery storage	-0.124	0.4983	0.4602	-0.336	0.9260
Grid H_2 storage	0	0	0	0	0.0000
CW-STES+ICE storage	0.1085	0.0036	0.0115	-0.0121	0.3775
HW-STES storage	0.2689	0.0413	0.0469	-0.0356	4.1629
UTES storage	3.2268	6.9336	1.1263	-4.6249	415.5232
Firebrick storage	1.1871	0.3871	0.371	-0.2739	17.8625
Non-grid H_2 storage	-0.5789	17.9099	-1.2104	-0.5417	24.2942
Energy supplied plus taken from storage (C+D)	***20,189***	***5,266***	***2,790***	***35,877***	***310,308***

Table S20. Parameters for determining costs of energy from electricity and heat generators in both the base-WWS case and EGS cases.

	Capital cost new installations ($million/MW)	O&M Cost ($/kW/y)	Decom-missioning cost (% of capital cost)	Lifetime (years)	TDM losses (% of energy generated)
Onshore wind electricity	1.01 (0.84-1.18)	37.5 (35-40)	1.25 (1.2-1.3)	30 (25-35)	7.5 (5-10)
Offshore wind electricity	2.34 (1.87-2.80)	80 (60-100)	2 (2-2)	30 (25-35)	7.5 (5-10)
Residential PV electricity	1.84 (1.56-2.11)	27.5 (25-30)	0.75 (0.5-1)	44 (41-47)	1.5 (1-2)
Commercial/government PV	1.27 0.87-1.66)	16.5 (13-20)	0.75 (0.5-1)	46 (43-49)	1.5 (1-2)
Utility-scale PV electricity	0.71 (0.58-0.84)	19.5 (16.5-22.5)	0.75 (0.5-1)	48.5 (45-52)	7.5 (5-10)
CSP electricity with storage[a]	5.33 (4.07-6.58)	50 (40-60)	1.25 (1-1.5)	45 (40-50)	7.5 (5-10)
CSP electricity no storage[a]	2.64 (2.37-2.90)	45 (36-54)	1.25 (1-1.5)	45 (40-50)	7.5 (5-10)
Traditional geothermal elec.	4.64 (3.97-5.31)	45 (36-54)	2.5 (2-3)	45 (40-50)	7.5 (5-10)
Enhanced geothermal elec.[b]	9.0 (4.64-13.4)	45 (36-54)	2.5 (2-3)	45 (40-50)	7.5 (5-10)
Hydroelectricity	2.78 (2.37-3.20)	15.5 (15-16)	2.5 (2-3)	85 (70-100)	7.5 (5-10)
Wave electricity	4.14 (2.85-5.43)	175 (100-250)	2 (2-2)	45 (40-50)	7.5 (5-10)
Tidal electricity	3.68 (2.95-4.41)	125 (50-200)	2.5 (2-3)	45 (40-50)	7.5 (5-10)
Solar heat	1.18 (1.06-1.29)	50 (40-60)	1.25 (1-1.5)	35 (30-40)	3 (2-4)
Geothermal heat	4.64 (3.97-5.31)	45 (36-54)	2 (1-3)	45 (40-50)	7.5 (5-10)

Capital costs (per MW-el of nameplate capacity for electricity generators and per MW-th for heat generators) are an average of 2022 and 2050 values. 2050 costs are derived and sourced in the spreadsheet analysis[3], which uses the same methodology as in Ref. S13.

O&M=Operation and maintenance. TDM=transmission/distribution/maintenance losses. TDM losses are a percentage of all energy produced by the generator and are an average over short and long-distance (high-voltage direct current) power lines and heat pipelines. Maintenance losses account for forced and unforced maintenance.

Short-distance transmission costs are $0.0105 (0.01-0.011)/kWh. Distribution costs are $0.02375 (0.023-0.0245)/kWh. Long-distance transmission costs are $0.0089 (0.0042-0.010)/kWh from Ref. S8 but brought up to USD 2022. These costs assume 1,500 to 2,000 km HVDC lines, a capacity factor usage of the lines of ~50% and a capital cost of ~$400 (300-460)/MWtr-km. Table S15 gives the total new HVDC line length and capacity needed and the fraction of all non-rooftop-PV and non-curtailed electricity generated that is subject to HVDC transmission by region. The discount rate used for generation, storage, transmission/distribution, and social costs is a social discount rate of 2 (1-3)%.

[a]The capital cost of CSP with storage includes the cost of extra mirrors and land but excludes costs of phase-change material and storage tanks, which are given in Table S22. The cost of CSP with storage depends on the ratio of the CSP storage maximum charge rate plus direct electricity use rate (which equals the maximum discharge rate) to the CSP maximum discharge rate. For this table, for the purpose of benchmarking the "CSP with storage" cost, we use a ratio of 3.2:1. (In other words, if 3.2 units of sunlight come in, a maximum of 2.2 units can go to storage and a maximum of 1 unit can be discharged directly as electricity at the same time.) The ratio for "CSP no storage" is 1:1. In our actual simulations and cost calculations, we assume a ratio of 2.612:1 for CSP with storage (footnote to Table S14) and find the cost for this assumed ratio by interpolating between the "CSP with storage" benchmark value and the "CSP no storage" value in this table.

[b]The mean, low, and high capital costs provided for enhanced geothermal electricity were the capital costs of each the mean-cost, low-cost, and high-cost EGS cases simulated here.

Table S21. Parameters for determining costs of hydrogen in both the base-WWS case and EGS cases.

	Capital cost new installations	Installation factor	O&M Cost (annual fraction of capital cost)	Full-load life (y)	Calendar life (y)	Efficiency
Electrolyzer	\$334.5 (232-437)/kW-consumed[a]	1.25 (1.2-1.3)[e]	0.078[f]	10[g]	40[i]	0.96[j]
Rectifier	\$94 (84-103)/kW-consumed[b]	1.25 (1.2-1.3)[e]	0.01[f]	10[g]	40[i]	0.99[k]
Compressor	\$39.3 (35-43)/kW-consumed[b]	1.87[f]	0.04[f]	10[g]	40[i]	0.88[l]
H_2 Storage	\$250 (200-300)/kg-H_2-stored[c] \$11.8 (9.5-14.2)/kWh-stored[c]	1.25 (1.2-1.3)[e]	0.01[f]	15 (10-20)[h]	15 (10-20)[h]	0.997[l]
Fuel cell	\$500 (400-600)/kW-generated[d]	1.33[d]	0.035[d]	11[d]	40[i]	0.536[m]
Overall						0.447[n]

Capital costs are averages of 2022 and 2050 values and in USD 2022. The discount rate used is the social discount rate of 2 (1-3)%. Amortization times for determining annual costs equal actual equipment lifetimes (as determined below under footnote g). Additional costs accounted for include the costs of water to produce hydrogen and the costs of dispensing hydrogen fuel to fuel-cell vehicles and to cool the hydrogen fuel. These costs are included and referenced in Table S23 (footnote).

[a]The low value is the "future potential" value from Penev et al.[S47] and the high value is the "moderate 2030" value from Mongird et al.[S48]. \$334.5/kW is an average of the two.

[b]Mongird et al.[S48]. A rectifier is needed to convert AC electricity to DC electricity, which is used by the electrolyzer.

[c]The mean hydrogen storage container capital cost is approximately the "future case" estimate of \$245/kg-H_2 from Houchins and James[S49]. Dividing the cost per kg-H_2-stored by the higher heating value of hydrogen (39.39 kWh/kg-H_2) and by the fuel cell overall efficiency (0.536) gives the cost of hydrogen storage per kWh of electricity stored.

[d]From Chadly et al.[S50], assumed here for 2035.

[e]From NREL[S51]. Installation factors account for the labor and materials cost of installation.

[f]From Penev et al.[S47].

[g]The electrolyzer full-load life (life with a use factor unity) today is 7-8.5 years[S52]. This is assumed here to increase to 10 years by 2035, the year for which calculations are performed. Rectifier and compressor full-load lives are estimated to be the same as that of an electrolyzer. Electrolyzer, rectifier, compressor, and fuel cell actual lifetimes are calculated in the model as a function of use factor. They are calculated as the full-load life of the equipment divided by the use factor, with the result limited by the calendar life of the equipment.

[h]James et al.[S53] for the mean value. Hydrogen storage lifetime is assumed to be independent of use factor.

[i]The electrolyzer calendar life today is 30 years[S48]. This is assumed here to increase to 40 years by 2035, the year for which calculations are performed. Rectifier, compressor, and fuel cell full-load lives are assumed to be the same as that of an electrolyzer.

[j]Hodges et al.[S54] measured electrolyzer efficiencies of 95%-98% relative to the higher heating value of hydrogen (39.39 kWh/kg-H_2=141.8 MJ/kg-H_2). 96% is assumed for 2035.

[k]ABB[S55] estimates current rectifier efficiencies greater than 98%. The efficiency is assumed to be 99% in 2035.

[l]Jacobson[S56]. The storage efficiency assumes that a small portion of hydrogen leaks between electrolyzer and fuel cell.

[m]Assumes a 2035 fuel cell energy conversion efficiency of 65%, an energy to DC electricity efficiency of 84.6% (the rest goes into heat evaporating water), and a DC to AC inverter efficiency of 97.5%[S56].

[n]The overall efficiency is the product of the efficiencies of the individual components.

Table S22. Present value of mean 2022 to 2050 lifecycle costs of new storage capacity and round-trip efficiencies of the non-hydrogen storage technologies in both the base-WWS case and EGS cases. Table S21 provides hydrogen storage cost information.

Storage technology	Present-value of lifecycle cost of new storage ($/kWh—electricity or equivalent electricity, in the case of cold and heat storage)			Round-trip charge/store/ discharge efficiency (%)
	Middle	Low	High	
Electricity				
PHS	14	12	16	80
CSPS	20	15	23	55, 28.72, 99
LI Batteries	60	30	90	89.5
Cold				
CW-STES	12	0.4	40	84.7
ICE	100	40	160	82.5
Low-T Heat				
HW-STES	12	0.4	40	83
UTES	1.6	0.4	4	56
Process Heat				
Firebricks	6	3	9	98

PHS=pumped hydropower storage; CSPS=concentrated solar power with storage; LI Batteries=lithium-ion batteries; CW-STES=cold water sensible-heat thermal energy storage; ICE=ice storage; HW-STES=hot water sensible-heat thermal energy storage; UTES=underground thermal energy storage in boreholes or water pits.

All values reflect averages between 2022 and 2050. From Ref. S13, except as follows.

PHS efficiency is the ratio of electricity delivered to the sum of electricity delivered and electricity used to pump the water. The 2022-2050 mean PHS round-trip efficiency estimated here (80%) can be compared with the U.S.-average value in 2019 of 79%[S57].

The CSPS cost is for the phase-change material and storage tanks. In the model, only the heat captured by the working fluid due to reflection of sunlight off of CSP mirrors can be stored. The three CSPS efficiencies are as follows. 55% of incoming sunlight is reflected to the central tower, where it is absorbed by the working fluid (the remaining 45% of sunlight is lost to reflection and absorption by the CSP mirrors); without storage, 28.72% of heat absorbed by the working fluid is converted to electricity (the remaining 71.28% of heat is lost); and with storage, 99% of heat received by the working fluid that goes into storage is recovered and available to the steam turbine after storage[S58] and, of that, 28.72% is converted to electricity. Thus, the overall efficiency of CSP without storage is 15.785% and that with storage is 15.638%.

Irvine and Rinaldo[S59] project LI battery cell costs for Tesla batteries to be ~$25/kWh by 2035. We estimate that the total system cost for an installed battery pack will be more than twice this, ~$60/kWh (or $240/kW for 4-hour batteries), by 2035 and take this as the mean between 2022 and 2050. Hanley[S60] reported lithium-iron-phosphate battery back prices from CATL and BYD in January 2024 dropping to ~$56/kWh, suggesting a price decline to $60/kWh by 2035 is reasonable or even conservative (prices may actually be lower). For LI battery storage, the 2022-2050 mean round-trip efficiency is taken as the roundtrip efficiency of a 2021 Tesla Powerpack with four hours of storage[S61]. Battery efficiency is the ratio of electricity delivered to electricity put into the battery.

CW-STES, ICE, HW-STES, and UTES costs were updated to reflect average values between 2022 and 2050 rather than values in 2016, which they were previously based on. UTES costs were also updated with data from Denmark (Jacobson[S56], p. 65). In addition, the thermal energy storage (CW-STES, ICE, HW-STEES, and UTES) costs in $/kW-th were multiplied by the mean coefficient of performance (COP) of all heat pumps (an average of air-source and ground-source) used here (=4 kWh-th/kWh-electricity) to give the costs in $/kW-equivalent electricity. The reason is that most all energy in this study is carried in units of electricity, and heat pumps are assumed to provide heat or cold for thermal storage media. Thus, storage capacities are limited to the electricity needed to produce the needed heat or cold. Since the storage size for heat or cold as equivalent electricity is smaller than the storage size of heat or cold itself, the storage cost per unit equivalent electricity must be proportionately larger (by a factor of COP) for costs to be calculated consistently. The cost of heat pumps is assumed to be $160 (132-188)/kW-electricity, or $40 (33-47)/kW-th, based on data for large heat pumps (> 500 tons) projected to between 2022 and 2050.

CW-STES and HW-STES efficiencies are the ratios of the energy returned as cooling and heating, respectively, after storage, to the electricity input into storage. The UTES efficiency is the fraction of heated fluid entering underground storage that is ultimately returned during the year (either short or long term) as air or water heat for a building.

Process heat is low- medium-, and high-temperature heat for industrial processes. The costs of firebrick storage for process heat are estimated as 1/10th those of LI-batteries[S6,S62]. The roundtrip efficiency is from Rondo[6].

Storage costs per unit energy generated are calculated as the product of the maximum energy storage capacity (Table S14) and the lifecycle-averaged capital cost of storage per unit maximum energy storage capacity (this table), annualized with the same discount rate as for power generators (Table S21), but with average 2022 to 2050 storage lifetimes of 17 (12 to 22) years for batteries, 40 years for firebricks, and 32.5 (25 to 40) years all other storage technologies, all divided by the annual average end-use demand met. At least one stationary storage battery (lithium-iron-phosphate) is warrantied up to 15,000 cycles (or 15 years)[S63]. 15,000 cycles are equivalent to one cycle per day (365 cycles per year) for 41.1 years, so this battery may last much longer than the 15-year warranty. As such, the 17-year mean battery life here is likely underestimated.

Table S23a. Base-WWS-case annual hydrogen produced and breakdown of the cost per kilogram of hydrogen produced. Mean, low, and high totals are given, but only the breakdown of the mean value is provided. Tables S20-S22 and the footnote to this table provide mean, low, and high capital cost, installation factor, and discount rate information. All costs are in units of 2022 \$/kg-H_2-produced. Non-grid and grid hydrogen are merged together. The fuel cells are for grid hydrogen.

Region	(a) Non-grid plus grid H_2 produced (Tg-H_2/y)	(b) Mean non-grid plus grid H_2 electricity cost (\$/kg-H_2)	(c) Mean non-grid plus grid H_2 electrolyzer + rectifier cost (\$/kg-H_2)	(d) Mean non-grid plus grid H_2 compressor cost (\$/kg-H_2)	(e) Mean non-grid plus grid H_2 water + dispensing + cooling cost (\$/kg-H_2)	(f) Mean non-grid plus grid H_2 storage cost (\$/kg-H_2)	(g) Mean grid H_2 fuel cell cost (\$/kg-H_2)	(h) Mean non-grid plus grid total H_2 cost (\$/kg-H_2) =b+c+d+e+f+g	(i) Low non-grid plus grid total H_2 cost (\$/kg-H_2)	(j) High non-grid plus grid total H_2 cost (\$/kg-H_2)
Africa-East	0.857	4.64	1.47	0.018	0.18	0.07	0.00	6.38	4.63	8.93
Africa-North	4.575	3.70	1.46	0.018	0.18	0.29	0.14	5.79	4.40	7.59
Africa-South	1.608	3.96	1.45	0.018	0.18	1.01	0.75	7.38	5.35	10.28
Africa-West	1.157	5.71	1.47	0.018	0.18	0.51	0.90	8.79	6.47	12.02
Australia	1.587	3.67	1.47	0.018	0.18	0.15	0.00	5.49	4.20	7.11
Canada	2.521	3.75	1.47	0.018	0.18	3.67	0.00	9.10	6.28	13.67
Central America	2.014	4.15	1.47	0.018	0.18	1.62	0.00	7.44	5.42	10.46
Central Asia	2.682	3.67	1.36	0.017	0.18	0.41	0.33	5.96	4.53	7.86
China region	66.883	3.88	1.45	0.018	0.18	0.36	0.28	6.16	4.67	8.15
Cuba	0.040	4.54	1.47	0.018	0.18	0.07	0.00	6.29	4.57	8.73
Europe	31.031	4.12	1.05	0.013	0.18	1.62	0.22	7.21	5.17	10.38
Haiti region	0.280	4.76	0.79	0.010	0.18	3.81	0.60	10.15	7.05	15.27
Iceland	0.022	3.37	0.41	0.006	0.18	0.00	0.00	3.97	3.19	4.93
India region	18.050	3.85	1.46	0.018	0.18	0.73	0.53	6.78	4.96	9.32
Israel	0.156	4.87	1.58	0.020	0.18	1.61	1.61	9.88	6.88	14.45
Jamaica	0.050	4.69	1.47	0.018	0.18	1.32	0.00	7.69	5.33	11.33
Japan	5.646	4.36	1.42	0.018	0.18	1.14	0.29	7.41	5.43	10.24
Madagascar	0.033	5.62	2.64	0.033	0.18	0.72	2.69	11.88	8.71	16.10
Mauritius	0.051	4.39	1.41	0.018	0.18	1.34	0.57	7.91	5.53	11.86
Mideast	13.948	3.61	1.46	0.018	0.18	0.65	0.15	6.07	4.51	8.24
New Zealand	0.229	3.91	1.47	0.018	0.18	0.22	0.09	5.90	4.46	7.80
Philippines	0.692	4.66	1.47	0.018	0.18	0.37	0.36	7.06	5.10	9.87
Russia region	8.851	3.61	1.21	0.015	0.18	1.32	0.00	6.34	4.63	8.93
South Am-NW	2.463	4.05	1.47	0.018	0.18	0.07	0.00	5.79	4.48	7.41
South Am-SE	6.338	4.10	1.47	0.018	0.18	0.73	0.00	6.51	4.90	8.68
Southeast Asia	11.262	5.33	1.46	0.018	0.18	0.29	0.56	7.84	5.87	10.44
South Korea	4.984	5.21	1.23	0.015	0.18	2.52	0.84	10.00	7.04	14.63
Taiwan	1.654	5.14	1.29	0.016	0.18	5.08	1.21	12.92	8.67	19.96
United States	14.080	4.15	1.46	0.018	0.18	0.22	0.39	6.42	4.88	8.42
All regions	**203.75**	**4.05**	**1.39**	**0.017**	**0.18**	**0.77**	**0.29**	**6.70**	**4.97**	**9.14**

Costs are averages of 2022 and 2050 values and in USD 2022. The mean H_2 electricity cost for each region is the "Total LCOE" from Table S24 multiplied by 47.1 kWh/kg-H_2 for electrolysis plus compression. The value for "All regions" is the average of each regional value weighted by the hydrogen production in the region. Table S21 provides electrolyzer, rectifier, compressor, storage, and fuel cell capital costs, installation factors, operation and maintenance costs, lifetime information, and efficiencies. It also provides the discount rate used. For the electrolyzer plus rectifier and compressor, calculated annualized costs (\$/kW/y) are converted to costs per kg-H_2 by multiplying by 41.46 kWh/kg-H_2 and 5.64 kWh/kg-H_2, respectively, then dividing by 8,760 hours per year and by the hydrogen use factors for the region from Table S17. Storage costs per kg-H_2-produced equal annualized storage costs (\$/kg-H_2-stored/y) multiplied by the ratio of the H_2 storage tank size to the H_2 production per year, both from Table S17. The water cost for electrolysis is estimated as \$0.0071 (\$0.0047-\$0.0094)/kg-H_2-produced[S64]. The estimated costs to dispense hydrogen fuel to vehicles and to cool the hydrogen fuel to -40 °C are \$0.17 (0.12-0.21)/kg-H_2 and \$0.22 (0.18-0.27)/kg-H_2, respectively[S53]. However, because only ~45% of the non-grid H_2 needed worldwide will be for vehicles, the dispensing and cooling costs are multiplied by 0.45. Thus, the resulting summed cost of water, dispensing, and cooling for non-grid hydrogen is \$0.183 (0.14-0.225)/kg-H_2.

Table S23b. Annual hydrogen produced and breakdown of the cost per kilogram of hydrogen produced, in the EGS cases. Mean, low, and high totals are given, but only the breakdown of the mean value is provided. Tables S20-S22 and the footnote to this table provide mean, low, and high capital cost, installation factor, and discount rate information. All costs are in units of 2022 \$/kg-H_2-produced. Non-grid and grid hydrogen are merged together. The fuel cells are for grid hydrogen. See footnote of Table S23a for more details.

Region	(a) Non-grid plus grid H_2 produced (Tg-H_2/y)	(b) Mean non-grid plus grid H_2 electricity cost (\$/kg-H_2)	(c) Mean non-grid plus grid H_2 electrolyzer + rectifier cost (\$/kg-H_2)	(d) Mean non-grid plus grid H_2 compressor cost (\$/kg-H_2)	(e) Mean non-grid plus grid H_2 water + dispensing + cooling cost (\$/kg-H_2)	(f) Mean non-grid plus grid H_2 storage cost (\$/kg-H_2)	(g) Mean grid H_2 fuel cell cost (\$/kg-H_2)	(h) Mean non-grid plus grid total H_2 cost (\$/kg-H_2) =b+c+d+e+f+g	(i) Low non-grid plus grid total H_2 cost (\$/kg-H_2)	(j) High non-grid plus grid total H_2 cost (\$/kg-H_2)
Africa-East	0.857	4.56	1.47	0.018	0.18	0.07	0.00	6.31	4.63	8.71
Africa-North	4.570	3.78	1.46	0.018	0.18	0.29	0.08	5.82	4.41	7.64
Africa-South	1.595	4.00	1.46	0.018	0.18	0.29	0.76	6.71	4.98	9.02
Africa-West	1.161	5.67	1.46	0.018	0.18	0.51	0.90	8.75	6.40	11.99
Australia	1.587	3.72	1.47	0.018	0.18	0.15	0.00	5.54	4.24	7.16
Canada	2.521	3.52	1.47	0.018	0.18	2.20	0.00	7.40	5.25	10.67
Central America	2.014	4.14	1.47	0.018	0.18	1.62	0.00	7.43	5.41	10.41
Central Asia	2.725	3.79	1.34	0.017	0.18	0.40	0.32	6.06	4.59	8.00
China region	67.524	3.96	1.44	0.018	0.18	0.36	0.27	6.23	4.70	8.26
Cuba	0.040	4.44	1.47	0.018	0.18	0.07	0.00	6.19	4.55	8.45
Europe	28.574	4.20	1.14	0.014	0.18	1.76	0.23	7.53	5.37	10.88
Haiti region	0.252	4.38	0.84	0.011	0.18	1.66	0.66	7.74	5.67	10.86
Iceland	0.022	3.50	0.41	0.006	0.18	0.00	0.00	4.10	3.27	5.14
India region	18.130	3.89	1.46	0.018	0.18	0.73	0.53	6.80	4.99	9.33
Israel	0.155	4.82	1.59	0.020	0.18	1.47	1.62	9.69	6.76	14.11
Jamaica	0.050	4.72	1.47	0.018	0.18	1.32	0.00	7.72	5.34	11.38
Japan	5.656	4.35	1.42	0.018	0.18	1.13	0.29	7.39	5.40	10.23
Madagascar	0.033	5.05	2.65	0.033	0.18	0.72	2.70	11.32	8.24	15.41
Mauritius	0.050	4.15	1.44	0.018	0.18	1.15	0.58	7.53	5.45	10.57
Mideast	13.941	3.68	1.46	0.018	0.18	0.29	0.15	5.78	4.36	7.64
New Zealand	0.229	3.87	1.47	0.018	0.18	0.22	0.09	5.85	4.41	7.74
Philippines	0.692	4.75	1.47	0.018	0.18	0.37	0.36	7.15	5.15	10.03
Russia region	8.851	3.70	1.09	0.014	0.18	1.32	0.00	6.30	4.59	8.91
South Am-NW	2.463	4.03	1.47	0.018	0.18	0.07	0.00	5.78	4.44	7.42
South Am-SE	6.338	3.98	1.47	0.018	0.18	0.29	0.00	5.94	4.53	7.73
Southeast Asia	11.853	5.02	1.39	0.017	0.18	0.28	0.53	7.42	5.57	9.82
South Korea	4.851	5.18	1.27	0.016	0.18	2.59	0.86	10.10	7.07	14.81
Taiwan	1.728	5.08	1.23	0.015	0.18	4.87	1.16	12.54	8.47	19.19
United States	14.126	4.14	1.46	0.018	0.18	0.22	0.38	6.41	4.86	8.41
All regions	**202.59**	**4.08**	**1.39**	**0.017**	**0.18**	**0.71**	**0.33**	**6.71**	**4.97**	**9.12**

Table S24. Cost results from LOADMATCH. Base-WWS-case ("base") and EGS mid-cost case ("EGS") summaries of WWS mean capital costs ($ trillion in USD 2022) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) averaged over each simulation. Also shown are the annual energy consumption and the resulting aggregate annual energy. The last row shows the percent increases in total LCOE and the total annual energy cost if the baseline battery system cost is increased from the mean value in Table S22 ($60/kWh-electricity storage) to the high value ($90/kWh-electricity storage), or by a factor of 1.5. All LCOEs are averages between 2022 and 2050.

	Africa-East base	Africa-East EGS	Africa-North base	Africa-North EGS	Africa-South base	Africa-South EGS	Africa-West base	Africa-West EGS
Capital cost new generators only ($tril)	0.427	0.480	0.804	0.935	0.588	0.686	0.884	0.927
Cap cost generators-storage-H_2-HVDC ($tril)	**0.598**	**0.622**	**1.006**	**1.126**	**0.793**	**0.868**	**1.074**	**1.117**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.143	0.141	0.140	0.141	0.162	0.158	0.122	0.122
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.375	4.634	3.370	3.623	3.555	3.834	6.964	6.881
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.001	0.001	0.011	0.011	0.016	0.016	0	0
LI battery storage	1.113	0.695	0.187	0.131	0.491	0.409	1.004	1.004
Grid H_2 fuel cells	0	0	0.044	0.026	0.122	0.122	0.129	0.129
CSPS + PHS storage	0.008	0.008	0.004	0.004	0.012	0.012	0.006	0.006
CW-STES + ICE storage	0.001	0.001	0.002	0.002	0.003	0.003	0.001	0.001
HW-STES storage	0.017	0.017	0.003	0.003	0.006	0.006	0.005	0.005
UTES storage	0.251	0.251	0.004	0.004	0.083	0.083	0.052	0.052
Heat pumps for filling district heating/cooling	0.248	0.248	0.024	0.024	0.092	0.092	0.091	0.091
Firebrick storage	0.014	0.014	0.011	0.011	0.012	0.012	0.015	0.015
Non-grid + grid merged H_2 prod/compress/storage	0.255	0.255	0.629	0.629	0.430	0.313	0.310	0.311
Total LCOE (¢/kWh-all-energy)	**9.85**	**9.69**	**7.85**	**8.03**	**8.41**	**8.49**	**12.12**	**12.04**
LCOE (¢/kWh-replacing BAU electricity)	9.055	8.895	7.161	7.342	7.775	7.967	11.642	11.559
GW annual avg. end-use demand (Table S6)	67.0	67.0	162.2	162.2	113.8	113.8	92.8	92.8
TWh/y end-use demand (GW x 8,760 h/y)	586	586	1,421	1,421	997	997	813	813
Annual energy cost ($billion/y)	**57.8**	**56.8**	**111.6**	**114.2**	**83.8**	**84.6**	**98.5**	**97.8**
% rise in LCOE & annual cost if 1.5x battery cost	5.65	3.59	1.19	0.81	2.92	2.41	4.14	4.17

	Austr-alia base	Austr-alia EGS	Canada base	Canada EGS	Central America base	Central America EGS	Central Asia base	Central Asia EGS
Capital cost new generators only ($tril)	0.363	0.426	0.563	0.605	0.801	0.882	0.801	0.937
Cap cost generators-storage-H_2-HVDC ($tril)	**0.466**	**0.520**	**0.794**	**0.823**	**0.949**	**1.008**	**0.967**	**1.099**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.168	0.170	0.189	0.226	0.113	0.115	0.148	0.147
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.389	3.608	3.369	3.098	4.459	4.587	3.610	3.902
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.083	0.083	0.031	0.031	0.029	0.029	0	0
LI battery storage	0.303	0.184	0.000	0.000	0.204	0.048	0.036	0.015
Grid H_2 fuel cells	0	0	0	0	0	0	0.064	0.064
CSPS + PHS storage	0.012	0.012	0	0	0.006	0.006	0.010	0.010
CW-STES + ICE storage	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
HW-STES storage	0.002	0.002	0.002	0.002	0.004	0.004	0.014	0.014
UTES storage	0.002	0.002	0.000	0.000	0.006	0.006	0.039	0.039
Heat pumps for filling district heating/cooling	0.003	0.003	0.002	0.002	0.007	0.007	0.040	0.040
Firebrick storage	0.013	0.013	0.012	0.012	0.014	0.014	0.013	0.013
Non-grid + grid merged H_2 prod/compress/storage	0.389	0.389	0.942	0.683	0.553	0.553	0.385	0.385
Total LCOE (¢/kWh-all-energy)	**7.79**	**7.89**	**7.97**	**7.48**	**8.82**	**8.79**	**7.78**	**8.05**
LCOE (¢/kWh-replacing BAU electricity)	7.363	7.465	6.999	6.763	8.228	8.201	7.280	7.551
GW annual avg. end-use demand (Table S6)	84.7	84.7	163.3	163.3	136.8	136.8	156.8	156.8
TWh/y end-use demand (GW x 8,760 h/y)	742	742	1,431	1,431	1,199	1,199	1,373	1,373
Annual energy cost ($billion/y)	**57.8**	**58.5**	**114.1**	**107.0**	**105.7**	**105.4**	**106.9**	**110.6**
% rise in LCOE & annual cost if 1.5x battery cost	1.94	1.17	0.00	0.00	1.16	0.27	0.23	0.09

	China region base	China region EGS	Cuba base	Cuba EGS	Europe base	Europe EGS	Haiti base	Haiti EGS
Capital cost new generators only ($tril)	11.632	13.494	0.037	0.041	3.517	4.140	0.050	0.055
Cap cost generators-storage-H_2-HVDC ($tril)	**15.520**	**17.375**	**0.048**	**0.050**	**5.373**	**5.944**	**0.065**	**0.064**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.182	0.185	0	0	0.199	0.199	0	0
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.518	3.710	4.263	4.492	3.432	3.635	4.559	4.661
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.173	0.173	0	0	0.128	0.128	0	0
LI battery storage	0.083	0.069	1.672	1.223	0	0	0	0
Grid H_2 fuel cells	0.080	0.080	0	0	0.088	0.088	0.231	0.231
CSPS + PHS storage	0.006	0.006	0.067	0.067	0.011	0.011	0.031	0.031
CW-STES + ICE storage	0.002	0.002	0.006	0.006	0.002	0.002	0.002	0.002
HW-STES storage	0.006	0.006	0.013	0.013	0.005	0.005	0.000	0.000
UTES storage	0.084	0.084	0.005	0.005	0.241	0.201	0.002	0.002
Heat pumps for filling district heating/cooling	0.072	0.072	0.040	0.040	0.049	0.049	0.001	0.001
Firebrick storage	0.014	0.014	0.017	0.017	0.008	0.008	0.013	0.013
Non-grid + grid merged H_2 prod/compress/storage	0.585	0.586	0.139	0.139	1.165	1.159	1.847	0.937
Total LCOE (¢/kWh-all-energy)	**8.23**	**8.41**	**9.65**	**9.43**	**8.75**	**8.91**	**10.11**	**9.30**

LCOE (¢/kWh-replacing BAU electricity)	7.446	7.626	9.433	9.214	7.257	7.460	8.247	8.349
GW annual avg. end-use demand (Table S6)	2,626	2,625.6	5.7	5.7	872.7	872.7	8.3	8.3
TWh/y end-use demand (GW x 8,760 h/y)	23,001	23,001	50	50	7,644	7,644	72	72
Annual energy cost ($billion/y)	**1,893**	**1,934.9**	**4.8**	**4.7**	**669.0**	**681.0**	**7.3**	**6.7**
% rise in LCOE & annual cost if 1.5x battery cost	0.51	0.41	8.7	6.5	0	0	0	0
	Iceland base	Iceland EGS	India region base	India region EGS	Israel base	Israel EGS	Jamaica base	Jamaica EGS
Capital cost new generators only ($tril)	0.002	0.005	5.277	6.136	0.076	0.081	0.012	0.013
Cap cost generators-storage-H_2-HVDC ($tril)	**0.0027**	**0.0052**	**7.102**	**7.794**	**0.112**	**0.115**	**0.016**	**0.017**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.000	0.000	0.167	0.165	0	0	0	0
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	1.812	2.094	3.382	3.616	3.971	4.006	3.933	4.012
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	1.828	1.828	0.012	0.012	0.279	0.279	0	0
LI battery storage	0	0	0.408	0.265	1.751	1.626	1.547	1.547
Grid H_2 fuel cells	0	0	0.104	0.104	0.220	0.220	0	0
CSPS + PHS storage	0	0	0.003	0.003	0.008	0.008	0.007	0.007
CW-STES + ICE storage	0.002	0.002	0.002	0.002	0.002	0.002	0	0
HW-STES storage	0.003	0.003	0.005	0.005	0.015	0.015	0.025	0.025
UTES storage	0	0	0.081	0.081	0.148	0.148	0.039	0.026
Heat pumps for filling district heating/cooling	0.005	0.005	0.089	0.089	0.056	0.056	0.065	0.065
Firebrick storage	0.021	0.021	0.019	0.019	0.007	0.007	0.013	0.013
Non-grid + grid merged H_2 prod/compress/storage	0.052	0.052	0.468	0.468	0.463	0.443	0.907	0.907
Total LCOE (¢/kWh-all-energy)	**7.15**	**7.43**	**8.16**	**8.25**	**10.34**	**10.23**	**9.96**	**10.03**
LCOE (¢/kWh-replacing BAU electricity)	7.067	7.348	7.487	7.576	9.655	9.565	8.912	8.991
GW annual avg. end-use demand (Table S6)	3.0	3.0	1,055.8	1,055.8	13.0	13.0	1.9	1.9
TWh/y end-use demand (GW x 8,760 h/y)	26	26	9,249	9,249	114	114	16	16
Annual energy cost ($billion/y)	**1.8**	**1.9**	**755.1**	**763.3**	**11.8**	**11.7**	**1.6**	**1.7**
% rise in LCOE & annual cost if 1.5x battery cost	1.48	1.48	2.50	1.60	8.5	7.9	7.77	7.71
	Japan base	Japan EGS	Mada-gascar base	Mada-gascar EGS	Mauritius base	Mauritius EGS	Mideast base	Mideast EGS
Capital cost new generators only ($tril)	0.860	0.949	0.038	0.035	0.007	0.008	2.960	3.590
Cap cost generators-storage-H2-HVDC ($tril)	**1.163**	**1.246**	**0.043**	**0.039**	**0.011**	**0.011**	**4.070**	**4.564**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.151	0.152	0	0	0	0	0.195	0.190
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.219	4.231	7.212	5.989	3.166	3.472	3.028	3.365
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.047	0.047	0.002	0.002	0.061	0.061	0.041	0.041
LI battery storage	0.227	0.193	0.611	0.611	0.545	0.545	0.243	0.167
Grid H2 fuel cells	0.107	0.107	0.263	0.263	0.217	0.217	0.034	0.034
CSPS + PHS storage	0.040	0.040	0.013	0.013	0.008	0.008	0.001	0.001
CW-STES + ICE storage	0	0	0.005	0.005	0.006	0.006	0.001	0.001
HW-STES storage	0.002	0.002	0.010	0.010	0.008	0.008	0.002	0.002
UTES storage	0.015	0.015	0.016	0.016	0.743	0.013	0.112	0.093
Heat pumps for filling district heating/cooling	0.005	0.005	0.018	0.018	0.014	0.014	0.030	0.030
Firebrick storage	0.007	0.007	0.011	0.011	0.008	0.008	0.016	0.016
Non-grid + grid merged H_2 prod/compress/storage	1.017	1.017	0.349	0.349	1.122	1.040	0.527	0.444
Total LCOE (¢/kWh-all-energy)	**9.26**	**9.24**	**11.94**	**10.71**	**9.32**	**8.82**	**7.65**	**7.81**
LCOE (¢/kWh-replacing BAU electricity)	8.190	8.169	11.531	10.308	7.428	7.734	6.947	7.202
GW annual avg. end-use demand (Table S6)	174.7	174.7	3.8	3.8	1.5	1.5	698.7	698.7
TWh/y end-use demand (GW x 8,760 h/y)	1,530	1,530	33	33	13	13	6,121	6,121
Annual energy cost ($billion/y)	**141.7**	**141.4**	**4.0**	**3.6**	**1.3**	**1.2**	**468.5**	**477.8**
% rise in LCOE & annual cost if 1.5x battery cost	1.23	1.05	2.56	2.85	2.92	3.09	1.59	1.07
	New Zealand base	New Zealand EGS	Philip-pines base	Philip-pines EGS	Russia region base	Russia region EGS	South Am-NW base	South Am-NW EGS
Capital cost new generators only ($tril)	0.063	0.069	0.249	0.273	0.887	1.092	0.477	0.519
Cap cost generators-storage-H2-HVDC ($tril)	**0.078**	**0.084**	**0.332**	**0.357**	**1.390**	**1.587**	**0.589**	**0.631**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.079	0.086	0.076	0.077	0.226	0.228	0.215	0.217
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.818	3.800	4.449	4.654	2.774	2.999	4.338	4.309
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.090	0.090	0	0	0.004	0.004	0.001	0.001
LI battery storage	0.495	0.413	1.189	1.189	0	0	0	0
Grid H2 fuel cells	0.017	0.017	0.077	0.077	0	0	0	0
CSPS + PHS storage	0.018	0.018	0.006	0.006	0.004	0.004	0.011	0.011
CW-STES + ICE storage	0	0	0.006	0.006	0.002	0.002	0.003	0.003
HW-STES storage	0.001	0.001	0.036	0.036	0.006	0.006	0.014	0.014
UTES storage	0.001	0.001	0.129	0.129	0.139	0.139	0.017	0.011
Heat pumps for filling district heating/cooling	0.002	0.002	0.048	0.048	0.056	0.056	0.016	0.016
Firebrick storage	0.013	0.013	0.011	0.011	0.010	0.010	0.011	0.011
Non-grid + grid merged H_2 prod/compress/storage	0.351	0.351	0.433	0.433	1.021	0.976	0.541	0.541
Total LCOE (¢/kWh-all-energy)	**8.31**	**8.22**	**9.89**	**10.09**	**7.67**	**7.85**	**8.59**	**8.56**
LCOE (¢/kWh-replacing BAU electricity)	7.936	7.842	9.222	9.427	6.396	6.623	7.961	7.934
GW annual avg. end-use demand (Table S6)	14.1	14.1	37.2	37.2	269.9	269.9	90.6	90.6
TWh/y end-use demand (GW x 8,760 h/y)	124	124	326	326	2,364	2,364	794	794
Annual energy cost ($billion/y)	**10.3**	**10.1**	**32.2**	**32.9**	**181.3**	**185.6**	**68.2**	**68.0**
% rise in LCOE & annual cost if 1.5x battery cost	2.98	2.51	6.02	5.89	0.00	0.00	0.00	0.00

	South Am-SE base	South Am-SE EGS	Southeast Asia base	South-east Asia EGS	South Korea base	South Korea EGS	Taiwan base	Taiwan EGS
Capital cost new generators only ($tril)	1.961	2.078	5.563	5.457	1.069	1.113	0.648	0.699
Cap cost generators-storage-H2-HVDC ($tril)	**2.311**	**2.409**	**6.391**	**6.199**	**1.382**	**1.421**	**0.847**	**0.868**
Components of total LCOE (¢/kWh-all-energy)								
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.167	0.172	0.134	0.140	0	0	0	0
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.552	4.371	6.711	6.204	5.157	5.130	4.939	5.097
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.042	0.042	0.001	0.001	0.033	0.033	0.015	0.015
LI battery storage	0	0	0.402	0.249	0.436	0.403	0.632	0.439
Grid H2 fuel cells	0	0	0.124	0.124	0.331	0.331	0.270	0.270
CSPS + PHS storage	0.004	0.004	0	0	0.010	0.010	0.010	0.010
CW-STES + ICE storage	0.002	0.002	0.002	0.002	0	0	0.002	0.002
HW-STES storage	0.001	0.001	0.004	0.004	0.002	0.002	0.005	0.005
UTES storage	0.003	0.003	0.012	0.006	0.060	0.056	0.117	0.015
Heat pumps for filling district heating/cooling	0.004	0.004	0.044	0.044	0.031	0.031	0.020	0.020
Firebrick storage	0.016	0.016	0.016	0.016	0.011	0.011	0.016	0.016
Non-grid + grid merged H_2 prod/compress/storage	0.491	0.401	0.435	0.437	1.560	1.558	1.464	1.465
Total LCOE (¢/kWh-all-energy)	**8.71**	**8.44**	**11.31**	**10.65**	**11.06**	**10.99**	**10.91**	**10.78**
LCOE (¢/kWh-replacing BAU electricity)	8.175	8.000	10.786	10.131	9.392	9.332	9.293	9.259
GW annual avg. end-use demand (Table S6)	355.0	355.0	578.5	578.5	144.3	144.3	84.8	84.8
TWh/y end-use demand (GW x 8,760 h/y)	3,109	3,109	5,068	5,068	1,264	1,264	743	743
Annual energy cost ($billion/y)	**270.7**	**262.5**	**573.2**	**539.9**	**139.7**	**138.9**	**81.1**	**80.1**
% rise in LCOE & annual cost if 1.5x battery cost	0	0	1.78	1.17	1.97	1.84	2.9	2.0

	U.S base	U.S. EGS	All regions base	All regions EGS
Capital cost new generators only ($tril)	5.252	5.721	45.867	51.447
Cap cost generators-storage-H2-HVDC ($tril)	**6.546**	**6.962**	**60.039**	**64.925**
Components of total LCOE (¢/kWh-all-energy)				
Short-dist. transmission	1.050	1.050	1.050	1.050
Long-distance transmission	0.174	0.181	0.170	0.172
Distribution	2.375	2.375	2.375	2.375
Electricity generation	4.350	4.407	3.889	4.007
Additional hydro turbines	0	0	0	0
Geothermal + solar thermal heat generation	0.068	0.068	0.082	0.082
LI battery storage	0.283	0.207	0.210	0.152
Grid H2 fuel cells	0.066	0.066	0.078	0.077
CSPS + PHS storage	0.006	0.006	0.006	0.006
CW-STES + ICE storage	0.001	0.001	0.002	0.002
HW-STES storage	0.003	0.003	0.005	0.005
UTES storage	0.057	0.057	0.085	0.078
Heat pumps for filling district heating/cooling	0.050	0.050	0.055	0.055
Firebrick storage	0.010	0.010	0.013	0.013
Non-grid + grid merged H_2 prod/compress/storage	0.320	0.320	0.621	0.602
Total LCOE (¢/kWh-all-energy)	**8.81**	**8.80**	**8.64**	**8.68**
LCOE (¢/kWh-replacing BAU electricity)	8.360	8.346	7.841	7.903
GW annual avg. end-use demand (Table S6)	945.4	945.4	8,961.8	8,961.8
TWh/y end-use demand (GW x 8,760 h/y)	8,282	8,282	78,506	78,506
Annual energy cost ($billion/y)	**729.9**	**728.8**	**6,782.9**	**6,811.6**
% rise in LCOE & annual cost if 1.5x battery cost	1.61	1.18	1.21	0.88

LI=lithium ion; CSPS=storage associated with concentrated solar power; PHS=pumped hydropower storage; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; UTES=Underground thermal energy storage in boreholes or water pits; firebrick storage is storage of low- to high-temperature heat for industrial processes in firebricks.

The LCOEs are derived from capital costs, annual O&M, and end-of-life decommissioning costs that vary by technology (Tables S20-S22) and that are a function of lifetime (Tables S20-S22) and a social discount rate for an intergenerational project of 2.0 (1-3)%, all divided by the total annualized end-use demand met, given in the present table. Capital costs are an average between 2022 and 2050, as are the LCOEs.

Capital cost of generators-storage-H_2-HVDC ($trillion) is the capital cost of new electricity and heat generation, short- and long-distance (HVDC) transmission and distribution, battery storage, concentrated solar power with storage, pumped hydropower storage, cold water storage, ice storage, hot water storage, underground thermal energy storage, ground- and air-source electric heat pumps for district heating and cooling, and hydrogen production and use-electrolyzers, rectifiers, storage tanks, water, dispensing, cooling, and fuel cells.

Since the total end-use demand includes heat, cold, hydrogen, and electricity demands (all energy), the "electricity generator" cost, for example, is a cost per unit all energy rather than per unit electricity alone. The 'Total LCOE' gives the overall cost of energy, and the 'Electricity LCOE' gives the cost of energy for the electricity portion of demand replacing BAU electricity end use. It is the total LCOE less the costs for UTES and HW-STES storage, H_2, and less the portion of long-distance transmission associated with H_2.

Short-distance transmission costs are $0.0105 (0.01-0.011)/kWh.

Distribution costs are $0.02375 (0.023-0.0245)/kWh.

Long-distance transmission costs are $0.0089 (0.0042-0.010)/kWh from Ref. S8 but brought up to USD 2022, which assumes 1,500 to 2,000 km HVDC lines, a capacity factor usage of the lines of ~50% and a capital cost of ~$400 (300-460)/MWtr-km. Table S15 gives the total HVDC line length and capacity and the fraction of all non-rooftop-PV and non-curtailed electricity generated that is subject to HVDC transmission by region.

Storage costs are derived from cost data in Table S22. This study assumes that almost all electricity storage and thermal-energy storage needed in 2050 will be built from scratch. The exception is PHS, whose 2023 installations, with a 150-country total given in Table S8, are assumed to be paid for already.

H_2 costs are broken down in Table S23.

Table S25a. Modeled LOADMATCH annual private and social costs in the base-WWS case. 2050 regional and country annual average end-use (a) BAU demand and (b) WWS demand; (c) percentage difference between WWS and BAU demand; (d) present value of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and all-distance transmission and distribution; mean levelized private costs of all (e) BAU and (f) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050); (g) mean WWS private (equals social) energy cost per year; (h) mean BAU private energy cost per year; (i) mean BAU health cost per year; (j) mean BAU climate cost per year; (k) BAU total social cost per year; (l) percentage difference between WWS and BAU private energy cost; and (m) percentage difference between WWS and BAU social energy cost. All costs are in USD 2022. H=8760 hours per year.

Region or country	(a)[1] 2050 BAU Annual average end-use demand (GW)	(b)[1] 2050 WWS Annual average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[2] WWS mean total capital cost ($tril 2022)	(e)[3] BAU mean private energy cost (¢/kWh-all energy)	(f)[4] WWS mean private energy cost (¢/kWh-all energy)	(g)[5] WWS mean annual all-energy private and social cost = bfH ($bil/y)	(h)[5] BAU mean annual all-energy private cost = aeH ($bil/y)	(i)[6] BAU mean annual BAU health cost ($bil/y)	(j)[7] BAU mean annual climate cost ($bil/y)	(k) BAU mean annual BAU total social cost =h+i+j ($bil/y)	(l) WWS minus BAU private energy cost = (g-h)/h (%)	(m) WWS minus BAU social energy cost = (g-k)/k (%)
Africa-East	**228.6**	**67.0**	**-70.7**	**0.598**	**8.02**	**9.85**	**57.8**	**160.5**	**727.7**	**107.1**	**995**	**-64.0**	**-94.2**
Eritrea	1.3	0.3	-75.5	0.003	8.02	9.85	0.3	0.9	10.6	0.8	12	-69.8	-97.8
Ethiopia	71.8	17.5	-75.6	0.147	8.02	9.85	15.1	50.4	263.2	20.2	334	-70.0	-95.5
Kenya	34.7	10.3	-70.4	0.085	8.02	9.85	8.9	24.4	69.1	26.3	120	-63.6	-92.6
Rwanda	6.2	1.6	-73.7	0.018	8.02	9.85	1.4	4.4	26.6	2.0	33	-67.6	-95.7
South Sudan	1.7	0.4	-73.1	0.004	8.02	9.85	0.4	1.2	30.1	1.5	33	-67.0	-98.8
Sudan	31.7	10.2	-67.7	0.086	8.02	9.85	8.8	22.2	160.6	24.2	207	-60.3	-95.7
Tanzania	45.9	13.6	-70.4	0.123	8.02	9.85	11.7	32.2	62.4	23.4	118	-63.6	-90.1
Uganda	35.4	12.9	-63.5	0.133	8.02	9.85	11.2	24.9	105.1	8.7	139	-55.2	-92.0
Africa-North	**405.3**	**162.2**	**-60.0**	**1.006**	**11.45**	**7.85**	**111.6**	**406.4**	**668.7**	**718.9**	**1,794**	**-72.5**	**-93.8**
Algeria	129.2	43.5	-66.3	0.276	8.02	9.85	29.9	129.5	86.4	217.9	434	-76.9	-93.1
Egypt	171.6	78.5	-54.3	0.466	8.02	9.85	54.0	172.1	382.5	301.2	856	-68.6	-93.7
Libya	28.8	11.4	-60.5	0.083	8.02	9.85	7.8	28.9	16.5	74.0	119	-72.9	-93.4
Morocco	40.0	17.3	-56.7	0.104	8.02	9.85	11.9	40.1	97.5	84.4	222	-70.3	-94.6
Niger	7.2	1.8	-75.8	0.014	8.02	9.85	1.2	7.2	56.3	3.4	67	-83.4	-98.2
Tunisia	28.5	9.8	-65.5	0.063	8.02	9.85	6.8	28.6	29.4	38.0	96	-76.3	-92.9
Africa-South	**265.4**	**113.8**	**-57.1**	**0.793**	**9.27**	**8.41**	**83.8**	**215.4**	**424.9**	**565.8**	**1,206**	**-61.1**	**-93.0**
Angola	27.1	8.7	-67.8	0.070	8.02	9.85	6.4	22.0	106.2	34.1	162	-70.7	-96.0
Botswana	4.7	1.7	-62.5	0.012	8.02	9.85	1.3	3.8	12.1	9.0	25	-66.0	-94.8
Mozambique	17.9	6.3	-64.8	0.045	8.02	9.85	4.6	14.5	73.3	11.8	100	-68.0	-95.3
Namibia	4.0	1.6	-60.0	0.012	8.02	9.85	1.2	3.3	6.9	5.3	15	-63.6	-92.3
South Africa	175.3	81.0	-53.8	0.553	8.02	9.85	59.7	142.2	130.0	480.1	752	-58.1	-92.1
Eswatini, Kingd.	2.5	1.2	-50.1	0.009	8.02	9.85	0.9	2.0	6.4	1.7	10	-54.7	-91.0
Zambia	21.6	8.4	-61.2	0.056	8.02	9.85	6.2	17.6	62.7	9.7	90	-64.8	-93.1
Zimbabwe	12.4	4.8	-61.4	0.033	8.02	9.85	3.5	10.1	27.4	14.2	52	-65.0	-93.2
Africa-West	**290.6**	**92.8**	**-68.1**	**1.074**	**9.64**	**8.16**	**98.5**	**245.5**	**1,835**	**263.4**	**2,344**	**-59.9**	**-95.8**
Benin	8.9	2.3	-74.6	0.029	8.02	9.85	2.4	7.5	34.8	7.8	50	-68.1	-95.2
Cameroon	17.5	4.8	-72.8	0.067	8.02	9.85	5.1	14.8	66.9	13.0	95	-65.8	-94.7
Congo	4.5	1.3	-71.2	0.023	8.02	9.85	1.4	3.8	23.3	8.8	36	-63.8	-96.2
Congo, DR	46.1	11.1	-76.0	0.161	8.02	9.85	11.8	39.0	85.1	4.6	129	-69.8	-90.9
Côte d'Ivoire	21.9	6.9	-68.4	0.088	8.02	9.85	7.4	18.5	76.1	17.4	112	-60.2	-93.4
Equatorial Guin.	3.1	1.4	-53.5	0.018	8.02	9.85	1.5	2.6	13.0	4.6	20	-41.5	-92.5
Gabon	11.2	6.9	-38.1	0.097	8.02	9.85	7.4	9.5	7.4	6.0	23	-22.2	-67.7
Ghana	21.4	8.7	-59.3	0.098	8.02	9.85	9.3	18.1	95.4	29.2	143	-48.8	-93.5
Nigeria	140.7	44.0	-68.7	0.439	8.02	9.85	46.7	118.9	1,382	154.6	1,655	-60.7	-97.2
Senegal	10.0	3.9	-60.7	0.038	8.02	9.85	4.2	8.5	32.9	14.5	56	-50.6	-92.5
Togo	5.1	1.4	-72.8	0.018	8.02	9.85	1.5	4.3	18.7	3.0	26	-65.8	-94.3
Australia	**189.2**	**84.7**	**-55.2**	**0.466**	**10.24**	**7.79**	**57.8**	**169.7**	**46.7**	**345.7**	**562**	**-66.0**	**-89.7**
Canada	**418.1**	**163.3**	**-60.9**	**0.794**	**8.07**	**7.97**	**114.1**	**295.5**	**56.4**	**517.5**	**869**	**-61.4**	**-86.9**
Central America	**332.8**	**136.8**	**-58.9**	**0.949**	**10.31**	**8.82**	**105.7**	**300.5**	**495.1**	**599.9**	**1,396**	**-64.8**	**-92.4**
Costa Rica	8.0	3.5	-55.5	0.029	10.31	8.82	2.7	7.2	6.1	8.4	22	-61.9	-87.4
El Salvador	6.0	2.7	-55.3	0.022	10.31	8.82	2.1	5.4	9.0	8.2	23	-61.8	-90.8
Guatemala	22.6	6.7	-70.4	0.042	10.31	8.82	5.2	20.4	50.2	21.0	92	-74.6	-94.3
Honduras	7.8	3.0	-61.2	0.023	10.31	8.82	2.3	7.0	25.2	10.8	43	-66.8	-94.6
Mexico	268.0	113.9	-57.5	0.789	10.31	8.82	88.0	242.0	380.6	531.3	1,154	-63.6	-92.4
Nicaragua	4.8	1.6	-66.4	0.010	10.31	8.82	1.2	4.3	14.8	5.6	25	-71.2	-95.0
Panama	15.7	5.4	-65.6	0.035	10.31	8.82	4.2	14.2	9.1	14.5	38	-70.6	-89.0
Central Asia	**410.4**	**156.8**	**-61.8**	**0.967**	**10.46**	**7.78**	**106.9**	**376.1**	**1,342**	**630.7**	**2,348**	**-71.6**	**-95.4**

Kazakhstan	85.3	30.6	-64.2	0.174	10.46	7.78	20.8	78.2	146.0	201.2	425	-73.4	-95.1
Kyrgyz Rep.	6.3	3.0	-51.4	0.013	10.46	7.78	2.1	5.7	20.9	8.8	35	-63.8	-94.1
Pakistan	194.9	81.9	-58.0	0.556	10.46	7.78	55.8	178.6	967.9	241.9	1,388	-68.7	-96.0
Tajikistan	6.0	3.2	-46.2	0.007	10.46	7.78	2.2	5.5	31.5	7.8	45	-60.0	-95.1
Turkmenistan	51.4	16.2	-68.6	0.096	10.46	7.78	11.0	47.1	26.0	55.3	128	-76.6	-91.4
Uzbekistan	66.6	21.9	-67.0	0.122	10.46	7.78	15.0	61.0	149.3	115.6	326	-75.5	-95.4
China region	**5,139.0**	**2,625.6**	**-48.9**	**15.520**	**9.65**	**8.23**	**1,893.1**	**4,345.5**	**11,392**	**9,697.5**	**25,435**	**-56.4**	**-92.6**
China	5,055.8	2,586.5	-48.8	15.221	9.65	8.23	1,864.8	4,275.1	11,187	9,544.2	25,007	-56.4	-92.5
Hong Kong	42.2	16.6	-60.6	0.140	9.65	8.23	12.0	35.7	59.3	41.8	137	-66.4	-91.2
Korea, DPR	30.2	18.3	-39.4	0.132	9.65	8.23	13.2	25.6	115.0	77.5	218	-48.4	-93.9
Mongolia	10.8	4.2	-60.6	0.028	9.65	8.23	3.1	9.1	30.6	33.9	74	-66.4	-95.8
Cuba	**10.0**	**5.7**	**-42.8**	**0.048**	**11.71**	**9.65**	**4.8**	**10.2**	**39.5**	**21.7**	**71**	**-52.9**	**-93.2**
Europe	**2,060.5**	**872.7**	**-57.6**	**5.373**	**10.20**	**8.75**	**669.0**	**1,840.6**	**2,196**	**2,457.6**	**6,494**	**-63.7**	**-89.7**
Albania	3.8	1.8	-51.8	0.009	10.20	8.75	1.4	3.4	24.4	3.9	32	-58.7	-95.6
Austria	42.9	19.8	-53.9	0.131	10.20	8.75	15.2	38.3	27.7	44.5	111	-60.4	-86.3
Belarus	32.5	11.4	-65.0	0.082	10.20	8.75	8.7	29.0	68.8	45.4	143	-70.0	-93.9
Belgium	64.0	26.4	-58.8	0.178	10.20	8.75	20.2	57.1	30.7	63.8	152	-64.6	-86.7
Bosnia-Herzeg.	8.4	3.4	-58.9	0.020	10.20	8.75	2.6	7.5	43.8	18.5	70	-64.7	-96.2
Bulgaria	20.6	9.2	-55.3	0.091	10.20	8.75	7.0	18.4	38.7	33.4	90	-61.6	-92.2
Croatia	13.3	5.5	-58.9	0.059	10.20	8.75	4.2	11.9	23.1	14.6	50	-64.7	-91.5
Cyprus	3.9	1.7	-55.7	0.011	10.20	8.75	1.3	3.4	3.2	6.0	13	-62.0	-89.7
Czech Rep.	41.5	17.3	-58.2	0.129	10.20	8.75	13.3	37.0	41.8	68.5	147	-64.1	-91.0
Denmark	23.0	9.0	-61.0	0.063	10.20	8.75	6.9	20.6	13.5	20.3	54	-66.5	-87.3
Estonia	5.7	1.9	-66.9	0.014	10.20	8.75	1.4	5.1	1.9	8.7	16	-71.6	-90.8
Finland	37.9	19.8	-47.8	0.127	10.20	8.75	15.2	33.8	7.4	24.4	66	-55.2	-76.9
France	227.9	102.3	-55.1	0.611	10.20	8.75	78.5	203.6	139.8	213.6	557	-61.5	-85.9
Germany	331.9	140.8	-57.6	0.828	10.20	8.75	108.0	296.5	249.5	441.1	987	-63.6	-89.1
Gibraltar	7.0	1.7	-75.3	0.015	10.20	8.75	1.3	6.2	0.3	0.5	7	-78.8	-81.2
Greece	31.4	12.4	-60.4	0.067	10.20	8.75	9.5	28.0	43.8	39.1	111	-66.0	-91.4
Hungary	30.0	12.3	-59.0	0.090	10.20	8.75	9.4	26.8	48.7	33.2	109	-64.8	-91.3
Ireland	18.6	8.2	-55.7	0.057	10.20	8.75	6.3	16.6	11.5	24.6	53	-62.0	-88.0
Italy	197.9	79.6	-59.8	0.482	10.20	8.75	61.0	176.8	219.7	231.1	628	-65.5	-90.3
Kosovo	2.9	1.5	-49.8	0.011	10.20	8.75	1.1	2.6	1.8	7.1	12	-56.9	-90.3
Latvia	7.2	2.9	-59.7	0.018	10.20	8.75	2.2	6.5	12.2	5.5	24	-65.4	-90.7
Lithuania	11.1	4.6	-58.6	0.035	10.20	8.75	3.5	9.9	20.8	11.0	42	-64.5	-91.6
Luxembourg	5.5	2.1	-62.0	0.015	10.20	8.75	1.6	4.9	2.1	5.3	12	-67.4	-87.0
Macedonia	3.5	1.7	-51.6	0.011	10.20	8.75	1.3	3.1	15.6	7.4	26	-58.5	-95.0
Malta	5.0	1.6	-68.9	0.010	10.20	8.75	1.2	4.4	1.5	1.4	7	-73.3	-83.9
Moldova	4.9	1.8	-62.3	0.013	10.20	8.75	1.4	4.4	7.2	8.3	20	-67.6	-92.9
Montenegro	1.5	0.7	-52.1	0.004	10.20	8.75	0.5	1.3	7.2	3.6	12	-58.9	-95.5
Netherlands	92.7	36.8	-60.3	0.218	10.20	8.75	28.2	82.8	50.9	93.0	227	-65.9	-87.5
Norway	44.5	20.7	-53.4	0.065	10.20	8.75	15.9	39.8	8.0	33.3	81	-60.0	-80.4
Poland	121.1	47.3	-60.9	0.323	10.20	8.75	36.3	108.2	176.4	217.1	502	-66.5	-92.8
Portugal	28.9	13.1	-54.7	0.071	10.20	8.75	10.0	25.8	19.0	27.4	72	-61.1	-86.1
Romania	44.8	17.0	-62.1	0.102	10.20	8.75	13.0	40.1	188.7	59.4	288	-67.5	-95.5
Serbia	19.2	8.3	-57.0	0.057	10.20	8.75	6.3	17.2	68.3	47.1	133	-63.1	-95.2
Slovakia	17.8	8.1	-54.7	0.053	10.20	8.75	6.2	15.9	17.7	26.4	60	-61.1	-89.7
Slovenia	7.5	3.4	-54.2	0.022	10.20	8.75	2.6	6.7	5.3	9.1	21	-60.7	-87.6
Spain	154.4	63.1	-59.1	0.349	10.20	8.75	48.4	137.9	100.0	164.5	402	-64.9	-88.0
Sweden	54.8	29.6	-46.1	0.150	10.20	8.75	22.7	49.0	15.6	26.8	91	-53.7	-75.2
Switzerland	29.1	13.7	-52.8	0.061	10.20	8.75	10.5	26.0	17.8	25.9	70	-59.5	-84.9
Ukraine	59.2	31.3	-47.1	0.206	10.20	8.75	24.0	52.9	244.6	114.3	412	-54.6	-94.2
United King.	202.9	78.8	-61.2	0.516	10.20	8.75	60.4	181.2	177.2	228.6	587	-66.7	-89.7
Haiti region	**20.2**	**8.3**	**-59.1**	**0.065**	**10.77**	**10.11**	**7.3**	**19.1**	**45.3**	**34.3**	**99**	**-61.6**	**-92.6**
Dominican Rep	15.3	7.0	-54.4	0.053	10.77	10.11	6.2	14.4	24.2	30.8	69	-57.2	-91.1
Haiti	5.0	1.3	-73.7	0.012	10.77	10.11	1.2	4.7	21.1	3.5	29	-75.3	-96.1
Iceland	**5.1**	**3.0**	**-42.2**	**0.0027**	**7.39**	**7.15**	**1.8**	**3.3**	**0.4**	**2.3**	**6**	**-44.9**	**-70.0**
India region	**1,997.3**	**1,055.8**	**-47.1**	**7.102**	**9.86**	**8.16**	**755.1**	**1,724.7**	**9,546**	**4,053.2**	**15,323**	**-56.2**	**-95.1**
Bangladesh	78.1	37.6	-51.9	0.257	9.86	8.16	26.9	67.4	650.6	150.6	869	-60.1	-96.9
India	1,866.9	997.2	-46.6	6.701	9.86	8.16	713.2	1,612.0	8,677	3,856.2	14,145	-55.8	-95.0
Nepal	29.5	11.0	-62.7	0.080	9.86	8.16	7.9	25.5	106.0	21.6	153	-69.1	-94.9
Sri Lanka	22.9	10.0	-56.1	0.063	9.86	8.16	7.2	19.7	111.6	24.8	156	-63.6	-95.4
Israel	**27.2**	**13.0**	**-52.0**	**0.112**	**11.30**	**10.34**	**11.8**	**26.9**	**17.8**	**46.4**	**91**	**-56.1**	**-87.0**
Jamaica	**4.9**	**1.9**	**-61.6**	**0.016**	**11.50**	**9.96**	**1.6**	**4.9**	**5.3**	**6.7**	**17**	**-66.7**	**-90.3**
Japan	**329.2**	**174.7**	**-46.9**	**1.163**	**10.50**	**9.26**	**141.7**	**302.8**	**322.4**	**577.6**	**1,203**	**-53.2**	**-88.2**
Madagascar	**13.7**	**3.8**	**-72.1**	**0.043**	**9.70**	**11.94**	**4.0**	**11.6**	**74.5**	**5.0**	**91**	**-65.7**	**-95.6**
Mauritius	**4.1**	**1.5**	**-62.2**	**0.011**	**10.80**	**9.32**	**1.3**	**3.9**	**3.8**	**5.1**	**13**	**-67.4**	**-90.1**
Mideast	**1,523.3**	**698.7**	**-54.1**	**4.070**	**11.43**	**7.65**	**468.5**	**1,525.0**	**1,148**	**2,940.5**	**5,614**	**-69.3**	**-91.7**
Armenia	5.7	1.8	-67.6	0.008	11.43	7.65	1.2	5.7	15.4	6.5	28	-78.3	-95.5
Azerbaijan	21.6	7.4	-65.6	0.044	11.43	7.65	5.0	21.6	83.0	35.9	141	-77.0	-96.5
Bahrain	17.1	9.8	-42.7	0.051	11.43	7.65	6.5	17.1	4.1	42.7	64	-61.6	-89.8

Iran	494.4	209.5	-57.6	1.273	11.43	7.65	140.5	495.0	249.5	889.2	1,634	-71.6	-91.4
Iraq	69.6	27.4	-60.7	0.195	11.43	7.65	18.4	69.7	114.4	220.2	404	-73.7	-95.5
Jordan	14.4	6.9	-52.3	0.039	11.43	7.65	4.6	14.4	9.1	26.9	50	-68.1	-90.9
Kuwait	62.8	27.9	-55.6	0.153	11.43	7.65	18.7	62.9	12.2	127.5	203	-70.3	-90.8
Lebanon	7.0	2.3	-67.0	0.013	11.43	7.65	1.5	7.0	13.2	19.8	40	-77.9	-96.1
Oman	62.4	25.0	-59.9	0.148	11.43	7.65	16.8	62.5	16.6	106.3	185	-73.2	-91.0
Qatar	73.5	31.3	-57.5	0.164	11.43	7.65	21.0	73.6	5.3	146.0	225	-71.5	-90.7
Saudi Arabia	312.4	160.7	-48.6	0.950	11.43	7.65	107.7	312.7	179.5	711.2	1,203	-65.5	-91.0
Syria	11.5	5.3	-53.5	0.032	11.43	7.65	3.6	11.5	58.9	29.2	100	-68.9	-96.4
Türkiye	181.7	84.1	-53.7	0.471	11.43	7.65	56.4	182.0	277.5	331.6	791	-69.0	-92.9
UAE	184.2	97.6	-47.0	0.518	11.43	7.65	65.4	184.4	14.8	235.1	434	-64.5	-84.9
Yemen	5.0	1.8	-64.4	0.012	11.43	7.65	1.2	5.0	94.3	12.4	112	-76.2	-98.9
New Zealand	**26.4**	**14.1**	**-46.5**	**0.078**	**8.02**	**8.31**	**10.3**	**18.5**	**10.0**	**33.1**	**62**	**-44.6**	**-83.3**
Philippines	**87.9**	**37.2**	**-57.7**	**0.332**	**10.10**	**9.89**	**32.2**	**77.7**	**906.0**	**194.6**	**1,178**	**-58.6**	**-97.3**
Russia region	**748.3**	**269.9**	**-63.9**	**1.390**	**10.31**	**7.67**	**181.3**	**675.6**	**1,025**	**1,444.4**	**3,145**	**-73.2**	**-94.2**
Georgia	9.5	3.7	-61.6	0.013	10.31	7.67	2.5	8.6	33.3	10.8	53	-71.4	-95.3
Russia	738.8	266.2	-64.0	1.377	10.31	7.67	178.8	667.0	991.5	1,433.6	3,092	-73.2	-94.2
South Am-NW	**227.7**	**90.6**	**-60.2**	**0.589**	**8.41**	**8.59**	**68.2**	**167.7**	**281.6**	**342.9**	**792**	**-59.3**	**-91.4**
Bolivia	17.7	5.7	-67.9	0.038	8.41	8.59	4.3	13.0	35.3	23.4	72	-67.2	-94.0
Colombia	67.7	26.3	-61.2	0.177	8.41	8.59	19.8	49.9	85.8	99.2	235	-60.4	-91.6
Curacao	5.0	1.5	-70.0	0.008	8.41	8.59	1.1	3.6	0.1	2.4	6	-69.4	-81.8
Ecuador	28.5	10.6	-62.9	0.074	8.41	8.59	7.9	21.0	22.8	44.6	88	-62.1	-91.0
Guyana	1.6	0.7	-54.2	0.006	8.41	8.59	0.5	1.2	2.4	3.3	7	-53.1	-92.0
Peru	47.1	19.1	-59.5	0.114	8.41	8.59	14.4	34.7	64.5	57.5	157	-58.6	-90.8
Suriname	1.5	0.6	-62.7	0.004	8.41	8.59	0.4	1.1	1.5	2.6	5	-61.9	-92.0
Trinidad/Tobago	10.1	7.3	-27.5	0.040	8.41	8.59	5.5	7.4	1.8	26.8	36	-25.9	-84.7
Venezuela	48.6	19.0	-60.9	0.128	8.41	8.59	14.3	35.8	67.3	83.2	186	-60.1	-92.3
South Am-SE	**784.0**	**355.0**	**-54.7**	**2.311**	**8.40**	**8.71**	**270.7**	**576.7**	**595.1**	**769.4**	**1,941**	-53.1	-86.1
Argentina	131.9	46.8	-64.5	0.251	8.41	8.59	35.7	97.0	121.2	180.8	399	-63.2	-91.0
Brazil	565.1	263.5	-53.4	1.862	8.41	8.59	201.0	415.7	419.8	480.2	1,316	-51.7	-84.7
Chile	65.8	34.2	-47.9	0.158	8.41	8.59	26.1	48.4	34.2	91.7	174	-46.0	-85.0
Paraguay	11.7	5.4	-53.5	0.014	8.41	8.59	4.1	8.6	14.1	8.1	31	-51.8	-86.5
Uruguay	9.6	4.9	-48.3	0.026	8.41	8.59	3.8	7.0	5.9	8.7	22	-46.4	-82.5
Southeast Asia	**1,207.6**	**578.5**	**-52.1**	**6.391**	**10.30**	**11.31**	**573.2**	**1,089.2**	**2,392**	**2,110.0**	**5,591**	**-47.4**	**-89.7**
Brunei	5.1	1.6	-69.8	0.017	10.30	11.31	1.5	4.6	0.8	11.7	17	-66.9	-91.1
Cambodia	17.4	8.2	-52.7	0.073	10.30	11.31	8.2	15.7	52.3	21.7	90	-48.0	-90.9
Indonesia	403.5	207.1	-48.7	2.084	10.30	11.31	205.2	363.9	1,113	813.7	2,291	-43.6	-91.0
Lao PDR	7.9	3.8	-51.9	0.007	10.30	11.31	3.7	7.1	37.0	31.4	75	-47.2	-95.0
Malaysia	154.8	71.1	-54.1	0.814	10.30	11.31	70.5	139.7	194.9	341.8	676	-49.5	-89.6
Myanmar	40.6	12.2	-69.9	0.087	10.30	11.31	12.1	36.6	267.6	40.3	344	-66.9	-96.5
Singapore	185.7	59.5	-67.9	1.411	10.30	11.31	59.0	167.5	29.9	68.8	266	-64.8	-77.8
Thailand	219.1	106.3	-51.5	1.012	10.30	11.31	105.4	197.6	289.6	330.7	818	-46.7	-87.1
Vietnam	173.4	108.6	-37.4	0.886	10.30	11.31	107.6	156.4	406.1	450.0	1,012	-31.2	-89.4
South Korea	**289.3**	**144.3**	**-50.1**	**1.382**	**10.74**	**11.06**	**139.7**	**272.2**	**121.2**	**477.3**	**871**	**-48.7**	**-84.0**
Taiwan	**157.0**	**84.8**	**-46.0**	**0.847**	**10.80**	**10.91**	**81.1**	**148.6**	**92.2**	**337.6**	**578**	**-45.4**	**-86.0**
United States	**2,356.7**	**945.4**	**-59.9**	**6.546**	**10.66**	**8.81**	**729.9**	**2,200.7**	**1,065**	**3,200.0**	**6,466**	**-66.8**	**-88.7**
All regions	**19,560**	**8,962**	**-54.2**	**60.0**	**10.05**	**8.64**	**6,783**	**17,215**	**36,875**	**32,506**	**86,596**	**-60.6**	**-92.2**

[1]From Table S4.

[2]The total capital cost includes the capital cost of new WWS electricity and heat generators; new equipment for electricity storage, low-temperature building heat storage, and hydrogen storage; hydrogen electrolyzers and compressors; ground- and air-source electric heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2022 and 2050.

[3]This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2022 and 2050.

[4]The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat). It is an average between 2022 and 2050.

[5]The annual private cost of WWS or BAU energy equals the cost per unit energy from Column (f) or (e), respectively, multiplied by the energy consumed per year, which equals the end-use demand from Column (b) or (a), respectively, multiplied by 8,760 hours per year.

[6]The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 from Table S26a, Column (a), multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy[13]) and by a value of statistical life (VOSL) calculated for each country and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts[13]. See Ref. S3 for values of VOSL in each country and Note S9 for a discussion.

[7]The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S26a, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S26a, Column (f) (in USD 2022), which is updated from values in Ref. S13, which were in 2013 USD. See Note S9 for a discussion.

Table S25b. EGS-mid-cost-case LOADMATCH-modeled annual private and social costs. 2050 regional and country annual average end-use (a) BAU demand and (b) WWS demand; (c) percentage difference between WWS and BAU demand; (d) present value of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and all-distance transmission and distribution; mean levelized private costs of all (e) BAU and (f) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050); (g) mean WWS private (equals social) energy cost per year; (h) mean BAU private energy cost per year; (i) mean BAU health cost per year; (j) mean BAU climate cost per year; (k) BAU total social cost per year; (l) percentage difference between WWS and BAU private energy cost; and (m) percentage difference between WWS and BAU social energy cost. All costs are in USD 2022. H=8760 hours per year.

Region or country	(a)[1] 2050 BAU Annual average end-use demand (GW)	(b)[1] 2050 WWS Annual average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[2] WWS mean total capital cost ($tril 2022)	(e)[3] BAU mean private energy cost (¢/kWh-all energy)	(f)[4] WWS mean private energy cost (¢/kWh-all energy)	(g)[5] WWS mean annual all-energy private and social cost = bfH ($bil/y)	(h)[5] BAU mean annual all-energy private cost = aeH ($bil/y)	(i)[6] BAU mean annual BAU health cost ($bil/y)	(j)[7] BAU mean annual climate cost ($bil/y)	(k) BAU mean annual BAU total social cost =h+i+j ($bil/y)	(l) WWS minus BAU private energy cost = (g-h)/h (%)	(m) WWS minus BAU social energy cost = (g-k)/k (%)
Africa-East	**228.6**	**67.0**	**-70.7**	**0.622**	**8.02**	**9.69**	**56.8**	**160.5**	**727.7**	**107.1**	**995**	**-64.6**	**-94.3**
Eritrea	1.3	0.3	-75.5	0.003	8.02	9.69	0.3	0.9	10.6	0.8	12	-70.3	-97.8
Ethiopia	71.8	17.5	-75.6	0.154	8.02	9.69	14.9	50.4	263.2	20.2	334	-70.5	-95.5
Kenya	34.7	10.3	-70.4	0.089	8.02	9.69	8.7	24.4	69.1	26.3	120	-64.2	-92.7
Rwanda	6.2	1.6	-73.7	0.018	8.02	9.69	1.4	4.4	26.6	2.0	33	-68.2	-95.8
South Sudan	1.7	0.4	-73.1	0.004	8.02	9.69	0.4	1.2	30.1	1.5	33	-67.5	-98.8
Sudan	31.7	10.2	-67.7	0.090	8.02	9.69	8.7	22.2	160.6	24.2	207	-61.0	-95.8
Tanzania	45.9	13.6	-70.4	0.128	8.02	9.69	11.5	32.2	62.4	23.4	118	-64.2	-90.2
Uganda	35.4	12.9	-63.5	0.136	8.02	9.69	11.0	24.9	105.1	8.7	139	-55.9	-92.1
Africa-North	**405.3**	**162.2**	**-60.0**	**1.126**	**11.45**	**8.03**	**114.2**	**406.4**	**668.7**	**718.9**	**1,794**	**-71.9**	**-93.6**
Algeria	129.2	43.5	-66.3	0.308	8.02	9.69	30.6	129.5	86.4	217.9	434	-76.4	-92.9
Egypt	171.6	78.5	-54.3	0.525	8.02	9.69	55.2	172.1	382.5	301.2	856	-67.9	-93.5
Libya	28.8	11.4	-60.5	0.091	8.02	9.69	8.0	28.9	16.5	74.0	119	-72.3	-93.3
Morocco	40.0	17.3	-56.7	0.117	8.02	9.69	12.2	40.1	97.5	84.4	222	-69.6	-94.5
Niger	7.2	1.8	-75.8	0.016	8.02	9.69	1.2	7.2	56.3	3.4	67	-83.0	-98.2
Tunisia	28.5	9.8	-65.5	0.070	8.02	9.69	6.9	28.6	29.4	38.0	96	-75.8	-92.8
Africa-South	**265.4**	**113.8**	**-57.1**	**0.868**	**9.27**	**8.49**	**84.6**	**215.4**	**424.9**	**565.8**	**1,206**	**-60.7**	**-93.0**
Angola	27.1	8.7	-67.8	0.074	8.02	9.69	6.5	22.0	106.2	34.1	162	-70.5	-96.0
Botswana	4.7	1.7	-62.5	0.013	8.02	9.69	1.3	3.8	12.1	9.0	25	-65.7	-94.8
Mozambique	17.9	6.3	-64.8	0.049	8.02	9.69	4.7	14.5	73.3	11.8	100	-67.7	-95.3
Namibia	4.0	1.6	-60.0	0.013	8.02	9.69	1.2	3.3	6.9	5.3	15	-63.3	-92.2
South Africa	175.3	81.0	-53.8	0.611	8.02	9.69	60.2	142.2	130.0	480.1	752	-57.7	-92.0
Eswatini, Kingd.	2.5	1.2	-50.1	0.010	8.02	9.69	0.9	2.0	6.4	1.7	10	-54.3	-90.9
Zambia	21.6	8.4	-61.2	0.062	8.02	9.69	6.2	17.6	62.7	9.7	90	-64.5	-93.1
Zimbabwe	12.4	4.8	-61.4	0.036	8.02	9.69	3.6	10.1	27.4	14.2	52	-64.7	-93.1
Africa-West	**290.6**	**92.8**	**-68.1**	**1.117**	**9.64**	**8.25**	**97.8**	**245.5**	**1,835**	**263.4**	**2,344**	**-60.1**	**-95.8**
Benin	8.9	2.3	-74.6	0.030	8.02	9.69	2.4	7.5	34.8	7.8	50	-68.3	-95.2
Cameroon	17.5	4.8	-72.8	0.066	8.02	9.69	5.0	14.8	66.9	13.0	95	-66.0	-94.7
Congo	4.5	1.3	-71.2	0.022	8.02	9.69	1.4	3.8	23.3	8.8	36	-64.0	-96.2
Congo, DR	46.1	11.1	-76.0	0.160	8.02	9.69	11.7	39.0	85.1	4.6	129	-70.0	-90.9
Côte d'Ivoire	21.9	6.9	-68.4	0.089	8.02	9.69	7.3	18.5	76.1	17.4	112	-60.5	-93.5
Equatorial Guin.	3.1	1.4	-53.5	0.019	8.02	9.69	1.5	2.6	13.0	4.6	20	-41.9	-92.5
Gabon	11.2	6.9	-38.1	0.099	8.02	9.69	7.3	9.5	7.4	6.0	23	-22.8	-67.9
Ghana	21.4	8.7	-59.3	0.103	8.02	9.69	9.2	18.1	95.4	29.2	143	-49.2	-93.6
Nigeria	140.7	44.0	-68.7	0.470	8.02	9.69	46.4	118.9	1,382	154.6	1,655	-61.0	-97.2
Senegal	10.0	3.9	-60.7	0.040	8.02	9.69	4.2	8.5	32.9	14.5	56	-50.9	-92.6
Togo	5.1	1.4	-72.8	0.018	8.02	9.69	1.5	4.3	18.7	3.0	26	-66.1	-94.4
Australia	**189.2**	**84.7**	**-55.2**	**0.520**	**10.24**	**7.89**	**58.5**	**169.7**	**46.7**	**345.7**	**562**	**-65.5**	**-89.6**
Canada	**418.1**	**163.3**	**-60.9**	**0.823**	**8.07**	**7.48**	**107.0**	**295.5**	**56.4**	**517.5**	**869**	**-63.8**	**-87.7**
Central America	**332.8**	**136.8**	**-58.9**	**1.008**	**10.31**	**8.79**	**105.4**	**300.5**	**495.1**	**599.9**	**1,396**	**-64.9**	**-92.4**
Costa Rica	8.0	3.5	-55.5	0.031	10.31	8.79	2.7	7.2	6.1	8.4	22	-62.0	-87.5
El Salvador	6.0	2.7	-55.3	0.024	10.31	8.79	2.1	5.4	9.0	8.2	23	-61.9	-90.9
Guatemala	22.6	6.7	-70.4	0.045	10.31	8.79	5.2	20.4	50.2	21.0	92	-74.7	-94.4
Honduras	7.8	3.0	-61.2	0.024	10.31	8.79	2.3	7.0	25.2	10.8	43	-66.9	-94.6
Mexico	268.0	113.9	-57.5	0.836	10.31	8.79	87.7	242.0	380.6	531.3	1,154	-63.8	-92.4
Nicaragua	4.8	1.6	-66.4	0.010	10.31	8.79	1.2	4.3	14.8	5.6	25	-71.3	-95.0
Panama	15.7	5.4	-65.6	0.037	10.31	8.79	4.2	14.2	9.1	14.5	38	-70.7	-89.0
Central Asia	**410.4**	**156.8**	**-61.8**	**1.099**	**10.46**	**8.05**	**110.6**	**376.1**	**1,342**	**630.7**	**2,348**	**-70.6**	**-95.3**

Kazakhstan	85.3	30.6	-64.2	0.200	10.46	8.05	21.6	78.2	146.0	201.2	425	-72.4	-94.9
Kyrgyz Rep.	6.3	3.0	-51.4	0.015	10.46	8.05	2.1	5.7	20.9	8.8	35	-62.6	-93.9
Pakistan	194.9	81.9	-58.0	0.624	10.46	8.05	57.8	178.6	967.9	241.9	1,388	-67.7	-95.8
Tajikistan	6.0	3.2	-46.2	0.011	10.46	8.05	2.3	5.5	31.5	7.8	45	-58.6	-94.9
Turkmenistan	51.4	16.2	-68.6	0.109	10.46	8.05	11.4	47.1	26.0	55.3	128	-75.8	-91.1
Uzbekistan	66.6	21.9	-67.0	0.140	10.46	8.05	15.5	61.0	149.3	115.6	326	-74.6	-95.3
China region	**5,139.0**	**2,625.6**	**-48.9**	**17.375**	**9.65**	**8.41**	**1,934.9**	**4,345.5**	**11,392**	**9,697.5**	**25,435**	**-55.5**	**-92.4**
China	5,055.8	2,586.5	-48.8	17.049	9.65	8.41	1,906.0	4,275.1	11,187	9,544.2	25,007	-55.4	-92.4
Hong Kong	42.2	16.6	-60.6	0.155	9.65	8.41	12.2	35.7	59.3	41.8	137	-65.7	-91.1
Korea, DPR	30.2	18.3	-39.4	0.141	9.65	8.41	13.5	25.6	115.0	77.5	218	-47.2	-93.8
Mongolia	10.8	4.2	-60.6	0.030	9.65	8.41	3.1	9.1	30.6	33.9	74	-65.7	-95.8
Cuba	**10.0**	**5.7**	**-42.8**	**0.050**	**11.71**	**9.43**	**4.7**	**10.2**	**39.5**	**21.7**	**71**	**-53.9**	**-93.4**
Europe	**2,060.5**	**872.7**	**-57.6**	**5.944**	**10.20**	**8.91**	**681.0**	**1,840.6**	**2,196**	**2,457.6**	**6,494**	**-63.0**	**-89.5**
Albania	3.8	1.8	-51.8	0.010	10.20	8.91	1.4	3.4	24.4	3.9	32	-57.9	-95.5
Austria	42.9	19.8	-53.9	0.146	10.20	8.91	15.5	38.3	27.7	44.5	111	-59.7	-86.0
Belarus	32.5	11.4	-65.0	0.087	10.20	8.91	8.9	29.0	68.8	45.4	143	-69.4	-93.8
Belgium	64.0	26.4	-58.8	0.190	10.20	8.91	20.6	57.1	30.7	63.8	152	-64.0	-86.4
Bosnia-Herzeg.	8.4	3.4	-58.9	0.023	10.20	8.91	2.7	7.5	43.8	18.5	70	-64.1	-96.1
Bulgaria	20.6	9.2	-55.3	0.098	10.20	8.91	7.2	18.4	38.7	33.4	90	-60.9	-92.1
Croatia	13.3	5.5	-58.9	0.063	10.20	8.91	4.3	11.9	23.1	14.6	50	-64.1	-91.4
Cyprus	3.9	1.7	-55.7	0.013	10.20	8.91	1.3	3.4	3.2	6.0	13	-61.3	-89.5
Czech Rep.	41.5	17.3	-58.2	0.138	10.20	8.91	13.5	37.0	41.8	68.5	147	-63.5	-90.8
Denmark	23.0	9.0	-61.0	0.068	10.20	8.91	7.0	20.6	13.5	20.3	54	-65.9	-87.1
Estonia	5.7	1.9	-66.9	0.015	10.20	8.91	1.5	5.1	1.9	8.7	16	-71.0	-90.6
Finland	37.9	19.8	-47.8	0.138	10.20	8.91	15.4	33.8	7.4	24.4	66	-54.4	-76.5
France	227.9	102.3	-55.1	0.681	10.20	8.91	79.9	203.6	139.8	213.6	557	-60.8	-85.7
Germany	331.9	140.8	-57.6	0.914	10.20	8.91	109.9	296.5	249.5	441.1	987	-62.9	-88.9
Gibraltar	7.0	1.7	-75.3	0.016	10.20	8.91	1.3	6.2	0.3	0.5	7	-78.4	-80.9
Greece	31.4	12.4	-60.4	0.076	10.20	8.91	9.7	28.0	43.8	39.1	111	-65.4	-91.3
Hungary	30.0	12.3	-59.0	0.097	10.20	8.91	9.6	26.8	48.7	33.2	109	-64.2	-91.2
Ireland	18.6	8.2	-55.7	0.061	10.20	8.91	6.4	16.6	11.5	24.6	53	-61.3	-87.8
Italy	197.9	79.6	-59.8	0.541	10.20	8.91	62.1	176.8	219.7	231.1	628	-64.9	-90.1
Kosovo	2.9	1.5	-49.8	0.011	10.20	8.91	1.1	2.6	1.8	7.1	12	-56.1	-90.1
Latvia	7.2	2.9	-59.7	0.020	10.20	8.91	2.3	6.5	12.2	5.5	24	-64.8	-90.6
Lithuania	11.1	4.6	-58.6	0.038	10.20	8.91	3.6	9.9	20.8	11.0	42	-63.9	-91.4
Luxembourg	5.5	2.1	-62.0	0.015	10.20	8.91	1.6	4.9	2.1	5.3	12	-66.8	-86.7
Macedonia	3.5	1.7	-51.6	0.012	10.20	8.91	1.3	3.1	15.6	7.4	26	-57.7	-94.9
Malta	5.0	1.6	-68.9	0.011	10.20	8.91	1.2	4.4	1.5	1.4	7	-72.8	-83.6
Moldova	4.9	1.8	-62.3	0.014	10.20	8.91	1.4	4.4	7.2	8.3	20	-67.1	-92.8
Montenegro	1.5	0.7	-52.1	0.004	10.20	8.91	0.6	1.3	7.2	3.6	12	-58.1	-95.4
Netherlands	92.7	36.8	-60.3	0.236	10.20	8.91	28.7	82.8	50.9	93.0	227	-65.3	-87.3
Norway	44.5	20.7	-53.4	0.084	10.20	8.91	16.2	39.8	8.0	33.3	81	-59.3	-80.0
Poland	121.1	47.3	-60.9	0.355	10.20	8.91	36.9	108.2	176.4	217.1	502	-65.9	-92.6
Portugal	28.9	13.1	-54.7	0.081	10.20	8.91	10.2	25.8	19.0	27.4	72	-60.4	-85.9
Romania	44.8	17.0	-62.1	0.114	10.20	8.91	13.3	40.1	188.7	59.4	288	-66.9	-95.4
Serbia	19.2	8.3	-57.0	0.063	10.20	8.91	6.5	17.2	68.3	47.1	133	-62.4	-95.1
Slovakia	17.8	8.1	-54.7	0.058	10.20	8.91	6.3	15.9	17.7	26.4	60	-60.4	-89.5
Slovenia	7.5	3.4	-54.2	0.024	10.20	8.91	2.7	6.7	5.3	9.1	21	-60.0	-87.3
Spain	154.4	63.1	-59.1	0.393	10.20	8.91	49.2	137.9	100.0	164.5	402	-64.3	-87.8
Sweden	54.8	29.6	-46.1	0.170	10.20	8.91	23.1	49.0	15.6	26.8	91	-52.9	-74.8
Switzerland	29.1	13.7	-52.8	0.072	10.20	8.91	10.7	26.0	17.8	25.9	70	-58.7	-84.6
Ukraine	59.2	31.3	-47.1	0.228	10.20	8.91	24.4	52.9	244.6	114.3	412	-53.8	-94.1
United King.	202.9	78.8	-61.2	0.565	10.20	8.91	61.5	181.2	177.2	228.6	587	-66.1	-89.5
Haiti region	**20.2**	**8.3**	**-59.1**	**0.064**	**10.77**	**9.30**	**6.7**	**19.1**	**45.3**	**34.3**	**99**	**-64.7**	**-93.2**
Dominican Rep	15.3	7.0	-54.4	0.053	10.77	9.30	5.7	14.4	24.2	30.8	69	-60.6	-91.8
Haiti	5.0	1.3	-73.7	0.011	10.77	9.30	1.1	4.7	21.1	3.5	29	-77.3	-96.4
Iceland	**5.1**	**3.0**	**-42.2**	**0.0052**	**7.39**	**7.43**	**1.9**	**3.3**	**0.4**	**2.3**	**6**	**-42.7**	**-68.8**
India region	**1,997.3**	**1,055.8**	**-47.1**	**7.794**	**9.86**	**8.25**	**763.3**	**1,724.7**	**9,546**	**4,053.2**	**15,323**	**-55.7**	**-95.0**
Bangladesh	78.1	37.6	-51.9	0.290	9.86	8.25	27.2	67.4	650.6	150.6	869	-59.7	-96.9
India	1,866.9	997.2	-46.6	7.347	9.86	8.25	720.9	1,612.0	8,677	3,856.2	14,145	-55.3	-94.9
Nepal	29.5	11.0	-62.7	0.089	9.86	8.25	8.0	25.5	106.0	21.6	153	-68.7	-94.8
Sri Lanka	22.9	10.0	-56.1	0.069	9.86	8.25	7.3	19.7	111.6	24.8	156	-63.2	-95.4
Israel	**27.2**	**13.0**	**-52.0**	**0.115**	**11.30**	**10.23**	**11.7**	**26.9**	**17.8**	**46.4**	**91**	**-56.5**	**-87.2**
Jamaica	**4.9**	**1.9**	**-61.6**	**0.017**	**11.50**	**10.03**	**1.7**	**4.9**	**5.3**	**6.7**	**17**	**-66.5**	**-90.3**
Japan	**329.2**	**174.7**	**-46.9**	**1.246**	**10.50**	**9.24**	**141.4**	**302.8**	**322.4**	**577.6**	**1,203**	**-53.3**	**-88.2**
Madagascar	**13.7**	**3.8**	**-72.1**	**0.039**	**9.70**	**10.71**	**3.6**	**11.6**	**74.5**	**5.0**	**91**	**-69.2**	**-96.1**
Mauritius	**4.1**	**1.5**	**-62.2**	**0.011**	**10.80**	**8.82**	**1.2**	**3.9**	**3.8**	**5.1**	**13**	**-69.2**	**-90.6**
Mideast	**1,523.3**	**698.7**	**-54.1**	**4.564**	**11.43**	**7.81**	**477.8**	**1,525.0**	**1,148**	**2,940.5**	**5,614**	**-68.7**	**-91.5**
Armenia	5.7	1.8	-67.6	0.010	11.43	7.81	1.3	5.7	15.4	6.5	28	-77.9	-95.5
Azerbaijan	21.6	7.4	-65.6	0.049	11.43	7.81	5.1	21.6	83.0	35.9	141	-76.5	-96.4
Bahrain	17.1	9.8	-42.7	0.058	11.43	7.81	6.7	17.1	4.1	42.7	64	-60.9	-89.6

Iran	494.4	209.5	-57.6	1.422	11.43	7.81	143.3	495.0	249.5	889.2	1,634	-71.0	-91.2
Iraq	69.6	27.4	-60.7	0.212	11.43	7.81	18.7	69.7	114.4	220.2	404	-73.1	-95.4
Jordan	14.4	6.9	-52.3	0.043	11.43	7.81	4.7	14.4	9.1	26.9	50	-67.4	-90.7
Kuwait	62.8	27.9	-55.6	0.173	11.43	7.81	19.1	62.9	12.2	127.5	203	-69.7	-90.6
Lebanon	7.0	2.3	-67.0	0.015	11.43	7.81	1.6	7.0	13.2	19.8	40	-77.4	-96.1
Oman	62.4	25.0	-59.9	0.166	11.43	7.81	17.1	62.5	16.6	106.3	185	-72.6	-90.8
Qatar	73.5	31.3	-57.5	0.186	11.43	7.81	21.4	73.6	5.3	146.0	225	-70.9	-90.5
Saudi Arabia	312.4	160.7	-48.6	1.063	11.43	7.81	109.9	312.7	179.5	711.2	1,203	-64.9	-90.9
Syria	11.5	5.3	-53.5	0.036	11.43	7.81	3.7	11.5	58.9	29.2	100	-68.2	-96.3
Türkiye	181.7	84.1	-53.7	0.532	11.43	7.81	57.5	182.0	277.5	331.6	791	-68.4	-92.7
UAE	184.2	97.6	-47.0	0.586	11.43	7.81	66.7	184.4	14.8	235.1	434	-63.8	-84.6
Yemen	5.0	1.8	-64.4	0.013	11.43	7.81	1.2	5.0	94.3	12.4	112	-75.7	-98.9
New Zealand	**26.4**	**14.1**	**-46.5**	**0.084**	**8.02**	**8.22**	**10.1**	**18.5**	**10.0**	**33.1**	**62**	**-45.2**	**-83.5**
Philippines	**87.9**	**37.2**	**-57.7**	**0.357**	**10.10**	**10.09**	**32.9**	**77.7**	**906.0**	**194.6**	**1,178**	**-57.7**	**-97.2**
Russia region	**748.3**	**269.9**	**-63.9**	**1.587**	**10.31**	**7.85**	**185.6**	**675.6**	**1,025**	**1,444.4**	**3,145**	**-72.5**	**-94.1**
Georgia	9.5	3.7	-61.6	0.016	10.31	7.85	2.5	8.6	33.3	10.8	53	-70.7	-95.2
Russia	738.8	266.2	-64.0	1.571	10.31	7.85	183.1	667.0	991.5	1,433.6	3,092	-72.5	-94.1
South Am-NW	**227.7**	**90.6**	**-60.2**	**0.631**	**8.41**	**8.56**	**68.0**	**167.7**	**281.6**	**342.9**	**792**	**-59.5**	**-91.4**
Bolivia	17.7	5.7	-67.9	0.041	8.41	8.56	4.3	13.0	35.3	23.4	72	-67.3	-94.1
Colombia	67.7	26.3	-61.2	0.189	8.41	8.56	19.7	49.9	85.8	99.2	235	-60.5	-91.6
Curacao	5.0	1.5	-70.0	0.009	8.41	8.56	1.1	3.6	0.1	2.4	6	-69.5	-81.8
Ecuador	28.5	10.6	-62.9	0.078	8.41	8.56	7.9	21.0	22.8	44.6	88	-62.3	-91.0
Guyana	1.6	0.7	-54.2	0.007	8.41	8.56	0.5	1.2	2.4	3.3	7	-53.3	-92.0
Peru	47.1	19.1	-59.5	0.124	8.41	8.56	14.3	34.7	64.5	57.5	157	-58.7	-90.9
Suriname	1.5	0.6	-62.7	0.004	8.41	8.56	0.4	1.1	1.5	2.6	5	-62.0	-92.0
Trinidad/Tobago	10.1	7.3	-27.5	0.045	8.41	8.56	5.5	7.4	1.8	26.8	36	-26.1	-84.8
Venezuela	48.6	19.0	-60.9	0.135	8.41	8.56	14.2	35.8	67.3	83.2	186	-60.2	-92.4
South Am-SE	**784.0**	**355.0**	**-54.7**	**2.409**	**8.40**	**8.44**	**262.5**	**576.7**	**595.1**	**769.4**	**1,941**	-54.5	-86.5
Argentina	131.9	46.8	-64.5	0.280	8.41	8.56	34.6	97.0	121.2	180.8	399	-64.3	-91.3
Brazil	565.1	263.5	-53.4	1.900	8.41	8.56	194.8	415.7	419.8	480.2	1,316	-53.1	-85.2
Chile	65.8	34.2	-47.9	0.182	8.41	8.56	25.3	48.4	34.2	91.7	174	-47.7	-85.5
Paraguay	11.7	5.4	-53.5	0.018	8.41	8.56	4.0	8.6	14.1	8.1	31	-53.3	-86.9
Uruguay	9.6	4.9	-48.3	0.029	8.41	8.56	3.7	7.0	5.9	8.7	22	-48.0	-83.1
Southeast Asia	**1,207.6**	**578.5**	**-52.1**	**6.199**	**10.30**	**10.65**	**539.9**	**1,089.2**	**2,392**	**2,110.0**	**5,591**	**-50.4**	**-90.3**
Brunei	5.1	1.6	-69.8	0.017	10.30	10.65	1.4	4.6	0.8	11.7	17	-68.8	-91.6
Cambodia	17.4	8.2	-52.7	0.075	10.30	10.65	7.7	15.7	52.3	21.7	90	-51.1	-91.4
Indonesia	403.5	207.1	-48.7	2.109	10.30	10.65	193.3	363.9	1,113	813.7	2,291	-46.9	-91.6
Lao PDR	7.9	3.8	-51.9	0.011	10.30	10.65	3.5	7.1	37.0	31.4	75	-50.2	-95.3
Malaysia	154.8	71.1	-54.1	0.798	10.30	10.65	66.4	139.7	194.9	341.8	676	-52.5	-90.2
Myanmar	40.6	12.2	-69.9	0.093	10.30	10.65	11.4	36.6	267.6	40.3	344	-68.8	-96.7
Singapore	185.7	59.5	-67.9	1.167	10.30	10.65	55.6	167.5	29.9	68.8	266	-66.8	-79.1
Thailand	219.1	106.3	-51.5	1.017	10.30	10.65	99.2	197.6	289.6	330.7	818	-49.8	-87.9
Vietnam	173.4	108.6	-37.4	0.912	10.30	10.65	101.4	156.4	406.1	450.0	1,012	-35.2	-90.0
South Korea	**289.3**	**144.3**	**-50.1**	**1.421**	**10.74**	**10.99**	**138.9**	**272.2**	**121.2**	**477.3**	**871**	**-49.0**	**-84.0**
Taiwan	**157.0**	**84.8**	**-46.0**	**0.868**	**10.80**	**10.78**	**80.1**	**148.6**	**92.2**	**337.6**	**578**	**-46.1**	**-86.2**
United States	**2,356.7**	**945.4**	**-59.9**	**6.962**	**10.66**	**8.80**	**728.8**	**2,200.7**	**1,065**	**3,200.0**	**6,466**	**-66.9**	**-88.7**
All regions	**19,560**	**8,962**	**-54.2**	**64.9**	**10.05**	**8.64**	**6,812**	**17,215**	**36,875**	**32,506**	**86,596**	**-60.4**	**-92.1**

[1]From Table S4.

[2]The total capital cost includes the capital cost of new WWS electricity and heat generators; new equipment for electricity storage, low-temperature building heat storage, and hydrogen storage; hydrogen electrolyzers and compressors; ground- and air-source electric heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2022 and 2050.

[3]This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2022 and 2050.

[4]The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat). It is an average between 2022 and 2050.

[5]The annual private cost of WWS or BAU energy equals the cost per unit energy from Column (f) or (e), respectively, multiplied by the energy consumed per year, which equals the end-use demand from Column (b) or (a), respectively, multiplied by 8,760 hours per year.

[6]The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 from Table S26b, Column (a), multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy[13]) and by a value of statistical life (VOSL) calculated for each country and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts[13]. See Ref. S3 for values of VOSL in each country and Note S9 for a discussion.

[7]The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S26b, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S26b, Column (f) (in USD 2022), which is updated from values in Ref. S13, which were in 2013 USD. See Note S9 for a discussion.

Table S26a. Base-case air-pollution-health costs and climate costs. (a) Estimated 2050 air pollution mortalities per year due to all sources of air pollution (about 90% of which are due to energy sources); (b) 2050 carbon dioxide-equivalent emissions (CO_2e) from energy sources; (c) cost per tonne-CO_2e-eliminated of converting to WWS; (d) BAU energy cost per tonne-CO_2e emitted; (e) BAU health cost per tonne-CO_2e emitted; (f) BAU climate cost per tonne-CO_2e emitted (social cost of carbon); (g) BAU total social cost per tonne-CO_2e emitted; (h) BAU health cost per unit-all-BAU-energy produced; and (i) BAU climate cost per unit-all-BAU-energy produced.

Region or country	(a)[1] 2050 BAU air pollution mortal-ities/y	(b)[2] 2050 BAU CO_2e (Mton-ne/y)	(c)[3] 2050 WWS energy cost ($/ tonne-$CO_2e$-elim-inated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa-East	**352,941**	**185**	**312.8**	**869**	**3,940**	**580**	**5,389**	**36.3**	**5.3**
Eritrea	6,539	1	197.6	655	7,600	578	8,833	93.0	7.1
Ethiopia	158,991	35	434.7	1,448	7,558	580	9,586	41.9	3.2
Kenya	25,307	45	196.0	538	1,525	580	2,643	22.7	8.6
Rwanda	15,084	3	411.5	1,271	7,767	579	9,617	49.0	3.7
South Sudan	16,389	3	153.4	464	11,921	578	12,963	205.8	10.0
Sudan	47,497	42	211.1	532	3,842	580	4,953	57.9	8.7
Tanzania	25,445	40	289.9	798	1,545	580	2,923	15.5	5.8
Uganda	57,689	15	741.4	1,654	6,986	580	9,220	33.9	2.8
Africa-North	**143,269**	**1,240**	**90.0**	**328**	**539**	**580**	**1,446**	**18.8**	**20.2**
Algeria	12,023	376	79.6	345	230	580	1,154	7.6	19.3
Egypt	62,449	520	103.9	331	736	580	1,647	25.4	20.0
Libya	2,341	128	61.2	226	129	580	935	6.6	29.4
Morocco	17,009	146	81.8	275	670	580	1,525	27.9	24.1
Niger	44,757	6	205.0	1,232	9,569	579	11,380	88.9	5.4
Tunisia	4,690	66	103.2	435	449	579	1,463	11.8	15.2
Africa-South	**127,785**	**976**	**85.9**	**221**	**435**	**580**	**1,236**	**18.3**	**24.3**
Angola	21,748	59	109.4	374	1,805	580	2,758	44.7	14.4
Botswana	1,614	15	83.3	245	779	580	1,604	29.5	21.9
Mozambique	48,179	20	228.3	714	3,609	579	4,902	46.8	7.5
Namibia	1,026	9	130.7	360	757	579	1,696	19.5	14.9
South Africa	19,145	828	72.0	172	157	580	908	8.5	31.3
Eswatini, Kingd.	1,225	3	314.8	695	2,210	579	3,484	29.5	7.7
Zambia	19,586	17	368.2	1,045	3,733	580	5,358	33.1	5.1
Zimbabwe	15,262	24	144.0	411	1,120	580	2,111	25.2	13.1
Africa-West	**510,062**	**454**	**216.8**	**540**	**4,040**	**580**	**5,160**	**72.1**	**10.3**
Benin	17,007	13	179.6	562	2,593	580	3,735	44.5	9.9
Cameroon	24,291	22	226.1	661	2,986	580	4,226	43.6	8.5
Congo	5,228	15	90.5	250	1,543	579	2,372	59.5	22.4
Congo, DR	99,258	8	1,484	4,919	10,752	581	16,252	21.1	1.1
Côte d'Ivoire	25,461	30	245.4	617	2,533	580	3,730	39.6	9.1
Equatorial Guin.	1,279	8	192.1	328	1,650	580	2,559	48.4	17.0
Gabon	877	10	716.6	921	718	580	2,219	7.5	6.1
Ghana	28,086	50	183.8	359	1,894	579	2,833	50.8	15.6
Nigeria	281,785	267	175.3	446	5,182	580	6,207	112.1	12.5
Senegal	14,400	25	167.3	338	1,313	580	2,232	37.4	16.5
Togo	12,390	5	285.0	834	3,609	580	5,024	41.7	6.7
Australia	**3,950**	**596**	**96.8**	**284**	**78**	**580**	**942**	**2.8**	**20.9**
Canada	**4,851**	**893**	**127.8**	**331**	**63**	**580**	**974**	**1.5**	**14.1**
Central America	**68,745**	**1,035**	**102.1**	**290**	**478**	**580**	**1,348**	**17.0**	**20.6**
Costa Rica	898	15	188.2	494	422	580	1,496	8.8	12.1
El Salvador	1,826	14	146.1	382	631	579	1,593	17.0	15.6
Guatemala	10,917	36	143.1	564	1,387	580	2,530	25.3	10.6
Honduras	7,177	19	125.2	377	1,358	580	2,315	37.1	15.8
Mexico	43,517	917	96.0	264	415	580	1,259	16.2	22.6
Nicaragua	3,301	10	127.3	442	1,525	579	2,547	35.5	13.5
Panama	1,109	25	166.8	567	366	580	1,513	6.7	10.5
Central Asia	**292,197**	**1,088**	**98.2**	**346**	**1,233**	**580**	**2,158**	**37.3**	**17.5**
Kazakhstan	11,953	347	60.0	225	421	580	1,225	19.5	26.9
Kyrgyz Republic	4,765	15	137.0	379	1,378	579	2,337	38.1	16.0
Pakistan	240,236	417	133.7	428	2,319	580	3,327	56.7	14.2
Tajikistan	8,223	13	163.0	408	2,338	579	3,325	60.0	14.9
Turkmenistan	2,567	95	115.3	493	272	580	1,344	5.8	12.3

Uzbekistan	24,453	200	74.9	306	748	579	1,633	25.6	19.8
China region	**1,167,972**	**16,731**	**113.1**	**260**	**681**	**580**	**1,520**	**25.3**	**21.5**
China	1,108,491	16,466	113.3	260	679	580	1,519	25.3	21.5
Hong Kong	4,159	72	166.0	494	822	580	1,896	16.1	11.3
Korea, DPR	51,128	134	98.7	191	860	580	1,630	43.5	29.3
Mongolia	4,194	59	52.3	156	523	580	1,259	32.4	35.9
Cuba	**4,926**	**37**	**128.9**	**273**	**1,055**	**580**	**1,908**	**45.2**	**24.8**
Europe	**217,232**	**4,240**	**157.8**	**434**	**518**	**580**	**1,532**	**12.2**	**13.6**
Albania	2,904	7	211.7	512	3,673	580	4,765	73.1	11.5
Austria	2,283	77	197.7	499	360	580	1,440	7.4	11.8
Belarus	6,603	78	111.0	370	877	580	1,826	24.2	16.0
Belgium	2,601	110	183.5	519	279	580	1,378	5.5	11.4
Bosnia-Herzeg.	5,312	32	83.0	235	1,376	580	2,191	59.6	25.1
Bulgaria	4,371	58	122.3	319	672	580	1,571	21.5	18.5
Croatia	2,035	25	166.3	472	916	580	1,968	19.8	12.5
Cyprus	238	10	125.7	331	305	580	1,216	9.4	17.9
Czech Rep.	4,057	118	112.4	313	354	580	1,247	11.5	18.9
Denmark	1,122	35	197.0	589	387	580	1,556	6.7	10.0
Estonia	194	15	96.3	339	129	580	1,047	3.9	17.5
Finland	641	42	360.1	803	175	580	1,558	2.2	7.4
France	12,319	369	212.8	552	379	579	1,511	7.0	10.7
Germany	20,560	761	141.9	390	328	580	1,297	8.6	15.2
Gibraltar	20	0.90	1,469	6,935	292	578	7,806	0.4	0.8
Greece	4,633	67	141.1	415	649	579	1,644	15.9	14.2
Hungary	5,163	57	164.5	468	851	580	1,899	18.6	12.6
Ireland	888	42	148.8	391	271	580	1,242	7.1	15.1
Italy	20,243	399	153.0	443	551	579	1,574	12.7	13.3
Kosovo	285	12	91.3	212	150	579	941	7.2	27.9
Latvia	1,031	9	236.2	682	1,290	579	2,551	19.3	8.7
Lithuania	1,922	19	185.5	522	1,094	579	2,196	21.4	11.3
Luxembourg	119	9	174.8	536	225	580	1,341	4.3	11.0
Macedonia	2,024	13	102.0	246	1,229	580	2,056	51.0	24.1
Malta	132	2	487.7	1,825	619	580	3,024	3.5	3.2
Moldova	1,633	14	98.6	305	501	579	1,385	16.8	19.4
Montenegro	861	6	87.7	213	1,151	579	1,943	55.0	27.7
Netherlands	3,763	160	176.0	516	317	580	1,413	6.3	11.4
Norway	566	58	276.5	691	138	579	1,409	2.0	8.6
Poland	18,570	375	96.9	289	471	580	1,339	16.6	20.5
Portugal	1,940	47	212.3	546	403	580	1,529	7.5	10.8
Romania	16,771	102	127.2	391	1,843	580	2,814	48.0	15.1
Serbia	7,350	81	78.1	212	841	580	1,632	40.5	27.9
Slovakia	1,779	46	135.7	349	388	580	1,317	11.3	16.9
Slovenia	516	16	166.2	423	333	579	1,335	8.0	14.0
Spain	9,296	284	170.5	486	352	580	1,418	7.4	12.2
Sweden	1,273	46	490.5	1,059	339	580	1,978	3.3	5.6
Switzerland	1,346	45	235.7	582	399	579	1,560	7.0	10.2
Ukraine	34,473	197	121.8	268	1,241	580	2,089	47.1	22.0
United Kingdom	15,395	394	153.2	459	449	579	1,488	10.0	12.9
Haiti region	**17,122**	**59**	**123.8**	**323**	**765**	**580**	**1,667**	**25.5**	**19.4**
Dominican Rep.	3,683	53	116.1	271	454	580	1,305	18.0	23.0
Haiti	13,439	6	191.9	778	3,521	580	4,879	48.7	8.0
Iceland	**36**	**4**	**452.5**	**821**	**108**	**580**	**1,509**	**1.0**	**5.2**
India region	**1,631,058**	**6,993**	**108.0**	**247**	**1,365**	**580**	**2,191**	**54.6**	**23.2**
Bangladesh	193,713	260	103.5	260	2,505	580	3,344	95.1	22.0
India	1,379,245	6,653	107.2	242	1,304	580	2,126	53.1	23.6
Nepal	39,183	37	211.2	683	2,840	580	4,103	41.0	8.4
Sri Lanka	18,917	43	168.0	462	2,614	580	3,656	55.8	12.4
Israel	**1,682**	**80**	**147.7**	**336**	**222**	**580**	**1,138**	**7.5**	**19.5**
Jamaica	**1,044**	**12**	**140.9**	**423**	**455**	**579**	**1,457**	**12.4**	**15.7**
Japan	**32,274**	**997**	**142.2**	**304**	**323**	**579**	**1,207**	**11.2**	**20.0**
Madagascar	**41,239**	**9**	**466.4**	**1,359**	**8,724**	**580**	**10,662**	**62.3**	**4.1**
Mauritius	**408**	**9**	**143.0**	**438**	**427**	**580**	**1,445**	**10.5**	**14.3**
Mideast	**147,234**	**5,073**	**92.3**	**301**	**226**	**580**	**1,106**	**8.6**	**22.0**
Armenia	2,107	11	109.8	506	1,379	580	2,465	31.1	13.1
Azerbaijan	7,958	62	80.4	349	1,342	579	2,271	43.9	18.9
Bahrain	327	74	88.8	232	56	580	867	2.8	28.6
Iran	30,131	1,534	91.6	323	163	580	1,065	5.8	20.5
Iraq	15,205	380	48.3	183	301	580	1,064	18.8	36.1
Jordan	1,419	46	99.3	311	195	580	1,086	7.2	21.3
Kuwait	830	220	85.0	286	56	580	921	2.2	23.2
Lebanon	1,816	34	45.1	204	387	580	1,171	21.7	32.5

Oman	1,432	183	91.4	341	91	580	1,011	3.0	19.5
Qatar	290	252	83.2	292	21	580	893	0.8	22.7
Saudi Arabia	13,561	1,227	87.8	255	146	580	981	6.6	26.0
Syria	11,128	50	71.1	228	1,169	580	1,977	58.5	29.0
Türkiye	33,172	572	98.5	318	485	579	1,382	17.4	20.8
UAE	1,015	406	161.3	455	37	579	1,071	0.9	14.6
Yemen	26,843	21	55.7	234	4,393	579	5,205	214.9	28.3
New Zealand	**822**	**57**	**179.6**	**324**	**174**	**579**	**1,078**	**4.3**	**14.3**
Philippines	**163,620**	**336**	**95.9**	**232**	**2,699**	**580**	**3,510**	**117.7**	**25.3**
Russia region	**96,266**	**2,492**	**72.8**	**271**	**411**	**580**	**1,262**	**15.6**	**22.0**
Georgia	4,234	19	131.9	461	1,788	580	2,829	40.0	12.9
Russia	92,032	2,473	72.3	270	401	580	1,250	15.3	22.1
South Am-NW	**46,466**	**591**	**115.3**	**284**	**476**	**580**	**1,339**	**14.1**	**17.2**
Bolivia	8,248	40	106.0	323	875	579	1,777	22.8	15.1
Colombia	13,300	171	115.5	291	502	580	1,372	14.5	16.7
Curacao	9	4	270.4	883	20	580	1,482	0.2	5.5
Ecuador	3,929	77	103.3	273	296	580	1,149	9.1	17.9
Guyana	535	6	97.8	209	432	580	1,221	17.4	23.3
Peru	10,594	99	144.9	350	650	580	1,580	15.6	13.9
Suriname	211	4	93.8	246	342	581	1,169	11.7	19.8
Trinidad/Tobago	185	46	119.2	161	40	580	780	2.1	30.3
Venezuela	9,455	144	99.5	249	469	580	1,298	15.8	19.5
South Am-SE	**78,344**	**1,327**	**203.9**	**435**	**448**	**580**	**1,463**	**8.7**	**11.2**
Argentina	14,427	312	114.6	311	389	580	1,279	10.5	15.7
Brazil	56,927	828	242.6	502	507	580	1,588	8.5	9.7
Chile	3,517	158	165.1	306	216	580	1,102	5.9	15.9
Paraguay	2,746	14	295.8	613	1,004	580	2,197	13.7	7.9
Uruguay	727	15	251.9	470	392	580	1,441	7.0	10.4
Southeast Asia	**386,563**	**3,641**	**157.5**	**299**	**657**	**580**	**1,536**	**22.6**	**19.9**
Brunei	54	20	75.9	229	41	580	850	1.9	26.0
Cambodia	15,114	37	218.0	420	1,398	579	2,397	34.3	14.2
Indonesia	160,660	1,404	146.2	259	793	580	1,632	31.5	23.0
Lao PDR	7,798	54	69.1	131	683	580	1,394	53.8	45.7
Malaysia	18,360	590	119.5	237	331	580	1,147	14.4	25.2
Myanmar	65,879	69	174.7	527	3,852	580	4,959	75.2	11.3
Singapore	1,825	119	496.6	1,410	252	579	2,241	1.8	4.2
Thailand	34,306	571	184.6	346	508	579	1,433	15.1	17.2
Vietnam	82,567	776	138.7	202	523	580	1,304	26.7	29.6
South Korea	**10,054**	**823**	**169.7**	**331**	**147**	**580**	**1,058**	**4.8**	**18.8**
Taiwan	**6,878**	**582**	**139.1**	**255**	**158**	**580**	**993**	**6.7**	**24.5**
United States	**77,432**	**5,521**	**132.2**	**399**	**193**	**580**	**1,171**	**5.2**	**15.5**
All regions	**5,632,472**	**56,082**	**120.95**	**307**	**658**	**580**	**1,544**	**21.5**	**19.0**

[1]2050 BAU mortalities/y due to air pollution are calculated from 2019 indoor plus outdoor country-specific air pollution mortalities/y provided directly by WHO[S65,S66]. WHO calculates 2019 mortalities/y by multiplying age-standardized mortality rates per unit population for each country for different air-pollution-related causes of death (lower respiratory tract illness; trachea, bronchus, and lung cancers; heart disease; stroke; and chronic obstructive pulmonary disease) by the 2019 population of the country. The 2019 values are then extrapolated to 2050 using Equation S35 from Ref. S13. The extrapolation accounts for the projected 2050 population of each country, the fractional rate of change per year in each country in the air pollution death rate due to emission controls, and the estimated change in exposed population per unit change in population. It does not account for the change in age distribution with time. All components of the calculation for each country are given in Ref. S3. The result is a lower air pollution death rate in 2050 summed over all 150 countries (5.64 million/y in 2050 versus 7.19 million/y in 2019) and in most countries due to improved BAU emission-reduction technologies between 2019 and 2050.

[2]CO_2e=CO_2-equivalent emissions. This accounts for the emissions of CO_2 plus the emissions of other greenhouse gases multiplied by their global warming potentials. The emissions from these 150 countries represented 99.64% of world anthropogenic CO_2e emissions in 2023[S67].

[3]Calculated as the WWS private energy and total social cost from Table S25a, Column (g) divided by the CO_2e emission rate from Column (b) of the present table.

[4]Columns (d)-(g) are calculated as the BAU private energy cost, health cost, climate cost, and total social costs from Table S25a, Columns (h)-(k), respectively, each divided by the CO_2e emissions from Column (b) of the present table.

[5]Columns (h)-(i) are calculated as the BAU health and climate costs from Table S25a, Columns (i)-(j), respectively, each divided by the BAU end-use demand from Table S25a, Column (a) and by 8,760 hours per year.

Table S26b. EGS-mid-cost-case air-pollution-health costs and climate costs. (a) Estimated 2050 air pollution mortalities per year due to all sources of air pollution (about 90% of which are due to energy sources); (b) 2050 carbon dioxide-equivalent emissions (CO_2e) from energy sources; (c) cost per tonne-CO_2e-eliminated of converting to WWS; (d) BAU energy cost per tonne-CO_2e emitted; (e) BAU health cost per tonne-CO_2e emitted; (f) BAU climate cost per tonne-CO_2e emitted (social cost of carbon); (g) BAU total social cost per tonne-CO_2e emitted; (h) BAU health cost per unit-all-BAU-energy produced; and (i) BAU climate cost per unit-all-BAU-energy produced

Region or country	(a)[1] 2050 BAU air pollution mortal-ities/y	(b)[2] 2050 BAU CO_2e (Mton-ne/y)	(c)[3] 2050 WWS energy cost ($/ tonne-$CO_2e$-elim-inated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa-East	**352,941**	**185**	**307.7**	**869**	**3,940**	**580**	**5,389**	**36.3**	**5.3**
Eritrea	6,539	1	194.4	655	7,600	578	8,833	93.0	7.1
Ethiopia	158,991	35	427.6	1,448	7,558	580	9,586	41.9	3.2
Kenya	25,307	45	192.9	538	1,525	580	2,643	22.7	8.6
Rwanda	15,084	3	404.9	1,271	7,767	579	9,617	49.0	3.7
South Sudan	16,389	3	151.0	464	11,921	578	12,963	205.8	10.0
Sudan	47,497	42	207.6	532	3,842	580	4,953	57.9	8.7
Tanzania	25,445	40	285.2	798	1,545	580	2,923	15.5	5.8
Uganda	57,689	15	729.4	1,654	6,986	580	9,220	33.9	2.8
Africa-North	**143,269**	**1,240**	**92.0**	**328**	**539**	**580**	**1,446**	**18.8**	**20.2**
Algeria	12,023	376	81.4	345	230	580	1,154	7.6	19.3
Egypt	62,449	520	106.3	331	736	580	1,647	25.4	20.0
Libya	2,341	128	62.6	226	129	580	935	6.6	29.4
Morocco	17,009	146	83.7	275	670	580	1,525	27.9	24.1
Niger	44,757	6	209.7	1,232	9,569	579	11,380	88.9	5.4
Tunisia	4,690	66	105.6	435	449	579	1,463	11.8	15.2
Africa-South	**127,785**	**976**	**86.7**	**221**	**435**	**580**	**1,236**	**18.3**	**24.3**
Angola	21,748	59	110.4	374	1,805	580	2,758	44.7	14.4
Botswana	1,614	15	84.0	245	779	580	1,604	29.5	21.9
Mozambique	48,179	20	230.3	714	3,609	579	4,902	46.8	7.5
Namibia	1,026	9	131.9	360	757	579	1,696	19.5	14.9
South Africa	19,145	828	72.7	172	157	580	908	8.5	31.3
Eswatini, Kingd.	1,225	3	317.6	695	2,210	579	3,484	29.5	7.7
Zambia	19,586	17	371.5	1,045	3,733	580	5,358	33.1	5.1
Zimbabwe	15,262	24	145.3	411	1,120	580	2,111	25.2	13.1
Africa-West	**510,062**	**454**	**215.4**	**540**	**4,040**	**580**	**5,160**	**72.1**	**10.3**
Benin	17,007	13	178.4	562	2,593	580	3,735	44.5	9.9
Cameroon	24,291	22	224.5	661	2,986	580	4,226	43.6	8.5
Congo	5,228	15	89.9	250	1,543	579	2,372	59.5	22.4
Congo, DR	99,258	8	1,474	4,919	10,752	581	16,252	21.1	1.1
Côte d'Ivoire	25,461	30	243.7	617	2,533	580	3,730	39.6	9.1
Equatorial Guin.	1,279	8	190.8	328	1,650	580	2,559	48.4	17.0
Gabon	877	10	711.7	921	718	580	2,219	7.5	6.1
Ghana	28,086	50	182.5	359	1,894	579	2,833	50.8	15.6
Nigeria	281,785	267	174.1	446	5,182	580	6,207	112.1	12.5
Senegal	14,400	25	166.2	338	1,313	580	2,232	37.4	16.5
Togo	12,390	5	283.0	834	3,609	580	5,024	41.7	6.7
Australia	**3,950**	**596**	**98.1**	**284**	**78**	**580**	**942**	**2.8**	**20.9**
Canada	**4,851**	**893**	**119.9**	**331**	**63**	**580**	**974**	**1.5**	**14.1**
Central America	**68,745**	**1,035**	**101.8**	**290**	**478**	**580**	**1,348**	**17.0**	**20.6**
Costa Rica	898	15	187.6	494	422	580	1,496	8.8	12.1
El Salvador	1,826	14	145.7	382	631	579	1,593	17.0	15.6
Guatemala	10,917	36	142.6	564	1,387	580	2,530	25.3	10.6
Honduras	7,177	19	124.8	377	1,358	580	2,315	37.1	15.8
Mexico	43,517	917	95.7	264	415	580	1,259	16.2	22.6
Nicaragua	3,301	10	126.9	442	1,525	579	2,547	35.5	13.5
Panama	1,109	25	166.3	567	366	580	1,513	6.7	10.5
Central Asia	**292,197**	**1,088**	**101.7**	**346**	**1,233**	**580**	**2,158**	**37.3**	**17.5**
Kazakhstan	11,953	347	62.1	225	421	580	1,225	19.5	26.9
Kyrgyz Republic	4,765	15	141.8	379	1,378	579	2,337	38.1	16.0
Pakistan	240,236	417	138.4	428	2,319	580	3,327	56.7	14.2
Tajikistan	8,223	13	168.7	408	2,338	579	3,325	60.0	14.9
Turkmenistan	2,567	95	119.3	493	272	580	1,344	5.8	12.3

Uzbekistan	24,453	200	77.6	306	748	579	1,633	25.6	19.8
China region	**1,167,972**	**16,731**	**115.6**	**260**	**681**	**580**	**1,520**	**25.3**	**21.5**
China	1,108,491	16,466	115.8	260	679	580	1,519	25.3	21.5
Hong Kong	4,159	72	169.6	494	822	580	1,896	16.1	11.3
Korea, DPR	51,128	134	100.8	191	860	580	1,630	43.5	29.3
Mongolia	4,194	59	53.5	156	523	580	1,259	32.4	35.9
Cuba	**4,926**	**37**	**125.9**	**273**	**1,055**	**580**	**1,908**	**45.2**	**24.8**
Europe	**217,232**	**4,240**	**160.6**	**434**	**518**	**580**	**1,532**	**12.2**	**13.6**
Albania	2,904	7	215.5	512	3,673	580	4,765	73.1	11.5
Austria	2,283	77	201.2	499	360	580	1,440	7.4	11.8
Belarus	6,603	78	113.0	370	877	580	1,826	24.2	16.0
Belgium	2,601	110	186.8	519	279	580	1,378	5.5	11.4
Bosnia-Herzeg.	5,312	32	84.5	235	1,376	580	2,191	59.6	25.1
Bulgaria	4,371	58	124.5	319	672	580	1,571	21.5	18.5
Croatia	2,035	25	169.3	472	916	580	1,968	19.8	12.5
Cyprus	238	10	127.9	331	305	580	1,216	9.4	17.9
Czech Rep.	4,057	118	114.4	313	354	580	1,247	11.5	18.9
Denmark	1,122	35	200.5	589	387	580	1,556	6.7	10.0
Estonia	194	15	98.1	339	129	580	1,047	3.9	17.5
Finland	641	42	366.5	803	175	580	1,558	2.2	7.4
France	12,319	369	216.6	552	379	579	1,511	7.0	10.7
Germany	20,560	761	144.4	390	328	580	1,297	8.6	15.2
Gibraltar	20	0.90	1,495	6,935	292	578	7,806	0.4	0.8
Greece	4,633	67	143.7	415	649	579	1,644	15.9	14.2
Hungary	5,163	57	167.4	468	851	580	1,899	18.6	12.6
Ireland	888	42	151.4	391	271	580	1,242	7.1	15.1
Italy	20,243	399	155.7	443	551	579	1,574	12.7	13.3
Kosovo	285	12	93.0	212	150	579	941	7.2	27.9
Latvia	1,031	9	240.5	682	1,290	579	2,551	19.3	8.7
Lithuania	1,922	19	188.8	522	1,094	579	2,196	21.4	11.3
Luxembourg	119	9	177.9	536	225	580	1,341	4.3	11.0
Macedonia	2,024	13	103.9	246	1,229	580	2,056	51.0	24.1
Malta	132	2	496.5	1,825	619	580	3,024	3.5	3.2
Moldova	1,633	14	100.4	305	501	579	1,385	16.8	19.4
Montenegro	861	6	89.3	213	1,151	579	1,943	55.0	27.7
Netherlands	3,763	160	179.2	516	317	580	1,413	6.3	11.4
Norway	566	58	281.4	691	138	579	1,409	2.0	8.6
Poland	18,570	375	98.6	289	471	580	1,339	16.6	20.5
Portugal	1,940	47	216.1	546	403	580	1,529	7.5	10.8
Romania	16,771	102	129.5	391	1,843	580	2,814	48.0	15.1
Serbia	7,350	81	79.5	212	841	580	1,632	40.5	27.9
Slovakia	1,779	46	138.1	349	388	580	1,317	11.3	16.9
Slovenia	516	16	169.2	423	333	579	1,335	8.0	14.0
Spain	9,296	284	173.6	486	352	580	1,418	7.4	12.2
Sweden	1,273	46	499.3	1,059	339	580	1,978	3.3	5.6
Switzerland	1,346	45	240.0	582	399	579	1,560	7.0	10.2
Ukraine	34,473	197	124.0	268	1,241	580	2,089	47.1	22.0
United Kingdom	15,395	394	155.9	459	449	579	1,488	10.0	12.9
Haiti region	**17,122**	**59**	**113.9**	**323**	**765**	**580**	**1,667**	**25.5**	**19.4**
Dominican Rep.	3,683	53	106.8	271	454	580	1,305	18.0	23.0
Haiti	13,439	6	176.5	778	3,521	580	4,879	48.7	8.0
Iceland	**36**	**4**	**470.3**	**821**	**108**	**580**	**1,509**	**1.0**	**5.2**
India region	**1,631,058**	**6,993**	**109.2**	**247**	**1,365**	**580**	**2,191**	**54.6**	**23.2**
Bangladesh	193,713	260	104.6	260	2,505	580	3,344	95.1	22.0
India	1,379,245	6,653	108.4	242	1,304	580	2,126	53.1	23.6
Nepal	39,183	37	213.5	683	2,840	580	4,103	41.0	8.4
Sri Lanka	18,917	43	169.8	462	2,614	580	3,656	55.8	12.4
Israel	**1,682**	**80**	**146.1**	**336**	**222**	**580**	**1,138**	**7.5**	**19.5**
Jamaica	**1,044**	**12**	**141.9**	**423**	**455**	**579**	**1,457**	**12.4**	**15.7**
Japan	**32,274**	**997**	**141.9**	**304**	**323**	**579**	**1,207**	**11.2**	**20.0**
Madagascar	**41,239**	**9**	**418.6**	**1,359**	**8,724**	**580**	**10,662**	**62.3**	**4.1**
Mauritius	**408**	**9**	**135.3**	**438**	**427**	**580**	**1,445**	**10.5**	**14.3**
Mideast	**147,234**	**5,073**	**94.2**	**301**	**226**	**580**	**1,106**	**8.6**	**22.0**
Armenia	2,107	11	111.9	506	1,379	580	2,465	31.1	13.1
Azerbaijan	7,958	62	82.0	349	1,342	579	2,271	43.9	18.9
Bahrain	327	74	90.6	232	56	580	867	2.8	28.6
Iran	30,131	1,534	93.4	323	163	580	1,065	5.8	20.5
Iraq	15,205	380	49.3	183	301	580	1,064	18.8	36.1
Jordan	1,419	46	101.3	311	195	580	1,086	7.2	21.3
Kuwait	830	220	86.7	286	56	580	921	2.2	23.2
Lebanon	1,816	34	46.0	204	387	580	1,171	21.7	32.5

Oman	1,432	183	93.2	341	91	580	1,011	3.0	19.5
Qatar	290	252	84.9	292	21	580	893	0.8	22.7
Saudi Arabia	13,561	1,227	89.6	255	146	580	981	6.6	26.0
Syria	11,128	50	72.5	228	1,169	580	1,977	58.5	29.0
Türkiye	33,172	572	100.5	318	485	579	1,382	17.4	20.8
UAE	1,015	406	164.5	455	37	579	1,071	0.9	14.6
Yemen	26,843	21	56.8	234	4,393	579	5,205	214.9	28.3
New Zealand	**822**	**57**	**177.6**	**324**	**174**	**579**	**1,078**	**4.3**	**14.3**
Philippines	**163,620**	**336**	**97.9**	**232**	**2,699**	**580**	**3,510**	**117.7**	**25.3**
Russia region	**96,266**	**2,492**	**74.5**	**271**	**411**	**580**	**1,262**	**15.6**	**22.0**
Georgia	4,234	19	135.1	461	1,788	580	2,829	40.0	12.9
Russia	92,032	2,473	74.0	270	401	580	1,250	15.3	22.1
South Am-NW	**46,466**	**591**	**114.9**	**284**	**476**	**580**	**1,339**	**14.1**	**17.2**
Bolivia	8,248	40	105.6	323	875	579	1,777	22.8	15.1
Colombia	13,300	171	115.0	291	502	580	1,372	14.5	16.7
Curacao	9	4	269.4	883	20	580	1,482	0.2	5.5
Ecuador	3,929	77	102.9	273	296	580	1,149	9.1	17.9
Guyana	535	6	97.5	209	432	580	1,221	17.4	23.3
Peru	10,594	99	144.3	350	650	580	1,580	15.6	13.9
Suriname	211	4	93.5	246	342	581	1,169	11.7	19.8
Trinidad/Tobago	185	46	118.7	161	40	580	780	2.1	30.3
Venezuela	9,455	144	99.1	249	469	580	1,298	15.8	19.5
South Am-SE	**78,344**	**1,327**	**197.7**	**435**	**448**	**580**	**1,463**	**8.7**	**11.2**
Argentina	14,427	312	111.1	311	389	580	1,279	10.5	15.7
Brazil	56,927	828	235.2	502	507	580	1,588	8.5	9.7
Chile	3,517	158	160.1	306	216	580	1,102	5.9	15.9
Paraguay	2,746	14	286.8	613	1,004	580	2,197	13.7	7.9
Uruguay	727	15	244.2	470	392	580	1,441	7.0	10.4
Southeast Asia	**386,563**	**3,641**	**148.3**	**299**	**657**	**580**	**1,536**	**22.6**	**19.9**
Brunei	54	20	71.5	229	41	580	850	1.9	26.0
Cambodia	15,114	37	205.3	420	1,398	579	2,397	34.3	14.2
Indonesia	160,660	1,404	137.7	259	793	580	1,632	31.5	23.0
Lao PDR	7,798	54	65.0	131	683	580	1,394	53.8	45.7
Malaysia	18,360	590	112.6	237	331	580	1,147	14.4	25.2
Myanmar	65,879	69	164.5	527	3,852	580	4,959	75.2	11.3
Singapore	1,825	119	467.7	1,410	252	579	2,241	1.8	4.2
Thailand	34,306	571	173.9	346	508	579	1,433	15.1	17.2
Vietnam	82,567	776	130.6	202	523	580	1,304	26.7	29.6
South Korea	**10,054**	**823**	**168.7**	**331**	**147**	**580**	**1,058**	**4.8**	**18.8**
Taiwan	**6,878**	**582**	**137.4**	**255**	**158**	**580**	**993**	**6.7**	**24.5**
United States	**77,432**	**5,521**	**132.0**	**399**	**193**	**580**	**1,171**	**5.2**	**15.5**
All regions	**5,632,472**	**56,082**	**121.46**	**307**	**658**	**580**	**1,544**	**21.5**	**19.0**

[1]See footnote 1 of Table S26a.

[2]See footnote 2 of Table S26a.

[3]Calculated as the WWS private energy and total social cost from Table S25b, Column (g) divided by the CO_2e emission rate from Column (b) of the present table.

[4]Columns (d)-(g) are calculated as the BAU private energy cost, health cost, climate cost, and total social costs from Table S25b, Columns (h)-(k), respectively, each divided by the CO_2e emissions from Column (b) of the present table.

[5]Columns (h)-(i) are calculated as the BAU health and climate costs from Table S25b, Columns (i)-(j), respectively, each divided by the BAU end-use demand from Table S25b, Column (a) and by 8,760 hours per year.

Table S27. Footprint and spacing areas per MW of nameplate capacity and installed power densities for WWS electricity or heat generation technologies.

WWS technology	Footprint (m^2/MW)	Spacing (km^2/MW)	Installed power density (MW/km^2)
Onshore wind	3.22	0.0505	19.8
Offshore wind	3.22	0.139	7.2
Wave device	700	0.033	30.3
All geothermal plants	3,290	0	304
Hydropower plant	502,380	0	2.0
Tidal turbine	290	0.004	250
Residential roof PV	5,230	0	191.2
Commercial/govt. roof PV	5,230	0	191.2
Utility-scale solar PV plant	12,220	0	81.8
Utility CSP plant	29,350	0	34.1
Solar thermal for heat	1,430	0	700

From Ref. S13. Spacing areas for onshore and offshore wind are based on data from Enevoldsen and Jacobson[S68]. The installed power density is the inverse of the spacing except, if spacing is zero, it is the inverse of the footprint.

Table S28a. Base-WWS-case footprint areas for *new* utility PV farms, CSP plants, solar thermal plants for heat, geothermal plants for electricity and heat, and hydropower plants and spacing areas for new onshore wind turbines, for each grid region.

Region	(a) Region land area (km^2)	(b) Footprint area (% of region land area)	(c) Spacing area (% of region land area)	(d) Footprint + spacing area (% of region land area)	(e) Footprint + spacing area (km^2)
Africa-East	5,286,165	0.038	0.091	0.129	6,822
Africa-North	7,005,090	0.032	0.140	0.172	12,014
Africa-South	5,783,635	0.034	0.100	0.134	7,741
Africa-West	5,182,970	0.047	0.360	0.407	21,079
Australia	7,682,300	0.020	0.067	0.087	6,650
Canada	9,093,510	0.009	0.181	0.190	17,257
Central America	2,429,460	0.103	0.532	0.635	15,432
Central Asia	4,697,670	0.051	0.238	0.289	13,588
China region	11,063,254	0.593	1.090	1.682	186,103
Cuba	106,440	0.143	0.334	0.477	508
Europe	5,671,860	0.299	0.634	0.934	52,949
Haiti region	75,880	0.159	1.342	1.501	1,139
Iceland	100,250	0.001	0.036	0.037	37
India region	3,309,420	0.973	1.639	2.612	86,447
Israel	21,640	3.829	0.646	4.475	969
Jamaica	10,830	0.346	0.119	0.465	50
Japan	364,560	1.138	0.079	1.218	4,439
Madagascar	581,795	0.032	0.119	0.151	877
Mauritius	2,040	2.735	0.220	2.956	60
Mideast	6,327,218	0.245	0.586	0.830	52,532
New Zealand	263,310	0.114	0.325	0.439	1,156
Philippines	298,170	0.695	0.206	0.901	2,687
Russia region	16,446,360	0.019	0.158	0.178	29,189
South Am-NW	4,961,634	0.036	0.213	0.250	12,388
South Am-SE	12,410,682	0.033	0.333	0.366	45,385
Southeast Asia	4,027,647	0.431	0.062	0.493	19,852
South Korea	97,350	7.101	0.006	7.107	6,918
Taiwan	36,193	7.456	0.304	7.760	2,809
United States	9,147,420	0.358	0.690	1.048	95,865
All regions	**122,484,753**	**0.182**	**0.392**	**0.574**	**702,942**

Footprint areas are the physical land areas, water surface areas, or sea floor surface areas removed from use for any other purpose by an energy technology. Rooftop PV is not included in the footprint calculation because it does not take up new land. Conventional hydro new footprint is zero because no new dams are proposed as part of these roadmaps. Spacing areas are areas between wind turbines needed to avoid interference of the wake of one turbine with the next. Such spacing area can be used for multiple purposes, including farmland, rangeland, open space, or utility PV. Offshore wind, wave, and tidal are not included because they don't take up new land.

Table S27 gives the installed power densities applied in this table for each energy generator. Areas are given as a percentage of the region land area, which excludes inland or coastal water bodies. For comparison, the total area and land area of Earth are 510.1 and 144.6 million km^2, respectively.

Table S28b. All EGS-cases footprint areas for *new* utility PV farms, CSP plants, solar thermal plants for heat, geothermal plants for electricity and heat, and hydropower plants and spacing areas for new onshore wind turbines, for each grid region. See footnote of Table S28a for more details.

Region	(a) Region land area (km^2)	(b) Footprint area (% of region land area)	(c) Spacing area (% of region land area)	(d) Footprint + spacing area (% of region land area)	(e) Footprint + spacing area (km^2)
Africa-East	5,286,165	0.034	0.085	0.119	6,304
Africa-North	7,005,090	0.029	0.119	0.148	10,393
Africa-South	5,783,635	0.034	0.079	0.113	6,552
Africa-West	5,182,970	0.047	0.306	0.353	18,318
Australia	7,682,300	0.017	0.058	0.075	5,763
Canada	9,093,510	0.009	0.107	0.116	10,547
Central America	2,429,460	0.075	0.532	0.607	14,757
Central Asia	4,697,670	0.049	0.210	0.260	12,189
China region	11,063,254	0.514	0.877	1.391	153,875
Cuba	106,440	0.107	0.334	0.441	469
Europe	5,671,860	0.244	0.523	0.767	43,503
Haiti region	75,880	0.145	1.160	1.306	990
Iceland	100,250	0.001	0.003	0.004	4
India region	3,309,420	0.973	1.212	2.185	72,321
Israel	21,640	3.109	0.646	3.755	813
Jamaica	10,830	0.320	0.110	0.430	47
Japan	364,560	1.138	0.079	1.218	4,439
Madagascar	581,795	0.032	0.065	0.097	564
Mauritius	2,040	2.395	0.201	2.595	53
Mideast	6,327,218	0.229	0.531	0.761	48,116
New Zealand	263,310	0.090	0.238	0.328	865
Philippines	298,170	0.606	0.206	0.811	2,420
Russia region	16,446,360	0.015	0.144	0.159	26,140
South Am-NW	4,961,634	0.030	0.176	0.206	10,206
South Am-SE	12,410,682	0.028	0.243	0.271	33,641
Southeast Asia	4,027,647	0.371	0.062	0.433	17,438
South Korea	97,350	5.308	0.006	5.314	5,173
Taiwan	36,193	5.977	0.231	6.208	2,247
United States	9,147,420	0.291	0.624	0.915	83,655
All regions	**122,484,753**	**0.160**	**0.323**	**0.483**	**591,802**

Table S29. Estimated mean number of long-term, full-time construction and operation jobs per MW-nameplate capacity of different electric power sources and storage types in the United States. A full-time job is a job that requires 2,080 hours per year of work. The job numbers include direct, indirect, and induced jobs. These job numbers are scaled to different countries as described in the footnote of Table S30.

Electric power generator	Construction Jobs/MW or Jobs/km	Operation Jobs/MW or Jobs/km
Onshore wind electricity	0.24	0.37
Offshore wind electricity	0.31	0.63
Wave electricity	0.15	0.57
All geothermal electricity	0.71	0.46
Hydropower electricity	0.14	0.30
Tidal electricity	0.16	0.61
Residential rooftop PV	0.88	0.32
Commercial/government rooftop PV	0.65	0.16
Utility PV electricity	0.24	0.85
CSP electricity	0.31	0.86
Solar thermal for heat	0.71	0.85
Geothermal heat	0.14	0.46
Pumped hydro storage (PHS)	0.77	0.3
CSP storage (CSPS)	0.62	0.3
Battery storage	0.092	0.2
Chilled-water storage (CW-STES)	0.15	0.3
Ice storage (ICE)	0.15	0.3
Hot water storage (HW-STES)	0.15	0.3
Underground heat storage (UTES)	0.15	0.3
Producing heat pumps for district heat	0.15	0.3
Producing and storing hydrogen	0.32	0.3
AC transmission (jobs/km)	0.073	0.062
AC distribution (jobs/km)	0.033	0.028
HVDC transmission (jobs/km)	0.094	0.080

From Ref. S20. See Note S11 for more details.

Table S30. Modeled changes in the numbers of long-term, full-time jobs. Base-WWS case and EGS cases estimated numbers of long-term, full-time jobs created and lost due to transitioning from BAU energy to WWS across all energy sectors in each region. (a) Jobs produced; (b) jobs lost; (c) net jobs produced (long-term, full-time jobs produced minus lost) in each case.

	Base-WWS case			EGS cases		
Region	(a) Jobs produced	(b) Jobs lost	(c) Net jobs	(a) Jobs produced	(b) Jobs lost	(c) Net jobs
Africa-East	907,226	1,013,176	-105,950	841,291	1,013,176	-171,885
Africa-North	964,786	993,317	-28,531	922,090	993,317	-71,227
Africa-South	856,590	672,361	184,229	836,514	672,361	164,153
Africa-West	1,280,704	1,296,458	-15,754	1,228,792	1,296,458	-67,666
Australia	495,776	409,960	85,816	454,645	409,960	44,685
Canada	496,345	734,911	-238,566	416,048	734,911	-318,863
Central America	846,186	520,294	325,892	749,484	520,294	229,190
Central Asia	968,740	803,218	165,522	932,750	803,218	129,532
China region	14,857,715	3,363,346	11,494,369	13,812,272	3,363,346	10,448,926
Cuba	60,022	14,275	45,747	51,955	14,275	37,680
Europe	5,295,150	2,232,348	3,062,802	4,876,807	2,232,348	2,644,459
Haiti region	69,071	39,331	29,740	65,311	39,331	25,980
Iceland	5,398	4,458	940	4,742	4,458	284
India region	7,408,462	2,705,651	4,702,811	7,107,977	2,705,651	4,402,326
Israel	166,328	47,665	118,663	146,839	47,665	99,174
Jamaica	20,491	5,608	14,883	19,892	5,608	14,284
Japan	905,093	283,988	621,105	899,887	283,988	615,899
Madagascar	73,020	71,515	1,505	65,395	71,515	-6,120
Mauritius	13,297	4,292	9,005	12,386	4,292	8,094
Mideast	3,577,851	3,573,350	4,501	3,415,092	3,573,350	-158,258
New Zealand	84,865	39,770	45,095	74,132	39,770	34,362
Philippines	471,593	149,343	322,250	434,799	149,343	285,456
Russia region	1,006,502	1,226,828	-220,326	930,527	1,226,828	-296,301
South Am-NW	619,161	599,512	19,649	560,357	599,512	-39,155
South Am-SE	1,930,843	1,343,757	587,086	1,753,355	1,343,757	409,598
Southeast Asia	4,531,064	1,856,976	2,674,088	4,137,107	1,856,976	2,280,131
South Korea	1,125,746	220,207	905,539	962,963	220,207	742,756
Taiwan	571,963	107,800	464,163	505,366	107,800	397,566
United States	5,753,876	3,029,906	2,723,970	5,102,203	3,029,906	2,072,297
All regions	**55,363,864**	**27,363,621**	**28,000,243**	**51,320,978**	**27,363,621**	**23,957,357**

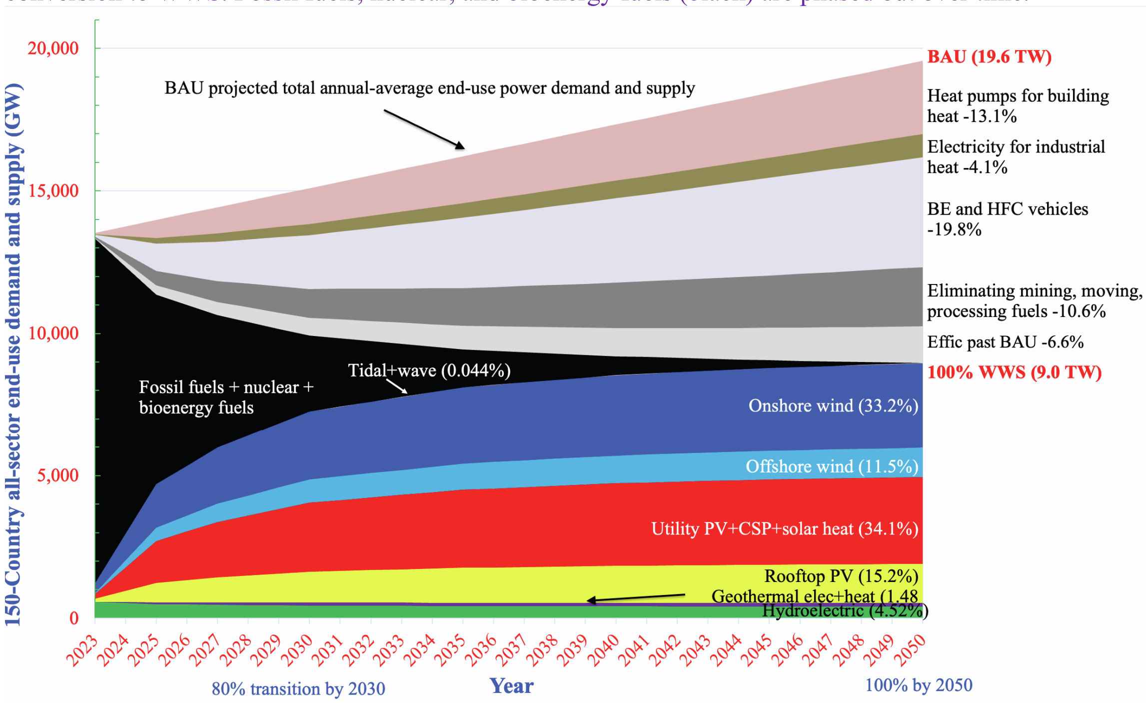
Job losses are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, bioenergy fuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke, are retained. For transportation, the jobs lost are those due to transporting fossil fuels through truck, train, barge, ship, or pipeline; the jobs not lost are those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion machines, including autos, ships, and industrial machines.

Job creation accounts for new direct, indirect, and induced jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including HVDC transmission) industries. It also accounts for the building of electric heat pumps to supply district heating and cooling. However, it does not account for changes in jobs in the production of electric appliances, vehicles, and machines or in increasing building energy efficiency. Construction jobs are for new WWS devices only. Operation jobs are for new and existing devices.

Jobs for electricity generation technologies are the number of long-term, full-time jobs per MW in each country multiplied by the 2050 final nameplate capacities (Table S10) minus the 2023 nameplate capacities (Table S9) for each device for construction jobs and the 2050 nameplate capacities alone for operation jobs. The jobs per MW for each device in each country is calculated with the methodology in Ref. S8 to scale U.S. jobs from Table S29 by year and country. For storage, the number of jobs per MW from Table S29 is multiplied by the maximum discharge rate of the storage technology for each region (Table S14). The transmission/distribution jobs are calculated as in the spreadsheet analysis[3].

Supplemental Figures

Figure S1. Base-WWS-case timelines of a transition of 150 countries to 100% WWS. (Top) An 80% transition by 2030 and 100% by 2050. (Bottom) An 80% transition by 2030 and 100% by 2035. The 2050 values are the same in both figures. The top line is energy supply (which equals demand) among the 150 countries in a BAU case. The five shades of colors below that, down to the 100% WWS line, are energy reductions upon electrification and production of all electricity and some heat to WWS. The shades of colors below the 100% WWS line are the WWS sources of electricity and/or heat generation upon complete conversion to WWS. Fossil fuels, nuclear, and bioenergy fuels (black) are phased out over time.



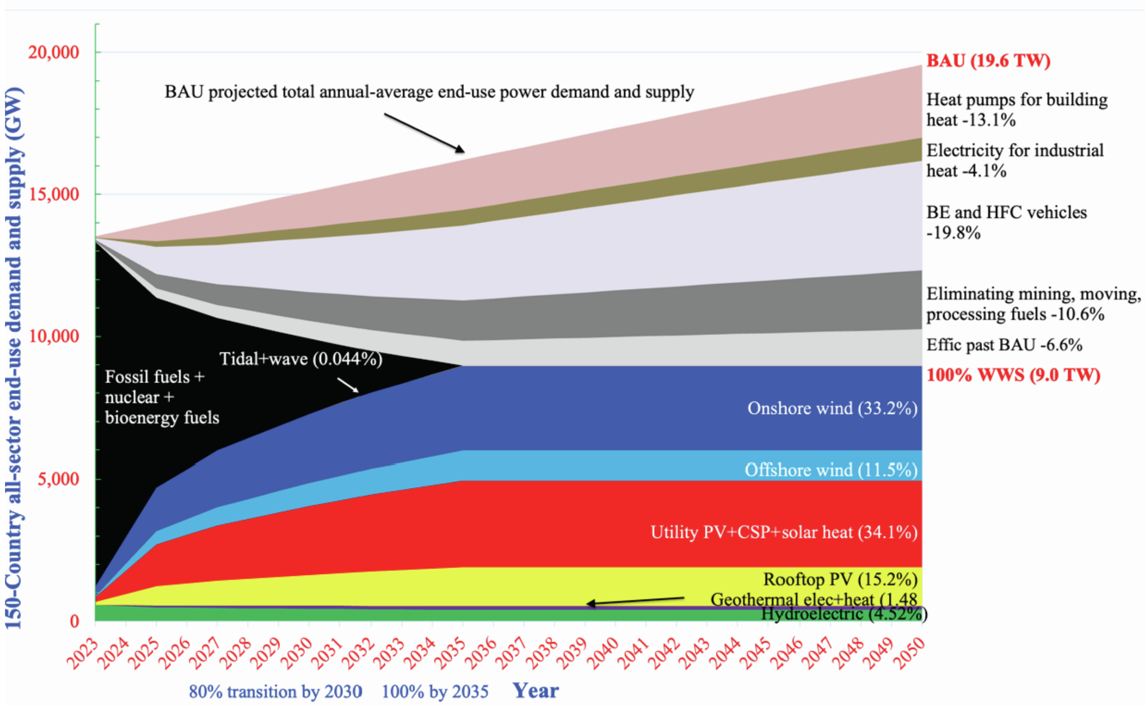


Figure S2. 2050 base-WWS-case end-use demand and capital cost to meet the demand by region. Data from Table S24.

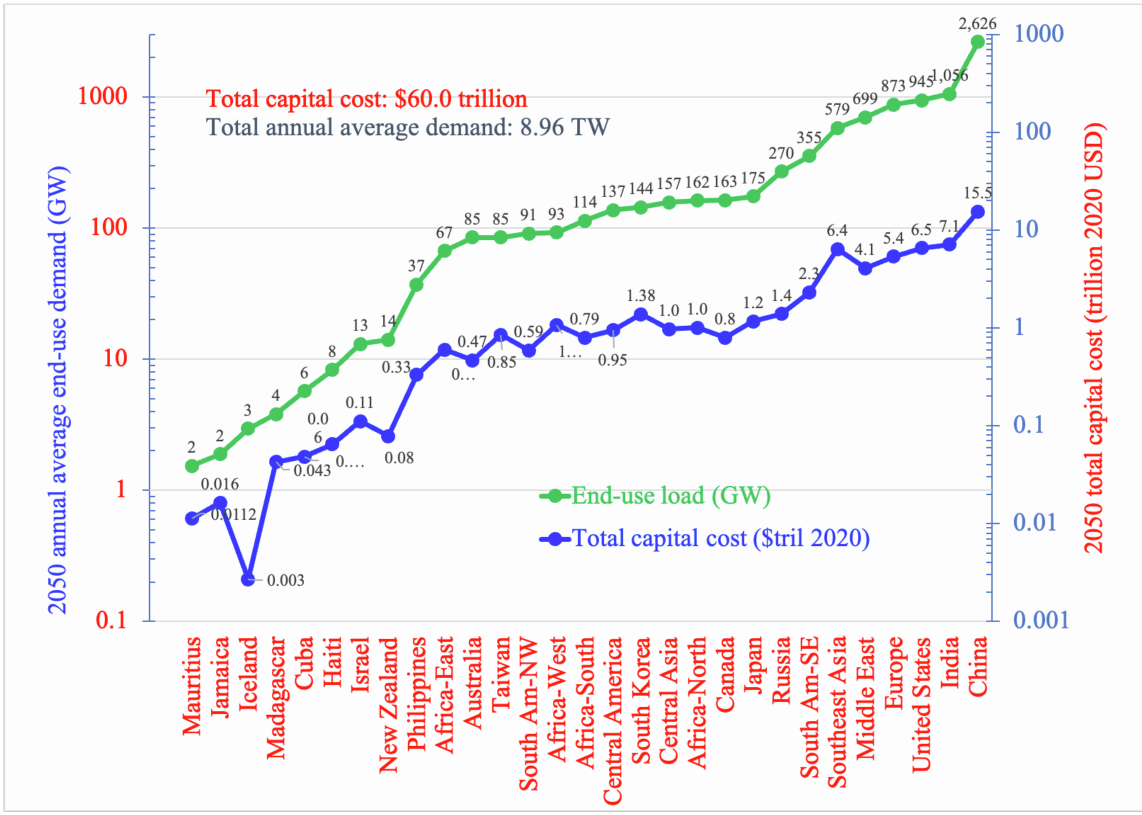
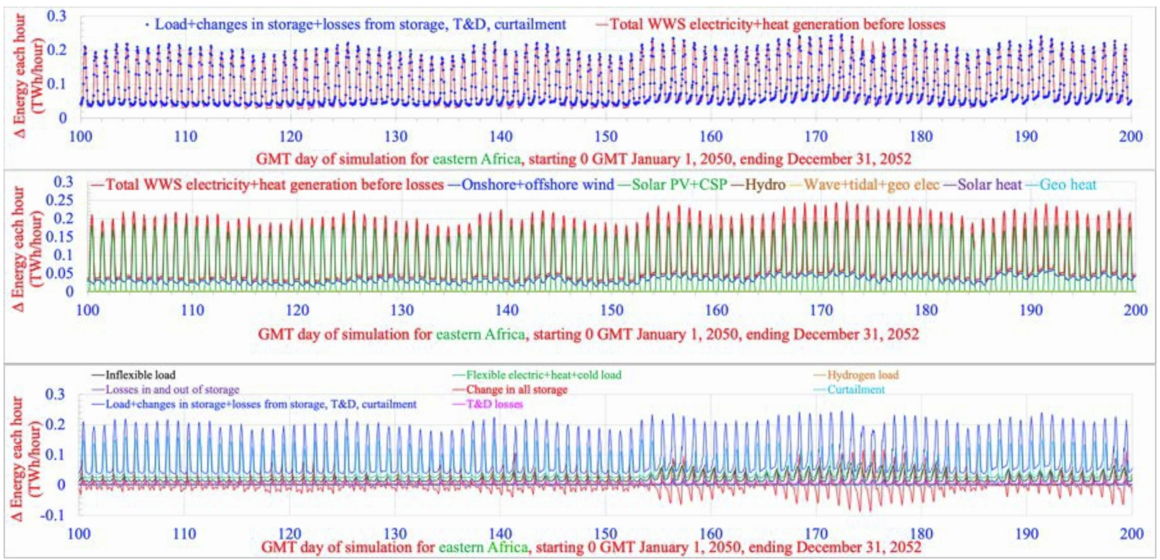


Figure S3. Africa-East hourly time series for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases, showing the matching of all-energy demand (load) with supply, storage, and losses. Table S1 defines the regions. First row: modeled time-dependent total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in storage (PHS, CSPS, battery, grid H_2, CW-STES, ICE, HW-STES, UTES, firebrick, and hydrogen storage); and curtailment. The model was run at 30-s resolution. Results are shown hourly, so units are energy output (TWh) per hour increment, thus also in units of power (TW) averaged over the hour. No load loss occurred during any 30-s interval during any three-year simulation. Raw GATOR-GCMOM results for solar, wind, heat demand, and cold demand were provided and fed into LOADMATCH at 30-s time increments. LOADMATCH modified the magnitudes, but not time series, of GATOR-GCMOM results, as described in this document. Figures for all EGS cost cases are identical to each other. The differences in “Changes in storage” line in each respective third panel between the base-WWS and EGS cases is a difference in battery storage.

Base-WWS case



All EGS cases

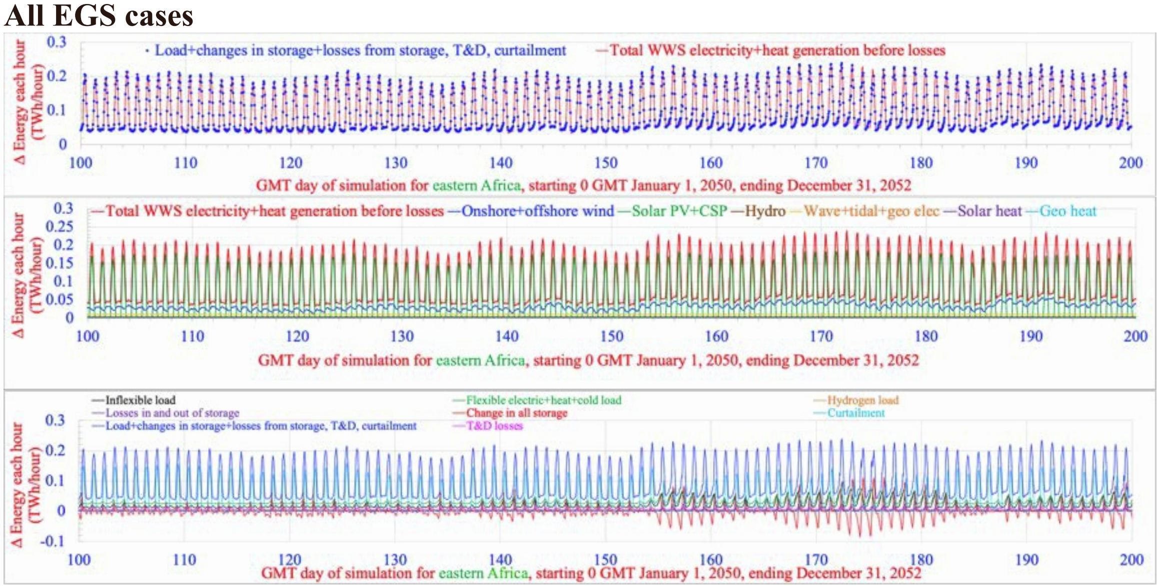
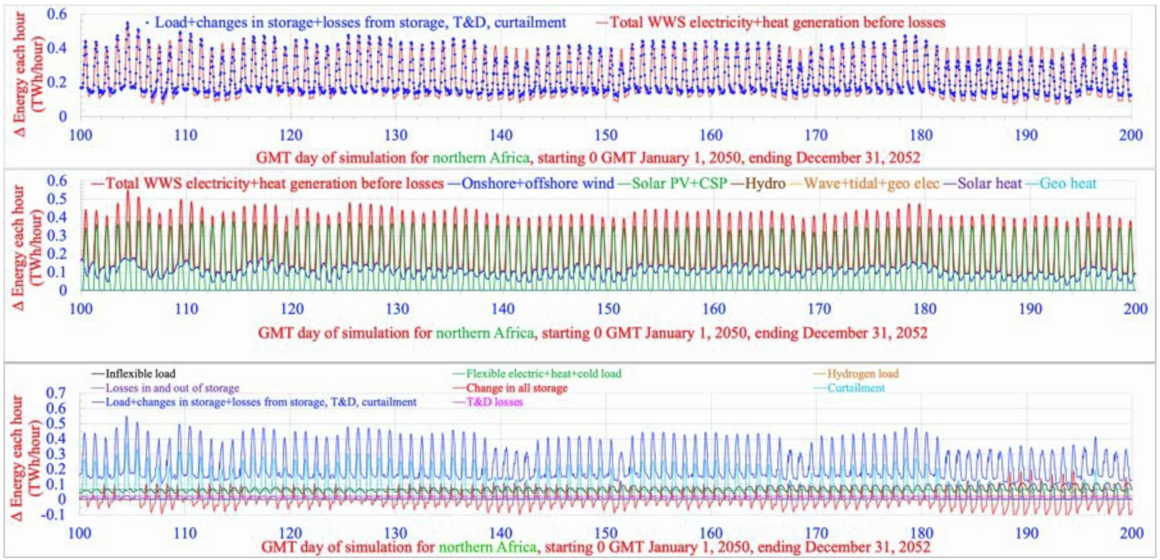


Figure S4. Africa-North hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

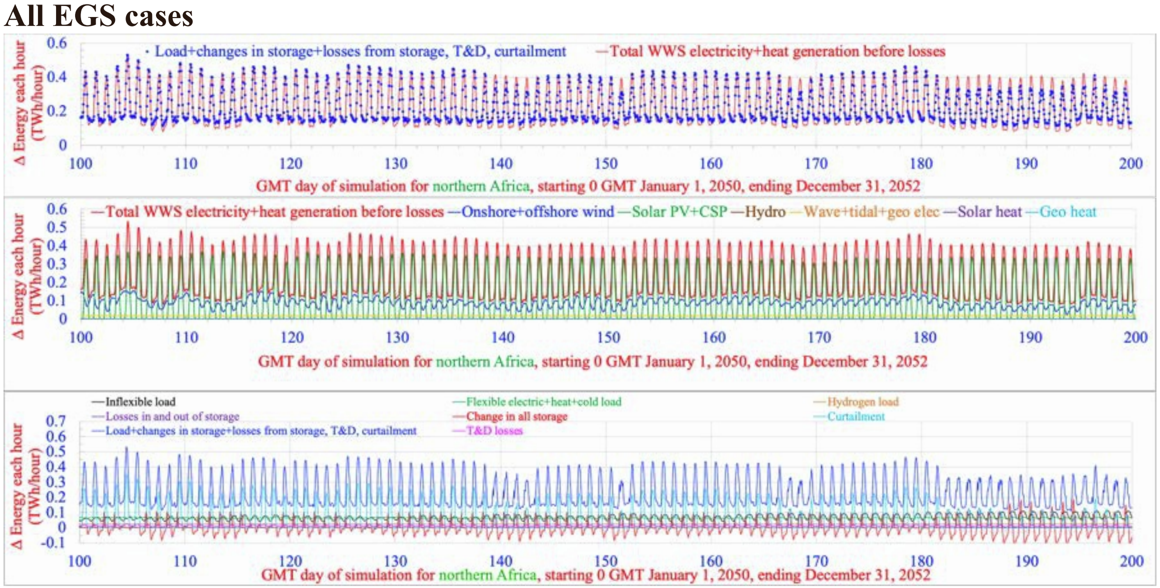
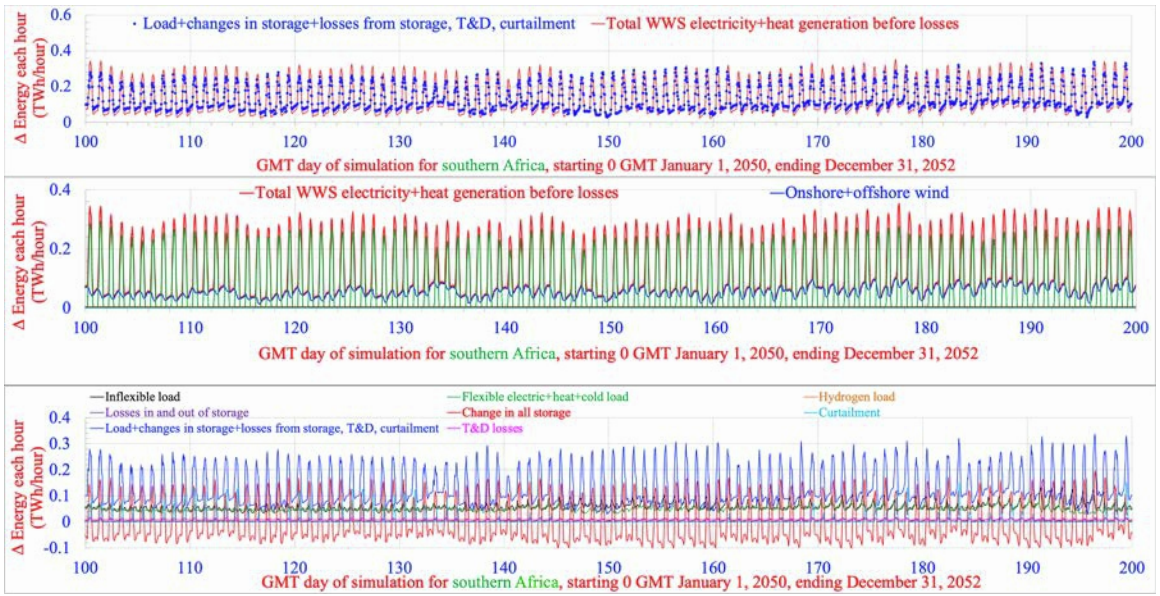


Figure S5. Africa-South hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

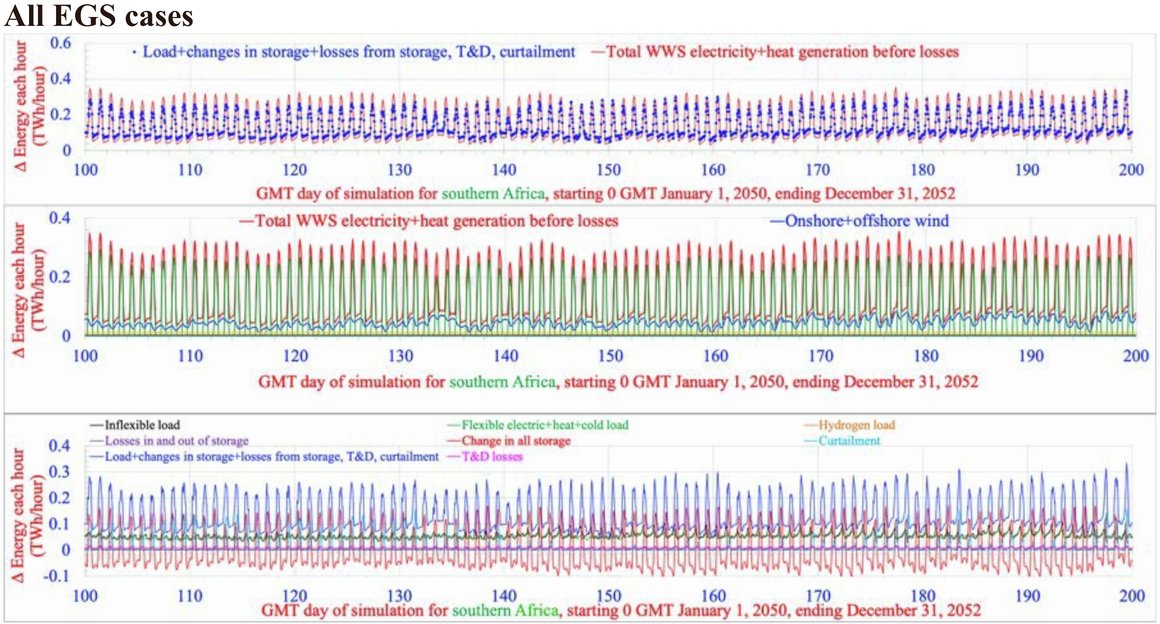
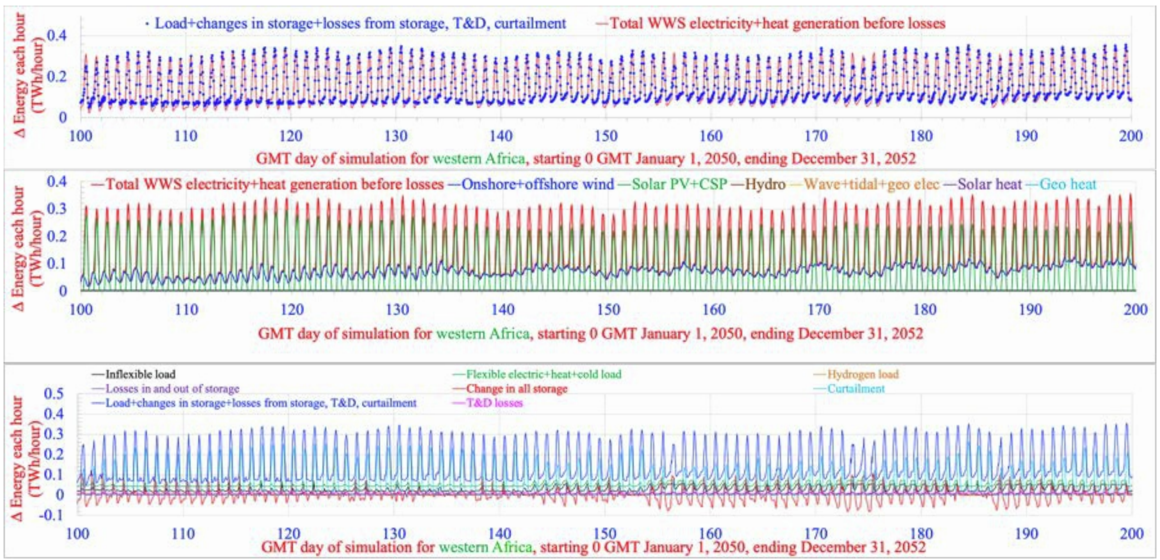


Figure S6. Africa-West hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

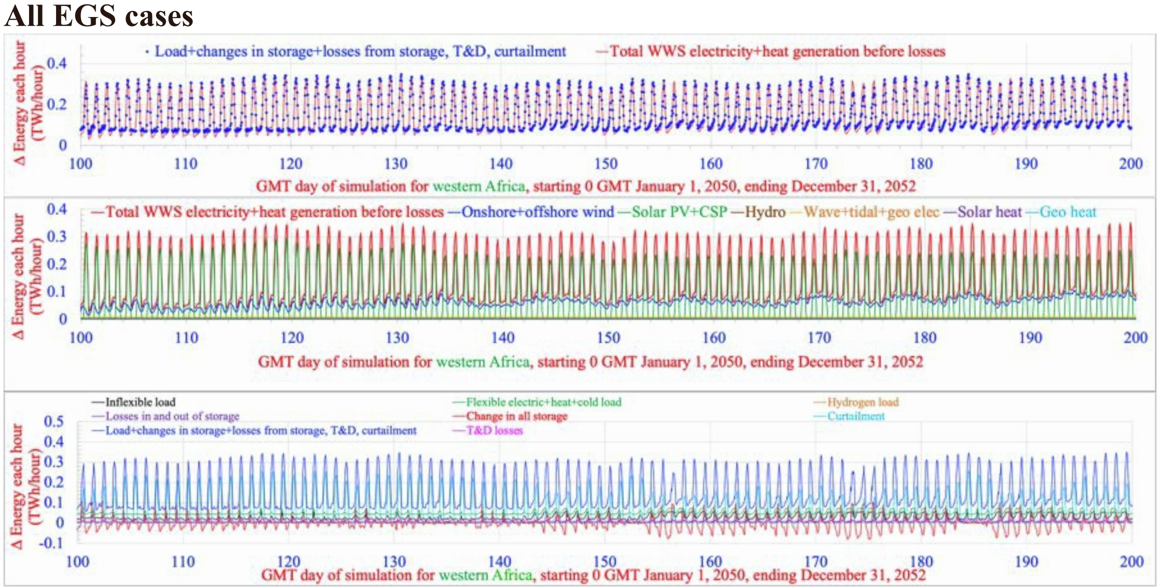
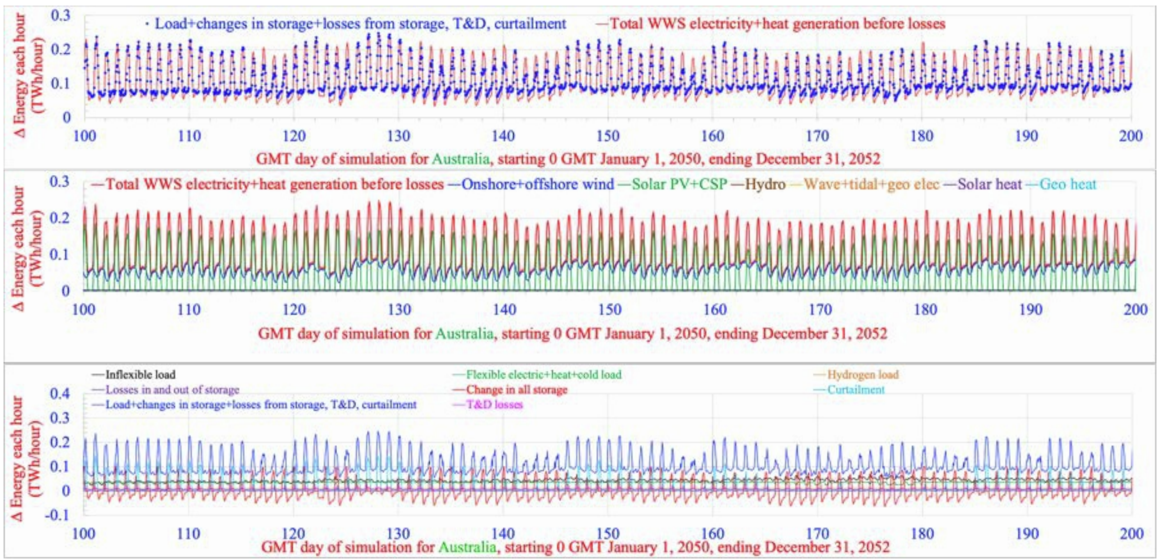


Figure S7. Australia hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

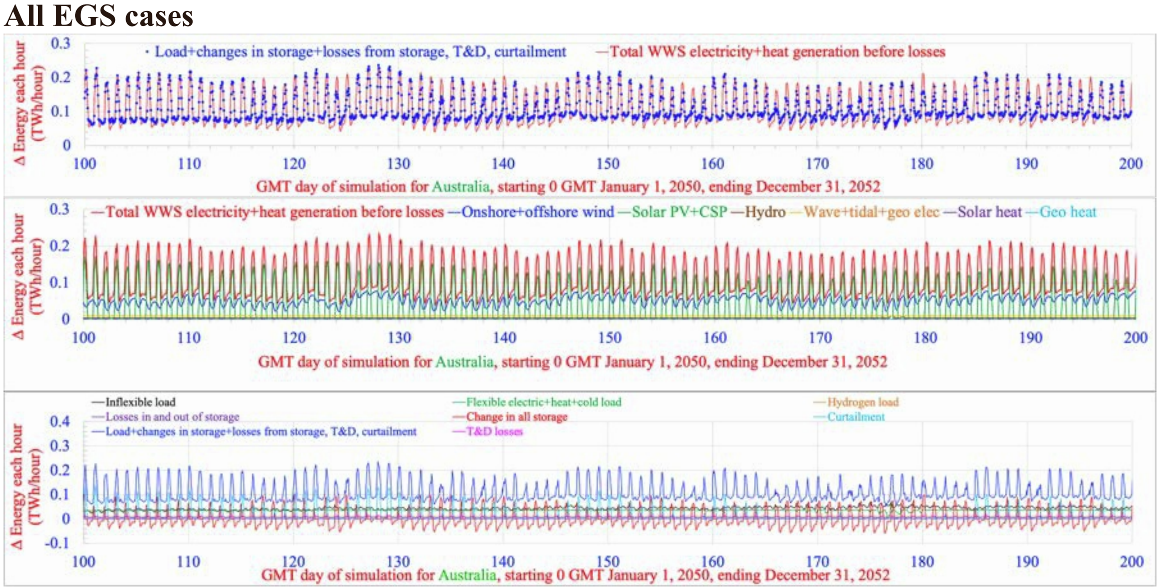
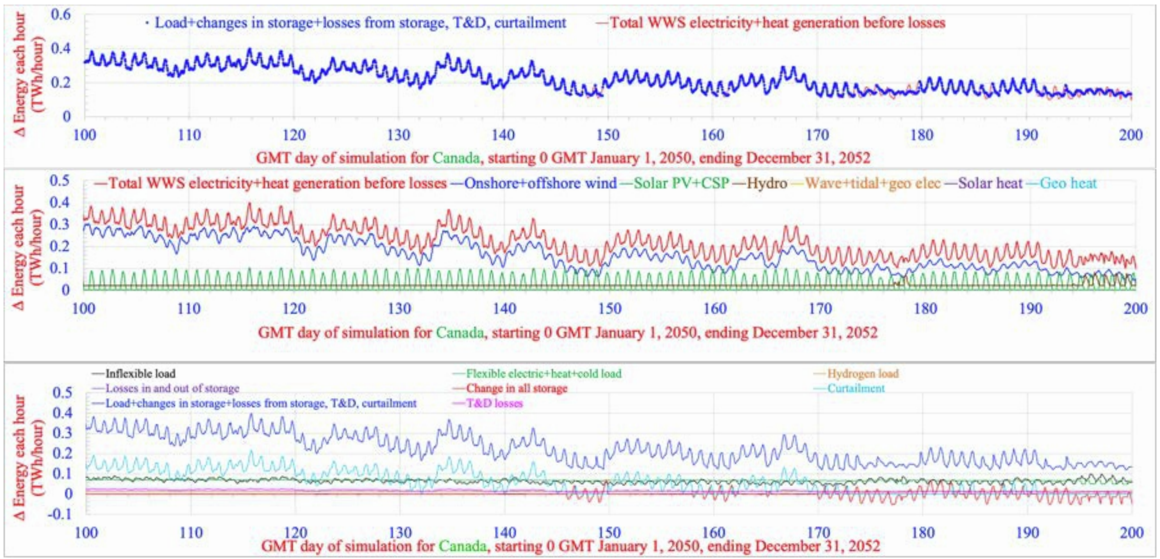


Figure S8. Canada hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

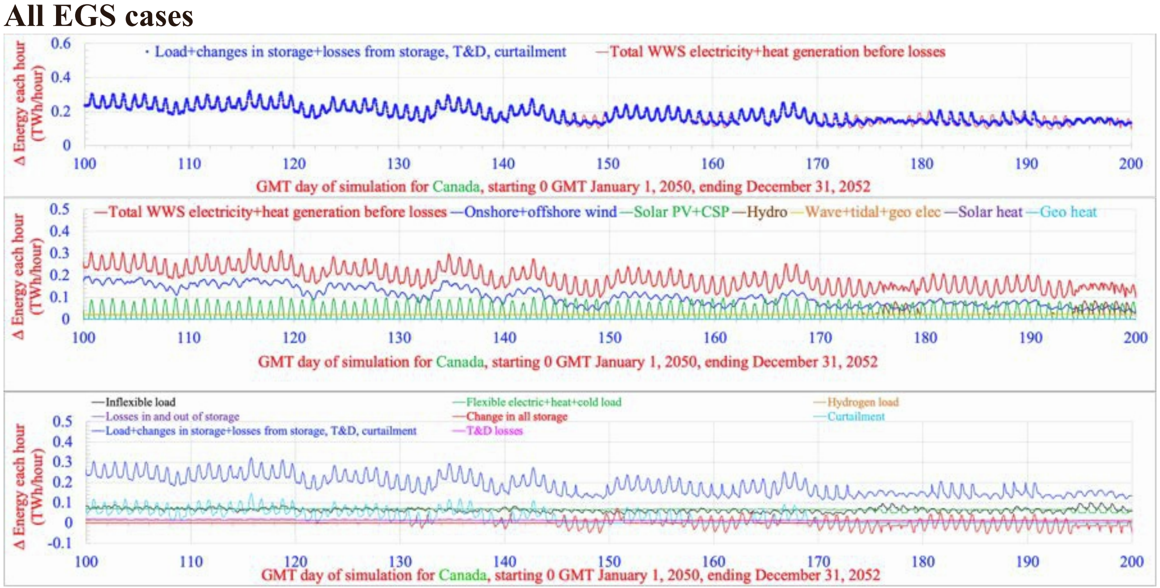
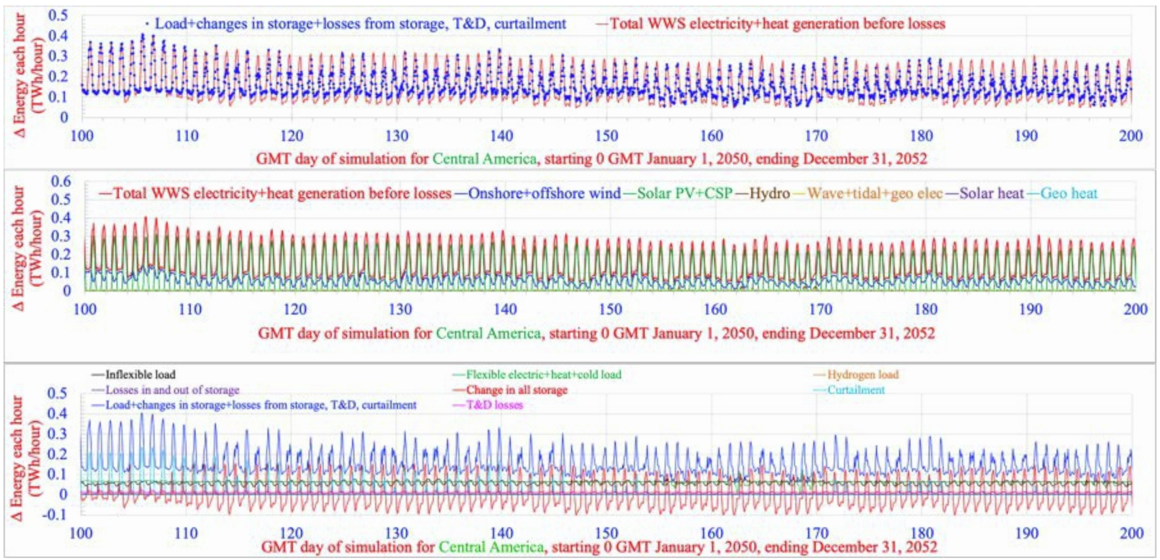


Figure S9. Central America hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

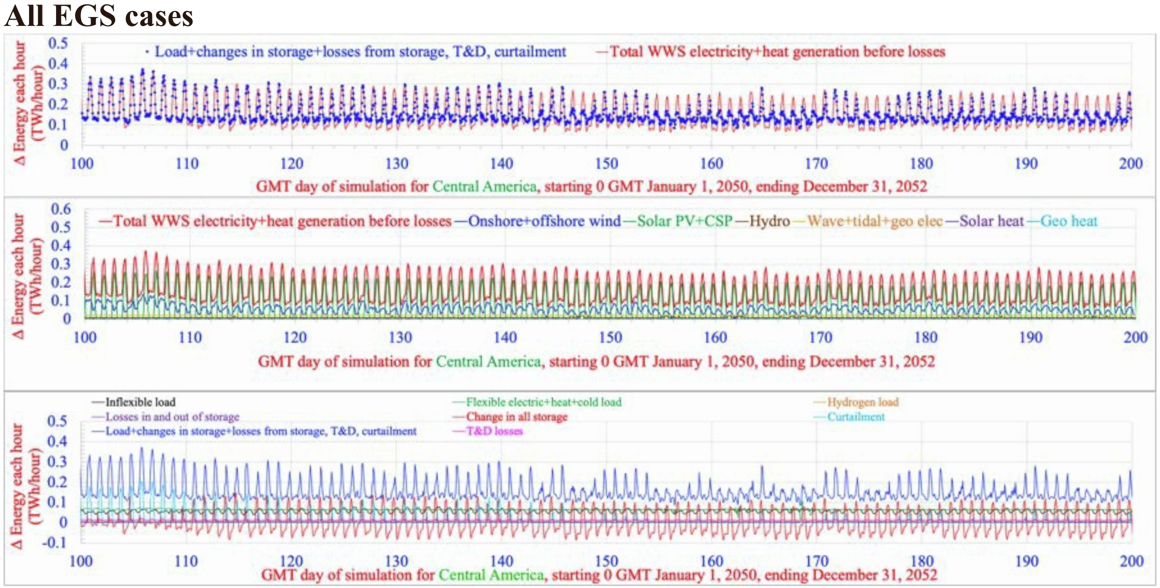
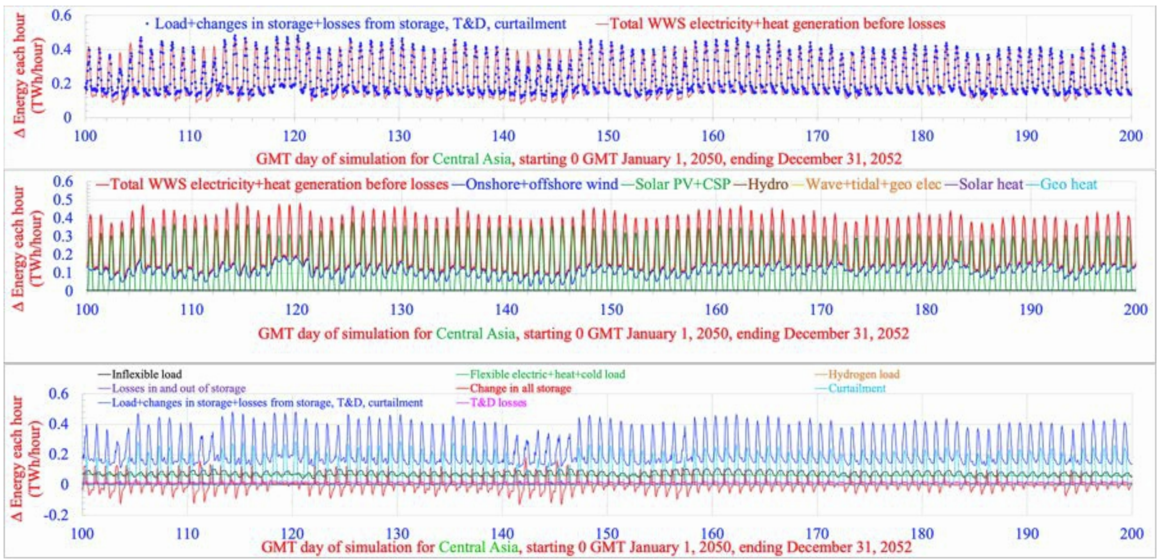


Figure S10. Central Asia hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

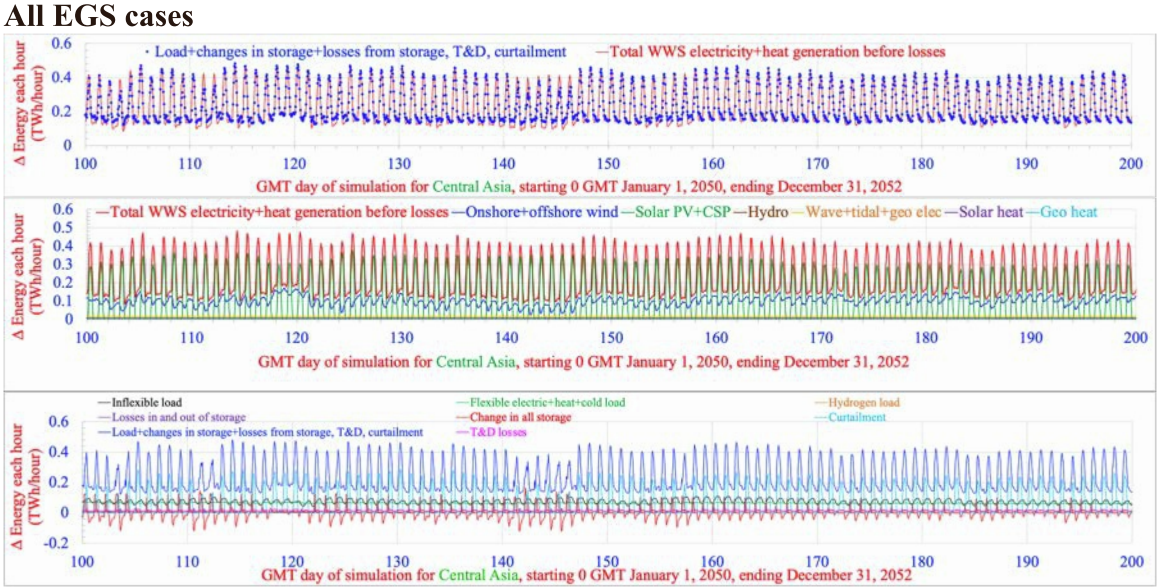
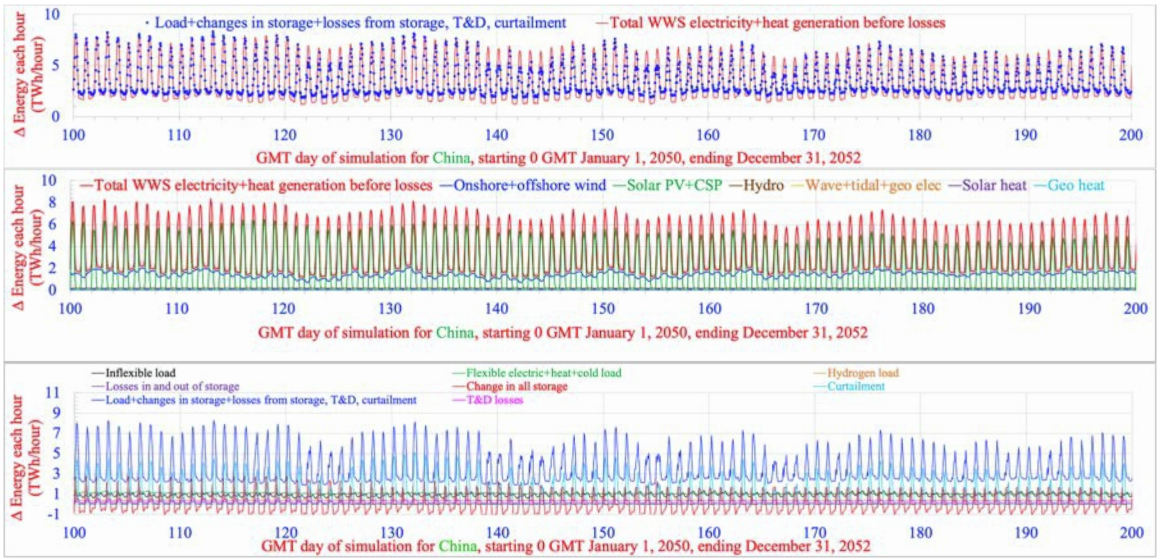


Figure S11. China region hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

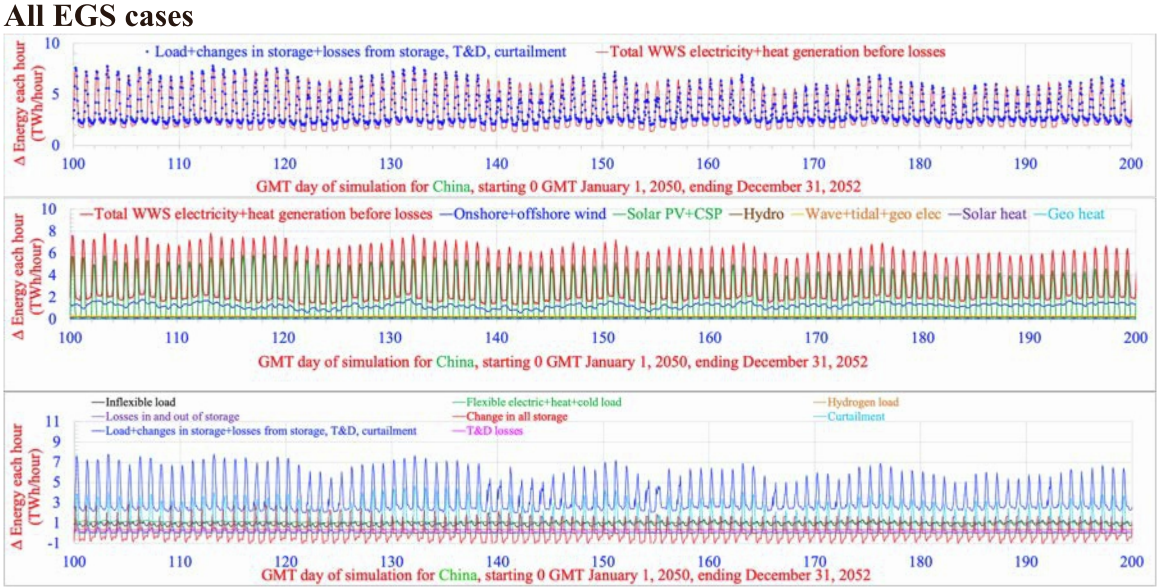
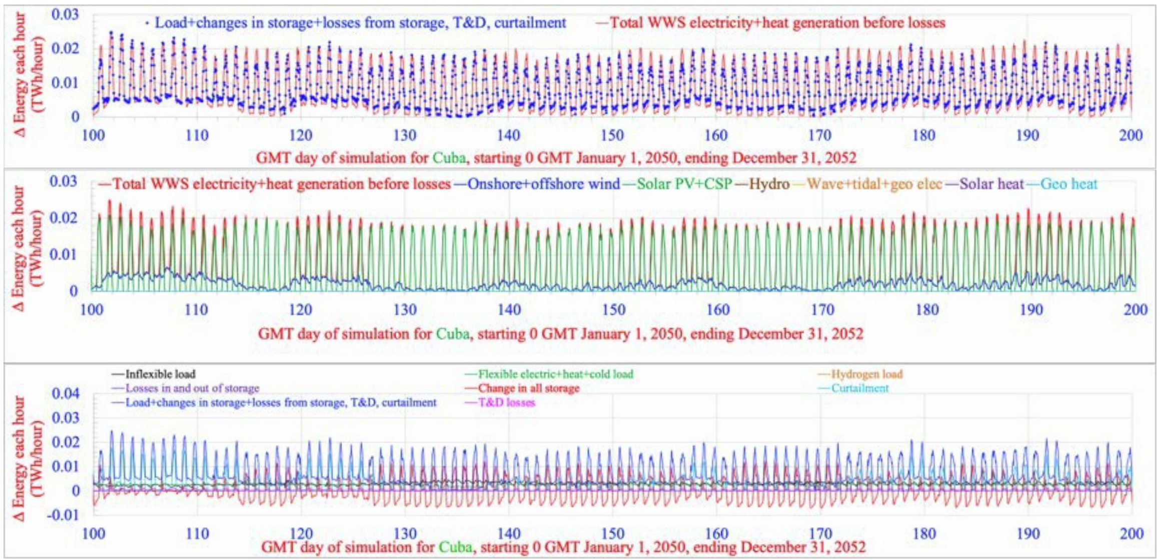


Figure S12. Cuba hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

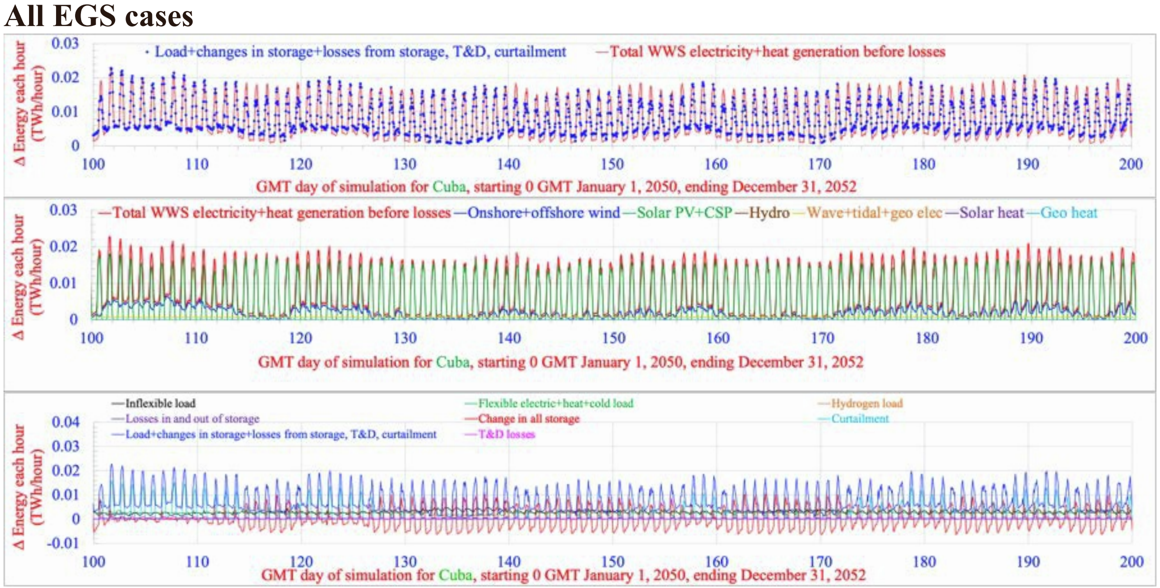
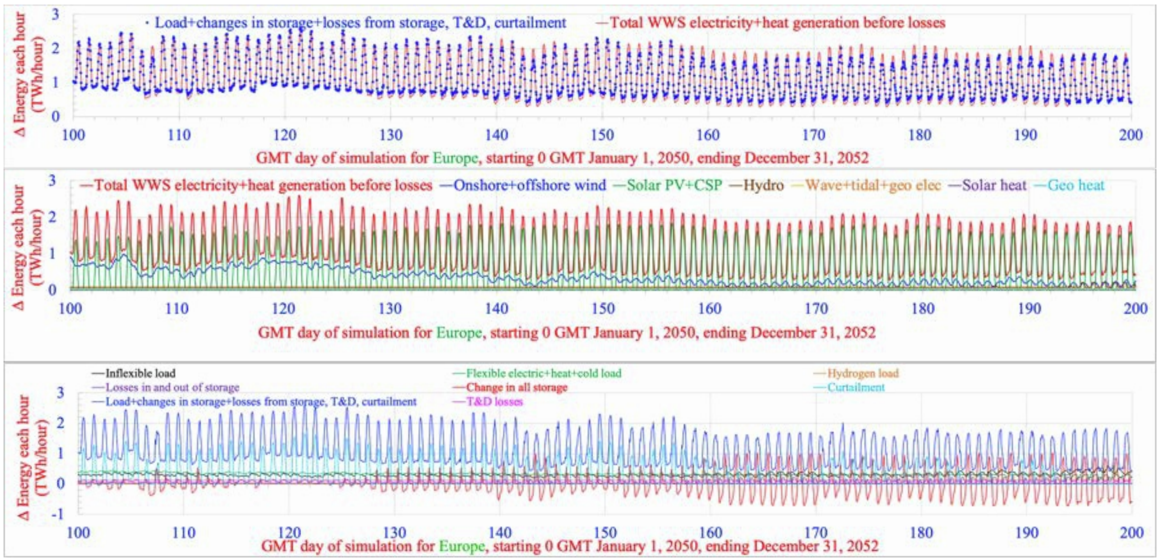


Figure S13. Europe hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

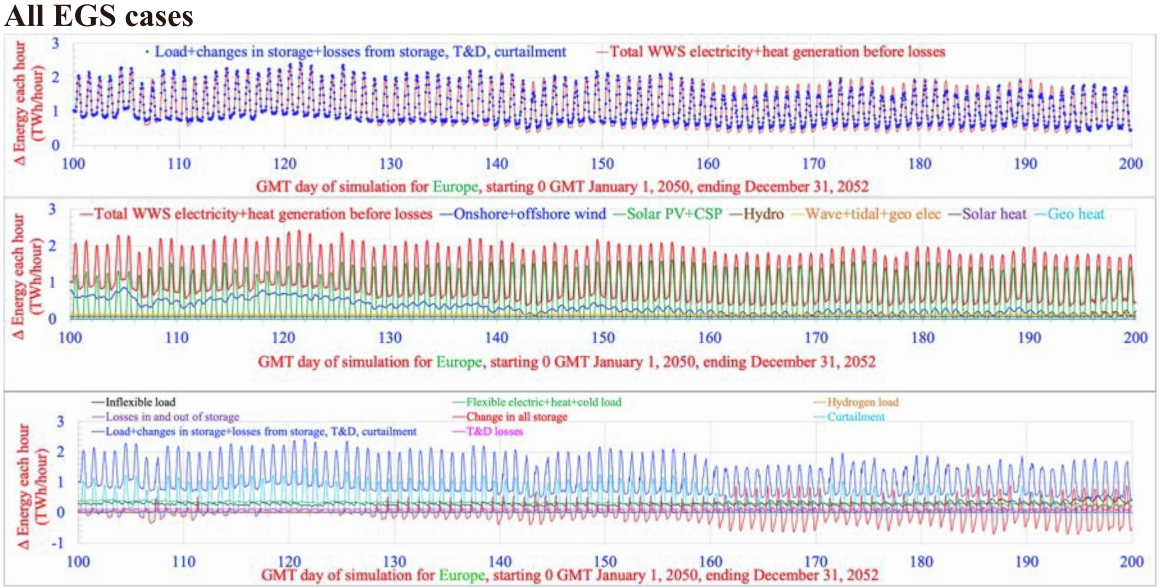
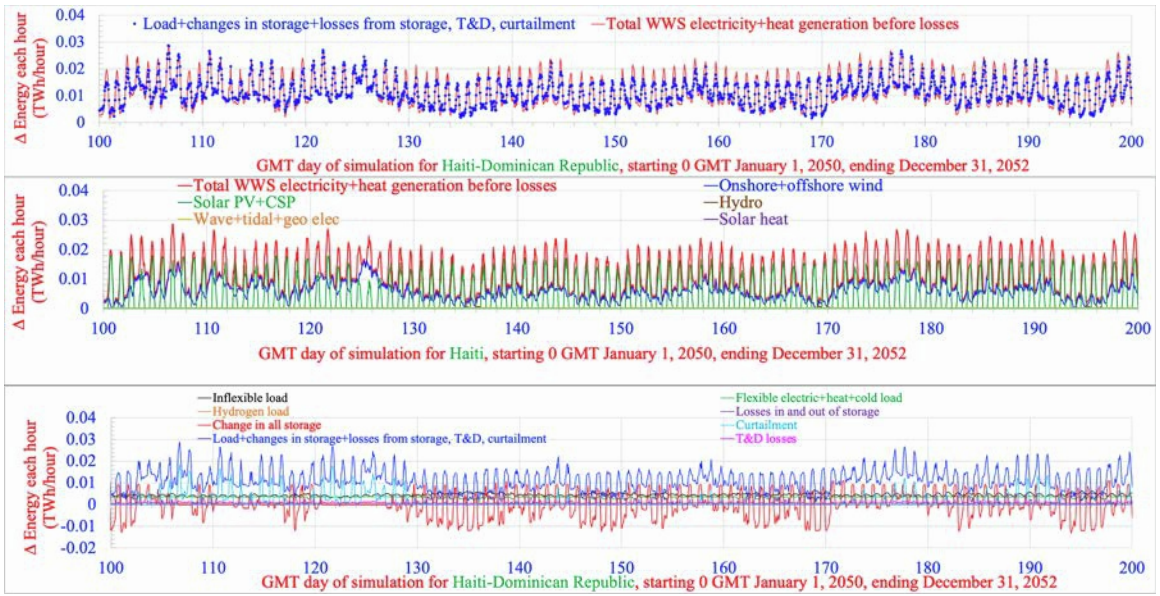


Figure S14. Haiti region hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

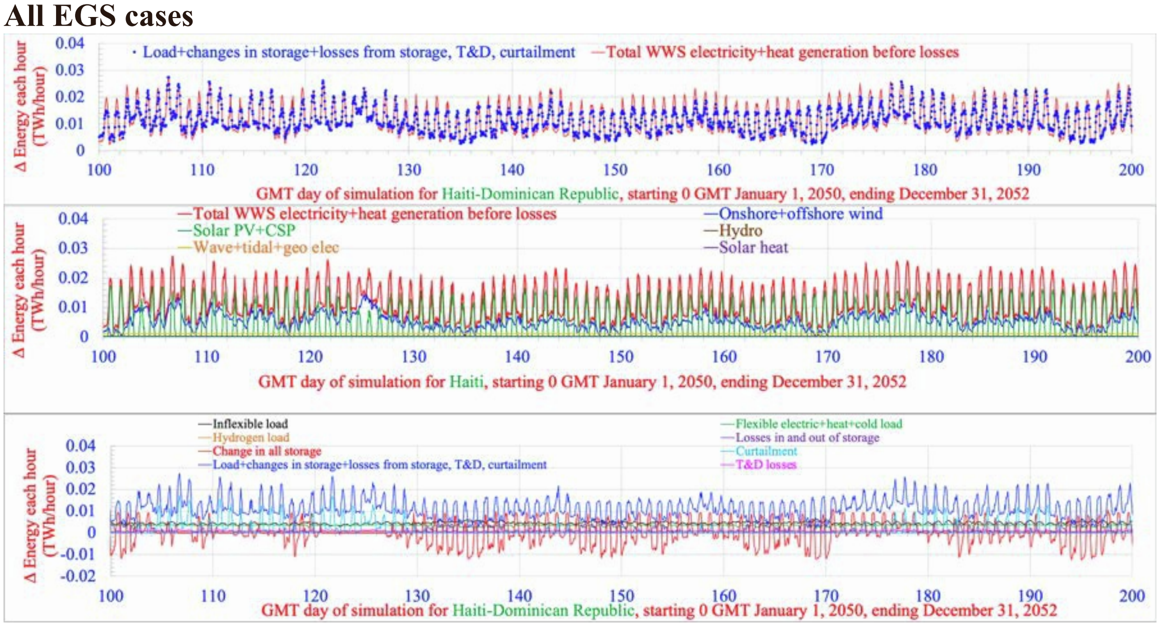
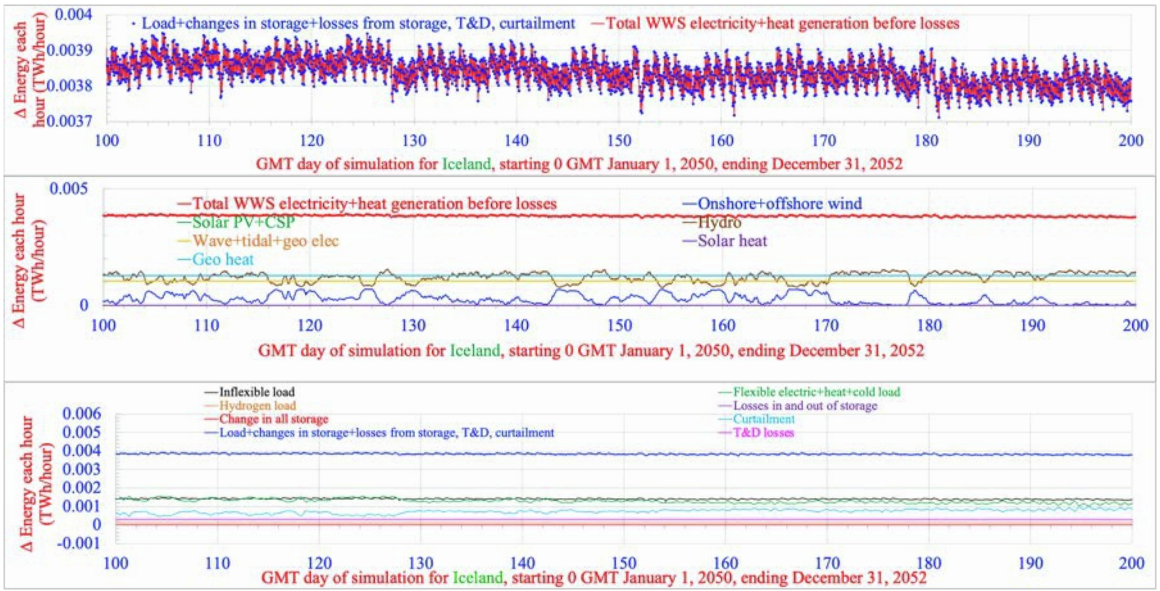


Figure S15. Iceland hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

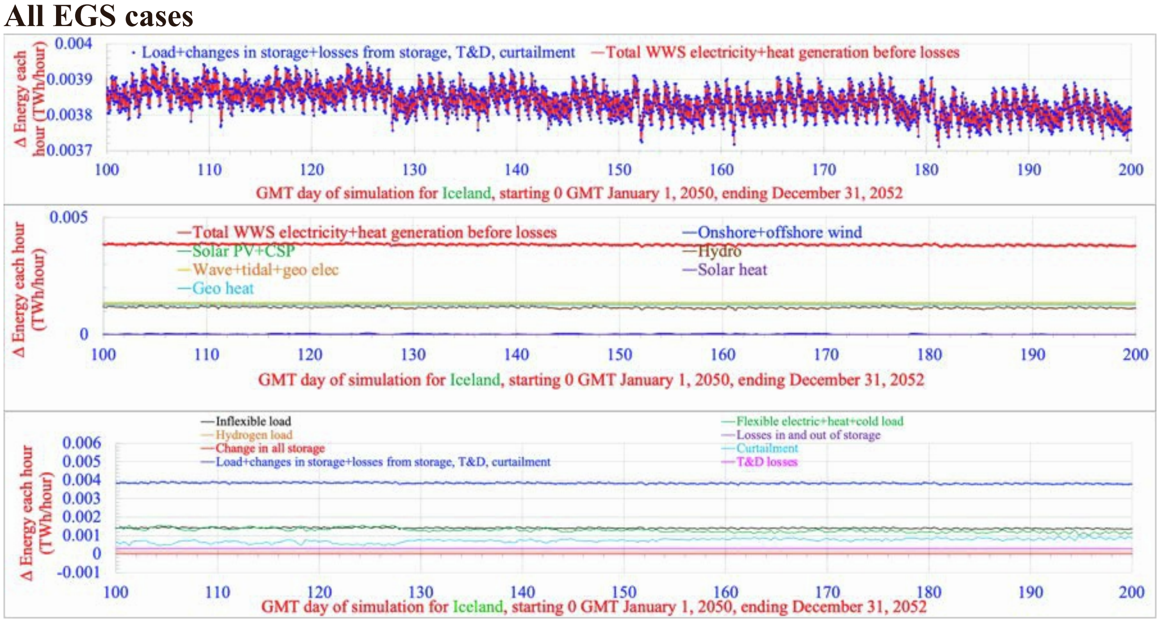
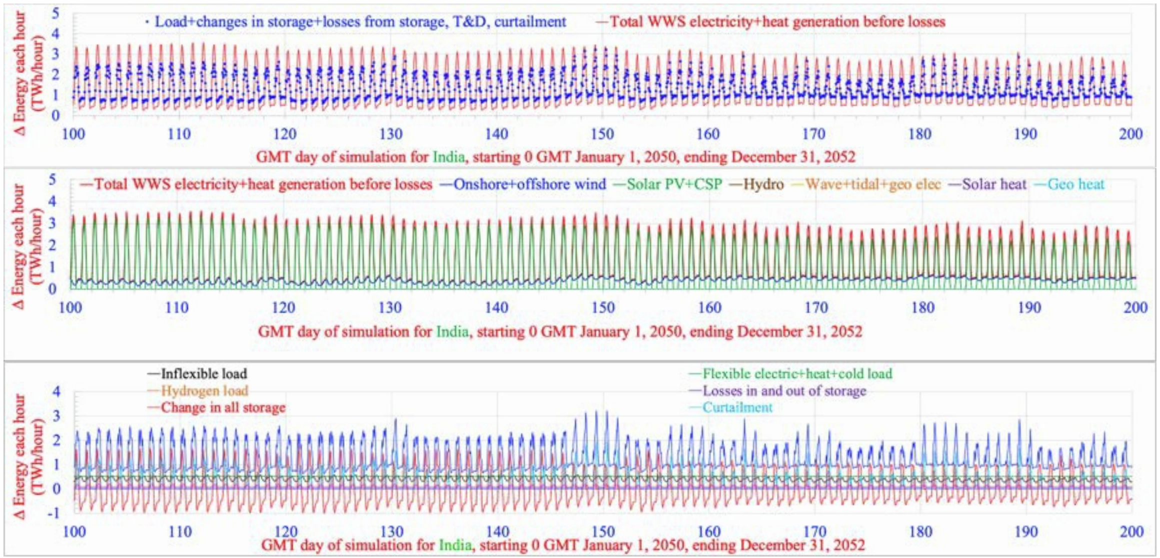


Figure S16. India region hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

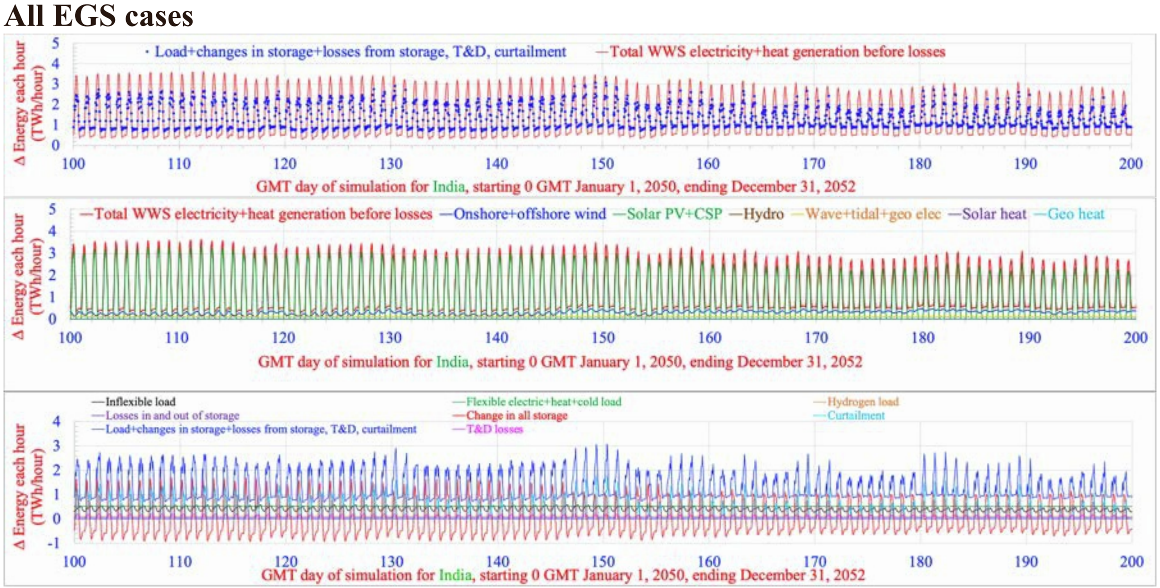
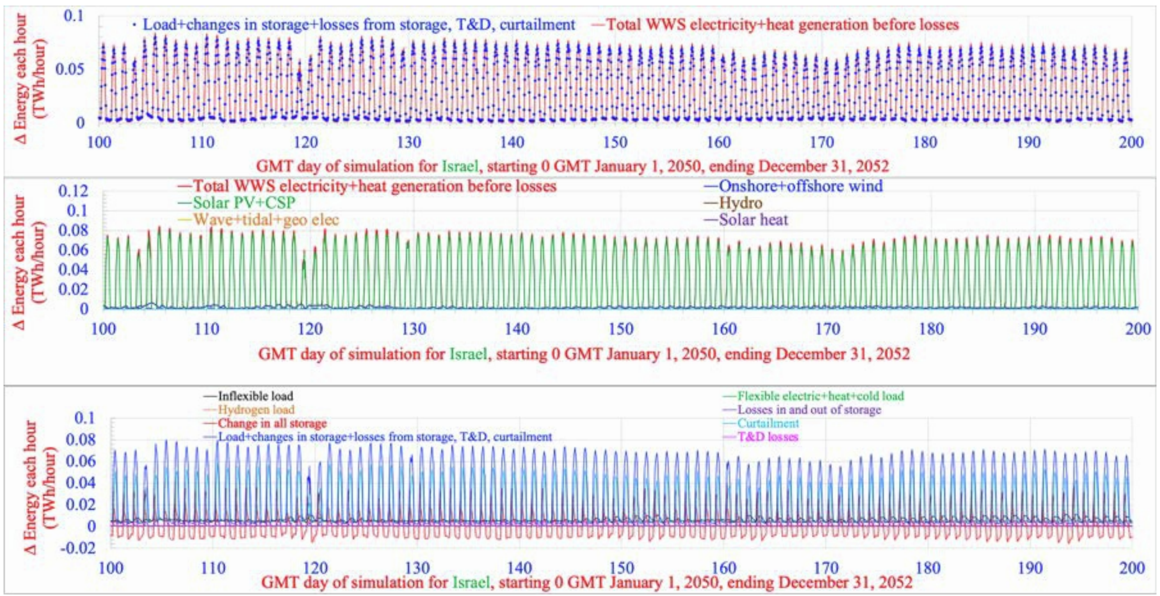


Figure S17. Israel hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

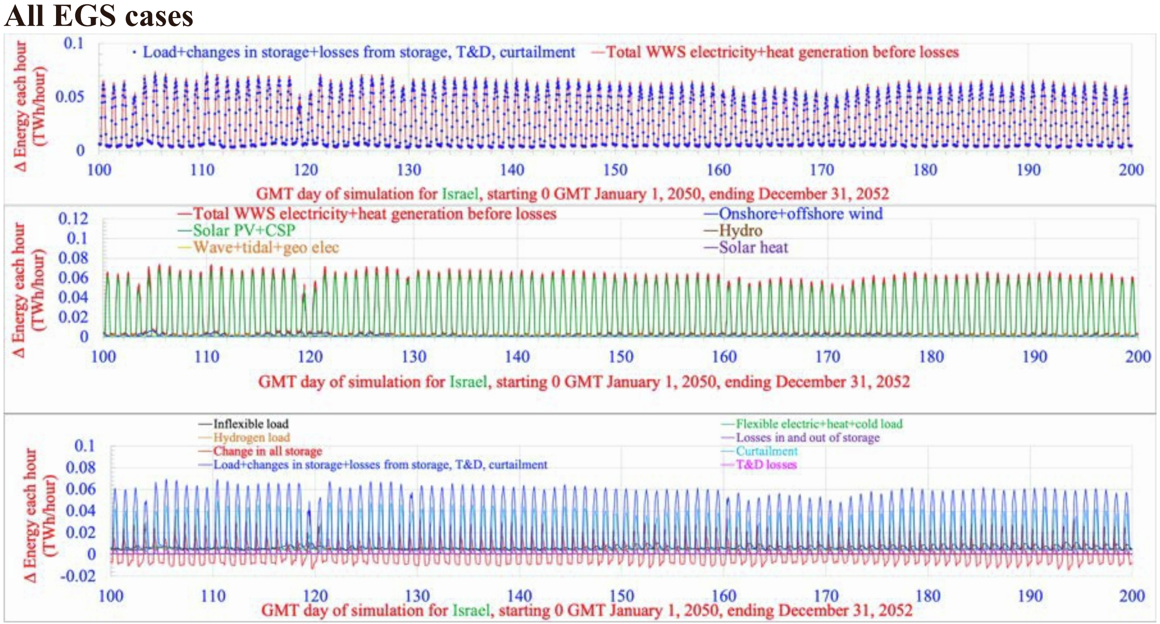
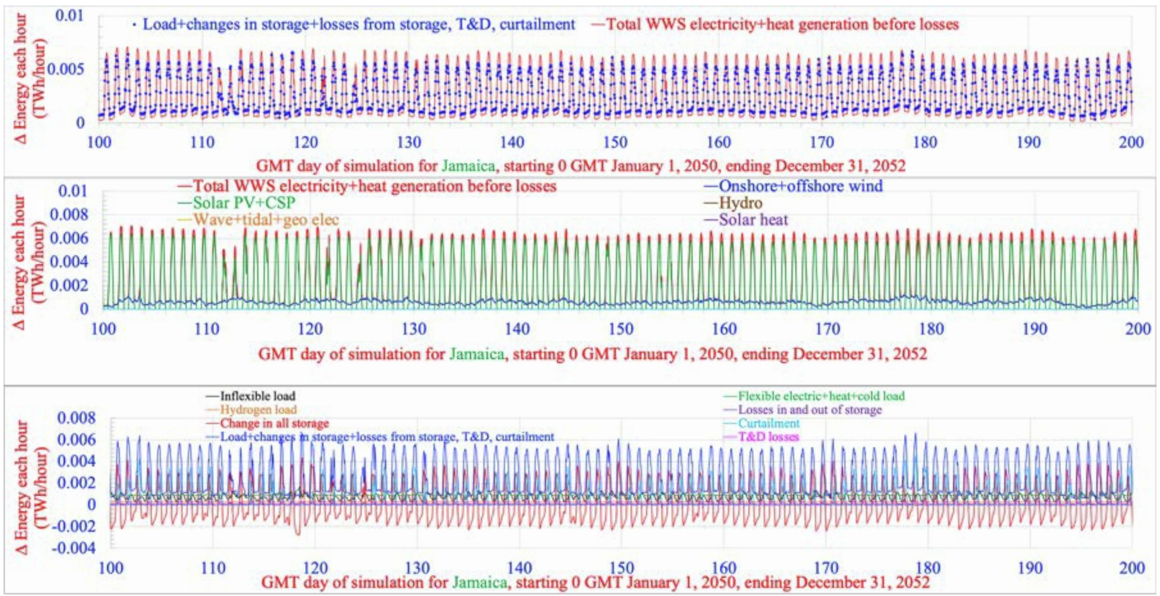


Figure S18. Jamaica hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

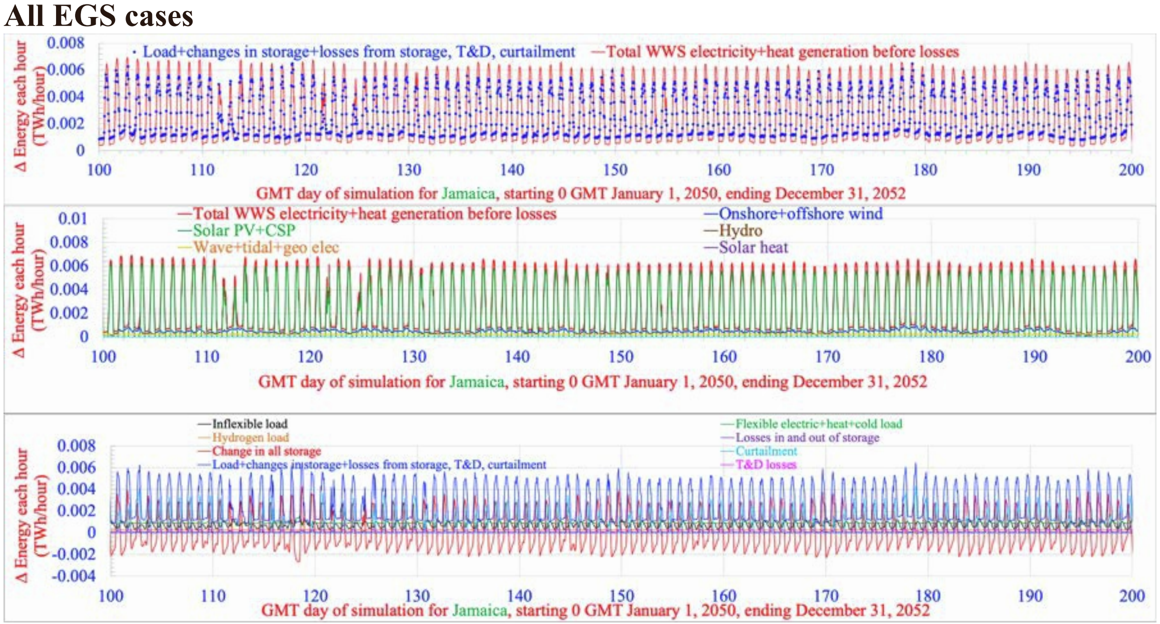
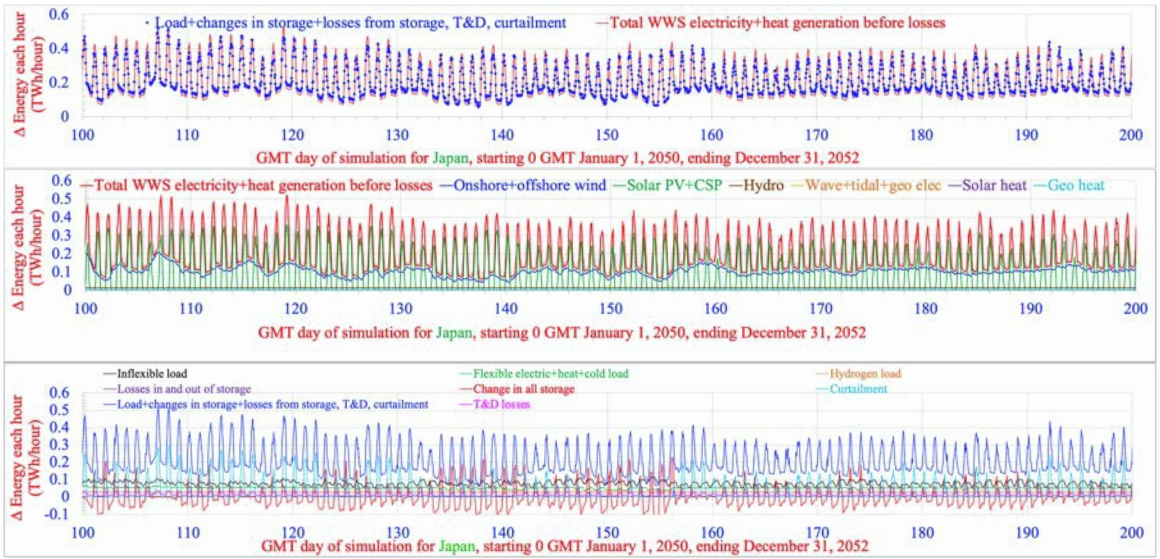


Figure S19. Japan hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

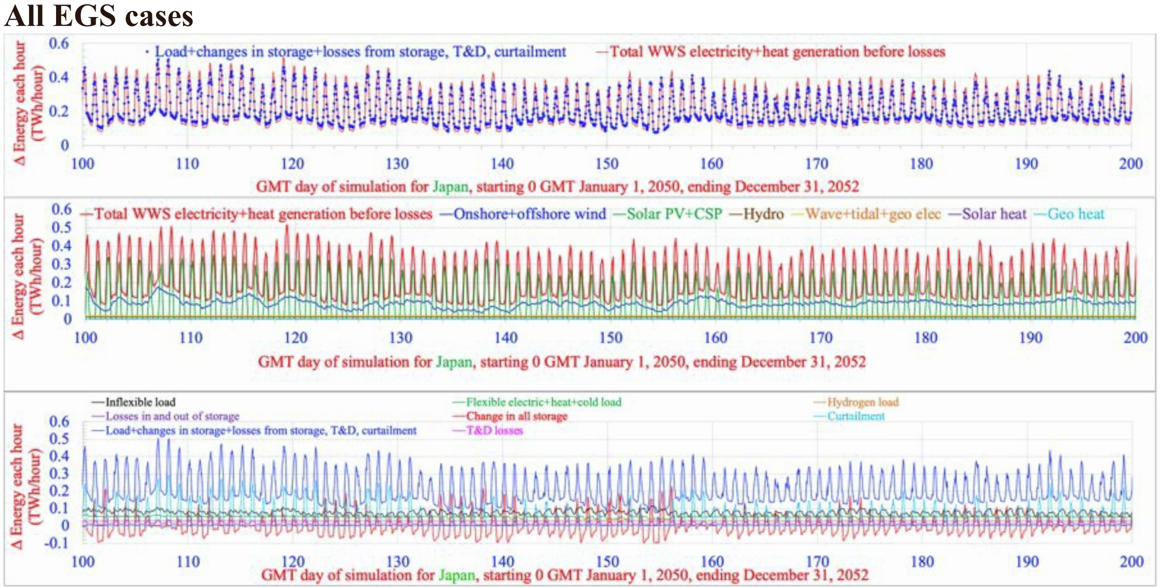
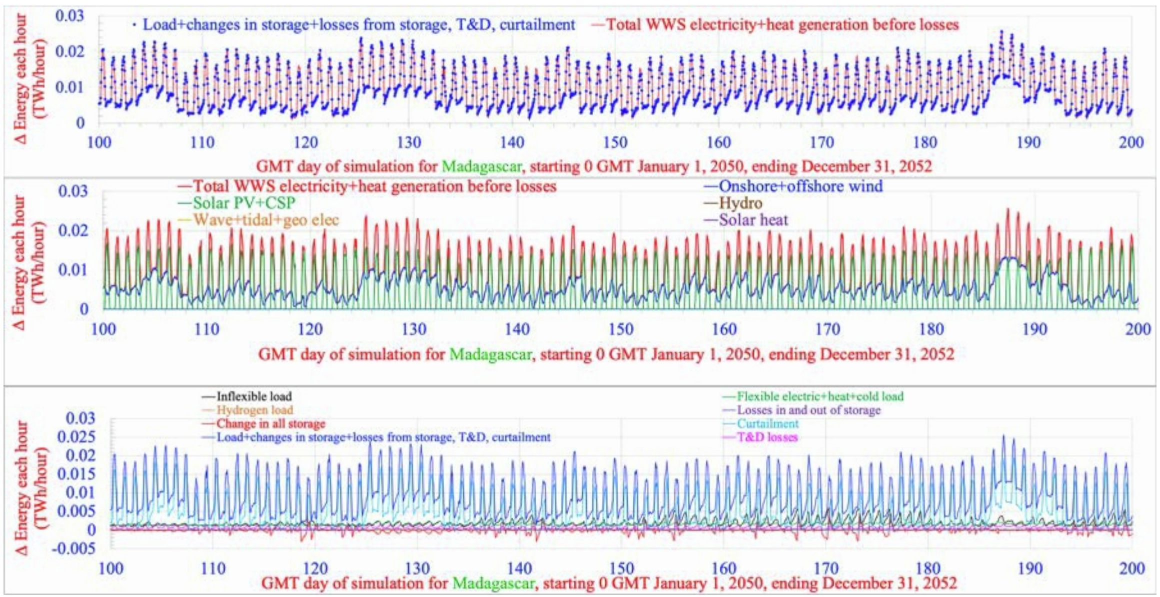


Figure S20. Madagascar hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

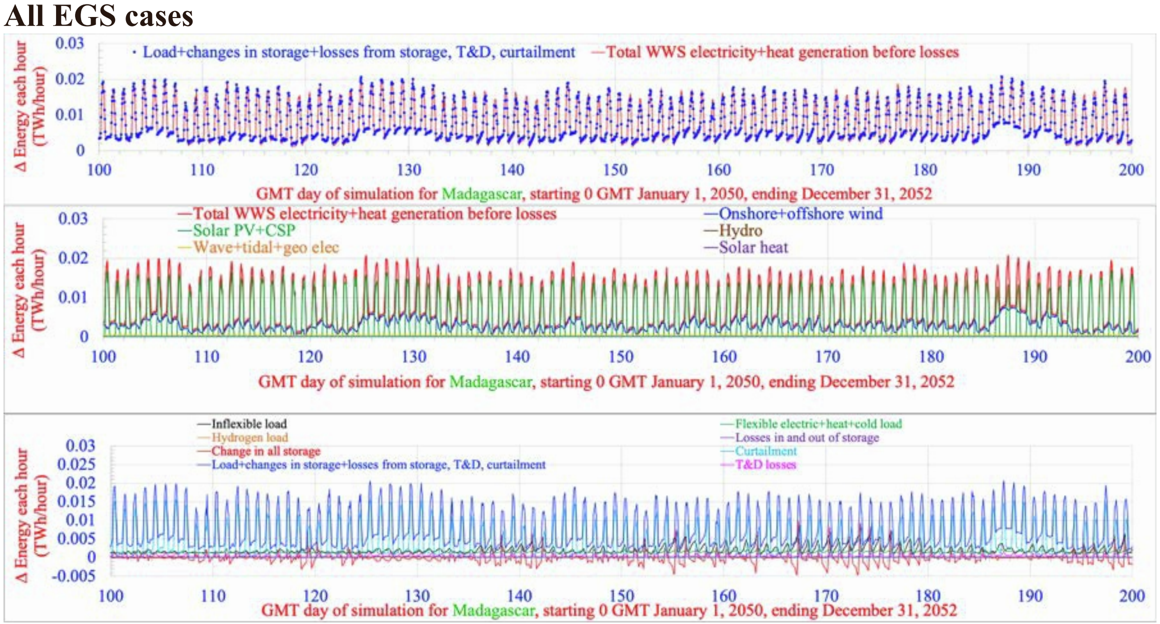
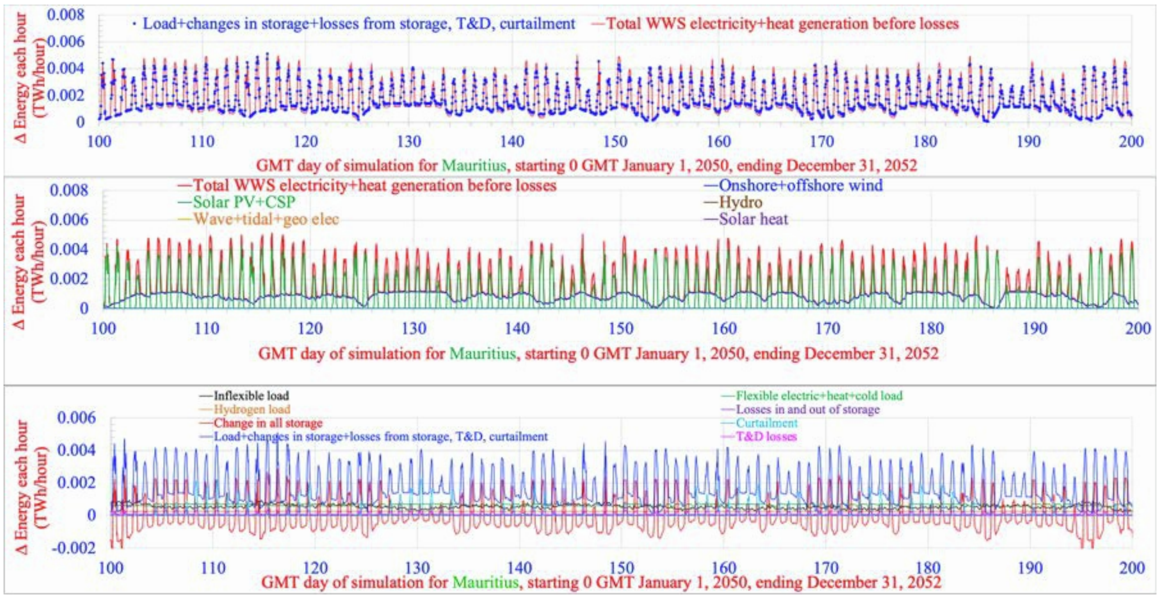


Figure S21. Mauritius hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

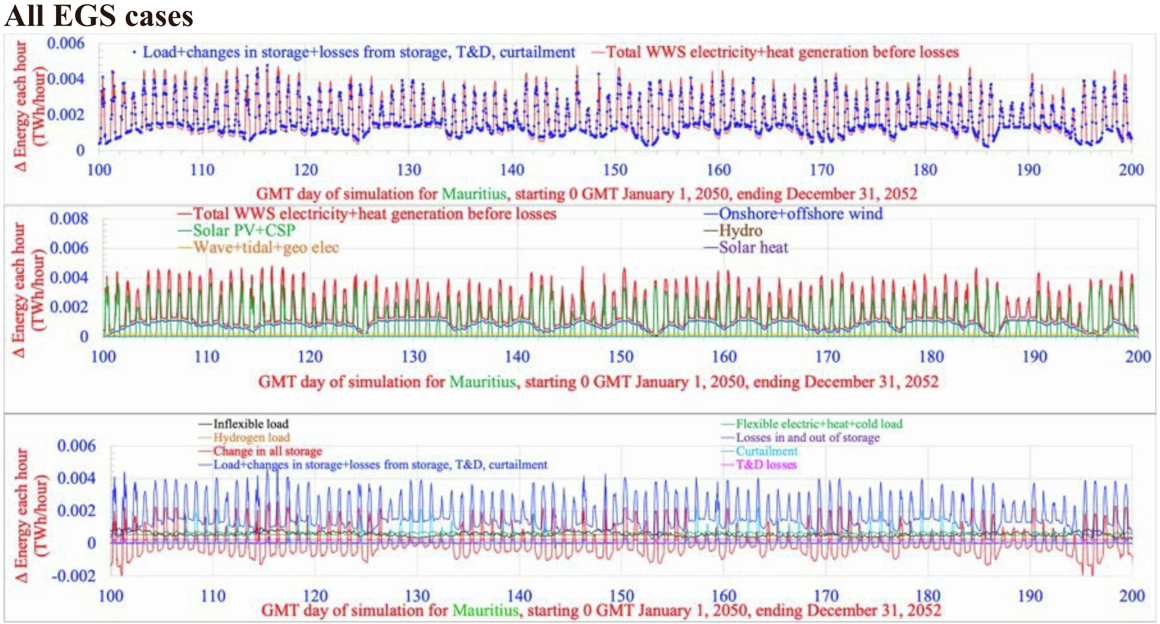
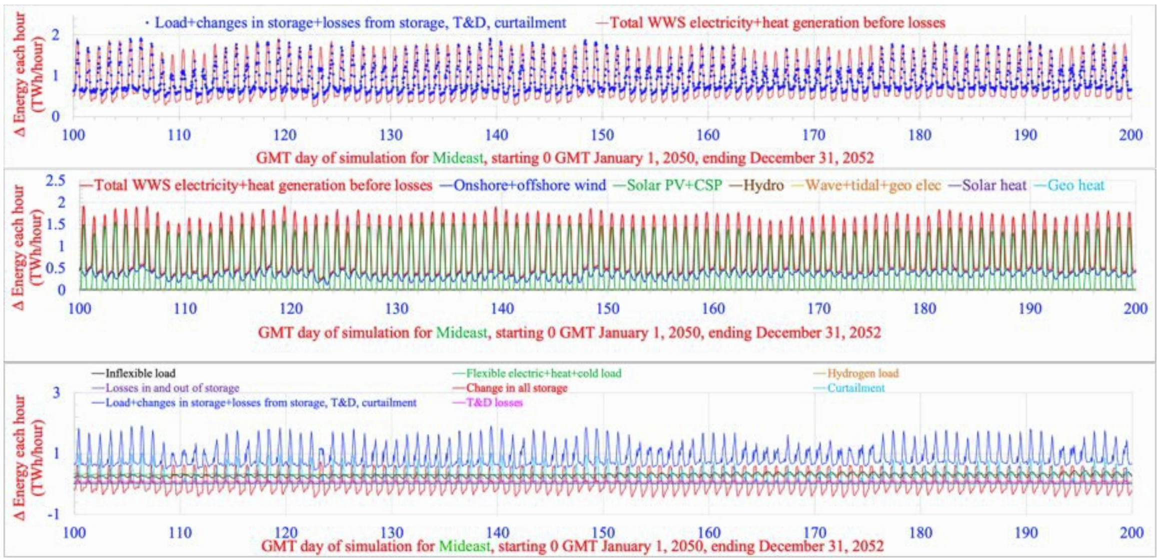


Figure S22. Mideast hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

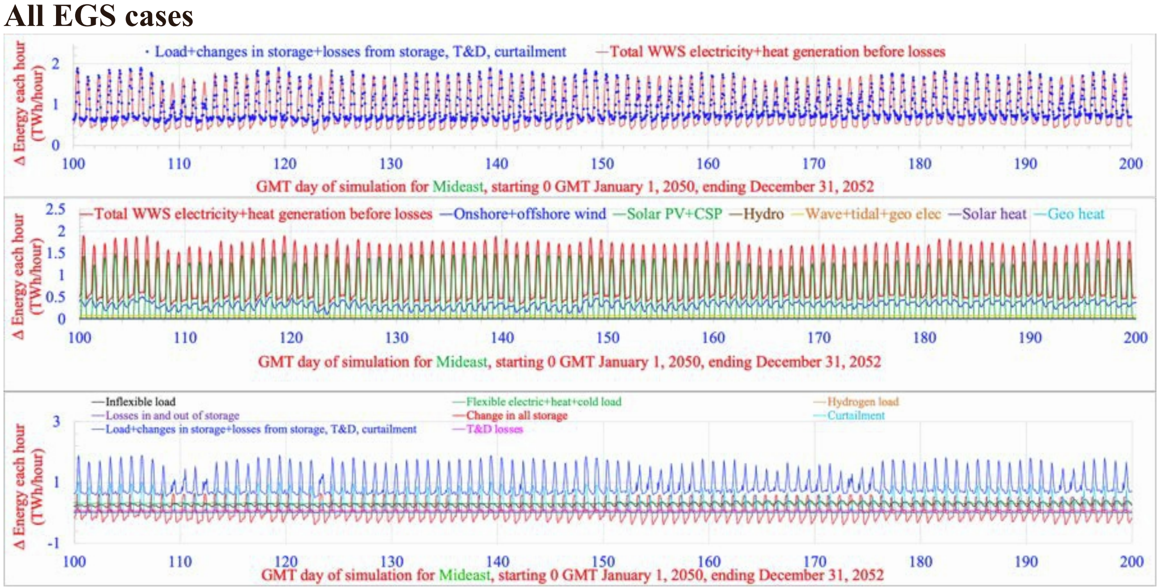
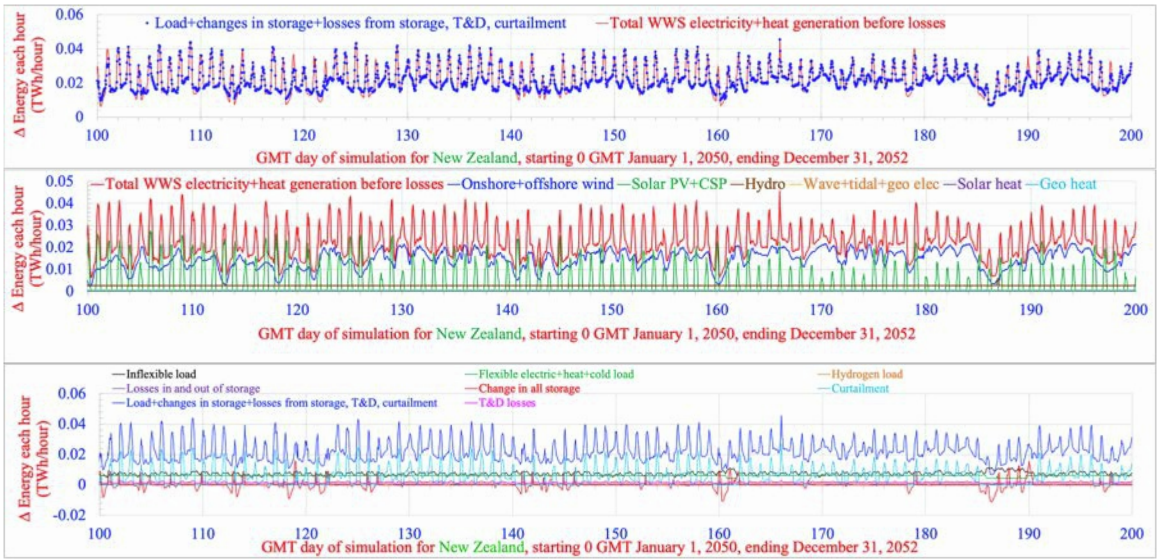


Figure S23. New Zealand hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

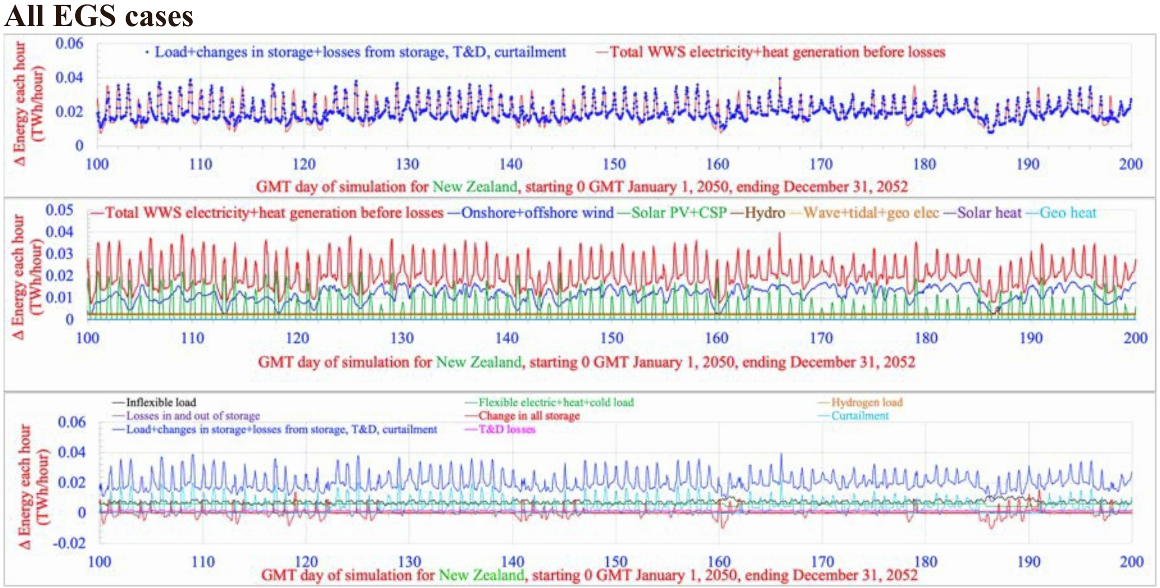
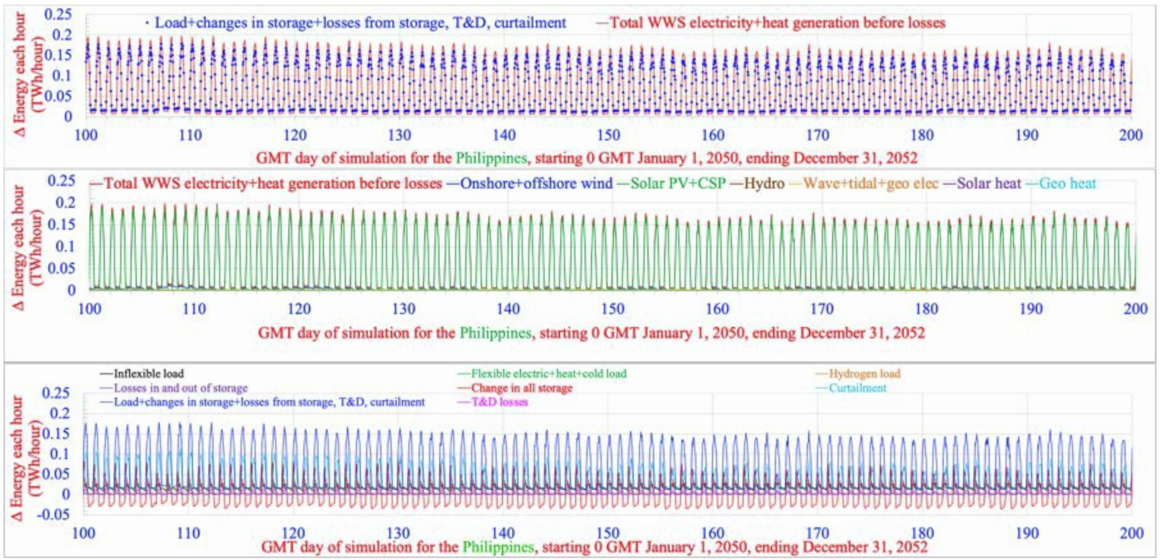


Figure S24. Philippines hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

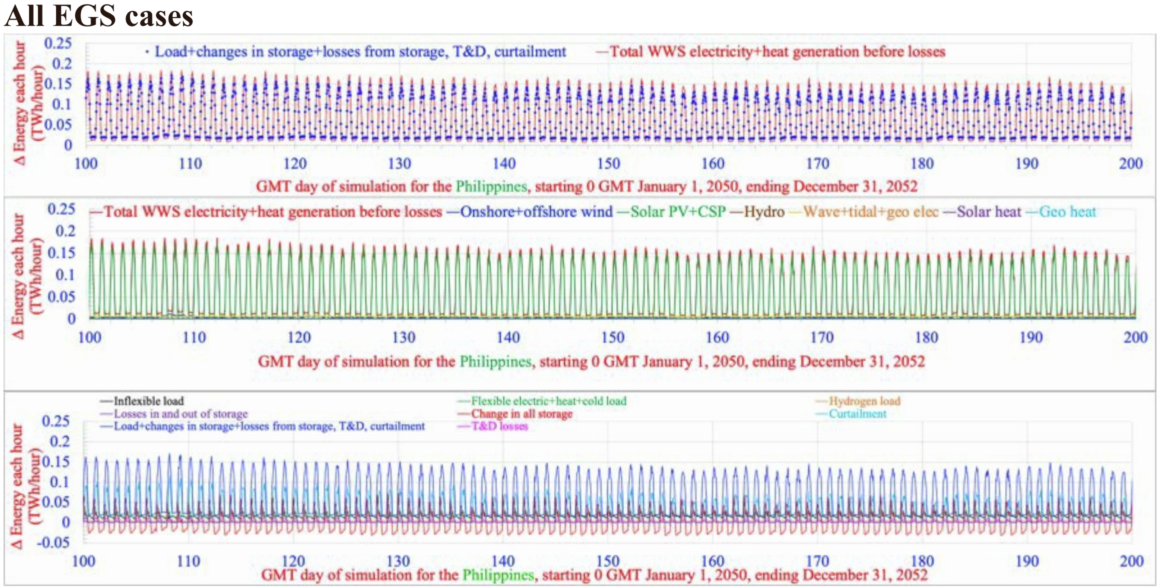
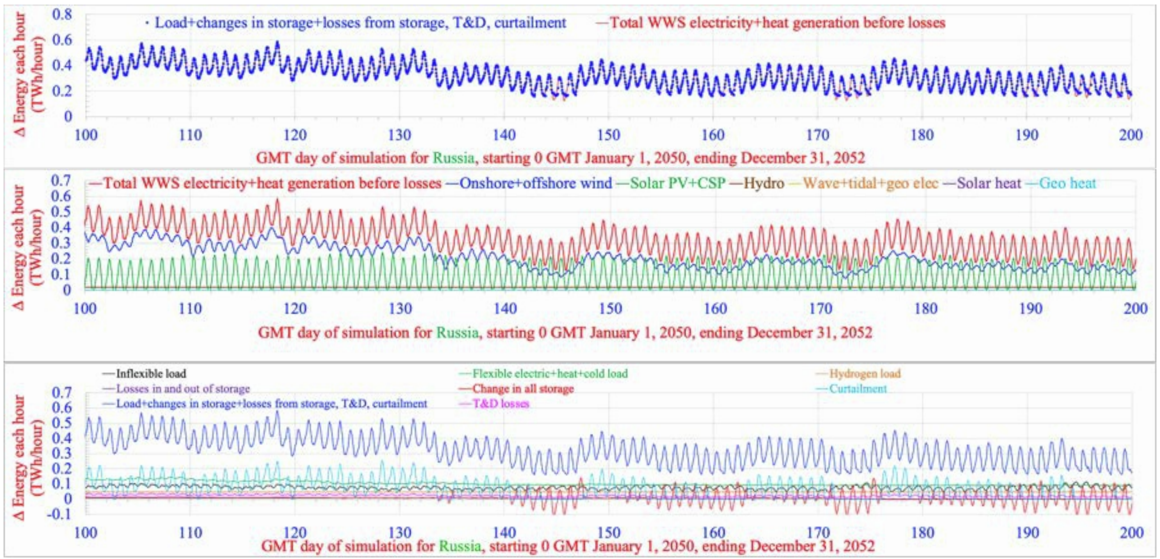


Figure S25. Russia region hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

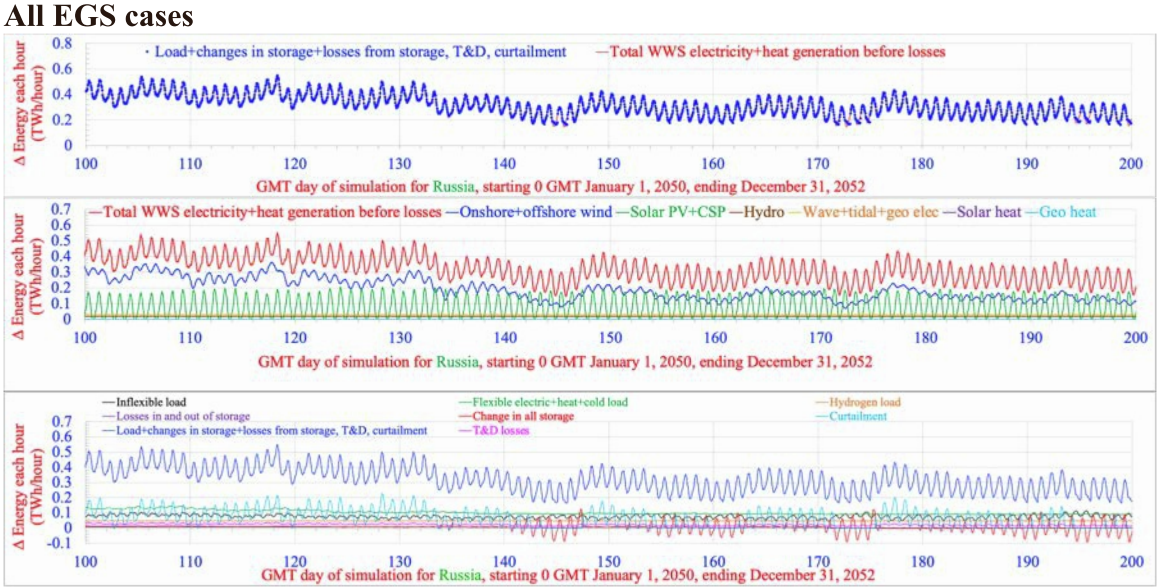
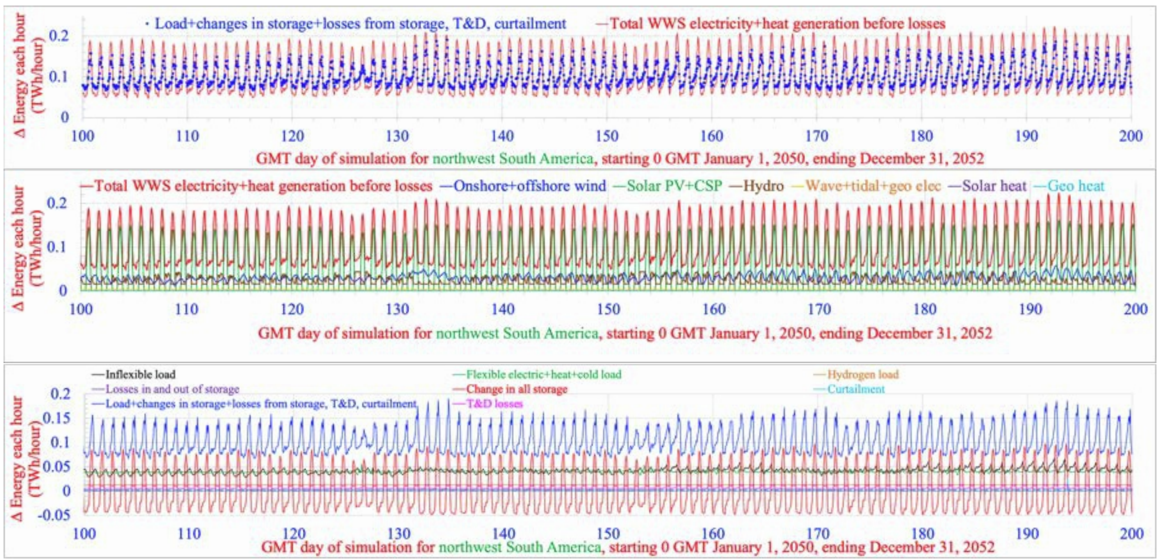


Figure S26. Northwest South America hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

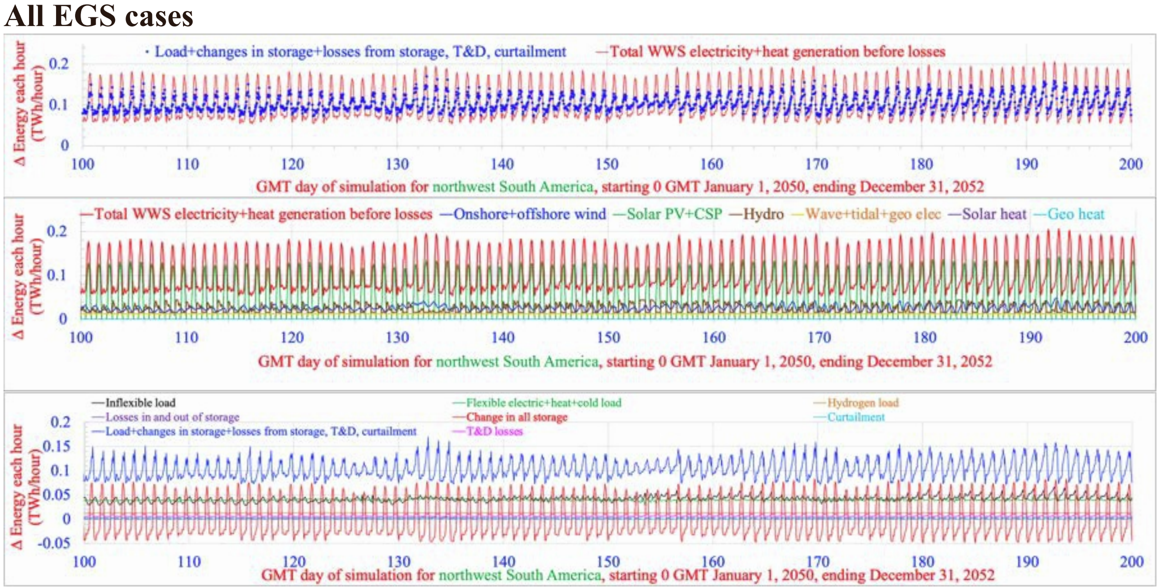
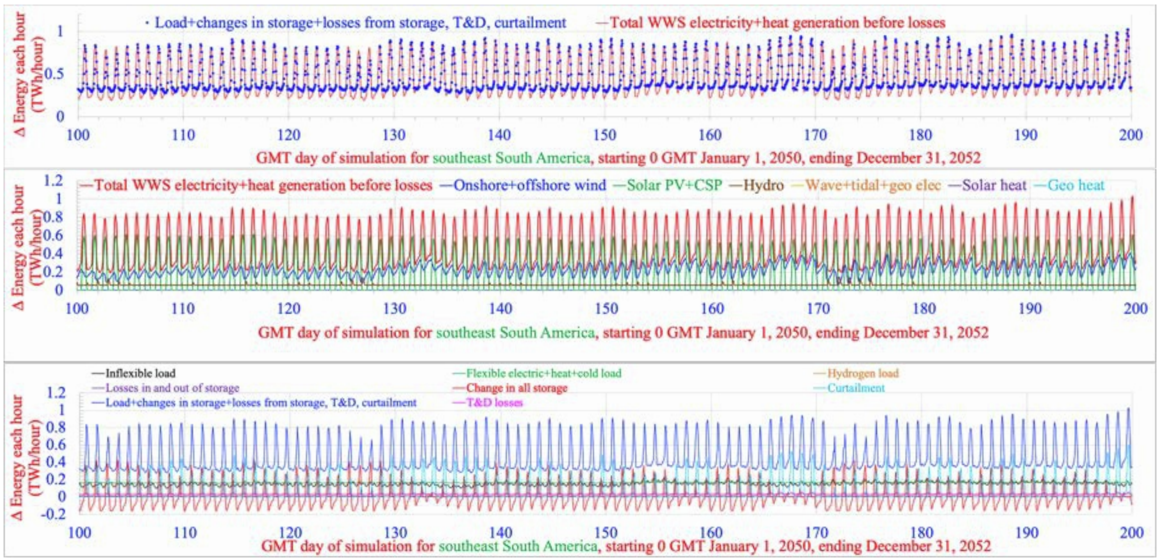


Figure S27. Southeast South America hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

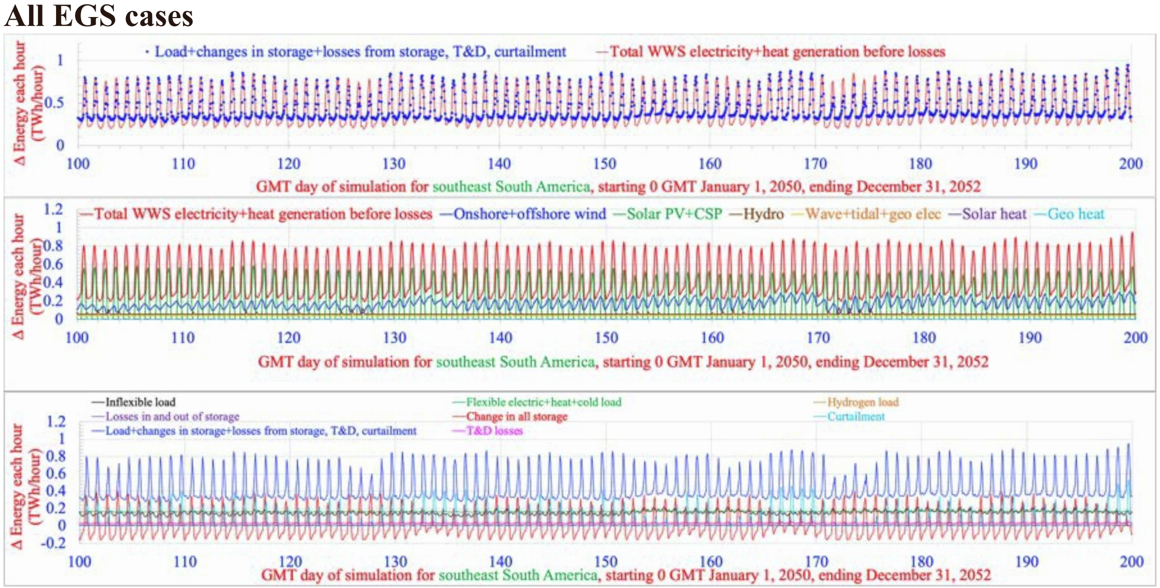
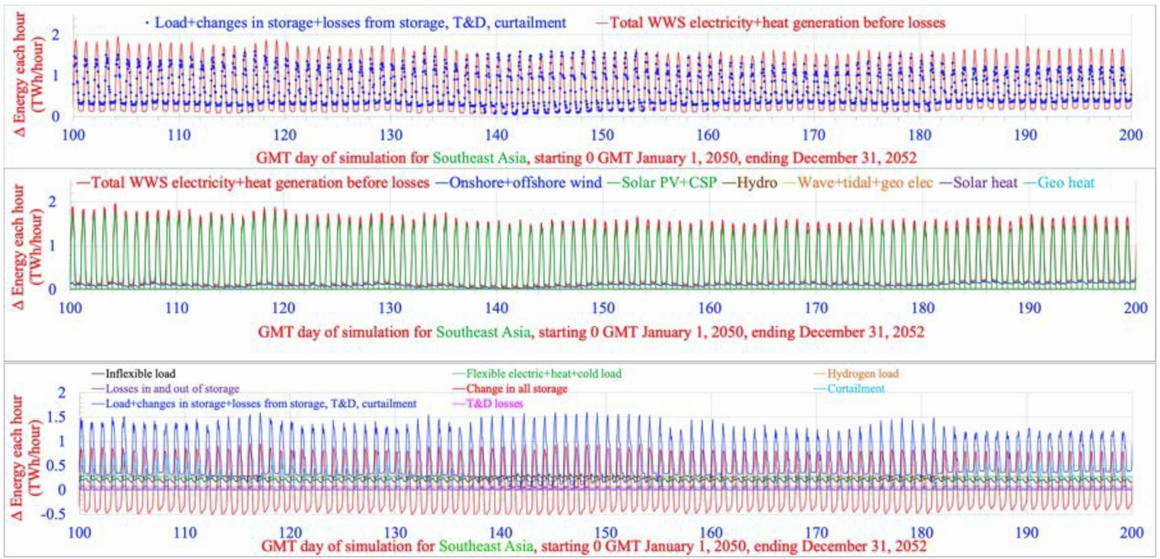


Figure S28. Southeast Asia hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

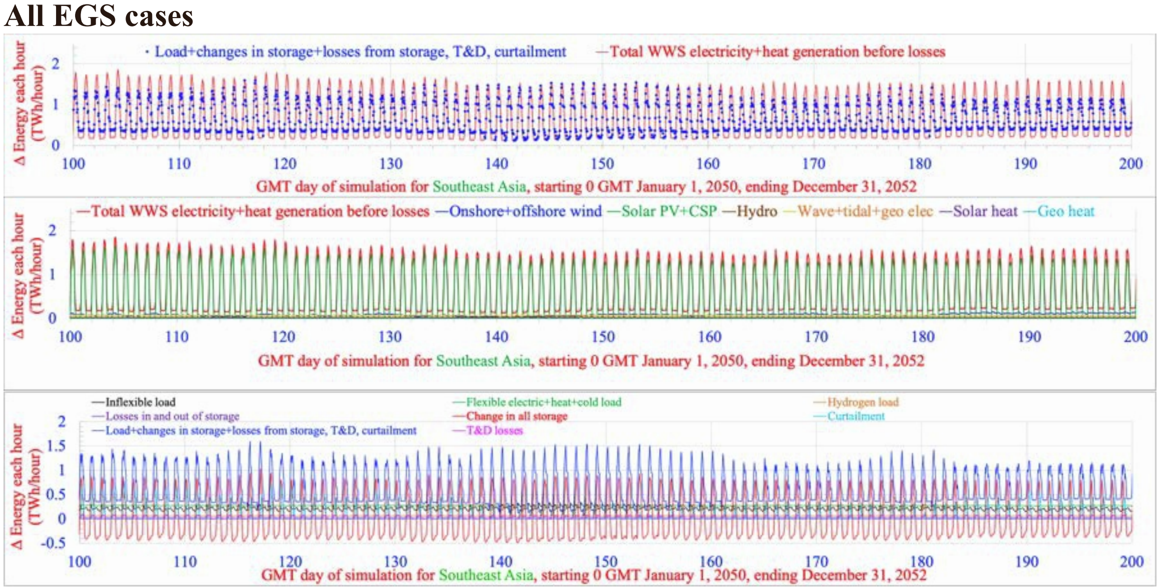
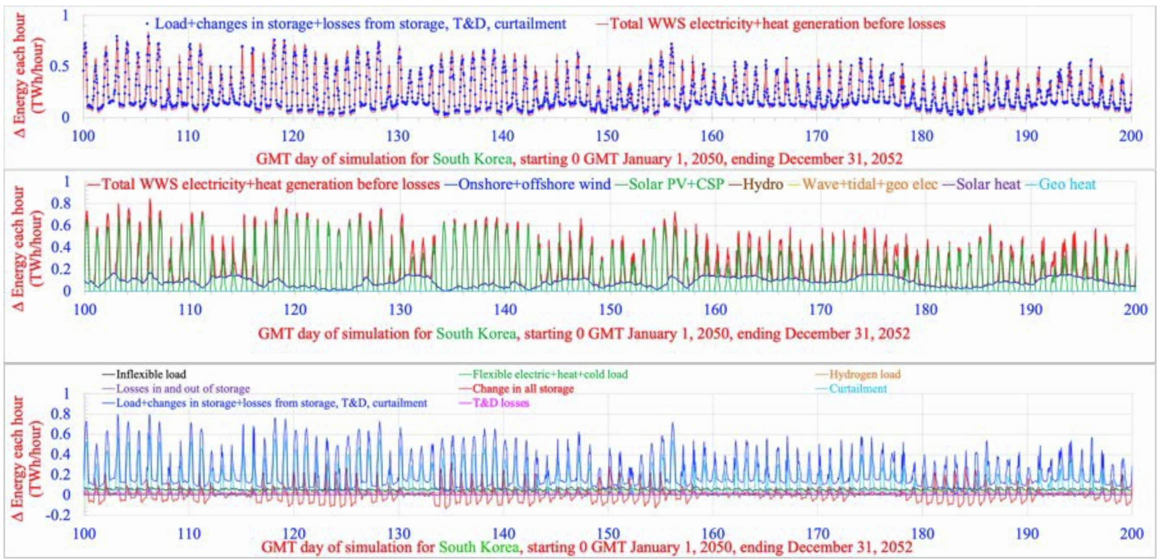


Figure S29. South Korea hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

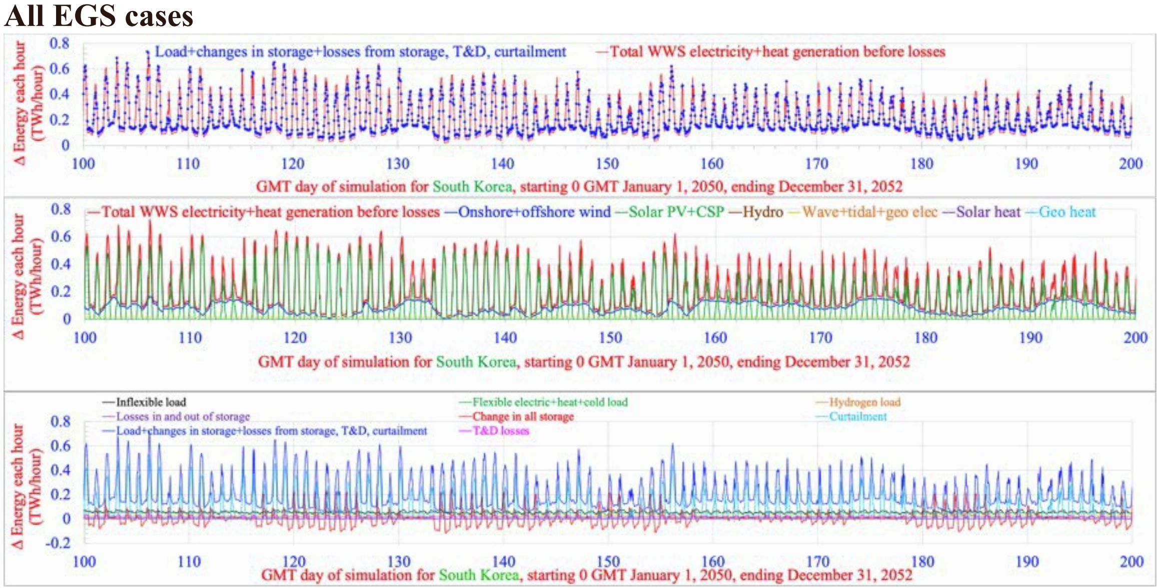
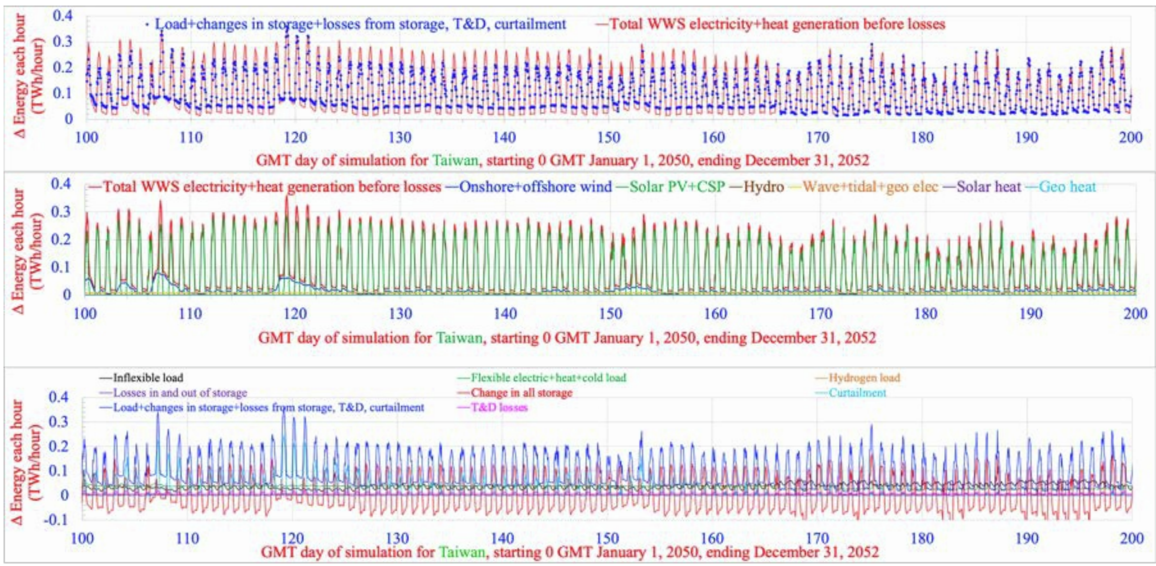


Figure S30. Taiwan hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

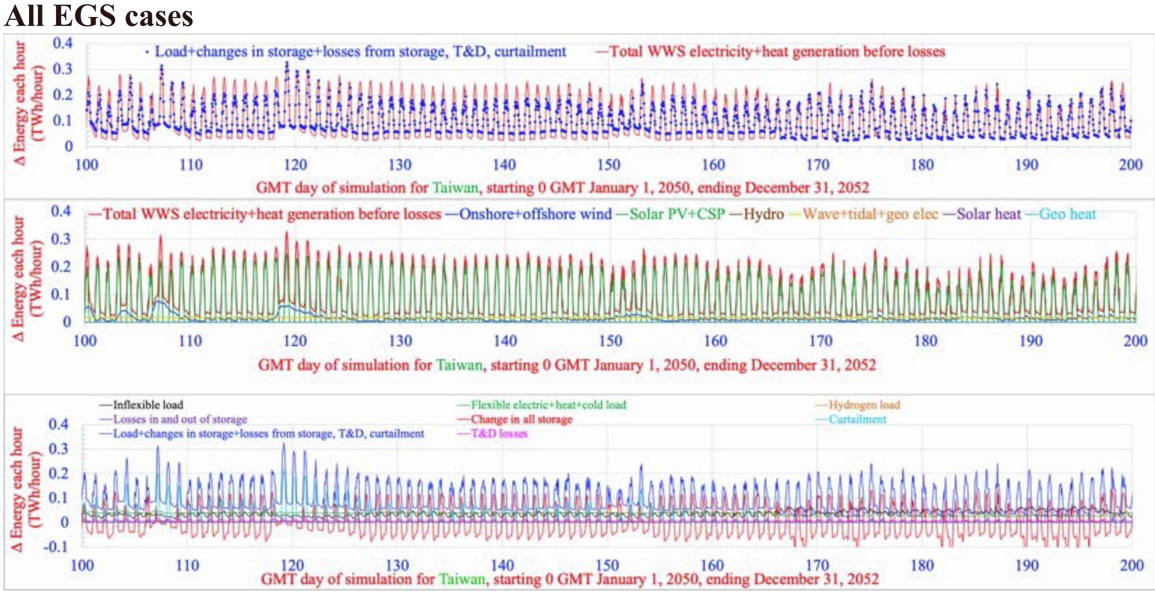
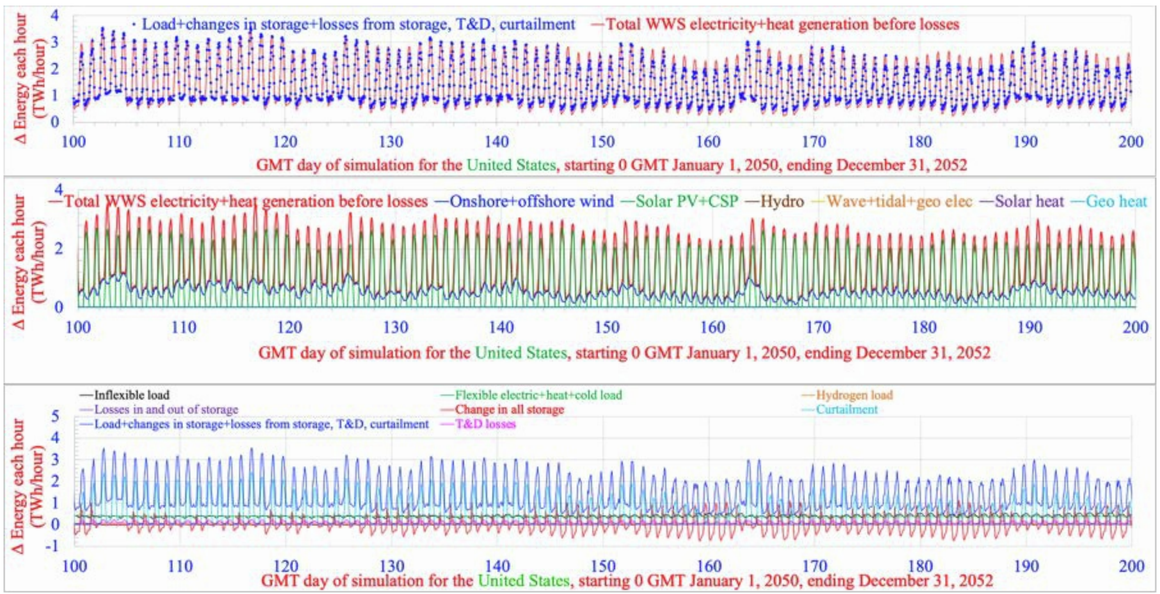


Figure S31. United States hourly time series output plots for a 100-day period during the three-year (2050-2052) simulations, for the base-WWS-case and the EGS-cases. First row: modeled total WWS power generation versus demand plus changes in storage plus losses (storage, T&D, and curtailment losses). Second row: a breakdown of WWS power generation by source. Third row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in all storage; and curtailment. Please see the caption of Figure S3 for more details.

Base-WWS case



All EGS cases

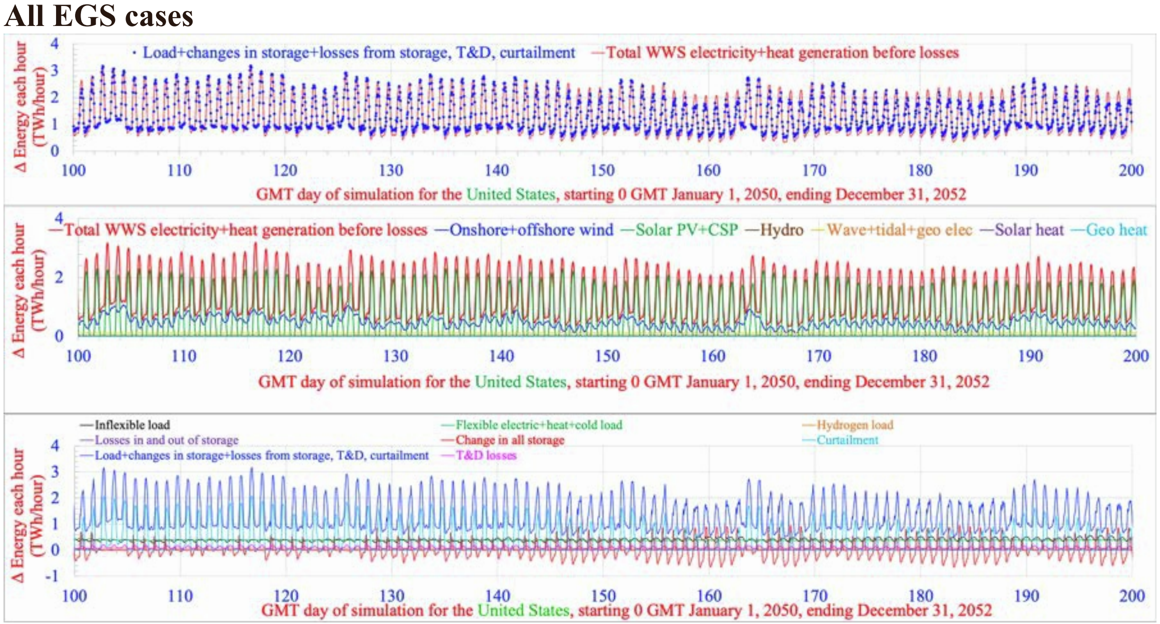


Figure S32. Base-WWS-case land required for each WWS electricity and heat generator in 2050, summed over all 150 countries. PV+CSP+ST = photovoltaics plus concentrated solar power plus solar thermal. Geothermal includes geothermal electricity and heat. Table S28a provides the same parameters for each of the 29 grid regions examined here. Figure S5 provides the land required as a percent of each regions land area.

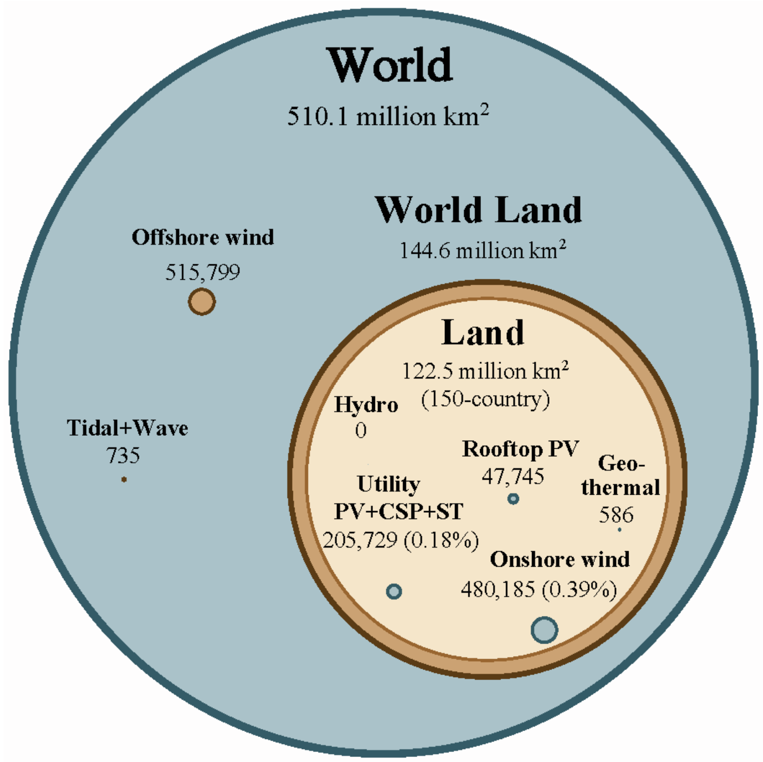
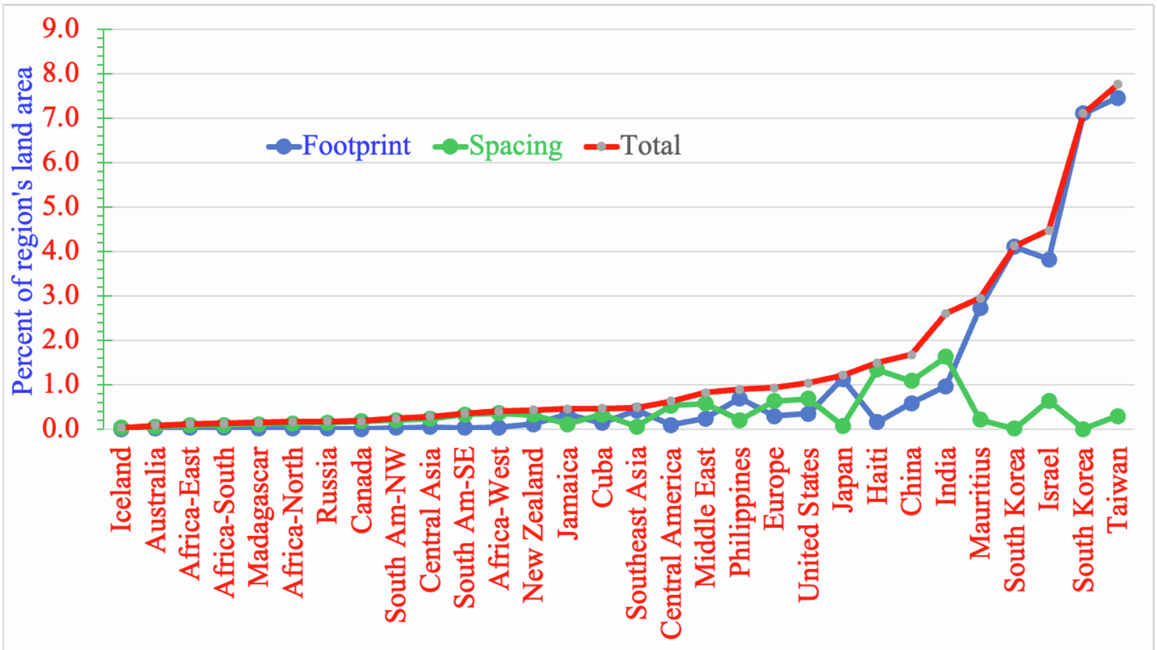
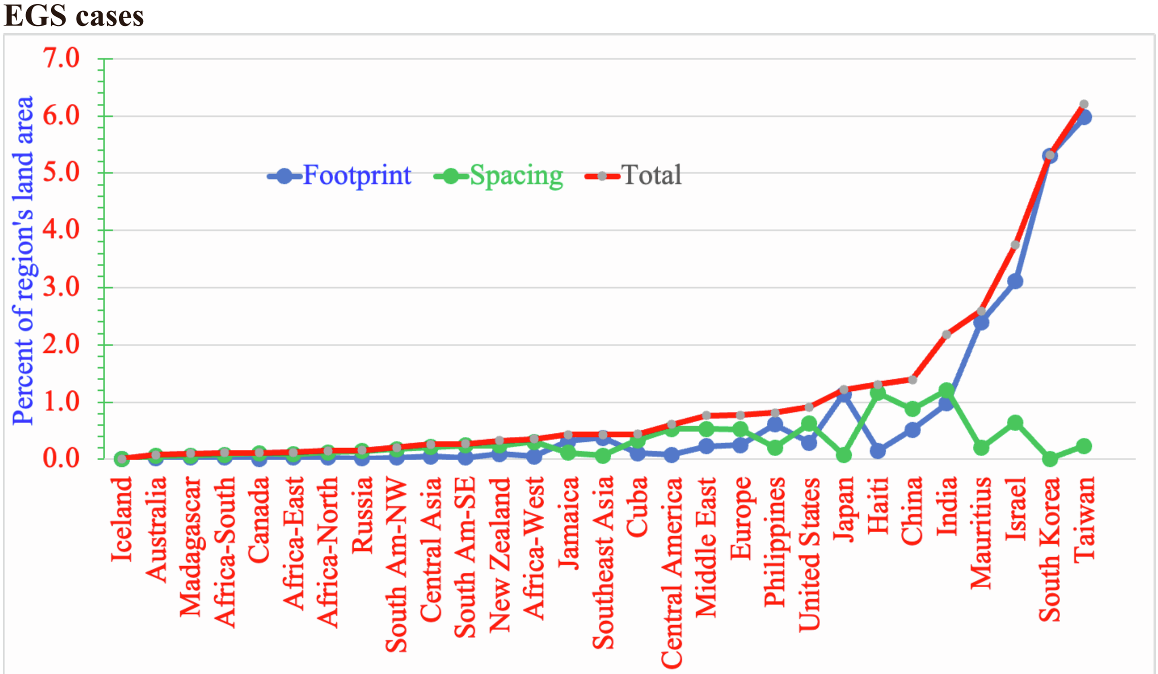


Figure S33. Base-WWS-case and EGS cases footprint and spacing areas required in 2050 to transition each of the 29 regions encompassing the 150 countries studied here. Data from Tables S28a,b.

Base-WWS case



EGS cases



Supplemental References

S1. Katalenich, S.M., and Jacobson, M.Z. (2022). Toward battery electric and hydrogen fuel cell military vehicles for land, air, and sea. *Energy 254*, 124355.

S2. Jacobson, M.Z., Sambor, D.J., Fan, Y.F., and Mühlbauer, A. (2024). Effects of firebricks for industrial process heat on the cost of matching all-sector energy demand with 100% wind-water-solar supply in 149 countries. *PNAS Nexus 3*, pgae274.

S3. Jacobson, M.Z., and Delucchi, M.A. (2025). Spreadsheets for 150-country WWS study. http://web.stanford.edu/group/efmh/jacobson/Articles/I/150Country/150-Countries.xlsx

S4. IEA (International Energy Agency). (2024). Energy Statistics Data Browser. OECD Publishing, Paris. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?

S5. EIA (Energy Information Administration). (2016). U.S. International Energy Outlook 2016. DOE/EIA-0484. http://www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf

S6. Rondo. (2024). The Rondo heat battery. https://rondo.com

S7. Jacobson, M.Z., von Krauland, A.-K., Song, K., and Krull, A.N. (2023). Impacts of green hydrogen for steel, ammonia, and long-distance transport on the cost of meeting electricity, heat, cold, and hydrogen demand in 145 countries running on 100% wind-water-solar. *Smart Energy 11*, 100106.

S8. Jacobson M.Z., Delucchi, M.A., Bauer, Z.A.F., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., Erwin, J.R., Fobi, S.N., Goldstrom, O.K., Hennessy, E.M., Liu, J., Lo, J., Meyer, C.B., Morris, S.B., Moy, K.R., O'Neill, P.L., Petkov, I., Redfern, S., Schucker, R., Sontag, M.A., Wang, J., Weiner, E., and Yachanin, A.S. (2017). 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world. *Joule 1*, 108-121.

S9. Jacobson M.Z. (2001). GATOR-GCMOM: A global through urban scale air pollution and weather forecast model: 1. Model design and treatment of subgrid soil, vegetation, roads, rooftops, water, sea ice, and snow. *J. Geophys. Res.: Atmospheres 106*, 5385-5401.

S10. Jacobson, M.Z. (2014). Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects. *J. Geophys. Res. 119*, 8980-9002.

S11. Jacobson M.Z., and Archer, C.L. (2012). Saturation wind power potential and its implications for wind energy. *Proc. Natl. Acad. Sci. 109*, 15,679-15,684.

S12. Jacobson, M.Z., and Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy 169,* 55-66.

S13. Jacobson M.Z., Delucchi, M.A., Cameron, M.A., Coughlin, S.J., Hay, C., Manogaran, I.P., Shu, Y., and von Krauland, A.-K. (2019). Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. *One Earth 1*, 449-463.

S14. Jacobson M.Z., Kaufman, Y.J., and Rudich, Y. (2007). Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions. *J. Geophys. Res.: Atmospheres 112*, D24205.
S15. Jacobson, M.Z. (2021). On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts. *Smart Energy 1*, 100009.
S16. Jacobson M.Z., Delucchi, M.A., Cameron, M.A, and Frew, B.A. (2015). A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc. Nat. Acad. Sci. 112*, 15,060-15,065.
S17. Jacobson M.Z., Delucchi, M.A., Cameron, M.A., and Mathiesen, B.V. (2018). Matching demand with supply at low cost among 139 countries within 20 world regions with 100 percent intermittent wind, water, and sunlight (WWS) for all purposes. *Renewable Energy 123*, 236-248 .
S18. Jacobson, M.Z. (2021). The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected. *Renewable Energy 179*, 1065-1075.
S19. Jacobson, M.Z., von Krauland, A.-K., Coughlin, S.J., Palmer, F.C., and Smith, M.M. (2022). Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage. *Renewable Energy 184*, 430-444.
S20. Jacobson, M.Z., von Krauland, A.-K., Coughlin, S.J., Dukas, E., Nelson, A.J.H., Palmer, F.C., and Rasmussen, K.R. (2022). Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. *Energy and Environmental Sciences 15*, 3343-3359.
S21. Jacobson, M.Z. (2024). Batteries or hydrogen or both for grid electricity storage upon full electrification of 145 countries with wind-water-solar? *iScience 27*, 108988.
S22. Jacobson, M.Z., Fu, D., Sambor, D.J., and Mühlbauer, (2025). A. Energy, health, and climate costs of carbon-capture and direct-air-capture versus 100%-wind-water-solar climate policies in 149 countries. *Environmental Science & Technology 59,* 3034-3045.
S23. Bryans, G., Fox, B., and Crossley, P.A. (2005). Impact of tidal generation on power system operation in Ireland. *IEEE Transactions on Power Systems 20*, 2034-2040.
S24. IEA (International Energy Agency). (2021). Hydropower special market report. https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf
S25. ENTSO-E (European Network of Transmission System Operators for Electricity). (2016). European load data. https://www.entsoe.eu/db-query/country-packages/production-consumption-exchange-package
S26. Neocarbon Energy. (2016). Future energy system. http://neocarbonenergy.fi/internetofenergy/
S27. EIA (Energy Information Administration). (2021). U.S. product supplied of finished motor gasoline. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MGFUPUS2&f=M
S28. USDOE (United States Department of Energy). (2021). Fuel economy in cold weather. https://www.energy.gov/energysaver/fuel-economy-cold-weather

S29. Geotab. (2020). To what degree does temperate impact EV range. https://www.geotab.com/blog/ev-range/
S30. Archer, C.L., and Jacobson, M.Z. (2007). Supplying baseload power and reducing transmission requirements by interconnecting wind farms. *J. Applied Meteorol. and Climatology 46*, 1701-1717.
S31. Drupp, M.A., Freeman, M.C., Groom, B., and Nesje, F. (2018). Discounting disentangled. *American Economic Journal: Economic Policy 10*, 109-134.
S32. Moore, M.A., Boardman, A.E., Vining, A.R., Weimer, D.L., and Greenberg, D.H. (2004). Just give me a number! Practical values for the social discount rate. *Journal of Policy Analysis and Management 23*, 789-812.
S33. NCEE (National Center for Environmental Economics). (2014). Guidelines for Preparing Economic Analyses. U.S. Environmental Protection Agency.
S34. DOT (U.S. Department of Transportation). (2023). Departmental Guidance on Valuation of a Statistical Life Economic Analysis. https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis
S35. Van den Bergh, J.C.J.M., and Botzen, W.J.W. (2014). A lower bound the social cost of carbon emissions. *Nature Climate Change 4*, 253-258.
S36. Moore, F.C., and Diaz, D.B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change 5*, 127-131.
S37. Burke, M., Hsiang, S.M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature 527*, 235-239.
S38. Jacobson, M.Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science 2*, 148-173.
S39. NREL (National Renewable Energy Laboratory). (2019). Jobs and Economic Development Impact Models (JEDI). https://www.nrel.gov/analysis/jedi
S40. IHA (International Hydropower Association). (2021). 2021 hydropower status report. https://www.hydropower.org/publications/2021-hydropower-status-report
S41. Fischer, D., and Madani, H. (2017). On heat pumps in smart grids: A review. *Renewable and Sustainable Energy Reviews 70*, 342-357.
S42. IRENA. (International Renewable Energy Agency). (2024). Renewable capacity statistics 2023. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_RE_Capacity_Statistics_2024.pdf
S43. Weiss, W., and Spork-Dur, M. (2020). Solar heat worldwide. https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2020.pdf
S44. Lund, J.W., and Toth, A.N. (2020). Direct utilization of geothermal energy 2020 worldwide review. Proc. World Geothermal Congress. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01018.pdf
S45. Forsberg C., and Stack D.C. (2024). Electrically Conductive Firebrick System, U.S. Patent: 11,877,376 B2. January 16, 2024. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11877376
S46. Electrified Thermal Solutions. (2024). https://electrifiedthermal.com
S47. Penev, M.N., Rustagi, N., Hunter, C., and Eichman, J. (2019). Energy storage: Days of service sensitivity analysis. https://www.nrel.gov/docs/fy19osti/73520.pdf

S48. Mongird, K., Viswanathan, V., Alam, J., Vartanian, C., Sprenkle, V., and Baxter, R. (2020). 2020 grid energy storage technology cost and performance assessment. https://www.pnnl.gov/sites/default/files/media/file/Hydrogen_Methodology.pdf
S49. Houchins C., and James, B.D. (2022). Hydrogen storage cost analysis, 2022 Annual Merit Review and Peer Evaluation Meeting, Department of Energy. https://www.hydrogen.energy.gov/pdfs/review22/st235_houchins_2022_p.pdf
S50. Chadly, A., Azar, E., Maalouf, M., and Mayyas, A. (2022). Techno-economic analysis of energy storage systems using reversible fuel cells and rechargeable batteries in green buildings. *Energy 247*, 123466.
S51. NREL (National Renewable Energy Laboratory). (2014). Hydrogen station compression, storage, and dispensing technical status and costs. https://www.nrel.gov/docs/fy14osti/58564.pdf
S52. Christensen A. (2021). Assessment of hydrogen production costs from electrolysis: United States and Europe. https://theicct.org/wp-content/uploads/2021/06/final_icct2020_assessment_of-_hydrogen_production_costs-v2.pdf
S53. James, B.D., Houchins, C., Huya-Kouadio, J.M., and DeSantis, D.A. (2016). Final report: Hydrogen storage system cost analysis, Strategic analysis. https://www.osti.gov/servlets/purl/1343975
S54. Hodges, A., Hoang, A.L., Tsekouras, G., Wagner, K., Lee, C.-Y., and Swiegers, G.F. (2022). A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen. *Nature Communications 13*, 1304.
S55. ABB (ASEA Brown Boveri). (2021). High-power rectifiers for hydrogen production. https://library.e.abb.com/public/c99b560b59ed43db8025ab36b67ebdb3/ABB_Brochure_Hydrogen_A_2021_LowRes.pdf
S56. Jacobson, M.Z. (2020). *100% Clean, Renewable Energy and Storage for Everything*; Cambridge University Press: New York.
S57. EIA (Energy Information Administration). (2021). Monthly round-trip efficiency by storage technology (Jan 2018-Dec 2019). https://www.eia.gov/todayinenergy/detail.php?id=46756
S58. Mancini, T. (2006). Advantages of using molten salt. Sandia National Laboratories. https://www.webcitation.org/60AE7heEZ?url=http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/salt.htm
S59. Irvine, M., and Rinaldo, M. (2020). Tesla's battery day and the energy transition. https://www.dnv.com/feature/tesla-battery-day-energy-transition.html
S60. Hanley, S. (2024) CATL, BYD to slash battery prices by 50% in 2024. BOOM! EVs Win! https://cleantechnica.com/2024/02/26/catl-byd-to-slash-battery-prices-by-50-in-2024-boom-evs-win/
S61. Tesla. (2021). Powerpack. https://www.tesla.com/powerpack
S62. Stack D.C., and Forsberg C. (2019). Performance of firebrick resistance-heated energy storage for industrial heat applications and round-trip electricity storage. *Appl. Energy* 242, 782-796.
S63. Sonnen. (2021). Take a look inside ecoLinx. https://sonnenusa.com/en/sonnen-ecolinx/#specifications
S64. Jacobson, M.Z., Colella, W.G., and Golden, D.M. (2005). Cleaning the air and improving health with hydrogen fuel cell vehicles. *Science 308*, 1901-1905.

S65. WHO (World Health Organization). (2022). Household air pollution attributable deaths. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/household-air-pollution-attributable-deaths
S66. WHO (World Health Organization). (2022). Ambient air pollution attributable deaths. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/ambient-air-pollution-attributable-deaths
S67. European Commission. (2024). Edgar-emissions database for global atmospheric research, GHG emissions of all world countries, https://edgar.jrc.ec.europa.eu/report_2024
S68. Enevoldsen, P., and Jacobson, M.Z. (2021). Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. *Energy for Sustainable Development 60*, 40-51.