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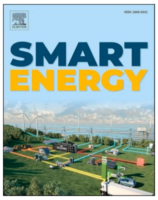

Impacts of green hydrogen for steel, ammonia, and long-distance transport on the cost of meeting electricity, heat, cold, and hydrogen demand in 145 countries running on 100% wind-water-solar

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ABSTRACT

As the world moves to clean, renewable energy, questions arise as to how best to produce and use hydrogen. Here, we propose using hydrogen produced only by electrolysis with clean, renewable electricity (green hydrogen). We then test the impact of producing such hydrogen intermittently versus continuously for steel and ammonia manufacturing and long-distance transport via fuel cells on the cost of matching electricity, heat, cold, and hydrogen demand with supply and storage on grids worldwide. An estimated 79, 32, and 91 Tg-H_2/y of green hydrogen are needed in 2050 among 145 countries, for steel, ammonia, and long-distance transport, respectively. Producing and compressing such hydrogen for these processes may consume ~12.1% of the energy needed for end-use sectors in these countries after they transition to 100% wind-water-solar (WWS) in all such sectors. This is less than the energy needed for fossil fuels to power the same processes. Due to the variability of WWS electricity, producing green hydrogen intermittently, rather than continuously, thus with electrolyzer use factors significantly below unity (0.2–0.65), may reduce overall energy costs with 100% WWS. This result is subject to model uncertainties but appears robust. In sum, grid operators should incorporate intermittent green hydrogen production and use in planning.

1. Introduction

As the world transitions from fossil fuels, bioenergy, and uranium to clean, renewable, and safe energy sources to address air pollution, global warming, and energy security, questions arise as to how hydrogen should be produced, what it should be used for, and whether its use can improve grid stability. In this study, hydrogen's source is narrowed to electrolysis, where the electricity originates from wind-water-solar (WWS) electricity (green hydrogen). Green hydrogen's uses are then limited to steel and ammonia manufacturing and long-distance transport. Finally, the impacts of producing green hydrogen intermittently, instead of continuously, on the cost of grid stability are modeled in 145 countries after they have transitioned to 100% WWS all-sector energy economies. Table S2 summarizes the main components of a WWS system: WWS electricity and heat generation; electricity, heat, and cold, storage; hydrogen production, storage, and use; electric machines and appliances; and electricity and heat grids.

Previous studies have examined the potential impacts of emissions, including hydrogen leaks, from producing and using hydrogen for fuel cells, on stratospheric ozone [1]; tropospheric gas pollution and climate [2,3]; tropospheric and stratospheric gas pollution [4]; tropospheric gas and particle pollution and climate [5,6]; and tropospheric and stratospheric ozone, gas, and particle pollution, and climate [7].

With respect to hydrogen production, Jacobson et al. [5] and Colella et al. [6] compared the impacts on pollution and climate-relevant emissions of hydrogen produced by wind-electrolysis (green hydrogen), steam methane reforming (SMR) (gray hydrogen), and coal gasification (brown or black hydrogen). Howarth and Jacobson [8] and Bauer et al. [9] compared the carbon-equivalent emissions of gray versus blue hydrogen (gray hydrogen with carbon capture).

The three applications of green hydrogen treated here are steel and ammonia manufacturing and long-distance transport through fuel cells by aircraft, ship, train, semi-truck, and military vehicle. Green hydrogen may also be used chemically in other industrial processes, but these processes are not treated here. All industrial heat in the present study is provided with electric heaters, such as arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, and heat pumps, where all electricity comes from WWS.

Several applications of hydrogen - for heating buildings, powering passenger vehicles, and producing grid electricity - are also not treated here. Hydrogen should not be piped, either on its own or in a mixture with natural gas, to homes for air or water heating [10]. The better alternative is to heat buildings with WWS-powered electric heat pumps. Although using green hydrogen in fuel cells for passenger vehicles is

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clean [5,6], a fuel cell passenger vehicle requires 1.7–3.8 times the number of wind turbines or solar panels as does a battery-electric vehicle to move the same distance [11]. Third, although hydrogen storage capacity is less expensive than is battery storage capacity and although using green hydrogen for stationary electricity storage is clean, green hydrogen may require 2–3.4 times the number of wind turbines or solar panels to provide the same electricity as a battery [11] and fuel cells are more expensive than batteries per kW for discharging electricity. As such, it is not clear whether green hydrogen should be used for grid electricity. Another potential application is to produce green hydrogen in a remote WWS microgrid, then use the hydrogen in either a stationary fuel cell to generate electricity and heat for buildings [12–14] or a vehicle fuel cell [15]. This application is not treated here for simplicity.

Some studies have included green hydrogen for transport and/or industry in 100%-renewable electric grids [16–21]. This study differs by comparing the cost of matching electricity, heat, cold, and hydrogen demand with supply and storage when using different electrolyzer use factors for producing hydrogen for steel, ammonia, and long-distance transport. Several studies have treated ammonia production from green hydrogen [22–26]. One of these studies estimated electrolyzer use factors that minimize the costs of green hydrogen and ammonia produced from it [22]. One study has examined the potential impact of green hydrogen for global steel production on global electricity and heat demand, but it did not examine the impact of electrolyzer use factor [27]. A novelty of this study is that it examines the impact of the intermittent versus continuous production of green hydrogen for ammonia and steel manufacturing and long-distance transport together on the cost of matching electricity, heat, cold, and hydrogen demand with supply and storage.

2. Applications of hydrogen in this study

This section discusses the green hydrogen applications considered here and the quantities of hydrogen needed for each.

2.1. Steel manufacturing

Steel is manufactured from iron ore (Fe_2O_3) in two stages: ironmaking and steelmaking. During ironmaking, molten pure iron (Fe) has historically been extracted from iron ore through either the pig-iron or direct-reduction process.

With the pig-iron process (also called the blast furnace process), Fe_2O_3 is mixed with coke and limestone ($CaCO_3$) in a blast furnace heated to 1400–1500 °C. Oxygen from air forced through the furnace bottom reacts with the coke to form carbon monoxide (CO), which reacts with the iron ore to release molten iron metal (pig iron) and process carbon dioxide (CO_2) by $Fe_2O_3(s)+3CO(g) \rightarrow 2Fe(l)+3CO_2(g)$. The limestone decomposes to CaO and CO_2. The CaO reacts with sandy remnants of the iron ore to form slag, which is removed.

With direct reduction, iron ore reacts with syngas (a CO/H_2 mixture) at 800-1200 °C in a shaft furnace or rotary kiln to produce pure iron by $Fe_2O_3(s)+3CO/3H_2 \rightarrow 2Fe(l)+3CO_2/3H_2O$. Direct-reduction differs from the pig-iron process in that the former produces less process CO_2, because the reaction includes some hydrogen, and requires less energy since the reaction occurs at a lower temperature than in a blast furnace. However, direct reduction also emits CO_2 from the SMR process that produces syngas and emits CH_4 during the mining and transport of natural gas for syngas production. Of the world's iron for steel manufacturing 92% is pig iron; most of the rest is directly-reduced iron (Table S5).

With most steelmaking, molten raw iron from the blast furnace is mixed with scrap steel and placed in a basic oxygen furnace. Oxygen is then blown through the furnace, reacting with carbon impurities in the iron to form CO_2, which is released. CaO reacts with additional impurities, phosphorous and sulfur. The products rise to the top as slag and are removed. Carbon and other alloying elements are then added for strengthening. The molten steel is poured into a pre-shaped mold, where it cools and hardens.

In sum, steel manufacturing releases CO_2 during (a) fossil fuel combustion to produce heat, (b) reaction of coke with iron ore, (c) decomposition of limestone, (d) reaction of carbon with oxygen during steelmaking, and (e) vaporization of graphite to carbon in an arc furnace. Overall, ironmaking in a blast furnace plus steelmaking in a basic oxygen furnace emits ~1870 kg-CO_2/tonne-steel [28]. Of this, ironmaking emits ~70–80%.

Hydrogen direct-reduction (HDR) [28] is an alternative process that uses pure hydrogen, instead of syngas, to extract iron from iron ore: $Fe_2O_3(s)+3H_2(g) \rightarrow 2Fe(l)+3H_2O(g)$. This reaction occurs at 800 °C and eliminates process CO_2. Steel is then produced by combining the iron with carbon and other alloying elements, ideally in an electric arc furnace, since it uses one-fifth the energy of a basic oxygen furnace [29]. Some CO_2 still results from the decomposition of limestone and from the arc furnace electrodes. Provided that the heat for ironmaking is obtained with an electric resistance furnace, the hydrogen used is green hydrogen, an electric arc furnace is used for steelmaking, and all electricity is from 100% WWS, HDR emits only 53 kg-CO_2/tonne-steel, or 2.8% the emissions of the blast furnace/basic oxygen furnace process [28].

The first commercial reduction of iron ore to iron with hydrogen occurred in Trinidad and Tobago in 1999 [27,30]. In June 2021, a steel plant in Lulea, Sweden, extracted iron using green hydrogen for the first time. A month later, it produced nearly-carbon-free steel. In 2022, Sweden's national steel company announced it will replace all its blast furnaces with green-hydrogen systems [31]. Green steel plants are also being planned for Spain, France, and Germany [32].

Here, we assume the same annual iron production from iron ore for steel in 2050 as in 2020 (1.45 Gt-Fe/y). This is justified by the fact that in 2021, 32.3% of all steel produced worldwide was from recycled scrap steel [33]. Whereas recycling rates were high in some countries and regions (e.g., 57.6% in the European Union, 69.2% in the U.S. and 86.3% in Turkey), they were low in others (e.g., 21.9% in China; 36.0% in Japan, and 41.8% in Russia) [33]. It is assumed here that, overall, crude steel production will grow, but an increasing share of such production will come from recycled scrap steel, leaving changes in the annual iron production from iron ore flat. The hydrogen needed to purify 1.45 Gt-Fe/y for steel production in 145 countries in 2050 is estimated as be 78.7 Tg-H_2/y (Table 1, S5, S8). Using HDR instead of the blast furnace process may reduce the annual-average electric power needed for hydrogen production, compression, and heat for ironmaking alone by ~17.7% (Table S5, Column g). The annual-average electric power needed to produce and compress 78.7 Tg-H_2/y is 423.2 GW (derived from Table S8).

Another method of reducing iron ore to pure iron is electrowinning [27,34]. Although clean and needing less electricity than HDR, this process may not be commercial until 2025–2040 [27], so we focus only on HDR.

2.2. Ammonia manufacturing

About 80% of ammonia (NH_3) manufactured worldwide is used to make fertilizer. The rest is for cleaning; purifying water; refrigerating; and manufacturing plastics, explosives, textiles, pesticides, dyes, and chemicals [35]. The most common way to produce ammonia is the Haber-Bosch process, $N_2+3H_2 \rightarrow 2NH_3$. In 2020, ~146.85 Tg/y of nitrogen in ammonia were produced among 145 countries (Table S6). This necessitated ~31.7 Tg/y of hydrogen (Table 1, S6, S8). Most all hydrogen for ammonia today is from SMR. Here, we assume that, in 2050, all hydrogen for ammonia will be green and produced in the same quantity as in 2020. This assumption is based simplistically on the possibility that more ammonia will be replaced by substitute chemicals in the future for fertilizers and non-fertilizer applications given the potent air pollution health impacts of ammonia. If green hydrogen

Table 1

2050 estimated mass of hydrogen needed per year by region for (a) steel manufacturing, (b) ammonia manufacturing, (c) long-distance hydrogen fuel cell-electric vehicles, and (d) the sum of these. Also shown are the annual-average power demand (not nameplate capacity) to produce and compress hydrogen for (e) steel plus ammonia manufacturing, (f) transportation, and (g) steel and ammonia manufacturing and transportation. Table S8 provides values by country.

Region or country	(a) 2021 and 2050 Tg-H_2/y needed to purify iron by hydrogen direct reduction	(b) 2020 and 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, ammonia, and vehicles = a + b + c	(e) 2050 average power demand to produce and compress H_2 for steel and ammonia (GW)	(f) 2050 average power demand to produce and compress H_2 for transport (GW)	(g) 2050 average power demand to produce and compress H_2 for steel, ammonia, and transport = e + f (GW)
Africa	0.70	1.638	6.333	8.674	12.587	34.05	46.64
Australia	0.206	0.345	1.210	1.761	2.964	6.51	9.47
Canada	0.422	0.841	1.419	2.682	6.792	7.63	14.42
Central America	0.460	0.024	1.978	2.462	2.605	10.63	13.24
Central Asia	0.168	1.131	1.282	2.581	6.985	6.89	13.88
China Region	47.05	8.420	13.13	68.60	298.2	70.60	368.8
Cuba	0	0	0.067	0.067	0	0.36	0.36
Europe	5.828	3.687	13.59	23.11	51.16	73.07	124.2
Haiti Region	0	0	0.136	0.136	0	0.73	0.73
Iceland	0	0	0.025	0.025	0	0.14	0.14
India Region	6.314	2.815	10.52	19.65	49.09	56.55	105.6
Israel	0	0	0.148	0.148	0	0.80	0.80
Jamaica	0	0	0.062	0.062	0	0.33	0.33
Japan	3.807	0.139	1.586	5.532	21.21	8.53	29.74
Mauritius	0	0	0.069	0.069	0	0.37	0.37
Mideast	3.065	3.178	7.887	14.13	33.57	42.41	75.97
New Zealand	0.038	0.027	0.204	0.269	0.349	1.10	1.45
Philippines	0	0	0.848	0.848	0	4.56	4.56
Russia Region	3.325	3.525	1.962	8.811	36.83	10.55	47.38
South America	1.879	1.107	6.043	9.028	16.05	32.49	48.54
Southeast Asia	0.731	1.803	10.61	13.14	13.62	57.04	70.66
South Korea	2.513	0	1.690	4.203	13.51	9.09	22.60
Taiwan	0.823	0	0.738	1.561	4.426	3.97	8.40
United States	1.392	3.023	9.711	14.13	23.73	52.21	75.95
All regions	**78.72**	**31.70**	**91.24**	**201.7**	**593.7**	**490.6**	**1084.3**

Multiply annual-average power demand by 8760 h/y to obtain GWh/y. Column (a) is from Table S5; column (b) is from Table S6; column (c) is from Table S7; column (d) is the sum of the first three columns; column (e) is the sum of columns (a) and (b), all multiplied by 47.1 TWh/Tg-H_2 (Footnote to Table S6) and divided by 8760 h per year; column (f) is column (c) multiplied by 47.1 TWh/Tg-H_2 and divided by 8760 h per year; column (g) is the sum of columns (e) and (f).

replaces 31.7 Tg/y of SMR-derived hydrogen, the worldwide annual-average electric power needed for hydrogen production and compression for ammonia manufacturing might decrease by ~18.8% (Table S6, Column e). The annual-average power needed to produce and compress such green hydrogen for ammonia manufacturing is 170.5 GW (Table S6).

2.3. *Long-distance transport using hydrogen fuel cells*

Katalenich and Jacobson [36] examined whether short- and long-distance land, air, and sea military and civilian vehicles can be transitioned to battery-electric and/or hydrogen fuel cell-electric vehicles while maintaining vehicle range, mass, volume, and power- or thrust-to-weight ratios. The study found that all vehicles, including armored tanks, freight trains, boats, oceangoing vessels, helicopters, prop planes, and jumbo jets, may be transitioned with hydrogen fuel cells, and in some cases, with batteries, but in all cases using advancements and solutions identified in the literature. For example, a future hydrogen-fuel-cell Boeing 747-8 may travel the same range and maintain the same thrust-to-weight ratio as a jet fuel version, but with 22% lower mass and 21% larger volume.

Despite the challenges of implementing green hydrogen for long-distance aircraft and ships, it is important to evaluate this solution because no other clean, renewable energy solution is on the horizon. For example, whereas certain biofuels and synthetic fuels (electro-fuels, or e-fuels, which are manufactured from carbon dioxide and other chemicals) can replace jet fuel as well, they are not nearly so clean as green hydrogen, and therefore are not considered here. Specifically, both biofuels and e-fuels are combusted, creating gas and particle air pollutants that allow for the continuation of contrails and health- and/or climate-affecting gases and particles (CO_2, CO, CH_4, reactive organic gases, oxides of nitrogen, and black and brown carbon particles). Green hydrogen used in fuel cells eliminates all gas emissions aside from water vapor and all particle emissions from aircraft, thus eliminates all new particles on which contrails can form. The water vapor emissions from hydrogen fuel cells, which are slightly lower per kilometer than the emissions from jet fuel combustion, can still condense on existing background particles, but the optical thickness of the resulting contrails worldwide is estimated to be only ~30% of that today [11]. Further, the energy required to refine a biofuel or synthesize an e-fuel is substantial, resulting in CO_2 and pollution emissions that offset a good portion of the CO_2 saved by growing a biofuel crop or capturing CO_2. Even if renewable electricity is used to produce such fuels, those renewables are prevented from replacing fossil fuel power plants and their CO_2 and air pollution emissions, fuel mining, and infrastructure, allowing those problems to accrue and fossil fuels to persist into the future [11]. Thus, green hydrogen for long-distance transport is the cleanest possible method of continuing such transport until batteries can do that job.

Here, it is assumed that medium- and long-haul aircraft (3–6 h and >6 h flight time, respectively), long-haul ships, long-haul trucks (>1000 km), and long-haul trains are transitioned to hydrogen-fuel cell equivalents. Of the ~30 million commercial airline flights each year worldwide, about 15% by number and 46% by distance flown are medium- or long-haul flights; the rest are short-haul flights [37].

The transition of long-distance transport to fuel cell transport is accomplished by first examining the breakdown of refined oil products for final consumption (motor gasoline, gas and diesel oils, liquefied petroleum gas and ethane, residual fuel oil, crude oil and natural gas liquids, naphtha, jet kerosene, other kerosene, and other oil products) from IEA [38] in each country and assigning a fraction of each to the transport sector (with the basis described in Footnote b of Table S7). A portion of each oil product included in the transport sector is then assigned to battery-electric vehicles (Footnote c of Table S7) and the rest, to hydrogen-fuel-cell-electric vehicles. The resulting 145-country sum of hydrogen needed for transport in 2050 is ~91.2 Tg-H_2/y (Table 1, S7, S8). The annual-average electric power needed to produce and compress such green hydrogen for transport is 490.6 GW (Table S7).

In sum, the hydrogen needed and changes in energy resulting from replacing fossil systems with hydrogen systems for steel and ammonia manufacturing and long-distance transport are calculated by country (Table 1 and S5–S8) and added to a spreadsheet model [39]. The data are then used in another model, LOADMATCH, to examine grid stability worldwide with 100% WWS.

Hydrogen in this study is assumed to be stored only in tanks rather than in underground caverns. Caverns are available only in limited locations, and storing in caverns would require extensive pipelines to provide the hydrogen to steel and ammonia factories and to vehicle fueling stations. Instead, it is assumed here that electricity is transmitted to steel and ammonia factories, airports, docks, and other transport hubs, where the hydrogen is produced, stored, and used, eliminating most need for hydrogen pipelines. This will require substantially more transmission and distribution lines to these locations than presently exist. In fact, the 100% WWS plans for the 145 countries treated here require ~87% more electricity for all purposes than in a 2050 BAU case (Table S4). At the same time, such countries need 55.9% less overall energy in 2050 with WWS than with BAU. Thus, instead of 21.3% of 2018 load needed for end-use sectors being electricity among these countries, almost 100% of 2050 load will be electricity (and the rest will be direct heat), but the total 2050 WWS load for end-use sectors will be 55.9% lower than the total 2050 BAU load. This study accounts for the estimated cost of short- and long-distance transmission and distribution to move electricity from generators to steel and ammonia factories, transport hubs, and all other new locations needed (Table S23). The study also accounts for the maximum storage tank sizes needed (Table 2).

Although it is assumed here that no hydrogen will be transported by

Table 2

(a) Mass of hydrogen needed for steel and ammonia manufacturing and long-distance vehicle transport in each region; (b) Annual-average power demand (not nameplate capacity) to produce (by electrolysis) and compress the needed hydrogen (47.1 TWh/Tg-H_2 – see Table S6 footnote for details); (c) peak power demand during any 30-s LOADMATCH time step during the simulation needed to produce H_2; (d) the baseline hydrogen electrolyzer and compressor use factor, determined as the average load divided by the peak instantaneous load; (e) electrolyzer and compressor lifetimes, calculated as the smaller of the full-load lifetime (10 years) divided by the use factor, and the calendar life (40 years); (f) electrolyzer size needed, which is calculated as the peak load needed from column (c) multiplied by the ratio of the electrolyzer energy needed (41.46 kWh/kg-H_2) to produce hydrogen to the total energy needed (47.1 kWh/kg-H_2) to produce plus compress hydrogen (Table S6 footnote); (g) compressor size needed, calculated as the peak load needed from column (c) multiplied by the ratio of the compressor energy needed (5.64 kWh/kg-H_2) to the total electrolyzer plus compressor energy needed; and (h) the storage tank size needed, calculated as the total hydrogen mass needed per year from column (a) multiplied by the number of days of hydrogen storage needed from Table S17, divided by 365 days per year.

Region	(a) 2050 Tg-H_2/y needed	(b) 2050 Average power demand to produce + compress H_2 (GW)	(c) 2050 peak power demand to produce + compress H_2 = f + g (GW)	(d) H_2 use factor = b/c (frac.)	(e) Electro-lyzer + compressor lifetime = min (10 y/d,40y) (y)	(f) Electro-lyzer size needed (GW)	(g) Compres-sor size needed (GW)	(h) H_2 storage tank size needed (Tg-H_2)
Africa	8.67	46.64	310.9	0.15	40	273.7	37.23	0.2852
Australia	1.76	9.47	63.13	0.15	40	55.57	7.56	0.0965
Canada	2.68	14.42	14.42	1.00	10	12.69	1.73	0
Central America	2.46	13.24	88.27	0.15	40	77.70	10.57	0.1012
Central Asia	2.58	13.88	92.54	0.15	40	81.46	11.08	0.0142
China	68.60	368.8	2458	0.15	40	2164	294.4	1.6912
Cuba	0.067	0.36	2.41	0.15	40	2.12	0.29	0.0057
Europe	23.11	124.2	828.2	0.15	40	729.0	99.18	1.8992
Haiti	0.136	0.73	4.88	0.15	40	4.30	0.58	0.0041
Iceland	0.025	0.14	0.46	0.30	33.9	0.40	0.06	0.0001
India	19.65	105.7	704.4	0.15	40	620.1	84.35	0.0538
Israel	0.148	0.80	5.31	0.15	40	4.67	0.64	0.0126
Jamaica	0.062	0.33	2.22	0.15	40	1.95	0.27	0.0009
Japan	5.53	29.74	198.3	0.15	40	174.5	23.74	0.0758
Mauritius	0.069	0.37	2.46	0.15	40	2.17	0.29	0.0009
Mideast	14.13	75.96	506.4	0.15	40	445.8	60.64	0.3484
New Zealand	0.27	1.45	9.65	0.15	40	8.49	1.16	0.0007
Philippines	0.85	4.56	30.40	0.15	40	26.76	3.64	0.0232
Russia	8.81	47.37	226.4	0.21	40	199.2	27.10	0.0483
South America	9.03	48.55	323.7	0.15	40	284.9	38.76	0.0247
Southeast Asia	13.14	70.65	471.0	0.15	40	414.6	56.40	0.2880
South Korea	4.20	22.60	150.7	0.15	40	132.6	18.04	0.1727
Taiwan	1.56	8.39	55.97	0.15	40	49.27	6.70	0.1711
United States	14.12	75.94	506.3	0.15	40	445.7	60.62	0.3870
All regions	**201.7**	**1084**	**7057**	**0.154**	**39.9**	**6212**	**845.0**	**5.7054**

pipeline or stored underground, a hydrogen system with some pipelines and underground storage may be built in some countries or regions, depending on costs, policies, and other factors.

3. Methods

Hundreds of studies have examined grid stability with 100% renewable energy [40]. Among them, Jacobson et al. [20] simulated the impact on energy costs, health costs, climate costs, job creation and loss, and land use change from switching the all-sector energy economies of 145 countries, allocated into 24 world regions, from fossil fuels, bioenergy, and uranium, to 100% WWS plus storage. The methodology used in the present study is the same as in Jacobson et al. [20], except that here, (a) hydrogen replaces fossil-fuels for steel and ammonia manufacturing, (b) the changes in energy required to manufacture steel and ammonia with hydrogen instead of with fossil fuels are calculated, and (c) hydrogen loads and changes in energy for long distance transport are calculated based on the final consumption of each oil product used in transportation in each country rather than on a flat percent of transportation oil final consumption. The time-dependent 30-s resolution wind and solar fields from the GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model) weather-climate-air pollution model, used as inputs into LOADMATCH, are the same as in the previous study as are all other inputs, including load data. Table S4 provides the updated 2050 energy requirements here by sector and country.

The WWS electricity-generating technologies treated here include onshore and offshore wind turbines (Wind); tidal and wave devices, geothermal electric power plants, and hydroelectric power plants (Water); and rooftop/utility solar photovoltaics (PV) and concentrated solar power (CSP) plants (Solar). WWS heat sources include solar thermal and geothermal heat generators. WWS storage technologies include electricity, heat, cold, and hydrogen storage. WWS electricity must be transported via alternating current (AC), high-voltage AC (HVAC), and/or high-voltage direct current (HVDC) transmission lines and AC distribution lines. Some equipment in a WWS system includes electric vehicles, heat pumps, induction cooktops, arc furnaces, lawn mowers, and leaf blowers (Table S2).

The main steps in this analysis are as follows:

(1) project business-as-usual (BAU) annual-average power demand from 2018 to 2050 for each of seven fuel types in each of six end-use energy sectors, for each of 145 countries (Note S2);
(2) estimate the 2050 reduction in such demand due to electrifying or providing direct heat for each fuel type in each sector in each country and providing the electricity and heat with WWS (Note S2);
(3) during step (2), replace BAU steel and ammonia manufacturing and BAU long-distance transport vehicles with green-hydrogen steel and ammonia manufacturing and green-hydrogen fuel cell-electric vehicles;
(4) estimate mixes of wind-water-solar (WWS) electricity and heat generators that can meet the 2050 annual-average demand in each country (Note S2);
(5) use a prognostic global weather-climate-air pollution model (GATOR-GCMOM), which accounts for competition among wind turbines for available kinetic energy, to predict wind and solar radiation fields and building heat and cold loads every 30 s for three years in each country (Note S3);
(6) group the 145 countries into 24 world regions (Table S1) and use the LOADMATCH model to match variable electricity, heat, cold, and hydrogen demand with variable supply, storage, and demand response (DR) in each region every 30 s for the three years (2050–2052) (Notes S4–S6);
(7) evaluate energy, health, and climate costs of WWS vs BAU (Note S7);
(8) calculate the land area needed for WWS energy generators (Note S8); and
(9) calculate changes in WWS versus BAU employment numbers (Note S9)

In summary, three types of models are used: a spreadsheet model (Steps 1–4, Note S2), a 3-D global weather-climate-air pollution model (GATOR-GCMOM) (Step 5, Note S3), and a grid integration model (LOADMATCH) (Steps 6–9, Notes S4–S6).

With regard to the spreadsheet calculations, 2018 BAU energy consumption in end-use sectors (also called end-use energy, total final consumption or final energy) (Note S2) from IEA [38] is first projected to 2050 for each of 145 countries, representing over 99.7% of world fossil-fuel CO_2 emissions. End-use energy is energy directly used by a consumer. It is the energy embodied in electricity, natural 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 energy in end-use sectors, including the energy lost during transmission and distribution. IEA provides end-use energy data for each of seven energy categories (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) in each country. The projections from 2018 to 2050 (Note S2) are by fuel type, energy sector, and region of the world. They assume moderate economic growth, policy changes by world region, population growth, energy growth, use of some renewable energy, and modest energy efficiency measures.

2050 BAU end-use demand for each fuel type in each end-use sector in each country is then converted to electricity, electrolytic hydrogen, or heat. The electricity and heat are produced by WWS, assuming the conversion factors by fuel type and sector given in Table S3 (Note S2). Such conversion factors assume the use of vehicles or equipment running primarily on electricity (Note S2). Overall, about 95% of the technologies needed for a transition are already commercialized. Those not commercialized include long-distance aircraft and ships powered by hydrogen fuel cells, and some industrial processes.

Once BAU loads in 2050 are converted to electricity and heat loads to be met by WWS generators, WWS generator nameplate capacities are estimated for each of the 145 countries to meet the loads (Note S2).

2050 nameplate capacities of each generator for each country are then placed in the country's geographic boundaries within GATOR-GCMOM (Note S3). GATOR-GCMOM is run globally for three years (2050–2052). Modeled parameters are aggregated over each country and written to a file every 30 s. Parameters include instantaneous electric power from onshore and offshore wind, solar rooftop PV, utility scale PV, and CSP; direct heat from solar thermal; and building heat and cold loads. From the wind data, time-dependent wave power output is also derived.

The time-dependent data from the file are then input into LOADMATCH [16–20] (Notes S4–S6), which simulates the matching of electricity, heat, cold, and hydrogen demand with supply, storage, and demand response over time. LOADMATCH is a trial-and-error simulation model. It works by running multiple simulations for each grid region, one at a time. Table S1 lists the grid regions treated here. Solutions assume perfect grid connections. However, transmission and distribution costs and losses are accounted for (Note S4). Each simulation advances forward one timestep at a time, just as the real world does, for any number of years that sufficient input data are available for. The main constraint is that the sum of the electricity, heat, cold, and hydrogen loads plus losses, adjusted by demand response, must equal energy supply and storage during every timestep of the simulation. The simulation stops if load is not met during a timestep. Inputs (either the nameplate capacity of one or more generators; the storage peak charge rate, peak discharge rate, or capacity; characteristics of demand response, or minimum electrolyzer use factor) are then adjusted one at a time after examining what caused the load 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 load is met during each time step of the entire simulation. After load 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 load during every timestep. For example, if a solution fails and storage capacity has been depleted, storage capacity may be increased. If a solution fails at night, wind generation may be increased. If a solution fails during the day in low latitude, solar may be increased. The lowest cost solution among the set of successful simulations 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.

A trial-and-error model does not know what the weather will be during the next timestep. This differs from an optimization model, which solves among all timesteps simultaneously. Because a trial-and-error model is non-iterative, it requires less than a minute for a 3-y simulation that uses a 30-s timestep. This is 1/500th to 1/100,000th the computer time of an optimization model for the same number of timesteps, regardless of computer architecture. However, a trial-and-error model, unlike an optimization model, does not determine a least cost solution. Instead, it produces a set of viable solutions, from which the lowest-cost one is selected.

Table S2 summarizes processes in LOADMATCH. Note S4 describes the model's time-dependent inputs. Note S5 discusses the development of time-dependent load profiles in LOADMATCH and maximum storage sizes. Note S6 describes the model's order of operation, including how the model treats excess generation over demand and excess demand over generation and how it treats hydropower.

LOADMATCH is run here for three years (2050–2052) with a 30-s timestep in an effort to match all-sector demand with supply, storage, and demand-response in each of 24 world regions encompassing the 145 countries examined (Table S1). A 30-s timestep is used for three reasons. First, the GATOR-GCMOM model, which provides input data for LOADMATCH, uses a 30-s time step, so LOADMATCH uses the same time step for consistency. Second, LOADMATCH runs so quickly, it is advantageous to use a short time step. Third, a 1-h time step always underestimates modeled peak loads, thus underestimates the peak generation and storage needed to balance such loads. This is because a load averaged over 1 h consists of 120 30-s loads higher than and lower than the average. Once LOADMATCH simulations are complete, energy costs, health costs, climate costs, and employment numbers between WWS and BAU and land requirements of WWS are estimated (Note S7).

4. Results

Although hydrogen is not used here to provide grid electricity storage, it is used for other purposes that may reduce the cost of keeping the grid stable with 100% WWS. This is because, with 100% WWS, more electricity is produced than the grid or storage can handle during many hours each year. Today, much of this excess electricity is shed. In a 100% WWS world, less shedding will occur because most excess electricity will be used to produce heat, cold, and hydrogen for immediate use or storage. Here, we examine the overall cost of energy of producing hydrogen intermittently with 100% WWS electricity.

Producing green hydrogen with WWS requires a rectifier to convert AC to DC electricity, an electrolyzer to convert water to hydrogen and oxygen using DC electricity, water for the electrolyzer, a compressor to compress hydrogen for storage, and storage containers. For fuel cell vehicles, hydrogen fuel dispensers and cooling equipment are also needed. Table S22 provides a breakdown of the hydrogen cost derived in this study. It indicates that electricity use comprises the greatest portion of cost, followed by electrolyzer plus rectifier cost, then storage cost, then water/dispensing/cooling cost, then compressor cost.

From a business point of view, rectifiers, electrolyzers, and compressors should be operated full time (with a use factor of unity) to minimize cost. However, we hypothesize that, at high WWS and hydrogen penetrations, running this equipment intermittently (with sub-unity use factors) reduces overall system cost.

The reason is as follows. At high WWS penetrations, WWS electricity is oversupplied during many hours of the year. If more electricity is available than can be used or stored, the excess is normally shed. If, instead, excess electricity is used to produce hydrogen, that electricity is not wasted. However, in that case, hydrogen is produced during only a fraction of a year, so its use factor is below unity. Thus, the nameplate capacities of rectifiers, electrolyzers, and compressors must be increased to ensure the same annual quantity of hydrogen is produced as with a unity use factor. Higher nameplate capacities mean higher capital costs.

Fortunately, the impact of higher capital costs on overall hydrogen cost is largely offset by the longer lifetimes of rectifiers, electrolyzers, and compressors with lower use factors. This is because equipment life is inversely proportional to use factor until the calendar life of the equipment is reached. A longer life means a longer amortization time for determining cost. The full-load (unity use factor) life of an electrolyzer today is ~7–8.5 years [41], and the calendar life is ~30 years [42]. These lives are estimated to increase here to 10 and 40 years, respectively, by 2035, the year for which the cost calculations are performed. Electrolyzer (and rectifier and compressor) lifetimes are calculated as the full-load life divided by the use factor, limited by the calendar life, resulting in the variation of lifetime with use factor given in Fig. 1. The increase in equipment life with decreasing use factor offsets much of the equipment's higher capital cost with lower use factor.

Fig. 1 shows the sensitivity of hydrogen cost and overall energy cost to rectifier, electrolyzer, and compressor use factor in the U.S. for two cases. In Case 1, the only parameter varying with use factor is utility PV plus onshore wind nameplate capacity. In Case 2, the only parameter varying is hydrogen storage tank size. In both cases, rectifier, electrolyzer, and compressor nameplate capacities and lifetimes decrease with increasing use factor (Fig. 1).

In Case 1 [Fig. 1(a)], the utility PV plus onshore wind nameplate capacity are assumed to increase with increasing use factor in order to ensure sufficient wind or solar is available during the additional hours that hydrogen is produced during the year. Since this additional nameplate capacity produces more electricity in the annual average than is needed to produce and compress hydrogen, electricity shedding increases with increasing use factor as well. Because rectifier, electrolyzer, and compressor sizes decrease with increasing use factor, the cost per kilogram of hydrogen produced decreases with increasing use factor. However, this cost decrease is partly offset by the increase in electricity cost due to the higher nameplate capacity of solar plus wind with increasing use factor, resulting in a minimum overall cost of energy in Case 1 of 8.72 ¢/kWh, occurring at a use factor of 0.6. At higher use factors, the increase in wind plus solar cost more than offsets the decrease in hydrogen equipment cost, causing the overall energy cost to increase as well.

In Case 2 [Fig. 1(b)], hydrogen storage tank size is assumed to increase with increasing use factor to make up for the decreasing rectifier, electrolyzer, and compressor sizes, thus hydrogen production at a given moment, with increasing use factor. These two competing cost factors (lower hydrogen-producing equipment cost and higher storage cost) result in the cost of hydrogen per kilogram and the overall cost of energy first decreasing then increasing with increasing use factor. The minimum overall cost in Case 2, 8.78 ¢/kWh, occurs at a use factor of 0.25. Beyond a certain use factor, though, increasing storage size no longer helps. Instead, it is necessary to increase solar or wind nameplate capacity, such as in Case 1, to make up for the more frequent use of electrolyzers but smaller electrolyzer size. Optimal use factors of 0.2–0.65 were found for other regions, including the China region, as well. For comparison, Armijo and Philibert [25] found optimal electrolyzer use factors of 0.41–0.62 for a hypothetical wind-solar system producing hydrogen to make ammonia in Argentina and Chile.

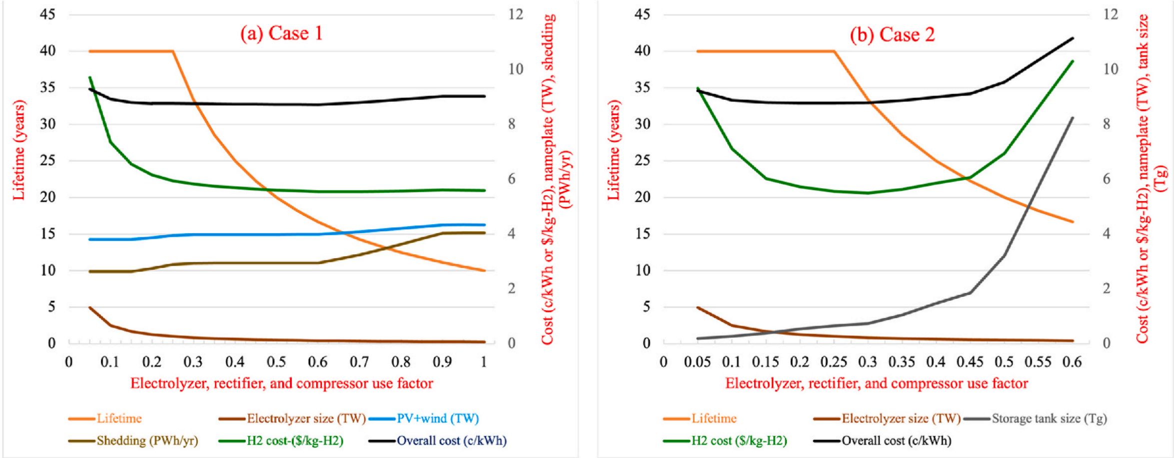

Fig. 1. Variation of several parameters with electrolyzer, rectifier, and compressor use factor in two cases of grid stability across the U.S., modeled over three-year simulations. (a) In the first case (Case 1) only utility PV and onshore wind nameplate capacities are varied with use factor and hydrogen storage tank size is held constant at 0.387 Tg. (b) In the second case (Case 2), only hydrogen storage tank size is varied and utility PV (2.191 TW) and onshore wind (1.611 TW) nameplate capacities are held constant.

It is assumed here that electrolyzer, rectifier, and compressor lifetimes vary from their full-load lifetime (10 years, when the use factor is 1) to their calendar lifetime (40 years, when their use factor is 0.25), inversely proportional to the use factor (see text). Compressor and rectifier lifetimes are proportional to electrolyzer lifetime. In Case 1, PV nameplate capacities rise from 2.191 TW to 2.278 TW between use factors of 0.05 and 0.6 and are constant thereafter. The onshore wind nameplate capacity is a constant 1.611 TW for use factors of 0.05–0.6, after which it rises. For this case, the figure shows the variation in electrolyzer, compressor, and rectifier lifetime, electrolyzer size, utility PV plus onshore wind nameplate capacity, energy shed per year during the simulation, the cost per unit mass of hydrogen produced, and overall energy cost. The hydrogen cost includes the costs of electricity, electrolyzers, rectifiers, compressors, storage tanks, water, and cooling and dispensing hydrogen to vehicles. Table S22 provides a breakdown of the hydrogen cost for the U.S. when the use factor is 0.15. For Case 2, the figure shows the variation in storage tank size and costs with use factor. The variations of lifetime and electrolyzer size are the same as in Case 1. The annual hydrogen production in both cases is 14.125 Tg-H_2/y. Producing and compressing this hydrogen requires an annual average of 74.94 GW of power (at 47.1 kWh/kg-H_2, with 41.46 kWh/kg-H_2 for electrolysis and 5.64 kWh/kg-H_2 for compression).

Jorgensen and Ropenus [43] calculated that, if wind provided 100% of West Denmark's electricity, the minimum cost of hydrogen would occur at an electrolyzer use factor of 0.5, also within the range found here. Zhang et al. [44] calculated the cost of hydrogen for different electrolyzer use factors when electrolytic hydrogen, produced from 56%-renewable electricity, powered 5.3 million fuel cell vehicles in California. The study found that use factors of 0.8–0.9 minimized hydrogen cost. Like in the present study, this range is less than unity, but it is higher than the range found here, which is for a 100% renewable scenario.

To demonstrate the robust benefits of using a lower use factor, simulations of grid stability were performed among 145 countries in 24 regions when hydrogen was produced for steel, ammonia, and long-distance transport with electrolyzer use factors of mostly 0.15, but also higher (Table 2). The resulting average 2020–2050 hydrogen cost among all countries is $6.47 (4.80–8.83)/kg-$H_2$-produced (Table S22). The capital cost among all-sector and countries for a 100% WWS system is $61.3 trillion (2020 USD) (Table 3). Because WWS reduces annual energy costs by $11 trillion/y, or by 61.7%, versus BAU (Table 3), driven largely by a 55.9% reduction in energy needs (Table 3, Note S10), the capital cost payback time due to energy cost savings is ~5.6 years. Because WWS reduces annual social (energy plus health plus climate) costs by $76 trillion/y, or by 91.8% versus BAU (Table 3), the capital cost payback time due to social cost savings is $<$ 1 year. Thus, even with a use factor much below unity, green hydrogen coupled with 100% WWS energy keeps grids stable at much lower cost than does BAU energy.

Some uncertainties about the study arise due to uncertainties in future demand for hydrogen; future demand for all energy; future electrolyzer and fuel cell efficiencies and costs; future battery storage costs; modeled wind and solar fields; and treatment of transmission as perfect. Thus, the results here may change as more data become available.

5. Discussion and conclusions

In sum, this study finds that about 201.7 Tg-H_2/y of green hydrogen may be needed among the 145 countries examined for the three hydrogen uses proposed here in a 100% WWS world: 78.7 Tg-H_2/y for steel, 31.7 Tg-H_2/y for ammonia, and 91.2 Tg-H_2/y for long-distance transport (Table 1). Producing and compressing green hydrogen for these purposes in 2050 may consume ~12.1% (1084 GW) of the power needed for end-use sectors in 145 countries (based on data in Tables 1 and 3). This breaks down to 170.5 GW, 423.2 GW, and 490.6 GW to produce and compress hydrogen for ammonia manufacturing, steel manufacturing, and long-distance transport, respectively. Using green hydrogen for these processes is estimated to require less energy than using fossil fuels to power these processes.

Green hydrogen production is useful when coupled with a 100% WWS grid, because such a grid often produces more electricity than needed for immediate use or than electricity storage can handle. Normally, this excess electricity is shed. However, rectifiers, electrolyzers, and compressors, needed for hydrogen production, can absorb such excess electricity. They will also absorb non-excess electricity when hydrogen is needed immediately.

Because excess WWS electricity is produced only intermittently, most (but not all) hydrogen is ideally produced intermittently as well, thus with a sub-unity use factor. However, when the hydrogen-equipment use factor falls below unity, more equipment (thus more capital cost) is needed to ensure the same annual hydrogen production. Some of this higher cost is offset by the longer lifetime, thus longer amortization time, of equipment with a lower use factor. Additional cost is offset because, either a lower nameplate capacity of wind and solar or less hydrogen storage is needed with a lower use factor. In sum, the lowest cost of hydrogen production integrated with 100% WWS occurs at a hydrogen-equipment use factor below unity, between 0.2 and 0.65 in the test cases provided. As such, it is more cost-effective from an overall system perspective to produce hydrogen intermittently rather

Table 3
2050 annual-average end-use (a) BAU power demand and (b) WWS power demand; (c) percentage difference between WWS and BAU demands; (d) mean value of capital cost, averaged between 2020 and 2050, of new WWS energy in USD 2020; mean value of levelized private energy cost (¢/kWh-all-energy-sectors, averaged between 2020 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 and (m) WWS and BAU social energy cost.

Region	(a) 2050 BAU Annual-average end-use power demand (GW)	(b) 2050 WWS Annual-average end-use power demand (GW)	(c) 2050 WWS minus BAU power demand= (b-a)/a (%)	(d) WWS mean capital cost ($tril 2020)	(e) BAU mean (¢/kWh-all energy)	(f) WWS mean (¢/kWh-all energy)	(g) WWS mean annual all-energy private cost = social cost = bfH ($bil/y)	(h) BAU mean annual all-energy private cost = aeH ($bil/y)	(i) BAU mean annual BAU health cost ($bil/y)	(j) 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	1382	482.1	−65.1	3.671	10.09	8.64	364.7	1222	3982	1783	6987	−70.2	−94.8
Australia	208.8	92.3	−55.8	0.627	10.28	8.49	68.6	188.0	34.6	399.5	622.1	−63.5	−89.0
Canada	442.5	170.3	−61.5	0.638	8.03	6.47	96.4	311.3	42.3	518.3	871.8	−69.0	−88.9
Central America	378.2	156.5	−58.6	1.449	10.49	10.89	149.3	347.6	323.5	588.9	1260	−57.1	−88.2
Central Asia	446.5	166.9	−62.6	1.101	10.30	8.00	117.0	402.7	1011	699.6	2114	−71.0	−94.5
China	5076	2424	−52.3	14.44	9.55	8.12	1724	4248	10,757	8496	23,501	−59.4	−92.7
Cuba	15.8	9.0	−43.0	0.103	11.64	12.12	9.5	16.1	37.5	30.9	84.4	−40.6	−88.7
Europe	2288	958.3	−58.1	5.832	10.01	8.65	726.3	2005	1772	2858	6635	−63.8	−89.1
Haiti	19.1	7.6	−60.3	0.055	10.90	8.71	5.8	18.3	36.2	30.7	85.1	−68.2	−93.2
Iceland	5.6	3.2	−42.9	0.002	7.51	6.86	1.9	3.7	0.4	2.9	7.0	−48.7	−72.8
India	2011	1007	−49.9	7.029	9.88	8.25	727.5	1740	9472	3756	14,968	−58.2	−95.1
Israel	26.1	12.8	−51.0	0.139	11.21	12.29	13.8	25.6	15.7	50.3	91.7	−46.3	−85.0
Jamaica	5.5	2.6	−53.7	0.022	11.38	9.69	2.2	5.5	3.4	7.4	16.3	−60.6	−86.7
Japan	355.4	186.3	−47.6	1.234	10.48	9.16	149.6	326.3	261.5	678.1	1266	−54.2	−88.2
Mauritius	5.2	1.9	−63.3	0.021	10.64	11.73	1.9	4.8	3.7	5.5	14.0	−59.5	−86.1
Middle East	1520	706.5	−53.5	4.543	11.39	8.03	496.8	1517	858.4	2900	5276	−67.3	−90.6
New Zealand	32.4	16.7	−48.5	0.094	8.11	8.14	11.9	23.0	5.2	35.7	63.9	−48.3	−81.3
Philippines	93.9	41.0	−56.3	0.397	10.19	10.43	37.5	83.8	677.3	194.3	955.5	−55.3	−96.1
Russia	787.8	268.3	−65.9	1.309	10.18	7.32	172.0	702.4	601.8	1248	2552	−75.5	−93.3
South America	1091	468.7	−57.0	2.902	8.44	8.36	343.3	806.4	749.8	1161	2718	−57.4	−87.4
Southeast Asia	1301	584.6	−55.1	6.435	10.39	11.59	593.4	1183	1936	2047	5166	−49.9	−88.5
South Korea	304.9	154.4	−49.4	1.736	10.53	12.58	170.2	281.2	104.4	526.9	912.5	−39.5	−81.3
Taiwan	165.3	89.9	−45.6	0.940	10.60	11.70	92.2	153.5	85.9	357.0	596.4	−40.0	−84.5
United States	2398	959.5	−60.0	6.563	10.42	8.79	739.2	2189	829.7	3382	6400	−66.2	−88.5
All regions	**20,359**	**8970**	**−55.9**	**61.28**	**9.98**	**8.67**	**6815**	**17,805**	**33,601**	**31,757**	**83,163**	**−61.72**	**−91.81**

All costs are in 2020 USD.
H = 8760 h per year. Multiply end-use power demand (GW) by H to obtain annual energy use (GWh/y).
Energy costs are for new electricity, heat, cold, and hydrogen generation and storage (including heat pumps for district heating/cooling), and new all-distance transmission/distribution.
Tables S20–S24 give cost parameters. A social discount rate of 2 (1–3)% is used (Note S7).

than continuously. The results here are subject to model uncertainties, but conclusion appears robust.

With such low use factors, why not just use dedicated WWS electricity generators to produce green hydrogen? The reason is that, when some WWS generators are sequestered solely for hydrogen production, they cannot be called upon to provide grid electricity, heat, or cold in a time of high electricity, heat, or cold demand or low overall WWS supply, increasing the need for electricity and heat storage. Economies of scale suggests that interconnecting all WWS generators and adding loads (such as green hydrogen production) that can absorb excess electricity, results in the most cost-effective system. Thus, grid operators should incorporate intermittent green hydrogen production in grid planning.

Author contributions

Conceptualization, M.Z.J.; Methodology, M.Z.J.; Investigation, M.Z. J., A.-K.V.K., K.S., A.N.K.; Software, M.Z.J.; Writing – Original Draft, M.Z.J.; Writing – Review & Editing, M.Z.J., A.-K.V.K., K.S., A.N.K; Visualization, M.Z.J.; Supervision, M.Z.J.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100106.

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Supplementary Information

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

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Smart Energy

This supplementary information file contains some additional description of the models used plus additional results and tables related to this study.

Supporting Text

Note S1. Summary

This study examines the cost of matching electricity, heat, cold, and hydrogen demand with supply, storage, and demand response in 145 countries when using green hydrogen for steel and ammonia manufacturing and for long-distance transport. Green hydrogen is defined as hydrogen produced only from clean, renewable (zero air pollution and zero carbon) wind-water-solar (WWS) electricity. The study extends a previous one (Jacobson et al., 2022) that examined the ability of the same 145 countries grouped into 24 world regions to avoid blackouts upon a transition of all energy sectors to 100% WWS and storage. The 24 regions (Table S1) include a mix of nine large multi-country regions (Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, South America, and Southeast Asia) and 15 individual countries or pairs of countries (Australia, Canada, Cuba, Haiti-Dominican Republic, Israel, Iceland, Jamaica, Japan, Mauritius, New Zealand, the Philippines, Russia-Georgia, South Korea, Taiwan, and the United States). In that study, hydrogen was used in fuel cells for long-distance transport, where the fraction of all transport using hydrogen fuel cells was set to a constant that was the same for all countries. Here, the fraction is varied based on current fuel use in each country. In addition, hydrogen for steel and ammonia manufacturing are accounted for. This SI describes the model in more detail and summarizes the results in multiple tables.

Note S2. Methodology

This section describes the methodology for developing year-2050 roadmaps to transition each of 145 countries to 100% WWS among all energy sectors to meet annual-average load. It includes a discussion of the treatment of hydrogen. It then describes the grid integration studies for each region or country to meet continuous load every 30 seconds for three years. The main steps in performing the analysis described here are as follows:

(1) Project business-as-usual (BAU) power demand from 2018 to 2050 for each of seven fuel types in each of six end-use energy sectors, for each of 145 countries;
(2) estimate the 2050 reduction in demand due to electrifying or providing direct heat for each fuel type in each end-use sector in each country and providing the electricity and heat with WWS;
(3) during step (2), replace BAU steel and ammonia manufacturing and BAU long-distance transport vehicles with green-H_2 steel and ammonia manufacturing and green-H_2 fuel cell-electric vehicles;
(4) perform resource analyses then estimating mixes of wind-water-solar (WWS) electricity and heat generators required to meet the aggregate demand in each country in the annual average;
(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 loads every 30 seconds for three years in each region;
(6) group the 145 countries into 24 world regions and using a model (LOADMATCH) to match variable electricity, heat, cold, and hydrogen demand with variable supply, storage (electricity, heat, cold, and hydrogen storage), and demand response (DR) in each region every 30 seconds, from 2050 to 2052;
(7) evaluate energy, health, and climate costs of WWS vs BAU;
(8) calculate land area requirements of WWS; and
(9) calculate changes in WWS versus BAU jobs numbers.

Thus, three types of models are used: a spreadsheet model (Steps 1-4), a 3-D global weather-climate-air pollution model (Step 5), and a model that matches electricity, heat, cold, and hydrogen demand with supply, storage, and demand response assuming perfect grid interconnection (Steps 6-9). We start with 2018 business-as-usual (BAU) energy consumption data for each of several end-use energy sectors for each country, from IEA (2022). Energy consumption for end-use sectors is also called end-use energy, total final consumption, or final energy. It is energy used directly by a consumer. It is the energy embodied in electricity, natural 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, natural gas, biomass, uranium, or renewable (e.g., hydroelectric, solar, wind) electricity, before the fuel has been subjected to any conversion process.

For each country, the data include energy in each of seven energy categories (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).

These data are projected for each fuel type in each sector in each country from 2018 to 2040 using "BAU reference scenario" projections from EIA (2016) 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 reduced energy use. EIA refers to their reference scenario as their BAU scenario. The 2050 BAU end-use energy for each fuel type in each end-use sector in each of 145 countries is then set equal to the corresponding 2018 end-use energy from IEA (2022) multiplied by the EIA 2050-to-2018 end-use energy consumption ratio, available after the extrapolation, for each fuel type, end-use sector, and region containing the country.

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

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

Liquid fuel (mostly gasoline and diesel) and natural 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 will also power short-haul (<3 h) aircraft flights. HFC vehicles will make up all long-distance ships, trains, and trucks; medium- and long-distance aircraft; and long-distance military vehicles (Katalenich and Jacobson, 2022). The footnote to Table S7 describes how oil for final consumption in the transport sector in each country is partitioned between BE and HFC vehicles. Column (d) shows the resulting partitioning. Gasoline lawnmowers, leaf blowers, and chainsaws are converted to electric equivalents.

High- and medium-temperature industrial processes are electrified with electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, and electron beam heaters. Low-temperature heat for industry is assumed to be provided with electric heat pumps and CSP steam. Green hydrogen for steel and ammonia manufacturing replaces

BAU fuels for these processes, as described and quantified in Tables S5 and S6, respectively. All electricity for industry is provided by WWS sources.

In each country, a mix of WWS resources is estimated to meet the all-sector annual-average end-use energy demand. 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. Jacobson et al. (2017) provide the methodology for the resource analysis performed here for each country. Table S7 of Jacobson et al. (2022) shows solar rooftop PV potentials by country.

Next, a first estimate of the nameplate capacities of a mix of WWS generators needed to meet annual-average all-purpose load is made in each country. 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 PV in each country must be less than the respective rooftop area suitable for PV; (4) the nameplate capacity of conventional hydro is the same as in 2020; and (6) wind and solar, which are complementary in nature, are used in roughly equal proportions where feasible.

The first estimate mix of generator sizes is determined iteratively in the accompanying spreadsheet (Jacobson and Delucchi, 2022). The nameplate capacities from the spreadsheet of onshore and offshore wind electricity, rooftop and utility PV electricity, CSP electricity, and solar thermal heat supply are then used as inputs into the global weather-climate-air-pollution model, GATOR-GCMOM (Note S3) to predict power output by country from each generator every 30 seconds during 2050-2052. From the offshore wind predictions, time-dependent wave power estimates are derived. From modeled outdoor temperatures in each near-surface grid cell, heating and cooling loads in buildings are calculated every 30 seconds, as described in Note S3. Results are then aggregated by country.

The time-dependent wind, solar, and wave power supplies and building thermal loads from GATOR-GCMOM are then input into the LOADMATCH grid integration model (Notes S4-S6, Table S2).

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 (Jacobson, 2001; Jacobson et al., 2007; Jacobson and Archer, 2012; Jacobson and Jadhav, 2018). It simulates weather, climate, and air pollution on the global through urban scales. The main processes treated are as follows:

Gas processes (emissions, gas photochemistry, gas transport, gas-to-particle conversion, gas-cloud interactions, and gas 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, condensation/evaporation, dissolution, ice crystal formation, graupel formation, lightning formation, convection, and precipitation; drop breakup).

Transport processes (horizontal and vertical 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; heating rates; actinic fluxes; radiation through gases, aerosols, clouds, snow, sea ice, and ocean water).

Meteorological processes (wind, temperature, pressure, 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, radiative transfer through the ocean).

GATOR-GCMOM simulates feedbacks 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 (Jacobson et al., 2019).

For the data used here, the model was run at $4^{o}\times5^{o}$ 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, the bottom five layers above the ground were at 30-m resolution; the next seven were at 50-m resolution, one was at 100-m resolution, and the last two were at 200-m resolution. Vertical resolution from 1 to 21 km was 500 m.

Onshore wind turbines, with nameplate capacity determined from the initial spreadsheet estimate of generators needed to meet 2050 end-use load, were placed in windy areas in each country in GATOR-GCMOM. Offshore turbines were placed in coastal water in each country with a coastline. The wind turbine blades in the model crossed five vertical model layers. Spatially-varying model-predicted wind speeds were used to calculate wind power output from each turbine every 30 s. This calculation accounted for the reduction in the wind's kinetic energy and speed due to the competition among wind turbines for limited available kinetic energy (Jacobson and Archer, 2012).

Rooftop solar PV panels, utility PV panels, CSP plants, and solar thermal plants, with nameplate capacities needed to meet 2050 end-use load estimated from the spreadsheets, were placed in GATOR-GCMOM in urban areas (rooftop PV) and in southern parts of each country in the Northern Hemisphere and northern parts of each country in the Southern Hemisphere (utility PV, CSP, and solar thermal).

The model calculates the temperature-dependence of PV output (Jacobson and Jadhav, 2018) and the reduction in sunlight to buildings and the ground due to the conversion of radiation to electricity by solar devices (Jacobson and Jadhav, 2018; Jacobson et al., 2019). It also accounts for (1) changes in air and ground temperature due to power extraction by solar and wind devices and subsequent electricity use (Jacobson and Jadhav, 2018; Jacobson et al., 2019); (2) impacts of time-dependent gas, aerosol, and cloud concentrations on solar radiation and wind fields (Jacobson et al., 2007); (3) radiation to rooftop PV panels at a fixed optimal tilt (Jacobson and Jadhav, 2018); 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 (Jacobson and Jadhav, 2018).

Finally, GATOR-GCMOM was used to calculate building cooling and heating loads in each country every 30 s during 2050-2052. The model predicted the ambient air temperature in each of multiple surface grid cells in each country and compared it with an ideal building interior temperature, set to 294.261 K (70 °F). It then calculated how much heating or cooling energy was 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). Jacobson (2021a) provides full details. The time series loads among all grid cells in a country were then summed to obtain countrywide load time series, which were output for use in LOADMATCH.

Note S4. Description of and Processes in the LOADMATCH Model

This note discusses the LOADMATCH model (Jacobson et al., 2015; 2018; 2019, 2021a,b, 2022) and its main processes. LOADMATCH is a trial-and-error simulation model written in Fortran. Its goal is to match time-dependent electricity, heat, cold, and hydrogen demand with supply, storage, and demand response without failure. It works by running multiple simulations for each grid region, 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 was run for 1 to 6 years, 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 seconds and the simulation period is three years for each region.

The main constraint during a simulation is that the summed electricity, heat, cold, and hydrogen load and losses, adjusted by demand response, must match energy supply and storage every timestep for an entire simulation period. If load 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 load mismatch (thus it is a "trial-and-error" model). Another simulation is then run from the beginning. New simulations are run until load is met every time step of the simulation period. After load 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 load every timestep. The lowest cost solution 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 will be during the next timestep. Because a trial-and-error model is non-iterative, it requires less than a minute for a 3-year simulation that uses a 30-s timestep. This is 1/500th to 1/100,000th the computer time of an optimization model for the same number of timesteps, 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 many of the processes treated in LOADMATCH. Model inputs are as follows:

(1) GATOR-GCMOM-predicted time-dependent electricity 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;
(2) GATOR-GCMOM-predicted time-dependent heat from solar thermal devices;
(3) GATOR-GCMOM-predicted time-dependent building heat and cold loads;
(4) assumed time-dependent profiles of tidal electricity and geothermal electricity and heat supply;
(5) hydropower electricity production varying with time, depending on need for backup electricity and constrained by the 2020 annual hydropower output, the 2020 peak hydropower discharge rate (nameplate capacity), a recharge rate due to rainfall and runoff, and the current water available in reservoirs above half capacity;
(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);
(7) specifications of underground thermal energy storage (UTES);
(8) specifications of ice storage (ICE);
(9) specifications of electricity storage in pumped hydropower storage (PHS), phase-change materials coupled with CSP (CSP-PCM), and batteries;
(10) specifications of hydrogen electrolyzer, rectifier, compressor, and storage tank sizes and the quantity of hydrogen needed for steel and ammonia manufacturing and long-distance transport (this study);
(11) specifications of electric heat pumps needed for district heating and cooling;
(12) specifications of district heating and individual building electric heat pump coefficient of performance;
(13) specifications of a demand response system;

(14) specifications of losses along short- and long-distance transmission and distribution lines;
(15) assumed or data-derived time-dependent electricity, heat, cold, and hydrogen loads; and
(16) specifications of scheduled and unscheduled maintenance downtimes for generators, storage, and transmission.

From model results, differences in energy, health, and climate costs and job creation and losses between BAU and WWS are estimated. Land requirements of WWS are also calculated. The calculation of cost requires specifications of WWS electricity and heat generator costs; electricity, heat, cold, and hydrogen storage costs; hydrogen electrolyzer, rectifier, compressor, dispenser, and cooling costs; transmission and distribution costs; air pollution costs; and climate costs. Changes in job numbers require specifications of job data for generators, storage, hydrogen, and transmission/distribution. Land requirements require specification of the installed power density of different types of land-based generators.

LOADMATCH is used here to match time-dependent (30-s resolution) electricity and heat loads and losses with supply, storage, and demand response during 2050-2052. Notes S5-S6 describe demand response. Whereas GATOR-GCMOM provides time-dependent wind, solar, and wave electricity supplies and solar heat supplies for LOADMATCH, geothermal electricity and heat supplies and tidal electricity supplies are assumed to be baseload and constant throughout the year. Hydroelectricity is consumed as needed but limited by the 2020 peak discharge rate (nameplate capacity) of hydropower and by the amount of water that gave the 2020 annual-average hydropower output. Rainfall and runoff replenish hydropower reservoirs continuously during the year (Table S16, footnotes).

For this study, both the nameplate capacity and installed capacity of hydropower are assumed to be equal. The nameplate capacity of a technology is the peak output (discharge) rate of the technology's generators or other devices producing electricity. The installed capacity for all technologies aside from hydropower equals the nameplate capacity. For hydropower, it is the smaller of the nameplate capacity and the upper limit of the annual-average power produced by available water in a hydropower reservoir (Rahi and Kumar, 2016). Thus, for example, a hydropower plant may produce no more than an average of 1 GW of annual-average power during a year (installed capacity) due to water limitations but may have a much higher peak instantaneous electricity production rate (nameplate capacity) of 10 GW due to the construction of turbines that allow hydropower to meet peaks in grid electricity demand better.

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, 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 counties or pairs of countries (Cuba, Haiti-Dominican Republic, Iceland, Israel, Jamaica, 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-shed 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 S17). Jacobson (2021b) 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. Time-Dependent Thermal and Electricity Load Profiles in LOADMATCH

This note discusses the development of time-dependent load profiles at 30-s time resolution for use in LOADMATCH. We start with the annual-average 2050 WWS energy loads for each sector in each country from Table S4. These loads are separated into (1) electricity and direct heat loads needed for low-temperature heating; (2) electric loads needed for cooling and refrigeration; (3) electricity loads needed to produce, compress, and store hydrogen to run hydrogen fuel cell-electric vehicles with or to manufacture steel and ammonia with; and (4) all other electricity loads (including industrial high-temperature heat loads), as described in Section S1.3.3 of Jacobson et al. (2019) and updated in Jacobson (2021a). Each of these loads is then divided further into flexible and inflexible loads. Flexible loads include electricity and direct heat loads that can be used to fill cold and low-temperature heat storage (district heat storage or building water tank storage), electricity loads used to produce and compress hydrogen (since all hydrogen can be stored), and remaining electricity and direct heat loads subject to demand response. Inflexible loads are all loads that are not flexible. Table S17 gives the percent of building heating and cooling loads subject to district heating in each region.

Loads 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 loads are met. Loads subject to heat/cold storage can be met with such storage or with electricity, either currently available or stored. Inflexible loads must be met immediately with electricity that is currently available or stored.

To summarize, total annual-average cooling and low-temperature heating loads consist of flexible loads subject to storage, flexible loads subject to demand response, and inflexible loads. Such annual-average cooling and low-temperature heating loads for each country are converted to time-dependent cooling and low-temperature heating loads using the time-dependent cooling and low-temperature heating load output from GATOR-GCMOM for each country (Note S3). In LOADMATCH, the cooling and low-temperature heating load 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 load subject to storage required for a 100% WWS region in 2050 from Table S10 to the annual-average cooling or heating load from the GATOR-GCMOM time series, just calculated. This gives time-dependent 2050-2052 cooling and heating loads for each region that, when averaged over time, exactly match the estimated 2050 annual-average loads from Table S10.

Annual-average 2050-2052 inflexible electric loads (in the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors) in each region are converted to time-dependent 2050-2052 inflexible electric loads for the region by projecting contemporary time-dependent electric load data for the region forward to 2050-2052. Contemporary hourly load data for European countries are for 2014 (ENTSOE, 2016). Those for almost all remaining countries are for 2030 (Neocarbon Energy, 2016). Since load 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 annual-average inflexible load reflects those of each original country.

The 2050-2052 inflexible time-series loads for each country are then obtained by multiplying the 2014 or 2030 time-series electric loads, respectively, for the country by the ratio of the annual-average 2050 inflexible load for the region that the country resides in (Table S10) to the sum of the annual-average 2014 or 2030 inflexible load profiles among all countries in the region.

Finally, all remaining loads (all non-heating, non-cooling flexible loads), which include most electric loads for transportation (for electric and hydrogen fuel cell vehicles), for high-temperature industrial heat, and for steel and ammonia manufacturing with hydrogen, are distributed evenly during the year.

For transportation, this assumption is roughly justified by the fact that, between 2016-2019 in the U.S., for example, the minimum and maximum monthly U.S. gasoline supplies were 7.76% and 8.73%, respectively, of the annual supply (EIA, 2021b), 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 ^{o}F (-6.67 ^{o}C) than at 77 ^{o}F (25 ^{o}C) (USDOE, 2021), whereas BEV range is ~40% lower between those two temperatures (Geotab, 2020). 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.

Eighty-five percent of electricity loads for vehicles and 70% of electricity loads for high-temperature industrial heat are assumed to be flexible loads subject to demand response or storage. As such, these loads can be shifted forward in time if necessary or pulled from storage whenever electricity storage is sufficient available. The load for producing and compressing hydrogen for fuel cell vehicles comprises 33.7% of the total transportation load among the 145 countries (Table S7). The load for producing and compressing hydrogen for steel and ammonia manufacturing comprises 12.6% of the total industrial load [Table 1, column (e) divided by Table S9, column (e)]. The load for producing and compressing hydrogen for both transportation and industry comprises 12.1% of the all-purpose load needed for end-use sectors [Table 1, column (g) divided by Table S9, column (a)]. All these loads are flexible, so hydrogen can be produced whenever excess electricity is available, and the hydrogen can then be stored and used as needed. Since 100% of electric loads for hydrogen production and compression for vehicles (33.7% of transportation electric loads) are flexible and 85% of all transportation loads are flexible, 77.4% of all electric loads for battery-electric vehicles are flexible.

Once time-dependent load profiles are developed, maximum electricity, heat, and cold storage sizes and times are estimated (Tables S16, S17).

Note S6. Order of Operation in LOADMATCH

In this section, 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 load. The total load, whether for electricity or heat, consists of flexible and inflexible loads. Whereas flexible loads may be shifted forward in time with demand response, inflexible loads must be met immediately. If WWS instantaneous electricity or heat supply exceeds the instantaneous inflexible electricity or heat load, then the supply is used to satisfy that load. The excess WWS is then used to satisfy as much current flexible electric or heat load as possible. If any excess electricity exists after inflexible and current flexible loads are met, the excess electricity is sent to fill electricity storage or used to produce heat, cold, or hydrogen, which is either stored or used immediately.

Electricity storage is filled first. Excess CSP high-temperature heat goes to CSP thermal energy storage. If CSP storage is full, remaining high-temperature heat produces electricity that is used, along with excess electricity from other sources, to charge battery storage followed by pumped hydropower storage, cold water storage, ice storage, hot water tank storage, and underground thermal energy storage. Remaining excess electricity is used to produce hydrogen. Any residual after that is shed. Hydropower dam storage is filled naturally with rainfall and runoff as described in a footnote to Table S16.

Heat and cold storage are filled by using excess electricity to power an air-, water-, or ground-source heat pump to move heat or cold from the air, water, or ground, respectively, to a thermal storage medium. Hydrogen storage is filled by using electricity in an electrolyzer 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 heat loads, 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 load exceeds WWS electricity or heat supply. When current inflexible plus flexible electricity load exceeds the current WWS electricity supply from the grid, the first step is to use electricity storage (CSP, battery, pumped hydro, and hydropower storage, in that order) to fill in the gap in supply. The electricity is used to supply the inflexible load first, followed by the flexible load. Hydropower's output from reservoir storage during a given time step is limited by the smallest among three factors: the current energy available in the reservoir above a limit of half the reservoir's capacity, the hydropower turbine nameplate capacity multiplied by the time step, and the energy needed during the time step to keep the grid stable (footnote to Table S16).

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

If the inflexible plus flexible heat load subject to storage exceeds immediate WWS heat supply, then centralized stored heat (in district heating water tanks and underground storage) is used to satisfy district heat loads subject to storage, and distributed heat storage (in hot water tanks) is used to satisfy individual building water heat loads. If stored heat becomes exhausted, then any remaining low-temperature air or water heat load becomes either an inflexible load (85%), which must be met immediately with electricity, or a flexible load (15%), which can either be met with electricity or shifted forward in time with demand response and turned into an inflexible load.

Similarly, if the inflexible plus flexible cold load subject to storage exceeds cold storage (in ice or water), excess cold load becomes either an inflexible load (85%), which must be met immediately with electricity, or a flexible load (15%), which can be met with electricity or shifted forward in time with demand response and turned into an inflexible load.

Finally, if the current hydrogen load depletes hydrogen storage, the remaining hydrogen load becomes an inflexible electrical load that must be met immediately with current electricity.

In any of the cases above, if electricity is not available to meet the remaining inflexible load, 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 S7. Energy, Air Pollution, and Climate Costs

Once LOADMATCH simulations are complete, the resulting energy costs, health costs, and climate costs between WWS and BAU are estimated. All costs are evaluated with a social discount rate of 2 (1-3)% (Jacobson et al., 2019) since the analysis here is a social cost analysis. Social cost analyses are from the perspective of society, not of an individual or firm in the market. Thus, social cost analyses must use a social discount rate, even for the private-market-cost portion of the total social cost.

BAU air pollution cost estimates (Table S24) are based on the projected number of air pollution deaths per year by country that are due to energy in 2050, multiplied by a 2050 value of statistical life for each country and by cost factors for morbidity (1.15) and non-health environmental impacts (1.1) (Jacobson et al., 2019). Ninety percent of the total anthropogenic air pollution deaths from Table S25 are due to energy. (Jacobson et al., 2019). The 2050 value of statistical life (millions of dollars per mortality) by country was updated for 2020 USD from Jacobson et al. (2019) for each country. Air pollution deaths due to WWS energy are assumed to be zero since 100% WWS results in zero emissions, even during the mining and manufacturing of WWS equipment.

BAU climate costs are estimated based on the mean social cost of carbon applied to estimated anthropogenic CO_2-equivalent emissions in 2050 from Table S25. The mean social cost of carbon in 2050 in each country is estimated in Table S25, Column (f), which is an update to USD 2020 from values in Jacobson et al. (2019).

Note S8. Land Requirements

Footprint is the physical area on the top surface of soil or water needed for each energy device. 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 S26 provides estimated footprint and spacing areas per megawatt of nameplate capacity of WWS electricity and heat generating technologies considered here.

Applying the footprint and spacing areas per megawatt nameplate capacity from Table S26 to the new nameplate capacities needed to provide grid stability (obtained by subtracting the existing nameplate capacities in Table S11 from the existing plus new nameplate capacities in Table S12) gives the total new land footprint and spacing areas required for each country and region, as shown in Table S27.

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 S9. Employment Changes

A final metric discussed relevant to policy decision-making is net job creation and loss. Table S28 provides estimated numbers of permanent, full-time construction and operation jobs per megawatt of new nameplate capacity or 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 from the table.

The number of jobs per MW was derived for the United States primarily from the Jobs and Economic Development Impact (JEDI) models (NREL, 2019). 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 will 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 S10. Summary of Energy, Storage, Cost, Land, and Employment Results

S10.1. Energy Demand and Generation Results

The results here differ from those in Jacobson et al. (2022) due to the updated treatment of hydrogen here, as described in the main text. Tables 3 and S4 indicate that transitioning from BAU to 100% WWS in 145 countries reduces 2050 annual-average end-use power demand by an average of 55.9%. Of this, 38.0 percentage points are due to the efficiency of using WWS electricity over combustion; 11.3 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels; and 6.6 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Table S4). Of the 38.4% reduction due to the efficiency advantage of WWS electricity, 20.3 percentage points are due to the efficiency advantage of WWS transportation, 4.2 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.5 percentage points are due to the efficiency advantage of using heat pumps instead of combustion heaters. Whereas all-purpose energy demand declines by 55.9%, the energy is almost 100% electricity (with some direct heat), causing world-average electricity consumption in 2050 to increase by 87% compared with a BAU case in 2050 (Table S4). In 2018, electricity comprised 21.3% of all end-use energy among the same 145 countries (Jacobson and Delucchi, 2022).

Table S12 provides the final nameplate capacities for each generator from the simulations in each region, and Table S13 gives the ratio of the final nameplate capacities needed to meet continuous load in LOADMATCH to the initial estimated nameplate capacities needed to meet annual-average load. The ratios are referred to as "capacity adjustment factors." Only ~11% more overall generator nameplate capacity is needed, summed over all 145 countries, to meet continuous 2050 load than to meet annually-averaged 2050 load (41.274 TW from the "All regions" row of Table S12 vs. 37.202 TW from estimates of nameplate generators to meet annual-average load in Jacobson and Delucchi, 2022). The difference is due to oversizing generation in order to meet continuous load. Storage is also needed to meet continuous load (Table S16).

Table S14 gives the regional-average capacity factor (CF) of each generator over each three-year simulation. Table S15 gives the percent of electricity plus heat produced (for both load and losses) from each WWS energy generator, averaged over all 145 countries and for each region, respectively, over the three-year simulations.

S10.2. Storage Results

The total battery storage capacity among all 145 countries is 69.27 TWh per cycle (Table S16). For comparison, the total hydropower storage capacity in reservoirs is ~4,567 TWh per year, which is close to the 2020 world hydropower output (IHA, 2021). Thus, the annual storage capacity of hydropower is equivalent to the annual storage of all batteries cycling 66 times. The number of battery cycles needed per year in the simulations varied from 0 to 210, with 12 regions needing 64 cycles or less per year [column (d) of Table S17]. The peak discharge rate of batteries among all countries is 17.32 TW (Table S16).

For comparison, that of hydropower is 1.16 TW (Table S16), which is all existing (Table S11).

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 hours 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, storage times of greater than four hours and up to 53.7 hours, while not needed, can be advantageous for a region. Batteries with storage times longer than ~53.7 hours were never needed nor advantageous in the present study [Table S17, column (f)]. The ratio of the maximum storage capacity (TWh) to the maximum battery discharge rate (TW) that actually occurred during each simulation ranged from four hours to 53.7 hours. This ratio is the maximum number of hours of storage ever needed at the maximum discharge rate that actually occurred during a simulation. If this ratio exceeds four hours (the number of hours of storage at the peak discharge rate assumed for all simulations), then the battery peak discharge rate assumed was greater than that needed, so the peak discharge rate assumed can be decreased, without any impact on the results, if the number of hours of storage at that peak discharge rate is proportionately increased in order to maintain constant storage capacity.

S10.3. Cost Results

The net present value of the capital cost to transition all 145 countries while keeping the grid stable is $61.3 trillion (USD 2020), with new electricity and heat generators comprising $45.6 trillion of this (Table S23). The remaining costs are for electricity, heat, cold, and hydrogen storage; hydrogen electrolysis and compression; heat pumps for district heating; and long-distance transmission. The capital cost does not include the capital costs of new electric appliances and machines (e.g., heat pumps for 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 S23 provides a dissection of the levelized cost of energy (LCOE) for each region.

Among all 145 countries, the 2050 BAU annual social cost is $83.2 trillion/y, which consists of a 2050 private energy cost ($17.8 trillion/y), health cost ($33.6 trillion/y), and climate cost ($31.8 trillion/y) (Tables 3 and S24). To determine BAU energy costs across all sectors, we assume that the BAU cost per unit-all-energy equals the BAU 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 to 100% WWS reduces both social and private energy costs to \$6.8 trillion/y, or by 91.8% and 61.7%, respectively (Tables 3 and S24). The significant decrease in private energy cost between BAU and WWS occurs because WWS reduces energy demand by 55.9% (Tables 3 and S4) and the cost per unit energy by 13.1% (Table 3). The decrease in social energy cost occurs because WWS eliminates health and climate costs in addition to reducing energy needs and cost.

The WWS capital cost divided by the difference between the BAU and WWS annual private and social energy costs is the payback time due to the WWS private and social cost savings, respectively. The 145-country payback time due to annual private energy cost savings is a mean of 5.6 years. That due to social cost savings is 0.8 years. The capital cost is paid back through energy sales rather than subsidies.

Among all world regions, the average WWS LCOE, between 2020 and 2050, that results in a stable grid, is 8.67 ¢/kWh (Tables 3 and S23). This cost is dominated by the costs of electricity generation (3.76 ¢/kWh), electricity distribution (2.38 ¢/kWh), short-distance transmission (1.05 ¢/kWh), hydrogen production/compression/storage (0.62 ¢/kWh), battery storage (0.45 ¢/kWh), long-distance transmission (0.17 ¢/kWh), geothermal plus solar heat generation (0.08 ¢/kWh), heat pumps for district heating (0.07 ¢/kWh), underground heat storage (0.06 ¢/kWh), CSP and pumped hydro storage (0.03 ¢/kWh), and hot water storage (0.01 ¢/kWh) (Table S23).

S10.4. New Land Area Requirements

The total new land area for footprint (before removing the fossil fuel infrastructure) required with 100% WWS is about 0.16% of the 145-country land area (Table S27), almost all for utility PV and CSP. 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. Table S27 indicates that the spacing area for onshore wind to power the 145 countries is about 0.37% of the 145-country land area. Together, the new land footprint plus spacing area for 100% WWS across all energy sectors represents 0.53% of the 145-country land area, and most of this land area is multi-purpose spacing land.

S10.5. Employment Change Results

Table S29 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 S9). It also accounts for the building of 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 S29 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 S29 indicates that transitioning to 100% WWS may produce 52.6 million new long-term, full-time jobs. Also, 27.2 million jobs may be lost, for a net increase of 25.4 million long-term, full-time jobs produced among the 145 countries. Net job gains occur in 21 out of 24 regions, although not all countries within each region with job gains. Only the regions of Africa, Canada, and Russia experience net job losses. Locations with fewer net job gains or net job losses are usually locations with a substantial fossil fuel industry. However, some countries with high fossil fuel employment (e.g., Saudi Arabia) have net job gains because of the large buildout of WWS infrastructure per capita in those countries. More jobs, not accounted for here, may arise from the need to build more electrical appliances and to improve building energy efficiency.

S10.6. Energy Conservation and Grid Stability

LOADMATCH exactly conserves energy over the three-year simulations for every region. For example, “End-use load plus losses” for “All regions” in Table S18 equals 11,747 GW averaged over the simulations, and this exactly equals “Supply plus changes in storage.” Of that total, 8,970 GW is “annual-average end-use load,” 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, losses going in and out of storage, and shedding losses.

Supporting Tables

Table S1. The 24 world regions comprised of 145 countries treated in this study.

Region	Country(ies) Within Each Region
Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, Tanzania, Togo, Tunisia, Zambia, Zimbabwe
Australia	Australia
Canada	Canada
Central America	Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
Central Asia	Kazakhstan, Kyrgyz Republic, Pakistan, Tajikistan, Turkmenistan, Uzbekistan
China	China, Hong Kong, Democratic People's Republic of Korea, Mongolia
Cuba	Cuba
Europe	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	Dominican Republic, Haiti
Iceland	Iceland
India	Bangladesh, India, Nepal, Sri Lanka
Israel	Israel
Jamaica	Jamaica
Japan	Japan
Mauritius	Mauritius
Mideast	Armenia, Azerbaijan, Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
New Zealand	New Zealand
Philippines	Philippines
Russia	Georgia, Russia
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Curacao, Ecuador, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Southeast Asia	Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Singapore, Thailand, Vietnam
South Korea	Korea, Republic of
Taiwan	Taiwan
United States	United States

Table S2. Several of the processes treated in the LOADMATCH model simulations for matching demand with supply, storage, and demand response. This table also summarizes the main components of a wind-water-solar (WWS) energy system.

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
Geothermal electricity
Tidal and wave electricity
Solar and geothermal heat
WWS storage for grid electricity
Existing hydropower dams with water turbines (no uprating turbines)
Pumped hydropower storage with water turbines
CSP storage with steam turbines
Batteries
WWS heat and cold storage
Heat storage in water tanks and soil
Cold storage in water tanks and soil
WWS hydrogen production, storage, and use
Green hydrogen production by electrolysis using WWS electricity
Hydrogen compression
Hydrogen storage
Hydrogen for steel and ammonia manufacturing in industry*
Hydrogen fuel cell-electric long-distance aircraft, ships, trains, trucks, military vehicles^
WWS machines and appliances
Battery-electricity vehicles for all but long-distance (where hydrogen fuel cell vehicles used)
Battery-electric construction machines and agricultural equipment
Electric heat pumps for building cooling and air/water heating
Electric heat pumps for district heating and cooling
Electric heat pumps for low-temperature industrial heat
Electric heat pump dryers
Electric induction cooktops, lawn mowers, leaf blowers
Electric arc and resistance 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 shedding and generator downtime calculated
Costs, jobs, and land use
Costs of all generation, all storage, short- and long-distance transmission/distribution
Costs of hydrogen rectifiers, electrolyzers, compressors, storage, dispensing, cooling
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 in LOADMATCH
Onshore and offshore wind, roof PV, utility PV, CSP, solar heat, wave supply
Heat and cold loads 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

*Added as part of this study.

^Modified 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. The factors are the ratio of BAU work-output/energy-input to WWS work-output/energy-input, 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
Natural 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 loads include electricity and heat consumed by households, excluding transportation.

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

Industrial loads 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 loads 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 loads 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 loads 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 natural 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 the BAU case. The improvements are calculated as the product of (a) the ratio of energy use, by fuel and energy sector, of the EIA (2016)'s *high efficiency all scenarios* (HEAS) case and their *reference* (BAU) case and (b) additional estimates of slight efficiency improvements beyond those in the HEAS case (Jacobson et al., 2019).

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.

Natural gas includes end-use energy embodied in natural gas. Does not include natural 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) 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 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) 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 medium and high-temperature heating processes (above 100 °C). It also assumes that heat pumps replace those fuels for low-temperature heating processes. The electricity-to-fuel ratio for high-temperature replacement is 0.88 (=0.854/0.97), where 0.854 is the mean COP for natural 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 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 (2022) 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, footnote), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen is accounted for (Table S6, footnote).

[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 S7). The percent varies by country, as shown in Table S7, Column (d). 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 *natural 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 S4. 1st row of each country: 2018 annually-averaged end-use load (power demand) (GW) and percentage of the load by sector. 2nd row: projected 2050 annually-averaged end-use BAU load (GW) and percentage of the total load by sector. 3rd row: estimated 2050 total end-use load (GW) and percentage of total load by sector if 100% of end-use delivered BAU load in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU load 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 load (=all energy load) in the 2050 WWS case to the electricity load in the 2050 BAU case. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases, Column (k) shows that all energy decreases.

Country	Scenario	(a) Total annual-average end-use load (GW)	(b) Residential % of total end-use load	(c) Commercial % of total end-use load	(d) Industry % of total end-use load	(e) Transport % of total end-use load	(f) Ag-for-fish % of total end-use load	(g) Military-other % of total end-use load	(h) % change end-use load with WWS due to higher work: energy ratio	(i) % change end-use load with WWS due to eliminating upstream	(j) % change end-use load with WWS due to efficiency beyond BAU	(k) Overall % change in end-use load with WWS	(l) WWS:BAU electricity load
Albania	BAU 2018	3.0	22.7	9.5	23.8	38.7	5.23	0.00					
	BAU 2050	4.4	27.0	11.7	20.5	36.9	3.97	0.00					
	WWS 2050	2.1	34.9	16.0	27.3	19.7	2.17	0.00	-39.6	-4.5	-9.0	-53.1	1.37
Algeria	BAU 2018	58.0	29.4	1.3	27.5	36.6	0.40	4.81					
	BAU 2050	142.6	21.7	1.1	21.3	51.6	0.34	4.02					
	WWS 2050	43.8	23.2	2.0	40.3	29.0	0.60	4.86	-43.6	-18.2	-7.5	-69.3	2.38
Angola	BAU 2018	14.3	54.2	5.1	13.1	27.5	0.06	0.05					
	BAU 2050	24.5	44.5	4.3	14.8	36.2	0.06	0.05					
	WWS 2050	7.9	41.6	2.6	27.3	28.5	0.04	0.03	-55.7	-4.2	-8.0	-67.9	2.47
Argentina	BAU 2018	83.5	22.4	7.4	33.1	31.6	5.53	0.00					
	BAU 2050	144.4	21.4	6.8	29.6	38.0	4.18	0.00					
	WWS 2050	51.1	21.3	11.6	45.3	19.3	2.54	0.00	-40.8	-16.5	-7.4	-64.6	1.96
Armenia	BAU 2018	3.0	31.6	3.0	16.0	34.6	1.42	13.44					
	BAU 2050	4.8	32.6	3.2	12.5	40.6	1.02	10.20					
	WWS 2050	1.5	37.1	5.1	28.6	13.4	1.57	14.18	-40.2	-18.4	-10.0	-68.6	1.39
Australia	BAU 2018	132.2	10.6	8.3	39.0	39.5	2.65	0.00					
	BAU 2050	208.8	10.4	11.8	41.2	34.5	2.15	0.00					
	WWS 2050	92.3	12.5	19.0	48.0	19.2	1.26	0.00	-34.6	-14.8	-6.4	-55.8	1.58
Austria	BAU 2018	37.7	22.3	8.3	33.2	34.3	1.87	0.00					
	BAU 2050	47.9	21.6	8.7	30.3	37.9	1.54	0.00					
	WWS 2050	20.9	18.2	11.4	45.0	24.2	1.11	0.00	-38.5	-11.2	-6.8	-56.4	1.70
Azerbaijan	BAU 2018	12.6	34.7	6.9	23.3	30.0	5.10	0.00					
	BAU 2050	19.1	37.4	9.3	21.5	28.0	3.84	0.00					
	WWS 2050	6.4	35.8	19.4	20.4	20.8	3.67	0.00	-46.7	-10.7	-9.4	-66.8	1.34
Bahrain	BAU 2018	9.4	11.5	7.4	54.4	26.6	0.07	0.00					
	BAU 2050	17.6	14.5	8.6	52.4	24.4	0.07	0.00					
	WWS 2050	9.6	19.7	12.3	58.1	9.8	0.10	0.00	-22.7	-15.7	-7.2	-45.5	1.36
Bangladesh	BAU 2018	42.8	48.2	2.1	30.9	14.6	3.72	0.42					
	BAU 2050	82.7	38.1	2.5	31.9	23.6	3.51	0.42					
	WWS 2050	35.8	26.6	3.8	58.0	9.0	1.85	0.75	-39.8	-8.1	-8.8	-56.7	1.96
Belarus	BAU 2018	25.8	26.7	10.9	34.5	22.0	5.92	0.00					
	BAU 2050	37.5	28.3	12.5	31.7	22.7	4.70	0.00					
	WWS 2050	12.8	25.1	17.7	37.9	15.5	3.82	0.00	-47.5	-12.7	-5.7	-65.8	1.86
Belgium	BAU 2018	63.5	16.8	9.6	30.3	41.5	1.66	0.10					
	BAU 2050	73.3	16.7	10.6	30.9	40.2	1.55	0.09					
	WWS 2050	30.5	13.0	13.4	46.4	26.1	1.13	0.04	-43.7	-8.1	-6.6	-58.4	2.11

Benin	BAU 2018	5.9	37.7	8.2	1.8	51.9	0.45	0.00					
	BAU 2050	11.0	26.0	9.2	2.0	62.5	0.48	0.00					
	WWS 2050	2.6	22.3	11.2	6.8	59.1	0.59	0.00	-69.2	-1.2	-6.1	-76.5	7.17
Bolivia	BAU 2018	10.0	12.8	3.4	31.4	49.6	2.75	0.00					
	BAU 2050	18.3	8.9	3.2	26.6	59.4	2.04	0.00					
	WWS 2050	5.2	13.7	7.5	41.8	34.1	3.05	0.00	-42.9	-23.1	-5.8	-71.7	2.96
Bosnia & Herz.	BAU 2018	6.2	37.0	7.5	27.9	26.7	0.90	0.00					
	BAU 2050	9.0	38.6	9.1	25.6	26.0	0.69	0.00					
	WWS 2050	3.8	36.1	13.3	34.3	15.9	0.45	0.00	-40.2	-9.0	-8.4	-57.7	1.38
Botswana	BAU 2018	2.8	32.5	4.8	17.2	43.5	1.44	0.58					
	BAU 2050	5.4	24.8	6.1	17.1	49.9	1.50	0.62					
	WWS 2050	2.1	22.1	11.3	33.1	30.3	2.05	1.19	-52.3	-2.2	-7.6	-62.1	1.98
Brazil	BAU 2018	325.6	10.8	5.2	42.4	36.2	5.03	0.37					
	BAU 2050	591.3	8.8	5.1	42.1	38.8	4.83	0.33					
	WWS 2050	272.1	10.8	8.2	58.0	18.6	3.68	0.72	-37.0	-11.5	-5.5	-54.0	2.14
Brunei	BAU 2018	2.7	7.7	7.6	56.5	26.7	0.00	1.48					
	BAU 2050	5.2	8.2	10.3	48.2	31.9	0.00	1.38					
	WWS 2050	1.5	19.3	28.1	25.8	25.8	0.00	0.97	-37.1	-29.4	-5.0	-71.5	1.44
Bulgaria	BAU 2018	14.8	20.0	10.2	34.8	33.4	1.67	0.00					
	BAU 2050	22.4	23.1	13.0	30.3	32.3	1.27	0.00					
	WWS 2050	10.0	27.2	19.1	35.6	17.3	0.78	0.00	-36.4	-11.3	-7.6	-55.3	1.31
Cambodia	BAU 2018	9.6	44.5	5.8	20.9	28.1	0.00	0.65					
	BAU 2050	17.3	34.5	7.0	21.6	36.2	0.00	0.66					
	WWS 2050	6.8	23.2	11.4	42.6	22.6	0.00	0.33	-52.0	-1.1	-7.5	-60.5	2.93
Cameroon	BAU 2018	9.9	64.5	15.2	5.9	12.9	0.07	1.44					
	BAU 2050	15.8	52.7	19.4	7.5	18.3	0.09	1.88					
	WWS 2050	4.3	40.4	16.5	22.5	16.0	0.25	4.38	-63.6	-0.9	-8.2	-72.6	2.37
Canada	BAU 2018	320.9	14.9	11.0	42.3	28.8	3.00	0.03					
	BAU 2050	442.5	13.4	11.8	45.5	26.5	2.76	0.02					
	WWS 2050	170.3	16.1	19.0	44.1	18.8	1.99	0.04	-32.8	-22.7	-6.1	-61.5	1.44
Chile	BAU 2018	38.8	15.8	6.5	39.7	35.2	2.51	0.20					
	BAU 2050	67.5	14.7	10.3	38.9	33.4	2.37	0.22					
	WWS 2050	34.9	12.5	11.5	57.5	16.4	1.79	0.42	-36.4	-4.8	-7.0	-48.3	1.76
China	BAU 2018	2,798.8	16.4	4.4	57.1	16.4	2.14	3.62					
	BAU 2050	4,970.5	17.6	4.5	48.7	24.9	1.47	2.83					
	WWS 2050	2,382.8	15.9	5.4	63.7	10.2	1.18	3.56	-31.5	-14.3	-6.3	-52.1	1.78
Colombia	BAU 2018	43.8	18.7	5.0	32.3	37.4	0.75	5.90					
	BAU 2050	70.5	16.5	5.2	31.6	40.9	0.62	5.30					
	WWS 2050	27.5	18.9	8.6	45.6	22.6	0.58	3.68	-43.5	-11.0	-6.5	-61.0	2.00
Congo	BAU 2018	2.7	57.4	13.8	5.5	23.3	0.00	0.00					
	BAU 2050	4.6	45.4	17.7	6.2	30.7	0.00	0.00					
	WWS 2050	1.3	38.3	23.3	12.6	25.8	0.00	0.00	-60.9	-2.0	-8.3	-71.2	2.23
Congo, DR	BAU 2018	26.0	90.2	0.1	4.4	4.2	1.03	0.00					
	BAU 2050	35.8	84.4	0.3	6.7	6.9	1.64	0.00					
	WWS 2050	8.5	68.5	1.0	22.2	7.0	1.29	0.00	-65.2	-0.6	-10.6	-76.4	3.67
Costa Rica	BAU 2018	5.5	11.3	9.6	23.7	52.9	1.82	0.65					
	BAU 2050	8.6	11.6	10.6	20.0	55.6	1.57	0.56					
	WWS 2050	3.9	17.4	16.8	34.7	29.2	1.51	0.42	-46.4	-1.5	-7.2	-55.0	1.88
Côte d'Ivoire	BAU 2018	10.0	59.3	9.6	9.0	20.8	1.33	0.01					
	BAU 2050	16.6	46.9	12.7	10.6	28.2	1.59	0.02					
	WWS 2050	5.1	35.9	16.6	23.5	22.3	1.59	0.04	-58.6	-2.0	-8.5	-69.0	2.40
Croatia	BAU 2018	10.0	30.4	10.8	24.7	31.0	3.11	0.00					
	BAU 2050	14.8	31.9	14.0	22.1	29.6	2.37	0.00					
	WWS 2050	6.0	30.4	21.7	27.9	18.8	1.32	0.00	-42.7	-8.1	-8.5	-59.2	1.54
Cuba	BAU 2018	11.0	15.0	3.3	55.6	14.1	2.56	9.41					
	BAU 2050	15.8	16.4	4.1	52.0	16.6	2.35	8.55					
	WWS 2050	9.0	18.0	5.4	63.8	8.6	1.16	2.99	-31.8	-4.9	-6.2	-42.9	2.48
Curacao	BAU 2018	3.2	3.3	0.9	15.2	80.6	0.00	0.00					
	BAU 2050	5.2	2.4	1.0	14.1	82.6	0.00	0.00					
	WWS 2050	1.4	4.1	2.8	14.3	78.7	0.00	0.00	-59.4	-9.4	-4.1	-72.8	9.03
Cyprus	BAU 2018	2.8	15.2	11.2	11.9	58.8	2.06	0.80					

	BAU 2050	4.2	16.7	15.3	9.6	56.2	1.59	0.62					
	WWS 2050	1.8	26.2	25.4	15.6	30.6	1.49	0.69	-46.4	-2.0	-8.3	-56.6	1.56
Czech Republic	BAU 2018	35.8	25.6	11.5	34.3	26.1	2.29	0.15					
	BAU 2050	43.9	25.6	12.4	33.8	26.1	1.97	0.13					
	WWS 2050	18.0	20.0	16.5	43.7	18.3	1.35	0.06	-41.1	-11.2	-6.7	-59.0	1.56
Denmark	BAU 2018	21.9	26.7	12.1	20.4	36.5	4.29	0.03					
	BAU 2050	26.1	27.8	13.5	21.2	33.6	3.86	0.03					
	WWS 2050	9.7	25.3	20.3	27.4	23.6	3.42	0.01	-48.1	-8.2	-6.6	-62.8	1.71
Dominican Rep.	BAU 2018	9.1	21.3	6.7	25.5	44.1	2.36	0.00					
	BAU 2050	14.0	16.9	7.6	25.4	48.0	2.14	0.00					
	WWS 2050	6.3	17.3	11.8	42.6	25.6	2.63	0.00	-44.9	-2.9	-7.3	-55.1	1.88
Ecuador	BAU 2018	18.4	12.7	7.3	17.9	51.3	2.59	8.15					
	BAU 2050	28.0	10.3	7.7	16.9	55.9	2.22	7.05					
	WWS 2050	10.0	14.6	12.8	29.2	37.7	1.25	4.48	-53.1	-4.9	-6.2	-64.2	2.03
Egypt	BAU 2018	83.2	22.4	5.5	39.6	30.1	2.30	0.10					
	BAU 2050	186.8	19.5	7.0	34.1	37.3	2.07	0.08					
	WWS 2050	88.8	22.8	11.4	47.7	16.1	2.04	0.04	-32.8	-11.9	-7.8	-52.4	1.75
El Salvador	BAU 2018	3.7	20.9	5.7	23.5	48.6	0.00	1.29					
	BAU 2050	5.5	16.6	7.0	21.3	53.8	0.00	1.26					
	WWS 2050	2.4	17.0	12.2	38.7	29.9	0.00	2.26	-47.6	-1.4	-7.5	-56.5	1.92
Equator. Guinea	BAU 2018	3.1	5.4	2.3	75.6	15.4	0.00	1.27					
	BAU 2050	6.6	4.3	2.5	75.4	16.7	0.00	1.20					
	WWS 2050	4.1	3.4	2.5	87.3	6.4	0.00	0.54	-29.7	-3.8	-3.4	-36.9	10.19
Eritrea	BAU 2018	0.7	73.1	7.0	3.5	16.3	0.00	0.00					
	BAU 2050	1.1	61.7	10.0	4.5	23.7	0.00	0.00					
	WWS 2050	0.3	49.9	15.2	12.7	22.2	0.00	0.00	-61.8	-0.8	-9.6	-72.2	2.32
Estonia	BAU 2018	4.8	25.8	13.4	24.3	32.8	3.42	0.30					
	BAU 2050	6.0	26.4	14.9	25.7	29.8	2.96	0.27					
	WWS 2050	2.1	23.9	24.8	27.5	20.9	2.27	0.60	-45.6	-12.8	-6.6	-65.0	1.30
Ethiopia	BAU 2018	55.0	86.7	1.4	3.7	7.3	0.45	0.45					
	BAU 2050	76.9	79.5	2.2	5.2	11.8	0.63	0.63					
	WWS 2050	18.0	64.1	4.4	17.4	13.0	0.54	0.54	-66.1	-0.2	-10.2	-76.5	6.36
Finland	BAU 2018	36.2	19.0	11.1	46.9	19.6	2.62	0.71					
	BAU 2050	42.6	21.0	13.0	44.3	18.8	2.35	0.65					
	WWS 2050	22.3	18.1	14.6	55.4	10.2	1.39	0.26	-34.3	-6.9	-6.5	-47.7	1.61
France	BAU 2018	204.6	23.9	15.0	23.6	34.4	2.85	0.34					
	BAU 2050	248.6	25.0	16.8	23.1	32.3	2.52	0.30					
	WWS 2050	111.6	24.2	21.7	30.8	21.4	1.70	0.18	-40.2	-6.3	-8.6	-55.1	1.35
Gabon	BAU 2018	6.1	27.9	0.9	65.8	5.2	0.09	0.11					
	BAU 2050	11.8	20.0	1.1	72.6	6.1	0.09	0.11					
	WWS 2050	7.3	9.0	1.1	87.2	2.5	0.10	0.06	-31.2	-4.1	-3.5	-38.7	10.39
Georgia	BAU 2018	5.6	29.0	12.1	19.8	34.5	0.64	3.90					
	BAU 2050	8.6	29.9	15.3	15.8	35.4	0.49	3.03					
	WWS 2050	3.6	23.2	23.2	31.5	16.1	0.44	5.63	-40.2	-7.7	-10.2	-58.0	1.47
Germany	BAU 2018	301.7	23.8	12.8	32.0	29.8	1.58	0.03					
	BAU 2050	361.0	23.7	13.8	31.4	29.7	1.39	0.03					
	WWS 2050	154.6	18.7	16.7	44.8	18.9	0.88	0.01	-41.4	-8.3	-7.4	-57.2	1.64
Ghana	BAU 2018	10.7	40.4	4.8	17.4	35.8	1.61	0.00					
	BAU 2050	20.7	32.0	6.1	18.3	41.9	1.63	0.00					
	WWS 2050	8.4	29.6	8.9	35.7	24.9	0.81	0.00	-50.4	-1.2	-8.0	-59.6	2.05
Gibraltar	BAU 2018	5.6	0.0	0.1	0.1	99.5	0.00	0.36					
	BAU 2050	6.0	0.0	0.1	0.1	99.4	0.00	0.37					
	WWS 2050	1.5	0.0	0.4	0.2	98.2	0.00	1.19	-69.5	-1.9	-4.2	-75.6	49.98
Greece	BAU 2018	26.8	19.0	9.1	23.9	45.4	1.39	1.14					
	BAU 2050	32.5	19.5	12.1	25.6	40.6	1.25	1.01					
	WWS 2050	13.0	24.4	21.9	26.1	25.1	1.95	0.51	-40.7	-11.9	-7.5	-60.1	1.40
Guatemala	BAU 2018	16.2	60.2	3.6	8.4	27.7	0.00	0.00					
	BAU 2050	20.2	49.7	4.3	9.4	36.7	0.00	0.00					
	WWS 2050	5.8	38.3	9.0	23.1	29.6	0.00	0.00	-60.8	-1.8	-8.6	-71.2	2.68
Haiti	BAU 2018	4.6	74.7	1.6	8.8	14.9	0.00	0.00					
	BAU 2050	5.1	66.4	1.5	10.3	21.9	0.00	0.00					

	WWS 2050	1.3	47.2	1.5	30.7	20.6	0.00	0.00	-64.9	-0.5	-8.9	-74.3	15.33
Honduras	BAU 2018	6.0	40.9	9.4	15.0	32.9	1.72	0.09					
	BAU 2050	8.2	33.1	10.2	14.8	40.1	1.66	0.08					
	WWS 2050	3.0	26.2	14.7	32.3	25.8	0.89	0.05	-54.1	-0.8	-8.1	-62.9	2.18
Hong Kong	BAU 2018	36.0	4.9	10.7	8.2	76.2	0.00	0.03					
	BAU 2050	82.6	4.7	11.6	6.6	77.0	0.00	0.02					
	WWS 2050	29.8	8.7	23.6	13.1	54.6	0.00	0.03	-55.4	-2.0	-6.5	-63.9	2.24
Hungary	BAU 2018	25.9	29.8	10.8	30.0	26.0	3.29	0.19					
	BAU 2050	31.7	30.1	10.9	29.1	26.8	2.87	0.17					
	WWS 2050	12.6	22.5	13.6	42.9	18.6	2.32	0.12	-43.5	-9.2	-7.6	-60.3	1.75
Iceland	BAU 2018	5.0	13.5	13.7	42.1	23.0	7.43	0.27					
	BAU 2050	5.6	14.4	14.6	41.5	22.2	7.01	0.26					
	WWS 2050	3.2	9.1	13.5	62.6	10.8	3.90	0.11	-34.9	-2.1	-5.9	-43.0	1.21
India	BAU 2018	797.9	29.0	4.3	40.8	18.3	4.88	2.67					
	BAU 2050	1,870.8	20.3	4.0	40.5	28.0	4.55	2.65					
	WWS 2050	951.6	15.9	3.8	60.3	12.9	5.00	2.05	-36.0	-6.4	-6.7	-49.1	2.40
Indonesia	BAU 2018	215.4	21.5	3.7	38.8	34.7	1.13	0.18					
	BAU 2050	423.9	16.1	4.6	37.2	40.9	1.05	0.16					
	WWS 2050	191.9	14.7	7.4	55.9	21.2	0.63	0.07	-42.7	-6.1	-6.0	-54.7	2.77
Iran	BAU 2018	253.8	27.9	5.8	35.7	26.3	4.09	0.22					
	BAU 2050	444.0	24.0	5.1	38.3	28.1	4.35	0.24					
	WWS 2050	186.3	17.4	5.7	58.7	13.2	4.55	0.44	-39.5	-11.2	-7.3	-58.0	2.82
Iraq	BAU 2018	36.7	19.5	0.8	32.2	44.2	0.00	3.36					
	BAU 2050	62.1	17.9	1.0	32.5	44.9	0.00	3.69					
	WWS 2050	23.1	27.0	2.1	35.0	28.3	0.00	7.61	-42.6	-13.8	-6.3	-62.7	1.99
Ireland	BAU 2018	16.7	21.7	11.6	22.7	42.0	1.97	0.00					
	BAU 2050	18.9	21.2	13.3	22.6	40.9	1.88	0.00					
	WWS 2050	8.0	19.2	16.9	38.6	23.9	1.40	0.00	-45.7	-4.2	-7.7	-57.6	1.75
Israel	BAU 2018	21.5	12.9	10.3	24.7	46.0	1.58	4.52					
	BAU 2050	26.1	15.1	14.2	24.8	40.4	1.45	4.07					
	WWS 2050	12.8	24.0	21.8	28.8	19.1	2.31	3.98	-35.2	-7.4	-8.4	-51.0	1.28
Italy	BAU 2018	168.4	25.2	13.3	25.8	33.2	2.39	0.09					
	BAU 2050	215.7	24.1	13.9	24.5	35.5	2.01	0.07					
	WWS 2050	83.6	18.8	20.4	34.7	24.6	1.61	0.04	-42.3	-11.1	-7.8	-61.2	1.52
Jamaica	BAU 2018	3.7	5.4	7.7	38.7	47.7	0.50	0.00					
	BAU 2050	5.5	5.5	6.4	35.0	52.6	0.44	0.00					
	WWS 2050	2.6	7.5	4.6	59.3	28.4	0.19	0.00	-47.8	-1.0	-4.8	-53.7	4.14
Japan	BAU 2018	370.8	15.2	17.4	36.1	29.5	1.66	0.19					
	BAU 2050	355.4	15.9	19.1	34.4	29.2	1.24	0.17					
	WWS 2050	186.3	15.8	20.6	47.2	15.7	0.57	0.06	-31.2	-8.6	-7.8	-47.6	1.52
Jordan	BAU 2018	9.1	21.3	7.3	13.9	50.2	3.40	3.87					
	BAU 2050	15.8	21.1	7.3	14.5	49.6	3.64	3.84					
	WWS 2050	6.9	31.6	10.9	22.3	26.9	6.52	1.76	-44.9	-3.3	-8.2	-56.4	1.51
Kazakhstan	BAU 2018	65.4	23.1	10.7	45.7	14.0	3.36	3.06					
	BAU 2050	87.2	22.1	11.2	45.6	15.2	3.00	2.82					
	WWS 2050	33.6	18.8	10.0	57.4	10.0	1.96	1.82	-41.4	-15.0	-5.0	-61.4	1.97
Kenya	BAU 2018	23.6	69.4	0.6	7.7	21.6	0.28	0.36					
	BAU 2050	37.1	57.1	1.2	9.8	31.1	0.35	0.45					
	WWS 2050	10.4	41.5	3.2	28.1	26.6	0.25	0.32	-62.5	-0.6	-8.8	-71.9	4.08
Korea, DPR	BAU 2018	6.9	3.1	0.0	52.1	8.9	0.00	35.95					
	BAU 2050	13.3	1.9	0.0	51.7	10.7	0.00	35.70					
	WWS 2050	7.4	0.6	0.0	72.0	4.7	0.00	22.73	-37.1	-2.3	-5.4	-44.8	2.59
Korea, Rep. of	BAU 2018	217.4	13.1	13.1	40.8	30.5	1.60	0.81					
	BAU 2050	304.9	11.4	15.2	42.5	28.8	1.49	0.66					
	WWS 2050	154.4	8.4	20.1	56.1	13.4	1.65	0.26	-32.5	-9.6	-7.3	-49.4	1.47
Kosovo	BAU 2018	2.0	37.5	10.1	22.0	28.4	2.02	0.00					
	BAU 2050	3.0	41.7	11.8	17.9	27.1	1.56	0.00					
	WWS 2050	1.4	43.4	15.2	25.7	14.3	1.35	0.00	-40.7	-3.5	-10.2	-54.3	1.23
Kuwait	BAU 2018	31.3	12.3	3.3	53.1	30.8	0.51	0.00					
	BAU 2050	57.4	16.0	4.0	50.7	28.9	0.52	0.00					
	WWS 2050	23.5	28.9	7.6	46.1	16.5	0.99	0.00	-31.4	-21.7	-5.9	-59.0	1.50

Kyrgyzstan	BAU 2018	5.5	62.8	7.6	15.8	12.3	0.63	0.94					
	BAU 2050	7.3	62.7	8.3	14.6	13.1	0.56	0.82					
	WWS 2050	3.4	61.7	7.9	22.1	6.7	0.75	0.73	-40.7	-1.6	-11.0	-53.3	1.20
Lao PDR	BAU 2018	4.2	40.3	12.1	13.3	34.2	0.06	0.00					
	BAU 2050	7.6	32.4	9.7	14.0	43.9	0.07	0.00					
	WWS 2050	2.8	26.6	12.5	31.9	28.8	0.15	0.00	-54.5	-0.8	-7.8	-63.2	2.00
Latvia	BAU 2018	5.7	28.5	13.7	23.1	30.2	4.35	0.14					
	BAU 2050	8.1	29.5	16.6	20.1	30.2	3.50	0.11					
	WWS 2050	3.2	22.8	21.8	33.4	19.7	2.22	0.05	-50.8	-2.6	-6.8	-60.2	2.05
Lebanon	BAU 2018	7.3	18.8	5.3	13.9	55.3	0.00	6.71					
	BAU 2050	13.2	20.3	6.3	14.3	52.5	0.00	6.74					
	WWS 2050	6.2	28.9	10.5	26.0	24.6	0.00	10.06	-43.3	-1.0	-9.1	-53.4	1.30
Libya	BAU 2018	14.4	13.4	1.5	25.3	55.3	1.00	3.45					
	BAU 2050	31.4	12.8	2.0	23.5	57.4	0.97	3.35					
	WWS 2050	13.2	19.1	3.7	39.1	30.1	1.81	6.22	-48.3	-3.2	-6.5	-58.0	2.40
Lithuania	BAU 2018	8.6	22.6	10.0	28.8	36.9	1.66	0.11					
	BAU 2050	12.6	23.7	12.0	26.7	36.2	1.33	0.08					
	WWS 2050	5.0	21.4	16.7	37.5	23.3	1.00	0.04	-43.9	-10.5	-6.0	-60.4	2.01
Luxembourg	BAU 2018	5.8	11.3	10.9	15.4	61.9	0.52	0.00					
	BAU 2050	6.5	11.5	12.3	15.6	60.1	0.50	0.00					
	WWS 2050	2.5	9.0	17.1	31.0	42.5	0.36	0.00	-53.2	-2.3	-6.6	-62.2	2.12
Macedonia, Nor.	BAU 2018	2.5	25.6	11.2	24.1	38.1	1.06	0.00					
	BAU 2050	3.8	31.1	13.6	19.3	35.3	0.80	0.00					
	WWS 2050	1.9	36.1	17.1	27.8	18.3	0.73	0.00	-37.7	-2.6	-9.7	-50.0	1.29
Malaysia	BAU 2018	79.1	5.6	7.4	45.0	40.2	1.71	0.00					
	BAU 2050	169.0	5.4	8.7	40.3	44.1	1.46	0.00					
	WWS 2050	80.7	8.0	13.6	56.3	21.4	0.71	0.00	-38.6	-7.8	-5.8	-52.3	1.99
Malta	BAU 2018	3.8	3.0	4.2	2.1	90.4	0.24	0.07					
	BAU 2050	5.5	4.2	5.9	1.7	88.0	0.19	0.06					
	WWS 2050	1.7	10.0	13.8	4.6	71.3	0.18	0.15	-62.4	-1.8	-5.6	-69.8	2.94
Mauritius	BAU 2018	2.3	8.0	5.8	12.0	73.8	0.23	0.12					
	BAU 2050	5.1	7.5	6.7	10.9	74.5	0.21	0.11					
	WWS 2050	1.9	13.2	13.0	24.4	48.9	0.29	0.23	-55.4	-1.5	-6.3	-63.2	2.15
Mexico	BAU 2018	189.1	12.7	2.9	38.4	41.0	3.11	1.91					
	BAU 2050	312.5	12.6	4.8	38.0	39.5	3.06	2.10					
	WWS 2050	133.7	14.6	6.5	52.1	20.4	2.55	3.84	-39.5	-11.6	-6.1	-57.2	1.79
Moldova, Rep.	BAU 2018	4.3	43.3	8.9	20.1	23.7	3.55	0.44					
	BAU 2050	6.0	44.1	10.9	17.6	24.2	2.83	0.37					
	WWS 2050	2.3	34.7	15.1	32.2	15.9	1.84	0.22	-50.5	-2.4	-8.9	-61.8	1.86
Mongolia	BAU 2018	5.4	25.2	7.9	33.6	18.7	2.21	12.30					
	BAU 2050	9.9	19.9	6.3	35.0	23.5	2.24	13.04					
	WWS 2050	3.9	17.2	4.0	53.9	14.1	1.37	9.43	-53.1	-3.4	-3.7	-60.2	2.34
Montenegro	BAU 2018	1.0	32.4	11.5	19.5	35.9	0.65	0.00					
	BAU 2050	1.6	36.6	15.0	15.0	32.9	0.48	0.00					
	WWS 2050	0.8	38.6	21.1	22.6	17.4	0.31	0.00	-37.2	-1.9	-10.9	-50.0	1.16
Morocco	BAU 2018	22.3	24.1	7.7	20.0	40.9	7.27	0.00					
	BAU 2050	44.6	17.6	8.7	20.2	46.3	7.25	0.00					
	WWS 2050	19.4	18.7	9.4	37.5	28.7	5.75	0.00	-48.3	-0.9	-7.2	-56.5	2.04
Mozambique	BAU 2018	6.8	37.7	14.7	23.9	22.9	0.08	0.78					
	BAU 2050	12.7	28.0	16.0	26.5	28.4	0.09	0.88					
	WWS 2050	5.3	17.6	9.2	54.7	16.8	0.10	1.65	-49.9	-1.5	-7.0	-58.4	1.61
Myanmar	BAU 2018	26.9	55.5	3.7	20.8	10.7	6.57	2.69					
	BAU 2050	44.7	45.9	4.2	23.1	16.7	7.17	2.95					
	WWS 2050	15.7	31.1	6.2	46.8	9.9	4.10	1.79	-52.6	-4.3	-8.0	-65.0	3.22
Namibia	BAU 2018	2.5	9.1	0.1	9.9	39.4	18.79	22.74					
	BAU 2050	5.1	5.6	0.1	9.8	43.5	17.96	23.00					
	WWS 2050	1.9	2.6	0.0	21.0	28.3	9.49	38.61	-54.2	-0.8	-7.1	-62.1	1.92
Nepal	BAU 2018	18.7	73.5	2.6	8.1	13.5	2.17	0.18					
	BAU 2050	28.5	63.8	2.6	10.2	20.5	2.60	0.23					
	WWS 2050	7.9	46.1	3.5	29.0	18.6	2.15	0.64	-62.6	-0.4	-9.2	-72.2	4.74
Netherlands	BAU 2018	88.4	14.4	10.2	30.8	38.9	5.69	0.10					

	BAU 2050	104.5	15.0	11.5	31.6	36.6	5.23	0.09					
	WWS 2050	41.6	12.0	16.0	43.8	23.7	4.49	0.04	-43.7	-10.0	-6.6	-60.2	2.09
New Zealand	BAU 2018	20.7	9.5	7.7	33.5	44.7	4.30	0.28					
	BAU 2050	32.4	10.0	10.6	36.9	38.0	4.12	0.33					
	WWS 2050	16.7	12.8	14.8	50.8	17.6	3.54	0.50	-36.4	-5.2	-6.9	-48.5	1.75
Nicaragua	BAU 2018	3.5	42.5	11.1	15.8	28.1	2.06	0.41					
	BAU 2050	4.7	34.4	11.7	16.4	34.9	2.05	0.45					
	WWS 2050	1.6	27.0	15.1	30.8	24.1	1.88	1.00	-53.6	-3.4	-8.0	-65.0	2.02
Niger	BAU 2018	4.2	78.4	1.4	4.0	16.1	0.03	0.00					
	BAU 2050	6.3	68.5	2.0	5.2	24.2	0.04	0.00					
	WWS 2050	1.6	58.8	3.4	15.3	22.4	0.14	0.00	-64.5	-0.9	-9.6	-75.0	3.41
Nigeria	BAU 2018	193.2	72.6	2.3	8.7	16.3	0.00	0.12					
	BAU 2050	294.0	61.3	3.3	11.0	24.2	0.00	0.15					
	WWS 2050	70.6	49.2	4.6	24.8	21.2	0.00	0.13	-64.0	-3.6	-8.3	-76.0	8.04
Norway	BAU 2018	34.0	16.1	11.5	49.5	21.0	1.73	0.20					
	BAU 2050	47.3	16.8	12.7	48.0	21.0	1.35	0.16					
	WWS 2050	20.7	26.5	20.0	40.3	11.8	1.37	0.07	-22.8	-25.9	-7.6	-56.3	1.00
Oman	BAU 2018	35.2	5.9	27.2	37.9	25.8	0.17	3.04					
	BAU 2050	59.9	8.0	21.6	41.0	26.1	0.19	3.11					
	WWS 2050	26.0	13.5	17.0	54.0	13.8	0.33	1.43	-40.6	-11.6	-4.5	-56.6	2.91
Pakistan	BAU 2018	124.3	46.6	3.3	27.1	21.6	1.07	0.33					
	BAU 2050	233.1	36.8	3.5	28.3	30.0	1.12	0.32					
	WWS 2050	96.0	25.9	4.8	52.6	14.4	2.09	0.16	-45.8	-5.0	-8.0	-58.8	2.95
Panama	BAU 2018	11.5	6.6	6.2	9.0	78.1	0.15	0.01					
	BAU 2050	18.5	5.5	6.8	7.4	80.1	0.12	0.01					
	WWS 2050	6.0	9.2	15.1	17.4	58.2	0.07	0.02	-60.0	-1.6	-5.8	-67.4	3.05
Paraguay	BAU 2018	8.8	26.7	6.2	25.7	41.4	0.00	0.00					
	BAU 2050	12.9	22.4	7.8	23.0	46.7	0.00	0.00					
	WWS 2050	5.7	20.9	13.6	40.2	25.3	0.00	0.00	-46.7	-1.4	-7.3	-55.4	2.15
Peru	BAU 2018	29.4	17.8	6.2	30.9	44.0	1.01	0.00					
	BAU 2050	47.4	13.0	6.0	28.8	51.3	0.88	0.00					
	WWS 2050	18.7	12.7	8.9	49.8	27.3	1.24	0.00	-42.8	-11.4	-6.3	-60.5	2.06
Philippines	BAU 2018	47.2	21.2	13.1	25.0	39.4	1.24	0.00					
	BAU 2050	93.9	17.0	12.5	23.4	45.9	1.18	0.00					
	WWS 2050	41.0	18.1	15.8	38.8	26.0	1.37	0.00	-45.8	-3.1	-7.4	-56.3	1.76
Poland	BAU 2018	103.8	25.0	10.2	29.5	30.3	5.04	0.00					
	BAU 2050	126.7	22.9	11.6	29.3	31.8	4.36	0.00					
	WWS 2050	48.9	17.8	17.7	41.4	20.6	2.52	0.00	-43.0	-12.4	-6.0	-61.4	1.70
Portugal	BAU 2018	25.2	14.0	10.4	31.1	42.0	2.43	0.14					
	BAU 2050	30.2	15.1	13.3	30.7	38.6	2.19	0.12					
	WWS 2050	13.5	16.3	20.5	38.6	22.9	1.58	0.05	-39.4	-8.8	-7.1	-55.3	1.58
Qatar	BAU 2018	44.1	5.7	2.2	70.1	20.9	0.00	1.07					
	BAU 2050	78.8	7.8	2.7	68.3	20.1	0.00	1.12					
	WWS 2050	33.2	13.8	4.9	67.6	11.6	0.00	2.07	-24.3	-29.5	-4.1	-57.9	2.74
Romania	BAU 2018	34.1	30.1	7.7	34.1	25.2	2.20	0.82					
	BAU 2050	48.4	31.9	9.2	31.3	25.1	1.79	0.65					
	WWS 2050	18.9	25.4	11.8	44.5	16.7	1.22	0.33	-44.6	-9.0	-7.3	-60.9	1.77
Russia	BAU 2018	683.1	28.8	7.2	39.1	23.0	1.86	0.00					
	BAU 2050	779.2	27.5	7.3	36.6	27.1	1.39	0.00					
	WWS 2050	264.7	24.6	10.7	49.3	14.2	1.30	0.00	-40.4	-19.3	-6.3	-66.0	1.72
Saudi Arabia	BAU 2018	188.4	9.2	7.7	45.7	37.0	0.30	0.03					
	BAU 2050	349.0	11.6	9.1	44.6	34.4	0.30	0.03					
	WWS 2050	183.6	16.2	13.5	53.9	15.9	0.44	0.04	-32.9	-8.0	-6.6	-47.4	2.15
Senegal	BAU 2018	3.7	39.9	6.4	15.0	37.0	0.36	1.30					
	BAU 2050	6.9	29.2	8.1	16.0	44.8	0.41	1.47					
	WWS 2050	2.6	21.4	13.6	32.1	29.1	0.83	2.98	-52.2	-1.4	-8.1	-61.7	2.21
Serbia	BAU 2018	12.5	30.0	9.4	34.6	24.1	1.80	0.00					
	BAU 2050	18.8	34.6	11.2	30.0	22.8	1.37	0.00					
	WWS 2050	8.9	37.8	13.6	35.0	12.7	0.92	0.00	-36.1	-8.5	-8.4	-53.0	1.26
Singapore	BAU 2018	95.4	1.0	2.6	13.9	82.4	0.00	0.04					
	BAU 2050	216.6	1.0	2.9	11.2	84.8	0.00	0.03					

	WWS 2050	69.7	2.2	6.8	22.4	68.5	0.00	0.07	-59.7	-3.6	-4.5	-67.8	4.60
Slovak Republic	BAU 2018	15.3	17.8	11.4	45.2	24.4	1.16	0.00					
	BAU 2050	20.0	16.8	11.7	42.0	28.6	0.94	0.00					
	WWS 2050	8.6	13.2	15.1	56.5	14.6	0.65	0.00	-32.8	-17.8	-6.4	-57.0	1.78
Slovenia	BAU 2018	7.1	20.0	8.0	28.4	41.7	1.37	0.45					
	BAU 2050	8.3	21.7	10.0	27.2	39.3	1.25	0.41					
	WWS 2050	3.9	18.8	14.5	42.6	23.3	0.62	0.18	-42.5	-3.5	-7.4	-53.5	1.60
South Africa	BAU 2018	117.6	15.1	6.9	48.1	26.2	2.55	1.21					
	BAU 2050	234.2	12.9	8.4	45.2	29.7	2.56	1.21					
	WWS 2050	103.2	15.1	10.6	54.6	16.8	1.99	0.94	-36.5	-13.9	-5.5	-55.9	1.63
South Sudan	BAU 2018	0.7	27.8	2.1	19.0	47.2	3.92	0.00					
	BAU 2050	1.4	21.4	2.1	17.0	55.5	4.05	0.00					
	WWS 2050	0.4	25.6	2.7	15.7	51.4	4.67	0.00	-55.8	-10.9	-5.7	-72.5	2.82
Spain	BAU 2018	136.5	14.4	10.5	29.5	42.6	2.66	0.31					
	BAU 2050	166.0	15.1	12.2	30.4	39.6	2.35	0.28					
	WWS 2050	69.0	17.8	18.3	36.2	25.7	1.67	0.27	-39.5	-12.1	-6.8	-58.4	1.57
Sri Lanka	BAU 2018	14.8	29.8	4.6	24.0	39.7	0.00	1.92					
	BAU 2050	28.6	22.1	5.0	23.3	47.7	0.00	1.81					
	WWS 2050	11.5	17.7	8.2	45.1	28.2	0.00	0.89	-51.8	-1.4	-6.4	-59.6	2.98
Sudan	BAU 2018	17.2	43.5	13.7	11.3	29.4	1.51	0.56					
	BAU 2050	32.0	34.3	15.2	12.6	35.6	1.65	0.59					
	WWS 2050	11.2	31.8	13.0	27.2	25.1	2.60	0.34	-56.6	-1.1	-7.3	-65.0	2.54
Suriname	BAU 2018	0.8	17.2	7.9	15.7	42.3	16.51	0.34					
	BAU 2050	1.2	16.0	9.0	14.8	45.8	14.13	0.32					
	WWS 2050	0.5	23.3	15.5	26.1	27.5	7.07	0.63	-49.0	-3.4	-7.7	-60.0	1.42
Sweden	BAU 2018	45.9	21.7	11.9	35.9	28.6	1.89	0.00					
	BAU 2050	55.4	24.0	14.1	32.6	27.7	1.63	0.00					
	WWS 2050	30.3	23.7	16.0	44.3	15.1	0.87	0.00	-33.1	-4.6	-7.6	-45.3	1.35
Switzerland	BAU 2018	26.5	25.3	15.9	19.5	37.8	0.53	1.03					
	BAU 2050	32.1	24.9	17.5	18.4	37.9	0.48	0.92					
	WWS 2050	14.3	23.6	21.6	28.3	25.4	0.71	0.40	-43.0	-3.7	-8.6	-55.2	1.30
Syria	BAU 2018	8.5	21.3	4.3	28.6	39.1	3.59	3.15					
	BAU 2050	14.4	19.1	4.1	29.8	39.9	3.67	3.36					
	WWS 2050	6.3	24.1	4.9	42.6	22.6	1.67	4.16	-42.3	-6.4	-7.2	-55.9	1.70
Taiwan	BAU 2018	80.4	9.6	8.4	53.4	26.7	1.03	0.81					
	BAU 2050	165.3	9.5	9.3	49.0	30.5	0.94	0.76					
	WWS 2050	89.9	11.7	11.8	60.8	14.1	0.77	0.83	-31.0	-7.7	-6.9	-45.6	1.39
Tajikistan	BAU 2018	3.9	27.6	7.7	29.1	14.9	6.55	14.22					
	BAU 2050	5.8	33.9	11.7	24.1	14.3	5.29	10.71					
	WWS 2050	3.4	36.4	15.2	31.9	6.0	6.92	3.59	-28.4	-1.1	-10.9	-40.3	1.13
Tanzania	BAU 2018	24.2	69.6	0.8	10.9	11.0	5.05	2.61					
	BAU 2050	38.1	57.3	1.4	14.8	15.8	7.03	3.65					
	WWS 2050	11.4	38.3	3.6	38.7	12.4	4.59	2.44	-60.9	-0.3	-8.7	-70.0	5.81
Thailand	BAU 2018	122.3	10.1	5.3	44.2	36.6	3.15	0.70					
	BAU 2050	257.5	8.1	6.1	38.9	43.5	2.72	0.65					
	WWS 2050	116.9	9.4	9.7	57.2	21.4	1.24	1.11	-39.0	-10.0	-5.6	-54.6	2.40
Togo	BAU 2018	2.8	66.5	10.1	4.6	18.9	0.00	0.00					
	BAU 2050	4.5	54.4	13	5.9	26.7	0.00	0.00					
	WWS 2050	1.2	44.0	12.7	18.9	24.0	0.00	0.00	-64.9	-0.5	-8.4	-73.8	3.24
Trinidad & Tob.	BAU 2018	9.6	5.0	1.2	73.8	20.0	0.00	0.00					
	BAU 2050	15.4	5.0	1.3	73.0	20.7	0.00	0.00					
	WWS 2050	8.5	5.3	3.1	84.2	8.8	0.00	0.00	4.0	-44.8	-4.1	-44.8	5.18
Tunisia	BAU 2018	11.6	24.9	8	28.2	32.9	6.02	0.00					
	BAU 2050	30.0	15.1	6.8	21.8	51.6	4.62	0.00					
	WWS 2050	10.7	17.6	11.6	44.8	21.8	4.10	0.00	-39.4	-17.7	-7.3	-64.4	2.13
Turkey	BAU 2018	144.6	18.9	11.5	35.5	30.0	4.16	0.00					
	BAU 2050	173.7	19.3	12.9	34.2	29.9	3.69	0.00					
	WWS 2050	81.3	17.1	16.2	48.0	15.6	3.21	0.00	-37.4	-8.6	-7.3	-53.2	1.85
Turkmenistan	BAU 2018	28.0	1.8	34	18.6	22.8	1.62	21.06					
	BAU 2050	40.0	2.2	33.5	19.1	27.0	1.35	16.75					
	WWS 2050	9.2	6.2	30.8	26.0	18.4	4.59	15.54	-54.8	-18.8	-3.5	-77.0	3.31

Ukraine	BAU 2018	71.1	31.1	8	39.1	18.3	3.53	0.00					
	BAU 2050	104.2	33.9	9.5	34.7	19.1	2.77	0.00					
	WWS 2050	48.2	25.0	12.1	52.4	10.2	1.86	0.00	-35.5	-10.3	-8.0	-53.7	1.81
United Arab Em.	BAU 2018	108.5	4.6	4.2	43.5	44.6	0.00	3.08					
	BAU 2050	205.6	6.0	4.8	45.7	40.5	0.00	3.02					
	WWS 2050	110.9	8.3	6.8	63.1	17.3	0.00	4.32	-38.3	-2.2	-5.5	-46.0	3.49
United Kingdom	BAU 2018	195.3	25.8	11.6	22.9	37.8	1.01	0.84					
	BAU 2050	232.4	26.6	12.8	24.3	34.6	0.91	0.76					
	WWS 2050	87.9	23.9	18.8	31.3	24.7	0.84	0.38	-44.8	-9.3	-8.1	-62.2	1.58
United States	BAU 2018	2,172.8	16.6	13.3	25.7	41.9	1.29	1.24					
	BAU 2050	2,397.7	14.9	14.9	30.1	37.4	1.38	1.32					
	WWS 2050	959.5	18.7	19.4	37.9	20.0	1.05	2.58	-40.8	-12.2	-7.0	-60.0	1.57
Uruguay	BAU 2018	6.8	16.0	6.3	43.4	29.9	4.45	0.00					
	BAU 2050	10.0	15.4	7.5	39.5	33.6	4.00	0.00					
	WWS 2050	5.1	16.3	10.2	55.6	15.6	2.15	0.00	-38.1	-4.1	-6.4	-48.6	2.16
Uzbekistan	BAU 2018	48.5	30.8	9.9	37.7	15.9	4.51	1.26					
	BAU 2050	73.2	31.1	9.9	35.4	19.0	3.57	1.04					
	WWS 2050	21.2	28.8	11.2	41.9	8.5	9.20	0.70	-41.0	-22.9	-7.0	-71.0	2.02
Venezuela	BAU 2018	49.2	10.0	6.3	52.2	31.3	0.11	0.00					
	BAU 2050	78.7	10.0	6.8	50.7	32.4	0.10	0.00					
	WWS 2050	28.0	15.7	12.6	51.0	20.1	0.21	0.00	-36.8	-22.8	-4.9	-64.5	2.07
Vietnam	BAU 2018	80.8	16.5	4.7	54.6	22.1	2.06	0.00					
	BAU 2050	159.1	15.2	3.9	52.8	26.1	1.97	0.00					
	WWS 2050	98.6	14.7	3	70.9	10.1	1.35	0.00	-30.4	-1.2	-6.4	-38.0	2.08
Yemen	BAU 2018	3.0	27.7	3.5	19.3	44.0	2.08	3.40					
	BAU 2050	4.8	22.4	3.1	21.2	47.6	2.26	3.42					
	WWS 2050	1.7	28.1	3.1	34.1	30.4	1.24	2.92	-51.2	-5.2	-7.0	-63.4	2.49
Zambia	BAU 2018	13.0	60.4	1.2	29.8	7.3	0.52	0.80					
	BAU 2050	21.9	49.3	1.7	37.6	9.8	0.63	0.93					
	WWS 2050	10.2	27.1	2.3	64.1	5.3	0.68	0.51	-44.6	-0.6	-8.0	-53.2	2.76
Zimbabwe	BAU 2018	13.9	73.9	1.2	8.0	10.2	5.54	1.23					
	BAU 2050	21.5	63.2	2.1	10.6	14.8	7.69	1.57					
	WWS 2050	6.3	46.8	5.5	28.4	12.0	6.08	1.19	-60.1	-0.8	-9.7	-70.6	2.53
All Countries	**BAU 2018**	**13,102**	**20.8**	**8.2**	**38.1**	**29.2**	**2.22**	**1.52**					
	BAU 2050	**20,359**	**19.1**	**8**	**37.6**	**31.7**	**2.05**	**1.48**					
	WWS 2050	**8,970**	**17.3**	**10.4**	**52.4**	**16.2**	**1.82**	**1.83**	**-38.0**	**-11.3**	**-6.6**	**-55.9**	**1.87**

2018 BAU values are from IEA (2022). These values are projected to 2050 using U.S. Energy Information Administration (EIA, 2016) "reference scenario" projections, 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 load includes, among other loads, 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, footnote), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen (Table S6, footnote). Multiply annual-average load (GW) by 8,760 hours per year to obtain annual energy per year (GWh/y) consumed.

Table S5. (a) 2021 pig iron production, (b) 2021 directly-reduced iron production, (c) 2021 total iron production, (d) 2021 and assumed 2050 hydrogen needed to reduce iron oxide to pure iron via hydrogen reduction, (e) 2050 WWS annual-average power needed for electrolysis to produce such hydrogen and for heat to purify iron from iron oxide by hydrogen reduction, (f) 2050 BAU annual-average power needed for heat to purify iron from iron oxide in a blast furnace, and (g) 2050 difference between WWS and BAU annual-average end-use power needed to produce steel. Hydrogen production for iron purification in 2050 and 2021 is assumed to be the same because steel recycling is assumed to increase, making up the growth in overall steel production between 2021 and 2050 (Section 2.A. of the main text).

Region or country	(a) 2021 Pig iron produced (million metric tonnes-Fe/y)	(b) 2021 Directly-reduced iron produced (million metric tonnes-Fe/y)	(c) 2021 Total iron produced (million metric tonnes-Fe/y) (=a+b)	(d) 2021 and 2050 Tg-H$_2$/y produced to purify iron by hydrogen direct reduction	(e) 2050 WWS power (GW) needed for electrolysis and compression to produce H$_2$ by electrolysis and for heat to purify iron by H$_2$ reduction	(f) 2050 BAU annual-average power (GW) needed for heat to purify iron from iron oxide in a blast furnace	(g) 2050 WWS minus BAU annual-average power (GW) needed to produce steel (=e-f)
Africa	**3.38**	**9.6**	**12.98**	**0.70**	**4.57**	**5.55**	**-0.98**
Algeria	0.30	3.1	3.40	0.18	1.20	1.46	-0.26
Angola	0	0	0	0	0	0	0
Benin	0	0	0	0	0	0	0
Botswana	0	0	0	0	0	0	0
Cameroon	0	0	0	0	0	0	0
Congo	0	0	0	0	0	0	0
Congo, DR	0	0	0	0	0	0	0
Côte d'Ivoire	0	0	0	0	0	0	0
Egypt	0.18	5.4	5.58	0.30	1.96	2.39	-0.42
Equator. Guinea	0	0	0	0	0	0	0
Eritrea	0	0	0	0	0	0	0
Ethiopia	0	0	0	0	0	0	0
Gabon	0	0	0	0	0	0	0
Ghana	0	0	0	0	0	0	0
Kenya	0	0	0	0	0	0	0
Libya	0	0.9	0.9	0.05	0.32	0.39	-0.07
Morocco	0	0	0	0	0	0	0
Mozambique	0	0	0	0	0	0	0
Namibia	0	0	0	0	0	0	0
Niger	0	0	0	0	0	0	0
Nigeria	0	0	0	0	0	0	0
Senegal	0	0	0	0	0	0	0
South Africa	2.90	0.2	3.10	0.17	1.09	1.33	-0.24
South Sudan	0	0	0	0	0	0	0
Sudan	0	0	0	0	0	0	0
Tanzania	0	0	0	0	0	0	0
Togo	0	0	0	0	0	0	0
Tunisia	0	0	0	0	0	0	0
Zambia	0	0	0	0	0	0	0
Zimbabwe	0	0	0	0	0	0	0
Australia	**3.8**	**0**	**3.8**	**0.206**	**1.338**	**1.627**	**-0.288**
Canada	**6.2**	**1.6**	**7.8**	**0.422**	**2.747**	**3.339**	**-0.592**
Central America	**2.7**	**5.8**	**8.5**	**0.460**	**2.994**	**3.639**	**-0.645**
Costa Rica	0	0	0	0	0	0	0
El Salvador	0	0	0	0	0	0	0
Guatemala	0	0	0	0	0	0	0
Honduras	0	0	0	0	0	0	0

Mexico	2.7	5.8	8.	0.460	2.994	3.639	-0.645
Nicaragua	0	0	0	0	0	0	0
Panama	0	0	0	0	0	0	0
Central Asia	**3.1**	**0**	**3.1**	**0.168**	**1.092**	**1.327**	**-0.235**
Kazakhstan	3.1	0	3.1	0.168	1.092	1.327	-0.235
Kyrgyz Republic	0	0	0	0	0	0	0
Pakistan	0	0	0	0	0	0	0
Tajikistan	0	0	0	0	0	0	0
Turkmenistan	0	0	0	0	0	0	0
Uzbekistan	0	0	0	0	0	0	0
China Region	**868.85**	**0**	**868.8**	**47.048**	**306.030**	**371.939**	**-65.909**
China	868.6	0	868.6	47.035	305.942	371.832	-65.890
Hong Kong	0	0	0	0	0	0	0
Korea, DPR	0.25	0	0.25	0.014	0.088	0.107	-0.019
Mongolia	0	0	0	0	0	0	0
Cuba	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Europe	**107.026**	**0.6**	**107.626**	**5.828**	**37.909**	**46.073**	**-8.164**
Albania	0	0	0	0	0	0	0
Austria	6.1	0	6.1	0.330	2.149	2.611	-0.463
Belarus	0	0	0	0	0	0	0
Belgium	4.2	0	4.2	0.227	1.479	1.798	-0.319
Bosnia-Herzeg.	0.739	0	0.739	0.040	0.260	0.316	-0.056
Bulgaria	0	0	0	0	0	0	0
Croatia	0	0	0	0	0	0	0
Cyprus	0	0	0	0	0	0	0
Czech Rep.	3.9	0	3.9	0.211	1.374	1.670	-0.296
Denmark	0	0	0	0	0	0	0
Estonia	0	0	0	0	0	0	0
Finland	2.5	0	2.5	0.135	0.881	1.070	-0.190
France	9.5	0	9.5	0.514	3.346	4.067	-0.721
Germany	25.7	0.5	26.2	1.419	9.228	11.216	-1.987
Gibraltar	0	0	0	0	0	0	0
Greece	0	0	0	0	0	0	0
Hungary	0.6	0	0.6	0.032	0.211	0.257	-0.046
Ireland	0	0	0	0	0	0	0
Italy	3.9	0	3.9	0.211	1.374	1.670	-0.296
Kosovo	0	0	0	0	0	0	0
Latvia	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0
Luxembourg	0	0	0	0	0	0	0
Macedonia	0	0	0	0	0	0	0
Malta	0	0	0	0	0	0	0
Moldova	0	0	0	0	0	0	0
Montenegro	0	0	0	0	0	0	0
Netherlands	5.9	0	5.9	0.319	2.078	2.526	-0.448
Norway	0.08	0	0.08	0.004	0.028	0.034	-0.006
Poland	3.6	0	3.6	0.195	1.268	1.541	-0.273
Portugal	0	0	0	0	0	0	0
Romania	2.1	0	2.1	0.114	0.740	0.899	-0.159
Serbia	1.107	0	1.107	0.060	0.390	0.474	-0.084
Slovakia	3.1	0	3.1	0.168	1.092	1.327	-0.235
Slovenia	0	0	0	0	0	0	0
Spain	4.0	0	4.0	0.217	1.409	1.712	-0.303
Sweden	3.0	0.1	3.1	0.168	1.092	1.327	-0.235
Switzerland	0	0	0	0	0	0	0
Ukraine	21.2	0	21.2	1.148	7.467	9.075	-1.608
United Kingdom	5.8	0	5.8	0.314	2.043	2.483	-0.440
Haiti Region	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Dominican Rep.	0	0	0	0	0	0	0
Haiti	0	0	0	0	0	0	0
Iceland	**0**	**0**	**0**	**0**	**0**	**0**	**0**
India Region	**77.6**	**39.0**	**116.6**	**6.314**	**41.069**	**49.914**	**-8.845**

Bangladesh	0	0	0	0	0	0	0
India	77.6	39.0	116.6	6.314	41.069	49.914	-8.845
Nepal	0	0	0	0	0	0	0
Sri Lanka	0	0	0	0	0	0	0
Israel	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Jamaica	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Japan	**70.3**	**0**	**70.3**	**3.807**	**24.761**	**30.094**	**-5.333**
Mauritius	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Mideast	**13.1**	**43.5**	**56.6**	**3.065**	**19.936**	**24.229**	**-4.294**
Armenia	0	0	0	0	0	0	0
Azerbaijan	0	0	0	0	0	0	0
Bahrain	0	1.4	1.4	0.076	0.493	0.599	-0.106
Iran	2.7	29.8	32.5	1.760	11.447	13.913	-2.465
Iraq	0	0	0	0	0	0	0
Jordan	0	0	0	0	0	0	0
Kuwait	0	0	0	0	0	0	0
Lebanon	0	0	0	0	0	0	0
Oman	0	1.7	1.7	0.092	0.599	0.728	-0.129
Qatar	0	0.8	0.8	0.043	0.282	0.342	-0.061
Saudi Arabia	0	6.1	6.1	0.330	2.149	2.611	-0.463
Syria	0	0	0	0	0	0	0
Turkey	10.4	0	10.4	0.563	3.663	4.452	-0.789
UAE	0	3.7	3.7	0.200	1.303	1.584	-0.281
Yemen	0	0	0	0	0	0	0
New Zealand	**0.7**	**0**	**0.7**	**0.038**	**0.247**	**0.300**	**-0.053**
Philippines	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Russia Region	**53.6**	**7.8**	**61.4**	**3.325**	**21.627**	**26.284**	**-4.658**
Georgia	0	0	0	0	0	0	0
Russia	53.	7.8	61.400	3.325	21.627	26.284	-4.658
South America	**31.499**	**3.2**	**34.699**	**1.879**	**12.222**	**14.854**	**-2.632**
Argentina	2.1	1.4	3.5	0.190	1.233	1.498	-0.266
Bolivia	0	0	0	0	0	0	0
Brazil	28.5	0	28.5	1.543	10.038	12.200	-2.162
Chile	0.7	0	0.7	0.038	0.247	0.300	-0.053
Colombia	0.164	0	0.164	0.009	0.058	0.070	-0.012
Curacao	0	0	0	0	0	0	0
Ecuador	0	0	0	0	0	0	0
Paraguay	0.035	0	0.035	0.002	0.012	0.015	-0.003
Peru	0	0	0	0	0	0	0
Suriname	0	0	0	0	0	0	0
Trinidad/Tobago	0	1.5	1.5	0.081	0.528	0.642	-0.114
Uruguay	0	0	0	0	0	0	0
Venezuela	0	0.3	0.3	0.016	0.106	0.128	-0.023
Southeast Asia	**12.7**	**0.8**	**13.5**	**0.731**	**4.755**	**5.779**	**-1.024**
Brunei	0	0	0	0	0	0	0
Cambodia	0	0	0	0	0	0	0
Indonesia	2.9	0.1	3.0	0.162	1.057	1.284	-0.228
Lao PDR	0	0	0	0	0	0	0
Malaysia	0	0.7	0.7	0.038	0.247	0.300	-0.053
Myanmar	0	0	0	0	0	0	0
Singapore	0	0	0	0	0	0	0
Thailand	0	0	0	0	0	0	0
Vietnam	9.800	0	9.800	0.531	3.452	4.195	-0.743
South Korea	**46.4**	**0**	**46.4**	**2.513**	**16.343**	**19.863**	**-3.520**
Taiwan	**15.2**	**0**	**15.2**	**0.823**	**5.354**	**6.507**	**-1.153**
United States	**22.2**	**3.5**	**25.7**	**1.392**	**9.052**	**11.002**	**-1.950**
All regions	**1,338**	**115.4**	**1,454**	**78.72**	**512.05**	**622.32**	**-110.28**

Pig iron and directly reduced iron data are from the World Steel Association (2022). Pig iron is crude iron from a blast furnace, produced by $Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(l) + 3CO_2(g)$. $Fe_2O_3(s)$ is mixed with coke (coal baked in an airless furnace to burn off impurities) in a blast furnace at 1,400-1,500 °C to melt out the Fe (pig iron), producing also N_2 and CO_2. The energy to produce pig iron in a blast furnace is 13.5 GJ/tonne-iron = 3.75 kWh/kg-Fe (Marteslaro, 2016).

Directly-reduced iron (sponge iron) is pure iron produced by the reaction $Fe_2O_3(s) + 3CO/3H_2 \rightarrow 2Fe(l) + 3CO_2/3H_2O$ at 800-1,200 °C in a shaft furnace or rotary kiln, where the CO/H_2 mixture is syngas. No blast furnace is needed. Syngas is produced from the first step in steam reforming of natural gas: $CH_4 + H_2O \rightarrow CO + 3H_2$. Hydrogen direct reduction involves the reaction $Fe_2O_3(s) + 3H_2(g) \rightarrow 2Fe(l) + 3H_2O(g)$ at 800 °C in a shaft furnace (Vogl et al., 2018). The ratio of the mass of H_2 consumed to pure iron (Fe) produced with direct hydrogen reduction = 0.0541. This process is similar to the directly-reduced iron process but with pure hydrogen replacing syngas. The pure hydrogen can be produced by electrolysis, where the electricity comes from WWS (green hydrogen), whereas syngas is produced by steam reforming of natural gas (gray hydrogen). Once pure iron is obtained in either case, steel is produced by combining the iron with trace amounts of carbon in either a basic oxygen furnace (11.0 GJ/tonne-pig iron = 3.06 kWh/kg-Fe) or in an electric arc furnace (2.0 GJ/tonne-pig iron = 0.63 kWh/kg-Fe) (Martelaro, 2016). Steel is made of 98-99% iron. Most of rest is carbon.

Whereas the energy required to produce pure iron in a blast furnace is 3.75 kWh/kg-Fe, that to produce it from the hydrogen reduction method is 3.09 kWh/kg-Fe (2.55 kWh/kg-Fe for the electrolyzer plus compressor and 0.54 kWh/kg-Fe for ore heating) (Vogl et al., 2018). As such, the hydrogen reduction method reduces the energy needed to produce pure iron. Energy needs would be minimized further by using an electric arc furnace instead of a basic oxygen furnace to produce steel from pure iron during steelmaking. However, this study assumes simplistically and conservatively that steelmaking with an electric arc furnace uses the same amount of energy as steelmaking with a blast furnace.

Table S6. 2050 difference in annual-average power required by country and region when hydrogen (H_2) for ammonia (NH_3) manufacturing is produced by electrolysis using WWS electricity (green hydrogen) instead of by steam methane reforming (SMR) powered and fed by natural gas. In both cases, hydrogen produces ammonia via the Haber-Bosch process. The 2050 quantity of hydrogen produced is assumed to be the same as that in 2020.

Region or country	(a) 2020 NH_3 production (kilotonnes -N/y)	(b) 2020 and 2050 Tg-H_2/y produced to make NH_3	(c) 2050 WWS annual-average power (GW) needed to produce H_2 for NH_3 by electrolysis	(d) 2050 BAU annual-average power (GW) needed to produce NH_3 by SMR	(e) 2050 WWS minus BAU annual-average power (GW) needed to produce NH_3 = c-d
Africa	**7,589**	**1.638**	**8.810**	**10.851**	**-2.041**
Algeria	2,200	0.475	2.554	3.145	-0.592
Angola	0	0	0	0	0
Benin	0	0	0	0	0
Botswana	0	0	0	0	0
Cameroon	0	0	0	0	0
Congo	0	0	0	0	0
Congo, DR	0	0	0	0	0
Côte d'Ivoire	0	0	0	0	0
Egypt	4,200	0.907	4.875	6.005	-1.130
Equator. Guinea	0	0	0	0	0
Eritrea	0	0	0	0	0
Ethiopia	0	0	0	0	0
Gabon	0	0	0	0	0
Ghana	0	0	0	0	0
Kenya	0	0	0	0	0
Libya	25	0.005	0.029	0.036	-0.007
Morocco	0	0	0	0	0
Mozambique	0	0	0	0	0
Namibia	0	0	0	0	0
Niger	0	0	0	0	0
Nigeria	710	0.153	0.824	1.015	-0.191
Senegal	0	0	0	0	0
South Africa	450	0.097	0.522	0.643	-0.121
South Sudan	0	0	0	0	0
Sudan	0	0	0	0	0
Tanzania	0	0	0	0	0
Togo	0	0	0	0	0
Tunisia	0	0	0	0	0
Zambia	0	0	0	0	0
Zimbabwe	4	0.001	0.005	0.006	-0.001
Australia	**1,600**	**0.345**	**1.857**	**2.288**	**-0.430**
Canada	**3,895**	**0.841**	**4.521**	**5.569**	**-1.048**
Central America	**112**	**0.024**	**0.130**	**0.160**	**-0.030**
Costa Rica	0	0	0	0	0
El Salvador	0	0	0	0	0
Guatemala	0	0	0	0	0
Honduras	0	0	0	0	0
Mexico	112	0.024	0.130	0.160	-0.030
Nicaragua	0	0	0	0	0
Panama	0	0	0	0	0
Central Asia	**5,240**	**1.131**	**6.083**	**7.492**	**-1.409**
Kazakhstan	180	0.039	0.209	0.257	-0.048
Kyrgyz Republic	0	0	0	0	0
Pakistan	3,300	0.712	3.831	4.718	-0.888
Tajikistan	0	0	0	0	0
Turkmenistan	660	0.142	0.766	0.944	-0.178

Uzbekistan	1,100	0.237	1.277	1.573	-0.296
China Region	**39,000**	**8.420**	**45.27**	**55.761**	**-10.489**
China	39,000	8.420	45.27	55.761	-10.489
Hong Kong	0	0	0	0	0
Korea, DPR	0	0	0	0	0
Mongolia	0	0	0	0	0
Cuba	**0**	**0**	**0**	**0**	**0**
Europe	**17,079**	**3.687**	**19.83**	**24.419**	**-4.593**
Albania	0	0	0	0	0
Austria	420	0.091	0.488	0.601	-0.113
Belarus	763	0.165	0.886	1.091	-0.205
Belgium	850	0.184	0.987	1.215	-0.229
Bosnia-Herzeg.	0	0	0	0	0
Bulgaria	230	0.050	0.267	0.329	-0.062
Croatia	370	0.080	0.430	0.529	-0.100
Cyprus	0	0	0	0	0
Czech Rep.	93	0.020	0.108	0.133	-0.025
Denmark	0	0	0	0	0
Estonia	19	0.004	0.022	0.027	-0.005
Finland	78	0.017	0.091	0.112	-0.021
France	822	0.177	0.954	1.175	-0.221
Germany	2,330	0.503	2.705	3.331	-0.627
Gibraltar	0	0	0	0	0
Greece	100	0.022	0.116	0.143	-0.027
Hungary	430	0.093	0.499	0.615	-0.116
Ireland	0	0	0	0	0
Italy	620	0.134	0.720	0.886	-0.167
Kosovo	0	0	0	0	0
Latvia	0	0	0	0	0
Lithuania	843	0.182	0.979	1.205	-0.227
Luxembourg	0	0	0	0	0
Macedonia	0	0	0	0	0
Malta	0	0	0	0	0
Moldova	0	0	0	0	0
Montenegro	0	0	0	0	0
Netherlands	2,100	0.453	2.438	3.003	-0.565
Norway	330	0.071	0.383	0.472	-0.089
Poland	2,262	0.488	2.626	3.234	-0.608
Portugal	0	0	0	0	0
Romania	470	0.101	0.546	0.672	-0.126
Serbia	0	0	0	0	0
Slovakia	355	0.077	0.412	0.508	-0.095
Slovenia	0	0	0	0	0
Spain	420	0.091	0.488	0.601	-0.113
Sweden	0	0	0	0	0
Switzerland	10	0.002	0.012	0.014	-0.003
Ukraine	2,304	0.497	2.675	3.294	-0.620
United Kingdom	860	0.186	0.998	1.230	-0.231
Haiti Region	**0**	**0**	**0**	**0**	**0**
Dominican Rep.	0	0	0	0	0
Haiti	0	0	0	0	0
Iceland	**0**	**0**	**0**	**0**	**0**
India Region	**13,040**	**2.815**	**15.14**	**18.644**	**-3.507**
Bangladesh	840	0.181	0.975	1.201	-0.226
India	12,200	2.634	14.16	17.443	-3.281
Nepal	0	0	0	0	0
Sri Lanka	0	0	0	0	0
Israel	**0**	**0**	**0**	**0**	**0**
Jamaica	**0**	**0**	**0**	**0**	**0**
Japan	**643**	**0.139**	**0.746**	**0.919**	**-0.173**
Mauritius	**0**	**0**	**0**	**0**	**0**
Mideast	**14,721**	**3.178**	**17.09**	**21.048**	**-3.959**

Armenia	0	0	0	0	0
Azerbaijan	0	0	0	0	0
Bahrain	381	0.082	0.442	0.545	-0.102
Iran	3,600	0.777	4.179	5.147	-0.968
Iraq	90	0.019	0.104	0.129	-0.024
Jordan	0	0	0	0	0
Kuwait	0	0	0	0	0
Lebanon	0	0	0	0	0
Oman	1,730	0.374	2.008	2.474	-0.465
Qatar	3,300	0.712	3.831	4.718	-0.888
Saudi Arabia	4,300	0.928	4.992	6.148	-1.156
Syria	20	0.004	0.023	0.029	-0.005
Turkey	370	0.080	0.430	0.529	-0.100
UAE	930	0.201	1.080	1.330	-0.250
Yemen	0	0	0	0	0
New Zealand	**125**	**0.027**	**0.145**	**0.179**	**-0.034**
Philippines	**0**	**0**	**0**	**0**	**0**
Russia Region	**16,326**	**3.525**	**18.95**	**23.342**	**-4.391**
Georgia	200	0.043	0.232	0.286	-0.054
Russia	16,126	3.482	18.72	23.057	-4.337
South America	**5,126**	**1.107**	**5.950**	**7.329**	**-1.379**
Argentina	640	0.138	0.743	0.915	-0.172
Bolivia	0	0	0	0	0
Brazil	120	0.026	0.139	0.172	-0.032
Chile	0	0	0	0	0
Colombia	0	0	0	0	0
Curacao	0	0	0	0	0
Ecuador	0	0	0	0	0
Paraguay	0	0	0	0	0
Peru	11	0.002	0.013	0.016	-0.003
Suriname	0	0	0	0	0
Trinidad/Tobago	4,165	0.899	4.835	5.955	-1.120
Uruguay	0	0	0	0	0
Venezuela	190	0.041	0.221	0.272	-0.051
Southeast Asia	**8,350**	**1.803**	**9.693**	**11.939**	**-2.246**
Brunei	0	0	0	0	0
Cambodia	0	0	0	0	0
Indonesia	5,900	1.274	6.849	8.436	-1.587
Lao PDR	0	0	0	0	0
Malaysia	1,300	0.281	1.509	1.859	-0.350
Myanmar	0	0	0	0	0
Singapore	0	0	0	0	0
Thailand	0	0	0	0	0
Vietnam	1,150	0.248	1.335	1.644	-0.309
South Korea	**0**	**0**	**0**	**0**	**0**
Taiwan	**0**	**0**	**0**	**0**	**0**
United States	**14,000**	**3.023**	**16.25**	**20.017**	**-3.765**
All regions	**146,846**	**31.70**	**170.5**	**209.96**	**-39.49**

(a) From USGS (2021).

(b) Equal values from column (a) multiplied by 0.2159 Tg-H_2/Tg-N, assuming the Haber-Bosch reaction $N_2 + 3H_2 \rightarrow 2NH_3$ for producing ammonia, divided by 1,000 kilotonnes per Tg.

(c) Equal values from column (b) multiplied by 47.1 TWh/Tg-H_2 and by 1,000 GW/TW and divided by 8,760 hours per year. The 47.1 TWh/Tg-H_2 is the rectifier plus electrolyzer energy needed to make hydrogen (41.46 kWh/kg-H_2) and to compress it (5.64 kWh/kg-H_2). The 2035 electrolyzer and rectifier efficiency against the higher heating value of hydrogen (39.39 kWh/kg-H_2=141.8 MJ/kg-H_2) is assumed to be 95%: ~96% for electrolysis (Hodges et al., 2022) and ~99% for the rectifier (ABB, 2021). The compressor energy needed is from Jacobson et al. (2005).

(d) Values equal those from column (b) multiplied by 58.01 TWh/Tg-H_2 of energy needed for the SMR process and by 1,000 GW/TW and divided by 8,760 hours per year. The energy needed for SMR is calculated as 26.54 g-CH_4/MJ multiplied by the higher heating value of hydrogen of 141.8 MJ/kg-H_2, multiplied by the higher heating value of methane of 55.5 MJ/kg-CH_4 and divided by 3.6 MJ/kWh and by 1000 g/kg. The 26.54 g-CH_4/MJ is the sum of 14.04 g-CH_4/MJ used for feedstock conversion of CH_4 to H_2, 11.6 g-CH_4/MJ used for heat and high pressure, and 0.9 g-CH_4/MJ lost through 3.5% natural gas leaks and venting (Howarth and Jacobson, 2021).

(e) Values are the difference between columns (c) and (d).

Table S7. 2018 (a) annual-average power demand for oil used for final consumption for all purposes, (b) demand for oil for final consumption used for transport, (c) oil for final consumption used for transport that is converted to battery-electric transport (the rest is converted to hydrogen fuel cell-electric transport), (d) the fraction of oil for final consumption used for transport that is converted to battery-electric transport, (e) the fraction of the total transport load in 2050 used to produce and compress hydrogen, (f) the 2050 total transport annual-average load, (g) the 2050 transport sector annual-average load used to produce and compress hydrogen for fuel cell-electric vehicles, and (h) the mass of hydrogen produced per year in 2050 for hydrogen fuel cell-electric vehicles.

Region or country	(a) 2018 BAU total oil for final consumption (GW)	(b) 2018 BAU estimated oil for final consumption used in transport sector (GW)	(c) 2018 BAU estimated oil for final consumption used in transport sector converted to battery-electric transport (GW)	(d) 2018 fraction of BAU oil for final consumption used in transport sector converted to battery-electric transport (rest is converted to HFC-electric transport) (=c/b)	(e) 2050 fraction of WWS total transport sector load used to produce and compress H_2	(f) 2050 WWS total transport sector annual-average load (GW)	(g) 2050 WWS transport sector annual-average load used to produce and compress H_2 for HFC-electric transport (the rest is for battery-electric transport) =e x f	(h) 2050 Tg-H_2/y produced for HFC vehicles
Africa	**197.59**	**163.84**	**122.66**	**0.749**	**0.360**	**94.51**	**34.05**	**6.333**
Algeria	22.71	19.54	13.76	0.704	0.403	12.68	5.11	0.951
Angola	4.81	4.03	2.74	0.678	0.474	2.24	1.06	0.198
Benin	2.97	2.69	2.28	0.848	0.255	1.53	0.39	0.073
Botswana	1.27	1.13	0.91	0.804	0.316	0.62	0.20	0.037
Cameroon	1.80	1.42	1.07	0.755	0.382	0.69	0.26	0.049
Congo	0.67	0.57	0.42	0.738	0.404	0.34	0.14	0.026
Congo, DR	0.89	0.80	0.61	0.763	0.370	0.59	0.22	0.041
Côte d'Ivoire	2.66	2.35	1.69	0.721	0.424	1.15	0.49	0.091
Egypt	36.05	30.99	22.14	0.714	0.415	14.30	5.94	1.104
Equator. Guinea	0.00	0.00	0.00	0.740	0.401	0.26	0.11	0.020
Eritrea	0.15	0.11	0.07	0.636	0.521	0.07	0.03	0.006
Ethiopia	5.38	4.15	2.69	0.648	0.508	2.34	1.19	0.221
Gabon	0.40	0.33	0.23	0.700	0.441	0.18	0.08	0.015
Ghana	4.88	4.36	3.27	0.751	0.386	2.08	0.80	0.150
Kenya	5.68	4.57	3.43	0.749	0.389	2.77	1.08	0.200
Libya	8.40	7.69	6.60	0.859	0.239	3.97	0.95	0.176
Morocco	15.71	11.21	6.75	0.602	0.546	5.56	3.04	0.566
Mozambique	1.99	1.49	1.03	0.690	0.459	0.89	0.41	0.076
Namibia	1.55	1.33	0.95	0.713	0.434	0.55	0.24	0.044
Niger	0.54	0.50	0.40	0.801	0.321	0.35	0.11	0.021
Nigeria	23.94	21.65	19.86	0.917	0.146	14.94	2.19	0.407
Senegal	1.30	1.17	0.82	0.700	0.449	0.77	0.34	0.064
South Africa	35.36	26.94	20.36	0.756	0.361	17.29	6.24	1.161
South Sudan	0.37	0.32	0.21	0.662	0.492	0.19	0.10	0.018
Sudan	5.83	4.82	3.42	0.709	0.439	2.82	1.23	0.230
Tanzania	2.46	2.17	1.68	0.774	0.357	1.42	0.51	0.094
Togo	0.52	0.45	0.35	0.778	0.351	0.28	0.10	0.018
Tunisia	5.96	4.30	2.91	0.677	0.422	2.34	0.99	0.183
Zambia	1.60	1.31	0.93	0.709	0.431	0.54	0.23	0.043
Zimbabwe	1.72	1.44	1.09	0.753	0.372	0.75	0.28	0.052
Australia	**57.17**	**46.94**	**34.84**	**0.742**	**0.367**	**17.71**	**6.51**	**1.210**
Canada	**120.34**	**97.92**	**76.37**	**0.780**	**0.238**	**32.05**	**7.63**	**1.419**
Central America	**104.74**	**89.51**	**73.23**	**0.818**	**0.299**	**35.55**	**10.63**	**1.978**

Costa Rica	3.32	2.76	2.13	0.772	0.360	1.13	0.41	0.076
El Salvador	0.00	0.00	0.00	0.740	0.401	0.72	0.29	0.053
Guatemala	4.95	4.24	3.36	0.792	0.333	1.72	0.57	0.107
Honduras	2.61	2.18	1.64	0.753	0.385	0.78	0.30	0.056
Mexico	89.25	76.30	63.04	0.826	0.279	27.28	7.62	1.416
Nicaragua	1.46	1.21	0.89	0.738	0.403	0.40	0.16	0.030
Panama	3.15	2.82	2.16	0.766	0.367	3.51	1.29	0.240
Central Asia	**55.12**	**47.96**	**36.80**	**0.767**	**0.327**	**21.10**	**6.89**	**1.282**
Kazakhstan	15.40	13.48	10.39	0.771	0.304	3.37	1.02	0.190
Kyrgyz Republic	2.65	2.16	1.68	0.781	0.337	0.23	0.08	0.014
Pakistan	23.16	20.68	16.32	0.789	0.329	13.80	4.53	0.843
Tajikistan	1.26	1.04	0.73	0.703	0.442	0.21	0.09	0.017
Turkmenistan	8.10	6.88	4.86	0.706	0.390	1.69	0.66	0.123
Uzbekistan	4.56	3.72	2.82	0.756	0.282	1.81	0.51	0.095
China Region	**705.99**	**463.29**	**343.75**	**0.742**	**0.272**	**259.78**	**70.60**	**13.130**
China	699.08	457.33	339.65	0.743	0.256	242.60	62.14	11.557
Hong Kong	4.56	3.89	2.56	0.658	0.498	16.28	8.10	1.507
Korea, DPR	0.76	0.65	0.48	0.734	0.408	0.35	0.14	0.026
Mongolia	1.58	1.42	1.06	0.751	0.385	0.55	0.21	0.040
Cuba	**4.52**	**3.54**	**2.17**	**0.611**	**0.469**	**0.77**	**0.36**	**0.067**
Europe	**656.84**	**488.73**	**334.35**	**0.684**	**0.365**	**199.98**	**73.07**	**13.590**
Albania	1.42	1.13	0.73	0.650	0.454	0.41	0.19	0.034
Austria	14.35	10.78	7.18	0.666	0.305	5.05	1.54	0.287
Belarus	7.98	5.18	3.69	0.712	0.380	1.98	0.75	0.140
Belgium	25.46	16.33	10.61	0.650	0.443	7.97	3.53	0.657
Bosnia-Herzeg.	1.99	1.62	1.05	0.651	0.497	0.61	0.30	0.056
Bulgaria	5.02	3.69	2.45	0.663	0.454	1.73	0.78	0.146
Croatia	3.82	2.95	2.01	0.681	0.448	1.13	0.51	0.094
Cyprus	1.29	1.03	0.79	0.766	0.365	0.56	0.20	0.038
Czech Rep.	11.88	7.88	5.47	0.694	0.317	3.30	1.05	0.194
Denmark	7.10	5.72	4.05	0.707	0.389	2.28	0.89	0.165
Estonia	1.37	1.14	0.81	0.710	0.406	0.44	0.18	0.033
Finland	9.65	7.86	5.38	0.685	0.357	2.26	0.81	0.151
France	86.07	64.72	42.13	0.651	0.373	23.88	8.90	1.655
Germany	115.28	86.84	61.46	0.708	0.333	29.27	9.75	1.813
Gibraltar	0.00	0.00	0.00	0.740	0.401	1.43	0.57	0.107
Greece	11.17	9.01	6.50	0.721	0.404	3.25	1.32	0.245
Hungary	9.63	6.39	4.50	0.705	0.312	2.34	0.73	0.136
Ireland	8.04	5.44	3.62	0.665	0.468	1.91	0.90	0.167
Italy	59.60	45.09	30.61	0.679	0.321	20.54	6.60	1.227
Kosovo	0.00	0.00	0.00	0.740	0.401	0.20	0.08	0.015
Latvia	1.88	1.53	1.00	0.656	0.475	0.64	0.30	0.056
Lithuania	3.10	2.39	1.53	0.642	0.495	1.16	0.57	0.107
Luxembourg	3.01	2.56	1.68	0.655	0.450	1.04	0.47	0.087
Macedonia	1.25	1.00	0.64	0.644	0.510	0.35	0.18	0.033
Malta	0.38	0.32	0.23	0.721	0.422	1.19	0.50	0.094
Moldova	1.23	0.97	0.67	0.686	0.439	0.36	0.16	0.030
Montenegro	0.48	0.36	0.23	0.644	0.499	0.14	0.07	0.013
Netherlands	31.54	16.02	11.79	0.736	0.354	9.84	3.48	0.648
Norway	9.87	7.68	5.01	0.653	0.357	2.45	0.87	0.162
Poland	36.78	28.11	19.02	0.676	0.372	10.08	3.75	0.698
Portugal	10.15	7.90	5.21	0.660	0.443	3.09	1.37	0.255
Romania	11.20	8.24	5.59	0.678	0.432	3.16	1.37	0.254
Serbia	4.20	2.85	1.90	0.668	0.460	1.13	0.52	0.097
Slovakia	0.00	0.00	0.00	0.740	0.275	1.25	0.34	0.064
Slovenia	3.16	2.55	1.73	0.677	0.402	0.90	0.36	0.067
Spain	57.43	44.93	29.01	0.646	0.436	17.77	7.75	1.441
Sweden	11.52	9.77	6.92	0.708	0.274	4.58	1.26	0.233
Switzerland	3.96	3.29	3.17	0.963	0.038	3.65	0.14	0.026
Ukraine	13.47	10.58	7.30	0.690	0.344	4.90	1.69	0.314
United Kingdom	71.10	54.86	38.66	0.705	0.385	21.72	8.35	1.554
Haiti Region	**6.39**	**4.69**	**3.50**	**0.745**	**0.389**	**1.88**	**0.73**	**0.136**

Dominican Rep.	5.38	3.90	2.91	0.747	0.386	1.61	0.62	0.116
Haiti	1.01	0.80	0.59	0.736	0.406	0.27	0.11	0.020
Iceland	**0.80**	**0.64**	**0.44**	**0.688**	**0.392**	**0.35**	**0.14**	**0.025**
India Region	**285.26**	**185.21**	**126.50**	**0.683**	**0.432**	**130.83**	**56.55**	**10.517**
Bangladesh	6.32	5.08	3.26	0.642	0.473	3.21	1.52	0.282
India	270.42	172.89	117.99	0.682	0.432	122.90	53.09	9.874
Nepal	3.27	2.77	1.88	0.677	0.475	1.48	0.70	0.131
Sri Lanka	5.25	4.47	3.37	0.755	0.382	3.26	1.24	0.231
Israel	**11.31**	**7.75**	**6.18**	**0.797**	**0.326**	**2.44**	**0.80**	**0.148**
Jamaica	**2.28**	**2.10**	**1.43**	**0.683**	**0.459**	**0.73**	**0.33**	**0.062**
Japan	**186.61**	**114.36**	**87.01**	**0.761**	**0.292**	**29.25**	**8.53**	**1.586**
Mauritius	**0.71**	**0.63**	**0.47**	**0.742**	**0.399**	**0.93**	**0.37**	**0.069**
Mideast	**347.04**	**286.28**	**211.88**	**0.740**	**0.380**	**111.45**	**42.41**	**7.887**
Armenia	0.41	0.33	0.27	0.816	0.226	0.20	0.05	0.008
Azerbaijan	5.76	3.96	2.99	0.756	0.362	1.32	0.48	0.089
Bahrain	2.42	1.62	1.40	0.866	0.228	0.94	0.22	0.040
Iran	88.81	73.32	55.84	0.762	0.358	24.66	8.83	1.643
Iraq	21.37	17.47	13.56	0.776	0.354	6.55	2.32	0.432
Jordan	5.52	4.75	3.65	0.769	0.363	1.85	0.67	0.125
Kuwait	11.84	10.12	7.90	0.781	0.348	3.88	1.35	0.251
Lebanon	4.09	3.74	3.26	0.871	0.220	1.51	0.33	0.062
Oman	10.04	6.73	5.46	0.811	0.307	3.57	1.09	0.204
Qatar	8.43	6.99	5.14	0.735	0.407	3.84	1.57	0.291
Saudi Arabia	106.05	90.98	66.22	0.728	0.416	29.23	12.15	2.260
Syria	5.83	4.90	3.42	0.697	0.453	1.43	0.65	0.120
Turkey	49.39	36.14	22.65	0.627	0.495	12.69	6.28	1.168
UAE	24.78	23.23	18.56	0.799	0.324	19.24	6.24	1.160
Yemen	2.30	1.99	1.56	0.784	0.345	0.53	0.18	0.034
New Zealand	**8.60**	**7.43**	**5.65**	**0.760**	**0.374**	**2.94**	**1.10**	**0.204**
Philippines	**23.53**	**19.86**	**14.00**	**0.705**	**0.428**	**10.66**	**4.56**	**0.848**
Russia Region	**162.15**	**114.37**	**87.16**	**0.762**	**0.277**	**38.08**	**10.55**	**1.962**
Georgia	1.65	1.35	1.08	0.802	0.275	0.58	0.16	0.030
Russia	160.50	113.03	86.08	0.762	0.277	37.50	10.39	1.932
South America	**234.49**	**183.89**	**134.45**	**0.731**	**0.349**	**93.02**	**32.49**	**6.043**
Argentina	28.63	23.77	17.42	0.733	0.352	9.84	3.47	0.645
Bolivia	4.97	4.49	3.41	0.760	0.350	1.76	0.62	0.115
Brazil	125.85	90.69	64.57	0.712	0.339	50.73	17.19	3.198
Chile	19.80	17.03	11.79	0.693	0.411	5.72	2.35	0.437
Colombia	16.19	13.60	10.60	0.779	0.325	6.21	2.02	0.376
Curacao	0.82	0.62	0.40	0.638	0.519	1.12	0.58	0.108
Ecuador	0.00	0.00	0.00	0.740	0.399	3.78	1.51	0.281
Paraguay	3.48	2.96	2.14	0.725	0.398	1.45	0.58	0.108
Peru	12.75	11.13	7.66	0.688	0.435	5.12	2.23	0.414
Suriname	0.52	0.47	0.35	0.749	0.389	0.13	0.05	0.010
Trinidad/Tobago	1.31	1.17	0.91	0.782	0.347	0.74	0.26	0.048
Uruguay	2.45	1.98	1.47	0.745	0.380	0.80	0.30	0.057
Venezuela	17.72	15.97	13.71	0.859	0.239	5.61	1.34	0.249
Southeast Asia	**252.35**	**189.31**	**141.80**	**0.749**	**0.393**	**145.03**	**57.04**	**10.608**
Brunei	0.80	0.72	0.57	0.799	0.324	0.39	0.12	0.023
Cambodia	3.04	2.74	1.95	0.714	0.432	1.54	0.66	0.124
Indonesia	91.92	76.06	58.56	0.770	0.345	40.76	14.06	2.616
Lao PDR	0.00	0.00	0.00	0.740	0.401	0.80	0.32	0.060
Malaysia	36.13	32.06	25.63	0.799	0.311	17.27	5.37	0.998
Myanmar	8.64	7.27	5.26	0.723	0.411	1.56	0.64	0.119
Singapore	16.25	3.75	2.57	0.686	0.444	47.74	21.18	3.940
Thailand	68.83	43.65	30.09	0.689	0.429	24.99	10.72	1.993
Vietnam	26.74	23.08	17.16	0.744	0.396	9.98	3.95	0.735
South Korea	**120.85**	**52.02**	**36.03**	**0.693**	**0.438**	**20.73**	**9.09**	**1.690**
Taiwan	**47.97**	**20.61**	**16.16**	**0.784**	**0.314**	**12.64**	**3.97**	**0.738**
United States	**959.88**	**828.12**	**678.46**	**0.819**	**0.273**	**191.60**	**52.21**	**9.711**
All regions	**4,552.51**	**3,419.01**	**2,575.29**	**0.753**	**0.337**	**1,453.98**	**490.60**	**91.24**

(a) 2018 BAU oil for final consumption is from IEA (2022) and is the sum of oil for motor gasoline, gas/diesel oils, liquefied petroleum gas (LPG)/ethane, residual fuel oil, crude oil/natural gas liquids (NGL), naphtha, jet kerosene, other kerosene, and other oil products. Gas/diesel oils include diesel oil for diesel trucks, cars, and marine transport; light heating oil for industrial and commercial use; and gas oils used for petrochemical feedstocks. LPG is liquefied petroleum gas. Residual fuel oil is heavy fuel oil used for ships. NGL is natural gas liquids (ethane, propane, butane, isobutane, pentane, etc.). Butane and pentane are used to blend with gasoline and ethanol. Naphtha is used as a precursor to motor fuels, solvent for paint, dry cleaning, asphalt, rubber, and industrial extraction. Other kerosene is kerosene not used for aircraft. Of the total oil consumed among all countries in 2018 (4,553 GW), 1,376 GW was in motor gasoline, 1,613 GW was in gas/diesel oils, 451.1 GW was in LPG/ethane, 92.6 GW was in residual fuel oil, 14.1 GW was in crude oil/NG, 323.7 GW was in naphtha, 173.3 GW was in jet kerosene, 46.2 GW was in other kerosene, and 463.2 GW was in other oil products.

(b) 2018 BAU estimated oil for final consumption used in the transport sector is the sum of the quantity in each category in (a) multiplied by 97% for motor gasoline (the rest goes to the industrial, residential, and commercial sectors), 85% for gas/diesel oils, 100% for LPG/ethane, 95% for residual fuel oil, 10% for crude oil/NGL, 0% for naphtha, 100% for jet kerosene, 0% for other kerosene, and 0% for other oil products. These values are assumed to be the same for all countries and were approximated using U.S. data from EIA (2022) plus our own estimates.

(c) 2018 BAU estimated oil for final consumption used for transport that is converted to electric transport is the sum of the quantity in each category in (b) multiplied by 97% for motor gasoline, 50% for gas/diesel oils, 65% for LPG/ethane, 50% for residual fuel oil, 10% for crude oil/NGL, 0% for naphtha, 54% for jet kerosene, 0% for other kerosene, and 0% for other oil products. The percent for jet kerosene assumes all short-haul flights (54% of total miles flown worldwide from Wilkerson et al., 2010), will be electrified and all long-haul flights will run on hydrogen fuel cells.

(d) The 2018 fraction of BAU oil for final consumption used for transport converted to battery electric transport equals column (c) divided by column (b).

(e) The 2050 fraction of the WWS total transport load used to produce and compress H_2 accounts for the fraction of both oil and natural gas final consumption used for HFC-electric transport. Five percent of the natural gas final consumption for transport is converted to HFC-electric transport. The rest is converted to battery-electric transport. Column (d) gives the fraction of oil final consumption for transport by country used for HFC-electric transport. The calculation also accounts for the electricity:fuel ratio for each BE and HFC-electric vehicles and extra efficiency, both from Table S3 for each oil and natural gas from transport.

(f) 2050 WWS total transport load is from Table S4.

(g) 2050 WWS transport load needed to produce and compress H_2 equals column (e) multiplied by column (f).

(h) Hydrogen produced per year for fuel cell vehicles equals the annual load needed to produce and compress hydrogen (GW), from column (g), divided by 47.1 TWh/Tg-H_2 and by 1,000 GW/TW and multiplied by 8,760 hours per year. The 47.1 TWh/Tg-H_2 is for electrolysis and compression (see Footnote to Table S6 for details).

Table S8. 2050 estimated mass of hydrogen needed per year 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) the annual-average power needed to produce and compress hydrogen for steel plus ammonia manufacturing, (f) the annual-average power needed to produce and compress hydrogen for transportation, and (g) the annual-average power needed to produce and compress hydrogen for steel and ammonia manufacturing and transportation.

Region or country	(a) 2021 and 2050 Tg-H_2/y needed to purify iron by hydrogen direct reduction	(b) 2020 and 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, ammonia, and vehicles = a+b+c	(e) 2050 Annual-average power needed to produce and compress H_2 for steel and ammonia (GW)	(f) 2050 annual-average power needed to produce and compress H_2 for transport (GW)	(g) 2050 annual-average power needed to produce and compress H_2 for steel, ammonia, and transport= e+f (GW)
Africa	**0.70**	**1.638**	**6.333**	**8.674**	**12.587**	**34.05**	**46.64**
Algeria	0.18	0.475	0.951	1.610	3.544	5.11	8.66
Angola	0	0	0.198	0.198	0	1.06	1.06
Benin	0	0	0.073	0.073	0	0.39	0.39
Botswana	0	0	0.037	0.037	0	0.20	0.20
Cameroon	0	0	0.049	0.049	0	0.26	0.26
Congo	0	0	0.026	0.026	0	0.14	0.14
Congo, DR	0	0	0.041	0.041	0	0.22	0.22
Côte d'Ivoire	0	0	0.091	0.091	0	0.49	0.49
Egypt	0.30	0.907	1.104	2.313	6.499	5.94	12.43
Equator. Guinea	0	0	0.020	0.020	0	0.11	0.11
Eritrea	0	0	0.006	0.006	0	0.03	0.03
Ethiopia	0	0	0.221	0.221	0	1.19	1.19
Gabon	0	0	0.015	0.015	0	0.08	0.08
Ghana	0	0	0.150	0.150	0	0.80	0.80
Kenya	0	0	0.200	0.200	0	1.08	1.08
Libya	0.05	0.005	0.176	0.230	0.291	0.95	1.24
Morocco	0	0	0.566	0.566	0	3.04	3.04
Mozambique	0	0	0.076	0.076	0	0.41	0.41
Namibia	0	0	0.044	0.044	0	0.24	0.24
Niger	0	0	0.021	0.021	0	0.11	0.11
Nigeria	0	0.153	0.407	0.560	0.824	2.19	3.01
Senegal	0	0	0.064	0.064	0	0.34	0.34
South Africa	0.17	0.097	1.161	1.426	1.425	6.24	7.67
South Sudan	0	0	0.018	0.018	0	0.10	0.10
Sudan	0	0	0.230	0.230	0	1.23	1.23
Tanzania	0	0	0.094	0.094	0	0.51	0.51
Togo	0	0	0.018	0.018	0	0.10	0.10
Tunisia	0	0	0.183	0.183	0	0.99	0.99
Zambia	0	0	0.043	0.043	0	0.23	0.23
Zimbabwe	0	0.001	0.052	0.053	0.005	0.28	0.29
Australia	**0.206**	**0.345**	**1.210**	**1.761**	**2.964**	**6.51**	**9.47**
Canada	**0.422**	**0.841**	**1.419**	**2.682**	**6.792**	**7.63**	**14.42**
Central America	**0.460**	**0.024**	**1.978**	**2.462**	**2.605**	**10.63**	**13.24**
Costa Rica	0	0	0.076	0.076	0	0.41	0.41
El Salvador	0	0	0.053	0.053	0	0.29	0.29
Guatemala	0	0	0.107	0.107	0	0.57	0.57
Honduras	0	0	0.056	0.056	0	0.30	0.30
Mexico	0.460	0.024	1.416	1.901	2.605	7.62	10.22
Nicaragua	0	0	0.030	0.030	0	0.16	0.16
Panama	0	0	0.240	0.240	0	1.29	1.29
Central Asia	**0.168**	**1.131**	**1.282**	**2.581**	**6.985**	**6.89**	**13.88**

Kazakhstan	0.168	0.039	0.190	0.397	1.112	1.02	2.13
Kyrgyz Republic	0	0	0.014	0.014	0	0.08	0.08
Pakistan	0	0.712	0.843	1.556	3.831	4.53	8.36
Tajikistan	0	0	0.017	0.017	0	0.09	0.09
Turkmenistan	0	0.142	0.123	0.265	0.766	0.66	1.42
Uzbekistan	0	0.237	0.095	0.332	1.277	0.51	1.79
China Region	**47.05**	**8.420**	**13.13**	**68.60**	**298.2**	**70.60**	**368.8**
China	47.04	8.420	11.56	67.01	298.2	62.14	360.3
Hong Kong	0	0	1.507	1.507	0	8.10	8.10
Korea, DPR	0.014	0	0.026	0.040	0.073	0.14	0.21
Mongolia	0	0	0.040	0.040	0	0.21	0.21
Cuba	**0**	**0**	**0.067**	**0.067**	**0**	**0.36**	**0.36**
Europe	**5.828**	**3.687**	**13.59**	**23.11**	**51.16**	**73.07**	**124.2**
Albania	0	0	0.034	0.034	0	0.19	0.19
Austria	0.330	0.091	0.287	0.708	2.264	1.54	3.81
Belarus	0	0.165	0.140	0.305	0.886	0.75	1.64
Belgium	0.227	0.184	0.657	1.068	2.210	3.53	5.74
Bosnia-Herzeg.	0.040	0	0.056	0.096	0.215	0.30	0.52
Bulgaria	0	0.050	0.146	0.196	0.267	0.78	1.05
Croatia	0	0.080	0.094	0.174	0.430	0.51	0.94
Cyprus	0	0	0.038	0.038	0	0.20	0.20
Czech Rep.	0.211	0.020	0.194	0.426	1.243	1.05	2.29
Denmark	0	0	0.165	0.165	0	0.89	0.89
Estonia	0	0.004	0.033	0.037	0.022	0.18	0.20
Finland	0.135	0.017	0.151	0.303	0.818	0.81	1.63
France	0.514	0.177	1.655	2.347	3.720	8.90	12.62
Germany	1.419	0.503	1.813	3.734	10.333	9.75	20.08
Gibraltar	0	0	0.107	0.107	0	0.57	0.57
Greece	0	0.022	0.245	0.266	0.116	1.32	1.43
Hungary	0.032	0.093	0.136	0.261	0.674	0.73	1.40
Ireland	0	0	0.167	0.167	0	0.90	0.90
Italy	0.211	0.134	1.227	1.572	1.855	6.60	8.45
Kosovo	0	0	0.015	0.015	0	0.08	0.08
Latvia	0	0	0.056	0.056	0	0.30	0.30
Lithuania	0	0.182	0.107	0.289	0.979	0.57	1.55
Luxembourg	0	0	0.087	0.087	0	0.47	0.47
Macedonia	0	0	0.033	0.033	0	0.18	0.18
Malta	0	0	0.094	0.094	0	0.50	0.50
Moldova	0	0	0.030	0.030	0	0.16	0.16
Montenegro	0	0	0.013	0.013	0	0.07	0.07
Netherlands	0.319	0.453	0.648	1.421	4.156	3.48	7.64
Norway	0.004	0.071	0.162	0.238	0.406	0.87	1.28
Poland	0.195	0.488	0.698	1.381	3.674	3.75	7.43
Portugal	0	0	0.255	0.255	0	1.37	1.37
Romania	0.114	0.101	0.254	0.470	1.157	1.37	2.52
Serbia	0.060	0	0.097	0.157	0.322	0.52	0.84
Slovakia	0.168	0.077	0.064	0.309	1.315	0.34	1.66
Slovenia	0	0	0.067	0.067	0	0.36	0.36
Spain	0.217	0.091	1.441	1.748	1.652	7.75	9.40
Sweden	0.168	0	0.233	0.401	0.903	1.26	2.16
Switzerland	0	0.002	0.026	0.028	0.012	0.14	0.15
Ukraine	1.148	0.497	0.314	1.959	8.847	1.69	10.53
United Kingdom	0.314	0.186	1.554	2.053	2.687	8.35	11.04
Haiti Region	**0**	**0**	**0.136**	**0.136**	**0**	**0.73**	**0.73**
Dominican Rep.	0	0	0.116	0.116	0	0.62	0.62
Haiti	0	0	0.020	0.020	0	0.11	0.11
Iceland	**0**	**0**	**0.025**	**0.025**	**0**	**0.14**	**0.14**
India Region	**6.314**	**2.815**	**10.52**	**19.65**	**49.09**	**56.55**	**105.6**
Bangladesh	0	0.181	0.282	0.463	0.975	1.52	2.49
India	6.314	2.634	9.874	18.821	48.110	53.09	101.20
Nepal	0	0	0.131	0.131	0	0.70	0.70
Sri Lanka	0	0	0.231	0.231	0	1.24	1.24

Israel	**0**	**0**	**0.148**	**0.148**	**0**	**0.80**	**0.80**
Jamaica	**0**	**0**	**0.062**	**0.062**	**0**	**0.33**	**0.33**
Japan	**3.807**	**0.139**	**1.586**	**5.532**	**21.21**	**8.53**	**29.74**
Mauritius	**0**	**0**	**0.069**	**0.069**	**0**	**0.37**	**0.37**
Mideast	**3.065**	**3.178**	**7.887**	**14.13**	**33.57**	**42.41**	**75.97**
Armenia	0	0	0.008	0.008	0	0.05	0.05
Azerbaijan	0	0	0.089	0.089	0	0.48	0.48
Bahrain	0.076	0.082	0.040	0.198	0.850	0.22	1.07
Iran	1.760	0.777	1.643	4.180	13.641	8.83	22.47
Iraq	0	0.019	0.432	0.451	0.104	2.32	2.43
Jordan	0	0	0.125	0.125	0	0.67	0.67
Kuwait	0	0	0.251	0.251	0	1.35	1.35
Lebanon	0	0	0.062	0.062	0	0.33	0.33
Oman	0.092	0.374	0.204	0.669	2.503	1.09	3.60
Qatar	0.043	0.712	0.291	1.047	4.064	1.57	5.63
Saudi Arabia	0.330	0.928	2.260	3.518	6.768	12.15	18.92
Syria	0	0.004	0.120	0.125	0.023	0.65	0.67
Turkey	0.563	0.080	1.168	1.811	3.457	6.28	9.74
UAE	0.200	0.201	1.160	1.561	2.157	6.24	8.39
Yemen	0	0	0.034	0.034	0	0.18	0.18
New Zealand	**0.038**	**0.027**	**0.204**	**0.269**	**0.349**	**1.10**	**1.45**
Philippines	**0**	**0**	**0.848**	**0.848**	**0**	**4.56**	**4.56**
Russia Region	**3.325**	**3.525**	**1.962**	**8.811**	**36.83**	**10.55**	**47.38**
Georgia	0	0.043	0.030	0.073	0.232	0.16	0.39
Russia	3.325	3.482	1.932	8.739	36.596	10.39	46.99
South America	**1.879**	**1.107**	**6.043**	**9.028**	**16.05**	**32.49**	**48.54**
Argentina	0.190	0.138	0.645	0.972	1.762	3.47	5.23
Bolivia	0	0	0.115	0.115	0	0.62	0.62
Brazil	1.543	0.026	3.198	4.767	8.437	17.19	25.63
Chile	0.038	0	0.437	0.475	0.204	2.35	2.55
Colombia	0.009	0	0.376	0.384	0.048	2.02	2.07
Curacao	0	0	0.108	0.108	0	0.58	0.58
Ecuador	0	0	0.281	0.281	0	1.51	1.51
Paraguay	0.002	0	0.108	0.109	0.010	0.58	0.59
Peru	0	0.002	0.414	0.416	0.013	2.23	2.24
Suriname	0	0	0.010	0.010	0	0.05	0.05
Trinidad/Tobago	0.081	0.899	0.048	1.028	5.272	0.26	5.53
Uruguay	0	0	0.057	0.057	0	0.30	0.30
Venezuela	0.016	0.041	0.249	0.306	0.308	1.34	1.65
Southeast Asia	**0.731**	**1.803**	**10.61**	**13.14**	**13.62**	**57.04**	**70.66**
Brunei	0	0	0.023	0.023	0	0.12	0.12
Cambodia	0	0	0.124	0.124	0	0.66	0.66
Indonesia	0.162	1.274	2.616	4.052	7.722	14.06	21.79
Lao PDR	0	0	0.060	0.060	0	0.32	0.32
Malaysia	0.038	0.281	0.998	1.317	1.713	5.37	7.08
Myanmar	0	0	0.119	0.119	0	0.64	0.64
Singapore	0	0	3.940	3.940	0	21.18	21.18
Thailand	0	0	1.993	1.993	0	10.72	10.72
Vietnam	0.531	0.248	0.735	1.514	4.188	3.95	8.14
South Korea	**2.513**	**0**	**1.690**	**4.203**	**13.51**	**9.09**	**22.60**
Taiwan	**0.823**	**0**	**0.738**	**1.561**	**4.426**	**3.97**	**8.40**
United States	**1.392**	**3.023**	**9.711**	**14.13**	**23.73**	**52.21**	**75.95**
All regions	**78.72**	**31.70**	**91.24**	**201.7**	**593.7**	**490.6**	**1,084.3**

Column (a) is from Table S5; column (b) is from Table S6; column (c) is from Table S7; column (d) is the sum of the first three columns; column (e) is the sum of columns (a) and (b), all multiplied by 47.1 TWh/Tg-H_2 (Footnote to Table S6) and divided by 8,760 hours per year; column (f) is column (c) multiplied by 47.1 TWh/Tg-H_2 and divided by 8,760 hours per year; column (g) is the sum of columns (e) and (f).

Table S9. 2050 annual-average end-use electric plus heat load (GW) by sector and region after energy in all sectors has been converted to WWS. Instantaneous loads can be higher or lower than annual-average loads. Values for each region equal the sum over all country values from Table S4 in each region, where Table S1 defines the regions. Multiply average load (GW) by 8,760 hours per year to obtain energy per year (GWh/y).

Region	(a) Total	(b) Residential	(c) Commercial	(e) Industrial	(f) Transport	(g) Agriculture-forestry-fishing	(h) Military-other
Africa	482.15	139.01	37.09	197.89	94.51	7.88	5.77
Australia	92.29	11.55	17.58	44.29	17.71	1.16	0.00
Canada	170.29	27.35	32.41	75.04	32.05	3.38	0.06
Central America	156.49	24.57	11.77	75.85	35.55	3.53	5.22
Central Asia	166.87	41.26	13.78	82.94	21.10	5.31	2.49
China	2423.94	383.05	136.90	1529.15	259.78	28.11	86.96
Cuba	8.99	1.62	0.49	5.74	0.77	0.11	0.27
Europe	958.25	199.69	167.93	374.62	199.98	14.86	1.17
Haiti	7.60	1.71	0.76	3.09	1.88	0.17	0.00
Iceland	3.22	0.29	0.43	2.02	0.35	0.13	0.00
India	1006.84	166.59	39.06	601.98	130.83	48.45	19.93
Israel	12.77	3.07	2.79	3.68	2.44	0.30	0.51
Jamaica	2.56	0.19	0.12	1.51	0.73	0.01	0.00
Japan	186.33	29.53	38.46	87.92	29.25	1.06	0.12
Mauritius	1.89	0.25	0.25	0.46	0.93	0.01	0.00
Mideast	706.51	117.00	68.71	386.51	111.45	13.05	9.79
New Zealand	16.70	2.13	2.47	8.49	2.94	0.59	0.08
Philippines	41.02	7.41	6.49	15.90	10.66	0.56	0.00
Russia	268.31	65.89	29.14	131.55	38.08	3.45	0.21
South America	468.71	61.32	43.17	254.84	93.02	12.81	3.56
Southeast Asia	584.57	69.27	46.74	316.53	145.03	5.20	1.80
South Korea	154.39	13.02	31.08	86.61	20.73	2.55	0.40
Taiwan	89.91	10.53	10.60	54.71	12.64	0.69	0.75
United States	959.46	179.38	190.27	363.44	191.60	10.05	24.73
Total 2050	**8970.1**	**1555.7**	**928.5**	**4704.7**	**1454.0**	**163.39**	**163.81**

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 S4, and summing the result over all countries in a region.

Table S10. Annual-average WWS all-sector inflexible and flexible loads (GW) for 2050 by region. "Total load" is the sum of "inflexible load" and "flexible load." "Flexible load" is the sum of "cold load subject to storage," "low-temperature heat load subject to storage," "load for H_2" production, compression, and storage (accounting for leaks as well), and "all other loads subject to demand response (DR)." Annual-average loads are distributed in time at 30-s resolution, as described in the text. Instantaneous loads, either flexible or inflexible, can be much higher or lower than annual-average loads. Also shown is the annual hydrogen mass needed in each region, estimated as the H_2 load multiplied by 8,760 h/y and divided by 47.1 kWh/kg-H_2. Table S1 defines the regions.

Region	Total end-use load (GW)	Inflexible load (GW)	Flexible load (GW)	Cold load subject to storage (GW)	Low-temperature heat load subject to storage (GW)	All other loads subject to DR	Load for H_2 (GW)	H_2 needed (Tg-H_2/y)
Africa	482.1	233.1	249.0	9.5	30.7	162.3	46.6	8.67
Australia	92.3	47.8	44.5	0.5	2.9	31.7	9.5	1.76
Canada	170.3	86.7	83.6	0.6	9.7	58.8	14.4	2.68
Central America	156.5	72.7	83.8	1.7	5.3	63.6	13.2	2.46
Central Asia	166.9	89.2	77.7	0.2	7.6	56.0	13.9	2.58
China	2,423.9	1,112	1,312	29.1	172.0	742.1	368.8	68.59
Cuba	9.0	4.4	4.6	0.3	0.4	3.6	0.4	0.07
Europe	958.3	426.9	531.4	11.4	128.8	267.0	124.2	23.11
Haiti	7.6	3.7	3.9	0.1	0.3	2.7	0.7	0.14
Iceland	3.2	1.2	2.0	0.0	0.6	1.3	0.1	0.03
India	1,006.8	470.1	536.8	11.7	42.1	377.3	105.7	19.65
Israel	12.8	6.7	6.1	0.3	0.7	4.3	0.8	0.15
Jamaica	2.6	1.1	1.4	0.0	0.0	1.1	0.3	0.06
Japan	186.3	102.3	84.1	0.4	7.2	46.8	29.7	5.53
Mauritius	1.9	0.6	1.2	0.1	0.1	0.7	0.4	0.07
Mideast	706.5	342.4	364.1	2.9	22.4	262.8	76.0	14.13
New Zealand	16.7	8.8	7.9	0.0	0.4	6.1	1.4	0.27
Philippines	41.0	17.9	23.1	1.7	2.8	14.1	4.6	0.85
Russia	268.3	109.9	158.4	3.4	42.0	65.7	47.4	8.81
South America	468.7	222.2	246.5	7.3	13.1	177.6	48.5	9.03
Southeast Asia	584.6	257.4	327.2	8.1	19.3	229.1	70.7	13.14
South Korea	154.4	81.8	72.5	0.4	6.8	42.8	22.6	4.20
Taiwan	89.9	43.4	46.5	0.6	4.2	33.3	8.4	1.56
United States	959.5	484.5	475.0	7.4	53.4	338.2	75.9	14.12
Total	**8,970.1**	**4,227**	**4,743**	**97.5**	**572.9**	**2,989**	**1,084**	**201.66**

Table S11. Existing nameplate capacity (GW) by WWS generator in each region and each country within each region in 2020 (except solar heat data are from 2018 and geothermal heat data are from 2019).

Region or country	On-shore wind	Off-shore wind	Residential roof PV	Com /gov roof PV	Utility PV	CSP with storage	Geo-thermal elec-tricity	Hydro	Tidal	Wave	Solar heat	Geothermal heat
Africa	**6.483**	**0**	**1.751**	**1.751**	**5.253**	**1.076**	**0.8313**	**31.516**	**0.0004**	**0**	**2.654**	**0.1942**
Algeria	0.010	0	0.085	0.085	0.254	0.025	0	0.269	0	0	0	0.0777
Angola	0	0	0.003	0.003	0.008	0	0	3.836	0	0	0	0
Benin	0	0	0.001	0.001	0.002	0	0	0.033	0	0	0	0
Botswana	0	0	0.001	0.001	0.004	0	0	0	0	0	0.009	0
Cameroon	0	0	0.003	0.003	0.008	0	0	0.822	0	0	0	0
Congo	0	0	0.000	0.000	0.001	0	0	0.218	0	0	0	0
Congo, DR	0	0	0.004	0.004	0.012	0	0	2.76	0	0	0	0
Côte d'Ivoire	0	0	0.003	0.003	0.008	0	0	0.879	0	0	0	0
Egypt	1.465	0	0.335	0.335	1.004	0.021	0	2.876	0	0	0	0.044
Equator. Guinea	0	0	0.000	0.000	0.000	0	0	0.128	0	0	0	0
Eritrea	0.001	0	0.004	0.004	0.013	0	0	0	0	0	0	0
Ethiopia	0.324	0	0.004	0.004	0.012	0	0.0073	4.074	0	0	0	0.0022
Gabon	0	0	0.000	0.000	0.001	0	0	0.331	0	0	0	0
Ghana	0	0	0.014	0.014	0.042	0	0	1.584	0.0004	0	0.002	0
Kenya	0.338	0	0.021	0.021	0.064	0	0.824	0.837	0	0	0	0.0185
Libya	0	0	0.001	0.001	0.003	0	0	0	0	0	0	0
Morocco	1.405	0	0.041	0.041	0.122	0.53	0	1.305	0	0	0.316	0.005
Mozambique	0	0	0.011	0.011	0.033	0	0	2.216	0	0	0.002	0
Namibia	0.006	0	0.029	0.029	0.087	0	0	0.347	0	0	0.032	0
Niger	0	0	0.005	0.005	0.016	0	0	0	0	0	0	0
Nigeria	0.003	0	0.006	0.006	0.017	0	0	2.111	0	0	0.003	0.0007
Senegal	0.050	0	0.031	0.031	0.093	0	0	0.081	0	0	0.003	0
South Africa	2.636	0	1.098	1.098	3.294	0.5	0	0.684	0	0	1.521	0.0023
South Sudan	0	0	0.000	0.000	0.001	0	0	0	0	0	0	0
Sudan	0	0	0.004	0.004	0.011	0	0	1.923	0	0	0	0
Tanzania	0	0	0.005	0.005	0.016	0	0	0.596	0	0	0	0
Togo	0	0	0.001	0.001	0.002	0	0	0.049	0	0	0	0
Tunisia	0.245	0	0.019	0.019	0.057	0	0	0.066	0	0	0.724	0.0438
Zambia	0	0	0.020	0.020	0.059	0	0	2.4	0	0	0	0
Zimbabwe	0	0	0.003	0.003	0.010	0	0	1.091	0	0	0.042	0
Australia	**9.457**	**0**	**3.525**	**3.525**	**10.575**	**0.002**	**0.0001**	**7.45**	**0**	**0.001**	**6.451**	**0.0944**
Canada	**13.577**	**0**	**0.665**	**0.665**	**1.995**	**0**	**0**	**81.823**	**0**	**0.02**	**0.637**	**1.8313**
Central America	**9.327**	**0**	**1.389**	**1.389**	**4.167**	**0.014**	**1.6136**	**19.857**	**0**	**0**	**3.027**	**0.1655**
Costa Rica	0.394	0	0.011	0.011	0.034	0	0.262	2.331	0	0	0	0.0018
El Salvador	0	0	0.086	0.086	0.257	0	0.2044	0.575	0	0	0	0.0034
Guatemala	0.107	0	0.020	0.020	0.061	0	0.0492	1.559	0	0	0	0.0023
Honduras	0.241	0	0.103	0.103	0.308	0	0.039	0.837	0	0	0	0.0019
Mexico	8.128	0	1.126	1.126	3.378	0.014	0.906	12.612	0	0	3.027	0.1561
Nicaragua	0.186	0	0.003	0.003	0.010	0	0.153	0.157	0	0	0	0
Panama	0.270	0	0.040	0.040	0.119	0	0	1.786	0	0	0	0
Central Asia	**1.774**	**0**	**0.492**	**0.492**	**1.476**	**0**	**0**	**24.956**	**0**	**0**	**0**	**0.0029**
Kazakhstan	0.486	0	0.344	0.344	1.031	0	0	2.73	0	0	0	0
Kyrgyz Republic	0	0	0.000	0.000	0.000	0	0	3.892	0	0	0	0
Pakistan	1.287	0	0.147	0.147	0.442	0	0	9.929	0	0	0	0
Tajikistan	0	0	0	0	0	0	0	6.395	0	0	0	0.0029
Turkmenistan	0	0	0	0	0	0	0	0.005	0	0	0	0
Uzbekistan	0.001	0	0.001	0.001	0.002	0	0	2.005	0	0	0	0
China Region	**278.48**	**9.996**	**50.793**	**50.793**	**152.380**	**0.521**	**0.0258**	**343.7**	**0**	**0.005**	**337.62**	**40.63**
China	278.32	9.996	50.767	50.767	152.300	0.521	0.0258	338.67	0	0.005	337.62	40.61
Hong Kong	0	0	0.000	0.000	0.000	0	0	0	0	0	0	0
Korea, DPR	0.001	0	0.008	0.008	0.025	0	0	5.01	0	0	0	0
Mongolia	0.156	0	0.018	0.018	0.054	0	0	0.023	0	0	0	0.0227

Cuba	**0.012**	**0**	**0.033**	**0.033**	**0.098**	**0**	**0**	**0.068**	**0**	**0**	**0**	**0**
Europe	**184.90**	**25.015**	**32.227**	**32.227**	**96.680**	**2.3212**	**0.896**	**166.3**	**0.0001**	**0.2431**	**39.166**	**31.637**
Albania	0	0	0.003	0.003	0.010	0	0	2.39	0	0	0.181	0.0162
Austria	3.224	0	0.444	0.444	1.332	0	0.0009	9.001	0	0	3.583	1.0958
Belarus	0.120	0	0.032	0.032	0.095	0	0	0.097	0	0	0	0.01
Belgium	2.459	2.262	1.129	1.129	3.388	0	0	0.12	0	0	0.483	0.3057
Bosnia-Herzeg.	0.135	0	0.007	0.007	0.021	0	0	2.093	0	0	0	0.036
Bulgaria	0.703	0	0.215	0.215	0.644	0	0	1.725	0	0	0.1	0.1094
Croatia	0.803	0	0.017	0.017	0.051	0	0.01	1.848	0	0	0.161	0.0793
Cyprus	0.158	0	0.040	0.040	0.120	0	0	0	0	0	0.551	0.0103
Czech Rep.	0.337	0	0.415	0.415	1.244	0	0	1.097	0	0	0.781	0.3245
Denmark	4.478	1.703	0.260	0.260	0.780	0	0	0.009	0	0	1.175	0.7436
Estonia	0.320	0	0.026	0.026	0.078	0	0	0.008	0	0	0.012	0.063
Finland	2.515	0.071	0.078	0.078	0.235	0	0	3.263	0	0	0.048	2.3
France	17.947	0.002	2.345	2.345	7.034	0.009	0.0159	19.671	0	0.214	1.951	2.5976
Germany	55.122	7.689	10.756	10.756	32.269	0.002	0.04	4.658	0	0	13.877	4.8063
Gibraltar	0	0	0.000	0.000	0.000	0	0	0	0.0001	0	0	0
Greece	4.113	0	0.649	0.649	1.948	0	0	2.697	0	0	3.299	0.2595
Hungary	0.329	0	0.391	0.391	1.172	0	0.003	0.056	0	0	0.229	1.0237
Ireland	4.326	0.025	0.008	0.008	0.024	0	0	0.237	0	0	0.233	0.2009
Italy	10.852	0	4.319	4.319	12.956	0.0061	0.797	14.908	0	0	3.305	1.425
Kosovo	0.032	0	0.002	0.002	0.006	0	0	0.092	0	0	0	0
Latvia	0.066	0	0.001	0.001	0.004	0	0	1.576	0	0	0.011	0.0016
Lithuania	0.548	0	0.030	0.030	0.089	0	0	0.116	0	0	0.013	0.1255
Luxembourg	0.166	0	0.039	0.039	0.117	0	0	0.034	0	0	0.046	0
Macedonia	0.037	0	0.019	0.019	0.056	0	0	0.674	0	0	0.068	0.0474
Malta	0	0	0.037	0.037	0.110	0	0	0	0	0	0.051	0
Moldova	0.034	0	0.001	0.001	0.003	0	0	0.076	0	0	0	0
Montenegro	0.118	0	0.001	0.001	0.004	0	0	0.658	0	0	0	0
Netherlands	4.174	2.611	2.043	2.043	6.128	0	0	0.038	0	0.0021	0.46	1.7191
Norway	3.977	0.002	0.030	0.030	0.091	0	0	31.556	0	0	0.031	1.1502
Poland	6.614	0	0.787	0.787	2.362	0	0	0.605	0	0	1.791	0.756
Portugal	5.461	0.025	0.205	0.205	0.615	0	0.0291	4.373	0	0	0.77	0.0211
Romania	3.030	0	0.277	0.277	0.832	0.0001	0.0001	6.221	0	0	0.143	0.2451
Serbia	0.397	0	0.006	0.006	0.017	0	0	2.484	0	0	0	0.1153
Slovakia	0.003	0	0.119	0.119	0.356	0	0	1.505	0	0	0.121	0.2303
Slovenia	0.003	0	0.053	0.053	0.160	0	0	1.344	0	0	0.104	0.2656
Spain	27.259	0.005	2.357	2.357	7.071	2.304	0	14.292	0	0.005	3.018	0.544
Sweden	9.811	0.192	0.283	0.283	0.850	0	0	16.379	0	0	0.374	6.68
Switzerland	0.087	0	0.624	0.624	1.871	0	0	13.852	0	0	1.186	2.1968
Ukraine	1.402	0	1.466	1.466	4.399	0	0	4.666	0	0	0	1.607
United Kingdom	13.740	10.428	2.713	2.713	8.138	0	0	1.879	0	0.022	1.01	0.5247
Haiti Region	**0.370**	**0**	**0.075**	**0.075**	**0.224**	**0**	**0**	**0.676**	**0**	**0**	**0**	**0**
Dominican Rep.	0.370	0	0.074	0.074	0.222	0	0	0.616	0	0	0	0
Haiti	0	0	0.001	0.001	0.002	0	0	0.06	0	0	0	0
Iceland	**0.002**	**0**	**0.001**	**0.001**	**0.004**	**0**	**0.756**	**2.086**	**0**	**0**	**0**	**2.373**
India Region	**38.880**	**0**	**7.915**	**7.915**	**23.744**	**0.2285**	**0**	**49.08**	**0**	**0**	**9.457**	**0.3612**
Bangladesh	0.003	0	0.060	0.060	0.181	0	0	0.23	0	0	0	0
India	38.625	0	7.797	7.797	23.390	0.2285	0	45.763	0	0	9.457	0.3576
Nepal	0	0	0.012	0.012	0.036	0	0	1.278	0	0	0	0.0036
Sri Lanka	0.252	0	0.046	0.046	0.138	0	0	1.809	0	0	0	0
Israel	**0.027**	**0**	**0.238**	**0.238**	**0.714**	**0.248**	**0**	**0.007**	**0**	**0**	**3.351**	**0.0824**
Jamaica	**0.099**	**0**	**0.019**	**0.019**	**0.056**	**0**	**0**	**0.03**	**0**	**0**	**0**	**0**
Japan	**4.373**	**0.085**	**13.400**	**13.400**	**40.200**	**0**	**0.525**	**22.379**	**0**	**0**	**2.58**	**2.5705**
Mauritius	**0.011**	**0**	**0.017**	**0.017**	**0.050**	**0**	**0**	**0.061**	**0**	**0**	**0.093**	**0**
Mideast	**10.262**	**0**	**2.415**	**2.415**	**7.246**	**0.2011**	**1.613**	**48.849**	**0**	**0**	**19.061**	**3.7754**
Armenia	0.003	0	0.019	0.019	0.057	0	0	1.293	0	0	0	0.0015
Azerbaijan	0.066	0	0.008	0.008	0.024	0	0	1.131	0	0	0	0
Bahrain	0.001	0	0.002	0.002	0.006	0	0	0	0	0	0	0
Iran	0.303	0	0.083	0.083	0.248	0	0	11.129	0	0	0	0.0822
Iraq	0	0	0.043	0.043	0.130	0	0	2.513	0	0	0	0
Jordan	0.515	0	0.272	0.272	0.815	0	0	0.012	0	0	0.882	0.1533

Kuwait	0.012	0	0.009	0.009	0.026	0.05	0	0	0	0	0	0
Lebanon	0.003	0	0.013	0.013	0.039	0	0	0.282	0	0	0.583	0
Oman	0.050	0	0.022	0.022	0.065	0	0	0	0	0	0	0
Qatar	0	0	0.001	0.001	0.003	0	0	0	0	0	0	0
Saudi Arabia	0.003	0	0.072	0.072	0.215	0.05	0	0	0	0	0	0.045
Syria	0.001	0	0.000	0.000	0.001	0	0	1.505	0	0	0	0
Turkey	9.305	0	1.333	1.333	4.000	0.001	1.613	30.984	0	0	17.596	3.4884
UAE	0	0	0.488	0.488	1.463	0.1001	0	0	0	0	0	0
Yemen	0	0	0.051	0.051	0.152	0	0	0	0	0	0	0.005
New Zealand	**0.784**	**0**	**0.028**	**0.028**	**0.085**	**0**	**0.984**	**5.354**	**0**	**0**	**0.112**	**0.518**
Philippines	**0.443**	**0**	**0.210**	**0.210**	**0.629**	**0**	**1.9279**	**3.7**	**0**	**0**	**0**	**0.0017**
Russia Region	0.966	0	0.286	0.286	0.857	0	0.074	51.976	0	0.002	0.018	0.5022
Georgia	0.021	0	0	0	0.001	0	0	3.449	0	0	0	0.0692
Russia	0.945	0	0.286	0.286	0.857	0	0.074	48.527	0	0.002	0.018	0.433
South America	**25.769**	**0**	**2.524**	**2.524**	**7.572**	**0.1**	**0.04**	**175.63**	**0.0001**	**0**	**11.590**	**0.6207**
Argentina	2.624	0	0.153	0.153	0.458	0	0	10.366	0	0	0.0311	0.2048
Bolivia	0.027	0	0.024	0.024	0.072	0	0	0.735	0	0	0	0.001
Brazil	17.750	0	1.576	1.576	4.729	0	0	109.24	0.0001	0	11.258	0.3634
Chile	2.829	0	0.621	0.621	1.864	0.1	0.04	6.945	0	0	0.248	0.0226
Colombia	0.510	0	0.021	0.021	0.064	0	0	11.941	0	0	0	0.02
Curacao	0.047	0	0.002	0.002	0.007	0	0	0	0	0	0	0
Ecuador	0.021	0	0.006	0.006	0.017	0	0	5.076	0	0	0	0.0052
Paraguay	0	0	0.000	0.000	0.000	0	0	8.81	0	0	0	0
Peru	0.376	0	0.066	0.066	0.199	0	0	5.396	0	0	0	0.003
Suriname	0	0	0.001	0.001	0.004	0	0	0.19	0	0	0	0
Trinidad/Tobago	0	0	0.001	0.001	0.002	0	0	0	0	0	0	0
Uruguay	1.514	0	0.051	0.051	0.154	0	0	1.538	0	0	0.053	0
Venezuela	0.071	0	0.001	0.001	0.003	0	0	15.393	0	0	0	0.0007
Southeast Asia	**2.206**	**0.099**	**4.359**	**4.359**	**13.078**	**0.005**	**2.1313**	**45.057**	**0**	**0**	**0.11**	**0.154**
Brunei	0	0	0.000	0.000	0.001	0	0	0	0	0	0	0
Cambodia	0	0	0.042	0.042	0.125	0	0	1.33	0	0	0	0
Indonesia	0.154	0	0.034	0.034	0.103	0	2.131	6.121	0	0	0	0.0023
Lao PDR	0	0	0.004	0.004	0.013	0	0	7.376	0	0	0	0
Malaysia	0	0	0.299	0.299	0.896	0	0	6.275	0	0	0	0.005
Myanmar	0	0	0.017	0.017	0.050	0	0	3.331	0	0	0	0
Singapore	0.001	0	0.066	0.066	0.197	0	0	0	0	0	0	0
Thailand	1.538	0	0.597	0.597	1.790	0.005	0.0003	3.513	0	0	0.11	0.1285
Vietnam	0.513	0.099	3.301	3.301	9.902	0	0	17.111	0	0	0	0.0182
South Korea	**1.515**	**0.136**	**2.915**	**2.915**	**8.745**	**0**	**0**	**1.806**	**0**	**0.256**	**1.324**	**1.4898**
Taiwan	**0.726**	**0.128**	**1.163**	**1.163**	**3.490**	**0**	**0**	**2.092**	**0**	**0**	**1.22**	**0.0001**
United States	**122.28**	**0.042**	**14.763**	**14.763**	**44.288**	**1.758**	**2.587**	**79.145**	**0**	**0**	**17.935**	**20.713**
All regions	**712.72**	**35.50**	**141.20**	**141.20**	**423.61**	**6.47**	**14.01**	**1,164**	**0.0006**	**0.53**	**456.40**	**107.72**

Onshore and offshore wind, solar PV, CSP, geothermal electricity, and wave electricity are from IRENA (2021). 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. Hydropower values are from IHA (2021). Solar thermal values are for 2018 and from Weiss and Spork-Dur, 2020). Tidal values are from various sources. Geothermal heat values are for 2019 and from Lund and Toth (2020).

Table S12. Final 2050 total (existing plus new) nameplate capacity (GW) by generator needed in each country and region to supply 100% of all load plus losses continuously with WWS across all energy sectors in each region (as determined by LOADMATCH). Nameplate capacity equals the maximum possible instantaneous discharge rate. The nameplate capacity for each generator in each region multiplied by the mean capacity factor for the generator in the region (Table S14) gives the simulation-averaged power output from the generator in the region (Table S15).

Region or country	Onshore wind	Offshore wind	Residential roof PV	Com /gov roof PV	Utility PV	CSP with storage	Geothermal electricity	Hydro	Wave	Tidal	Solar thermal	Geothermal heat
Africa	**486.0**	**151.9**	**350.0**	**633.7**	**536.5**	**27.73**	**3.61**	**31.52**	**3.507**	**0.832**	**2.654**	**0.1942**
Algeria	33.92	5.26	31.11	71.65	60.38	2.51	0.00	0.269	0.347	0.020	0.000	0.0777
Angola	19.34	3.83	3.21	7.02	2.48	0.35	0.00	3.836	0.052	0.027	0.000	0
Benin	5.77	1.35	2.41	4.25	2.75	0.22	0.00	0.033	0.052	0.005	0.000	0
Botswana	2.40	0.00	1.15	2.58	2.64	0.12	0.00	0.000	0.000	0.000	0.009	0
Cameroon	12.35	0.58	2.47	5.39	4.71	0.26	0.00	0.822	0.063	0.011	0.000	0
Congo	4.42	1.22	0.95	2.10	1.10	0.00	0.00	0.218	0.025	0.006	0.000	0
Congo, DR	25.59	0.83	5.02	11.04	10.72	0.53	0.00	2.760	0.093	0.002	0.000	0
Côte d'Ivoire	14.64	2.26	2.81	6.14	3.21	0.31	0.00	0.879	0.079	0.013	0.000	0
Egypt	63.76	37.87	52.39	119.98	60.46	4.59	0.00	2.876	0.000	0.036	0.000	0.044
Equator. Guinea	1.34	4.35	7.51	3.40	10.47	0.35	0.00	0.128	0.083	0.009	0.000	0
Eritrea	0.31	0.10	0.19	0.41	0.21	0.02	0.00	0.000	0.000	0.008	0.000	0
Ethiopia	19.61	0.00	9.68	21.09	21.84	0.99	1.71	4.074	0.000	0.000	0.000	0.0022
Gabon	12.96	10.38	7.68	8.03	8.92	0.00	0.00	0.331	0.135	0.018	0.000	0
Ghana	11.87	4.29	7.11	15.49	8.10	0.61	0.00	1.584	0.139	0.013	0.002	0
Kenya	16.78	3.39	4.65	10.30	5.41	0.53	1.81	0.837	0.149	0.013	0.000	0.0185
Libya	12.14	7.42	10.45	23.87	11.40	0.87	0.00	0.000	0.000	0.029	0.000	0
Morocco	14.26	7.30	12.69	29.27	14.67	1.11	0.00	1.305	0.147	0.030	0.316	0.005
Mozambique	7.86	1.41	2.18	4.83	2.50	0.25	0.00	2.216	0.032	0.123	0.002	0
Namibia	2.82	0.69	1.20	2.71	1.39	0.13	0.00	0.347	0.014	0.027	0.032	0
Niger	2.02	0.00	1.23	2.73	2.83	0.12	0.00	0.000	0.000	0.000	0.000	0
Nigeria	45.09	0.00	64.02	139.5	146.00	4.74	0.00	2.111	1.176	0.018	0.003	0.0007
Senegal	3.16	0.92	1.62	3.56	1.86	0.16	0.00	0.081	0.041	0.013	0.003	0
South Africa	87.35	46.48	84.67	72.38	97.88	5.95	0.00	0.684	0.663	0.039	1.521	0.0023
South Sudan	0.32	0.00	0.25	0.54	0.56	0.02	0.00	0.000	0.000	0.000	0.000	0
Sudan	9.40	3.74	7.25	15.97	8.30	0.64	0.00	1.923	0.000	0.018	0.000	0
Tanzania	16.78	5.23	7.74	16.92	8.81	0.69	0.00	0.596	0.191	0.327	0.000	0
Togo	2.84	0.66	1.21	1.65	1.38	0.10	0.00	0.049	0.024	0.003	0.000	0
Tunisia	7.23	2.30	8.66	14.44	16.01	0.63	0.00	0.066	0.000	0.022	0.724	0.0438
Zambia	20.30	0.00	4.83	10.58	11.04	0.56	0.09	2.400	0.000	0.000	0.000	0
Zimbabwe	9.37	0.00	3.70	5.90	8.51	0.35	0.00	1.091	0.000	0.000	0.042	0
Australia	**80.33**	**19.22**	**38.05**	**65.18**	**257.8**	**4.86**	**0.40**	**7.450**	**0.576**	**0.500**	**6.451**	**0.0944**
Canada	**176.8**	**37.70**	**14.01**	**103.4**	**43.32**	**0.00**	**5.00**	**81.82**	**0.942**	**2.000**	**0.637**	**1.8313**
Central America	**414.3**	**92.95**	**51.00**	**114.9**	**251.4**	**8.05**	**10.69**	**19.86**	**2.390**	**0.325**	**3.027**	**0.1655**
Costa Rica	7.69	1.71	0.59	1.28	2.87	0.10	1.19	2.331	0.029	0.024	0.000	0.0018
El Salvador	5.44	0.65	0.44	0.96	2.15	0.07	1.02	0.575	0.021	0.009	0.000	0.0034
Guatemala	15.64	1.76	1.06	2.34	5.22	0.18	2.26	1.559	0.050	0.011	0.000	0.0023
Honduras	13.76	1.47	0.97	2.14	4.77	0.16	0.59	0.837	0.044	0.018	0.000	0.0019
Mexico	337.4	81.41	45.77	103.4	225.8	7.17	5.18	12.612	2.141	0.100	3.027	0.1561
Nicaragua	6.88	0.88	0.47	1.03	2.31	0.08	0.45	0.157	0.021	0.019	0.000	0
Panama	27.45	5.07	1.69	3.69	8.28	0.29	0.00	1.786	0.085	0.145	0.000	0
Central Asia	**244.6**	**21.23**	**116.7**	**163.3**	**211.9**	**7.97**	**0.00**	**24.956**	**1.640**	**0.021**	**0.000**	**0.0029**
Kazakhstan	64.34	0.00	15.60	40.36	33.86	0.00	0.00	2.730	0.000	0.000	0.000	0
Kyrgyz Republic	4.81	0.00	0.92	2.29	2.23	0.13	0.00	3.892	0.000	0.000	0.000	0
Pakistan	114.8	21.23	86.54	86.92	143.97	6.08	0.00	9.929	1.640	0.021	0.000	0
Tajikistan	1.79	0.00	0.35	0.87	0.86	0.05	0.00	6.395	0.000	0.000	0.000	0.0029
Turkmenistan	18.82	0.00	4.25	10.39	9.90	0.55	0.00	0.005	0.000	0.000	0.000	0
Uzbekistan	39.99	0.00	9.01	22.45	21.10	1.16	0.00	2.005	0.000	0.000	0.000	0
China Region	**2,163**	**758.2**	**1,055**	**989.7**	**4,460**	**132.2**	**1.86**	**343.7**	**8.711**	**2.175**	**337.6**	**40.633**
China	2,146	665.5	1,051	983.8	4,409	132.1	1.86	338.7	8.375	2.000	337.6	40.610

Hong Kong	0.14	90.99	0.93	0.43	34.78	0.00	0.00	0.000	0.336	0.016	0.000	0
Korea, DPR	10.27	1.76	2.20	2.32	7.68	0.11	0.00	5.010	0.000	0.159	0.000	0
Mongolia	6.97	0.00	1.22	3.15	7.84	0.00	0.00	0.023	0.000	0.000	0.000	0.0227
Cuba	**17.60**	**4.81**	**4.76**	**14.93**	**19.68**	**0.48**	**0.00**	**0.068**	**0.051**	**0.047**	**0.000**	**0**
Europe	**1,187**	**454.7**	**342.6**	**500.0**	**1,125**	**16.17**	**3.19**	**166.3**	**4.809**	**5.576**	**39.17**	**31.637**
Albania	1.72	0.48	0.51	1.68	0.86	0.08	0.00	2.390	0.000	0.010	0.181	0.0162
Austria	30.58	0.00	8.22	10.84	27.38	0.00	0.00	9.001	0.000	0.000	3.583	1.0958
Belarus	17.39	0.00	4.00	5.94	33.96	0.00	0.01	0.097	0.000	0.000	0.000	0.01
Belgium	10.33	15.66	2.05	2.88	110.5	0.00	0.00	0.120	0.000	0.003	0.483	0.3057
Bosnia-Herzeg.	3.10	0.45	1.32	4.42	3.50	0.06	0.00	2.093	0.000	0.002	0.000	0.036
Bulgaria	12.94	8.21	4.25	8.78	7.14	0.00	0.00	1.725	0.000	0.010	0.100	0.1094
Croatia	3.37	0.00	3.89	5.57	13.05	0.23	0.01	1.848	0.000	0.066	0.161	0.0793
Cyprus	0.66	1.41	1.04	1.63	1.77	0.09	0.00	0.000	0.027	0.015	0.551	0.0103
Czech Rep.	22.66	0.00	6.24	9.64	42.93	0.00	0.00	1.097	0.000	0.000	0.781	0.3245
Denmark	15.55	5.20	2.58	2.22	12.34	0.00	0.00	0.009	0.151	0.073	1.175	0.7436
Estonia	3.28	1.70	0.67	0.84	2.79	0.00	0.00	0.008	0.000	0.048	0.012	0.063
Finland	44.71	12.39	3.34	2.63	27.02	0.00	0.00	3.263	0.000	0.023	0.048	2.3
France	125.9	45.22	56.85	76.37	99.36	4.49	0.04	19.67	0.809	1.000	1.951	2.5976
Germany	231.5	72.44	49.11	80.75	164.9	0.00	0.04	4.658	1.129	0.035	13.88	4.8063
Gibraltar	0.00	7.67	0.00	0.00	0.13	0.00	0.00	0.000	0.018	0.001	0.000	0
Greece	21.68	3.97	3.64	11.75	6.17	0.64	0.45	2.697	0.183	0.109	3.299	0.2595
Hungary	8.35	0.00	7.82	10.57	38.93	0.00	0.38	0.056	0.000	0.000	0.229	1.0237
Ireland	12.98	3.58	4.98	2.02	9.16	0.00	0.00	0.237	0.051	0.025	0.233	0.2009
Italy	126.5	35.27	38.83	40.57	59.84	4.70	1.00	14.91	1.204	0.075	3.305	1.425
Kosovo	1.38	0.00	0.27	0.91	0.90	0.02	0.80	0.092	0.000	0.000	0.000	0
Latvia	4.94	1.30	1.38	1.45	2.22	0.00	0.00	1.576	0.000	0.013	0.011	0.0016
Lithuania	8.62	3.36	2.41	3.69	5.71	0.00	0.00	0.116	0.000	0.004	0.013	0.1255
Luxembourg	0.70	0.00	0.15	0.24	12.23	0.00	0.00	0.034	0.000	0.000	0.046	0
Macedonia	1.53	0.00	1.00	2.44	3.37	0.00	0.00	0.674	0.000	0.000	0.068	0.0474
Malta	0.14	4.06	0.16	0.11	3.26	0.08	0.00	0.000	0.025	0.008	0.051	0
Moldova	3.66	0.00	1.43	0.98	4.76	0.00	0.00	0.076	0.000	0.000	0.000	0
Montenegro	0.83	0.20	0.22	0.75	0.37	0.01	0.00	0.658	0.000	0.009	0.000	0
Netherlands	17.53	41.34	3.14	3.90	98.99	0.00	0.00	0.038	0.000	0.012	0.460	1.7191
Norway	9.96	2.69	4.20	1.39	6.69	0.00	0.00	31.56	0.049	0.166	0.031	1.1502
Poland	69.85	19.60	22.36	59.49	37.59	0.00	0.11	0.605	0.000	0.012	1.791	0.756
Portugal	18.73	3.41	4.18	11.41	7.11	0.69	0.10	4.373	0.096	0.322	0.770	0.0211
Romania	27.70	6.30	7.77	12.24	12.62	0.00	0.10	6.221	0.000	0.008	0.143	0.2451
Serbia	5.30	0.00	5.58	10.25	18.41	0.00	0.00	2.484	0.000	0.000	0.000	0.1153
Slovakia	12.51	0.00	3.88	4.78	12.73	0.00	0.00	1.505	0.000	0.000	0.121	0.2303
Slovenia	5.89	1.04	1.34	2.89	2.59	0.00	0.10	1.344	0.000	0.003	0.104	0.2656
Spain	110.9	22.22	28.75	40.20	47.75	5.09	0.05	14.292	0.469	1.000	3.018	0.544
Sweden	45.62	12.38	5.31	4.12	28.79	0.00	0.00	16.379	0.000	0.100	0.374	6.68
Switzerland	15.36	0.00	3.06	10.50	10.20	0.00	0.00	13.852	0.000	0.000	1.186	2.1968
Ukraine	66.97	20.03	27.37	24.42	42.88	0.00	0.00	4.666	0.000	0.039	0.000	1.607
United Kingdom	65.87	103.1	19.26	24.75	103.73	0.00	0.00	1.879	0.599	2.386	1.010	0.5247
Haiti Region	**5.31**	**2.92**	**2.17**	**9.04**	**17.94**	**0.38**	**0.68**	**0.676**	**0.000**	**0.052**	**0.000**	**0**
Dominican Rep.	4.38	2.18	1.61	7.17	13.33	0.30	0.68	0.616	0.000	0.024	0.000	0
Haiti	0.93	0.74	0.56	1.87	4.61	0.08	0.00	0.060	0.000	0.029	0.000	0
Iceland	**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.89**	**2.086**	**0.010**	**0.038**	**0.000**	**2.373**
India Region	**668.2**	**108.0**	**89.46**	**1,361**	**2,097**	**92.85**	**0.28**	**49.08**	**4.938**	**0.874**	**9.457**	**0.3612**
Bangladesh	5.35	7.85	5.45	30.08	156.28	4.13	0.00	0.230	0.592	0.150	0.000	0
India	647.0	96.97	82.10	1,305	1,893	86.62	0.28	45.76	4.172	0.700	9.457	0.3576
Nepal	5.71	0.00	1.25	6.45	37.18	1.10	0.00	1.278	0.000	0.000	0.000	0.0036
Sri Lanka	10.09	3.22	0.67	18.86	10.63	1.00	0.00	1.809	0.173	0.024	0.000	0
Israel	**3.34**	**5.42**	**1.15**	**14.32**	**57.73**	**0.63**	**0.00**	**0.007**	**0.000**	**0.009**	**3.351**	**0.0824**
Jamaica	**0.38**	**3.23**	**2.68**	**2.67**	**3.76**	**0.16**	**0.00**	**0.030**	**0.000**	**0.020**	**0.000**	**0**
Japan	**10.81**	**303.8**	**22.27**	**14.99**	**373.6**	**0.00**	**1.46**	**22.379**	**2.667**	**2.200**	**2.580**	**2.5705**
Mauritius	**0.16**	**3.51**	**0.43**	**0.26**	**3.95**	**0.04**	**0.00**	**0.061**	**0.013**	**0.007**	**0.093**	**0**
Mideast	**673.8**	**139.8**	**331.1**	**355.23**	**1,668**	**36.79**	**1.74**	**48.849**	**0.441**	**0.284**	**19.06**	**3.7754**
Armenia	2.12	0.00	0.39	0.96	1.48	0.06	0.03	1.293	0.000	0.000	0.000	0.0015
Azerbaijan	8.74	0.00	3.14	7.76	12.02	0.13	0.00	1.131	0.000	0.000	0.000	0
Bahrain	0.20	2.90	1.11	0.54	38.12	0.48	0.00	0.000	0.000	0.006	0.000	0

Iran	231.5	44.01	123.9	112.4	291.6	10.11	0.01	11.129	0.000	0.036	0.000	0.0822
Iraq	36.11	1.05	12.49	29.58	46.86	1.46	0.00	2.513	0.000	0.003	0.000	0
Jordan	8.61	0.47	3.34	5.89	12.28	0.35	0.00	0.012	0.000	0.002	0.882	0.1533
Kuwait	1.28	9.00	3.17	1.99	96.59	1.25	0.00	0.000	0.000	0.013	0.000	0
Lebanon	0.88	4.06	3.03	1.75	15.05	0.31	0.00	0.282	0.000	0.008	0.583	0
Oman	22.15	9.25	13.75	8.72	53.72	1.36	0.00	0.000	0.411	0.032	0.000	0
Qatar	0.83	10.16	1.85	1.04	141.80	1.68	0.00	0.000	0.000	0.014	0.000	0
Saudi Arabia	176.5	29.09	114.82	89.55	404.35	9.29	0.00	0.000	0.000	0.038	0.000	0.045
Syria	7.91	2.10	2.71	6.47	5.21	0.32	0.00	1.505	0.000	0.007	0.000	0
Turkey	137.0	3.58	31.57	77.42	108.98	4.26	1.61	30.984	0.000	0.072	17.60	3.4884
UAE	38.12	23.77	14.80	8.93	436.71	5.62	0.00	0.000	0.000	0.024	0.000	0
Yemen	1.78	0.37	1.02	2.25	2.73	0.10	0.10	0.000	0.031	0.030	0.000	0.005
New Zealand	**38.06**	**1.63**	**4.96**	**6.97**	**21.99**	**0.57**	**2.00**	**5.354**	**0.077**	**0.200**	**0.112**	**0.518**
Philippines	**23.93**	**20.30**	**15.18**	**54.38**	**126.2**	**1.60**	**5.73**	**3.700**	**0.563**	**0.500**	**0.000**	**0.0017**
Russia Region	**507.1**	**51.07**	**55.49**	**74.18**	**159.6**	**0.00**	**0.50**	**51.98**	**2.051**	**0.359**	**0.018**	**0.5022**
Georgia	3.88	0.29	0.36	0.91	0.95	0.00	0.00	3.449	0.000	0.009	0.000	0.0692
Russia	503.3	50.78	55.12	73.26	158.7	0.00	0.50	48.527	2.051	0.350	0.018	0.433
South America	**1,145**	**105.1**	**121.7**	**258.4**	**354.5**	**23.13**	**5.35**	**175.6**	**4.828**	**1.188**	**11.59**	**0.6207**
Argentina	66.63	9.16	11.83	28.59	31.95	2.36	1.01	10.37	0.000	0.057	0.031	0.2048
Bolivia	8.88	0.00	1.03	2.26	5.41	0.20	1.26	0.735	0.000	0.000	0.000	0.001
Brazil	753.6	59.41	71.41	156.8	188.0	13.05	0.00	109.2	3.515	0.200	11.26	0.3634
Chile	32.50	7.78	11.08	18.35	26.51	2.49	1.63	6.945	0.186	0.100	0.248	0.0226
Colombia	81.73	6.84	7.65	16.81	20.25	1.39	0.00	11.94	0.328	0.500	0.000	0.02
Curacao	0.18	2.70	0.17	0.07	4.39	0.08	0.00	0.000	0.000	0.010	0.000	0
Ecuador	29.24	1.24	2.03	4.48	8.91	0.40	0.04	5.076	0.053	0.210	0.000	0.0052
Paraguay	3.94	0.00	0.40	0.90	2.10	0.08	0.00	8.810	0.000	0.000	0.000	0
Peru	56.63	0.01	4.11	8.96	21.52	0.82	1.41	5.396	0.117	0.035	0.000	0.003
Suriname	0.98	0.14	0.14	0.31	0.38	0.02	0.00	0.190	0.006	0.011	0.000	0
Trinidad/Tobago	0.27	9.47	2.81	0.97	21.38	0.44	0.00	0.000	0.127	0.010	0.000	0
Uruguay	7.95	0.84	1.16	2.72	3.07	0.23	0.00	1.538	0.068	0.015	0.053	0
Venezuela	102.1	7.52	7.84	17.15	20.64	1.56	0.00	15.39	0.428	0.039	0.000	0.0007
Southeast Asia	**54.35**	**1,431**	**491.0**	**577.3**	**1,119**	**28.66**	**13.76**	**45.06**	**4.421**	**0.635**	**0.110**	**0.154**
Brunei	0.05	3.84	1.62	1.44	3.36	0.08	0.00	0.000	0.023	0.006	0.000	0
Cambodia	1.57	6.78	4.61	10.08	9.48	0.41	0.00	1.330	0.000	0.012	0.000	0
Indonesia	39.25	236.4	141.2	311.8	294.2	11.02	9.79	6.121	1.493	0.269	0.000	0.0023
Lao PDR	0.01	0.00	0.01	0.02	0.03	0.00	0.00	7.376	0.000	0.000	0.000	0
Malaysia	2.84	210.8	91.56	67.49	203.3	4.55	0.00	6.275	1.163	0.054	0.000	0.005
Myanmar	5.75	10.72	8.26	18.35	17.06	0.97	0.00	3.331	0.267	0.200	0.000	0
Singapore	0.02	656.4	3.44	0.97	31.29	0.00	3.85	0.000	0.000	0.007	0.000	0
Thailand	4.42	145.2	131.4	99.14	335.6	6.56	0.12	3.513	0.000	0.043	0.110	0.1285
Vietnam	0.43	160.4	108.9	68.00	224.5	5.08	0.00	17.11	1.475	0.045	0.000	0.0182
South Korea	**2.14**	**374.7**	**67.56**	**119.7**	**363.1**	**9.07**	**0.00**	**1.806**	**0.000**	**1.000**	**1.324**	**1.4898**
Taiwan	**3.73**	**103.0**	**34.06**	**60.46**	**117.6**	**0.00**	**33.64**	**2.092**	**0.903**	**0.027**	**1.220**	**0.0001**
United States	**1,611**	**377.3**	**234.2**	**347.8**	**2,191**	**32.85**	**6.52**	**79.15**	**6.752**	**0.350**	**17.94**	**20.71**
All regions	**9,518**	**4,571**	**3,445**	**5,842**	**15,579**	**424.2**	**97.30**	**1,164**	**50.29**	**19.22**	**456.4**	**107.7**

Table S13. LOADMATCH capacity adjustment factors (CAFs), which show the ratio of the final nameplate capacity of a generator to meet load continuously, after running LOADMATCH, to the pre-LOADMATCH initial nameplate capacity estimated to meet load 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 the initial, pre-LOADMATCH nameplate-capacity assumption).

Region	(a) Onshore wind CAF	(b) Off-shore wind CAF	(c) Res. Roof PV CAF	(d) Com./Gov Roof PV CAF	(e) Utility PV CAF	(f) CSP turbine factor	(g) Solar Thermal CAF
Africa	1.15	1	1	1	1	1	1
Australia	1.18	0.7	0.75	0.75	1.95	1	1
Canada	1.15	0.9	0.2	0.7	0.5	0	1
Central America	1.7	1.5	0.7	0.7	3	1	1
Central Asia	2	0.9	0.85	0.85	0.9	1	0
China	1.4	0.7	0.55	0.55	1.7	1	1
Cuba	1.9	1.3	1	1.4	3.6	1	0
Europe	1.4	1	0.68	0.9	1	1	1
Haiti	0.8	1	0.5	1	3.6	1	0
Iceland	0.29	0.03	0	0	0	0	0
India	0.9	0.6	0.1	1.3	1.4	1.6	1
Israel	1.3	0.88	0.1	2.3	2.6	1	1
Jamaica	0.8	1.45	0.9	1	1.1	1	0
Japan	0.2	2	0.2	0.2	1.3	0	1
Mauritius	1.6	2.5	0.2	0.2	1.6	0.4	1
Mideast	2	0.8	0.75	0.75	1.25	1	1
New Zealand	2.7	0.4	0.6	0.6	2.3	0.7	1
Philippines	1.9	0.9	0.55	0.9	4	0.8	0
Russia	1.77	0.55	0.35	0.35	0.8	0	1
South America	1.25	0.72	0.6	0.6	1.38	1	1
Southeast Asia	0.2	2	1	1	1.8	1	1
South Korea	0.1	2	0.9	2.5	1.2	1	1
Taiwan	0.5	1.8	0.7	2.5	1.21	0	1
United States	1.7	0.95	0.45	0.45	2.35	1	1

All generators not on this list have a CAF=1. Table S12 provides final nameplate capacities 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 S14. Simulation-averaged 2050-2052 capacity factors (percentage of nameplate capacity produced as electricity before transmission, distribution, or maintenance losses) by region in this study. The mean capacity factors in this table equal the simulation-averaged power output supplied by each generator in each region from Table S15 divided by the final nameplate capacity of each generator in each region from Table S12.

Region	Onshore wind	Offshore wind	Rooftop PV	Utility PV	CSP with storage	Geothermal electricity	Hydropower	Wave	Tidal	Solar thermal	Geothermal heat
Africa	0.373	0.443	0.202	0.217	0.76	0.809	0.437	0.175	0.223	0.111	0.54
Australia	0.337	0.427	0.197	0.229	0.79	0.904	0.479	0.332	0.247	0.109	0.54
Canada	0.501	0.587	0.177	0.18	0	0.862	0.588	0.297	0.235	0.097	0.54
Central America	0.293	0.306	0.199	0.221	0.82	0.84	0.439	0.126	0.229	0.12	0.54
Central Asia	0.538	0.508	0.2	0.237	0.82	0	0.433	0.121	0.216	0	0.54
China	0.471	0.372	0.2	0.221	0.73	0.896	0.479	0.139	0.243	0.109	0.54
Cuba	0.423	0.306	0.166	0.178	0.7	0	0.449	0.379	0.232	0	0
Europe	0.444	0.513	0.171	0.176	0.67	0.861	0.47	0.203	0.237	0.093	0.54
Haiti	0.321	0.428	0.213	0.232	0.79	0.876	0.455	0	0.216	0	0
Iceland	0.573	0.625	0	0	0	0.925	0.679	0.317	0.253	0	0.54
India	0.454	0.411	0.197	0.227	0.78	0.857	0.449	0.133	0.233	0.11	0.54
Israel	0.47	0.365	0.236	0.259	0.89	0	0.484	0	0.252	0.132	0.54
Jamaica	0.344	0.388	0.213	0.23	0.79	0	0.408	0	0.208	0	0
Japan	0.388	0.449	0.177	0.2	0	0.909	0.479	0.141	0.248	0.097	0.54
Mauritius	0.437	0.408	0.204	0.222	0.75	0	0.483	0.316	0.251	0.113	0
Mideast	0.49	0.492	0.221	0.251	0.86	0.798	0.431	0.135	0.233	0.113	0.54
New Zealand	0.506	0.563	0.177	0.197	0.65	0.885	0.479	0.353	0.242	0.097	0.54
Philippines	0.241	0.299	0.206	0.229	0.8	0.858	0.453	0.133	0.234	0	0.54
Russia	0.478	0.579	0.173	0.197	0	0.863	0.475	0.256	0.236	0.095	0.54
South America	0.177	0.362	0.189	0.207	0.72	0.883	0.637	0.149	0.239	0.11	0.54
Southeast Asia	0.124	0.217	0.199	0.214	0.73	0.879	0.445	0.178	0.226	0.116	0.54
South Korea	0.366	0.352	0.179	0.193	0.63	0	0.485	0	0.251	0.097	0.54
Taiwan	0.266	0.345	0.182	0.196	0	0.927	0.489	0.144	0.255	0.1	0.54
United States	0.379	0.294	0.197	0.207	0.86	0.891	0.471	0.294	0.244	0.104	0.54
Average	0.403	0.344	0.196	0.218	0.76	0.887	0.501	0.182	0.239	0.108	0.54

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). In all cases, capacity factors are before transmission, distribution, maintenance, storage, and shedding losses, which are summarized for each region in Tables S18 and S19. T&D loss rates are given in Table S20. The symbol "—" indicates no installation of the technology. Rooftop 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 (Jacobson and Jadhav, 2018).

Table S15. LOADMATCH 2050-2052 simulation-averaged all-sector projected WWS end-use power supplied (which equals power consumed plus power lost due to transmission, distribution, and maintenance losses; storage losses; and shedding losses), by region and percentage of such supply met by each generator. 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 S14) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table S12). The 2050 total WWS supply is also obtained from Column (f) of Table S18.

Region	Annual-average total WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with stor-age (%)	Geothermal elec-tricity (%)	Hydro power (%)	Wave (%)	Tidal (%)	Solar ther-mal heat (%)	Geo-ther-mal heat (%)
Africa	602.4	30.11	11.17	32.91	19.34	3.50	0.485	2.288	0.102	0.031	0.049	0.017
Australia	123.4	21.96	6.65	16.48	47.77	3.10	0.293	2.891	0.155	0.100	0.568	0.041
Canada	193.7	45.78	11.42	10.77	4.02	0	2.225	24.857	0.145	0.243	0.032	0.511
Central America	263.7	46.09	10.77	12.52	21.10	2.50	3.406	3.308	0.114	0.028	0.138	0.034
Central Asia	266.2	49.46	4.05	21.05	18.84	2.44	0.000	4.063	0.075	0.002	0	0.001
China	3,018	33.75	9.34	13.52	32.67	3.20	0.055	5.453	0.040	0.018	1.224	0.728
Cuba	16.1	46.29	9.17	20.29	21.78	2.10	0	0.190	0.120	0.068	0	0
Europe	1,218	43.32	19.15	11.84	16.27	0.88	0.225	6.418	0.080	0.109	0.301	1.404
Haiti	10.7	15.90	11.68	22.31	38.78	2.79	5.563	2.873	0	0.106	0	0
Iceland	4.11	13.99	0.04	0	0	0	20.03	34.43	0.076	0.231	0	31.20
India	1,207	25.14	3.68	23.66	39.47	6.03	0.020	1.824	0.054	0.017	0.086	0.016
Israel	23.2	6.77	8.53	15.78	64.41	2.39	0	0.015	0	0.009	1.902	0.192
Jamaica	3.53	3.71	35.45	32.30	24.54	3.53	0	0.346	0	0.119	0	0
Japan	236.8	1.77	57.65	2.79	31.61	0	0.561	4.532	0.159	0.231	0.106	0.587
Mauritius	2.60	2.69	55.20	5.43	33.76	1.16	0	1.135	0.154	0.062	0.406	0
Mideast	1,027	32.16	6.70	14.78	40.68	3.09	0.135	2.050	0.006	0.006	0.209	0.199
New Zealand	31.7	60.78	2.90	6.66	13.68	1.17	5.580	8.08	0.086	0.152	0.034	0.883
Philippines	63.1	9.14	9.64	22.71	45.71	2.03	7.798	2.660	0.119	0.186	0	0.001
Russia	351.6	68.90	8.41	6.37	8.93	0	0.123	7.016	0.149	0.024	0.001	0.077
South America	521.5	38.80	7.29	13.79	14.06	3.18	0.906	21.46	0.138	0.055	0.245	0.064
Southeast Asia	824.3	0.82	37.71	25.79	29.11	2.54	1.468	2.435	0.095	0.017	0.002	0.010
South Korea	243.9	0.32	54.05	13.72	28.74	2.32	0	0.359	0	0.103	0.053	0.330
Taiwan	109.3	0.91	32.49	15.77	21.13	0	28.53	0.937	0.119	0.006	0.112	0.000
United States	1,377	44.31	8.06	8.33	33.03	2.04	0.422	2.707	0.144	0.006	0.136	0.813
All regions	**11,738**	**32.66**	**13.40**	**15.54**	**28.90**	**2.76**	**0.735**	**4.970**	**0.078**	**0.039**	**0.420**	**0.496**

Table S16. Aggregate (among all countries in each region) maximum instantaneous charge rates, maximum instantaneous discharge rates, and maximum energy storage capacities of the different types of electricity storage (PHS, CSP-PCM, batteries, hydropower), cold storage (CW-STES, ICE), and heat storage (HW-STES, UTES) technologies treated here, by region. Table S17 gives the maximum number of hours of storage at the maximum discharge rate. The product of the maximum discharge rate and hours of storage gives the maximum energy storage capacity. The maximum storage capacities are either of electricity for the electricity storage options or of thermal energy for the hot and cold storage options.

	Africa			**Australia**			**Canada**			**Central America**		
Storage technology	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh
PHS	27.8	27.8	0.39	10.7	10.7	0.150	16.6	16.6	0.233	6.00	6.00	0.084
CSP-elec.	27.7	27.7	--	4.86	4.86	--	0	0	--	8.05	8.05	--
CSP-PCM	44.7	--	0.6	7.84	--	0.110	0	--	0	12.98	--	0.182
Batteries	730	730	2.92	190	190	0.76	50	50	0.200	870	870	3.48
Hydropower	13.4	31.5	117.2	3.46	7.45	30.3	36.22	81.82	317.3	8.46	19.86	74.1
CW-STES	3.79	3.79	0.053	0.211	0.211	0.0029	0.248	0.248	0.0035	0.672	0.672	0.0094
ICE	5.68	5.68	0.080	0.316	0.316	0.0044	0.372	0.372	0.0052	1.01	1.01	0.0141
HW-STES	143.9	143.9	1.15	9.19	9.19	0.074	24.33	24.33	0.341	27.69	27.69	0.221
UTES-heat	2.85	143.95	103.6	6.55	9.19	0.221	2.47	24.33	5.839	3.19	27.69	0.664
UTES-elec.	143.9	--	--	9.19	--	--	24.33	--	--	27.69	--	--
	Central Asia			**China Region**			**Cuba**			**Europe**		
PHS	12.0	12.0	0.168	126.2	126.2	1.767	3.00	3.00	0.042	208.1	208.1	2.91
CSP-elec.	7.97	7.97	--	132.2	132.2	--	0.481	0.481	--	16.17	16.17	--
CSP-PCM	12.84	--	0.180	213.2	--	2.984	0.776	--	0.011	26.07	--	0.365
Batteries	115	115	0.46	2,000	2,000	8.00	95	95	0.380	900	900	3.60
Hydropower	10.44	24.96	91.4	158.0	343.7	1,384	0.030	0.068	0.260	75.36	166.3	660.2
CW-STES	0.066	0.066	0.0009	11.63	11.63	0.1628	0.101	0.101	0.0014	4.54	4.54	0.0636
ICE	0.099	0.099	0.0014	17.44	17.44	0.2442	0.152	0.152	0.0021	6.82	6.82	0.0954
HW-STES	27.02	27.02	0.216	558.2	558.2	2.791	1.67	1.67	0.013	311.1	311.1	1.867
UTES-heat	0.0029	27.02	12.971	378.2	558.2	160.8	0.00	1.67	2.084	70.80	311.1	37.333
UTES-elec.	27.02	--	--	558.2	--	--	1.67	--	--	311.1	--	--
	Haiti			**Iceland**			**India**			**Israel**		
PHS	2.00	2.00	0.028	0	0	0	25.8	25.8	0.361	11.1	11.1	0.155
CSP-elec.	0.378	0.378	--	0	0	--	92.85	92.85	--	0.625	0.625	--
CSP-PCM	0.61	--	0.009	0	--	0	149.7	--	2.096	1.01	--	0.014
Batteries	22	22	0.088	0	0	0	4,300	4,300	17.20	200	200	0.800
Hydropower	0.300	0.676	2.63	0.99	2.09	8.7	21.44	49.08	187.8	0.0033	0.0070	0.0289
CW-STES	0.033	0.033	.00046	0.018	0.018	0.00025	4.67	4.67	0.0653	0.109	0.109	0.0015
ICE	0.049	0.049	.00069	0.027	0.027	.00037	7.00	7.00	0.0980	0.164	0.164	0.0023
HW-STES	4	4	0	1.05	1.05	0.0084	326.5	326.5	2.612	2.95	2.95	0.024
UTES-heat	0	3.97	0.190	2	1	0	9.82	326.5	101.87	3.43	2.95	1.772
UTES-elec.	3.97	--	--	0	--	--	326.5	--	--	8.86	--	--
	Jamaica			**Japan**			**Mauritius**			**Mideast**		
PHS	3.00	3.00	0.042	176.7	176.7	2.47	40.0	40.0	0.560	14.5	14.5	0.203
CSP-elec.	0.157	0.157	--	0	0	--	0.040	0.040	--	36.79	36.79	--
CSP-PCM	0.254	--	0.0036	0	--	0	0.065	--	0.0009	59.32	--	0.830
Batteries	6	6	0.0220	440	440	1.76	0	0	0	1,300	1,300	5.20
Hydropower	0.012	0.03	0.1042	10.45	22.38	91.5	0.029	0.061	0.251	20.42	48.85	178.9
CW-STES	0	0	0	0.149	0.149	0.0021	0.028	0.028	.00039	1.16	1.16	0.0162
ICE	0	0	0	0.224	0.224	0.0031	0.042	0.042	.00059	1.74	1.74	0.0244
HW-STES	0.92	0.92	0.0074	21.57	21.57	0.173	0.101	0.101	0.0008	72.47	72.47	0.580
UTES-heat	0	0.92	0.0665	5.15	21.57	2.588	0.093	0.101	0.0483	22.84	72.47	17.392
UTES-elec.	0.09	--	--	21.57	--	--	0.101	--	--	217.4	--	--
	New Zealand			**Philippines**			**Russia**			**South America**		
PHS	6.0	6.0	0.084	22.4	22.4	0.314	20.8	20.8	0.292	19.5	19.5	0.273
CSP-elec.	0.57	0.57	--	1.60	1.60	--	0	0	--	23.13	23.13	--
CSP-PCM	0.92	--	0.013	2.58	--	0.036	0	--	0	37.29	--	0.522

Batteries	0	0	0	220	220	0.880	0	0	0	0	0	0
Hydropower	2.43	5.35	21.3	1.63	3.70	14.3	23.16	51.98	202.8	77.73	175.63	680.9
CW-STES	0.0043	0.0043	.00006	0.68	0.68	0.0095	1.37	1.37	0.0191	2.93	2.93	0.0410
ICE	0.01	0.01	0.0001	1.02	1.02	0.0142	2.05	2.05	0.0287	4.40	4.40	0.0616
HW-STES	1.07	1.07	0.009	26.50	26.50	0.212	100.42	100.42	1.004	61.79	61.79	0.494
UTES-heat	0.63	1.07	0.129	0.00	26.50	9.541	0.52	100.42	12.05	12.21	61.79	37.073
UTES-elec.	1.07	--	--	5.30	--	--	100.42	--	--	61.79	--	--
	Southeast Asia			**South Korea**			**Taiwan**			**United States**		
PHS	53.5	53.5	0.749	96.5	96.5	1.35	49.1	49.1	0.687	96.0	96.0	1.34
CSP-elec.	28.66	28.66	--	9.07	9.07	--	0	0	--	32.85	32.85	--
CSP-PCM	46.22	--	0.647	14.63	--	0.205	0	--	0	52.97	--	0.742
Batteries	950	950	3.80	1,150	1,150	4.60	1,100	1,100	4.40	2,680	2,680	10.72
Hydropower	19.29	45.06	169.0	0.85	1.81	7.473	1.00	2.09	8.724	36.25	79.15	317.5
CW-STES	3.25	3.25	0.0455	0.149	0.149	0.0021	0.23	0.23	0.0033	2.97	2.97	0.0416
ICE	4.87	4.87	0.0682	0.223	0.223	0.0031	0.35	0.35	0.0049	4.46	4.46	0.0624
HW-STES	129.6	129.6	1.037	18.28	18.28	0.146	20.45	20.45	0.164	167.6	167.6	1.341
UTES-heat	0.264	129.6	15.554	2.81	18.28	4.386	1.22	20.45	2.454	38.65	167.6	8.05
UTES-elec.	129.6	--	--	96.5	96.5	1.35	20.45	--	--	167.6	--	--
	All regions											
PHS	1,047	1,047	14.66									
CSP-elec.	424	424	--									
CSP-PCM	684	--	9.58									
Batteries	17,318	17,318	69.27									
Hydropower	521	1,164	4,567									
CW-STES	39.0	39.0	0.546									
ICE	58.5	58.5	0.819									
HW-STES	2,058	2,058	14.49									
UTES-heat	564	2,058	536.68									
UTES-elec.	2,186	--	--									

PHS=pumped hydropower storage; PCM=Phase-change materials; CSP=concentrated solar power; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; and UTES=Underground thermal energy storage (either boreholes, water pits, or aquifers). The peak energy storage capacity equals the maximum discharge rate multiplied by the maximum number of hours of storage at the maximum discharge rate. Table S17 gives maximum storage times at the maximum discharge rate.

Pumped hydro storage for 2050 in a country or region is estimated as the existing (in 2020) nameplate capacity in the country or region multiplied by the ratio of existing plus pending capacity to existing capacity for the U.S. (from FERC, 2021). If a country has no existing pumped hydro, a minimum is imposed to account for the addition of pumped hydro between 2021 and 2050.

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 direct CSP electricity production rate (CSP-elec) equals the maximum electricity discharge rate, which equals the nameplate capacity of the generator. The maximum charge rate of CSP phase-change material storage (CSP-PCM) 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 energy storage capacity equals the maximum electricity discharge rate multiplied by the maximum number of hours of storage at full discharge, set to 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 in 2050 is its 2020 nameplate capacity. Hydropower dam storage is filled naturally with rainfall and runoff. In 2050, hydropower's recharge rate is assumed to equal its 2020 annual energy output (TWh/y) in each region. Thus, its annual-average power recharge rate (GW) is the annual energy output divided by 8,760 h/y. This power recharge rate is applied each 30-s time step during a year so that the annual energy recharge rate equals hydropower's 2020 energy output. Given the substantial interannual variation of both monthly rainfall and runoff in each region (e.g., USGS, 2023), this simplistic treatment of water recharging may be as representative as any. Hydropower's output from reservoir storage during a given time step is limited by the smallest among three factors: the current energy available in the reservoir above a limit of half the reservoir's capacity (thus no energy is drawn if the reservoir is less than half full), the peak hydropower discharge rate (hydropower turbine nameplate capacity, provided in this table) multiplied by the time step, and the energy needed during the time step to keep the grid stable. The reservoir maximum energy capacity (this table) is assumed to equal hydropower's 2020 annual energy output.

The CW-STES peak discharge rate is set equal to 40% of the annual-average cold load (for air conditioning and refrigeration) subject to storage, which is given in Table S10 for each region. The ICE storage discharge rate is set to 60% of the same annual-average cold load subject to storage. The peak charge rate is set equal to the peak discharge rate. Heat pumps are used to produce both cold water and ice. Table S21 (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 load subject to storage during any 30-second period of the two-year 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 S21 (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 loads, they are higher than the annual-average low-temperature heat loads subject to storage in Table S10. The peak charge rate is set equal to the peak discharge rate.

UTES heat stored in underground soil (borehole storage) or water (water pit or aquifer storage) can be charged with either solar or geothermal heat or excess electricity (assuming the electricity produces heat with an electric heat pump at 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 divided by the coefficient of performance of a heat pump=4). When no solar thermal collectors are used, such as in all simulations here, 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 load 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 load 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 S21 (footnotes) provides the cost of the heat pumps per kW-electricity consumed to charge storage with electricity.

Table S17. Maximum number of days of storage at the maximum discharge rate (given in Table S16 for each region) of (a) underground thermal energy storage (UTES), (b) hot water thermal energy storage (HW-STES), and (c) hydrogen storage (H_2). (d) Battery full cycles per year; (e) the maximum discharge rate during any time interval of the simulation; and (f) the number of hours of battery storage actually needed for the simulation, which equals the ratio of the storage capacity of batteries (TWh) from Table S16 divided by the maximum discharge rate during any time interval of the simulation (TW) from Column (e). The maximum discharge rate actually occurring is always less than or equal to the maximum discharge rate allowed in Table S16. (g) additional HVDC line length needed in each region; (h) additional HVDC line capacity needed in each region; (i) fraction of non-roof PV and non-shed energy that is subject to HVDC transmission in each region; and (j) the fraction of building heating and cooling load that is subject to district heating and cooling in the baseline case.

Region	(a) UTES (days)	(b) HW-STES (hours)	(c) H_2 (days)	(d) Battery full cycles per year	(e) Max battery discharge rate occurring during simulation (TW)	(f) Ratio of max storage capacity (TWh) to max battery dis-charge rate (TW) during simu-lation (hours)	(g) HVDC line length (km)	(h) HVDC line capacity (MW)	(i) Frac-tion of non-roof PV/non-shed elect-ricity subject to HVDC	(j) Fraction of building heating/ cooling subject to district heating/ cooling
Africa	30	8	12	171	0.302	9.7	3,057	192,210	0.3	0.1
Australia	1	8	20	210	0.08	9.5	2,857	47,526	0.3	0.1
Canada	10	14	0	114	0.05	4.0	3,359	98,341	0.3	0.2
Central America	1	8	15	22	0.129	26.9	2,266	56,257	0.2	0.1
Central Asia	20	8	2	78	0.114	4.0	2,394	75,041	0.3	0.01
China	12	5	9	176	1.42	5.6	3,067	1,319,436	0.3	0.3
Cuba	52	8	31	32	0.01	39.5	0	0	0	0.2
Europe	5	6	30	92	0.6	6.0	3,006	542,503	0.3	0.5
Haiti	2	0	11	141	0.007	11.8	0	0	0	0.05
Iceland	0	8	1	0	0	--	0	0	0	0.92
India	13	8	1	114	0.997	17.3	3,186	474,072	0.3	0.1
Israel	25	8	31	38	0.016	48.9	0	0	0	0.2
Jamaica	3	8	5	167	0.003	8.6	0	0	0	0
Japan	5	8	5	46	0.139	12.7	3,005	79,025	0.2	0.1
Mauritius	20	8	5	0	0	--	0	0	0	0.2
Mideast	10	8	9	125	0.494	10.5	2,628	372,677	0.3	0.05
New Zealand	5	8	1	0	0	--	2,012	4,964	0.15	0.05
Philippines	15	8	10	74	0.055	15.9	2,484	12,472	0.2	0.2
Russia	5	10	2	0	0	--	2,915	167,117	0.3	0.5
South America	25	8	1	0	0	--	3,432	256,457	0.3	0.1
Southeast Asia	5	8	8	182	0.422	9.0	2,708	253,338	0.3	0.1
South Korea	10	8	15	22	0.141	32.6	0	0	0	0.15
Taiwan	5	8	40	21	0.082	53.7	0	0	0	0.15
United States	2	8	10	62	0.74	14.5	2,662	568,906	0.3	0.2

For all regions, the maximum number of hours of CSP storage at the maximum discharge rate is 22.6 h; those for PHS, cold water storage (CW-STES), and ICE storage are 14 h; and that for battery storage is 4 h. The maximum number of hours of storage multiplied by the maximum discharge rate in Table S16 equals the maximum storage capacity in Table S16.

No battery-related values are shown for Iceland since Iceland requires no battery storage (Table S16).

The product of Columns (g), (h) and \$400/MW-km (Jacobson et al., 2017) gives the capital cost of HVDC transmission.

Table S18. 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 S19 by dividing values from the table in units of TWh per simulation by the number of hours of simulation. Figure S1 shows the time series of matching demand with supply and changes in storage for each region. 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) Annua-average end-use load (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Shedding losses (GW)	**(e) End-use load+ 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	482.15	33.28	18.82	69.62	**603.9**	602.5	1.399	**603.9**
Australia	92.28	8.00	2.62	20.46	**123.4**	123.4	-0.015	**123.4**
Canada	170.28	13.27	2.49	7.81	**193.9**	193.7	0.189	**193.9**
Central America	156.49	17.79	2.11	87.37	**263.8**	263.8	-0.036	**263.8**
Central Asia	166.87	16.60	2.60	80.01	**266.1**	266.2	-0.136	**266.1**
China	2,423.9	200.24	70.72	327.85	**3,022.7**	3018.6	4.090	**3,022.7**
Cuba	8.99	1.01	0.37	5.70	**16.06**	16.1	-0.011	**16.06**
Europe	958.29	82.51	30.82	145.56	**1,217.2**	1217.7	-0.516	**1,217.2**
Haiti	7.60	0.66	0.40	2.05	**10.71**	10.71	-0.002	**10.71**
Iceland	3.17	0.31	0.00	0.63	**4.11**	4.11	0.000	**4.11**
India	1,006.8	73.34	40.37	88.40	**1,208.9**	1,207.0	1.960	**1,208.9**
Israel	12.77	1.50	0.67	8.31	**23.25**	23.17	0.078	**23.25**
Jamaica	2.56	0.20	0.06	0.72	**3.54**	3.53	0.002	**3.54**
Japan	186.33	17.35	2.78	30.36	**236.82**	236.83	-0.011	**236.82**
Mauritius	1.89	0.19	0.08	0.45	**2.60**	2.60	0.005	**2.60**
Mideast	706.51	67.82	17.44	235.49	**1,027.3**	1,027.0	0.216	**1,027.3**
New Zealand	16.70	2.25	0.10	12.65	**31.71**	31.7	-0.001	**31.71**
Philippines	41.02	3.87	1.99	16.39	**63.27**	63.1	0.196	**63.27**
Russia	268.30	25.03	9.65	48.71	**351.69**	351.6	0.068	**351.69**
South America	468.71	34.75	5.89	12.25	**521.60**	521.7	-0.077	**521.60**
Southeast Asia	584.57	49.08	14.96	175.95	**824.56**	824.6	-0.015	**824.56**
South Korea	154.38	16.29	3.15	70.15	**243.97**	244.0	-0.041	**243.97**
Taiwan	89.91	7.16	2.39	9.80	**109.25**	109.3	-0.034	**109.25**
United States	959.46	96.30	19.78	301.23	**1,376.8**	1,376.9	-0.101	**1,376.8**
All regions	8,970	768.8	250.2	1,757.9	**11,747**	11,740	7.208	**11,747**

Table S19. Budget of total end-use energy demand met, energy lost, WWS energy supplied, and changes in storage, during the three-year (26,291.4875 hour) simulation for each region and summed over all regions. All units are TWh over the simulation. Divide by the number of hours of simulation to obtain simulation-averaged power values, which are provided in Table S18 for key parameters.

	Africa	Australia	Canada	Central America	Central Asia
A1. Total end use demand	**12,676**	**2,426**	**4,477**	**4,114**	**4,387**
Electricity for electricity inflexible demand	6,291	1,285	2,352	1,936	2,348
Electricity for electricity, heat, cold storage + DR	5,159	892	1,746	1,830	1,674
Electricity for H_2 direct use + H_2 storage	1,226	249	379	348	365
A2. Total end use demand	**12,676**	**2,426**	**4,477**	**4,114**	**4,387**
Electricity for direct use, electricity storage, + H_2	11,812	2,372	4,290	3,960	4,186
Low-T heat load met by heat storage	802	52	186	140	200
Cold load met by cold storage	62.12	2.54	1.08	13.99	1.57
A3. Total end use demand	**12,676**	**2,426**	**4,477**	**4,114**	**4,387**
Electricity for direct use, electricity storage, DR	10,395	2,088	3,826	3,582	3,818
Electricity for H_2 direct use + H_2 storage	1,226	249	379	348	365
Electricity + heat for heat subject to storage	806	76	255	140	200
Electricity for cold load subject to storage	248.96	13.84	16.28	44.16	4.34
B. Total losses	**3,200**	**817**	**620**	**2,820**	**2,608**
Transmission, distribution, downtime losses	875	210	349	468	437
Losses CSP storage	3.61	1	0.00	0.41	0.35
Losses PHS storage	0.27	0.1196	2.6820	0.0198	0.3420
Losses battery storage	167	53.2	7.59	25.6	11.9
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	11	0.5	0.19	2.5	0.3
Losses HW-STES storage	106	5.7	25	26.9	36.3
Losses UTES storage	207	8.6	30	0.0	19.1
Losses from shedding	1,831	538	205	2,297	2,104
Net end-use demand plus losses (A1 + B)	***15,877***	***3,243***	***5,097***	***6,935***	***6,996***
C. Total WWS supply before T&D losses	**15,840**	**3,244**	**5,092**	**6,936**	**6,999**
Onshore + offshore wind electricity	6,539	928	2,913	3,944	3,746
Rooftop + utility PV+ CSP electricity	8,830	2,184	753	2,504	2,964
Hydropower electricity	362.5	93.8	1,265.6	229.4	284.4
Wave electricity	16.16	5.03	7.37	7.94	5.23
Geothermal electricity	76.7854	9.5047	113.2666	236.2056	0
Tidal electricity	4.8689	3.2488	12.387	1.961	0.117
Solar heat	7.7406	18.4275	1.6265	9.5528	0
Geothermal heat	2.7599	1.3416	26.0254	2.3516	0.0416
D. Net taken from (+) or added to (-) storage	**36.7945**	**-0.3904**	**4.9586**	**-0.9422**	**-3.5659**
CSP storage	0.1321	0.0159	0	-0.0182	-0.045
PHS storage	-0.0389	-0.0374	0.1745	-0.0084	-0.042
Battery storage	0.71	0.0071	0.15	-0.348	-0.115
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.1193	0.0055	-0.0004	-0.0024	-0.0006
HW-STES storage	1.0364	-0.0184	0.2554	-0.0221	-0.0541
UTES storage	25.8193	-0.0551	4.379	-0.0664	-3.2428
Non-grid H_2 storage	9.0163	-0.3079	0	-0.4766	-0.0666
Energy supplied plus taken from storage (C+D)	***15,877***	***3,243***	***5,097***	***6,935***	***6,996***

	China	Cuba	Europe	Haiti	Iceland
A1. Total end use demand	**63,727**	**236**	**25,194.9**	**200**	**83**

Electricity for electricity inflexible demand	29,896	119	11,473.7	100	31
Electricity for electricity, heat, cold storage + DR	24,136	108	10,454.9	81	49
Electricity for H_2 direct use + H_2 storage	9,695	10	3,266.3	19	4
A2. Total end use demand	**63,727**	**236**	**25,194.9**	**200**	**83**
Electricity for direct use, electricity storage, + H_2	59,219	224	21,802.6	191	69
Low-T heat load met by heat storage	4,368	10	3,354.8	8	15
Cold load met by cold storage	139.49	2.21	37.46	0.59	0.00
A3. Total end use demand	**63,727**	**236**	**25,194.9**	**200**	**83**
Electricity for direct use, electricity storage, DR	48,744	210	18,242.4	170	65
Electricity for H_2 direct use + H_2 storage	9,695	10	3,266.3	19	4
Electricity + heat for heat subject to storage	4,523	11	3,387.5	8	15
Electricity for cold load subject to storage	764.42	6.67	298.66	2.14	0.00
B. Total losses	**15,744**	**186**	**6,807**	**82**	**25**
Transmission, distribution, downtime losses	5,265	27	2,169.37	17	8
Losses CSP storage	15.08	0.03	0.6666	0.04	0.00
Losses PHS storage	5.5143	0.0028	10	0.0013	0.0000
Losses battery storage	468	3.99	111	4.1	0.00
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	25	0.40	7	0.1	0.00
Losses HW-STES storage	437	1.08	553	0.0	0.00
Losses UTES storage	909	4.15	128	6.3	0.00
Losses from shedding	8,620	150	3,827.0	53.9	16.7
Net end-use demand plus losses (A1 + B)	***79,471***	***422***	***32,001.6***	***281.7***	***108.1***
C. Total WWS supply before T&D losses	**79,363**	**423**	**32,015.2**	**282**	**108**
Onshore + offshore wind electricity	34,193	234	19,999.8	78	15
Rooftop + utility PV+ CSP electricity	39,204	187	9,282.0	180	0
Hydropower electricity	4,327.5	0.8	2,054.7	8.1	37.2
Wave electricity	31.78	0.51	25.74	0.00	0.08
Geothermal electricity	43.8315	0	72.13	15.6697	21.6528
Tidal electricity	13.888	0.287	34.819	0.298	0.250
Solar heat	971.8804	0	96.332	0	0
Geothermal heat	577.4566	0	449.6054	0	33.7242
D. Net taken from (+) or added to (-) storage	**107.545**	**-0.2803**	**-13.5685**	**-0.0495**	**-0.0016**
CSP storage	1.4155	-0.0011	-0.0365	-0.0008	0
PHS storage	-0.1767	-0.0042	-0.2913	-0.0028	0
Battery storage	1.8185	-0.038	-0.36	-0.0088	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	-0.0275	-0.0004	-0.0159	-0.0001	-0.0003
HW-STES storage	2.512	-0.0013	-0.1867	0	-0.0042
UTES storage	104.5645	-0.2084	-3.7333	-0.0188	0
Non-grid H_2 storage	-2.5613	-0.0269	-8.9448	-0.0181	0.0029
Energy supplied plus taken from storage (C+D)	***79,471***	***422***	***32,001.6***	***281.7***	***108.1***

	India	Israel	Jamaica	Japan	Mauritius
A1. Total end use demand	**26,471**	**336**	**67**	**4,899**	**50**
Electricity for electricity inflexible demand	12,686	182	29	2,699	19
Electricity for electricity, heat, cold storage + DR	11,007	133	29	1,417	21
Electricity for H_2 direct use + H_2 storage	2,778	21	9	782	10
A2. Total end use demand	**26,471**	**336**	**67**	**4,899**	**50**
Electricity for direct use, electricity storage, + H_2	25,441	316	66	4,713	48
Low-T heat load met by heat storage	982	19	1	184	2
Cold load met by cold storage	48.25	1.33	0.00	1.83	0.59

A3. Total end use demand	**26,471**	**336**	**67**	**4,899**	**50**
Electricity for direct use, electricity storage, DR	22,278	289	58	3,919	36
Electricity for H_2 direct use + H_2 storage	2,778	21	9	782	10
Electricity + heat for heat subject to storage	1,108	19	1	188	2
Electricity for cold load subject to storage	306.75	7.17	0.00	9.81	1.84
B. Total losses	**5,314**	**275**	**26**	**1,328**	**19**
Transmission, distribution, downtime losses	1,928	39	5	456	5
Losses CSP storage	13.19	0.08	0.02	0.00	0.00
Losses PHS storage	0.0021	0.03	0.19	1.80	1.43
Losses battery storage	654	10	1	27	0
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	8.71	0.24	0.00	0.33	0.11
Losses HW-STES storage	122.31	1	0	25	0
Losses UTES storage	262.89	6	0	19	0
Losses from shedding	2,324	219	19	798	12
Net end-use demand plus losses (A1 + B)	***31,785***	***611***	***93***	***6,226***	***68***
C. Total WWS supply before T&D losses	**31,733**	**609**	**93**	**6,227**	**68**
Onshore + offshore wind electricity	9,145	93	36	3,700	40
Rooftop + utility PV+ CSP electricity	21,948	503	56	2,142	28
Hydropower electricity	578.9	0	0	282	1
Wave electricity	17.23	0	0	10	0
Geothermal electricity	6.31	0	0	34.8924	0
Tidal electricity	5.36	0.057	0.111	14.374	0.043
Solar heat	27	11.5871	0	6.5945	0.2775
Geothermal heat	5	1.171	0	36.5304	0
D. Net taken from (+) or added to (-) storage	**51.529**	**2.055**	**0.0418**	**-0.2963**	**0.1386**
CSP storage	0.9574	0.0127	-0.0004	0	0.0003
PHS storage	-0.018	-0.0155	-0.0042	-0.2474	0.0534
Battery storage	3.3797	0.143	-0.0022	-0.0787	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.001	0.0005	0	-0.0003	0.0009
HW-STES storage	2	0.0213	-0.0007	0.1553	0.0007
UTES storage	43.6296	1.3678	0.0532	-0.2375	0.0435
Non-grid H_2 storage	1.0979	0.5252	-0.0039	0.1123	0.0398
Energy supplied plus taken from storage (C+D)	***31,785***	***611***	***93***	***6,226***	***68***

	Mideast	**New Zealand**	**Philip-pines**	**Russia**	**South America**
A1. Total end use demand	**18,575**	**439**	**1,078**	**7,054**	**12,323**
Electricity for electricity inflexible demand	9,061	231	497	2,986	5,963
Electricity for electricity, heat, cold storage + DR	7,518	170	461	2,822	5,083
Electricity for H_2 direct use + H_2 storage	1,997	38	120	1,246	1,276
A2. Total end use demand	**18,575**	**439**	**1,078**	**7,054**	**12,323**
Electricity for direct use, electricity storage, + H_2	17,977	428	992	5,975	11,930
Low-T heat load met by heat storage	581	11	73	1,057	344
Cold load met by cold storage	17.99	0.06	13.17	22.02	49.42
A3. Total end use demand	**18,575**	**439**	**1,078**	**7,054**	**12,323**
Electricity for direct use, electricity storage, DR	15,912	390	841	4,615	10,510
Electricity for H_2 direct use + H_2 storage	1,997	38	120	1,246	1,276
Electricity + heat for heat subject to storage	590	11	73	1,104	344
Electricity for cold load subject to storage	76.29	0.29	44.51	89.79	192.72

B. Total losses	**8,433**	**395**	**585**	**2,192**	**1,391**
Transmission, distribution, downtime losses	1,783	59	102	658	914
Losses CSP storage	4.43	0.01	0.19	0.00	2.39
Losses PHS storage	0.06	1.77	0.08	4.94	27.23
Losses battery storage	216	0	22	0	0
Losses grid H_2 storage	0	0	0	0	0
Losses CW-STES + ICE storage	3.25	0.01	2.38	3.98	8.92
Losses HW-STES storage	56	1	10	205	44
Losses UTES storage	179	0	18	40	72
Losses from shedding	6,191	333	431	1,281	322
Net end-use demand plus losses (A1 + B)	***27,008***	***834***	***1,663***	***9,246***	***13,714***
C. Total WWS supply before T&D losses	**27,003**	**834**	**1,658**	**9,245**	**13,716**
Onshore + offshore wind electricity	10,491	531	311	7,147	6,323
Rooftop + utility PV+ CSP electricity	15,808	179	1,168	1,414	4,257
Hydropower electricity	553	67	44	649	2,943
Wave electricity	2	1	2	14	19
Geothermal electricity	36.558	46.5203	129.3001	11.3466	124.2522
Tidal electricity	1.737	1.271	3.084	2.234	7.470
Solar heat	56.4519	0.2852	0	0.0448	33.6144
Geothermal heat	53.6542	7.3616	0.0237	7.1371	8.8217
D. Net taken from (+) or added to (-) storage	**5.6779**	**-0.0212**	**5.1573**	**1.7927**	**-2.0153**
CSP storage	0.5782	-0.0013	0.0216	0	0.3539
PHS storage	-0.0203	-0.0028	-0.0157	-0.073	0.2459
Battery storage	0.7681	0	0.1681	0	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	-0.0029	0.0001	0.0216	-0.012	0.0924
HW-STES storage	0.5218	-0.0009	0.2014	-0.2511	-0.0487
UTES storage	4.3816	-0.0129	4.7957	0.0821	-3.7073
Non-grid H_2 storage	-0.5487	-0.0035	-0.0355	2.0466	1.0486
Energy supplied plus taken from storage (C+D)	***27,008***	***834***	***1,663***	***9,246***	***13,714***

	Southeast Asia	**South Korea**	**Taiwan**	**United States**	**All regions**
A1. Total end use demand	**15,369**	**4,059**	**2,364**	**25,226**	**235,833**
Electricity for electricity inflexible demand	6,889	2,158	1,157	12,889	113,278
Electricity for electricity, heat, cold storage + DR	6,623	1,306	986	10,340	94,048
Electricity for H_2 direct use + H_2 storage	1,858	594	221	1,997	28,507
A2. Total end use demand	**15,369**	**4,059**	**2,364**	**25,226**	**235,833**
Electricity for direct use, electricity storage, + H_2	14,790	3,878	2,255	23,803	220,740
Low-T heat load met by heat storage	508	179	107	1,393	14,573
Cold load met by cold storage	71.20	1.89	1.47	29.72	520
A3. Total end use demand	**15,369**	**4,059**	**2,364**	**25,226**	**235,833**
Electricity for direct use, electricity storage, DR	12,790	3,276	2,017	21,629	189,701
Electricity for H_2 direct use + H_2 storage	1,858	594	221	1,997	28,507
Electricity + heat for heat subject to storage	508	179	111	1,405	15,063
Electricity for cold load subject to storage	213.52	9.79	15.29	195.23	2,562
B. Total losses	**6,310**	**2,355**	**509**	**10,972**	**73,011**
Transmission, distribution, downtime losses	1,290	428	188	2,532	20,213
Losses CSP storage	3.13	0.64	0.00	2.13	47
Losses PHS storage	1.87	0.32	0.26	0.38	60
Losses battery storage	230	34	31	220	2,297
Losses grid H_2 storage	0	0	0	0	0

Losses CW-STES + ICE storage	12.86	0.34	0.27	5.37	94
Losses HW-STES storage	89	27	18	210	1,998
Losses UTES storage	56	21	14	82	2,083
Losses from shedding	4,626	1,844	258	7,920	46,219
Net end-use demand plus losses (A1 + B)	***21,679***	***6,414***	***2,872***	***36,197***	*308,844*
C. Total WWS supply before T&D losses	**21,679**	**6,415**	**2,873**	**36,200**	**308,654**
Onshore + offshore wind electricity	8,354	3,488	960	18,956	142,162
Rooftop + utility PV+ CSP electricity	12,453	2,873	1,060	15,714	145,693
Hydropower electricity	528	23	27	980	15,341
Wave electricity	21	0	3	52	240
Geothermal electricity	318.0787	0	819.6151	152.826	2,269
Tidal electricity	3.780	6.608	0.179	2.243	121
Solar heat	0.3349	3.3858	3.2135	49.065	1,298
Geothermal heat	2.1889	21.1719	0.0014	294.3594	1,531
D. Net taken from (+) or added to (-) storage	**-0.4036**	**-1.09**	**-0.8886**	**-2.6606**	**190**
CSP storage	-0.0323	0.0988	0	-0.0741	3.3767
PHS storage	-0.0374	-0.135	-0.0344	-0.1344	-0.8660
Battery storage	-0.19	-0.3833	-0.1857	-0.935	4.4998
Grid H_2 storage	0	0	0	0	0.0000
CW-STES+ICE storage	-0.0057	-0.0002	-0.0001	-0.0101	0.1624
HW-STES storage	-0.0519	0.1316	0.1375	0.9825	7.7972
UTES storage	0.3968	-0.3333	-0.1227	-0.8045	176.9701
Non-grid H_2 storage	-0.483	-0.4686	-0.6833	-1.6849	-2.4240
Energy supplied plus taken from storage (C+D)	***21,679***	***6,414***	***2,872***	***36,197***	***308,844***

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 S21. Generated electricity is shed 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 (formerly Repower) 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 S20. Parameters for determining costs of energy from electricity and heat generators.

	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	1.02 (0.85-1.18)	37.5 (35-40)	1.25 (1.2-1.3)	30 (25-35)	7.5 (5-10)
Offshore wind	1.96 (1.49-2.44)	80 (60-100)	2 (2-2)	30 (25-35)	7.5 (5-10)
Residential PV	1.93 (1.76-1.10)	27.5 (25-30)	0.75 (0.5-1)	44 (41-47)	1.5 (1-2)
Commercial/government PV	1.29 (0.93-1.66)	16.5 (13-20)	0.75 (0.5-1)	46 (43-49)	1.5 (1-2)
Utility-scale PV	0.75 (0.67-0.84)	19.5 (16.5-22.5)	0.75 (0.5-1)	48.5 (45-52)	7.5 (5-10)
CSP with storage[a]	4.58 (3.59-5.57)	50 (40-60)	1.25 (1-1.5)	45 (40-50)	7.5 (5-10)
Geothermal electricity	4.63 (3.97-5.29)	45 (36-54)	2.5 (2-3)	45 (40-50)	7.5 (5-10)
Hydropower	2.78 (2.36-3.20)	15.5 (15-16)	2.5 (2-3)	85 (70-100)	7.5 (5-10)
Wave	4.10 (2.82-5.39)	175 (100-250)	2 (2-2)	45 (40-50)	7.5 (5-10)
Tidal	3.65 (2.93-4.38)	125 (50-200)	2.5 (2-3)	45 (40-50)	7.5 (5-10)
Solar thermal heat	1.17 (1.06-1.29)	50 (40-60)	1.25 (1-1.5)	35 (30-40)	3 (2-4)
Geothermal heat	4.63 (3.97-5.29)	45 (36-54)	2 (1-3)	45 (40-50)	7.5 (5-10)

Capital costs (per MW of nameplate capacity) are an average of 2020 and 2050 values. 2050 costs are derived and sourced in Jacobson and Delucchi (2022), which uses the same methodology as in Jacobson et al. (2019). For comparison the capital costs of onshore wind and utility-scale PV from Lazard (2021) for 2021 are $1.025-1.35 million/MW and $0.8-0.95 million/MW, respectively.

O&M=Operation and maintenance. TDM=transmission/distribution/maintenance. 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) lines.

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 (in USD 2020) (Jacobson et al., 2017, but brought up to USD 2020), 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 S17 gives the total new HVDC line length and capacity needed and the fraction of all non-rooftop-PV and non-shed 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 S21. 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 S16) 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.

Table S21. Present value of mean 2020 to 2050 lifecycle costs of new storage capacity and round-trip efficiencies of the storage technologies treated here.

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
CSP-PCM	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
Heat				
HW-STES	12	0.4	40	83
UTES	1.6	0.4	4	56

PHS=pumped hydropower storage; CSP-PCM=concentrated solar power with phase change material for 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 (modeled as borehole).

All values reflect averages between 2020 and 2050. From Jacobson et al. (2019), 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 2020-2050 mean PHS round-trip efficiency estimated here (80%) can be compared with the U.S.-average value in 2019 of 79% (EIA, 2021a).

The CSP-PCM cost is for the PCM 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 CSP-PCM 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 (Mancini, 2006) 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 (2020) 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, by 2035 and take this as the mean between 2020 and 2050. For LI battery storage, the 2020-2050 mean round-trip efficiency is taken as the roundtrip efficiency of a 2021 Tesla Powerpack with four hours of storage (Tesla, 2021). 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 2020 and 2050 rather than values in 2016, which they were previously based on. UTES costs were also updated with data from Denmark (Jacobson, 2020, 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 heat pumps 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 a larger amount of heat or cold. Since the storage size for heat or cold as equivalent electricity is smaller than the storage size of the 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 2020 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.

Storage costs per unit energy generated are the product of the maximum energy storage capacity (Table S16) 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 S20), but with average 2020 to 2050 storage lifetimes of 17 (12 to 22) years for batteries and 32.5 (25 to 40) years all other storage, all divided by the annual-average end-use load met. At least one stationary storage battery (lithium-iron-phosphate) is warrantied up to 15,000 cycles (or 15 years) (Sonnen, 2021). 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 S22. Mean cost per kilogram of hydrogen produced of (a) electricity for electrolysis and compression, (b) electrolyzers and rectifiers, (c) compressors, (d) water for electrolysis plus H_2 fuel cooling and dispensing, (e) storage containers, and (f) the sum of all cost components, from the simulations. (g) Same as (f), but low estimated cost based on low electricity cost, capital costs, installation factor, and discount rate. (h) Same as (f) but high estimated cost based on high electricity cost, capital costs, installation factor, and discount rate.

Region	(a) Mean electricity cost (\$/kg-H_2-produced)	(b) Mean electro-lyzer + rectifier cost (\$/kg-H_2-produced)	(c) Mean compres-sor cost (\$/kg-H_2-produced)	(d) Mean water + dispensing + cooling cost (\$/kg-H_2-produced)	(e) Mean H_2 storage cost (\$/kg-H_2-produced)	(f) Mean total green H_2 cost (\$/kg-H_2-produced) =a+b+c+d+e	(g) Low total green H_2 cost (\$/kg-H_2-produced)	(h) High total green H_2 cost (\$/kg-H_2-produced)
Africa	4.07	1.47	0.018	0.18	0.88	6.62	4.85	9.26
Australia	4.00	1.47	0.018	0.18	1.47	7.14	5.18	10.04
Canada	3.04	0.41	0.006	0.18	0.00	3.64	2.98	4.46
Central America	5.13	1.47	0.018	0.18	1.10	7.90	5.70	11.17
Central Asia	3.77	1.47	0.018	0.18	0.15	5.59	4.31	7.25
China	3.82	1.47	0.018	0.18	0.66	6.16	4.63	8.28
Cuba	5.71	1.47	0.018	0.18	2.28	9.66	6.52	14.77
Europe	4.07	1.47	0.018	0.18	2.20	7.95	5.66	11.51
Haiti	4.10	1.47	0.018	0.18	0.81	6.58	4.87	9.07
Iceland	3.23	0.78	0.010	0.18	0.07	4.28	3.39	5.43
India	3.88	1.47	0.018	0.18	0.07	5.63	4.17	7.64
Israel	5.79	1.47	0.018	0.18	2.28	9.74	6.41	15.22
Jamaica	4.56	1.47	0.018	0.18	0.37	6.60	4.96	8.88
Japan	4.32	1.47	0.018	0.18	0.37	6.36	4.76	8.52
Mauritius	5.53	1.47	0.018	0.18	0.37	7.57	5.61	10.22
Mideast	3.78	1.47	0.018	0.18	0.66	6.11	4.58	8.24
New Zealand	3.84	1.47	0.018	0.18	0.07	5.58	4.38	7.07
Philippines	4.91	1.47	0.018	0.18	0.73	7.32	5.23	10.50
Russia	3.45	1.05	0.013	0.18	0.15	4.84	3.83	6.14
South America	3.94	1.47	0.018	0.18	0.07	5.68	4.41	7.28
Southeast Asia	5.46	1.47	0.018	0.18	0.59	7.72	5.77	10.42
South Korea	5.93	1.47	0.018	0.18	1.10	8.70	6.16	12.55
Taiwan	5.51	1.47	0.018	0.18	2.94	10.12	6.66	15.80
United States	4.14	1.47	0.018	0.18	0.73	6.55	4.87	8.91
All regions	**4.07**	**1.44**	**0.018**	**0.18**	**0.76**	**6.47**	**4.80**	**8.83**

Costs are averages of 2020 and 2050 values and in 2020 USD. The mean electricity cost is the "Total LCOE" from Table S23 multiplied by 47.1 kWh/kg-H_2 for electrolysis plus compression. Thus, the electricity cost used here for estimating hydrogen production cost is based on the time-average of all electricity produced rather than the cost of electricity at the time the hydrogen is produced. The estimated hydrogen electrolyzer capital cost is \$334.5 (232-437)/kW, where \$232/kW is the "future potential" value from Penev et al. (2019) and \$437/kW is the "moderate 2030" value from Mongird et al. (2020). \$334.5/kW is an average of the two. The rectifier capital cost is \$94 (84-103)/kW, where the values are the moderate, low, and high values, respectively from Mongird et al. (2020). A rectifier is needed to convert AC electricity to DC electricity used by the electrolyzer. The estimated compressor capital cost is \$39.3 (35-43)/kW, also from Mongird et al. (2020). The hydrogen storage container capital cost is estimated as \$250 (200-300)/kg-H_2-stored, where the mean value is approximately the "future case" estimate of \$245/kg-H_2 from Houchins and James (2022). The electrolyzer, rectifier, and storage installation factors, which account for the labor and materials cost of installation are all assumed to be 1.25 (1.2-1.3) (NREL, 2014). The compressor installation factor is assumed to be 1.87 (Penev et al., 2019). The electrolyzer, rectifier, compressor, and storage annual O&M costs are estimated as 7.8%, 1%, 4%, and 1% of the respective capital costs (Penev et al., 2019). The discount rate used is the social discount rate of 2 (1-3)%. Amortization times for determining annual costs equal equipment lifetimes. Electrolyzer, rectifier, and compressor lifetimes (Figure 1) are a function of use factor. Table 2 gives the use factors for each region used to derive the results in this table. The hydrogen storage container lifetime is estimated as 15 (10-20) years (James et al., 2016). For the electrolyzer plus rectifier and compressor, the 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 factor for the region from Table 2. 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 size to the H_2 production per year, both from Table 2. The water cost for electrolysis is estimated as \$0.0071 (\$0.0047-\$0.0094)/kg-H_2-produced (Jacobson et al., 2005). 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 (NREL, 2014). However, because only ~45% of the H_2 needed worldwide will be for vehicles (Table 1), the dispensing and cooling costs are multiplied by 0.45. Thus, the resulting summed cost of water, dispensing, and cooling is \$0.183 (0.14-0.225)/kg- H_2.

Table S23. Summary of WWS mean capital costs ($ trillion in 2020 USD) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) averaged over each simulation, for each region. Also shown is the energy consumed per year in each case and the resulting aggregate annual energy cost to the region. The last row in each case is the percent increase in the total LCOE and the total annual energy cost if the baseline battery system cost is increased from the mean value in Table S21 ($60/kWh-electricity storage) to the high value ($90/kWh-electricity storage), or by a factor of 1.5. All costs are averages between 2020 and 2050.

	Africa	Australia	Canada	Central America	Central Asia	China	Cuba
Capital cost new generators only ($tril)	2.826	0.470	0.464	1.112	0.924	10.428	0.073
Cap cost generators-storage-H_2-HVDC ($tril)	**3.671**	**0.627**	**0.638**	**1.449**	**1.101**	**14.442**	**0.103**
Components of total LCOE (¢/kWh-all-energy)							
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.142	0.171	0.226	0.095	0.125	0.195	0.000
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.833	3.591	2.506	5.467	3.811	3.214	5.527
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.006	0.072	0.028	0.022	0.000	0.177	0.000
LI battery storage	0.352	0.479	0.068	1.294	0.160	0.192	2.460
Grid H_2 production/compression/storage/fuel cell	0	0	0	0	0	0	0
CSP-PCM + PHS storage	0.023	0.028	0.012	0.020	0.023	0.021	0.058
CW-STES + ICE storage	0.003	0.001	0.001	0.002	0.000	0.002	0.004
HW-STES storage	0.019	0.006	0.016	0.011	0.010	0.009	0.012
UTES storage	0.224	0.003	0.036	0.004	0.081	0.069	0.242
Heat pumps for filling district heating/cooling	0.083	0.028	0.040	0.049	0.045	0.064	0.052
Non-grid H_2 production/compression/storage	0.524	0.684	0.108	0.498	0.321	0.754	0.338
Total LCOE (¢/kWh-all-energy)	**8.636**	**8.489**	**6.465**	**10.887**	**8.003**	**8.121**	**12.117**
LCOE (¢/kWh-replacing BAU electricity)	7.771	7.751	6.247	10.316	7.535	7.196	11.475
GW annual avg. end-use demand (Table S9)	482.1	92.3	170.3	156.5	166.9	2,423.9	9.0
TWh/y end-use demand (GW x 8,760 h/y)	4,224	808	1,492	1,371	1,462	21,234	79
Annual energy cost ($billion/y)	**364.7**	**68.6**	**96.4**	**149.2**	**117.0**	**1,724.4**	**9.5**
% rise in LCOE & annual cost if 1.5x battery cost	2.04	2.83	0.53	5.94	1.00	1.19	10.1
	Europe	Haiti	Iceland	India	Israel	Jamaica	Japan
Capital cost new generators only ($tril)	3.951	0.045	0.002	4.763	0.079	0.019	0.896
Cap cost generators-storage-H_2-HVDC ($tril)	**5.832**	**0.055**	**0.0023**	**7.029**	**0.139**	**0.022**	**1.234**
Components of total LCOE (¢/kWh-all-energy)							
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.198	0.000	0.000	0.175	0.000	0.000	0.148
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.455	3.887	1.597	3.008	4.011	4.924	4.149
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.115	0.000	1.676	0.010	0.277	0.000	0.045
LI battery storage	0.219	0.674	0.000	0.994	3.645	0.501	0.550
Grid H_2 production/compression/storage/fuel cell	0	0	0	0	0	0	0
CSP-PCM + PHS storage	0.025	0.048	0.000	0.030	0.122	0.168	0.102
CW-STES + ICE storage	0.002	0.002	0.002	0.002	0.003	0.000	0.000
HW-STES storage	0.015	0.000	0.021	0.020	0.014	0.023	0.007
UTES storage	0.041	0.026	0.000	0.106	0.145	0.027	0.015
Heat pumps for filling district heating/cooling	0.090	0.145	0.046	0.090	0.129	0.055	0.032
Non-grid H_2 production/compression/storage	1.067	0.507	0.096	0.389	0.522	0.564	0.691
Total LCOE (¢/kWh-all-energy)	**8.652**	**8.714**	**6.863**	**8.249**	**12.293**	**9.687**	**9.164**
LCOE (¢/kWh-replacing BAU electricity)	7.413	8.036	6.701	7.625	11.483	9.018	8.396
GW annual avg. end-use demand (Table S9)	958.3	7.6	3.2	1,006.8	12.8	2.6	186.3
TWh/y end-use demand (GW x 8,760 h/y)	8,394	67	28	8,820	112	22	1,632
Annual energy cost ($billion/y)	**726.3**	**5.8**	**1.9**	**727.5**	**13.8**	**2.2**	**149.6**
% rise in LCOE & annual cost if 1.5x battery cost	1.26	3.87	1.54	6.03	14.8	2.59	3.00
	Mauritius	Mideast	New Zealand	Philippines	Russia	South America	Southeast Asia
Capital cost new generators only ($tril)	0.011	3.458	0.084	0.286	0.948	2.319	5.576
Cap cost generators-storage-H_2-HVDC ($tril)	**0.021**	**4.543**	**0.094**	**0.397**	**1.309**	**2.902**	**6.435**
Components of total LCOE (¢/kWh-all-energy)							

Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.000	0.161	0.070	0.088	0.212	0.219	0.137
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.656	3.333	4.165	4.619	2.962	4.156	6.935
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.049	0.039	0.076	0.000	0.004	0.028	0.001
LI battery storage	0	0.428	0	1.249	0	0	0.378
Grid H_2 production/compression/storage/fuel cell	0	0	0	0	0	0	0
CSP-PCM + PHS storage	2.709	0.018	0.056	0.079	0.009	0.020	0.026
CW-STES + ICE storage	0.005	0.001	0	0.006	0.002	0.002	0.002
HW-STES storage	0.003	0.006	0.004	0.040	0.029	0.008	0.014
UTES storage	0.027	0.026	0.008	0.243	0.047	0.083	0.028
Heat pumps for filling district heating/cooling	0.015	0.057	0.018	0.108	0.104	0.037	0.062
Non-grid H_2 production/compression/storage	0.844	0.533	0.321	0.568	0.524	0.384	0.580
Total LCOE (¢/kWh-all-energy)	**11.734**	**8.026**	**8.143**	**10.425**	**7.318**	**8.360**	**11.587**
LCOE (¢/kWh-replacing BAU electricity)	10.845	7.387	7.786	9.456	6.576	7.826	10.888
GW annual avg. end-use demand (Table S9)	1.9	706.5	16.7	41.0	268.3	468.7	584.6
TWh/y end-use demand (GW x 8,760 h/y)	17	6,189	146	359	2,350	4,106	5,121
Annual energy cost ($billion/y)	**1.9**	**496.8**	**11.9**	**37.5**	**172.0**	**343.3**	**593.4**
% rise in LCOE & annual cost if 1.5x battery cost	0	2.67	0	5.99	0	0	1.63

	South Korea	Taiwan	United States	All regions
Capital cost new generators only ($tril)	1.322	0.590	4.911	45.556
Cap cost generators-storage-H_2-HVDC ($tril)	**1.736**	**0.940**	**6.563**	**61.283**
Components of total LCOE (¢/kWh-all-energy)				
Short-dist. transmission	1.050	1.050	1.050	1.050
Long-distance transmission	0.000	0.000	0.184	0.174
Distribution	2.375	2.375	2.375	2.375
Electricity generation	6.370	4.328	3.975	3.763
Additional hydro turbines	0	0	0	0
Geothermal + solar thermal heat generation	0.030	0.014	0.067	0.078
LI battery storage	1.734	2.848	0.650	0.449
Grid H_2 production/compression/storage/fuel cell	0	0	0	0
CSP-PCM + PHS storage	0.093	0.066	0.020	0.027
CW-STES + ICE storage	0.000	0.001	0.001	0.002
HW-STES storage	0.007	0.014	0.011	0.013
UTES storage	0.030	0.028	0.009	0.062
Heat pumps for filling district heating/cooling	0.033	0.063	0.049	0.066
Non-grid H_2 production/compression/storage	0.862	0.914	0.404	0.615
Total LCOE (¢/kWh-all-energy)	**12.585**	**11.702**	**8.794**	**8.673**
LCOE (¢/kWh-replacing BAU electricity)	11.653	10.682	8.307	7.896
GW annual avg. end-use demand (Table S9)	154.4	89.9	959.5	8,970
TWh/y end-use demand (GW x 8,760 h/y)	1,352	788	8,405	78,578
Annual energy cost ($billion/y)	**170.2**	**92.2**	**739.2**	**6,815**
% rise in LCOE & annual cost if 1.5x battery cost	6.89	12.2	3.70	2.59

LI=lithium ion; CSP=concentrated solar power; PCM=Phase-change materials; 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; and UTES=Underground thermal energy storage (either boreholes, water pits, or aquifers).

The LCOEs are derived from capital costs, annual O&M, and end-of-life decommissioning costs that vary by technology (Table S20) and that are a function of lifetime (Table S20) 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 2020 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, heat pumps for district heating and cooling, and hydrogen production and use (electrolyzers, rectifiers, storage tanks, water, dispensing, and cooling).

Since the total end-use load includes heat, cold, hydrogen, and electricity loads (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 load 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 (in USD 2020) (Jacobson et al., 2017, but brought up to USD 2020), 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 S17 gives the total HVDC line length and capacity and the fraction of all non-rooftop-PV and non-shed electricity generated that is subject to HVDC transmission by region. Storage costs are derived as described in Table S21.

H_2 costs are derived as in Note S38 and Note S43 of Jacobson et al. (2019). These costs exclude electricity costs, which are included separately in the present table.

Table S24. 2050 regional and country annual-average end-use (a) BAU load and (b) WWS load; (c) percentage difference between WWS and BAU load; (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 2020 USD. H=8760 hours per year.

Region or country	(a)[1] 2050 BAU Annual-average end-use load (GW)	(b)[1] 2050 WWS Annual-average end-use load (GW)	(c) 2050 WWS minus BAU load = (b-a)/a (%)	(d)[2] WWS mean total capital cost ($tril 2020)	(e)[3] BAU mean private energy cost (¢/kWh -all energy)	(f)[4] WWS mean private energy cost (¢/kWh -all energy)	(g)[5] WWS mean annual all-energy private and social cost = bfH ($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	**1,381.8**	**482.1**	**-65.1**	**3.671**	**10.09**	**8.64**	**364.7**	**1,221.9**	**3,982**	**1,782.6**	**6,987**	**-70.2**	**-94.8**
Algeria	142.7	43.8	-69.3	0.332	10.09	8.64	33.1	126.1	74.7	228.6	429	-73.7	-92.3
Angola	24.5	7.9	-67.9	0.060	10.09	8.64	6.0	21.7	94.0	32.7	148	-72.5	-96.0
Benin	11.0	2.6	-76.5	0.027	10.09	8.64	2.0	9.8	33.7	10.3	54	-79.9	-96.4
Botswana	5.4	2.1	-62.1	0.014	10.09	8.64	1.6	4.8	6.8	8.9	20	-67.6	-92.4
Cameroon	15.8	4.3	-72.6	0.038	10.09	8.64	3.3	14.0	68.9	12.8	96	-76.6	-96.6
Congo	4.6	1.3	-71.2	0.015	10.09	8.64	1.0	4.0	19.5	7.4	31	-75.3	-96.8
Congo, DR	35.8	8.5	-76.4	0.077	10.09	8.64	6.4	31.6	77.1	3.8	112	-79.8	-94.3
Côte d'Ivoire	16.6	5.1	-69.0	0.046	10.09	8.64	3.9	14.7	97.0	17.2	129	-73.5	-97.0
Egypt	186.8	88.8	-52.4	0.614	10.09	8.64	67.2	165.1	373.0	323.3	861	-59.3	-92.2
Equat. Guinea	6.6	4.1	-36.9	0.046	10.09	8.64	3.1	5.8	9.0	4.4	19	-46.0	-83.7
Eritrea	1.1	0.3	-72.4	0.002	10.09	8.64	0.2	1.0	10.9	0.9	13	-76.4	-98.2
Ethiopia	76.9	18.0	-76.5	0.126	10.09	8.64	13.6	68.0	243.5	23.1	335	-79.9	-95.9
Gabon	11.8	7.3	-38.7	0.079	10.09	8.64	5.5	10.5	8.5	4.4	23	-47.6	-76.6
Ghana	20.7	8.4	-59.6	0.078	10.09	8.64	6.3	18.3	83.4	21.3	123	-65.5	-94.9
Kenya	37.1	10.4	-71.9	0.076	10.09	8.64	7.9	32.8	46.7	25.1	105	-76.0	-92.5
Libya	31.4	13.2	-58.0	0.114	10.09	8.64	10.0	27.8	20.0	65.9	114	-64.1	-91.2
Morocco	44.6	19.4	-56.5	0.138	10.09	8.64	14.7	39.4	57.1	93.6	190	-62.8	-92.3
Mozambique	12.7	5.3	-58.4	0.034	10.09	8.64	4.0	11.2	36.3	11.7	59	-64.4	-93.3
Namibia	5.1	1.9	-62.1	0.015	10.09	8.64	1.5	4.5	6.2	5.6	16	-67.6	-91.1
Niger	6.3	1.6	-75.0	0.013	10.09	8.64	1.2	5.5	63.1	3.0	72	-78.6	-98.3
Nigeria	294.0	70.6	-76.0	0.610	10.09	8.64	53.4	260.0	1,972	127.0	2,358	-79.5	-97.7
Senegal	6.9	2.6	-61.7	0.020	10.09	8.64	2.0	6.1	28.6	12.4	47	-67.2	-95.8
South Africa	234.2	103.2	-55.9	0.711	10.09	8.64	78.1	207.1	118.2	626.4	952	-62.3	-91.8
South Sudan	1.4	0.4	-72.5	0.003	10.09	8.64	0.3	1.2	34.2	1.5	37	-76.5	-99.2
Sudan	32.0	11.2	-65.0	0.080	10.09	8.64	8.5	28.3	215.3	27.0	271	-70.1	-96.9
Tanzania	38.1	11.4	-70.0	0.096	10.09	8.64	8.7	33.7	73.6	16.9	124	-74.3	-93.0
Togo	4.5	1.2	-73.9	0.012	10.09	8.64	0.9	4.0	18.1	3.6	26	-77.6	-96.5
Tunisia	30.0	10.7	-64.4	0.081	10.09	8.64	8.1	26.5	25.5	40.6	93	-69.5	-91.3
Zambia	21.9	10.2	-53.2	0.073	10.09	8.64	7.7	19.3	49.3	9.5	78	-60.0	-90.1
Zimbabwe	21.5	6.3	-70.6	0.043	10.09	8.64	4.8	19.0	18.7	13.8	51	-74.8	-90.7
Australia	**208.8**	**92.3**	**-55.8**	**0.627**	**10.28**	**8.49**	**68.6**	**188.0**	**34.6**	**399.5**	**622**	**-63.5**	**-89.0**
Canada	**442.5**	**170.3**	**-61.5**	**0.638**	**8.03**	**6.47**	**96.4**	**311.3**	**42.3**	**518.3**	**872**	**-69.0**	**-88.9**
Central America	**378.2**	**156.5**	**-58.6**	**1.449**	**10.49**	**10.89**	**149.2**	**347.6**	**323.5**	**588.9**	**1,260**	**-57.1**	**-88.2**
Costa Rica	8.6	3.9	-55.1	0.029	10.49	10.89	3.7	7.9	6.6	8.9	23	-53.4	-84.3
El Salvador	5.5	2.4	-56.5	0.019	10.49	10.89	2.3	5.1	7.4	7.1	20	-54.9	-88.3
Guatemala	20.2	5.8	-71.2	0.052	10.49	10.89	5.6	18.6	32.0	21.1	72	-70.1	-92.2
Honduras	8.2	3.0	-62.9	0.034	10.49	10.89	2.9	7.5	10.7	10.3	28	-61.5	-89.9
Mexico	312.5	133.7	-57.2	1.229	10.49	10.89	127.5	287.1	252.4	524.1	1,064	-55.6	-88.0
Nicaragua	4.7	1.6	-65.1	0.018	10.49	10.89	1.6	4.3	8.3	5.8	18	-63.7	-91.5

Panama	18.5	6.0	-67.4	0.067	10.49	10.89	5.8	17.0	6.2	11.6	35	-66.2	-83.4
Central Asia	**446.5**	**166.9**	**-62.6**	**1.101**	**10.30**	**8.00**	**117.0**	**402.7**	**1,011**	**699.6**	**2,114**	**-71.0**	**-94.5**
Kazakhstan	87.2	33.6	-61.4	0.206	10.30	8.00	23.6	78.6	91.5	235.7	406	-70.0	-94.2
Kyrgyz Rep.	7.3	3.4	-53.3	0.015	10.30	8.00	2.4	6.6	16.0	10.1	33	-63.7	-92.7
Pakistan	233.1	96.0	-58.8	0.680	10.30	8.00	67.3	210.2	795.7	288.5	1,294	-68.0	-94.8
Tajikistan	5.8	3.4	-40.4	0.008	10.30	8.00	2.4	5.2	19.6	7.6	32	-53.7	-92.5
Turkmenistan	40.0	9.2	-77.0	0.060	10.30	8.00	6.4	36.0	20.2	76.9	133	-82.1	-95.2
Uzbekistan	73.2	21.2	-71.0	0.131	10.30	8.00	14.9	66.0	68.3	80.7	215	-77.5	-93.1
China Region	**5,076.3**	**2,423.9**	**-52.3**	**14.442**	**9.55**	**8.12**	**1,724.4**	**4,248.4**	**10,757**	**8,495.7**	**23,501**	**-59.4**	**-92.7**
China	4,970.5	2,382.8	-52.1	14.119	9.55	8.12	1,695.1	4,159.8	10,602	8,338.2	23,100	-59.3	-92.7
Hong Kong	82.7	29.8	-63.9	0.258	9.55	8.12	21.2	69.2	54.7	56.8	181	-69.3	-88.2
Korea, DPR	13.3	7.4	-44.8	0.040	9.55	8.12	5.2	11.2	81.8	54.4	147	-53.1	-96.4
Mongolia	9.9	3.9	-60.2	0.026	9.55	8.12	2.8	8.3	18.3	46.4	73	-66.2	-96.2
Cuba	**15.8**	**9.0**	**-43.0**	**0.103**	**11.64**	**12.12**	**9.5**	**16.1**	**37.5**	**30.9**	**84**	**-40.6**	**-88.7**
Europe	**2,287.7**	**958.3**	**-58.1**	**5.832**	**10.01**	**8.65**	**726.3**	**2,005.4**	**1,772**	**2,858.0**	**6,635**	**-63.8**	**-89.1**
Albania	4.4	2.1	-53.1	0.011	10.01	8.65	1.6	3.9	14.3	4.8	23	-59.4	-93.2
Austria	47.9	20.9	-56.4	0.117	10.01	8.65	15.8	42.0	20.3	53.3	116	-62.3	-86.3
Belarus	37.5	12.8	-65.8	0.084	10.01	8.65	9.7	32.9	50.2	56.3	139	-70.5	-93.0
Belgium	73.3	30.5	-58.4	0.179	10.01	8.65	23.1	64.3	26.1	76.9	167	-64.0	-86.2
Bosnia-Herzeg.	9.0	3.8	-57.7	0.022	10.01	8.65	2.9	7.9	29.1	28.5	65	-63.4	-95.6
Bulgaria	22.4	10.0	-55.3	0.072	10.01	8.65	7.6	19.6	38.2	36.8	95	-61.4	-92.0
Croatia	14.8	6.0	-59.2	0.040	10.01	8.65	4.6	13.0	21.5	16.3	51	-64.7	-91.0
Cyprus	4.2	1.8	-56.6	0.013	10.01	8.65	1.4	3.7	3.6	6.3	14	-62.5	-89.8
Czech Rep.	43.9	18.0	-59.0	0.113	10.01	8.65	13.6	38.5	32.0	77.8	148	-64.6	-90.8
Denmark	26.1	9.7	-62.9	0.054	10.01	8.65	7.3	22.9	11.7	22.9	57	-67.9	-87.2
Estonia	6.0	2.1	-65.0	0.015	10.01	8.65	1.6	5.3	2.8	13.6	22	-69.8	-92.7
Finland	42.6	22.3	-47.7	0.141	10.01	8.65	16.9	37.3	6.0	32.0	75	-54.7	-77.6
France	248.6	111.6	-55.1	0.715	10.01	8.65	84.6	217.9	115.0	231.7	565	-61.2	-85.0
Germany	361.0	154.6	-57.2	0.879	10.01	8.65	117.2	316.5	223.0	517.4	1,057	-63.0	-88.9
Gibraltar	6.0	1.5	-75.5	0.018	10.01	8.65	1.1	5.2	0.2	0.5	6	-78.9	-81.5
Greece	32.5	13.0	-60.1	0.081	10.01	8.65	9.8	28.5	42.0	48.3	119	-65.5	-91.7
Hungary	31.7	12.6	-60.3	0.090	10.01	8.65	9.5	27.8	37.8	37.5	103	-65.7	-90.7
Ireland	18.9	8.0	-57.6	0.051	10.01	8.65	6.1	16.5	9.8	26.9	53	-63.3	-88.6
Italy	215.7	83.6	-61.2	0.527	10.01	8.65	63.4	189.1	188.7	244.1	622	-66.5	-89.8
Kosovo	3.0	1.4	-54.3	0.010	10.01	8.65	1.0	2.6	1.7	7.2	12	-60.5	-91.0
Latvia	8.1	3.2	-60.2	0.020	10.01	8.65	2.5	7.1	10.0	7.1	24	-65.6	-89.9
Lithuania	12.6	5.0	-60.4	0.038	10.01	8.65	3.8	11.0	14.0	11.7	37	-65.8	-89.7
Luxembourg	6.5	2.5	-62.2	0.015	10.01	8.65	1.9	5.7	1.7	7.2	15	-67.3	-87.2
Macedonia	3.8	1.9	-49.9	0.013	10.01	8.65	1.5	3.4	11.0	7.6	22	-56.7	-93.4
Malta	5.6	1.7	-69.9	0.015	10.01	8.65	1.3	4.9	1.1	0.9	7	-73.9	-81.6
Moldova	6.0	2.3	-61.8	0.016	10.01	8.65	1.7	5.3	5.9	7.8	19	-67.0	-90.8
Montenegro	1.6	0.8	-50.0	0.004	10.01	8.65	0.6	1.4	3.9	3.7	9	-56.8	-93.3
Netherlands	104.5	41.6	-60.2	0.246	10.01	8.65	31.5	91.6	43.8	115.2	251	-65.6	-87.4
Norway	47.3	20.7	-56.3	0.068	10.01	8.65	15.7	41.4	7.7	35.3	84	-62.2	-81.5
Poland	126.7	48.9	-61.4	0.343	10.01	8.65	37.1	111.0	131.4	233.9	476	-66.6	-92.2
Portugal	30.2	13.5	-55.3	0.079	10.01	8.65	10.2	26.4	15.6	35.7	78	-61.3	-86.8
Romania	48.4	18.9	-60.9	0.114	10.01	8.65	14.3	42.4	141.8	66.8	251	-66.2	-94.3
Serbia	18.8	8.9	-53.0	0.060	10.01	8.65	6.7	16.5	37.6	60.1	114	-59.3	-94.1
Slovakia	20.0	8.6	-57.0	0.052	10.01	8.65	6.5	17.5	16.6	26.5	61	-62.8	-89.2
Slovenia	8.3	3.9	-53.5	0.024	10.01	8.65	2.9	7.3	5.2	11.3	24	-59.8	-87.7
Spain	166.0	69.0	-58.4	0.413	10.01	8.65	52.3	145.5	88.8	190.9	425	-64.0	-87.7
Sweden	55.4	30.3	-45.3	0.156	10.01	8.65	23.0	48.6	11.6	33.0	93	-52.7	-75.3
Switzerland	32.1	14.3	-55.2	0.067	10.01	8.65	10.9	28.1	13.9	29.0	71	-61.3	-84.7
Ukraine	104.2	48.2	-53.7	0.309	10.01	8.65	36.6	91.3	183.2	166.9	441	-60.0	-91.7
United King.	232.4	87.9	-62.2	0.551	10.01	8.65	66.6	203.7	153.3	268.5	626	-67.3	-89.4
Haiti Region	**19.1**	**7.6**	**-60.3**	**0.055**	**10.90**	**8.71**	**5.8**	**18.3**	**36.2**	**30.7**	**85**	**-68.2**	**-93.2**
Dominican Rep	14.0	6.3	-55.1	0.043	10.90	8.71	4.8	13.4	20.3	27.1	61	-64.1	-92.1
Haiti	5.1	1.3	-74.3	0.012	10.90	8.71	1.0	4.9	15.9	3.6	24	-79.5	-95.9
Iceland	**5.6**	**3.2**	**-42.9**	**0.0023**	**7.51**	**6.86**	**1.9**	**3.7**	**0.4**	**2.9**	**7**	**-48.6**	**-72.8**
India Region	**2,010.5**	**1,006.8**	**-49.9**	**7.029**	**9.88**	**8.25**	**727.5**	**1,739.6**	**9,472**	**3,756.5**	**14,968**	**-58.2**	**-95.1**
Bangladesh	82.7	35.8	-56.7	0.290	9.88	8.25	25.9	71.5	523.1	130.5	725	-63.9	-96.4
India	1,870.8	951.6	-49.1	6.591	9.88	8.25	687.6	1,618.7	8,755	3,571.0	13,944	-57.5	-95.1

Nepal	28.5	7.9	-72.2	0.067	9.88	8.25	5.7	24.7	99.9	19.4	144	-76.8	-96.0
Sri Lanka	28.6	11.5	-59.6	0.081	9.88	8.25	8.3	24.7	94.0	35.6	154	-66.2	-94.6
Israel	**26.1**	**12.8**	**-51.0**	**0.139**	**11.21**	**12.29**	**13.8**	**25.6**	**15.7**	**50.3**	**92**	**-46.3**	**-85.0**
Jamaica	**5.5**	**2.6**	**-53.7**	**0.022**	**11.38**	**9.69**	**2.2**	**5.5**	**3.4**	**7.4**	**16**	**-60.6**	**-86.7**
Japan	**355.4**	**186.3**	**-47.6**	**1.234**	**10.48**	**9.16**	**149.6**	**326.3**	**261.5**	**678.1**	**1,266**	**-54.2**	**-88.2**
Mauritius	**5.2**	**1.9**	**-63.2**	**0.021**	**10.64**	**11.73**	**1.9**	**4.8**	**3.7**	**5.5**	**14**	**-59.5**	**-86.1**
Mideast	**1,520.1**	**706.5**	**-53.5**	**4.543**	**11.39**	**8.03**	**496.8**	**1,517.3**	**858.4**	**2,900.1**	**5,276**	**-67.3**	**-90.6**
Armenia	4.8	1.5	-68.6	0.008	11.39	8.03	1.1	4.8	10.1	5.0	20	-77.9	-94.7
Azerbaijan	19.1	6.4	-66.8	0.044	11.39	8.03	4.5	19.1	37.8	30.6	87	-76.6	-94.9
Bahrain	17.6	9.6	-45.5	0.054	11.39	8.03	6.8	17.6	2.1	41.9	62	-61.6	-89.0
Iran	444.0	186.3	-58.0	1.257	11.39	8.03	131.0	443.2	171.2	828.9	1,443	-70.4	-90.9
Iraq	62.1	23.1	-62.7	0.178	11.39	8.03	16.3	61.9	90.6	233.4	386	-73.7	-95.8
Jordan	15.8	6.9	-56.4	0.043	11.39	8.03	4.8	15.7	11.3	33.5	60	-69.3	-92.0
Kuwait	57.4	23.5	-59.0	0.142	11.39	8.03	16.5	57.3	12.6	116.9	187	-71.1	-91.1
Lebanon	13.2	6.2	-53.4	0.039	11.39	8.03	4.3	13.2	9.0	32.4	55	-67.2	-92.1
Oman	59.9	26.0	-56.6	0.167	11.39	8.03	18.3	59.8	8.3	109.6	178	-69.5	-89.7
Qatar	78.8	33.2	-57.9	0.191	11.39	8.03	23.3	78.7	3.6	125.8	208	-70.4	-88.8
Saudi Arabia	349.0	183.6	-47.4	1.202	11.39	8.03	129.1	348.4	124.7	725.8	1,199	-62.9	-89.2
Syria	14.4	6.3	-55.9	0.041	11.39	8.03	4.5	14.3	47.5	34.4	96	-68.9	-95.4
Turkey	173.7	81.3	-53.2	0.517	11.39	8.03	57.2	173.3	229.7	306.1	709	-67.0	-91.9
UAE	205.6	110.9	-46.0	0.647	11.39	8.03	78.0	205.2	11.2	262.9	479	-62.0	-83.7
Yemen	4.8	1.7	-63.5	0.013	11.39	8.03	1.2	4.8	88.8	12.9	106	-74.3	-98.8
New Zealand	**32.4**	**16.7**	**-48.5**	**0.094**	**8.11**	**8.14**	**11.9**	**23.0**	**5.2**	**35.7**	**64**	**-48.3**	**-81.3**
Philippines	**93.9**	**41.0**	**-56.3**	**0.397**	**10.19**	**10.43**	**37.5**	**83.8**	**677.3**	**194.3**	**955**	**-55.3**	**-96.1**
Russia Region	**787.8**	**268.3**	**-65.9**	**1.309**	**10.18**	**7.32**	**172.0**	**702.4**	**601.8**	**1,248.3**	**2,552**	**-75.5**	**-93.3**
Georgia	8.6	3.6	-58.0	0.012	10.18	7.32	2.3	7.7	31.1	11.4	50	-69.8	-95.4
Russia	779.2	264.7	-66.0	1.297	10.18	7.32	169.7	694.7	570.6	1,236.8	2,502	-75.6	-93.2
South America	**1,090.8**	**468.7**	**-57.0**	**2.902**	**8.44**	**8.36**	**343.3**	**806.4**	**749.8**	**1,161.3**	**2,718**	**-57.4**	**-87.4**
Argentina	144.4	51.1	-64.6	0.245	8.44	8.36	37.4	106.8	98.3	198.1	403	-64.9	-90.7
Bolivia	18.3	5.2	-71.7	0.031	8.44	8.36	3.8	13.5	22.7	24.3	61	-72.0	-93.8
Brazil	591.3	272.1	-54.0	1.751	8.44	8.36	199.3	437.1	352.7	494.7	1,285	-54.4	-84.5
Chile	67.5	34.9	-48.3	0.170	8.44	8.36	25.6	49.9	38.6	97.1	186	-48.8	-86.2
Colombia	70.5	27.5	-61.0	0.191	8.44	8.36	20.1	52.1	72.8	86.0	211	-61.4	-90.5
Curacao	5.2	1.4	-72.8	0.011	8.44	8.36	1.0	3.9	0.1	5.9	10	-73.0	-89.4
Ecuador	28.0	10.0	-64.2	0.064	8.44	8.36	7.3	20.7	16.1	40.4	77	-64.6	-90.5
Paraguay	12.9	5.7	-55.4	0.015	8.44	8.36	4.2	9.5	12.4	8.4	30	-55.8	-86.1
Peru	47.4	18.7	-60.5	0.127	8.44	8.36	13.7	35.1	77.0	55.9	168	-60.9	-91.8
Suriname	1.2	0.5	-59.9	0.003	8.44	8.36	0.4	0.9	1.6	2.0	4	-60.3	-92.1
Trinidad/Tob.	15.4	8.5	-44.8	0.055	8.44	8.36	6.2	11.4	2.6	32.5	46	-45.3	-86.6
Uruguay	10.0	5.1	-48.6	0.024	8.44	8.36	3.7	7.4	5.2	6.5	19	-49.1	-80.4
Venezuela	78.8	28.0	-64.5	0.215	8.44	8.36	20.5	58.2	49.8	109.3	217	-64.8	-90.6
Southeast Asia	**1,300.7**	**584.6**	**-55.1**	**6.435**	**10.39**	**11.59**	**593.4**	**1,183.3**	**1,936**	**2,046.6**	**5,166**	**-49.9**	**-88.5**
Brunei	5.2	1.5	-71.5	0.018	10.39	11.59	1.5	4.8	0.5	9.0	14	-68.1	-89.4
Cambodia	17.3	6.8	-60.5	0.056	10.39	11.59	6.9	15.7	40.4	21.3	77	-56.0	-91.1
Indonesia	423.9	191.9	-54.7	1.775	10.39	11.59	194.7	385.6	1,038	806.9	2,231	-49.5	-91.3
Lao PDR	7.6	2.8	-63.2	0.004	10.39	11.59	2.8	6.9	31.6	8.8	47	-58.9	-94.0
Malaysia	169.0	80.7	-52.3	0.976	10.39	11.59	81.9	153.7	95.6	320.9	570	-46.7	-85.6
Myanmar	44.7	15.7	-65.0	0.109	10.39	11.59	15.9	40.7	197.5	62.3	300	-60.9	-94.7
Singapore	216.6	69.7	-67.8	1.440	10.39	11.59	70.8	197.0	33.2	68.9	299	-64.1	-76.3
Thailand	257.5	116.9	-54.6	1.121	10.39	11.59	118.7	234.3	289.6	354.8	879	-49.3	-86.5
Vietnam	159.1	98.6	-38.0	0.938	10.39	11.59	100.1	144.7	209.1	393.8	748	-30.8	-86.6
South Korea	**304.9**	**154.4**	**-49.4**	**1.736**	**10.53**	**12.58**	**170.2**	**281.2**	**104.4**	**526.9**	**913**	**-39.5**	**-81.3**
Taiwan	**165.3**	**89.9**	**-45.6**	**0.940**	**10.60**	**11.70**	**92.2**	**153.5**	**85.9**	**357.0**	**596**	**-40.0**	**-84.5**
United States	**2,397.8**	**959.5**	**-60.0**	**6.563**	**10.42**	**8.79**	**739.2**	**2,188.6**	**829.7**	**3,381.7**	**6,400**	**-66.2**	**-88.5**
All regions	**20,359**	**8,970.1**	**-55.9**	**61.3**	**9.98**	**8.67**	**6,815**	**17,805**	**33,601**	**31,757**	**83,163**	**-61.7**	**-91.8**

[1] From Table S4.

[2] 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; and long-distance (HVDC) transmission lines. Capital costs are an average between 2020 and 2050.

[3] This is the BAU electricity-sector cost of energy per unit energy. It is assumed to equal the BAU all-energy cost of energy per unit energy and is an average between 2020 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 2020 and 2050.

[5] The annual private cost of WWS or BAU energy equals the cost per unit energy from Column (f) or (g), respectively, multiplied by the energy consumed per year, which equals the end-use load 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 mortalities per year in 2050 from Table S25, Column (a), multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy) and by a statistical cost of life calculated for each country, calculated as in Jacobson et al. (2019), and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts (Jacobson et al., 2019).

[7] The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S25, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S25, Column (f) (in 2020 USD), which is updated from values in Jacobson et al. (2019), which were in 2013 USD.

Table S25. Regional (a) estimated air pollution mortalities per year in 2050-2052 due to all anthropogenic sources (about 90% of which are energy); (b) carbon-equivalent emissions (CO_2e) in the BAU case; (c) cost per tonne-CO_2e of eliminating CO_2e with 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; (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 (Deaths/y)	(b)[2] 2050 BAU CO_2e (Mton-ne/y)	(c)[3] 2050 WWS ($/ tonne-$CO_2$e-elim-inated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2$e-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2$e-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2$e-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2$e-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa	**1,173,737**	**3,192**	**114.3**	**383**	**1,247**	**558**	**2,189**	**32.9**	**14.7**
Algeria	10,788	409	80.9	308	183	558	1,049	6.0	18.3
Angola	19,997	59	101.8	371	1,606	558	2,535	43.7	15.2
Benin	17,080	18	106.1	528	1,822	558	2,908	34.9	10.7
Botswana	940	16	97.6	301	424	558	1,283	14.2	18.7
Cameroon	25,940	23	142.8	610	3,007	558	4,175	49.8	9.2
Congo	4,535	13	75.9	308	1,482	559	2,349	48.6	18.3
Congo, DR	93,264	7	946.4	4,678	11,391	556	16,626	24.6	1.2
Côte d'Ivoire	33,702	31	126.6	478	3,157	558	4,193	66.7	11.8
Egypt	63,218	579	116.0	285	644	558	1,488	22.8	19.8
Equator. Guinea	919	8	397.5	736	1,140	559	2,435	15.6	7.7
Eritrea	6,912	2	134.4	569	6,410	560	7,539	113.7	9.9
Ethiopia	152,676	41	329.8	1,643	5,883	558	8,085	36.1	3.4
Gabon	1,054	8	694.7	1,325	1,080	558	2,963	8.2	4.2
Ghana	25,489	38	165.6	480	2,185	558	3,223	46.0	11.8
Kenya	17,759	45	175.3	730	1,039	558	2,328	14.4	7.7
Libya	2,943	118	84.5	235	169	558	963	7.3	24.0
Morocco	10,340	168	87.7	235	341	559	1,135	14.6	23.9
Mozambique	24,785	21	190.5	535	1,730	559	2,823	32.6	10.5
Namibia	961	10	146.1	451	624	559	1,634	14.0	12.5
Niger	52,061	5	221.4	1,036	11,795	558	13,389	114.9	5.4
Nigeria	417,387	227	234.9	1,144	8,676	559	10,379	76.6	4.9
Senegal	12,993	22	89.7	274	1,286	559	2,119	47.5	20.6
South Africa	18,075	1,122	69.6	185	105	558	848	5.8	30.5
South Sudan	19,243	3	103.4	439	12,393	559	13,391	284.9	12.9
Sudan	66,066	48	175.2	585	4,447	558	5,590	76.7	9.6
Tanzania	31,178	30	286.3	1,115	2,434	559	4,108	22.0	5.1
Togo	12,450	6	137.8	616	2,803	558	3,977	45.9	9.2
Tunisia	4,209	73	111.2	365	350	558	1,273	9.7	15.5
Zambia	15,983	17	455.4	1,137	2,897	559	4,593	25.7	5.0
Zimbabwe	10,790	25	194.0	771	758	559	2,087	9.9	7.3
Australia	**3,034**	**716**	**95.9**	**263**	**48**	**558**	**869**	**1.9**	**21.8**
Canada	**3,764**	**928**	**103.9**	**335**	**46**	**558**	**939**	**1.1**	**13.4**
Central America	**45,608**	**1,055**	**141.5**	**329**	**307**	**558**	**1,194**	**9.8**	**17.8**
Costa Rica	1,008	16	231.3	496	416	559	1,470	8.8	11.8
El Salvador	1,558	13	179.8	398	581	558	1,537	15.3	14.7
Guatemala	7,217	38	147.2	492	848	558	1,898	18.1	11.9
Honduras	3,162	18	156.8	407	581	558	1,546	15.0	14.4
Mexico	29,973	939	135.8	306	269	558	1,133	9.2	19.1
Nicaragua	1,908	10	150.8	416	792	558	1,766	20.0	14.1
Panama	782	21	278.1	822	300	558	1,680	3.8	7.1
Central Asia	**235,560**	**1,253**	**93.4**	**321**	**807**	**558**	**1,687**	**25.9**	**17.9**
Kazakhstan	7,774	422	55.9	186	217	558	961	12.0	30.9
Kyrgyz Republic	3,796	18	131.9	363	883	558	1,805	25.0	15.8
Pakistan	204,993	517	130.2	407	1,540	558	2,506	39.0	14.1

Tajikistan	5,315	14	178.0	384	1,446	559	2,389	38.8	15.0
Turkmenistan	2,073	138	46.8	262	147	558	967	5.8	22.0
Uzbekistan	11,609	145	102.8	456	472	558	1,487	10.7	12.6
China Region	**1,134,535**	**15,212**	**113.4**	**279**	**707**	**558**	**1,545**	**24.2**	**19.1**
China	1,090,244	14,930	113.5	279	710	558	1,547	24.4	19.2
Hong Kong	3,982	102	208.8	680	538	558	1,776	7.6	7.8
Korea, DPR	37,703	97	53.7	115	839	559	1,512	70.0	46.6
Mongolia	2,606	83	33.6	99	221	559	879	21.2	53.7
Cuba	**4,851**	**55**	**172.8**	**291**	**679**	**559**	**1,528**	**27.2**	**22.3**
Europe	**179,603**	**5,119**	**141.9**	**392**	**346**	**558**	**1,296**	**8.8**	**14.3**
Albania	1,766	9	182.5	450	1,659	558	2,667	36.9	12.4
Austria	1,741	95	165.9	440	213	558	1,211	4.9	12.7
Belarus	5,001	101	96.3	326	497	558	1,381	15.3	17.1
Belgium	2,294	138	168.0	467	189	559	1,215	4.1	12.0
Bosnia-Herzeg.	3,661	51	56.6	155	571	559	1,284	36.9	36.1
Bulgaria	3,772	66	115.0	298	579	558	1,435	19.5	18.8
Croatia	1,966	29	157.3	446	741	559	1,745	16.6	12.5
Cyprus	280	11	122.8	327	318	558	1,203	9.7	17.1
Czech Rep.	3,217	139	97.8	276	229	558	1,064	8.3	20.2
Denmark	1,003	41	179.0	557	284	558	1,400	5.1	10.0
Estonia	298	24	65.2	216	116	559	891	5.4	25.9
Finland	544	57	295.0	652	106	558	1,315	1.6	8.6
France	10,527	415	203.9	525	277	558	1,360	5.3	10.6
Germany	19,077	926	126.5	342	241	558	1,141	7.0	16.4
Gibraltar	20	0.92	1,205	5,700	268	558	6,526	0.5	1.0
Greece	4,606	86	113.6	330	486	558	1,374	14.7	17.0
Hungary	4,162	67	142.4	415	564	559	1,538	13.6	13.5
Ireland	782	48	125.9	343	202	558	1,104	5.9	16.3
Italy	18,054	437	145.0	432	432	558	1,423	10.0	12.9
Kosovo	276	13	81.0	205	133	558	896	6.5	27.2
Latvia	878	13	192.2	558	787	558	1,902	14.1	10.0
Lithuania	1,346	21	179.7	525	669	559	1,753	12.7	10.6
Luxembourg	103	13	145.1	444	133	559	1,135	3.0	12.6
Macedonia	1,486	14	107.3	248	810	558	1,615	32.7	22.5
Malta	104	2	798.0	3,062	722	560	4,344	2.4	1.8
Moldova	1,384	14	123.9	375	418	558	1,352	11.2	14.9
Montenegro	481	7	90.7	210	589	558	1,357	28.1	26.6
Netherlands	3,352	206	152.7	444	212	558	1,215	4.8	12.6
Norway	567	63	247.4	655	121	558	1,334	1.9	8.5
Poland	14,360	419	88.5	265	314	558	1,137	11.8	21.1
Portugal	1,656	64	160.0	414	245	558	1,217	5.9	13.5
Romania	13,080	120	119.8	354	1,185	558	2,097	33.5	15.8
Serbia	4,208	108	62.4	154	350	558	1,062	22.8	36.4
Slovakia	1,732	47	137.5	369	349	558	1,277	9.5	15.1
Slovenia	533	20	144.3	359	258	558	1,175	7.2	15.6
Spain	8,585	342	153.1	426	260	558	1,244	6.1	13.1
Sweden	979	59	389.4	823	196	559	1,578	2.4	6.8
Switzerland	1,087	52	209.4	541	267	558	1,366	4.9	10.3
Ukraine	26,812	299	122.3	305	613	558	1,477	20.1	18.3
United Kingdom	13,823	481	138.4	423	319	558	1,300	7.5	13.2
Haiti Region	**13,695**	**55**	**105.7**	**333**	**659**	**558**	**1,550**	**21.6**	**18.3**
Dominican Rep.	3,217	49	98.8	275	419	558	1,252	16.6	22.1
Haiti	10,478	6	157.9	770	2,496	558	3,824	35.4	7.9
Iceland	**36**	**5**	**368.2**	**717**	**80**	**559**	**1,356**	**0.8**	**5.8**
India Region	**1,658,265**	**6,728**	**108.1**	**259**	**1,408**	**558**	**2,225**	**53.8**	**21.3**
Bangladesh	161,682	234	110.6	306	2,238	558	3,103	72.2	18.0
India	1,444,634	6,396	107.5	253	1,369	558	2,180	53.4	21.8
Nepal	38,313	35	164.9	711	2,879	558	4,148	40.0	7.8
Sri Lanka	13,636	64	131.0	388	1,476	558	2,423	37.6	14.2
Israel	**1,544**	**90**	**152.7**	**284**	**175**	**558**	**1,017**	**6.9**	**22.0**
Jamaica	**698**	**13**	**163.7**	**416**	**258**	**559**	**1,232**	**7.1**	**15.3**
Japan	**27,181**	**1,215**	**123.2**	**269**	**215**	**558**	**1,042**	**8.4**	**21.8**

Mauritius	**418**	**10**	**198.0**	**489**	**377**	**559**	**1,424**	**8.2**	**12.2**
Mideast	**118,866**	**5,195**	**95.6**	**292**	**165**	**558**	**1,016**	**6.4**	**21.8**
Armenia	1,429	9	117.3	530	1,117	559	2,206	24.0	12.0
Azerbaijan	3,755	55	81.5	348	689	558	1,596	22.5	18.3
Bahrain	172	75	90.1	235	28	558	821	1.3	27.1
Iran	21,479	1,485	88.2	298	115	558	972	4.4	21.3
Iraq	12,495	418	38.9	148	217	558	923	16.7	42.9
Jordan	1,836	60	80.7	263	188	558	1,009	8.2	24.2
Kuwait	888	209	79.0	274	60	558	892	2.5	23.3
Lebanon	1,289	58	74.6	227	156	558	941	7.8	28.0
Oman	747	196	93.0	305	43	558	905	1.6	20.9
Qatar	203	225	103.5	349	16	558	924	0.5	18.2
Saudi Arabia	9,771	1,300	99.3	268	96	558	922	4.1	23.7
Syria	9,310	62	72.2	233	770	558	1,561	37.7	27.4
Turkey	28,516	548	104.3	316	419	558	1,293	15.1	20.1
UAE	787	471	165.6	436	24	558	1,018	0.6	14.6
Yemen	26,189	23	53.3	207	3,854	559	4,620	212.0	30.7
New Zealand	**444**	**64**	**186.6**	**361**	**81**	**559**	**1,000**	**1.8**	**12.6**
Philippines	**126,965**	**348**	**107.6**	**241**	**1,946**	**558**	**2,746**	**82.4**	**23.6**
Russia Region	**59,101**	**2,236**	**76.9**	**314**	**269**	**558**	**1,142**	**8.7**	**18.1**
Georgia	4,111	21	113.1	375	1,519	558	2,452	41.3	15.2
Russia	54,990	2,215	76.6	314	258	558	1,130	8.4	18.1
South America	**110,082**	**2,080**	**165.0**	**388**	**360**	**558**	**1,306**	**7.8**	**12.2**
Argentina	12,153	355	105.5	301	277	558	1,136	7.8	15.7
Bolivia	5,510	44	86.9	310	521	558	1,390	14.2	15.2
Brazil	49,639	886	224.9	493	398	558	1,450	6.8	9.6
Chile	4,119	174	146.9	287	222	558	1,067	6.5	16.4
Colombia	11,703	154	130.5	338	473	558	1,369	11.8	13.9
Curacao	9	11	98.9	367	7	558	932	0.2	12.8
Ecuador	2,873	72	101.2	286	222	558	1,066	6.5	16.5
Paraguay	2,511	15	279.0	632	822	558	2,012	11.0	7.5
Peru	13,130	100	137.1	350	768	558	1,677	18.5	13.5
Suriname	225	4	96.1	242	425	557	1,224	14.8	19.4
Trinidad/Tobago	271	58	106.7	195	44	558	798	1.9	24.2
Uruguay	675	12	320.5	630	448	558	1,636	6.0	7.5
Venezuela	7,264	196	104.6	297	254	558	1,110	7.2	15.9
Southeast Asia	**316,266**	**3,666**	**161.9**	**323**	**528**	**558**	**1,409**	**17.0**	**18.0**
Brunei	36	16	93.4	293	33	558	884	1.2	19.7
Cambodia	12,111	38	181.5	412	1,060	558	2,030	26.7	14.1
Indonesia	155,525	1,445	134.7	267	718	558	1,543	28.0	21.7
Lao PDR	6,920	16	180.0	438	2,018	558	3,015	47.8	13.2
Malaysia	9,353	575	142.5	267	166	558	992	6.5	21.7
Myanmar	50,469	112	142.5	365	1,769	558	2,692	50.4	15.9
Singapore	2,107	123	574.1	1,598	269	559	2,426	1.8	3.6
Thailand	35,606	635	186.8	369	456	558	1,383	12.8	15.7
Vietnam	44,139	705	142.0	205	297	558	1,060	15.0	28.3
South Korea	**8,980**	**944**	**180.4**	**298**	**111**	**558**	**967**	**3.9**	**19.7**
Taiwan	**6,649**	**639**	**144.1**	**240**	**134**	**558**	**933**	**5.9**	**24.6**
United States	**62,694**	**6,057**	**122.0**	**361**	**137**	**558**	**1,057**	**4.0**	**16.1**
All regions	**5,292,576**	**56,873**	**119.83**	**313**	**591**	**558**	**1,462**	**18.8**	**17.8**

[1] 2050 country BAU mortalities due to air pollution are extrapolated from 2016 values from WHO (2017) using the method described in Jacobson et al. (2019).

[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 145 countries represent 99.7% of world anthropogenic CO_2e emissions.

[3] Calculated as the WWS private energy and total social cost from Table S24, Column (g) divided by the CO_2e emissions from Column (b) of the present table.

[4] Columns (d)-(g) are calculated as the BAU private energy, health, climate, and total social costs from Table S24, 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 S24, Columns (i)-(j), respectively, each divided by the BAU end-use load from Table S24, Column (a) and by 8,760 hours per year.

Table S26. 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
Geothermal plant	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
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 Jacobson et al. (2019). Spacing areas for onshore and offshore wind are based on data from Enevoldsen and Jacobson (2021). The installed power density is the inverse of the spacing except, if spacing is zero, it is the inverse of the footprint.

Table S27. 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 country within each grid region and for the grid region as a whole.

Region or country	Region or country land area (km^2)	Footprint area (km^2)	Spacing area (km^2)	Footprint area as percentage of the region land area (%)	Spacing area as a percentage of the region land area (%)
Africa	**23,016,180**	**7,284**	**24,217**	**0.03**	**0.11**
Algeria	2,381,740	808	1,713	0.03	0.07
Angola	1,246,700	40	977	0.00	0.08
Benin	112,760	40	292	0.04	0.26
Botswana	566,730	36	121	0.01	0.02
Cameroon	472,710	65	624	0.01	0.13
Congo	341,500	13	223	0.00	0.07
Congo, DR	2,267,050	146	1,293	0.01	0.06
Côte d'Ivoire	318,000	48	739	0.02	0.23
Egypt	995,450	861	3,146	0.09	0.32
Equator. Guinea	28,050	138	68	0.49	0.24
Eritrea	101,000	3	16	0.00	0.02
Ethiopia	1,000,000	302	974	0.03	0.10
Gabon	257,670	109	654	0.04	0.25
Ghana	227,540	116	600	0.05	0.26
Kenya	569,140	84	830	0.01	0.15
Libya	1,759,540	165	613	0.01	0.03
Morocco	446,300	195	649	0.04	0.15
Mozambique	786,380	38	397	0.00	0.05
Namibia	823,290	20	142	0.00	0.02
Niger	1,266,700	38	102	0.00	0.01
Nigeria	910,770	1,923	2,277	0.21	0.25
Senegal	192,530	26	157	0.01	0.08
South Africa	1,213,090	1,316	4,278	0.11	0.35
South Sudan	619,745	7	16	0.00	0.00
Sudan	1,886,000	120	475	0.01	0.03
Tanzania	885,800	128	848	0.01	0.10
Togo	54,390	20	143	0.04	0.26
Tunisia	155,360	213	353	0.14	0.23
Zambia	743,398	151	1,025	0.02	0.14
Zimbabwe	386,847	114	473	0.03	0.12
Australia	**7,682,300**	**3,165**	**3,579**	**0.04**	**0.05**
Canada	**9,093,510**	**521**	**8,241**	**0.01**	**0.09**
Central America	**2,429,460**	**3,287**	**20,452**	**0.14**	**0.84**
Costa Rica	51,060	41	369	0.08	0.72
El Salvador	20,720	28	275	0.14	1.33
Guatemala	107,160	76	784	0.07	0.73
Honduras	111,890	61	683	0.05	0.61
Mexico	1,943,950	2,942	16,631	0.15	0.86
Nicaragua	120,340	31	338	0.03	0.28
Panama	74,340	108	1,373	0.15	1.85
Central Asia	**4,697,670**	**2,805**	**12,261**	**0.06**	**0.26**
Kazakhstan	2,699,700	401	3,225	0.01	0.12
Kyrgyz Republic	191,800	31	243	0.02	0.13
Pakistan	770,880	1,932	5,733	0.25	0.74
Tajikistan	139,960	12	90	0.01	0.06
Turkmenistan	469,930	137	950	0.03	0.20
Uzbekistan	425,400	292	2,020	0.07	0.47
China Region	**11,063,254**	**56,504**	**95,183**	**0.51**	**0.86**
China	9,388,211	55,887	94,313	0.60	1.00
Hong Kong	1,073	425	7	39.61	0.66
Korea, DPR	120,410	97	518	0.08	0.43
Mongolia	1,553,560	95	344	0.01	0.02

Cuba	**106,440**	**253**	**888**	**0.24**	**0.83**
Europe	**5,671,860**	**12,976**	**50,615**	**0.23**	**0.89**
Albania	27,400	13	87	0.05	0.32
Austria	82,409	318	1,382	0.39	1.68
Belarus	202,910	414	872	0.20	0.43
Belgium	30,280	1,309	397	4.32	1.31
Bosnia-Herzeg.	51,000	44	150	0.09	0.29
Bulgaria	108,560	79	618	0.07	0.57
Croatia	55,960	165	130	0.30	0.23
Cyprus	9,240	23	26	0.25	0.28
Czech Rep.	77,230	509	1,127	0.66	1.46
Denmark	42,430	141	559	0.33	1.32
Estonia	42,390	33	149	0.08	0.35
Finland	303,890	327	2,131	0.11	0.70
France	547,561	1,260	5,450	0.23	1.00
Germany	348,540	1,621	8,908	0.47	2.56
Gibraltar	7	2	0	24.04	1.00
Greece	128,900	72	887	0.06	0.69
Hungary	90,530	463	405	0.51	0.45
Ireland	68,890	112	437	0.16	0.63
Italy	294,140	711	5,841	0.24	1.99
Kosovo	10,887	14	68	0.13	0.63
Latvia	62,180	27	246	0.04	0.40
Lithuania	62,674	69	408	0.11	0.65
Luxembourg	2,590	148	27	5.72	1.04
Macedonia	25,220	40	75	0.16	0.30
Malta	320	41	7	12.78	2.21
Moldova	32,860	58	183	0.18	0.56
Montenegro	13,450	5	36	0.04	0.27
Netherlands	33,720	1,135	675	3.37	2.00
Norway	365,268	81	302	0.02	0.08
Poland	306,220	431	3,194	0.14	1.04
Portugal	91,590	100	670	0.11	0.73
Romania	230,020	144	1,246	0.06	0.54
Serbia	87,460	225	248	0.26	0.28
Slovakia	48,088	151	632	0.31	1.31
Slovenia	20,140	30	297	0.15	1.48
Spain	498,800	579	4,223	0.12	0.85
Sweden	407,340	341	1,808	0.08	0.44
Switzerland	39,516	102	771	0.26	1.95
Ukraine	579,320	470	3,311	0.08	0.57
United Kingdom	241,930	1,168	2,633	0.48	1.09
Haiti Region	**75,880**	**230**	**249**	**0.30**	**0.33**
Dominican Rep.	48,320	171	202	0.35	0.42
Haiti	27,560	59	47	0.21	0.17
Iceland	**100,250**	**0**	**51**	**0.00**	**0.05**
India Region	**3,309,420**	**28,050**	**31,779**	**0.85**	**0.96**
Bangladesh	130,170	2,029	270	1.56	0.21
India	2,973,190	25,378	30,724	0.85	1.03
Nepal	143,350	486	288	0.34	0.20
Sri Lanka	62,710	158	497	0.25	0.79
Israel	**21,640**	**708**	**167**	**3.27**	**0.77**
Jamaica	**10,830**	**50**	**14**	**0.46**	**0.13**
Japan	**364,560**	**4,078**	**325**	**1.12**	**0.09**
Mauritius	**2,040**	**49**	**8**	**2.40**	**0.37**
Mideast	**6,327,218**	**21,363**	**33,507**	**0.34**	**0.53**
Armenia	28,470	19	107	0.07	0.38
Azerbaijan	82,658	150	438	0.18	0.53
Bahrain	760	480	10	63.13	1.32
Iran	1,628,550	3,857	11,673	0.24	0.72
Iraq	434,320	614	1,824	0.14	0.42
Jordan	88,780	150	409	0.17	0.46

Kuwait	17,820	1,215	64	6.82	0.36
Lebanon	10,230	193	44	1.88	0.43
Oman	309,500	696	1,116	0.22	0.36
Qatar	11,610	1,782	42	15.35	0.36
Saudi Arabia	2,149,690	5,210	8,914	0.24	0.41
Syria	183,630	73	399	0.04	0.22
Turkey	769,630	1,408	6,451	0.18	0.84
UAE	83,600	5,481	1,925	6.56	2.30
Yemen	527,970	35	90	0.01	0.02
New Zealand	**263,310**	**288**	**1,883**	**0.11**	**0.72**
Philippines	**298,170**	**1,593**	**1,186**	**0.53**	**0.40**
Russia Region	**16,446,360**	**1,942**	**25,561**	**0.01**	**0.16**
Georgia	69,490	12	195	0.02	0.28
Russia	16,376,870	1,930	25,366	0.01	0.15
South America	**17,175,466**	**4,932**	**56,500**	**0.03**	**0.33**
Argentina	2,736,690	457	3,233	0.02	0.12
Bolivia	1,083,300	75	447	0.01	0.04
Brazil	8,358,140	2,622	37,159	0.03	0.44
Chile	743,532	377	1,498	0.05	0.20
Colombia	1,109,500	287	4,102	0.03	0.37
Curacao	444	56	7	12.61	1.47
Ecuador	248,360	121	1,476	0.05	0.59
Paraguay	397,300	28	199	0.01	0.05
Peru	1,280,000	289	2,841	0.02	0.22
Suriname	156,000	5	49	0.00	0.03
Trinidad/Tobago	5,130	274	14	5.34	0.27
Uruguay	175,020	42	325	0.02	0.19
Venezuela	882,050	298	5,152	0.03	0.58
Southeast Asia	**4,027,647**	**14,391**	**2,633**	**0.36**	**0.07**
Brunei	5,270	43	3	0.83	0.05
Cambodia	176,520	126	79	0.07	0.04
Indonesia	1,811,570	3,942	1,975	0.22	0.11
Lao PDR	230,800	0	0	0.00	0.00
Malaysia	328,550	2,607	143	0.79	0.04
Myanmar	653,290	236	291	0.04	0.04
Singapore	687	393	1	57.16	0.14
Thailand	510,890	4,272	146	0.84	0.03
Vietnam	310,070	2,771	-4	0.89	0.00
South Korea	**97,350**	**4,596**	**31**	**4.72**	**0.03**
Taiwan	**36,193**	**1,505**	**152**	**4.16**	**0.42**
United States	**9,147,420**	**27,163**	**75,172**	**0.30**	**0.82**
All regions	**121,464,428**	**197,733**	**444,654**	**0.16**	**0.37**

*First number is percent land taken up by onshore utility PV; second number is percent equivalent land for offshore utility PV. Applies to Bahrain, Curacao, Gibraltar, Hong Kong, Malta, Qatar, and Singapore. If countries are unable to use so much offshore area for floating PV, other options are more rooftop PV, more offshore wind, or transmission interconnection with nearby countries.

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 S26 gives the installed power densities applied in this table. Areas are given both as an absolute area and 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 S28. 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 caption of Table S29.

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
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 (CSP-PCM)	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 Jacobson et al. (2022). See Note S9 for more details.

Table S29. Changes in the Numbers of Long-Term, Full-Time Jobs
Estimated long-term, full-time jobs created and lost due to transitioning from BAU energy to WWS across all energy sectors in each country. 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. It also accounts for the building of 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 losses 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.

Region or country	(a) Construction jobs produced	(b) Operation jobs produced	(c) Total jobs produced =a+b	(d) Total jobs lost	(e) Net change in jobs =c-d
Africa	**1,700,632**	**1,745,055**	**3,445,687**	**4,545,041**	**-1,099,354**
Algeria	146,341	144,806	291,147	411,482	-120,335
Angola	25,903	29,275	55,179	249,355	-194,176
Benin	16,469	15,859	32,329	36,585	-4,256
Botswana	7,309	7,512	14,821	9,320	5,501
Cameroon	21,236	22,564	43,801	83,159	-39,358
Congo	7,668	7,995	15,663	65,555	-49,892
Congo, DR	50,888	53,853	104,741	284,465	-179,724
Côte d'Ivoire	23,171	24,613	47,785	71,857	-24,072
Egypt	245,421	247,426	492,847	333,282	159,565
Equator. Guinea	20,477	22,483	42,960	35,419	7,541
Eritrea	1,677	1,546	3,223	7,991	-4,768
Ethiopia	75,217	76,213	151,430	334,804	-183,374
Gabon	31,673	35,610	67,284	51,514	15,770
Ghana	41,348	38,697	80,044	79,853	191
Kenya	37,444	39,848	77,293	160,636	-83,343
Libya	49,535	46,444	95,979	189,406	-93,427
Morocco	64,130	63,077	127,206	42,320	84,886
Mozambique	19,427	20,371	39,798	103,467	-63,669
Namibia	7,388	7,401	14,789	26,889	-12,100
Niger	10,566	10,056	20,622	33,811	-13,189
Nigeria	304,028	293,583	597,612	1,117,775	-520,163
Senegal	11,751	11,341	23,092	23,010	82
South Africa	271,209	311,863	583,071	239,448	343,623
South Sudan	2,235	2,106	4,341	26,622	-22,281
Sudan	42,317	39,842	82,159	130,461	-48,302
Tanzania	51,160	49,652	100,813	155,345	-54,532
Togo	8,406	8,316	16,721	30,216	-13,495
Tunisia	40,195	41,154	81,349	37,477	43,872
Zambia	38,643	42,026	80,668	87,949	-7,281
Zimbabwe	27,400	29,521	56,921	85,568	-28,647
Australia	**246,057**	**374,907**	**620,964**	**364,616**	**256,348**
Canada	**195,976**	**229,200**	**425,177**	**702,683**	**-277,506**
Central America	**513,064**	**772,469**	**1,285,534**	**559,964**	**725,570**
Costa Rica	11,422	17,413	28,835	11,159	17,676
El Salvador	8,349	13,222	21,571	8,184	13,387
Guatemala	20,536	29,104	49,640	50,988	-1,348
Honduras	16,421	24,337	40,758	19,143	21,615
Mexico	423,046	639,221	1,062,268	444,220	618,048
Nicaragua	8,338	11,783	20,121	11,855	8,266
Panama	24,952	37,389	62,341	14,415	47,926
Central Asia	502,740	549,313	1,052,053	885,570	166,483
Kazakhstan	80,202	83,514	163,716	216,438	-52,722

Kyrgyz Republic	8,739	9,872	18,611	6,716	11,895
Pakistan	323,791	360,360	684,151	411,954	272,197
Tajikistan	5,184	6,686	11,870	6,978	4,892
Turkmenistan	25,609	26,710	52,319	121,282	-68,963
Uzbekistan	59,215	62,171	121,386	122,202	-816
China Region	**4,685,909**	**7,683,417**	**12,369,326**	**3,007,406**	**9,361,920**
China	4,595,516	7,488,662	12,084,178	2,920,028	9,164,150
Hong Kong	55,419	146,892	202,310	38,140	164,170
Korea, DPR	22,067	31,165	53,231	27,390	25,841
Mongolia	12,908	16,699	29,607	21,848	7,759
Cuba	**46,938**	**61,733**	**108,671**	**20,726**	**87,945**
Europe	**2,109,404**	**3,193,515**	**5,302,919**	**2,282,091**	**3,020,828**
Albania	5,097	6,025	11,122	6,438	4,684
Austria	48,809	67,805	116,614	45,682	70,932
Belarus	36,189	51,599	87,788	30,240	57,548
Belgium	75,492	141,961	217,453	50,866	166,587
Bosnia-Herzeg.	10,783	11,785	22,568	13,999	8,569
Bulgaria	26,102	33,932	60,034	25,502	34,532
Croatia	19,012	23,236	42,247	18,074	24,173
Cyprus	5,320	6,698	12,018	2,986	9,032
Czech Rep.	48,919	69,237	118,156	45,493	72,663
Denmark	21,618	39,998	61,616	35,572	26,044
Estonia	5,845	8,867	14,713	11,195	3,518
Finland	44,623	75,905	120,528	49,149	71,379
France	237,671	320,054	557,725	205,090	352,635
Germany	310,301	516,246	826,547	284,874	541,673
Gibraltar	4,105	8,692	12,797	3,330	9,467
Greece	32,323	44,936	77,258	32,296	44,962
Hungary	43,957	57,550	101,507	31,254	70,253
Ireland	19,399	30,194	49,593	18,569	31,024
Italy	173,476	253,455	426,932	159,664	267,268
Kosovo	3,687	3,973	7,659	4,670	2,989
Latvia	7,810	10,090	17,900	13,501	4,399
Lithuania	14,758	19,272	34,030	14,432	19,598
Luxembourg	7,460	12,814	20,274	4,312	15,962
Macedonia	7,102	7,759	14,861	4,087	10,774
Malta	4,876	9,216	14,091	3,301	10,790
Moldova	9,041	11,329	20,370	8,015	12,355
Montenegro	2,156	2,495	4,652	2,525	2,127
Netherlands	84,218	165,649	249,867	103,044	146,823
Norway	24,919	46,602	71,521	215,796	-144,275
Poland	127,874	148,961	276,835	107,651	169,184
Portugal	30,833	42,541	73,374	34,248	39,126
Romania	42,037	55,053	97,090	60,925	36,165
Serbia	29,180	33,196	62,376	22,114	40,262
Slovakia	22,465	28,695	51,160	17,269	33,891
Slovenia	9,708	11,925	21,632	9,161	12,471
Spain	145,270	219,858	365,129	129,201	235,928
Sweden	53,041	96,712	149,753	68,455	81,298
Switzerland	28,051	39,016	67,067	28,505	38,562
Ukraine	118,895	155,985	274,880	106,762	168,118
United Kingdom	166,982	304,201	471,183	253,844	217,339
Haiti Region	**34,682**	**44,648**	**79,330**	**39,348**	**39,982**
Dominican Rep.	24,634	32,189	56,823	15,918	40,905
Haiti	10,048	12,458	22,506	23,430	-924
Iceland	**1,732**	**5,728**	**7,460**	**4,635**	**2,825**
India Region	**2,883,282**	**4,053,837**	**6,937,119**	**2,611,937**	**4,325,182**
Bangladesh	162,199	255,396	417,595	178,224	239,371
India	2,640,236	3,686,985	6,327,221	2,305,949	4,021,272
Nepal	44,456	67,394	111,850	81,596	30,254
Sri Lanka	36,391	44,062	80,453	46,168	34,285
Israel	**72,954**	**115,907**	**188,861**	**33,687**	**155,174**

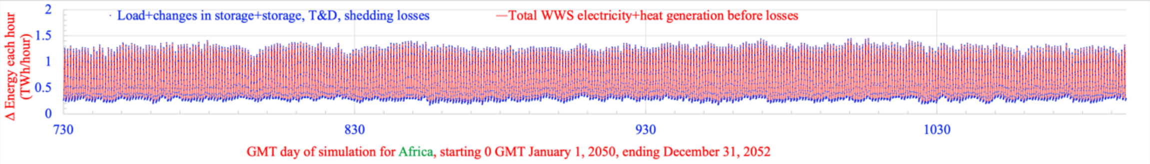
Jamaica	**14,200**	**12,788**	**26,988**	**5,617**	**21,371**
Japan	**468,334**	**613,770**	**1,082,103**	**260,005**	**822,098**
Mauritius	**35,963**	**19,597**	**55,560**	**5,543**	**50,017**
Mideast	**1,705,765**	**2,537,675**	**4,243,440**	**3,692,453**	**550,987**
Armenia	4,005	5,105	9,110	4,053	5,057
Azerbaijan	20,059	23,359	43,418	85,860	-42,442
Bahrain	23,478	44,666	68,143	52,125	16,018
Iran	458,864	619,896	1,078,760	845,831	232,929
Iraq	79,202	93,881	173,083	426,300	-253,217
Jordan	22,481	29,763	52,245	16,145	36,100
Kuwait	55,367	106,261	161,628	253,173	-91,545
Lebanon	18,223	30,963	49,187	13,161	36,026
Oman	62,187	96,236	158,423	157,681	742
Qatar	70,994	138,440	209,433	293,984	-84,551
Saudi Arabia	409,380	583,825	993,205	988,951	4,254
Syria	19,184	23,574	42,757	24,569	18,188
Turkey	215,467	286,964	502,431	125,714	376,717
UAE	238,877	445,533	684,410	394,325	290,085
Yemen	7,996	9,210	17,206	10,581	6,625
New Zealand	**38,855**	**55,047**	**93,902**	**39,965**	**53,937**
Philippines	**201,776**	**286,675**	**488,451**	**137,336**	**351,115**
Russia Region	**392,377**	**629,955**	**1,022,332**	**1,254,245**	**-231,913**
Georgia	5,438	8,095	13,533	7,855	5,678
Russia	386,938	621,860	1,008,799	1,246,390	-237,591
South America	**959,962**	**1,289,689**	**2,249,650**	**1,965,734**	**283,916**
Argentina	83,098	105,626	188,724	197,295	-8,571
Bolivia	13,610	16,535	30,146	54,397	-24,251
Brazil	542,838	733,966	1,276,804	925,761	351,043
Chile	58,435	77,273	135,708	91,126	44,582
Colombia	68,802	89,246	158,048	185,593	-27,545
Curacao	4,813	9,236	14,049	4,261	9,788
Ecuador	25,691	34,233	59,924	76,516	-16,592
Paraguay	7,746	10,805	18,551	36,392	-17,841
Peru	48,528	63,414	111,942	82,691	29,251
Suriname	1,471	1,775	3,245	500	2,745
Trinidad/Tobago	20,887	36,594	57,481	67,072	-9,591
Uruguay	10,131	13,709	23,841	17,292	6,549
Venezuela	73,910	97,277	171,187	226,838	-55,651
Southeast Asia	**2,100,716**	**1,984,738**	**4,085,455**	**1,987,573**	**2,097,882**
Brunei	6,295	5,756	12,051	33,511	-21,460
Cambodia	30,933	27,129	58,062	44,553	13,509
Indonesia	665,015	591,008	1,256,023	761,441	494,582
Lao PDR	3,357	5,486	8,843	29,551	-20,708
Malaysia	306,924	298,029	604,952	293,793	311,159
Myanmar	55,083	51,325	106,408	131,930	-25,522
Singapore	210,127	127,538	337,665	97,357	240,308
Thailand	432,883	467,710	900,593	365,181	535,412
Vietnam	390,099	410,758	800,857	230,256	570,601
South Korea	**579,848**	**668,223**	**1,248,071**	**195,903**	**1,052,168**
Taiwan	**314,068**	**420,023**	**734,092**	**109,361**	**624,731**
United States	**1,981,797**	**3,467,701**	**5,449,498**	**2,478,720**	**2,970,778**
All regions	**21,787,031**	**30,815,610**	**52,602,643**	**27,190,159**	**25,412,484**

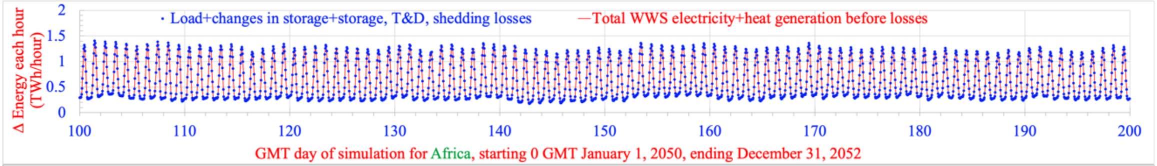
Jobs for electricity generation technologies are the number of long-term, full-time jobs per MW in each country multiplied by the 2050 final nameplate capacities (Table S12) minus the 2020 nameplate capacities (Table S11) for each device for construction jobs and the 2050 nameplate capacities alone for operation jobs. The jobs per MW for each device in each country is calculated with the methodology in Jacobson et al. (2017) to scale U.S. jobs from Table S28 by year and country. For storage, the number of jobs per MW from Table S28 is multiplied by the maximum discharge rate of the storage technology for each region (Table S16). The transmission/distribution jobs are calculated as in the spreadsheet (Jacobson and Delucchi, 2022).

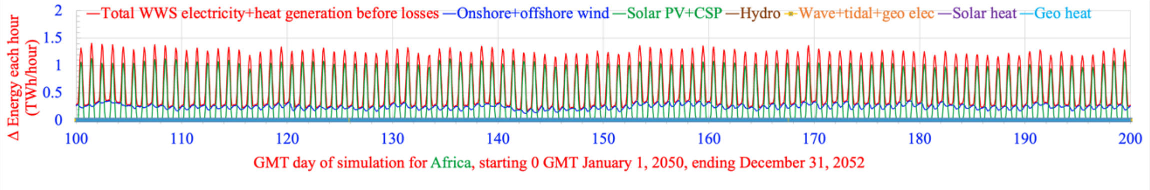
Supporting Figures

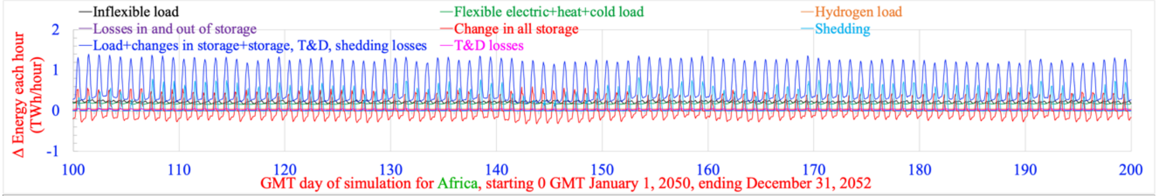
Figure S1. 2050-2052 hourly time series showing the matching of all-energy demand with supply and storage for the regions defined in Table S1. First row: modeled time-dependent total WWS power generation versus load plus losses plus changes in storage plus shedding for the last year of the three-year simulation. Second row: same as first row, but for a window of 100 days early in the simulation. Third row: a breakdown of WWS power generation by source during the window. Fourth row: a breakdown of inflexible load; flexible electric, heat, and cold load; flexible hydrogen load; losses in and out of storage; transmission and distribution losses; changes in storage; and shedding. Fifth row: A breakdown of solar PV+CSP electricity production, onshore plus offshore wind electricity production, building total cold load, and building total heat load (as used in LOADMATCH), summed over each region for 10 days; 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. Raw GATOR-GCMOM results for solar, wind, heat load, and cold load 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 the main text.

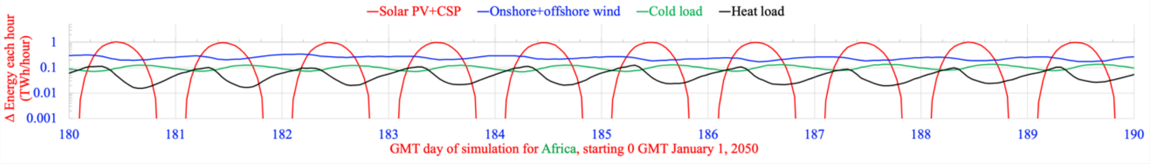
AFRICA


Δ Energy each hour (TWh/hour)
2
1.5
1
0.5
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Africa, starting 0 GMT January 1, 2050, ending December 31, 2052

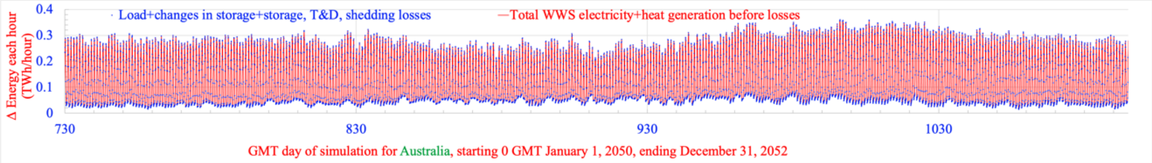

Δ Energy each hour (TWh/hour)
2
1.5
1
0.5
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa, starting 0 GMT January 1, 2050, ending December 31, 2052

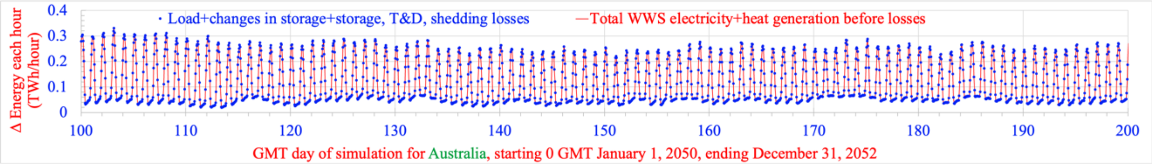

Δ Energy each hour (TWh/hour)
2
1.5
1
0.5
0
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa, starting 0 GMT January 1, 2050, ending December 31, 2052

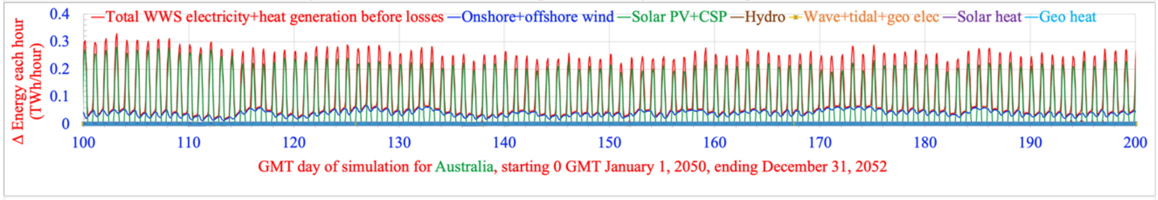

Δ Energy each hour (TWh/hour)
2
1
0
-1
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa, starting 0 GMT January 1, 2050, ending December 31, 2052

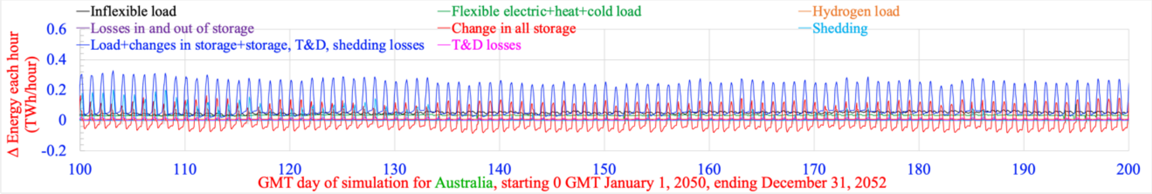

Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Africa, starting 0 GMT January 1, 2050

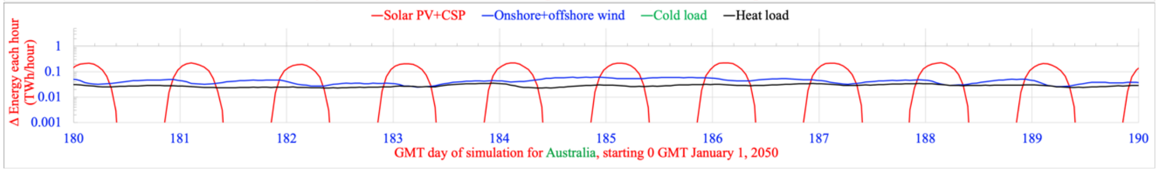
AUSTRALIA


Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Australia, starting 0 GMT January 1, 2050, ending December 31, 2052

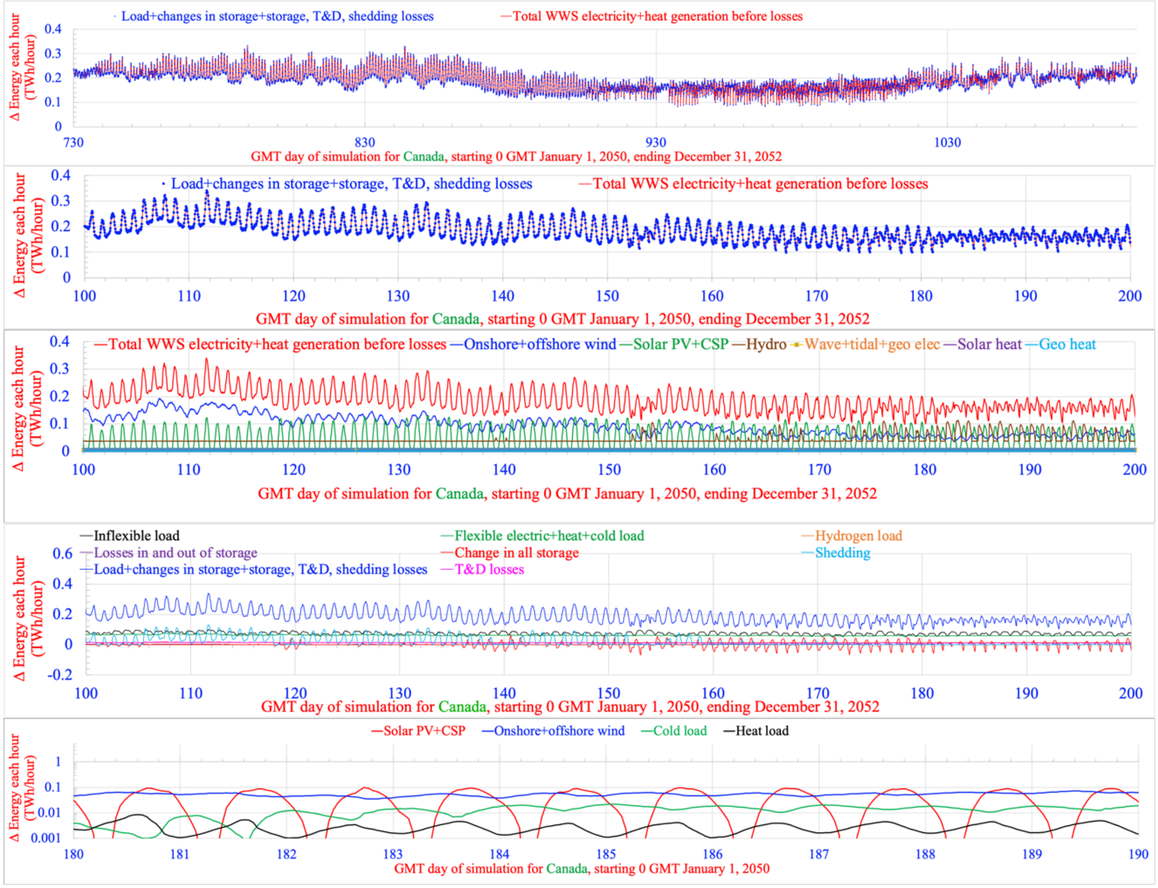

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Australia, starting 0 GMT January 1, 2050, ending December 31, 2052


Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Australia, starting 0 GMT January 1, 2050, ending December 31, 2052

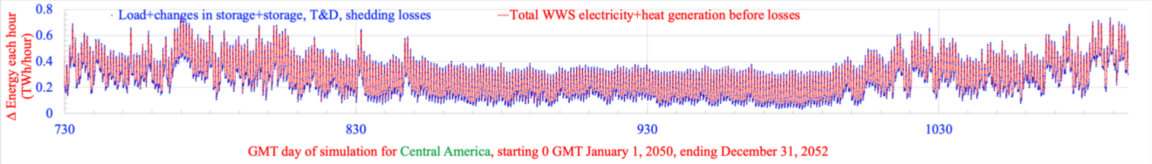

—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
0.6
0.4
0.2
0
-0.2
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Australia, starting 0 GMT January 1, 2050, ending December 31, 2052

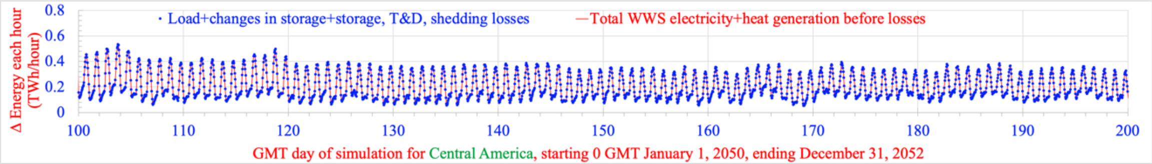

—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Australia, starting 0 GMT January 1, 2050

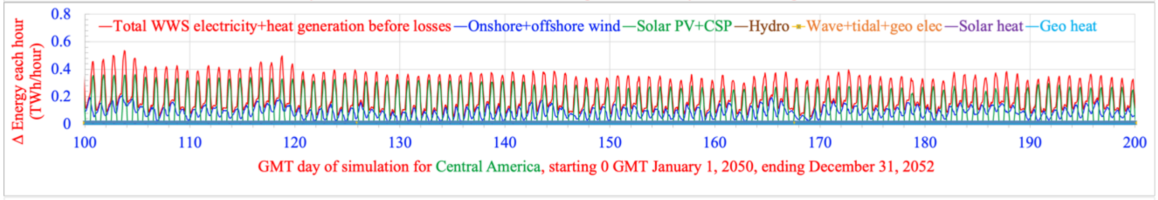
CANADA

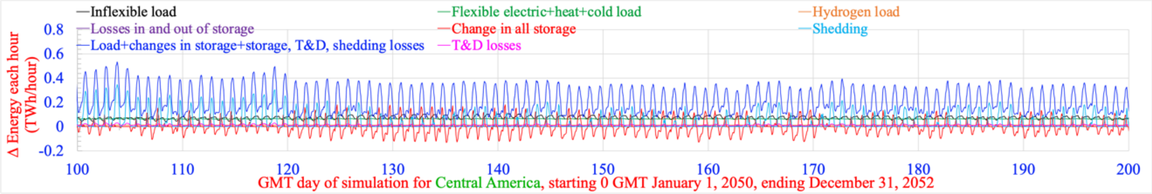

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
730
830
930
1030
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
0.6
0.4
0.2
0
-0.2
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Canada, starting 0 GMT January 1, 2050

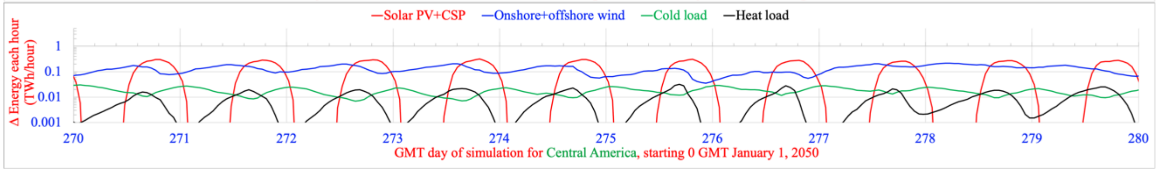
CENTRAL AMERICA



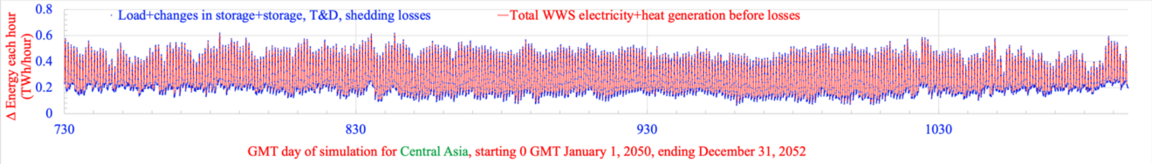


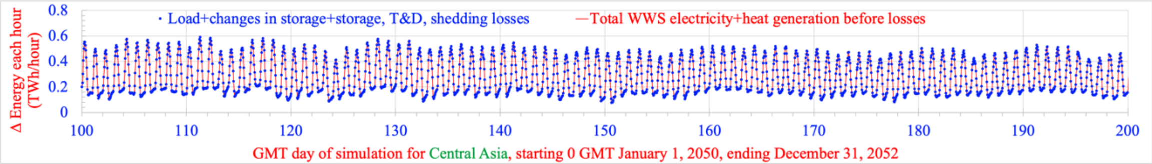


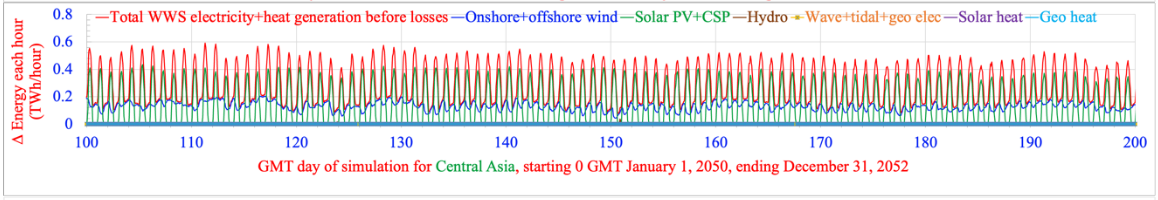


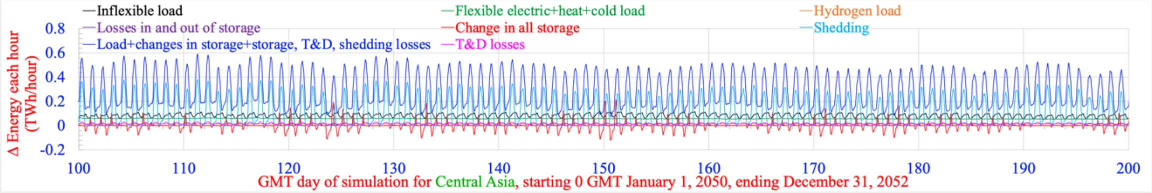


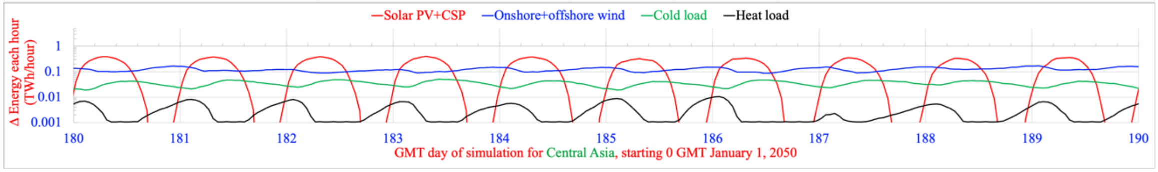
CENTRAL ASIA



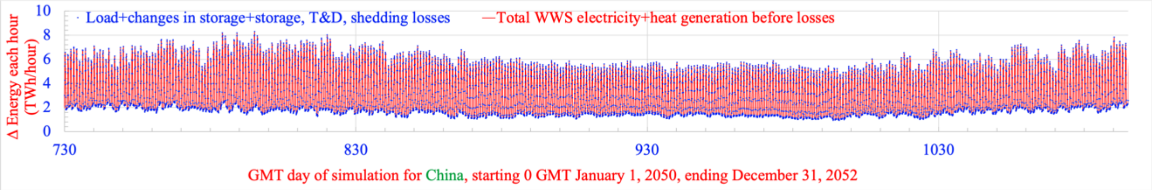


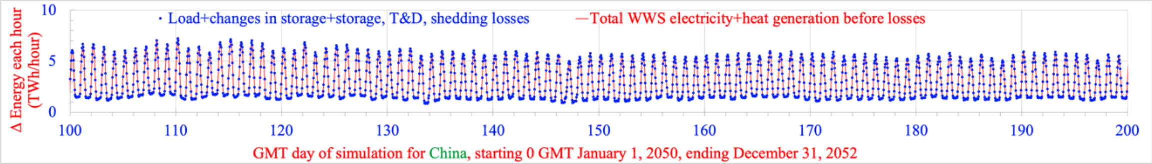


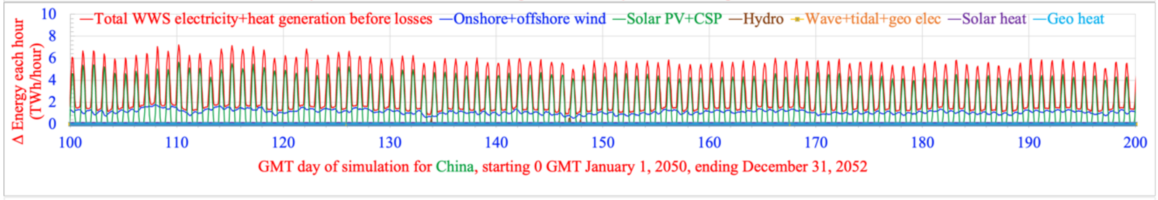


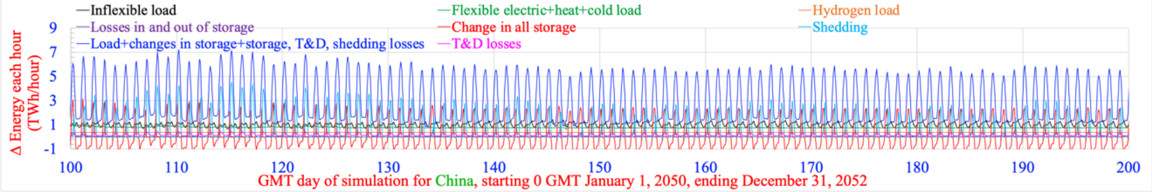


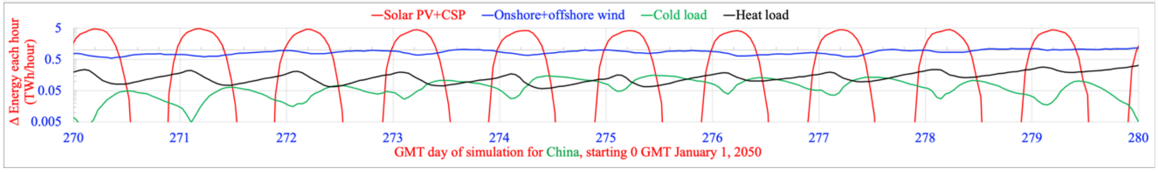
CHINA REGION



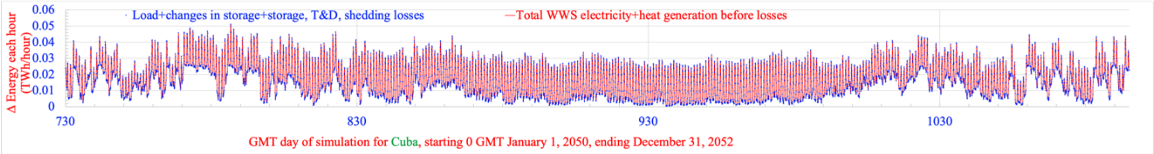




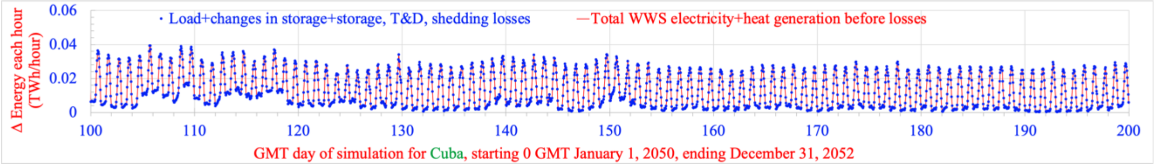




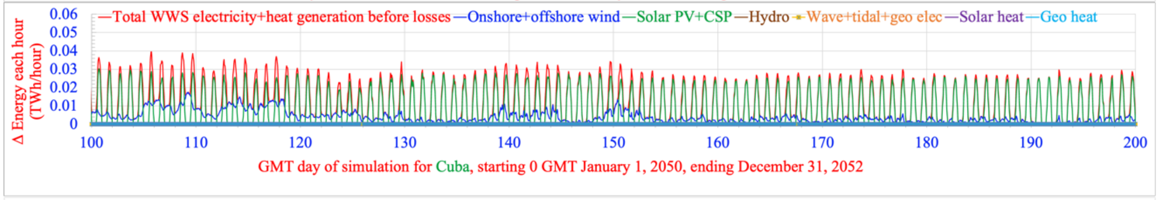
CUBA



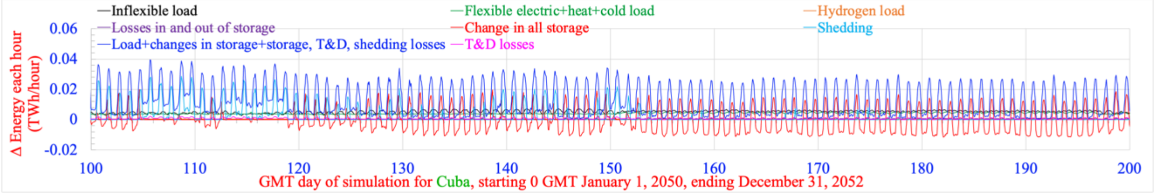
Δ Energy each hour (TWh/hour)
0.06
0.05
0.04
0.03
0.02
0.01
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052



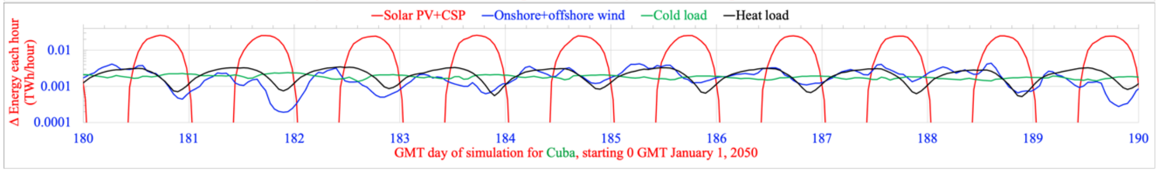
Δ Energy each hour (TWh/hour)
0.06
0.04
0.02
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052



Δ Energy each hour (TWh/hour)
0.06
0.05
0.04
0.03
0.02
0.01
0
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052

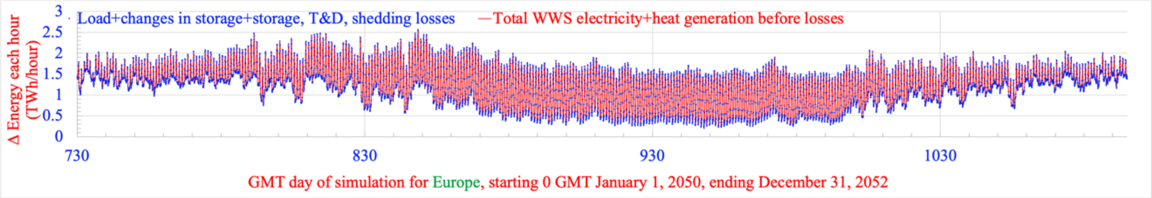


Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
0.06
0.04
0.02
0
-0.02
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052

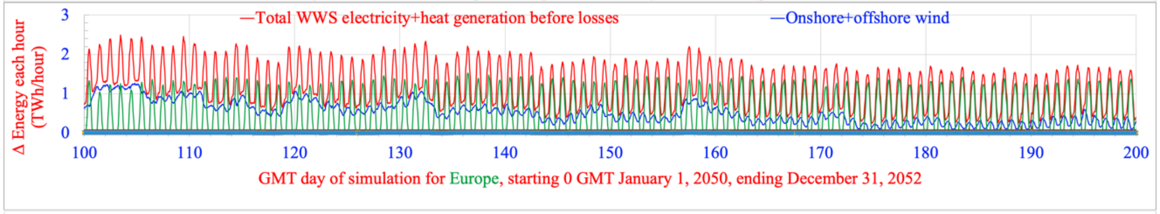


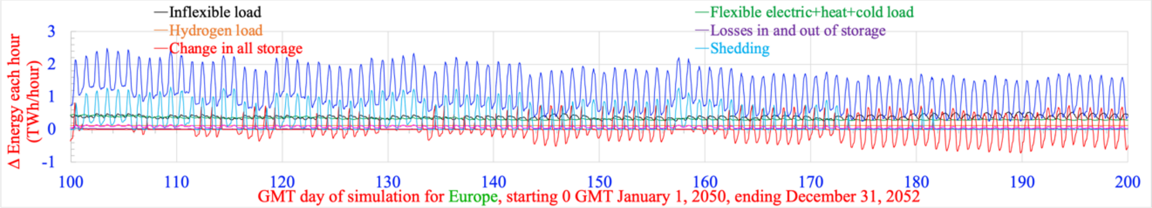
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
0.01
0.001
0.0001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050

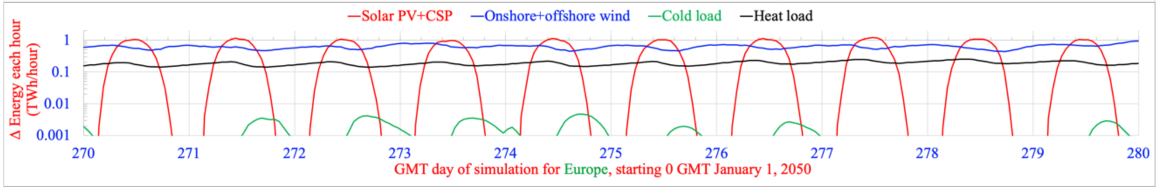
EUROPE


Δ Energy each hour (TWh/hour)
3
2.5
2
1.5
1
0.5
0
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

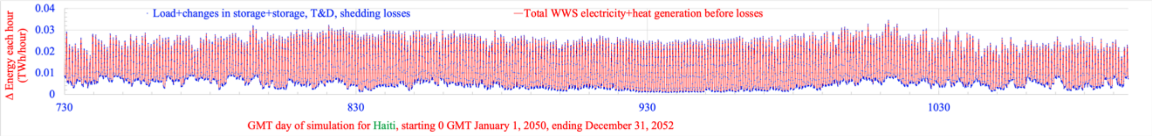

Δ Energy each hour (TWh/hour)
3
2
1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

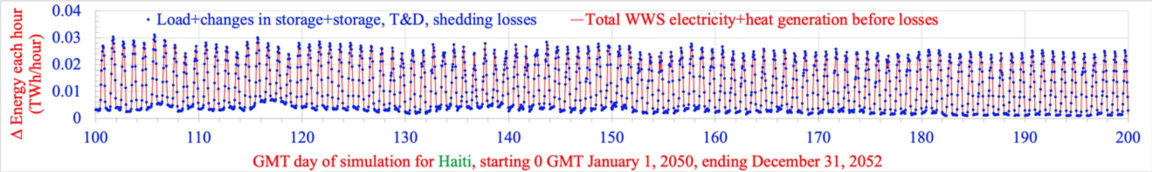

Δ Energy each hour (TWh/hour)
3
2
1
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

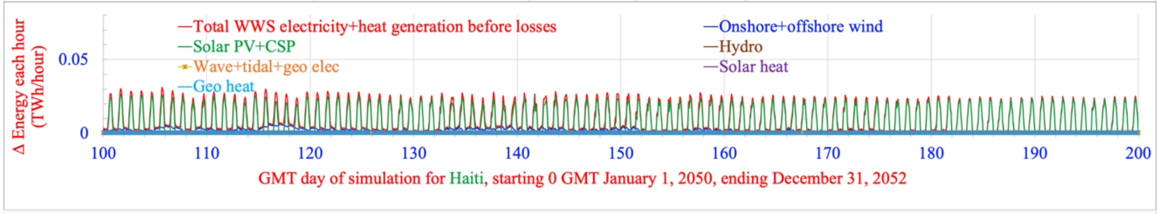

—Inflexible load
—Hydrogen load
—Change in all storage
—Flexible electric+heat+cold load
—Losses in and out of storage
—Shedding
Δ Energy each hour (TWh/hour)
3
2
1
0
-1
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

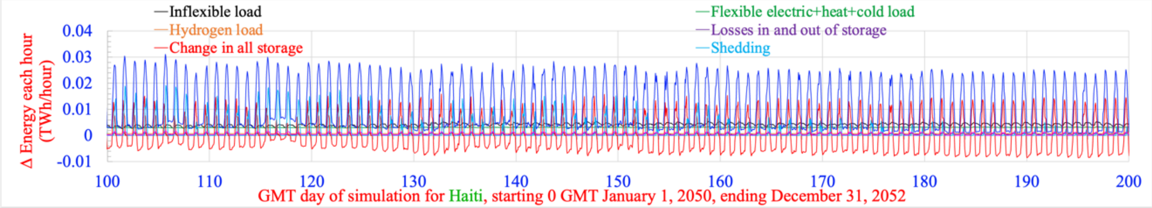

—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
270
271
272
273
274
275
276
277
278
279
280
GMT day of simulation for Europe, starting 0 GMT January 1, 2050

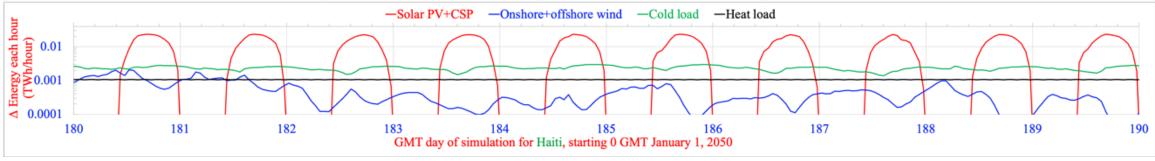
HAITI REGION



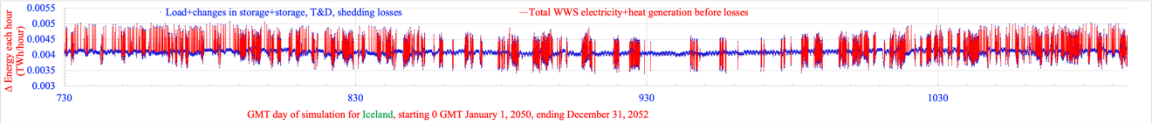


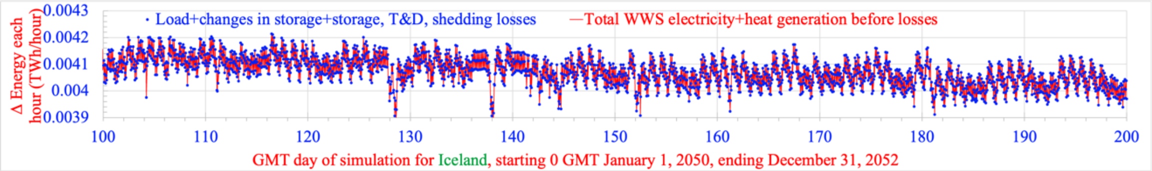


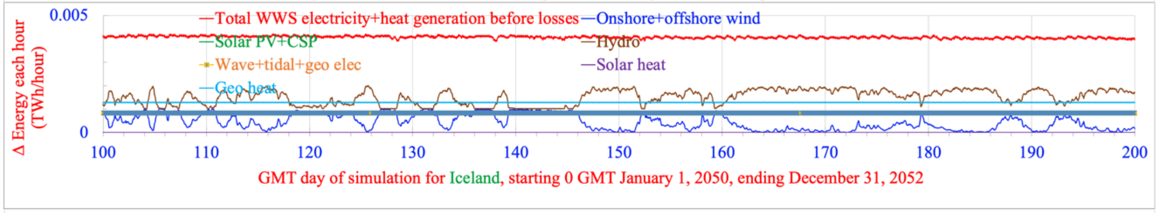


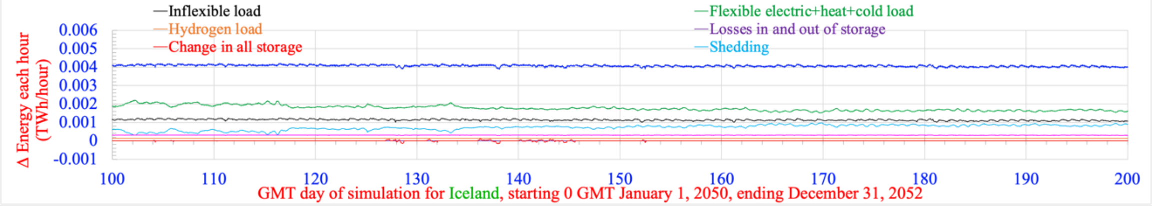


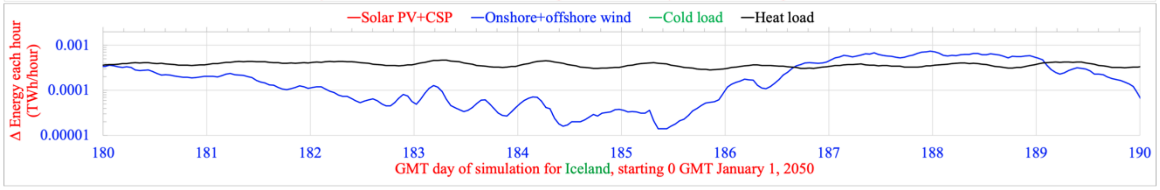
ICELAND


Δ Energy each hour (TWh/hour)
0.0055
0.005
0.0045
0.004
0.0035
0.003
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

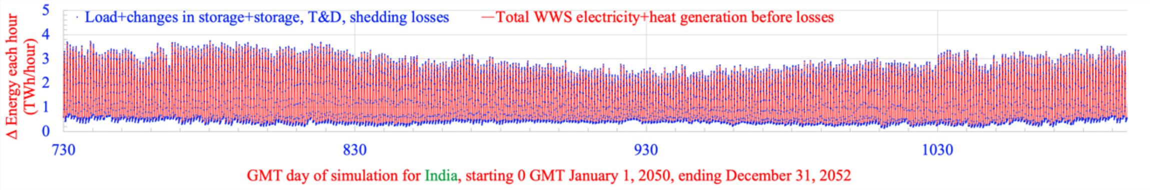

Δ Energy each hour (TWh/hour)
0.0043
0.0042
0.0041
0.004
0.0039
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

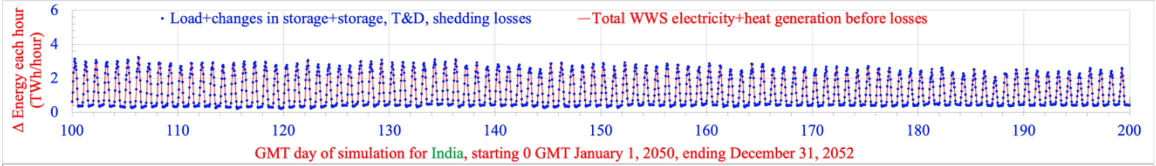

Δ Energy each hour (TWh/hour)
0.005
0
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

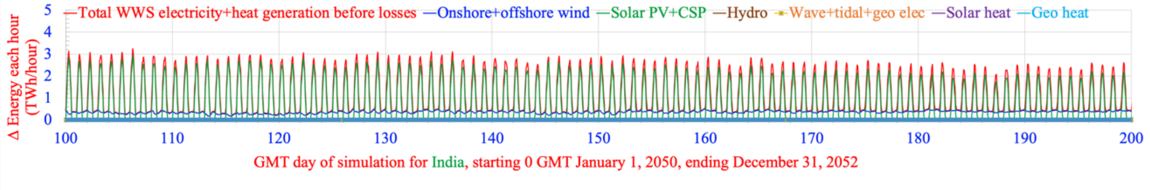

Δ Energy each hour (TWh/hour)
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

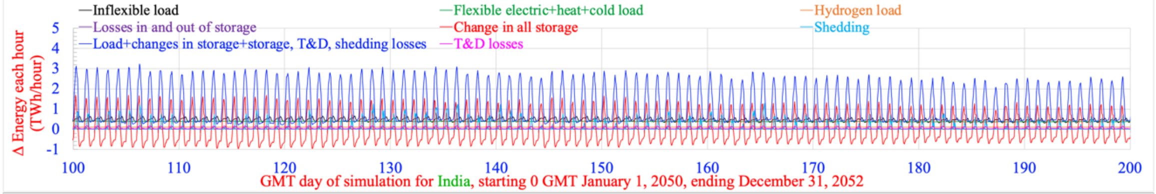

Δ Energy each hour (TWh/hour)
0.001
0.0001
0.00001
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050

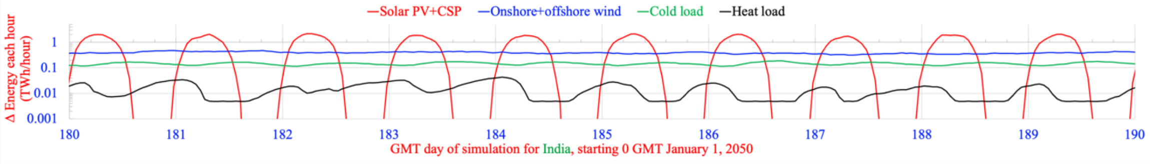
INDIA REGION



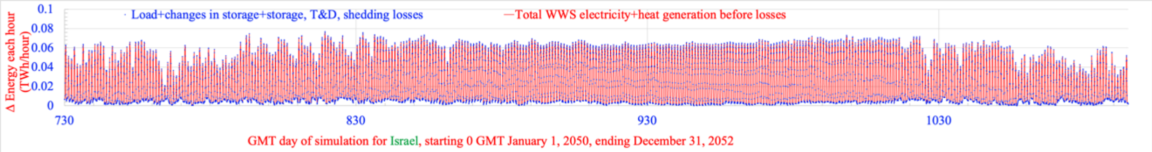




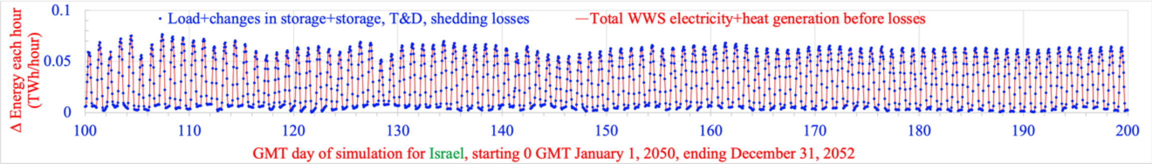




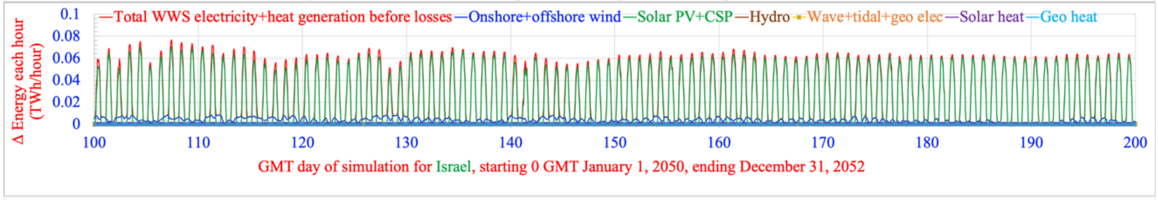
ISRAEL



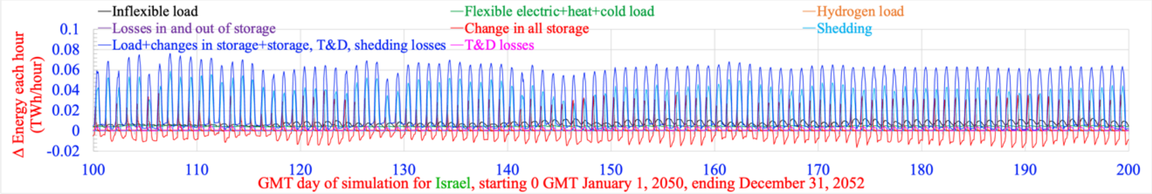
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.1
0.08
0.06
0.04
0.02
0
730
830
930
1030
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052



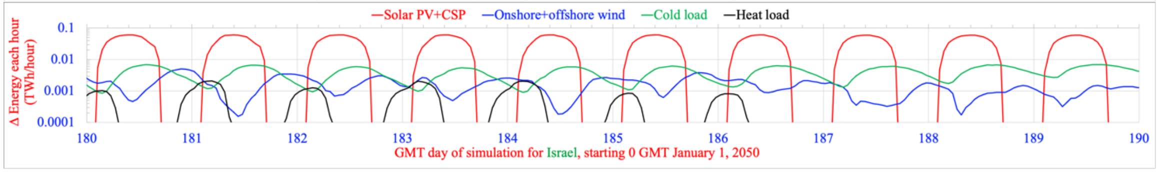
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.1
0.05
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052



—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
Δ Energy each hour (TWh/hour)
0.1
0.08
0.06
0.04
0.02
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052

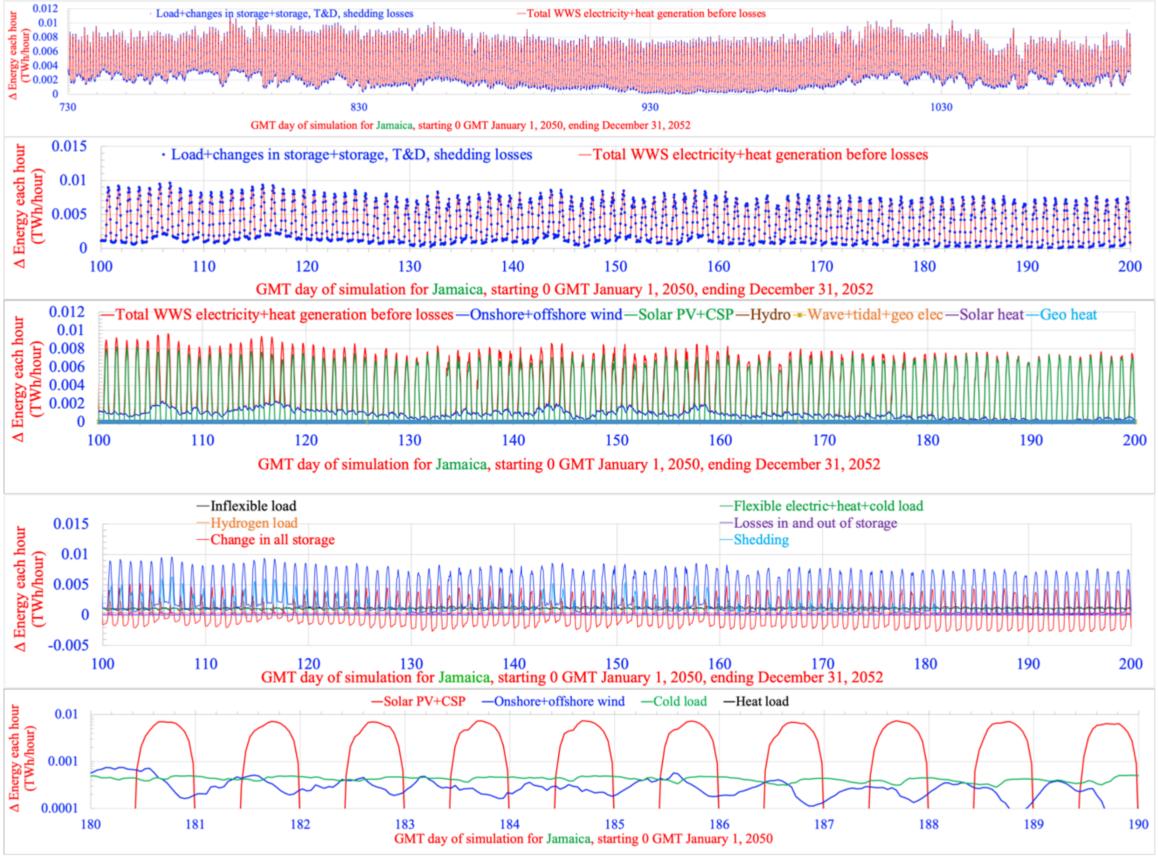


—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
0.1
0.08
0.06
0.04
0.02
0
-0.02
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052

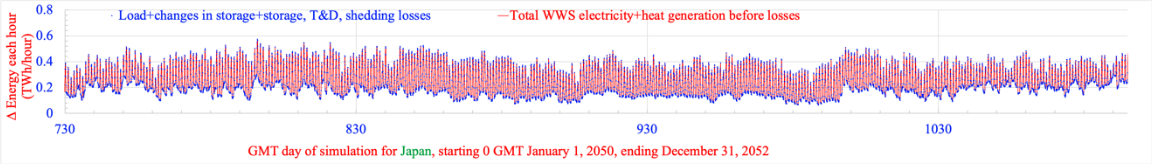


—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
0.1
0.01
0.001
0.0001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Israel, starting 0 GMT January 1, 2050

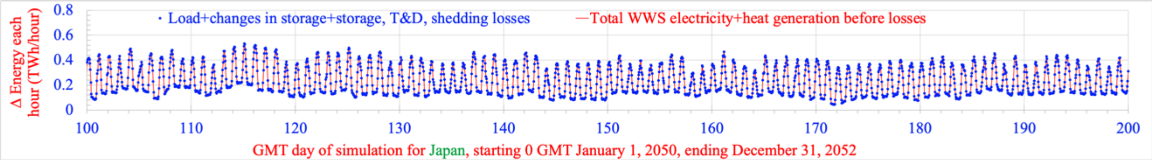
JAMAICA


Δ Energy each hour (TWh/hour)
0.012
0.01
0.008
0.006
0.004
0.002
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.015
0.01
0.005
0
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.012
0.01
0.008
0.006
0.004
0.002
0
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.015
0.01
0.005
0
-0.005
Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.01
0.001
0.0001
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050

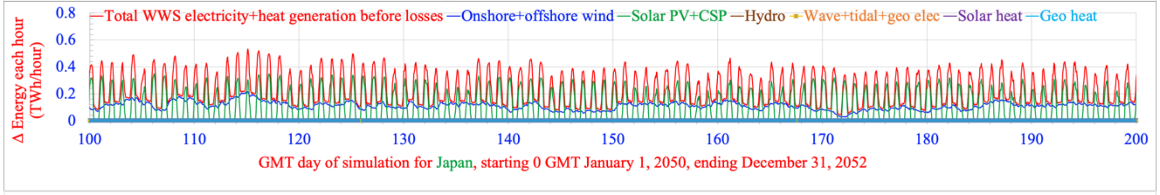
JAPAN



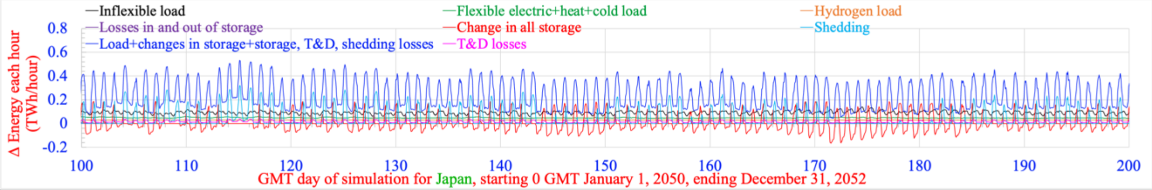
Δ Energy each hour (TWh/hour)
0.8
0.6
0.4
0.2
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



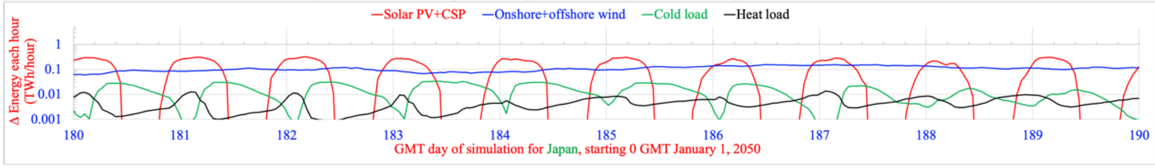
Δ Energy each hour (TWh/hour)
0.8
0.6
0.4
0.2
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



Δ Energy each hour (TWh/hour)
0.8
0.6
0.4
0.2
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052

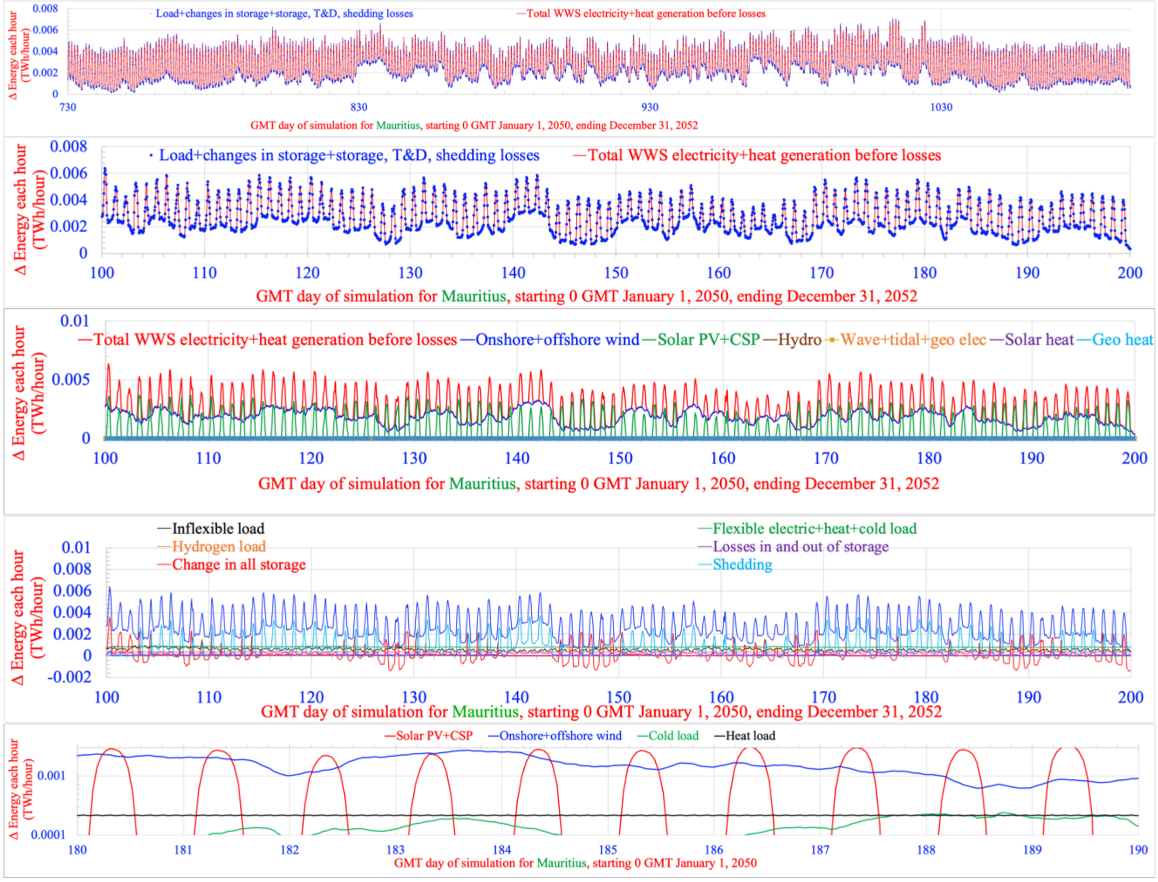


—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
0.8
0.6
0.4
0.2
0
-0.2
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



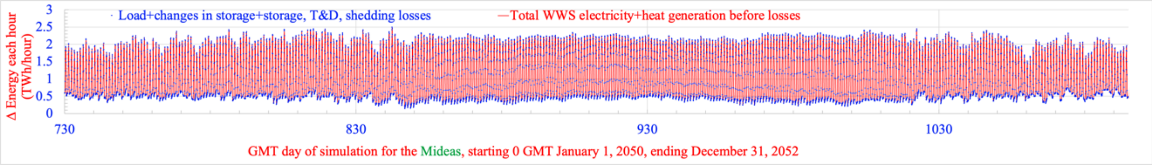
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Japan, starting 0 GMT January 1, 2050

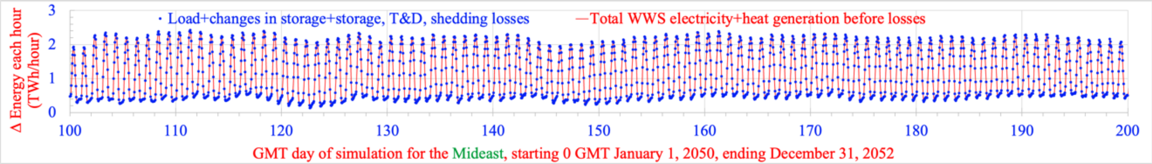
MAURITIUS

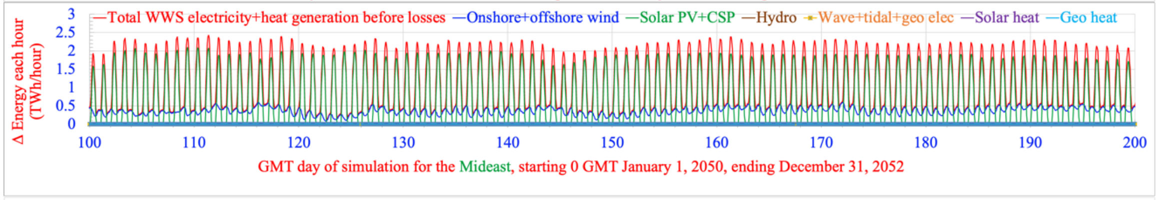


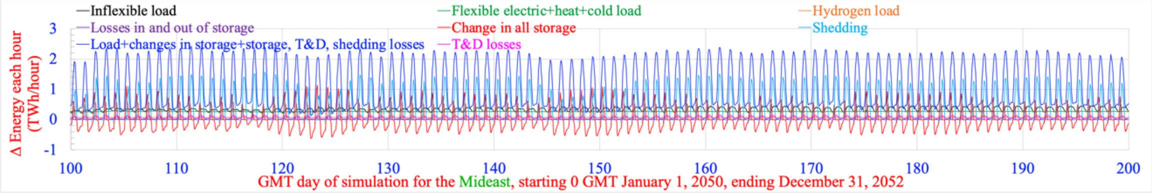
Δ Energy each hour (TWh/hour)
0.008
0.006
0.004
0.002
0
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.008
0.006
0.004
0.002
0
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.01
0.005
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—Inflexible load
—Hydrogen load
—Change in all storage
—Flexible electric+heat+cold load
—Losses in and out of storage
—Shedding
0.01
0.008
0.006
0.004
0.002
0
-0.002
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
0.001
0.0001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050

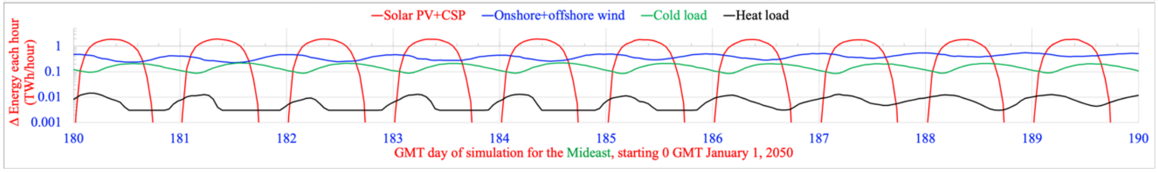
MIDEAST


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
3
2.5
2
1.5
1
0.5
0
730
830
930
1030
GMT day of simulation for the Mideas, starting 0 GMT January 1, 2050, ending December 31, 2052

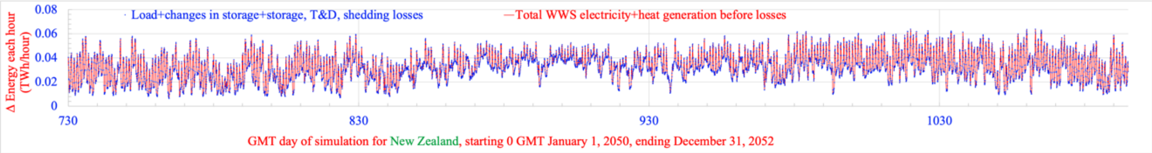

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
3
2
1
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052

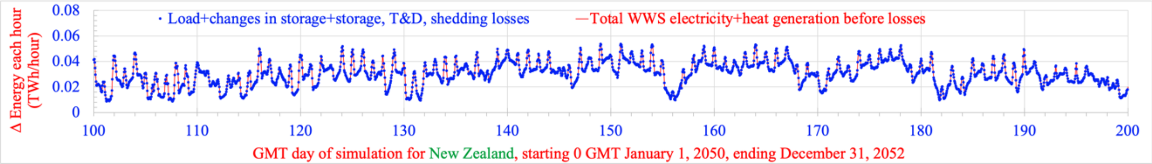

Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
3
2.5
2
1.5
1
0.5
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052

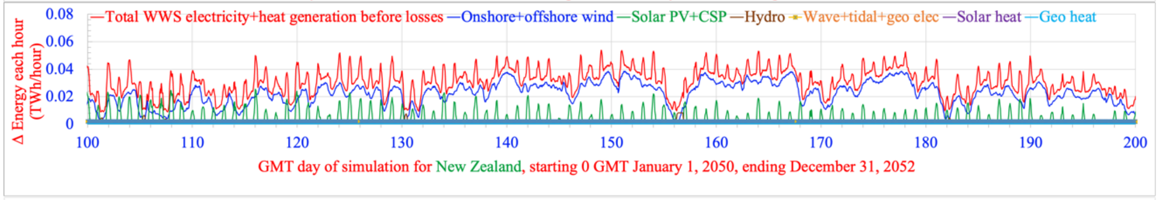

Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
3
2
1
0
-1
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052

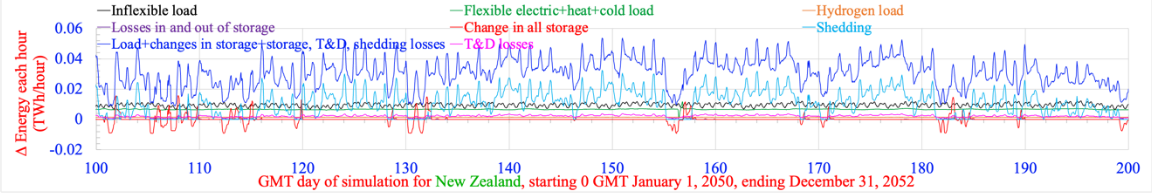

Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050

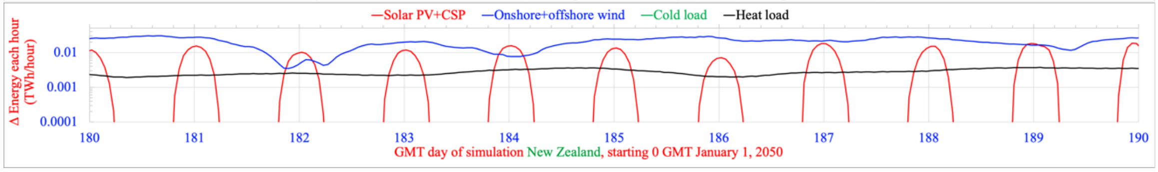
NEW ZEALAND


Δ Energy each hour (TWh/hour)
0.08
0.06
0.04
0.02
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052

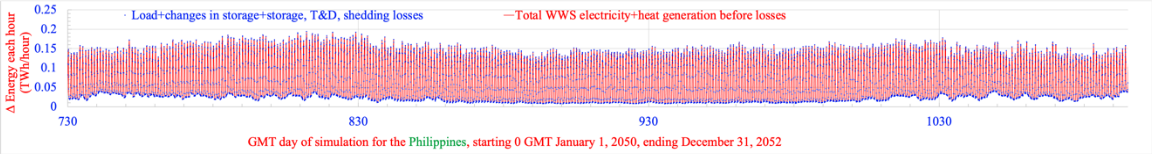

Δ Energy each hour (TWh/hour)
0.08
0.06
0.04
0.02
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052

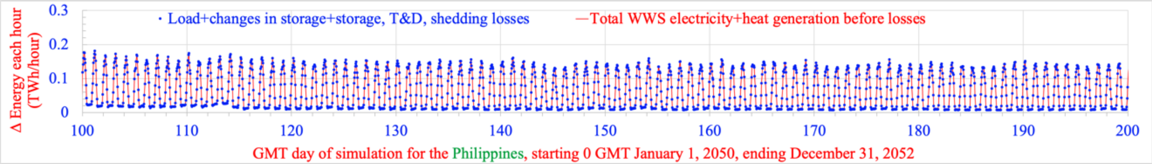

Δ Energy each hour (TWh/hour)
0.08
0.06
0.04
0.02
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052

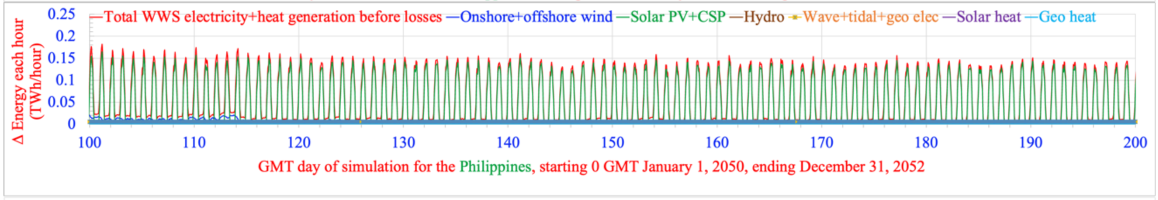

Δ Energy each hour (TWh/hour)
0.06
0.04
0.02
0
-0.02
—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052

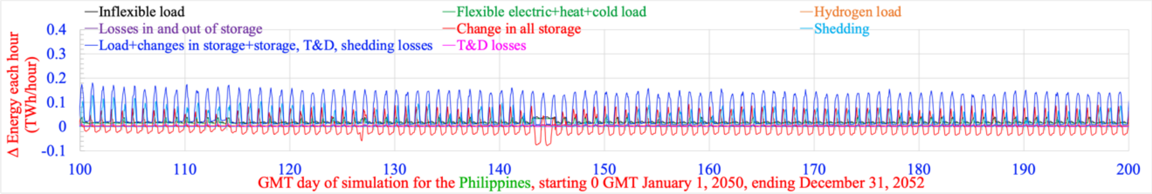

Δ Energy each hour (TWh/hour)
0.01
0.001
0.0001
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation New Zealand, starting 0 GMT January 1, 2050

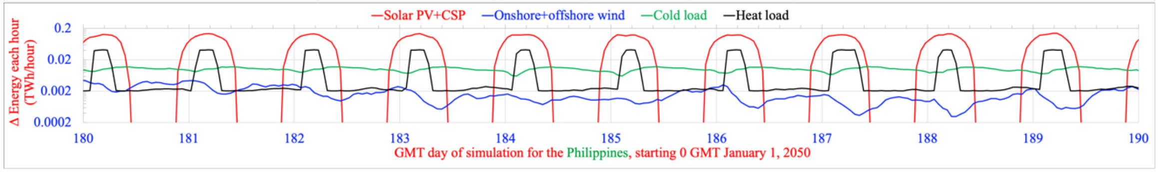
PHILIPPINES



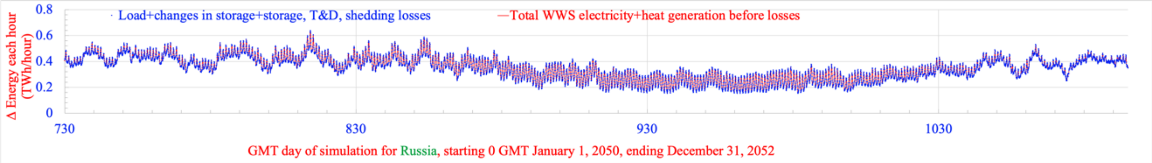


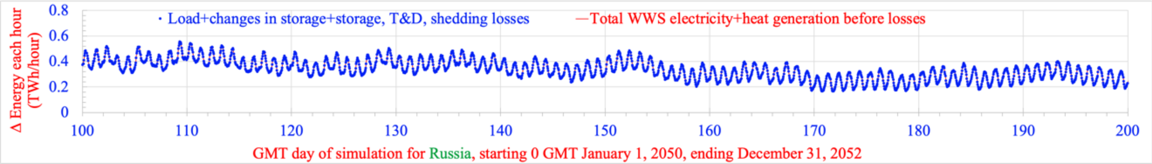


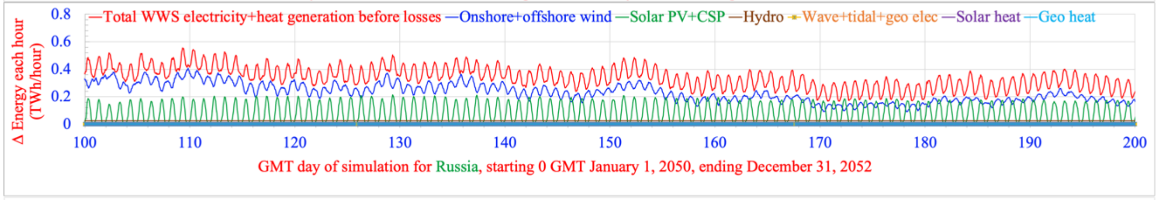


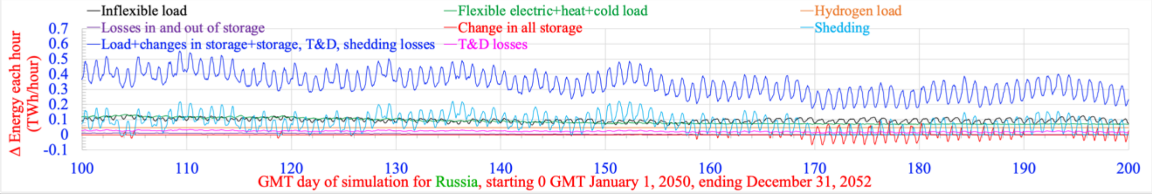


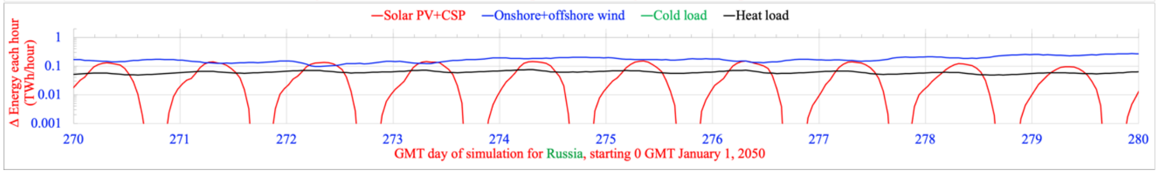
RUSSIA REGION



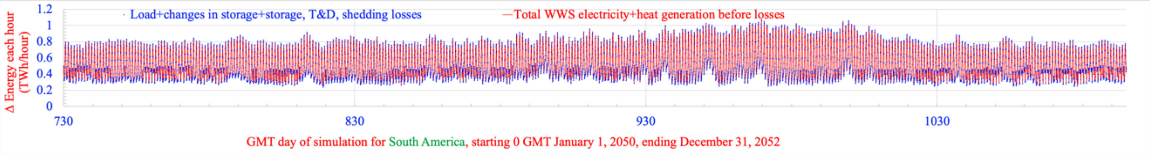


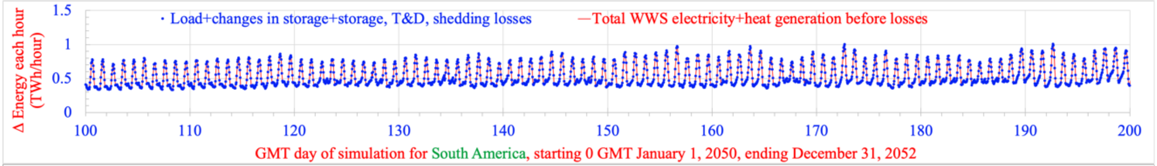


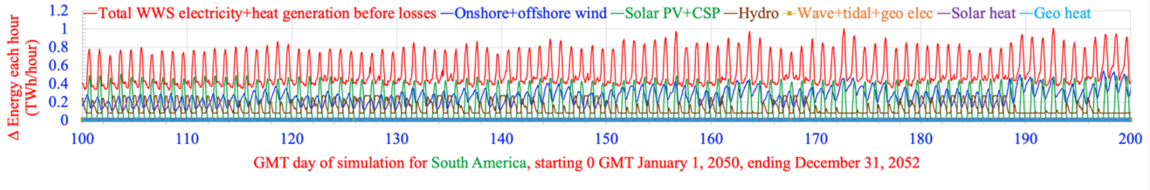


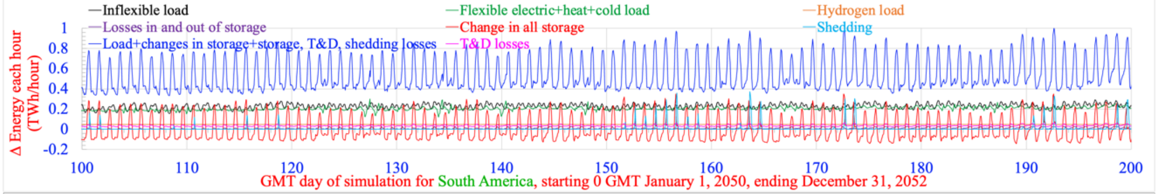


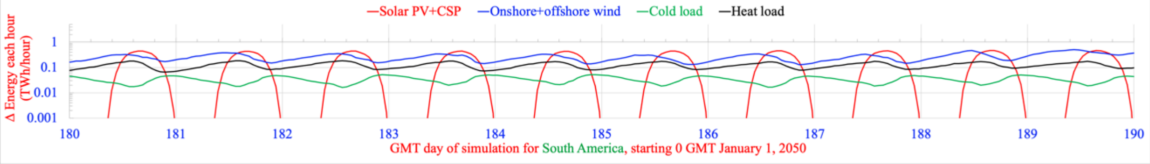
SOUTH AMERICA



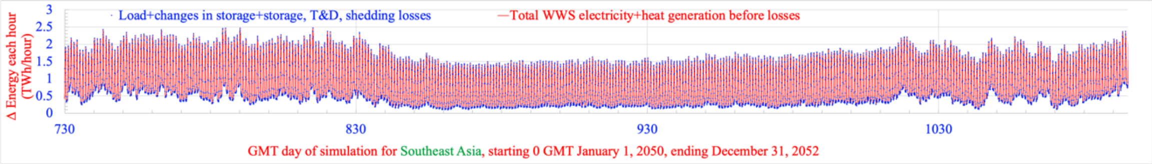


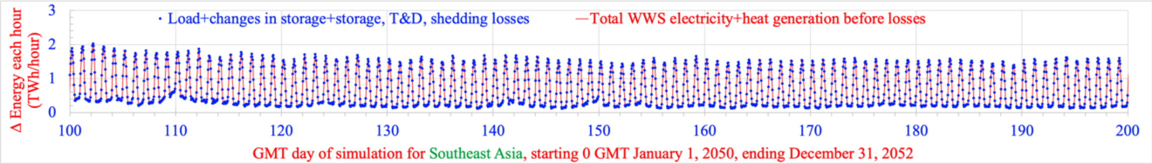


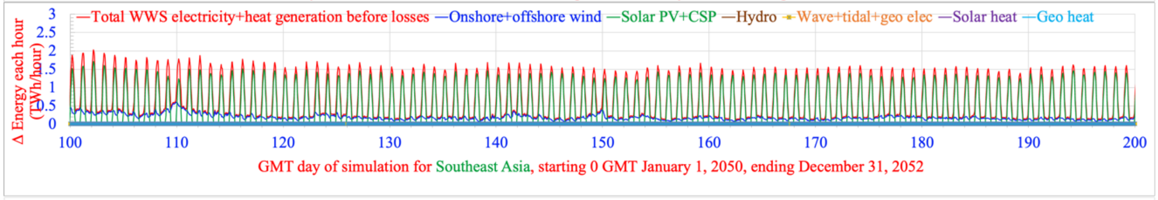


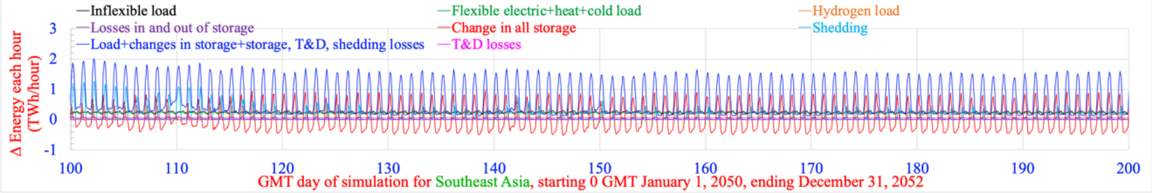


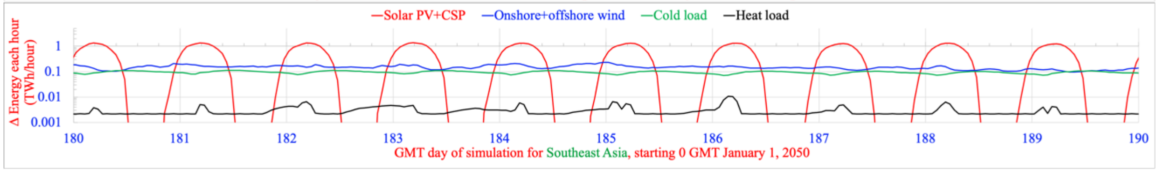
SOUTHEAST ASIA



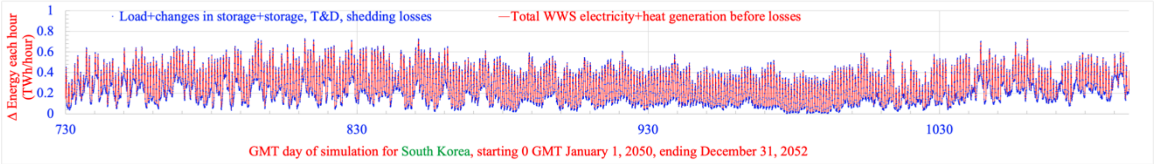




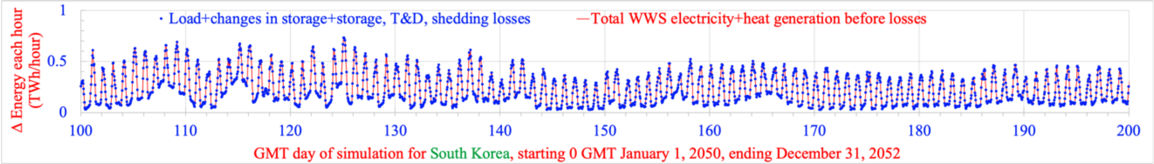




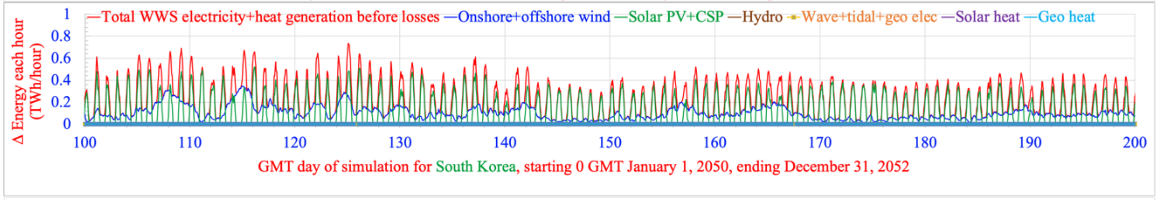
SOUTH KOREA



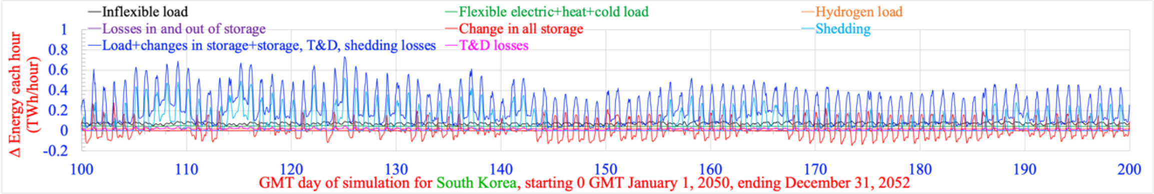
Δ Energy each hour (TWh/hour)
1
0.8
0.6
0.4
0.2
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052



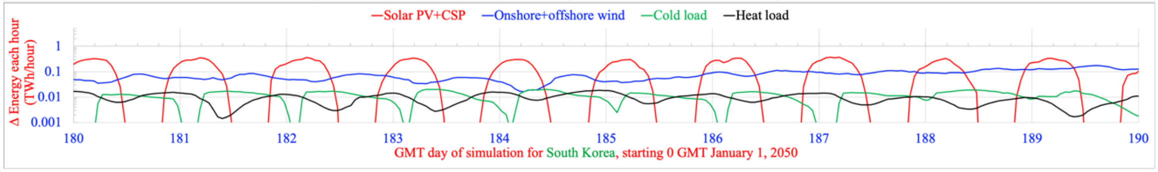
Δ Energy each hour (TWh/hour)
1
0.5
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052



Δ Energy each hour (TWh/hour)
1
0.8
0.6
0.4
0.2
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052

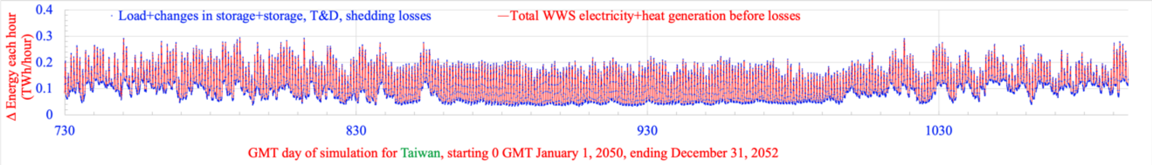


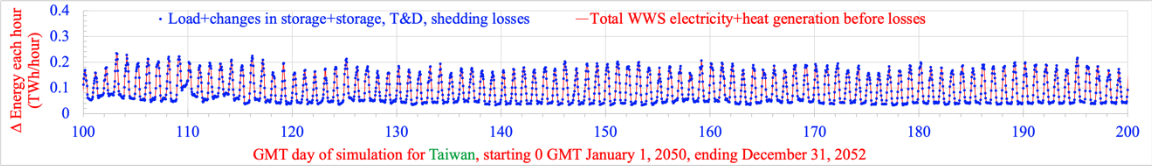
—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
1
0.8
0.6
0.4
0.2
0
-0.2
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052

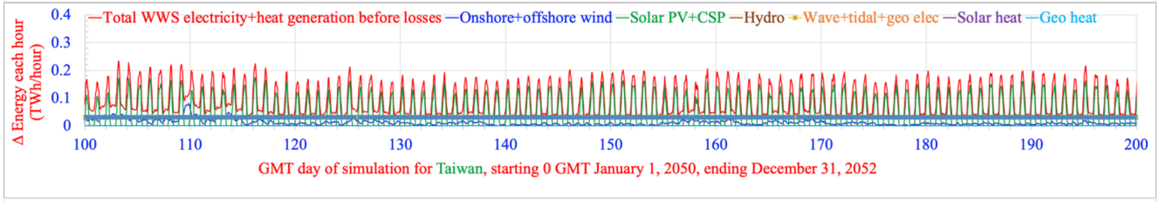


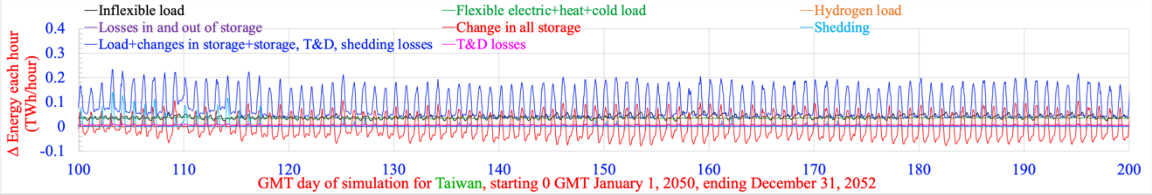
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050

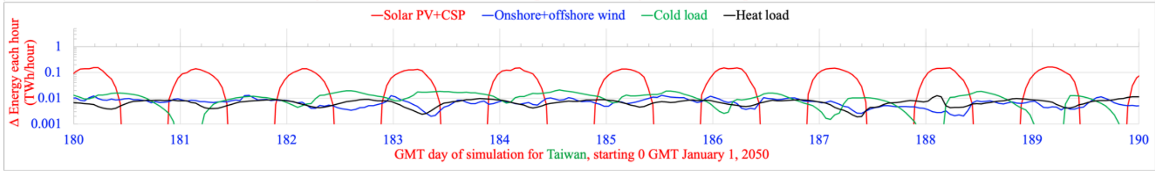
TAIWAN


Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
730
830
930
1030
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052

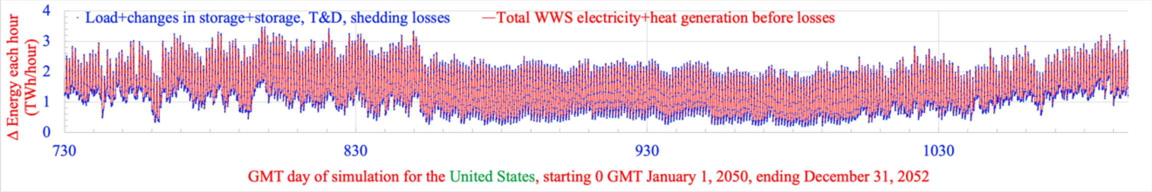

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052

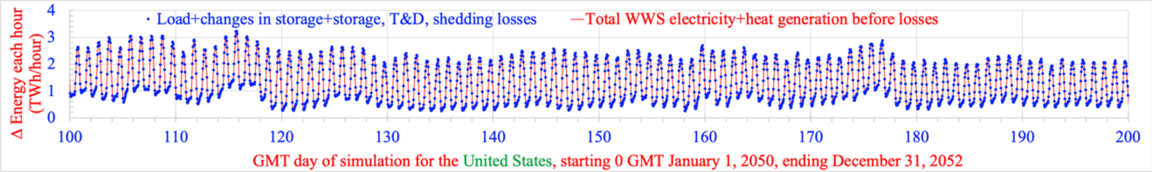

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052

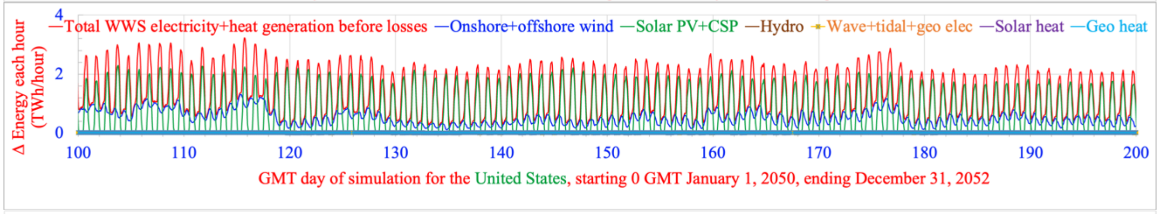

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
-0.1
—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052

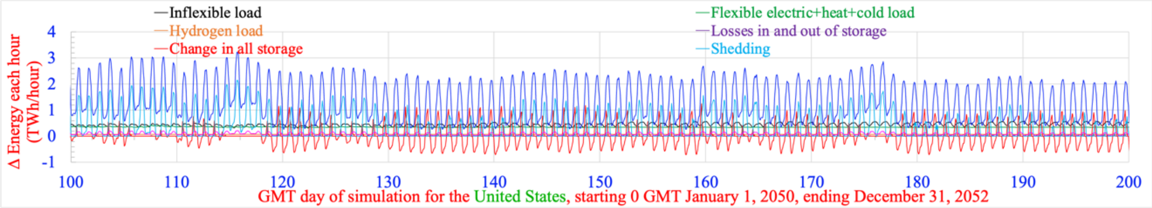

Δ Energy each hour (TWh/hour)
1
0.1
0.01
0.001
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050

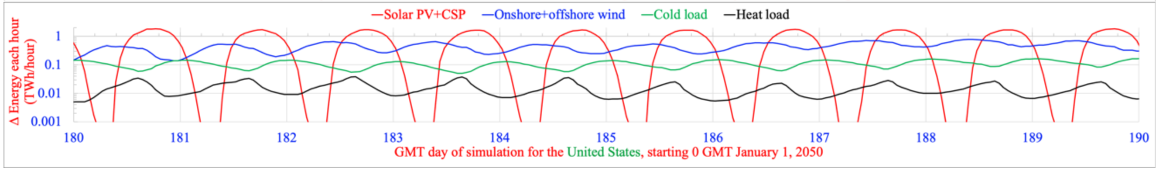
UNITED STATES











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