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Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries†

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Global warming, air pollution, and energy insecurity are three of the greatest problems facing humanity. Roadmaps are developed and grid analyses are performed here for 145 countries to address these problems. The roadmaps call for a 100% transition of all-purpose business-as-usual (BAU) energy to wind-water-solar (WWS) energy, efficiency, and storage, ideally by 2035, but by no later than 2050, with at least 80% by 2030. Grid stability analyses find that the countries, grouped into 24 regions, can exactly match demand with 100% WWS supply and storage, from 2050–2052. Worldwide, WWS reduces end-use energy by 56.4%, private annual energy costs by 62.7% (from \$17.8 to \$6.6 trillion per year), and social (private plus health plus climate) annual energy costs by 92.0% (from \$83.2 to \$6.6 trillion per year) at a present-value cost of ∼\$61.5 trillion. The mean payback times of the capital cost due to energy- and social-cost savings are 5.5 and 0.8 years, respectively. WWS is estimated to create 28.4 million more long-term, full-time jobs than lost worldwide and may need only ∼0.17% and ∼0.36% of world land for new footprint and spacing, respectively. Thus, WWS requires less energy, costs less, and creates more jobs than BAU. Sensitivity test indicate the following. Increasing district heating and cooling may reduce costs by allowing flexible loads to replace inflexible loads, thereby replacing electricity storage and overgeneration with low-cost heat storage. A battery cost that is 50% higher than in the base case increases mean overall energy costs by only 3.2 (0.03–14.5)%. Almost all regions need fewer hours of load shifting than assumed in the base case, suggesting that actual load shifting may be easier than assumed. Increasing the use of electricity for hydrogen fuel-cell-electric vehicles instead of for battery-electric vehicles increases overall cost in most regions tested, due to the greater efficiency of battery-electric vehicles, but decreases overall cost in some regions by improving grid stability. Finally, shifting battery vehicle charging from day-night to mostly day charging reduces cost in the regions tested; shifting to mostly night charging increases cost. Ninety-five percent of the technologies needed to implement the plans proposed are already commercial.

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Broader context

The world is undergoing a transition to clean, renewable energy to reduce air pollution, global warming, and energy insecurity. To minimize damage, all energy should ideally be transitioned by 2035. Whether this occurs will depend substantially on social and political factors. One concern is that a transition to intermittent wind and solar will cause blackouts. To analyze this issue, we examine the ability of 145 countries grouped into 24 regions to avoid blackouts under realistic weather conditions that affect both energy demand and supply, when energy for all purposes originates from 100% clean, renewable (zero air pollution and zero carbon) Wind-Water-Solar (WWS) and storage. Three-year (2050–52) grid stability analyses for all regions indicate that transitioning to WWS can keep the grid stable at low-cost, everywhere. Batteries are the main electricity storage option in most regions. No batteries with more than four hours of storage are needed. Instead, long-duration storage is obtained by concatenating batteries with 4 hour storage. The new land footprint and spacing areas required for WWS systems are small relative to the land covered by the fossil fuel industry. The transition may create millions more long-term, full-time jobs than lost and will eliminate carbon and air pollution from energy.

1. Introduction

Global warming, air pollution, and energy insecurity remain three of the greatest problems facing the world. The Earth's

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average global warming from 2011 to 2020 compared with 1850 to 1900 was about 1.09 °C.[1] If nothing is done, and, even if CO_2 emissions stay constant at 2020 levels rather than rise, enough additional CO_2 (500 billion tonnes) will accumulate in the air to warm the Earth 1.5 °C (with a 50% probability) relative to 1850–1900 levels, by 2032. Enough additional CO_2 (850 billion tonnes) will accumulate to warm the Earth 2 °C by 2041.[1]

In 2019, 55.4 million people died worldwide.[2] Air pollution contributed to about 7 million (12.6%) of the deaths, making it the second leading cause of death after heart disease.[3] Of the air pollution deaths, ~4.4 million were due to outdoor pollution and ~2.6 million were due to indoor pollution. Indoor air pollution arises because 2.6 billion people burn fuels for cooking and heating indoors.[3] Air pollution also causes hundreds of millions of illnesses (morbidities) each year. The deaths and illnesses arise when air pollution particles (mostly) and gases trigger or exacerbate heart disease, stroke, chronic obstruction pulmonary disease (chronic bronchitis and emphysema), lower respiratory tract infection (flu, bronchitis, and pneumonia), lung cancer, and asthma.

Energy insecurity is the third major problem due to business-as-usual (BAU) fuels. Energy insecurity arises for at least four reasons: diminishing availability of fossil fuels and uranium; reliance on centralized power plants and refineries; reliance on the need for a continuous supply of fuel that is subject to disruption arising from international war, civil war, embargos, bans, and labor disputes; and environmental damage due to continuous and widespread fuel mining and pollution.[4,5]

It is postulated here that a transition entirely to a clean, renewable wind-water-solar (WWS) electricity, heat, storage, transmission, and equipment system (Fig. S1, ESI†) will substantially reduce or eliminate these three problems and at low cost. Given their severity and their rapid growth, these problems must be addressed quickly. Ideally, 80% of the problems will be solved by 2030 and 100%, by 2035–2050 (Section 3.1). Given the goals of addressing air pollution and energy insecurity simultaneously with global warming, the transition must also avoid emissions of air pollutants and improve energy security. For these reasons, we do not include carbon capture (CC), direct air capture (DAC), bioenergy (B), nuclear power (N), or blue hydrogen (BH). Such technologies either increase or hold constant fuel mining (CC, DAC, BH), increase or hold constant air pollution (CC, DAC, B, BH), reduce little CO_2 while locking in combustion pollution (CC, DAC, B, BH), are costly (CC, DAC, N), have long time lags between planning and operation (N), or carry meltdown, weapons proliferation, waste, and mining risks (N).[4] Given that eliminating 80% of all emissions by 2030 and 100% by 2035–2050 with WWS, without these technologies, avoids 1.5 °C warming (Section 3.1), such non-WWS technologies are also not needed.

Many research groups have examined 100% renewable energy (RE) systems in one or all energy sectors and have found that RE systems keep the grid stable at low cost.[6–39] Most closely related to this study, are studies to transition 139 countries[21] and 143 countries[25,35,36] to 100% WWS across all energy sectors while keeping the grid stable. All energy sectors include electricity, transportation, building heating/cooling, industry, agriculture-forestry-fishing, and the military. This study, which examines a transition of 145 countries, improves upon the previous studies in several respects.

First, two additional countries (Lao, PDR and Equatorial Guinea) are included beyond the 143-country studies. For grid stability analysis purposes, the 145 countries are grouped into 24 regions (Table 1), as in the 143-country studies.

Second, raw end-use energy consumption data for each sector in each country originate here from 2018 (the latest update)[40] rather than from 2016[25,35,36] or 2012.[21] Similarly, new cost data for electricity generation, storage, and installed nameplate capacities are used. The new costs, in particular, are lower than were the previous costs for several WWS technologies.

Third, a significant unique feature of this study is the calculation and use of building heating and cooling loads worldwide every 30 seconds for a full three years, 2050–2052. The loads are calculated consistently with wind and solar generation in each country using a weather prediction/climate model. In the previous base studies,[25,40] such loads were estimated from daily heating and cooling degree day data.

Fourth, four-hour batteries are concatenated here to provide both long-duration electricity storage and substantial instantaneous peaking power. Because battery costs have dropped dramatically and because four-hour batteries are now readily available, it is now justifiable to include a larger penetration of batteries than in the previous studies.

Fifth, five new sensitivity tests are performed. In one, the fraction of district heating and cooling is increased in the most expensive regions, which are mostly small countries and islands, to examine the impact of increasing district heating and cooling on the cost of keeping the grid stable. In the second, the percent increases in the levelized and annual costs of energy are estimated when battery costs are 50% higher than those assumed in the base case. This sensitivity test is important because future battery costs are expected to drop but are uncertain, and a large share of electricity storage here is battery storage. In the third test, the maximum number of hours needed to shift a flexible load forward in time is reduced from a baseline value of eight hours to see how many hours of load shifting are actually needed in each region. If the maximum time needed is less than eight hours, then implementing demand response should be easier than proposed here. In the fourth test, the cost of increasing the penetration of electrolytic hydrogen fuel-cell-electric vehicles at the expense of battery-electric vehicles is examined. Finally, the cost of constant day and night *versus* mostly day *versus* mostly night battery-electric vehicle charging is examined.

2. Methodology

WWS electricity-generating technologies include onshore and offshore wind turbines (Wind); tidal and wave devices, geothermal electric power plants, and hydroelectric power plants (Water); and

Table 1 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	Republic of Korea
Taiwan	Taiwan
United States	United States

rooftop/utility solar photovoltaics (PV) and concentrated solar power (CSP) plants (Solar) (Fig. S1, ESI†). WWS heat generators include solar thermal and geothermal heat generators. WWS storage technologies include electricity, heat, cold, and hydrogen storage (Fig. S1, ESI†). 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. WWS equipment includes electric and hydrogen fuel cell vehicles, heat pumps, induction cooktops, arc furnaces, resistance furnaces, lawn mowers, leaf blowers, *etc.* (Fig. S1, ESI†).

The main purpose of this analysis is to quantify the costs and benefits of moving from a business-as-usual (BAU) to a WWS energy system. The main steps are as follows:

(1) Project BAU end-use energy demand from 2018 to 2050 for each of seven fuel types in each of six energy-use sectors, for each of 145 countries in a spreadsheet (Note S2, ESI†);

(2) Estimate the 2050 reduction in 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, ESI†);

(3) Perform resource analyses, then estimate mixes of wind-water-solar (WWS) electricity and heat generators required to meet the total demand in each country in the annual average (Note S2, ESI†);

(4) Use a prognostic global weather-climate-air pollution computer 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 country (Note S3, ESI†);

(5) Group the 145 countries into 24 world regions and use a computer model (LOADMATCH) to match variable energy demand with variable energy supply, storage, and demand response (DR) in each region every 30 seconds, from 2050 to 2052 (Notes S4–S6, ESI†);

(6) Evaluate energy, health, and climate costs of WWS *vs.* BAU (Note S7, ESI†);

(7) Calculate land area requirements due to WWS energy generators (Note S8, ESI†);

(8) Calculate changes in WWS *versus* BAU employment numbers (Note S9, ESI†); and.

(9) Discuss and evaluate uncertainties (Main text).

In summary, three types of models are used: a spreadsheet model (Steps 1–3, Note S2, ESI†), a 3-D global weather-climate-air pollution model (GATOR-GCMOM) (Step 4, Note S3, ESI†), and a grid integration model (LOADMATCH) (Steps 5–8, Notes S4–S6, ESI†).

With regard to the spreadsheet calculations, 2018 end-use BAU energy consumption from IEA[40] is first projected to 2050 for each country. End-use energy differs from primary energy (Note S2, ESI†). IEA provides end-use energy data for each of seven fuel types (oil, natural gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat) in each of six energy sectors (residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other) in each of 145 countries. These countries represent over 99.7%

of world fossil-fuel CO_2 emissions. The countries without data include primarily a handful of countries in Africa and several small island countries. The projections from 2018 to 2050 (Note S2, ESI†) 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 energy sector in each country is then converted to electricity, electrolytic hydrogen (primarily for use in fuel cells for long-distance, heavy transportation), or heat. The electricity and heat are then provided by WWS, using the conversion factors by fuel type and sector given in Table S3 (ESI†) (Note S2). The factors assume the use of equipment running primarily on electricity in each energy sector (Fig. S1, ESI†).

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. Existing solar and geothermal direct heating are retained as they are. 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 (Fig. S1, ESI†).

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 provided by electric heat pumps and CSP steam (Fig. S1, ESI†). All electricity for industry is provided by WWS sources.

Liquid- and natural-gas-fueled vehicles are transitioned to battery-electric (BE) vehicles and some hydrogen fuel-cell-electric (HFC) vehicles, where the hydrogen is produced by electrolysis with WWS electricity (green, or electrolytic, hydrogen) (Fig. S1, ESI†). BE vehicles dominate all-distance light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance (<1000 km) commercial trucks, trains (aside from those powered by electric rails or overhead wires), ferries, speedboats, ships, and short-haul (<1500 km) aircraft. Hydrogen fuel-cell-electric vehicles power all long-distance transport by road, rail, water, and air. They also power long-distance air, water, and land military transport.[41] Gasoline lawnmowers, leaf blowers, and chainsaws are converted to electric equivalents.

Having technologies already available is critical for ensuring a rapid transition. Overall, about 95% of the technologies needed for a transition are already commercialized. The main technologies that are not commercialized are long-distance aircraft and ships powered by hydrogen fuel cells and some industrial processes. However, technical feasibility studies of long-distance transport with fuel cells have been performed.[41]

Once all annual-average 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, ESI†). Such estimates rely on a resource analysis for each country (Note S2, ESI†). Table S7 (ESI†), for example, shows the limits of residential and commercial rooftop PV by country, that cannot be exceeded.

2050 nameplate capacities of each generator for each country are then placed in the country's geographic boundaries within the GATOR-GCMOM model (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model).[42,43] The model simulates feedbacks among meteorology, solar and thermal-infrared radiation, gases, aerosol particles, cloud particles, oceans, sea ice, snow, soil, and vegetation. Model results have been compared with data in 34 peer-reviewed studies and with results from other models in 14 intercomparisons.[25] GATOR-GCMOM accounts for the reduction in the wind's kinetic energy and speed due to the competition among wind turbines for available kinetic energy,[42] the temperature-dependence of PV output,[43] and the reduction in sunlight to, thus cooling of, buildings and the ground due to the conversion of radiation to electricity by solar PV, among other factors (Note S3, ESI†).

GATOR-GCMOM is run here for three years (2050–2052) on the global scale at $4^\circ \times 5^\circ$ horizontal resolution and with 68 vertical layers up to 60 km, with the bottom five layers each having 30 m resolution. Modeled parameters are aggregated over each country and written to a file every 30 seconds for the three years. Such 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. Heat and cold loads are derived from modeled outdoor air temperatures, a specified indoor temperature, and assumptions about building areas and *U*-values[35] (Note S3, ESI†). From the wind data, time-dependent wave power output is also derived.

The time-dependent data from the file are then input into LOADMATCH[16,21,25,35,36] (Notes S4–S6, ESI†), which simulates the matching of energy demand with supply and storage over time. LOADMATCH is a trial-and-error simulation model. It works by running multiple simulations for each grid region, one at a time. 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. 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 storage capacity; or characteristics of demand response) are then adjusted one at a time based on an examination of 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. The lowest cost solution in this set 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.

Table S2 (ESI†) summarizes processes in LOADMATCH. Note S4 (ESI†) describes the model's time-dependent inputs. Note S6 (ESI†) describes the model's order of operation, including how the model treats excess generation over demand and excess demand over generation.

Time-dependent loads are determined as follows. Annual average end-use WWS loads in each sector of each region from Table S5 (ESI†) are separated into (1) electricity and 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 for fuel cells used in transportation, and (4) all other electricity loads (including high-temperature industrial heat loads). Each of these loads is further divided into flexible and inflexible loads (Table S6, ESI†). Flexible loads include electricity and heat loads that can be used to fill cold and low-temperature heat storage, all electricity used to produce hydrogen (since all hydrogen can be stored), and remaining electricity and heat loads subject to demand response. Inflexible loads are all loads that are not flexible. The inflexible loads must be met immediately. Demand response can be used to shift flexible loads forward in time one time step at a time, but by no more than eight hours, until the loads are met. A sensitivity test is performed here to examine whether the limit can be less than eight-hours.

The continuous profiles of heat and cold loads from GATOR-GCMOM are then used to distribute 2050 annual-average inflexible and flexible loads into continuous time-dependent (30 s resolution) loads, as described in Note S5 (ESI†). Such loads and WWS supplies from GATOR-GCMOM for each of the 145 countries are subsequently summed to obtain time-dependent loads and supplies for each of the 24 world regions (Table 1). Maximum electricity, heat, and cold storage sizes and times are then estimated (Tables S13 and S14, ESI†).

LOADMATCH is run from 2050–2052 with 30 s timesteps 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 1). 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)%,[25] 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.[25]

3. Results

3.1. Energy demand and generation results

Fig. 1 shows two possible timelines to transition to 100% WWS. In both cases, an 80% transition occurs by 2030. In one case, 100% occurs by 2035; in the other, 100% occurs by 2050. The 2050 BAU and WWS end-use energy consumptions and generator mixes are the same in both cases. If the second timeline (80% by 2030 and 100% by 2050) is met, and if 80% and 100% of 2020 non-energy emissions are also eliminated by 2030 and 2050, respectively, then about 340 billion additional tonnes of CO_2 will accumulate in the air by 2050. Accordingly, such a transition timeline will avoid 1.5 °C warming because it will result in less than the 500 billion tonne accumulated-CO_2 emission allowance.[1] To reduce climate damage further and to reduce the enormous loss of life from air pollution and the dangers due to energy insecurity, a 2035 timeline for a complete transition is also proposed.

Fig. 1 and Table 2 (and Table S4 for each country, ESI†), indicate that transitioning from BAU to 100% WWS in 145 countries reduces 2050 annual average end-use power demand by an average of 56.4%. Of this, 38.4 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 6.64 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU. Of the 38.4% reduction due to the efficiency advantage of WWS electricity, 20.5 percentage points are due to the efficiency advantage of WWS transportation, 4.3 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.6 percentage points are due to the efficiency advantage of using heat pumps instead of combustion heaters. Whereas all-purpose energy demand declines by 56.4%, the remaining energy is almost all electricity (with some direct heat), causing world-average electricity consumption to increase by 85% compared with BAU (Table 2).

From the annual average 2050 end-use load data for each country (Table S4, ESI†), generator nameplate capacities are estimated by country in a spreadsheet.[44] LOADMATCH simulations are initiated with these estimates and then run. If load is not met, nameplate capacities and other parameters are adjusted until load is met for all three years, at which point the nameplate capacities are final (Table S9, ESI†). The following percentages of final nameplate capacities needed in 2050, averaged over all countries, had already been installed as of 2020: onshore wind-7.56%; offshore wind-0.8%; residential rooftop PV-4.13%; commercial/government rooftop PV-2.39%; utility PV-2.61%; CSP-1.54%; geothermal electricity-14.4%; hydropower-100%; tidal power-0.001%; and wave power-2.76%.

The ratio of the final nameplate capacity needed to meet continuous load (from LOADMATCH) to that needed to meet annually-averaged load (from the spreadsheet[44]) is the capacity adjustment factor (Table S10, ESI†). Table 3 shows that only 13% more generator nameplate capacity is needed, summed over all 145 countries, to meet continuous 2050 load than to meet annually-averaged 2050 load. The difference is due to oversizing generation in order to meet continuous load. Storage (Table S13, ESI†) is also needed to meet continuous load.

Table S11 (ESI†) gives average capacity factor (CF) by generator and region over the three-year simulations. The mean modeled CF of wind offshore of the China region, for example, was ∼37.2%. Mean annual wind speeds offshore of China at

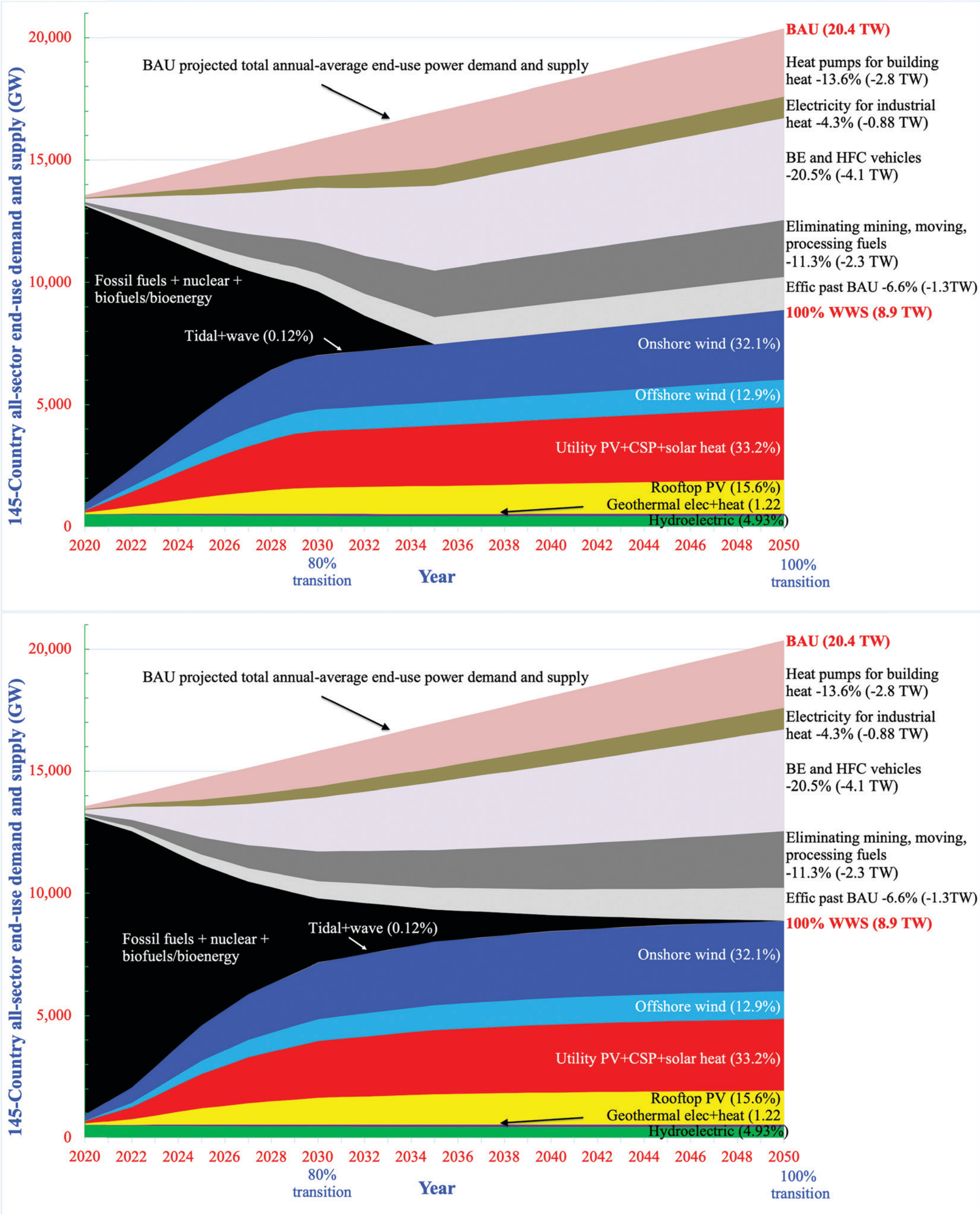

Fig. 1 Timeline for transitioning 145 countries to 100% WWS by 2035 (first panel) and 2050 (second panel), with 80% by 2030 in both cases. The figures also show five types of reductions in energy requirements that occur along the way. Table S4 (ESI†) provides the energy data for the figure and for each of the 145 countries. Table S12 (ESI†) provides the 2050 percent mix of WWS resources for the figure and for each of the 24 regions.

100 m hub height are mostly 7–8 m s^{-1} (giving CFs of 29–37%), but with a hotspot of >9.5 m s^{-1} (CF of 51%) offshore of the Fujian province.[45] The three-year CF of 37.2%, determined here from GATOR-GCMOM, appears consistent with this source.

Table 3 and Table S12 (ESI†) give the 2050–2052 mix of electricity plus heat produced (including both load and losses) from each energy generator, averaged over all 145 countries and for each region, respectively. 46.0% of all energy produced among all countries is solar and 45.0% is wind. The Russia region has the highest percent of energy from wind (77.4%). Israel had the highest percent from solar (83.7%).

3.2. Storage results

The total battery storage capacity among all 145 countries is 84.51 TWh per cycle (Table S13, ESI†). For comparison, the total hydropower storage capacity in reservoirs is ~4567 TWh per year, which is close to the 2020 world hydropower output.[46] Thus, the annual storage capacity of hydropower is equivalent to the annual storage of all batteries cycling 54 times.

Table 2 1st row: 2018 annually-averaged end-use load (GW), summed among 145 countries, and percentage of the load by sector. 2nd row: projected 2050 annually-averaged end-use BAU load (GW), summed among 145 countries, and percentage of the total load by sector. 3rd row: estimated 2050 end-use load (GW), summed among 145 countries, and percentage of total load by sector if 100% of end-use delivered BAU load in 2050 is instead provided by WWS. Column (k) provides the percentage decreases in 2050 total BAU load due to transitioning from BAU to WWS, including the effects of lower energy use arising from (h) 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 the 2050 electricity load (= all energy load) with WWS to that with BAU. Although column (l) shows that WWS increases electricity consumption *versus* BAU, column (k) shows that WWS decreases all energy consumption

Scenario	(a) Total annual average end-use load (GW)	(b) Residential % of total end-use load	(c) Commercial % of total end-use load	(d) Indus-try % of total end-use load	(e) Trans-port % 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 up-stream	(j) % change end-use load w/WWS due to effic-iency beyond BAU	(k) Ove-rall % change in end-use load with WWS	(l) WWS:BAU electricity load
BAU 2018	13 102.3	20.8	8.2	38.1	29.2	2.22	1.52					
BAU 2050	20 358.8	19.1	8	37.6	31.7	2.05	1.48					
WWS 2050	8880.6	17.5	10.5	50.5	17.9	1.84	1.84	−38.4	−11.3	−6.64	−56.4	1.85

2018 BAU values are from IEA.[40] Table S2 (ESI), footnote, defines the sectors. 2018 values are projected to 2050 as described in Note S2 (ESI). 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, as described in Note S3 (ESI). Of the 38.4% reduction due to electrifying end-uses, 20.5, 4.3, and 13.6 percentage points are due to the efficiency of electric transport, industrial heat, and building heat, respectively.

The number of battery cycles needed per year in the simulations varied from 0 to 290, with eight regions needing less than 54 cycles per year (Table S14, ESI†). The comparison between hydropower and batteries is relevant because existing hydropower will be used for both baseload and peaking power (like a battery) in a future with high penetrations of intermittent renewables on the grid. Since all batteries store enough energy to supply power for four hours at the peak discharge rate of the batteries, the total peak discharge rate of batteries among all countries is 21.13 TW. For comparison, that of hydropower is 1.16 TW (Table S13, ESI†), which is also currently available in these countries (Table S8, ESI†). Thus, battery storage in this study meets higher peaks in electricity demand than does conventional hydropower.

The world also has up to 3200 TWh of low-cost and 23 200 TWh of low and high-cost pumped hydropower storage (PHS) capacity potential.[47] Both capacities are much greater than the 14.7 TWh of PHS and 84.51 TWh of batteries proposed here across 145 countries (Table S13, ESI†). As such, PHS could be substituted for batteries in many situations. In fact, the cost per storage capacity of PHS is lower than that of batteries (Table S18, ESI†), and PHS does not require mining or chemicals. Whereas more PHS is possible, batteries are often preferred because they are easier to site and face fewer objections during permitting.

All batteries here are assumed to store electricity for four hours at their peak discharge rate. To obtain longer storage, batteries are concatenated in series. In other words, if 8 h storage is needed, then one 4 h battery is depleted before a second 4 h battery is depleted. Minimizing hours of storage maximizes the flexibility of batteries to meet peaks in demand (GW) and also to store electricity for long periods (GW h). For example, suppose 100 batteries, each with 4 h storage and each with 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 1000 kW, or anything in between.

In sum, batteries with longer than 4 h storage are not necessary for keeping the grid stable since batteries can be concatenated in series to obtain longer-duration storage. However, storage times of greater than four hours and up to 62.1 hours, while not needed, can be advantageous for a region. Batteries with storage times longer than ∼62.1 hours are never needed nor advantageous in the present study.

The ratio of the maximum storage capacity (TWh) to the maximum battery discharge rate (TW) that actually occurs during each simulation ranges from four hours for Russia and South America to 62.1 hours for Taiwan [Table S14, Column (f), ESI†]. This ratio is the maximum number of hours of storage ever needed at the maximum discharge rate that actually occurs during a simulation. If this ratio exceeds four hours (the number of hours of storage at the peak discharge rate assumed for all simulations), then the battery peak discharge rate assumed is 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

Table 3 Nameplate capacities by WWS generator needed to meet 2050 (a) annual average and (b) continuous all-purpose end-use load plus transmission/distribution/maintenance losses, storage losses, and shedding losses for 145 countries/24 world regions. (c) Nameplate capacities already installed as of 2020 (except that solar thermal heat is for 2018 and geothermal heat is for 2019). (d) Average (among all countries) percent of 2050 end-use load plus losses supplied by the final nameplate capacities

WWS technology	(a) 2050 initial existing plus new nameplate capacity to meet annual-average load plus losses (GW)	(b) 2050 final existing plus new nameplate capacity to meet continuous load plus losses (GW)	(c) Nameplate capacity already installed 2020 (GW)	(d) Percent of 2050 WWS load plus losses supplied by each generator
Onshore wind	6983	9430	712.72	32.1
Offshore wind	3946	4421	35.50	12.9
Res. roof PV	6032	3422	141.2	5.70
Com/gov roof PV	7381	5912	141.2	9.86
Utility PV plant	10 258	16 244	423.61	30.0
CSP plant	395	419.7	6.47	2.73
Geothermal electricity	97.3	97.3	14.01	0.73
Hydroelectricity	1164	1164	1164	4.93
Wave electricity	50.3	50.3	0.0006	0.08
Tidal electricity	19.2	19.2	0.53	0.04
Solar thermal heat	456.4	456.4	456.4	0.42
Geothermal heat	107.7	107.7	107.72	0.49
Total all	**36 889**	**41 742**	**3203**	**100**

All values are summed over 145 countries in 24 regions, except values in column (d) are outputs by energy device, summed over all countries divided by total load plus losses among all countries. ''Annual average load plus losses'' is all-purpose end-use energy demand plus losses per year divided by 8760 hours per year. ''Initial'' nameplate capacities (meeting annual-average demand) are nameplate capacities at the start of a LOADMATCH simulation. ''Final'' nameplate capacities are those needed to match load plus losses after LOADMATCH simulations. Table S9 (ESI) gives final nameplate capacities by country/region. Table S8 (ESI) gives nameplate capacities already installed by country/region in 2020. Table S12 (ESI) gives values in column (d) by region.

discharge rate is proportionately increased in order to maintain constant storage capacity.

For example, for Taiwan, if the battery storage time were increased from four to 62.1 hours, the peak discharge rate could be reduced from 1300 GW (Table S13, ESI†) to 1300 GW × 4 hours/62.1 hours = 84 GW while maintaining the same maximum storage capacity (5.2 TWh). If this occurs, then Taiwan's maximum storage capacity and maximum discharge rate will both be reached sometime during the simulation. With four hours of storage, only the maximum storage capacity is reached. With more than 62.1 hours of storage and a 84 GW maximum discharge rate (which is reached), the maximum storage capacity is never reached, which is why there is no need for storage longer than 62.1 hours.

Finally, models that use one-hour time steps will predict lower peak discharge rates, thus higher ratios of peak storage capacity to peak discharge (more hours of battery storage needed) than models using a 30 s time step, such as the one used here. As such, models using a one-hour time step may incorrectly conclude that long-duration batteries are needed. The reason is that one-hour time steps intrinsically result in lower peak discharge rates than 30 s time steps because the average peak discharge rate over one hour is an average over 30 s peak discharge rates that are both higher and lower than the average. A 30 s time step captures the highest of these values. A one-hour time step does not. It captures only the average among all 30 s values.

3.3. Cost results

The net present value of the capital cost to transition all 145 countries while keeping the grid stable is \$61.5 trillion (USD 2020), with new electricity and heat generators comprising \$45.7 trillion of this (Table 4 and Tables S19, S20, ESI†). The remaining costs are for electricity, heat, cold, and hydrogen storage; hydrogen electrolysis and compression; heat pumps for district heating; and long-distance transmission. It is assumed simplistically that the present value of the capital cost of new electric appliances and machines (*e.g.*, heat pumps for buildings, electric vehicles, industrial equipment) equals the present value of the capital plus fuel costs of their fossil-fuel counterparts. If WWS did not replace BAU, most appliances and machines would be replaced in any case within 15 years with BAU versions, so these costs are not reported as new capital costs required. Individual regional capital costs range from \$2.8 billion for Iceland to \$13.3 trillion for the China region. The cost to the U.S. is ∼\$6.7 trillion, and the cost for Europe is ∼\$5.9 trillion. The proposed annual outlay of capital follows the same trajectory as the proposed pace of transition shown in Fig. 1, namely 80% by 2030 and 100% by 2035 or 2050. Table S19 (ESI†) provides a breakdown by components of the resulting levelized cost of energy (LCOE).

Among all 145 countries, the 2050 BAU annual social cost is \$83.2 trillion per year, which consists of a 2050 private energy cost (\$17.8 trillion per year), health cost (\$33.6 trillion per year), and climate cost (\$31.8 trillion per year) (Table 4 and Table S20, ESI†). 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 \$6.6 trillion per year, or by 92.0% and

Table 4 2050 annual-average end-use (a) BAU load and (b) WWS load; (c) percentage difference between WWS and BAU loads; (d) mean value of capital cost, averaged between 2020 and 2050, of new WWS energy in USD 2020; mean value of levelized private costs (¢ per 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 load (GW)	(b) 2050 WWS annual average end-use load (GW)	(c) 2050 WWS minus BAU load = (b − a)/a (%)	(d) WWS mean capital cost ($tril 2020)	(e) BAU mean (¢ per kWh-all energy)	(f) WWS mean (¢ per kWh-all energy)	(g) WWS mean annual all-energy private cost = social cost = bfH ($billion per year)	(h) BAU mean annual all-energy private cost = aeH ($billion per year)	(i) BAU mean annual BAU health cost ($billion per year)	(j) BAU mean annual climate cost ($billion per year)	(k) BAU mean annual BAU total social cost = h + i + j ($billion per year)	(l) WWS minus BAU private energy cost = (g − h)/h (%)	(m) WWS minus BAU social energy cost = (g − k)/k (%)
Africa	1381.8	488.5	−64.7	3.658	10.09	8.39	359.1	1221.9	3982.3	1782.6	6986.7	−70.6	−94.9
Australia	208.8	92.3	−55.8	0.617	10.28	8.23	66.5	188.0	34.6	399.5	622.1	−64.6	−89.3
Canada	442.5	168.0	−62.0	0.645	8.03	6.53	96.1	311.3	42.3	518.3	871.8	−69.1	−89.0
Central America	378.2	160.7	−57.5	1.533	10.49	11.05	155.5	347.6	323.5	588.9	1260.0	−55.3	−87.7
Central Asia	446.5	167.0	−62.6	1.214	10.30	8.53	124.7	402.7	1011.3	699.6	2113.6	−69.0	−94.1
China	5076.3	2358.8	−53.5	13.333	9.55	7.61	1571.5	4248.4	10 757.0	8495.7	23 501.0	−63.0	−93.3
Cuba	15.8	9.0	−42.9	0.106	11.64	12.24	9.6	16.1	37.5	30.9	84.4	−40.0	−88.6
Europe	2287.7	948.7	−58.5	5.946	10.01	8.42	699.9	2005.4	1772.0	2858.0	6635.4	−65.1	−89.5
Haiti	19.1	7.8	−59.2	0.056	10.90	8.54	5.8	18.3	36.2	30.7	85.1	−68.0	−93.1
Iceland	5.6	3.2	−42.6	0.0028	7.51	6.98	1.9	3.7	0.4	2.9	7.0	−47.5	−72.2
India	2010.5	982.4	−51.1	6.869	9.88	8.15	701.0	1739.6	9471.6	3756.5	14 968	−59.7	−95.3
Israel	26.1	13.1	−49.6	0.143	11.21	12.13	14.0	25.6	15.7	50.3	92	−45.5	−84.8
Jamaica	5.5	2.6	−53.0	0.023	11.38	9.60	2.2	5.5	3.4	7.4	16.3	−60.3	−86.6
Japan	355.4	174.5	−50.9	1.151	10.48	8.89	135.9	326.3	261.5	678.1	1265.9	−58.3	−89.3
Mauritius	5.2	2.0	−61.4	0.024	10.64	12.40	2.2	4.8	3.7	5.5	14.0	−55.0	−84.6
Middle East	1520.1	708.1	−53.4	4.665	11.39	8.06	500.1	1517.3	858.4	2900.1	5275.7	−67.0	−90.5
New Zealand	32.4	17.0	−47.6	0.107	8.11	8.79	13.1	23.0	5.2	35.7	63.9	−43.2	−79.5
Philippines	93.9	41.8	−55.5	0.393	10.19	10.02	36.7	83.8	677.3	194.3	955.5	−56.2	−96.2
Russia	787.8	254.7	−67.7	1.194	10.18	6.99	156.0	702.4	601.8	1248.3	2552.5	−77.8	−93.9
South America	1090.8	467.9	−57.1	3.502	8.44	9.22	378.0	806.4	749.8	1161.3	2717.6	−53.1	−86.1
Southeast Asia	1300.7	591.7	−54.5	6.825	10.39	11.76	609.4	1183.3	1935.8	2046.6	5165.7	−48.5	−88.2
South Korea	304.9	151.3	−50.4	1.764	10.53	12.57	166.6	281.2	104.4	526.9	912.5	−40.8	−81.7
Taiwan	165.3	90.7	−45.1	0.986	10.60	11.80	93.8	153.5	85.9	357.0	596.4	−38.9	−84.3
United States	2397.8	979.0	−59.2	6.712	10.42	8.66	742.4	2188.6	829.7	3381.7	6400.0	−66.1	−88.4
All regions	**20 359**	**8881**	**−56.4**	**61.5**	**9.98**	**8.54**	**6642**	**17 805**	**33 601**	**31 757**	**83 163**	**−62.7**	**−92.0**

All costs are in 2020 USD. H = 8760 hours per year. 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 S17–S20 (ESI) give cost parameters. A social discount rate of 2 (1–3)% is used

62.7%, respectively (Table 4 and Table S20, ESI†). The significant decrease in private energy cost between BAU and WWS occurs because WWS reduces energy demand by 56.4% (Tables 2 and 4) and the cost per unit energy by 14.3%. The decrease in social energy cost occurs because WWS eliminates health and climate costs as well. In summary, the WWS annual social energy cost is only 8% that of BAU, and the WWS annual private energy cost is only 37.3% that of BAU.

Because the BAU annual energy cost and annual social cost are both much greater than is the annual social (= energy) cost of WWS (Table 4), continuing to use the existing BAU fossil-fuel infrastructure for even one year costs society tremendously.

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 5.5 years, with a range of 0.9 to 21.9 years for different countries. That due to social cost savings is 0.8 (0.1–6.7) years. Thus, the capital cost of WWS pays for itself with energy, health, and climate cost savings rapidly. The amount paid back is through energy sales rather than subsidies.

Among all world regions, the WWS LCOE, averaged between 2020 and 2050, that results in a stable grid, is 8.54 ¢ per kWh (Table 4 and Table S19, ESI†). This cost is dominated by the costs of electricity generation (3.80 ¢ per kWh), distribution (2.38 ¢ per kWh), short-distance transmission (1.05 ¢ per kWh), battery storage (0.55 ¢ per kWh), hydrogen production (0.31 ¢ per kWh), long-distance transmission (0.17 ¢ per kWh), underground heat storage (0.09 ¢ per kWh), geothermal plus solar heat generation (0.08 ¢ per kWh), heat pumps for district heating (0.07 ¢ per kWh), CSP and pumped hydro storage (0.03 ¢ per kWh), and hot water storage (0.01 ¢ per kWh). The range of the average LCOE among all 24 regions is from 6.5 ¢ per kWh (Canada) to 12.6 ¢ per kWh (South Korea).

The 2020–2050 average WWS LCOE is relatively low for large regions (*e.g.*, Africa, Australia, Canada, China region, Europe, India region, Middle East, Russia region, and the United States) and for small countries with good WWS resources (*e.g.*, Iceland, New Zealand) (Table 4). Large land areas permit greater geographical dispersion of wind and solar. Connecting geographically-dispersed renewable resources *via* the grid reduces overall intermittency. Large land areas also have a good balance of solar and wind, which are complementary in nature. Finally, large regions often have existing hydropower that can provide peaking power. Iceland also has substantial hydropower, along with geothermal and wind.

LCOEs are highest in small countries with high population densities (*e.g.*, Cuba, Israel, Mauritius, South Korea, and Taiwan). Nevertheless, the 2050 WWS annual private energy cost in all these regions is 39% to 55% lower than that of BAU. Thus, a move to WWS reduces annual energy costs substantially, even in the lowest-benefit cases.

Of the 5.3 million air pollution deaths per year from energy expected in 2050 in a BAU scenario, about 27.3% are expected to occur in India and 20.6% in China (Table S21, ESI†).

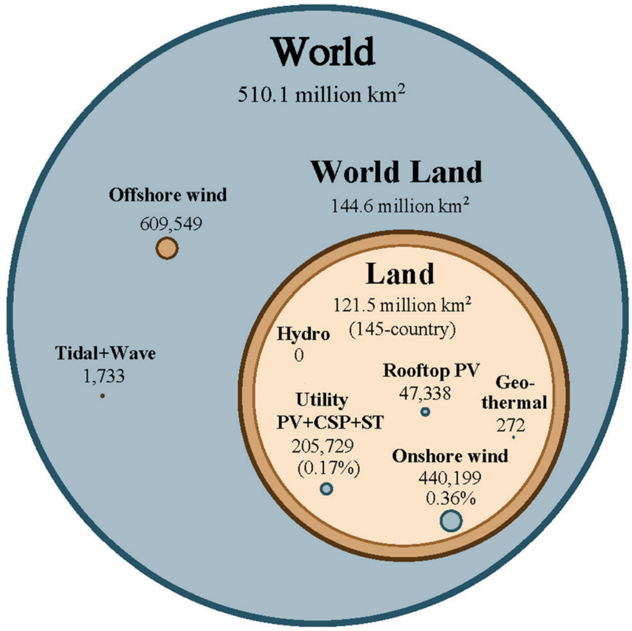

Fig. 2 New land area (km^2) required for footprint on the ground, which applies to utility PV + CSP + ST (solar thermal) and geothermal electricity and heat, and for spacing, which applies to onshore wind, among the 145 countries examined. Ocean spacing areas for new offshore wind, tidal, and wave power are also shown as is the area for new rooftop PV, which doesn't require new land. No new land for hydropower is needed. The values are determined by dividing the difference between the world total new plus existing nameplate capacities from Table S9 (ESI†) and the world total existing nameplate capacities from Table S8 (ESI†) by the installed power densities from Table S22 (ESI†).

The CO_2e emissions in China alone are 26.3% of all emissions among the 145 countries and more than the sum of emissions from 128 of the 145 countries (Table S21, ESI†). The 2nd-through-16th top emitting countries emit 48% of all CO_2e emissions. The 145-country average BAU health and climate costs ($591 and $558 per tonne-$CO_2$e, respectively) are similar to each other, but both are much higher than the BAU energy cost ($313 per tonne-$CO_2$e) (Table S21, ESI†). Combining these three numbers gives the BAU social cost ($1460 per tonne-$CO_2$e). Transitioning to WWS, on the other hand, has only an energy cost associated with it, which is only $117 per tonne-$CO_2$e-eliminated, thus only 8% the cost of not eliminating BAU emissions.

3.4. Land area and employment change results

Averaged over 145 countries, the new WWS infrastructure requires ∼0.17% of the 145-country land for footprint and ∼0.36% of the land for spacing (Fig. 2 and Table S23, ESI†). The maximum onshore wind spacing area required for any country is 2.56% (Germany). If this land spacing cannot be accommodated, some of the onshore wind can be shifted offshore. Similarly, utility PV that occupies more than 2% of a country's land footprint is proposed to be shifted to floating offshore PV. This occurs only in small countries/administrative regions with coastal access (*e.g.*, Bahrain, Curacao, Gibraltar, Hong Kong, Malta, Qatar, and Singapore). Alternatively, it can

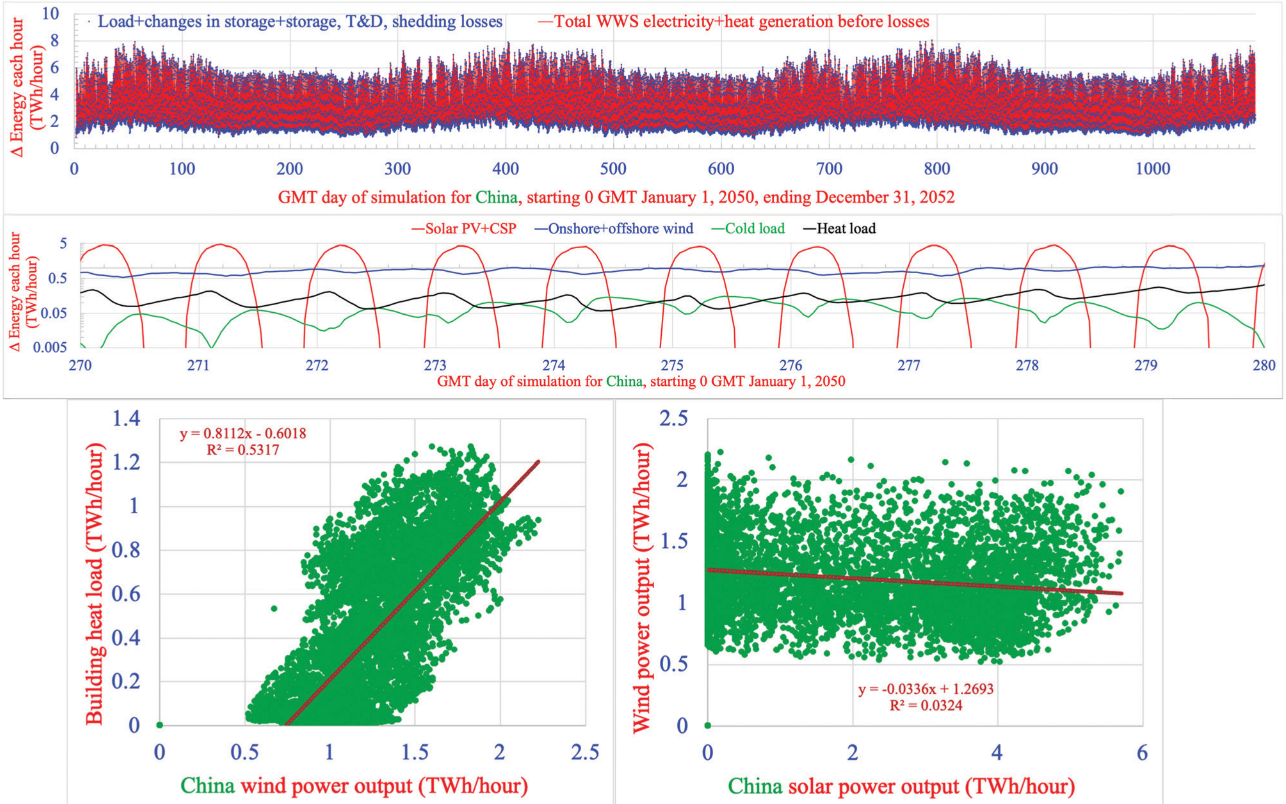

Fig. 3 2050–2052 hourly time series showing the matching of all-energy demand with supply and storage for the China region (Table 1). First row: modeled time-dependent total WWS power generation *versus* load plus losses plus changes in storage plus shedding for the full three-year simulation period. Second row: 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; third row: correlation plots of building heat load *versus* wind power output and wind power output *versus* solar power output, obtained from all hourly data during the simulation. Table S26 (ESI†) summarizes the correlations. 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. Fig. S2 (ESI†) provides these and additional plots for all regions.

be shifted to more rooftop PV or offshore wind. Alternatively, these locales may import the additional WWS electricity from neighboring countries, either through a common land border or an undersea cable. Interconnecting is more cost effective, particularly in such cases where WWS resources are tight in a country.[36]

WWS may produce 55.6 million new long-term, full-time jobs. Also, 27.2 million jobs may be lost, for a net increase of 28.4 million long-term, full-time jobs produced among the 145 countries (Table S25, ESI†). Job numbers account for construction and operation jobs in energy generation, transmission, and storage. The numbers also account for direct jobs, indirect jobs, and induced jobs (Note S9, ESI†). Net jobs increase in 21 out of 24 world regions. Net losses occur in Africa, Canada, and the Russia region. These regions depend heavily on fossil fuels. However, more jobs, not accounted for here, may arise from the need to build more electrical appliances and to improve building energy efficiency.

3.5. 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 S15 (ESI†) equals 11 719 GW averaged over the simulations, and this exactly equals ''Supply plus changes in storage.'' Of that total, 8880.5 GW is ''annual average end-use load,'' which is the exact total, within roundoff error, shown in Table S4 (ESI†) for ''All Countries.'' Among all regions, ~6.5% of end-use load plus losses are transmission, distribution, and downtime losses; 2.4% are losses going in and out of storage, 15.8% are losses due to shedding; and the rest (75.3%) is load. Iceland has the lowest percentage of shedding (0%). Israel has the highest percentage (38.1%).

Further, no load loss occurred at any time in any region (Fig. 3 and Fig. S2, ESI†). Fig. 3, for example, shows this for China, whose CO_2e emissions are greater than the combined emissions of 128 of the 145 countries examined. Two reasons that 100% WWS keeps the grid stable are (1) the positive correlation between building heat load and wind energy supply in cold regions and (2) the negative correlation between wind energy supply and solar energy supply in all world regions (Fig. 3 and Fig. S2, ESI†). Correlations between heat load and wind supply are very strong or strong in 11 regions and moderate in another five regions (Table S26, ESI†). The only regions where they are negative are in warm countries (Cuba and the Philippines). Ref. 35 found similar results for the same regions, but here, data were available for three years rather than one year, thus for more extreme and diverse weather conditions. Likely due to the longer time series, the correlations here are very strong or strong in three more regions than in ref. 35. Correlations are strongest mostly for large, cold regions (Canada, Europe, Russia, China, United States) but also for Central America. The implication of this result is that electrifying building heating with electric heat pumps and simultaneously increasing wind electricity supply in most countries improves their ability to match overall load at low cost. Similarly, since wind and solar are complementary in nature, combining wind with solar provides more hours of overall power, facilitating the matching of overall load with supply.

4. Discussion

4.1. Comparison with previous global studies

The results from this study can be compared most directly with those from ref. 25, the 143-country/24 region study, which was based on energy data from 2016 rather than 2018. That study relied less on battery storage and more on CSP storage than here, because at the time, battery costs were higher than today. That study also obtained building heating and cooling loads from heating and cooling degree data by country rather than from a weather prediction model in which heating and cooling loads were calculated consistently with wind and solar generation. That study found 57.1%, 61%, and 91% reductions in annual energy need, annual private cost, and annual social cost, respectively, for WWS *versus* BAU, compared with 56.4%, 62.7% and ∼92% reductions, respectively, found here. The slightly lower energy benefit here reflects the slightly lesser reduction in energy requirements due to eliminating the energy needed to mine/transport/refine fuels in the present study *versus* in the previous study. The greater cost reduction here reflects the lower cost per unit energy of WWS *versus* BAU in the present study. The consistency in overall results reflects the robustness of the conclusions despite the differences in input data and some methods used.

A relevant independent previous global study of 100% renewables is that of Ram *et al.*[27] That study similarly concludes that "*a global transition to 100% renewable energy across all sectors – power, heat, transport, and desalination before 2050 is feasible*." Conclusions in that study were reached with an optimization model with an hour time step *versus* a trial-and-error model with a 30 s time step used here (Note S4, ESI†). That study also assumed the production of synthetic combustion fuels from renewable electricity and biofuels produced from sustainable agriculture, neither of which are included in WWS studies. It also proposed/modeled a greater fraction of end use electricity from solar PV. The present study has a more even mix of wind and PV. Despite these differences, the overall conclusion is similar, strengthening the results found in both studies. Dozens of additional papers[6–39] have also affirmed the feasibility and low-cost nature of 100% renewable electricity or all energy in different parts of the world.

Another global study examining 100% renewables is described in Teske.[24] In that study, a global climate model coupled with energy-related modules was used to examine the impact of electrifying all energy and providing all electricity with renewables while also reducing non-energy greenhouse gas emissions. It concludes that electrifying, then deploying available 100% renewables and efficiency while increasing reforestation and decreasing deforestation as fast as possible, can avoid 1.5 °C warming at low cost while creating jobs. Thus, the main conclusion, that a transition to 100% renewables at low cost is similar to that found here. However, that study did not examine transitions in individual countries. It also treated balancing supply with demand at the hour time scale *versus* the 30 second time scale here. None of the studies above examined the impact of concatenating batteries or of calculating building heating and cooling loads from the climate model.

4.2. Uncertainty about transmission system

This study has many uncertainties. One is the assumption of a perfectly-interconnected transmission system in each region. The regions simulated here (Table 1) 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. In all cases, perfectly-interconnected transmission is assumed, but transmission and distribution costs and losses in each region are accounted for. For example, transmission plus distribution costs here comprise an average of 42.1 (27.2–55.9)% of the total LCOE, with distribution costs alone comprising 27.8 (18.9–36.4)% of the total LCOE (Table S19, ESI†). The ranges encompass the lowest and highest regional values. On average, among all regions, 6.5% of all energy produced is lost during transmission and distribution (Table S16, ESI†). Long-distance HVDC transmission is added in 16 out of 24 regions (Table S14, ESI†). Whereas the perfect-transmission assumption causes the greatest cost uncertainty with respect to the larger domains, it causes less uncertainty with respect to the 11 small domains, since they are already well-interconnected. However, since the larger regions have more land available for low-cost utility PV and onshore wind, the cost of energy in such regions is generally lower than in the smaller regions before transmission is considered. Thus, a higher cost of transmission than estimated in big regions would still mean low-cost energy in those regions. Finally, because stable solutions are found for domains of all sizes, this assumption has no impact on the ability of grids to stay stable, only on the cost of grid stability, as shown in ref. 36.

4.3. Uncertainty about future load and WWS supply

Another uncertainty is whether the time-dependent load and supply data are sufficiently representative of the real world in 2050 and whether they capture extreme weather. First, the GATOR-GCMOM simulations were run under 2050 climate, greenhouse gas, and natural and anthropogenic pollutant emission conditions after all energy was converted to WWS. Second, since GATOR-GCMOM predicts the weather continuously worldwide, the simulations account statistically for extreme weather events. Third, all wind and solar supplies in

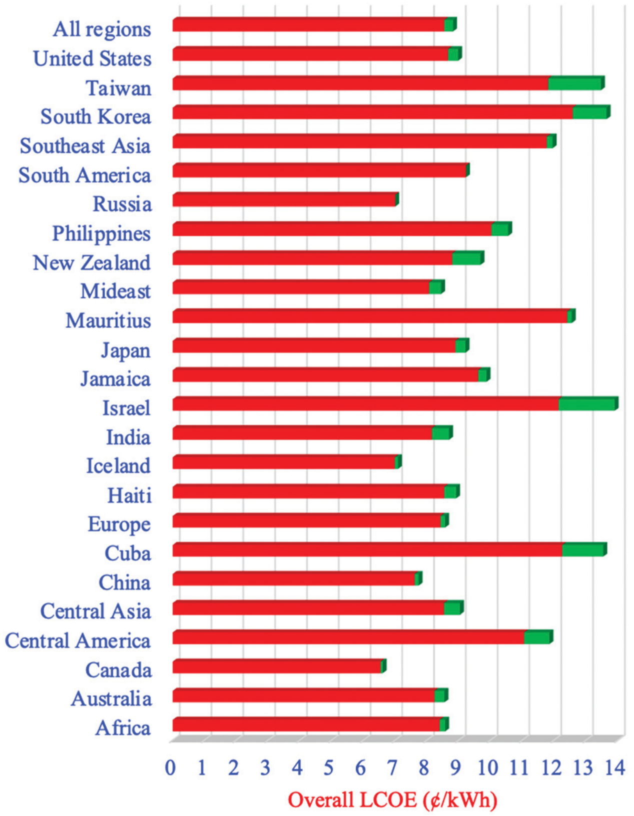

Fig. 4 Sensitivity of the overall 2050 levelized cost of energy (LCOE) with WWS, in 2020 USD, to a 50% higher battery cost (\$90 instead of \$60 kW^{-1} h^{-1}-electricity storage). Red is the baseline cost (Table 4). Green is the incremental cost due to higher-cost batteries.

GATOR-GCMOM are calculated in the same model and simultaneously with building heat and cold loads and are at a resolution of 30 seconds.

4.4. Uncertainty about simulation duration

A related uncertainty is whether three years is a sufficient simulation period to account for variations in weather and costs of energy. For some previous analyses, LOADMATCH simulated for six years[16] and five years.[21] Stable grids were found in all cases while accounting for variable and extreme weather. In all cases, like here, WWS costs were substantially lower than BAU costs. As such, it seems unlikely that a longer simulation would make much difference in the main conclusions here.

4.5. Uncertainty about whether real grid will stay stable

A further uncertainty is whether the grid will stay stable in the real world even though the model indicates it will. Whereas the LOADMATCH model is designed to ensure no loss of load, which is a stricter requirement than the industry standard of a loss of load once every ten years, the model examines only a finite set of conditions. In the real world, many more conditions arise. This could give rise to grid instability. However, we assume that real grid planners will build a 100% WWS grid step by step and put sufficient safeguards in to ensure grid stability by the time 100% WWS is reached.

4.6. Sensitivity of overall LCOE to battery costs

Another uncertainty is about the cost estimates used. This uncertainty is captured by the use of low, mean, and high energy, air pollution damage, and climate damage costs. For example, Table S17 (ESI†) gives low, mean, and high estimates of capital cost, operation and maintenance cost, decommissioning cost, energy generator lifetimes, and transmission/distribution/downtime losses. Table S18 (ESI†) gives ranges in storage costs. Ref. 50 provides the resulting low and high costs in each region.

To illustrate the sensitivity of results to cost estimates, we analyze the impact of a 2035 battery system cost of \$90 kW^{-1} h^{-1}-electricity-storage (in 2020 USD) instead of the baseline cost of \$60 kW^{-1} h^{-1} (Table S18, ESI†). This sensitivity test is relevant because, although battery system cost is declining rapidly, it is possible it may not decline to \$60 kW^{-1} h^{-1} by 2035. Results (Fig. 4 and Table S19, ESI†) indicate that a 50% higher battery system cost increases both overall LCOE and total annual energy costs by 3.2 (0.03–14.5)%, with the mean being the world average and the variation being the lowest and highest increase among all regions. This result indicates that, even if battery system cost is 50% higher than estimated here, both the LCOE and annual energy cost are still much lower than in the BAU case. For example, worldwide, the new total LCOE and annual cost would be 8.84 ¢ per kWh and \$6.86 trillion per year, respectively, which are still 11.4% and 61.4% lower, respectively, than in the BAU case (Table 4).

4.7. Sensitivity of overall LCOE to district heating penetration

A related uncertainty is the extent to which district heating and cooling will be implemented. The baseline case assumes 23 (0–92)% worldwide of building heating and cooling may be subject to district heating and cooling (Table S14, ESI†). All but four regions, Iceland (92%), Europe (50%), Russia region (50%), and China region (30%) are assumed to have 20% or less district heating. About 92% of buildings in Iceland are currently subject to district heating. The current percent district heating in some other countries are as follows: Latvia (65%), Denmark (63%), Estonia (62%), Lithuania (57%), Sweden (>50%), Finland (>50%), Poland (>50%), Northern China (>50%), and Russia (>50%).[48]

An important question is the impact of an increase in the fraction of district heating and cooling on the storage and overgeneration requirements, thus the cost of energy. Whereas more district heating and cooling requires more centralized thermal energy storage and electric heat pumps to provide heat and cold for that storage, more district heating/cooling also creates more flexible loads that do not need instantaneous electricity. This means that less battery storage and electricity overgeneration are needed to meet immediate demand for electric heat pumps in buildings. As such, more district heating means more-expensive electricity storage and overgeneration may be replaced with lower-cost heat/cold storage and centralized heat pumps. District heating also requires pipes and other infrastructure to bring heat and cold to buildings. However, it avoids the need for heat pumps, hot water tanks, and associated electrical wiring in individual building. Before its impact on grid stability is taken into account, district heating/cooling may be less expensive than decentralized heating/cooling, even for piping district heat and cold to areas outside of a city.[49] For this reason, we assume the additional cost of pipes and other non-energy/storage infrastructure associated with large-scale district heating is offset by the non-energy infrastructure cost of a decentralized system, so don't include either in our calculation.

Results here indicate that increasing the fraction of district heating/cooling uniformly decreases overall LCOE. This is because it decreases battery and/or offshore wind oversizing requirements, thus their costs, more than it increases thermal energy storage and additional centralized heat pump needs and their costs (Fig. 5 and Fig. S3, ESI†). The cost reduction is particularly beneficial for small countries, including island countries, where the base LCOE with 100% WWS is high. Increasing the penetration of district heating/cooling substantially is more difficult in large countries due to the long distances many buildings are from urban areas in big countries. The purpose of these sensitivities is not to suggest that the fraction of district heating/cooling will rise to near 100%, but just to show the incremental impact of an increase or decrease in the fraction.

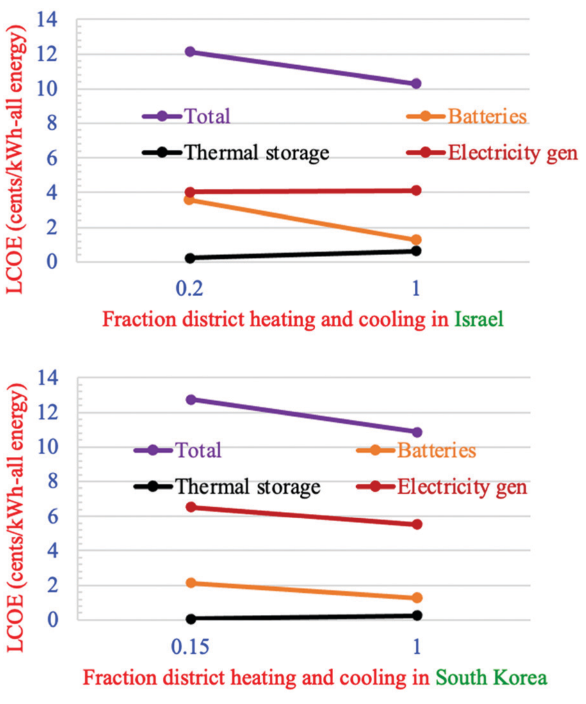

Fig. 5 Sensitivity of the levelized cost and some of its components to the fraction of all buildings in two countries where hot and cold air and hot water are supplied by district heating and cooling. Fig. S3 (ESI†) shows results for additional countries/regions. The components included are the cost of batteries, thermal storage, and/or total electricity generation. Thermal storage costs include the costs of UTES, HW-STES, CW-STES, ICE storage, and heat pumps to provide heat and cold for thermal energy storage (Table S19, ESI†). The only component of total electricity generation that is changing is the quantity of offshore wind. The low fraction district heating and cooling is the baseline value for each country and gives the baseline LCOE given in Table 4.

4.8. Sensitivity of results to hours of load shifting

Another uncertainty is whether the assumed maximum number of hours of load shifting for flexible loads is necessary. In the baseline case, flexible loads can be shifted forward with demand response by up to eight hours in LOADMATCH. Sensitivity simulations were run in each region to examine whether the exact same result, including LCOE, could be obtained with fewer than eight hours of maximum load shifting. The result is that eight hours was needed in only two of the 24 regions (Table S14, ESI†). Five regions needed no load shifting. Six regions needed a maximum of two hours. Nine regions needed a maximum of four hours. Two regions needed a maximum of six hours. As such, load shifting may be less necessary and easier to implement in most regions than assumed in this study.

4.9. Sensitivity of overall LCOE to hydrogen vehicle penetration

Another uncertainty is the extent of the future adoption of electrolytic hydrogen fuel-cell-electric *versus* battery-electric vehicles. The base case here assumes[44] that 24% of oil-based fuels and 5% of natural-gas-based fuels used for transportation will be replaced with enough electricity to produce hydrogen to run equivalent fuel-cell-electric vehicles, mostly for long-distance airplanes, ships, trains, trucks, and military vehicles. The rest will be replaced with electricity for battery-electric vehicles. Sensitivity tests are run here to examine cases in some countries, where 5% and 50%, instead of 24%, of oil-based fuels are replaced with enough electrolytic hydrogen for fuel-cell-electric vehicles (with no change in the replacement of natural-gas-based fuels).

Using electricity to produce hydrogen for fuel-cell-electric vehicles instead of for battery-electric vehicles has two major opposing impacts on cost. It increases cost since the plug-to-wheel efficiency of short- and moderate-distance electrolytic hydrogen fuel-cell-electric vehicles is much less than that of same-range battery-electric vehicles. This disadvantage of hydrogen decreases then disappears in the limit for long-distance vehicles due to the wasted energy needed to carry extra batteries in long-distance battery-electric vehicles. On the other hand, increasing hydrogen decreases cost by improving grid stability. One reason is that, when too much WWS electricity is available, the excess can always be used to produce hydrogen, which is either stored or used immediately. Whereas excess electricity can also be stored in stationary batteries to provide electricity for battery-electric vehicles, stationary batteries are more expensive than is hydrogen storage. A second reason is that, when too little electricity on the grid is available for battery-electric vehicles, either more generators or more electricity storage is needed; for hydrogen fuel cell vehicles, only more lower-cost hydrogen storage is needed. In sum, using electrolytic hydrogen increases cost due to the lower efficiency of most hydrogen fuel cell vehicles (efficiency effect) but decreases cost by improving grid stability (grid stability effect). This analysis, though, ignores the potential for batteries in battery-electric vehicles to provide electricity back to the grid.

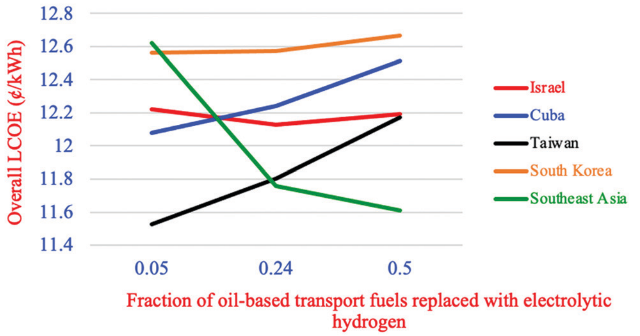

Fig. 6 Sensitivity of the overall 2050 WWS levelized cost of energy (LCOE), in 2020 USD, to changing the fraction of oil-based transport fuel replaced with electrolytic hydrogen for fuel-cell-electric vehicles, instead of for battery-electric vehicles. The base-case fraction is 0.24.

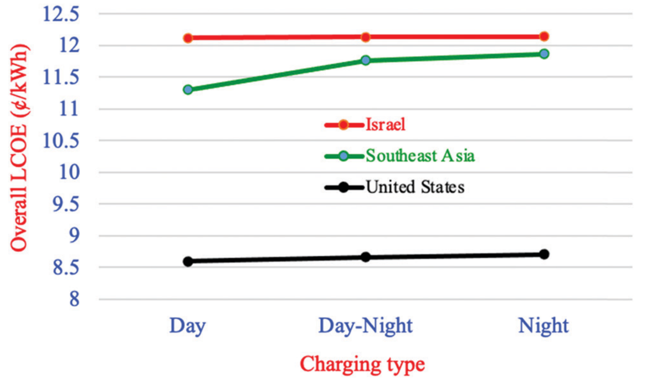

Fig. 7 Sensitivity of the overall 2050 WWS levelized cost of energy (LCOE), in 2020 USD, to predominantly (60%) daytime (8 AM–4 PM) charging ("Day") *versus* equal charging every day-night hour ("Day–Night") *versus* predominantly (60%) nighttime (11 PM–7 AM) charging ("Night"), as described in the text. "Day–Night" is the base case.

Results here indicate (Fig. 6) that, in most regions tested (*e.g.*, Cuba, South Korea, Taiwan), increasing the use of electricity for hydrogen fuel-cell-electric vehicles instead of for battery-electric vehicles increases overall cost because the efficiency effect dominated the grid stability effect. However, in Southeast Asia, the grid stability effect dominated at all penetrations tested. In Israel, the grid stability effect dominated at low penetrations of hydrogen, and the efficiency effect dominated at high penetrations. In Israel, for example, increasing the hydrogen penetration from 5% to 24% decreased overall LCOE slightly (from 12.22 to 12.13 ¢ per kWh), due to decreases in electricity and heat generation costs of 0.32 ¢ per kWh, electricity storage costs of 0.17 ¢ per kWh, and all thermal-energy storage costs of 0.01 ¢ per kWh, mostly offset by increases in hydrogen production/compression/storage costs of 0.41 ¢ per kWh. However, increasing the penetration further from 24% to 50% increased overall LCOE from 12.13 to 12.19 ¢ per kWh due to an increase in hydrogen production/compression/storage costs of 0.49 ¢ per kWh mostly offset by decreases in electricity storage costs of 0.21 ¢ per kWh, decreases in electricity plus heat generation costs of 0.21 ¢ per kWh, and decreases in thermal-energy storage costs of 0.01 ¢ per kWh.

4.10. Sensitivity of overall LCOE to battery-electric vehicle charging profile

One more uncertainty is the time-dependent charging profile of electric vehicles. The base-case assumption is that the profile is constant seasonally (as justified in Note S5, ESI†) and during day and night, except to the extent that demand response shifts the time of some charging. Here, sensitivity tests are run to examine the impacts on cost of assuming (a) 60% charging spread between 11 PM and 7 AM (night charging), when electricity demand is otherwise usually lowest, and 40% evenly spread during all other hours of the day, and (b) 60% charging between 8 AM and 4 PM (day charging), when most solar electricity is usually available. In all three cases tested (Fig. 7), day charging is the least expensive and night charging is the most expensive. The base case is in-between. Day charging reduces overall LCOE by 0.46 ¢ per kWh in Southeast Asia and by 0.065 ¢ per kWh in the U.S., whereas night charging increases LCOE by 0.10 ¢ per kWh in Southeast Asia and by 0.04 ¢ per kWh in the U.S., relative to the base case. In Israel, day charging also reduces LCOE, but only by ∼0.01 ¢ per kWh. Night charging also increases LCOE, but only by ∼0.01 ¢ per kWh. Thus, shifting charging to daytime helps to reduce LCOE, but more so in some locations than in others. Similarly, shifting to night charging increases LCOE, but more so in some locations than in others. The low impact in Israel was likely due to the substantial storage already needed to otherwise keep the grid stable there.

4.11. Political uncertainty

A political, rather than modeling, uncertainty is whether the timeline proposed in the study (80% transition by 2030 and 100% ideally by 2035 but no later than 2050) can be met. Worldwide, about 8.2% of the WWS infrastructure needed to power all-purpose energy had been installed as of 2020. Many countries had virtually nothing installed. Norway and Tajikistan had over 60% installed. For countries where no transition has occurred so far, a 10% transition per year is needed for eight years (2022 to 2030). For countries with 60% installed, a 5% transition per year is needed for eight years. In all cases, the scale of transition required is enormous. Whether the pace needed can be obtained depends on whether policymakers can garner sufficient political will and on whether manufacturing and deployment can be ramped up fast enough. Political will, itself, affects the speed of the buildout of generation, storage, and transmission. Political will is adversely affected by lobbyists for conventional energy, other people with vested interest in the current energy infrastructure, the difficulty in changing some people's opinions about whether we should move off of fossil-fuels, and confusion sown by those against a renewable energy transition. In addition, for countries engaged in international or civil war, political will to transition is not a top priority, and building new infrastructure may not even be feasible during the conflict. This study does not guarantee sufficient political will is available. Instead, it examines the consequences of a transition if sufficient will is obtained. It also provides confidence to those who may be on the fence that a transition is possible and will have several benefits.

5. Conclusions

The world needs a rapid transition to clean, renewable energy to address air pollution, climate, and energy security issues. Here, roadmaps to transition 145 countries to 100% clean, renewable WWS energy and storage across all energy sectors are developed. The full transition should occur no later than 2050, but ideally by 2035, with no less than 80% by 2030. Grid stability analyses are performed after the countries are divided into 24 world regions. No-load-loss solutions are found in all regions for the three-year period, 2050–2052. Costs are estimated, and sensitivity tests are performed to examine the impacts of several factors on them.

Across 145 countries, a transition to 100% WWS reduces the annual base-case private energy cost by 62.7% (from \$17.8 down to \$6.6 trillion per year in 2020 USD) compared with BAU. This is due to 56.4% less end-use energy consumption and a 14.3% lower private cost per unit energy. WWS reduces the annual social energy cost (private cost plus health and climate costs) by 92% (from \$83.2 to \$6.6 trillion per year) because WWS eliminates health (\$33.6 trillion per year) and climate (\$31.8 trillion per year) costs along with reducing private energy costs. These results suggest a substantial private and social cost benefit of transitioning. The results are consistent with previous studies despite the new data and the differences in approach compared with those studies. Robustness across independent studies strengthens the case that a clean, renewable energy future is possible.

The net present value of the capital cost of transitioning to WWS worldwide is $\sim$\$61.5 trillion over all years of the transition between today and 2050. This is the estimated net present value of a worldwide Green New Deal. The 145-country payback time due to annual private energy cost savings between BAU and WWS is 5.5 (0.9–21.9) years. The payback time due to annual social energy cost savings between BAU and WWS is 0.8 (0.1–6.7) years. Thus, the capital cost of WWS pays for itself with energy, health, and climate cost savings rapidly, and the payback is through energy sales rather through subsidies. However, the speed of a transition would benefit substantially from government assistance.

Transitioning to 100% WWS in 145 countries decreases energy requirements and annual private and social costs while creating about 28.4 million more long-term, full-time jobs than lost. A 100% WWS economy uses only about 0.53% of the 145-country land area, with 0.17% for footprint and 0.36% for spacing.

Sensitivity tests indicate that (1) increasing the fraction of district heating and cooling in the most expensive countries, which are all small countries, reduces costs significantly by replacing inflexible loads with flexible loads, thereby replacing electricity storage and overgeneration with low-cost heat storage; (2) if mean battery costs are 50% higher than in the base case (\$90 instead of \$60 kW^{-1} h^{-1}-electricity storage), overall LCOEs and annual energy costs increase by only 3.2 (0.3–14.5)%; (3) all but four regions need four or fewer hours of load shifting rather than the eight hours assumed in the base case, suggesting that actual load shifting may be easier than in the base case; (4) increasing the use of electricity for hydrogen fuel-cell-electric instead of battery-electric vehicles increases overall LCOE in most regions, due to the greater efficiency of battery-electric vehicles, but it decreases overall LCOE in some regions by improving grid stability; and (5) shifting the time of battery-electric vehicle charging from evenly-distributed day-night charging to primarily day charging reduces overall LCOE in the regions tested; shifting to primarily night charging increases LCOE.

Many additional uncertainties exist. One of the greatest is whether sufficient political will can be obtained to affect a transition at the rapid pace needed. However if political will can be obtained, then transitioning the world entirely to clean, renewable energy should substantially reduce energy needs, costs, air pollution mortality, global warming, and energy insecurity while creating jobs, compared with BAU.

Data and materials availability

All spreadsheet derivations for the 145 country roadmaps are available.[44] All data from this paper, including data going into all plots, and the LOADMATCH model are available upon request from jacobson@stanford.edu. Infographic maps of results by country are available at **https://sites.google.com/stanford.edu/wws-roadmaps/home**.

Author contributions

Conceptualization, M. Z. J.; methodology, M. Z. J.; investigation, M. Z. J., A.-K. V. K., S. J. C.; software, M. Z. J.; writing – original draft, M. Z. J.; writing – review & editing, M. Z. J., A.-K. V. K., S. J. C.; E. D.; A. J. H. N.; F. C. P.; K. R. R.; visualization, M. Z. J., E. D.; A. J. H. N.; F. C. P.; K. R. R.; supervision, M. Z. J.

Conflicts of interest

Authors declare no competing interests.

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Supplementary Information

Low-Cost Solutions to Global Warming, Air Pollution, and Energy Insecurity for 145 Countries

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This supplementary information file contains some additional description of the models plus additional tables and figures to help explain more fully the methods and results found in this study.

Supporting Text

Note S1. Summary

Countries around the world are undergoing a transition to clean, renewable energy to reduce air pollution, climate-damaging pollutants, and energy insecurity. To minimize damage, all energy should ideally be transitioned by 2035. Whether this occurs will depend substantially on social and political factors. One potential barrier is the concern that a transition to intermittent wind and solar will cause blackouts. To analyze this issue, we examine the ability of 145 countries grouped into 24 world regions to avoid blackouts under realistic weather conditions that affect both energy demand and supply, when energy for all purposes originates from 100% clean, renewable (zero air pollution and zero carbon) Wind-Water-Solar (WWS) and storage. The 24 regions include a mix of seven large multi-country regions (Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, South America, and Southeast Asia) and 17 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). Three-year (2050-52) grid stability analyses for all regions indicate that transitioning to WWS can keep the grid stable, even under variable weather conditions, at low-cost, everywhere. Annual energy costs are 62.7 (38.9-77.8)% lower and social costs (energy plus health plus climate) costs are 92.0 (72.2-96.2)% lower than in business-as-usual (BAU) cases. Batteries are the main electricity storage option in most regions. No batteries with more than 4 hours of storage are needed. Instead, long-duration storage is obtained by concatenating batteries with 4-hour storage. The new land footprint and spacing areas required for WWS systems are small relative to the land taken up by the fossil fuel industry. The transition may create millions more long-term, full-time jobs than lost and will eliminate not only carbon, but also air pollution, from energy. There is little downside to a transition.

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 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) Projecting business-as-usual (BAU) end-use energy demand from 2018 to 2050 for each of seven fuel types in each of six energy-use sectors, for each of 145 countries;
(2) estimating the 2050 reduction in 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;
(3) performing 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;
(4) using 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 country;
(5) grouping the 145 countries into 24 world regions and using a model (LOADMATCH) to match variable energy demand with variable energy supply, storage, and demand response (DR) in each region every 30 seconds, from 2050 to 2052;
(6) evaluating energy, health, and climate costs of WWS vs BAU;
(7) calculating land area requirements of WWS;
(8) calculating changes in WWS versus BAU jobs numbers; and
(9) discussing and evaluating uncertainties.

Thus, three types of models are used for this study: a spreadsheet model (Steps 1-3), a 3-D global weather-climate-air pollution model (Step 4), and a grid model (Steps 5-8). We start with 2018 business-as-usual (BAU) end-use energy consumption data for each country from IEA (2021). 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 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 end-use energy in each of the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors, and for each of six energy categories (oil, natural gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat).

These data are projected for each fuel type in each sector in each country from 2018 to 2040 using “BAU reference scenario” projections for each of 16 world regions (EIA, 2016). 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 energy sector in each of 145 countries is then set equal to the corresponding 2018 end-use energy from IEA (2021) multiplied by the EIA 2050-to-2018 energy consumption ratio, available after the extrapolation, for each fuel type, energy sector, and region containing the country.

The 2050 BAU end-use energy for each fuel type in each sector and country is then transitioned to 2050 WWS electricity and heat using the factors in Table S3. Thus, for example, the source of residential and commercial building heat is converted from fossil fuel, wood, or waste heat to air- and ground-source heat pumps running on WWS electricity. Building cooling is also provided by heat pumps powered by WWS electricity.

Liquid fuel (mostly gasoline and diesel) and natural gas vehicles are transitioned primarily to battery electric (BE) vehicles and some hydrogen fuel cell (HFC) vehicles, where the hydrogen is produced with WWS electricity (i.e., green hydrogen). BE vehicles are assumed to dominate short- and long-distance light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance (<1,200 km) heavy-duty trucks, trains (except where powered by electric rails or overhead wires), ferries, speedboats, and ships. Batteries will also power short-haul (<1,500 km) aircraft flights. HFC vehicles will make up all long-distance, heavy payload transport by road, rail, water, and air, as well as heavy-duty air, water, and land military transportation machines (Katalenich and Jacobson, 2022).

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.

Next, 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.

Solar rooftop PV technical potentials are calculated here using the method in Section S5.2.2 of Jacobson et al. (2017). Table S7 shows the results by country. The 145-country-wide 2050 rooftop area suitable for PV (south facing in the Northern Hemisphere, north facing in the Southern Hemisphere, and unshaded) over residential buildings and associated parking structures is ~116,000 km^2 and, for all other buildings (commercial, government, industrial), is ~49,000 km^2. The associated technical potentials of solar PV are ~27.8 TW and ~11.7 TW nameplate capacity, respectively.

Next, we make a first estimate of the nameplate capacities of a mix of WWS generators needed to meet annual average all-purpose load 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 (Table S7); (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 mix is calculated iteratively with the method in the accompanying spreadsheet (Jacobson and Delucchi, 2021). The spreadsheet-derived first-estimate nameplate capacities of onshore and offshore wind electricity, rooftop and utility PV electricity, CSP electricity, and solar thermal heat supply are then input 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 in the model, heating and cooling loads in buildings are calculated every 30 seconds. Results are then aggregated by country (Jacobson, 2021a).

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). 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 S13, footnotes). LOADMATCH is used to match time-dependent (30-s resolution) electricity and heat loads and losses with supply, storage, and demand response during 2050-2052. Notes S4-S6 describe demand response.

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. In all cases, perfectly-interconnected transmission is assumed. However, we account for transmission and distribution costs and losses (Table S17). 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 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 S14).

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; et al., 2007; and Archer, 2012; 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).

The model is run here at $4^o \times 5^o$ 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 are at 30-m resolution; the next seven are at 50-m resolution, one is at 100-m resolution, and the last two are at 200-m resolution. Vertical resolution from 1 to 21 km is 500 m.

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

Rooftop solar PV panels, utility PV panels, CSP plants, and solar thermal plants, with nameplate capacity determined from the initial estimate of generators needed to meet 2050 end-use load, are placed in urban areas (rooftop PV) and in southern parts of each country in the Northern Hemisphere and northern parts in the Southern Hemisphere (utility PV, CSP, and solar thermal) in GATOR-GCMOM. 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 calculates a 30-s-resolution time series of building cooling and heating loads in each country for 2050-2052. The model predicts the ambient air temperature in each of multiple surface grid cells in each country and compares it with an ideal building interior temperature, set here to 294.261 K (70 °F). It then calculates how much heating or cooling energy is needed every 30 s to maintain the interior temperature among all buildings in the grid cell (assuming an average *U*-value and surface area for buildings and a given number of buildings in each grid cell) (Jacobson et al., 2021a). The time series loads among all grid cells in a country are then summed to obtain country values, which are 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) and its main processes. LOADMATCH is a trial-and-error simulation model written in Fortran. 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 has been run for 1 to 6 years, but there is no technical or computational limit for the model running for hundreds or thousands of years, given sufficient input data.

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 with 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) time-dependent electricity produced from onshore and offshore wind turbines, wave devices, tidal turbines, rooftop PV panels, utility PV plants, CSP plants, and geothermal plants;
(2) a hydropower plant peak discharge rate (nameplate capacity), which is set to the present-day nameplate capacity, a hydropower plant mean recharge rate (from rainfall), and a hydropower plant annual average electricity output;
(3) time-dependent geothermal heat and solar-thermal heat generation rates;
(4) 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);
(5) specifications of underground thermal energy storage (UTES), including borehole, water pit, and aquifer storage;

(6) specifications of ice storage (ICE);
(7) specifications of electricity storage in pumped hydropower storage (PHS), phase-change materials coupled with CSP (CSP-PCM), and batteries;
(8) specifications of hydrogen (for use in transportation) electrolysis, compression, and storage equipment;
(9) specifications of electric heat pumps for air and water heating and cooling;
(10) specifications of a demand response system;
(11) specifications of losses along short- and long-distance transmission and distribution lines;
(12) time-dependent electricity, heat, cold, and hydrogen loads; and
(13) 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 loss between BAU and WWS are estimated. Land requirements of WWS are also calculated. Calculations of cost require specifications of generator, storage, transmission, and distribution costs and air pollution and climate costs due to BAU fuels. Changes in job numbers require specifications of job data for generators, storage, and transmission/distribution. Land requirements require specification of the installed power density of generators.

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 1 GW of annual average power (installed capacity) due to water limitations but have a much higher peak instantaneous electricity production rate of 10 GW (nameplate capacity) due to the construction of turbines to allow hydropower to meet peaks in grid electricity demand better.

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 for fuel cells used for transportation, and (4) all other electricity loads (including industrial heat loads), as described in Section S1.3.3 of Jacobson et al. (2019) and updated in Jacobson (2021). 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 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 S14 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 a maximum of eight hours. 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 cooling and low-temperature heating, 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 required for a 100% WWS region in 2050 from Table S6 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 S6.

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 scaling contemporary time -dependent electric load data for the region forward to 2050-2052. Contemporary hourly load data for European are for 2014 (ENTSOE, 2026). Those for almost all remaining countries are for 2030 (Neocarbon Energy, 2021). 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 a nearby country, but with the magnitude each hour scaled so that the annual average inflexible load reflected those of the original countries.

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 the country resides in (Table S6) to the sum of the annual average inflexible loads from the 2014 or 2030 time-dependent profiles among the 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) and for high-temperature industrial heat, 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) (U.S. DOE, 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-winter difference in BEV electricity consumption will be less than the summer-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 at whenever storage has sufficient electricity. Loads for producing hydrogen for fuel cell vehicles comprise 13.5% of all transportation loads and 6.8% of all-purpose loads among the 145 countries (Tables S6 and S5). 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 for vehicles (13.5% of transportation electric loads) are flexible and 85% of all transportation loads are flexible, 82.7% of all electric loads for electric vehicles are flexible.

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 in a phase-change material. 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.

Heat and cold storage are filled by using excess electricity to power an air source or ground source heat pump to move heat or cold from the air, water, or ground to the 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.

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 WWS direct heat supply, then stored district heat (in water tanks and underground storage) is used to satisfy district heat loads subject to storage, and building heat storage (in hot water tanks) is used to satisfy 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. Calculation of Air Pollution and Climate Costs

BAU air pollution cost estimates are based on the projected number of air pollution deaths per year due to energy in 2050 by country multiplied by a value of statistical life for each country and cost factors for morbidity and non-health environmental impacts. Table S21, Column (a) gives the estimated total number of BAU air pollution deaths by country in 2050.

Multiplying the total numbers of 2050 air pollution deaths per year from Table S21 by 90% (the estimated percentage of total air pollution mortalities that are due to energy) gives the estimated numbers of deaths per year due to energy. Multiplying those numbers by a statistical cost of life (million dollars per mortality) updated for 2020 USD from Jacobson et al. (2019) for each country and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts (Jacobson et al., 2019) gives the 2050 annual BAU health cost by region and country in Table S20.

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 S21. The mean social cost of carbon in 2050 in each country is estimated in Table S21, Column (f), which is an update to USD 2020 from Jacobson et al. (2019).

Note S8. Calculation of Land Requirements

Footprint is the physical area on the top surface of soil or water needed for each energy device. It does not include areas 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 panels), open space, or open water. Table S22 provides estimated footprint and spacing areas per megawatt of nameplate capacity of WWS electricity and heat generation technologies considered here.

Applying the footprint and spacing areas per megawatt nameplate capacity from Table S22 to the new nameplate capacities needed to provide grid stability (obtained by subtracting the existing nameplate capacities in Table S8 from the existing plus new nameplate capacities in Table S9) gives the total land footprint and spacing areas required for each country and region, as shown in Table S23.

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).

The total new land area for footprint (before removing the fossil fuel infrastructure) required with 100% WWS is about 0.17% of the 145-country land area (Table S23), 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 S23 indicates that the spacing area for onshore wind to power the U.S. is about 0.36% of the 145-country land area.

Together, the new land footprint and spacing areas for 100% WWS across all energy sectors are 0.53% of U.S. land area, and most of this land area is multi-purpose spacing land.

Note S9. Calculation of Job Changes

A final metric discussed relevant to policy decision-making is net job creation and loss. Table S24 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 value in the table.

The jobs per unit nameplate capacity in the table were 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. Values are the same as in Jacobson et al. (2019), except that new values for constructing and operating heat pumps for district heat were added and HVDC job numbers were updated. Transmission/distribution job numbers came from Jacobson et al. (2017).

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.

Table S25 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. 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 S25 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 S25 indicates that transitioning to 100% WWS may create about 28.4 million more long-term, full-time jobs than lost among 145 countries. Net job gains occur in all regions, but not in all countries within each region. 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 high job losses in the 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.

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.

Parameter	Is the process treated?
Onshore and offshore wind electricity	Yes
Residential, commercial/government rooftop PV electricity	Yes
Utility PV electricity	Yes
CSP electricity	Yes
Geothermal electricity	Yes
Tidal and wave electricity	Yes
Direct solar and geothermal heat	Yes
Battery storage	Yes
CSP storage	Yes
Pumped hydropower storage	Yes
Existing hydropower dam storage	Yes
Added hydropower turbines	No
Heat storage (water tanks, underground)	Yes
Cold storage (water tanks, ice)	Yes
Hydrogen storage in tanks	Yes
Hydrogen fuel cell vehicles for long-distance, heavy transport	Yes
Battery-electric vehicles for all other transport	Yes
District heating	Yes
Electric heat pumps for building cooling and air/water heating	Yes
Electric furnaces and heat pumps for industrial heat	Yes
Wind, PV, CSP, solar heat, wave supply calculated in GATOR-GCMOM	Yes
Building heat and cold loads calculated in GATOR-GCMOM	Yes
Array losses due to wind turbines competing for kinetic energy	Yes
Losses from T&D, storage, shedding, downtime	Yes
Perfect transmission interconnections	Yes
Costs of all generation, all storage, short- and long-distance T&D	Yes
Avoided cost of air pollution damage	Yes
Avoided cost of climate damage	Yes
Land footprint and spacing requirements	Yes
Changes in job numbers	Yes

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/.52[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/.52[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 and are based on the assumption of 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 (2021)'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 ºC). 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 (2021) for each country.

[f]The electricity-to-fuel ratio for a battery-electric (BE) vehicle is 0.21; that for a hydrogen fuel cell (HFC) vehicle is 0.52. 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 0.52 ratio for HFC vehicles is calculated assuming 85% of vehicles have a ratio of 0.46 and 15% have a ratio of 0.87. The 0.46 value is the low tank-to-wheel efficiency of an ICE vehicle (0.17) divided by the high efficiency of an HFC vehicle (0.37). The 0.87 value is the high efficiency of an ICE vehicle (0.20) divided by the low efficiency of an HFC vehicle (0.23). 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 end-use fuel from oil used for transportation, 76% is replaced with electricity (the rest is replaced with electrolytic hydrogen). The 76% is multiplied by the electricity-to-fuel ratio for BE vehicles to determine the WWS electricity used for BE transportation replacing oil and 24% 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 electrified with BE vehicles and 5% is 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 (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 up-stream	(j) % change end-use load w/WWS due to efficiency beyond BAU	(k) Over-all % 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					
	BAU 2050	4.4	27	11.7	20.5	36.9	3.97	0					
	WWS 2050	2.1	34.6	15.9	27.2	20.2	2.16	0	-39.3	-4.5	-9	-52.8	1.38
Algeria	BAU 2018	58.0	29.4	1.3	27.5	36.6	0.4	4.81					
	BAU 2050	142.6	21.7	1.1	21.3	51.6	0.34	4.02					
	WWS 2050	43.3	23.5	2.1	37.5	31.3	0.61	4.92	-44	-18.2	-7.5	-69.7	2.36
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	8.0	41	2.5	26.9	29.6	0.04	0.03	-55.1	-4.2	-8	-67.4	2.51
Argentina	BAU 2018	83.5	22.4	7.4	33.1	31.6	5.53	0					
	BAU 2050	144.4	21.4	6.8	29.6	38	4.18	0					
	WWS 2050	51.0	21.4	11.6	43.6	20.9	2.55	0	-40.8	-16.5	-7.3	-64.7	1.96
Armenia	BAU 2018	3.0	31.6	3	16	34.6	1.42	13.44					
	BAU 2050	4.8	32.6	3.2	12.5	40.6	1.02	10.2					
	WWS 2050	1.5	36.5	5.1	28.2	14.8	1.54	13.96	-39.7	-18.5	-10	-68.1	1.41
Australia	BAU 2018	132.2	10.6	8.3	39	39.5	2.65	0					
	BAU 2050	208.8	10.4	11.8	41.2	34.5	2.15	0					
	WWS 2050	92.3	12.5	19.1	46.1	21.1	1.26	0	-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					
	BAU 2050	47.9	21.6	8.7	30.3	37.9	1.54	0					
	WWS 2050	20.6	18.5	11.6	43.6	25.3	1.12	0	-39.1	-11.2	-6.8	-57	1.68
Azerbaijan	BAU 2018	12.6	34.7	6.9	23.3	30	5.1	0					
	BAU 2050	19.1	37.4	9.3	21.5	28	3.84	0					
	WWS 2050	6.5	35	18.9	19.9	22.6	3.59	0	-45.9	-10.7	-9.4	-66	1.37
Bahrain	BAU 2018	9.4	11.5	7.4	54.4	26.6	0.07	0					
	BAU 2050	17.6	14.5	8.6	52.4	24.4	0.07	0					
	WWS 2050	9.3	20.3	12.7	54.6	12.3	0.1	0	-24.4	-15.6	-7.1	-47.1	1.32
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	57.8	9.2	1.85	0.75	-39.7	-8.1	-8.8	-56.7	1.96
Belarus	BAU 2018	25.8	26.7	10.9	34.5	22	5.92	0					
	BAU 2050	37.5	28.3	12.5	31.7	22.7	4.7	0					

	WWS 2050	12.8	25.2	17.8	36.4	16.7	3.84	0	-47.6	-12.7	-5.7	-66	1.85
Belgium	BAU 2018	63.5	16.8	9.6	30.3	41.5	1.66	0.1					
	BAU 2050	73.3	16.7	10.6	30.9	40.2	1.55	0.09					
	WWS 2050	30.2	13.1	13.5	44.9	27.2	1.15	0.04	-44.2	-8	-6.6	-58.9	2.09
Benin	BAU 2018	5.9	37.7	8.2	1.8	51.9	0.45	0					
	BAU 2050	11.0	26	9.2	2	62.5	0.48	0					
	WWS 2050	2.9	19.9	10.1	6.1	63.4	0.53	0	-66.5	-1.2	-6.1	-73.8	8.01
Bolivia	BAU 2018	10.0	12.8	3.4	31.4	49.6	2.75	0					
	BAU 2050	18.3	8.9	3.2	26.6	59.4	2.04	0					
	WWS 2050	5.4	13.2	7.2	40.2	36.5	2.94	0	-41.7	-23.2	-5.8	-70.7	3.07
Bosnia & Herz.	BAU 2018	6.2	37	7.5	27.9	26.7	0.9	0					
	BAU 2050	9.0	38.6	9.1	25.6	26	0.69	0					
	WWS 2050	3.7	37.3	13.7	31.4	17.1	0.47	0	-41.7	-9	-8.4	-59.1	1.33
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	1.5	0.62					
	WWS 2050	2.2	21	10.8	31.6	33.5	1.96	1.14	-50.5	-2.2	-7.6	-60.3	2.08
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	271.9	10.8	8.2	56.8	19.9	3.68	0.72	-37	-11.5	-5.5	-54	2.14
Brunei	BAU 2018	2.7	7.7	7.6	56.5	26.7	0	1.48					
	BAU 2050	5.2	8.2	10.3	48.2	31.9	0	1.38					
	WWS 2050	1.6	18.6	27.1	24.8	28.6	0	0.94	-35.8	-29.5	-5.1	-70.3	1.49
Bulgaria	BAU 2018	14.8	20	10.2	34.8	33.4	1.67	0					
	BAU 2050	22.4	23.1	13	30.3	32.3	1.27	0					
	WWS 2050	10.0	27.1	19	35.1	17.9	0.78	0	-36.3	-11.3	-7.6	-55.1	1.32
Cambodia	BAU 2018	9.6	44.5	5.8	20.9	28.1	0	0.65					
	BAU 2050	17.3	34.5	7	21.6	36.2	0	0.66					
	WWS 2050	6.9	22.7	11.2	41.8	24	0	0.33	-51.2	-1.1	-7.5	-59.8	2.98
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	4.4	39.6	16.2	22.1	17.5	0.25	4.3	-63	-0.9	-8.2	-72.1	2.41
Canada	BAU 2018	320.9	14.9	11	42.3	28.8	3	0.03					
	BAU 2050	442.5	13.4	11.8	45.5	26.5	2.76	0.02					
	WWS 2050	168.0	16.3	19.3	41.5	20.8	2.02	0.04	-33.3	-22.6	-6.1	-62	1.42
Chile	BAU 2018	38.8	15.8	6.5	39.7	35.2	2.51	0.2					
	BAU 2050	67.5	14.7	10.3	38.9	33.4	2.37	0.22					
	WWS 2050	35.2	12.4	11.4	56.9	17.2	1.78	0.42	-36	-4.8	-7	-47.9	1.78
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	2,317.0	16.4	5.6	62	11.2	1.21	3.66	-32.9	-14.2	-6.3	-53.4	1.73
Colombia	BAU 2018	43.8	18.7	5	32.3	37.4	0.75	5.9					
	BAU 2050	70.5	16.5	5.2	31.6	40.9	0.62	5.3					
	WWS 2050	28.2	18.4	8.4	44.2	24.8	0.57	3.58	-42.4	-11	-6.5	-60	2.05
Congo	BAU 2018	2.7	57.4	13.8	5.5	23.3	0	0					
	BAU 2050	4.6	45.4	17.7	6.2	30.7	0	0					
	WWS 2050	1.4	37.4	22.7	12.3	27.6	0	0	-60.1	-2	-8.3	-70.4	2.29
Congo, DR	BAU 2018	26.0	90.2	0.1	4.4	4.2	1.03	0					
	BAU 2050	35.8	84.4	0.3	6.7	6.9	1.64	0					
	WWS 2050	8.5	67.9	1	22	7.8	1.28	0	-65	-0.6	-10.6	-76.2	3.70
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	55.6	1.57	0.56					
	WWS 2050	4.0	16.8	16.2	33.4	31.7	1.46	0.41	-44.7	-1.5	-7.2	-53.3	1.95
Côte d'Ivoire	BAU 2018	10.0	59.3	9.6	9	20.8	1.33	0.01					
	BAU 2050	16.6	46.9	12.7	10.6	28.2	1.59	0.02					
	WWS 2050	5.2	35.2	16.3	23.1	23.8	1.57	0.04	-58	-2	-8.5	-68.4	2.45
Croatia	BAU 2018	10.0	30.4	10.8	24.7	31	3.11	0					
	BAU 2050	14.8	31.9	14	22.1	29.6	2.37	0					
	WWS 2050	5.9	30.9	22	25.6	20.1	1.35	0	-43.4	-8	-8.5	-59.9	1.51
Cuba	BAU 2018	11.0	15	3.3	55.6	14.1	2.56	9.41					
	BAU 2050	15.8	16.4	4.1	52	16.6	2.35	8.55					
	WWS 2050	9.0	18	5.4	63.8	8.6	1.16	3	-31.8	-4.9	-6.2	-42.9	2.48

Curacao	BAU 2018	3.2	3.3	0.9	15.2	80.6	0	0					
	BAU 2050	5.2	2.4	1	14.1	82.6	0	0					
	WWS 2050	1.5	4.1	2.8	14	79.1	0	0	-58.8	-9.4	-4.1	-72.2	9.22
Cyprus	BAU 2018	2.8	15.2	11.2	11.9	58.8	2.06	0.8					
	BAU 2050	4.2	16.7	15.3	9.6	56.2	1.59	0.62					
	WWS 2050	1.9	25.2	24.5	15	33.2	1.44	0.66	-44.7	-2	-8.3	-54.9	1.62
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	20.1	16.5	42.8	19.2	1.35	0.06	-41.2	-11.2	-6.7	-59.1	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	9.8	24.9	20	27	24.8	3.37	0.01	-47.5	-8.2	-6.6	-62.3	1.74
Dominican Rep.	BAU 2018	9.1	21.3	6.7	25.5	44.1	2.36	0					
	BAU 2050	14.0	16.9	7.6	25.4	48	2.14	0					
	WWS 2050	6.5	16.8	11.5	41.5	27.6	2.56	0	-43.6	-2.9	-7.3	-53.9	1.93
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	10.4	14	12.3	28.1	40.1	1.2	4.33	-51.7	-4.9	-6.2	-62.8	2.11
Egypt	BAU 2018	83.2	22.4	5.5	39.6	30.1	2.3	0.1					
	BAU 2050	186.8	19.5	7	34.1	37.3	2.07	0.08					
	WWS 2050	87.2	23.2	11.6	45.4	17.7	2.08	0.04	-33.7	-11.9	-7.8	-53.3	1.72
El Salvador	BAU 2018	3.7	20.9	5.7	23.5	48.6	0	1.29					
	BAU 2050	5.5	16.6	7	21.3	53.8	0	1.26					
	WWS 2050	2.5	16.5	11.8	37.5	32	0	2.2	-46.2	-1.4	-7.5	-55.2	1.98
Equator. Guinea	BAU 2018	3.1	5.4	2.3	75.6	15.4	0	1.27					
	BAU 2050	6.6	4.3	2.5	75.4	16.7	0	1.2					
	WWS 2050	4.2	3.3	2.4	86.7	7	0	0.54	-29.3	-3.8	-3.4	-36.5	10.26
Eritrea	BAU 2018	0.7	73.1	7	3.5	16.3	0	0					
	BAU 2050	1.1	61.7	10	4.5	23.7	0	0					
	WWS 2050	0.3	49.6	15.1	12.6	22.7	0	0	-61.7	-0.8	-9.6	-72.1	2.33
Estonia	BAU 2018	4.8	25.8	13.4	24.3	32.8	3.42	0.3					
	BAU 2050	6.0	26.4	14.9	25.7	29.8	2.96	0.27					
	WWS 2050	2.1	23.6	24.5	26.9	22.2	2.24	0.6	-45.1	-12.8	-6.7	-64.6	1.32
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	18.1	63.8	4.4	17.3	13.3	0.54	0.54	-66	-0.2	-10.2	-76.4	6.39
Finland	BAU 2018	36.2	19	11.1	46.9	19.6	2.62	0.71					
	BAU 2050	42.6	21	13	44.3	18.8	2.35	0.65					
	WWS 2050	22.0	18.4	14.8	54.4	10.8	1.41	0.26	-34.9	-6.9	-6.5	-48.3	1.59
France	BAU 2018	204.6	23.9	15	23.6	34.4	2.85	0.34					
	BAU 2050	248.6	25	16.8	23.1	32.3	2.52	0.3					
	WWS 2050	111.3	24.2	21.8	30	22	1.71	0.18	-40.3	-6.3	-8.6	-55.2	1.34
Gabon	BAU 2018	6.1	27.9	0.9	65.8	5.2	0.09	0.11					
	BAU 2050	11.8	20	1.1	72.6	6.1	0.09	0.11					
	WWS 2050	7.3	9	1.1	87.1	2.7	0.1	0.06	-31.1	-4.1	-3.5	-38.6	10.41
Georgia	BAU 2018	5.6	29	12.1	19.8	34.5	0.64	3.9					
	BAU 2050	8.6	29.9	15.3	15.8	35.4	0.49	3.03					
	WWS 2050	3.6	23.1	23.1	29.5	18.1	0.44	5.62	-40.1	-7.7	-10.2	-57.9	1.47
Germany	BAU 2018	301.7	23.8	12.8	32	29.8	1.58	0.03					
	BAU 2050	361.0	23.7	13.8	31.4	29.7	1.39	0.03					
	WWS 2050	154.4	18.7	16.7	43.6	20.1	0.88	0.01	-41.5	-8.3	-7.4	-57.2	1.64
Ghana	BAU 2018	10.7	40.4	4.8	17.4	35.8	1.61	0					
	BAU 2050	20.7	32	6.1	18.3	41.9	1.63	0					
	WWS 2050	8.6	28.8	8.7	34.7	26.9	0.79	0	-49.3	-1.2	-8	-58.5	2.11
Gibraltar	BAU 2018	5.6	0	0.1	0.1	99.5	0	0.36					
	BAU 2050	6.0	0	0.1	0.1	99.4	0	0.37					
	WWS 2050	1.6	0	0.3	0.2	98.4	0	1.08	-67.1	-1.9	-4.2	-73.1	55.04
Greece	BAU 2018	26.8	19	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	13.2	24	21.5	25.3	26.7	1.91	0.5	-40	-12	-7.5	-59.4	1.43
Guatemala	BAU 2018	16.2	60.2	3.6	8.4	27.7	0	0					

	BAU 2050	20.2	49.7	4.3	9.4	36.7	0	0					
	WWS 2050	6.1	36.7	8.6	22.1	32.5	0	0	-59.6	-1.8	-8.6	-69.9	2.80
Haiti	BAU 2018	4.6	74.7	1.6	8.8	14.9	0	0					
	BAU 2050	5.1	66.4	1.5	10.3	21.9	0	0					
	WWS 2050	1.3	46.2	1.4	30.1	22.2	0	0	-64.4	-0.5	-8.9	-73.8	15.64
Honduras	BAU 2018	6.0	40.9	9.4	15	32.9	1.72	0.09					
	BAU 2050	8.2	33.1	10.2	14.8	40.1	1.66	0.08					
	WWS 2050	3.1	25.4	14.3	31.4	28	0.87	0.04	-53	-0.8	-8.1	-61.8	2.25
Hong Kong	BAU 2018	36.0	4.9	10.7	8.2	76.2	0	0.03					
	BAU 2050	82.6	4.7	11.6	6.6	77	0	0.02					
	WWS 2050	30.5	8.5	23.1	12.8	55.5	0	0.03	-54.6	-2	-6.5	-63.1	2.29
Hungary	BAU 2018	25.9	29.8	10.8	30	26	3.29	0.19					
	BAU 2050	31.7	30.1	10.9	29.1	26.8	2.87	0.17					
	WWS 2050	12.6	22.6	13.6	41.7	19.6	2.33	0.12	-43.6	-9.2	-7.6	-60.4	1.75
Iceland	BAU 2018	5.0	13.5	13.7	42.1	23	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	13.4	62.3	11.3	3.88	0.11	-34.6	-2.1	-5.9	-42.6	1.22
India	BAU 2018	797.9	29	4.3	40.8	18.3	4.88	2.67					
	BAU 2050	1870.8	20.3	4	40.5	28	4.55	2.65					
	WWS 2050	926.7	16.3	3.9	58.5	14	5.14	2.11	-37.4	-6.4	-6.7	-50.5	2.34
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	193.9	14.6	7.4	53.8	23.6	0.62	0.07	-42.2	-6.1	-6	-54.2	2.80
Iran	BAU 2018	253.8	27.9	5.8	35.7	26.3	4.09	0.22					
	BAU 2050	444.0	24	5.1	38.3	28.1	4.35	0.24					
	WWS 2050	184.9	17.5	5.8	56.8	14.9	4.58	0.45	-39.8	-11.2	-7.3	-58.4	2.80
Iraq	BAU 2018	36.7	19.5	0.8	32.2	44.2	0	3.36					
	BAU 2050	62.1	17.9	1	32.5	44.9	0	3.69					
	WWS 2050	24.0	26.1	2	33.7	30.9	0	7.33	-41.2	-13.8	-6.3	-61.3	2.06
Ireland	BAU 2018	16.7	21.7	11.6	22.7	42	1.97	0					
	BAU 2050	18.9	21.2	13.3	22.6	40.9	1.88	0					
	WWS 2050	8.1	19	16.7	38.2	24.7	1.39	0	-45.3	-4.2	-7.7	-57.1	1.77
Israel	BAU 2018	21.5	12.9	10.3	24.7	46	1.58	4.52					
	BAU 2050	26.1	15.1	14.2	24.8	40.4	1.45	4.07					
	WWS 2050	13.1	23.3	21.2	28	21.4	2.25	3.87	-33.8	-7.4	-8.4	-49.6	1.32
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	83.9	18.7	20.3	33.9	25.4	1.61	0.04	-42.2	-11.1	-7.8	-61.1	1.52
Jamaica	BAU 2018	3.7	5.4	7.7	38.7	47.7	0.5	0					
	BAU 2050	5.5	5.5	6.4	35	52.6	0.44	0					
	WWS 2050	2.6	7.4	4.5	58.3	29.6	0.19	0	-47.1	-1	-4.8	-52.9	4.21
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	174.5	16.9	22	42	18.3	0.61	0.07	-34.6	-8.5	-7.7	-50.9	1.42
Jordan	BAU 2018	9.1	21.3	7.3	13.9	50.2	3.4	3.87					
	BAU 2050	15.8	21.1	7.3	14.5	49.6	3.64	3.84					
	WWS 2050	7.1	30.6	10.5	21.6	29.3	6.3	1.71	-43.4	-3.3	-8.2	-54.9	1.56
Kazakhstan	BAU 2018	65.4	23.1	10.7	45.7	14	3.36	3.06					
	BAU 2050	87.2	22.1	11.2	45.6	15.2	3	2.82					
	WWS 2050	33.2	19.1	10.1	55.7	11.2	1.99	1.85	-42	-15	-5	-61.9	1.94
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	10.7	40.3	3.1	27.3	28.7	0.24	0.31	-61.7	-0.6	-8.8	-71.1	4.20
Korea, DPR	BAU 2018	6.9	3.1	0	52.1	8.9	0	35.95					
	BAU 2050	13.3	1.9	0	51.7	10.7	0	35.7					
	WWS 2050	7.3	0.6	0	71.3	5.2	0	22.9	-37.5	-2.3	-5.4	-45.2	2.58
Korea, Rep. of	BAU 2018	217.4	13.1	13.1	40.8	30.5	1.6	0.81					
	BAU 2050	304.9	11.4	15.2	42.5	28.8	1.49	0.66					
	WWS 2050	151.3	8.6	20.5	54.3	14.6	1.68	0.27	-33.5	-9.6	-7.3	-50.4	1.44
Kosovo	BAU 2018	2.0	37.5	10.1	22	28.4	2.02	0					
	BAU 2050	3.0	41.7	11.8	17.9	27.1	1.56	0					

	WWS 2050	1.4	42.8	15	25.3	15.6	1.33	0	-40	-3.5	-10.2	-53.6	1.24
Kuwait	BAU 2018	31.3	12.3	3.3	53.1	30.8	0.51	0					
	BAU 2050	57.4	16	4	50.7	28.9	0.52	0					
	WWS 2050	24.0	28.2	7.4	45.1	18.3	0.97	0	-30.4	-21.8	-5.9	-58.1	1.54
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	61.2	7.9	21.9	7.5	0.74	0.73	-40.3	-1.6	-11	-52.9	1.21
Lao PDR	BAU 2018	4.2	40.3	12.1	13.3	34.2	0.06	0					
	BAU 2050	7.6	32.4	9.7	14	43.9	0.07	0					
	WWS 2050	2.9	25.9	12.2	31	30.8	0.14	0	-53.4	-0.8	-7.8	-62.1	2.06
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	3.5	0.11					
	WWS 2050	3.3	22.7	21.7	33.1	20.3	2.21	0.05	-50.5	-2.6	-6.8	-59.9	2.07
Lebanon	BAU 2018	7.3	18.8	5.3	13.9	55.3	0	6.71					
	BAU 2050	13.2	20.3	6.3	14.3	52.5	0	6.74					
	WWS 2050	6.5	27.4	10	24.6	28.4	0	9.55	-40.8	-1	-9.2	-50.9	1.37
Libya	BAU 2018	14.4	13.4	1.5	25.3	55.3	1	3.45					
	BAU 2050	31.4	12.8	2	23.5	57.4	0.97	3.35					
	WWS 2050	14.0	18	3.5	36.6	34.3	1.7	5.87	-45.8	-3.2	-6.5	-55.5	2.55
Lithuania	BAU 2018	8.6	22.6	10	28.8	36.9	1.66	0.11					
	BAU 2050	12.6	23.7	12	26.7	36.2	1.33	0.08					
	WWS 2050	4.5	23.6	18.3	30.5	26.4	1.1	0.05	-47.6	-10.5	-6	-64	1.83
Luxembourg	BAU 2018	5.8	11.3	10.9	15.4	61.9	0.52	0					
	BAU 2050	6.5	11.5	12.3	15.6	60.1	0.5	0					
	WWS 2050	2.5	8.9	16.9	30.6	43.3	0.36	0	-52.7	-2.3	-6.6	-61.6	2.15
Macedonia, Nor.	BAU 2018	2.5	25.6	11.2	24.1	38.1	1.06	0					
	BAU 2050	3.8	31.1	13.6	19.3	35.3	0.8	0					
	WWS 2050	1.9	35.9	17	27.6	18.7	0.72	0	-37.4	-2.6	-9.7	-49.7	1.29
Malaysia	BAU 2018	79.1	5.6	7.4	45	40.2	1.71	0					
	BAU 2050	169.0	5.4	8.7	40.3	44.1	1.46	0					
	WWS 2050	82.6	7.8	13.3	54.3	24	0.7	0	-37.5	-7.8	-5.8	-51.1	2.03
Malta	BAU 2018	3.8	3	4.2	2.1	90.4	0.24	0.07					
	BAU 2050	5.5	4.2	5.9	1.7	88	0.19	0.06					
	WWS 2050	1.8	9.5	12.9	4.3	73	0.17	0.14	-60.5	-1.8	-5.6	-67.9	3.12
Mauritius	BAU 2018	2.3	8	5.8	12	73.8	0.23	0.12					
	BAU 2050	5.1	7.5	6.7	10.9	74.5	0.21	0.11					
	WWS 2050	2.0	12.6	12.4	23.2	51.4	0.27	0.22	-53.5	-1.5	-6.3	-61.4	2.26
Mexico	BAU 2018	189.1	12.7	2.9	38.4	41	3.11	1.91					
	BAU 2050	312.5	12.6	4.8	38	39.5	3.06	2.1					
	WWS 2050	136.8	14.2	6.4	49.8	23.4	2.49	3.75	-38.5	-11.6	-6.1	-56.2	1.83
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	34.4	15	31.9	16.6	1.82	0.22	-50.2	-2.4	-8.9	-61.4	1.88
Mongolia	BAU 2018	5.4	25.2	7.9	33.6	18.7	2.21	12.3					
	BAU 2050	9.9	19.9	6.3	35	23.5	2.24	13.04					
	WWS 2050	4.0	16.9	3.9	53.1	15.4	1.35	9.29	-52.5	-3.4	-3.7	-59.6	2.38
Montenegro	BAU 2018	1.0	32.4	11.5	19.5	35.9	0.65	0					
	BAU 2050	1.6	36.6	15	15	32.9	0.48	0					
	WWS 2050	0.8	38.4	21	22.5	17.8	0.31	0	-37	-1.9	-10.9	-49.8	1.17
Morocco	BAU 2018	22.3	24.1	7.7	20	40.9	7.27	0					
	BAU 2050	44.6	17.6	8.7	20.2	46.3	7.25	0					
	WWS 2050	19.4	18.7	9.4	37.5	28.7	5.76	0	-48.3	-0.9	-7.2	-56.4	2.04
Mozambique	BAU 2018	6.8	37.7	14.7	23.9	22.9	0.08	0.78					
	BAU 2050	12.7	28	16	26.5	28.4	0.09	0.88					
	WWS 2050	5.3	17.4	9.1	54.2	17.7	0.1	1.64	-49.4	-1.5	-7	-57.9	1.63
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	15.8	30.8	6.2	46.4	10.7	4.08	1.78	-52.3	-4.3	-8	-64.7	3.25
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					
	WWS 2050	2.0	2.5	0	20.5	29.9	9.3	37.73	-53.4	-0.8	-7.1	-61.2	1.97

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	2.6	0.23					
	WWS 2050	8.0	45.6	3.4	28.7	19.5	2.14	0.63	-62.3	-0.4	-9.2	-71.9	4.79
Netherlands	BAU 2018	88.4	14.4	10.2	30.8	38.9	5.69	0.1					
	BAU 2050	104.5	15	11.5	31.6	36.6	5.23	0.09					
	WWS 2050	40.9	12.2	16.3	40.8	26.2	4.56	0.05	-44.3	-10	-6.6	-60.9	2.06
New Zealand	BAU 2018	20.7	9.5	7.7	33.5	44.7	4.3	0.28					
	BAU 2050	32.4	10	10.6	36.9	38	4.12	0.33					
	WWS 2050	17.0	12.6	14.5	49.6	19.4	3.48	0.49	-35.5	-5.2	-6.9	-47.6	1.78
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	1.7	26.4	14.8	30.1	26	1.84	0.98	-52.8	-3.4	-8	-64.2	2.07
Niger	BAU 2018	4.2	78.4	1.4	4	16.1	0.03	0					
	BAU 2050	6.3	68.5	2	5.2	24.2	0.04	0					
	WWS 2050	1.6	56.8	3.3	14.8	24.9	0.13	0	-63.6	-0.9	-9.6	-74.1	3.53
Nigeria	BAU 2018	193.2	72.6	2.3	8.7	16.3	0	0.12					
	BAU 2050	294.0	61.3	3.3	11	24.2	0	0.15					
	WWS 2050	74.1	46.9	4.4	23	25.5	0	0.12	-62.8	-3.6	-8.3	-74.8	8.44
Norway	BAU 2018	34.0	16.1	11.5	49.5	21	1.73	0.2					
	BAU 2050	47.3	16.8	12.7	48	21	1.35	0.16					
	WWS 2050	20.3	26.9	20.3	39	12.4	1.39	0.07	-23.6	-25.8	-7.5	-57	0.99
Oman	BAU 2018	35.2	5.9	27.2	37.9	25.8	0.17	3.04					
	BAU 2050	59.9	8	21.6	41	26.1	0.19	3.11					
	WWS 2050	25.5	13.7	17.2	51	16.3	0.34	1.46	-41.3	-11.6	-4.5	-57.4	2.86
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	1.12	0.32					
	WWS 2050	97.6	25.5	4.8	51.4	16.1	2.06	0.15	-45.1	-5	-8	-58.1	3.00
Panama	BAU 2018	11.5	6.6	6.2	9	78.1	0.15	0.01					
	BAU 2050	18.5	5.5	6.8	7.4	80.1	0.12	0.01					
	WWS 2050	6.5	8.6	14.1	16.2	61	0.07	0.02	-57.6	-1.6	-5.8	-65	3.27
Paraguay	BAU 2018	8.8	26.7	6.2	25.7	41.4	0	0					
	BAU 2050	12.9	22.4	7.8	23	46.7	0	0					
	WWS 2050	5.9	20.5	13.3	39.2	27	0	0	-45.8	-1.4	-7.3	-54.5	2.19
Peru	BAU 2018	29.4	17.8	6.2	30.9	44	1.01	0					
	BAU 2050	47.4	13	6	28.8	51.3	0.88	0					
	WWS 2050	19.0	12.5	8.8	49	28.5	1.22	0	-42.1	-11.4	-6.3	-59.9	2.09
Philippines	BAU 2018	47.2	21.2	13.1	25	39.4	1.24	0					
	BAU 2050	93.9	17	12.5	23.4	45.9	1.18	0					
	WWS 2050	41.8	17.7	15.5	38	27.4	1.35	0	-45	-3.1	-7.4	-55.5	1.79
Poland	BAU 2018	103.8	25	10.2	29.5	30.3	5.04	0					
	BAU 2050	126.7	22.9	11.6	29.3	31.8	4.36	0					
	WWS 2050	48.0	18.1	18.1	39.3	21.9	2.58	0	-43.8	-12.4	-5.9	-62.1	1.67
Portugal	BAU 2018	25.2	14	10.4	31.1	42	2.43	0.14					
	BAU 2050	30.2	15.1	13.3	30.7	38.6	2.19	0.12					
	WWS 2050	13.6	16.2	20.4	38.2	23.6	1.57	0.05	-39	-8.8	-7.1	-54.9	1.59
Qatar	BAU 2018	44.1	5.7	2.2	70.1	20.9	0	1.07					
	BAU 2050	78.8	7.8	2.7	68.3	20.1	0	1.12					
	WWS 2050	30.9	14.8	5.3	64	13.7	0	2.23	-27.7	-29.1	-4.1	-60.8	2.55
Romania	BAU 2018	34.1	30.1	7.7	34.1	25.2	2.2	0.82					
	BAU 2050	48.4	31.9	9.2	31.3	25.1	1.79	0.65					
	WWS 2050	18.8	25.6	11.9	43.2	17.7	1.23	0.34	-44.9	-9	-7.3	-61.2	1.76
Russia	BAU 2018	683.1	28.8	7.2	39.1	23	1.86	0					
	BAU 2050	779.2	27.5	7.3	36.6	27.1	1.39	0					
	WWS 2050	251.0	25.9	11.3	45.2	16.3	1.37	0	-42.3	-19.2	-6.3	-67.8	1.63
Saudi Arabia	BAU 2018	188.4	9.2	7.7	45.7	37	0.3	0.03					
	BAU 2050	349.0	11.6	9.1	44.6	34.4	0.3	0.03					
	WWS 2050	185.2	16	13.4	52.9	17.3	0.44	0.04	-32.4	-8	-6.6	-46.9	2.17
Senegal	BAU 2018	3.7	39.9	6.4	15	37	0.36	1.3					
	BAU 2050	6.9	29.2	8.1	16	44.8	0.41	1.47					
	WWS 2050	2.7	21	13.3	31.4	30.5	0.81	2.92	-51.4	-1.4	-8.1	-60.9	2.26
Serbia	BAU 2018	12.5	30	9.4	34.6	24.1	1.8	0					

	BAU 2050	18.8	34.6	11.2	30	22.8	1.37	0					
	WWS 2050	8.8	38	13.7	33.9	13.4	0.93	0	-36.4	-8.5	-8.4	-53.3	1.25
Singapore	BAU 2018	95.4	1	2.6	13.9	82.4	0	0.04					
	BAU 2050	216.6	1	2.9	11.2	84.8	0	0.03					
	WWS 2050	72.5	2.1	6.6	21.5	69.7	0	0.07	-58.4	-3.6	-4.5	-66.5	4.78
Slovak Republic	BAU 2018	15.3	17.8	11.4	45.2	24.4	1.16	0					
	BAU 2050	20.0	16.8	11.7	42	28.6	0.94	0					
	WWS 2050	8.2	13.8	15.8	53.4	16.3	0.68	0	-34.8	-17.7	-6.3	-58.8	1.70
Slovenia	BAU 2018	7.1	20	8	28.4	41.7	1.37	0.45					
	BAU 2050	8.3	21.7	10	27.2	39.3	1.25	0.41					
	WWS 2050	3.9	18.6	14.3	42.2	24.1	0.61	0.18	-42	-3.5	-7.4	-53	1.62
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	105.0	14.8	10.4	53.6	18.3	1.95	0.92	-35.7	-13.9	-5.5	-55.2	1.65
South Sudan	BAU 2018	0.7	27.8	2.1	19	47.2	3.92	0					
	BAU 2050	1.4	21.4	2.1	17	55.5	4.05	0					
	WWS 2050	0.4	25	2.6	15.3	52.4	4.57	0	-55.2	-10.9	-5.7	-71.8	2.89
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	68.8	17.8	18.4	35.3	26.5	1.67	0.28	-39.6	-12.1	-6.8	-58.6	1.57
Sri Lanka	BAU 2018	14.8	29.8	4.6	24	39.7	0	1.92					
	BAU 2050	28.6	22.1	5	23.3	47.7	0	1.81					
	WWS 2050	11.9	17.1	7.9	43.6	30.4	0	0.87	-50.4	-1.4	-6.4	-58.2	3.07
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	11.4	31.2	12.7	26.7	26.6	2.55	0.33	-55.9	-1.1	-7.3	-64.3	2.59
Suriname	BAU 2018	0.8	17.2	7.9	15.7	42.3	16.5	0.34					
	BAU 2050	1.2	16	9	14.8	45.8	14.1	0.32					
	WWS 2050	0.5	22.6	15	25.3	29.6	6.89	0.61	-47.7	-3.4	-7.7	-58.8	1.46
Sweden	BAU 2018	45.9	21.7	11.9	35.9	28.6	1.89	0					
	BAU 2050	55.4	24	14.1	32.6	27.7	1.63	0					
	WWS 2050	29.9	24.1	16.2	42.7	16.1	0.89	0	-33.9	-4.6	-7.6	-46.1	1.33
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	15.0	22.6	20.7	27.1	28.6	0.68	0.39	-40.9	-3.7	-8.6	-53.2	1.35
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	6.4	23.7	4.9	41.9	23.8	1.65	4.1	-41.6	-6.4	-7.2	-55.3	1.73
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	30.5	0.94	0.76					
	WWS 2050	90.7	11.6	11.7	59.4	15.7	0.77	0.82	-30.5	-7.7	-6.9	-45.1	1.40
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	3.5	36.2	15.1	31.8	6.4	6.89	3.59	-28.1	-1.1	-10.9	-40.1	1.13
Tanzania	BAU 2018	24.2	69.6	0.8	10.9	11	5.05	2.61					
	BAU 2050	38.1	57.3	1.4	14.8	15.8	7.03	3.65					
	WWS 2050	11.6	37.7	3.5	38.1	13.8	4.51	2.4	-60.5	-0.3	-8.7	-69.5	5.90
Thailand	BAU 2018	122.3	10.1	5.3	44.2	36.6	3.15	0.7					
	BAU 2050	257.5	8.1	6.1	38.9	43.5	2.72	0.65					
	WWS 2050	118.4	9.3	9.5	56.5	22.4	1.23	1.09	-38.4	-10	-5.7	-54	2.43
Togo	BAU 2018	2.8	66.5	10.1	4.6	18.9	0	0					
	BAU 2050	4.5	54.4	13	5.9	26.7	0	0					
	WWS 2050	1.2	42.7	12.7	18.3	26.4	0	0	-64.1	-0.5	-8.4	-73	3.34
Trinidad & Tob.	BAU 2018	9.6	5	1.2	73.8	20	0	0					
	BAU 2050	15.4	5	1.3	73	20.7	0	0					
	WWS 2050	5.0	9	3.1	70.8	17.1	0	0	-30.3	-34.4	-3.1	-67.8	3.02
Tunisia	BAU 2018	11.6	24.9	8	28.2	32.9	6.02	0					
	BAU 2050	30.0	15.1	6.8	21.8	51.6	4.62	0					
	WWS 2050	10.8	17.4	11.6	44.3	22.7	4.06	0	-38.9	-17.7	-7.3	-64	2.15
Turkey	BAU 2018	144.6	18.9	11.5	35.5	30	4.16	0					
	BAU 2050	173.7	19.3	12.9	34.2	29.9	3.69	0					

	WWS 2050	80.6	17.2	16.2	47.3	16	3.24	0	-37.8	-8.6	-7.2	-53.6	1.84
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	1.35	16.75					
	WWS 2050	8.7	6.6	30.8	20.8	20.7	4.82	16.37	-55.9	-18.8	-3.4	-78.1	3.14
Ukraine	BAU 2018	71.1	31.1	8	39.1	18.3	3.53	0					
	BAU 2050	104.2	33.9	9.5	34.7	19.1	2.77	0					
	WWS 2050	42.1	28.7	12.1	44.9	12.2	2.14	0	-41.5	-10.2	-7.9	-59.6	1.58
United Arab Em.	BAU 2018	108.5	4.6	4.2	43.5	44.6	0	3.08					
	BAU 2050	205.6	6	4.8	45.7	40.5	0	3.02					
	WWS 2050	113.7	8.1	6.8	61.4	19.5	0	4.21	-37	-2.2	-5.5	-44.7	3.58
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	87.8	24	18.8	29.7	26.4	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	979.0	18.3	19.4	36	22.7	1.03	2.53	-39.9	-12.2	-7	-59.2	1.60
Uruguay	BAU 2018	6.8	16	6.3	43.4	29.9	4.45	0					
	BAU 2050	10.0	15.4	7.5	39.5	33.6	4	0					
	WWS 2050	5.2	16.1	10.2	54.7	17	2.12	0	-37.3	-4.1	-6.4	-47.8	2.19
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	3.57	1.04					
	WWS 2050	20.5	29.8	11.2	39.2	9.6	9.52	0.72	-42.1	-22.9	-7	-72	1.95
Venezuela	BAU 2018	49.2	10	6.3	52.2	31.3	0.11	0					
	BAU 2050	78.7	10	6.8	50.7	32.4	0.1	0					
	WWS 2050	28.9	15.2	12.6	48.6	23.4	0.2	0	-35.4	-22.9	-4.9	-63.2	2.15
Vietnam	BAU 2018	80.8	16.5	4.7	54.6	22.1	2.06	0					
	BAU 2050	159.1	15.2	3.9	52.8	26.1	1.97	0					
	WWS 2050	97.0	14.9	3	69.3	11.4	1.37	0	-31.5	-1.2	-6.4	-39	2.05
Yemen	BAU 2018	3.0	27.7	3.5	19.3	44	2.08	3.4					
	BAU 2050	4.8	22.4	3.1	21.2	47.6	2.26	3.42					
	WWS 2050	1.8	27	3.1	32.7	33.3	1.19	2.8	-49.7	-5.2	-7	-61.9	2.59
Zambia	BAU 2018	13.0	60.4	1.2	29.8	7.3	0.52	0.8					
	BAU 2050	21.9	49.3	1.7	37.6	9.8	0.63	0.93					
	WWS 2050	10.3	27	2.3	63.9	5.6	0.68	0.51	-44.4	-0.6	-8	-53	2.77
Zimbabwe	BAU 2018	13.9	73.9	1.2	8	10.2	5.54	1.23					
	BAU 2050	21.5	63.2	2.1	10.6	14.8	7.69	1.57					
	WWS 2050	6.4	46.2	5.5	28	13.1	6.01	1.18	-59.7	-0.8	-9.7	-70.2	2.57
All Countries	**BAU 2018**	**13,102.3**	**20.8**	**8.2**	**38.1**	**29.2**	**2.22**	**1.52**					
	BAU 2050	**20,358.8**	**19.1**	**8**	**37.6**	**31.7**	**2.05**	**1.48**					
	WWS 2050	**8,880.6**	**17.5**	**10.5**	**50.5**	**17.9**	**1.84**	**1.84**	**-38.4**	**-11.3**	**-6.64**	**-56.4**	**1.85**

2018 BAU values are from IEA (2021). 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, as described in the text.

Table S5. 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.

Region	Total	Resi-dential	Com-mercial	Trans-port	Industrial	Agricul-ture-fores-try-fishing	Military-other
Africa	488.5	139.0	37.1	193.1	105.6	7.89	5.77
Australia	92.3	11.5	17.6	42.5	19.4	1.17	0.00
Canada	168.0	27.4	32.4	69.7	35.0	3.39	0.06
Central America	160.7	24.6	11.8	74.3	41.3	3.54	5.22
Central Asia	167.0	41.3	13.8	80.4	23.7	5.31	2.49
China	2,358.8	383.0	136.9	1446.7	277.1	28.13	86.96
Cuba	9.00	1.62	0.49	5.74	0.78	0.11	0.27
Europe	948.7	199.7	167.9	355.0	210.1	14.88	1.17
Haiti	7.80	1.71	0.76	3.09	2.08	0.17	0.00
Iceland	3.24	0.29	0.43	2.02	0.37	0.13	0.00
India	982.4	166.6	39.1	570.3	138.0	48.47	19.94
Israel	13.1	3.07	2.79	3.68	2.81	0.30	0.51
Jamaica	2.60	0.19	0.12	1.51	0.77	0.01	0.00
Japan	174.5	29.5	38.5	73.4	32.0	1.07	0.12
Mauritius	1.99	0.25	0.25	0.46	1.02	0.01	0.00
Mideast	708.1	117.0	68.7	375.8	123.7	13.06	9.79
New Zealand	17.0	2.13	2.47	8.42	3.29	0.59	0.08
Philippines	41.8	7.41	6.49	15.9	11.4	0.56	0.00
Russia	254.7	65.9	29.1	114.5	41.5	3.45	0.21
South America	467.9	61.3	43.2	246.5	100.6	12.82	3.56
Southeast Asia	591.7	69.3	46.7	310.4	158.3	5.21	1.80
South Korea	151.3	13.0	31.1	82.2	22.0	2.55	0.40
Taiwan	90.7	10.5	10.6	53.9	14.2	0.69	0.75
United States	979.0	179.4	190.3	352.8	221.7	10.06	24.73
Total 2050	8880.6	1555.7	928.5	4482.2	1587.0	163.52	163.84

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 S6. 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/yr and divided by 59.01 kWh/kg-H_2. Table S1 defines the regions.

Region	Total end-use load (GW)	Inflex-ible load (GW)	Flex-ible load (GW)	Cold load subject to storage (GW)	Low-temp-erature heat load subject to storage (GW)	Load for H_2 (GW)	All other loads sub-ject to DR	H_2 needed (Tg-H_2/yr)
Africa	488.5	232.6	255.8	9.4	30.6	45.2	170.6	6.71
Australia	92.3	47.1	45.1	0.5	2.9	8.0	33.8	1.18
Canada	168.0	84.6	83.4	0.6	9.7	10.9	62.2	1.62
Central America	160.7	72.8	87.9	1.7	5.3	17.9	63.0	2.66
Central Asia	167.0	88.4	78.6	0.2	7.6	9.7	61.1	1.45
China	2,359	1,076	1,283.	28.3	170.7	84.1	1,000	12.5
Cuba	9.00	4.39	4.61	0.25	0.40	0.29	3.66	0.04
Europe	948.7	419.4	529.3	11.1	128.3	74.1	315.9	11.00
Haiti	7.80	3.77	4.03	0.08	0.31	0.91	2.74	0.13
Iceland	3.24	1.18	2.06	0.04	0.55	0.14	1.33	0.02
India	982.4	456.9	525.5	11.5	42.1	56.4	415.6	8.37
Israel	13.1	6.77	6.37	0.27	0.73	1.24	4.13	0.18
Jamaica	2.60	1.12	1.48	0	0.03	0.33	1.12	0.05
Japan	174.5	95.3	79.3	0.3	7.1	11.2	60.6	1.67
Mauritius	1.99	0.66	1.33	0.07	0.08	0.45	0.73	0.07
Mideast	708.1	339.5	368.6	2.9	22.4	53.6	289.7	7.95
New Zealand	17.0	8.80	8.18	0.01	0.40	1.44	6.32	0.21
Philippines	41.8	18.0	23.8	1.7	2.8	4.9	14.4	0.72
Russia	254.7	103.4	151.3	3.2	41.5	14.0	92.7	2.08
South America	467.9	219.2	248.7	7.3	13.0	38.1	190.3	5.65
Southeast Asia	591.7	256.4	335.2	8.1	19.3	66.7	241.1	9.91
South Korea	151.3	79.8	71.5	0.4	6.8	9.3	55.0	1.38
Taiwan	90.7	43.3	47.4	0.6	4.2	5.8	36.9	0.86
United States	979.0	483.9	495.0	7.4	53.3	90.9	343.4	13.50
Total	**8,880.6**	**4142.9**	**4,738**	**95.6**	**570.1**	**605.6**	**3,467.**	**89.9**

Table S7. 2050 rooftop areas suitable for solar PV panels and the potential PV nameplate capacity fitting in the suitable rooftop areas, for 145 countries. Residential values include rooftops over associated residential parking areas. Commercial/government values include institutional buildings (e.g., schools) and industrial buildings. About 12.3% and 50.4% of potential residential and commercial/government rooftop areas, respectively, are proposed to be installed by 2050 based on the final nameplate capacities for all countries from Table S9. The methodology for determining suitable rooftop area is described in Jacobson et al. (2017) and summarized in the footnote below.

Country	Residential rooftop area suitable for PVs in 2050 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)	Commercial/govt. roof-top area suitable for PVs in 2050 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)	Country	Residential rooftop area suitable for PVs in 2050 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)	Commercial/govt. rooftop area suitable for PVs in 2050 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)
Albania	27	6,343	19	4,457	Kuwait	29	6,825	15	3,595
Algeria	722	172,657	410	98,090	Kyrgyzstan	79	18,874	32	7,772
Angola	786	188,041	294	70,253	Lao PDR	170	40,571	50	12,073
Argentina	635	151,995	445	106,496	Latvia	12	2,970	22	5,206
Armenia	29	6,928	17	4,072	Lebanon	23	5,485	12	2,888
Australia	953	227,927	574	137,246	Libya	212	50,624	120	28,693
Austria	81	19,396	65	15,613	Lithuania	21	5,046	39	9,261
Azerbaijan	146	34,978	91	21,679	Luxembourg	2	386	2	375
Bahrain	11	2,588	4	1,017	Macedonia, Nor.	21	5,117	14	3,273
Bangladesh	1,412	337,619	224	53,511	Malaysia	966	231,149	370	88,532
Belarus	37	8,783	63	15,031	Malta	2	412	1	175
Belgium	22	5,244	19	4,545	Mauritius	25	6,011	7	1,766
Benin	275	65,890	44	10,639	Mexico	2,080	497,569	1,053	251,800
Bolivia	277	66,317	110	26,413	Moldova	16	3,709	8	2,011
Bosnia & Herz.	41	9,825	26	6,317	Mongolia	52	12,527	49	11,822
Botswana	65	15,572	36	8,495	Montenegro	6	1,479	5	1,139
Brazil	3,877	927,203	1,725	412,470	Morocco	482	115,331	220	52,718
Brunei	20	4,707	8	1,851	Mozambique	726	173,711	111	26,507
Bulgaria	54	13,007	52	12,537	Myanmar	1,033	247,090	241	57,733
Cambodia	359	85,786	63	15,045	Namibia	47	11,325	24	5,631
Cameroon	513	122,761	119	28,555	Nepal	438	104,845	61	14,548
Canada	404	96,685	778	185,972	Netherlands	33	7,917	55	13,036
Chile	253	60,406	167	39,873	New Zealand	85	20,397	65	15,491
China	16,004	3,827,777	9,817	2,347,998	Nicaragua	113	26,912	34	8,235
Taiwan	308	73,776	134	31,964	Niger	843	201,591	72	17,248
Colombia	1,008	241,207	382	91,371	Nigeria	5,211	1,246,228	1,422	340,101
Congo	209	50,051	69	16,496	Norway	42	10,147	81	19,311
Congo, DR	2,162	517,040	268	64,009	Oman	112	26,680	63	14,990
Costa Rica	73	17,423	30	7,236	Pakistan	2,756	659,132	761	181,931
Côte d'Ivoire	549	131,276	118	28,309	Panama	116	27,814	46	11,082
Croatia	45	10,675	34	8,246	Paraguay	142	34,003	62	14,855
Cuba	149	35,693	71	17,064	Peru	718	171,662	287	68,628
Curacao	2	394	1	160	Philippines	2,230	533,393	577	137,913
Cyprus	30	7,223	10	2,377	Poland	205	49,026	355	84,886
Czech Republic	58	13,876	59	14,070	Portugal	139	33,321	70	16,657
Denmark	24	5,662	41	9,775	Qatar	17	4,108	8	1,899
Dominican Rep.	100	23,806	46	10,900	Romania	182	43,559	88	21,058
Ecuador	456	109,077	149	35,601	Russia	926	221,449	1,727	413,101
Egypt	2,053	490,921	742	177,350	Saudi Arabia	1,142	273,130	634	151,583
El Salvador	59	14,194	22	5,146	Senegal	329	78,709	63	15,154
Equatorial Guinea	46	11,034	18	4,393	Serbia	62	14,833	61	14,699
Eritrea	154	36,809	16	3,882	Singapore	29	6,964	6	1,540
Estonia	6	1,413	11	2,657	Slovak Republic	42	10,152	39	9,366
Ethiopia	3,872	926,148	295	70,628	Slovenia	17	4,034	19	4,444
Finland	30	7,099	74	17,640	South Africa	701	167,704	365	87,271

France	535	128,062	466	111,490	South Sudan	498	119,201	58	13,804
Gabon	98	23,374	41	9,925	Spain	554	132,424	250	59,716
Georgia	40	9,475	26	6,296	Sri Lanka	585	139,820	122	29,109
Germany	454	108,574	493	117,809	Sudan	1,584	378,955	368	88,066
Ghana	535	127,961	131	31,387	Suriname	24	5,771	10	2,402
Gibraltar	0	14	0	6	Sweden	48	11,411	87	20,764
Greece	84	20,106	72	17,291	Switzerland	83	19,948	71	16,895
Guatemala	309	73,974	93	22,318	Syria	311	74,455	149	35,642
Haiti	94	22,573	15	3,620	Tajikistan	116	27,860	35	8,298
Honduras	163	38,890	49	11,631	Tanzania	1,085	259,622	187	44,778
Hong Kong	14	3,433	5	1,215	Thailand	1,410	337,161	518	123,983
Hungary	72	17,229	72	17,134	Togo	194	46,516	21	5,089
Iceland	3	777	6	1,499	Trinidad & Tob.	27	6,554	9	2,113
India	20,075	4,801,528	5,526	1,321,635	Tunisia	134	32,043	73	17,506
Indonesia	6,264	1,498,214	2,015	481,900	Turkey	948	226,706	656	156,988
Iran	1,279	305,786	773	184,810	Turkmenistan	129	30,875	85	20,346
Iraq	682	163,129	385	92,192	Ukraine	232	55,602	204	48,719
Ireland	48	11,458	54	12,963	United Arab Em	123	29,531	65	15,503
Israel	78	18,770	36	8,556	United Kingdom	192	45,934	324	77,400
Italy	703	168,258	254	60,670	United States	8,087	1,934,268	5,509	1,317,664
Jamaica	43	10,326	14	3,294	Uruguay	40	9,650	25	5,934
Japan	757	181,054	425	101,686	Uzbekistan	339	81,160	175	41,924
Jordan	74	17,612	40	9,654	Venezuela	697	166,684	273	65,343
Kazakhstan	419	100,138	385	92,186	Vietnam	1,397	334,072	353	84,501
Kenya	1,265	302,450	207	49,611	Yemen	674	161,297	168	40,098
Korea, DPR	148	35,334	45	10,874	Zambia	602	143,994	152	36,250
Korea, Rep. of	481	114,932	265	63,459	Zimbabwe	346	82,865	49	11,788
Kosovo	13	3,084	8	1,909	**All Countries**	**116,225**	**27,798,049**	**49,073**	**11,737,091**

Rooftops considered include those over residential buildings (excluding parking), residential parking, commercial/government/institutional buildings (including parking), and industrial buildings (including parking). Residential rooftops and residential parking rooftop areas are then combined into residential rooftop values reported here and commercial/government/institutional building rooftops and industrial building rooftops are combined into commercial/government values reported here.

The total rooftop area for each type of building is the product of the floor area per capita, the population, an overhang multiplier, and a pitch (slope) multiplier, divided by the average number of stories (Jacobson et al., 2017). The floor area per capita depends on the fraction of the country's population that is urban versus rural and some other factors. The potential rooftop or canopy area over residential parking spaces in each country is computed as a function of the number of passenger cars per person, the number of parking spaces per car, the average parking space area per car, the percentage of parking spaces that are covered, and the percentage of covered spaces with exposed roof (Jacobson et al., 2017).

The rooftop area suitable for PV is the fraction of roof area that is south facing (in the Northern Hemisphere) or flat and non-shaded. The fraction is calculated as a function of the following parameters in each country: average building height (the greater the average height, the greater the variation in height, and the more likely buildings shade one-another); average rooftop area (the greater the area, the more likely some significant portion of the area is unshaded); the percentage of rooftop area that is flat (the entire area of a flat roof is often suitable for PV); and the average slope of pitched roofs (the steeper the roof, the less suitable it is for PVs if it is pitched away from the sun) (Jacobson et al., 2017).

The potential nameplate capacity of PV is the suitable area multiplied by a maximum possible installed power density of PV in 2050, estimate at 239 W/m^2.

Table S8. 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	Resi-dential roof PV	Com /gov roof PV	Utility PV	CSP with storage	Geo-ther-mal elec-tricity	Hydro	Tidal	Wave	Solar heat	Geoth ermal 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 S9. 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 S11) gives the simulation-averaged power output from the generator in the region (Table S12).

Region or country	On-shore wind	Off-shore wind	Res-ident-ial roof PV	Com /gov roof PV	Util-ity PV	CSP with stor-age	Geo-ther-mal elec-tricity	Hydro	Wav e	Tidal	Solar ther-mal	Geo-ther-mal heat
Africa	**489.9**	**154.1**	**357.62**	**641.51**	**549.57**	**28.17**	**3.61**	**31.52**	**3.604**	**0.839**	**2.654**	**0.194**
Algeria	33.52	5.26	30.74	70.79	59.61	2.48	0	0.269	0.347	0.020	0	0.078
Angola	19.73	3.91	3.28	7.16	2.53	0.35	0	3.836	0.053	0.027	0	0
Benin	5.77	1.72	3.07	4.25	3.51	0.25	0	0.033	0.058	0.005	0	0
Botswana	2.51	0.00	1.20	2.71	2.77	0.12	0	0	0	0	0.009	0
Cameroon	12.60	0.58	2.52	5.50	4.82	0.27	0	0.822	0.065	0.011	0	0
Congo	4.54	1.26	0.97	2.15	1.13	0	0	0.218	0.026	0.006	0	0
Congo, DR	25.84	0.83	5.07	11.15	10.83	0.54	0	2.760	0.093	0.002	0	0
Côte d'Ivoire	14.95	2.31	2.87	6.27	3.28	0.31	0	0.879	0.081	0.013	0	0
Egypt	62.57	37.16	51.41	117.74	59.33	4.51	0	2.876	0	0.036	0	0.044
Equator. Guinea	1.34	4.39	7.57	3.40	10.55	0.35	0	0.128	0.083	0.009	0	0
Eritrea	0.31	0.10	0.19	0.42	0.21	0.02	0	0	0	0.008	0	0
Ethiopia	19.72	0.00	9.73	21.20	21.96	1.00	1.71	4.074	0	0	0	0.002
Gabon	12.96	10.41	7.70	8.03	8.94	0	0	0.331	0.135	0.018	0	0
Ghana	11.87	4.49	7.43	15.95	8.47	0.62	0	1.584	0.144	0.013	0.002	0
Kenya	17.37	3.51	4.81	10.67	5.60	0.55	1.81	0.837	0.154	0.013	0	0.019
Libya	12.87	8.14	11.47	23.97	12.51	0.93	0	0	0	0.029	0	0
Morocco	14.27	7.30	12.69	29.29	14.68	1.11	0	1.305	0.147	0.030	0.316	0.005
Mozambique	7.97	1.43	2.20	4.89	2.53	0.26	0	2.216	0.032	0.125	0.002	0
Namibia	2.89	0.70	1.23	2.78	1.42	0.14	0	0.347	0.015	0.027	0.032	0
Niger	2.09	0	1.28	2.82	2.92	0.12	0	0	0	0	0	0
Nigeria	45.09	0	67.76	147.71	154.54	4.98	0	2.111	1.235	0.018	0.003	0.001
Senegal	3.22	0.94	1.66	3.64	1.90	0.17	0	0.081	0.042	0.013	0.003	0
South Africa	88.88	47.49	86.51	72.38	100.01	6.06	0	0.684	0.674	0.039	1.521	0.002
South Sudan	0.33	0	0.25	0.55	0.57	0.02	0	0	0	0	0	0
Sudan	9.60	3.82	7.41	16.31	8.48	0.66	0	1.923	0	0.018	0	0
Tanzania	17.06	5.31	7.86	17.20	8.96	0.70	0	0.596	0.194	0.333	0	0
Togo	2.84	0.71	1.30	1.65	1.48	0.10	0	0.049	0.024	0.003	0	0
Tunisia	7.31	2.34	8.80	14.44	16.27	0.63	0	0.066	0	0.022	0.724	0.044
Zambia	20.39	0	4.85	10.63	11.09	0.57	0.09	2.400	0	0	0	0
Zimbabwe	9.49	0	3.78	5.90	8.67	0.36	0	1.091	0	0	0.042	0
Australia	**80.30**	**19.21**	**38.04**	**65.16**	**257.68**	**4.86**	**0.40**	**7.450**	**0.576**	**0.500**	**6.451**	**0.094**
Canada	**173.6**	**36.29**	**14.01**	**103.44**	**41.70**	**0**	**5.00**	**81.82**	**0.926**	**2.000**	**0.637**	**1.831**
Central America	**428.0**	**95.83**	**52.50**	**118.26**	**258.82**	**8.29**	**10.69**	**19.86**	**2.461**	**0.337**	**3.027**	**0.166**
Costa Rica	8.31	1.85	0.63	1.38	3.10	0.11	1.19	2.331	0.031	0.024	0	0.002
El Salvador	5.75	0.68	0.46	1.02	2.28	0.08	1.02	0.575	0.022	0.009	0	0.003
Guatemala	16.87	1.89	1.15	2.53	5.63	0.20	2.26	1.559	0.054	0.011	0	0.002
Honduras	14.29	1.53	1.01	2.22	4.95	0.17	0.59	0.837	0.046	0.018	0	0.002
Mexico	346.0	83.47	46.92	106.05	231.51	7.35	5.18	12.61	2.195	0.100	3.027	0.156
Nicaragua	7.11	0.91	0.49	1.07	2.39	0.08	0.45	0.157	0.022	0.019	0	0
Panama	29.74	5.50	1.84	4.00	8.97	0.31	0	1.786	0.092	0.157	0	0
Central Asia	**193.2**	**21.23**	**118.50**	**161.50**	**239.79**	**8.01**	**0**	**24.96**	**1.669**	**0.021**	**0**	**0.003**
Kazakhstan	50.77	0	15.38	39.81	37.11	0	0	2.730	0	0	0	0
Kyrgyz Republic	3.91	0	0.93	2.32	2.52	0.13	0	3.892	0	0	0	0
Pakistan	91.85	21.23	89.09	86.92	166.09	6.19	0	9.929	1.669	0.021	0	0
Tajikistan	1.46	0	0.36	0.89	0.98	0.05	0	6.395	0	0	0	0.003
Turkmenistan	14.32	0	4.04	9.88	10.46	0.52	0	0.005	0	0	0	0
Uzbekistan	30.88	0	8.69	21.67	22.63	1.12	0	2.005	0	0	0	0
China Region	**2,100**	**735.4**	**1,016.**	**989.79**	**4,296**	**128.30**	**1.86**	**343.70**	**8.711**	**2.174**	**337.6**	**40.63**
China	2,082	640.7	1,011.	983.84	4,245	128.19	1.86	338.7	8.375	2.000	337.6	40.61

Hong Kong	0.14	93.03	0.93	0.43	35.56	0	0	0	0.336	0.016	0	0
Korea, DPR	10.16	1.73	2.18	2.32	7.58	0.11	0	5.010	0	0.157	0	0
Mongolia	7.08	0	1.24	3.20	7.96	0	0	0.023	0	0	0	0.023
Cuba	**17.61**	**4.82**	**4.76**	**14.94**	**19.15**	**0.48**	**0**	**0.068**	**0.051**	**0.047**	**0**	**0**
Europe	**1,174**	**450.0**	**337.79**	**500.75**	**1,109.**	**16.17**	**3.19**	**166.3**	**4.816**	**5.570**	**39.17**	**31.64**
Albania	1.72	0.49	0.52	1.71	0.87	0.08	0	2.390	0	0.010	0.181	0.016
Austria	30.07	0	8.05	10.84	26.80	0	0	9.001	0	0	3.583	1.096
Belarus	17.29	0	4.00	5.94	33.71	0	0.01	0.097	0	0	0	0.010
Belgium	10.33	15.66	2.05	2.88	108.62	0	0	0.120	0	0.003	0.483	0.306
Bosnia-Herzeg.	3.10	0.45	1.23	4.14	3.22	0.05	0	2.093	0	0.002	0	0.036
Bulgaria	13.00	8.26	4.27	8.78	7.19	0	0	1.725	0	0.010	0.100	0.109
Croatia	3.37	0.00	3.77	5.57	12.66	0.22	0.01	1.848	0	0.066	0.161	0.079
Cyprus	0.66	1.49	1.10	1.63	1.86	0.09	0	0	0.028	0.015	0.551	0.010
Czech Rep.	22.62	0	6.24	9.64	42.83	0	0	1.097	0	0	0.781	0.325
Denmark	15.80	5.30	2.58	2.22	12.58	0	0	0.009	0.154	0.073	1.175	0.744
Estonia	3.32	1.73	0.67	0.84	2.84	0	0	0.008	0	0.048	0.012	0.063
Finland	44.15	12.21	3.34	2.63	26.64	0	0	3.263	0	0.023	0.048	2.300
France	125.5	44.99	56.85	76.37	98.84	4.48	0.04	19.67	0.807	1.000	1.951	2.598
Germany	231.5	72.21	49.11	80.75	164.39	0	0.04	4.658	1.129	0.035	13.88	4.806
Gibraltar	0.00	8.44	0.00	0.00	0.15	0	0	0	0.018	0.001	0	0
Greece	22.13	4.09	3.75	11.85	6.35	0.65	0.45	2.697	0.187	0.109	3.299	0.260
Hungary	8.35	0	7.82	10.57	38.74	0	0.38	0.056	0	0	0.229	1.024
Ireland	13.11	3.64	4.98	2.02	9.31	0	0	0.237	0.051	0.025	0.233	0.201
Italy	126.5	35.50	39.09	40.57	60.24	4.71	1.00	14.91	1.207	0.075	3.305	1.425
Kosovo	1.42	0	0.28	0.94	0.92	0.02	0.80	0.092	0	0	0	0
Latvia	4.99	1.31	1.40	1.45	2.25	0	0	1.576	0	0.013	0.011	0.002
Lithuania	7.83	2.87	2.41	3.69	4.89	0	0	0.116	0	0.004	0.013	0.126
Luxembourg	0.70	0	0.15	0.24	12.43	0	0	0.034	0	0	0.046	0.000
Macedonia	1.53	0	1.01	2.44	3.41	0	0	0.674	0	0	0.068	0.047
Malta	0.14	4.34	0.16	0.11	3.47	0.09	0	0	0.027	0.008	0.051	0
Moldova	3.70	0	1.44	0.98	4.82	0	0	0.076	0	0	0	0
Montenegro	0.83	0.20	0.23	0.76	0.37	0.01	0	0.658	0	0.009	0	0
Netherlands	17.53	40.56	3.14	3.90	97.13	0	0	0.038	0	0.012	0.460	1.719
Norway	9.44	2.54	3.97	1.39	6.32	0	0	31.56	0.046	0.158	0.031	1.150
Poland	68.54	18.89	22.17	59.49	36.23	0	0.11	0.605	0	0.012	1.791	0.756
Portugal	18.91	3.47	4.25	11.41	7.22	0.70	0.10	4.373	0.097	0.326	0.770	0.021
Romania	27.43	6.22	7.67	12.24	12.46	0	0.10	6.221	0	0.008	0.143	0.245
Serbia	5.30	0	5.50	10.25	18.16	0	0	2.484	0	0	0.000	0.115
Slovakia	11.91	0	3.65	4.78	11.97	0	0	1.505	0	0	0.121	0.230
Slovenia	5.97	1.04	1.36	2.89	2.68	0	0.10	1.344	0	0.003	0.104	0.266
Spain	110.4	22.10	28.59	40.20	47.49	5.07	0.05	14.29	0.467	1.000	3.018	0.544
Sweden	44.70	12.08	5.31	4.12	28.10	0	0	16.38	0	0.100	0.374	6.680
Switzerland	16.58	0.00	3.30	11.34	11.01	0	0	13.85	0	0	1.186	2.197
Ukraine	58.05	16.90	23.10	24.42	36.19	0	0	4.666	0	0.039	0	1.607
United Kingdom	65.87	103.1	19.26	24.75	103.67	0	0	1.879	0.598	2.385	1.010	0.525
Haiti Region	**5.31**	**2.74**	**2.26**	**9.35**	**18.19**	**0.39**	**0.68**	**0.676**	**0**	**0.052**	**0**	**0**
Dominican Rep.	4.38	2.05	1.68	7.48	13.53	0.31	0.68	0.616	0	0.024	0	0
Haiti	0.93	0.69	0.58	1.87	4.66	0.08	0	0.060	0	0.029	0	0
Iceland	**1.54**	**0.00**	**0.00**	**0.00**	**0.00**	**0**	**0.89**	**2.086**	**0.010**	**0.038**	**0**	**2.373**
India Region	**651.2**	**108.2**	**86.51**	**1,361.**	**2,158.**	**90.58**	**0.28**	**49.08**	**4.945**	**0.874**	**9.457**	**0.361**
Bangladesh	5.35	7.85	5.45	30.08	167.69	4.14	0	0.230	0.593	0.150	0	0
India	629.7	96.97	79.10	1,305.	1,938	84.30	0.28	45.76	4.172	0.700	9.457	0.358
Nepal	5.71	0	1.27	6.45	40.47	1.11	0	1.278	0	0	0	0.004
Sri Lanka	10.44	3.34	0.69	19.52	11.78	1.04	0	1.809	0.179	0.024	0	0
Israel	**3.34**	**5.42**	**1.15**	**14.32**	**61.65**	**0.64**	**0**	**0.007**	**0**	**0.009**	**3.351**	**0.082**
Jamaica	**0.38**	**3.30**	**2.74**	**2.67**	**3.50**	**0.16**	**0**	**0.030**	**0**	**0.020**	**0**	**0**
Japan	**10.81**	**274.3**	**22.27**	**14.99**	**441.06**	**0.00**	**1.46**	**22.38**	**2.487**	**2.200**	**2.580**	**2.571**
Mauritius	**0.16**	**3.73**	**0.46**	**0.26**	**3.15**	**0.04**	**0**	**0.061**	**0.013**	**0.007**	**0.093**	**0**
Mideast	**707.7**	**139.9**	**331.6**	**356.13**	**1,674.**	**36.86**	**1.74**	**48.85**	0.436	0.284	**19.06**	**3.775**
Armenia	2.29	0	0.40	0.99	1.52	0.06	0.03	1.293	0	0	0	0.002
Azerbaijan	9.18	0	3.25	8.04	12.44	0.13	0	1.131	0	0	0	0
Bahrain	0.21	2.90	1.11	0.54	36.66	0.47	0	0	0	0.006	0	0

Iran	241.1	44.01	122.63	112.38	287.48	10.03	0.01	11.13	0	0.036	0	0.082
Iraq	39.39	1.05	12.98	30.74	48.73	1.52	0	2.513	0	0.003	0	0
Jordan	9.35	0.47	3.51	5.89	12.94	0.36	0	0.012	0	0.002	0.882	0.153
Kuwait	1.34	9.00	3.17	1.99	99.55	1.28	0	0	0	0.013	0	0
Lebanon	0.92	4.06	3.03	1.75	16.83	0.33	0	0.282	0	0.008	0.583	0
Oman	23.26	9.25	13.75	8.72	51.41	1.34	0	0	0.404	0.032	0	0
Qatar	0.87	10.16	1.85	1.04	129.93	1.57	0	0	0	0.014	0	0
Saudi Arabia	186.9	29.09	116.03	89.55	408.99	9.37	0	0	0	0.038	0	0.045
Syria	8.45	2.14	2.75	6.58	5.29	0.32	0	1.505	0	0.007	0	0
Turkey	142.4	3.58	31.25	76.64	107.78	4.22	1.61	30.98	0	0.072	17.60	3.488
UAE	40.03	23.77	14.80	8.93	451.20	5.76	0	0	0	0.024	0	0
Yemen	1.87	0.39	1.08	2.37	2.88	0.11	0.10	0	0.032	0.030	0	0.005
New Zealand	**21.47**	**1.68**	**5.11**	**6.97**	**16.26**	**0.59**	**2.00**	**5.354**	**0.079**	**0.200**	**0.112**	**0.518**
Philippines	**23.93**	**20.80**	**15.56**	**55.72**	**129.27**	**1.64**	**5.73**	**3.700**	**0.576**	**0.500**	**0**	**0.002**
Russia Region	**487.0**	**50.24**	**55.49**	**74.18**	**143.96**	**0**	**0.50**	**51.976**	**1.936**	**0.359**	**0.018**	**0.502**
Georgia	3.96	0.32	0.36	0.91	0.95	0	0	3.449	0	0.009	0	0.069
Russia	483.0	49.92	55.12	73.26	143.00	0	0.50	48.527	1.936	0.350	0.018	0.433
South America	**1,155**	**101.0**	**122.59**	**260.13**	**321.84**	**23.12**	**5.35**	**175.63**	**4.809**	**1.198**	**11.59**	**0.621**
Argentina	66.49	9.14	11.81	28.53	29.57	2.35	1.01	10.366	0	0.057	0.031	0.205
Bolivia	9.34	0	1.08	2.38	5.28	0.21	1.26	0.735	0	0	0	0.001
Brazil	752.7	59.34	71.33	156.65	174.14	13.03	0	109.24	3.511	0.200	11.26	0.363
Chile	32.79	7.88	11.23	18.35	24.91	2.52	1.63	6.945	0.187	0.100	0.248	0.023
Colombia	84.52	7.07	7.92	17.39	19.43	1.44	0	11.941	0.339	0.500	0	0.020
Curacao	0.18	2.76	0.17	0.07	4.16	0.08	0	0.000	0	0.010	0	0
Ecuador	30.72	1.24	2.13	4.71	8.77	0.42	0.04	5.076	0.056	0.221	0	0.005
Paraguay	4.23	0	0.43	0.96	2.09	0.08	0	8.810	0	0	0	0
Peru	57.75	0.01	4.19	9.13	20.36	0.83	1.41	5.396	0.120	0.035	0	0.003
Suriname	1.01	0.14	0.15	0.32	0.36	0.02	0	0.190	0.006	0.011	0	0
Trinidad/Tobago	0.27	4.71	2.81	0.97	9.87	0.26	0	0	0.074	0.010	0	0
Uruguay	8.10	0.85	1.18	2.77	2.90	0.23	0	1.538	0.069	0.015	0.053	0
Venezuela	106.6	7.85	8.18	17.90	19.99	1.63	0	15.39	0.447	0.039	0	0.001
Southeast Asia	**54.35**	**1,459**	**496.06**	**582.09**	**1,743.**	**28.92**	**13.76**	**45.06**	**4.415**	**0.635**	**0.110**	**0.154**
Brunei	0.05	4.04	1.71	1.44	5.40	0.09	0	0	0.024	0.006	0	0
Cambodia	1.57	6.96	4.74	10.36	14.87	0.41	0	1.330	0	0.012	0	0
Indonesia	39.25	239.6	143.14	316.00	455.50	11.15	9.79	6.121	1.510	0.269	0	0.002
Lao PDR	0.01	0	0.01	0.02	0.05	0.00	0	7.376	0	0	0	0
Malaysia	2.84	210.8	94.47	67.49	328.97	4.66	0	6.275	1.163	0.054	0	0.005
Myanmar	5.75	10.90	8.40	18.67	26.52	0.98	0	3.331	0.269	0.200	0	0
Singapore	0.02	684.4	3.44	0.97	49.85	0	3.85	0	0	0.007	0	0
Thailand	4.42	145.2	133.57	99.14	526.46	6.64	0.12	3.513	0	0.043	0.110	0.129
Vietnam	0.43	157.0	106.60	68.00	335.68	4.99	0	17.11	1.449	0.045	0	0.018
South Korea	**2.14**	**365.1**	**67.56**	**162.82**	**353.77**	**8.89**	**0**	**1.806**	**0**	**1.000**	**1.324**	**1.490**
Taiwan	**3.73**	**104.9**	**34.06**	**60.46**	**119.82**	**0**	**33.64**	**2.092**	**0.914**	**0.027**	**1.220**	**.0001**
United States	**1,645**	**263.6**	**239.15**	**355.17**	**2,286.**	**33.55**	**6.52**	**79.15**	**6.895**	**0.350**	**17.94**	**20.71**
All regions	**9,430**	**4,421**	**3,422**	**5,912**	**16,244**	**419.7**	**97.3**	**1,164**	**50.3**	**19.2**	**456.4**	**107.7**

Table S10. 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 our 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	1.6	0.9	0.85	0.85	1	1	0
China	1.4	0.7	0.55	0.55	1.7	1	1
Cuba	1.9	1.3	1	1.4	3.5	1	0
Europe	1.4	1	0.68	0.9	1	1	1
Haiti	0.8	0.9	0.5	1	3.5	1	0
Iceland	0.44	0.03	0	0	0	0	0
India	0.9	0.6	0.1	1.3	1.5	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	0
Japan	0.2	2	0.2	0.2	1.7	0	1
Mauritius	1.6	2.5	0.2	0.2	1.2	0.4	1
Mideast	2.1	0.8	0.75	0.75	1.25	1	1
New Zealand	1.49	0.4	0.6	0.6	1.65	0.7	1
Philippines	1.9	0.9	0.55	0.9	4	0.8	0
Russia	1.8	0.6	0.35	0.35	0.8	0	1
South America	1.25	0.72	0.6	0.6	1.28	1	1
Southeast Asia	0.2	2	1	1	2.75	1	1
South Korea	0.1	2	0.9	3.4	1.2	1	1
Taiwan	0.5	1.8	0.7	2.5	1.21	0	1
United States	1.7	0.65	0.45	0.45	2.4	1	1

All generators not on this list have a CAF=1. Table S9 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 S11. 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 S12 divided by the final nameplate capacity of each generator in each region from Table S9.

Region	Onshore wind	Off-shore wind	Rooftop PV	Utility PV	CSP with storage	Geo-thermal elec-tricity	Hydr opow er	Wave	Tidal	Solar therm al	Geo-thermal 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	0.477	0.332	0.247	0.109	0.54
Canada	0.501	0.587	0.177	0.18	--	0.862	0.583	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	--	0.43	0.121	0.216	--	0.54
China	0.471	0.372	0.2	0.221	0.73	0.896	0.489	0.139	0.243	0.109	0.54
Cuba	0.423	0.306	0.166	0.178	0.7	--	0.449	0.379	0.232	--	--
Europe	0.444	0.513	0.171	0.176	0.67	0.861	0.467	0.203	0.237	0.093	0.54
Haiti	0.321	0.428	0.213	0.232	0.79	0.876	0.455	--	0.216	--	--
Iceland	0.573	0.625	--	--	--	0.925	0.611	0.313	0.253	--	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	--	0.484	--	0.252	0.132	0.54
Jamaica	0.344	0.388	0.213	0.23	0.79	--	0.408	--	0.208	--	--
Japan	0.388	0.449	0.177	0.20	--	0.909	0.479	0.141	0.248	0.097	0.54
Mauritius	0.437	0.408	0.204	0.222	0.75	--	0.483	0.317	0.251	0.113	--
Mideast	0.49	0.492	0.221	0.251	0.86	0.798	0.429	0.135	0.233	0.113	0.54
New Zealand	0.506	0.563	0.177	0.197	0.65	0.885	0.469	0.352	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	--	0.54
Russia	0.478	0.579	0.173	0.197	--	0.863	0.473	0.256	0.236	0.095	0.54
South America	0.177	0.362	0.189	0.207	0.72	0.883	0.612	0.15	0.239	0.11	0.54
Southeast Asia	0.124	0.217	0.199	0.214	0.73	0.879	0.446	0.178	0.226	0.116	0.54
South Korea	0.366	0.352	0.179	0.193	0.63	--	0.485	--	0.251	0.097	0.54
Taiwan	0.266	0.345	0.182	0.196	--	0.927	0.489	0.144	0.255	0.10	0.54
United States	0.379	0.294	0.197	0.207	0.86	0.891	0.47	0.294	0.244	0.104	0.54
Average	**0.401**	**0.343**	**0.196**	**0.218**	**0.77**	**0.887**	**0.499**	**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 S15 and S16. T&D loss rates are given in Table S17. 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 S12. 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/yr) 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 S11) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table S9). The 2050 total WWS supply is also obtained from Column (f) of Table S15.

Region	Annual average total WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with stor-age (%)	Geoth ermal elec-tricity (%)	Hydro power (%)	Wave (%)	Tidal (%)	Solar ther-mal heat (%)	Geo-ther-mal heat (%)
Africa	611.1	29.92	11.18	32.94	19.53	3.50	0.48	2.25	0.103	0.031	0.048	0.017
Australia	123.3	21.96	6.66	16.48	47.77	3.10	0.29	2.89	0.155	0.100	0.568	0.041
Canada	190.5	45.70	11.18	10.94	3.93	--	2.26	25.05	0.144	0.247	0.032	0.520
Central America	271.5	46.26	10.79	12.52	21.10	2.50	3.31	3.21	0.115	0.029	0.134	0.033
Central Asia	245.1	42.44	4.40	22.87	23.16	2.67	--	4.38	0.083	0.002	--	0.001
China	2,936	33.68	9.31	13.63	32.35	3.20	0.06	5.72	0.041	0.018	1.258	0.748
Cuba	16.0	46.57	9.22	20.42	21.30	2.12	--	0.19	0.121	0.068	--	--
Europe	1,206	43.28	19.15	11.90	16.20	0.89	0.23	6.45	0.081	0.110	0.304	1.418
Haiti	10.8	15.78	10.89	22.96	39.04	2.86	5.52	2.85	--	0.105	--	--
Iceland	4.3	20.65	0.04	--	--	--	19.25	29.79	0.073	0.225	--	29.98
India	1,211	24.42	3.68	23.55	40.49	5.86	0.02	1.82	0.054	0.017	0.086	0.016
Israel	24.2	6.48	8.16	15.11	65.86	2.35	--	0.014	--	0.009	1.821	0.181
Jamaica	3.5	3.73	36.43	32.84	22.93	3.60	--	0.35	--	0.120	--	--
Japan	237.0	1.77	52.00	2.79	37.28	--	0.56	4.53	0.148	0.231	0.106	0.586
Mauritius	2.5	2.78	60.54	5.83	27.77	1.26	--	1.17	0.168	0.064	0.419	--
Mideast	1,045	33.18	6.58	14.55	40.10	3.04	0.13	2.01	0.006	0.006	0.205	0.195
New Zealand	22.2	49.00	4.27	9.64	14.45	1.71	7.98	11.31	0.125	0.218	0.049	1.262
Philippines	64.3	8.97	9.68	22.82	45.93	2.04	7.65	2.61	0.119	0.182	--	0.001
Russia	338.3	68.76	8.60	6.62	8.37	--	0.13	7.28	0.146	0.025	0.001	0.080
South America	511.1	39.94	7.15	14.18	13.03	3.25	0.93	21.02	0.141	0.056	0.250	0.066
Southeast Asia	966.6	0.70	32.80	22.20	38.69	2.18	1.25	2.08	0.081	0.015	0.001	0.009
South Korea	246.4	0.32	52.15	16.71	27.73	2.25	--	0.36	--	0.102	0.052	0.327
Taiwan	110.4	0.90	32.77	15.61	21.31	--	28.24	0.93	0.119	0.006	0.111	0.000
United States	1,379	45.18	5.62	8.50	34.40	2.08	0.42	2.70	0.147	0.006	0.135	0.812
All regions	11,776	32.10	12.89	15.56	30.02	2.73	0.73	4.93	0.078	0.039	0.419	0.494

Table S13. 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 S14 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 dis-charge rate GW	Max stor-age capac-ity TWh	Max charge rate GW	Max dis-charge rate GW	Max stor-age capac-ity TWh	Max charge rate GW	Max dis-charge rate GW	Max stor-age capac-ity TWh	Max charge rate GW	Max dis-charge rate GW	Max stor-age capac-ity 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.	28.2	28.2	--	4.86	4.86	--	0	0	--	8.29	8.29	--
CSP-PCM	45.4	--	0.6	7.84	--	0.110	0	--	0	13.36	--	0.187
Batteries	750	750	3.00	250	250	1.00	100	100	0.400	1,100	1,100	4.40
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	3.77	3.77	0.053	0.208	0.208	0.0029	0.237	0.237	0.0033	0.668	0.668	0.0094
ICE	5.66	5.66	0.079	0.312	0.312	0.0044	0.355	0.355	0.0050	1.00	1.00	0.0140
HW-STES	143.9	143.9	1.15	9.17	9.17	0.073	24.17	24.17	0.338	27.66	27.66	0.221
UTES-heat	2.85	143.92	103.6	6.55	9.17	0.880	2.47	24.17	5.801	3.19	27.66	0.664
UTES-elec.	143.9	----	--	9.17	--	--	24.17	--	--	27.66	--	--
	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.	8.01	8.01	--	128.3	128.3	--	0.482	0.482	--	16.17	16.17	--
CSP-PCM	12.92	--	0.181	206.9	--	2.896	0.777	--	0.011	26.08	--	0.365
Batteries	730	730	2.92	2,600	2,600	10.40	100	100	0.400	1,200	1,200	4.80
Hydropower	10.44	24.96	91.4	158.0	343.7	1384.0	0.030	0.068	0.260	75.36	166.3	660.2
CW-STES	0.066	0.066	0.0009	11.30	11.30	0.1583	0.101	0.101	0.0014	4.44	4.44	0.0621
ICE	0.098	0.098	0.0014	16.96	16.96	0.2374	0.152	0.152	0.0021	6.65	6.65	0.0931
HW-STES	27.02	27.02	0.216	553.9	553.9	2.770	1.67	1.67	0.013	309.7	309.7	1.858
UTES-heat	0.0029	27.02	12.969	378.2	553.9	358.9	0.00	1.67	2.004	70.80	309.7	74.332
UTES-elec.	27.02	----	--	553.9	--	--	1.67	--	--	309.7	--	--
	Haiti			Iceland			India			Israel		
PHS	2.00	2.00	0.028	0	0	0	28.8	28.8	0.403	11.1	11.1	0.155
CSP-elec.	0.389	0.389	--	0	0	--	90.58	90.58	--	0.643	0.643	--
CSP-PCM	0.63	--	0.009	0	--	0	146.1	--	2.045	1.04	--	0.015
Batteries	25	25	0.100	0	0	0	4,600	4,600	18.40	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	4.58	4.58	0.0641	0.109	0.109	0.0015
ICE	0.049	0.049	.00069	0.027	0.027	.00037	6.87	6.87	0.0962	0.164	0.164	0.0023
HW-STES	0	0	0	1.05	1.05	0.0084	326.1	326.1	2.608	2.95	2.95	0.024
UTES-heat	0	3.97	0.095	0	0	0	9.82	326.1	70.43	3.43	2.95	1.063
UTES-elec.	3.97	--	--	0	--	--	326.1	--	--	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.	0.160	0.160	--	0	0	--	0.042	0.042	--	36.86	36.86	--
CSP-PCM	0.258	--	0.0036	0	--	0	0.068	--	0.0010	59.44	--	0.832
Batteries	6	6	0.0240	480	480	1.92	3	3	0.0100	2,300	2,300	9.20
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	0.133	0.133	0.0019	0.028	0.028	.00039	1.15	1.15	0.0161
ICE	0	0	0	0.200	0.200	0.0028	0.042	0.042	.00059	1.73	1.73	0.0242
HW-STES	0.92	0.92	0.0074	21.31	21.31	0.170	0.101	0.101	0.0008	72.40	72.40	0.579
UTES-heat	0	0.92	0.0665	5.15	21.31	2.557	0.093	0.101	0.0604	22.84	72.40	17.375
UTES-elec.	0.28	--	--	21.31	--	--	0.101	--	--	217.2	--	--
	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.	0.59	0.59	--	1.64	1.64	--	0	0	--	23.12	23.12	--
CSP-PCM	0.94	--	0.013	2.64	--	0.037	0	--	0	37.28	--	0.522

Batteries	130	130	0.520	190	190	0.760	15	15	0.060	10	10	0.040
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	1.27	1.27	0.0178	2.91	2.91	0.0408
ICE	0.01	0.01	0.0001	1.02	1.02	0.0142	1.91	1.91	0.0267	4.37	4.37	0.0611
HW-STES	1.07	1.07	0.009	26.50	26.50	0.212	99.22	99.22	0.992	61.69	61.69	0.493
UTES-heat	0.63	1.07	0.257	0.00	26.50	9.541	0.52	99.22	11.91	12.21	61.69	44.415
UTES-elec.	1.07	--	--	5.30	--	--	99.22	--	--	61.69	--	--
	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.	28.92	28.92	--	8.89	8.89	--	0	0	--	33.55	33.55	--
CSP-PCM	46.63	--	0.653	14.33	--	0.201	0	--	0	54.09	--	0.757
Batteries	950	950	3.80	1,390	1,390	5.56	1,300	1,300	5.20	2,700	2,700	10.80
Hydropower	19.38	45.06	169.7	0.85	1.81	7.473	1.00	2.09	8.724	36.25	79.15	317.5
CW-STES	3.23	3.23	0.0452	0.142	0.142	0.0020	0.23	0.23	0.0032	2.94	2.94	0.0412
ICE	4.84	4.84	0.0678	0.213	0.213	0.0030	0.35	0.35	0.0049	4.41	4.41	0.0618
HW-STES	129.6	129.6	1.037	18.16	18.16	0.145	20.42	20.42	0.163	167.3	167.3	1.338
UTES-heat	0.264	129.6	15.549	2.81	18.16	4.360	1.22	20.42	4.900	38.65	167.3	40.14
UTES-elec.	129.6	--	--	18.16	--	--	20.42	--	--	167.3	--	--
	All regions											
PHS	1,050	1,050	14.70									
CSP-elec.	420	420	--									
CSP-PCM	677	--	9.47									
Batteries	21,129	21,129	84.51									
Hydropower	521	1,164	4,567									
CW-STES	38.3	38.3	0.536									
ICE	57.4	57.4	0.803									
HW-STES	2,046	2,046	14.43									
UTES-heat	562	2,049	781.94									
UTES-elec.	2,178	--	--									

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 S14 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 S17). 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 can be recharged only naturally by rainfall and runoff, and its annual-average recharge rate approximately equals its 2020 annual energy output (TWh/yr) divided by the number of hours per year. Hydro is recharged each time step at this recharge rate. The maximum hydropower energy storage capacity available in all reservoirs is also assumed to equal hydro's 2020 annual energy output. Whereas the present table gives hydro's maximum storage capacity, its output from storage during a given time step is limited by the smallest among three factors: the current energy available in the reservoir, the peak hydro discharge rate multiplied by the time step, and the energy needed during the time step to keep the grid stable.

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 S6 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. The exception is Hawaii, where it is 10% of the discharge rate. Heat pumps are used to produce both cold water and ice. Table S18 (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 S18 (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 S6. The peak charge rate is set equal to the peak discharge rate. The exception is Hawaii, where it is 10% of the 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 exception is Hawaii, where it is set to 10% of this value. 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 S18 (footnotes) provides the cost of the heat pumps per kW-electricity consumed to charge storage with electricity.

Table S14. Maximum number of days of storage at the maximum discharge rate (given in Table S13 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 S13 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 S13. (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; (j) the maximum number of hours that flexible loads could be shifted forward in time due to demand response, during sensitivity tests, that gave the exact same result as when the baseline case maximum of eight hours was used; and (k) the fraction of building heating and cooling load that was 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 discharge rate (TW) during simu-lation (hours)	(g) HVDC line length (km)	(h) HVDC line capacity (MW)	(i) Fraction of non-roof PV/non-shed energy subject to HVDC	(j) Max hours of demand response needed	(k) Fraction of building heating/ cooling subject to district heating/ cooling
Africa	30	8	9	173	0.343	8.7	3,053	194,625	0.3	4	0.1
Australia	4	8	10	168	0.082	12.3	2,857	47,580	0.3	4	0.1
Canada	10	14	0	71	0.074	5.4	3,367	96,717	0.3	4	0.2
Central America	1	8	10	17	0.133	33.2	2,261	57,718	0.2	6	0.1
Central Asia	20	8	10	33	0.126	23.1	2,602	74,389	0.3	8	0.01
China	27	5	5	245	1.559	6.7	3,068	1,284,749	0.3	6	0.3
Cuba	50	8	65	30	0.01	39.0	0	0	0	2	0.2
Europe	10	6	50	86	0.638	7.5	3,006	538,500	0.3	2	0.5
Haiti	1	0	10	126	0.008	12.6	0	0	0	2	0.05
Iceland	0	8	1	--	--	0.0	0	0	0	0	0.92
India	9	8	6	113	0.936	19.7	3,099	460,456	0.3	0	0.1
Israel	15	8	25	38	0.016	49.2	0	0	0	0	0.2
Jamaica	3	8	15	157	0.003	9.5	0	0	0	4	0
Japan	5	8	5	66	0.133	14.4	2,813	74,625	0.2	0	0.1
Mauritius	25	8	35	118	0.002	5.0	0	0	0	0	0.2
Mideast	10	8	7	74	0.513	17.9	2,587	374,443	0.3	4	0.05
New Zealand	10	8	10	16	0.018	28.2	2,923	4,833	0.15	8	0.05
Philippines	15	8	10	87	0.055	13.7	2,482	12,665	0.2	4	0.2
Russia	5	10	5	90	0.015	4.0	2,875	158,405	0.3	2	0.5
South America	30	8	90	290	0.01	4.0	3,496	253,404	0.3	4	0.1
Southeast Asia	5	8	5	182	0.431	8.8	2,337	262,489	0.3	4	0.1
South Korea	10	8	18	24	0.151	36.8	0	0	0	2	0.15
Taiwan	10	8	40	20	0.084	62.1	0	0	0	4	0.15
United States	10	8	20	65	0.701	15.4	2,712	579,931	0.3	2	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 S13 equals the maximum storage capacity in Table S13.

No battery-related values are shown for Iceland since Iceland requires no battery storage (Table S13).

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

Table S15. 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 S16 by dividing values from the table in units of TWh per simulation by the number of hours of simulation. Figure S2 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) Annual 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	488.48	33.75	19.16	71.0	**612.4**	611.2	1.18	**612.4**
Australia	92.26	8.00	2.74	20.3	**123.3**	123.3	-0.01	**123.3**
Canada	167.97	13.04	2.35	7.4	**190.7**	190.5	0.19	**190.7**
Central America	160.68	18.31	2.06	90.4	**271.5**	271.5	-0.04	**271.5**
Central Asia	166.96	15.02	4.02	59.2	**245.2**	245.1	0.08	**245.2**
China	2,358.8	194.57	91.50	300.5	**2,945.3**	2,936.7	8.59	**2,945.3**
Cuba	9.00	1.00	0.37	5.6	**16.0**	16.0	-0.01	**16.0**
Europe	948.74	81.66	33.90	140.8	**1,205.1**	1,205.8	-0.66	**1,205.1**
Haiti	7.80	0.66	0.41	1.9	**10.8**	10.8	0.00	**10.8**
Iceland	3.19	0.32	0.00002	0.77	**4.28**	4.28	-0.00006	**4.28**
India	982.40	73.66	40.79	115.9	**1,212.8**	1,210.9	1.83	**1,212.8**
Israel	13.14	1.58	0.64	8.91	**24.26**	24.20	0.06	**24.26**
Jamaica	2.60	0.19	0.06	0.7	**3.5**	3.5	0.00	**3.5**
Japan	174.54	17.37	3.57	41.5	**237.0**	237.0	0.00	**237.0**
Mauritius	1.99	0.18	0.05	0.3	**2.5**	2.5	0.01	**2.5**
Mideast	708.08	69.19	17.89	250.6	**1,045.8**	1,045.5	0.25	**1,045.8**
New Zealand	16.98	1.54	0.16	3.5	**22.2**	22.2	0.00	**22.2**
Philippines	41.79	3.94	2.00	16.8	**64.5**	64.3	0.19	**64.5**
Russia	254.66	24.03	9.65	50.0	**338.4**	338.3	0.03	**338.4**
South America	467.93	33.94	6.05	6.1	**514.1**	511.2	2.83	**514.1**
Southeast Asia	591.67	59.64	14.69	300.9	**966.9**	966.9	-0.07	**966.9**
South Korea	151.25	16.00	3.70	75.4	**246.4**	246.4	-0.03	**246.4**
Taiwan	90.70	7.24	2.69	9.7	**110.4**	110.4	-0.03	**110.4**
United States	978.96	96.31	20.98	282.4	**1,378.7**	1,379.0	-0.32	**1,378.7**
All regions	8,880.5	771.2	279.4	1,861.4	**11,793**	11,778.4	14.1	**11,793**

Table S16. 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 S15 for key parameters. Figure S2 shows the time series of matching demand with supply and changes in storage for each region.

	Africa	Australia	Canada	Central America	Central Asia
A1. Total end use demand	**12,843**	**2,426**	**4,416**	**4,224**	**4,390**
Electricity for electricity inflexible demand	6,276	1,269	2,305	1,938	2,337
Electricity for electricity, heat, cold storage + DR	5,379	947	1,824	1,816	1,797
Electricity for H_2 direct use + H_2 storage	1,188	209	287	470	256
A2. Total end use demand	**12,843**	**2,426**	**4,416**	**4,224**	**4,390**
Electricity for direct use, electricity storage, + H_2	11,976	2,372	4,241	4,070	4,201
Low-T heat load met by heat storage	806	52	174	140	188
Cold load met by cold storage	61.26	2.42	0.91	14.45	1.14
A3. Total end use demand	**12,843**	**2,426**	**4,416**	**4,224**	**4,390**
Electricity for direct use, electricity storage, DR	10,601	2,127	3,860	3,570	3,929
Electricity for H_2 direct use + H_2 storage	1,188	209	287	470	256
Electricity + heat for heat subject to storage	806	76	254	140	200
Electricity for cold load subject to storage	248.01	13.66	15.54	43.94	4.31
B. Total losses	**3,257**	**817**	**599**	**2,913**	**2,058**
Transmission, distribution, downtime losses	887	210	343	481	395
Losses CSP storage	3.67	1	0.00	0.40	0.74
Losses PHS storage	0.23	0.0497	1.2163	0.0198	0.0425
Losses battery storage	173	55.9	9.42	24.2	32.6
Losses CW-STES + ICE storage	11	0.4	0.16	2.6	0.2
Losses HW-STES storage	106	5.5	23	26.9	26.1
Losses UTES storage	210	9.4	28	0.0	46.1
Losses from shedding	1,866	534	194	2,378	1,557
Net end-use demand plus losses (A1 + B)	***16,100***	***3,242***	***5,015***	***7,137***	***6,447***
C. Total WWS supply before T&D losses	**16,069**	**3,243**	**5,010**	**7,138**	**6,445**
Onshore + offshore wind electricity	6,603	928	2,849	4,073	3,019
Rooftop + utility PV+ CSP electricity	8,995	2,184	745	2,578	3,138
Hydropower electricity	362.3	93.5	1,254.8	229.3	282.5
Wave electricity	16.56	5.02	7.24	8.18	5.32
Geothermal electricity	76.7854	9.5047	113.2666	236.2056	0
Tidal electricity	4.9087	3.2488	12.387	2.035	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	**31.0671**	**-0.3516**	**5.0783**	**-0.9874**	**2.1793**
CSP storage	0.1344	0.0164	0	-0.0187	-0.011
PHS storage	-0.0389	-0.0374	0.1745	-0.0084	-0.042
Battery storage	0.7392	-0.0302	0.3	-0.44	-0.73
CW-STES+ICE storage	0.1189	0.0055	-0.0004	-0.0023	-0.0006
HW-STES storage	1.0362	-0.0183	0.2538	-0.0221	0.162
UTES storage	26.4577	-0.22	4.3505	-0.0664	2.9158
H_2 storage	2.6197	-0.0676	0	-0.4295	-0.115
Energy supplied plus taken from storage (C+D)	***16,100***	***3,242***	***5,015***	***7,137***	***6,447***

	China	Cuba	Europe	Haiti	Iceland
A1. Total end use demand	**62,015**	**237**	**24,943.8**	**205**	**84**
Electricity for electricity inflexible demand	29,043	119	11,251.2	100	31

Electricity for electricity, heat, cold storage + DR	30,760	109	11,744.9	81	49
Electricity for H_2 direct use + H_2 storage	2,212	8	1,947.6	24	4
A2. Total end use demand	**62,015**	**237**	**24,943.8**	**205**	**84**
Electricity for direct use, electricity storage, + H_2	57,685	224	21,544.4	196	69
Low-T heat load met by heat storage	4,232	10	3,369.0	8	15
Cold load met by cold storage	98.03	2.18	30.41	0.59	0.00
A3. Total end use demand	**62,015**	**237**	**24,943.8**	**205**	**84**
Electricity for direct use, electricity storage, DR	54,571	212	19,332.3	171	66
Electricity for H_2 direct use + H_2 storage	2,212	8	1,947.6	24	4
Electricity + heat for heat subject to storage	4,489	11	3,372.3	8	15
Electricity for cold load subject to storage	743.00	6.67	291.53	2.14	0.00
B. Total losses	**15,422**	**183**	**6,741**	**79**	**29**
Transmission, distribution, downtime losses	5,115	26	2,146.95	17	8
Losses CSP storage	17.31	0.03	0.7431	0.05	0.00
Losses PHS storage	11.4020	0.0038	5	0.0010	0.0000
Losses battery storage	846	4.02	137	4.2	0.00
Losses CW-STES + ICE storage	18	0.39	5	0.1	0.00
Losses HW-STES storage	328	1.06	536	0.0	0.00
Losses UTES storage	1,185	4.16	206	6.3	0.00
Losses from shedding	7,900	147	3,702.3	50.6	20.2
Net end-use demand plus losses (A1 + B)	***77,437***	***420***	***31,684.4***	***283.7***	***112.5***
C. Total WWS supply before T&D losses	**77,211**	**420**	**31,701.7**	**284**	**113**
Onshore + offshore wind electricity	33,184	234	19,787.5	76	23
Rooftop + utility PV+ CSP electricity	37,971	184	9,191.6	184	0
Hydropower electricity	4,416.8	0.8	2,044.0	8.1	33.5
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	13.879	0.287	34.779	0.298	0.253
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	**225.909**	**-0.2931**	**-17.3316**	**-0.0431**	**-0.0015**
CSP storage	1.4127	-0.0011	-0.0365	-0.0009	0
PHS storage	-0.1767	-0.0042	-0.2913	-0.0028	0
Battery storage	5.4043	-0.04	-0.48	-0.01	0
CW-STES+ICE storage	-0.0263	-0.0004	-0.0155	-0.0001	-0.0003
HW-STES storage	2.4927	-0.0013	-0.1858	0	-0.0042
UTES storage	216.5664	-0.2004	-7.4332	-0.0091	0
H_2 storage	0.2359	-0.0458	-8.8893	-0.0202	0.003
Energy supplied plus taken from storage (C+D)	***77,437***	***420***	***31,684.4***	***283.7***	***112.5***

	India	Israel	Jamaica	Japan	Mauritius
A1. Total end use demand	**25,829**	**346**	**68**	**4,589**	**52**
Electricity for electricity inflexible demand	12,361	184	29	2,520	19
Electricity for electricity, heat, cold storage + DR	11,986	129	30	1,774	22
Electricity for H_2 direct use + H_2 storage	1,482	32	9	295	12
A2. Total end use demand	**25,829**	**346**	**68**	**4,589**	**52**
Electricity for direct use, electricity storage, + H_2	24,830	326	67	4,412	50
Low-T heat load met by heat storage	952	18	1	175	2
Cold load met by cold storage	46.66	1.36	0.00	1.44	0.59
A3. Total end use demand	**25,829**	**346**	**68**	**4,589**	**52**
Electricity for direct use, electricity storage, DR	22,939	287	59	4,099	37
Electricity for H_2 direct use + H_2 storage	1,482	32	9	295	12

Electricity + heat for heat subject to storage	1,107	19	1	186	2
Electricity for cold load subject to storage	301.04	7.17	0.00	8.77	1.84
B. Total losses	**6,057**	**292**	**24**	**1,643**	**14**
Transmission, distribution, downtime losses	1,937	41	5	457	5
Losses CSP storage	12.88	0.08	0.02	0.00	0.00
Losses PHS storage	0.0024	0.03	0.06	0.86	0.44
Losses battery storage	693	10	1	42	0
Losses CW-STES + ICE storage	8.43	0.25	0.00	0.26	0.11
Losses HW-STES storage	123.88	1	0	20	0
Losses UTES storage	234.62	5	0	30	0
Losses from shedding	3,048	234	17	1,092	8
Net end-use demand plus losses (A1 + B)	***31,886***	***638***	***92***	***6,232***	***66***
C. Total WWS supply before T&D losses	**31,837**	**636**	**92**	**6,232**	**66**
Onshore + offshore wind electricity	8,943	93	37	3,351	42
Rooftop + utility PV+ CSP electricity	22,254	530	55	2,497	23
Hydropower electricity	578.9	0	0	282	1
Wave electricity	17.26	0	0	9	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	**48.0023**	**1.5982**	**0.0145**	**0.0444**	**0.3312**
CSP storage	0.9354	0.0131	-0.0004	0	0.0003
PHS storage	-0.0201	-0.0155	-0.0042	-0.2474	-0.0497
Battery storage	3.7855	0.2387	-0.0024	0.2058	0.009
CW-STES+ICE storage	0.001	0.0014	0	-0.0003	0.0009
HW-STES storage	2	0.0213	-0.0007	0.1534	0.0007
UTES storage	40.9141	0.9569	0.0338	-0.1103	0.0543
H_2 storage	-0.0916	0.3825	-0.0116	0.0433	0.3156
Energy supplied plus taken from storage (C+D)	***31,886***	***638***	***92***	***6,232***	***66***

	Mideast	New Zealand	Philip-pines	Russia	South America
A1. Total end use demand	**18,616**	**446**	**1,099**	**6,695**	**12,302**
Electricity for electricity inflexible demand	8,984	232	500	2,803	5,889
Electricity for electricity, heat, cold storage + DR	8,224	177	471	3,525	5,413
Electricity for H_2 direct use + H_2 storage	1,409	38	128	368	1,001
A2. Total end use demand	**18,616**	**446**	**1,099**	**6,695**	**12,302**
Electricity for direct use, electricity storage, + H_2	18,021	436	1,013	5,622	11,914
Low-T heat load met by heat storage	578	11	73	1,055	343
Cold load met by cold storage	17.57	0.05	13.17	17.63	45.31
A3. Total end use demand	**18,616**	**446**	**1,099**	**6,695**	**12,302**
Electricity for direct use, electricity storage, DR	16,543	398	853	5,154	10,768
Electricity for H_2 direct use + H_2 storage	1,409	38	128	368	1,001
Electricity + heat for heat subject to storage	589	11	73	1,090	343
Electricity for cold load subject to storage	75.65	0.28	44.51	83.65	191.38
B. Total losses	**8,879**	**137**	**597**	**2,201**	**1,213**
Transmission, distribution, downtime losses	1,819	40	104	632	892
Losses CSP storage	4.47	0.03	0.20	0.00	2.37
Losses PHS storage	0.02	0.02	0.09	6.20	25.71
Losses battery storage	228	3	22	2	4

Losses CW-STES + ICE storage	3.17	0.01	2.38	3.19	8.18
Losses HW-STES storage	55	1	10	205	43
Losses UTES storage	180	1	18	38	76
Losses from shedding	6,589	92	441	1,315	162
Net end-use demand plus losses (A1 + B)	*27,495*	*583*	*1,696*	*8,896*	*13,515*
C. Total WWS supply before T&D losses	**27,489**	**583**	**1,691**	**8,895**	**13,441**
Onshore + offshore wind electricity	10,928	311	315	6,881	6,331
Rooftop + utility PV+ CSP electricity	15,859	150	1,197	1,333	4,092
Hydropower electricity	552	66	44	647	2,825
Wave electricity	2	1	2	13	19
Geothermal electricity	36.558	46.5203	129.3001	11.3466	124.2522
Tidal electricity	1.737	1.271	3.084	2.234	7.538
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	**6.5028**	**-0.0176**	**5.0874**	**0.762**	**74.3895**
CSP storage	0.5889	-0.0013	0.022	0	0.3912
PHS storage	-0.0203	-0.0084	-0.0157	-0.073	0.2459
Battery storage	0.4223	-0.0104	0.1757	-0.015	0.036
CW-STES+ICE storage	-0.0029	0.0001	0.0215	-0.0111	0.0917
HW-STES storage	0.5213	-0.0007	0.2014	-0.248	0.0764
UTES storage	5.3121	-0.0257	4.7206	-0.4006	-0.4364
H_2 storage	-0.3186	0.0288	-0.0381	1.5097	73.9847
Energy supplied plus taken from storage (C+D)	*27,495*	*583*	*1,696*	*8,896*	*13,515*

	Southeast Asia	South Korea	Taiwan	United States	All regions
A1. Total end use demand	**15,556**	**3,976**	**2,385**	**25,738**	**233,482**
Electricity for electricity inflexible demand	6,853	2,104	1,151	12,863	111,161
Electricity for electricity, heat, cold storage + DR	6,948	1,628	1,082	10,485	106,399
Electricity for H_2 direct use + H_2 storage	1,755	245	152	2,390	15,921
A2. Total end use demand	**15,556**	**3,976**	**2,385**	**25,738**	**233,482**
Electricity for direct use, electricity storage, + H_2	14,966	3,797	2,274	24,307	218,616
Low-T heat load met by heat storage	508	178	110	1,402	14,397
Cold load met by cold storage	81.74	1.67	1.26	29.15	469
A3. Total end use demand	**15,556**	**3,976**	**2,385**	**25,738**	**233,482**
Electricity for direct use, electricity storage, DR	13,081	3,544	2,107	21,753	200,059
Electricity for H_2 direct use + H_2 storage	1,755	245	152	2,390	15,921
Electricity + heat for heat subject to storage	508	178	110	1,402	14,988
Electricity for cold load subject to storage	212.29	9.35	15.18	193.36	2,513
B. Total losses	**9,864**	**2,501**	**517**	**10,509**	**76,544**
Transmission, distribution, downtime losses	1,568	421	190	2,532	20,274
Losses CSP storage	3.11	0.70	0.00	2.26	50
Losses PHS storage	1.43	0.32	0.32	0.08	54
Losses battery storage	231	45	34	235	2,835
Losses CW-STES + ICE storage	14.77	0.30	0.23	5.27	85
Losses HW-STES storage	92	25	17	207	1,852
Losses UTES storage	44	27	19	102	2,471
Losses from shedding	7,910	1,983	256	7,425	48,923
Net end-use demand plus losses (A1 + B)	*25,420*	*6,478*	*2,901*	*36,248*	*310,026*
C. Total WWS supply before T&D losses	**25,422**	**6,479**	**2,902**	**36,256**	**309,656**
Onshore + offshore wind electricity	8,516	3,399	977	18,418	139,318

Rooftop + utility PV+ CSP electricity	16,033	3,026	1,071	16,307	149,600
Hydropower electricity	528	23	27	979	15,278
Wave electricity	21	0	3	53	241
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	**-1.896**	**-0.7517**	**-0.8032**	**-8.3417**	**370**
CSP storage	-0.0326	0.1457	0	-0.0757	3.4819
PHS storage	-0.0374	-0.135	-0.0344	-0.1344	-0.9768
Battery storage	-0.19	-0.3218	-0.1916	-0.9169	7.9382
CW-STES+ICE storage	-0.0056	0	-0.0001	-0.01	0.1651
HW-STES storage	-0.0518	0.1308	0.1387	1.004	8.1379
UTES storage	-0.7774	-0.315	-0.245	-4.014	288.0287
H_2 storage	-0.8009	-0.2563	-0.4708	-4.1947	63.3732
Energy supplied plus taken from storage (C+D)	***25,420***	***6,478***	***2,901***	***36,248***	***310,026***

End-use demands in A1, A2, A3 should be identical. Transmission/distribution/maintenance loss rates are given in Table S17. Round-trip storage efficiencies are given in Table S18. 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 S17. Parameters for determining costs of energy from electricity and heat generators.

	Capital cost new installations ($million/MW)	O&M Cost ($/kW/yr)	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 (2021), 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 S14 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 S18. 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 S13) 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 S18. 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 coal 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 S13) 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 S17), 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 is 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 S19. Summary of 2050 WWS mean capital costs of new electricity plus heat generators; electricity, heat, cold, and hydrogen storage (including heat pumps to supply district heating and cooling), and all-distance transmission/distribution ($ 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 Tables S18 ($60/kWh-electricity storage) to the high value ($90/kWh-electricity storage), or a factor of 1.5.

	Africa	Australia	Canada	Central America	Central Asia	China	Cuba
Capital cost new generators only ($tril)	2.871	0.470	0.456	1.146	0.895	10.102	0.073
Cap cost generators-storage-H_2-HVDC ($tril)	**3.658**	**0.617**	**0.645**	**1.533**	**1.214**	**13.333**	**0.106**
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	0.172	0.226	0.095	0.135	0.195	0.000
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.840	3.591	2.504	5.484	3.609	3.208	5.498
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.006	0.072	0.028	0.021	0.000	0.182	0.000
LI battery storage	0.357	0.631	0.139	1.594	1.018	0.257	2.587
CSP-PCM + PHS storage	0.023	0.028	0.013	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	0.018	0.006	0.016	0.011	0.010	0.009	0.012
UTES storage	0.221	0.010	0.036	0.004	0.081	0.159	0.232
Heat pumps for filling district heating/cooling	0.082	0.028	0.040	0.048	0.045	0.065	0.052
H_2 production/compression/storage	0.273	0.267	0.103	0.345	0.181	0.084	0.373
Total LCOE (¢/kWh-all-energy)	**8.391**	**8.231**	**6.530**	**11.048**	**8.527**	**7.605**	**12.241**
LCOE (¢/kWh-replacing BAU electricity)	7.784	7.905	6.320	10.629	8.202	7.282	11.573
GW annual avg. end-use demand (Table S5)	488.5	92.3	168.0	160.7	167.0	2,358.8	9.0
TWh/y end-use demand (GW x 8,760 h/y)	4,279	808	1,471	1,408	1,463	20,663	79
Annual energy cost ($billion/yr)	**359.1**	**66.5**	**96.1**	**155.5**	**124.7**	**1,571.5**	**9.6**
% rise in LCOE & annual cost if 1.5x battery cost	2.13	3.83	1.06	7.21	5.97	1.69	10.6
	Europe	Haiti	Iceland	India	Israel	Jamaica	Japan
Capital cost new generators only ($tril)	3.909	0.045	0.002	4.776	0.082	0.019	0.888
Cap cost generators-storage-H_2-HVDC ($tril)	**5.946**	**0.056**	**0.0028**	**6.868**	**0.143**	**0.023**	**1.151**
Components of total LCOE (¢/kWh-all-energy)							
Short-dist. transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.199	0.000	0.000	0.169	0.000	0.000	0.140
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.457	3.806	1.744	3.088	4.041	4.869	4.318
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.116	0.000	1.666	0.010	0.269	0.000	0.048
LI battery storage	0.294	0.746	0.000	1.090	3.542	0.538	0.640
CSP-PCM + PHS storage	0.026	0.047	0.000	0.030	0.119	0.166	0.109
CW-STES + ICE storage	0.002	0.002	0.002	0.002	0.003	0.000	0.000
HW-STES storage	0.015	0.000	0.021	0.021	0.014	0.022	0.008
UTES storage	0.082	0.013	0.000	0.075	0.084	0.027	0.015
Heat pumps for filling district heating/cooling	0.091	0.142	0.046	0.092	0.125	0.064	0.034
H_2 production/compression/storage	0.715	0.360	0.075	0.143	0.505	0.492	0.151
Total LCOE (¢/kWh-all-energy)	**8.421**	**8.540**	**6.979**	**8.146**	**12.128**	**9.603**	**8.888**
LCOE (¢/kWh-replacing BAU electricity)	7.503	8.026	6.837	7.805	11.399	8.997	8.672
GW annual avg. end-use demand (Table S5)	948.7	7.8	3.2	982.4	13.1	2.6	174.5
TWh/y end-use demand (GW x 8,760 h/y)	8,311	68	28	8,606	115	23	1,529
Annual energy cost ($billion/yr)	**699.9**	**5.8**	**1.9**	**701.0**	**14.0**	**2.2**	**135.9**
% rise in LCOE & annual cost if 1.5x battery cost	1.74	4.37	1.52	6.69	14.6	2.80	3.60
	Mauri-tius	Mideast	New Zealand	Philip-pines	Russia	South America	Southeast Asia

Capital cost new generators only ($tril)	0.011	3.499	0.064	0.292	0.913	2.301	6.119
Cap cost generators-storage-H_2-HVDC ($tril)	**0.023**	**4.665**	**0.107**	**0.393**	**1.194**	**3.502**	**6.825**
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	0.159	0.097	0.088	0.208	0.221	0.121
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.445	3.376	3.052	4.622	3.012	4.139	7.443
Additional hydro turbines	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.047	0.039	0.075	0.000	0.004	0.028	0.001
LI battery storage	0.293	0.756	1.782	1.058	0.014	0.005	0.374
CSP-PCM + PHS storage	2.577	0.018	0.055	0.078	0.010	0.020	0.026
CW-STES + ICE storage	0.005	0.001	0.000	0.006	0.002	0.002	0.002
HW-STES storage	0.003	0.006	0.004	0.040	0.031	0.008	0.014
UTES storage	0.032	0.026	0.016	0.238	0.049	0.099	0.027
Heat pumps for filling district heating/cooling	0.014	0.057	0.018	0.106	0.108	0.037	0.061
H_2 production/compression/storage	1.558	0.200	0.263	0.361	0.129	1.238	0.264
Total LCOE (¢/kWh-all-energy)	**12.399**	**8.062**	**8.787**	**10.022**	**6.991**	**9.221**	**11.758**
LCOE (¢/kWh-replacing BAU electricity)	10.792	7.761	8.478	9.266	6.663	7.822	11.378
GW annual avg. end-use demand (Table S5)	2.0	708.1	17.0	41.8	254.7	467.9	591.7
TWh/y end-use demand (GW x 8,760 h/y)	17	6,203	149	366	2,231	4,099	5,183
Annual energy cost ($billion/yr)	**2.2**	**500.1**	**13.1**	**36.7**	**156.0**	**378.0**	**609.4**
% rise in LCOE & annual cost if 1.5x battery cost	1.18	4.69	10.14	5.28	0.10	0.03	1.59

	South Korea	Taiwan	United States	All regions
Capital cost new generators only ($tril)	1.351	0.596	4.816	45.696
Cap cost generators-storage-H_2-HVDC ($tril)	**1.764**	**0.986**	**6.712**	**61.468**
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	0.187	0.172
Distribution	2.375	2.375	2.375	2.375
Electricity generation	6.546	4.338	3.787	3.799
Additional hydro turbines	0	0	0	0
Geothermal + solar thermal heat generation	0.031	0.013	0.066	0.079
LI battery storage	2.139	3.337	0.642	0.554
CSP-PCM + PHS storage	0.095	0.066	0.020	0.027
CW-STES + ICE storage	0.000	0.001	0.001	0.002
HW-STES storage	0.008	0.014	0.011	0.013
UTES storage	0.030	0.056	0.043	0.092
Heat pumps for filling district heating/cooling	0.033	0.063	0.048	0.066
H_2 production/compression/storage	0.266	0.488	0.429	0.310
Total LCOE (¢/kWh-all-energy)	**12.573**	**11.801**	**8.657**	**8.538**
LCOE (¢/kWh-replacing BAU electricity)	12.236	11.180	8.110	8.046
GW annual avg. end-use demand (Table S5)	151.3	90.7	979.0	8,880.6
TWh/y end-use demand (GW x 8,760 h/y)	1,325	795	8,576	77,794
Annual energy cost ($billion/yr)	**166.6**	**93.8**	**742.4**	**6,641.9**
% rise in LCOE & annual cost if 1.5x battery cost	8.51	14.1	3.71	3.25

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 S17) and that are a function of lifetime (Table S17) 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 generators; electricity, heat, cold, and hydrogen storage; hydrogen electrolyzers and compressors; and long-distance (HVDC) transmission.

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 S14 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 S18.
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 S20. 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	**1,382**	**488.5**	**-64.7**	**3.658**	**10.09**	**8.39**	**359.1**	**1,222**	**3,982**	**1,782.6**	**6,987**	**-70.6**	**-94.9**
Algeria	142.7	43.3	-69.7	0.322	10.09	8.39	31.8	126.1	74.7	228.6	429	-74.8	-92.6
Angola	24.5	8.0	-67.4	0.060	10.09	8.39	5.9	21.7	94.0	32.7	148	-72.9	-96.0
Benin	11.0	2.9	-73.8	0.029	10.09	8.39	2.1	9.8	33.7	10.3	54	-78.2	-96.0
Botswana	5.4	2.2	-60.3	0.014	10.09	8.39	1.6	4.8	6.8	8.9	20	-67.0	-92.3
Cameroon	15.8	4.4	-72.1	0.038	10.09	8.39	3.2	14.0	68.9	12.8	96	-76.8	-96.6
Congo	4.6	1.4	-70.4	0.015	10.09	8.39	1.0	4.0	19.5	7.4	31	-75.4	-96.8
Congo, DR	35.8	8.5	-76.2	0.077	10.09	8.39	6.3	31.6	77.1	3.8	112	-80.2	-94.4
Côte d'Ivoire	16.6	5.2	-68.4	0.046	10.09	8.39	3.9	14.7	97.0	17.2	129	-73.7	-97.0
Egypt	186.8	87.2	-53.3	0.590	10.09	8.39	64.1	165.1	373.0	323.3	861	-61.2	-92.6
Equat. Guinea	6.6	4.2	-36.5	0.046	10.09	8.39	3.1	5.8	9.0	4.4	19	-47.2	-84.0
Eritrea	1.1	0.3	-72.2	0.002	10.09	8.39	0.2	1.0	10.9	0.9	13	-76.9	-98.3
Ethiopia	76.9	18.1	-76.4	0.124	10.09	8.39	13.3	68.0	243.5	23.1	335	-80.4	-96.0
Gabon	11.8	7.3	-38.6	0.078	10.09	8.39	5.3	10.5	8.5	4.4	23	-49.0	-77.2
Ghana	20.7	8.6	-58.5	0.079	10.09	8.39	6.3	18.3	83.4	21.3	123	-65.5	-94.9
Kenya	37.1	10.7	-71.1	0.076	10.09	8.39	7.9	32.8	46.7	25.1	105	-76.0	-92.5
Libya	31.4	14.0	-55.5	0.118	10.09	8.39	10.3	27.8	20.0	65.9	114	-63.0	-91.0
Morocco	44.6	19.4	-56.4	0.135	10.09	8.39	14.3	39.4	57.1	93.6	190	-63.8	-92.5
Mozambique	12.7	5.3	-57.9	0.034	10.09	8.39	3.9	11.2	36.3	11.7	59	-65.0	-93.4
Namibia	5.1	2.0	-61.3	0.015	10.09	8.39	1.4	4.5	6.2	5.6	16	-67.8	-91.1
Niger	6.3	1.6	-74.2	0.014	10.09	8.39	1.2	5.5	63.1	3.0	72	-78.5	-98.3
Nigeria	294.0	74.1	-74.8	0.631	10.09	8.39	54.5	260.0	1,972	127.0	2,358	-79.1	-97.7
Senegal	6.9	2.7	-60.9	0.020	10.09	8.39	2.0	6.1	28.6	12.4	47	-67.5	-95.8
South Africa	234.2	105.0	-55.2	0.708	10.09	8.39	77.2	207.1	118.2	626.4	952	-62.7	-91.9
South Sudan	1.4	0.4	-71.9	0.003	10.09	8.39	0.3	1.2	34.2	1.5	37	-76.6	-99.2
Sudan	32.0	11.4	-64.3	0.080	10.09	8.39	8.4	28.3	215.3	27.0	271	-70.3	-96.9
Tanzania	38.1	11.6	-69.5	0.096	10.09	8.39	8.6	33.7	73.6	16.9	124	-74.6	-93.1
Togo	4.5	1.2	-73.0	0.013	10.09	8.39	0.9	4.0	18.1	3.6	26	-77.5	-96.5
Tunisia	30.0	10.8	-64.0	0.080	10.09	8.39	7.9	26.5	25.5	40.6	93	-70.0	-91.4
Zambia	21.9	10.3	-53.0	0.072	10.09	8.39	7.6	19.3	49.3	9.5	78	-60.9	-90.3
Zimbabwe	21.5	6.4	-70.2	0.043	10.09	8.39	4.7	19.0	18.7	13.8	51	-75.2	-90.9
Australia	**208.8**	**92.3**	**-55.8**	**0.617**	**10.28**	**8.23**	**66.5**	**188.0**	**34.6**	**399.5**	**622**	**-64.6**	**-89.3**
Canada	**442.5**	**168.0**	**-62.0**	**0.645**	**8.03**	**6.53**	**96.1**	**311.3**	**42.3**	**518.3**	**872**	**-69.1**	**-89.0**
Central America	**378.2**	**160.7**	**-57.5**	**1.533**	**10.49**	**11.05**	**155.5**	**347.6**	**323.5**	**588.9**	**1,260**	**-55.3**	**-87.7**
Costa Rica	8.6	4.0	-53.4	0.032	10.49	11.05	3.9	7.9	6.6	8.9	23	-50.9	-83.4
El Salvador	5.5	2.5	-55.2	0.021	10.49	11.05	2.4	5.1	7.4	7.1	20	-52.8	-87.8
Guatemala	20.2	6.1	-69.9	0.056	10.49	11.05	5.9	18.6	32.0	21.1	72	-68.3	-91.8
Honduras	8.2	3.1	-61.8	0.036	10.49	11.05	3.0	7.5	10.7	10.3	28	-59.8	-89.4
Mexico	312.5	136.8	-56.2	1.295	10.49	11.05	132.4	287.1	252.4	524.1	1,064	-53.9	-87.6
Nicaragua	4.7	1.7	-64.2	0.019	10.49	11.05	1.6	4.3	8.3	5.8	18	-62.3	-91.1

Panama	18.5	6.5	-65.0	0.074	10.49	11.05	6.3	17.0	6.2	11.6	35	-63.2	-82.0
Central Asia	**446.5**	**167.0**	**-62.6**	**1.214**	**10.30**	**8.53**	**124.7**	**402.7**	**1,011**	**699.6**	**2,114**	**-69.0**	**-94.1**
Kazakhstan	87.2	33.2	-61.9	0.222	10.30	8.53	24.8	78.6	91.5	235.7	406	-68.5	-93.9
Kyrgyz Rep.	7.3	3.4	-52.9	0.018	10.30	8.53	2.6	6.6	16.0	10.1	33	-61.0	-92.1
Pakistan	233.1	97.6	-58.1	0.764	10.30	8.53	72.9	210.2	795.7	288.5	1,294	-65.3	-94.4
Tajikistan	5.8	3.5	-40.1	0.011	10.30	8.53	2.6	5.2	19.6	7.6	32	-50.4	-92.0
Turkmenistan	40.0	8.7	-78.1	0.062	10.30	8.53	6.5	36.0	20.2	76.9	133	-81.9	-95.1
Uzbekistan	73.2	20.5	-72.0	0.138	10.30	8.53	15.3	66.0	68.3	80.7	215	-76.8	-92.9
China Region	**5,076.3**	**2,358.8**	**-53.5**	**13.333**	**9.55**	**7.61**	**1,571.5**	**4,248.4**	**10,757**	**8,495.7**	**23,501**	**-63.0**	**-93.3**
China	4,970.5	2,317.0	-53.4	13.016	9.55	7.61	1,543.7	4,159.8	10,602	8,338.2	23,100	-62.9	-93.3
Hong Kong	82.7	30.5	-63.1	0.255	9.55	7.61	20.3	69.2	54.7	56.8	181	-70.6	-88.7
Korea, DPR	13.3	7.3	-45.2	0.038	9.55	7.61	4.9	11.2	81.8	54.4	147	-56.4	-96.7
Mongolia	9.9	4.0	-59.6	0.025	9.55	7.61	2.7	8.3	18.3	46.4	73	-67.8	-96.4
Cuba	**15.8**	**9.0**	**-42.9**	**0.106**	**11.64**	**12.24**	**9.6**	**16.1**	**37.5**	**30.9**	**84**	**-40.0**	**-88.6**
Europe	**2,287.7**	**948.7**	**-58.5**	**5.946**	**10.01**	**8.42**	**699.9**	**2,005.4**	**1,772**	**2,858**	**6,635**	**-65.1**	**-89.5**
Albania	4.4	2.1	-52.8	0.011	10.01	8.42	1.5	3.9	14.3	4.8	23	-60.3	-93.3
Austria	47.9	20.6	-57.0	0.119	10.01	8.42	15.2	42.0	20.3	53.3	116	-63.8	-86.9
Belarus	37.5	12.8	-66.0	0.085	10.01	8.42	9.4	32.9	50.2	56.3	139	-71.4	-93.3
Belgium	73.3	30.2	-58.9	0.182	10.01	8.42	22.3	64.3	26.1	76.9	167	-65.4	-86.7
Bosnia-Herzeg.	9.0	3.7	-59.1	0.022	10.01	8.42	2.7	7.9	29.1	28.5	65	-65.6	-95.9
Bulgaria	22.4	10.0	-55.1	0.074	10.01	8.42	7.4	19.6	38.2	36.8	95	-62.2	-92.2
Croatia	14.8	5.9	-59.9	0.041	10.01	8.42	4.4	13.0	21.5	16.3	51	-66.3	-91.4
Cyprus	4.2	1.9	-54.9	0.014	10.01	8.42	1.4	3.7	3.6	6.3	14	-62.1	-89.7
Czech Rep.	43.9	18.0	-59.1	0.116	10.01	8.42	13.3	38.5	32.0	77.8	148	-65.6	-91.1
Denmark	26.1	9.8	-62.3	0.056	10.01	8.42	7.3	22.9	11.7	22.9	57	-68.2	-87.4
Estonia	6.0	2.1	-64.6	0.016	10.01	8.42	1.6	5.3	2.8	13.6	22	-70.2	-92.8
Finland	42.6	22.0	-48.3	0.143	10.01	8.42	16.2	37.3	6.0	32.0	75	-56.5	-78.4
France	248.6	111.3	-55.2	0.733	10.01	8.42	82.1	217.9	115.0	231.7	565	-62.3	-85.5
Germany	361.0	154.4	-57.2	0.906	10.01	8.42	113.9	316.5	223.0	517.4	1,057	-64.0	-89.2
Gibraltar	6.0	1.6	-73.1	0.020	10.01	8.42	1.2	5.2	0.2	0.5	6	-77.3	-80.2
Greece	32.5	13.2	-59.4	0.085	10.01	8.42	9.7	28.5	42.0	48.3	119	-65.8	-91.8
Hungary	31.7	12.6	-60.4	0.093	10.01	8.42	9.3	27.8	37.8	37.5	103	-66.7	-91.0
Ireland	18.9	8.1	-57.1	0.053	10.01	8.42	6.0	16.5	9.8	26.9	53	-63.9	-88.8
Italy	215.7	83.9	-61.1	0.545	10.01	8.42	61.9	189.1	188.7	244.1	622	-67.3	-90.1
Kosovo	3.0	1.4	-53.6	0.011	10.01	8.42	1.0	2.6	1.7	7.2	12	-61.0	-91.1
Latvia	8.1	3.3	-59.9	0.021	10.01	8.42	2.4	7.1	10.0	7.1	24	-66.2	-90.1
Lithuania	12.6	4.5	-64.0	0.036	10.01	8.42	3.3	11.0	14.0	11.7	37	-69.7	-90.9
Luxembourg	6.5	2.5	-61.6	0.016	10.01	8.42	1.8	5.7	1.7	7.2	15	-67.7	-87.4
Macedonia	3.8	1.9	-49.7	0.013	10.01	8.42	1.4	3.4	11.0	7.6	22	-57.6	-93.5
Malta	5.6	1.8	-68.0	0.016	10.01	8.42	1.3	4.9	1.1	0.9	7	-73.0	-81.0
Moldova	6.0	2.3	-61.4	0.016	10.01	8.42	1.7	5.3	5.9	7.8	19	-67.5	-91.0
Montenegro	1.6	0.8	-49.7	0.005	10.01	8.42	0.6	1.4	3.9	3.7	9	-57.7	-93.5
Netherlands	104.5	40.9	-60.9	0.249	10.01	8.42	30.2	91.6	43.8	115.2	251	-67.1	-88.0
Norway	47.3	20.3	-57.0	0.069	10.01	8.42	15.0	41.4	7.7	35.3	84	-63.8	-82.2
Poland	126.7	48.0	-62.1	0.346	10.01	8.42	35.4	111.0	131.4	233.9	476	-68.1	-92.6
Portugal	30.2	13.6	-54.9	0.082	10.01	8.42	10.0	26.4	15.6	35.7	78	-62.0	-87.1
Romania	48.4	18.8	-61.2	0.116	10.01	8.42	13.8	42.4	141.8	66.8	251	-67.4	-94.5
Serbia	18.8	8.8	-53.3	0.061	10.01	8.42	6.5	16.5	37.6	60.1	114	-60.7	-94.3
Slovakia	20.0	8.2	-58.8	0.051	10.01	8.42	6.1	17.5	16.6	26.5	61	-65.4	-90.0
Slovenia	8.3	3.9	-53.0	0.025	10.01	8.42	2.9	7.3	5.2	11.3	24	-60.4	-87.9
Spain	166.0	68.8	-58.6	0.424	10.01	8.42	50.7	145.5	88.8	190.9	425	-65.1	-88.1
Sweden	55.4	29.9	-46.1	0.158	10.01	8.42	22.0	48.6	11.6	33.0	93	-54.7	-76.3
Switzerland	32.1	15.0	-53.2	0.075	10.01	8.42	11.1	28.1	13.9	29.0	71	-60.6	-84.4
Ukraine	104.2	42.1	-59.6	0.277	10.01	8.42	31.1	91.3	183.2	166.9	441	-66.0	-93.0
United King.	232.4	87.8	-62.2	0.567	10.01	8.42	64.8	203.7	153.3	268.5	626	-68.2	-89.6
Haiti Region	**19.1**	**7.8**	**-59.2**	**0.056**	**10.90**	**8.54**	**5.8**	**18.3**	**36.2**	**30.7**	**85**	**-68.0**	**-93.1**
Dominican Rep	14.0	6.5	-53.9	0.044	10.90	8.54	4.8	13.4	20.3	27.1	61	-63.9	-92.1
Haiti	5.1	1.3	-73.8	0.012	10.90	8.54	1.0	4.9	15.9	3.6	24	-79.5	-95.9
Iceland	**5.6**	**3.2**	**-42.6**	**0.0028**	**7.51**	**6.98**	**1.9**	**3.7**	**0.4**	**2.9**	**7**	**-47.5**	**-72.2**
India Region	**2,010.5**	**982.4**	**-51.1**	**6.868**	**9.88**	**8.15**	**701.0**	**1,739.6**	**9,472**	**3,756.5**	**14,968**	**-59.7**	**-95.3**
Bangladesh	82.7	35.8	-56.7	0.294	9.88	8.15	25.6	71.5	523.1	130.5	725	-64.3	-96.5
India	1,870.8	926.7	-50.5	6.422	9.88	8.15	661.2	1,618.7	8,755.	3,571.0	13,944	-59.2	-95.3

Nepal	28.5	8.0	-71.9	0.069	9.88	8.15	5.7	24.7	99.9	19.4	144	-76.9	-96.0
Sri Lanka	28.6	11.9	-58.2	0.083	9.88	8.15	8.5	24.7	94.0	35.6	154	-65.6	-94.5
Israel	**26.1**	**13.1**	**-49.6**	**0.143**	**11.21**	**12.13**	**14.0**	**25.6**	**15.7**	**50.3**	**92**	**-45.5**	**-84.8**
Jamaica	**5.5**	**2.6**	**-53.0**	**0.023**	**11.38**	**9.60**	**2.2**	**5.5**	**3.4**	**7.4**	**16**	**-60.3**	**-86.6**
Japan	**355.4**	**174.5**	**-50.9**	**1.151**	**10.48**	**8.89**	**135.9**	**326.3**	**261.5**	**678.1**	**1,266**	**-58.3**	**-89.3**
Mauritius	**5.2**	**2.0**	**-61.4**	**0.023**	**10.64**	**12.40**	**2.2**	**4.8**	**3.7**	**5.5**	**14**	**-55.0**	**-84.6**
Mideast	**1,520.1**	**708.1**	**-53.4**	**4.665**	**11.39**	**8.06**	**500.1**	**1,517.3**	**858.4**	**2,900.1**	**5,276**	**-67.0**	**-90.5**
Armenia	4.8	1.5	-68.1	0.008	11.39	8.06	1.1	4.8	10.1	5.0	20	-77.4	-94.6
Azerbaijan	19.1	6.5	-66.0	0.047	11.39	8.06	4.6	19.1	37.8	30.6	87	-76.0	-94.8
Bahrain	17.6	9.3	-47.1	0.054	11.39	8.06	6.6	17.6	2.1	41.9	62	-62.6	-89.3
Iran	444.0	184.9	-58.4	1.279	11.39	8.06	130.6	443.2	171.2	828.9	1,443	-70.5	-91.0
Iraq	62.1	24.0	-61.3	0.190	11.39	8.06	17.0	61.9	90.6	233.4	386	-72.6	-95.6
Jordan	15.8	7.1	-54.9	0.046	11.39	8.06	5.0	15.7	11.3	33.5	60	-68.1	-91.7
Kuwait	57.4	24.0	-58.1	0.148	11.39	8.06	17.0	57.3	12.6	116.9	187	-70.3	-90.9
Lebanon	13.2	6.5	-50.9	0.042	11.39	8.06	4.6	13.2	9.0	32.4	55	-65.2	-91.6
Oman	59.9	25.5	-57.4	0.168	11.39	8.06	18.0	59.8	8.3	109.6	178	-69.8	-89.8
Qatar	78.8	30.9	-60.8	0.182	11.39	8.06	21.8	78.7	3.6	125.8	208	-72.3	-89.5
Saudi Arabia	349.0	185.2	-46.9	1.241	11.39	8.06	130.8	348.4	124.7	725.8	1,199	-62.5	-89.1
Syria	14.4	6.4	-55.2	0.043	11.39	8.06	4.5	14.3	47.5	34.4	96	-68.3	-95.3
Turkey	173.7	80.6	-53.6	0.528	11.39	8.06	56.9	173.3	229.7	306.1	709	-67.2	-92.0
UAE	205.6	113.7	-44.7	0.677	11.39	8.06	80.3	205.2	11.2	262.9	479	-60.9	-83.2
Yemen	4.8	1.8	-61.9	0.014	11.39	8.06	1.3	4.8	88.8	12.9	106	-73.0	-98.8
New Zealand	**32.4**	**17.0**	**-47.6**	**0.107**	**8.11**	**8.79**	**13.1**	**23.0**	**5.2**	**35.7**	**64**	**-43.2**	**-79.5**
Philippines	**93.9**	**41.8**	**-55.5**	**0.393**	**10.19**	**10.02**	**36.7**	**83.8**	**677.3**	**194.3**	**955**	**-56.2**	**-96.2**
Russia Region	**787.8**	**254.7**	**-67.7**	**1.194**	**10.18**	**6.99**	**156.0**	**702.4**	**601.8**	**1,248.3**	**2,552**	**-77.8**	**-93.9**
Georgia	8.6	3.6	-57.9	0.011	10.18	6.99	2.2	7.7	31.1	11.4	50	-71.1	-95.6
Russia	779.2	251.0	-67.8	1.182	10.18	6.99	153.7	694.7	570.6	1,236.8	2,502	-77.9	-93.9
South America	**1,090.8**	**467.9**	**-57.1**	**3.502**	**8.44**	**9.22**	**378.0**	**806.4**	**749.8**	**1,161.3**	**2,718**	**-53.1**	**-86.1**
Argentina	144.4	51.0	-64.7	0.310	8.44	9.22	41.2	106.8	98.3	198.1	403	-61.4	-89.8
Bolivia	18.3	5.4	-70.7	0.039	8.44	9.22	4.3	13.5	22.7	24.3	61	-67.9	-92.8
Brazil	591.3	271.9	-54.0	2.098	8.44	9.22	219.6	437.1	352.7	494.7	1,285	-49.8	-82.9
Chile	67.5	35.2	-47.9	0.216	8.44	9.22	28.4	49.9	38.6	97.1	186	-43.0	-84.7
Colombia	70.5	28.2	-60.0	0.234	8.44	9.22	22.8	52.1	72.8	86.0	211	-56.3	-89.2
Curacao	5.2	1.5	-72.2	0.013	8.44	9.22	1.2	3.9	0.1	5.9	10	-69.6	-88.1
Ecuador	28.0	10.4	-62.9	0.080	8.44	9.22	8.4	20.7	16.1	40.4	77	-59.4	-89.1
Paraguay	12.9	5.9	-54.5	0.023	8.44	9.22	4.7	9.5	12.4	8.4	30	-50.3	-84.4
Peru	47.4	19.0	-59.9	0.153	8.44	9.22	15.4	35.1	77.0	55.9	168	-56.1	-90.8
Suriname	1.2	0.5	-58.7	0.004	8.44	9.22	0.4	0.9	1.6	2.0	4	-54.8	-91.1
Trinidad/Tob.	15.4	5.0	-67.8	0.038	8.44	9.22	4.0	11.4	2.6	32.5	46	-64.8	-91.4
Uruguay	10.0	5.2	-47.8	0.031	8.44	9.22	4.2	7.4	5.2	6.5	19	-43.0	-78.0
Venezuela	78.8	28.9	-63.2	0.261	8.44	9.22	23.4	58.2	49.8	109.3	217	-59.8	-89.2
Southeast Asia	**1,300.7**	**591.7**	**-54.5**	**6.825**	**10.39**	**11.76**	**609.4**	**1,183.3**	**1,936**	**2,046.6**	**5,166**	**-48.5**	**-88.2**
Brunei	5.2	1.6	-70.3	0.020	10.39	11.76	1.6	4.8	0.5	9.0	14	-66.4	-88.9
Cambodia	17.3	6.9	-59.8	0.059	10.39	11.76	7.1	15.7	40.4	21.3	77	-54.5	-90.8
Indonesia	423.9	193.9	-54.2	1.862	10.39	11.76	199.7	385.6	1,038	806.9	2,231	-48.2	-91.0
Lao PDR	7.6	2.9	-62.1	0.003	10.39	11.76	2.9	6.9	31.6	8.8	47	-57.1	-93.8
Malaysia	169.0	82.6	-51.1	1.057	10.39	11.76	85.1	153.7	95.6	320.9	570	-44.6	-85.1
Myanmar	44.7	15.8	-64.7	0.113	10.39	11.76	16.3	40.7	197.5	62.3	300	-60.0	-94.6
Singapore	216.6	72.5	-66.5	1.493	10.39	11.76	74.7	197.0	33.2	68.9	299	-62.1	-75.0
Thailand	257.5	118.4	-54.0	1.239	10.39	11.76	122.0	234.3	289.6	354.8	879	-47.9	-86.1
Vietnam	159.1	97.0	-39.0	0.981	10.39	11.76	99.9	144.7	209.1	393.8	748	-31.0	-86.6
South Korea	**304.9**	**151.3**	**-50.4**	**1.764**	**10.53**	**12.57**	**166.6**	**281.2**	**104.4**	**526.9**	**913**	**-40.8**	**-81.7**
Taiwan	**165.3**	**90.7**	**-45.1**	**0.986**	**10.60**	**11.80**	**93.8**	**153.5**	**85.9**	**357.0**	**596**	**-38.9**	**-84.3**
United States	**2,397.8**	**979.0**	**-59.2**	**6.712**	**10.42**	**8.66**	**742.4**	**2,188.6**	**829.7**	**3,381.7**	**6,400**	**-66.1**	**-88.4**
All regions	**20,359**	**8,881**	**-56.4**	**61.5**	**9.98**	**8.54**	**6,642**	**17,805**	**33,601**	**31,757**	**83,163**	**-62.7**	**-92.0**

[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 S21, 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 S21, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S21, Column (f) (in 2020 USD), which is updated from values in Jacobson et al. (2019), which were in 2013 USD.

Table S21. Regional (a) estimated air pollution mortalities per year in 2050-2052 due to anthropogenic sources (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_2e$-elim-inated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa	**1,173,737**	**3,192**	**112.5**	**383**	**1,247**	**558**	**2,189**	**32.9**	**14.7**
Algeria	10,788	409	77.7	308	183	558	1,049	6.0	18.3
Angola	19,997	59	100.5	371	1,606	558	2,535	43.7	15.2
Benin	17,080	18	115.1	528	1,822	558	2,908	34.9	10.7
Botswana	940	16	99.4	301	424	558	1,283	14.2	18.7
Cameroon	25,940	23	141.3	610	3,007	558	4,175	49.8	9.2
Congo	4,535	13	75.6	308	1,482	559	2,349	48.6	18.3
Congo, DR	93,264	7	927.4	4,678	11,391	556	16,626	24.6	1.2
Côte d'Ivoire	33,702	31	125.4	478	3,157	558	4,193	66.7	11.8
Egypt	63,218	579	110.7	285	644	558	1,488	22.8	19.8
Equator. Guinea	919	8	388.8	736	1,140	559	2,435	15.6	7.7
Eritrea	6,912	2	131.5	569	6,410	560	7,539	113.7	9.9
Ethiopia	152,676	41	321.9	1,643	5,883	558	8,085	36.1	3.4
Gabon	1,054	8	676.2	1,325	1,080	558	2,963	8.2	4.2
Ghana	25,489	38	165.4	480	2,185	558	3,223	46.0	11.8
Kenya	17,759	45	175.4	730	1,039	558	2,328	14.4	7.7
Libya	2,943	118	87.0	235	169	558	963	7.3	24.0
Morocco	10,340	168	85.2	235	341	559	1,135	14.6	23.9
Mozambique	24,785	21	187.1	535	1,730	559	2,823	32.6	10.5
Namibia	961	10	145.3	451	624	559	1,634	14.0	12.5
Niger	52,061	5	222.5	1,036	11,795	558	13,389	114.9	5.4
Nigeria	417,387	227	239.7	1,144	8,676	559	10,379	76.6	4.9
Senegal	12,993	22	88.9	274	1,286	559	2,119	47.5	20.6
South Africa	18,075	1,122	68.8	185	105	558	848	5.8	30.5
South Sudan	19,243	3	102.6	439	12,393	559	13,391	284.9	12.9
Sudan	66,066	48	173.6	585	4,447	558	5,590	76.7	9.6
Tanzania	31,178	30	282.7	1,115	2,434	559	4,108	22.0	5.1
Togo	12,450	6	138.3	616	2,803	558	3,977	45.9	9.2
Tunisia	4,209	73	109.3	365	350	558	1,273	9.7	15.5
Zambia	15,983	17	444.3	1,137	2,897	559	4,593	25.7	5.0
Zimbabwe	10,790	25	190.9	771	758	559	2,087	9.9	7.3
Australia	**3,034**	**716**	**93.0**	**263**	**48**	**558**	**869**	**1.9**	**21.8**
Canada	**3,764**	**928**	**103.5**	**335**	**46**	**558**	**939**	**1.1**	**13.4**
Central America	**45,608**	**1,055**	**147.4**	**329**	**307**	**558**	**1,194**	**9.8**	**17.8**
Costa Rica	1,008	16	243.5	496	416	559	1,470	8.8	11.8
El Salvador	1,558	13	188.1	398	581	558	1,537	15.3	14.7
Guatemala	7,217	38	155.9	492	848	558	1,898	18.1	11.9
Honduras	3,162	18	163.7	407	581	558	1,546	15.0	14.4
Mexico	29,973	939	141.0	306	269	558	1,133	9.2	19.1
Nicaragua	1,908	10	156.9	416	792	558	1,766	20.0	14.1
Panama	782	21	302.8	822	300	558	1,680	3.8	7.1
Central Asia	**235,560**	**1,253**	**99.5**	**321**	**807**	**558**	**1,687**	**25.9**	**17.9**
Kazakhstan	7,774	422	58.8	186	217	558	961	12.0	30.9
Kyrgyz Republic	3,796	18	141.8	363	883	558	1,805	25.0	15.8
Pakistan	204,993	517	141.1	407	1,540	558	2,506	39.0	14.1

Tajikistan	5,315	14	190.5	384	1,446	559	2,389	38.8	15.0
Turkmenistan	2,073	138	47.4	262	147	558	967	5.8	22.0
Uzbekistan	11,609	145	105.9	456	472	558	1,487	10.7	12.6
China Region	**1,134,535**	**15,212**	**103.3**	**279**	**707**	**558**	**1,545**	**24.2**	**19.1**
China	1,090,244	14,930	103.4	279	710	558	1,547	24.4	19.2
Hong Kong	3,982	102	199.8	680	538	558	1,776	7.6	7.8
Korea, DPR	37,703	97	49.9	115	839	559	1,512	70.0	46.6
Mongolia	2,606	83	32.0	99	221	559	879	21.2	53.7
Cuba	**4,851**	**55**	**174.7**	**291**	**679**	**559**	**1,528**	**27.2**	**22.3**
Europe	**179,603**	**5,119**	**136.7**	**392**	**346**	**558**	**1,296**	**8.8**	**14.3**
Albania	1,766	9	178.8	450	1,659	558	2,667	36.9	12.4
Austria	1,741	95	159.3	440	213	558	1,211	4.9	12.7
Belarus	5,001	101	93.2	326	497	558	1,381	15.3	17.1
Belgium	2,294	138	161.7	467	189	559	1,215	4.1	12.0
Bosnia-Herzeg.	3,661	51	53.2	155	571	559	1,284	36.9	36.1
Bulgaria	3,772	66	112.4	298	579	558	1,435	19.5	18.8
Croatia	1,966	29	150.5	446	741	559	1,745	16.6	12.5
Cyprus	280	11	124.0	327	318	558	1,203	9.7	17.1
Czech Rep.	3,217	139	95.1	276	229	558	1,064	8.3	20.2
Denmark	1,003	41	177.0	557	284	558	1,400	5.1	10.0
Estonia	298	24	64.3	216	116	559	891	5.4	25.9
Finland	544	57	283.8	652	106	558	1,315	1.6	8.6
France	10,527	415	197.9	525	277	558	1,360	5.3	10.6
Germany	19,077	926	122.9	342	241	558	1,141	7.0	16.4
Gibraltar	20	0.92	1,292	5,700	268	558	6,526	0.5	1.0
Greece	4,606	86	112.6	330	486	558	1,374	14.7	17.0
Hungary	4,162	67	138.2	415	564	559	1,538	13.6	13.5
Ireland	782	48	123.8	343	202	558	1,104	5.9	16.3
Italy	18,054	437	141.5	432	432	558	1,423	10.0	12.9
Kosovo	276	13	80.1	205	133	558	896	6.5	27.2
Latvia	878	13	188.4	558	787	558	1,902	14.1	10.0
Lithuania	1,346	21	159.0	525	669	559	1,753	12.7	10.6
Luxembourg	103	13	143.3	444	133	559	1,135	3.0	12.6
Macedonia	1,486	14	105.0	248	810	558	1,615	32.7	22.5
Malta	104	2	825.5	3,062	722	560	4,344	2.4	1.8
Moldova	1,384	14	121.8	375	418	558	1,352	11.2	14.9
Montenegro	481	7	88.7	210	589	558	1,357	28.1	26.6
Netherlands	3,352	206	146.3	444	212	558	1,215	4.8	12.6
Norway	567	63	237.0	655	121	558	1,334	1.9	8.5
Poland	14,360	419	84.6	265	314	558	1,137	11.8	21.1
Portugal	1,656	64	157.1	414	245	558	1,217	5.9	13.5
Romania	13,080	120	115.6	354	1,185	558	2,097	33.5	15.8
Serbia	4,208	108	60.3	154	350	558	1,062	22.8	36.4
Slovakia	1,732	47	128.0	369	349	558	1,277	9.5	15.1
Slovenia	533	20	141.9	359	258	558	1,175	7.2	15.6
Spain	8,585	342	148.4	426	260	558	1,244	6.1	13.1
Sweden	979	59	373.3	823	196	559	1,578	2.4	6.8
Switzerland	1,087	52	213.0	541	267	558	1,366	4.9	10.3
Ukraine	26,812	299	103.9	305	613	558	1,477	20.1	18.3
United Kingdom	13,823	481	134.7	423	319	558	1,300	7.5	13.2
Haiti Region	**13,695**	**55**	**106.3**	**333**	**659**	**558**	**1,550**	**21.6**	**18.3**
Dominican Rep.	3,217	49	99.5	275	419	558	1,252	16.6	22.1
Haiti	10,478	6	158.0	770	2,496	558	3,824	35.4	7.9
Iceland	**36**	**5**	**376.7**	**717**	**80**	**559**	**1,356**	**0.8**	**5.8**
India Region	**1,658,265**	**6,728**	**104.2**	**259**	**1,408**	**558**	**2,225**	**53.8**	**21.3**
Bangladesh	161,682	234	109.4	306	2,238	558	3,103	72.2	18.0
India	1,444,634	6,396	103.4	253	1,369	558	2,180	53.4	21.8
Nepal	38,313	35	164.5	711	2,879	558	4,148	40.0	7.8
Sri Lanka	13,636	64	133.6	388	1,476	558	2,423	37.6	14.2
Israel	**1,544**	**90**	**155.0**	**284**	**175**	**558**	**1,017**	**6.9**	**22.0**
Jamaica	**698**	**13**	**165.0**	**416**	**258**	**559**	**1,232**	**7.1**	**15.3**
Japan	**27,181**	**1,215**	**111.9**	**269**	**215**	**558**	**1,042**	**8.4**	**21.8**

Mauritius	**418**	**10**	**219.9**	**489**	**377**	**559**	**1,424**	**8.2**	**12.2**
Mideast	**118,866**	**5,195**	**96.3**	**292**	**165**	**558**	**1,016**	**6.4**	**21.8**
Armenia	1,429	9	119.7	530	1,117	559	2,206	24.0	12.0
Azerbaijan	3,755	55	83.8	348	689	558	1,596	22.5	18.3
Bahrain	172	75	87.8	235	28	558	821	1.3	27.1
Iran	21,479	1,485	87.9	298	115	558	972	4.4	21.3
Iraq	12,495	418	40.6	148	217	558	923	16.7	42.9
Jordan	1,836	60	83.8	263	188	558	1,009	8.2	24.2
Kuwait	888	209	81.1	274	60	558	892	2.5	23.3
Lebanon	1,289	58	79.0	227	156	558	941	7.8	28.0
Oman	747	196	91.9	305	43	558	905	1.6	20.9
Qatar	203	225	96.9	349	16	558	924	0.5	18.2
Saudi Arabia	9,771	1,300	100.6	268	96	558	922	4.1	23.7
Syria	9,310	62	73.6	233	770	558	1,561	37.7	27.4
Turkey	28,516	548	103.8	316	419	558	1,293	15.1	20.1
UAE	787	471	170.5	436	24	558	1,018	0.6	14.6
Yemen	26,189	23	55.8	207	3,854	559	4,620	212.0	30.7
New Zealand	**444**	**64**	**204.7**	**361**	**81**	**559**	**1,000**	**1.8**	**12.6**
Philippines	**126,965**	**348**	**105.4**	**241**	**1,946**	**558**	**2,746**	**82.4**	**23.6**
Russia Region	**59,101**	**2,236**	**69.8**	**314**	**269**	**558**	**1,142**	**8.7**	**18.1**
Georgia	4,111	21	108.3	375	1,519	558	2,452	41.3	15.2
Russia	54,990	2,215	69.4	314	258	558	1,130	8.4	18.1
South America	**110,082**	**2,080**	**181.7**	**388**	**360**	**558**	**1,306**	**7.8**	**12.2**
Argentina	12,153	355	116.1	301	277	558	1,136	7.8	15.7
Bolivia	5,510	44	99.5	310	521	558	1,390	14.2	15.2
Brazil	49,639	886	247.9	493	398	558	1,450	6.8	9.6
Chile	4,119	174	163.3	287	222	558	1,067	6.5	16.4
Colombia	11,703	154	147.9	338	473	558	1,369	11.8	13.9
Curacao	9	11	111.4	367	7	558	932	0.2	12.8
Ecuador	2,873	72	116.0	286	222	558	1,066	6.5	16.5
Paraguay	2,511	15	313.7	632	822	558	2,012	11.0	7.5
Peru	13,130	100	153.6	350	768	558	1,677	18.5	13.5
Suriname	225	4	109.3	242	425	557	1,224	14.8	19.4
Trinidad/Tobago	271	58	68.6	195	44	558	798	1.9	24.2
Uruguay	675	12	359.2	630	448	558	1,636	6.0	7.5
Venezuela	7,264	196	119.4	297	254	558	1,110	7.2	15.9
Southeast Asia	**316,266**	**3,666**	**166.2**	**323**	**528**	**558**	**1,409**	**17.0**	**18.0**
Brunei	36	16	98.6	293	33	558	884	1.2	19.7
Cambodia	12,111	38	187.6	412	1,060	558	2,030	26.7	14.1
Indonesia	155,525	1,445	138.2	267	718	558	1,543	28.0	21.7
Lao PDR	6,920	16	188.1	438	2,018	558	3,015	47.8	13.2
Malaysia	9,353	575	148.1	267	166	558	992	6.5	21.7
Myanmar	50,469	112	145.9	365	1,769	558	2,692	50.4	15.9
Singapore	2,107	123	605.8	1,598	269	559	2,426	1.8	3.6
Thailand	35,606	635	192.0	369	456	558	1,383	12.8	15.7
Vietnam	44,139	705	141.7	205	297	558	1,060	15.0	28.3
South Korea	**8,980**	**944**	**176.5**	**298**	**111**	**558**	**967**	**3.9**	**19.7**
Taiwan	**6,649**	**639**	**146.6**	**240**	**134**	**558**	**933**	**5.9**	**24.6**
United States	**62,694**	**6,057**	**122.6**	**361**	**137**	**558**	**1,057**	**4.0**	**16.1**
All regions	**5,292,576**	**56,873**	**116.79**	**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 all world anthropogenic CO_2e emissions.

[3]Calculated as the WWS private energy and total social cost from Table S20, 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 S20, 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 S20, Columns (i)-(j), respectively, each divided by the BAU end-use load from Table S20, Column (a) and by 8,760 hours per year.

Table S22. 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 S23. 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**	**7,456**	**24,414**	**0.03**	**0.11**
Algeria	2,381,740	797	1,692	0.03	0.07
Angola	1,246,700	41	996	0.00	0.08
Benin	112,760	50	292	0.04	0.26
Botswana	566,730	37	127	0.01	0.02
Cameroon	472,710	67	636	0.01	0.13
Congo	341,500	14	229	0.00	0.07
Congo, DR	2,267,050	148	1,305	0.01	0.06
Côte d'Ivoire	318,000	49	755	0.02	0.24
Egypt	995,450	844	3,086	0.08	0.31
Equator. Guinea	28,050	139	68	0.50	0.24
Eritrea	101,000	3	16	0.00	0.02
Ethiopia	1,000,000	303	979	0.03	0.10
Gabon	257,670	109	654	0.04	0.25
Ghana	227,540	121	600	0.05	0.26
Kenya	569,140	87	860	0.02	0.15
Libya	1,759,540	180	650	0.01	0.04
Morocco	446,300	195	650	0.04	0.15
Mozambique	786,380	38	402	0.00	0.05
Namibia	823,290	20	146	0.00	0.02
Niger	1,266,700	39	106	0.00	0.01
Nigeria	910,770	2,034	2,277	0.22	0.25
Senegal	192,530	27	160	0.01	0.08
South Africa	1,213,090	1,345	4,355	0.11	0.36
South Sudan	619,745	8	17	0.00	0.00
Sudan	1,886,000	123	485	0.01	0.03
Tanzania	885,800	130	862	0.01	0.10
Togo	54,390	21	143	0.04	0.26
Tunisia	155,360	217	357	0.14	0.23
Zambia	743,398	152	1,030	0.02	0.14
Zimbabwe	386,847	116	479	0.03	0.12
Australia	**7,682,300**	**3,164**	**3,578**	**0.04**	**0.05**
Canada	**9,093,510**	**502**	**8,082**	**0.01**	**0.09**
Central America	**2,429,460**	**3,385**	**21,144**	**0.14**	**0.87**
Costa Rica	51,060	44	400	0.09	0.78
El Salvador	20,720	30	290	0.14	1.40
Guatemala	107,160	81	846	0.08	0.79
Honduras	111,890	63	709	0.06	0.63
Mexico	1,943,950	3,017	17,061	0.16	0.88
Nicaragua	120,340	32	350	0.03	0.29
Panama	74,340	117	1,488	0.16	2.00
Central Asia	**4,697,670**	**3,147**	**9,667**	**0.07**	**0.21**
Kazakhstan	2,699,700	441	2,539	0.02	0.09
Kyrgyz Republic	191,800	35	198	0.02	0.10
Pakistan	770,880	2,206	4,573	0.29	0.59
Tajikistan	139,960	13	74	0.01	0.05
Turkmenistan	469,930	143	723	0.03	0.15
Uzbekistan	425,400	309	1,559	0.07	0.37
China Region	**11,063,254**	**54,388**	**91,978**	**0.49**	**0.83**
China	9,388,211	53,762	91,108	0.57	0.97
Hong Kong	1,073	435	7	2.0/38.50*	0.66
Korea, DPR	120,410	96	513	0.08	0.43
Mongolia	1,553,560	97	350	0.01	0.02

Cuba	**106,440**	**247**	**889**	**0.23**	**0.83**
Europe	**5,671,860**	**12,786**	**49,967**	**0.23**	**0.88**
Albania	27,400	13	87	0.05	0.32
Austria	82,409	311	1,356	0.38	1.64
Belarus	202,910	411	867	0.20	0.43
Belgium	30,280	1,286	397	4.25	1.31
Bosnia-Herzeg.	51,000	41	150	0.08	0.29
Bulgaria	108,560	80	621	0.07	0.57
Croatia	55,960	161	130	0.29	0.23
Cyprus	9,240	24	26	0.26	0.28
Czech Rep.	77,230	508	1,125	0.66	1.46
Denmark	42,430	144	572	0.34	1.35
Estonia	42,390	34	152	0.08	0.36
Finland	303,890	323	2,102	0.11	0.69
France	547,561	1,253	5,431	0.23	0.99
Germany	348,540	1,615	8,908	0.46	2.56
Gibraltar	7	2	0.077	2.0/24.48*	1.10
Greece	128,900	74	910	0.06	0.71
Hungary	90,530	460	405	0.51	0.45
Ireland	68,890	113	444	0.16	0.64
Italy	294,140	717	5,841	0.24	1.99
Kosovo	10,887	14	70	0.13	0.64
Latvia	62,180	27	249	0.04	0.40
Lithuania	62,674	59	367	0.09	0.59
Luxembourg	2,590	150	27	5.81	1.04
Macedonia	25,220	41	75	0.16	0.30
Malta	320	44	7	2.0/11.65*	2.21
Moldova	32,860	59	185	0.18	0.56
Montenegro	13,450	5	36	0.04	0.27
Netherlands	33,720	1,112	675	3.30	2.00
Norway	365,268	76	276	0.02	0.08
Poland	306,220	414	3,127	0.14	1.02
Portugal	91,590	101	679	0.11	0.74
Romania	230,020	142	1,232	0.06	0.54
Serbia	87,460	222	248	0.25	0.28
Slovakia	48,088	142	601	0.30	1.25
Slovenia	20,140	31	301	0.15	1.50
Spain	498,800	575	4,200	0.12	0.84
Sweden	407,340	333	1,762	0.08	0.43
Switzerland	39,516	112	833	0.28	2.11
Ukraine	579,320	389	2,861	0.07	0.49
United Kingdom	241,930	1,167	2,633	0.48	1.09
Haiti Region	**75,880**	**233**	**249**	**0.31**	**0.33**
Dominican Rep.	48,320	174	202	0.36	0.42
Haiti	27,560	59	47	0.22	0.17
Iceland	**100,250**	**0**	**78**	**0.00**	**0.08**
India Region	**3,309,420**	**28,729**	**30,921**	**0.87**	**0.93**
Bangladesh	130,170	2,168	270	1.67	0.21
India	2,973,190	25,861	29,849	0.87	1.00
Nepal	143,350	527	288	0.37	0.20
Sri Lanka	62,710	173	514	0.28	0.82
Israel	**21,640**	**756**	**167**	**3.49**	**0.77**
Jamaica	**10,830**	**47**	**14**	**0.43**	**0.13**
Japan	**364,560**	**4,902**	**325**	**1.34**	**0.09**
Mauritius	**2,040**	**39**	**8**	**1.92**	**0.37**
Mideast	**6,327,218**	**21,440**	**35,218**	**0.34**	**0.56**
Armenia	28,470	20	116	0.07	0.41
Azerbaijan	82,658	156	460	0.19	0.56
Bahrain	760	462	11	2.0/58.74*	1.39
Iran	1,628,550	3,804	12,161	0.23	0.75
Iraq	434,320	638	1,989	0.15	0.46
Jordan	88,780	159	446	0.18	0.50

Kuwait	17,820	1,252	67	7.03	0.38
Lebanon	10,230	215	46	2.10	0.45
Oman	309,500	667	1,172	0.22	0.38
Qatar	11,610	1,634	44	2.0/12.07*	0.38
Saudi Arabia	2,149,690	5,269	9,440	0.25	0.44
Syria	183,630	74	426	0.04	0.23
Turkey	769,630	1,392	6,723	0.18	0.87
UAE	83,600	5,662	2,021	6.77	2.42
Yemen	527,970	37	95	0.01	0.02
New Zealand	**263,310**	**218**	**1,045**	**0.08**	**0.40**
Philippines	**298,170**	**1,633**	**1,186**	**0.55**	**0.40**
Russia Region	**16,446,360**	**1,750**	**24,543**	**0.01**	**0.15**
Georgia	69,490	12	199	0.02	0.29
Russia	16,376,870	1,738	24,344	0.01	0.15
South America	**17,175,466**	**4,533**	**57,010**	**0.03**	**0.33**
Argentina	2,736,690	428	3,225	0.02	0.12
Bolivia	1,083,300	74	470	0.01	0.04
Brazil	8,358,140	2,453	37,116	0.03	0.44
Chile	743,532	358	1,513	0.05	0.20
Colombia	1,109,500	279	4,243	0.03	0.38
Curacao	444	53	7	2.0/10.0*	1.47
Ecuador	248,360	120	1,550	0.05	0.62
Paraguay	397,300	28	214	0.01	0.05
Peru	1,280,000	276	2,898	0.02	0.23
Suriname	156,000	5	51	0.00	0.03
Trinidad/Tobago	5,130	128	14	2.50	0.27
Uruguay	175,020	40	333	0.02	0.19
Venezuela	882,050	292	5,377	0.03	0.61
Southeast Asia	**4,027,647**	**22,030**	**2,633**	**0.55**	**0.07**
Brunei	5,270	68	3	1.30	0.05
Cambodia	176,520	192	79	0.11	0.04
Indonesia	1,811,570	5,917	1,975	0.33	0.11
Lao PDR	230,800	0	0	0.00	0.00
Malaysia	328,550	4,146	143	1.26	0.04
Myanmar	653,290	352	291	0.05	0.04
Singapore	687	619	1	2.0/88.16*	0.14
Thailand	510,890	6,607	146	1.29	0.03
Vietnam	310,070	4,127	-4	1.33	0.00
South Korea	**97,350**	**4,477**	**31**	**4.60**	**0.03**
Taiwan	**36,193**	**1,532**	**152**	**4.23**	**0.42**
United States	**9,147,420**	**28,335**	**76,900**	**0.31**	**0.84**
All regions	**121,464,428**	**205,729**	**440,199**	**0.17**	**0.36**

*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 S22 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 S24. 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 S25.

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

Taken from Jacobson et al. (2019), except "producing heat pumps for district heat" values are estimated here and HVDC transmission job numbers were slightly updated. Values for solar thermal for heat and geothermal heat were taken from values for utility PV and geothermal electricity, respectively. Values for transmission were derived in Jacobson et al. (2017). Jobs for battery construction and operation were estimated low to account for economies of scale and automation of battery manufacturing. Please see Note S9 for more details.

Table S25. 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	**1,898,635**	**1,691,945**	**3,590,580**	**4,545,041**	**-954,461**
Algeria	159,765	135,891	295,656	411,482	-115,826
Angola	29,161	28,443	57,604	249,355	-191,751
Benin	19,443	17,606	37,049	36,585	464
Botswana	8,401	7,497	15,898	9,320	6,578
Cameroon	23,175	22,252	45,427	83,159	-37,732
Congo	8,338	7,972	16,310	65,555	-49,245
Congo, DR	54,316	52,888	107,204	284,465	-177,261
Côte d'Ivoire	25,457	24,216	49,672	71,857	-22,185
Egypt	271,433	228,399	499,833	333,282	166,551
Equator. Guinea	22,050	21,927	43,977	35,419	8,558
Eritrea	1,792	1,503	3,296	7,991	-4,695
Ethiopia	81,883	73,517	155,400	334,804	-179,404
Gabon	34,258	34,454	68,712	51,514	17,198
Ghana	45,616	38,413	84,029	79,853	4,176
Kenya	42,339	39,252	81,591	160,636	-79,045
Libya	57,010	47,296	104,306	189,406	-85,100
Morocco	70,952	59,858	130,810	42,320	88,490
Mozambique	21,527	19,716	41,243	103,467	-62,224
Namibia	8,252	7,240	15,492	26,889	-11,397
Niger	11,472	10,110	21,582	33,811	-12,229
Nigeria	345,505	295,643	641,148	1,117,775	-476,627
Senegal	12,925	11,113	24,038	23,010	1,028
South Africa	312,147	299,835	611,983	239,448	372,535
South Sudan	2,417	2,086	4,503	26,622	-22,119
Sudan	47,152	38,716	85,867	130,461	-44,594
Tanzania	56,015	48,474	104,489	155,345	-50,856
Togo	9,114	8,426	17,540	30,216	-12,676
Tunisia	44,366	39,851	84,216	37,477	46,739
Zambia	42,392	40,473	82,865	87,949	-5,084
Zimbabwe	29,961	28,877	58,839	85,568	-26,729
Australia	**294,709**	**370,042**	**664,751**	**364,616**	**300,135**
Canada	**192,875**	**234,612**	**427,488**	**702,683**	**-275,195**
Central America	**629,663**	**812,400**	**1,442,063**	**559,964**	**882,099**
Costa Rica	14,631	18,821	33,451	11,159	22,292
El Salvador	10,273	13,958	24,230	8,184	16,046
Guatemala	25,606	31,525	57,131	50,988	6,143
Honduras	18,944	25,439	44,383	19,143	25,240
Mexico	519,612	669,444	1,189,056	444,220	744,836
Nicaragua	9,646	12,300	21,946	11,855	10,091
Panama	30,952	40,913	71,865	14,415	57,450
Central Asia	**627,606**	**646,285**	**1,273,891**	**885,570**	**388,321**
Kazakhstan	102,521	100,618	203,140	216,438	-13,298

Kyrgyz Republic	11,248	11,824	23,071	6,716	16,355
Pakistan	404,109	423,855	827,965	411,954	416,011
Tajikistan	7,747	8,711	16,458	6,978	9,480
Turkmenistan	30,489	30,151	60,640	121,282	-60,642
Uzbekistan	71,492	71,125	142,617	122,202	20,415
China Region	**5,277,627**	**6,922,939**	**12,200,567**	**3,007,406**	**9,193,161**
China	5,173,358	6,734,920	11,908,279	2,920,028	8,988,251
Hong Kong	65,859	142,857	208,716	38,140	170,576
Korea, DPR	24,092	29,148	53,240	27,390	25,850
Mongolia	14,318	16,014	30,332	21,848	8,484
Cuba	**53,709**	**61,549**	**115,258**	**20,726**	**94,532**
Europe	**2,317,061**	**3,000,816**	**5,317,877**	**2,282,091**	**3,035,786**
Albania	5,659	5,727	11,386	6,438	4,948
Austria	53,094	63,361	116,455	45,682	70,773
Belarus	39,080	49,120	88,199	30,240	57,959
Belgium	81,793	135,077	216,870	50,866	166,004
Bosnia-Herzeg.	11,124	10,647	21,771	13,999	7,772
Bulgaria	28,625	32,387	61,012	25,502	35,510
Croatia	20,084	21,747	41,831	18,074	23,757
Cyprus	5,956	6,632	12,588	2,986	9,602
Czech Rep.	53,171	66,063	119,233	45,493	73,740
Denmark	24,286	38,795	63,081	35,572	27,509
Estonia	6,423	8,628	15,051	11,195	3,856
Finland	49,435	71,289	120,724	49,149	71,575
France	264,003	300,268	564,271	205,090	359,181
Germany	347,190	489,432	836,622	284,874	551,748
Gibraltar	4,864	9,242	14,106	3,330	10,776
Greece	36,082	43,398	79,480	32,296	47,184
Hungary	46,876	55,222	102,097	31,254	70,843
Ireland	21,516	29,085	50,601	18,569	32,032
Italy	194,288	240,063	434,351	159,664	274,687
Kosovo	4,106	3,819	7,925	4,670	3,255
Latvia	8,655	9,625	18,280	13,501	4,779
Lithuania	14,774	16,567	31,341	14,432	16,909
Luxembourg	8,166	12,575	20,741	4,312	16,429
Macedonia	7,612	7,491	15,103	4,087	11,016
Malta	5,583	9,470	15,053	3,301	11,752
Moldova	9,676	11,041	20,717	8,015	12,702
Montenegro	2,365	2,381	4,745	2,525	2,220
Netherlands	92,766	156,186	248,951	103,044	145,907
Norway	29,099	42,509	71,608	215,796	-144,188
Poland	137,633	137,729	275,362	107,651	167,711
Portugal	34,377	40,577	74,954	34,248	40,706
Romania	46,219	51,407	97,626	60,925	36,701
Serbia	31,064	31,391	62,455	22,114	40,341
Slovakia	23,476	25,940	49,416	17,269	32,147
Slovenia	10,764	11,429	22,193	9,161	13,032
Spain	161,346	207,535	368,881	129,201	239,680
Sweden	59,394	90,209	149,603	68,455	81,148
Switzerland	33,438	38,398	71,836	28,505	43,331
Ukraine	114,893	129,152	244,045	106,762	137,283
United Kingdom	188,108	289,205	477,313	253,844	223,469
Haiti Region	**40,725**	**44,515**	**85,241**	**39,348**	**45,893**
Dominican Rep.	29,664	32,055	61,719	15,918	45,801
Haiti	11,061	12,460	23,522	23,430	92
Iceland	**2,002**	**5,850**	**7,852**	**4,635**	**3,217**
India Region	**3,335,303**	**3,966,804**	**7,302,107**	**2,611,937**	**4,690,170**
Bangladesh	184,794	263,839	448,634	178,224	270,410
India	3,056,842	3,587,266	6,644,107	2,305,949	4,338,158
Nepal	50,238	70,633	120,871	81,596	39,275
Sri Lanka	43,429	45,066	88,495	46,168	42,327
Israel	**85,281**	**117,882**	**203,163**	**33,687**	**169,476**

Jamaica	**15,967**	**12,130**	**28,096**	**5,617**	**22,479**
Japan	**556,469**	**630,995**	**1,187,464**	**260,005**	**927,459**
Mauritius	**36,700**	**18,804**	**55,504**	**5,543**	**49,961**
Mideast	**2,086,999**	**2,628,244**	**4,715,243**	**3,692,453**	**1,022,790**
Armenia	4,927	5,399	10,326	4,053	6,273
Azerbaijan	24,127	24,698	48,825	85,860	-37,035
Bahrain	27,582	44,303	71,885	52,125	19,760
Iran	554,158	637,998	1,192,156	845,831	346,325
Iraq	95,149	100,248	195,396	426,300	-230,904
Jordan	27,078	31,732	58,810	16,145	42,665
Kuwait	69,274	111,529	180,803	253,173	-72,370
Lebanon	22,723	33,932	56,655	13,161	43,494
Oman	74,597	97,366	171,963	157,681	14,282
Qatar	82,038	132,224	214,263	293,984	-79,721
Saudi Arabia	511,188	609,933	1,121,121	988,951	132,170
Syria	22,964	24,907	47,870	24,569	23,301
Turkey	257,168	294,863	552,031	125,714	426,317
UAE	304,686	469,263	773,949	394,325	379,624
Yemen	9,341	9,849	19,190	10,581	8,609
New Zealand	**51,022**	**64,623**	**115,645**	**39,965**	**75,680**
Philippines	**228,355**	**277,126**	**505,481**	**137,336**	**368,145**
Russia Region	**409,432**	**542,203**	**951,635**	**1,254,245**	**-302,610**
Georgia	5,956	7,415	13,370	7,855	5,515
Russia	403,476	534,788	938,264	1,246,390	-308,126
South America	**1,051,806**	**1,175,991**	**2,227,797**	**1,965,734**	**262,063**
Argentina	93,134	94,131	187,265	197,295	-10,030
Bolivia	15,142	15,809	30,952	54,397	-23,445
Brazil	596,379	672,291	1,268,670	925,761	342,909
Chile	65,821	69,778	135,599	91,126	44,473
Colombia	76,396	85,352	161,748	185,593	-23,845
Curacao	5,062	8,841	13,903	4,261	9,642
Ecuador	28,807	33,169	61,976	76,516	-14,540
Paraguay	9,286	9,992	19,278	36,392	-17,114
Peru	52,774	59,477	112,251	82,691	29,560
Suriname	1,617	1,712	3,329	500	2,829
Trinidad/Tobago	13,591	18,385	31,977	67,072	-35,095
Uruguay	11,338	12,732	24,070	17,292	6,778
Venezuela	82,459	94,321	176,780	226,838	-50,058
Southeast Asia	**2,687,913**	**2,413,052**	**5,100,965**	**1,987,573**	**3,113,392**
Brunei	8,137	7,255	15,392	33,511	-18,119
Cambodia	38,362	32,655	71,017	44,553	26,464
Indonesia	840,304	692,706	1,533,010	761,441	771,569
Lao PDR	4,841	5,032	9,873	29,551	-19,678
Malaysia	401,835	381,186	783,021	293,793	489,228
Myanmar	69,155	59,102	128,257	131,930	-3,673
Singapore	261,074	129,808	390,882	97,357	293,525
Thailand	574,682	600,938	1,175,620	365,181	810,439
Vietnam	489,523	504,369	993,893	230,256	763,637
South Korea	**713,075**	**673,222**	**1,386,297**	**195,903**	**1,190,394**
Taiwan	**372,860**	**446,729**	**819,588**	**109,361**	**710,227**
United States	**2,406,342**	**3,424,730**	**5,831,072**	**2,478,720**	**3,352,352**
All regions	**25,372,136**	**30,183,488**	**55,555,625**	**27,190,159**	**28,365,466**

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 S9) minus the 2020 nameplate capacities (Table S8) 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 S24 by year and country. For storage, the number of jobs per MW from Table S24 is multiplied by the maximum discharge rate of the storage technology for each region (Table S13). The transmission/distribution jobs are calculated as in the spreadsheet (Jacobson and Delucchi, 2021).

Table S26. R values from scatterplot of hourly (during the year) GATOR-GCMOM-modeled (a) heat load versus wind energy output and (b) wind energy output versus solar energy output. The plots for each value are shown in Figure S2, last row, for each region

Region	(a) Heat load vs. wind power output	(b) Wind vs. solar power output
Africa	0.35	(0.33)
Australia	**0.63**	(0.20)
Canada	**0.82**	(0.22)
Central America	**0.81**	(0.19)
Central Asia	*0.58*	(0.33)
China	**0.73**	(0.18)
Cuba	(0.15)	(0.19)
Europe	**0.81**	(0.38)
Haiti	0.08	(0.17)
Iceland	*0.50*	--
India	*0.45*	(0.17)
Israel	0.15	(0.28)
Jamaica	0.24	(0.19)
Japan	**0.61**	(0.22)
Mauritius	0.04	(0.16)
Mideast	*0.44*	(0.33)
New Zealand	0.28	(0.15)
Philippines	(0.05)	(0.14)
Russia	**0.76**	(0.36)
South America	**0.71**	(0.01)
Southeast Asia	**0.73**	(0.00)
South Korea	*0.51*	(0.10)
Taiwan	**0.71**	(0.16)
United States	**0.73**	(0.23)

Correlations are very strong for R=0.8-1; strong for R=0.6-0.79; moderate for R=0.4-0.59; weak for 0.2-0.39; and very weak for 0-0.19 (Evans, 1996). Very strong and strong R values are in bold; moderate values are in italics, and the rest are plain. Parentheses indicate negative correlations. All other correlations are positive. – means no solar installed for the Iceland roadmap.

Supporting Figures

Figure S1. Main generation, transmission, storage, and use components of a 100% WWS system to provide energy for all purposes.

WWS Generation

WWS electricity generation
- Onshore/offshore wind
- Rooftop/utility photovoltaics
- Concentrated solar power
- Geothermal
- Hydro
- Tidal & wave

WWS heat generation
- Solar thermal/CSP steam
- Geothermal heat

WWS Grid

Transmission/distribution (T&D)
- AC/HVAC/HVDC lines
- Distribution lines
- Grid management
  - Software
  - Demand response

WWS Storage

Electricity storage
- Batteries
- CSP storage
- Pumped hydropower storage
- Hydropower reservoirs
- Flywheels
- Compressed air
- Gravitational storage

District heat storage
- Water tanks
- Boreholes/water pits/aquifers

District cold storage
- Water tanks/ice
- Aquifers

Building heat storage
- Water tank storage
- Thermal mass

Hydrogen storage
- Hydrogen storage tanks

WWS Equipment

Building and district air+water heating
- Electric heat pumps

Building and district cooling
- Electric heat pumps

Industrial heat
- Arc/induction/resistance furnaces
- Dielectric heaters
- Electron beam heaters
- Heat pumps/CSP steam

Hydrogen generation/compression
- Electrolyzers/compressors

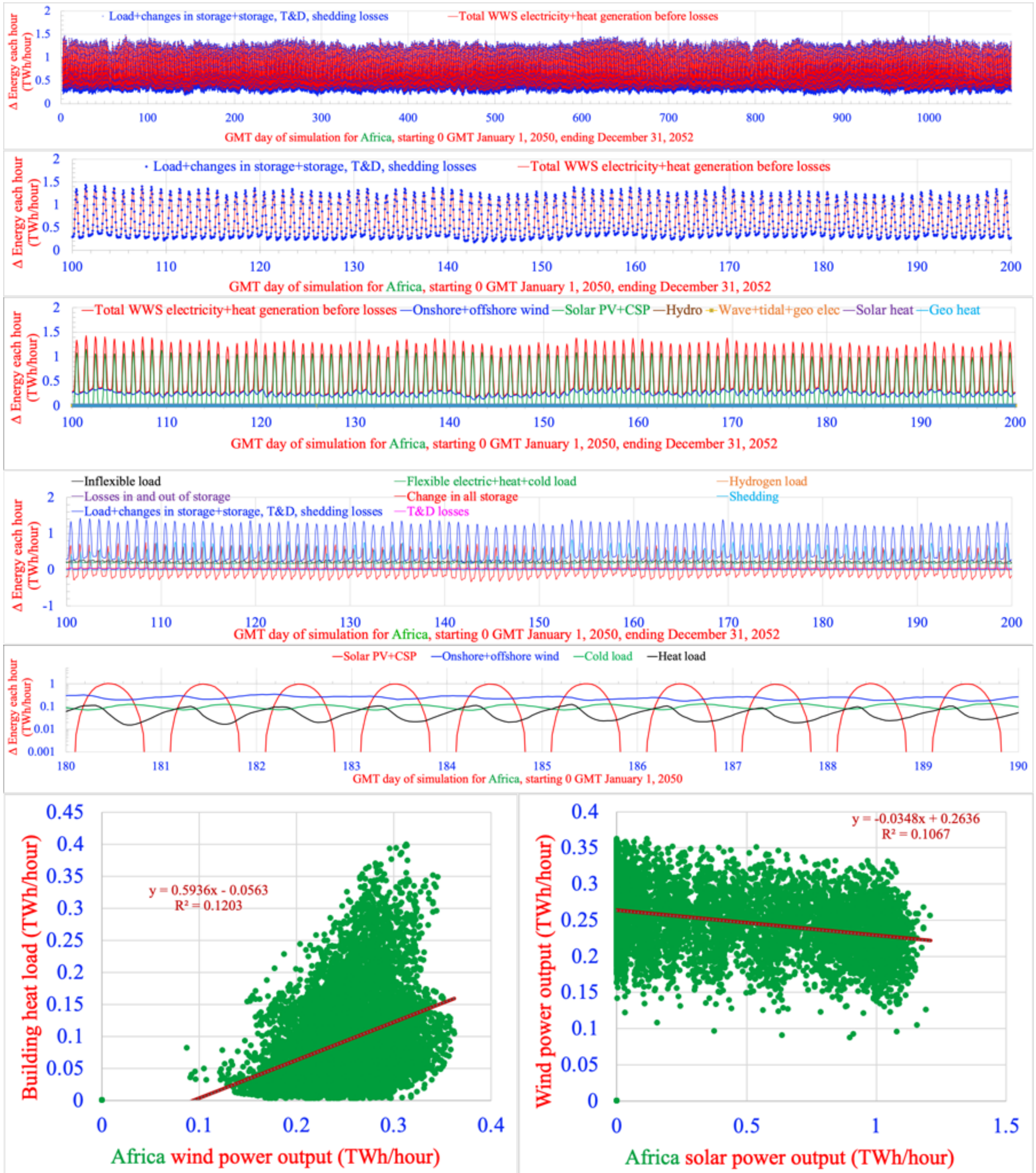
Transportation vehicles
- Battery-electric
- Hydrogen fuel cell

Some appliances/machines
- Induction cooktops
- Electric leafblowers/lawnmowers
- Heat pump dryers

Efficiency/reduce energy use
- Insulate/weatherize buildings
- LED lights/efficient appliances
- Telecommute/improve public transit

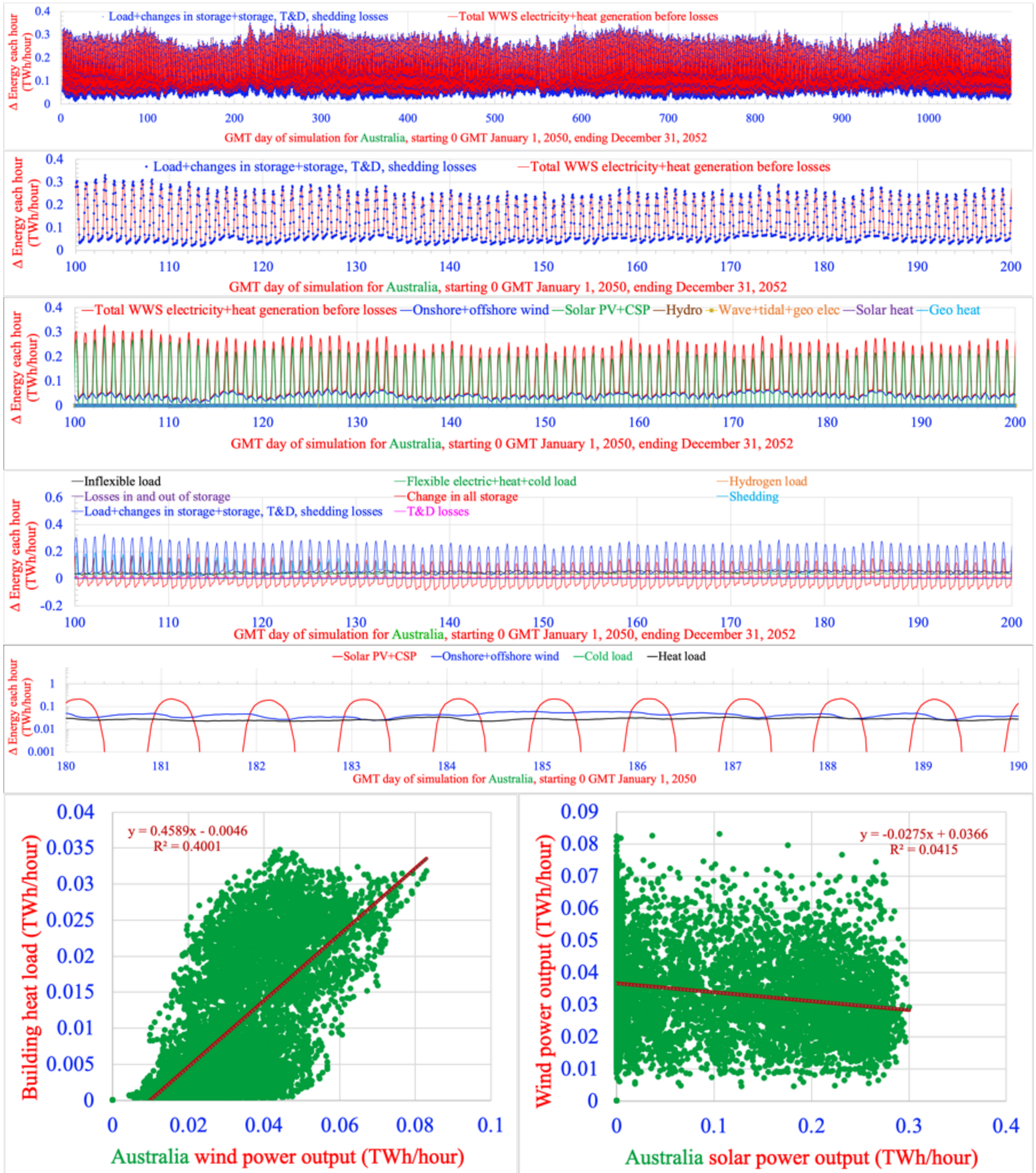
Figure S2. 2050-2052 hourly time series showing the matching of all-energy demand with supply and storage for the regions defined in Table S1. First row: modeled time-dependent total WWS power generation versus load plus losses plus changes in storage plus shedding for the full three-year simulation period. Second row: same as first row, but for a window of 100 days during 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; Sixth row: correlation plots of building heat load versus wind power output and wind power output versus solar power output, obtained from all hourly data during the simulation. No wind versus solar plot is shown for Iceland because no solar is installed in Iceland for this study. Correlations are very strong for R=0.8-1 (R^2=0.64-1); strong for R=0.6-0.8 (R^2=0.36-0.64); moderate for R=0.4-0.6 (R^2=0.16-0.36); weak for 0.2-0.4 (R^2=0.04-0.16); and very weak for 0-0.2 (R^2=0-0.04) (Evans, 1996). 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



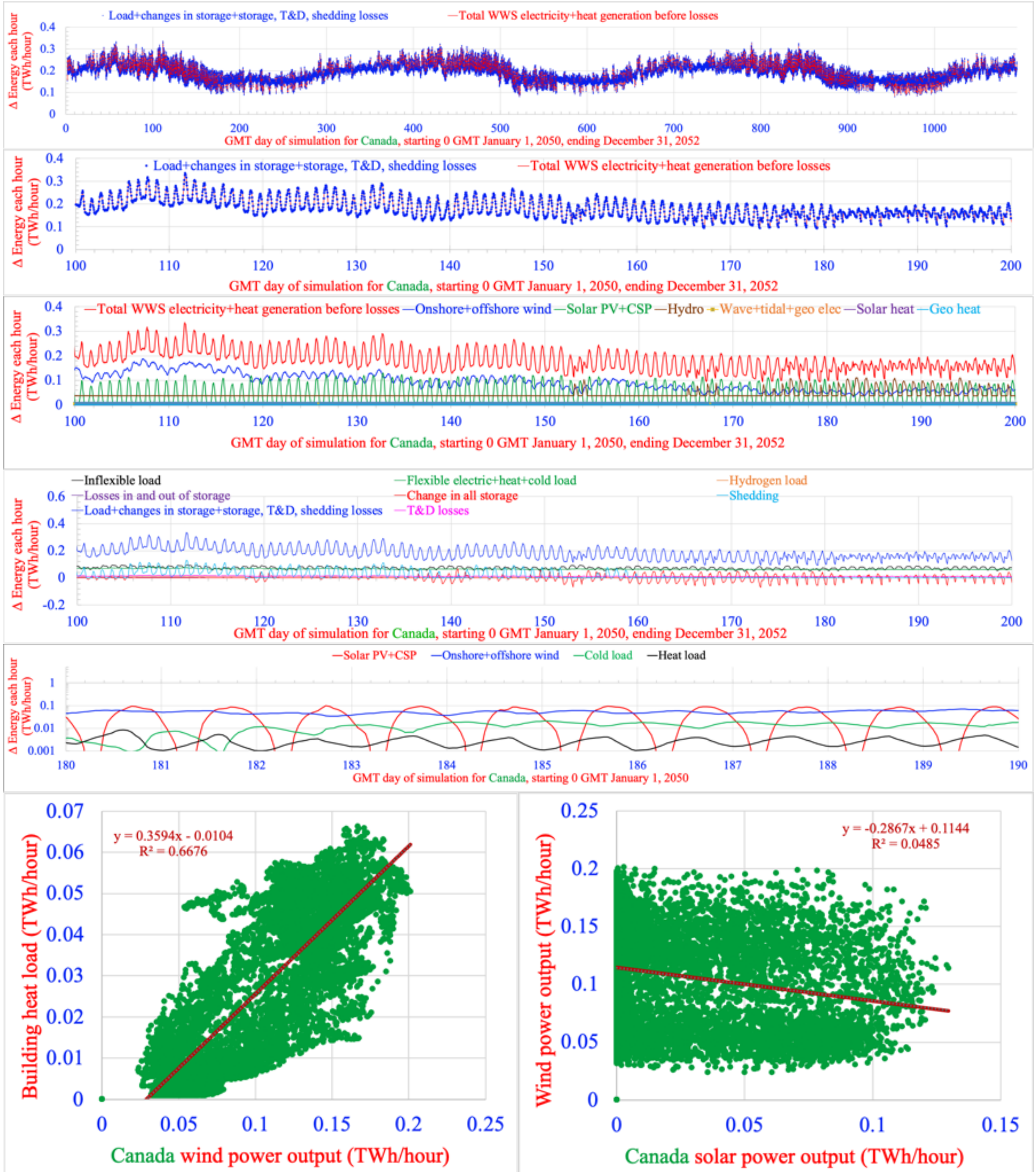
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Africa, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
GMT day of simulation for Africa, starting 0 GMT January 1, 2050
y = 0.5936x - 0.0563
R² = 0.1203
Building heat load (TWh/hour)
Africa wind power output (TWh/hour)
y = -0.0348x + 0.2636
R² = 0.1067
Wind power output (TWh/hour)
Africa solar power output (TWh/hour)

AUSTRALIA

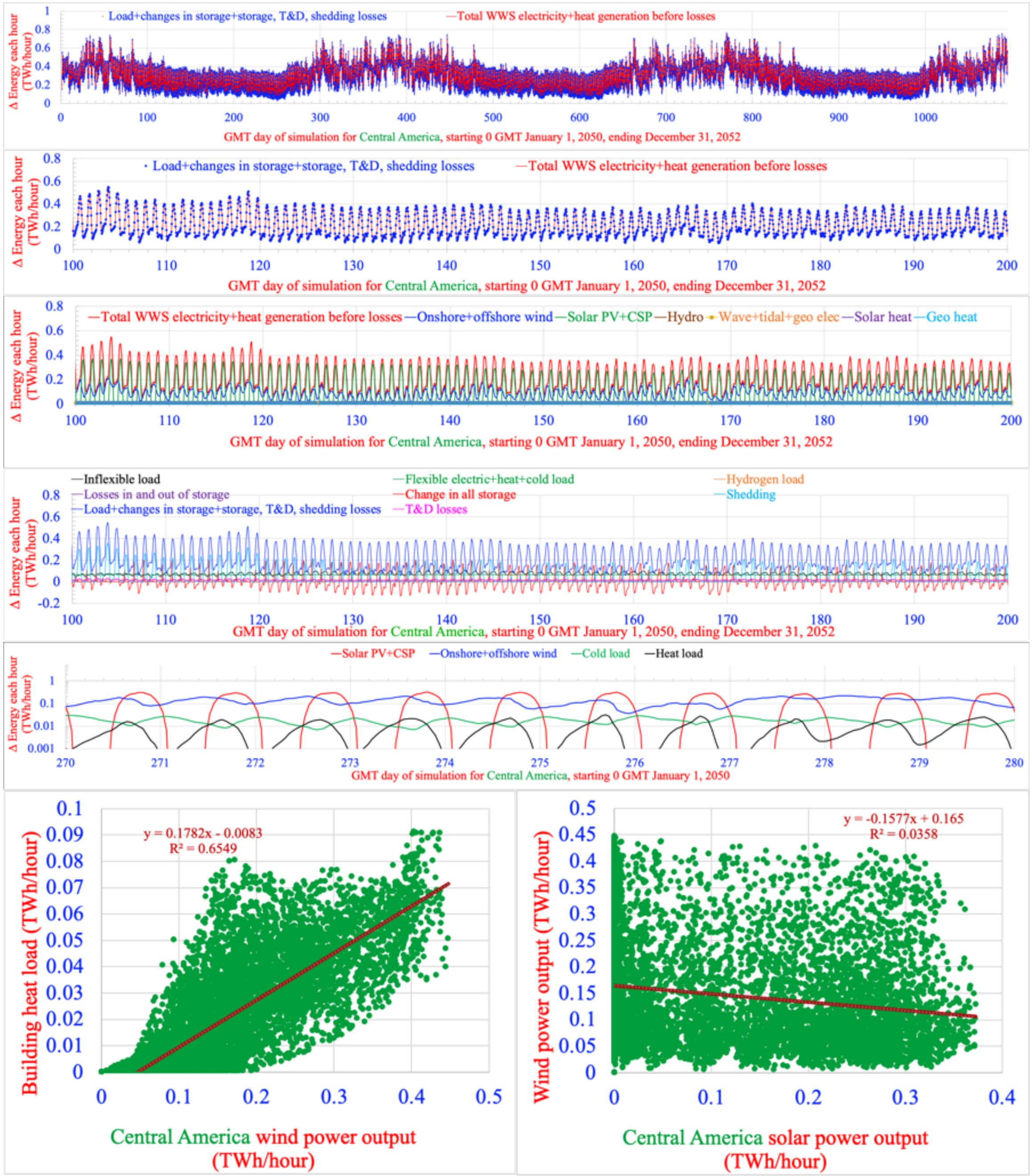


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Australia, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
GMT day of simulation for Australia, starting 0 GMT January 1, 2050
y = 0.4589x - 0.0046
R² = 0.4001
Building heat load (TWh/hour)
Australia wind power output (TWh/hour)
y = -0.0275x + 0.0366
R² = 0.0415
Wind power output (TWh/hour)
Australia solar power output (TWh/hour)

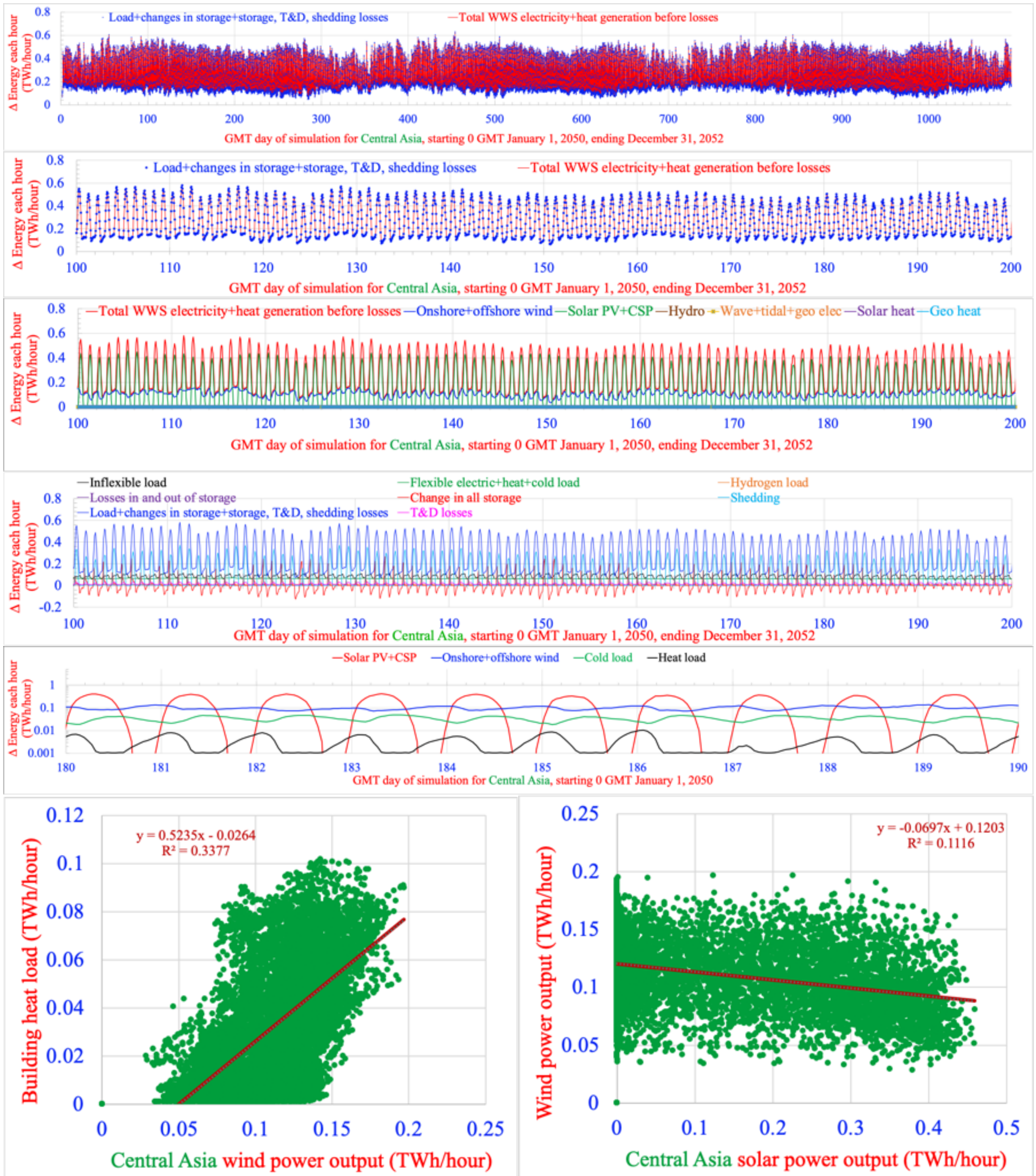
CANADA


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
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
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
GMT day of simulation for Canada, starting 0 GMT January 1, 2050
y = 0.3594x - 0.0104
R² = 0.6676
Building heat load (TWh/hour)
Canada wind power output (TWh/hour)
y = -0.2867x + 0.1144
R² = 0.0485
Wind power output (TWh/hour)
Canada solar power output (TWh/hour)

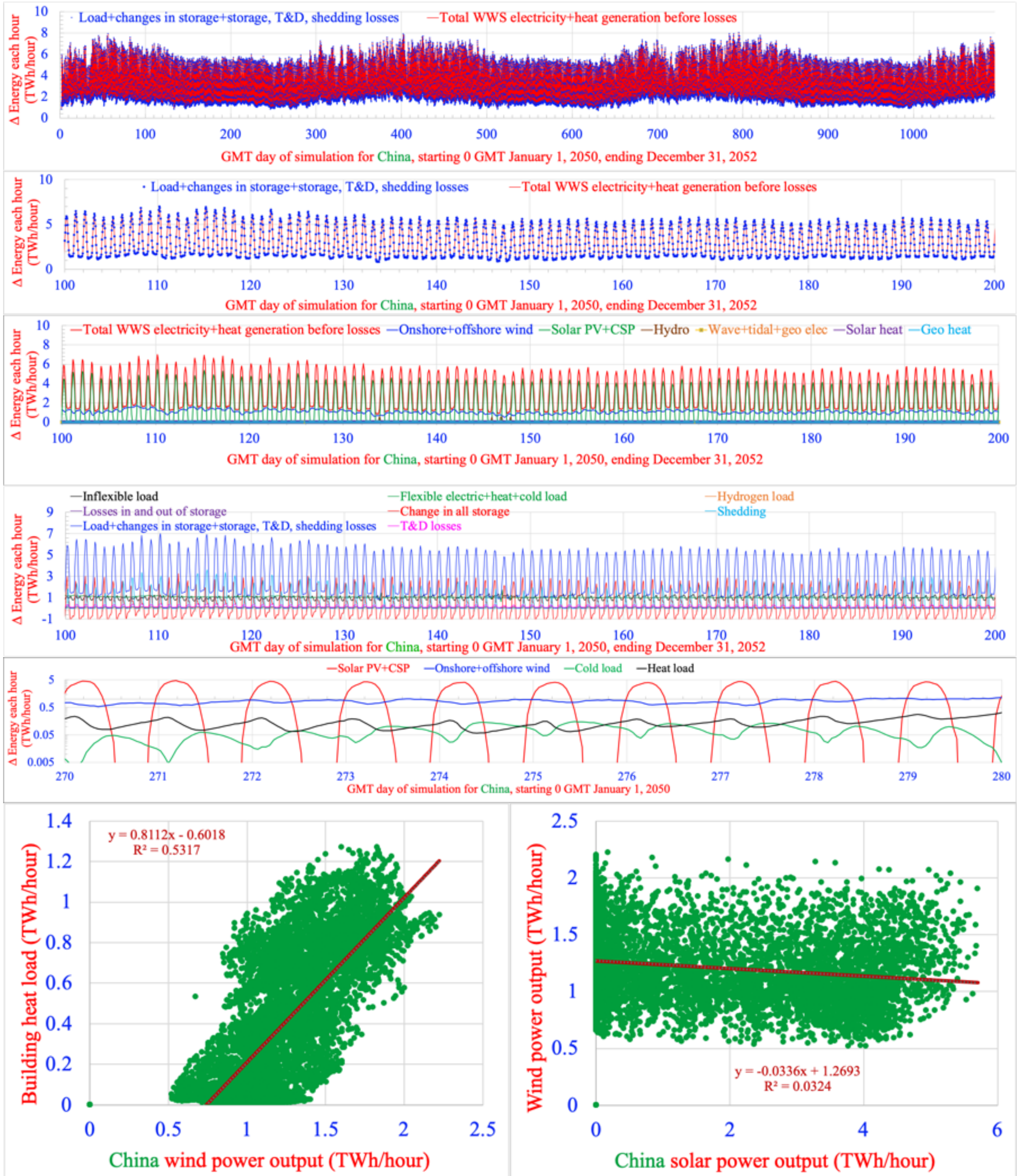
CENTRAL AMERICA



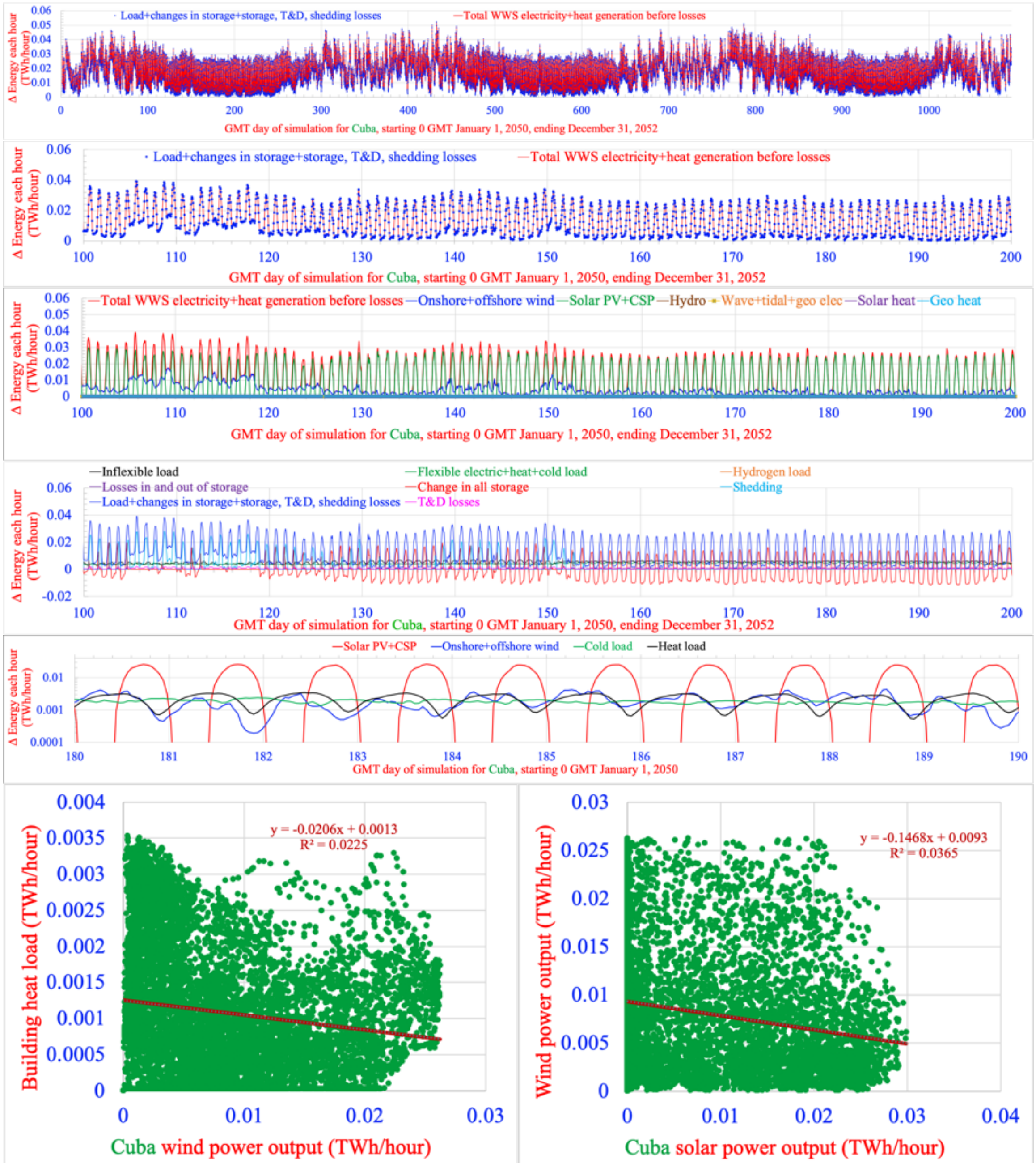
CENTRAL ASIA



CHINA REGION

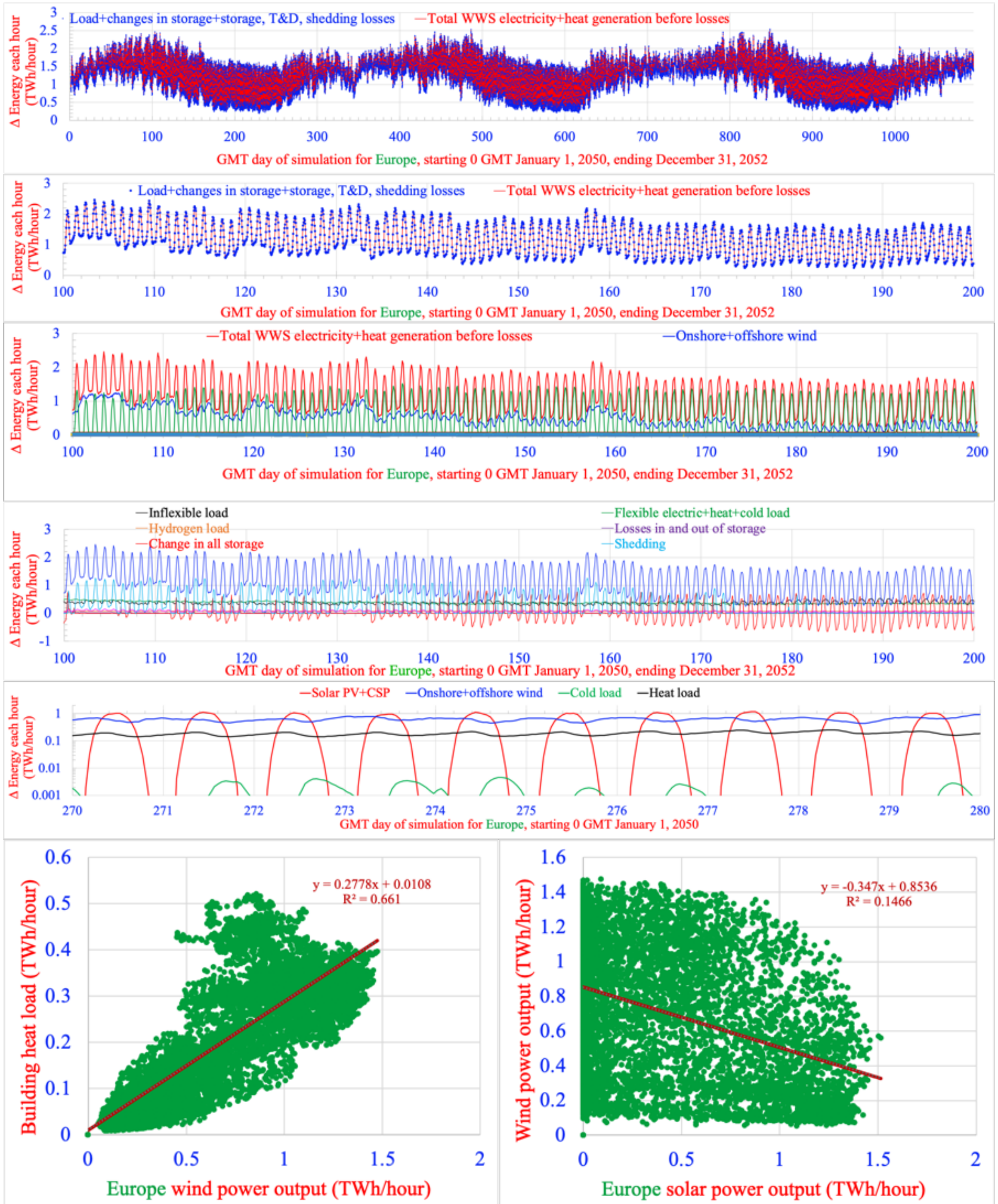


CUBA

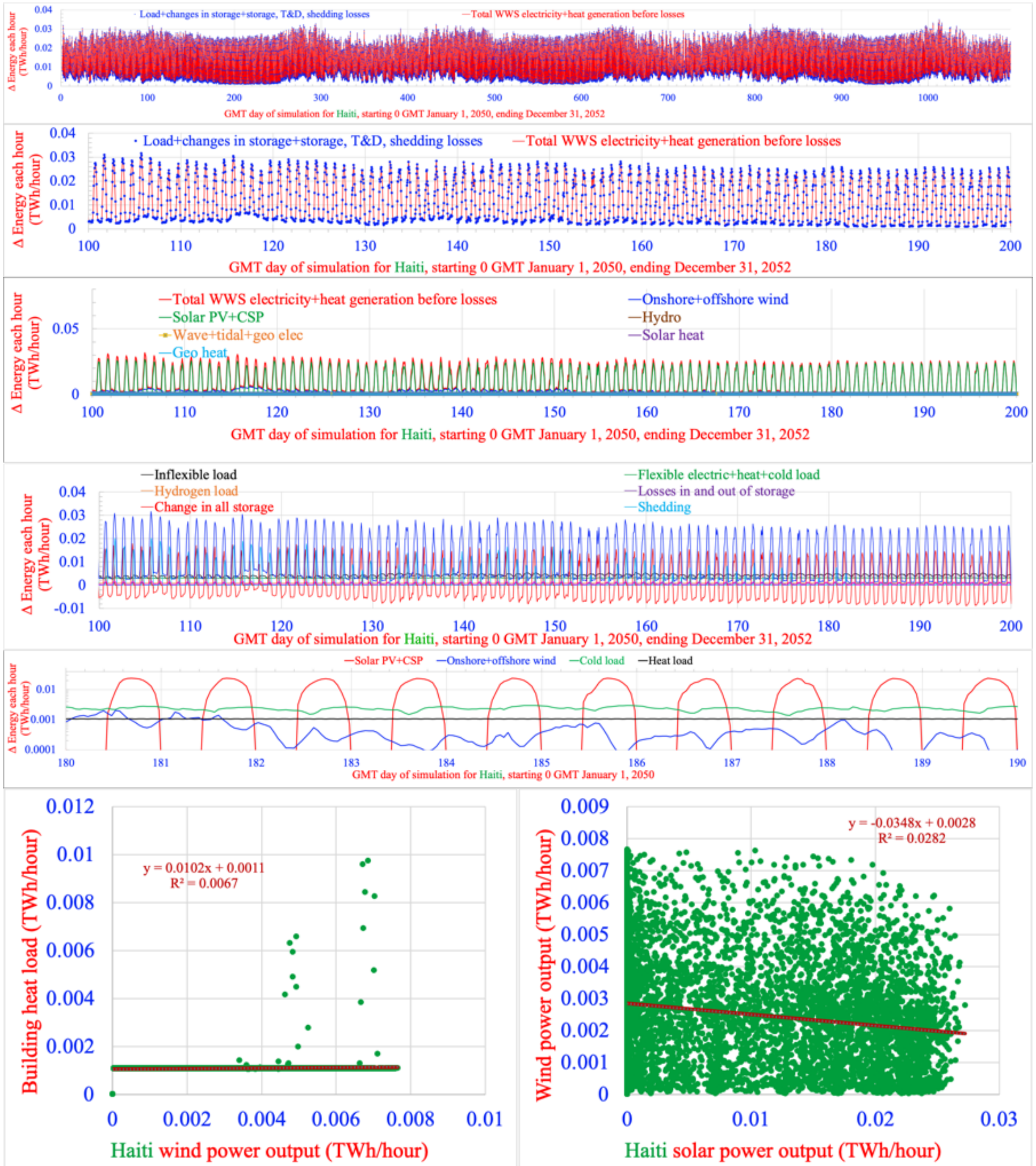


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Cold load
Heat load
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050
y = -0.0206x + 0.0013
R² = 0.0225
Building heat load (TWh/hour)
Cuba wind power output (TWh/hour)
y = -0.1468x + 0.0093
R² = 0.0365
Wind power output (TWh/hour)
Cuba solar power output (TWh/hour)

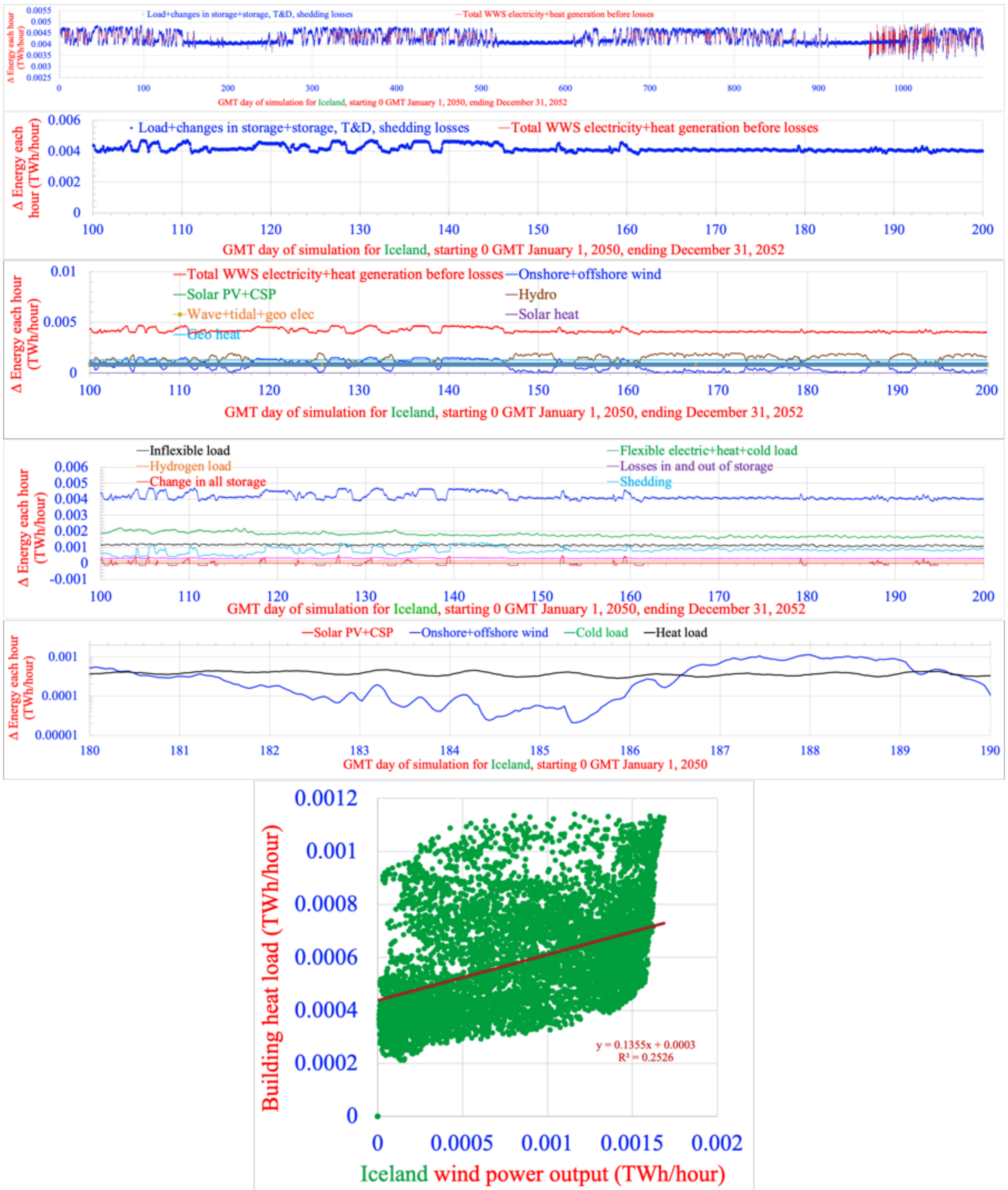
EUROPE


Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Europe, 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)
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
Δ Energy each hour (TWh/hour)
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)
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)
GMT day of simulation for Europe, starting 0 GMT January 1, 2050
y = 0.2778x + 0.0108
R² = 0.661
Building heat load (TWh/hour)
Europe wind power output (TWh/hour)
y = -0.347x + 0.8536
R² = 0.1466
Wind power output (TWh/hour)
Europe solar power output (TWh/hour)

HAITI REGION

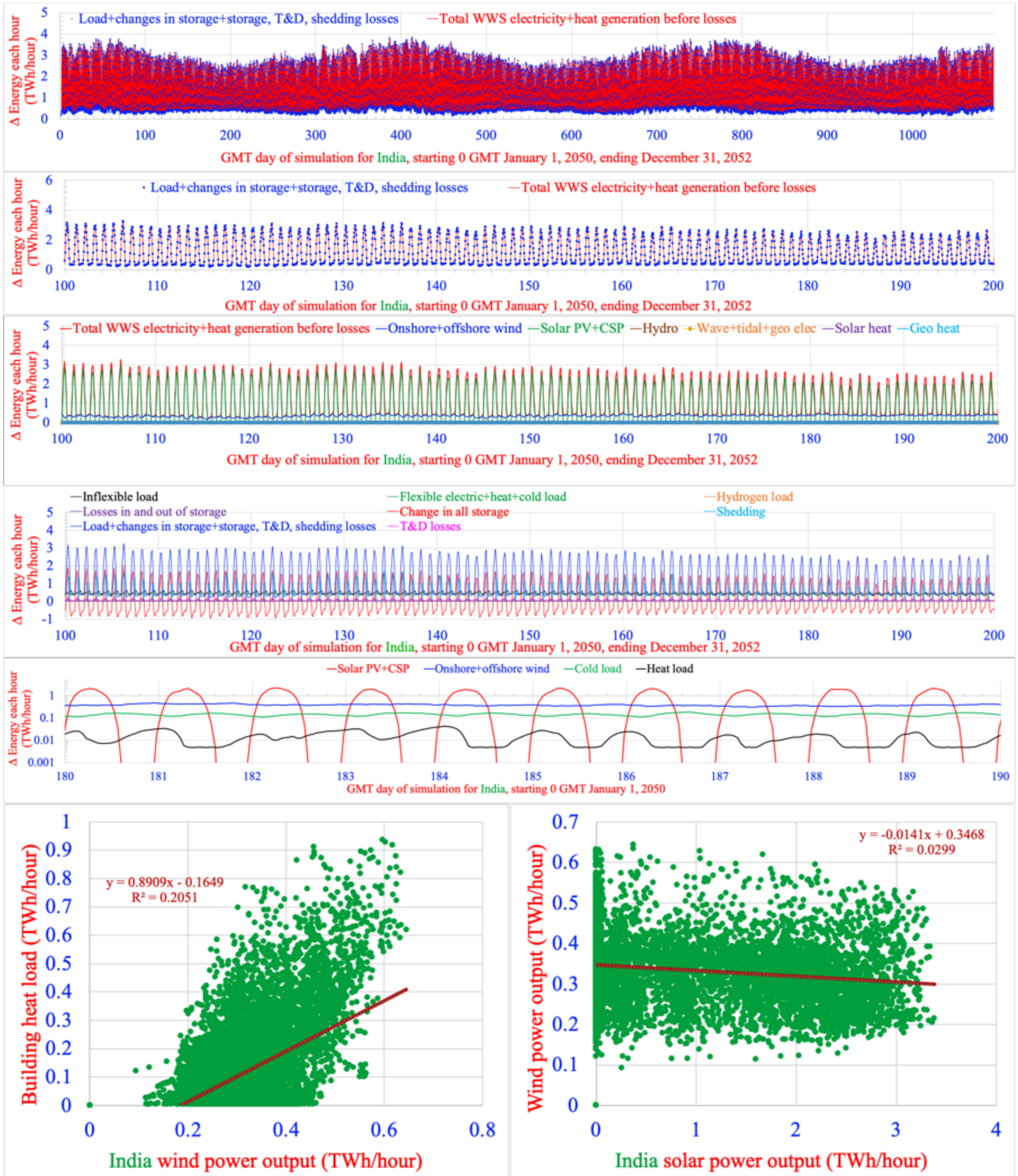


ICELAND

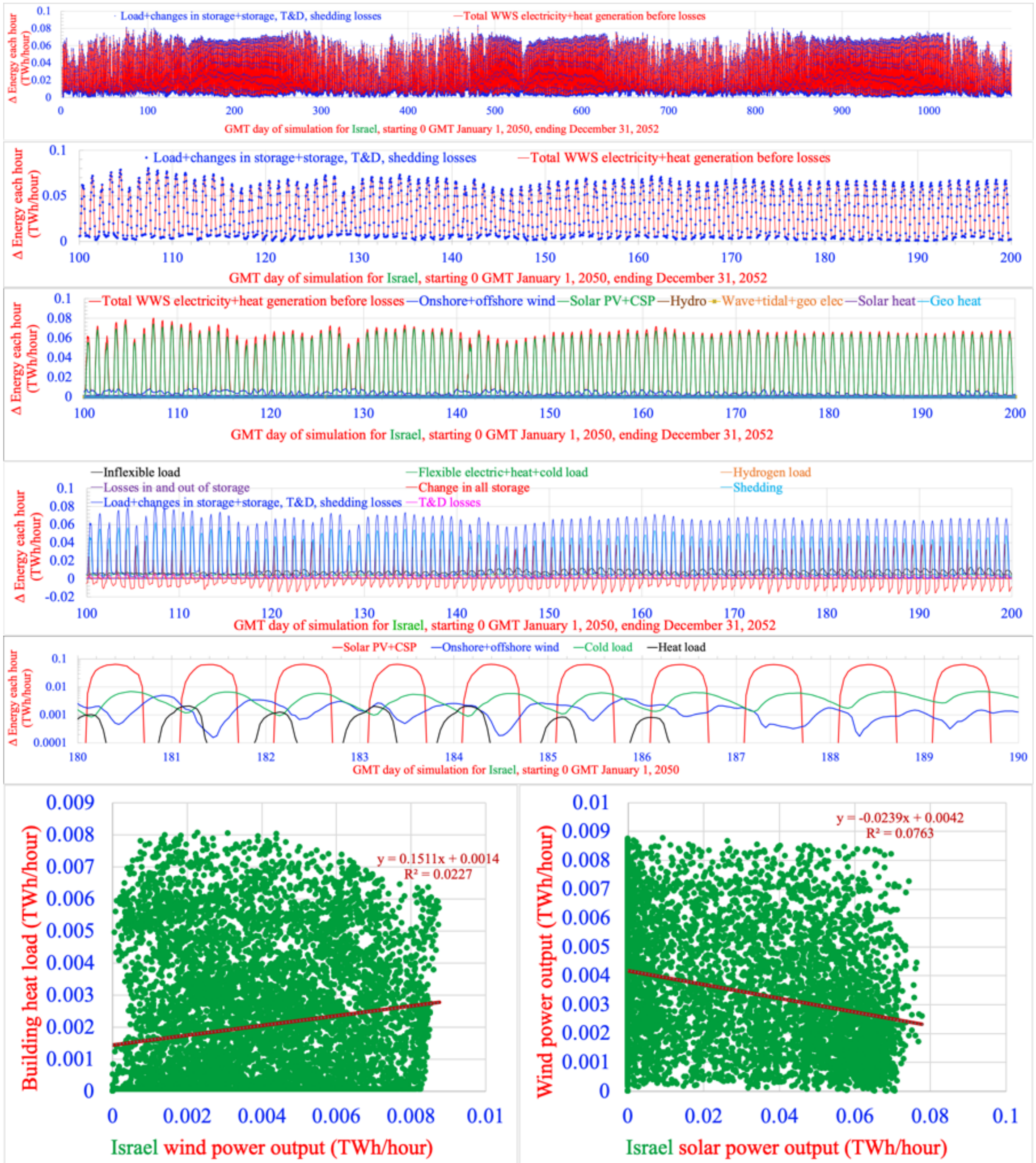


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050
Building heat load (TWh/hour)
Iceland wind power output (TWh/hour)
y = 0.1355x + 0.0003
R² = 0.2526

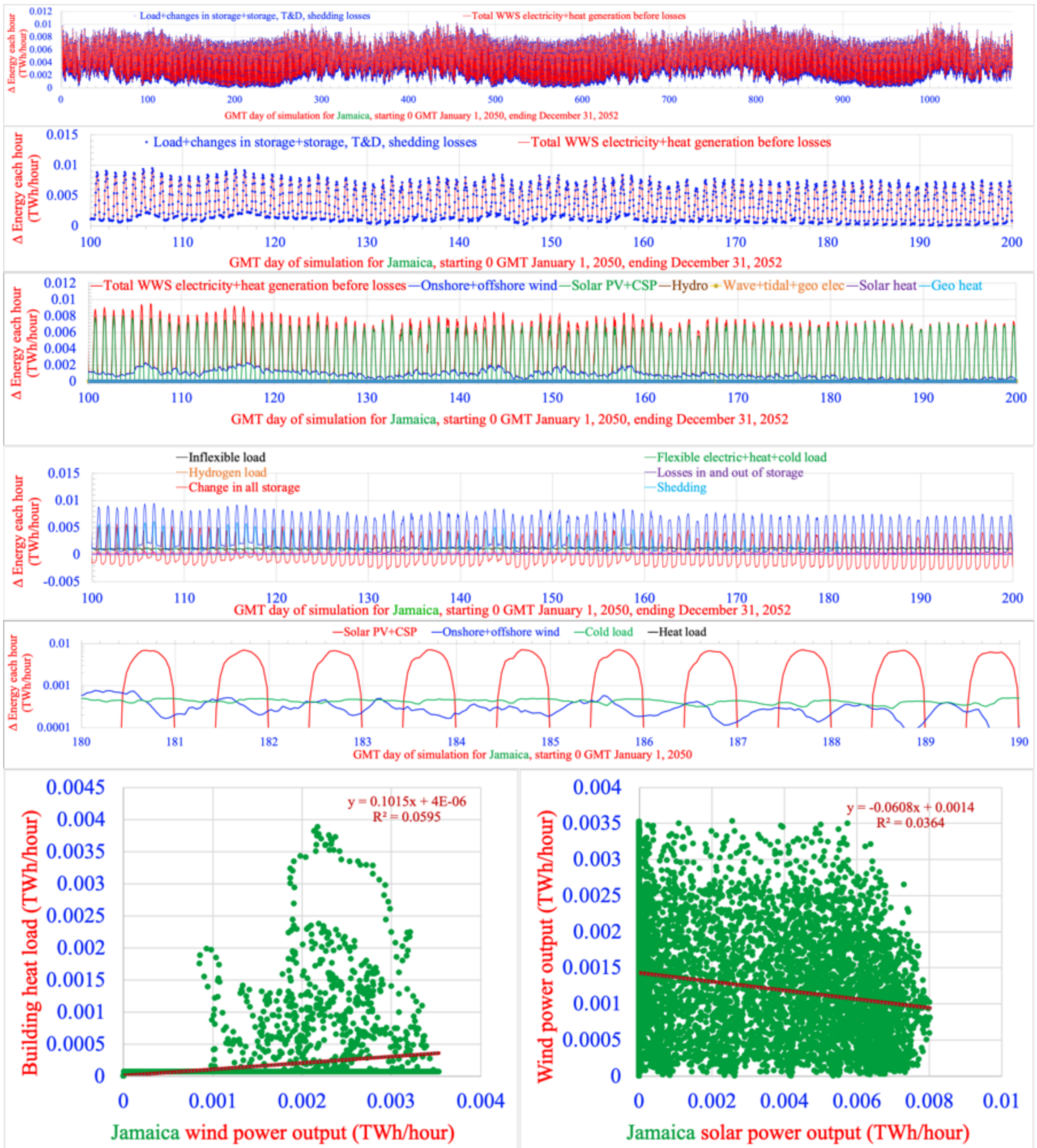
INDIA REGION



ISRAEL

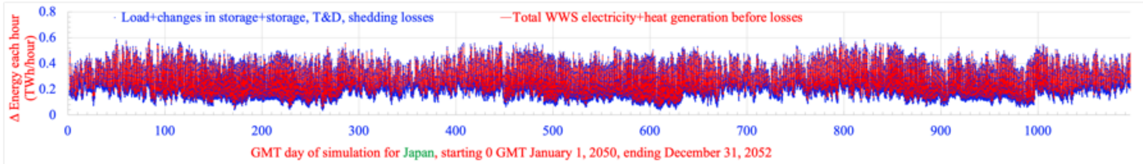

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Cold load
Heat load
GMT day of simulation for Israel, starting 0 GMT January 1, 2050
y = 0.1511x + 0.0014
R² = 0.0227
Building heat load (TWh/hour)
Israel wind power output (TWh/hour)
y = -0.0239x + 0.0042
R² = 0.0763
Wind power output (TWh/hour)
Israel solar power output (TWh/hour)

JAMAICA



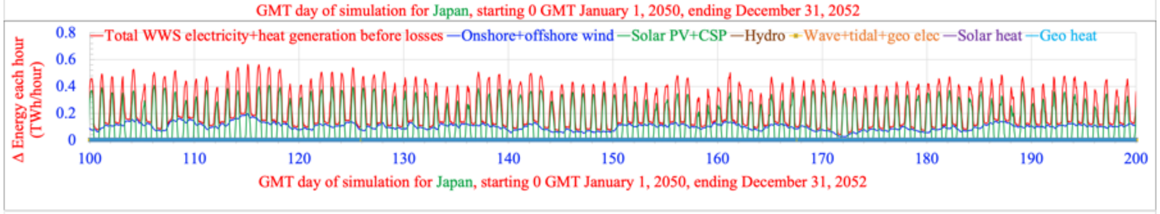
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050
y = 0.1015x + 4E-06
R² = 0.0595
Building heat load (TWh/hour)
Jamaica wind power output (TWh/hour)
y = -0.0608x + 0.0014
R² = 0.0364
Wind power output (TWh/hour)
Jamaica solar power output (TWh/hour)

JAPAN

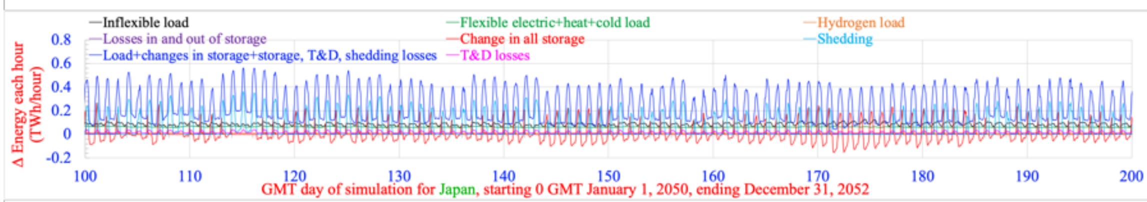


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052

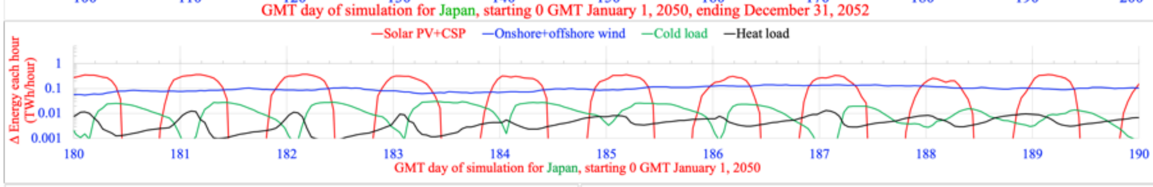
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



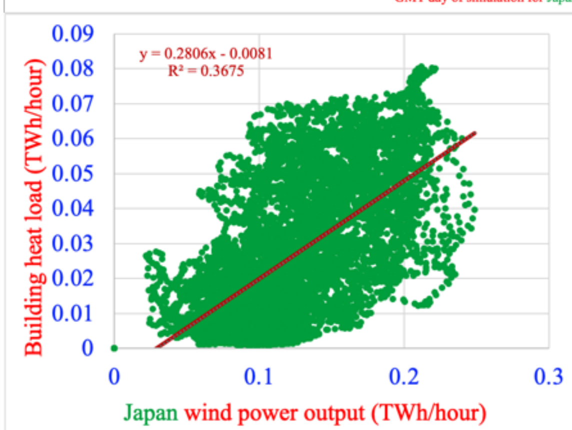
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



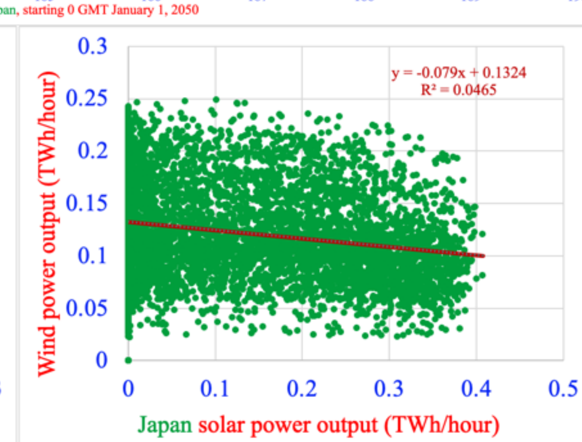
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052



Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
GMT day of simulation for Japan, starting 0 GMT January 1, 2050

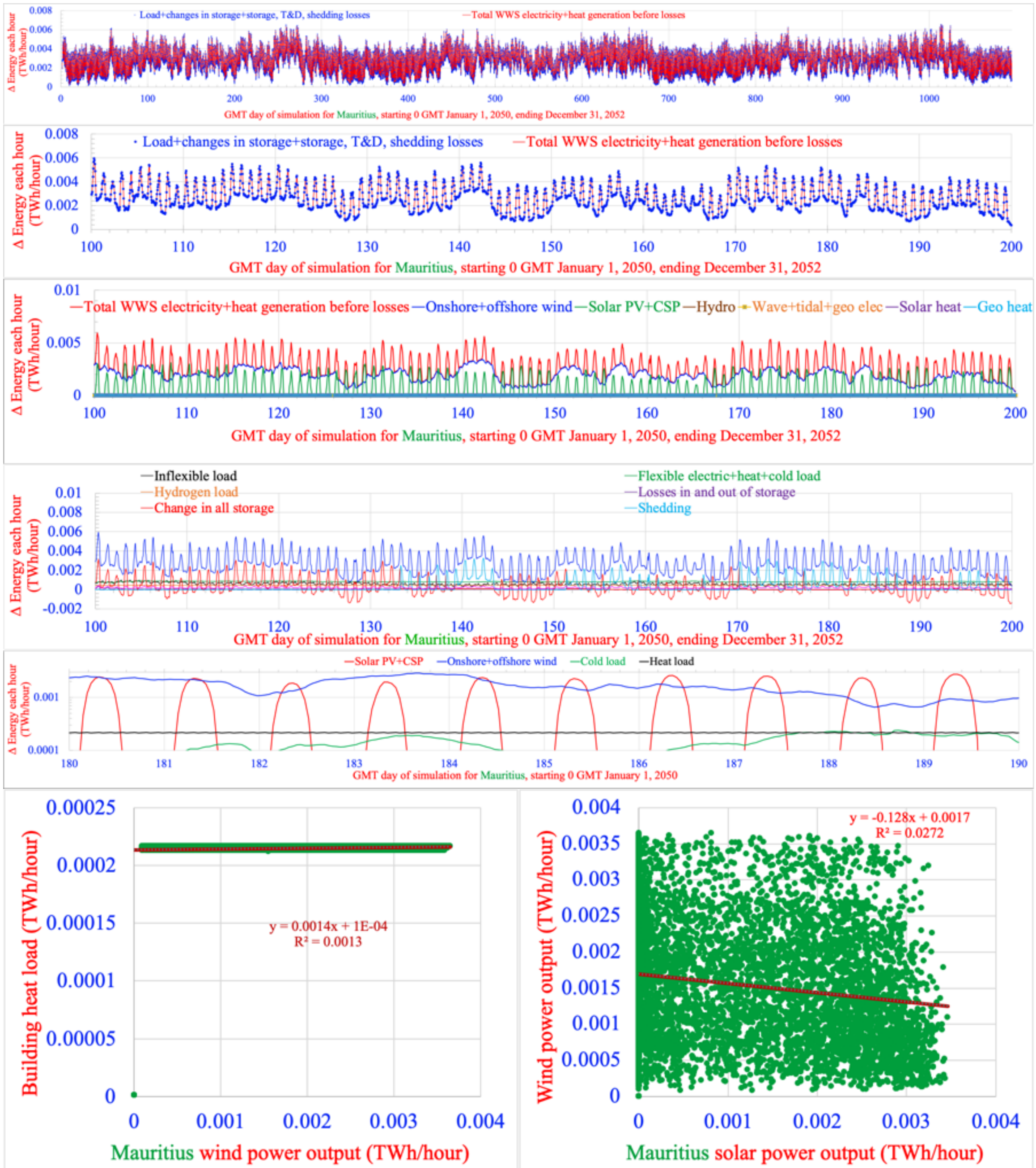


y = 0.2806x - 0.0081
R² = 0.3675
Building heat load (TWh/hour)
Japan wind power output (TWh/hour)



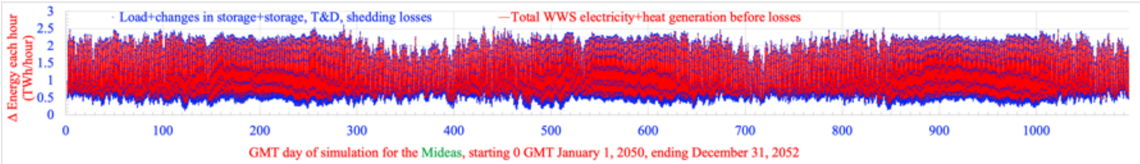
y = -0.079x + 0.1324
R² = 0.0465
Wind power output (TWh/hour)
Japan solar power output (TWh/hour)

MAURITIUS

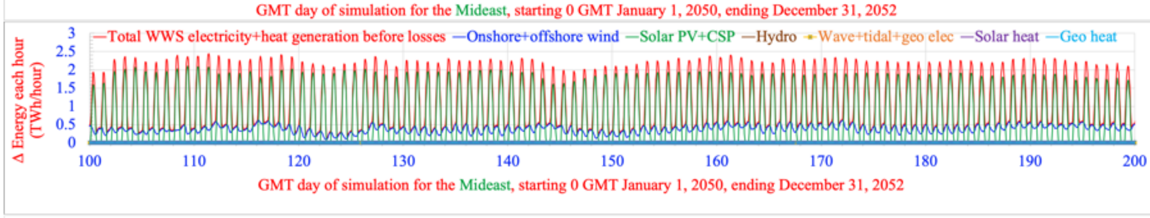


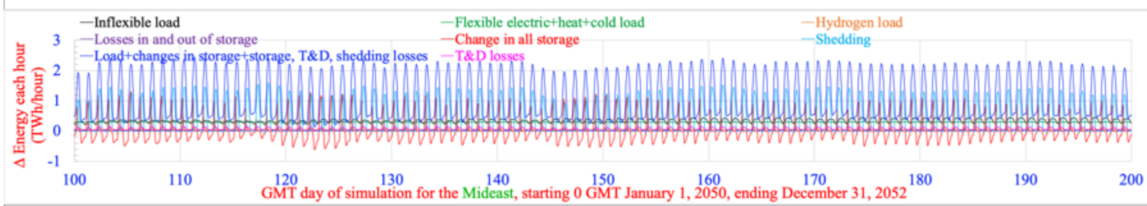
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
Cold load
Heat load
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050
Building heat load (TWh/hour)
Mauritius wind power output (TWh/hour)
y = 0.0014x + 1E-04
R² = 0.0013
Wind power output (TWh/hour)
Mauritius solar power output (TWh/hour)
y = -0.128x + 0.0017
R² = 0.0272

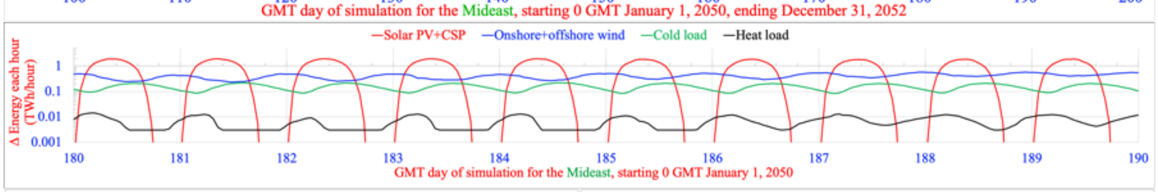
MIDEAST

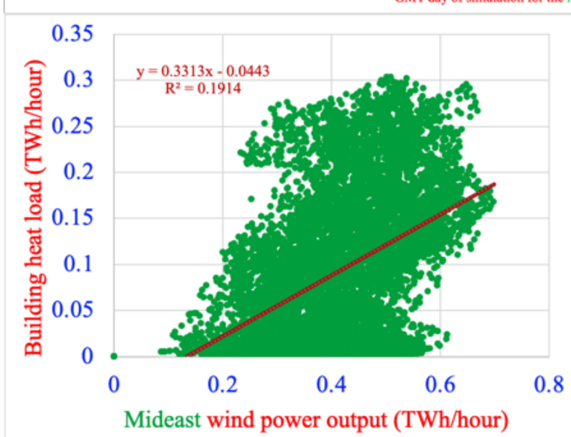

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for the Mideas, starting 0 GMT January 1, 2050, ending December 31, 2052

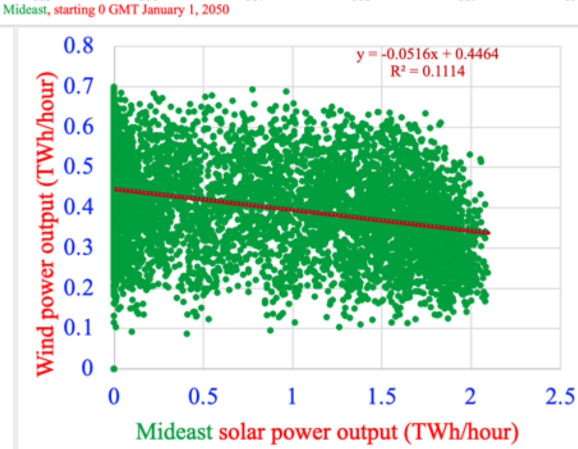

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052


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)
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052

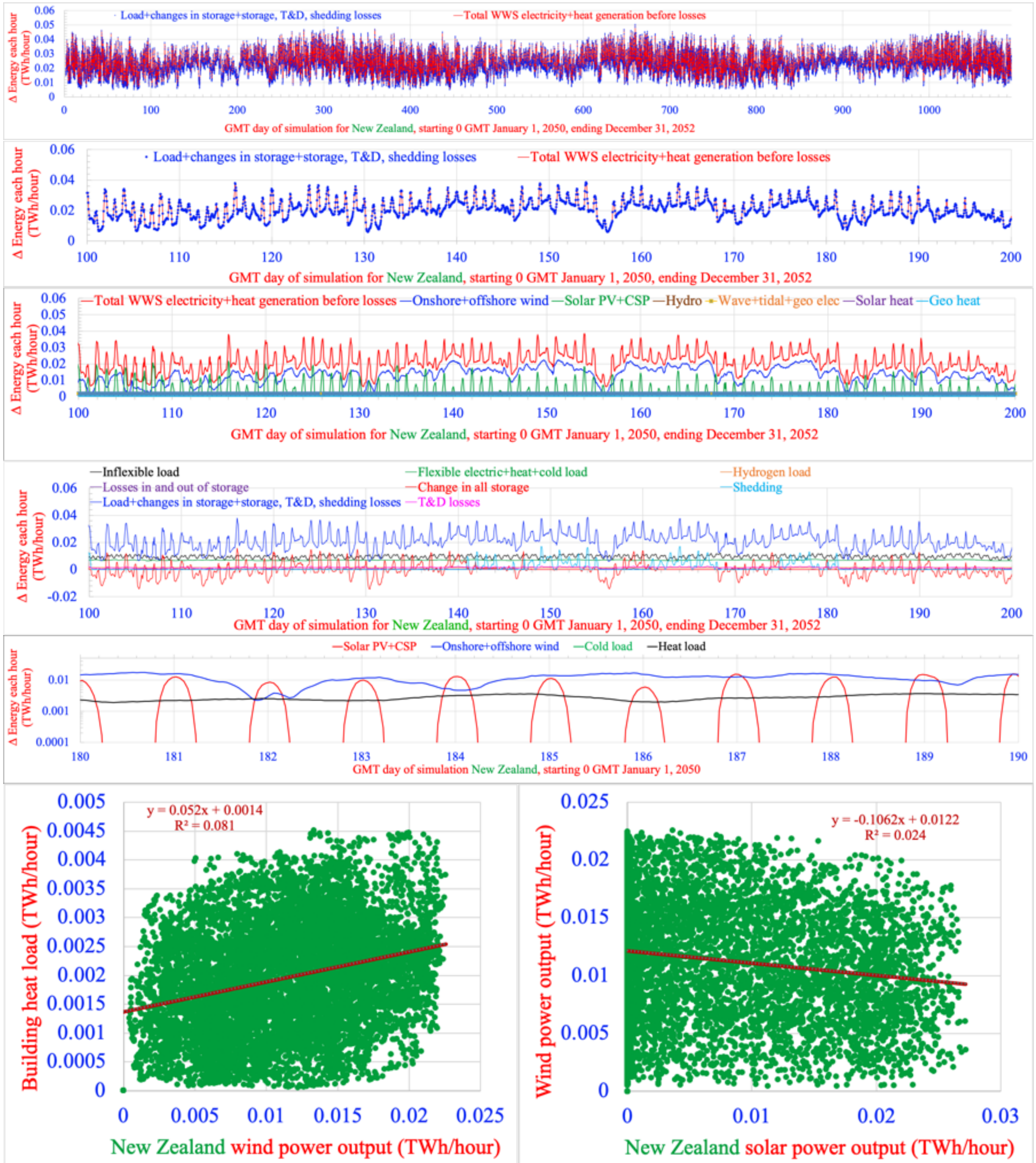

Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052


Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050


y = 0.3313x - 0.0443
R² = 0.1914
Building heat load (TWh/hour)
Mideast wind power output (TWh/hour)

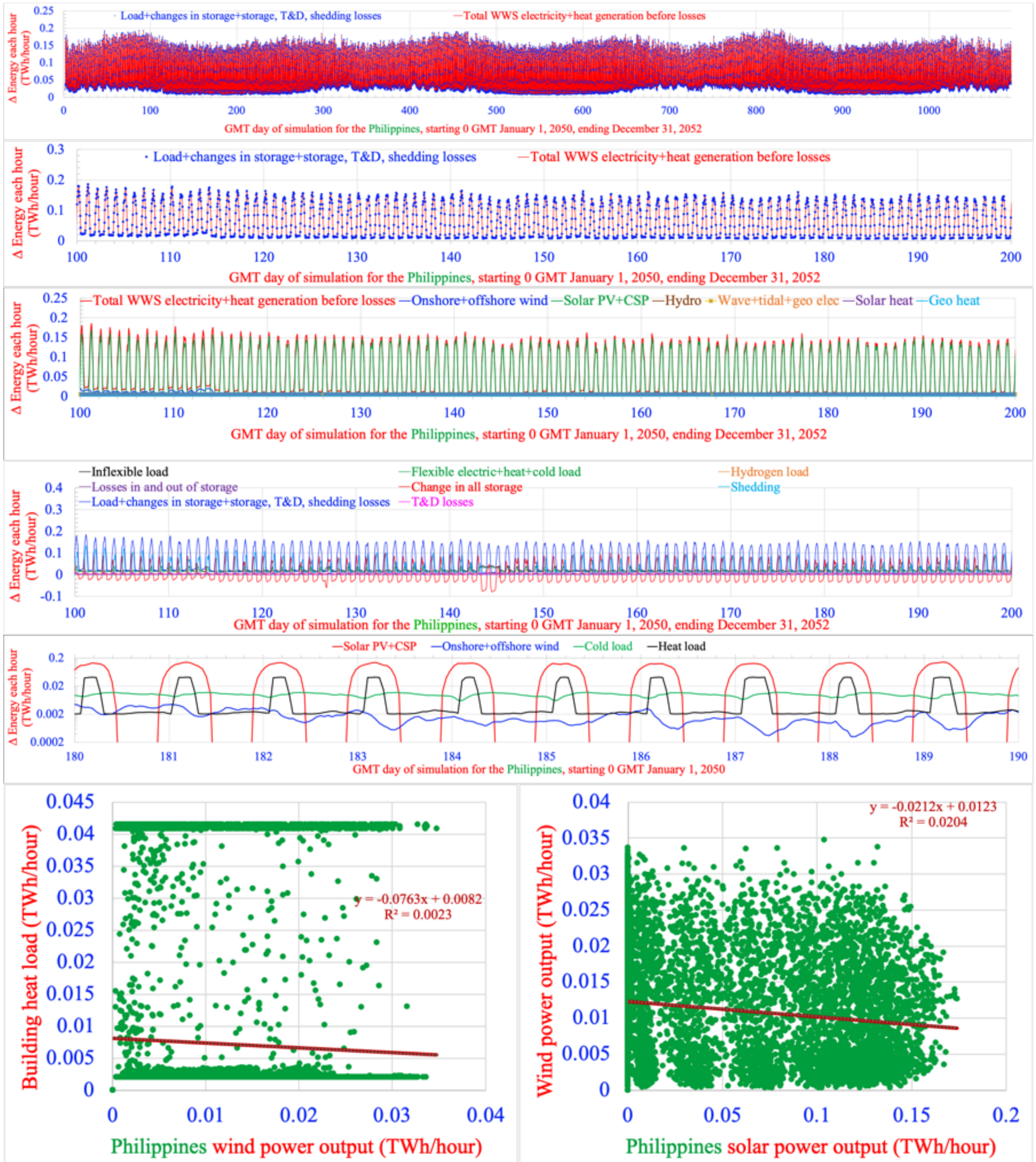

y = -0.0516x + 0.4464
R² = 0.1114
Wind power output (TWh/hour)
Mideast solar power output (TWh/hour)

NEW ZEALAND

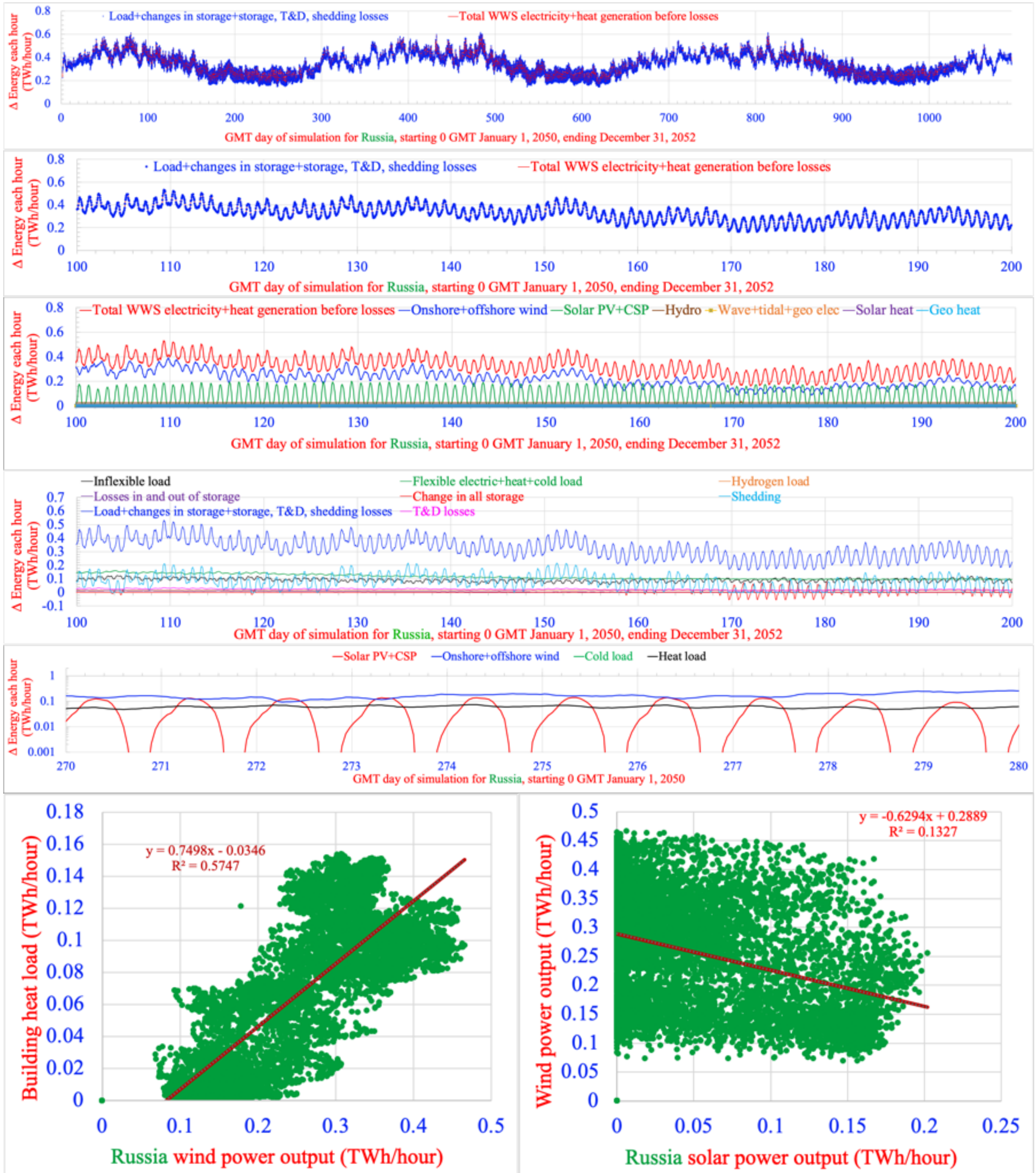


Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052
—Total WWS electricity+heat generation before losses —Onshore+offshore wind —Solar PV+CSP —Hydro —Wave+tidal+geo elec —Solar heat —Geo heat
—Inflexible load
—Losses in and out of storage
—Load+changes in storage+storage, T&D, shedding losses
—Flexible electric+heat+cold load
—Change in all storage
—T&D losses
—Hydrogen load
—Shedding
—Solar PV+CSP —Onshore+offshore wind —Cold load —Heat load
GMT day of simulation New Zealand, starting 0 GMT January 1, 2050
y = 0.052x + 0.0014
R² = 0.081
Building heat load (TWh/hour)
New Zealand wind power output (TWh/hour)
y = -0.1062x + 0.0122
R² = 0.024
Wind power output (TWh/hour)
New Zealand solar power output (TWh/hour)

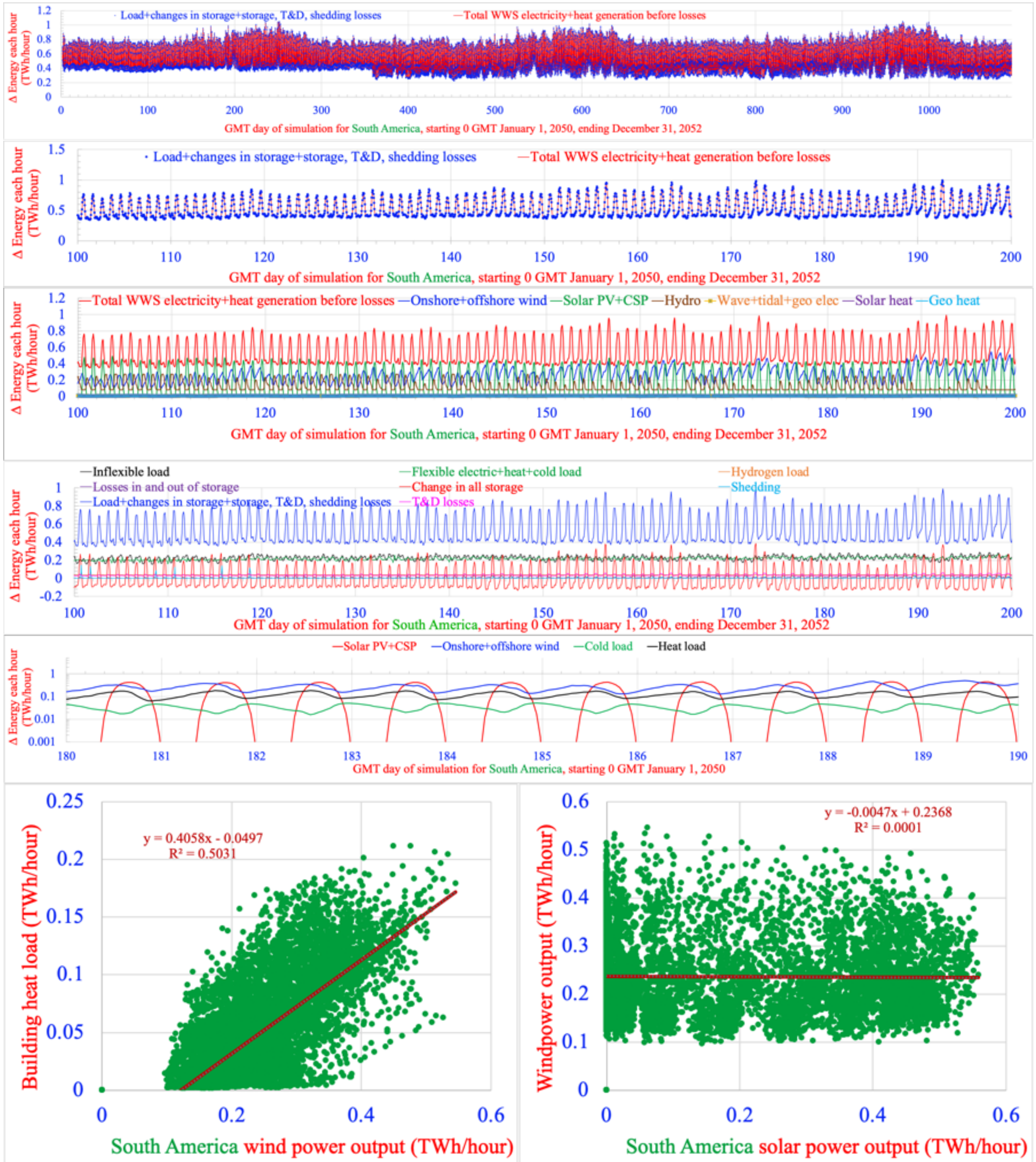
PHILIPPINES



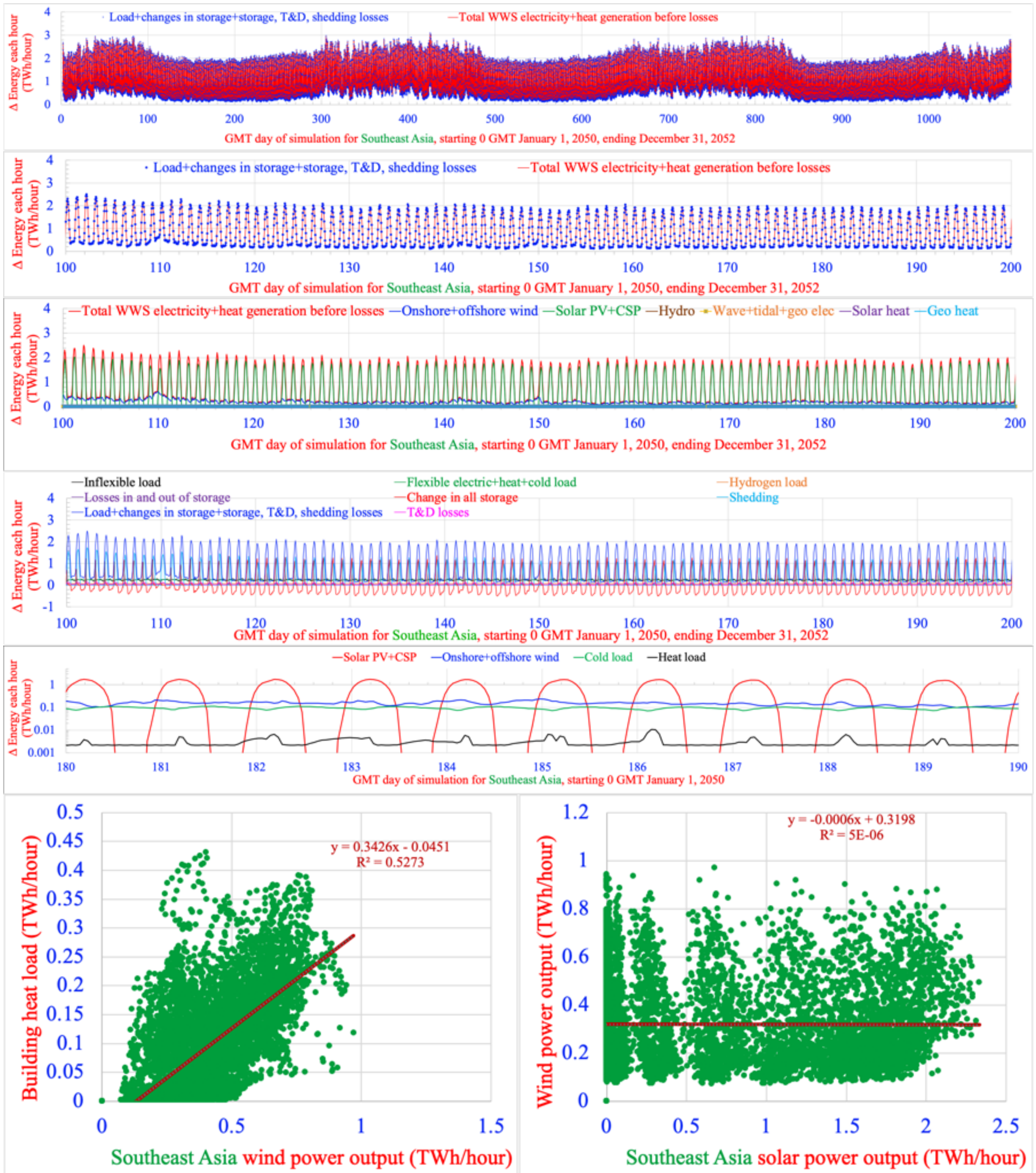
RUSSIA REGION



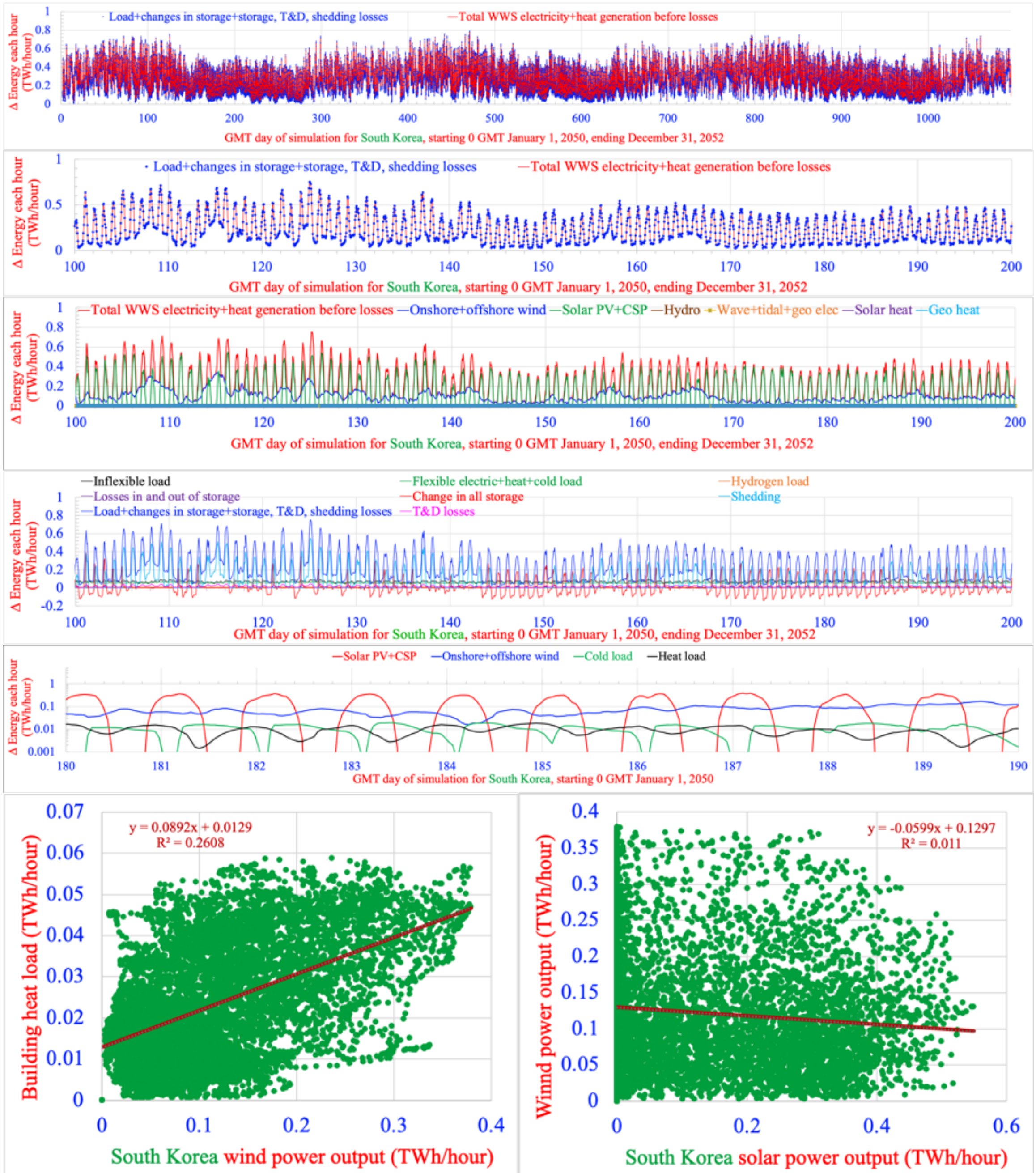
SOUTH AMERICA



SOUTHEAST ASIA

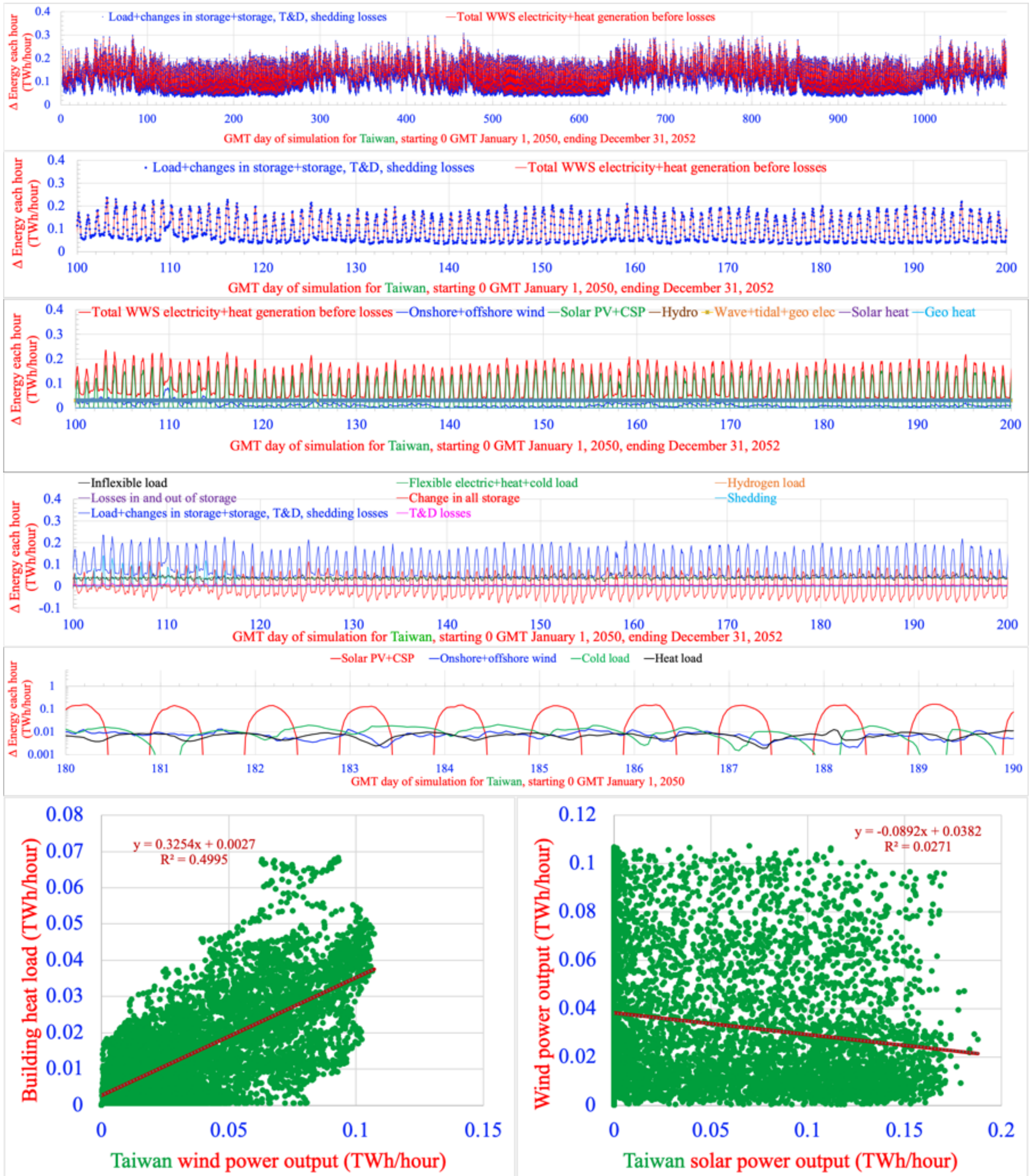


SOUTH KOREA



Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
Wave+tidal+geo elec
—Solar heat
—Geo heat
—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—T&D losses
—Cold load
—Heat load
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050
y = 0.0892x + 0.0129
R² = 0.2608
Building heat load (TWh/hour)
South Korea wind power output (TWh/hour)
y = -0.0599x + 0.1297
R² = 0.011
Winnd power output (TWh/hour)
South Korea solar power output (TWh/hour)

TAIWAN


Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
T&D losses
Cold load
Heat load
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050
y = 0.3254x + 0.0027
R² = 0.4995
Building heat load (TWh/hour)
Taiwan wind power output (TWh/hour)
y = -0.0892x + 0.0382
R² = 0.0271
Wind power output (TWh/hour)
Taiwan solar power output (TWh/hour)

UNITED STATES

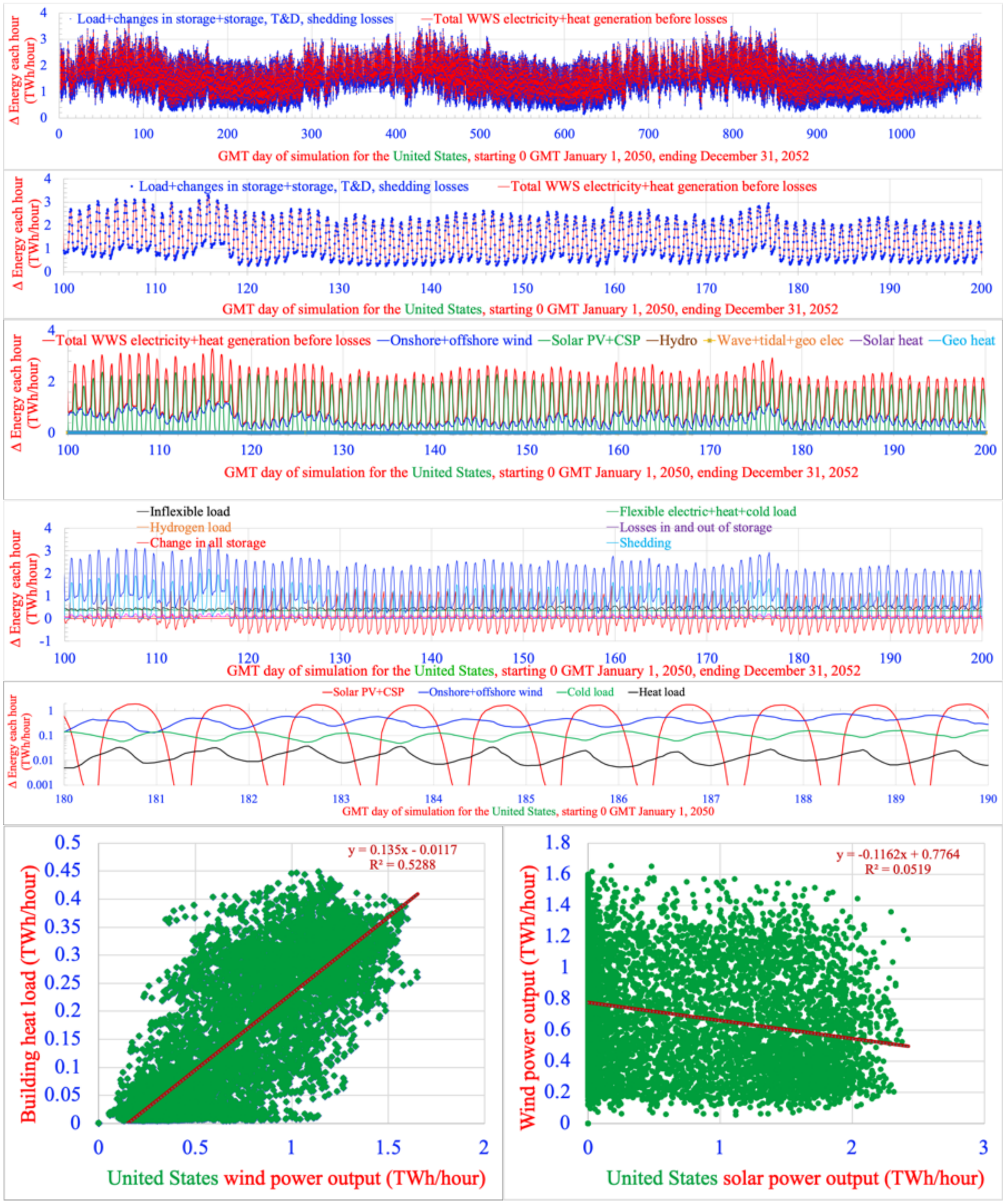
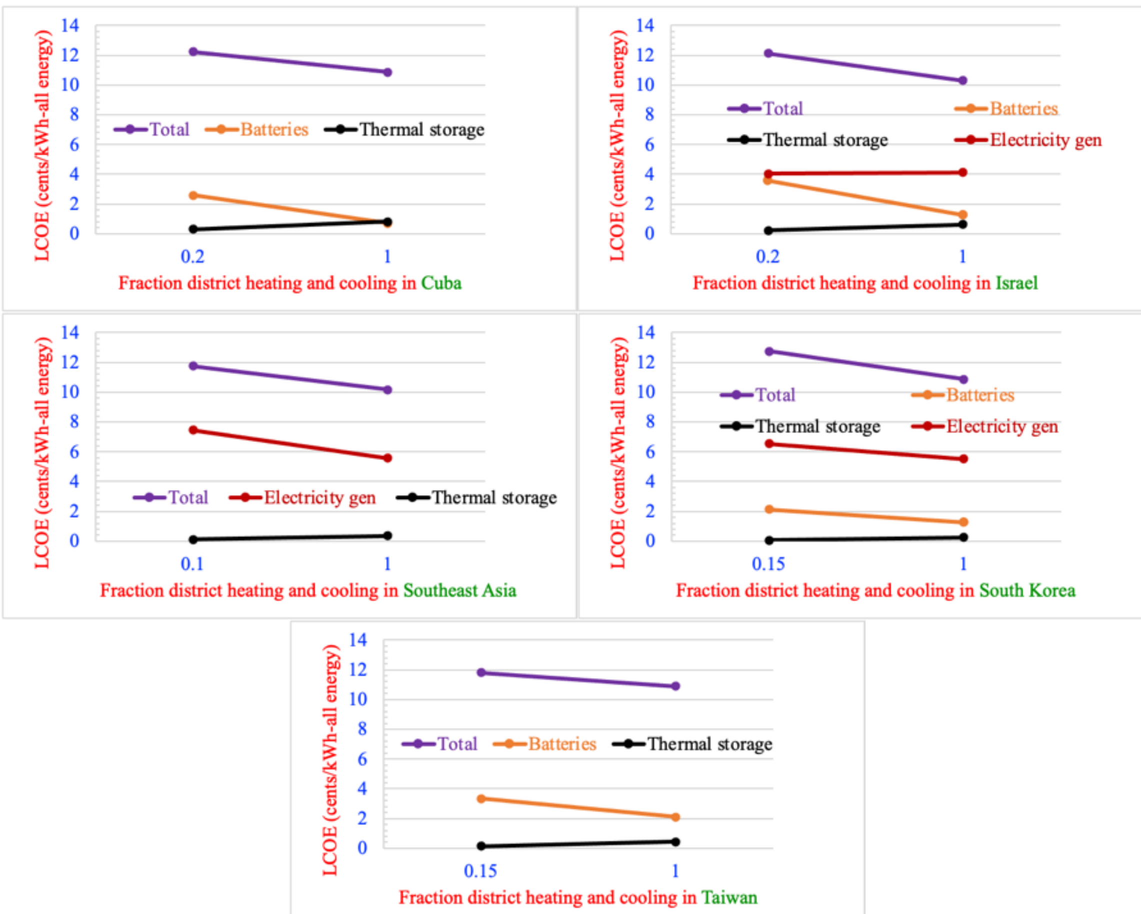


Figure S3. Sensitivity of the levelized cost and some of its components to the fraction of all building hot and cold air and water supply from district heating and cooling in selected countries. The components included are the cost of batteries, thermal storage, and/or total electricity generation. Thermal storage costs include the costs of UTES, HW-STES, CW-STES, ICE storage, and heat pumps to provide heat and cold for thermal energy storage (Table S19). The only component of total electricity generation that is changing is the quantity of offshore wind. The low fraction district heating and cooling is the baseline value for each country. The countries chosen are among those with the highest LCOEs with 100% WWS at the baseline fraction of district heating and cooling in Table 4.



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