On the Energy, Health, and Climate Costs of "All-of-the-Above" Versus 100% Wind-Water-Solar (WWS) Climate Policies: Analysis Across 149 Countries

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Abstract.

Air pollution causes >7 million deaths annually; global temperatures are >1.1°C higher than 1850-1900; and energy insecurity is rising. This study first examines whether 149 countries can transition 100% of their business-as-usual energy to electricity and heat powered by 100% wind-water-solar (WWS) energy to solve these problems. WWS eliminates energy-related air pollution deaths and carbon-dioxide-equivalent (CO_2e) emissions while reducing all-purpose end-use energy needs by ~54.4%, annual energy costs by ~59.6%, and annual social (energy+health+climate) costs by ~91.8%, resulting in energy- and social-cost payback times of 5.9 and 0.78 years, respectively, among the 149 nations. Conversely, "all-of-the-above" (AOTA) climate policies promoting carbon capture (CC) from fossil-fuel and bioenergy sources and synthetic direct air carbon capture (SDACC) trigger, with full penetration, 149-country social costs of \$60-70 trillion/y (8.9x-10.5x WWS costs), by increasing, relative to WWS, air pollution, CO_2e, energy requirements, and energy costs. Thus, policies promoting CC and SDACC should be abandoned.

1. Introduction

Combustion generates energy - electricity, heat, and motion. Combustion also produces gases and particles that create air pollution and global warming. Each year, outdoor and indoor air pollution kills >7 million people and causes injury to billions more[1,2]. Pollution also harms animals, crops, vegetation, materials, works of art, and visibility. Global warming from 2011 to 2020 was ~1.1°C relative to the 1850 to 1900 period[2] and has increased since then[4]. Based on the remaining carbon budget, 80% of the gas and particle emissions that cause warming must be eliminated by 2030 and 100% by 2035-2050 to avoid sustained 1.5°C warming[5]. Global warming increases wildfires, urban air pollution, heat stroke, heat stress, vector-borne disease, famine, species extinction, sea-level rise, floods, droughts, and hurricanes, among other problems[6]. The fuels burned that cause global warming are primarily fossil fuels (coal, oil and its products, and fossil gas) and bioenergy (solid biomass, liquid biofuels, and biogas)[6]. Energy insecurity is a third major problem the world faces today. Several types of energy insecurity arise due to diminishing fossil fuel and uranium supplies; reliance on centralized power plants and refineries; reliance on fuel supplies subject to human interference or long-distance transport; and reliance on fuels subject to catastrophic risk[6].

Because every year that combustion continues, millions more people die, global warming speeds closer to 1.5°C, and energy security risks rise, a rapid solution to all three problems is needed. A solution to solve all three problems together proposed in 2009 was to transition 100% of all business-as-usual (BAU) energy to electricity and heat powered by 100% wind-water-solar (WWS) sources[7]. WWS is a system consisting of clean, renewable electricity and heat generators, storage devices, electric appliances and machines, and an expanded transmission/distribution system (Methods and Table S2). More recent studies on transitioning to WWS include those on transitioning 139 countries[8], 143 countries[9], and 145 countries[5]. Hundreds of other studies have also examined the ability of countries, states, provinces, cities, or towns to transition to 100% renewable electricity and/or heat in one or more energy sectors[10,11,12].

With respect to addressing climate change, policymakers and researchers have substantially promoted "all-of-the-above" (AOTA) climate policies. Such strategies originate with the U.S. Obama Administration[13]. AOTA policies support a transition not only to WWS, but also to fossil fuels and bioenergy with or without carbon capture (CC), synthetic direct air carbon capture (SDACC), and/or nuclear power. AOTA policies were codified in U.S. law most recently under the 2022 Inflation Reduction Act[14,15]. Advocates of AOTA policies often reference an Intergovernmental Panel on Climate Change (IPCC) report[16] to support their contention that AOTA technologies are both beneficial and needed for fighting climate change. However, no explicit effort is made, through AOTA policies, to address air pollution or energy security simultaneously with climate. Further, some AOTA strategies, such as attaching CC to fossil and bioenergy sources and using SDACC to offset other CO_2 emissions, have been found, in case studies, to increase air pollution, CO_2, private energy costs, fossil mining, and/or land use relative to using WWS[17-19]. CC and SDACC are also not commercially competitive without subsidies at this time.

To date, though, no study has examined the impact of an AOTA strategy versus a WWS strategy on a country or the world while accounting for total social cost (private energy cost plus health cost plus climate cost). The purpose of this study is to perform such an analysis across 149 countries with a new energy data set and considering two specific AOTA policies: attaching CC to fossil fuel and bioenergy stationary CO_2 sources and using SDACC to offset mobile and distributed CO_2 sources. The study first compares the cost and benefit among the 149 countries of meeting BAU demand with BAU energy sources versus electrifying BAU energy and meeting the new demand with 100% WWS energy. It then compares both scenarios with applying CC/SDACC to all BAU energy-related CO_2 sources without electrification and using either BAU or WWS electricity to power the CC/SDACC equipment. Such scenarios examine whether CC/SDACC can help reduce CO_2e, air pollution, energy needs, or private and social energy cost relative to WWS.

The BAU and WWS scenarios here build on previous work for 145 countries[5,20,21] by extending the work to 149 countries (adding Eswatini, Madagascar, Rwanda, and Uganda) and using new (2020) International Energy Agency (IEA) energy data[22]. IEA does not currently have data available for more countries. The 149 countries are responsible for 99.75% of world fossil-fuel CO_2 emissions (Table 2). The work is carried out with three types of models: a spreadsheet model that feeds its output into GATOR-GCMOM, a global weather-climate-air pollution model, which in turn supplies its output into LOADMATCH, a model that matches demand with supply, storage, and demand response (Methods). For LOADMATCH, the 149 countries are combined into 29 regions (Table S1), including 13 multi-country regions (East Africa, North Africa, Southern Africa, West Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, Northwest South America, Southeast South America, and Southeast Asia) and 16 individual countries or pairs of countries (Australia, Canada, Cuba, Haiti-Dominican Republic, Israel, Iceland, Jamaica, Japan, Madagascar, Mauritius, New Zealand, the Philippines, Russia-Georgia, South Korea, Taiwan, and the United States). Unlike in previous studies that included only 24 regions[5,20,21], Africa here is separated into four regions and South America, into two. Madagascar is also added as a region. Grid analyses are performed with LOADMATCH in each region for all four cases (BAU, WWS, and CC/SDACC powered by either BAU or WWS).

2. BAU versus WWS Results

Simulations with LOADMATCH are first run for three years (2050-2052) with a 30-s time step to obtain WWS results that are compared with BAU results. Grid stability is obtained in all regions (Figure S4) in seven ways (see Methods). The capital cost of a transition to 100% WWS among all 29 regions is ~\$58.2 trillion (2020 USD), including \$15.0 trillion for the China region, \$7.1 trillion for the India region, \$6.7 trillion for Southeast Asia, \$5.7 trillion for the U.S., and \$5.1 trillion for Europe (Table 1). The 2050 mean annual WWS private energy cost among all regions is \$6.8 trillion/y (Table 1), which is 59.6% (\$9.7 trillion/y) lower than BAU's private energy cost of \$16.5 trillion/y (Table 1). Dividing the WWS capital cost by the annual private energy cost savings gives the 2050 private energy cost payback time due to WWS of 5.9 y, with a range of 1.1-15.1 y among all regions (Table 1).

With BAU, an estimated 5.4 million people die per year in 2050 from energy- plus non-energy-related air pollution across the 149 countries (Tables 2, S26). Of these mortalities, ~90% are estimated to be due to energy[9]. This is justified here as follows. In this study, WWS replaces both indoor and outdoor energy sources of air pollution. WHO[1,2] estimates that in 2019, 7.39 million people died worldwide (and 7.19 million died in the 149 countries) from all air pollution sources and ascribes 43.8% (3.23 million/y) of the worldwide deaths to indoor air pollution and 56.2% (4.15 million/y) to outdoor air pollution. All indoor air pollution deaths in the WHO[1] dataset are due to energy – the indoor burning of biomass (e.g., wood, dung, brush) and fossil fuels for heating and cooking, primarily in developing countries. As evidence, WHO[1] ascribes zero indoor air pollution deaths to Australia, Austria, Belgium, Canada, Iceland, Ireland, Italy, the United Kingdom, the United States, and other developed countries. This assumption is conservative given that natural gas and/or wood is burned in many homes in developed countries for cooking and/or heating. Lelieveld et al.[23] estimate that 65% (3.61 million/y) of all outdoor air pollution deaths from anthropogenic sources in 2015 were due to fossil fuel emissions. Fossil fuel emissions all result from combustion for energy. Simply adding the 3.23 million indoor and the 3.61 million fossil-fuel outdoor air pollution mortalities/y and dividing by 7.39 million total air pollution mortalities/y gives 92.6% of air pollution deaths attributable to energy. However, many of the remaining outdoor air pollution deaths are also due to bioenergy. On the other hand, Lelieveld et al.[23] calculated their numbers in a different way and for a different year from WHO[2]. Considering both factors but erring on the side of caution, we estimate ~90% of all air pollution deaths are due to energy.

Non-energy anthropogenic emissions include open biomass burning, halogens, nitrous oxide from fertilizers and industry, methane from agriculture and landfills, chemically-produced CO_2 from cement and steel, road dust, and construction dust. Among these, only open biomass burning, road dust, and construction dust result in air pollutants that may affect human health appreciably. Natural emissions that can affect health include natural soil dust, sea spray, volcanic gases and particles, pollen, spores, bacteria, and viruses. Open biomass burning may cause ~250,000 mortalities/y[24], or ~3.4% of the 2019 total air pollution deaths calculated by WHO. By far most mass of road dust, construction dust, soil dust, sea spray, volcanic particles, pollen, spores, bacteria, and viruses is in particles larger than 2.5 μm-diameter. Such particles have less effect on health than combustion particles, which center around 0.1 μm-diameter so penetrate deeper into human lungs and thus to the blood stream, than the larger particles. Thus, even a focus on non-energy sources of pollution suggests at least 90% of air pollution deaths are due to energy.

Whereas the percent of air pollution deaths attributable to different sources, such as energy, likely differs by country[25], the use of a constant percent in each country here has no impact on the conclusions, because it does not affect the 149-country mortality rates, which the conclusions are based on.

The 2050 health cost of energy-related mortalities (based on the value of statistical life, VOSL), associated morbidities, and associated non-health, non-climate environmental damage costs due to energy-related air pollution (Note S8), is estimated here as ~\$33.8 trillion/y (Table 1). This cost decreases to zero with 100% WWS, because WWS eliminates 100% of energy-related air pollution emissions, including during mining for and production of WWS equipment. However, mining for WWS materials will still cause some soil dust particle emissions. As stated, though, soil particles are mostly large so do not penetrate deep into human lungs; thus, their health effects are smaller than those of combustion particles.

In 2050, energy-related emissions of CO_2 and other climate-warming pollutants are estimated to be ~55.3 gigatonnes-CO_2-equivalent (CO_2e)/y across 149 countries (Table 2). The 2050 climate cost damage of such emissions, based on the mean social cost of carbon of \$558/tonne-CO_2e (Note S8), is ~\$30.9 trillion/y (Table 1). The 2050 climate cost damage due to WWS energy-related CO_2e emissions is zero because WWS eliminates climate-warming pollutants from energy.

Summing BAU's 2050 annual private energy, health, and climate costs yields a total BAU social cost of \$81.2 trillion/y (Table 1). Converting to 100% WWS eliminates the energy-related health and climate costs and reduces the private energy cost to \$6.67 trillion/y

(Table 1), which equals the WWS social energy cost. Thus, WWS reduces annual social energy cost by 91.8% ($74.4 trillion/y) in 2050, giving a social cost payback time due to switching of 0.78 years, with a range of 0.33-2.24 years among all regions (Table 1).

Transitioning to WWS may also produce 48.2 million new long-term, full-time jobs while costing 25.3 million jobs, resulting in a net increase of 22.9 million long-term, full-time jobs produced among the 149 countries (Table S30). Net job gains occur in 25 out of 29 regions, although not all countries within a region gain jobs. Only West Africa, Canada, Madagascar, and the Russia region experience net job losses. Regions with net job losses are usually regions with a substantial fossil fuel industry. However, some countries with high fossil fuel employment (e.g., Saudi Arabia) experience net job gains because of the large buildout of WWS infrastructure in those countries. More jobs also arise from the need to build more electrical appliances and to improve building energy efficiency. Such job changes were not accounted for here.

The new land needed for WWS footprint (defined in Note S9) (before removing the fossil fuel infrastructure) is ~0.13% of the 149-country land area (Table S28), almost all for utility photovoltaic (PV) and concentrated solar power (CSP). WWS does not require mined fuels to power WWS equipment, so no footprint is associated with mining of fuels for energy with WWS. However, both WWS and BAU require mining of raw materials to build WWS or BAU infrastructures. The only land spacing area needed with WWS is between onshore wind turbines. This spacing area equals ~0.38% of the 149-country land area (Table S28). New land footprint plus spacing areas for 100% WWS thus represents ~0.51% (623,900 km^2) of the 149-country land area, and most of this land is multi-purpose spacing. Even the footprint for utility PV that is raised a few meters above farmland (agrivoltaics) can allow crops to grow, thus also be used for dual purposes.

3. Discussion/Conclusions

The main hypothesis of this study is that policy efforts to address climate should simultaneously tackle air pollution and energy security. AOTA climate policies call for reducing greenhouse gas emissions but not emissions of any chemicals that cause air pollution health problems (e.g., oxides of nitrogen, organic gases, carbon monoxide, sulfur oxides, ammonia, or particulate matter). Regulations of non-greenhouse gas air pollution emissions are instead set by government agencies worldwide. Such regulations generally call for slow reductions, but not elimination, of air pollutant emissions and are weakly enforced in most of the world, which is why air pollution mortality rates exceed 7 million/y worldwide[1,2].

It is hypothesized here that AOTA climate policies promoting (1) CC attached to fossil fuel or bioenergy stationary sources and (2) SDACC for offsetting other CO_2 emissions (a) permit the continuation or increase of air pollution, (b) hinder electrification and the elimination of fuel mining, thus hinder energy demand reductions, (c) discourage reductions in non-CO_2 greenhouse gas emissions, (d) decrease only a portion of CO_2e emissions, (e) exacerbate energy insecurity, and (f) drive up energy and social costs.

This hypothesis is tested by considering two scenarios beyond the BAU and WWS scenarios already examined. In both new scenarios, CC is attached to all BAU energy-related stationary CO_2 emission sources and SDACC is used to offset all mobile and distributed CO_2 emission sources. The electricity required to run the CC and SDACC equipment is assumed to be either BAU electricity (BAU-CC-BAU scenario) or WWS electricity (BAU-CC-WWS scenario). Both scenarios satisfy the main goal of AOTA climate policies, which is to reduce CO_2.

In both new scenarios, 2050 BAU end-use energy demand is reduced by 6.74% (Table S4) due to end-use energy efficiency improvements beyond those in the BAU case, before CC/SDACC is applied, just as in the WWS scenario. In addition, 9.8% of the remaining BAU energy in 2050 in both scenarios is assumed to come from WWS and 2.3% is assumed to come from nuclear (based on the 2020 nuclear output relative to overall demand). For simplicity, neither is assumed to produce CO_2e emissions during its operation although nuclear emits heat and water vapor and requires energy for mining and refining uranium during its operation[6]. Also, 85% of the net CO_2e emissions from the remaining BAU energy share consists of CO_2 emissions. Next, CC and SDACC equipment have capture efficiencies of 80% and increase non-WWS, non-nuclear BAU energy requirements by 25%. SDACC is assumed to have the same capture efficiency and energy requirements as CC even though capturing CO_2 from the air is more energy intense than capturing it from an exhaust stream because CO_2 in the air is more dilute than in an exhaust stream[17]. The additional BAU electricity needed to power CC and SDACC equipment in the new scenarios is produced proportionately by the same generators, including nuclear, as in the 2050 BAU scenario.

The assumption that 85% of net CO_2e emissions are CO_2 emissions accounts for the fact that net global warming is the sum of gross warming from greenhouse gases, black and brown carbon particles, anthropogenic heat and moisture fluxes, and the urban heat island affect, offset by gross cooling due to cooling aerosol particles (Fig. 1.2 of Ref.[6]). The difference between gross warming and gross cooling is net warming. CO_2 is estimated to contribute to 85% of such net warming in 2050.

The assumed 80% capture efficiency accounts for the fact that CO_2 capture efficiencies today in 19 real-world plants (coal-fired power plants, natural gas processing facilities, hydrogen production, gasification, fertilizer, ethanol, and steel) range from 10-80%, with more than half under 50%[26]. None is close to the optimal efficiency of 95%. The 80% capture efficiency here assumes that real-world average efficiencies increase dramatically from less than 50% to 80% in 2050.

The CC energy penalty is the percent of fuel that must be dedicated to CC for a fixed quantity of work output[27]. It has a theoretical range of ~11-40%[27]. CC needs energy for CO_2 separation, compression, transport, and storage[27]. IPCC estimates the energy penalty increases fuel requirements for electricity generation by 13-44%[28]. Here, we assume CC requires 25% additional energy from every stationary CO_2 source it is attached to.

Figures 1-4 show results among all scenarios for 2050, summed over the 149 countries. Whereas WWS reduces end-use demand by 54.4% (due to the efficiency of electricity over combustion, eliminating energy to mine fuels, and efficiency improvements beyond BAU), the AOTA scenarios do not increase electrification or reduce mining. They only reduce demand due to energy efficiency improvements (6.74%). The reasons are (1) when CC is added to a stationary emission source, the source continues to operate, so it cannot be replaced with a more efficient, cleaner source; (2) when SDACC offsets CO_2 emissions from a mobile or distributed source, there is less incentive, funding, and energy available to replace that mobile/distributed source; and (3) using CC/SDACC requires BAU fuel mining to continue to provide energy for the underlying CO_2 source. In fact, CC/SDACC require additional electricity to run. As a result, overall energy requirements increase with

CC/SDACC versus BAU, regardless of whether CC/SDACC are powered by BAU or WWS electricity (Figure 1).

The net increase in polluting-electricity use with CC/SDACC relative to BAU increases the energy-related 2050 air pollution mortality rate among the 149 countries from 4.9 to 5.7 million mortalities/y versus BAU when CC and SDACC are powered by BAU electricity (Figure 2). When CC/SDACC are powered by WWS electricity, the air pollution mortality rate decreases slightly, down to 4.5 million mortalities/y, due to the end-use energy efficiency improvement. On the other hand, WWS reduces air pollution mortalities from 4.9 to 0 million/y relative to BAU (Figure 2). Even if the death rates in the AOTA cases were 1/10th those in the BAU case, those in the AOTA cases would still far exceed those in the WWS case.

In the BAU-CC-BAU case, CO_2e emissions first decrease by 6.74% due to energy efficiency improvements then by another 68% due to CC/SDACC. The 68% arises because CC/SDACC reduce 80% of the CO_2 they are assigned to capture, and CO_2 comprises ~85% of CO_2e emissions. However, CO_2e then increases by 25% due to the energy penalty (Figure 3). The same applies in the BAU-CC-WWS case, except no increase in CO_2e due to an energy penalty applies. Energy-related CO_2e emissions decline to zero in the WWS case.

Finally, Figure 4 shows the overall social cost of energy in each scenario. Energy, air pollution, and climate costs are all larger with CC/SDACC than with WWS. Specifically, in both AOTA cases, private energy costs are \$18.8 trillion/y, or 2.82 times that in the WWS case (\$6.7 trillion/y). In the BAU-CC-WWS case, the total social cost (\$59.6 trillion/y USD 2020) is 8.9 times that in the WWS-alone case (\$6.7 trillion/y). In the BAU-CC-BAU case, total social cost (\$69.7 trillion/y) is 10.5 times that in the WWS-alone case. Thus, CC/SDACC, even when powered by WWS, increases both private energy cost and total social cost tremendously while maintaining energy security problems associated with fossil fuels.

This analysis assumes that 100% of CO_2 captured is sequestered. However, 73% of CO_2 captured worldwide is used for enhanced oil recovery[29], during which, up to 40% of the CO_2 captured is released back to the air[30]. As such, Figures 1-4 may underestimate substantially the social cost associated with CC and SDACC.

The largest portion of social cost attributable to CC/SDACC is the enormous air pollution health cost. The average social cost of unabated air pollution (BAU case) in 2050, based on VOSL (\$611/tonne-CO_2e or \$0.24/kWh), is found here to exceed the social cost of carbon (\$558/tonne-CO_2e, or \$0.186/kWh) and the private cost of BAU energy (\$299/tonne-CO_2e, or \$0.0996/kWh) across the 149 countries (Tables 1, 2). This suggests that the world should focus on eliminating air pollution and climate-warming pollution together to minimize social energy costs. Reducing CO_2 but not air pollution by using CC/SDACC increases social cost significantly compared with eliminating CO_2 and air pollution emissions by using 100% WWS.

As discussed in Section 2, energy generates ~90% of air pollution emissions. It also produces ~75-80% of CO_2e emissions. Non-energy emission sources, listed in Section 2, may be addressed with technology or policy[6]. For example, chemical CO_2 from ordinary Portland cement can be eliminated by replacing calcite with basalt during cement production[31] or switching to geopolymer cement[6]. Chemical CO_2 from steel production can be eliminated by replacing coal with hydrogen during iron purification[20].

The only way to eliminate all air-pollutant and climate-warming gases and particles from energy is to eliminate combustion. Catalytic converters, scrubbers, particle filters, CC, and SDACC reduce emissions or ambient levels of only specific gases or particles, but never to zero. Further, unlike growing trees (natural direct air carbon capture), pollution abatement technologies always require materials to build and energy to run. They also prevent electrification of the CO_2 source they are capturing from and prevent the elimination of fuel mining for the CO_2 source.

In sum, AOTA climate policies that propose the use of CC and/or SDACC to reduce energy-related CO_2, will instead increase air pollution, CO_2e emissions, energy requirements, private energy costs, and social energy costs substantially relative to policies requiring 100% WWS. Whereas this study compared unrealistically-extreme AOTA cases of 100% carbon removal with 100% replacement of carbon-emitting sources by WWS, the conclusions should apply to any level of carbon removal above zero. The conclusions should be intuitive given that WWS energy in 2050 will consist primarily of electricity, and the electricity will come mostly from solar, wind, and existing hydropower. Such WWS sources virtually eliminate air pollutant and greenhouse gas emissions. On the other hand, CC and SDACC increase or do not reduce air pollution, require more energy and equipment, and increase CO_2 compared with WWS. Given the speed and magnitude of changes needed for an energy transition, AOTA policies promoting CC and SDACC may, in the limit, cause millions of unnecessary air pollution deaths each year and substantial climate damage in both the short term (by slowing the elimination of black and brown carbon, ozone, and methane) and long term (by slowing the elimination of CO_2). As such, policies promoting CC and SDACC should be abandoned.

4. Methods

WWS consists of clean, renewable electricity and heat generators, storage devices, electric appliances and machines, and a transmission/distribution system (Table S2). WWS electricity generators include onshore and offshore wind turbines (Wind); tidal and wave devices, geothermal electric power plants, and hydroelectric power plants (Water); and rooftop/utility solar PV and CSP plants (Solar) (Table S2). WWS heat sources include solar and geothermal heat. WWS electricity storage technologies include conventional hydropower storage (CHS), pumped hydropower storage (PHS), CSP storage (CSPS), battery storage (BS), and green hydrogen storage (GHS). Heat is stored in water tanks, soil, and water pits. Cold is stored in water tanks and ice. Green hydrogen is produced from electrolyzers running on WWS electricity and stored for grid and non-grid purposes (steel and ammonia manufacturing and extra long-distance transport). Building temperatures are controlled with heating/cooling units in individual building or with district heating/cooling systems (Table S15). Heat pumps running on WWS electricity are used for (a) air and water heating, air conditioning, and drying clothes in buildings; (b) heating and cooling water for district heating/cooling systems; and (c) low-temperature heating for industry. High-and medium-temperature heating for industry relies on arc furnaces, induction furnaces, resistance furnaces, electron beam heaters, and dielectric heaters running on WWS electricity. Transport relies on battery-electric vehicles for all but very-long-distance trucks, airplanes, ships, and trains, which move via hydrogen fuel cell-electric propulsion. Electric induction cooktops replace gas stoves; electric lawnmowers and leaf blowers replace fossil versions (Table S2). WWS electricity is transported via alternating current (AC), high-voltage AC (HVAC), and/or high-voltage direct current (HVDC) transmission lines and AC distribution lines. WWS also assumes energy efficiency improvements (more efficient appliances, machines, and insulation) and reduced energy use (e.g., improved public transit; increased biking, telecommuting) beyond those with BAU.

This study involves three types of computational models. A spreadsheet model (Ref. [32] and Note S2) is used to project 2020 end-use energy demand (total final consumption) from IEA[22] for 149 countries to 2050 in a BAU scenario, and then to estimate nameplate capacities of WWS generators needed to meet such demand in the annual average (Table S8). These capacities are then input into GATOR-GCMOM (Note S3), a time- and space-dependent 3-D global weather-climate-air pollution model. A third model, LOADMATCH[5,8,9] (Notes S4-S7), then uses GATOR-GCMOM output to simulate matching time-dependent total energy demand (Table S4) with generation, storage, and demand response in each of 29 regions (Table S1) encompassing the 149 countries. Total energy demand includes electricity, heat, cold, and hydrogen demand. During LOADMATCH simulations, generator and storage nameplate capacities are updated (Tables S8, S10, S14) to ensure demand is met.

4.A. Spreadsheet Model

The spreadsheet model is used to project IEA total final consumption, also called energy consumption in end-use sectors, from 2020 to 2050 in a BAU scenario for each of seven fuel types (oil, natural gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat) in each of six end-use energy sectors (residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other), and for each of 149 countries (Note S2). The projections (Note S2) are by fuel type, energy sector, and region of the world. They assume moderate economic growth, policy changes by world region, population growth, energy growth, use of some renewable energy, modest energy efficiency measures, and reductions in energy use. Based on this calculation, BAU total final annual-average power consumption among all 149 countries increased from 12.6 TW in 2020 to 18.9 TW in 2050, or by 50.6% (Table S4).

The spreadsheet model is then used to estimate the 2050 reduction in BAU energy demand due to converting each fuel type in each end-use sector in each country to electricity, electrolytic hydrogen, or heat, and providing the electricity, hydrogen, and heat with WWS technologies (Note S2). The reductions in end-use demand are calculated with the conversion factors by fuel type and energy sector given in Table S3. Such conversion factors assume the use of vehicles, equipment, and machines running primarily on electricity (Note S2). Overall, about 95% of the technologies needed for a transition are already commercial. Those not commercial include long-distance aircraft and ships, which are proposed to be powered by near-term-technology hydrogen fuel cells[33], and some industrial processes.

Finally, the spreadsheet model is used to estimate nameplate capacities of WWS electricity and heat generators that can meet the annual-average demand in each country (Note S2; Table S8). Table S4 provides the 2020 end-use demands, the 2050 BAU end-use demands projected from 2020, and the 2050 WWS end-use demands converted from 2050 BAU demands, for each energy sector in each country.

4.B. GATOR-GCMOM

2050 nameplate capacities from the spreadsheet model for each WWS energy generator in each country are used as input into GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model), which is a global air pollution-weather-climate model (Note S3). It is used here to predict meteorological data and building heating and cooling requirements at a 30-s time resolution, 2- by 2.5-degree horizontal space resolution, and 30-m vertical resolution (in the bottom 1 km) globally. Parameters output include onshore and offshore near-surface wind electricity supply, rooftop solar PV electricity supply, utility PV electricity supply, CSP electricity supply, solar heat supply, building cooling demand, and building heating demand in each of 149 countries from 2050-2052. The model is initialized here under 2050 climate conditions. Wind calculations assume a hub height of 100 m, but turbine blades spanning multiple model layers (thus heights) in the vertical (Note S3). The model accounts for competition among wind turbines for available kinetic energy in all three spatial dimensions. It also calculates changes in air temperature due to wind turbine extraction of kinetic energy, PV extraction of solar radiation, CSP extraction of solar radiation, and extraction of solar radiation by solar thermal devices. Time- and space-dependent wave electricity output from GATOR-GCMOM is calculated as proportional to time-dependent offshore wind output. GATOR-GCMOM calculates building cooling and heating demands by comparing modeled temperatures over time in each near-surface model grid cell within each country with an assumed comfort temperature for buildings while accounting for building characteristics (Note S3). GATOR-GCMOM output is fed offline into LOADMATCH.

4.C. LOADMATCH

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

LOADMATCH is not an optimization model, so it does not find the lowest-cost solution. Instead, it produces a set of low-cost solutions from which the lowest cost is determined. Its advantage is that treats many more processes while taking orders of magnitude less computer time at a much shorter time step than an optimization model, requiring only minutes to solve multi-year simulations with a 30-s time step (Note S4).

Table S2 summarizes the processes in LOADMATCH. Note S4 describes many of the model’s inputs. LOADMATCH treats several electricity storage options: CHS, PHS, CSPS, BS, and GHS (Table S2), with maximum charge rates, discharge rates, storage capacities, and storage times given in Table S14. Grid stability is obtained in all regions in the following eight ways.

4.C.i. Overgeneration

Table S8 shows that, averaged among all regions and energy-generating technologies, about 9.5% more nameplate capacity of generators is needed to meet continuous demand than to meet annual-average demand. This overgeneration helps to keep the grid stable by providing extra electricity that can be stored directly or converted to and stored as heat, cold, or hydrogen.

4.C.ii. Electrifying non-Electricity Sectors

Electrifying, to the extent possible, all non-electricity sectors, then providing the electricity with WWS reduces end-use demand by an average of 54.4% among all regions (Tables 1 and S4). Of this, 36.8 percentage points are due to the efficiency of using WWS electricity over combustion; 10.9 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels and uranium; and 6.74 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Table S4). Of the 36.8% reduction due to the efficiency of WWS electricity, 19.7 percentage points are due to the efficiency advantage of WWS transportation, 4.1 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.1 percentage points are due to the efficiency advantage of using heat pumps instead of combustion heaters. Whereas all-purpose energy demand declines by 54.4% with WWS, the energy is almost all electricity (with the rest, direct heat), so the world-average electricity consumption increases by 85% compared with BAU (Table S4). Reducing overall energy demand by more than half helps WWS electricity and heat supplies match demand continuously. Increasing electricity demand also creates new opportunities to create new flexible demands that can be met by demand response (such as electric vehicle charging) or by storage (such as hydrogen use in steel and ammonia factories).

4.C.iii. Storing Excess Electricity

The electricity storage options in LOADMATCH include CHS, PHS, CSPS, BS, and GHS. Among the 29 regions simulated, four (Canada, Haiti region, Iceland, and Russia) require no battery storage (Table S14). In those regions, electricity storage is supplied by either CHS alone (Iceland); CHS and PHS (Canada and Russia); or CHS, PHS, CSPS, and GHS (Haiti region). Thus, in three regions, no storage aside from CHS and/or PHS is needed. Among the regions that use BS, all but five (Central America, Cuba, Jamaica, South America-NW, and South America-SE) also use GHS. Combining BS with GHS often reduces the cost of grid stability relative to BS alone[21]. One region (Haiti region) includes GHS but no BS.

BS assumes four-hour batteries with the measured efficiency of a 2021 lithium-ion Tesla Powerpack and a projected 2035 cost per kWh of lithium-ion batteries given in Table S22. Although batteries store electricity for only four hours at their peak discharge rate, longer storage times are obtained by concatenating batteries in series[5]. For example, concatenating 100 4-h batteries, each with a peak discharge rate of 10 kW, allows for either 400 hours of storage at a peak discharge rate of 10 kW or 4 h of storage at a peak discharge rate of 1,000 kW, or anything in between. Thus, batteries with longer than 4-h storage are never "necessary" for keeping the grid stable. However, BS is most cost optimal if both its maximum discharge rate and its maximum storage capacity are reached (see Note S11.2 for an analysis).

Here, BS and GHS are treated together in 20 of the 29 grid regions. GHS includes hydrogen gas production via electrolysis and compression with WWS electricity, hydrogen storage, and use of fuel cells to convert stored hydrogen back to grid electricity (Tables S14, S17, S21). Combining GHS with BS reduces the cost of grid stability in many regions versus BS alone[21]. Non-grid green hydrogen here is produced, compressed, and stored for steel and ammonia manufacturing and long-distance transport[20]. Table S5 summarizes the 2050 quantity of hydrogen needed by country and region for each non-grid use. For the present study, the same rectifiers, electrolyzers, compressors, and storage tanks are used for non-grid hydrogen as for GHS. Sharing hydrogen production and storage for both grid and non-grid purposes reduces costs in more regions, due to economies of scale, than separating the production and storage of hydrogen between grid and non-grid uses[21]. Hydrogen is not piped or shipped in the model. Electricity is transmitted and electrolytic hydrogen is produced and stored at steel and ammonia factories and long-distance transport hubs (e.g., airports, docks, train stations, major truck stops, and military bases), minimizing the need for hydrogen piping or shipping. Fuel cells for GHS then produce grid electricity from the communally-stored hydrogen at the non-grid hydrogen storage locations.

CH's total nameplate capacity, energy storage capacity, and annual recharge rate are allocated between peaking and baseload power while conserving several properties by solving a set of six equations and six unknowns (Note S5). CH's total nameplate capacity, reservoir energy capacity, and recharge rate in each country are limited to ~2020 values (Table S14). The total CH storage capacity in all hydropower reservoirs among the 149 countries examined is ~1,569 TWh (Table S14), which is close to the reported worldwide storage capacity[34]. For comparison, the total battery storage capacity among the 149 countries is 37.71 TWh (Table S14). Thus, the storage capacity of existing CHS is 41.6 times that of batteries needed. However, batteries needed in 2050 also have a peak discharge rate of 9.43 TW, whereas CHS has a peak discharge rate in 2022 of 1.25 TW (Table S14). Thus, BS is used mostly for peaking, whereas CHS is used mostly for energy storage in this study.

4.C.iv. Using Excess Electricity for Heat and Cold Storage

Total end-use demand in this study is split into flexible and inflexible demands (Note S6 and Table S7). Inflexible demands are demands that must be met immediately. Flexible demands are (a) demands for electricity and heat that are used to supply cold and low-temperature heat storage (in district heat storage or building water tank storage), (b) demands for electricity used to produce and compress hydrogen (since all hydrogen can be stored), and (c) remaining electricity and direct heat demands subject to demand-response (DR) management. Table S7 provides the distribution of inflexible and flexible demands by regions. The table indicates that, among all regions, 47.5% of all demand is inflexible; the rest, flexible. Of the flexible demand, 2.18% is cold demand subject to storage, 12.5% is low-temperature heat demand subject to storage, 22.1% is demand for non-grid hydrogen, and 63.2% is demand subject to DR. Table S14 provides the maximum storage capacities and maximum discharge rates of cold storage in water tanks (CS-STES) and ice (ICE) and heat storage in water tanks (HW-STES) and underground soil and water pits (UTES-heat; UTES-elect).

4.C.v. Using Excess Electricity for Non-Grid Hydrogen Storage

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

One reason is, a lower use factor reduces the overgeneration of WWS electricity production needed to produce hydrogen, thus reduces generator nameplate capacities needed[20].

4.C.vi. Demand Response Management

Demand response helps to reduce current demand by shifting demand forward in 30-s increments, but by no more than eight hours, until the demand is met. In a case of 145 countries/24 regions, only two regions needed eight hours of load shifting for demands subject to DR[3]. Five regions needed no hours; six regions needed two hours; nine regions needed four hours; and two regions needed six hours. Thus, maximum load shifting may be less necessary than allowed here.

4.C.vii. Interconnecting Distant and Complementary WWS Resources

Although the wind is variable in nature, that variability decreases when wind energy is aggregated over large geographical regions[35]. Thus, interconnecting 19 geographically-dispersed wind farms over a 850-km x 850-km region may eliminate the number of zero-power hours during a year compared with one wind farm within that region[35]. What is more, because solar and wind are complementary in nature (when the wind is not blowing, the sun is often shining during the day and vice versa) for meteorological reasons[36], interconnecting wind and solar on the grid reduces variability of either one independently.

4.C.viii. Importing/Exporting Electricity and Heat

Finally, interconnecting geographically-dispersed WWS generation and storage over long distances, including across political boundaries, can help to lower the cost of matching demand with supply[37,38]. In this study, 13 regions are multi-country regions and two regions are 2-country regions (Table S1). Large regions have more diversity of weather and WWS resources, improving the ability of a combination of wind electricity, hydroelectricity, and solar PV electricity, in particular, to provide a regular electricity supply. Small regions may also be lucky in having a diversity of resources and weather patterns or may just have an abundance of a particular resource. On the one hand, the region calculated with the highest cost per unit energy here (Table 1, Figure S2) (the Haiti region) is small, with little hydropower resource, poor wind resource, but a good solar resource. On the other hand, Iceland, which is also small, has substantial hydropower, wind, and geothermal resources but little solar. Due to the ability of Iceland to use CHS as backup and to capture its fast winds, its energy cost is low (Table 1). The Haiti region, on the other hand, needs significant overgeneration and GHS backup to keep its energy cost under control. Europe maintains a low energy cost because it can import electricity from either the north (where wind and hydropower resources are high) or from the south (where solar resources are high).

Note S6 discusses the time-dependent demand profiles, maximum storage sizes, flexible and inflexible demand treatments, and the treatment of demand response in LOADMATCH. Note S7 describes the model's order of operation, including how it treats excess generation over demand and excess demand over generation. Note S7 also provides details of how LOADMATCH treats demand response. Once LOADMATCH simulations are complete, energy costs, health costs, climate costs, and employment numbers between WWS and BAU (Notes S8, S10) and new land requirements of WWS generators (Note S9) are estimated.

Whereas transmission and distribution (T&D) costs and losses are accounted for, this study assumes perfect transmission within each region simulated. Recent studies have found, however, that grid stability can be obtained at low cost regardless of whether European countries[37] or U.S. states[38] are islanded or interconnected, but interconnecting results in slightly lower-cost solutions than islanding. Since grid stability at low cost can be obtained even when countries or states are islanded, the assumption here of perfect transmission among countries in regions with multiple countries should have no impact on the conclusions here.

In the 2050 WWS case, short-distance transmission, long-distance transmission, and distribution costs, averaged among all 149 countries, are \$0.0105, \$0.00178, and \$0.02375/kWh-all-energy, respectively, and the annual end-use energy demand is 75,580 TWh/y (Table S24). Thus, annual T&D costs are ~\$2.72 trillion/y. In both AOTA scenarios, electricity consumption is 63,660 TWh/y (7.27 GW), calculated as the electricity consumption in the 2050 BAU scenario (4.66 TW, or 24.63% of total BAU end-use demand from Table S4) plus 2.61 TW (Figure 1) due to the energy penalty of capture equipment). T&D costs per unit energy in the AOTA cases are the same as in the WWS case, except with no long-distance transmission cost. Thus, annual T&D costs in the AOTA cases are \$2.18 trillion/y, or 19.9% lower than in the WWS case. However, overall annual private energy costs in the AOTA cases are \$18.8 trillion/y, or 2.82 times that in the WWS case (\$6.7 trillion/y) (Figure 4).

Author Contributions

Conceptualization, M.Z.J.; Methodology, M.Z.J.; Investigation, M.Z.J.; D.F.; Software, M.Z.J.; Writing – Original Draft, M.Z.J.; Writing – Review & Editing, M.Z.J., D.F., D.S., A.M.

Declaration of competing interest

There are no conflicts of interest to declare.

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Data Availability

The supplementary information, tables, and figures contain relevant results. The spreadsheet model used is publicly available online[32], as is the LOADMATCH source code: https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/24-05-03-LOADMATCH.pdf. This study did not develop the original GATOR-GCMOM code.

Appendix A. Supplementary data

Supplementary data to this article can be found online at…

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Table

Table 1. 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 (¢/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, (m) and WWS and BAU social energy cost; (n) energy cost payback time; and (o) social cost payback time.

Region	(a)[1] 2050 BAU Annual-average end-use demand (GW)	(b)[1] 2050 WWS Annual-average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[2] WWS mean total capital cost ($tril 2020)	(e)[3] BAU mean private energy cost (¢/kWh-all energy)	(f)[4] WWS mean private energy cost (¢/kWh-all energy)	(g)[5] WWS mean annual all-energy private and social cost = bfH ($bil/y)
Africa-East	224	64.2	-71.4	0.609	7.82	10.24	57.6
Africa-North	380	153.1	-59.7	0.999	11.34	8.00	107.3
Africa-South	278	118.5	-57.4	0.810	9.29	8.50	88.2
Africa-West	409	110.7	-72.9	1.272	9.96	11.90	115.4
Australia	201.5	88.9	-55.9	0.495	10.26	7.87	61.2
Canada	401.9	160.1	-60.2	0.573	8.09	6.40	89.7
Central America	301.0	127.3	-57.7	0.827	10.50	8.37	93.4
Central Asia	391.9	143.3	-63.4	0.924	10.24	8.01	100.6
China region	5,081	2,542.8	-50.0	14.97	9.53	8.39	1,870
Cuba	11.9	6.7	-44.0	0.055	11.65	9.33	5.5
Europe	2,054	876.4	-57.3	5.064	10.06	8.50	652.8
Haiti region	17.2	6.8	-60.4	0.092	11.00	15.74	9.4
Iceland	4.57	2.7	-40.6	0.001	7.43	7.21	1.7
India region	1,821	967.2	-46.9	7.135	9.82	8.86	750.7
Israel	24.7	12.4	-49.8	0.112	11.21	10.85	11.8
Jamaica	4.09	1.7	-57.7	0.016	11.40	10.69	1.6
Japan	329.1	175.7	-46.6	1.226	10.48	9.63	148.2
Madagascar	12.8	3.4	-73.4	0.037	9.34	11.80	3.5
Mauritius	4.17	1.6	-62.4	0.013	10.54	10.62	1.5
Mideast	1,383	647.5	-53.2	3.822	11.34	7.74	439.1
New Zealand	27.9	14.8	-46.9	0.093	8.22	8.91	11.6
Philippines	79.7	34.7	-56.5	0.292	10.20	9.51	28.9
Russia region	729.9	262.7	-64.0	1.276	10.14	7.37	169.7
South Am-NW	201.7	81.7	-59.5	0.532	8.30	8.67	62.1
South Am-SE	756.9	344.8	-54.4	2.210	8.37	8.56	258.5
Southeast Asia	1,180.2	560.3	-52.5	6.677	10.32	12.46	611.5
South Korea	279.8	142.0	-49.2	1.596	10.69	12.54	156.0
Taiwan	154.6	85.2	-44.9	0.791	10.70	10.61	79.2
United States	2,183.4	890.2	-59.2	5.722	10.58	8.75	682.0
All regions	**18,930**	**8,627**	**-54.4**	**58.24**	**9.96**	**8.82**	**6,668**

Region	(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 (%)	(n) Energy cost payback time (y) = d/(h-g)	(o) Social cost payback time (y) = d/(k-g)
Africa-East	154	755	102	1,012	-62.5	-94.3	6.3	0.64
Africa-North	378	613	725	1,716	-71.6	-93.7	3.7	0.62
Africa-South	227	333	601	1,161	-61.1	-92.4	5.9	0.76
Africa-West	357	2,415	266	3,038	-67.7	-96.2	5.3	0.44
Australia	181.1	34.6	333.5	549.2	-66.2	-88.8	4.1	1.01
Canada	284.8	42.2	498.1	825.2	-68.5	-89.1	2.9	0.78
Central America	276.8	323.7	508.0	1,108	-66.3	-91.6	4.5	0.81
Central Asia	351.7	1,011	631.0	1,994	-71.4	-95.0	3.7	0.49
China region	4,243	10,756	8,969	23,969	-55.9	-92.2	6.3	0.68
Cuba	12.2	37.5	24.0	73.6	-55.1	-92.6	8.2	0.81
Europe	1,810	1,772	2,627	6,209	-63.9	-89.5	4.4	0.91
Haiti region	16.5	36.2	30.2	83.0	-43.4	-88.7	12.9	1.25
Iceland	3.0	0.4	2.1	5.5	-43.2	-69.5	1.1	0.36
India region	1,567	9,472	3,604	14,642	-52.1	-94.9	8.7	0.51
Israel	24.3	15.7	43.8	83.8	-51.4	-85.9	9.0	1.56
Jamaica	4.1	3.4	7.9	15.4	-60.3	-89.5	6.7	1.19
Japan	302.2	261.5	638.1	1,202	-50.9	-87.7	8.0	1.16
Madagascar	10.4	51.7	6.4	69	-66.4	-94.9	5.3	0.56
Mauritius	3.9	3.7	5.0	12.5	-62.1	-88.3	5.4	1.17
Mideast	1,374	858.2	2,730	4,962	-68.0	-91.2	4.1	0.85
New Zealand	20.1	5.2	29.6	54.8	-42.5	-78.9	10.9	2.14
Philippines	71.2	677.3	178.4	926.9	-59.5	-96.9	6.9	0.33
Russia region	648.5	602.0	1,324	2,574	-73.8	-93.4	2.7	0.53
South Am-NW	146.7	242.6	326	716	-57.7	-91.3	6.3	0.81
South Am-SE	554.9	507.2	781	1,843	-53.4	-86.0	7.5	1.39
Southeast Asia	1,067	1,936	1,915	4,918	-42.7	-87.6	14.7	1.55
South Korea	262.0	104.4	503.4	869.7	-40.5	-82.1	15.1	2.24
Taiwan	144.9	85.9	347.4	578.3	-45.4	-86.3	12.0	1.58
United States	2,024	830.1	3,137	5,991	-66.3	-88.6	4.3	1.08
All regions	**16,519**	**33,789**	**30,893**	**81,200**	**-59.63**	**-91.79**	**5.9**	**0.78**

All costs are in 2020 USD. Tables S20-S23 give cost parameters. A social discount rate of 2 (1-3)% is used. H=8,760 hours per year.

[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; heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2020 and 2050.

[3] This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 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 (e), respectively, multiplied by the energy consumed per year, which equals the end-use demand from Column (b) or (a), respectively, multiplied by 8,760 hours per year.

[6] The 2050 annual BAU health cost equals the number of total air pollution mortalities per year in 2050 from Table 2, multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy) and by a VOSL calculated for each country, and multipliers for morbidities and non-health, non-climate environmental impacts (see Note S8).

[7] The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table 2, multiplied by the mean social cost of carbon in 2050 from Table 2 (in 2020 USD). See Note S8 for a discussion.

Table 2. Regional (a) estimated 2050 air pollution mortalities per year due to all sources of air pollution (about 90% of which are due to energy sources); (b) 2050 carbon dioxide-equivalent emissions (CO_2e) from energy sources; (c) cost per tonne-CO_2e-eliminated of converting to WWS; (d) BAU energy cost per tonne-CO_2e emitted; (e) BAU health cost per tonne-CO_2e emitted; (f) BAU climate cost per tonne-CO_2e emitted (social cost of carbon); (g) BAU total social cost per tonne-CO_2e emitted; (h) BAU health cost per unit-all-BAU-energy produced; and (i) BAU climate cost per unit-all-BAU-energy produced.

Region or country	(a)[1] 2050 BAU air pollution mortalities/y	(b)[2] 2050 BAU CO_2e (megatonne/y)	(c)[3] 2050 WWS energy cost ($/ tonne-$CO_2e$-eliminated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa-East	368,987	183	314	838	4,119	558	5,516	38.4	5.2
Africa-North	143,559	1,298	83	291	473	558	1,322	18.4	21.8
Africa-South	92,316	1,076	82	211	310	558	1,079	13.7	24.6
Africa-West	644,813	476	242	750	5,072	558	6,380	67.4	7.4
Australia	3,034	597	103	303	58	558	919	2.0	18.9
Canada	3,764	892	101	319	47	559	925	1.2	14.2
Central America	45,608	910	103	304	356	558	1,218	12.3	19.3
Central Asia	235,560	1,130	89	311	895	558	1,764	29.5	18.4
China region	1,134,535	16,066	116	264	669	558	1,492	24.2	20.1
Cuba	4,851	43	127	283	872	558	1,713	35.9	22.9
Europe	179,603	4,705	139	385	377	558	1,320	9.9	14.6
Haiti region	13,695	54	173	306	670	558	1,534	24.1	20.1
Iceland	36	4	441	777	109	559	1,445	1.0	5.3
India region	1,658,265	6,454	116	243	1,468	558	2,269	59.4	22.6
Israel	1,544	78	151	310	201	558	1,069	7.3	20.2
Jamaica	698	14	115	289	242	558	1,090	9.5	22.0
Japan	27,181	1,143	130	264	229	558	1,051	9.1	22.1
Madagascar	29,683	11	308	916	4,539	558	6,014	46.3	5.7
Mauritius	418	9	164	434	417	558	1,408	10.1	13.6
Mideast region	118,866	4,889	90	281	176	558	1,015	7.1	22.5
New Zealand	444	53	218	379	98	559	1,036	2.1	12.1
Philippines	126,965	320	90	223	2,119	558	2,901	97.0	25.5
Russia	59,101	2,371	72	274	254	558	1,086	9.4	20.7
South Am-NW	40,985	584	106	251	415	558	1,224	13.7	18.5
South Am-SE	69,097	1,398	185	397	363	558	1,318	7.6	11.8
Southeast Asia	316,266	3,430	178	311	564	558	1,434	18.7	18.5
South Korea	8,980	901	173	291	116	558	965	4.3	20.5
Taiwan	6,649	622	127	233	138	558	929	6.3	25.6
United States	62,694	5,617	121	360	148	558	1,067	4.3	16.4
All regions	**5,398,197**	**55,329**	**121**	**299**	**611**	**558**	**1,468**	**20.4**	**18.6**

[1] 2050 regional BAU mortalities due to air pollution are summed over country-specific values given in Table S26. See Footnote 1 of Table S26 for a discussion of how the country-specific mortalities are derived from WHO[1,2] data, which estimate 7.19 million air-pollution-related mortalities/y among the 149 countries in 2019.

[2] CO_2e emissions account for the emissions of CO_2 plus the emissions of other greenhouse gases multiplied by their global warming potentials. The emissions from this table represent 99.75% of world anthropogenic CO_2e emissions.

[3] Calculated as the WWS private energy and total social cost from Table 1, Column (g) divided by the CO_2e emission rate from Column (b) of the present table.

[4] Columns (d)-(g) are calculated as the BAU private energy cost, health cost, climate cost, and total social costs from Table 1, 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 1, Columns (i)-(j), respectively, each divided by the BAU end-use demand from Table 1, Column (a) and by 8,760 hours per year.

Figure 1. 2050 annually-averaged end-use demand across 149 countries in four cases: BAU, BAU, but where CC is attached to all BAU energy-related stationary CO_2 emission sources and SDACC is used to offset mobile and distributed CO_2 emission sources and CC/SDACC are powered by BAU electricity (BAU-CC-BAU), same as BAU-CC-BAU, but where CC/SDACC are powered by WWS electricity (BAU-CC-WWS), and 100% WWS. The BAU and WWS numbers are obtained from Table 1. The BAU-CC-BAU and BAU-CC-WWS numbers are calculated as follows: demand relative to BAU is first reduced by 6.74% (Table S4) due to energy efficiency improvements beyond those in the BAU case. The remaining non-WWS and non-nuclear portion of BAU power that results in CO_2 emissions (~ 87.9% of the remaining BAU power) is then increased by 25% in both CC cases to account for the energy penalty to run the CC equipment.

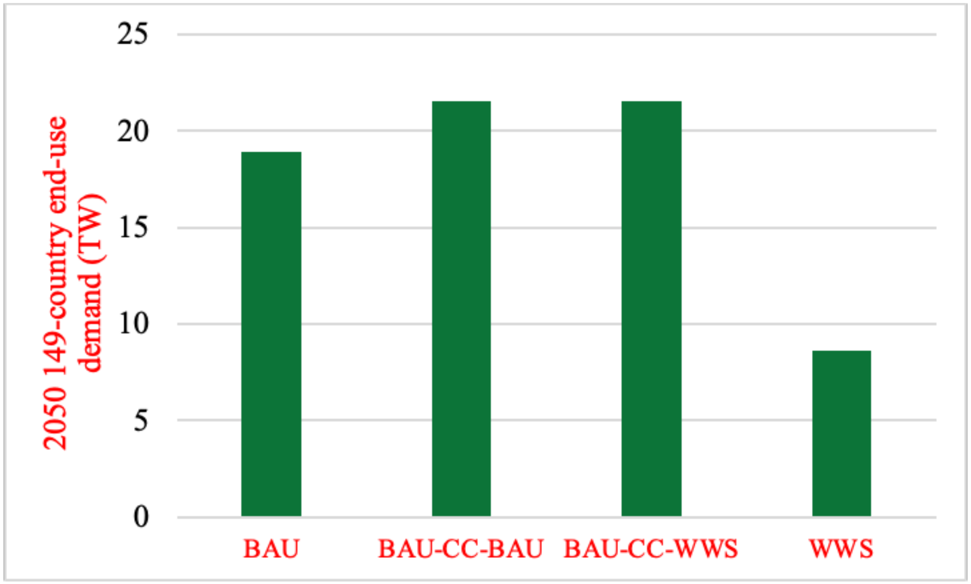


Figure 2. Number of 2050 energy-related air pollution mortalities/y across 149 countries in each case. The BAU value is 90% of the number from Table 2 (which provides energy plus non-energy air pollution mortality). 100% WWS eliminates all air pollution mortalities from energy. The BAU-CC-BAU value is calculated from the BAU value as follows: the BAU number is first reduced by 6.74% (Table S4) due to energy efficiency improvements beyond those in the BAU case. The resulting total is then increased by 25% to account for the energy penalty of using CC/SDACC, which increases air pollution by 25%. The BAU-CC-WWS number is calculated in the same way but without adding mortalities due to the energy penalty since the electricity in that case is from WWS.

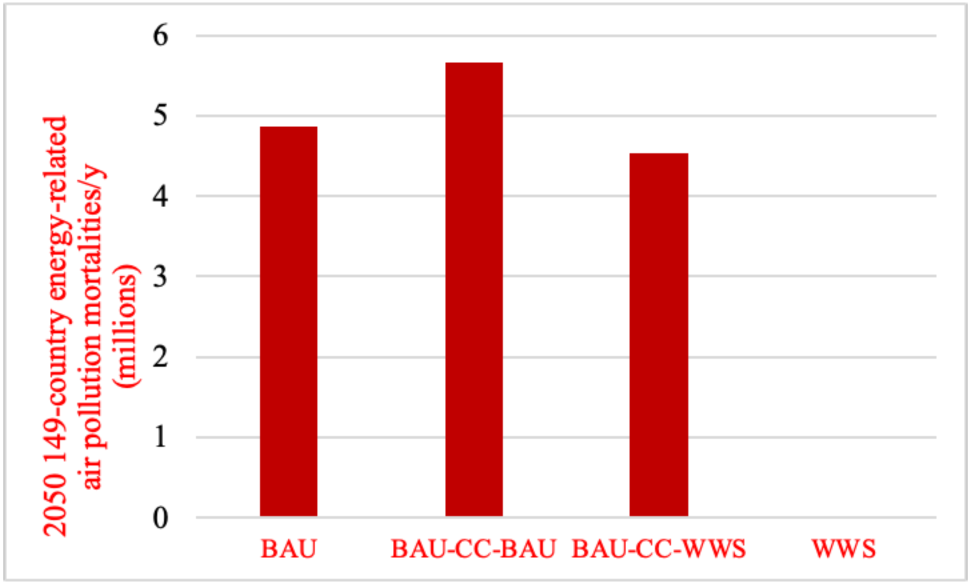


Figure 3. 2050 energy-related carbon dioxide-equivalent emissions in each case. BAU values are from Table 2. The BAU-CC-BAU number is calculated by first reducing the BAU number by 6.74% (Table S4) due to energy efficiency improvements beyond those in the BAU case. The resulting total is then reduced by 68% (85% of CO_2e emissions are assumed to be CO_2 and 80% of CO_2 is assumed to be captured), but that resulting total is then increased by 25% to account for the energy penalty of using CC/SDACC. The BAU-CC-WWS number is calculated in the same way but without adding emissions due to the energy penalty since the energy to run CC/SDACC in that case is obtained from WWS.

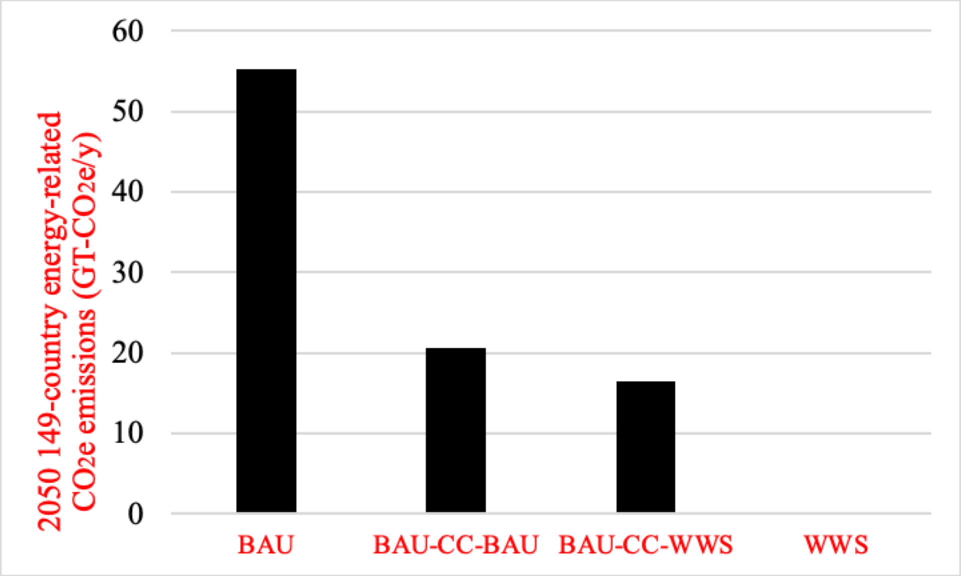
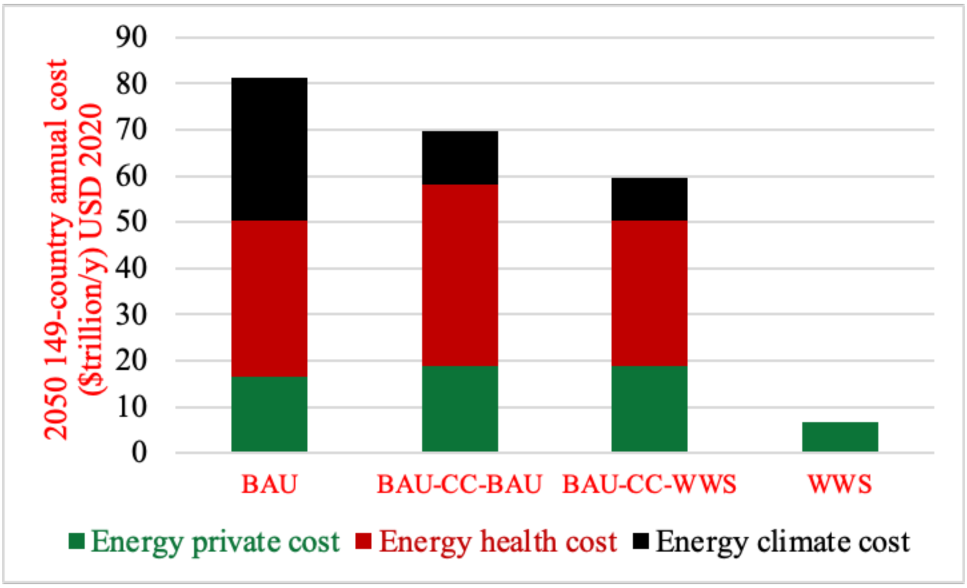


Figure 4. 2050 annual social cost of energy (USD 2020) across 149 countries in each case. The BAU and WWS numbers are from Table 1. The BAU-CC-BAU numbers are calculated as follows: annual private energy, health, and climate costs relative to BAU are first reduced by 6.74% (Table S4) due to energy efficiency improvements beyond those in the BAU case. Next, 87.9% of the resulting BAU energy is non-WWS and non-nuclear energy and needs CC/SDACC, thus that portion of the private energy cost is increased by 25% to account for the energy penalty of CC. The BAU health cost is also increased by 25%. The BAU climate cost is reduced by 68% (85% of CO_2e emissions are assumed to be CO_2 and 80% of CO_2 is assumed to be captured), but the total is then increased by 25% due to the energy penalty. In the BAU-CC-WWS case, the energy private cost is increased in the same was as in the BAU-CC-BAU case, but the air pollution cost is the same as in the BAU case since no new source of pollution is introduced, and the climate cost is decreased by 68% without an increase in climate cost due to the energy penalty.



Supplementary Information

On the Energy, Health, and Climate Costs of "All-of-the-Above" Versus 100% Wind-Water-Solar (WWS) Climate Policies: Analysis Across 149 Countries

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

Supporting Text

Note S1. Summary

This study examines matching all-purpose electricity and heat demand (load) with supply, storage, and demand response after all energy in 149 countries has been converted to electricity and heat provided from 100% wind-water-solar (WWS) sources. The 149 countries are combined into 29 grid regions for the analysis. Model simulations are carried out for three years at a 30-s time resolution. Green hydrogen (produced from WWS electricity) is produced, stored, and used for three non-grid purposes: steel and ammonia manufacturing and long-distance transport. Green hydrogen is also produced, stored, and used for grid electricity backup. The storage of green hydrogen for grid electricity use is referred to here as green hydrogen storage (GHS). Conventional hydropower storage (CHS), pumped hydroelectric storage (PHS), concentrated solar power (CSP) storage (CSPS), and battery storage (BS) also provide grid electricity storage here. Heat is stored in water tanks and in underground soil and water pits. Some heat is provided from solar and geothermal sources. Cold is stored in water tanks and ice. Hydrogen is stored in storage tanks. Transportation is electrified with battery-electric and hydrogen fuel cell vehicles. Buildings are electrified with electric heat pumps for air and water heating, air conditioning, and clothes drying and electric induction cooktops for cooking. District heating is used to heat and cool some buildings. Industry is electrified with electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, and heat pumps for process heat.

Table S1 lists the 29 regions and the 149 countries treated. The regions include a mix of 13 multi-country regions (East Africa, North Africa, South Africa, West Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, Northwest South America, Southeast South America, and Southeast Asia) and 16 individual countries or pairs of countries (Australia, Canada, Cuba, Haiti-Dominican Republic, Israel, Iceland, Jamaica, Japan, Madagascar, Mauritius, New Zealand, the Philippines, Russia-Georgia, South Korea, Taiwan, and the United States).

This SI describes the model in more detail and summarizes the results in multiple tables.

Note S2. Methodology

This note summarizes the overall methodology used in this study. It then describes the first, step, which is to use a spreadsheet model to develop year-2050 roadmaps to transition each of 149 countries to 100% WWS among all energy sectors in order to meet annual-average demand.

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

(1) project business-as-usual (BAU) end-use energy demand from 2020 to 2050 for each of seven fuel types in each of six energy-use sectors, for each of 149 countries;
(2) estimate the 2050 reduction in demand due to electrifying or providing direct heat for each fuel type in each energy sector in each country and providing that electricity and heat with WWS;
(3) during step (2), replace BAU steel and ammonia manufacturing with green-H_2 steel and ammonia manufacturing and replace BAU long-distance transport vehicles with green-hydrogen fuel cell-electric vehicles;
(4) perform resource analyses then estimate mixes of wind-water-solar (WWS) electricity and heat generators required to meet the aggregate demand in each country in the annual average;
(5) use a prognostic global weather-climate-air pollution model (GATOR-GCMOM), which accounts for competition among wind turbines for available kinetic energy, to estimate wind and solar radiation fields and building heat and cold demands every 30 s for three years in each region;
(6) group the 149 countries into 29 world regions and use a model (LOADMATCH) to match variable electricity, heat, cold, and hydrogen demand with variable supply, storage (electricity, heat, cold, and hydrogen storage), and demand response in each region every 30 s, from 2050 to 2052;
(7) evaluate energy, health, and climate costs of WWS vs BAU;
(8) calculate land area requirements of WWS; and
(9) calculate changes in WWS versus BAU jobs numbers.

Thus, three types of models are used for this study: a spreadsheet model (Steps 1-4), a 3-D global weather-climate-air pollution model (Step 5), and a model that matches electricity, heat, cold, and hydrogen demand with supply, storage, and demand response assuming perfect grid interconnection (Steps 6-9). The rest of this note describes the spreadsheet model which is available online (Jacobson and Delucchi, 2024). Note S3 describes GATOR-GCMOM. Notes S4-S7 describe LOADMATCH.

We start with 2020 business-as-usual (BAU) end-use energy consumption (also called total final consumption) data for each country from IEA (2023). End-use energy is energy directly used by a consumer. It is the energy embodied in electricity, fossil gas, gasoline, diesel, kerosene, and jet fuel that people use directly, including to extract and transport fuels themselves. It equals primary energy minus the energy lost in converting primary energy to end-use energy, including the energy lost during transmission and distribution. Primary energy is the energy naturally embodied in chemical bonds in raw fuels, such as coal, oil, fossil gas, biomass, uranium, or renewable (e.g., hydroelectric, solar, wind) electricity, before the fuel has been subjected to any conversion process.

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

These data are projected for each fuel type in each sector in each country from 2020 to 2040 using "BAU reference scenario" projections from EIA (2016) for each of 16 world regions. This is extended to 2075 using a ten-year moving linear extrapolation. The reference scenario is one of moderate economic growth and accounts for policies, population growth, economic and energy growth, the growth of some renewable energy, modest energy efficiency measures, and reductions in energy use. EIA refers to their reference scenario as their BAU scenario. The 2050 BAU end-use energy for each fuel type in each energy sector in each of 149 countries is then set equal to the corresponding 2020 end-use energy value for the fuel type and sector from IEA (2023) multiplied by the EIA 2050-to-2020 energy consumption ratio, available after the extrapolation, for the same fuel type and sector of the world region containing the country.

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

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

Liquid fuel (mostly gasoline, diesel, bunker fuel, and jet fuel) and fossil gas vehicles are transitioned to battery-electric (BE) vehicles and some hydrogen fuel cell-electric (HFC) vehicles, where the hydrogen is produced with WWS electricity (green hydrogen). BE vehicles are assumed to dominate short- and long-distance light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance (<1,000 km) heavy-duty trucks, trains (except when powered by electric rails or overhead wires), ferries, speedboats, and ships. Batteries also power short-haul (<3 h) aircraft flights. HFC vehicles make up all long-distance ships, trains, and trucks; medium- and long-distance aircraft; and long-distance military vehicles (Katalenich and Jacobson, 2022). Gasoline lawnmowers, leaf blowers, and chainsaws are converted to electric equivalents.

Mid- and high-temperature industrial processes are electrified with electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, and electron beam heaters. Low-temperature heat for industry is provided with electric heat pumps. Green hydrogen for steel and ammonia manufacturing replaces BAU fuels for these processes, as described in Jacobson et al. (2023). Table S5 summaries the annual hydrogen production by year for these processes, as well as for long-distance transport. All electricity for industry comes from WWS sources.

In each country, a mix of WWS resources is estimated in the spreadsheet to meet the all-sector annual-average end-use energy demand after electrification. The mix is determined after a WWS resource analysis is performed for each country and after the technical potential of each WWS resource in each country is estimated. Jacobson et al. (2017) provide the methodology for the resource analysis performed here for each country.

Next, a first estimate of the nameplate capacities of a mix of WWS generators needed to meet annual-average all-purpose end-use energy demand in each country is calculated iteratively in the spreadsheet (Jacobson and Delucchi, 2024). The penetration of each WWS electricity generator in each country is limited by the following constraints: (1) each generator type cannot produce more electricity in the country than the technical potential allows; (2) the land area taken up among all WWS land-based generators should be no more than a few percent of the land area of the country of interest; (3) the area of installed rooftop photovoltaics (PV) in each country must be less than the respective rooftop area suitable for PV; (4) the nameplate capacity of hydropower is the same as in 2022; and (6) wind and solar, which are complementary in nature, are used in roughly equal proportions where feasible.

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

Note S3. Description of GATOR-GCMOM and its Calculations

This note briefly summarizes the GATOR-GCMOM model and the main processes that it treats. GATOR-GCMOM is a three-dimension Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model (Jacobson, 2001; 2014; Jacobson et al., 2007; Jacobson and Archer, 2012; and Jacobson and Jadhav, 2018). It simulates weather, climate, and air pollution on the global, regional, and urban scales. The main processes treated are as follows:

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

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

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

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

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

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

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

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

GATOR-GCMOM simulates feedback among all these processes, in particular among meteorology, solar and thermal-infrared radiation, gases, aerosol particles, cloud particles, oceans, sea ice, snow, soil, and vegetation. Model predictions have been compared with data in 34 peer-reviewed studies. The model has also taken part in 14 model inter-comparisons (Jacobson et al., 2019).

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

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

Onshore wind turbines are placed in windy areas in each country in GATOR-GCMOM. Offshore turbines are placed in coastal water in each country that has a coastline. The wind turbine blades in the model cross five vertical model layers. Spatially-varying model-predicted wind speeds are used to calculate wind power output from each turbine every 30 s. This calculation accounts for the reduction in the wind's kinetic energy and speed due to the competition among wind turbines for limited available kinetic energy (Jacobson and Archer, 2012).

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

The model calculates the temperature-dependence of PV output (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 building cooling and heating demands in each country every 30 s. The model predicts the ambient air temperature in each of multiple surface grid cells in each country and compares it with an ideal building interior temperature, set to 294.261 K (70^{o}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 (2021a) provides full details. The time series demands among all grid cells in a country are then summed to obtain a countrywide demand time series for the country, which is then output for use in LOADMATCH.

Note S4. Description of and Processes in the LOADMATCH Model

This note discusses the LOADMATCH model (Jacobson et al., 2015; 2018; 2019; 2021a,b; 2022a,b, 2023, 2024) and its main processes. LOADMATCH is a trial-and-error simulation model written in Fortran. Its goal is to match time-dependent electricity, heat, cold, and hydrogen demand with supply, storage, and demand response without failure. It works by running multiple simulations for each grid region, one at a time. Each simulation marches forward one timestep at a time, just as the real world does, for any number of years for which sufficient input data are available. In past studies, the model was run for 1 to 6 years, but there is no technical or computational limit preventing the model from running for hundreds or thousands of years, given sufficient input data. In the present study, the time step used is 30 s, and the simulation period is three years for each region.

The main constraints are that electricity, heat, cold, and hydrogen demands plus losses, adjusted by demand response, must each meet corresponding WWS supplies and storage every 30-s timestep of a simulation. If a demand is not met during any timestep, the simulation stops. Inputs (either the nameplate capacity of one or more generators; the peak charge rate, peak discharge rate, or peak capacity of storage; or characteristics of demand response) are then adjusted one at a time based on an examination of what caused the demand mismatch (thus, LOADMATCH is a "trial-and-error" model). Another simulation is then run from the beginning. New simulations are run until demand is met every time step of the simulation period. After demand is met once, additional simulations are performed with further-adjusted inputs based on user intuition and experience to generate a set of solutions that match demand every timestep. The lowest-cost solution 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 when the time step is 30 s. 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 from onshore and offshore wind turbines, residential and commercial rooftop PV systems, utility PV plants, CSP plants, and wave devices in each region of interest, predicted by GATOR-GCMOM;
(2) time-dependent heat from solar thermal devices, predicted by GATOR-GCMOM;
(3) time-dependent building heat and cold demands, predicted by GATOR-GCMOM;
(4) baseload (constant) tidal electricity and geothermal electricity and heat supply, with magnitudes determined in the spreadsheet model;
(5) baseload and peaking hydropower electricity production (Note S5) constrained by 2022 annual hydropower output and nameplate capacity;
(6) specifications of hot-water and chilled-water sensible-heat thermal energy storage (HW-STES and CW-STES) (peak charge rate, peak discharge rate, peak storage capacity, losses into storage, and losses out of storage);
(7) specifications of underground thermal energy storage (UTES);
(8) specifications of ice storage (ICE);
(9) specifications of electricity storage in PHS, CSPS, BS, and GHS;

(10) specifications of hydrogen electrolyzer, rectifier, compressor, and storage tank sizes for non-grid versus grid applications, and the quantity of hydrogen needed for steel and ammonia manufacturing, long-distance transport, and grid electricity backup;
(11) specifications of electric heat pumps needed for district heating and cooling;
(12) specifications of district heating and individual building electric heat pump coefficient of performance;
(13) specifications of a demand response system;
(14) specifications of losses along short- and long-distance transmission and distribution lines;
(15) assumed or data-derived time-dependent electricity, heat, cold, and hydrogen demand profiles; and
(16) specifications of scheduled and unscheduled maintenance downtimes for generators, storage, and transmission.

From model results, differences in energy, health, and climate costs and job creation and loss between BAU and WWS are estimated. Land requirements of WWS are also calculated. The cost calculation requires specifications of WWS electricity and heat generator costs; the costs of electricity storage, low-temperature heat storage, cold storage, and hydrogen storage; the costs of hydrogen electrolyzers, rectifiers, compressors, dispensers, cooling equipment, and fuel cells; transmission and distribution costs; air pollution costs; and climate costs. Changes in job numbers require specifications of job data for generators, storage, hydrogen, and transmission/distribution. Land requirements require specification of the installed power density of different types of land-based generators.

LOADMATCH is used here to match time-dependent (30-s resolution) electricity and heat demands and losses with supply, storage, and demand response for three years, from 2050 to 2052. Note S5 summarizes the treatment of hydropower in the model. Note S6 discusses thermal and electricity demand profiles, maximum storage sizes, flexible and inflexible demands, and the treatment of demand response in the model. Note S7 discusses the order of operation in the model. Whereas GATOR-GCMOM provides time-dependent wind, solar, and wave electricity supplies and solar heat supplies for LOADMATCH, geothermal electricity and heat supplies and tidal electricity supplies are assumed to be constant throughout the year. Hydropower is used for both baseload and peaking electricity (Note S5).

Transmission in LOADMATCH is assumed to be perfectly interconnected. However, transmission and distribution costs and losses are accounted for (Table S20). The regions simulated here (Table S1) cover different spatial scales, from 11 relatively small regions (Cuba, Haiti-Dominican Republic, Iceland, Israel, Jamaica, Japan, Madagascar, Mauritius, New Zealand, Philippines, South Korea, and Taiwan) to the continental scale. Long-distance transmission costs increase when countries are interconnected versus isolated. For the smallest individual countries or pairs of countries (Cuba, Haiti-Dominican Republic, Iceland, Israel, Jamaica, Madagascar, Mauritius, South Korea, and Taiwan), no long-distance transmission is assumed because the distance across such entities is less than a typical HVDC transmission line length (1,000-2,000 km). For New Zealand, 15% of all non-rooftop PV and non-curtailed electricity consumed is assumed to be subject to long-distance transmission. For Central America, Japan, and the Philippines, 20% is assumed to be subject to long-distance transmission. For all other countries and regions, 30% is assumed to be subject to long-distance transmission (Table S15). Jacobson (2021b) evaluated the difference in cost when countries in several grid regions in Europe were isolated versus interconnected. The study found that interconnecting reduces aggregate annual energy costs, but whether isolated or interconnected, all countries can match all energy demand with supply and storage at low cost.

Note S5. Treatment of Hydropower for Both Baseload and Peaking

The annual hydropower output (TWh/y) in 2050 in each country is limited to the 2022 output in the country. This annual hydropower energy output is assumed to be exactly replenished each year by rainfall and runoff. The 2050 peak discharge rate (nameplate capacity) of hydropower in each country is also limited by the country's 2022 nameplate capacity. The nameplate capacity of hydropower is the peak discharge rate of its generators.

Jacobson (2024) solved a set of six equations and six unknowns to treat hydropower in each grid region in LOADMATCH for both baseload and peaking simultaneously. The six unknowns are the maximum storage capacity (TWh), total nameplate capacity (TW), and recharge rate (TW), of each baseload and peaking hydropower. These unknowns are solved considering three known quantities - the maximum storage capacity (TWh), total nameplate capacity (TW) and total recharge rate (TW) of baseload plus peaking hydropower in each region. The maximum storage capacity for 2050 equals the 2020 storage capacity by region, from IEA (2021), redistributed into the regions used here with the technique described in Jacobson (2024). The total hydropower nameplate capacity for 2050 is assumed to be the 2022 nameplate capacity of hydropower. The 2050 total recharge rate is assumed to equal the 2022 estimated hydropower output (TWh/y) divided by the number of hours per year. Table S14 provides values for all three known parameters as well as the resulting values for the unknown parameters for each region.

The six equations solved are as follows: (1) the sum of the maximum energy storage capacities (TWh) of baseload hydropower and peaking hydropower in each region must equal the overall maximum energy storage capacity among all hydropower reservoirs in a region; (2) the sum of the instantaneous average charge rates (TW) of baseload hydropower and of peaking hydropower in all reservoirs in the region equals the average charge rate, summed among all reservoirs in the region; (3) the sum of the maximum discharge rates (nameplate capacities) (TW) of generators assigned to baseload hydropower and peaking hydropower equals the total nameplate capacity of all generators among all hydropower plants in the region; (4) the maximum discharge rate (TW) of baseload hydropower in each region must equal the instantaneous average charge rate of baseload hydropower in the region; (5) the nameplate capacity of baseload hydropower multiplied by the hours of baseload storage at that nameplate capacity equals the maximum storage capacity of baseload power; and (6) the maximum energy storage capacity (TWh) of peaking hydropower equals the instantaneous average charge rate of peaking power (TW) multiplied by 8,760 h per year. In other words, the peaking portion of the reservoir must be filled fully once per year. Jacobson (2024) provides the solution implemented here to obtain the results shown in Table S14 for each region.

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

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

This note discusses the development of time-dependent demand profiles at 30-s time resolution for use in LOADMATCH. Demand profiles are developed starting with 2050 annual-average WWS energy demand values for each sector in each country from Table S4a. These demands are separated into (1) electricity and direct heat demands for low-temperature heating; (2) electricity demands for cooling and refrigeration; (3) electricity demands for producing, compressing, and storing hydrogen to run hydrogen fuel cell-electric vehicles with or to manufacture steel and ammonia with; and (4) all other electricity demands (including industrial process heat demands), as described in Section S1.3.3 of Jacobson et al. (2019) and updated in Jacobson (2021a).

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

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

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

Industrial process demand consists of inflexible process heat demand, flexible process heat demand subject to demand response, and industrial hydrogen demand. Inflexible industrial process heat demand consists of 30% of total industrial process demand. The inflexible industrial process heat demand is assumed to vary each hour with the same profile as the overall electricity demand in the country of the demand and must be met immediately with either current electricity or stored electricity. Industrial process heat demand subject to demand response consists of total industrial process demand minus inflexible industrial process demand and minus industrial process hydrogen demand. This demand subject to demand response is assumed to be constant every hour of every day. It is met first with current electricity or electricity storage. If demand remains, it is shifted forward in time by no more than eight hours with demand response. Industrial hydrogen demand (for steel and ammonia manufacturing) is assumed to be constant each hour of each day. It is met first from hydrogen storage. If no hydrogen is currently in storage, the remaining load becomes inflexible and must be met with current electricity or with electricity storage.

All annual-average 2050-2052 inflexible electricity demands (in the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors) in each region are converted to time-dependent 2050-2052 inflexible electricity demands for the region by projecting contemporary time-dependent electricity demand data for the region forward to 2050-2052. Contemporary hourly demand data for European countries are for 2014 (ENTSOE, 2016). Those for almost all remaining countries are for 2030 (Neocarbon Energy, 2016). Since demand profiles for Sudan, Zimbabwe, and Equatorial Guinea do not exist from either of these datasets, their profiles are assumed to be the same as those of a nearby country, but with the magnitude each hour scaled so that the resulting annual-average inflexible demand reflects that of each original country.

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

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

For vehicles, this assumption is roughly justified by the fact that, between 2016-2019 in the U.S., the minimum and maximum monthly U.S. gasoline supplies were 7.76% and 8.73%, respectively, of the annual supply (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°F (-6.67°C) than at 77°F (25°C) (USDOE, 2021), whereas BEV range is ~40% lower between those two temperatures (Geotab, 2020). Since gasoline consumption is greater during summer than winter, this implies that the summer minus winter difference in BEV electricity consumption will be less than the summer minus winter difference in gasoline consumption, justifying a relatively even spread during the year of electricity consumption with BEVs.

Fifteen percent of electricity demands for vehicles is assumed to be inflexible, and 85% is assumed to be flexible and subject to demand response. The flexible demands can be shifted forward in time if necessary or pulled from storage whenever electricity storage is sufficient available. The demand for producing and compressing hydrogen for fuel cell vehicles comprises 32.9% of the total transportation demand among the 149 countries [Table S5, Column (f) divided by Table S6, Column (f)]. The rest of the transportation demand (67.1%) is for powering battery-electric vehicles. The demand for producing and compressing hydrogen for steel and ammonia manufacturing comprises 12.8% of the total industrial demand [Table S5, Column (e) divided by Table S6, Column (e)]. The demand for producing and compressing hydrogen for both transportation and industry comprises 11.6% of the all-purpose demand [Table S5, Column (g) divided by Table S6, Column (a)]. All these demands are flexible, so hydrogen can be produced whenever excess electricity is available. The hydrogen can then be stored and used as needed. Of all transportation demands, 85% are flexible. This includes 100% of electricity demands for hydrogen production and compression for hydrogen fuel cell vehicles (32.9% of transportation electricity demands) and 77.6% of electricity demands for battery-electric vehicles (67.1% of transportation electricity demands).

Thirty percent of electricity demands for industrial process heat is inflexible, and 70% minus the energy needed for hydrogen production and storage for ammonia and steel manufacturing, is flexible and subject to demand response.

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

Note S7. Order of Operation in LOADMATCH

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

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

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

Heat and cold storage are filled by using excess electricity to power an air-, water-, or ground-source heat pump to move heat or cold from the air, water, or ground, respectively, to a thermal storage medium. Non-grid and grid hydrogen storage are filled by using electricity in an electrolyzer (after a rectifier converts AC to DC electricity for use in the rectifier) to produce hydrogen and in a compressor to compress the hydrogen, which is then moved to a storage tank.

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

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

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

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

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

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

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

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

Note S8. Calculations of Energy, Air Pollution, and Climate Costs

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

BAU air pollution health cost estimates (Table S25) are based on the projected number of all air pollution deaths per year in 2050 by country provided in Table S26 (with a description of the calculation in Footnote 1 of the table) multiplied by the fraction of such deaths that are due to energy-related emissions (0.9) (Jacobson et al., 2019), a 2050 value of statistical life (VOSL) for each country, a cost factor for morbidity (1.15), and a cost factor for non-health and non-climate environmental impacts (1.1) (Jacobson et al., 2019).

With BAU, an estimated 5.4 million people die per year in 2050 from energy- plus non-energy-related air pollution across the 149 countries (Table S26, Figure 2). Most deaths are in the India region (1.66 million/y), followed by the China region (1.13 million/y), West Africa (645,000/y), East Africa (369,000/y), Southeast Asia (316,000/y), Central Asia (236,000/y), and Europe (180,000/y). About 90% of these premature deaths are estimated to be due to energy generation and use (Jacobson et al., 2019).

The 2050 value of statistical life (VOSL) (millions of dollars per person) by country was updated for 2020 USD from Jacobson et al. (2019) for each country. Results are shown in Jacobson and Delucchi (2024) for each country. The mean VOSL in 2050 among all countries is \$5.54 million/person (USD 2020). The mean total cost of each life after accounting for associated morbidities and non-health environmental impacts is \$7.01 million/person. In the U.S., the 2050 VOSL and total cost are \$11.6 million/person and \$14.7 million/person (USD 2020). This is conservative relative to DOT (2023), who estimate the 2022 VOSL in the U.S. of \$12.5 million/person.

The 2050 BAU health cost of energy-related deaths (based on the value of statistical life), associated morbidities, and associated non-health, non-climate environmental damage due to energy-related air pollution, is estimated to be ~\$33.8 trillion/y (Table S25). Energy-related air pollution deaths due to WWS are assumed to equal zero since 100% WWS results in zero emissions associated with energy, even during the mining and manufacturing of WWS equipment.

2050 energy-related emissions of carbon dioxide and other climate-warming pollutants are estimated to be 55.3 gigatonnes (GT)-CO_2-equivalent (CO_2e)/y across 149 countries (Table S26). The highest emission rates are in the China region (16.1 GT/y), India region (6.5 GT/y), United States (5.6 GT/y), Mideast (4.9 GT/y), Europe (4.7 GT/y), Southeast Asia (3.4 GT/y), and the Russia region (2.4 GT/y).

BAU climate costs are estimated based on the mean social cost of carbon in each country and region (Table S26) multiplied by the estimated energy-related CO_2-equivalent emissions in 2050 (Table S26). The mean social cost of carbon in 2050 in each country is calculated as \$558 (\$315-\$1,188)/tonne-CO_2e (Jacobson and Delucchi, 2024), and is an update to USD 2020 from values in Jacobson et al. (2019). The 2050 estimate assumes 2010 values of \$250 (\$125-\$600)/tonne-CO_2e and growth factors of 1.5 (1.8-1.2)% per year between 2010 and 2050 and a multiplier of 1.226 to obtain values in USD 2020. The 2010 SCC is estimated as follows. Van den Bergh and Botzen (2014) suggest that the 2014 lower bound of the SCC should be at least \$125 per tonne-CO_2e. Moore and Diaz (2015) conclude that incorporating the effect of climate change on the rate of economic growth can increase the SCC to between \$200 and \$1,000 per tonne-CO_2e. Burke et al. (2014) similarly finds that accounting for the long-term effects of temperature rise on economic productivity results in climate change damage estimates that are 2.5 to 100 times higher than those from earlier studies. Nevertheless, we limit the upper limit of the 2010 SCC to \$600/tonne-CO_2e.

Note S9. Calculation of Land Requirements

Footprint is the physical area on the top surface of soil or water needed for each energy device (Jacobson, 2009). It does not include the area of underground structures. Spacing is the area between some devices, such as wind turbines, wave devices, and tidal turbines, needed to minimize interference of the wake of one turbine with downwind turbines. Spacing area can be used for multiple purposes, including rangeland, ranching land, industrial land (e.g., installing solar PV panels), open space, or open water. Table S27 provides estimated footprint and spacing areas per MW of nameplate capacity of WWS electricity and heat generating technologies considered here.

Applying the footprint and spacing areas per MW nameplate capacity from Table S27 to the new nameplate capacities needed to provide grid stability (obtained by subtracting the existing nameplate capacities in Table S9 from the existing plus new nameplate capacities in Table S10) gives the total new land footprint and spacing areas required for each country and region, as shown in Table S28.

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

Note S10. Calculation of Employment Changes

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

The number of jobs per MW was derived for the United States primarily from the Jobs and Economic Development Impact (JEDI) models (NREL, 2019). These models estimate the number of construction and operation jobs plus earnings due to building an electric power generator or transmission line. The models treat direct jobs, indirect jobs, and induced jobs.

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

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

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

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

Note S11. Summary of Energy, Storage, Cost, Land, and Employment Results

S11.1. Energy Demand and Generation Results

Table S4 provides the 2020 annual-average end-use BAU demand, the projected 2050 annual-average end-use BAU demand, and the 2050 annual-average end-use WWS demand by energy sector and country from the spreadsheet analysis done in this study.

Table S4 indicates that transitioning from BAU to 100% WWS in 2050 in 149 countries reduces the 2050 annual-average end-use power demand by an average of 54.4%, from 18.9 TW to 8.6 TW. Table S4b and Figure S1 show the end-use load by region. Of the total reduction, 36.8 percentage points are due to the efficiency of using WWS electricity over combustion; 10.9 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels; and 6.7 percentage points are due to end-use energy efficiency improvements and reduced energy use beyond those with BAU (Table S4). Of the 36.8% reduction due to the efficiency advantage of WWS electricity, 19.7 percentage points are due to the efficiency advantage of WWS transportation, 4.1 percentage points are due to the efficiency advantage of using WWS electricity for industrial heat, and 13.1 percentage points are due to the efficiency advantage of using heat pumps instead of combustion heaters. Whereas all-purpose energy demand declines by 54.4%, the energy is almost all electricity (with some direct heat), causing world-average electricity consumption to increase by 85% compared with BAU (Table S4).

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

Figure S4 shows LOADMATCH final results for each region. The figure shows hourly time series plots of the matching of all-purpose end-use demand with supply and changes in storage exactly every 30 s from 2050 to 2052. No failure occurs during any time step in any region. Thus, WWS avoids blackouts by ensuring that generation, storage, and demand response meets demand every 30 s for multiple years.

Table S9 provides the existing 2022 nameplate capacities of each electricity and heat generator by country. Table S10 provides the final nameplate capacities for each generator in each region, as determined by LOADMATCH.

Table S11 gives the ratio of the final nameplate capacities needed to meet continuous demand in LOADMATCH to the initial estimated nameplate capacities needed to meet annual-average demand, as determined from the spreadsheet analysis used to estimate such demands (Jacobson and Delucchi, 2024). The ratios are referred to as capacity adjustment factors (CAFs). Only ~9.5% more overall generator nameplate capacity is needed, summed over all 149 countries, to meet continuous 2050 demand than to meet annually-averaged 2050 demand (Table S8). The difference is due to oversizing generation in order to meet continuous demand. Storage is also needed to meet continuous demand (Tables S14-S16).

Table S12 gives the regional-average modeled capacity factor (CF) of each generator over the three-year simulations. Table S13 gives the percent of electricity plus heat produced (to meet demand and losses) from each WWS energy generator, averaged over the three-year simulations.

S11.2. Storage Results

Table S14 provides storage maximum charge rates, discharge rates and capacities. The total battery storage (BS) capacity among all 149 countries is 37.71 TWh (Table S14). For comparison, the total conventional hydropower (CH) storage capacity in reservoirs in the 149 countries is ~1,569 TWh, close to the worldwide storage capacity estimated by IEA (2021). Thus, the storage capacity of CHS already existing in the world is 41.6 times the storage capacity of batteries needed for these plans. However, BS needed in 2050 has a peak discharge rate of 9.43 TW, whereas CHS has a peak discharge rate of 1.25 TW, all of which already exists. Thus, BS in this study is used more for peaking, whereas CHS is used more for energy storage.

World hydropower output in 2020 was 4,370 TWh/y (IHA, 2021). Thus, hydropower consumed (cycled) 2.79 its storage capacity (1,569 TWh) in 2020. In the present study, the

149-country hydropower output in 2050 was 4,869 TWh/y (Table S19); thus, hydropower cycled 3.1 times per year. By contrast, the number of battery cycles needed per year in 2050 varied from 0 to 317, with 17 regions needing 100 cycles or less per year (Table S16). Table S16 also provides BS capacities and maximum charge and discharge rates for all regions.

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

If BS is used mostly for its storage capacity (rather than its peak discharge ability), BS is expensive, relative to green hydrogen storage (GHS), due to the high cost per kWh of BS. On the other hand, if BS is used primarily for peaking, then BS is inexpensive, relative to GHS, because of its low cost per kW compared with GHS. Because GHS has a lower cost per kWh of storage capacity but a higher cost per kW of peak discharge than does BS, combining GHS with BS reduces the cost of grid stability in locations where the ratio of the maximum storage capacity needed to maximum discharge rate needed (R_{ideal}) is high (Jacobson, 2024). R_{ideal} is the same as the maximum number of hours of storage needed at the maximum discharge rate.

Here, BS and GHS are treated together in 20 of the 29 grid regions. In three of those regions, neither BS nor GHS is used. In one, no BS is used. In five, no GHS is used. Among the regions all BS storage times are 4 h, but an analysis of R_{ideal} (Table S16) suggests that batteries with storage times of 4 h to 32.4 h would ensure batteries both fill their maximum storage capacity and discharge at their maximum rate at least once during a simulation. The upper limit of R_{ideal} would be higher without the inclusion of GHS (Jacobson, 2024). Including GHS reduces R_{ideal} compared with using batteries with no GHS. Thus, using GHS together with BS reduces the need to use batteries for storage capacity while maintaining their use for peaking.

Thus, batteries with longer than 4-h storage are not necessary for keeping the grid stable. However, storage times of greater than four hours and up to 32.4 h, while not needed, can be advantageous for a region. Batteries with storage times longer than ~32.4 h were never needed nor advantageous (Table S16). The ratio of the maximum storage capacity (TWh) to the maximum battery discharge rate (TW) that actually occurs during each simulation (R_{ideal}) ranges from four hours to 32.4 h. This ratio is the maximum number of hours of storage ever needed at the maximum discharge rate that actually occurred during a simulation. If this ratio exceeds four hours (the number of hours of storage at the peak discharge rate assumed for all simulations), then the battery peak discharge rate assumed 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 discharge rate is proportionately increased in order to maintain constant storage capacity. Including GHS reduces the ratio of the maximum storage capacity to the maximum discharge rate of batteries compared with using batteries with no GHS (Jacobson, 2023). Thus, using GHS together with BS reduces the need to use batteries for storage capacity while maintaining their use for peaking.

S11.3. Cost Results

The net present value of the capital cost to transition all 149 countries while keeping the grid stable is $58.2 trillion (USD 2020), with new electricity and heat generators comprising $42.1 trillion of this (Table S24, Figure S1). The remaining costs are for electricity, heat, cold, and hydrogen storage; hydrogen electrolysis and compression; heat pumps for district heating; and long-distance transmission. The capital cost does not include the capital costs of new electric appliances and machines (e.g., heat pumps for buildings, electric vehicles, industrial equipment) since it is assumed that their fossil-fuel counterparts will be replaced in any case within 15 years at similar cost. Table S24 provides a dissection of the levelized cost of energy (LCOE) for each region.

Among all 149 countries, the 2050 annual social cost for BAU energy, without a conversion to WWS, is $81.2 trillion/y, which consists of a 2050 private energy cost ($16.5 trillion/y), health cost ($33.8 trillion/y), and climate cost ($30.9 trillion/y) (Table S25). 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 all countries to 100% WWS reduces both social and private energy costs to $6.67 trillion/y, or by 91.8% and 59.6%, respectively (Table S25). The significant decrease in private energy cost between BAU and WWS occurs because WWS reduces energy demand by 54.4% (Table S25) and the cost per unit energy by ~9.6%. The decrease in social energy cost occurs because WWS eliminates health and climate costs in addition to reducing energy needs and cost.

The WWS capital cost divided by the difference between the BAU and WWS annual private and social energy costs is the payback time due to the WWS private and social cost savings, respectively. The 149-country payback time due to annual private energy cost savings is a mean of 5.9 years (Table 1). That due to social cost savings is 0.78 years (Table 1). The capital cost is paid back through energy sales rather than subsidies.

Among all world regions, the average WWS LCOE, between 2020 and 2050, that results in a stable grid, is 8.82 ¢/kWh (2020 USD) (Tables S24 and S25 and Figure S2). Averaged among all regions, this cost is dominated by the costs of electricity generation (3.73

¢/kWh), electricity distribution (2.38 ¢/kWh), short-distance transmission (1.05 ¢/kWh), non-grid green hydrogen production/compression/storage (0.92 ¢/kWh), battery storage (0.25 ¢/kWh), long-distance transmission (0.18 ¢/kWh), grid hydrogen production, storage, and use with fuel cells (0.09 ¢/kWh), geothermal plus solar heat generation (0.085 ¢/kWh), heat pumps for district heating (0.059 ¢/kWh), underground heat storage (0.067 ¢/kWh), CSPS and pumped hydro storage (0.011 ¢/kWh), hot water storage (0.009 ¢/kWh), and cold water and ice storage (0.002 ¢/kWh) (Table S24).

S11.4. New Land Area Requirements

The total new land area for footprint (before removing the fossil-fuel infrastructure) required with 100% WWS is about 0.13% of the 149-country land area (Table S28, Figure S3), 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. The spacing area for onshore wind to power the 149 countries is about 0.38% of the 149-country land area (Table S28, Figure S3).

Together, the new land footprint plus spacing areas for 100% WWS across all energy sectors represents 0.51% of the 149-country land area, and most of this land area is multi-purpose spacing land. Iceland has the lowest footprint plus spacing area as a percent of regional land area (0.03%); South Korea has the greatest (4.13%), dominated by footprint (Table S28, Figure S3). It is possible to reduce South Korea's footprint area in several ways: by using more offshore wind and less utility PV or putting some utility PV offshore, for example.

S11.5. Employment Change Results

Table S30 estimates the number of permanent, full-time jobs created and lost due to a transition in each country to 100% WWS by 2050. The job creation accounts for new direct, indirect, and induced jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including HVDC transmission) industries (Note S10). 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 S30 are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, biofuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke, are retained. For transportation sectors, the jobs lost are those due to transporting fossil fuels (e.g., through truck, train, barge, ship, or pipeline); the jobs not lost are those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion appliances, including automobiles, ships, or industrial machines.

Table S30 indicates that transitioning to 100% WWS may produce 48.2 million new long-term, full-time jobs. Also, 25.3 million jobs may be lost, for a net increase of 22.9 million long-term, full-time jobs produced among the 149 countries. Net job gains occur in 25 out of 29 regions, although not all countries within each region gain jobs. Only the regions of West Africa, Canada, Madagascar, and Russia experience net job losses. Locations with fewer net job gains or net job losses are usually locations with a substantial fossil-fuel industry. However, some countries with high fossil-fuel employment (e.g., Saudi Arabia) have net job gains because of the large buildout of WWS infrastructure per capita in those countries. More jobs, not accounted for here, may arise from the need to build more electrical appliances and to improve building energy efficiency.

S11.6. Energy Conservation and Grid Stability

LOADMATCH exactly conserves energy over the three-year simulations for every region. For example, "End-use demand plus losses" for "All regions" in Table S18 equals 11,027 GW averaged over the simulations, and this exactly equals "Supply plus changes in storage." Of that total, 8,627 GW is "annual-average end-use demand," which is the exact total, within roundoff error, shown in Table S4 for "All Countries." The rest of the total is the sum of transmission and distribution losses (711.6 GW), losses going in and out of storage (325.4 GW), and curtailment losses (1,363 GW). Thus, curtailment losses are 12.4% of total supply plus changes in storage.

Note S12. Some Hurdles to Overcome

What are some of the hurdles to a transition? A major hurdle is the competition among different ideas for solving the problems. Energy industries that do not benefit from a transition to WWS include the fossil-fuel industry, bioenergy industry, and nuclear industry. These industries have large shares in the current energy economy and would like to maintain their shares. They have proposed largely to continue with their technologies. The fossil-fuel industry has proposed to use carbon capture, synthetic direct air capture, blue hydrogen, and non-hydrogen electro-fuels. The agricultural industry has proposed to use ethanol and biodiesel with or without carbon capture for ground and air transportation and biomass with or without carbon capture for electricity. The nuclear industry has proposed to build and use small modular reactors and new-design large reactors. The diversion of funds into these resources appear to be opportunity costs that may increase CO_2, air pollution, costs, and delays, among other problems relative to using the same money for a WWS transition (Jacobson, 2023).

Other hurdles include up-front financing, zoning difficulties in expanding transmission lines, NIMBYism (not-in-my-backyard-ism) against new energy projects, social anxiety stemming from eliminating combustion vehicles and appliances, and lining up manufacturing capabilities rapidly. Also, a transition is difficult in countries engaged in conflict and countries in poverty (Jacobson, 2020). On the flip side, 95% of the technologies needed for a WWS transition are available commercially. The technologies not yet included are long-distance aircraft and ships and some industrial processes. However, it is expected that solutions for those technologies will be available by 2027-2035.

Finally, most of the hurdles exist regardless of the transition pathway. Yet, the social cost benefit of a WWS transition surpasses that of an "all-of-the-above" transition and far surpasses that of maintaining BAU (main text). Given the short time frame available for a transition (80% by 2030 and 100% by 2035-2050 in terms of climate and immediate in terms of air pollution), and the fact that most WWS technologies can be implemented quickly and at low cost, climate policies should ensure the rapid implementation of 100% WWS across all energy sectors.

Supporting Tables

Table S1. The 29 world grid regions and the 149 countries within those regions treated in this study.

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

Numbers in parentheses are the number of countries in each region.

Table S2. Several processes treated within, inputs into, and outputs from the LOADMATCH model for matching demand with supply, storage, and demand response.

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

*Process added as part of this study.

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

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

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

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

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

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

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

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

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

Extra efficiency is the effect of the additional efficiency and energy reduction measures in the WWS system beyond those in the BAU system. It assumes moderate economic growth. For example, in the case of fossil gas, oil, and biofuels for residential air and water heating, it is the additional efficiency due to better insulation of pipes and weatherizing homes. For residential electricity, it is due to more efficient light bulbs and appliances. In the industrial sector, it is due to faster implementation of more energy efficient technologies than in the BAU case. The improvements are calculated as the product of (a) the ratio of energy use, by fuel and energy sector, of the EIA (2016)'s *high efficiency all scenarios* (HEAS) case and their *reference* (BAU) case and (b) additional estimates of slight efficiency improvements beyond those in the HEAS case (Jacobson et al., 2019).

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

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

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

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

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

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

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

[a] The ratio 0.2 assumes electric heat pumps (mean coefficient of performance, COP, of 4, with a range of 3.2 to 5.2) 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 mid- and high-temperature heating processes (above 100 °C). It also assumes that heat pumps replace those fuels for low-temperature heating processes. The electricity-to-fuel ratio for mid- and high-temperature replacement is 0.88 (=0.854/0.97), where 0.854 is the mean COP for fossil gas, coal, or oil boilers and 0.97 is that for electric resistance furnaces. The COP for fossil fuel boilers assumes 80% have a COP of 0.8 and 20% have a COP of 107%, which can occur because some industrial boilers recapture waste heat and latent heat of condensation, and the COP is based on the lower heating value. The electricity-to-fuel ratio for heat pumps replacing low-temperature industrial heat processes is 0.21 (=0.854/4), where 0.854 was just defined and 4 is the mean COP of a heat pump. It is assumed that 15% of industrial heat will be with heat pumps (electricity-to-fuel ratio of 0.21) and 85% with mid- and high-temperature replacements (0.88), giving a mean replacement ratio of 0.78. The industrial sector electricity-to-fuel ratio and extra efficiency measure factors are applied only after industrial sector BAU energy used for mining and processing fossil fuels, biofuels, bioenergy, and uranium (industry "own use") has been removed from each fuel sector. The amount of industry own use is given in IEA (2023) for each country. The ratio and factors are also applied only after the change in energy between BAU and WWS during steel manufacturing due to purifying iron using green hydrogen in a shaft furnace instead of purifying iron from coke in a blast furnace is accounted for (Table S5,), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen is accounted for (Table S5).

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

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

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

Table S4a. 1st row of each country: 2020 annually-averaged end-use demand (GW) and percentage of the demand by sector. 2nd row: projected 2050 annually-averaged end-use BAU demand (GW) and percentage of the total demand by sector. 3rd row: estimated 2050 total end-use demand (GW) and percentage of total demand by sector if 100% of end-use delivered BAU demand in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU demand due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity demand (=all energy demand) in the 2050 WWS case to the electricity demand 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 demand (GW)	(b) Residential % of total	(c) Commercial % of total	(d) Industry % of total	(e) Transport % of total	(f) Ag-for-fish % of total	(g) Military-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to eliminating upstream	(j) % change end-use demand with WWS due to efficiency be-yond BAU	(k) Overall % change in end-use demand with WWS	(l) WWS:BAU electricity demand
Albania	BAU 2020	2.6	27.4	10.0	23.8	32.9	6.00	0.00					
	BAU 2050	3.8	32.4	11.9	20.2	30.9	4.61	0.00					
	WWS 2050	1.8	40.5	15.3	26.0	15.8	2.46	0.00	-37.16	-4.49	-9.76	-51.42	1.26
Algeria	BAU 2020	56.2	30.6	1.4	28.9	33.1	0.58	5.53					
	BAU 2050	121.1	24.4	1.3	24.7	44.1	0.54	5.04					
	WWS 2050	41.1	22.5	2.2	43.5	25.2	1.03	5.52	-43.49	-14.88	-7.66	-66.04	2.28
Angola	BAU 2020	14.1	58.8	4.3	15.1	21.6	0.04	0.03					
	BAU 2050	23.1	51.3	3.8	17.0	27.8	0.05	0.04					
	WWS 2050	7.9	48.3	2.1	29.0	20.5	0.03	0.02	-52.02	-4.79	-8.78	-65.59	1.91
Argentina	BAU 2020	73.2	24.7	7.5	35.9	26.1	5.85	0.00					
	BAU 2050	119.5	23.7	7.2	32.9	31.7	4.60	0.00					
	WWS 2050	45.3	21.6	11.8	49.0	15.1	2.57	0.00	-38.71	-15.72	-7.68	-62.12	1.89
Armenia	BAU 2020	3.5	32.8	3.0	14.1	33.9	3.59	12.60					
	BAU 2050	5.2	34.7	3.0	11.4	38.3	2.80	9.87					
	WWS 2050	1.6	37.3	4.1	26.1	15.9	2.34	14.30	-43.77	-14.68	-10.03	-68.48	1.48
Australia	BAU 2020	130.5	11.1	8.1	42.1	36.7	2.01	0.03					
	BAU 2050	201.5	10.7	11.3	44.0	32.3	1.67	0.03					
	WWS 2050	88.9	12.9	18.4	49.5	18.2	1.04	0.01	-33.14	-16.45	-6.30	-55.89	1.56
Austria	BAU 2020	35.5	24.4	8.8	34.4	30.4	1.92	0.00					
	BAU 2050	44.0	23.8	9.1	31.8	33.7	1.60	0.00					
	WWS 2050	19.5	19.6	11.5	45.7	22.1	1.17	0.00	-38.25	-10.75	-6.82	-55.82	1.69
Azerbaijan	BAU 2020	14.3	36.5	6.5	26.7	24.9	5.40	0.00					
	BAU 2050	20.5	39.8	8.5	23.8	23.6	4.24	0.00					
	WWS 2050	7.3	33.1	15.4	31.7	15.9	3.89	0.00	-46.44	-8.11	-9.73	-64.29	1.58
Bahrain	BAU 2020	8.9	12.1	7.4	58.8	21.6	0.10	0.00					
	BAU 2050	16.1	14.9	8.3	57.0	19.7	0.10	0.00					
	WWS 2050	9.5	18.8	10.8	62.9	7.3	0.13	0.00	-18.81	-14.97	-7.45	-41.23	1.30
Bangladesh	BAU 2020	39.3	48.1	2.4	31.3	13.9	3.70	0.53					
	BAU 2050	72.7	40.1	2.9	32.0	21.0	3.49	0.53					
	WWS 2050	33.8	31.2	4.3	53.8	7.8	2.06	0.87	-37.25	-6.95	-9.34	-53.54	1.70
Belarus	BAU 2020	24.2	27.4	10.5	35.3	20.8	5.97	0.00					
	BAU 2050	33.7	29.4	12.3	32.5	21.0	4.78	0.00					
	WWS 2050	11.8	25.6	17.6	38.6	14.4	3.82	0.00	-46.99	-12.14	-5.74	-64.87	1.80
Belgium	BAU 2020	55.1	18.8	10.7	32.0	36.5	1.93	0.09					
	BAU 2050	63.4	18.4	11.5	32.1	36.1	1.80	0.09					
	WWS 2050	27.1	14.1	13.7	47.8	23.0	1.32	0.06	-42.38	-7.95	-6.86	-57.19	2.00
Benin	BAU 2020	6.1	39.8	10.2	4.0	45.5	0.51	0.00					
	BAU 2050	10.7	29.0	11.5	4.3	54.6	0.55	0.00					

	WWS 2050	2.7	22.9	13.1	13.7	49.6	0.65	0.00	-67.90	-1.01	-6.32	-75.23	7.30
Bolivia	BAU 2020	8.8	16.0	3.4	30.5	46.3	3.48	0.33					
	BAU 2050	14.5	12.1	3.4	26.5	54.9	2.77	0.28					
	WWS 2050	5.0	15.1	6.8	46.3	28.6	2.65	0.65	-43.26	-16.53	-6.10	-65.89	2.95
Bosnia and Herzegovina	BAU 2020	5.8	41.4	8.7	21.1	27.7	1.08	0.00					
	BAU 2050	8.2	43.3	10.4	19.1	26.3	0.83	0.00					
	WWS 2050	3.4	39.8	15.0	28.1	16.6	0.53	0.00	-42.42	-7.12	-8.97	-58.52	1.40
Botswana	BAU 2020	2.2	32.7	5.7	16.6	42.6	1.54	0.80					
	BAU 2050	4.3	26.2	7.3	16.6	47.5	1.60	0.85					
	WWS 2050	1.7	23.7	13.3	31.7	27.4	2.34	1.65	-50.32	-1.86	-8.12	-60.30	1.75
Brazil	BAU 2020	324.8	11.6	4.9	43.3	34.8	5.31	0.00					
	BAU 2050	555.3	9.7	4.9	42.4	37.9	5.10	0.00					
	WWS 2050	256.4	12.0	7.9	58.1	18.2	3.87	0.00	-36.63	-11.68	-5.51	-53.83	2.14
Brunei	BAU 2020	2.7	7.6	8.2	61.6	21.8	0.00	0.78					
	BAU 2050	5.0	8.3	10.9	54.0	26.1	0.00	0.73					
	WWS 2050	1.6	17.9	26.5	36.4	18.8	0.00	0.46	-32.13	-30.67	-5.36	-68.17	1.24
Bulgaria	BAU 2020	14.2	22.2	9.0	34.9	32.1	1.76	0.00					
	BAU 2050	20.4	25.8	11.3	30.7	30.7	1.37	0.00					
	WWS 2050	9.1	29.3	16.5	36.1	17.1	0.93	0.00	-37.24	-10.47	-7.57	-55.29	1.35
Cambodia	BAU 2020	9.5	35.9	6.1	24.6	31.7	0.00	1.65					
	BAU 2050	16.9	27.6	7.4	24.5	38.9	0.00	1.59					
	WWS 2050	7.2	19.6	12.1	45.2	22.5	0.00	0.75	-49.02	-1.18	-7.28	-57.47	2.51
Cameroon	BAU 2020	10.7	63.4	14.8	6.0	14.2	0.07	1.57					
	BAU 2050	16.8	52.1	19.1	7.5	19.1	0.09	1.97					
	WWS 2050	4.6	39.5	16.1	23.3	16.6	0.26	4.28	-63.98	-0.61	-8.13	-72.71	2.54
Canada	BAU 2020	295.3	15.0	12.3	44.0	25.8	2.97	0.03					
	BAU 2050	401.9	13.8	12.6	46.5	24.4	2.72	0.02					
	WWS 2050	160.1	16.6	18.8	45.3	17.2	1.95	0.04	-31.48	-22.54	-6.14	-60.16	1.42
Chile	BAU 2020	36.4	17.6	5.9	41.2	32.7	2.36	0.25					
	BAU 2050	60.9	16.6	9.3	41.1	30.5	2.29	0.28					
	WWS 2050	32.7	13.4	10.4	58.7	15.2	1.76	0.52	-35.16	-3.83	-7.22	-46.21	1.71
China	BAU 2020	2,946.3	16.5	3.9	58.2	15.3	1.96	4.11					
	BAU 2050	4,986.4	18.3	4.2	51.4	21.5	1.38	3.28					
	WWS 2050	2,499.7	16.4	5.1	64.1	9.2	1.10	4.22	-30.66	-12.91	-6.30	-49.87	1.76
Colombia	BAU 2020	40.8	19.8	5.4	32.5	34.3	1.36	6.52					
	BAU 2050	63.1	17.7	5.8	31.9	38.0	1.13	5.48					
	WWS 2050	26.1	18.8	9.6	47.1	19.3	0.80	4.36	-41.71	-10.01	-6.98	-58.70	1.87
Congo	BAU 2020	2.6	59.8	13.8	5.6	20.8	0.00	0.00					
	BAU 2050	4.3	48.9	17.9	6.3	26.8	0.00	0.00					
	WWS 2050	1.2	41.9	22.4	12.7	23.0	0.00	0.00	-61.40	-2.07	-8.38	-71.85	2.27
Congo, DR	BAU 2020	27.0	89.8	0.2	4.6	4.4	1.01	0.00					
	BAU 2050	36.9	84.5	0.3	6.8	6.8	1.57	0.00					
	WWS 2050	8.8	68.6	1.0	22.6	6.6	1.23	0.00	-65.05	-0.61	-10.59	-76.25	3.44
Costa Rica	BAU 2020	4.7	14.1	9.8	24.1	49.9	1.94	0.15					
	BAU 2050	7.1	14.3	10.9	20.8	52.2	1.70	0.13					
	WWS 2050	3.3	20.3	17.0	34.6	26.5	1.61	0.05	-44.02	-1.58	-7.75	-53.36	1.69
Côte d'Ivoire	BAU 2020	10.7	59.2	9.4	11.1	19.1	1.18	0.02					
	BAU 2050	17.3	48.4	12.5	12.8	25.0	1.40	0.02					
	WWS 2050	5.4	37.5	15.5	26.3	19.2	1.46	0.06	-57.30	-2.76	-8.48	-68.54	2.32
Croatia	BAU 2020	9.3	32.4	10.9	23.8	29.2	3.69	0.00					
	BAU 2050	13.1	34.6	13.7	21.1	27.8	2.87	0.00					
	WWS 2050	5.5	31.5	19.9	29.5	17.4	1.67	0.00	-43.31	-6.43	-8.72	-58.46	1.58
Cuba	BAU 2020	8.4	20.1	3.7	47.6	14.7	2.48	11.41					
	BAU 2050	11.9	21.3	4.5	44.6	16.9	2.26	10.34					
	WWS 2050	6.7	23.8	6.0	56.3	9.0	1.12	3.68	-32.69	-4.16	-7.13	-43.98	1.99
Curacao	BAU 2020	2.9	3.6	0.9	7.0	88.5	0.00	0.00					
	BAU 2050	4.5	2.7	1.0	5.8	90.5	0.00	0.00					
	WWS 2050	1.4	4.2	2.6	14.8	78.4	0.00	0.00	-63.37	-1.77	-4.57	-69.71	9.52
Cyprus	BAU 2020	2.5	18.7	10.8	14.5	52.6	2.51	0.81					
	BAU 2050	3.5	20.6	14.5	12.0	50.3	1.98	0.64					
	WWS 2050	1.6	30.1	22.8	18.5	26.3	1.66	0.63	-43.72	-2.16	-8.48	-54.36	1.56

Czech Republic	BAU 2020	34.3	26.9	11.5	34.1	24.9	2.46	0.18					
	BAU 2050	41.9	26.8	12.1	32.9	25.9	2.11	0.16					
	WWS 2050	17.2	21.1	15.9	43.8	17.6	1.43	0.07	-41.19	-10.80	-6.86	-58.84	1.58
Denmark	BAU 2020	19.4	28.1	12.5	21.6	32.9	4.64	0.27					
	BAU 2050	23.0	29.1	13.5	21.9	31.1	4.15	0.24					
	WWS 2050	8.9	27.1	19.0	28.7	21.5	3.61	0.12	-46.62	-7.66	-6.76	-61.04	1.60
Dominican Republic	BAU 2020	8.5	23.2	7.0	26.4	41.0	2.43	0.00					
	BAU 2050	12.2	18.8	8.0	25.1	45.8	2.30	0.00					
	WWS 2050	5.5	18.2	12.1	42.7	24.3	2.77	0.00	-44.54	-2.59	-7.59	-54.72	1.84
Ecuador	BAU 2020	15.4	15.9	6.4	20.8	47.8	1.21	7.92					
	BAU 2050	22.5	13.2	7.2	19.6	52.0	1.06	7.00					
	WWS 2050	8.8	17.0	12.4	34.1	31.8	0.54	4.17	-49.97	-4.17	-6.76	-60.90	1.84
Egypt	BAU 2020	76.6	23.2	5.7	37.0	31.5	2.53	0.06					
	BAU 2050	165.0	19.9	7.0	31.7	39.1	2.29	0.05					
	WWS 2050	75.2	23.5	11.9	45.1	17.1	2.37	0.02	-33.15	-13.38	-7.87	-54.40	1.68
El Salvador	BAU 2020	3.3	22.8	6.0	24.4	45.7	0.00	1.22					
	BAU 2050	4.8	18.6	7.2	22.5	50.5	0.00	1.21					
	WWS 2050	2.1	19.2	12.1	39.7	26.8	0.00	2.11	-46.26	-1.40	-7.77	-55.43	1.85
Equatorial Guinea	BAU 2020	2.0	5.5	2.4	80.3	11.6	0.00	0.16					
	BAU 2050	3.8	5.8	2.6	78.8	12.6	0.00	0.16					
	WWS 2050	2.2	6.3	2.7	85.4	5.4	0.00	0.22	-25.68	-13.91	-3.42	-43.01	6.42
Eritrea	BAU 2020	0.9	78.8	5.1	2.1	13.8	0.14	0.00					
	BAU 2050	1.3	69.9	7.2	2.8	19.9	0.18	0.00					
	WWS 2050	0.3	60.3	10.2	8.4	21.0	0.15	0.00	-64.99	-0.59	-9.80	-75.37	3.28
Estonia	BAU 2020	4.3	29.3	14.6	17.9	34.7	3.42	0.01					
	BAU 2050	5.4	28.8	15.4	16.8	36.1	2.84	0.01					
	WWS 2050	1.9	25.9	25.1	24.8	22.0	2.10	0.00	-46.73	-10.19	-7.36	-64.29	1.40
Eswatini, Kingdom of	BAU 2020	1.4	33.0	3.0	36.2	23.4	4.35	0.00					
	BAU 2050	2.5	25.6	3.2	40.1	26.5	4.59	0.00					
	WWS 2050	1.3	15.9	3.6	63.1	12.3	5.04	0.00	-43.34	-0.56	-6.24	-50.15	3.66
Ethiopia	BAU 2020	57.2	86.6	1.4	4.4	6.7	0.43	0.43					
	BAU 2050	79.0	80.2	2.2	6.1	10.3	0.59	0.59					
	WWS 2050	18.8	63.4	4.3	20.3	11.0	0.50	0.50	-65.83	-0.20	-10.23	-76.25	5.95
Finland	BAU 2020	32.9	19.3	11.1	47.7	18.0	2.80	0.99					
	BAU 2050	38.4	21.2	12.8	44.8	17.9	2.50	0.90					
	WWS 2050	20.2	18.6	14.4	55.5	9.7	1.45	0.35	-33.96	-7.02	-6.48	-47.46	1.60
France	BAU 2020	180.1	26.8	14.7	23.9	30.8	3.32	0.44					
	BAU 2050	217.4	27.7	16.5	22.8	29.7	2.91	0.39					
	WWS 2050	99.7	26.6	21.2	31.0	19.0	1.87	0.25	-39.57	-5.55	-9.03	-54.15	1.32
Gabon	BAU 2020	6.0	27.8	0.9	65.5	5.6	0.08	0.10					
	BAU 2050	11.3	20.5	1.1	71.9	6.3	0.08	0.10					
	WWS 2050	6.9	9.3	1.1	86.8	2.6	0.09	0.07	-31.41	-4.09	-3.54	-39.05	10.07
Georgia	BAU 2020	5.7	32.7	9.6	19.4	32.6	0.57	5.10					
	BAU 2050	8.3	34.5	12.0	15.6	33.4	0.45	4.04					
	WWS 2050	3.3	26.2	18.6	31.0	15.9	0.45	7.89	-42.72	-6.87	-10.44	-60.03	1.52
Germany	BAU 2020	281.5	26.7	12.6	31.9	27.0	1.72	0.02					
	BAU 2050	330.7	26.3	13.5	31.3	27.3	1.53	0.02					
	WWS 2050	142.5	20.1	16.1	45.2	17.7	0.96	0.01	-41.71	-7.59	-7.61	-56.91	1.68
Ghana	BAU 2020	11.7	39.3	5.1	17.3	36.5	1.81	0.00					
	BAU 2050	21.8	32.3	6.4	18.2	41.4	1.83	0.00					
	WWS 2050	8.9	30.4	9.4	35.3	24.0	0.92	0.00	-49.80	-1.31	-8.18	-59.29	1.84
Gibraltar	BAU 2020	5.8	0.0	0.1	0.1	99.5	0.00	0.34					
	BAU 2050	6.2	0.0	0.1	0.1	99.5	0.00	0.35					
	WWS 2050	1.6	0.0	0.3	0.2	98.4	0.00	1.08	-68.93	-1.88	-4.15	-74.97	55.03
Greece	BAU 2020	23.8	23.5	8.9	24.4	39.7	1.61	1.86					
	BAU 2050	28.6	23.4	11.6	25.6	36.3	1.45	1.64					
	WWS 2050	11.7	27.8	20.5	26.5	22.1	2.22	0.80	-39.61	-11.60	-7.88	-59.10	1.38
Guatemala	BAU 2020	16.6	61.5	3.7	8.2	26.6	0.00	0.00					
	BAU 2050	20.2	51.9	4.3	9.1	34.7	0.00	0.00					
	WWS 2050	5.8	40.0	9.0	22.8	28.2	0.00	0.00	-61.11	-1.71	-8.73	-71.55	2.73
Haiti	BAU 2020	4.5	74.8	1.6	8.9	14.7	0.00	0.00					

	BAU 2050	5.0	67.2	1.5	10.3	21.0	0.00	0.00					
	WWS 2050	1.3	47.7	1.5	30.9	19.9	0.00	0.00	-64.92	-0.45	-8.99	-74.36	15.69
Honduras	BAU 2020	5.1	44.3	8.4	15.2	31.3	0.84	0.00					
	BAU 2050	6.7	37.1	9.1	15.3	37.7	0.82	0.00					
	WWS 2050	2.5	30.2	13.2	32.4	23.8	0.44	0.00	-52.84	-0.98	-8.45	-62.27	1.97
Hong Kong	BAU 2020	24.8	7.9	14.5	6.8	70.8	0.00	0.03					
	BAU 2050	53.8	7.6	15.5	5.4	71.5	0.00	0.03					
	WWS 2050	20.7	13.0	29.8	9.5	47.6	0.00	0.05	-51.94	-2.04	-7.58	-61.56	1.70
Hungary	BAU 2020	25.2	31.3	10.5	30.4	23.9	3.70	0.20					
	BAU 2050	30.3	31.8	10.6	29.3	24.8	3.27	0.18					
	WWS 2050	12.2	23.6	12.8	43.4	17.6	2.52	0.14	-43.58	-8.18	-7.81	-59.57	1.74
Iceland	BAU 2020	4.0	15.9	16.1	44.7	13.6	8.41	1.21					
	BAU 2050	4.6	16.8	17.2	43.9	13.2	7.85	1.15					
	WWS 2050	2.7	10.3	14.5	64.4	5.9	4.31	0.54	-31.95	-2.12	-6.54	-40.61	1.08
India	BAU 2020	777.8	27.3	3.3	45.7	16.3	4.85	2.49					
	BAU 2050	1,695.9	19.6	3.2	46.3	23.8	4.59	2.51					
	WWS 2050	914.9	14.4	2.9	65.4	10.6	4.90	1.82	-33.63	-6.05	-6.37	-46.05	2.54
Indonesia	BAU 2020	204.9	21.0	3.9	42.6	31.7	0.62	0.26					
	BAU 2050	385.0	16.4	4.7	41.0	37.0	0.58	0.24					
	WWS 2050	187.8	15.6	7.1	59.3	17.5	0.40	0.10	-39.96	-5.11	-6.14	-51.21	2.69
Iran	BAU 2020	250.7	28.1	5.9	37.1	24.6	4.12	0.22					
	BAU 2050	424.2	24.6	5.2	39.7	25.8	4.43	0.24					
	WWS 2050	179.3	17.7	5.6	59.5	12.1	4.73	0.44	-38.74	-11.63	-7.36	-57.73	2.78
Iraq	BAU 2020	30.4	24.5	0.8	26.7	44.4	0.00	3.62					
	BAU 2050	50.0	22.1	1.0	28.0	44.9	0.00	3.99					
	WWS 2050	21.2	28.9	1.9	37.0	25.0	0.00	7.22	-42.67	-7.59	-7.35	-57.61	1.84
Ireland	BAU 2020	15.2	26.6	15.7	21.1	34.5	2.07	0.00					
	BAU 2050	17.4	25.1	19.1	20.5	33.4	1.92	0.00					
	WWS 2050	7.8	20.9	26.6	32.0	19.0	1.37	0.00	-42.83	-3.65	-8.90	-55.38	1.55
Israel	BAU 2020	20.4	15.9	10.0	26.0	40.8	2.09	5.27					
	BAU 2050	24.7	18.0	13.4	25.8	36.1	1.90	4.69					
	WWS 2050	12.4	27.7	20.4	27.5	16.7	2.95	4.83	-32.60	-8.42	-8.78	-49.79	1.23
Italy	BAU 2020	149.3	27.2	12.6	28.3	29.3	2.63	0.04					
	BAU 2050	187.3	26.2	13.0	26.7	31.9	2.23	0.03					
	WWS 2050	74.0	20.4	18.0	37.5	22.3	1.81	0.02	-41.89	-10.69	-7.91	-60.49	1.51
Jamaica	BAU 2020	2.8	12.1	5.5	26.5	55.4	0.46	0.00					
	BAU 2050	4.1	10.1	5.2	25.1	59.2	0.40	0.00					
	WWS 2050	1.7	12.2	6.5	46.8	34.4	0.19	0.00	-50.65	-1.31	-5.76	-57.72	3.00
Japan	BAU 2020	343.0	17.0	18.0	35.8	27.2	1.81	0.20					
	BAU 2050	329.1	17.7	19.5	33.6	27.7	1.34	0.17					
	WWS 2050	175.7	16.9	20.5	46.9	15.0	0.61	0.06	-30.28	-8.28	-8.06	-46.62	1.48
Jordan	BAU 2020	8.0	26.3	8.0	15.6	42.5	4.11	3.52					
	BAU 2050	13.4	26.1	7.9	16.3	41.7	4.43	3.53					
	WWS 2050	6.4	36.0	10.8	23.8	20.7	7.24	1.48	-40.06	-3.16	-9.09	-52.31	1.35
Kazakhstan	BAU 2020	62.1	28.9	8.5	40.7	16.6	1.78	3.58					
	BAU 2050	80.8	28.0	8.8	40.2	18.3	1.53	3.24					
	WWS 2050	29.0	22.4	8.8	53.7	11.6	1.21	2.26	-43.36	-15.59	-5.17	-64.12	1.90
Kenya	BAU 2020	24.3	70.7	1.6	6.2	21.2	0.20	0.11					
	BAU 2050	36.8	60.1	2.0	7.9	29.7	0.25	0.14					
	WWS 2050	9.9	45.6	3.6	23.9	26.6	0.18	0.10	-63.62	-0.58	-9.04	-73.24	4.01
Korea, DPR	BAU 2020	18.2	11.0	3.1	61.7	9.7	1.90	12.59					
	BAU 2050	30.8	7.3	2.0	66.5	8.7	2.03	13.41					
	WWS 2050	18.3	3.7	1.2	85.6	3.7	0.84	5.00	-34.46	-2.68	-3.33	-40.46	6.24
Korea, Republic of	BAU 2020	206.5	13.4	13.2	40.6	30.3	1.83	0.68					
	BAU 2050	279.7	11.9	15.1	41.8	28.9	1.68	0.55					
	WWS 2050	142.0	9.1	19.9	55.4	13.6	1.77	0.22	-32.18	-9.71	-7.36	-49.24	1.47
Kosovo	BAU 2020	2.1	38.5	10.0	22.6	26.8	2.13	0.00					
	BAU 2050	3.0	43.5	11.4	18.4	25.0	1.64	0.00					
	WWS 2050	1.4	45.2	13.9	25.8	13.8	1.29	0.00	-38.97	-3.45	-10.40	-52.81	1.22
Kuwait	BAU 2020	32.7	10.4	5.3	62.2	21.6	0.47	0.00					
	BAU 2050	58.0	13.1	6.2	60.0	20.2	0.48	0.00					

	WWS 2050	25.5	22.1	10.9	55.3	10.9	0.85	0.00	-26.17	-24.00	-5.79	-55.97	1.51
Kyrgyzstan	BAU 2020	4.3	65.7	9.1	9.7	14.2	0.60	0.72					
	BAU 2050	6.1	67.6	9.5	8.4	13.4	0.48	0.58					
	WWS 2050	3.0	72.0	9.4	10.9	6.4	0.68	0.62	-37.12	-1.89	-12.23	-51.25	1.03
Lao PDR	BAU 2020	4.1	41.6	12.2	19.3	26.6	0.36	0.00					
	BAU 2050	6.9	34.8	9.9	20.7	34.2	0.39	0.00					
	WWS 2050	2.9	26.0	10.9	42.1	20.3	0.70	0.00	-48.62	-0.63	-8.39	-57.64	1.61
Latvia	BAU 2020	5.5	26.9	13.2	23.0	31.6	5.10	0.12					
	BAU 2050	7.5	28.5	15.9	20.1	31.2	4.15	0.09					
	WWS 2050	3.0	22.6	20.3	34.2	20.2	2.56	0.05	-50.82	-2.42	-6.66	-59.91	2.10
Lebanon	BAU 2020	5.7	21.6	5.9	12.8	52.7	0.00	7.03					
	BAU 2050	9.9	22.4	6.7	13.4	50.2	0.00	7.22					
	WWS 2050	4.7	30.6	11.2	24.4	22.9	0.00	10.91	-41.98	-0.91	-9.63	-52.53	1.22
Libya	BAU 2020	12.1	15.8	1.9	13.1	63.8	1.23	4.23					
	BAU 2050	24.9	15.4	2.4	11.4	65.4	1.21	4.16					
	WWS 2050	9.0	26.6	5.2	17.9	38.7	2.61	8.99	-52.06	-4.61	-7.22	-63.90	1.76
Lithuania	BAU 2020	8.3	22.6	9.2	28.3	37.8	1.84	0.15					
	BAU 2050	11.5	24.1	11.3	26.3	36.7	1.48	0.11					
	WWS 2050	4.7	21.3	15.6	38.9	23.0	1.04	0.06	-42.79	-10.54	-6.17	-59.50	2.01
Luxembourg	BAU 2020	5.1	12.8	12.8	16.2	57.6	0.61	0.00					
	BAU 2050	5.7	13.0	13.8	16.1	56.6	0.58	0.00					
	WWS 2050	2.2	10.0	17.9	31.9	39.8	0.42	0.00	-52.70	-2.18	-6.77	-61.64	2.04
Macedonia, North	BAU 2020	1.9	36.1	12.6	3.8	46.1	1.45	0.00					
	BAU 2050	2.9	41.1	14.5	3.5	39.9	1.04	0.00					
	WWS 2050	1.3	53.2	20.9	1.4	23.5	1.02	0.00	-41.67	-3.19	-10.90	-55.77	1.07
Madagascar	BAU 2020	7.9	57.3	26.5	7.4	6.9	0.04	1.89					
	BAU 2050	12.8	45.9	33.1	9.5	9.1	0.05	2.28					
	WWS 2050	3.4	33.6	26.1	28.1	8.7	0.14	3.41	-66.80	-0.18	-6.42	-73.40	7.49
Malaysia	BAU 2020	73.4	6.1	8.0	44.9	39.4	1.58	0.00					
	BAU 2050	148.3	6.0	9.0	40.4	43.1	1.36	0.00					
	WWS 2050	72.0	9.0	13.6	56.2	20.6	0.67	0.00	-37.95	-7.52	-5.99	-51.46	1.90
Malta	BAU 2020	3.6	3.6	4.2	2.4	89.4	0.34	0.07					
	BAU 2050	5.0	5.0	5.6	2.0	87.1	0.27	0.06					
	WWS 2050	1.5	11.9	12.5	5.0	70.3	0.26	0.15	-62.05	-1.85	-5.67	-69.57	2.87
Mauritius	BAU 2020	2.0	9.5	5.8	12.5	71.7	0.22	0.31					
	BAU 2050	4.2	9.1	6.6	11.6	72.2	0.21	0.30					
	WWS 2050	1.6	15.8	12.3	25.1	46.0	0.25	0.59	-54.34	-1.52	-6.56	-62.41	2.04
Mexico	BAU 2020	149.1	14.5	3.6	43.8	34.1	2.61	1.36					
	BAU 2050	241.6	14.2	5.7	43.4	32.5	2.63	1.50					
	WWS 2050	106.8	16.0	7.8	54.6	16.4	2.53	2.64	-35.61	-13.98	-6.20	-55.79	1.66
Moldova, Republic of	BAU 2020	3.9	44.2	8.8	18.2	23.7	4.45	0.59					
	BAU 2050	5.3	45.9	10.7	15.9	23.5	3.55	0.50					
	WWS 2050	2.0	37.5	15.4	28.5	15.9	2.41	0.28	-50.89	-2.26	-9.22	-62.37	1.72
Mongolia	BAU 2020	5.9	22.4	9.1	35.4	21.4	2.48	9.21					
	BAU 2050	10.4	18.3	7.2	36.0	26.4	2.47	9.65					
	WWS 2050	4.1	16.2	4.6	54.2	15.9	1.48	7.65	-52.46	-4.49	-3.71	-60.65	2.44
Montenegro	BAU 2020	0.9	34.2	12.6	20.3	32.3	0.68	0.00					
	BAU 2050	1.4	38.3	16.4	15.7	29.1	0.51	0.00					
	WWS 2050	0.7	38.9	23.0	22.8	15.0	0.36	0.00	-35.66	-2.13	-11.24	-49.04	1.12
Morocco	BAU 2020	20.7	27.5	8.2	19.1	37.6	7.64	0.00					
	BAU 2050	38.8	20.6	9.5	19.7	42.4	7.84	0.00					
	WWS 2050	16.9	21.2	9.9	36.8	25.5	6.58	0.00	-47.81	-0.87	-7.68	-56.36	1.87
Mozambique	BAU 2020	10.9	66.0	1.7	18.3	13.4	0.00	0.61					
	BAU 2050	16.9	55.3	2.2	23.3	18.4	0.00	0.80					
	WWS 2050	6.0	32.0	1.3	52.5	12.7	0.00	1.37	-53.76	-1.98	-8.70	-64.44	1.97
Myanmar	BAU 2020	26.7	55.6	3.8	21.0	10.6	6.44	2.64					
	BAU 2050	42.7	46.7	4.3	23.1	16.1	6.96	2.86					
	WWS 2050	15.1	31.6	6.4	46.9	9.4	3.92	1.72	-52.22	-4.11	-8.16	-64.49	3.05
Namibia	BAU 2020	2.2	10.4	0.1	9.1	38.2	18.91	23.27					
	BAU 2050	4.3	6.7	0.1	9.2	41.6	18.40	23.90					
	WWS 2050	1.6	3.1	0.0	19.4	26.9	9.68	40.83	-53.84	-0.77	-7.32	-61.93	1.87

Nepal	BAU 2020	19.5	73.2	2.7	9.6	12.2	2.07	0.17					
	BAU 2050	28.6	64.4	2.7	12.0	18.2	2.45	0.21					
	WWS 2050	8.2	45.3	3.4	32.8	16.0	2.01	0.58	-61.57	-0.35	-9.28	-71.20	4.62
Netherlands	BAU 2020	82.6	14.7	10.1	31.5	37.2	6.39	0.12					
	BAU 2050	98.1	15.1	11.3	31.7	36.1	5.75	0.11					
	WWS 2050	39.1	12.6	15.8	43.4	22.9	5.15	0.07	-42.63	-10.82	-6.64	-60.10	2.03
New Zealand	BAU 2020	18.1	11.6	9.3	34.0	39.0	5.73	0.36					
	BAU 2050	27.9	11.9	11.7	37.3	33.2	5.43	0.43					
	WWS 2050	14.8	14.3	15.3	50.4	15.0	4.37	0.62	-34.51	-5.00	-7.39	-46.90	1.63
Nicaragua	BAU 2020	3.5	43.5	11.1	15.4	27.3	2.25	0.42					
	BAU 2050	4.6	35.9	11.6	16.2	33.6	2.24	0.46					
	WWS 2050	1.6	28.1	14.9	30.4	23.7	1.89	1.05	-54.09	-3.54	-8.05	-65.68	2.04
Niger	BAU 2020	4.5	82.1	3.2	2.7	12.0	0.02	0.00					
	BAU 2050	6.4	74.1	4.6	3.6	17.7	0.03	0.00					
	WWS 2050	1.5	63.3	7.9	11.3	17.4	0.10	0.00	-65.59	-0.50	-10.05	-76.14	3.71
Nigeria	BAU 2020	187.1	75.6	2.5	9.0	12.7	0.00	0.12					
	BAU 2050	273.3	66.4	3.6	11.5	18.4	0.00	0.16					
	WWS 2050	65.7	53.1	5.0	25.4	16.4	0.00	0.13	-63.55	-3.75	-8.67	-75.97	7.65
Norway	BAU 2020	32.9	15.8	11.1	50.6	20.0	2.43	0.13					
	BAU 2050	44.6	16.5	12.3	48.7	20.5	1.92	0.10					
	WWS 2050	20.1	25.0	18.9	41.7	12.7	1.58	0.04	-22.48	-24.97	-7.46	-54.92	1.02
Oman	BAU 2020	32.9	6.4	28.5	41.3	20.5	0.20	3.16					
	BAU 2050	54.3	8.3	23.1	44.4	20.7	0.22	3.27					
	WWS 2050	23.4	14.1	17.5	55.6	10.8	0.41	1.51	-38.57	-13.88	-4.36	-56.81	2.79
Pakistan	BAU 2020	113.8	52.8	3.2	24.7	18.1	0.99	0.22					
	BAU 2050	195.8	43.5	3.6	26.6	25.0	1.06	0.22					
	WWS 2050	79.0	29.4	5.2	50.6	12.7	2.03	0.11	-47.54	-3.49	-8.61	-59.64	2.94
Panama	BAU 2020	10.4	7.9	5.6	8.2	78.1	0.13	0.01					
	BAU 2050	16.0	6.7	6.0	7.0	80.2	0.11	0.01					
	WWS 2050	5.2	11.3	12.9	16.8	58.9	0.07	0.02	-60.18	-1.67	-5.82	-67.68	2.90
Paraguay	BAU 2020	8.4	28.1	6.8	26.0	39.1	0.00	0.00					
	BAU 2050	11.9	24.5	8.4	23.5	43.6	0.00	0.00					
	WWS 2050	5.5	23.5	14.0	39.6	22.9	0.00	0.00	-44.62	-1.32	-7.72	-53.66	1.98
Peru	BAU 2020	25.5	21.9	6.4	31.2	39.2	1.24	0.00					
	BAU 2050	38.4	16.8	6.4	30.0	45.7	1.13	0.00					
	WWS 2050	15.7	15.3	9.2	49.6	24.4	1.51	0.00	-42.25	-10.25	-6.70	-59.21	1.89
Philippines	BAU 2020	43.8	30.4	14.0	22.3	32.0	1.33	0.00					
	BAU 2050	79.7	25.3	13.2	21.6	38.5	1.31	0.00					
	WWS 2050	34.7	25.3	15.5	36.0	21.8	1.51	0.00	-45.33	-2.95	-8.23	-56.51	1.57
Poland	BAU 2020	102.3	27.0	9.7	29.1	29.2	4.99	0.00					
	BAU 2050	122.2	25.8	11.0	28.9	29.9	4.38	0.00					
	WWS 2050	47.5	19.1	16.7	41.7	20.0	2.52	0.00	-44.05	-10.88	-6.16	-61.08	1.77
Portugal	BAU 2020	22.4	16.3	10.0	34.0	36.6	2.96	0.15					
	BAU 2050	26.7	17.4	12.8	32.9	34.2	2.65	0.14					
	WWS 2050	12.4	18.0	19.3	41.2	19.7	1.77	0.06	-37.76	-8.53	-7.31	-53.60	1.57
Qatar	BAU 2020	42.8	5.9	2.2	68.5	22.3	0.00	1.10					
	BAU 2050	73.8	7.7	2.7	67.0	21.5	0.00	1.16					
	WWS 2050	29.9	14.2	5.1	65.4	13.1	0.00	2.23	-24.93	-30.48	-4.08	-59.49	2.70
Romania	BAU 2020	33.6	31.5	7.2	32.5	25.9	2.09	0.80					
	BAU 2050	45.9	33.8	8.7	29.6	25.6	1.71	0.63					
	WWS 2050	18.0	26.6	11.1	43.9	17.0	1.09	0.32	-45.43	-7.78	-7.62	-60.83	1.83
Russia	BAU 2020	655.0	27.9	7.7	41.9	20.7	1.85	0.00					
	BAU 2050	721.6	27.3	8.0	39.6	23.7	1.42	0.00					
	WWS 2050	259.4	23.0	10.9	52.1	12.7	1.29	0.00	-39.49	-18.39	-6.17	-64.05	1.76
Rwanda	BAU 2020	4.1	82.9	2.7	6.6	7.3	0.00	0.47					
	BAU 2050	5.7	74.8	4.0	9.5	11.0	0.00	0.69					
	WWS 2050	1.5	52.9	7.4	28.9	10.3	0.00	0.51	-64.39	-0.20	-9.78	-74.37	7.23
Saudi Arabia	BAU 2020	162.7	10.9	8.0	44.2	36.5	0.33	0.03					
	BAU 2050	292.7	13.4	9.1	43.4	33.7	0.33	0.03					
	WWS 2050	151.9	19.1	13.6	50.7	16.0	0.50	0.05	-31.87	-9.37	-6.84	-48.09	1.90
Senegal	BAU 2020	4.5	38.7	3.2	18.7	39.3	0.12	0.00					

	BAU 2050	8.1	29.0	4.5	20.3	46.1	0.13	0.00					
	WWS 2050	3.2	21.2	8.7	40.8	29.1	0.26	0.01	-52.05	-1.29	-7.47	-60.81	2.50
Serbia	BAU 2020	12.8	36.1	8.9	29.7	23.7	1.56	0.00					
	BAU 2050	18.4	40.0	10.4	26.2	22.3	1.21	0.00					
	WWS 2050	8.2	41.5	13.0	31.4	13.1	0.89	0.00	-38.55	-8.49	-8.61	-55.65	1.24
Singapore	BAU 2020	85.1	1.2	2.9	13.8	82.0	0.00	0.04					
	BAU 2050	183.1	1.3	3.2	11.3	84.3	0.00	0.03					
	WWS 2050	58.8	2.8	7.4	22.9	66.8	0.00	0.07	-59.84	-3.46	-4.60	-67.91	4.13
Slovak Republic	BAU 2020	14.6	24.6	10.0	41.2	23.1	1.20	0.00					
	BAU 2050	18.3	24.1	10.7	39.1	25.1	1.01	0.00					
	WWS 2050	8.0	17.2	14.1	53.7	14.3	0.68	0.00	-34.58	-14.72	-6.84	-56.14	1.80
Slovenia	BAU 2020	6.2	22.1	8.9	30.0	36.8	1.55	0.56					
	BAU 2050	7.2	23.5	10.8	28.5	35.3	1.39	0.50					
	WWS 2050	3.4	19.8	15.1	43.3	20.9	0.70	0.21	-41.33	-3.95	-7.77	-53.05	1.51
South Africa	BAU 2020	99.9	13.6	5.9	52.6	24.3	2.35	1.22					
	BAU 2050	190.6	12.7	7.3	49.3	27.0	2.37	1.23					
	WWS 2050	87.1	15.0	10.2	57.0	14.9	1.92	0.95	-33.33	-15.20	-5.78	-54.32	1.58
South Sudan	BAU 2020	0.8	32.7	2.0	4.4	55.7	5.12	0.00					
	BAU 2050	1.6	24.7	2.1	4.6	63.3	5.27	0.00					
	WWS 2050	0.5	24.4	2.2	12.7	55.3	5.45	0.00	-62.54	-1.41	-6.64	-70.60	3.23
Spain	BAU 2020	117.4	16.2	10.1	31.8	38.2	3.37	0.35					
	BAU 2050	143.3	16.6	11.7	31.7	36.7	2.93	0.31					
	WWS 2050	60.8	19.1	17.8	37.9	22.8	2.01	0.36	-37.82	-12.71	-7.06	-57.59	1.55
Sri Lanka	BAU 2020	12.9	28.5	5.3	28.4	36.0	0.00	1.87					
	BAU 2050	23.7	21.9	5.8	27.5	43.0	0.00	1.76					
	WWS 2050	10.3	17.7	8.8	49.1	23.6	0.00	0.81	-48.50	-1.45	-6.48	-56.43	2.77
Sudan	BAU 2020	17.4	45.9	14.6	10.6	27.3	1.40	0.18					
	BAU 2050	30.8	37.2	16.6	11.9	32.5	1.55	0.19					
	WWS 2050	10.5	34.2	13.7	26.0	23.4	2.51	0.11	-57.21	-1.25	-7.47	-65.93	2.50
Suriname	BAU 2020	0.9	14.3	3.8	17.8	41.7	22.09	0.30					
	BAU 2050	1.4	14.0	4.0	17.0	45.3	19.41	0.30					
	WWS 2050	0.5	21.8	6.1	33.4	28.1	9.91	0.59	-51.41	-2.57	-6.82	-60.80	1.60
Sweden	BAU 2020	45.7	20.9	11.6	38.2	27.5	1.75	0.00					
	BAU 2050	54.6	22.9	13.8	34.7	27.1	1.51	0.00					
	WWS 2050	29.8	22.3	16.1	45.7	15.2	0.80	0.00	-32.77	-5.31	-7.34	-45.42	1.41
Switzerland	BAU 2020	23.8	27.5	16.9	21.1	33.0	0.58	0.97					
	BAU 2050	28.6	27.0	18.1	19.6	33.9	0.51	0.85					
	WWS 2050	13.5	24.5	20.9	28.6	24.9	0.72	0.36	-40.37	-3.71	-8.85	-52.93	1.30
Syria	BAU 2020	7.1	21.2	4.3	30.1	37.6	3.45	3.38					
	BAU 2050	11.7	19.2	4.1	31.4	38.0	3.56	3.63					
	WWS 2050	5.2	23.9	4.9	44.1	21.1	1.58	4.36	-41.08	-6.65	-7.24	-54.97	1.67
Taiwan	BAU 2020	79.5	10.4	8.4	53.8	25.4	1.18	0.79					
	BAU 2050	154.6	10.2	9.1	49.7	29.1	1.08	0.74					
	WWS 2050	85.2	12.4	11.3	61.5	13.2	0.86	0.80	-30.25	-7.69	-6.97	-44.90	1.38
Tajikistan	BAU 2020	4.2	29.4	8.5	21.9	18.5	7.07	14.67					
	BAU 2050	6.2	36.0	12.2	18.2	17.0	5.56	10.92					
	WWS 2050	3.5	41.6	16.9	22.3	7.5	7.77	3.92	-30.13	-3.03	-11.06	-44.22	1.04
Tanzania	BAU 2020	27.7	69.7	0.8	9.8	10.9	6.48	2.28					
	BAU 2050	42.5	58.5	1.4	13.0	15.0	8.92	3.14					
	WWS 2050	12.2	40.3	3.8	35.5	12.3	5.96	2.17	-62.16	-0.36	-8.84	-71.36	6.12
Thailand	BAU 2020	114.7	10.3	5.3	47.2	33.8	2.71	0.74					
	BAU 2050	225.7	8.9	6.0	42.4	39.6	2.38	0.70					
	WWS 2050	108.7	10.7	9.0	59.3	18.9	1.04	1.13	-37.35	-8.78	-5.71	-51.84	2.39
Togo	BAU 2020	3.1	66.7	10.0	5.2	18.1	0.01	0.00					
	BAU 2050	4.8	55.8	13.0	6.6	24.5	0.01	0.00					
	WWS 2050	1.3	45.0	12.3	20.7	21.9	0.03	0.00	-64.59	-0.51	-8.39	-73.48	3.34
Trinidad and Tobago	BAU 2020	7.7	6.6	1.5	75.6	16.3	0.00	0.00					
	BAU 2050	11.8	6.4	1.7	75.1	16.8	0.00	0.00					
	WWS 2050	7.6	5.6	1.9	86.4	6.0	0.00	0.00	21.62	-51.57	-5.32	-35.28	4.85
Tunisia	BAU 2020	10.6	27.9	7.9	26.9	31.0	6.24	0.00					
	BAU 2050	23.8	19.1	7.5	23.0	44.9	5.38	0.00					

	WWS 2050	9.2	20.7	11.9	42.9	19.8	4.67	0.00	-40.02	-13.56	-7.62	-61.20	1.95
Turkiye	BAU 2020	149.4	21.0	12.7	35.5	26.3	4.53	0.00					
	BAU 2050	169.1	22.0	13.5	34.7	25.8	4.10	0.00					
	WWS 2050	80.1	18.5	15.2	48.5	14.2	3.59	0.00	-38.19	-7.01	-7.46	-52.65	1.86
Turkmenistan	BAU 2020	24.9	2.1	30.3	17.5	24.5	1.82	23.75					
	BAU 2050	34.5	2.5	30.0	18.5	28.7	1.51	18.90					
	WWS 2050	7.6	7.1	27.4	21.8	20.0	5.35	18.35	-53.85	-20.49	-3.66	-77.99	2.85
Uganda	BAU 2020	16.6	58.6	4.2	26.3	9.5	1.31	0.00					
	BAU 2050	26.7	46.5	5.4	34.1	12.5	1.54	0.00					
	WWS 2050	10.7	21.7	3.3	66.9	7.3	0.77	0.00	-53.25	-0.26	-6.52	-60.04	12.51
Ukraine	BAU 2020	63.9	28.2	10.1	41.5	16.7	3.45	0.00					
	BAU 2050	89.3	32.1	11.6	36.7	16.9	2.76	0.00					
	WWS 2050	44.4	23.8	11.7	53.7	9.1	1.78	0.00	-33.48	-8.90	-7.88	-50.26	1.82
United Arab Emirates	BAU 2020	98.0	5.1	4.7	45.0	41.9	0.00	3.29					
	BAU 2050	179.6	6.4	5.3	47.1	38.0	0.00	3.26					
	WWS 2050	99.6	8.7	7.4	63.2	16.1	0.00	4.53	-36.60	-2.30	-5.66	-44.56	3.25
United Kingdom	BAU 2020	166.2	28.9	12.5	24.8	31.7	1.11	0.92					
	BAU 2050	197.3	29.4	13.3	25.7	29.8	0.99	0.82					
	WWS 2050	76.8	26.4	18.3	32.8	21.1	0.89	0.40	-43.05	-9.60	-8.42	-61.08	1.53
United States	BAU 2020	1,972.9	17.8	13.5	27.0	39.1	1.36	1.34					
	BAU 2050	2,183.4	16.2	15.0	30.6	35.5	1.38	1.37					
	WWS 2050	890.2	20.2	19.6	38.1	18.2	1.29	2.63	-39.41	-12.64	-7.18	-59.23	1.55
Uruguay	BAU 2020	6.6	17.0	6.1	45.1	28.0	3.72	0.00					
	BAU 2050	9.3	16.4	7.2	41.6	31.4	3.41	0.00					
	WWS 2050	4.9	16.8	9.7	57.4	14.3	1.83	0.00	-36.91	-4.05	-6.40	-47.35	2.19
Uzbekistan	BAU 2020	47.7	35.7	11.8	27.0	17.1	3.12	5.26					
	BAU 2050	68.6	37.0	11.7	24.1	20.4	2.52	4.30					
	WWS 2050	21.3	31.3	11.4	41.0	8.3	4.89	3.05	-45.79	-14.80	-8.33	-68.92	2.13
Venezuela	BAU 2020	29.4	10.3	7.3	45.7	36.6	0.13	0.00					
	BAU 2050	45.6	10.6	7.8	44.0	37.5	0.12	0.00					
	WWS 2050	16.7	17.8	15.0	44.7	22.2	0.25	0.00	-37.73	-20.08	-5.45	-63.26	1.73
Vietnam	BAU 2020	87.8	15.5	3.7	56.6	19.3	4.90	0.00					
	BAU 2050	166.6	14.4	4.3	54.4	22.3	4.53	0.00					
	WWS 2050	106.1	13.9	4.9	70.5	8.5	2.27	0.00	-28.00	-1.43	-6.87	-36.31	2.02
Yemen	BAU 2020	3.4	35.8	3.9	15.4	39.9	2.44	2.53					
	BAU 2050	5.0	27.9	3.4	18.0	45.2	2.83	2.74					
	WWS 2050	1.8	29.9	3.1	33.2	29.9	1.57	2.33	-53.50	-2.87	-7.56	-63.93	2.78
Zambia	BAU 2020	11.1	64.1	1.2	23.0	9.9	0.73	1.02					
	BAU 2050	17.9	54.1	1.7	29.0	13.0	0.88	1.20					
	WWS 2050	7.5	32.2	2.8	55.6	7.8	0.89	0.70	-48.64	-0.64	-8.73	-58.01	2.41
Zimbabwe	BAU 2020	12.7	76.8	1.1	7.8	7.8	5.48	1.04					
	BAU 2050	18.8	67.6	1.9	10.4	11.2	7.65	1.33					
	WWS 2050	5.4	49.6	5.1	28.8	9.4	6.07	1.06	-60.82	-0.61	-9.94	-71.38	2.69
All Countries	**BAU 2020**	**12,571.5**	**21.8**	**8.0**	**39.8**	**26.4**	**2.25**	**1.71**					
	BAU 2050	**18,930.3**	**20.4**	**7.8**	**39.7**	**28.4**	**2.07**	**1.63**					
	WWS 2050	**8,627.5**	**18.0**	**9.9**	**53.9**	**14.3**	**1.84**	**2.02**	**-36.83**	**-10.85**	**-6.74**	**-54.43**	**1.85**

2020 BAU values are from IEA (2023). 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 demand includes, among other demands, energy produced in each country for aircraft and shipping. 2050 WWS values are estimated from 2050 BAU values assuming electrification of end-uses and effects of additional energy-efficiency measures beyond those in the BAU case, using the factors from Table S3. In the case of the industrial sector, the factors are applied after accounting for the change in energy between BAU and WWS during steel manufacturing due to purifying iron using green hydrogen in a shaft furnace instead of purifying it using coke in a blast furnace (Table S5), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen (Table S5). Multiply annual-average demand (GW) by 8,760 hours per year to obtain annual energy per year (GWh/y) consumed. In 2020 and 2050, 22.71% and 24.63%, respectively, of the 149-country total BAU demand was for electricity.

Table S4b. Same as Table S4a, but by region.

Country	Scenario	(a) Total annual-average end-use demand (GW)	(b) Residential % of total	(c) Commercial % of total	(d) Industry % of total	(e) Transport % of total	(f) Ag-for-fish % of total	(g) Military-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to eliminating upstream	(j) % change end-use demand with WWS due to efficiency beyond BAU	(k) Overall % change in end-use demand with WWS	(l) WWS:BAU electricity demand
Africa-East	BAU 2020	148.9	72.5	3.23	8.90	12.9	1.74	0.64					
	BAU 2050	224.4	62.3	4.45	11.9	18.1	2.37	0.87					
	WWS 2050	64.2	44.1	5.55	32.5	15.4	1.88	0.60	-62.0	-0.5	-8.9	-71.4	4.90
Africa-North	BAU 2020	180.7	27.2	4.46	29.4	34.3	2.58	2.03					
	BAU 2050	380.0	22.0	5.13	25.9	42.8	2.38	1.90					
	WWS 2050	153.1	23.4	8.64	41.7	21.6	2.61	2.02	-40.2	-11.8	-7.8	-59.7	1.86
Africa-South	BAU 2020	154.4	30.6	4.62	39.7	21.4	2.36	1.34					
	BAU 2050	278.3	25.1	5.83	39.9	25.1	2.55	1.44					
	WWS 2050	118.5	20.7	8.34	52.7	14.8	1.97	1.45	-39.6	-11.1	-6.7	-57.4	1.70
Africa-West	BAU 2020	271.5	71.1	3.5	10.6	14.4	0.24	0.15					
	BAU 2050	409.2	61.0	4.9	13.5	20.2	0.32	0.19					
	WWS 2050	110.7	45.7	6.3	30.9	16.6	0.28	0.27	-56.9	-3.0	-8.0	-72.9	5.15
Australia	BAU 2020	130.5	11.1	8.1	42.1	36.7	2.01	0.03					
	BAU 2050	201.5	10.7	11.3	44	32.3	1.67	0.03					
	WWS 2050	88.9	12.9	18.4	49.5	18.2	1.04	0.01	-33.14	-16.45	-6.3	-55.89	1.56
Canada	BAU 2020	295.3	15	12.3	44	25.8	2.97	0.03					
	BAU 2050	401.9	13.8	12.6	46.5	24.4	2.72	0.02					
	WWS 2050	160.1	16.6	18.8	45.3	17.2	1.95	0.04	-31.48	-22.54	-6.14	-60.16	1.42
Central America	BAU 2020	192.7	19.6	4.17	36.7	36.2	2.14	1.09					
	BAU 2050	301	17.2	5.93	37.3	36.1	2.21	1.23					
	WWS 2050	127.3	17.5	8.57	50.1	19.3	2.20	2.26	-39.7	-11.6	-6.5	-57.7	1.73
Central Asia	BAU 2020	257.0	38.8	8.89	28.0	18.1	1.75	4.49					
	BAU 2050	391.9	35.8	8.64	27.8	22.8	1.51	3.37					
	WWS 2050	143.3	28.3	8.39	46.8	12.0	2.58	2.05	-46.5	-9.4	-7.5	-63.4	2.35
China region	BAU 2020	2,995.2	16.4	3.99	57.8	15.7	1.94	4.14					
	BAU 2050	5,081.4	18.1	4.31	51.0	22.0	1.37	3.32					
	WWS 2050	2,542.8	16.3	5.27	63.8	9.5	1.09	4.20	-31.0	-12.7	-6.3	-50.0	1.77
Cuba	BAU 2020	8.4	20.1	3.7	47.6	14.7	2.48	11.41					
	BAU 2050	11.9	21.3	4.5	44.6	16.9	2.26	10.34					
	WWS 2050	6.7	23.8	6	56.3	9	1.12	3.68	-32.69	-4.16	-7.13	-43.98	1.99
Europe	BAU 2020	1,676.8	24.9	11.6	30.3	30.2	2.74	0.28					
	BAU 2050	2,053.7	25.4	12.8	29.3	29.9	2.38	0.24					
	WWS 2050	876.4	22.2	17.0	39.9	19.1	1.69	0.14	-11.5	-2.8	-2.3	-57.3	5.20
Haiti region	BAU 2020	13.0	41.1	5.13	20.3	31.9	1.59	0.00					
	BAU 2050	17.2	32.9	6.11	20.8	38.6	1.63	0.00					
	WWS 2050	6.8	23.8	10.1	40.4	23.5	2.24	0.00	-50.5	-2.0	-8.0	-60.5	2.21
Iceland	BAU 2020	4	15.9	16.1	44.7	13.6	8.41	1.21					
	BAU 2050	4.6	16.8	17.2	43.9	13.2	7.85	1.15					
	WWS 2050	2.7	10.3	14.5	64.4	5.9	4.31	0.54	-31.95	-2.12	-6.54	-40.61	1.08
India region	BAU 2020	849.5	29.3	3.27	43.9	16.4	4.66	2.34					
	BAU 2050	1820.9	21.2	3.21	44.9	23.9	4.45	2.39					
	WWS 2050	967.2	15.3	3.02	64.5	10.7	4.72	1.77	-34.4	-5.9	-6.5	-46.9	2.51
Israel	BAU 2020	20.4	15.9	10	26	40.8	2.09	5.27					
	BAU 2050	24.7	18	13.4	25.8	36.1	1.9	4.69					
	WWS 2050	12.4	27.7	20.4	27.5	16.7	2.95	4.83	-32.6	-8.42	-8.78	-49.79	1.23
Jamaica	BAU 2020	2.8	12.1	5.5	26.5	55.4	0.46	0					
	BAU 2050	4.1	10.1	5.2	25.1	59.2	0.4	0					

	WWS 2050	1.7	12.2	6.5	46.8	34.4	0.19	0	-50.65	-1.31	-5.76	-57.72	3
Japan	BAU 2020	343	17	18	35.8	27.2	1.81	0.2					
	BAU 2050	329.1	17.7	19.5	33.6	27.7	1.34	0.17					
	WWS 2050	175.7	16.9	20.5	46.9	15	0.61	0.06	-30.28	-8.28	-8.06	-46.62	1.48
Madagascar	BAU 2020	7.9	57.3	26.5	7.4	6.9	0.04	1.89					
	BAU 2050	12.8	45.9	33.1	9.5	9.1	0.05	2.28					
	WWS 2050	3.4	33.6	26.1	28.1	8.7	0.14	3.41	-66.8	-0.18	-6.42	-73.4	7.49
Mauritius	BAU 2020	2.0	9.5	5.8	12.5	71.7	0.22	0.31					
	BAU 2050	4.2	9.1	6.6	11.6	72.2	0.21	0.3					
	WWS 2050	1.6	15.8	12.3	25.1	46	0.25	0.59	-54.34	-1.52	-6.56	-62.41	2.04
Mideast	BAU 2020	846.5	18.0	7.83	40.9	30.0	2.27	0.93					
	BAU 2050	1,383.4	17.6	7.61	42.2	29.5	2.12	1.00					
	WWS 2050	647.5	17.6	9.70	54.7	14.5	2.06	1.40	-20.9	-6.4	-3.9	-53.2	3.28
New Zealand	BAU 2020	18.1	11.6	9.3	34	39	5.73	0.36					
	BAU 2050	27.9	11.9	11.7	37.3	33.2	5.43	0.43					
	WWS 2050	14.8	14.3	15.3	50.4	15	4.37	0.62	-34.51	-5	-7.39	-46.9	1.63
Philippines	BAU 2020	43.8	30.4	14	22.3	32	1.33	0					
	BAU 2050	79.7	25.3	13.2	21.6	38.5	1.31	0					
	WWS 2050	34.7	25.3	15.5	36	21.8	1.51	0	-45.33	-2.95	-8.23	-56.51	1.57
Russia region	BAU 2020	660.7	27.9	7.72	41.7	20.8	1.84	0.04					
	BAU 2050	729.9	27.4	8.05	39.3	23.8	1.41	0.05					
	WWS 2050	262.7	23.0	11.0	51.8	12.7	1.28	0.10	-39.5	-18.3	-6.2	-64.0	1.76
South America -NW	BAU 2020	131.4	16.2	5.66	35.5	38.4	1.23	2.98					
	BAU 2050	201.7	14.0	5.99	34.3	42.1	1.05	2.52					
	WWS 2050	81.7	16.1	9.90	48.7	22.6	0.88	1.88	-38.8	-14.3	-6.3	-59.5	2.02
South America -SE	BAU 2020	449.4	14.6	5.5	41.6	33.2	5.04	0.02					
	BAU 2050	756.9	12.8	5.7	40.5	36.3	4.69	0.02					
	WWS 2050	344.8	13.6	8.8	56.7	17.5	3.41	0.05	-37.0	-11.4	-6.0	-54.4	2.05
Southeast Asia	BAU 2020	608.9	15.5	4.6	40.4	37.3	1.90	0.38					
	BAU 2050	1,180.2	12.4	5.3	37.5	42.7	1.71	0.35					
	WWS 2050	560.3	12.7	8.0	56.5	21.5	0.96	0.32	-41.2	-5.3	-6.0	-52.5	2.43
South Korea	BAU 2020	206.5	13.4	13.2	40.6	30.3	1.83	0.68					
	BAU 2050	279.7	11.9	15.1	41.8	28.9	1.68	0.55					
	WWS 2050	142	9.1	19.9	55.4	13.6	1.77	0.22	-32.18	-9.71	-7.36	-49.24	1.47
Taiwan	BAU 2020	79.5	10.4	8.4	53.8	25.4	1.18	0.79					
	BAU 2050	154.6	10.2	9.1	49.7	29.1	1.08	0.74					
	WWS 2050	85.2	12.4	11.3	61.5	13.2	0.86	0.8	-30.25	-7.69	-6.97	-44.9	1.38
United States	BAU 2020	1,972.90	17.8	13.5	27	39.1	1.36	1.34					
	BAU 2050	2,183.40	16.2	15	30.6	35.5	1.38	1.37					
	WWS 2050	890.2	20.2	19.6	38.1	18.2	1.29	2.63	-39.41	-12.64	-7.18	-59.23	1.55
All Regions	**BAU 2020**	**12,571.5**	**21.8**	**8.0**	**39.8**	**26.4**	**2.25**	**1.71**					
	BAU 2050	**18,930.3**	**20.4**	**7.8**	**39.7**	**28.4**	**2.07**	**1.63**					
	WWS 2050	**8,627.5**	**18.0**	**9.9**	**53.9**	**14.3**	**1.84**	**2.02**	**-36.83**	**-10.85**	**-6.74**	**-54.43**	**1.85**

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

Region or country	(a) 2050 Tg-H_2/y needed to purify iron by hydrogen direct reduction	(b) 2050 Tg-H_2/y needed to make NH_3	(c) 2050 Tg-H_2/y needed for HFC vehicles	(d) 2050 Total Tg-H_2/y produced for steel, ammonia, and vehicles = a+b+c	(e) 2050 Power needed to produce and compress H_2 for steel and ammonia (GW)	(f) 2050 power needed to produce and compress H_2 for transport (GW)	(g) 2050 power needed to produce and compress H_2 for steel, ammonia, and transport (GW) = e+f
Africa-East	**0**	**0**	**0.764**	**0.764**	**0**	**4.10**	**4.10**
Eritrea	0	0	0.006	0.006	0	0.034	0.034
Ethiopia	0	0	0.185	0.185	0	0.993	0.993
Kenya	0	0	0.192	0.192	0	1.033	1.033
Rwanda	0	0	0.011	0.011	0	0.059	0.059
South Sudan	0	0	0.024	0.024	0	0.127	0.127
Sudan	0	0	0.196	0.196	0	1.051	1.051
Tanzania	0	0	0.099	0.099	0	0.533	0.533
Uganda	0	0	0.051	0.051	0	0.272	0.272
Africa-North	**0.535**	**1.387**	**2.466**	**4.388**	**10.33**	**13.26**	**23.59**
Algeria	0.184	0.475	0.795	1.454	3.544	4.274	7.818
Egypt	0.302	0.907	0.979	2.188	6.499	5.265	11.764
Libya	0.049	0.005	0.116	0.170	0.291	0.623	0.914
Morocco	0	0	0.414	0.414	0	2.224	2.224
Niger	0	0	0.017	0.017	0	0.094	0.094
Tunisia	0	0	0.145	0.145	0	0.780	0.780
Africa-South	**0.168**	**0.098**	**1.3**	**1.566**	**1.43**	**6.98**	**8.41**
Angola	0	0	0.146	0.146	0	0.784	0.784
Botswana	0	0	0.027	0.027	0	0.143	0.143
Eswatini	0	0	0.009	0.009	0	0.049	0.049
Mozambique	0	0	0.063	0.063	0	0.338	0.338
Namibia	0	0	0.035	0.035	0	0.189	0.189
South Africa	0.168	0.097	0.934	1.199	1.425	5.021	6.446
Zambia	0	0	0.049	0.049	0	0.262	0.262
Zimbabwe	0	0.001	0.037	0.038	0.005	0.197	0.202
Africa-West	**0**	**0.153**	**0.877**	**1.03**	**0.82**	**4.71**	**5.53**
Benin	0	0	0.068	0.068	0	0.364	0.364
Cameroon	0	0	0.052	0.052	0	0.279	0.279
Congo	0	0	0.021	0.021	0	0.112	0.112
Congo, DR	0	0	0.035	0.035	0	0.187	0.187
Côte d'Ivoire	0	0	0.079	0.079	0	0.424	0.424
Equatorial Guin.	0	0	0.009	0.009	0	0.046	0.046
Gabon	0	0	0.015	0.015	0	0.079	0.079
Ghana	0	0	0.143	0.143	0	0.770	0.770
Nigeria	0	0.153	0.360	0.513	0.824	1.936	2.761
Senegal	0	0	0.076	0.076	0	0.409	0.409
Togo	0	0	0.019	0.019	0	0.103	0.103
Australia	**0.206**	**0.345**	**1.138**	**1.689**	**2.964**	**6.119**	**9.083**
Canada	**0.422**	**0.841**	**1.175**	**2.438**	**6.792**	**6.315**	**13.108**
Central America	**0.46**	**0.024**	**1.357**	**1.842**	**2.61**	**7.30**	**9.90**
Costa Rica	0	0	0.060	0.060	0	0.322	0.322
El Salvador	0	0	0.039	0.039	0	0.210	0.210
Guatemala	0	0	0.098	0.098	0	0.529	0.529
Honduras	0	0	0.042	0.042	0	0.226	0.226

Mexico	0.460	0.024	0.879	1.364	2.605	4.729	7.333
Nicaragua	0	0	0.028	0.028	0	0.149	0.149
Panama	0	0	0.211	0.211	0	1.135	1.135
Central Asia	**0.168**	**1.13**	**1.038**	**2.337**	**6.99**	**5.58**	**12.56**
Kazakhstan	0.168	0.039	0.193	0.400	1.112	1.039	2.150
Kyrgyz Republic	0	0	0.011	0.011	0	0.060	0.060
Pakistan	0	0.712	0.608	1.320	3.831	3.268	7.098
Tajikistan	0	0	0.021	0.021	0	0.111	0.111
Turkmenistan	0	0.142	0.110	0.253	0.766	0.592	1.358
Uzbekistan	0	0.237	0.095	0.332	1.277	0.509	1.786
China region	**47.049**	**8.42**	**11.232**	**66.7**	**298.24**	**60.39**	**358.63**
China	47.035	8.420	10.252	65.707	298.163	55.123	353.287
Hong Kong	0	0	0.911	0.911	0	4.897	4.897
Korea, DPR	0.014	0	0.024	0.037	0.073	0.129	0.201
Mongolia	0	0	0.045	0.045	0	0.241	0.241
Cuba	**0**	**0**	**0.052**	**0.052**	**0**	**0.279**	**0.279**
Europe	**5.826**	**3.688**	**11.266**	**20.787**	**51.16**	**60.58**	**111.74**
Albania	0	0	0.024	0.024	0	0.126	0.126
Austria	0.330	0.091	0.219	0.640	2.264	1.180	3.443
Belarus	0	0.165	0.121	0.286	0.886	0.651	1.537
Belgium	0.227	0.184	0.490	0.901	2.210	2.636	4.846
Bosnia-Herzeg.	0.040	0	0.053	0.093	0.215	0.285	0.500
Bulgaria	0	0.050	0.130	0.180	0.267	0.700	0.967
Croatia	0	0.080	0.079	0.159	0.430	0.427	0.857
Cyprus	0	0	0.030	0.030	0	0.159	0.159
Czech Rep.	0.211	0.020	0.178	0.410	1.243	0.958	2.202
Denmark	0	0	0.132	0.132	0	0.708	0.708
Estonia	0	0.004	0.031	0.036	0.022	0.169	0.191
Finland	0.135	0.017	0.124	0.276	0.818	0.667	1.485
France	0.514	0.177	1.304	1.996	3.720	7.011	10.731
Germany	1.419	0.503	1.537	3.459	10.333	8.265	18.598
Gibraltar	0	0	0.127	0.127	0	0.683	0.683
Greece	0	0.022	0.202	0.224	0.116	1.086	1.202
Hungary	0.032	0.093	0.119	0.245	0.674	0.642	1.316
Ireland	0	0	0.130	0.130	0	0.697	0.697
Italy	0.211	0.134	0.954	1.299	1.855	5.130	6.985
Kosovo	0	0	0.019	0.019	0	0.104	0.104
Latvia	0	0	0.054	0.054	0	0.291	0.291
Lithuania	0	0.182	0.098	0.280	0.979	0.527	1.505
Luxembourg	0	0	0.071	0.071	0	0.379	0.379
Macedonia, N.	0	0	0.030	0.030	0	0.159	0.159
Malta	0	0	0.086	0.086	0	0.461	0.461
Moldova	0	0	0.027	0.027	0	0.143	0.143
Montenegro	0	0	0.010	0.010	0	0.055	0.055
Netherlands	0.319	0.453	0.579	1.352	4.155	3.113	7.269
Norway	0.004	0.071	0.149	0.225	0.406	0.802	1.208
Poland	0.195	0.488	0.670	1.354	3.674	3.604	7.277
Portugal	0	0	0.198	0.198	0	1.066	1.066
Romania	0.114	0.101	0.242	0.458	1.157	1.303	2.460
Serbia	0.060	0	0.093	0.153	0.322	0.499	0.821
Slovakia	0.168	0.077	0.073	0.318	1.315	0.393	1.708
Slovenia	0	0	0.052	0.052	0	0.278	0.278
Spain	0.217	0.091	1.103	1.410	1.652	5.928	7.581
Sweden	0.168	0	0.221	0.389	0.903	1.190	2.093
Switzerland	0	0.002	0.152	0.154	0.012	0.817	0.828
Ukraine	1.148	0.497	0.263	1.908	8.847	1.412	10.259
United Kingdom	0.314	0.186	1.092	1.592	2.687	5.872	8.559
Haiti region	**0**	**0**	**0.117**	**0.117**	**0**	**0.63**	**0.63**
Dominican Rep.	0	0	0.098	0.098	0	0.524	0.524
Haiti	0	0	0.019	0.019	0	0.103	0.103
Iceland	**0**	**0**	**0.012**	**0.012**	**0**	**0.066**	**0.066**
India region	**6.314**	**2.815**	**8.065**	**17.193**	**49.09**	**43.36**	**92.44**

Bangladesh	0	0.181	0.226	0.407	0.975	1.214	2.189
India	6.314	2.634	7.552	16.499	48.110	40.603	88.712
Nepal	0	0	0.115	0.115	0	0.619	0.619
Sri Lanka	0	0	0.172	0.172	0	0.924	0.924
Israel	**0**	**0**	**0.127**	**0.127**	**0**	**0.683**	**0.683**
Jamaica	**0**	**0**	**0.047**	**0.047**	**0**	**0.255**	**0.255**
Japan	**3.807**	**0.139**	**1.390**	**5.335**	**21.214**	**7.473**	**28.687**
Madagascar	**0**	**0**	**0.026**	**0.026**	**0**	**0.138**	**0.138**
Mauritius	**0**	**0**	**0.052**	**0.052**	**0**	**0.278**	**0.278**
Mideast	**3.064**	**3.177**	**6.915**	**13.156**	**33.57**	**37.18**	**70.75**
Armenia	0	0	0.013	0.013	0	0.070	0.070
Azerbaijan	0	0	0.075	0.075	0	0.403	0.403
Bahrain	0.076	0.082	0.029	0.187	0.850	0.157	1.007
Iran	1.760	0.777	1.431	3.968	13.641	7.694	21.336
Iraq	0	0.019	0.359	0.378	0.104	1.928	2.033
Jordan	0	0	0.090	0.090	0	0.483	0.483
Kuwait	0	0	0.191	0.191	0	1.029	1.029
Lebanon	0	0	0.042	0.042	0	0.226	0.226
Oman	0.092	0.374	0.134	0.599	2.503	0.718	3.221
Qatar	0.043	0.712	0.320	1.076	4.064	1.719	5.783
Saudi Arabia	0.330	0.928	1.992	3.250	6.768	10.709	17.477
Syria	0	0.004	0.095	0.099	0.023	0.511	0.534
Turkiye	0.563	0.080	1.035	1.678	3.457	5.567	9.024
UAE	0.200	0.201	1.071	1.472	2.157	5.758	7.915
Yemen	0	0	0.038	0.038	0	0.206	0.206
New Zealand	**0.038**	**0.027**	**0.156**	**0.220**	**0.349**	**0.836**	**1.185**
Philippines	**0**	**0**	**0.585**	**0.585**	**0**	**3.144**	**3.144**
Russia region	**3.325**	**3.525**	**1.805**	**8.654**	**36.83**	**9.70**	**46.53**
Georgia	0	0.043	0.028	0.071	0.232	0.150	0.382
Russia	3.325	3.482	1.777	8.583	36.596	9.554	46.150
South Am-NW	**0.106**	**0.942**	**1.197**	**2.245**	**5.64**	**6.43**	**12.07**
Bolivia	0	0	0.092	0.092	0	0.495	0.495
Colombia	0.009	0	0.299	0.307	0.048	1.605	1.653
Curacao	0	0	0.107	0.107	0	0.575	0.575
Ecuador	0	0	0.197	0.197	0	1.058	1.058
Peru	0	0.002	0.310	0.312	0.013	1.666	1.679
Suriname	0	0	0.012	0.012	0	0.063	0.063
Trinidad/Tobago	0.081	0.899	0.029	1.009	5.272	0.154	5.425
Venezuela	0.016	0.041	0.151	0.209	0.308	0.814	1.122
South Am-SE	**1.773**	**0.164**	**3.931**	**5.867**	**10.41**	**21.14**	**31.55**
Argentina	0.190	0.138	0.489	0.816	1.762	2.628	4.390
Brazil	1.543	0.026	2.917	4.486	8.437	15.685	24.122
Chile	0.038	0	0.379	0.417	0.204	2.038	2.242
Paraguay	0.002	0	0.096	0.098	0.010	0.518	0.528
Uruguay	0	0	0.050	0.050	0	0.268	0.268
Southeast Asia	**0.731**	**1.803**	**8.229**	**10.763**	**13.62**	**44.25**	**57.88**
Brunei	0	0	0.017	0.017	0	0.093	0.093
Cambodia	0	0	0.128	0.128	0	0.690	0.690
Indonesia	0.162	1.274	1.865	3.301	7.722	10.029	17.751
Lao PDR	0	0	0.052	0.052	0	0.280	0.280
Malaysia	0.038	0.281	0.831	1.150	1.713	4.470	6.183
Myanmar	0	0	0.108	0.108	0	0.583	0.583
Singapore	0	0	2.923	2.923	0	15.716	15.716
Thailand	0	0	1.624	1.624	0	8.732	8.732
Vietnam	0.531	0.248	0.681	1.460	4.188	3.660	7.848
South Korea	**2.513**	**0**	**1.558**	**4.070**	**13.509**	**8.376**	**21.886**
Taiwan	**0.823**	**0**	**0.614**	**1.437**	**4.425**	**3.299**	**7.725**
United States	**1.392**	**3.023**	**8.131**	**12.545**	**23.734**	**43.718**	**67.452**
All regions	**78.72**	**31.70**	**75.62**	**186.1**	**593.7**	**406.6**	**1,000.3**

Same methodology as in Jacobson et al. (2023). Column (e) = Columns (a) plus (b), all multiplied by 47.1 TWh/Tg-H_2 and divided by 8,760 hours per year; Column (f) = Column (c) multiplied by 47.1 TWh/Tg-H_2 and divided by 8,760 hours per year.

Table S6. 2050 annual-average end-use electricity plus heat demand (GW) by sector and region after energy in all sectors has been converted to WWS. Instantaneous demands can be higher or lower than annual-average demands. Values for each region equal the sum over all country values from Table S4 in each region, where Table S1 defines the regions.

Region	(a) Total	(b) Residential	(c) Commercial	(e) Industrial	(f) Transport	(g) Agriculture-forestry-fishing	(h) Military-other
Africa-East	64.18	28.29	3.55	20.85	9.90	1.21	0.39
Africa-North	153.06	35.82	13.23	63.79	33.15	3.99	3.10
Africa-South	118.48	24.59	9.90	62.44	17.51	2.33	1.72
Africa-West	110.72	50.55	6.96	34.21	18.38	0.31	0.30
Australia	88.89	11.44	16.34	44.00	16.19	0.92	0.010
Canada	160.10	26.66	30.11	72.59	27.55	3.13	0.063
Central America	127.31	22.24	10.89	63.84	24.66	2.80	2.88
Central Asia	143.32	40.49	12.00	67.07	17.15	3.69	2.94
China region	2,542.8	413.0	134.0	1,621.4	240.0	27.83	106.65
Cuba	6.69	1.59	0.40	3.77	0.60	0.075	0.25
Europe	876.44	194.32	148.66	349.71	167.71	14.81	1.23
Haiti region	6.80	1.61	0.69	2.75	1.59	0.15	0
Iceland	2.71	0.28	0.39	1.75	0.16	0.12	0.015
India region	967.23	147.89	29.22	624.43	102.94	45.68	17.08
Israel	12.42	3.44	2.53	3.41	2.07	0.37	0.60
Jamaica	1.73	0.21	0.11	0.81	0.60	0.003	0
Japan	175.68	29.71	35.97	82.43	26.39	1.07	0.11
Madagascar	3.39	1.14	0.88	0.95	0.30	0.005	0.12
Mauritius	1.57	0.25	0.19	0.39	0.72	0.004	0.009
Mideast	647.51	113.91	62.81	354.24	94.17	13.34	9.04
New Zealand	14.81	2.12	2.27	7.46	2.22	0.65	0.092
Philippines	34.68	8.76	5.38	12.47	7.55	0.53	0
Russia region	262.73	60.56	28.80	136.18	33.58	3.36	0.26
South Am-NW	81.73	13.11	8.11	39.80	18.46	0.72	1.54
South Am-SE	344.82	47.10	30.24	195.27	60.30	11.75	0.17
Southeast Asia	560.26	71.04	44.99	316.73	120.37	5.37	1.77
South Korea	141.99	12.87	28.32	78.62	19.36	2.51	0.31
Taiwan	85.20	10.54	9.60	52.43	11.21	0.74	0.68
United States	890.21	180.24	174.20	339.26	161.65	11.48	23.40
Total 2050	**8,627.5**	**1,553.7**	**850.7**	**4,653.0**	**1,236.4**	**158.9**	**174.7**

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

Region	(a) Total end-use demand (GW) =b+c	(b) Inflexible demand (GW)	(c) Flexible demand (GW) =d+e +f+g	(d) Cold demand subject to storage (GW)	(e) Low-temperature heat demand subject to storage (GW)	(f) Demand subject to DR	(g) Demand for non-grid H_2 (GW)	(h) Non-grid H_2 needed (Tg-H_2/y)
Africa-East	64.2	29.2	35.0	0.5	9.5	20.9	4.10	0.76
Africa-North	153.1	72.4	80.7	1.9	6.9	48.3	23.59	4.39
Africa-South	118.5	63.7	54.8	2.3	4.9	39.2	8.41	1.56
Africa-West	110.7	49.9	60.8	1.0	17.0	37.3	5.53	1.03
Australia	88.9	46.2	42.6	0.4	2.8	30.4	9.08	1.69
Canada	160.1	82.4	77.7	0.7	9.3	54.7	13.11	2.44
Central America	127.3	61.9	65.4	1.2	4.9	49.5	9.90	1.84
Central Asia	143.3	77.6	65.8	0.3	7.3	45.6	12.56	2.34
China region	2,542.8	1,171	1,372	33.1	181.2	798.8	358.7	66.71
Cuba	6.7	3.3	3.4	0.3	0.4	2.5	0.28	0.05
Europe	876.4	394.3	482.1	12.8	120.2	237.4	111.7	20.78
Haiti region	6.8	3.4	3.4	0.1	0.3	2.4	0.63	0.12
Iceland	2.7	1.0	1.7	0.0	0.5	1.1	0.07	0.01
India region	967.2	454.3	513.0	11.0	36.5	373.1	92.45	17.20
Israel	12.4	6.8	5.6	0.2	0.8	4.0	0.68	0.13
Jamaica	1.7	0.7	1.0	0.0	0.0	0.7	0.26	0.05
Japan	175.7	97.3	78.4	0.3	6.9	42.5	28.69	5.34
Madagascar	3.4	1.9	1.5	0.1	0.3	1.0	0.14	0.03
Mauritius	1.6	0.6	1.0	0.1	0.1	0.6	0.28	0.05
Mideast	647.5	318.5	329.0	2.8	21.4	234.0	70.76	13.16
New Zealand	14.8	8.0	6.8	0.0	0.4	5.2	1.19	0.22
Philippines	34.7	15.9	18.8	1.6	2.9	11.1	3.14	0.58
Russia region	262.7	108.3	154.5	3.4	39.8	64.7	46.54	8.66
South Am-NW	81.7	38.0	43.7	1.5	3.0	27.2	12.07	2.24
South Am-SE	344.8	167.9	176.9	4.9	9.3	131.1	31.55	5.87
Southeast Asia	560.3	253.9	306.3	8.1	19.4	221.0	57.87	10.76
South Korea	142.0	75.3	66.7	0.5	6.3	38.0	21.88	4.07
Taiwan	85.2	41.0	44.2	1.2	3.9	31.3	7.72	1.44
United States	890.2	456.8	433.4	8.7	51.2	305.9	67.47	12.55
Total	**8,627.5**	**4,102**	**4,526**	**98.8**	**567.2**	**2,860**	**1,000**	**186.1**

Table S8. Nameplate capacities by WWS generator needed to meet 2050 (a) annual average and (b) continuous all-purpose end-use demand plus transmission/distribution/maintenance losses, storage losses, and shedding losses for 149 countries grouped in 29 world regions. (c) Nameplate capacities already installed as of 2022 (except that solar thermal heat is for 2020 and geothermal heat is for 2019). (d) Average (among all countries) percent of 2050 end-use demand plus losses that is supplied by the final nameplate capacity of each technology.

WWS Technology	(a) 2050 initial existing plus new nameplate capacity to meet annual-average demand plus losses (GW)	(b) 2050 final existing plus new nameplate capacity to meet continuous demand plus losses (GW)	(c) Nameplate capacity already installed 2022 (GW)	(d) Percent of 2050 WWS demand plus losses supplied by each generator
Onshore wind	7,115	10,015	835.2	35.13
Offshore wind	3.666	4,094	63.2	13.65
Res. roof PV	5,791	3,295	129.5	5.92
Com/gov roof PV	7.620	6,117	308.0	10.99
Utility PV plant	9,326	13,371	606.6	26.37
CSP plant	125	142.9	6.49	1.02
Geothermal electricity	97.6	97.6	14.8	0.79
Hydroelectricity	1,250	1,250	1,250	5.05
Wave electricity	30.5	30.49	0.0006	0.05
Tidal electricity	9.73	9.73	0.524	0.02
Solar thermal heat	490.9	490.9	490.9	0.49
Geothermal heat	107.7	107.7	107.7	0.53
Total all	**35,629**	**39,022**	**3,813**	**100**

All values are summed over 149 countries in 29 regions, except values in Column (d) are simulation-averaged outputs by energy device determined by summing outputs over all countries and dividing by total energy output among all devices and countries. Table S13 gives values in Column (d) by region. “Annual average demand plus losses” is all-purpose end-use energy demand plus losses per year divided by 8,760 hours per year. “Initial” nameplate capacities (meeting annual-average demand) are nameplate capacities at the start of a LOADMATCH simulation. “Final” nameplate capacities are those needed to match demand plus losses after LOADMATCH simulations. Table S10 gives final nameplate capacities by country/region. Table S9 gives nameplate capacities already installed by country/region in 2022. Table S11 gives the capacity adjustment factors that result in the differences between Columns (a) and (b).

Table S9. Existing nameplate capacity (GW) by WWS generator in each region in 2022 (except solar heat data are from 2020 and geothermal heat data are from 2019).

Region or country	On-shore wind	Off-shore wind	Residential roof PV	Com/gov roof PV	Utility PV	CSP	Geothermal electricity	Hydro	Tidal	Wave	Solar heat	Geothermal heat	Total
Africa-East	0.84	0	0.084	0.20	0.39	0	0.956	8.92	0	0	0	0.0207	**11.41**
Africa-North	3.45	0	0.34	0.80	1.58	0.585	0	4.33	0	0	1.43	0.171	**12.70**
Africa-South	3.11	0	0.81	1.94	3.81	0.5	0	11.33	0	0	1.85	0.0023	**23.36**
Africa-West	0.16	0	0.066	0.16	0.31	0	0	8.93	0.0004	0	0.0217	0.0007	**9.64**
Australia	10.13	0	3.32	7.90	15.56	0.003	0	7.71	0	0	6.78	0.0944	**51.51**
Canada	15.30	0	0.55	1.30	2.56	0	0	83.38	0	0.021	0.938	1.83	**105.86**
Central America	8.56	0	1.35	3.22	6.34	0.017	1.77	20.58	0	0	3.58	0.166	**45.59**
Central Asia	2.54	0	0.44	1.04	2.05	0	0	24.64	0	0	0	0.0029	**30.72**
China region	335.66	30.46	48.69	115.84	228.15	0.696	0.005	372.6	0	0.005	364	40.63	**1,537**
Cuba	0.012	0	0.032	0.08	0.15	0	0	0.072	0	0	0	0	**0.34**
Europe	209.94	30.66	27.96	66.51	131.00	2.315	0.877	194.4	0.0001	0.2401	40.31	31.64	**735.83**
Haiti region	0.42	0	0.092	0.22	0.43	0	0	0.705	0	0	0	0	**1.87**
Iceland	0.00	0	0.001	0.0021	0.0041	0	0.757	2.11	0	0	0	2.37	**5.25**
India region	42.19	0	7.96	18.93	37.28	0.343	0	51.51	0	0	11.48	0.361	**170.05**
Israel	0.03	0	0.52	1.23	2.42	0.242	0	0.006	0	0	3.449	0.082	**7.98**
Jamaica	0.10	0	0.012	0.0274	0.054	0	0	0.03	0	0	0	0	**0.22**
Japan	4.52	0.061	9.78	23.26	45.80	0	0.431	28.21	0	0	2.404	2.57	**117.03**
Madagascar	0	0	0.0041	0.0097	0.0192	0	0	0.164	0	0	0	0.0028	**0.20**
Mauritius	0.011	0	0.014	0.0324	0.0639	0	0	0.061	0	0	0.093	0	**0.27**
Mideast	12.49	0	2.21	5.27	10.38	0.2011	1.69	48.58	0	0	19.82	3.78	**104.42**
New Zealand	0.91	0	0.04	0.09	0.18	0	1.27	5.434	0	0	0.112	0.518	**8.55**
Philippines	0.44	0	0.20	0.48	0.94	0	1.93	3.037	0	0	0	0.0017	**7.04**
Russia region	2.25	0	0.23	0.54	1.07	0	0.074	54.48	0	0.002	0.019	0.502	**59.16**
South Am-NW	0.70	0	0.13	0.30	0.60	0	0	41.00	0	0	0	0.0299	**42.75**
South Am-SE	32.82	0	3.92	9.32	18.36	0.108	0.051	137.8	0.0001	0	13.65	0.591	**216.65**
Southeast Asia	5.23	1.094	3.09	7.35	14.48	0.005	2.34	51.99	0	0	0.11	0.154	**85.85**
South Korea	1.76	0.136	2.60	6.19	12.19	0	0	1.812	0	0.256	1.353	1.49	**27.78**
Taiwan	0.84	0.745	1.21	2.87	5.65	0	0	2.094	0	0	1.271	0.0001	**14.67**
United States	140.82	0.041	13.83	32.90	64.80	1.48	2.65	83.85	0	0	18.185	20.71	**379.28**
All regions	**835.22**	**63.20**	**129.5**	**308.0**	**606.6**	**6.50**	**14.81**	**1,250**	**0.00**	**0.52**	**490.9**	**107.7**	**3,813**

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 2020 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 S10. Final 2050 total (existing plus new) nameplate capacity (GW) by generator needed in each region to supply 100% of all end-use demand plus losses continuously with WWS across all energy sectors in the region (as determined by LOADMATCH). Nameplate capacity equals the maximum possible instantaneous discharge rate. The nameplate capacity of each generator in each region multiplied by the mean capacity factor for the generator in the region (from Table S12) gives the simulation-averaged power output from the generator in the region given in Table S13.

Region or country	Onshore wind	Offshore wind	Residential roof PV	Com /gov roof PV	Utility PV	CSP with storage	Geothermal electricity	Hydro	Tidal	Wave	Solar heat	Geothermal heat	Total
Africa-East	75.7	8.2	46.1	88.0	152.5	0.00	3.690	8.92	0.172	0.091	0.000	0.021	**383.6**
Africa-North	152	32.2	93.9	215.8	160	4.85	0.001	4.33	0.411	0.136	1.43	0.17	**665.4**
Africa-South	158	32.1	68.8	110.6	111	3.40	0.090	11.33	0.331	0.099	1.85	0.00	**498.1**
Africa-West	427	17.5	100.5	201.5	203	0.23	0.000	8.93	0.927	0.113	0.02	0.00	**959.8**
Australia	131	16.0	32.5	74.3	87	3.12	0.400	7.71	0.277	0.372	6.78	0.09	**359.6**
Canada	181	31.9	12.8	101.9	37	0.00	5.000	83.38	0.433	0.547	0.94	1.83	**456.9**
Central America	145	53.1	48.5	109.1	201	1.90	10.693	20.58	0.942	0.157	3.58	0.17	**594.8**
Central Asia	204	20.2	95.6	168.7	169	0.28	0.000	24.64	0.666	0.021	0.00	0.00	**682.8**
China region	2,867	873.6	1,022.9	989.2	3,595	46.21	1.860	372.61	8.549	2.098	364.00	40.63	**10,183**
Cuba	6	1.8	3.9	12.3	12	0.01	0.000	0.07	0.019	0.031	0.00	0.00	**36.3**
Europe	891	350.3	341.4	498.8	1,469	3.81	3.192	194.39	2.652	1.543	40.31	31.64	**3,829**
Haiti region	25	1.6	1.9	8.1	10	0.01	0.680	0.71	0.000	0.028	0.00	0.00	**48.2**
Iceland	1	0.0	0.0	0.0	0	0.00	0.890	2.11	0.003	0.004	0.00	2.37	**6.0**
India region	864	106.6	85.9	1,357.7	2,002	55.62	0.280	51.51	4.528	0.874	11.48	0.36	**4,540**
Israel	3	5.4	1.1	14.3	55	0.41	0.000	0.01	0.000	0.009	3.45	0.08	**83.3**
Jamaica	0	1.1	1.4	2.7	3	0.00	0.000	0.03	0.000	0.009	0.00	0.00	**8.7**
Japan	11	271.5	22.3	15.0	329	0.00	1.460	28.21	1.234	0.702	2.40	2.57	**684.9**
Madagascar	9	2.1	2.0	4.5	9	0.01	0.000	0.16	0.025	0.015	0.00	0.00	**26.9**
Mauritius	0	2.3	0.4	0.3	3	0.00	0.000	0.06	0.005	0.007	0.09	0.00	**6.3**
Mideast	670	130.5	264.2	358.6	1,154	11.53	1.821	48.58	0.201	0.262	19.82	3.78	**2,663**
New Zealand	31	10.2	4.1	7.0	15	0.01	2.000	5.43	0.033	0.048	0.11	0.52	**75.7**
Philippines	24	10.2	12.7	45.6	117	0.04	5.730	3.04	0.233	0.133	0.00	0.00	**218.4**
Russia region	494	49.5	49.2	67.9	156	0.00	0.500	54.48	0.998	0.358	0.02	0.50	**873.2**
South Am-NW	168	20.4	25.1	49.5	116	0.12	2.710	41.00	0.382	0.213	0.00	0.03	**423.7**
South Am-SE	648	100.9	167.1	371.8	266	0.19	2.640	137.84	1.750	0.372	13.65	0.59	**1,710**
Southeast Asia	54	1,187	486.7	585.7	1,278	0.93	13.757	51.99	2.188	0.509	0.11	0.15	**3,662**
South Korea	2	349.9	67.6	119.7	339	0.14	0.000	1.81	0.000	0.607	1.35	1.49	**883.7**
Taiwan	3	90.4	34.1	72.5	99	0.00	33.640	2.09	0.416	0.027	1.27	0.00	**337.1**
United States	1,771	317.1	202.4	465.5	1,223	10.11	6.520	83.85	3.113	0.350	18.19	20.71	**4,121**
All regions	**10,015**	**4,094**	**3,295**	**6,117**	**13,371**	**142.9**	**97.55**	**1,250**	**30.487**	**9.73**	**490.9**	**107.7**	**39,022**

Table S11. LOADMATCH capacity adjustment factors (CAFs), which show the ratio of the final nameplate capacity of a generator to meet demand continuously, after running LOADMATCH, to the pre-LOADMATCH initial nameplate capacity estimated to meet demand in the annual average. Thus, a CAF less than 1.0 means that the LOADMATCH-stabilized grid meeting continuous demand requires less than the nameplate capacity needed to meet annual-average demand (which is our initial, pre-LOADMATCH nameplate-capacity assumption).

Region	(a) Onshore wind CAF	(b) Off-shore wind CAF	(c) Utility PV CAF	(g) Res. Roof PV CAF	(h) Com./Gov Roof PV CAF	(i) CSP turbine factor	(j) Solar Thermal CAF
Africa-East	1.3	1	1	1	1.68	0	0
Africa-North	1.24	1	1	1	1	1	1
Africa-South	1.2	1	1	1	1.2	1	1
Africa-West	3.8	0.95	1	1	1	1	1
Australia	1.1	0.7	0.75	0.75	1.85	1	1
Canada	1.28	0.88	0.2	0.69	0.5	0	1
Central America	1	1.5	0.7	0.7	1.8	1	1
Central Asia	2	0.9	0.85	0.85	0.9	1	0
China region	1.4	0.7	0.55	0.55	1.7	1	1
Cuba	1	1	1	1.4	1.9	1	0
Europe	1.29	1	0.68	0.9	1.25	1	1
Haiti region	4	1	0.5	1	1.6	1	0
Iceland	0.63	0	0	0	0	0	0
India region	1.2	0.6	0.1	1.3	1.4	1.6	1
Israel	1.23	0.88	0.1	2.3	2.6	1	1
Jamaica	0.75	1.4	0.8	1	1.1	0.1	0
Japan	0.2	2	0.2	0.2	1.28	0	1
Madagascar	2.6	1.6	1	1	4	1	0
Mauritius	1	2.03	0.2	0.2	1.5	0.4	1
Mideast	1.8	0.8	0.7	0.75	1	1	1
New Zealand	2.5	3	0.6	0.6	1.95	0.3	1
Philippines	1.9	0.9	0.55	0.9	3.15	0.8	0
Russia region	1.76	0.55	0.31	0.32	0.8	0	1
South Am-NW	1.5	0.72	0.6	0.6	1.38	1	0
South Am-SE	1.25	0.9	1	1	1.38	0.1	1
Southeast Asia	0.2	2.11	1	1	1.7	1	1
South Korea	0.1	2	0.9	2.5	1.2	0.5	1
Taiwan	0.45	1.7	0.7	3	1.1	0	1
United States	1.7	0.95	0.45	0.45	2.34	1	1

All generators not on this list have a CAF=1. Table S10 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 S12. Simulation-averaged 2050-2052 capacity factors (percentage of nameplate capacity produced as electricity before transmission, distribution, maintenance, storage, or curtailment losses) by region. The mean capacity factors in this table equal the simulation-averaged power output supplied by each generator in each region from Table S13 divided by the final nameplate capacity of each generator in each region from Table S10.

Region	Onshore wind	Offshore wind	Rooftop PV	Utility PV	CSP with storage	Geothermal electricity	Hydropower	Wave	Tidal	Solar thermal	Geothermal heat
Africa-East	0.347	0.386	0.198	0.22	0	0.806	0.335	0.126	0.223	0	0.54
Africa-North	0.535	0.462	0.229	0.253	0.87	0.865	0.366	0.15	0.222	0.123	0.54
Africa-South	0.376	0.541	0.213	0.239	0.83	0.835	0.352	0.325	0.234	0.119	0.54
Africa-West	0.193	0.231	0.174	0.182	0.61	0	0.332	0.125	0.216	0.102	0.54
Australia	0.392	0.513	0.2	0.242	0.85	0.904	0.478	0.332	0.247	0.11	0.54
Canada	0.493	0.566	0.19	0.195	0	0.862	0.508	0.297	0.235	0.104	0.54
Central America	0.267	0.342	0.22	0.25	0.87	0.84	0.397	0.126	0.225	0.122	0.54
Central Asia	0.489	0.474	0.199	0.218	0.74	0	0.326	0.121	0.216	0	0.54
China region	0.428	0.397	0.197	0.223	0.74	0.896	0.497	0.139	0.244	0.108	0.54
Cuba	0.319	0.382	0.226	0.254	0.9	0	0.397	0.377	0.234	0	0
Europe	0.44	0.563	0.185	0.197	0.8	0.861	0.433	0.19	0.239	0.101	0.54
Haiti region	0.348	0.486	0.23	0.254	0.88	0.876	0.401	0	0.228	0	0
Iceland	0.512	0	0	0	0	0.925	0.558	0	0.241	0	0.54
India region	0.329	0.378	0.194	0.226	0.79	0.857	0.447	0.133	0.233	0.109	0.54
Israel	0.392	0.346	0.231	0.254	0.86	0	0.504	0	0.252	0.128	0.54
Jamaica	0.315	0.5	0.235	0.265	1.06	0	0.36	0	0.208	0	0
Japan	0.369	0.468	0.169	0.186	0	0.909	0.479	0.141	0.248	0.093	0.54
Madagascar	0.243	0.394	0.201	0.229	0.79	0	0.377	0.144	0.246	0	0.54
Mauritius	0.48	0.511	0.209	0.228	0.85	0	0.482	0.31	0.251	0.116	0
Mideast	0.472	0.41	0.215	0.227	0.78	0.798	0.453	0.135	0.235	0.119	0.54
New Zealand	0.475	0.555	0.19	0.206	0.68	0.885	0.477	0.353	0.242	0.104	0.54
Philippines	0.28	0.378	0.222	0.249	0.89	0.858	0.452	0.133	0.235	0	0.54
Russia region	0.489	0.597	0.177	0.198	0	0.863	0.35	0.256	0.236	0.097	0.54
South Am-NW	0.135	0.429	0.199	0.224	0.77	0.894	0.461	0.162	0.234	0	0.54
South Am-SE	0.206	0.435	0.209	0.223	0.97	0.872	0.457	0.148	0.239	0.115	0.54
Southeast Asia	0.104	0.219	0.189	0.206	0.71	0.879	0.426	0.177	0.232	0.111	0.54
South Korea	0.302	0.421	0.17	0.164	0.52	0	0.485	0	0.251	0.093	0.54
Taiwan	0.274	0.366	0.187	0.204	0	0.927	0.492	0.144	0.255	0.103	0.54
United States	0.38	0.337	0.211	0.222	0.87	0.891	0.277	0.294	0.244	0.112	0.54
Average	0.386	0.367	0.198	0.217	0.79	0.887	0.445	0.171	0.239	0.109	0.54

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). Capacity factors are determined before transmission, distribution, maintenance, storage, or curtailment losses, which are summarized for each region in Tables S18 and S19. T&D loss rates are given in Table S20. 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, 2020).

Table S13. LOADMATCH 2050-2052 simulation-averaged all-sector projected WWS end-use power supplied (which equals power consumed plus power lost during transmission, distribution, maintenance, and curtailment),, by region and percentage of such supply met by each generator. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/simulation) divided by the number of hours of simulation. The percentages for each region add to 100%. Multiply each percentage by the 2050 total supply to obtain the GW supply by each generator. Divide the GW supply from each generator by its capacity factor (Table S12) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table S10). The 2050 total WWS supply is also obtained from Column (f) of Table S18.

Region	Annual-average total WWS supply (GW)	Onshore wind (%)	Offshore wind (%)	Roof PV (%)	Utility PV (%)	CSP with storage (%)	Geothermal electricity (%)	Hydro power (%)	Wave (%)	Tidal (%)	Solar thermal heat (%)	Geothermal heat (%)
Africa-East	95.6	27.47	3.32	27.82	35.10	0.00	3.114	3.127	0.023	0.021	0.000	0.012
Africa-North	213.5	38.01	6.98	33.14	18.99	1.98	0.000	0.743	0.029	0.014	0.083	0.043
Africa-South	148.8	39.87	11.70	25.68	17.88	1.90	0.051	2.682	0.072	0.016	0.149	0.001
Africa-West	179.2	45.96	2.26	29.35	20.62	0.08	0.000	1.656	0.065	0.014	0.001	0.000
Australia	109.7	46.82	7.47	19.50	19.22	2.40	0.330	3.361	0.084	0.084	0.682	0.047
Canada	184.2	48.36	9.80	11.80	3.96	0.00	2.339	23.004	0.070	0.070	0.053	0.538
Central America	161.3	24.03	11.27	21.49	31.13	1.03	5.569	5.065	0.074	0.022	0.271	0.055
Central Asia	207.2	48.13	4.63	25.43	17.80	0.10	0.000	3.874	0.039	0.002	0.000	0.001
China region	3,058	40.15	11.33	12.97	26.24	1.12	0.055	6.063	0.039	0.017	1.289	0.718
Cuba	9.41	20.58	7.43	39.06	32.35	0.11	0	0.304	0.076	0.077	0.000	0.000
Europe	1,146	34.21	17.22	13.54	25.25	0.26	0.240	7.345	0.044	0.032	0.356	1.493
Haiti region	15.3	57.50	4.99	15.05	16.61	0.06	3.902	1.850	0.000	0.042	0.000	0.000
Iceland	3.62	9.30	0.00	0.00	0.00	0.00	22.73	32.55	0.000	0.027	0.000	35.40
India region	1,127	25.24	3.58	24.83	40.17	3.91	0.021	2.045	0.053	0.018	0.111	0.017
Israel	21.6	5.75	8.70	16.58	65.06	1.62	0	0.014	0.000	0.010	2.053	0.207
Jamaica	2.47	4.55	22.47	38.93	33.53	0.02	0	0.437	0.000	0.074	0.000	0.000
Japan	215.2	1.85	59.05	2.93	28.36	0.00	0.617	6.280	0.081	0.081	0.104	0.646
Madagascar	6.47	32.66	12.85	20.35	32.98	0.07	0.000	0.955	0.055	0.055	0.000	0.024
Mauritius	2.11	2.27	56.68	6.08	32.87	0.04	0.000	1.390	0.077	0.077	0.511	0.000
Mideast	803	39.37	6.67	16.69	32.66	1.13	0.181	2.741	0.003	0.008	0.295	0.254
New Zealand	30.2	48.44	18.62	6.94	10.52	0.02	5.850	8.57	0.038	0.038	0.038	0.926
Philippines	58.9	11.37	6.54	22.01	49.22	0.07	8.345	2.332	0.053	0.053	0.000	0.002
Russia region	343.1	70.52	8.61	6.05	8.96	0.00	0.126	5.558	0.074	0.025	0.001	0.079
South Am-NW	93.8	24.16	9.34	15.86	27.66	0.10	2.584	20.16	0.066	0.053	0.000	0.017
South Am-SE	417.3	32.04	10.52	27.01	14.20	0.04	0.552	15.10	0.062	0.021	0.375	0.077
Southeast Asia	766.5	0.74	33.86	26.40	34.37	0.09	1.578	2.889	0.051	0.015	0.002	0.011
South Korea	237.5	0.27	62.05	13.41	23.41	0.03	0.000	0.370	0.000	0.064	0.053	0.339
Taiwan	106.6	0.86	31.01	18.72	19.02	0.00	29.24	0.966	0.056	0.006	0.123	0.000
United States	1,245	54.11	8.57	11.33	21.80	0.70	0.467	1.869	0.074	0.007	0.164	0.899
All regions	**11,007**	**35.13**	**13.65**	**16.91**	**26.37**	**1.02**	**0.786**	**5.049**	**0.047**	**0.021**	**0.485**	**0.529**

Table S14. Aggregate (among all countries in each region) maximum instantaneous charge rates, maximum instantaneous discharge rates, maximum energy storage capacities, and hours of storage at the maximum discharge rate of the different types of electricity storage, cold storage, and heat storage technologies treated here, by region. Total hydropower values are split into baseload and peaking hydropower values, as described in Note S5. The maximum storage capacities are either of electricity, for the electricity storage options, or of thermal energy, for the hot and cold storage options.

	Africa-East				**Africa-North**				**Africa-South**			
Storage technology	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Hours storage at max discharge rate	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Hours storage at max discharge rate	Max charge rate GW	Max discharge rate GW	Max storage capacity TWh	Hours storage at max discharge rate
PHS	4.0	4.0	0.06	14.0	5.6	5.6	0.08	14.0	13.7	13.7	0.19	14.0
CSP-elec.	0.0	0.0	--	--	4.8	4.8	--	--	3.4	3.4	--	--
CSPS	0.0	--	0	0	7.8	--	0.1	22.6	5.5	--	0.1	22.6
Batteries	400	400	1.60	4.0	150	150	0.60	4.0	350	350	1.40	4.0
Hydropower	4.0	8.9	34.6	3,883	2.1	4.3	17.9	4,133	5.3	11.3	46.1	4,065
Base	3.0	3.0	25.8	8,640	1.5	1.5	13.4	8,640	4.0	4.0	34.4	8,640
Peaking	1.0	5.9	8.8	1,486	0.5	2.8	4.6	1,634	1.3	7.4	11.7	1,593
Grid H_2	5.0	5.0	0	0	20.0	20.0	0	0	30.0	30.0	0	0
CW-STES	0.21	0.21	0.003	14.0	0.74	0.74	0.010	14.0	0.94	0.94	0.013	14.0
ICE	0.31	0.31	0.004	14.0	1.12	1.12	0.016	14.0	1.40	1.40	0.020	14.0
HW-STES	71.6	89.5	0.18	2.0	24.2	26.8	0.05	2.0	42.7	47.4	0.09	2.0
UTES-heat	0.02	89.52	19.3	216.0	1.60	26.84	1.3	48.0	1.85	47.45	2.3	48.0
UTES-elec.	71.6	--	--	--	2.7	--	--	--	42.7	--	--	--
	Africa-West				**Australia**				**Canada**			
PHS	4.0	4.0	0.06	14.0	8.8	8.8	0.124	14.0	0.8	0.8	0.011	14.0
CSP-elec.	0.2	0.2	--	--	3.12	3.12	--	--	0	0	--	--
CSPS	0.4	--	0.0	22.6	5.03	--	0.070	22.6	0	--	0	0
Batteries	400	400	1.60	4.0	120	120	0.48	4.0	0	0	0	0
Hydropower	4.0	8.9	34.3	3,845	3.87	7.71	7.1	919	39.90	83.38	188.5	2,260
Base	3.0	3.0	25.6	8,640	3.66	3.66	5.3	1,440	22.00	22.00	31.7	1,440
Peaking	1.0	6.0	8.7	1,464	0.21	4.05	1.8	448	17.90	61.38	156.8	2,555
Grid H_2	40.0	40.0	0	0	10.0	10.0	0	0	0	0	0	0
CW-STES	0.38	0.38	0.005	14.0	0.143	0.143	0.0020	14.0	0.278	0.278	0.0039	14.0
ICE	0.58	0.58	0.008	14.0	0.214	0.214	0.0030	14.0	0.416	0.416	0.0058	14.0
HW-STES	48.4	48.4	0.10	2.0	0.90	9.00	0.018	2.0	2.28	22.78	0.182	8.0
UTES-heat	0.02	48.40	8.1	168.0	6.87	9.00	0.216	24.0	2.77	22.78	1.093	48.0
UTES-elec.	43.6	--	--	--	0.90	--	--	--	2.28	--	--	--
	Central America				**Central Asia**				**China region**			
PHS	6.00	6.00	0.084	14.0	12.0	12.0	0.168	14.0	160.3	160.3	2.244	14.0
CSP-elec.	1.90	1.90	--	--	0.28	0.28	--	--	46.2	46.2	--	--
CSPS	3.06	--	0.043	22.6	0.45	--	0.006	22.6	74.5	--	1.043	22.6
Batteries	180	180	0.72	4.0	90	90	0.36	4.0	1,000	1,000	4.00	4.0
Hydropower	9.47	20.58	24.8	1,204	11.13	24.64	39.9	1,618	185.2	372.6	272	729
Base	7.95	7.95	11.4	1,440	7.87	7.87	11.3	1,440	184.5	184.5	266	1,440
Peaking	1.52	12.64	13.3	1,056	3.26	16.77	28.5	1,701	0.7	188.1	6	31.4
Grid H_2	0.0	0.0	0	0	20.0	20.0	0	0	500.0	500.0	0	0
CW-STES	0.475	0.475	0.0066	14.0	0.108	0.108	0.0015	14.0	13.22	13.22	0.1851	14.0
ICE	0.71	0.71	0.0100	14.0	0.162	0.162	0.0023	14.0	19.83	19.83	0.2776	14.0
HW-STES	2.70	27.04	0.054	2.0	38.26	38.26	0.306	8.0	690.2	690.2	2.071	3.0
UTES-heat	3.75	27.04	0.649	24.0	0.0029	38.26	6.429	168.0	404.6	690.2	182.2	264.0
UTES-elec.	2.70	--	--	--	11.48	--	--	--	690.2	--	--	--
	Cuba				**Europe**				**Haiti region**			
PHS	3.00	3.00	0.042	14.0	100.4	100.4	1.41	14.0	2.00	2.00	0.028	14.0
CSP-elec.	0.012	0.012	--	--	3.81	3.81	--	--	0.011	0.011	--	--
CSPS	0.019	--	0.000	22.6	6.14	--	0.086	22.6	0.02	--	0	22.6
Batteries	48	48	0.192	4.0	15	15	0.06	4.0	0	0	0	0
Hydropower	0.034	0.072	0.089	1,238	95.20	194.4	247.6	1,274	0.337	0.705	0.88	1,249

Base	0.029	0.029	0.041	1,439	80.10	80.1	115.3	1,440	0.282	0.282	0.41	1,440
Peaking	0.006	0.043	0.048	1,105	15.10	114.3	132.3	1,157	0.054	0.423	0.47	1,122
Grid H_2	0	0	0	0	210.0	210.0	0	0	38.0	38.0	0	0
CW-STES	0.108	0.108	0.0015	14.0	5.11	5.11	0.0716	14.0	0.030	0.030	.00042	14.0
ICE	0.163	0.163	0.0023	14.0	7.67	7.67	0.1073	14.0	0.045	0.045	.00063	14.0
HW-STES	1.18	1.18	0.009	8.0	268.9	268.9	1.613	6.0	0	26	0	
UTES-heat	0	1.18	0.028	24.0	71.94	268.9	32.267	120.0	0	25.76	0.742	28.8
UTES-elec.	0.47	--	--	--	26.9	--	--	--	2.58	--	--	--
	Iceland				**India region**				**Israel**			
PHS	0	0	0	0.0	25.8	25.8	0.361	14.0	1.1	1.1	0.015	14.0
CSP-elec.	0	0	--	--	55.62	55.62	--	--	0.405	0.405	--	--
CSPS	0	--	0	0	89.7	--	1.256	22.6	0.65	--	0.009	22.6
Batteries	0	0	0	0	1,910	1,910	7.64	4.0	118	118	0.472	4.0
Hydropower	1.09	2.11	2.8	1,337	24.22	51.51	44.4	861	0.0030	0.0060	0.0021	342.5
Base	0.77	0.77	0.1	120	22.93	22.93	33.0	1,440	0.0030	0.0030	0.0021	685.0
Peaking	0.31	1.34	2.7	2,040	1.29	28.58	11.3	397	0.0000	0.0030	0.0000	0.0
Grid H_2	0	0	0	0	250.0	250.0	0	0	5.0	5.0	0	0
CW-STES	0.015	0.015	.00022	14.0	4.39	4.39	0.0615	14.0	0.064	0.064	0.0009	14.0
ICE	0.023	0.023	.00032	14.0	6.59	6.59	0.0922	14.0	0.096	0.096	0.0013	14.0
HW-STES	0.10	0.97	0.0019	2.0	339.9	339.9	2.719	8.0	3.20	3.20	0.026	8.0
UTES-heat	0	0	0	0	11.84	339.9	195.79	576.0	3.53	3.20	1.920	600.0
UTES-elec.	0	--	--	--	339.9	--	--	--	2.24	--	--	--
	Jamaica				**Japan**				**Madagascar**			
PHS	0.10	0.10	0.001	14.0	76.3	76.3	1.07	14.0	0.40	0.40	0.006	14.0
CSP-elec.	0.0004	0.0004	--	--	0	0	--	--	0	0.0060	--	--
CSPS	0.0006	--	.000008	20.0	0	--	0	0	0	--	.00014	22.7
Batteries	16	16	0.0640	4.0	200	200	0.80	4.0	15	15	0.06	4.0
Hydropower	0.013	0.03	0.0337	1,122	14.24	28.21	26.1	924	0.082	0.16	0.71	4,349
Base	0.011	0.01	0.0155	1,439	13.48	13.48	19.4	1,440	0.062	0.062	0.53	8,634
Peaking	0.002	0.02	0.0181	944	0.76	14.73	6.7	453	0.021	0.102	0.18	1,772
Grid H_2	0	0	0	0	40.0	40.0	0	0	1.90	1.90	0	0
CW-STES	0	0	0		0.128	0.128	0.0018	14.0	0.052	0.052	0.0007	14.0
ICE	0	0	0		0.192	0.192	0.0027	14.0	0.078	0.078	0.0011	14.0
HW-STES	0.81	1.02	0.0061	6.0	2.10	21.01	0.042	2.0	0.25	2.47	0.005	2.0
UTES-heat	0	1.02	0.0733	72.0	4.97	21.01	2.521	120.0	0.00	2.47	0.059	24.0
UTES-elec.	0.10	--	--	--	4.20	--	--	--	0.25	--	--	--
	Mauritius				**Mideast**				**New Zealand**			
PHS	0.10	0.10	0.0014	14.0	4.5	4.5	0.063	14.0	2.0	2.0	0.028	14.0
CSP-elec.	0.001	0.001	--	--	11.53	11.53	--	--	0.01	0.01	--	--
CSPS	0.002	--	0	22.7	18.59	--	0.260	22.6	0.01	--	0.000	22.4
Batteries	4.0	4.0	0.016	4.0	850	850	3.40	4.0	0.29	0.29	0.0012	4.0
Hydropower	0.031	0.061	0.057	931	22.01	48.58	14.9	307.6	2.67	5.43	4.9	900
Base	0.029	0.029	0.042	1,438	22.01	22.01	14.9	679.0	2.53	2.53	3.6	1,440
Peaking	0.002	0.032	0.015	460	0.00	26.57	0.0	0.0	0.14	2.91	1.3	430
Grid H_2	2.2	2.2	0	0	80.0	80.0	0	0	1.4	1.4	0	0
CW-STES	0.024	0.024	.00034	14.0	1.12	1.12	0.0157	14.0	0.0038	0.0038	.00005	13.9
ICE	0.037	0.037	.00051	14.0	1.68	1.68	0.0235	14.0	0.01	0.01	0.0001	14.0
HW-STES	0.191	1.913	0.0038	2.0	70.20	78.00	0.156	2.0	0.09	0.94	0.002	2.0
UTES-heat	0.093	1.913	0.0918	48.0	23.60	78.00	56.159	720.0	0.63	0.94	0.022	24.0
UTES-elec.	0.191	--	--	--	78.0	--	--	--	0.09	--	--	--
	Philippines				**Russia region**				**South America-NW**			
PHS	2.6	2.6	0.036	14.0	10.7	10.7	0.150	14.0	8.0	8.0	0.112	14.0
CSP-elec.	0.04	0.04	--	--	0	0	--	--	0.12	0.12	--	--
CSPS	0.07	--	0.001	22.6	0	--	0	0	0.20	--	0.003	22.6
Batteries	60	60	0.240	4.0	0	0	0	0	50	50	0.200	4.0
Hydropower	1.45	3.04	2.7	873	26.22	54.48	93.9	1,724	18.65	41.00	48.8	1,190
Base	1.37	1.37	2.0	1,440	18.55	18.55	26.7	1,440	15.65	15.65	22.5	1,440
Peaking	0.08	1.67	0.7	407	7.67	35.93	67.2	1,870	3.00	25.35	26.3	1,036
Grid H_2	30.0	30.0	0	0	0	0	0	0	0	0	0	0
CW-STES	0.64	0.64	0.0089	14.0	1.37	1.37	0.0191	14.0	0.60	0.60	0.0084	14.0
ICE	0.95	0.95	0.0134	14.0	2.05	2.05	0.0287	14.0	0.90	0.90	0.0126	14.0
HW-STES	11.28	28.20	0.226	8.0	94.35	94.35	0.943	10.0	7.41	18.53	0.148	8.0

UTES-heat	0	28.20	1.353	2.0	0.52	94.35	15.85	168.0	0.03	18.53	0.445	24.0
UTES-elec.	5.64	--	--	--	9.43	--	--	--	1.85	--	--	--
	South America-SE				**Southeast Asia**				**South Korea**			
PHS	11.4	11.4	0.160	14.0	2.0	2.0	0.027	14.0	16.5	16.5	0.23	14.0
CSP-elec.	0.19	0.19	--	--	0.93	0.93	--	--	0.14	0.14	--	--
CSPS	0.30	--	0.004	22.6	1.49	--	0.021	22.6	0.22	--	0.003	22.6
Batteries	300	300	1.200	4.0	1,100	1,100	4.40	4.0	260	260	1.04	4.0
Hydropower	66.82	137.84	174.9	1,269	23.01	51.99	42.1	811	0.93	1.81	1.695	935
Base	56.08	56.08	80.7	1,440	21.78	21.78	31.4	1,440	0.88	0.88	1.261	1,440
Peaking	10.75	81.76	94.1	1,151	1.23	30.21	10.8	357	0.05	0.94	0.433	463
Grid H_2	0	0	0	0	90.0	90.0	0	0	100.0	100.0	0	0
CW-STES	1.96	1.96	0.0275	14.0	3.26	3.26	0.0456	14.0	0.193	0.193	0.0027	14.0
ICE	2.94	2.94	0.0412	14.0	4.88	4.88	0.0684	14.0	0.289	0.289	0.0040	14.0
HW-STES	4.21	42.11	0.337	8.0	139.5	155.0	0.310	2.0	22.22	22.22	0.044	2.0
UTES-heat	14.24	42.11	1.011	24.0	0.264	155.0	7.440	48.0	2.84	22.22	1.600	72.0
UTES-elec.	4.21	--	--	--	62.0	--	--	--	8.89	--	--	--
	Taiwan				**United States**				**All Regions**			
PHS	9.1	9.1	0.127	14.0	67.5	67.5	0.95	14.0	559	559	7.82	14.0
CSP-elec.	0	0	--	--	10.11	10.11	--	--	143	143	--	--
CSPS	0	--	0	0	16.30	--	0.228	22.6	230	--	3.23	22.6
Batteries	290	290	1.16	4.0	1,500	1,500	6.00	4.0	9,426	9,426	37.71	4.0
Hydropower	1.08	2.09	1.973	942	41.52	83.85	196.1	2,339	604	1,250	1,569	1,256
Base	1.02	1.02	1.469	1,440	22.89	22.89	33.0	1,440	518	518	811	1,566
Peaking	0.06	1.07	0.505	470	18.63	60.96	163.2	2,676	87	732	758	1,036
Grid H_2	26.0	26.0	0	0	130.0	130.0	0	0	1,630	1,630	0	0
CW-STES	0.49	0.49	0.0069	14.0	3.48	3.48	0.0488	14.0	40	40	0.55	14.0
ICE	0.73	0.73	0.0103	14.0	5.23	5.23	0.0732	14.0	59	59	0.83	14.0
HW-STES	8.00	26.67	0.053	2.0	174.7	174.7	0.349	2.0	2,070	2,307	10.05	4.4
UTES-heat	1.27	26.67	1.280	48.0	38.90	174.7	16.77	96.0	596	2,306	557.1	241.6
UTES-elec.	5.33	--	--	--	157.2	--	--	--	1,578	--	--	--

PHS=pumped hydropower storage; CSP=concentrated solar power; PCM=Phase-change materials; 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 in soil. The maximum storage capacity equals the maximum discharge rate multiplied by the number of hours of storage at that rate.

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

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

Hydropower's maximum discharge rate (GW) in 2050 is its 2022 nameplate capacity, and its annual energy output (TWh/y) in 2050 is close to that in 2022 in every region. Water released from a dam during hydropower production is replenished naturally with rainfall and runoff. Hydropower reservoirs contain water for energy and non-energy purposes. About 50-60% of the water in a reservoir is generally used for energy (IEA, 2021). The hydropower storage capacity available for energy in all reservoirs worldwide is estimated as ~1,470 TWh, broken down as follows: North America: 370 TWh; China: 250 TWh; Latin America: 245 TWh; Europe: 215 TWh; Eurasia: 130 TWh; Africa: 125 TWh; Asia Pacific: 120 TWh; Middle East: 15 TWh (IEA, 2021-Figure 4.8). The maximum hydropower storage capacity (TWh) in each country here is estimated by multiplying these regional storage capacities by the ratio of the 2022 estimated hydroelectric energy output of the country to that of the region the country falls in. The maximum storage capacity in each region is then calculated simply by summing the maximum storage capacities among all countries in the region. The maximum storage capacity and the total nameplate capacity of hydropower generators in each region are then distributed between baseload and peaking power uses by solving a set of six equations and six unknowns: (1) the sum of the maximum energy storage capacities (TWh) for baseload and peaking power equals the total maximum energy storage capacity of all reservoirs in each region, as just determined; (2) the sum of the instantaneous average charge rates (TW) of power for baseload and peaking power equals the total average charge rate of the reservoir, which equals the annual average hydropower power output (TW) of the reservoir in 2022 (which equals the 2022 energy output in TWh/y divided by 8,760 hours per year); (3) the sum of the maximum discharge rates (TW) for each baseload and peaking power equals the total nameplate capacity of all hydropower generators in the region; (4) the maximum discharge rate (TW) of baseload power from generators equals the instantaneous average charge rate of baseload power; (5) the maximum energy storage capacity (TWh) for peaking power equals the instantaneous average charge rate of peaking power (TW) multiplied by 8,760 hours per year (in other words, the peaking portion of the reservoir must be filled once per year); and (6) the maximum energy storage capacity (TWh) for baseload power equals the instantaneous average charge rate of baseload power (TW0 multiplied by a designated number of hours of storage of baseload energy. Since the maximum discharge rate of baseload hydropower is assumed to equal its instantaneous average charge rate, there should be no need for baseload storage. However, in reality, discharged water for baseload power is not replenished immediately. As such, sufficient storage capacity is assigned to baseload hydropower so that, if full, baseload can supply 60 days (1,440 hours) straight of hydroelectricity without any replenishment. For Iceland and South America, 5 and 15 days, respectively, are assumed instead of 60 days. In sum, whereas baseload power is produced and discharged continuously in the model every 30 s, peaking power is also produced every 30 s but discharged only when needed due to a lack of other WWS resources available. Whereas the present table gives hydropower's maximum energy storage capacity available for each baseload and storage, hydropower's output from baseload or peaking storage during a time step is limited by the smallest among three factors: the actual energy currently available in storage for baseload or peaking, the maximum hydro discharge rate for peaking or baseload multiplied by the time step, and (in the case of peaking) the energy needed during the time step to keep the grid stable. In addition, energy in the peaking portion of reservoirs is limited by the maximum storage capacity in that portion. Thus, if peaking energy is not used fast enough, it cannot accumulate due to rainfall and runoff to more than the maximum capacity.

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

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

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

Grid H_2. The storage capacity and storage duration of green hydrogen storage (GHS) for grid electricity storage are set to zero in this table, but the peak charge and discharge rates are not. That is because hydrogen production and storage for grid and non-grid purposes are merged in this study. In such a case, the storage time depends on the discharge rate of both grid and non-grid hydrogen. Table S17 provides the storage time of grid hydrogen as if it is the only hydrogen stored and discharged and the storage time of non-grid hydrogen as if it is the only hydrogen stored and discharged.

Table S15. (a) HVDC line length needed in each region; (b) HVDC line capacity needed in each region; (c) fraction of non-roof PV and non-curtailed energy that is subject to HVDC transmission in each region; and (d) the fraction of building heating and cooling demand that is subject to district heating and cooling.

Region	(a) HVDC line length (km)	(b) HVDC line capacity (MW)	(c) Fraction of non-roof PV/non-curtailed electricity subject to HVDC	(d) Fraction of building heating/ cooling subject to district heating/ cooling
Africa-East	2,565	27,422	0.3	0.1
Africa-North	2,738	55,510	0.3	0.1
Africa-South	3,041	53,693	0.3	0.1
Africa-West	2,360	44,873	0.3	0.1
Australia	3,096	43,305	0.3	0.1
Canada	3,320	90,115	0.3	0.2
Central America	3,014	40,753	0.2	0.1
Central Asia	2,642	62,459	0.3	0.01
China region	3,177	1,423,304	0.3	0.3
Cuba	0	0	0	0.2
Europe	2,922	496,246	0.3	0.5
Haiti region	0	0	0	0.05
Iceland	0	0	0	0.92
India region	3,278	452,027	0.3	0.1
Israel	0	0	0	0.2
Jamaica	0	0	0	0
Japan	3,118	74,096	0.2	0.1
Madagascar	0	0	0	0.1
Mauritius	0	0	0	0.2
Mideast	3,081	342,506	0.3	0.05
New Zealand	1,870	4,387	0.15	0.05
Philippines	2,248	10,432	0.2	0.2
Russia region	2,925	164,129	0.3	0.5
South Am-NW	3,329	44,147	0.3	0.1
South Am-SE	3,155	154,535	0.3	0.1
Southeast Asia	2,792	247,857	0.3	0.1
South Korea	0	0	0	0.15
Taiwan	0	0	0	0.15
United States	2,732	503,467	0.3	0.2

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

Table S16. (a) Battery maximum charge and discharge rate (nameplate capacity); (b) battery storage capacity (batteries are all 4-hour batteries); (c) battery full charge and discharge cycles per year; (d) maximum battery discharge rate actually occurring during any time interval of each simulation; and (e) R_{ideal}, the number of hours of battery storage actually needed for each simulation, which equals the ratio of the battery storage capacity to the peak actual discharge rate during a simulation. The battery peak discharge rate during a simulation is always less than or equal to the battery nameplate capacity (maximum possible discharge rate) from column (a).

Region	(a) Battery max charge and dis-charge rate (GW)	(b) Battery capacity (TWh)	(c) Battery full cycles/year	(d) Battery peak actual discharge rate during simulation (TW)	(e) R_{ideal}=Ratio of battery storage capacity (TWh) to battery peak actual discharge rate (TW) during simulation (hours) = b / d
Africa-East	400	1.6	46	0.162	9.9
Africa-North	150	0.6	143	0.121	4.9
Africa-South	350	1.4	80	0.096	14.6
Africa-West	400	1.6	52	0.157	10.2
Australia	120	0.48	121	0.065	7.3
Canada	0	0	0	0	0
Central America	180	0.72	251	0.096	7.5
Central Asia	90	0.36	156	0.09	4.0
China region	1,000	4	252	1	4.0
Cuba	48	0.192	87	0.008	23.6
Europe	15	0.06	247	0.015	4.0
Haiti region	0	0	0	0	0
Iceland	0	0	0	0	0
India region	1,910	7.64	269	0.858	8.9
Israel	118	0.472	72	0.015	32.4
Jamaica	16.0	0.064	61	0.004	14.9
Japan	200	0.8	84	0.117	6.8
Madagascar	15	0.06	72	0.005	13.3
Mauritius	4.0	0.016	77	0.002	7.3
Mideast	850	3.4	195	0.406	8.4
New Zealand	0.3	0.0012	72	0	4.0
Philippines	60	0.24	206	0.054	4.4
Russia region	0	0	0	0	0
South Am-NW	50	0.2	317	0.05	4.0
South Am-SE	300	1.2	277	0.258	4.7
Southeast Asia	1,100	4.4	229	0.454	9.7
South Korea	260	1.04	91	0.146	7.1
Taiwan	290	1.16	68	0.074	15.8
United States	1,500	6	82	0.662	9.1
All regions	**9,426**	**37.71**		**4.915**	**7.7**

Table S17. (a) Annual hydrogen production for non-grid purposes; (b) annual hydrogen production for grid purposes; (c) electrolyzer plus compressor nameplate capacity (electrolyzers make up 88.03% of the total); (d) electrolyzer and compressor use factor, averaged over simulation; (e) storage time of hydrogen in communal storage tank if non-grid hydrogen is the only hydrogen stored and discharged (at the same rate as non-grid hydrogen production) in the storage tank; (f) size of communal hydrogen storage tank; (g) nameplate capacity of fuel cells used for producing grid electricity; (h) fuel cell use factor; (i) hours of electricity storage in the communal hydrogen storage tank as if grid hydrogen is the only hydrogen stored and discharge (at the peak discharge rate of the fuel cells); and (j) usable (non-waste) electricity storage capacity in the communal hydrogen storage tank if hydrogen were used only for electricity.

	Non-grid plus grid hydrogen						Grid hydrogen			
Region	(a) Non-grid H_2 produced (Tg-H_2/y)	(b) Grid H_2 produced (Tg-H_2/y)	(c) Electrolyzer plus compressor nameplate capacity (GW)	(d) Use factor of electrolyzer and compressor (frac)	(e) Grid plus non-grid H_2 storage times (days) = 365 days * f/a	(f) H_2 tank size (Tg)	(g) Fuel cell for grid electricity nameplate capacity (GW)	(h) Use factor of fuel cell (frac)	(i) Hours of electricity storage in H_2 tank if H_2 used only for electricity= j*1000/g	(j) Electricity storage capacity in H_2 tank if H_2 used only for electricity (TWh)
Africa-East	0.763	0	27.4	0.15	4	0.0084	5	0	35	0.18
Africa-North	4.388	0.12	157.3	0.15	6	0.0721	20	0.014	76	1.52
Africa-South	1.565	0.032	56.1	0.15	15	0.0643	30	0.003	45	1.36
Africa-West	1.029	0.014	40.0	0.14	11	0.0310	40	0.001	16	0.66
Australia	1.690	0.028	60.56	0.15	12	0.0556	10	0.007	117	1.17
Canada	2.438	0	13.11	1.00	0	0	0	0	0	0
Central America	1.842	0	66.02	0.15	23	0.1161	0	0	0	2.45
Central Asia	2.336	0.23	83.75	0.16	6	0.0384	20	0.027	41	0.81
China region	66.71	20.63	2,391	0.20	24	4.3863	500	0.099	185	92.6
Cuba	0.052	0	1.86	0.15	1	0.0001	0	0	0	0.003
Europe	20.78	15.12	744.9	0.26	29	1.6512	210	0.173	166	34.9
Haiti region	0.117	0.11	27.00	0.04	110	0.0352	38	0.007	20	0.74
Iceland	0.012	0	0.07	1.00	0	0	0	0	0	0
India region	17.20	0.46	616.4	0.15	55	2.5911	250	0.004	219	54.7
Israel	0.127	0.0020	5.00	0.14	32	0.0111	5	0.001	47	0.24
Jamaica	0.047	0	1.70	0.15	16	0.0021	0	0	0	0.044
Japan	5.336	0.28	191.3	0.16	30	0.4386	40	0.017	232	9.26
Madagascar	0.026	0.0019	1.9	0.08	63	0.0044	2	0.002	49	0.093
Mauritius	0.052	0.0033	2.20	0.13	30	0.0043	2	0.004	41	0.09
Mideast region	13.16	0.16	471.7	0.15	10	0.3606	80	0.005	95	7.61
New Zealand	0.221	0.032	7.90	0.17	2	0.0012	1	0.055	18	0.026
Philippines	0.585	0.066	30.00	0.12	11	0.0176	30	0.005	12	0.37
Russia	8.656	0	210.4	0.22	7.2	0.1707	0	0	0	3.61
South Am-NW	2.245	0	80.5	0.15	1	0.0062	0	0	0	0.13
South Am-SE	5.869	0	210.4	0.15	10	0.1608	0	0	0	3.40
Southeast Asia	10.76	0.42	385.8	0.16	66	1.9464	90	0.011	457	41.11
South Korea	4.070	0.72	145.9	0.18	37	0.4126	100	0.017	87	8.71
Taiwan	1.437	0.11	51.50	0.16	99	0.3897	26	0.011	317	8.23
United States	12.55	0.33	449.8	0.15	35	1.2034	130	0.006	195	25.4
All regions	**186.06**	**38.87**	**6,531**	**0.185**		**14.179**	**1,630**	**0.057**	**184**	**299.5**

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

Table S18. Budget of simulation-averaged end-use power demand met, energy lost, WWS energy supplied, and changes in storage, during the three-year (26,291.4875 hour) simulations for each region and summed for all regions. All units are GW averaged over the simulation and are derived from the data in Table S19 by dividing values from that table in units of TWh per simulation by the number of hours of simulation. TD&M losses are transmission, distribution, and maintenance losses. Wind turbine array losses are already accounted for in the "WWS supply before losses" numbers," since wind supply values come from GATOR-GCMOM, which accounts for such losses.

Region	(a) Annual-average end-use demand (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Curtail-ment losses (GW)	**(e) End-use demand+ losses =a+b+c+d (GW)**	(f) WWS supply before losses (GW)	(g) Changes in storage (GW)	**(h) Supply +changes in storage =f+g (GW)**
Africa-East	64.18	5.57	4.78	21.72	**96.3**	95.6	0.675	**96.3**
Africa-North	153.07	11.76	2.35	46.43	**213.6**	213.6	0.047	**213.6**
Africa-South	118.48	8.86	3.19	18.32	**148.9**	148.8	0.040	**148.9**
Africa-West	110.72	10.29	7.62	50.88	**179.5**	179.2	0.279	**179.5**
Australia	88.89	6.91	1.03	12.84	**109.7**	109.7	-0.002	**109.7**
Canada	160.09	12.51	0.60	11.02	**184.2**	184.2	0.044	**184.2**
Central America	127.31	10.00	2.75	21.27	**161.3**	161.3	0.000	**161.3**
Central Asia	143.32	12.38	3.31	48.41	**207.4**	207.2	0.204	**207.4**
China region	2,542.8	203.76	112.02	206.56	**3,065.1**	3,057.8	7.307	**3,065.1**
Cuba	6.69	0.49	0.27	1.97	**9.41**	9.4	0.003	**9.41**
Europe	876.48	76.45	58.20	136.43	**1,147.6**	1,146	1.597	**1,147.6**
Haiti region	6.80	1.01	0.55	6.92	**15.27**	15.28	-0.009	**15.27**
Iceland	2.67	0.27	0.00	0.68	**3.62**	3.62	0.000	**3.62**
India region	967.2	67.68	43.45	55.35	**1,133.7**	1,127.2	6.549	**1,133.7**
Israel	12.42	1.38	0.67	7.17	**21.64**	21.56	0.081	**21.64**
Jamaica	1.73	0.13	0.06	0.56	**2.48**	2.47	0.002	**2.48**
Japan	175.68	15.75	2.29	21.55	**215.27**	215.25	0.018	**215.27**
Madagascar	3.39	0.41	0.12	2.55	**6.48**	6.47	0.002	**6.48**
Mauritius	1.57	0.15	0.05	0.35	**2.12**	2.11	0.005	**2.12**
Mideast	647.52	52.06	17.31	87.90	**804.8**	802.7	2.051	**804.8**
New Zealand	14.81	2.14	0.15	13.15	**30.25**	30.2	0.002	**30.25**
Philippines	34.68	3.64	1.76	18.86	**58.94**	58.9	-0.001	**58.94**
Russia region	262.73	24.49	8.62	47.16	**343.00**	343.1	-0.112	**343.00**
South Am-NW	81.73	6.14	1.73	4.18	**93.78**	93.8	0.000	**93.78**
South Am-SE	344.83	24.47	5.38	42.85	**417.53**	417.4	0.095	**417.53**
Southeast Asia	560.26	45.36	20.13	140.75	**766.49**	766.6	-0.155	**766.49**
South Korea	141.98	15.90	5.00	74.60	**237.48**	237.5	-0.035	**237.48**
Taiwan	85.20	6.79	2.32	12.31	**106.62**	106.6	-0.008	**106.62**
United States	890.21	84.81	19.68	249.84	**1,244.5**	1,244.9	-0.307	**1,244.5**
All regions	8,627.4	711.6	325.4	1,362.6	**11,027**	11,009	18.373	**11,027**

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

	Africa-East	**Africa-North**	**Africa-South**	**Africa-East**	**Australia**
A1. Total end use demand	**1,687**	**4,024**	**3,115**	**2,911**	**2,337**
Electricity for electricity inflexible demand	780	2,020	1,732	1,388	1,263
Electricity for electricity, heat, cold storage + DR	800	1,384	1,161	1,378	835
Electricity for H_2 direct use + H_2 storage	108	620	221	145	239
A2. Total end use demand	**1,687**	**4,024**	**3,115**	**2,911**	**2,337**
Electricity for direct use, electricity storage, + H_2	1,439	3,931	2,993	2,528	2,310
Low-T heat demand met by heat storage	245	81	108	372	26
Cold demand met by cold storage	4.13	11.66	13.87	10.57	1.60
A3. Total end use demand	**1,687**	**4,024**	**3,115**	**2,911**	**2,337**
Electricity for direct use, electricity storage, DR	1,317	3,173	2,705	2,293	2,015
Electricity for H_2 direct use + H_2 storage	108	620	221	145	239
Electricity + heat for heat subject to storage	249	182	128	447	73
Electricity for cold demand subject to storage	13.76	48.88	61.55	25.27	9.37
B. Total losses	**843**	**1,592**	**799**	**1,808**	**546**
Transmission, distribution, downtime losses	147	309	233	270	182
Losses CSP storage	0.00	0.44	0.37	0.02	0
Losses PHS storage	0.00	0.50	0.18	0.02	0.2478
Losses battery storage	25	29	37	28	19.3
Losses grid H_2 storage	0	9	3	1	2
Losses CW-STES + ICE storage	1	2	3	2	0.3
Losses HW-STES storage	30	14	14	42	1.5
Losses UTES storage	70	7	27	127	3.4
Losses from curtailment	571	1,221	482	1,338	337
Net end-use demand plus losses (A1 + B)	***2,531***	***5,616***	***3,914***	***4,719***	***2,883***
C. Total WWS supply before T&D losses	**2,513**	**5,615**	**3,913**	**4,712**	**2,883**
Onshore + offshore wind electricity	774	2,525	2,017	2,272	1,565
Rooftop + utility PV+ CSP electricity	1,581	3,038	1,779	2,358	1,186
Hydropower electricity	78.6	41.7	104.9	78.0	96.9
Wave electricity	0.57	1.62	2.83	3.05	2.41
Geothermal electricity	78.2406	0.0227	1.9754	0	9.5047
Tidal electricity	0.5315	0.793	0.6054	0.6395	2.416
Solar heat	0	4.646	5.8112	0.0579	19.6642
Geothermal heat	0.2942	2.4231	0.0327	0.01	1.3416
D. Net taken from (+) or added to (-) storage	**17.7508**	**1.2399**	**1.043**	**7.3376**	**-0.0419**
CSP storage	0	0.0764	0.0128	0.001	0.0117
PHS storage	-0.0056	-0.0079	-0.0192	-0.0056	-0.0309
Battery storage	0.104	0.0906	0.6933	0.0358	0.0307
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0066	-0.002	0.0295	0.0116	0.0037
HW-STES storage	0.1611	0.0483	-0.0033	0.0871	-0.0008
UTES storage	17.1622	1.1593	-0.2278	7.3178	-0.0526
Non-grid H_2 storage	0.3224	-0.1248	0.5576	-0.1102	-0.0037
Energy supplied plus taken from storage (C+D)	***2,531***	***5,616***	***3,914***	***4,719***	***2,883***

	Canada	Central America	Central Asia	China region	Cuba
A1. Total end use demand	**4,209**	**3,347**	**3,768**	**66,853**	**176**
Electricity for electricity inflexible demand	2,338	1,727	2,061	32,806	95
Electricity for electricity, heat, cold storage + DR	1,527	1,360	1,376	24,617	74
Electricity for H_2 direct use + H_2 storage	345	260	330	9,430	7
A2. Total end use demand	**4,209**	**3,347**	**3,768**	**66,853**	**176**
Electricity for direct use, electricity storage, + H_2	4,150	3,306	3,595	63,594	170
Low-T heat demand met by heat storage	57	35	171	3,165	5
Cold demand met by cold storage	2.10	6.81	1.91	93.38	1.39
A3. Total end use demand	**4,209**	**3,347**	**3,768**	**66,853**	**176**
Electricity for direct use, electricity storage, DR	3,603	2,928	3,238	51,791	152
Electricity for H_2 direct use + H_2 storage	345	260	330	9,430	7
Electricity + heat for heat subject to storage	243	128	192	4,763	9
Electricity for cold demand subject to storage	18.25	31.22	7.10	868.97	7.12
B. Total losses	**634**	**894**	**1,685**	**13,733**	**72**
Transmission, distribution, downtime losses	329	263	325	5,357	13
Losses CSP storage	0.00	0.25	0.02	4.93	0.00
Losses PHS storage	1.1243	0.6273	0.9526	16.5583	0.0015
Losses battery storage	0.00	60.1	18.6	335	5.56
Losses grid H_2 storage	0	0	18	1,612	0
Losses CW-STES + ICE storage	0.38	1.2	0.3	17	0.25
Losses HW-STES storage	4	3.1	29.3	237	0.85
Losses UTES storage	11	7.0	20.1	722	0.54
Losses from curtailment	290	559	1,273	5,431	52
Net end-use demand plus losses (A1 + B)	***4,844***	***4,242***	***5,453***	***80,586***	***247***
C. Total WWS supply before T&D losses	**79,363**	**423**	**32,015.2**	**282**	**108**
Onshore + offshore wind electricity	34,193	234	19,999.8	78	15
Rooftop + utility PV+ CSP electricity	39,204	187	9,282.0	180	0
Hydropower electricity	4,327.5	0.8	2,054.7	8.1	37.2
Wave electricity	31.78	0.51	25.74	0.00	0.08
Geothermal electricity	43.8315	0	72.13	15.6697	21.6528
Tidal electricity	13.888	0.287	34.819	0.298	0.250
Solar heat	971.8804	0	96.332	0	0
Geothermal heat	577.4566	0	449.6054	0	33.7242
D. Net taken from (+) or added to (-) storage	**107.545**	**-0.2803**	**-13.5685**	**-0.0495**	**-0.0016**
CSP storage	1.4155	-0.0011	-0.0365	-0.0008	0
PHS storage	-0.1767	-0.0042	-0.2913	-0.0028	0
Battery storage	1.8185	-0.038	-0.36	-0.0088	0
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	-0.0275	-0.0004	-0.0159	-0.0001	-0.0003
HW-STES storage	2.512	-0.0013	-0.1867	0	-0.0042
UTES storage	104.5645	-0.2084	-3.7333	-0.0188	0
Non-grid H_2 storage	-2.5613	-0.0269	-8.9448	-0.0181	0.0029
Energy supplied plus taken from storage (C+D)	***79,471***	***422***	***32,001.6***	***281.7***	***108.1***

	Europe	Haiti region	Iceland	India region	Israel
A1. Total end use demand	**23,043.9**	**179**	**70**	**25,430**	**326**
Electricity for electricity inflexible demand	11,940.8	90	27	12,194	183
Electricity for electricity, heat, cold storage + DR	8,165.4	72	42	10,805	126
Electricity for H_2 direct use + H_2 storage	2,937.7	16	2	2,431	18

A2. Total end use demand	**23,043.9**	**179**	**70**	**25,430**	**326**
Electricity for direct use, electricity storage, + H_2	21,396.3	170	57	24,478	307
Low-T heat demand met by heat storage	1,601.3	7	13	919	18
Cold demand met by cold storage	46.35	1.12	0.00	32.61	0.67
A3. Total end use demand	**23,043.9**	**179**	**70**	**25,430**	**326**
Electricity for direct use, electricity storage, DR	16,609.3	153	55	21,752	284
Electricity for H_2 direct use + H_2 storage	2,937.7	16	2	2,431	18
Electricity + heat for heat subject to storage	3,160.9	8	13	959	20
Electricity for cold demand subject to storage	335.97	1.97	0.00	288.56	4.21
B. Total losses	**7,127**	**223**	**25**	**4,377**	**242**
Transmission, distribution, downtime losses	2,009.92	26	7	1,780	36
Losses CSP storage	0.2419	0.00	0.00	8.05	0.05
Losses PHS storage	37	0.0064	0.0000	0.5392	0.01
Losses battery storage	5	0.0	0.00	683	11
Losses grid H_2 storage	1,182	8	0	36	0
Losses CW-STES + ICE storage	8	0.2	0.00	5.88	0.12
Losses HW-STES storage	204	0.0	0.00	91.39	1
Losses UTES storage	94	5.9	0.00	317.40	4
Losses from curtailment	3,586.9	181.8	17.9	1,455	188
Net end-use demand plus losses (A1 + B)	***30,170.8***	***401.4***	***95.3***	***29,807***	***569***
C. Total WWS supply before T&D losses	**30,128.9**	**402**	**95**	**29,635**	**567**
Onshore + offshore wind electricity	15,493.0	251	9	8,540	82
Rooftop + utility PV+ CSP electricity	11,770.9	127	0	20,424	472
Hydropower electricity	2,212.6	7.4	31.0	605.9	0
Wave electricity	13.26	0.00	0.00	15.82	0
Geothermal electricity	72.27	15.6697	21.6528	6.31	0
Tidal electricity	9.707	0.168	0.026	5.36	0.057
Solar heat	107.4171	0	0	33	11.6355
Geothermal heat	449.6054	0	33.7242	5	1.171
D. Net taken from (+) or added to (-) storage	**41.9918**	**-0.2428**	**-0.0012**	**172.1841**	**2.1351**
CSP storage	-0.0034	0	0	0.5596	0.0082
PHS storage	1.2652	-0.0028	0	-0.018	-0.0015
Battery storage	-0.006	0	0	3.7416	0.339
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.161	-0.0001	-0.0003	0.0709	0.001
HW-STES storage	1.452	0	-0.001	3	0.023
UTES storage	29.0407	-0.0742	0	78.551	1.5446
Non-grid H_2 storage	10.0822	-0.1657	0	86.6956	0.2209
Energy supplied plus taken from storage (C+D)	***30,170.8***	***401.4***	***95.3***	***29,807***	***569***

	Jamaica	**Japan**	**Madagascar**	**Mauritius**	**Mideast**
A1. Total end use demand	**45**	**4,619**	**89**	**41**	**17,024**
Electricity for electricity inflexible demand	20	2,668	55	16	8,497
Electricity for electricity, heat, cold storage + DR	19	1,197	31	18	6,667
Electricity for H_2 direct use + H_2 storage	7	754	4	7	1,860
A2. Total end use demand	**45**	**4,619**	**89**	**41**	**17,024**
Electricity for direct use, electricity storage, + H_2	45	4,558	84	39	16,531
Low-T heat demand met by heat storage	1	60	4	2	479
Cold demand met by cold storage	0.00	0.79	1.09	0.50	13.65
A3. Total end use demand	**45**	**4,619**	**89**	**41**	**17,024**
Electricity for direct use, electricity storage, DR	38	3,673	75	30	14,527

Electricity for H_2 direct use + H_2 storage	7	754	4	7	1,860
Electricity + heat for heat subject to storage	1	183	7	2	563
Electricity for cold demand subject to storage	0.00	8.40	3.44	1.60	73.64
B. Total losses	**20**	**1,041**	**81**	**14**	**4,135**
Transmission, distribution, downtime losses	3	414	11	4	1,369
Losses CSP storage	0.00	0.00	0.00	0.00	1.46
Losses PHS storage	0.00	1.49	0.00	0.00	0.13
Losses battery storage	1	22	1	0	220
Losses grid H_2 storage	0	22	0	0	13
Losses CW-STES + ICE storage	0.00	0.14	0.20	0.09	2.46
Losses HW-STES storage	0	2	0	0	29
Losses UTES storage	0	12	1	0	189
Losses from curtailment	15	567	67	9	2,311
Net end-use demand plus losses (A1 + B)	***65***	***5,660***	***170***	***56***	***21,159***
C. Total WWS supply before T&D losses	**65**	**5,659**	**170**	**56**	**21,105**
Onshore + offshore wind electricity	18	3,446	77	33	9,719
Rooftop + utility PV+ CSP electricity	47	1,771	91	22	10,652
Hydropower electricity	0	355	2	1	579
Wave electricity	0	5	0	0	1
Geothermal electricity	0	34.8924	0	0	38.1951
Tidal electricity	0.048	4.585	0.094	0.043	1.617
Solar heat	0	5.8595	0	0.2843	62.2202
Geothermal heat	0	36.5304	0.04	0	53.6542
D. Net taken from (+) or added to (-) storage	**0.0491**	**0.4751**	**0.0422**	**0.1346**	**53.9296**
CSP storage	0	0	0	0	0.2
PHS storage	-0.0001	-0.1069	-0.0003	-0.0001	-0.0063
Battery storage	-0.0061	-0.0776	0.0417	0.0125	0.6495
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0	-0.0003	0.0016	0.0008	0.0002
HW-STES storage	-0.0006	0.0378	0.0009	0.0034	0.1404
UTES storage	0.0283	2.2689	-0.0059	0.0299	49.8579
Non-grid H_2 storage	0.0277	-1.6467	0.0041	0.0882	3.0879
Energy supplied plus taken from storage (C+D)	***65***	***5,660***	***170***	***56***	***21,159***

	New Zealand	**Philip-pines**	**Russia region**	**South Am-NW**	**South Am-SE**
A1. Total end use demand	**389**	**912**	**6,907**	**2,149**	**9,066**
Electricity for electricity inflexible demand	213	443	2,908	1,042	4,632
Electricity for electricity, heat, cold storage + DR	145	386	2,776	790	3,604
Electricity for H_2 direct use + H_2 storage	31	83	1,224	317	830
A2. Total end use demand	**389**	**912**	**6,907**	**2,149**	**9,066**
Electricity for direct use, electricity storage, + H_2	381	823	5,844	2,082	8,947
Low-T heat demand met by heat storage	9	75	1,041	56	84
Cold demand met by cold storage	0.05	13.21	21.66	11.29	34.62
A3. Total end use demand	**389**	**912**	**6,907**	**2,149**	**9,066**
Electricity for direct use, electricity storage, DR	348	711	4,548	1,714	7,862
Electricity for H_2 direct use + H_2 storage	31	83	1,224	317	830
Electricity + heat for heat subject to storage	10	76	1,046	78	245
Electricity for cold demand subject to storage	0.25	41.78	89.82	39.47	129.03
B. Total losses	**406**	**638**	**2,110**	**317**	**1,911**
Transmission, distribution, downtime losses	56	96	644	161	643

Losses CSP storage	0.00	0.01	0.00	0.02	0.02
Losses PHS storage	0.41	0.04	2.03	8.05	5.75
Losses battery storage	0	16	0	21	111
Losses grid H_2 storage	3	5	0	0	0
Losses CW-STES + ICE storage	0.01	2.38	3.91	2.04	6.25
Losses HW-STES storage	0	13	209	10	6
Losses UTES storage	1	9	12	4	13
Losses from curtailment	346	496	1,240	110	1,127
Net end-use demand plus losses (A1 + B)	***795***	***1,550***	***9,018***	***2,466***	***10,977***
C. Total WWS supply before T&D losses	**795**	**1,550**	**9,021**	**2,466**	**10,975**
Onshore + offshore wind electricity	533	278	7,138	826	4,671
Rooftop + utility PV+ CSP electricity	139	1,105	1,354	1,076	4,528
Hydropower electricity	68	36	501	497	1,657
Wave electricity	0	1	7	2	7
Geothermal electricity	46.5203	129.3001	11.3466	63.6993	60.5528
Tidal electricity	0.304	0.819	2.223	1.308	2.334
Solar heat	0.3056	0	0.0485	0	41.1304
Geothermal heat	7.3616	0.0237	7.1371	0.425	8.3968
D. Net taken from (+) or added to (-) storage	**0.0638**	**-0.0215**	**-2.954**	**0.0043**	**2.5097**
CSP storage	0.0001	0.0001	0	-0.0002	-0.0003
PHS storage	0.0243	-0.0018	-0.0376	-0.0112	0.0292
Battery storage	0.0005	0.0331	0	-0.0087	0.0818
Grid H_2 storage	0	0	0	0	0
CW-STES+ICE storage	0.0001	0.0138	-0.012	0.0189	0.0618
HW-STES storage	-0.0002	0.0649	0.0825	0.059	0.027
UTES storage	-0.0022	-0.0677	-3.9627	-0.0445	-0.1011
Non-grid H_2 storage	0.0413	-0.0639	0.9757	-0.0091	2.4113
Energy supplied plus taken from storage (C+D)	***795***	***1,550***	***9,018***	***2,466***	***10,977***

	Southeast Asia	**South Korea**	**Taiwan**	**United States**	**All regions**
A1. Total end use demand	**14,730**	**3,733**	**2,240**	**23,405**	**226,827**
Electricity for electricity inflexible demand	6,851	2,013	1,133	12,201	113,334
Electricity for electricity, heat, cold storage + DR	6,357	1,145	904	9,430	87,192
Electricity for H_2 direct use + H_2 storage	1,522	575	203	1,774	26,301
A2. Total end use demand	**14,730**	**3,733**	**2,240**	**23,405**	**226,827**
Electricity for direct use, electricity storage, + H_2	14,213	3,594	2,170	22,052	215,787
Low-T heat demand met by heat storage	471	136	67	1,322	10,633
Cold demand met by cold storage	45.17	2.28	3.65	30.72	407
A3. Total end use demand	**14,730**	**3,733**	**2,240**	**23,405**	**226,827**
Electricity for direct use, electricity storage, DR	12,485	2,978	1,901	20,055	183,015
Electricity for H_2 direct use + H_2 storage	1,522	575	203	1,774	26,301
Electricity + heat for heat subject to storage	509	166	104	1,347	14,913
Electricity for cold demand subject to storage	214.00	12.66	32.18	229.05	2,598
B. Total losses	**5,422**	**2,511**	**563**	**9,316**	**63,087**
Transmission, distribution, downtime losses	1,192	418	179	2,230	18,708
Losses CSP storage	0.11	0.01	0.00	0.53	17
Losses PHS storage	0.14	0.33	0.18	1.65	78
Losses battery storage	336	32	26	163	2,207
Losses grid H_2 storage	33	57	9	25	3,039
Losses CW-STES + ICE storage	8.16	0.41	0.66	5.55	73
Losses HW-STES storage	76	17	9	184	1,229

Losses UTES storage	77	25	16	137	1,913
Losses from curtailment	3,700	1,961	324	6,569	35,824
Net end-use demand plus losses (A1 + B)	***20,152***	***6,244***	***2,803***	***32,721***	***289,914***
C. Total WWS supply before T&D losses	**20,156**	**6,245**	**2,803**	**32,729**	**289,431**
Onshore + offshore wind electricity	6,973	3,892	894	20,515	141,192
Rooftop + utility PV+ CSP electricity	12,267	2,301	1,058	11,076	128,220
Hydropower electricity	582	23	27	612	14,612
Wave electricity	10	0	2	24	137
Geothermal electricity	318.079	0	819.6151	152.826	2,274
Tidal electricity	3.098	4.011	0.179	2.243	61
Solar heat	0.3196	3.3121	3.4539	53.6722	1,404
Geothermal heat	2.1889	21.1719	0.0014	294.3594	1,531
D. Net taken from (+) or added to (-) storage	**-4.0657**	**-0.9316**	**-0.2162**	**-8.0774**	**483**
CSP storage	0.0035	0.0002	0	-0.0228	1.3270
PHS storage	-0.0014	-0.023	-0.0064	-0.0945	0.6849
Battery storage	-0.0804	-0.104	0.2504	-0.6	8.4982
Grid H_2 storage	0	0	0	0	0.0000
CW-STES+ICE storage	0.0547	-0.0007	-0.0002	-0.0122	0.3949
HW-STES storage	0.2945	-0.0044	0.0507	-0.0028	7.4631
UTES storage	4.3381	1.1435	1.2162	-1.6773	358.1086
Non-grid H_2 storage	-8.6748	-1.9432	-1.7268	-5.6678	106.5775
Energy supplied plus taken from storage (C+D)	***20,152***	***6,244***	***2,803***	***32,721***	***289,914***

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

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

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

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

Table S20. Parameters for determining costs of energy from electricity and heat generators.

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

Capital costs (per MW of nameplate capacity) are an average of 2020 and 2050 values. 2050 costs are derived and sourced in Jacobson and Delucchi (2024), which uses the same methodology as in Jacobson et al. (2019).

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 S15 gives the total new HVDC line length and capacity needed and the fraction of all non-rooftop-PV and non-curtailed electricity generated that is subject to HVDC transmission by region. The discount rate used for generation, storage, transmission/distribution, and social costs is a social discount rate of 2 (1-3)%.

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

Table S21. Parameters for determining costs of hydrogen.

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

Capital costs are averages of 2020 and 2050 values and in 2020 USD. The discount rate used is the social discount rate of 2 (1-3)%. Amortization times for determining annual costs equal actual equipment lifetimes (as determined below under footnote g). Additional costs accounted for include the costs of water to produce hydrogen and the costs of dispensing hydrogen fuel to fuel-cell vehicles and to cool the hydrogen fuel. These costs are included and referenced in Table S23 (footnote).

[a] The low value is the "future potential" value from Penev et al. (2019) and the high value is the "moderate 2030" value from Mongird et al. (2020). $334.5/kW is an average of the two.

[b] Mongird et al. (2020). A rectifier is needed to convert AC electricity to DC electricity, which is used by the electrolyzer.

[c] The mean hydrogen storage container capital cost is approximately the "future case" estimate of $245/kg-$H_2$ from Houchins and James (2022). Dividing the cost per kg-H_2-stored by the higher heating value of hydrogen (39.39 kWh/kg-H_2) and by the fuel cell overall efficiency (0.536) gives the cost of hydrogen storage per kWh of electricity stored.

[d] From Chadly et al. (2022), assumed here for 2035.

[e] From NREL (2014). Installation factors account for the labor and materials cost of installation.

[f] From Penev et al. (2019).

[g] The electrolyzer full-load life (life with a use factor unity) today is 7-8.5 years (Christensen, 2020). This is assumed here to increase to 10 years by 2035, the year for which calculations are performed. Rectifier and compressor full-load lives are estimated to be the same as that of an electrolyzer. Electrolyzer, rectifier, compressor, and fuel cell actual lifetimes are calculated in the model as a function of use factor. They are calculated as the full-load life of the equipment divided by the use factor, with the result limited by the calendar life of the equipment.

[h] James et al. (2016) for the mean value. Hydrogen storage lifetime is assumed to be independent of use factor.

[i] The electrolyzer calendar life today is 30 years (Mongird et al., 2020). This is assumed here to increase to 40 years by 2035, the year for which calculations are performed. Rectifier, compressor, and fuel cell full-load lives are assumed to be the same as that of an electrolyzer.

[j] Hodges et al. (2022) measured electrolyzer efficiencies of 95%-98% relative to the higher heating value of hydrogen (39.39 kWh/kg-H_2=141.8 MJ/kg-H_2). 96% is assumed for 2035.

[k] ABB (2021) estimates current rectifier efficiencies greater than 98%. The efficiency is assumed to be 99% in 2035.

[l] Jacobson (2020). The storage efficiency assumes that a small portion of hydrogen leaks between electrolyzer and fuel cell.

[m] Assumes a 2035 fuel cell energy conversion efficiency of 65%, an energy to DC electricity efficiency of 84.6% (the rest goes into heat evaporating water), and a DC to AC inverter efficiency of 97.5% (Jacobson, 2020).

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

Table S22. Present value of mean 2020 to 2050 lifecycle costs of new storage capacity and round-trip efficiencies of the non-hydrogen storage technologies treated here. Table S21 provides hydrogen storage cost information.

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

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

All values reflect averages between 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 CSPS cost is for the phase-change material and storage tanks. In the model, only the heat captured by the working fluid due to reflection of sunlight off of CSP mirrors can be stored. The three CSPS efficiencies are as follows. 55% of incoming sunlight is reflected to the central tower, where it is absorbed by the working fluid (the remaining 45% of sunlight is lost to reflection and absorption by the CSP mirrors); without storage, 28.72% of heat absorbed by the working fluid is converted to electricity (the remaining 71.28% of heat is lost); and with storage, 99% of heat received by the working fluid that goes into storage is recovered and available to the steam turbine after storage (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 (or $240/kW for 4-hour batteries), by 2035 and take this as the mean between 2020 and 2050. Bloomberg NEF (2022) calculated average lithium-ion battery pack prices in December 2022 as $151/kWh but projected such prices would decline to below $100/kWh by 2026, suggesting again that a price decline to $60/kWh by 2035 is reasonable. For LI battery storage, the 2020-2050 mean round-trip efficiency is taken as the roundtrip efficiency of a 2021 Tesla Powerpack with four hours of storage (Tesla, 2021). Battery efficiency is the ratio of electricity delivered to electricity put into the battery.

CW-STES, ICE, HW-STES, and UTES costs were updated to reflect average values between 2020 and 2050 rather than values in 2016, which they were previously based on. UTES costs were also updated with data from Denmark (Jacobson, 2020, p. 65). In addition, the thermal energy storage (CW-STES, ICE, HW-STEES, and UTES) costs in $/kW-th were multiplied by the mean coefficient of performance (COP) of heat pumps used here (=4 kWh-th/kWh/electricity) to give the costs in $/kW-equivalent electricity. The reason is that most all energy in this study is carried in units of electricity, and heat pumps are assumed to provide heat or cold for thermal storage media. Thus, storage capacities are limited to the electricity needed to produce a larger amount of heat or cold. Since the storage size for heat or cold as equivalent electricity is smaller than the storage size of the heat or cold itself, the storage cost per unit equivalent electricity must be proportionately larger (by a factor of COP) for costs to be calculated consistently. The cost of heat pumps is assumed to be $160 (132-188)/kW-electricity, or $40 (33-47)/kW-th, based on data for large heat pumps (> 500 tons) projected to between 2020 and 2050.

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

Storage costs per unit energy generated are the product of the maximum energy storage capacity (Table S14) and the lifecycle-averaged capital cost of storage per unit maximum energy storage capacity (this table), annualized with the same discount rate as for power generators (Table S21), but with average 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 demand met. At least one stationary storage battery (lithium-iron-phosphate) is warrantied up to 15,000 cycles (or 15 years)

(Sonnen, 2021). 15,000 cycles are equivalent to one cycle per day (365 cycles per year) for 41.1 years, so this battery may last much longer than the 15-year warranty. As such, the 17-year mean battery life here is likely underestimated.

Table S23. Annual hydrogen produced and breakdown of cost per kilogram of hydrogen produced: Mean, low, and high totals are given, but only the breakdown of the mean value is provided. Tables S20-S22 and the footnote to this table provide mean, low, and high capital cost, installation factor, and discount rate information. All costs are in units of 2020 \$/kg-H_2-produced. Non-grid and grid hydrogen are merged together. The fuel cells are for grid hydrogen.

Region	(a) Non-grid plus grid H_2 produced (Tg-H_2/y)	(b) Mean non-grid plus grid H_2 electricity cost (\$/kg-H_2)	(c) Mean non-grid plus grid H_2 electrolyzer + rectifier cost (\$/kg-H_2)	(d) Mean non-grid plus grid H_2 compressor cost (\$/kg-H_2)	(e) Mean non-grid plus grid H_2 water + dispensing + cooling cost (\$/kg-H_2)	(f) Mean non-grid plus grid H_2 storage cost (\$/kg-H_2)	(g) Mean grid H_2 fuel cell cost (\$/kg-H_2)	(h) Mean non-grid plus grid total H_2 cost (\$/kg-H_2) =b+c+d+e+f+g	(i) Low non-grid plus grid total H_2 cost (\$/kg-H_2)	(j) High non-grid plus grid total H_2 cost (\$/kg-H_2)
Africa-East	0.76	4.82	1.47	0.018	0.18	0.29	0.27	7.06	4.98	10.19
Africa-North	4.51	3.77	1.43	0.018	0.18	0.43	0.19	6.02	4.51	8.01
Africa-South	1.60	4.00	1.44	0.018	0.18	1.08	0.79	7.51	5.42	10.50
Africa-West	1.04	5.60	1.57	0.020	0.18	0.80	1.60	9.78	7.13	13.47
Australia	1.72	3.70	1.45	0.018	0.18	0.87	0.24	6.46	4.78	8.81
Canada	2.44	3.01	0.41	0.006	0.18	0.00	0.00	3.61	2.96	4.38
Central America	1.84	3.94	1.47	0.018	0.18	1.69	0.00	7.30	5.26	10.38
Central Asia	2.56	3.77	1.34	0.017	0.18	0.40	0.33	6.04	4.56	8.03
China region	87.34	3.95	1.12	0.014	0.18	1.35	0.24	6.86	5.00	9.62
Cuba	0.05	4.39	1.47	0.018	0.18	0.07	0.00	6.14	4.43	8.55
Europe	35.90	4.00	0.86	0.011	0.18	1.23	0.24	6.54	4.82	9.08
Haiti region	0.22	7.41	4.96	0.062	0.18	4.23	7.12	23.96	16.62	34.34
Iceland	0.01	3.40	0.41	0.006	0.18	0.00	0.00	4.00	3.21	4.98
India region	17.66	4.17	1.43	0.018	0.18	3.94	0.59	10.33	6.94	15.95
Israel	0.13	5.11	1.59	0.020	0.18	2.31	1.62	10.84	7.36	16.27
Jamaica	0.05	5.04	1.47	0.018	0.18	1.18	0.00	7.88	5.39	11.75
Japan	5.62	4.54	1.40	0.017	0.18	2.09	0.30	8.52	6.06	12.29
Madagascar	0.03	5.56	2.83	0.035	0.18	4.31	2.88	15.79	10.83	23.35
Mauritius	0.06	5.00	1.64	0.020	0.18	2.07	1.67	10.59	7.47	15.26
Mideast	13.32	3.65	1.45	0.018	0.18	0.73	0.25	6.28	4.64	8.56
New Zealand	0.25	4.20	1.28	0.016	0.18	0.13	0.23	6.04	4.70	7.73
Philippines	0.65	4.48	1.89	0.024	0.18	0.73	1.93	9.23	6.72	12.65
Russia region	8.66	3.47	1.00	0.012	0.18	0.53	0.00	5.19	3.97	6.90
South Am-NW	2.24	4.08	1.47	0.018	0.18	0.07	0.00	5.83	4.47	7.51
South Am-SE	5.87	4.03	1.47	0.018	0.18	0.73	0.00	6.44	4.80	8.70
Southeast Asia	11.18	5.87	1.42	0.018	0.18	4.67	0.34	12.49	8.49	19.01
South Korea	4.79	5.91	1.25	0.016	0.18	2.31	0.87	10.53	7.49	15.19
Taiwan	1.55	5.00	1.36	0.017	0.18	6.74	0.70	14.00	9.16	22.24
United States	12.88	4.12	1.43	0.018	0.18	2.51	0.42	8.68	6.12	12.65
All regions	**224.94**	**4.13**	**1.22**	**0.015**	**0.18**	**1.75**	**0.29**	**7.58**	**5.44**	**10.84**

Costs are averages of 2020 and 2050 values and in 2020 USD. The mean H_2 electricity cost for each region is the "Total LCOE" from Table S24 multiplied by 47.1 kWh/kg-H_2 for electrolysis plus compression. The value for "All regions" is the average of each regional value weighted by the hydrogen production in the region. Table S21 provides electrolyzer, rectifier, compressor, storage, and fuel cell capital costs, installation factors, operation and maintenance costs, lifetime information, and efficiencies. It also provides the discount rate used. For the electrolyzer plus rectifier and compressor, calculated annualized costs (\$/kW/y) are converted to costs per kg-H_2 by multiplying by 41.46 kWh/kg-H_2 and 5.64 kWh/kg-H_2, respectively, then dividing by 8,760 hours per year and by the hydrogen use factors for the region from Table S17. Storage costs per kg-H_2-produced equal annualized storage costs (\$/kg-H_2-stored/y) multiplied by the ratio of the H_2 storage tank size to the H_2 production per year, both from Table S17. The water cost for electrolysis is estimated as \$0.0071 (\$0.0047-\$0.0094)/kg-H_2-produced (Jacobson et al., 2005). The estimated costs to dispense hydrogen fuel to vehicles and to cool the hydrogen fuel to -40 °C are \$0.17 (0.12-0.21)/kg-H_2 and \$0.22 (0.18-0.27)/kg-H_2, respectively (NREL, 2014). However, because only ~45% of the non-grid H_2 needed worldwide will be for vehicles, the dispensing and cooling costs are multiplied by 0.45. Thus, the resulting summed cost of water, dispensing, and cooling for non-grid hydrogen is \$0.183 (0.14-0.225)/kg-H_2.

Table S24. Summary of WWS mean capital costs ($ trillion in 2020 USD) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) averaged over the simulation period for each region. Also shown is the energy consumed per year and the resulting aggregate annual energy cost to the region. The last row in each case is the percent increase in the total LCOE and the total annual energy cost if the baseline battery system cost is increased from the mean value in Table S22 ($60/kWh-electricity storage) to the high value ($90/kWh-electricity storage), or by a factor of 1.5. All costs are averages between 2020 and 2050.

	Africa-East	Africa-North	Africa-South	Africa-West	Australia	Canada	Central America	Central Asia
Capital cost new generators only ($tril)	0.412	0.804	0.586	1.061	0.367	0.443	0.675	0.760
Cap cost generators-storage-H_2-HVDC ($tril)	**0.608**	**0.999**	**0.810**	**1.272**	**0.495**	**0.573**	**0.827**	**0.924**
Components of total LCOE (¢/kWh-all-energy)								
Short-distance transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.128	0.116	0.161	0.111	0.176	0.218	0.112	0.134
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.280	3.412	3.519	6.864	3.234	2.600	3.891	3.719
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.001	0.012	0.016	0.000	0.079	0.032	0.031	0.000
LI battery storage	1.451	0.228	0.688	0.841	0.314	0.000	0.329	0.146
Grid H_2 fuel cells	0.037	0.062	0.121	0.172	0.054	0.000	0.000	0.067
CSPS + PHS storage	0.008	0.014	0.020	0.005	0.022	0.000	0.010	0.011
CW-STES + ICE storage	0.001	0.002	0.003	0.001	0.001	0.001	0.001	0.000
HW-STES storage	0.022	0.003	0.006	0.007	0.002	0.009	0.003	0.017
UTES storage	0.314	0.009	0.020	0.077	0.003	0.007	0.005	0.047
Heat pumps for filling district heating/cooling	0.310	0.024	0.100	0.116	0.003	0.004	0.006	0.048
Non-grid + grid merged H_2 prod/compress/storage	0.267	0.693	0.419	0.277	0.555	0.104	0.555	0.396
Total LCOE (¢/kWh-all-energy)	**10.24**	**8.00**	**8.50**	**11.90**	**7.87**	**6.40**	**8.37**	**8.01**
LCOE (¢/kWh-replacing BAU electricity)	9.323	7.253	7.940	11.415	7.286	6.257	7.792	7.490
GW annual avg. end-use demand (Table S6)	64.2	153.1	118.5	110.7	88.9	160.1	127.3	143.3
TWh/y end-use demand (GW x 8,760 h/y)	562	1,341	1,038	970	779	1,402	1,115	1,255
Annual energy cost ($billion/y)	**57.6**	**107.3**	**88.2**	**115.4**	**61.2**	**89.7**	**93.3**	**100.6**
% rise in LCOE & annual cost if 1.5x battery cost	7.08	1.42	4.05	3.53	2.00	0.00	1.97	0.91
	China region	Cuba	Europe	Haiti region	Iceland	India region	Israel	Jamaica
Capital cost new generators only ($tril)	10.073	0.042	3.541	0.052	0.001	4.589	0.072	0.011
Cap cost generators-storage-H_2-HVDC ($tril)	**14.969**	**0.055**	**5.064**	**0.092**	**0.0014**	**7.135**	**0.112**	**0.016**
Components of total LCOE (¢/kWh-all-energy)								
Short-distance transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.207	0.000	0.193	0.000	0.000	0.178	0.000	0.000
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	3.181	3.965	3.456	5.905	1.752	3.148	3.980	4.068
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.179	0.000	0.127	0.000	1.993	0.013	0.293	0.000
LI battery storage	0.092	1.671	0.004	0.000	0.000	0.460	2.212	2.153
Grid H_2 fuel cells	0.094	0.000	0.114	2.669	0.000	0.123	0.192	0.000
CSPS + PHS storage	0.011	0.058	0.012	0.038	0.000	0.020	0.017	0.007
CW-STES + ICE storage	0.002	0.006	0.002	0.002	0.002	0.002	0.002	0.000
HW-STES storage	0.006	0.011	0.014	0.000	0.006	0.022	0.016	0.028
UTES storage	0.075	0.004	0.038	0.114	0.000	0.211	0.161	0.044
Heat pumps for filling district heating/cooling	0.076	0.034	0.047	0.053	0.005	0.098	0.061	0.074
Non-grid + grid merged H_2 prod/compress/storage	1.046	0.155	1.069	3.537	0.032	1.160	0.487	0.892
Total LCOE (¢/kWh-all-energy)	**8.39**	**9.33**	**8.50**	**15.74**	**7.21**	**8.86**	**10.85**	**10.69**
LCOE (¢/kWh-replacing BAU electricity)	7.162	9.125	7.308	12.039	7.172	7.352	10.122	9.653
GW annual avg. end-use demand (Table S6)	2,543	6.7	876.4	6.8	2.7	967.2	12.4	1.7
TWh/y end-use demand (GW x 8,760 h/y)	22,275	59	7,678	60	24	8,473	109	15
Annual energy cost ($billion/y)	**1,870**	**5.5**	**652.8**	**9.4**	**1.7**	**750.7**	**11.8**	**1.6**
% rise in LCOE & annual cost if 1.5x battery cost	0.55	9.0	0.02	0.00	1.57	2.59	10.2	10.07

	Japan	Mada-gascar	Mauritius	Mideast	New Zealand	Philippines	Russia region	South Am-NW
Capital cost new generators only ($tril)	0.866	0.030	0.009	2.764	0.085	0.229	0.905	0.422
Cap cost generators-storage-H_2-HVDC ($tril)	**1.226**	**0.037**	**0.013**	**3.822**	**0.093**	**0.292**	**1.276**	**0.531**
Components of total LCOE (¢/kWh-all-energy)								
Short-distance transmission	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.153	0.000	0.000	0.190	0.065	0.079	0.213	0.209
Distribution	2.375	2.375	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.224	6.320	4.170	3.029	4.948	4.413	2.931	4.292
Additional hydro turbines	0	0	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.047	0.002	0.059	0.044	0.086	0.000	0.004	0.001
LI battery storage	0.265	1.029	0.594	0.306	0.005	0.403	0.000	0.142
Grid H_2 fuel cells	0.109	0.267	0.670	0.059	0.045	0.413	0.000	0.000
CSPS + PHS storage	0.040	0.016	0.008	0.006	0.017	0.007	0.005	0.013
CW-STES + ICE storage	0.000	0.006	0.006	0.001	0.000	0.007	0.002	0.003
HW-STES storage	0.002	0.011	0.019	0.002	0.001	0.051	0.028	0.014
UTES storage	0.015	0.018	0.061	0.091	0.002	0.041	0.063	0.006
Heat pumps for filling district heating/cooling	0.005	0.020	0.034	0.032	0.002	0.068	0.055	0.016
Non-grid + grid merged H_2 prod/compress/storage	1.347	0.682	1.569	0.559	0.314	0.605	0.647	0.547
Total LCOE (¢/kWh-all-energy)	**9.63**	**11.80**	**10.62**	**7.74**	**8.91**	**9.51**	**7.37**	**8.67**
LCOE (¢/kWh-replacing BAU electricity)	8.238	11.065	8.932	7.038	8.586	8.739	6.542	8.054
GW annual avg. end-use demand (Table S6)	175.7	3.4	1.6	647.5	14.8	34.7	262.7	81.7
TWh/y end-use demand (GW x 8,760 h/y)	1,539	30	14	5,672	130	304	2,302	716
Annual energy cost ($billion/y)	**148.2**	**3.5**	**1.5**	**439.1**	**11.6**	**28.9**	**169.7**	**62.1**
% rise in LCOE & annual cost if 1.5x battery cost	1.38	4.36	2.80	1.97	0.03	2.12	0.00	0.82

	South Am-SE	Southeast Asia	South Korea	Taiwan	United States	All Regions
Capital cost new generators only ($tril)	1.812	5.406	1.314	0.585	4.174	42.092
Cap cost generators-storage-H_2-HVDC ($tril)	**2.210**	**6.677**	**1.596**	**0.791**	**5.722**	**58.239**
Components of total LCOE (¢/kWh-all-energy)						
Short-distance transmission	1.050	1.050	1.050	1.050	1.050	1.050
Long-distance transmission	0.165	0.144	0.000	0.000	0.180	0.178
Distribution	2.375	2.375	2.375	2.375	2.375	2.375
Electricity generation	4.233	6.853	6.817	4.453	3.836	3.725
Additional hydro turbines	0	0	0	0	0	0
Geothermal + solar thermal heat generation	0.043	0.001	0.033	0.015	0.073	0.085
LI battery storage	0.203	0.457	0.426	0.792	0.392	0.254
Grid H_2 fuel cells	0.000	0.077	0.336	0.146	0.070	0.090
CSPS + PHS storage	0.004	0.001	0.011	0.010	0.010	0.011
CW-STES + ICE storage	0.002	0.002	0.001	0.002	0.001	0.002
HW-STES storage	0.008	0.004	0.002	0.005	0.003	0.009
UTES storage	0.003	0.014	0.012	0.016	0.020	0.067
Heat pumps for filling district heating/cooling	0.003	0.050	0.030	0.022	0.052	0.059
Non-grid + grid merged H_2 prod/compress/storage	0.468	1.432	1.447	1.725	0.684	0.918
Total LCOE (¢/kWh-all-energy)	**8.56**	**12.46**	**12.54**	**10.61**	**8.75**	**8.82**
LCOE (¢/kWh-replacing BAU electricity)	8.060	10.945	11.049	8.842	7.974	7.749
GW annual avg. end-use demand (Table S6)	344.8	560.3	142.0	85.2	890.2	8,627.5
TWh/y end-use demand (GW x 8,760 h/y)	3,021	4,908	1,244	746	7,798	75,577
Annual energy cost ($billion/y)	**258.5**	**611.5**	**156.0**	**79.2**	**682.0**	**6,668.0**
% rise in LCOE & annual cost if 1.5x battery cost	1.18	1.83	1.70	3.7	2.24	1.44

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 in boreholes or water pits.

The LCOEs are derived from capital costs, annual O&M, and end-of-life decommissioning costs that vary by technology (Tables S20-S22) and that are a function of lifetime (Tables S20-S22) and a social discount rate for an intergenerational project of 2.0 (1-3)%, all divided by the total annualized end-use demand met, given in the present table. Capital costs are an average between 2020 and 2050, as are the LCOEs.

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

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

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

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

Long-distance transmission costs are $0.0089 (0.0042-0.010)/kWh (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 S15 gives the total HVDC line length and capacity and the fraction of all non-rooftop-PV and non-curtailed electricity generated that is subject to HVDC transmission by region.

Storage costs are derived from data in Table S22.

H_2 costs are broken down in Table S23.

Table S25. 2050 regional and country annual-average end-use (a) BAU demand and (b) WWS demand; (c) percentage difference between WWS and BAU demand; (d) present value of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and all-distance transmission and distribution; mean levelized private costs of all (e) BAU and (f) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050); (g) mean WWS private (equals social) energy cost per year; (h) mean BAU private energy cost per year; (i) mean BAU health cost per year; (j) mean BAU climate cost per year; (k) BAU total social cost per year; (l) percentage difference between WWS and BAU private energy cost; and (m) percentage difference between WWS and BAU social energy cost. All costs are in 2020 USD. H=8760 hours per year.

Region or country	(a)[1] 2050 BAU Annual-average end-use demand (GW)	(b)[1] 2050 WWS Annual-average end-use demand (GW)	(c) 2050 WWS minus BAU demand = (b-a)/a (%)	(d)[2] WWS mean total capital cost ($tril 2020)	(e)[3] BAU mean private energy cost (¢/kWh-all energy)	(f)[4] WWS mean private energy cost (¢/kWh-all energy)	(g)[5] WWS mean annual all-energy private and social cost = bfH ($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-East	**224.4**	**64.2**	**-71.4**	**0.608**	**7.82**	**10.24**	**57.6**	**153.7**	**755.4**	**102.4**	**1,012**	**-62.5**	**-94.3**
Eritrea	1.3	0.3	-75.4	0.003	7.82	10.24	0.3	0.9	10.8	1.0	13	-67.7	-97.8
Ethiopia	79.0	18.8	-76.3	0.170	7.82	10.24	16.8	54.2	243.4	23.1	321	-68.9	-94.7
Kenya	36.8	9.9	-73.2	0.089	7.82	10.24	8.8	25.2	46.7	26.9	99	-65.0	-91.1
Rwanda	5.7	1.5	-74.4	0.015	7.82	10.24	1.3	3.9	18.1	1.5	23	-66.5	-94.4
South Sudan	1.6	0.5	-70.7	0.004	7.82	10.24	0.4	1.1	34.2	1.5	37	-61.6	-98.9
Sudan	30.8	10.5	-65.9	0.094	7.82	10.24	9.4	21.1	215.3	24.2	261	-55.4	-96.4
Tanzania	42.5	12.2	-71.4	0.123	7.82	10.24	10.9	29.1	73.6	16.1	119	-62.5	-90.8
Uganda	26.7	10.7	-60.0	0.111	7.82	10.24	9.6	18.3	113.3	8.2	140	-47.7	-93.2
Africa-North	**380.0**	**153.1**	**-59.7**	**0.999**	**11.34**	**8.00**	**107.3**	**377.6**	**613.4**	**724.7**	**1,716**	**-71.6**	**-93.7**
Algeria	121.1	41.1	-66.0	0.284	7.82	10.24	28.8	120.3	74.8	207.6	403	-76.0	-92.8
Egypt	165.0	75.2	-54.4	0.464	7.82	10.24	52.7	163.9	373.0	311.3	848	-67.8	-93.8
Libya	24.9	9.0	-63.9	0.069	7.82	10.24	6.3	24.7	20.0	76.0	121	-74.5	-94.8
Morocco	38.8	16.9	-56.4	0.107	7.82	10.24	11.9	38.6	57.1	88.8	184	-69.2	-93.6
Niger	6.4	1.5	-76.1	0.012	7.82	10.24	1.1	6.4	63.1	3.0	72	-83.2	-98.5
Tunisia	23.8	9.2	-61.2	0.063	7.82	10.24	6.5	23.6	25.5	38.1	87	-72.6	-92.6
Africa-South	**278.3**	**118.5**	**-57.4**	**0.810**	**9.29**	**8.50**	**88.2**	**226.5**	**333.5**	**600.6**	**1,161**	**-61.1**	**-92.4**
Angola	23.1	7.9	-65.6	0.060	7.82	10.24	5.9	18.8	94.1	29.3	142	-68.5	-95.8
Botswana	4.3	1.7	-60.3	0.012	7.82	10.24	1.3	3.5	6.8	8.4	19	-63.7	-93.3
Mozambique	16.9	6.0	-64.4	0.041	7.82	10.24	4.5	13.7	36.3	10.4	60	-67.5	-92.6
Namibia	4.3	1.6	-61.9	0.013	7.82	10.24	1.2	3.5	6.2	4.9	15	-65.2	-91.7
South Africa	190.6	87.1	-54.3	0.584	7.82	10.24	64.8	155.1	118.2	522.6	796	-58.2	-91.9
Eswatini, Kingd.	2.5	1.3	-50.2	0.009	7.82	10.24	0.9	2.1	4.0	1.8	8	-54.4	-88.0
Zambia	17.9	7.5	-58.0	0.052	7.82	10.24	5.6	14.5	49.3	8.4	72	-61.6	-92.3
Zimbabwe	18.8	5.4	-71.4	0.038	7.82	10.24	4.0	15.3	18.7	14.7	49	-73.8	-91.8
Africa-West	**409.2**	**110.7**	**-72.9**	**1.272**	**9.96**	**8.86**	**115.4**	**357.1**	**2,415**	**265.9**	**3,038**	**-67.7**	**-96.2**
Benin	10.7	2.7	-75.2	0.039	7.82	10.24	2.8	9.4	33.7	10.4	53	-70.4	-94.8
Cameroon	16.8	4.6	-72.7	0.063	7.82	10.24	4.8	14.7	68.9	12.2	96	-67.4	-95.0
Congo	4.3	1.2	-71.9	0.021	7.82	10.24	1.3	3.7	19.5	8.9	32	-66.4	-96.1
Congo, DR	36.9	8.8	-76.3	0.127	7.82	10.24	9.1	32.2	77.0	4.0	113	-71.6	-91.9
Côte d'Ivoire	17.3	5.4	-68.5	0.075	7.82	10.24	5.7	15.1	97.0	17.4	130	-62.4	-95.6
Equatorial Guin.	3.8	2.2	-43.0	0.026	7.82	10.24	2.3	3.3	9.0	8.4	21	-31.9	-89.1
Gabon	11.3	6.9	-39.0	0.101	7.82	10.24	7.2	9.9	8.5	6.6	25	-27.2	-71.3
Ghana	21.8	8.9	-59.3	0.111	7.82	10.24	9.3	19.0	83.4	28.4	131	-51.4	-92.9
Nigeria	273.3	65.7	-76.0	0.658	7.82	10.24	68.4	238.5	1,971	152.5	2,362	-71.3	-97.1
Senegal	8.1	3.2	-60.8	0.031	7.82	10.24	3.3	7.1	28.6	14.4	50	-53.2	-93.4
Togo	4.8	1.3	-73.5	0.019	7.82	10.24	1.3	4.2	18.1	2.7	25	-68.4	-94.7
Australia	**201.5**	**88.9**	**-55.9**	**0.495**	**10.26**	**7.87**	**61.2**	**181.1**	**34.6**	**333.5**	**549**	**-66.2**	**-88.8**
Canada	**401.9**	**160.1**	**-60.2**	**0.573**	**8.09**	**6.40**	**89.7**	**284.8**	**42.2**	**498.1**	**825**	**-68.5**	**-89.1**
Central America	**301.0**	**127.3**	**-57.7**	**0.827**	**10.50**	**8.37**	**93.3**	**276.8**	**323.7**	**508.0**	**1,108**	**-66.3**	**-91.6**

Costa Rica	7.2	3.3	-53.4	0.016	10.50	8.37	2.4	6.6	6.6	7.9	21	-62.8	-88.4
El Salvador	4.8	2.1	-55.4	0.012	10.50	8.37	1.6	4.4	7.4	8.0	20	-64.5	-92.1
Guatemala	20.2	5.8	-71.6	0.037	10.50	8.37	4.2	18.6	32.0	19.7	70	-77.3	-94.0
Honduras	6.7	2.5	-62.2	0.019	10.50	8.37	1.9	6.2	10.7	9.5	26	-69.9	-92.9
Mexico	241.6	106.8	-55.8	0.694	10.50	8.37	78.3	222.1	252.5	445.9	921	-64.7	-91.5
Nicaragua	4.6	1.6	-65.7	0.012	10.50	8.37	1.1	4.2	8.2	4.9	17	-72.6	-93.4
Panama	16.0	5.2	-67.7	0.037	10.50	8.37	3.8	14.7	6.2	12.2	33	-74.2	-88.6
Central Asia	**391.9**	**143.3**	**-63.4**	**0.924**	**10.24**	**8.01**	**100.6**	**351.7**	**1,011**	**631.0**	**1,994**	**-71.4**	**-95.0**
Kazakhstan	80.8	29.0	-64.1	0.175	10.24	8.01	20.3	72.5	91.5	175.3	339	-71.9	-94.0
Kyrgyz Rep.	6.1	3.0	-51.2	0.013	10.24	8.01	2.1	5.5	16.0	8.9	30	-61.9	-93.2
Pakistan	195.8	79.0	-59.6	0.548	10.24	8.01	55.5	175.7	795.6	265.0	1,236	-68.4	-95.5
Tajikistan	6.2	3.5	-44.2	0.011	10.24	8.01	2.4	5.6	19.6	8.4	34	-56.4	-92.8
Turkmenistan	34.5	7.6	-78.0	0.049	10.24	8.01	5.3	30.9	20.2	69.1	120	-82.8	-95.6
Uzbekistan	68.6	21.3	-68.9	0.128	10.24	8.01	15.0	61.5	68.3	104.3	234	-75.7	-93.6
China region	**5,081.4**	**2,542.8**	**-50.0**	**14.969**	**9.53**	**8.39**	**1,869.6**	**4,243.3**	**10,756**	**8,969.2**	**23,969**	**-55.9**	**-92.2**
China	4,986.4	2,499.7	-49.9	14.613	9.53	8.39	1,837.9	4,164.0	10,601	8,823.6	23,589	-55.9	-92.2
Hong Kong	53.8	20.7	-61.6	0.208	9.53	8.39	15.2	44.9	54.7	40.1	140	-66.2	-89.1
Korea, DPR	30.8	18.3	-40.5	0.122	9.53	8.39	13.5	25.7	81.7	75.4	183	-47.6	-92.6
Mongolia	10.4	4.1	-60.7	0.027	9.53	8.39	3.0	8.7	18.3	30.1	57	-65.4	-94.7
Cuba	**11.9**	**6.7**	**-44.0**	**0.055**	**11.65**	**9.33**	**5.5**	**12.2**	**37.5**	**24.0**	**74**	**-55.1**	**-92.6**
Europe	**2,053.7**	**876.4**	**-57.3**	**5.064**	**10.06**	**8.50**	**652.8**	**1,809.7**	**1,772**	**2,626.9**	**6,209**	**-63.9**	**-89.5**
Albania	3.8	1.8	-51.4	0.008	10.06	8.50	1.4	3.3	14.3	3.8	21	-58.9	-93.6
Austria	44.0	19.5	-55.8	0.092	10.06	8.50	14.5	38.8	20.3	48.5	108	-62.7	-86.5
Belarus	33.7	11.8	-64.9	0.078	10.06	8.50	8.8	29.7	50.2	48.4	128	-70.3	-93.1
Belgium	63.4	27.1	-57.2	0.166	10.06	8.50	20.2	55.8	26.1	70.4	152	-63.8	-86.7
Bosnia-Herzeg.	8.2	3.4	-58.5	0.019	10.06	8.50	2.5	7.2	29.1	12.8	49	-64.9	-94.9
Bulgaria	20.4	9.1	-55.3	0.059	10.06	8.50	6.8	18.0	38.2	36.2	92	-62.2	-92.6
Croatia	13.1	5.5	-58.5	0.033	10.06	8.50	4.1	11.6	21.5	14.9	48	-64.9	-91.5
Cyprus	3.5	1.6	-54.3	0.010	10.06	8.50	1.2	3.1	3.6	5.6	12	-61.4	-90.3
Czech Rep.	41.9	17.2	-58.8	0.108	10.06	8.50	12.8	36.9	32.0	71.7	141	-65.2	-90.9
Denmark	23.0	8.9	-61.0	0.045	10.06	8.50	6.7	20.2	11.7	20.0	52	-67.1	-87.2
Estonia	5.4	1.9	-64.3	0.013	10.06	8.50	1.4	4.8	2.8	10.9	19	-69.8	-92.2
Finland	38.4	20.2	-47.5	0.123	10.06	8.50	15.0	33.8	6.0	28.6	69	-55.6	-78.1
France	217.4	99.7	-54.1	0.603	10.06	8.50	74.2	191.6	115.0	222.0	529	-61.2	-86.0
Germany	330.7	142.5	-56.9	0.772	10.06	8.50	106.1	291.4	223.1	489.0	1,003	-63.6	-89.4
Gibraltar	6.3	1.6	-75.0	0.022	10.06	8.50	1.2	5.5	0.2	0.5	6	-78.9	-81.4
Greece	28.6	11.7	-59.1	0.064	10.06	8.50	8.7	25.2	42.0	39.2	106	-65.4	-91.8
Hungary	30.3	12.2	-59.6	0.088	10.06	8.50	9.1	26.7	37.8	37.2	102	-65.8	-91.0
Ireland	17.4	7.8	-55.4	0.048	10.06	8.50	5.8	15.4	9.7	25.7	51	-62.3	-88.6
Italy	187.3	74.0	-60.5	0.429	10.06	8.50	55.1	165.1	188.7	234.7	588	-66.6	-90.6
Kosovo	3.0	1.4	-52.7	0.010	10.06	8.50	1.1	2.7	1.7	7.0	11	-60.1	-90.7
Latvia	7.5	3.0	-59.9	0.018	10.06	8.50	2.2	6.6	10.0	6.0	23	-66.1	-90.1
Lithuania	11.5	4.7	-59.5	0.035	10.06	8.50	3.5	10.2	14.0	11.5	36	-65.8	-90.2
Luxembourg	5.7	2.2	-61.6	0.014	10.06	8.50	1.6	5.0	1.7	6.2	13	-67.6	-87.4
Macedonia	2.9	1.3	-55.8	0.008	10.06	8.50	1.0	2.6	11.0	6.2	20	-62.6	-95.1
Malta	5.0	1.5	-69.5	0.013	10.06	8.50	1.1	4.4	1.1	1.5	7	-74.3	-83.8
Moldova	5.3	2.0	-62.3	0.014	10.06	8.50	1.5	4.7	5.9	7.9	18	-68.2	-91.9
Montenegro	1.4	0.7	-49.0	0.004	10.06	8.50	0.5	1.2	3.9	3.6	9	-56.9	-93.8
Netherlands	98.1	39.1	-60.1	0.226	10.06	8.50	29.1	86.4	43.7	107.8	238	-66.3	-87.8
Norway	44.6	20.1	-54.9	0.052	10.06	8.50	15.0	39.3	7.7	31.1	78	-61.9	-80.8
Poland	122.2	47.5	-61.1	0.322	10.06	8.50	35.4	107.7	131.4	235.6	475	-67.1	-92.5
Portugal	26.7	12.4	-53.6	0.061	10.06	8.50	9.2	23.5	15.7	28.4	68	-60.8	-86.4
Romania	45.9	18.0	-60.8	0.107	10.06	8.50	13.4	40.4	141.8	65.4	248	-66.9	-94.6
Serbia	18.4	8.2	-55.7	0.054	10.06	8.50	6.1	16.2	37.6	25.6	79	-62.5	-92.3
Slovakia	18.3	8.0	-56.1	0.049	10.06	8.50	6.0	16.1	16.6	27.5	60	-62.9	-90.1
Slovenia	7.2	3.4	-53.1	0.021	10.06	8.50	2.5	6.4	5.2	10.4	22	-60.3	-88.5
Spain	143.3	60.8	-57.6	0.325	10.06	8.50	45.3	126.3	88.9	170.4	386	-64.2	-88.3
Sweden	54.6	29.8	-45.4	0.144	10.06	8.50	22.2	48.1	11.6	28.6	88	-53.9	-74.9
Switzerland	28.6	13.5	-52.9	0.056	10.06	8.50	10.0	25.2	13.9	25.8	65	-60.2	-84.5
Ukraine	89.3	44.4	-50.3	0.283	10.06	8.50	33.1	78.7	183.2	153.9	416	-58.0	-92.0
United King.	197.4	76.8	-61.1	0.470	10.06	8.50	57.2	173.9	153.3	246.4	574	-67.1	-90.0
Haiti region	**17.2**	**6.8**	**-60.4**	**0.092**	**11.00**	**15.74**	**9.4**	**16.5**	**36.2**	**30.2**	**83**	**-43.4**	**-88.7**

Dominican Rep	12.2	5.5	-54.7	0.074	11.00	15.74	7.6	11.8	20.3	27.0	59	-35.2	-87.1
Haiti	5.0	1.3	-74.4	0.019	11.00	15.74	1.8	4.8	15.9	3.2	24	-63.4	-92.6
Iceland	**4.6**	**2.7**	**-40.6**	**0.0014**	**7.43**	**7.21**	**1.7**	**3.0**	**0.4**	**2.1**	**6**	**-43.2**	**-69.5**
India region	**1,820.9**	**967.2**	**-46.9**	**7.135**	**9.82**	**8.86**	**750.7**	**1,566.7**	**9,472**	**3,603.8**	**14,642**	**-52.1**	**-94.9**
Bangladesh	72.7	33.8	-53.5	0.271	9.82	8.86	26.2	62.5	523.1	128.9	715	-58.1	-96.3
India	1,695.9	914.9	-46.1	6.721	9.82	8.86	710.1	1,459.1	8,755	3,428.9	13,643	-51.3	-94.8
Nepal	28.6	8.2	-71.2	0.068	9.82	8.86	6.4	24.6	99.9	17.2	142	-74.0	-95.5
Sri Lanka	23.7	10.3	-56.4	0.076	9.82	8.86	8.0	20.4	94.0	28.8	143	-60.7	-94.4
Israel	**24.7**	**12.4**	**-49.8**	**0.112**	**11.21**	**10.85**	**11.8**	**24.3**	**15.7**	**43.8**	**84**	**-51.4**	**-85.9**
Jamaica	**4.1**	**1.7**	**-57.7**	**0.016**	**11.40**	**10.69**	**1.6**	**4.1**	**3.4**	**7.9**	**15**	**-60.3**	**-89.5**
Japan	**329.1**	**175.7**	**-46.6**	**1.226**	**10.48**	**9.63**	**148.2**	**302.2**	**261.5**	**638.1**	**1,202**	**-50.9**	**-87.7**
Madagascar	**12.8**	**3.4**	**-73.4**	**0.037**	**9.34**	**11.80**	**3.5**	**10.4**	**51.7**	**6.4**	**69**	**-66.4**	**-94.9**
Mauritius	**4.2**	**1.6**	**-62.4**	**0.013**	**10.54**	**10.62**	**1.5**	**3.9**	**3.7**	**4.9**	**13**	**-62.1**	**-88.3**
Mideast	**1,383.4**	**647.5**	**-53.2**	**3.822**	**11.34**	**7.74**	**439.1**	**1,374.3**	**858.2**	**2,729.8**	**4,962**	**-68.0**	**-91.2**
Armenia	5.2	1.6	-68.5	0.008	11.34	7.74	1.1	5.2	10.1	5.6	21	-78.5	-94.7
Azerbaijan	20.5	7.3	-64.3	0.047	11.34	7.74	5.0	20.4	37.8	30.8	89	-75.6	-94.4
Bahrain	16.1	9.5	-41.2	0.047	11.34	7.74	6.4	16.0	2.1	42.5	61	-59.9	-89.4
Iran	424.2	179.3	-57.7	1.120	11.34	7.74	121.6	421.4	171.3	805.9	1,399	-71.1	-91.3
Iraq	50.0	21.2	-57.6	0.151	11.34	7.74	14.4	49.7	90.6	201.6	342	-71.1	-95.8
Jordan	13.5	6.4	-52.3	0.036	11.34	7.74	4.3	13.4	11.3	27.6	52	-67.5	-91.7
Kuwait	58.0	25.5	-56.0	0.138	11.34	7.74	17.3	57.6	12.6	111.2	181	-69.9	-90.5
Lebanon	9.9	4.7	-52.5	0.028	11.34	7.74	3.2	9.9	9.0	29.2	48	-67.6	-93.4
Oman	54.3	23.4	-56.8	0.139	11.34	7.74	15.9	53.9	8.4	107.3	170	-70.5	-90.6
Qatar	73.8	29.9	-59.5	0.151	11.34	7.74	20.3	73.3	3.6	110.7	188	-72.3	-89.2
Saudi Arabia	292.7	151.9	-48.1	0.933	11.34	7.74	103.0	290.8	124.6	664.9	1,080	-64.6	-90.5
Syria	11.7	5.2	-55.0	0.031	11.34	7.74	3.6	11.6	47.5	29.3	88	-69.3	-96.0
Turkiye	169.1	80.1	-52.7	0.462	11.34	7.74	54.3	168.0	229.7	330.3	728	-67.7	-92.5
UAE	179.6	99.6	-44.6	0.519	11.34	7.74	67.5	178.4	11.0	219.3	409	-62.2	-83.5
Yemen	5.0	1.8	-63.9	0.012	11.34	7.74	1.2	4.9	88.6	13.6	107	-75.4	-98.9
New Zealand	**27.9**	**14.8**	**-46.9**	**0.093**	**8.22**	**8.91**	**11.6**	**20.1**	**5.2**	**29.6**	**55**	**-42.5**	**-78.9**
Philippines	**79.7**	**34.7**	**-56.5**	**0.292**	**10.20**	**9.51**	**28.9**	**71.2**	**677.3**	**178.4**	**927**	**-59.5**	**-96.9**
Russia region	**729.9**	**262.7**	**-64.0**	**1.276**	**10.14**	**7.37**	**169.7**	**648.5**	**602.0**	**1,323.9**	**2,574**	**-73.8**	**-93.4**
Georgia	8.3	3.3	-60.0	0.011	10.14	7.37	2.1	7.4	31.1	9.7	48	-70.9	-95.6
Russia	721.6	259.4	-64.1	1.265	10.14	7.37	167.5	641.1	570.8	1,314.3	2,526	-73.9	-93.4
South Am-NW	**201.7**	**81.7**	**-59.5**	**0.531**	**8.30**	**8.67**	**62.1**	**146.7**	**242.6**	**326.3**	**716**	**-57.7**	**-91.3**
Bolivia	14.5	5.0	-65.9	0.030	8.30	8.67	3.8	10.6	22.7	21.9	55	-64.4	-93.2
Colombia	63.1	26.1	-58.7	0.178	8.30	8.67	19.8	45.9	72.8	75.6	194	-56.9	-89.8
Curacao	4.5	1.4	-69.7	0.012	8.30	8.67	1.0	3.3	0.1	2.0	5	-68.4	-80.6
Ecuador	22.5	8.8	-60.9	0.053	8.30	8.67	6.7	16.4	16.1	40.1	73	-59.2	-90.8
Peru	38.4	15.7	-59.2	0.100	8.30	8.67	11.9	27.9	77.0	53.7	159	-57.4	-92.5
Suriname	1.4	0.5	-60.8	0.004	8.30	8.67	0.4	1.0	1.6	2.6	5	-59.1	-92.1
Trinidad/Tobago	11.8	7.6	-35.3	0.051	8.30	8.67	5.8	8.6	2.6	28.3	39	-32.4	-85.3
Venezuela	45.6	16.7	-63.3	0.105	8.30	8.67	12.7	33.2	49.8	102.1	185	-61.6	-93.1
South Am-SE	**756.9**	**344.8**	**-54.4**	**2.210**	**8.37**	**8.56**	**258.5**	**554.9**	**507.2**	**780.8**	**1,843**	-53.4	-86.0
Argentina	119.5	45.3	-62.1	0.244	8.30	8.67	33.9	87.6	98.3	184.3	370	-61.3	-90.8
Brazil	555.3	256.4	-53.8	1.758	8.30	8.67	192.2	407.1	352.7	489.9	1,250	-52.8	-84.6
Chile	60.9	32.8	-46.2	0.168	8.30	8.67	24.5	44.6	38.6	91.4	175	-45.0	-85.9
Paraguay	11.9	5.5	-53.7	0.014	8.30	8.67	4.1	8.7	12.4	8.7	30	-52.6	-86.1
Uruguay	9.3	4.9	-47.4	0.026	8.30	8.67	3.7	6.8	5.2	6.6	19	-46.2	-80.4
Southeast Asia	**1,180.2**	**560.3**	**-52.5**	**6.677**	**10.32**	**12.46**	**611.5**	**1,067.2**	**1,936**	**1,915.0**	**4,918**	**-42.7**	**-87.6**
Brunei	5.0	1.6	-68.2	0.019	10.32	12.46	1.7	4.5	0.5	8.7	14	-61.6	-87.3
Cambodia	16.9	7.2	-57.5	0.063	10.32	12.46	7.8	15.3	40.4	20.5	76	-48.7	-89.7
Indonesia	385.0	187.8	-51.2	1.795	10.32	12.46	205.0	348.1	1,038	726.7	2,113	-41.1	-90.3
Lao PDR	6.9	2.9	-57.7	0.008	10.32	12.46	3.2	6.2	31.6	24.8	63	-48.9	-94.9
Malaysia	148.3	72.0	-51.5	1.017	10.32	12.46	78.6	134.1	95.6	303.3	533	-41.4	-85.3
Myanmar	42.7	15.1	-64.5	0.127	10.32	12.46	16.5	38.6	197.5	48.3	284	-57.1	-94.2
Singapore	183.1	58.8	-67.9	1.534	10.32	12.46	64.1	165.6	33.2	70.1	269	-61.3	-76.1
Thailand	225.7	108.7	-51.8	1.109	10.32	12.46	118.6	204.1	289.6	325.0	819	-41.9	-85.5
Vietnam	166.6	106.1	-36.3	1.005	10.32	12.46	115.8	150.7	209.2	387.5	747	-23.1	-84.5
South Korea	**279.8**	**142.0**	**-49.2**	**1.596**	**10.69**	**12.54**	**156.0**	**262.0**	**104.4**	**503.4**	**870**	**-40.5**	**-82.1**
Taiwan	**154.6**	**85.2**	**-44.9**	**0.791**	**10.70**	**10.61**	**79.2**	**144.9**	**85.9**	**347.4**	**578**	**-45.4**	**-86.3**

United States	**2,183.4**	**890.2**	**-59.2**	**5.722**	**10.58**	**8.75**	**682.0**	**2,023.6**	**830.1**	**3,136.8**	**5,991**	**-66.3**	**-88.6**
All regions	**18,930**	**8,627**	**-54.4**	**58.2**	**9.96**	**8.82**	**6,668**	**16,519**	**33,789**	**30,893**	**81,200**	**-59.6**	**-91.8**

[1] From Table S4.

[2] The total capital cost includes the capital cost of new WWS electricity and heat generators; new equipment for electricity storage, low-temperature building heat storage, and hydrogen storage; hydrogen electrolyzers and compressors; heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2020 and 2050.

[3] This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 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 (e), respectively, multiplied by the energy consumed per year, which equals the end-use demand from Column (b) or (a), respectively, multiplied by 8,760 hours per year.

[6] The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 from Table S26, Column (a), multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy – Jacobson et al., 2019) and by a value of statistical life (VOSL) calculated for each country, 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). See Jacobson and Delucchi (2024) for values in each country and Note S8 for a discussion.

[7] The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S26, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S26, Column (f) (in 2020 USD), which is updated from values in Jacobson et al. (2019), which were in 2013 USD. See Note S8 for a discussion.

Table S26. Regional (a) estimated 2050 air pollution mortalities per year due to all sources of air pollution (about 90% of which are due to energy sources); (b) 2050 carbon dioxide-equivalent emissions (CO_2e) from energy sources; (c) cost per tonne-CO_2e-eliminated of converting to WWS; (d) BAU energy cost per tonne-CO_2e emitted; (e) BAU health cost per tonne-CO_2e emitted; (f) BAU climate cost per tonne-CO_2e emitted (social cost of carbon); (g) BAU total social cost per tonne-CO_2e emitted; (h) BAU health cost per unit-all-BAU-energy produced; and (i) BAU climate cost per unit-all-BAU-energy produced.

Region or country	(a)[1] 2050 BAU air pollution mortalities/y	(b)[2] 2050 BAU CO_2e (Mtonne/y)	(c)[3] 2050 WWS energy cost ($/tonne-$CO_2e$-eliminated)	(d)[4] 2050 BAU energy cost ($/tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
Africa-East	**368,987**	**183**	**314.1**	**838**	**4,119**	**558**	**5,516**	**38.4**	**5.2**
Eritrea	6,912	2	155.6	482	5,988	558	7,028	97.1	9.0
Ethiopia	152,676	41	408.0	1,312	5,896	558	7,766	35.2	3.3
Kenya	17,759	48	183.4	523	968	558	2,050	14.5	8.3
Rwanda	10,612	3	491.6	1,465	6,784	558	8,808	36.2	3.0
South Sudan	19,243	3	156.8	409	13,088	560	14,056	250.5	10.7
Sudan	66,066	43	217.5	488	4,970	558	6,016	79.7	9.0
Tanzania	31,178	29	379.0	1,011	2,554	558	4,123	19.8	4.3
Uganda	64,541	15	652.4	1,247	7,727	558	9,531	48.5	3.5
Africa-North	**143,559**	**1,298**	**82.6**	**291**	**473**	**558**	**1,322**	**18.4**	**21.8**
Algeria	10,788	372	77.5	324	201	558	1,083	7.0	19.6
Egypt	63,218	557	94.6	294	669	558	1,522	25.8	21.5
Libya	2,943	136	46.3	182	147	558	887	9.2	34.8
Morocco	10,340	159	74.7	243	359	558	1,160	16.8	26.1
Niger	52,061	5	202.5	1,203	11,876	558	13,638	111.9	5.3
Tunisia	4,209	68	94.7	346	373	558	1,277	12.2	18.3
Africa-South	**92,316**	**1,076**	**82.0**	**211**	**310**	**558**	**1,079**	**13.7**	**24.6**
Angola	19,997	53	112.6	358	1,790	558	2,706	46.5	14.5
Botswana	940	15	83.6	230	450	559	1,239	18.1	22.5
Mozambique	24,785	19	240.3	739	1,955	558	3,252	24.6	7.0
Namibia	961	9	138.4	397	711	558	1,665	16.6	13.0
South Africa	18,075	936	69.2	166	126	558	850	7.1	31.3
Eswatini, Kingd.	785	3	289.2	634	1,219	559	2,412	17.9	8.2
Zambia	15,983	15	370.3	964	3,270	558	4,793	31.5	5.4
Zimbabwe	10,790	26	151.9	580	707	558	1,845	11.3	8.9
Africa-West	**644,813**	**476**	**242.3**	**750**	**5,072**	**558**	**6,380**	**67.4**	**7.4**
Benin	17,080	19	149.4	505	1,815	558	2,878	35.8	11.0
Cameroon	25,940	22	218.3	670	3,141	558	4,369	46.7	8.3
Congo	4,535	16	79.3	236	1,231	559	2,027	51.9	23.6
Congo, DR	93,264	7	1,262	4,451	10,638	558	15,647	23.8	1.3
Côte d'Ivoire	33,702	31	181.5	483	3,104	558	4,146	64.0	11.5
Equatorial Guin.	919	15	149.6	220	597	558	1,375	27.1	25.3
Gabon	1,054	12	604.4	830	719	558	2,108	8.6	6.7
Ghana	25,489	51	182.1	375	1,642	558	2,575	43.7	14.8
Nigeria	417,387	273	250.6	874	7,220	559	8,652	82.3	6.4
Senegal	12,993	26	128.5	275	1,110	558	1,942	40.3	20.3
Togo	12,450	5	274.6	868	3,736	559	5,162	42.9	6.4
Australia	**3,034**	**597**	**102.5**	**303**	**58**	**558**	**919**	**2.0**	**18.9**
Canada	**3,764**	**892**	**100.6**	**319**	**47**	**559**	**925**	**1.2**	**14.2**
Central America	**45,608**	**910**	**102.6**	**304**	**356**	**558**	**1,218**	**12.3**	**19.3**
Costa Rica	1,008	14	173.0	465	470	559	1,495	10.6	12.6
El Salvador	1,558	14	109.6	308	517	558	1,384	17.6	19.0
Guatemala	7,217	35	119.6	527	907	558	1,993	18.1	11.1
Honduras	3,162	17	109.3	363	629	558	1,550	18.2	16.1
Mexico	29,973	799	98.1	278	316	558	1,153	11.9	21.1

Nicaragua	1,908	9	131.2	479	945	558	1,982	20.7	12.2
Panama	782	22	173.7	674	284	559	1,517	4.4	8.7
Central Asia	**235,560**	**1,130**	**89.0**	**311**	**895**	**558**	**1,764**	**29.5**	**18.4**
Kazakhstan	7,774	314	64.8	231	291	558	1,081	12.9	24.8
Kyrgyz Republic	3,796	16	130.0	341	1,001	558	1,900	30.0	16.8
Pakistan	204,993	475	116.8	370	1,676	558	2,604	46.4	15.5
Tajikistan	5,315	15	160.8	369	1,303	559	2,231	36.2	15.5
Turkmenistan	2,073	124	43.0	250	163	558	971	6.7	22.9
Uzbekistan	11,609	187	80.1	330	366	558	1,254	11.4	17.4
China region	**1,134,535**	**16,066**	**116.4**	**264**	**669**	**558**	**1,492**	**24.2**	**20.1**
China	1,090,244	15,805	116.3	263	671	558	1,492	24.3	20.2
Hong Kong	3,982	72	211.8	626	762	559	1,946	11.6	8.5
Korea, DPR	37,703	135	99.7	190	605	558	1,353	30.3	28.0
Mongolia	2,606	54	55.8	161	340	559	1,059	20.1	33.1
Cuba	**4,851**	**43**	**127.2**	**283**	**872**	**558**	**1,713**	**35.9**	**22.9**
Europe	**179,603**	**4,705**	**138.7**	**385**	**377**	**558**	**1,320**	**9.9**	**14.6**
Albania	1,766	7	199.5	486	2,093	558	3,137	43.4	11.6
Austria	1,741	87	166.9	447	234	559	1,240	5.3	12.6
Belarus	5,001	87	101.7	343	579	558	1,480	17.0	16.4
Belgium	2,294	126	160.1	442	207	558	1,207	4.7	12.7
Bosnia-Herzeg.	3,661	23	110.4	315	1,273	558	2,146	40.7	17.8
Bulgaria	3,772	65	104.7	277	588	558	1,424	21.4	20.3
Croatia	1,966	27	151.7	432	805	558	1,795	18.7	13.0
Cyprus	280	10	118.7	307	357	558	1,222	11.7	18.3
Czech Rep.	3,217	128	99.9	287	249	558	1,094	8.7	19.5
Denmark	1,003	36	185.7	564	325	558	1,447	5.8	10.0
Estonia	298	20	73.8	244	144	558	947	5.9	23.0
Finland	544	51	293.1	660	117	558	1,336	1.8	8.5
France	10,527	398	186.7	482	289	558	1,329	6.0	11.7
Germany	19,077	876	121.2	333	255	558	1,146	7.7	16.9
Gibraltar	20	0.88	1,321	6,251	280	559	7,090	0.5	0.9
Greece	4,606	70	124.3	359	598	558	1,516	16.7	15.6
Hungary	4,162	67	136.8	400	567	558	1,526	14.3	14.0
Ireland	782	46	125.9	334	212	558	1,104	6.4	16.8
Italy	18,054	420	131.1	393	449	558	1,400	11.5	14.3
Kosovo	276	13	84.3	211	136	558	905	6.5	26.6
Latvia	878	11	209.5	618	937	558	2,113	15.2	9.1
Lithuania	1,346	21	169.3	495	682	558	1,735	13.9	11.4
Luxembourg	103	11	146.5	452	153	558	1,164	3.4	12.4
Macedonia	1,486	11	86.7	232	987	559	1,778	42.8	24.2
Malta	104	3	437.8	1,701	440	558	2,698	2.6	3.3
Moldova	1,384	14	104.7	329	414	558	1,301	12.6	17.1
Montenegro	481	6	83.6	194	604	558	1,356	31.3	29.0
Netherlands	3,352	193	150.9	447	226	558	1,232	5.1	12.5
Norway	567	56	269.1	706	138	558	1,402	2.0	7.9
Poland	14,360	422	83.9	255	312	558	1,125	12.3	22.0
Portugal	1,656	51	181.3	462	308	558	1,328	6.7	12.1
Romania	13,080	117	114.4	345	1,212	558	2,116	35.3	16.3
Serbia	4,208	46	132.7	354	820	558	1,733	23.3	15.9
Slovakia	1,732	49	121.1	327	336	558	1,221	10.4	17.2
Slovenia	533	19	135.6	342	280	559	1,181	8.2	16.4
Spain	8,585	305	148.4	414	291	559	1,264	7.1	13.6
Sweden	979	51	433.6	940	226	559	1,725	2.4	6.0
Switzerland	1,087	46	217.6	547	301	558	1,406	5.5	10.3
Ukraine	26,812	276	120.0	285	665	558	1,508	23.4	19.7
United Kingdom	13,823	441	129.7	394	348	559	1,300	8.9	14.3
Haiti region	**13,695**	**54**	**173.3**	**306**	**670**	**558**	**1,534**	**24.1**	**20.1**
Dominican Rep.	3,217	48	157.3	243	420	558	1,221	19.0	25.3
Haiti	10,478	6	310.2	847	2,809	559	4,215	36.5	7.3
Iceland	**36**	**4**	**441.1**	**777**	**109**	**559**	**1,445**	**1.0**	**5.3**
India region	**1,658,265**	**6,454**	**116.3**	**243**	**1,468**	**558**	**2,269**	**59.4**	**22.6**
Bangladesh	161,682	231	113.5	271	2,266	558	3,095	82.2	20.2

India	1,444,634	6,141	115.6	238	1,426	558	2,222	58.9	23.1
Nepal	38,313	31	207.0	797	3,232	558	4,586	39.8	6.9
Sri Lanka	13,636	52	155.4	395	1,825	558	2,778	45.3	13.9
Israel	**1,544**	**78**	**150.6**	**310**	**201**	**558**	**1,069**	**7.3**	**20.2**
Jamaica	**698**	**14**	**114.8**	**289**	**242**	**558**	**1,090**	**9.5**	**22.0**
Japan	**27,181**	**1,143**	**129.7**	**264**	**229**	**558**	**1,051**	**9.1**	**22.1**
Madagascar	**29,683**	**11**	**307.8**	**916**	**4,539**	**558**	**6,014**	**46.3**	**5.7**
Mauritius	**418**	**9**	**164.3**	**434**	**417**	**558**	**1,408**	**10.1**	**13.6**
Mideast	**118,866**	**4,889**	**89.8**	**281**	**176**	**558**	**1,015**	**7.1**	**22.5**
Armenia	1,429	10	111.5	518	1,010	558	2,086	22.1	12.2
Azerbaijan	3,755	55	89.9	369	685	558	1,612	21.0	17.2
Bahrain	172	76	84.4	210	27	558	796	1.5	30.1
Iran	21,479	1,443	84.2	292	119	558	969	4.6	21.7
Iraq	12,495	361	39.8	138	251	558	947	20.7	46.0
Jordan	1,836	49	88.1	271	229	559	1,058	9.6	23.4
Kuwait	888	199	86.9	289	63	558	911	2.5	21.9
Lebanon	1,289	52	61.1	189	173	558	919	10.4	33.6
Oman	747	192	82.8	281	44	558	883	1.8	22.6
Qatar	203	198	102.1	369	18	558	946	0.6	17.1
Saudi Arabia	9,771	1,191	86.5	244	105	558	907	4.9	25.9
Syria	9,310	53	67.8	221	905	559	1,684	46.5	28.7
Turkiye	28,516	591	91.8	284	388	558	1,231	15.5	22.3
UAE	787	393	171.9	454	28	558	1,040	0.7	13.9
Yemen	26,189	24	49.6	201	3,623	558	4,382	204.0	31.4
New Zealand	**444**	**53**	**218.3**	**379**	**98**	**559**	**1,036**	**2.1**	**12.1**
Philippines	**126,965**	**320**	**90.4**	**223**	**2,119**	**558**	**2,901**	**97.0**	**25.5**
Russia region	**59,101**	**2,371**	**71.6**	**274**	**254**	**558**	**1,086**	**9.4**	**20.7**
Georgia	4,111	17	123.5	425	1,798	558	2,782	42.9	13.3
Russia	54,990	2,353	71.2	272	243	558	1,073	9.0	20.8
South Am-NW	**40,985**	**584**	**106.2**	**251**	**415**	**558**	**1,224**	**13.7**	**18.5**
Bolivia	5,510	39	96.0	269	581	558	1,408	17.9	17.2
Colombia	11,703	135	146.1	339	537	558	1,434	13.2	13.7
Curacao	9	4	291.0	921	21	559	1,501	0.2	5.0
Ecuador	2,873	72	93.0	228	223	558	1,010	8.1	20.3
Peru	13,130	96	123.4	290	799	558	1,647	22.9	16.0
Suriname	225	5	86.8	212	330	558	1,100	12.9	21.8
Trinidad/Tobago	271	51	114.3	169	51	558	778	2.5	27.4
Venezuela	7,264	183	69.6	181	273	558	1,012	12.5	25.6
South Am-SE	**69,097**	**1,398**	**184.9**	**397**	**363**	**558**	**1,318**	**7.6**	**11.8**
Argentina	12,153	330	102.8	266	298	558	1,122	9.4	17.6
Brazil	49,639	877	219.1	464	402	558	1,425	7.2	10.1
Chile	4,119	164	150.1	273	236	558	1,067	7.2	17.1
Paraguay	2,511	16	265.8	561	797	558	1,917	11.9	8.3
Uruguay	675	12	309.2	574	442	559	1,575	6.4	8.1
Southeast Asia	**316,266**	**3,430**	**178.3**	**311**	**564**	**558**	**1,434**	**18.7**	**18.5**
Brunei	36	16	112.3	292	34	558	884	1.2	19.7
Cambodia	12,111	37	214.2	417	1,102	558	2,078	27.3	13.8
Indonesia	155,525	1,302	157.5	267	798	558	1,624	30.8	21.6
Lao PDR	6,920	44	71.9	141	712	558	1,412	52.3	41.0
Malaysia	9,353	543	144.6	247	176	558	981	7.4	23.3
Myanmar	50,469	87	191.1	446	2,283	558	3,287	52.8	12.9
Singapore	2,107	126	510.3	1,317	264	558	2,139	2.1	4.4
Thailand	35,606	582	203.7	351	497	558	1,406	14.7	16.4
Vietnam	44,139	694	166.9	217	301	558	1,077	14.3	26.5
South Korea	**8,980**	**901**	**173.0**	**291**	**116**	**558**	**965**	**4.3**	**20.5**
Taiwan	**6,649**	**622**	**127.2**	**233**	**138**	**558**	**929**	**6.3**	**25.6**
United States	**62,694**	**5,617**	**121.4**	**360**	**148**	**558**	**1,067**	**4.3**	**16.4**
All regions	**5,398,197**	**55,329**	**120.52**	**299**	**611**	**558**	**1,468**	**20.4**	**18.6**

[1] 2050 BAU mortalities/y due to air pollution are calculated from 2019 indoor plus outdoor country-specific air pollution mortalities/y provided directly by WHO (2022a,b). WHO calculates 2019 mortalities/y by multiplying age-standardized mortality rates per unit population for each country for different air-pollution-related causes of death

(lower respiratory tract illness; trachea, bronchus, and lung cancers; heart disease; stroke; and chronic obstructive pulmonary disease) by the 2019 population of the country. The 2019 values are then extrapolated to 2050 using Equation S35 from Jacobson et al. (2019). The extrapolation accounts for the projected 2050 population of each country, the fractional rate of change per year in each country in the air pollution death rate due to emission controls, and the estimated change in exposed population per unit change in population. It does not account for the change in age distribution with time. All components of the calculation for each country are given in Jacobson and Delucchi (2024). The result is a lower air pollution death rate in 2050 summed over all 149 countries (5.4 million/y in 2050 versus 7.19 million/y in 2019) and in most countries due to improved BAU emission-reduction technologies between 2019 and 2050.

[2] CO_2e=CO_2-equivalent emissions. This accounts for the emissions of CO_2 plus the emissions of other greenhouse gases multiplied by their global warming potentials. The emissions from these 149 countries represent 99.75% of world anthropogenic CO_2e emissions.

[3] Calculated as the WWS private energy and total social cost from Table S25, Column (g) divided by the CO_2e emission rate from Column (b) of the present table.

[4] Columns (d)-(g) are calculated as the BAU private energy cost, health cost, climate cost, and total social costs from Table S25, 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 S25, Columns (i)-(j), respectively, each divided by the BAU end-use demand from Table S25, Column (a) and by 8,760 hours per year.

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

WWS technology	Footprint (m^2/MW)	Spacing (km^2/MW)	Installed power density (MW/km^2)
Onshore wind	3.22	0.0505	19.8
Offshore wind	3.22	0.139	7.2
Wave device	700	0.033	30.3
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 S28. Footprint areas for *new* utility PV farms, CSP plants, solar thermal plants for heat, geothermal plants for electricity and heat, and hydropower plants and spacing areas for new onshore wind turbines, for each grid region.

Region	(a) Region land area (km^2)	(b) Footprint area (% of region land area)	(c) Spacing area (% of region land area)	(d) Footprint + spacing area (% of region land area)	(e) Footprint + spacing area (km^2)
Africa-East	5,286,165	0.035	0.072	0.107	5,650
Africa-North	7,005,090	0.030	0.107	0.136	9,552
Africa-South	5,783,635	0.024	0.135	0.159	9,218
Africa-West	5,182,970	0.048	0.416	0.464	24,024
Australia	7,682,300	0.013	0.079	0.092	7,067
Canada	9,093,510	0.005	0.092	0.097	8,797
Central America	2,429,460	0.101	0.284	0.386	9,368
Central Asia	4,697,670	0.044	0.216	0.260	12,207
China region	11,063,254	0.384	1.156	1.540	170,317
Cuba	106,440	0.136	0.288	0.424	451
Europe	5,671,860	0.289	0.607	0.896	50,818
Haiti region	75,880	0.157	1.652	1.809	1,372
Iceland	100,250	0.000	0.033	0.033	33
India region	3,309,420	0.774	1.254	2.028	67,111
Israel	21,640	3.006	0.731	3.738	809
Jamaica	10,830	0.347	0.121	0.468	51
Japan	364,560	0.949	0.087	1.037	3,779
Madagascar	581,795	0.020	0.076	0.095	554
Mauritius	2,040	1.788	0.220	2.009	40
Mideast	6,327,218	0.226	0.525	0.751	47,518
New Zealand	263,310	0.072	0.574	0.646	1,701
Philippines	298,170	0.479	0.398	0.877	2,614
Russia region	16,446,360	0.012	0.151	0.163	26,735
South Am-NW	4,764,784	0.030	0.178	0.207	9,885
South Am-SE	12,410,682	0.024	0.250	0.275	34,090
Southeast Asia	4,027,647	0.385	0.062	0.447	17,986
South Korea	97,350	4.107	0.020	4.127	4,017
Taiwan	36,193	3.469	0.352	3.821	1,383
United States	9,147,420	0.158	0.900	1.057	96,717
All regions	**122,287,903**	**0.131**	**0.379**	**0.510**	**623,864**

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

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

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

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

From Jacobson et al. (2022). See Note S10 for more details.

Table S30. 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 region. (a) Jobs produced; (b) jobs lost; (c) net jobs produced (long-term, full-time jobs produced minus lost).

Region	(a) Jobs produced	(b) Jobs lost	(c) Net jobs
Africa-East	917,123	845,270	71,853
Africa-North	928,512	876,394	52,118
Africa-South	826,111	711,675	114,436
Africa-West	1,426,055	1,788,503	-362,448
Australia	437,754	394,526	43,228
Canada	363,141	670,313	-307,172
Central America	739,290	492,595	246,695
Central Asia	924,323	810,410	113,913
China region	12,154,099	3,039,032	9,115,067
Cuba	64,169	18,916	45,253
Europe	5,121,737	2,112,592	3,009,145
Haiti region	117,972	36,560	81,412
Iceland	9,669	3,895	5,774
India region	6,298,696	2,428,773	3,869,923
Israel	154,183	36,563	117,620
Jamaica	20,937	4,896	16,041
Japan	850,595	236,070	614,525
Madagascar	57,155	71,138	-13,983
Mauritius	13,708	4,552	9,156
Mideast	3,334,546	3,276,502	58,044
New Zealand	75,409	35,099	40,310
Philippines	376,148	130,615	245,533
Russia region	930,563	1,162,357	-231,794
South Am-NW	549,689	523,359	26,330
South Am-SE	1,769,180	1,227,633	541,547
Southeast Asia	4,152,632	1,694,827	2,457,805
South Korea	896,718	184,174	712,544
Taiwan	441,571	103,400	338,171
United States	4,245,395	2,376,408	1,868,987
All regions	**48,197,080**	**25,297,047**	**22,900,033**

Job 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.

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.

Jobs for electricity generation technologies are the number of long-term, full-time jobs per MW in each country multiplied by the 2050 final nameplate capacities (Table S10) minus the 2022 nameplate capacities (Table S9) for each device for construction jobs and the 2050 nameplate capacities alone for operation jobs. The jobs per MW for each device in each country is calculated with the methodology in Jacobson et al. (2017) to scale U.S. jobs from Table S29 by year and country. For storage, the number of jobs per MW from Table S29 is multiplied by the maximum discharge rate of the storage technology for each region (Table S14). The transmission/distribution jobs are calculated as in the spreadsheet (Jacobson and Delucchi, 2024).

Supporting Figures

Figure S1. 2050 end-use load and capital cost to meet the load by region. Data from Table S26.

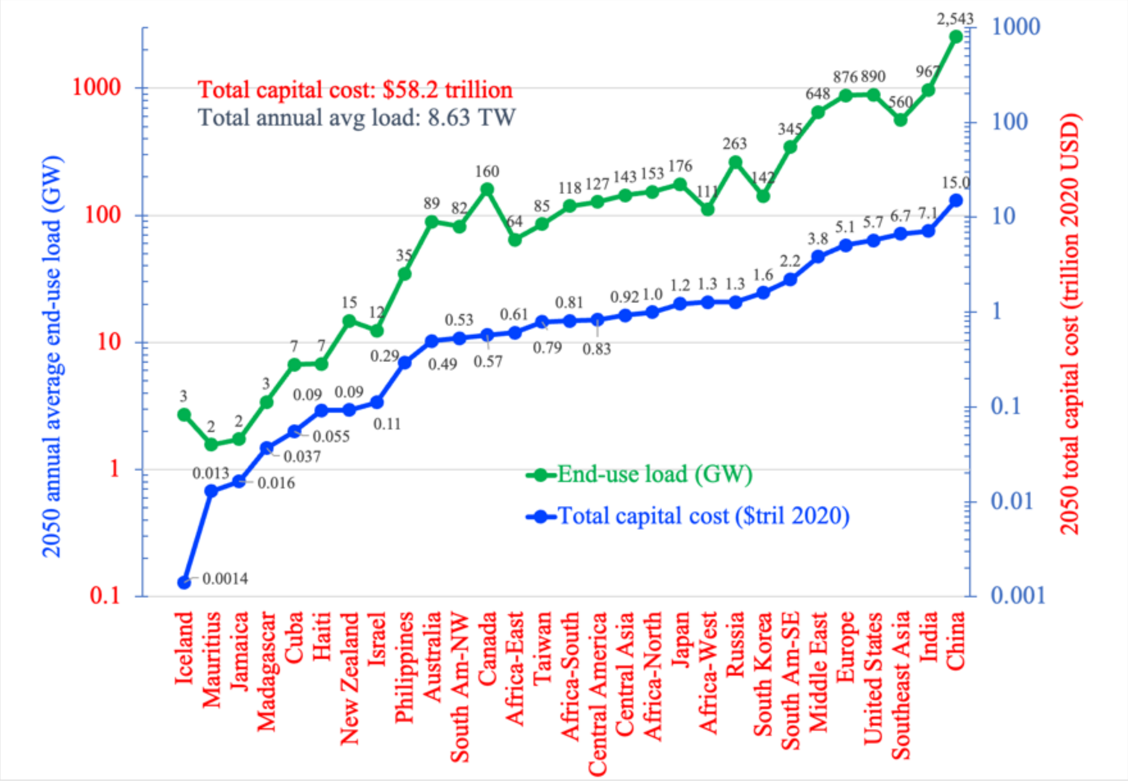


Figure S2. Low, medium, and high levelized cost of energy in the WWS case in each of the 29 regions and an average of all regions. Data from Tables S24 and S25.

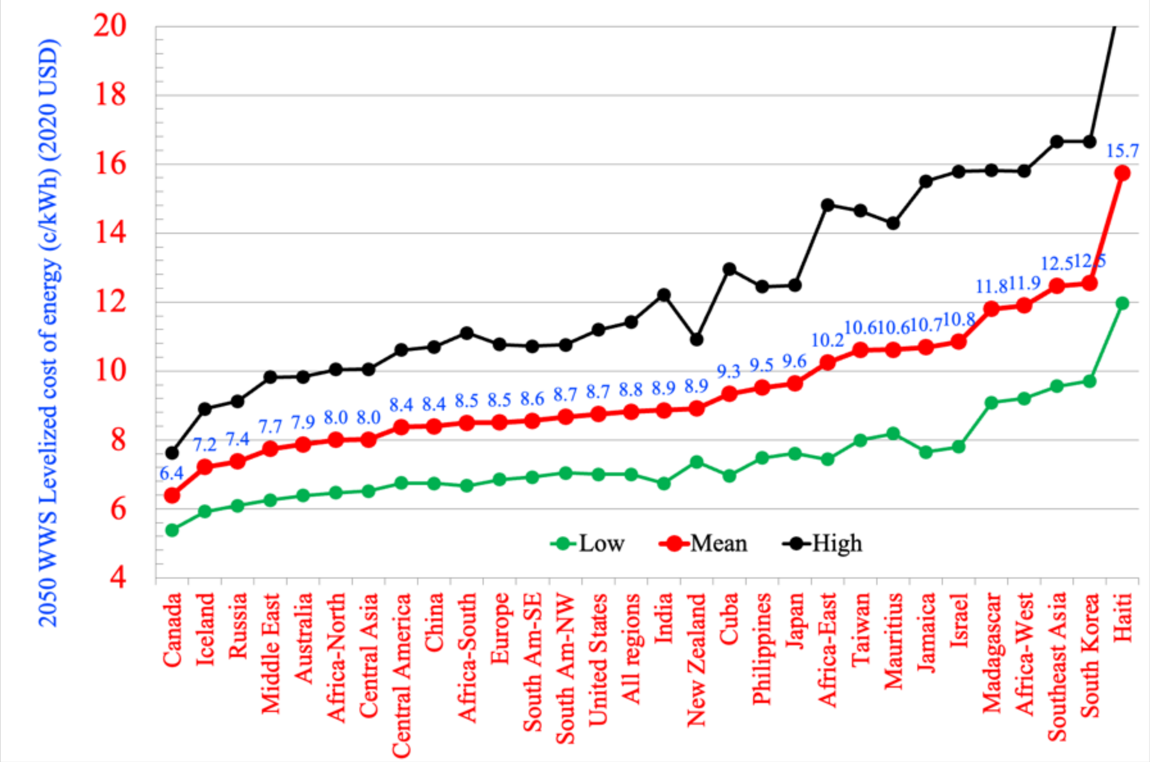


Figure S3. Footprint and spacing areas required to transition each of the 29 regions studied here. From Table S28.

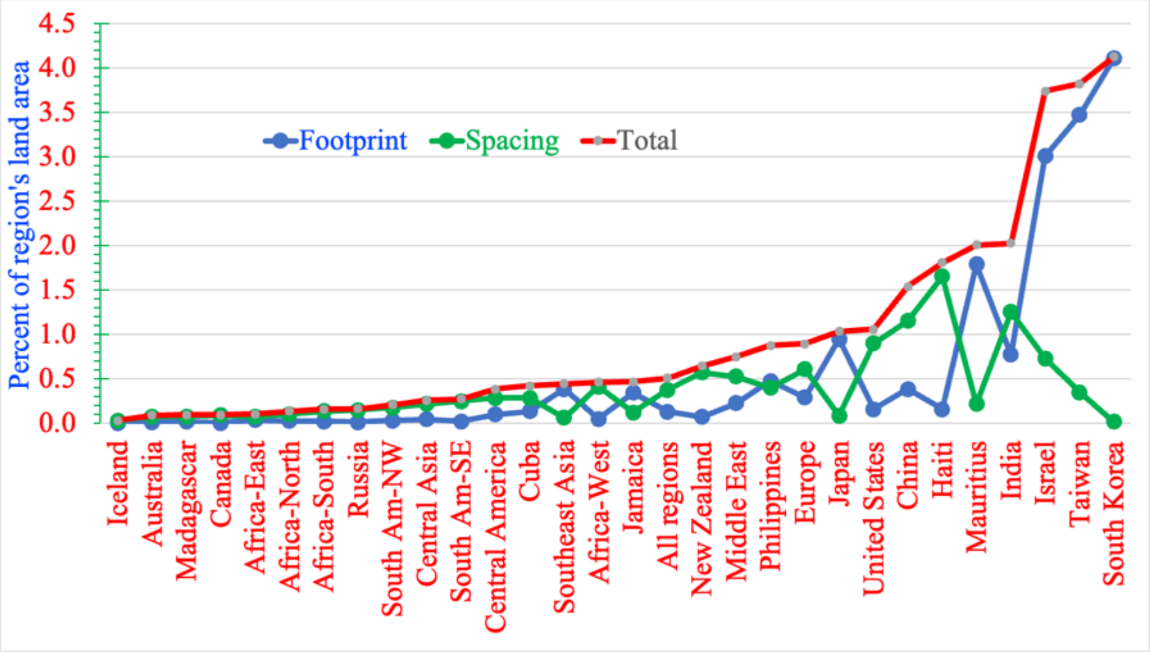
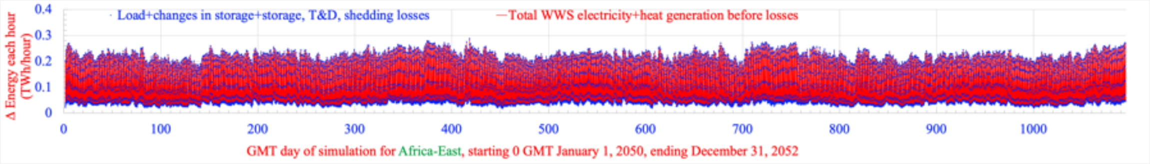
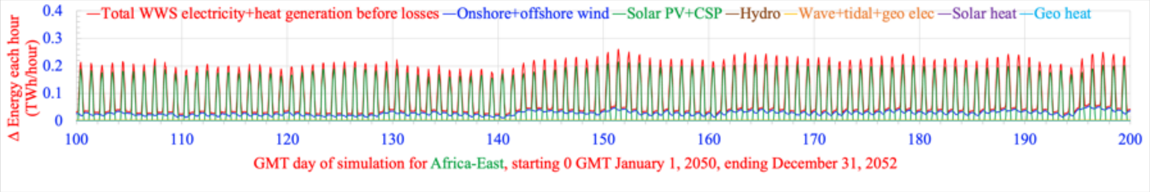


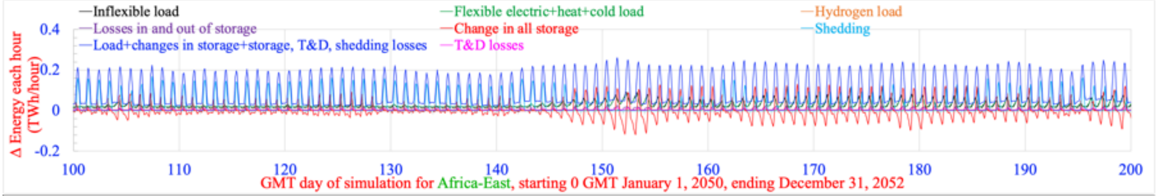
Figure S4. 2050-2052 hourly time series showing the matching of all-energy demand with supply and storage for the regions defined in Table S1. First row: modeled time-dependent total WWS power generation versus demand plus losses plus changes in storage plus shedding for the full three-year simulation 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 demand; flexible electric, heat, and cold demands; flexible hydrogen demand; 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 demand, and building total heat demand (as used in LOADMATCH), summed over the countries in each region for 10 days; Sixth row: correlation plots of building heat demand 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 demand, and cold demand were provided and fed into LOADMATCH at 30-s time increments. LOADMATCH modified the magnitudes, but not time series, of GATOR-GCMOM results, as described in this document.

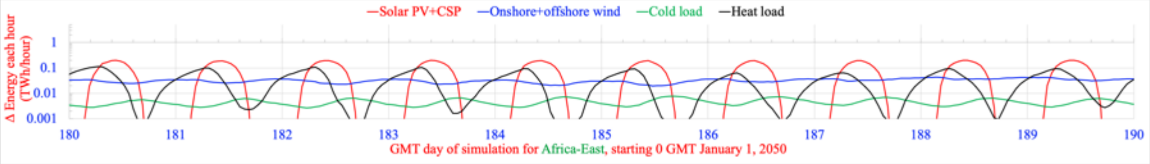
AFRICA-EAST

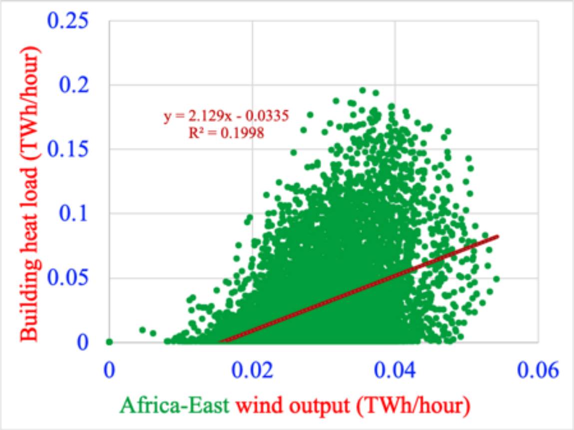

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Africa-East, starting 0 GMT January 1, 2050, ending December 31, 2052

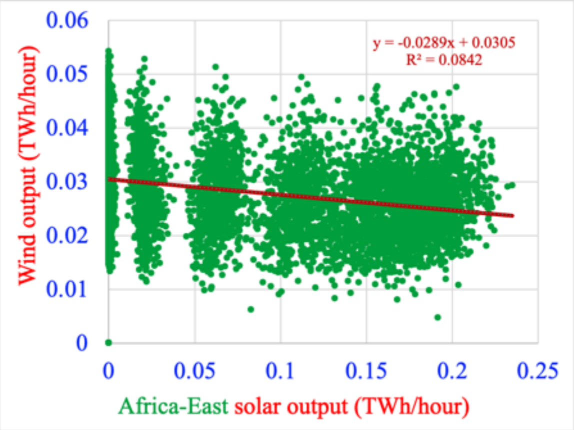

Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa-East, starting 0 GMT January 1, 2050, ending December 31, 2052


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

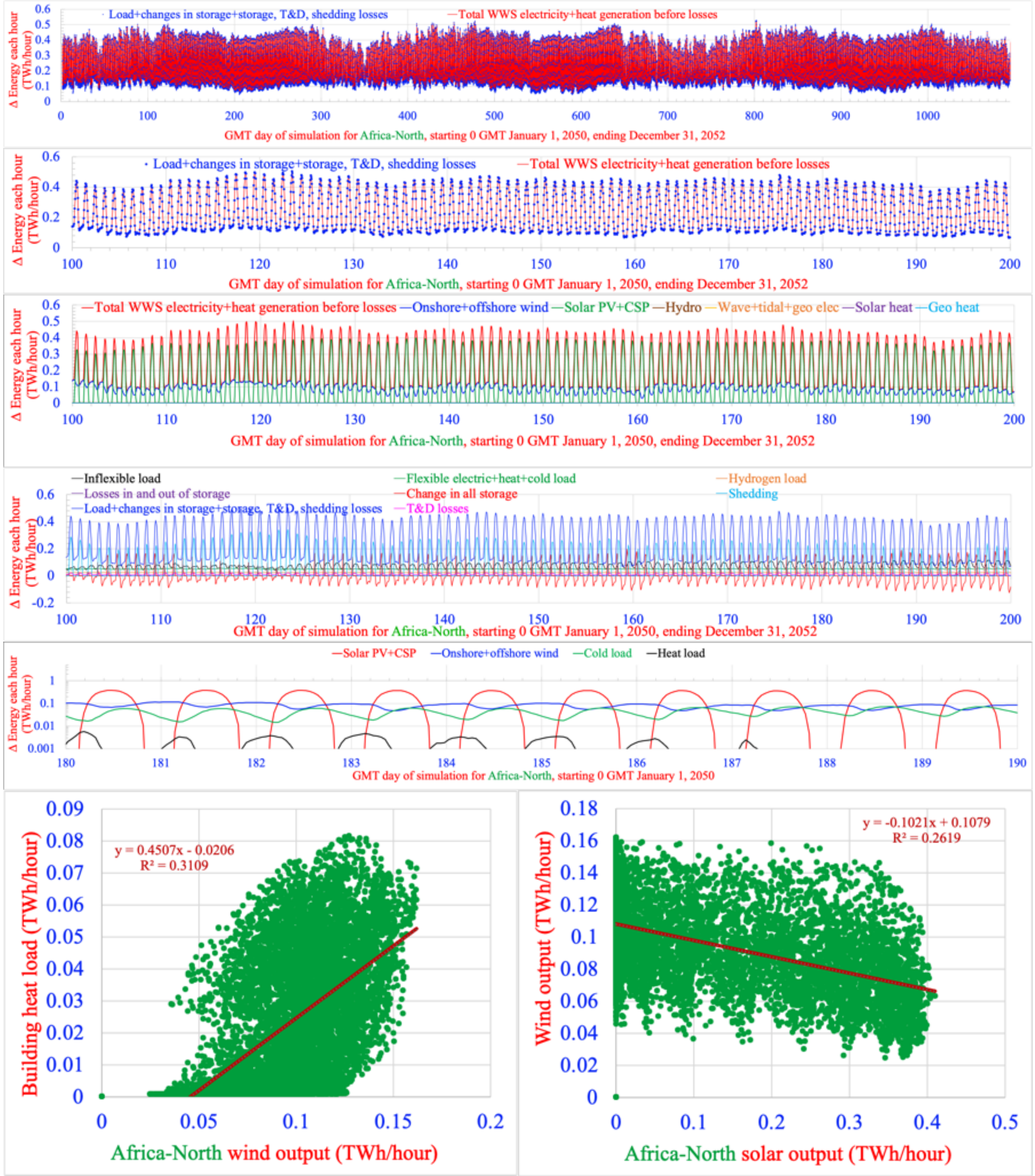

—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
0.4
0.2
0
-0.2
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation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


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

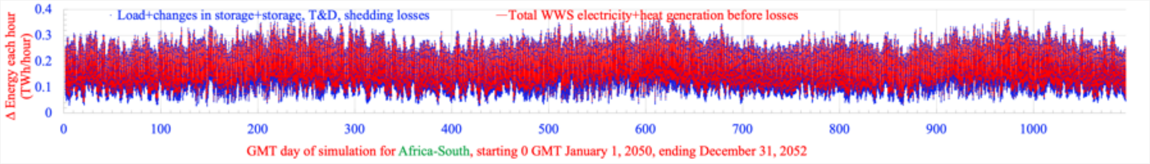

Building heat load (TWh/hour)
0.25
0.2
0.15
0.1
0.05
0
y = 2.129x - 0.0335
R² = 0.1998
0
0.02
0.04
0.06
Africa-East wind output (TWh/hour)

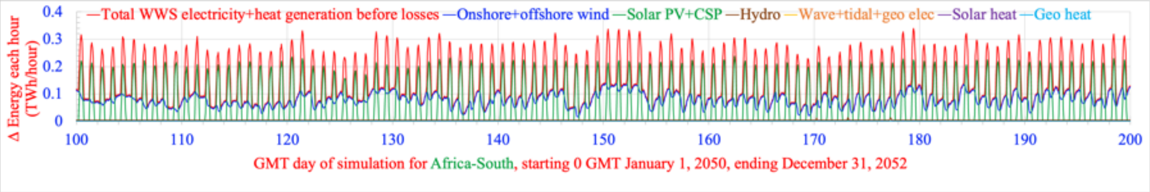

Wind output (TWh/hour)
0.06
0.05
0.04
0.03
0.02
0.01
0
y = -0.0289x + 0.0305
R² = 0.0842
0
0.05
0.1
0.15
0.2
0.25
Africa-East solar output (TWh/hour)

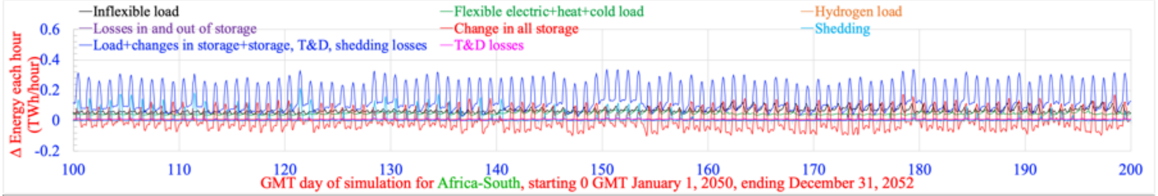
AFRICA-NORTH

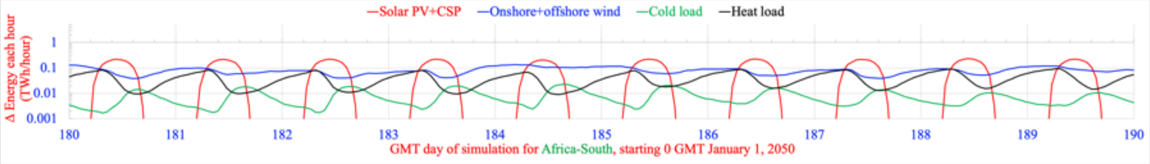


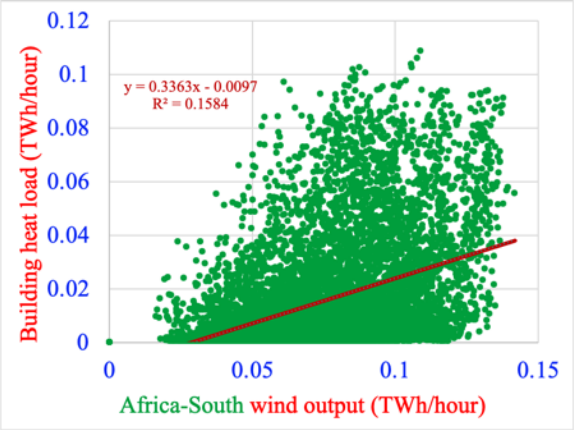
AFRICA-SOUTH

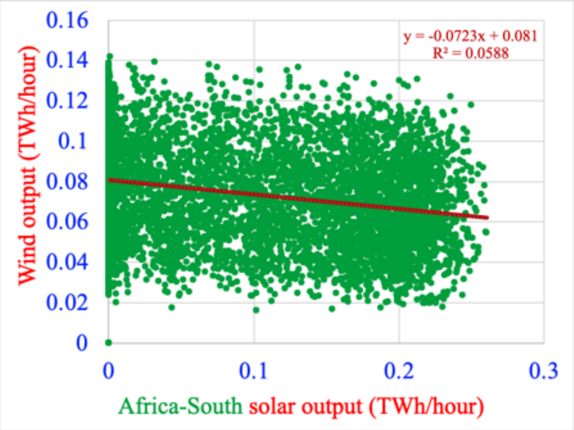




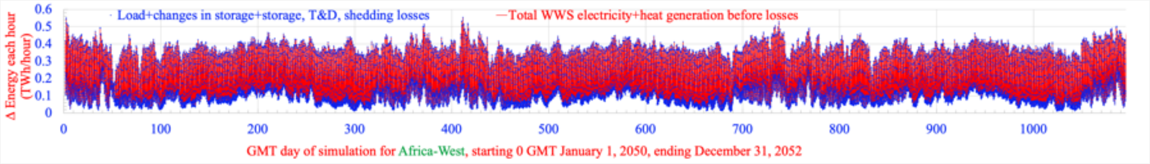




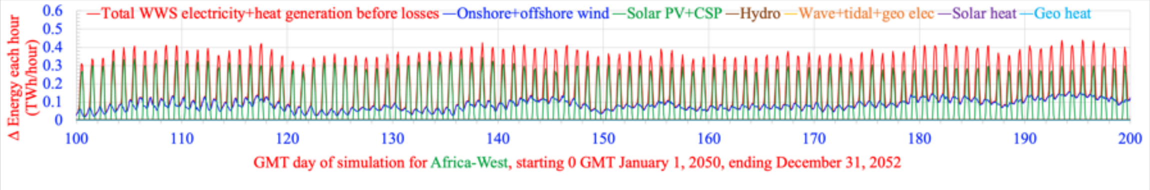


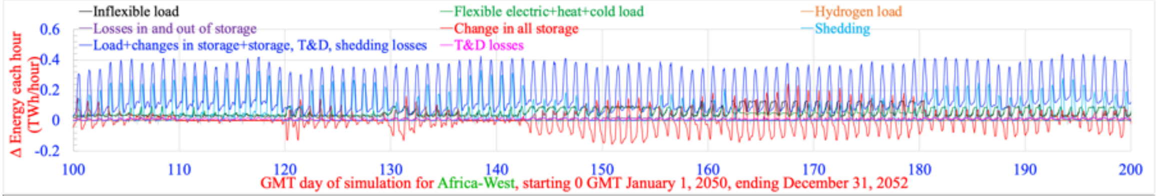


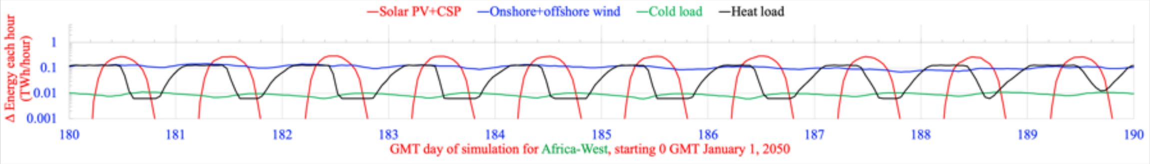
AFRICA-WEST

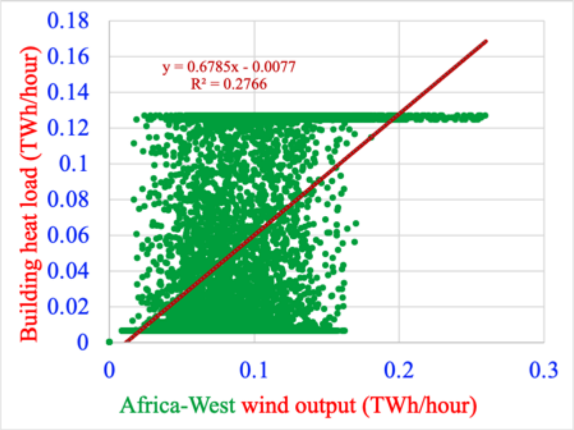

Δ Energy each hour (TWh/hour)
0
0.1
0.2
0.3
0.4
0.5
0.6
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Africa-West, starting 0 GMT January 1, 2050, ending December 31, 2052

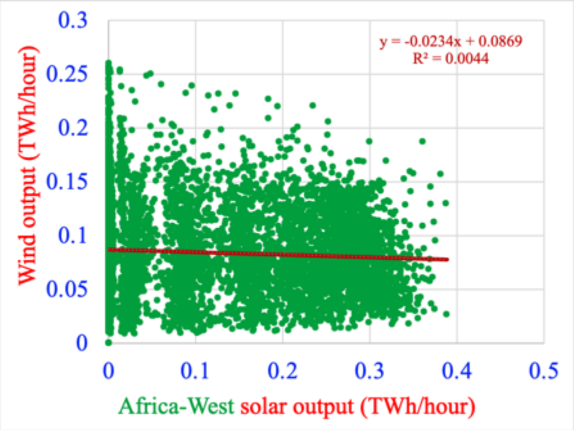

Δ Energy each hour (TWh/hour)
0
0.2
0.4
0.6
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa-West, starting 0 GMT January 1, 2050, ending December 31, 2052


Δ Energy each hour (TWh/hour)
0
0.1
0.2
0.3
0.4
0.5
0.6
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
—Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Africa-West, starting 0 GMT January 1, 2050, ending December 31, 2052

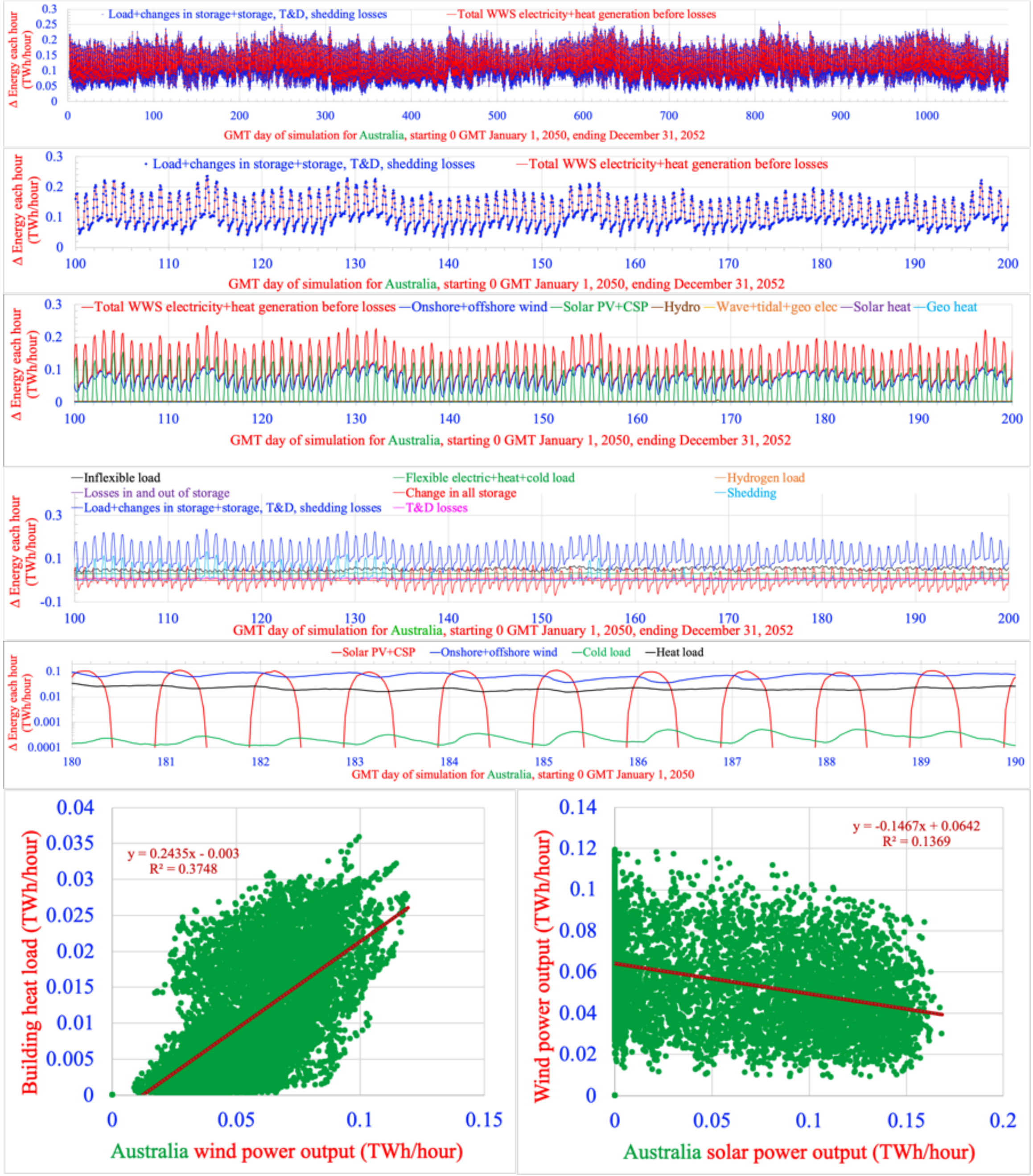

Δ Energy each hour (TWh/hour)
-0.2
0
0.2
0.4
0.6
—Inflexible load
—Losses in and out of storage
—Load+changes in storage+storage, T&D, shedding losses
—Flexible electric+heat+cold load
—Change in all storage
—T&D losses
—Hydrogen load
—Shedding
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation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


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

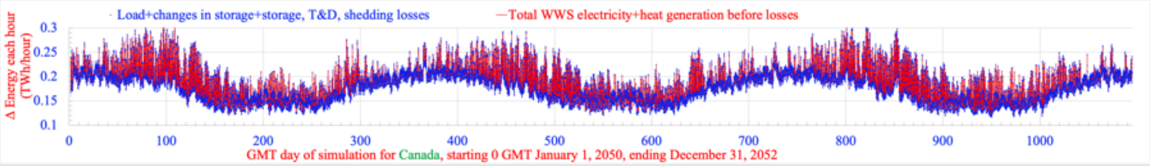

Building heat load (TWh/hour)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
y = 0.6785x - 0.0077
R² = 0.2766
0
0.1
0.2
0.3
Africa-West wind output (TWh/hour)


Wind output (TWh/hour)
0
0.05
0.1
0.15
0.2
0.25
0.3
y = -0.0234x + 0.0869
R² = 0.0044
0
0.1
0.2
0.3
0.4
0.5
Africa-West solar output (TWh/hour)

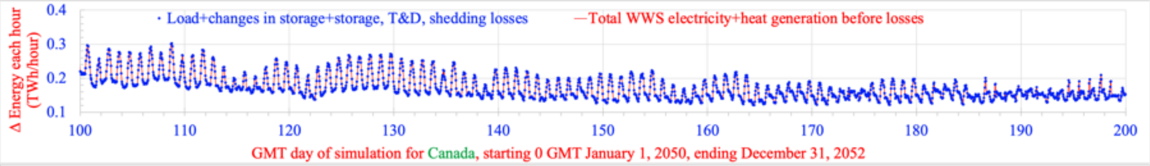
AUSTRALIA


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 = 0.2435x - 0.003
R² = 0.3748
Building heat load (TWh/hour)
Australia wind power output (TWh/hour)
y = -0.1467x + 0.0642
R² = 0.1369
Wind power output (TWh/hour)
Australia solar power output (TWh/hour)

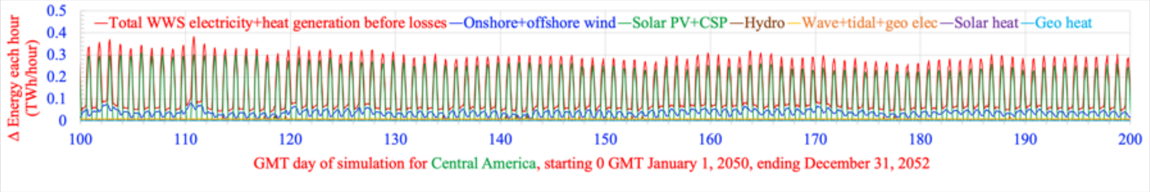
CANADA



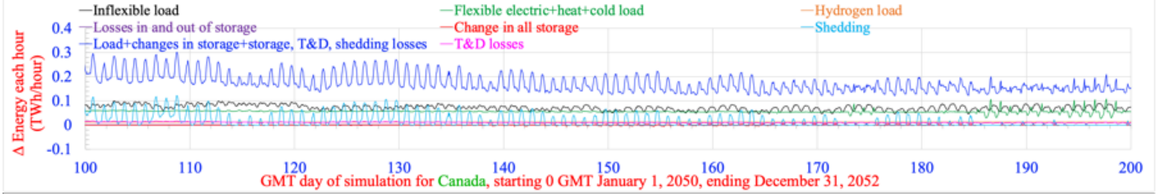
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.3
0.25
0.2
0.15
0.1
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052



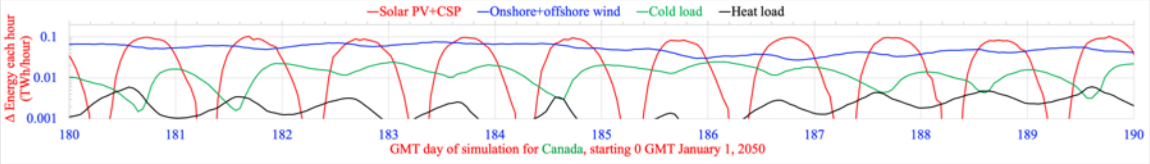
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Canada, starting 0 GMT January 1, 2050, ending December 31, 2052



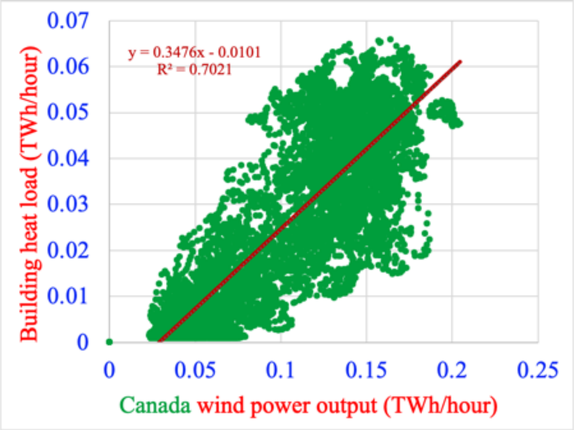
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
0.5
0.4
0.3
0.2
0.1
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Central America, starting 0 GMT January 1, 2050, ending December 31, 2052



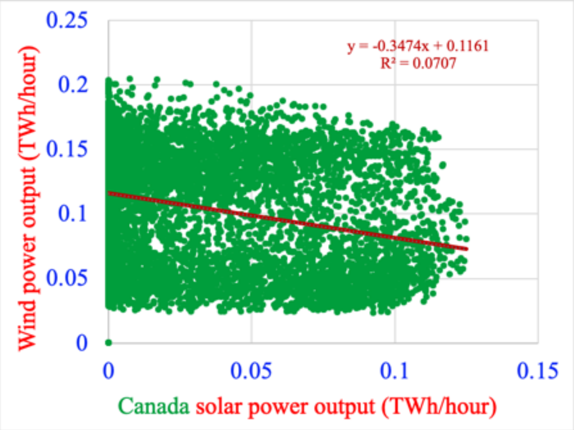
Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
0.4
0.3
0.2
0.1
0
-0.1
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation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



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

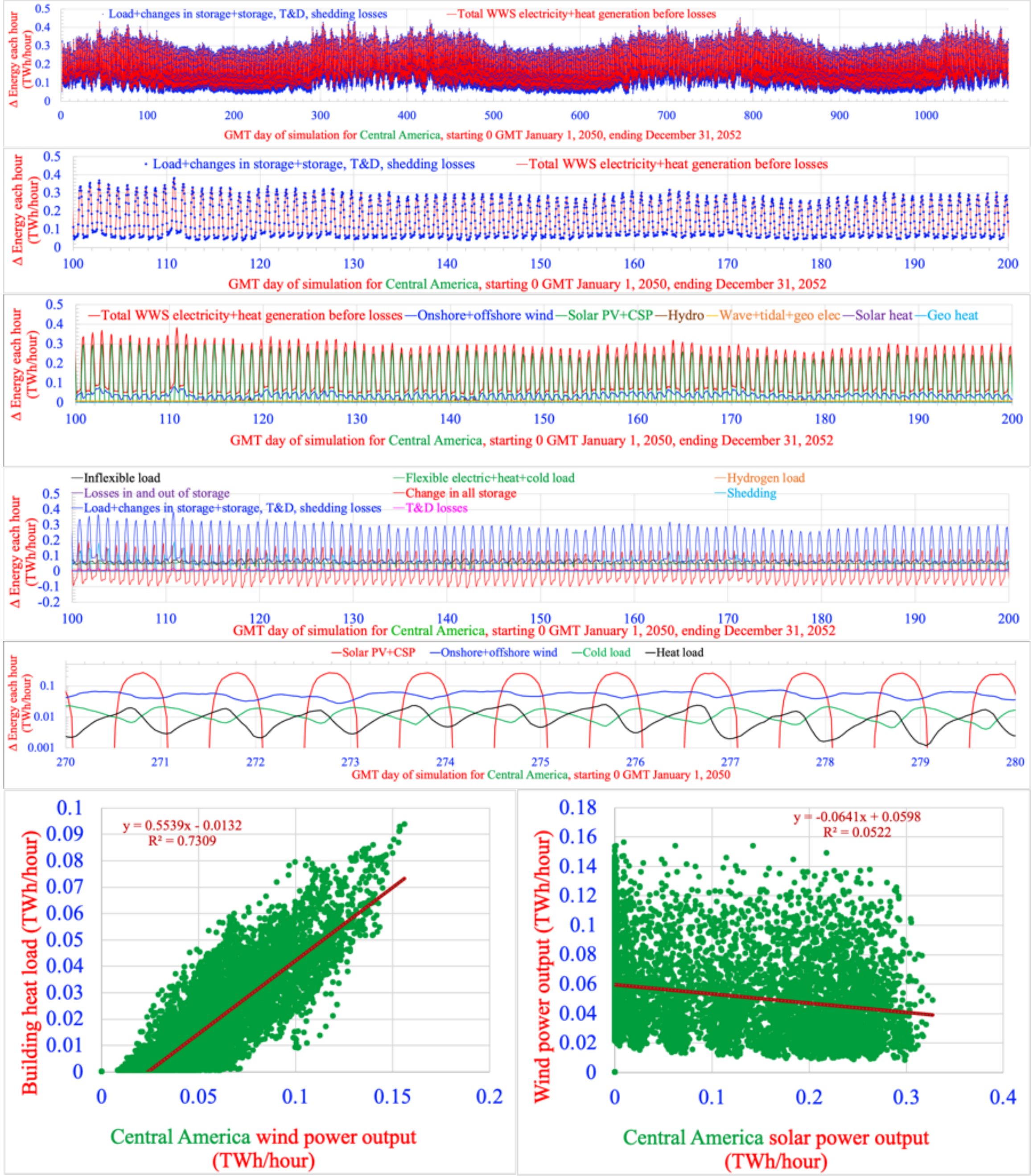


y = 0.3476x - 0.0101
R² = 0.7021
Building heat load (TWh/hour)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.05
0.1
0.15
0.2
0.25
Canada wind power output (TWh/hour)

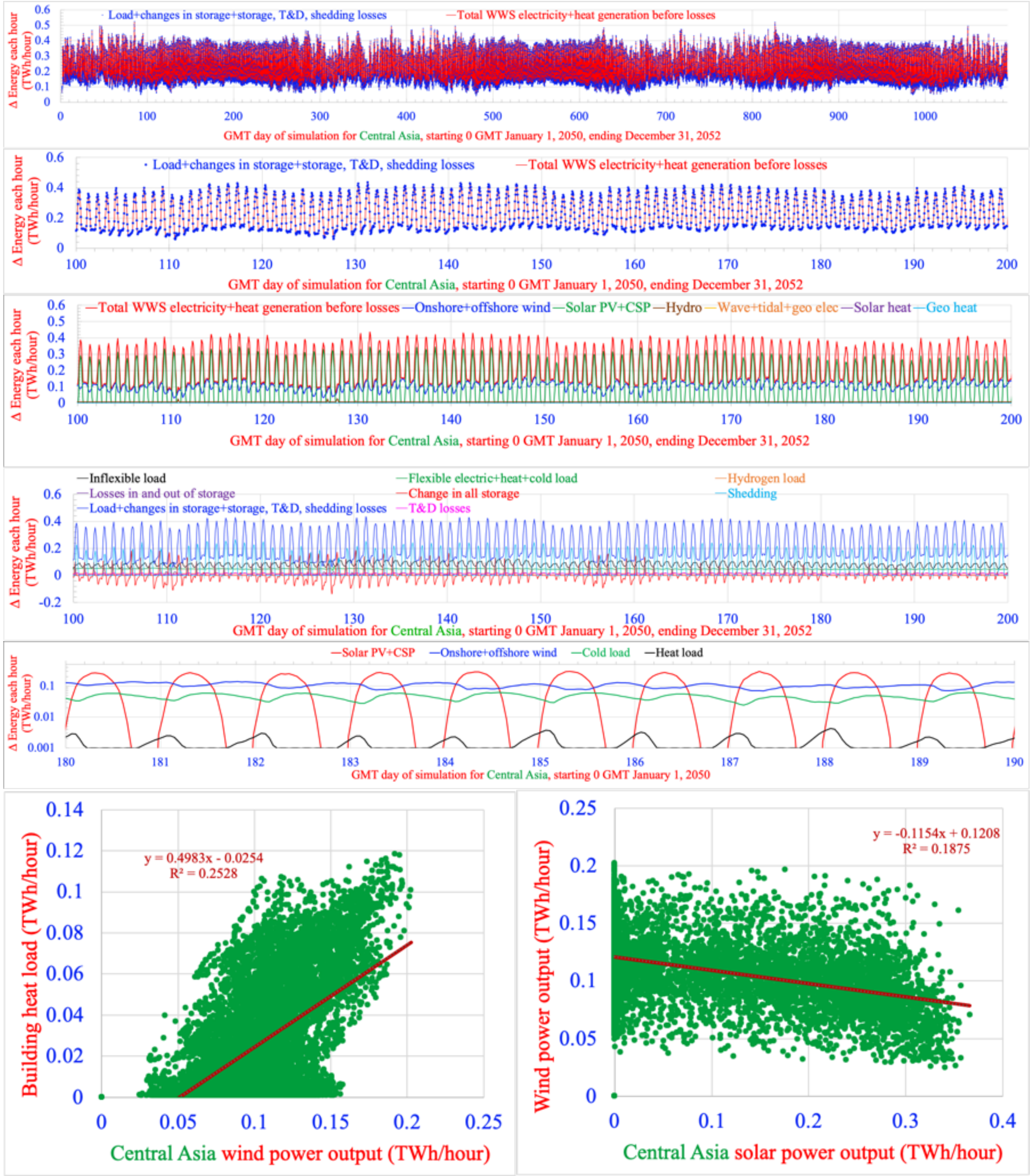


y = -0.3474x + 0.1161
R² = 0.0707
Wind power output (TWh/hour)
0.25
0.2
0.15
0.1
0.05
0
0
0.05
0.1
0.15
Canada solar power output (TWh/hour)

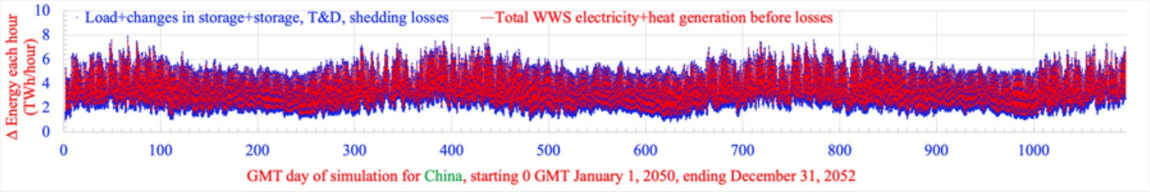
CENTRAL AMERICA

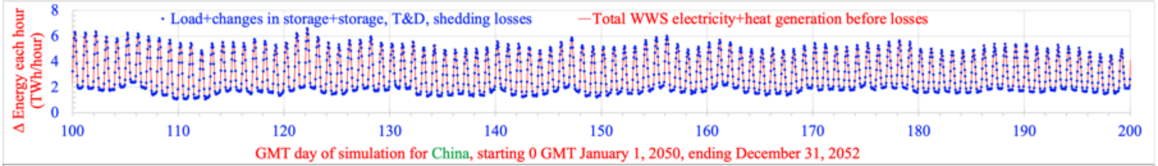


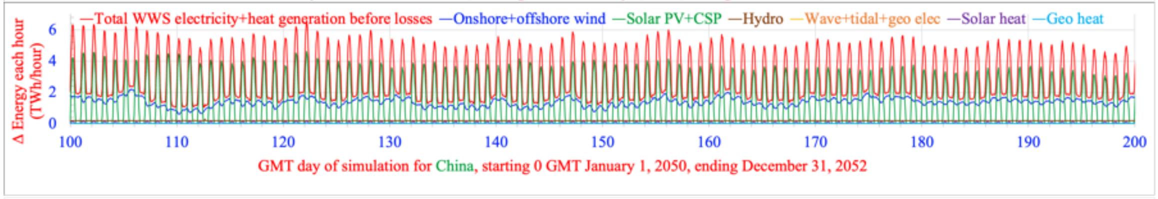
CENTRAL ASIA

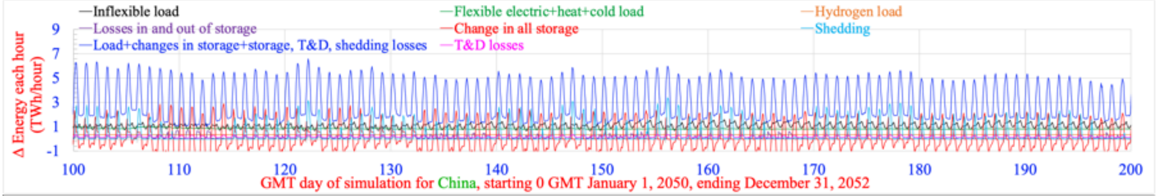


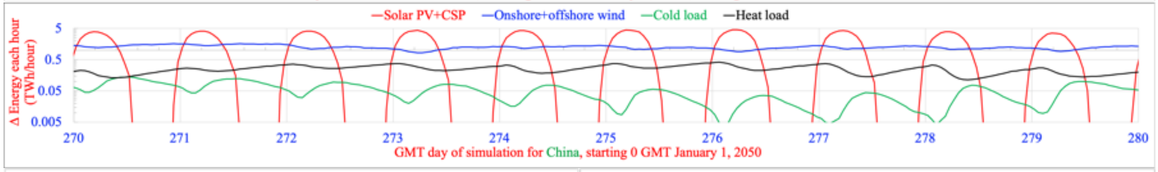
CHINA REGION

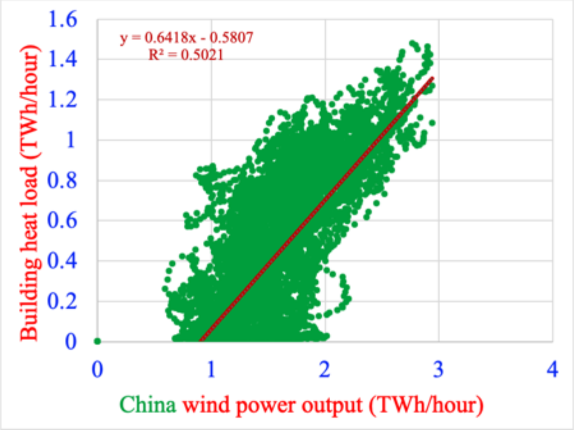


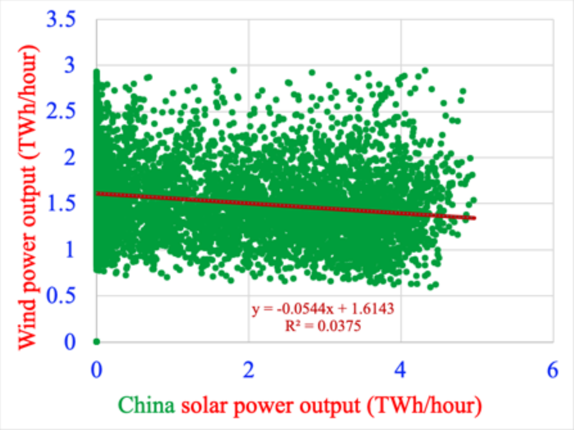




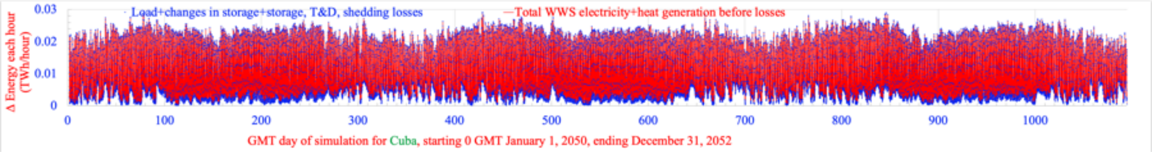


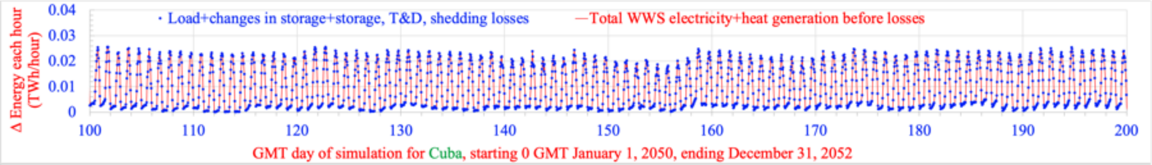


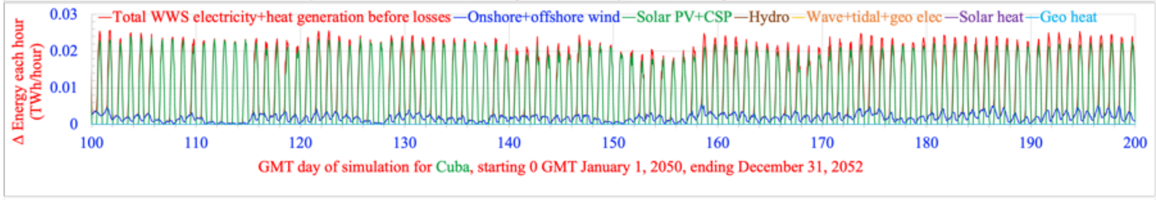


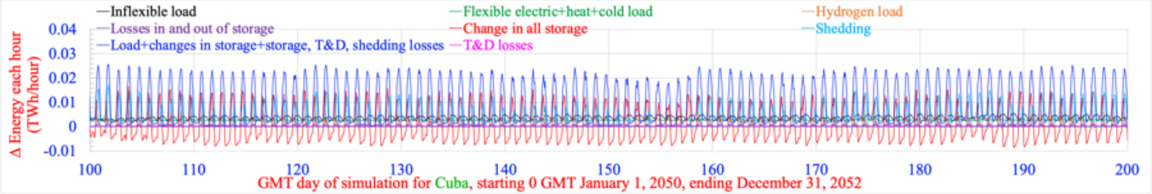


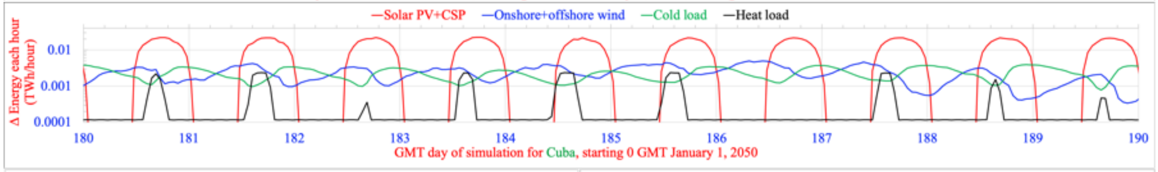
CUBA

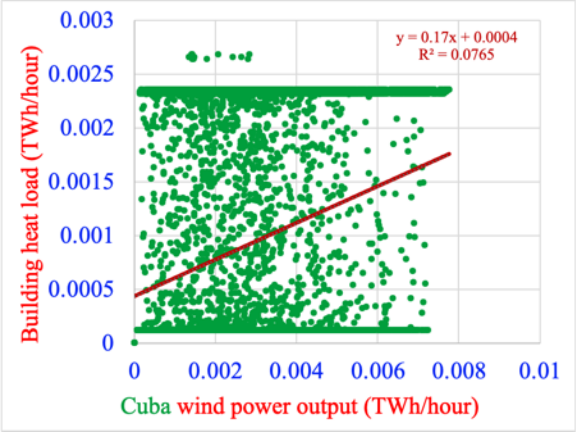

Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.03
0.02
0.01
0
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052

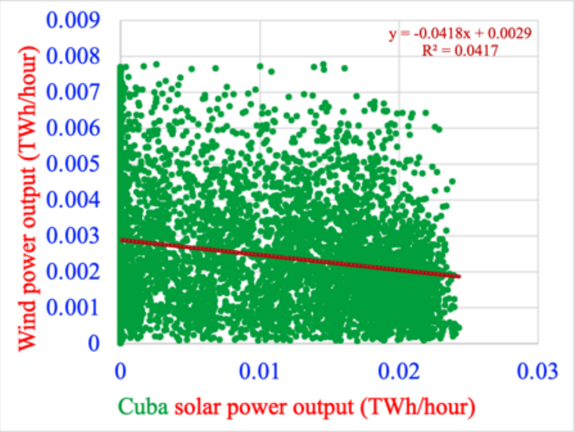

· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.04
0.03
0.02
0.01
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052


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

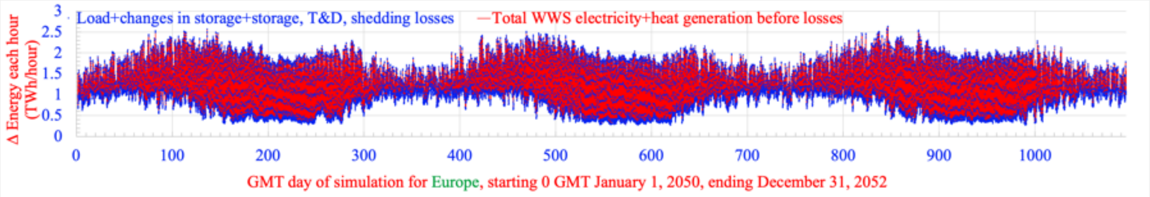

—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
0.04
0.03
0.02
0.01
0
-0.01
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Cuba, starting 0 GMT January 1, 2050, ending December 31, 2052


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

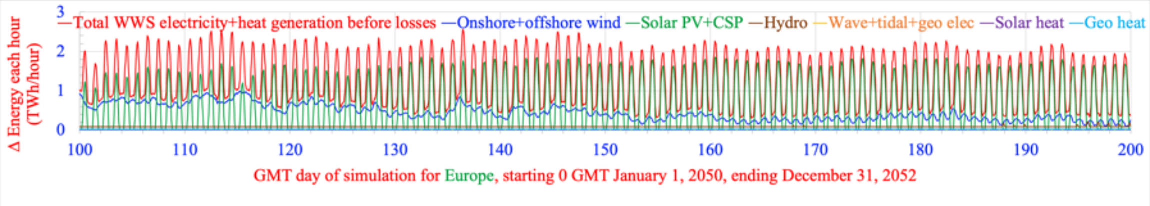

y = 0.17x + 0.0004
R² = 0.0765
Building heat load (TWh/hour)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.002
0.004
0.006
0.008
0.01
Cuba wind power output (TWh/hour)

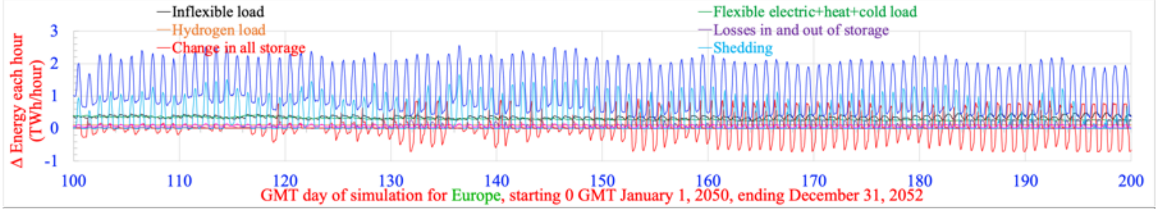

y = -0.0418x + 0.0029
R² = 0.0417
Wind power output (TWh/hour)
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
0.01
0.02
0.03
Cuba solar power output (TWh/hour)

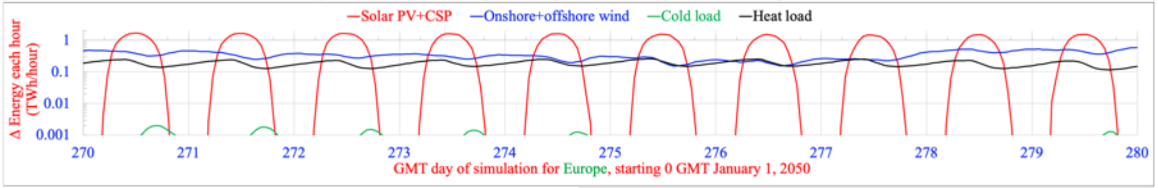
EUROPE

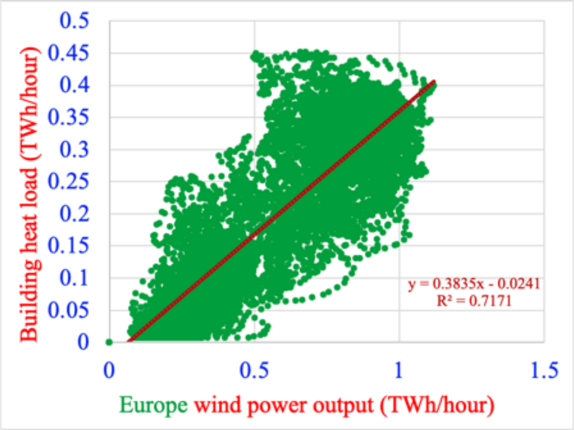

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
0.5
1
1.5
2
2.5
3
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

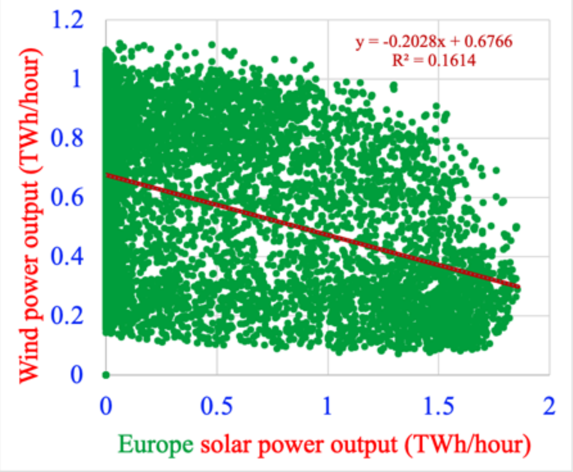

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
1
2
3
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052


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

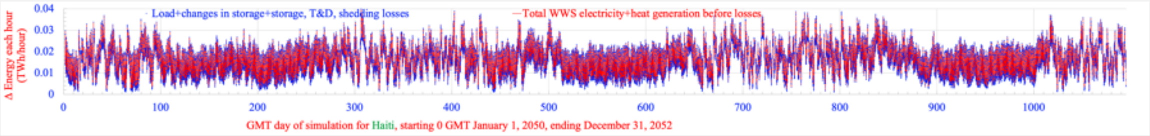

Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
Δ Energy each hour (TWh/hour)
-1
0
1
2
3
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Europe, starting 0 GMT January 1, 2050, ending December 31, 2052

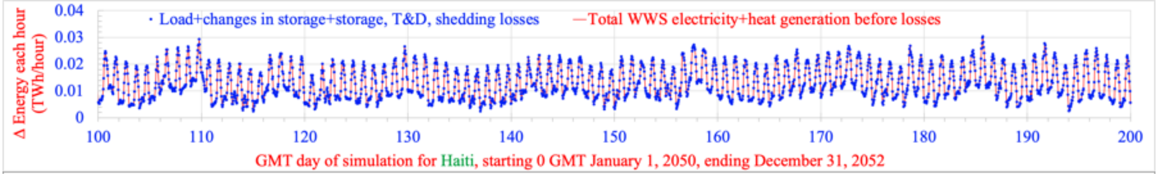

Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
0.001
0.01
0.1
1
270
271
272
273
274
275
276
277
278
279
280
GMT day of simulation for Europe, starting 0 GMT January 1, 2050

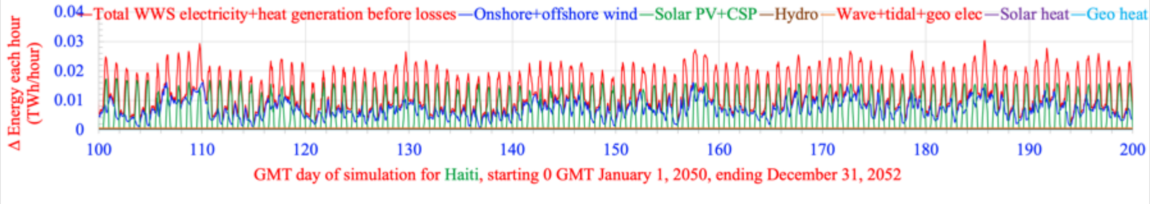

Building heat load (TWh/hour)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
0.5
1
1.5
y = 0.3835x - 0.0241
R² = 0.7171
Europe wind power output (TWh/hour)

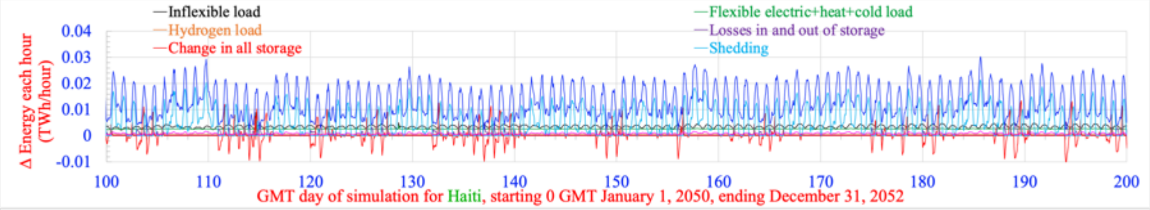

Wind power output (TWh/hour)
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
y = -0.2028x + 0.6766
R² = 0.1614
Europe solar power output (TWh/hour)

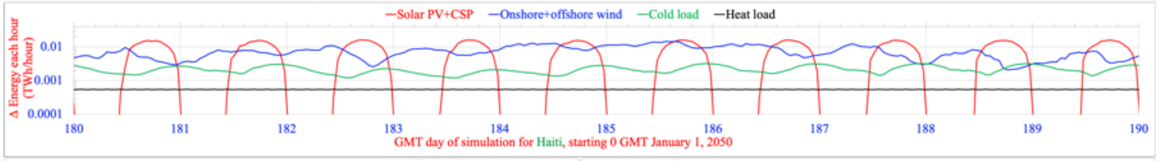
HAITI REGION

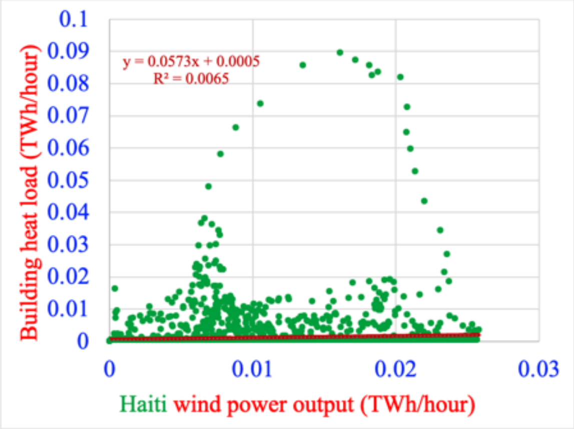


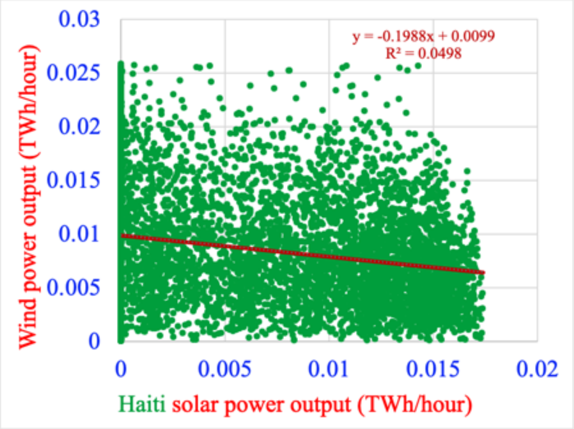




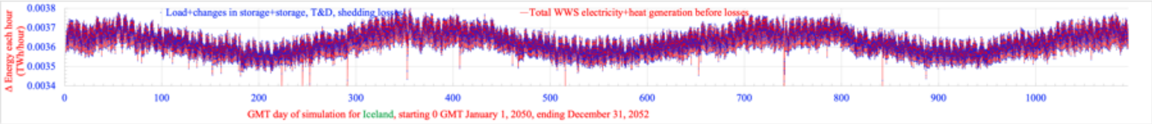




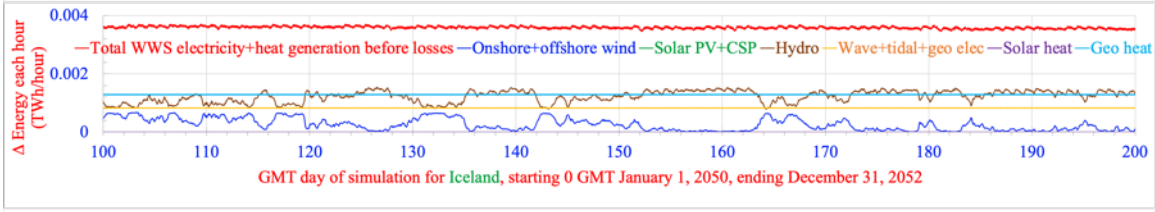


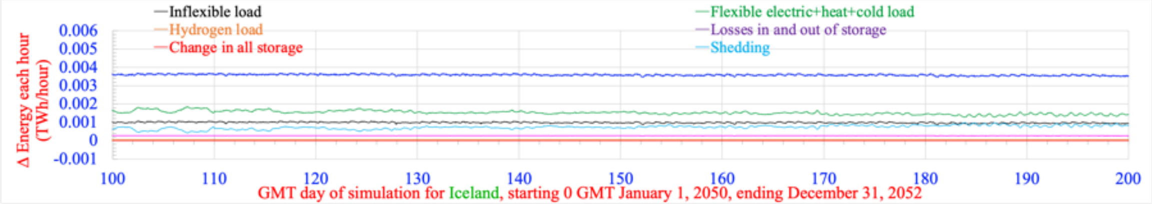


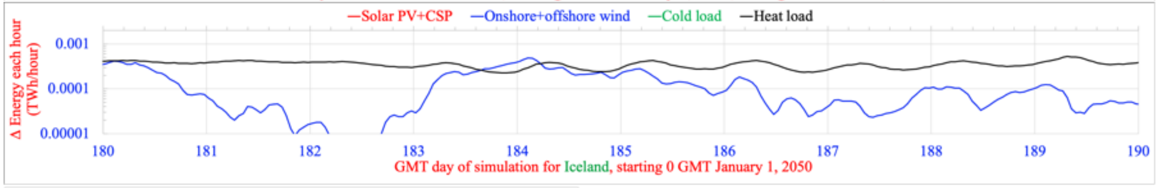
ICELAND

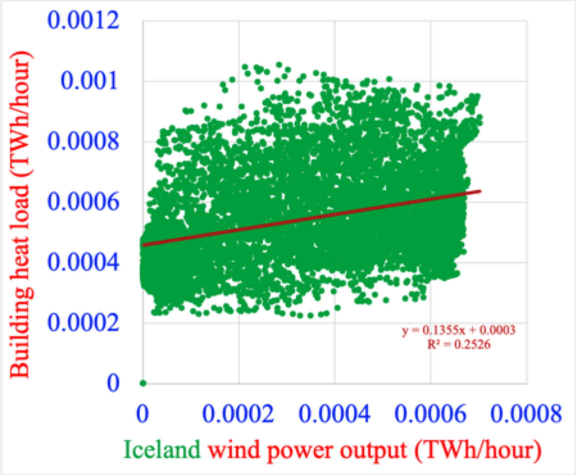

Δ Energy each hour (TWh/hour)
0.0038
0.0037
0.0036
0.0035
0.0034
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052


Δ Energy each hour (TWh/hour)
0.0038
0.0036
0.0034
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

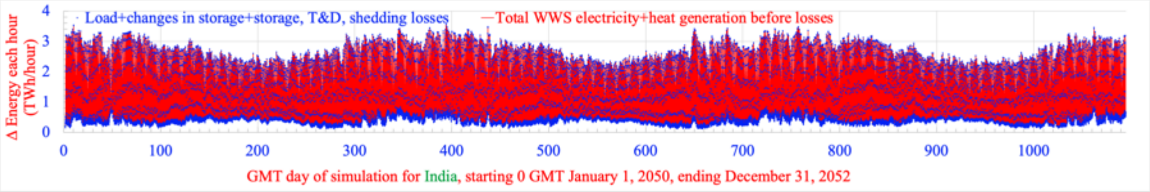

Δ Energy each hour (TWh/hour)
0.004
0.002
0
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
—Wave+tidal+geo elec
—Solar heat
—Geo heat
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050, ending December 31, 2052

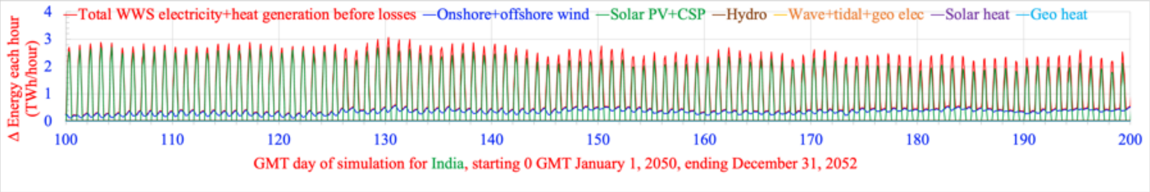

—Inflexible load
—Hydrogen load
—Change in all storage
—Flexible electric+heat+cold load
—Losses in and out of storage
—Shedding
Δ Energy each hour (TWh/hour)
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Iceland, starting 0 GMT January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

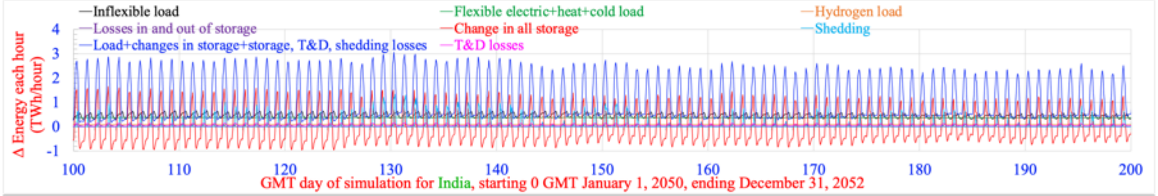

—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
0.001
0.0001
0.00001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Iceland, starting 0 GMT January 1, 2050

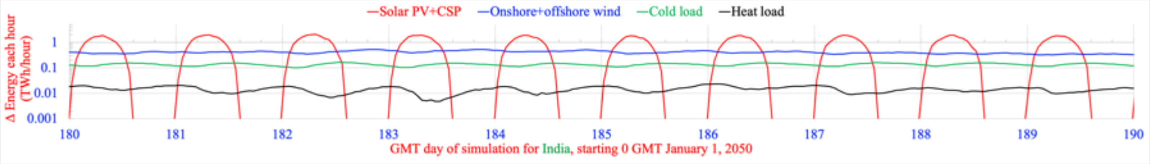

Building heat load (TWh/hour)
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
y = 0.1355x + 0.0003
R² = 0.2526
0
0.0002
0.0004
0.0006
0.0008
Iceland wind power output (TWh/hour)

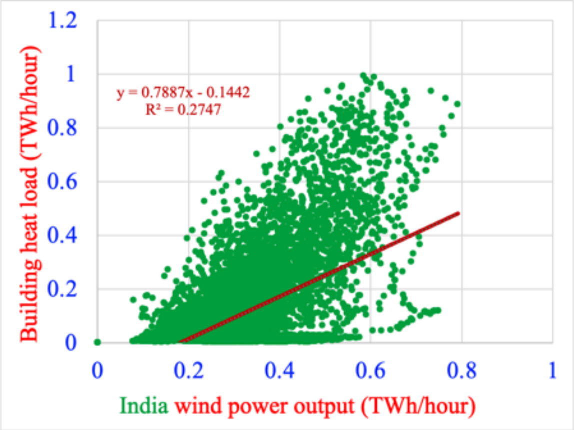
INDIA REGION

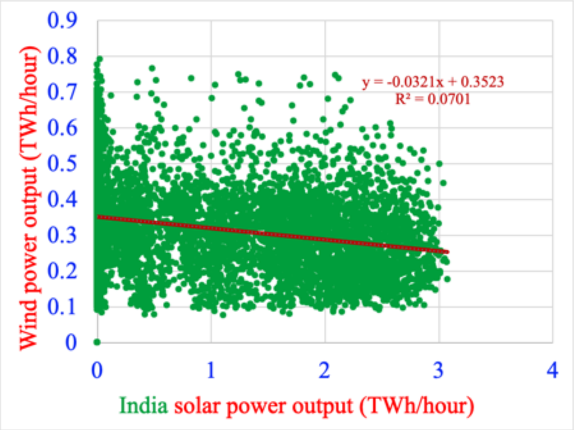




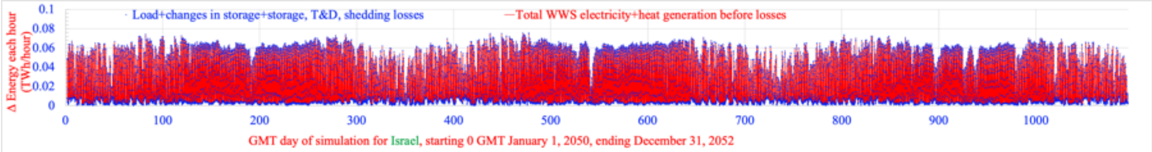


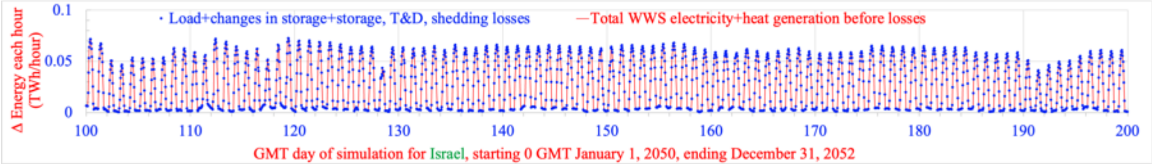


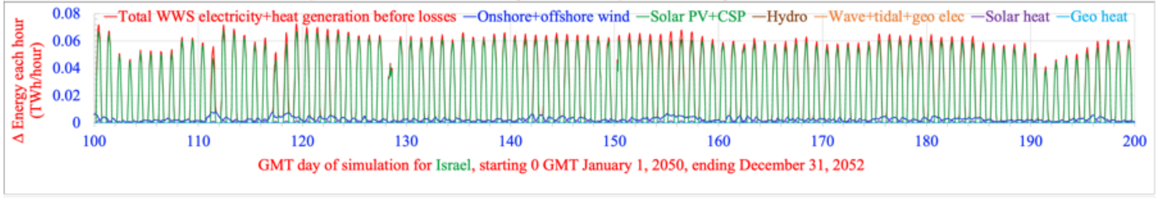


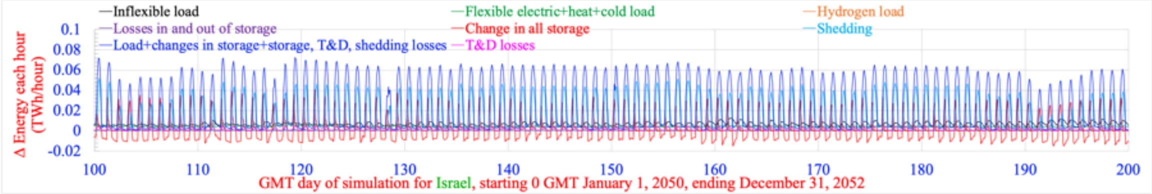


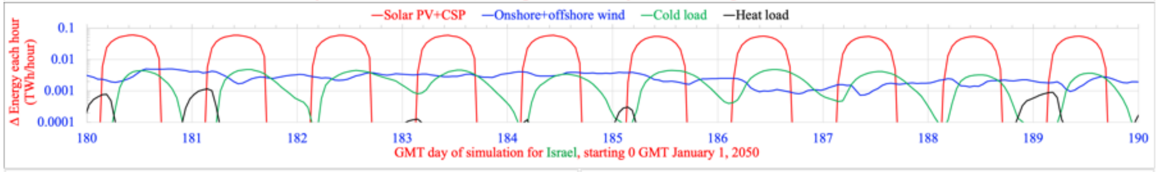
ISRAEL

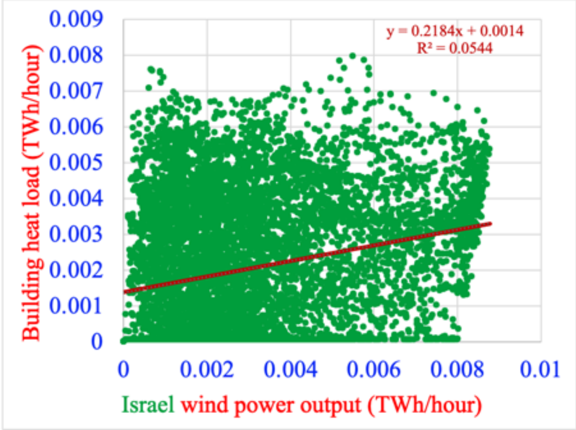

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.1
0.08
0.06
0.04
0.02
0
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052

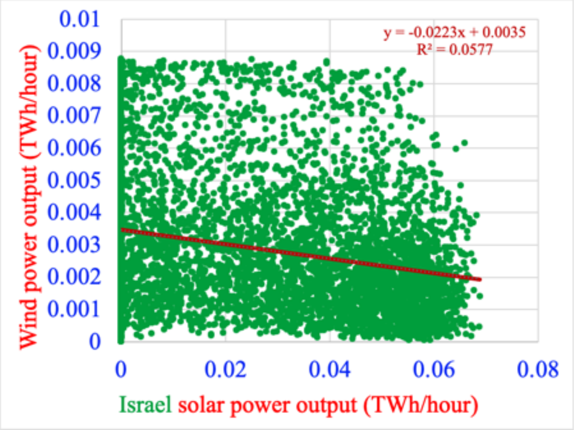

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.1
0.05
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Israel, starting 0 GMT January 1, 2050, ending December 31, 2052


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

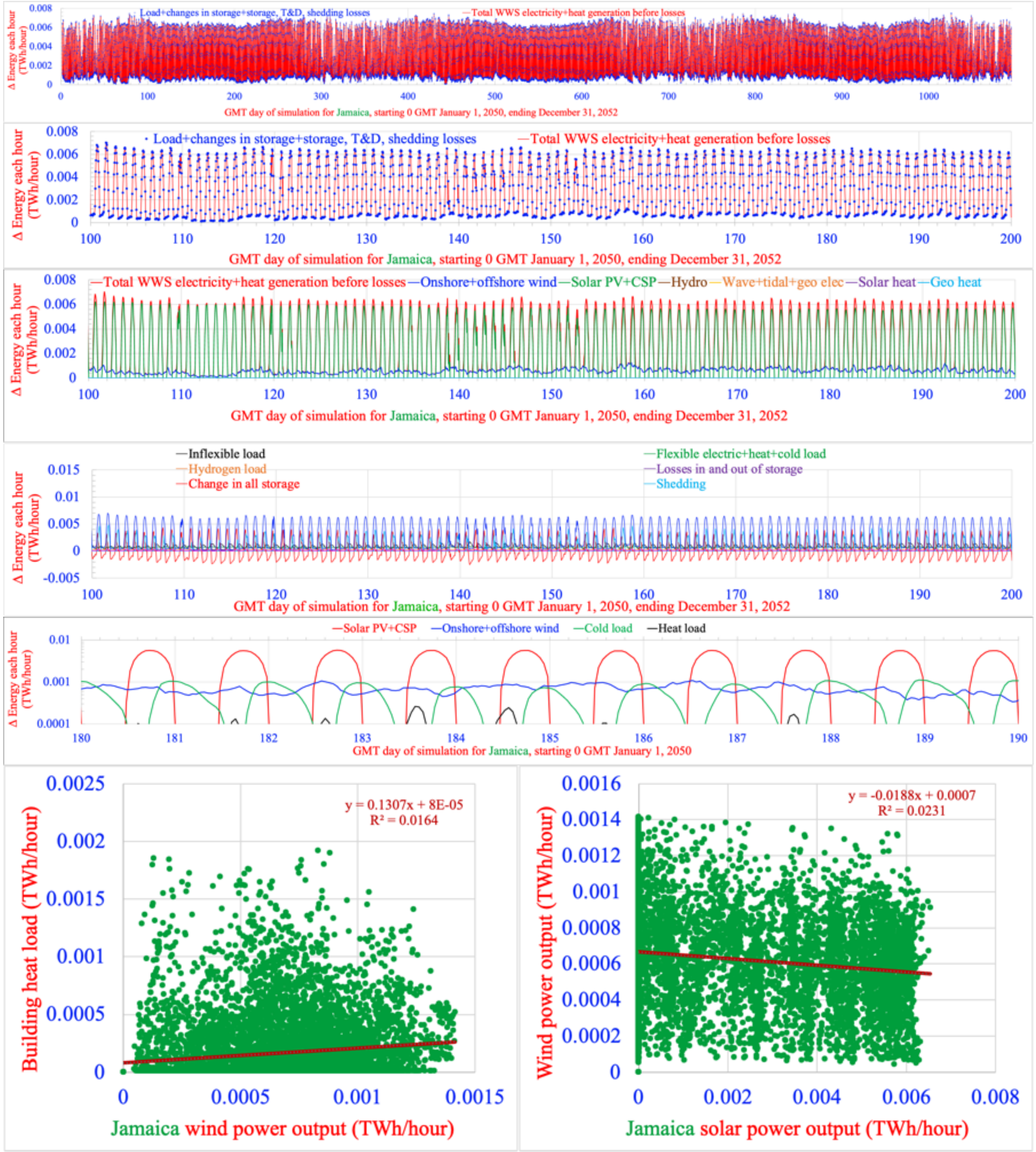

Inflexible load
Flexible electric+heat+cold load
Hydrogen load
Losses in and out of storage
Change in all storage
Shedding
Load+changes in storage+storage, T&D, shedding losses
T&D losses
Δ Energy each hour (TWh/hour)
0.1
0.08
0.06
0.04
0.02
0
-0.02
100
110
120
130
140
150
160
170
180
190
200
GMT day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


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

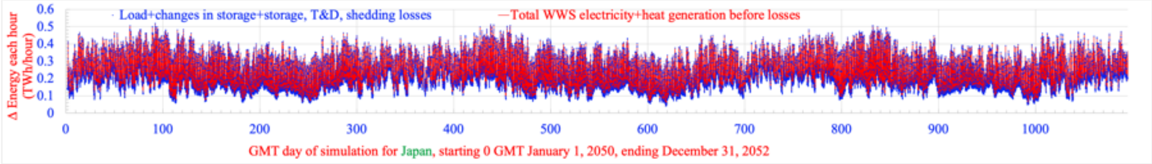

y = 0.2184x + 0.0014
R² = 0.0544
Building heat load (TWh/hour)
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
0.002
0.004
0.006
0.008
0.01
Israel wind power output (TWh/hour)

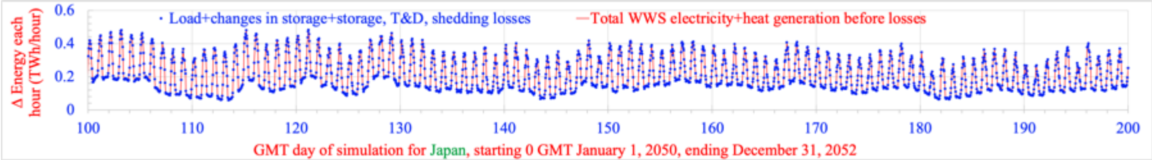

y = -0.0223x + 0.0035
R² = 0.0577
Wind power output (TWh/hour)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
0.02
0.04
0.06
0.08
Israel solar power output (TWh/hour)

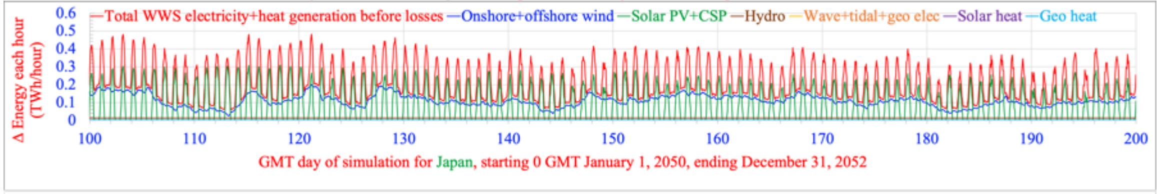
JAMAICA

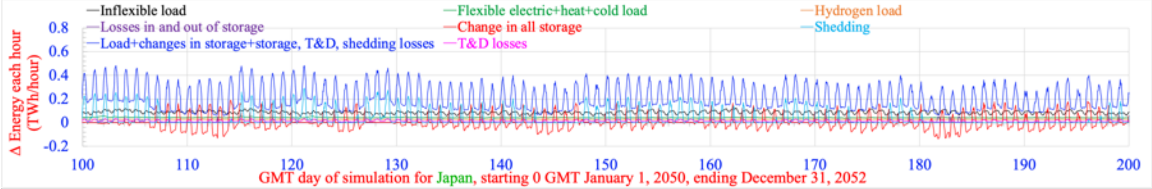

Δ Energy each hour (TWh/hour)
0.008
0.006
0.004
0.002
0
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
• Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
—Wave+tidal+geo elec
—Solar heat
—Geo heat
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.015
0.01
0.005
0
-0.005
—Inflexible load
—Hydrogen load
—Change in all storage
—Flexible electric+heat+cold load
—Losses in and out of storage
—Shedding
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
0.01
0.001
0.0001
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Jamaica, starting 0 GMT January 1, 2050
Building heat load (TWh/hour)
0.0025
0.002
0.0015
0.001
0.0005
0
y = 0.1307x + 8E-05
R² = 0.0164
0
0.0005
0.001
0.0015
Jamaica wind power output (TWh/hour)
Wind power output (TWh/hour)
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
y = -0.0188x + 0.0007
R² = 0.0231
0
0.002
0.004
0.006
0.008
Jamaica solar power output (TWh/hour)

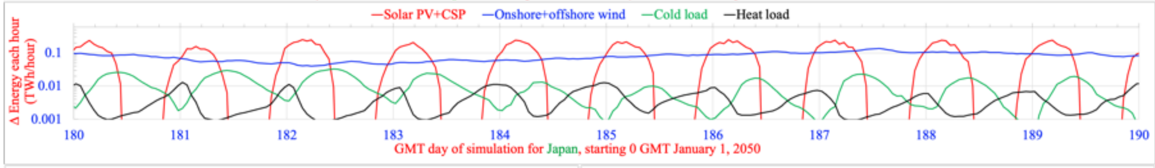
JAPAN

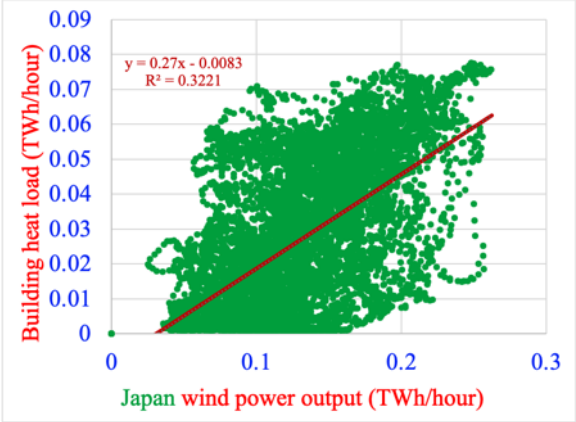

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052

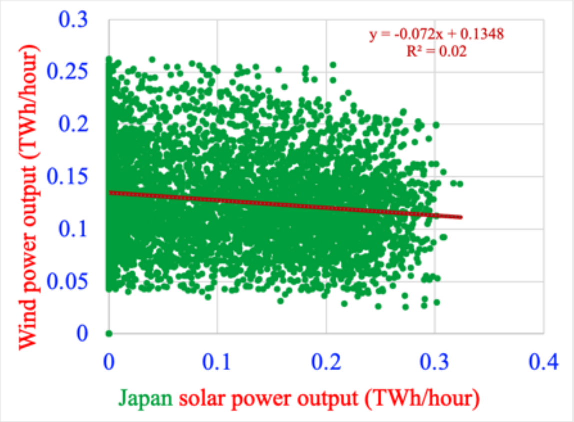

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
0.2
0.4
0.6
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052


Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
0
0.1
0.2
0.3
0.4
0.5
0.6
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Japan, starting 0 GMT January 1, 2050, ending December 31, 2052

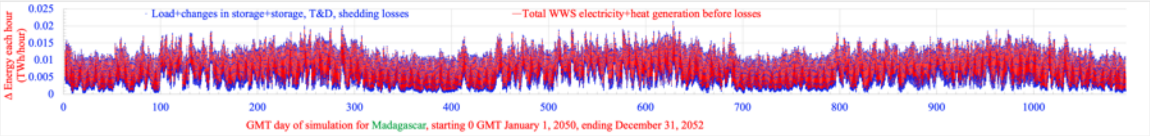

Inflexible load
Losses in and out of storage
Load+changes in storage+storage, T&D, shedding losses
Flexible electric+heat+cold load
Change in all storage
T&D losses
Hydrogen load
Shedding
Δ Energy each hour (TWh/hour)
-0.2
0
0.2
0.4
0.6
0.8
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation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

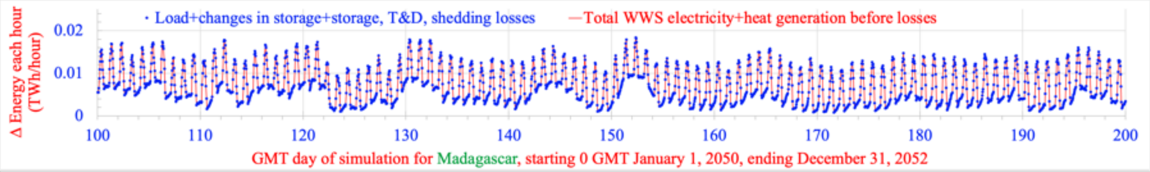

Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
Δ Energy each hour (TWh/hour)
0.001
0.01
0.1
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Japan, starting 0 GMT January 1, 2050

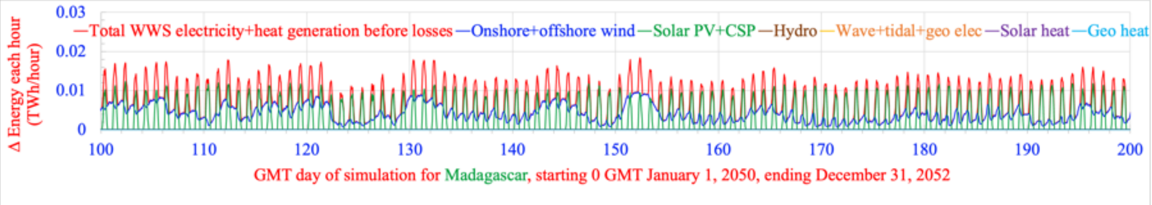

y = 0.27x - 0.0083
R² = 0.3221
Building heat load (TWh/hour)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
0.1
0.2
0.3
Japan wind power output (TWh/hour)

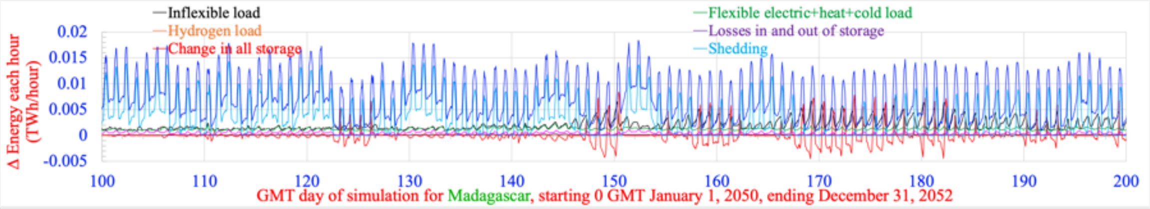

y = -0.072x + 0.1348
R² = 0.02
Wind power output (TWh/hour)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
Japan solar power output (TWh/hour)

MADAGASCAR

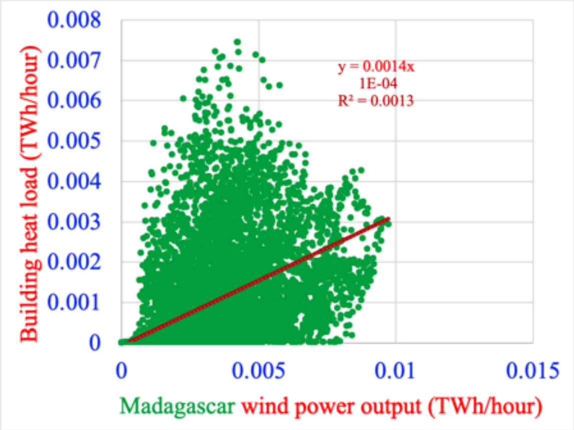

Δ Energy each hour (TWh/hour)
0.025
0.02
0.015
0.01
0.005
0
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Madagascar, starting 0 GMT January 1, 2050, ending December 31, 2052

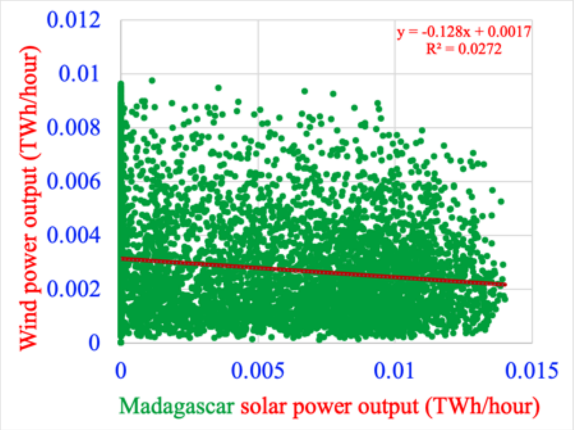

Δ Energy each hour (TWh/hour)
0.02
0.01
0
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Madagascar, starting 0 GMT January 1, 2050, ending December 31, 2052


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

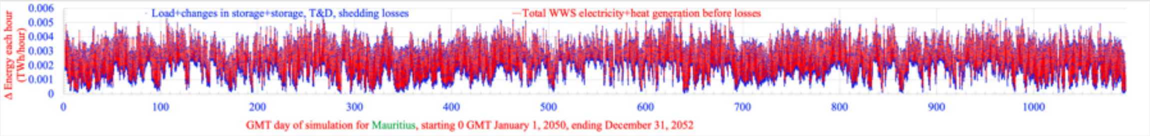

Δ Energy each hour (TWh/hour)
0.02
0.015
0.01
0.005
0
-0.005
—Inflexible load
—Hydrogen load
—Change in all storage
—Flexible electric+heat+cold load
—Losses in and out of storage
—Shedding
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Madagascar, starting 0 GMT January 1, 2050, ending December 31, 2052

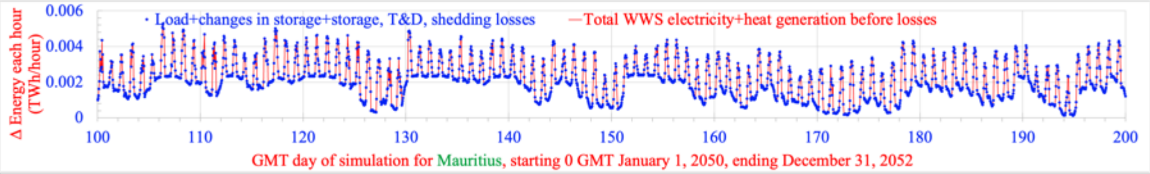

Δ Energy each hour (TWh/hour)
0.01
0.001
0.0001
0.00001
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Madagascar, starting 0 GMT January 1, 2050

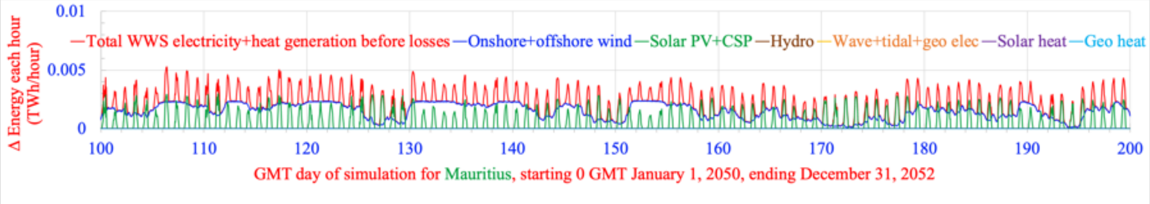

Building heat load (TWh/hour)
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
y = 0.0014x
1E-04
R² = 0.0013
0
0.005
0.01
0.015
Madagascar wind power output (TWh/hour)

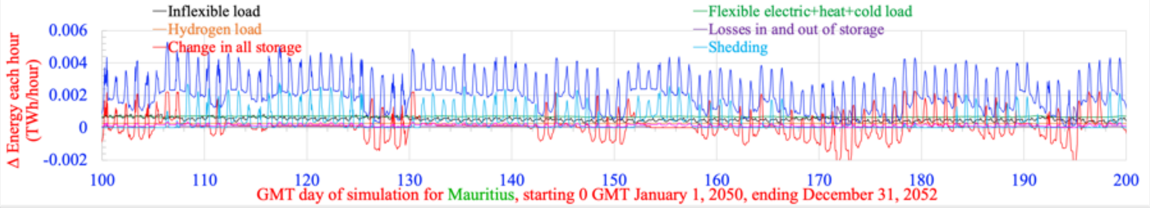

Wind power output (TWh/hour)
0.012
0.01
0.008
0.006
0.004
0.002
0
y = -0.128x + 0.0017
R² = 0.0272
0
0.005
0.01
0.015
Madagascar solar power output (TWh/hour)

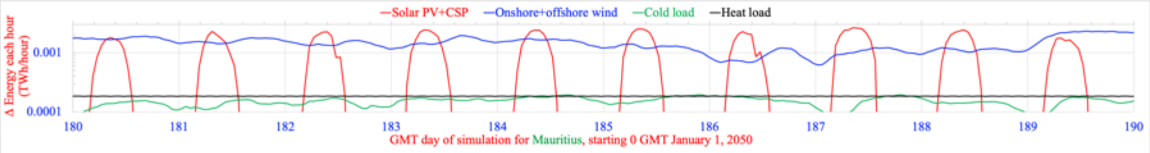
MAURITIUS

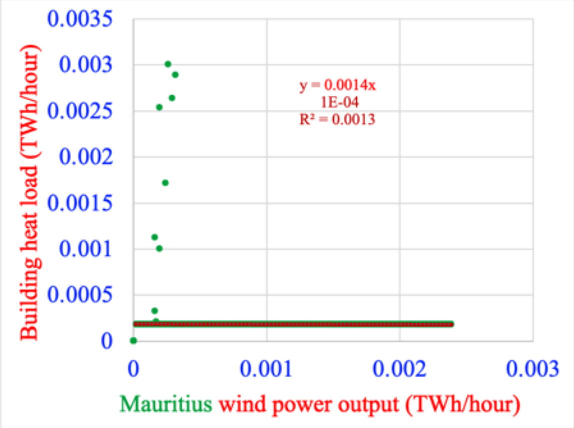

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.006
0.005
0.004
0.003
0.002
0.001
0
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052

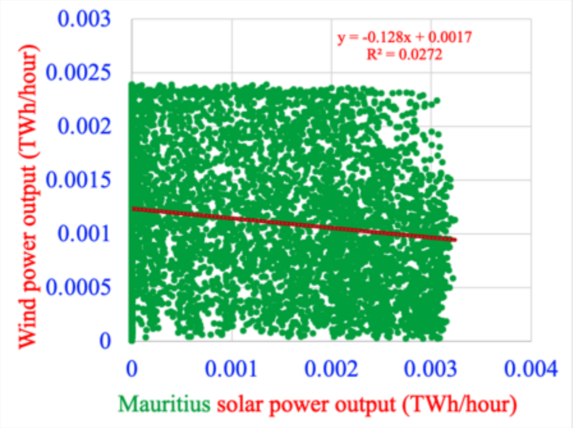

Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0.006
0.004
0.002
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052


Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
Δ Energy each hour (TWh/hour)
0.01
0.005
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December 31, 2052

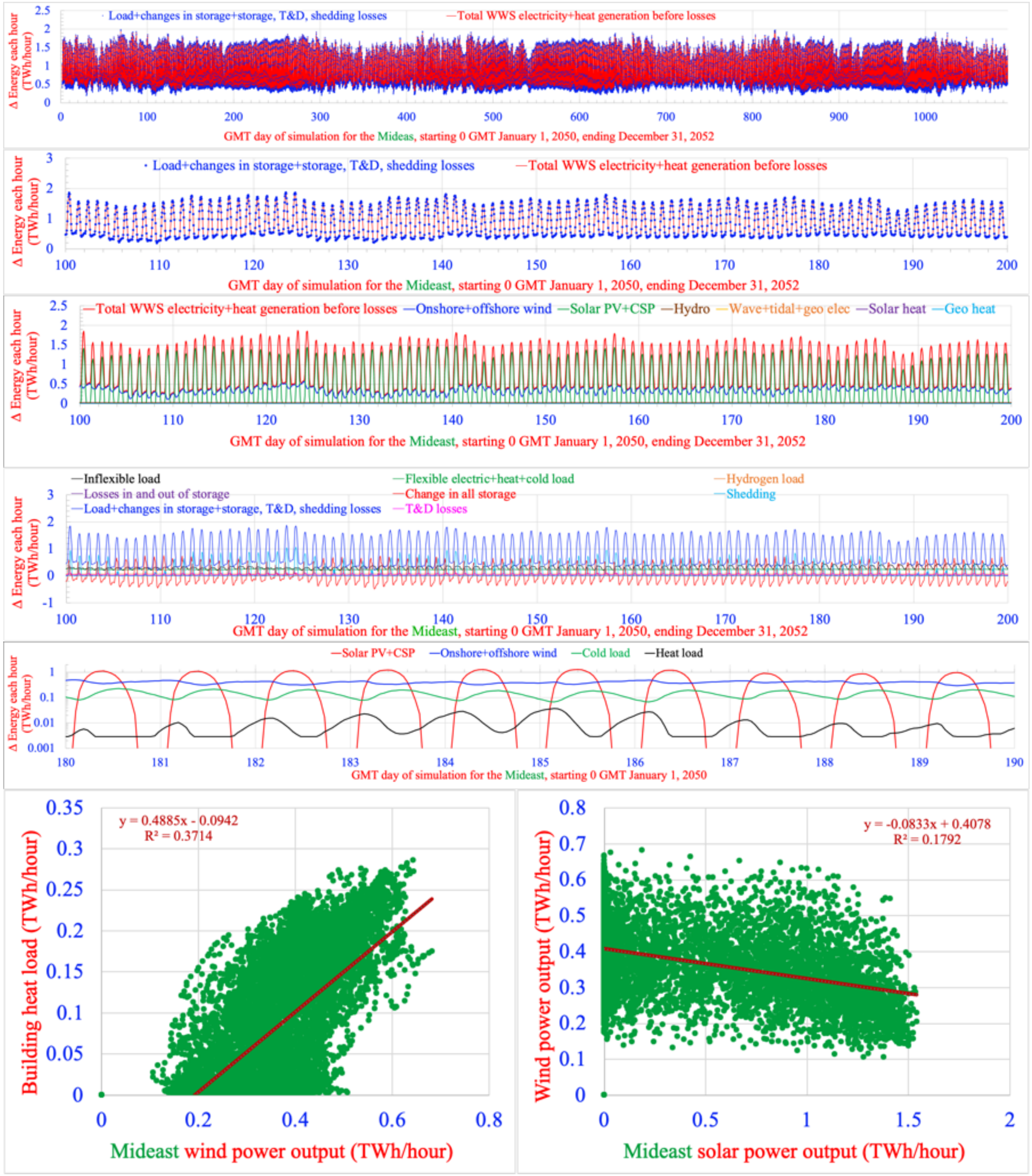

Inflexible load
Hydrogen load
Change in all storage
Flexible electric+heat+cold load
Losses in and out of storage
Shedding
Δ Energy each hour (TWh/hour)
0.006
0.004
0.002
0
-0.002
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Mauritius, starting 0 GMT January 1, 2050, ending December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


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

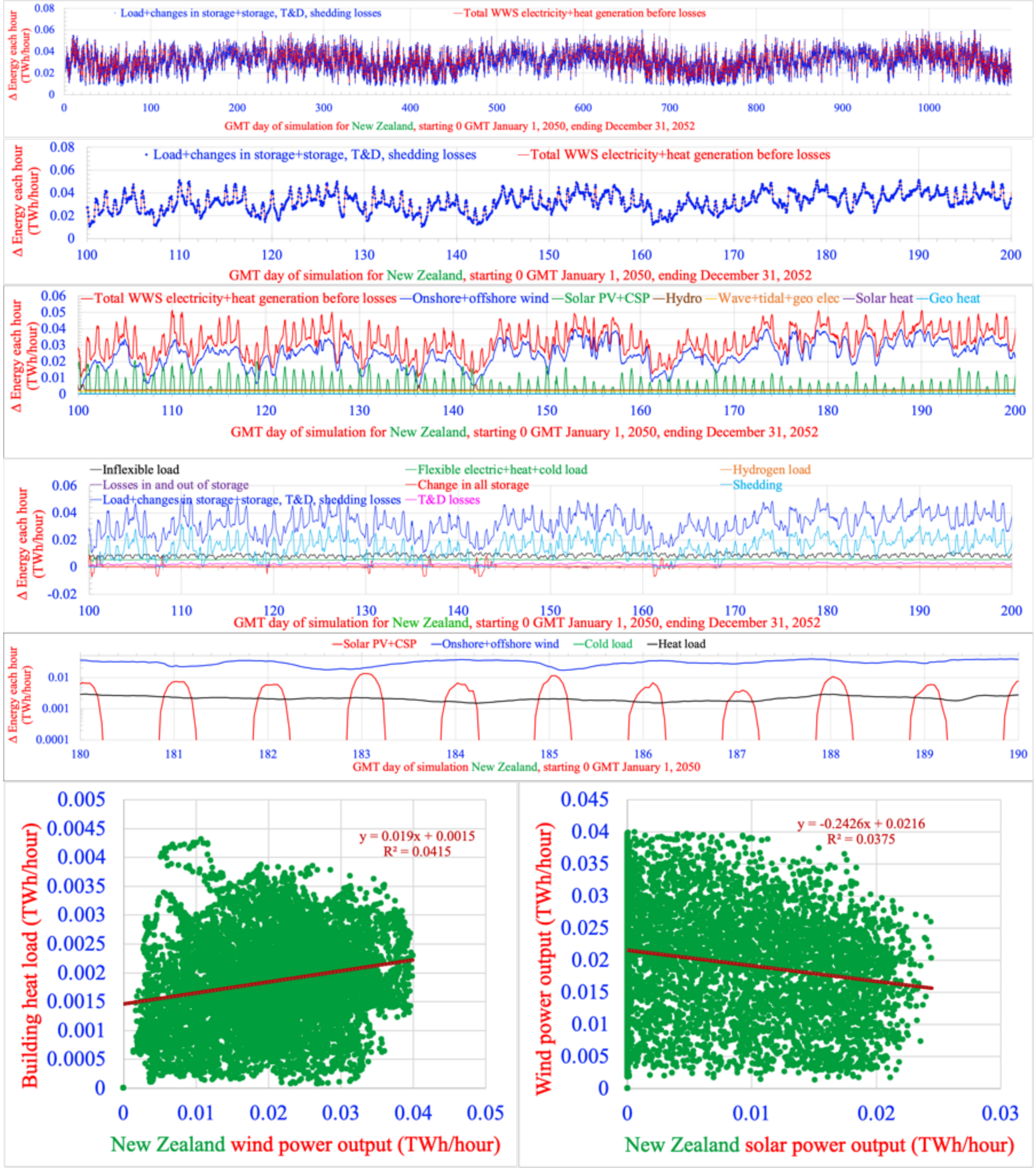

y = 0.0014x
1E-04
R² = 0.0013
Building heat load (TWh/hour)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.001
0.002
0.003
Mauritius wind power output (TWh/hour)


y = -0.128x + 0.0017
R² = 0.0272
Wind power output (TWh/hour)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.001
0.002
0.003
0.004
Mauritius solar power output (TWh/hour)

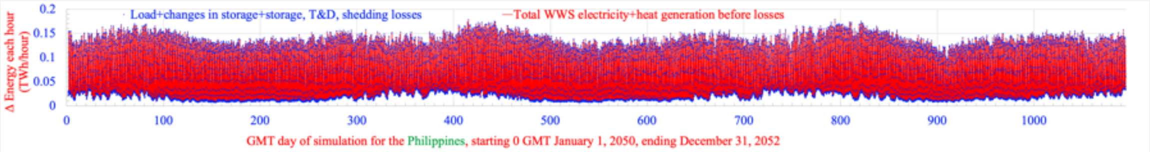
MIDEAST

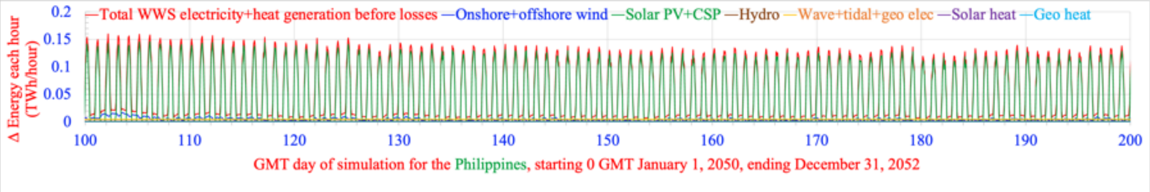

Δ Energy each hour (TWh/hour)
Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
GMT day of simulation for the Mideas, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—Total WWS electricity+heat generation before losses
—Onshore+offshore wind
—Solar PV+CSP
—Hydro
—Wave+tidal+geo elec
—Solar heat
—Geo heat
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—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
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
GMT day of simulation for the Mideast, starting 0 GMT January 1, 2050
y = 0.4885x - 0.0942
R² = 0.3714
Building heat load (TWh/hour)
Mideast wind power output (TWh/hour)
y = -0.0833x + 0.4078
R² = 0.1792
Wind power output (TWh/hour)
Mideast solar power output (TWh/hour)

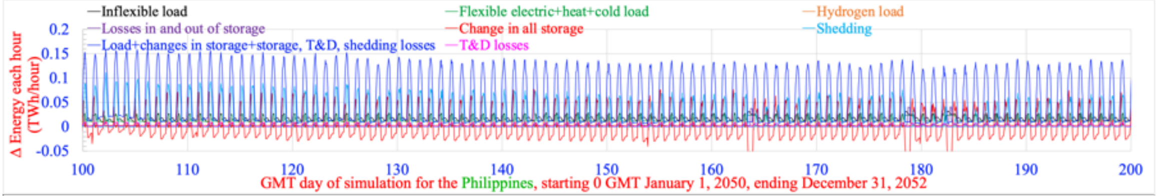
NEW ZEALAND

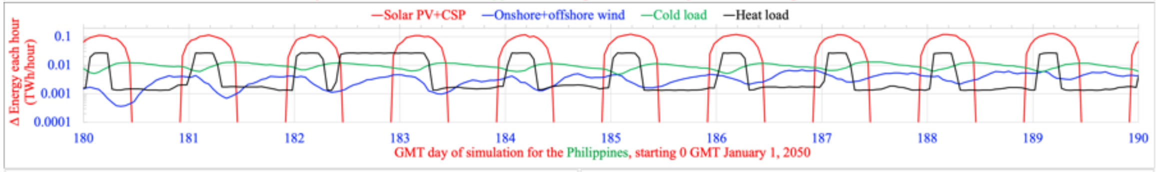

Δ Energy each hour (TWh/hour)
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
0.08
0.06
0.04
0.02
0
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
0.08
0.06
0.04
0.02
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
Total WWS electricity+heat generation before losses
Onshore+offshore wind
Solar PV+CSP
Hydro
Wave+tidal+geo elec
Solar heat
Geo heat
0.06
0.05
0.04
0.03
0.02
0.01
0
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
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
0.06
0.04
0.02
0
-0.02
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for New Zealand, starting 0 GMT January 1, 2050, ending December 31, 2052
Δ Energy each hour (TWh/hour)
Solar PV+CSP
Onshore+offshore wind
Cold load
Heat load
0.01
0.001
0.0001
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation New Zealand, starting 0 GMT January 1, 2050
Building heat load (TWh/hour)
y = 0.019x + 0.0015
R² = 0.0415
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.01
0.02
0.03
0.04
0.05
New Zealand wind power output (TWh/hour)
Wind power output (TWh/hour)
y = -0.2426x + 0.0216
R² = 0.0375
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.01
0.02
0.03
New Zealand solar power output (TWh/hour)

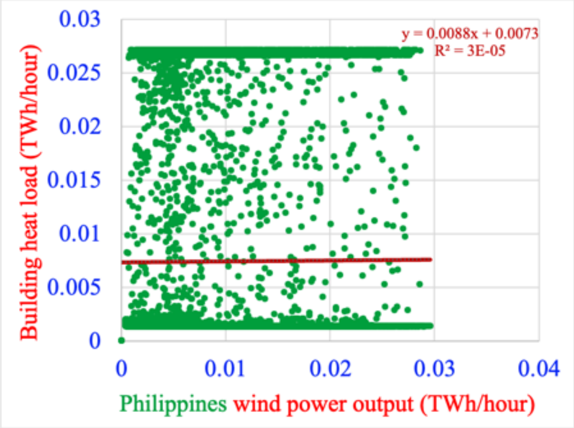
PHILIPPINES

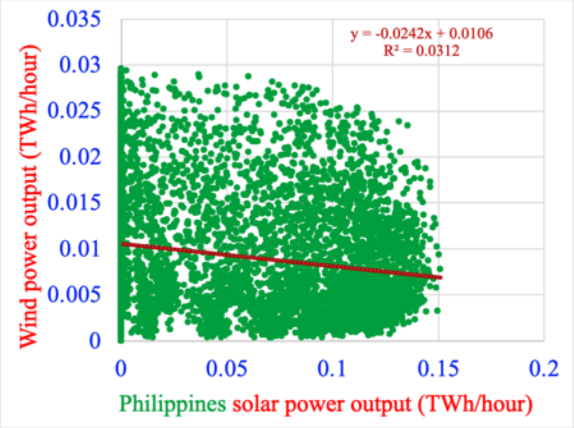




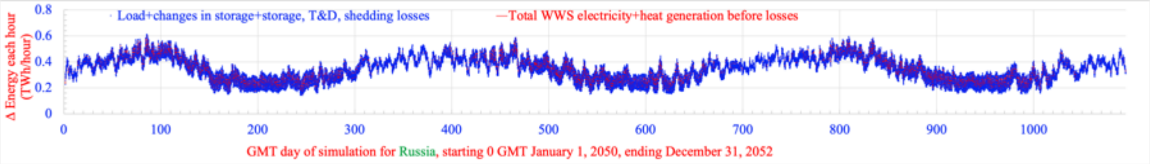


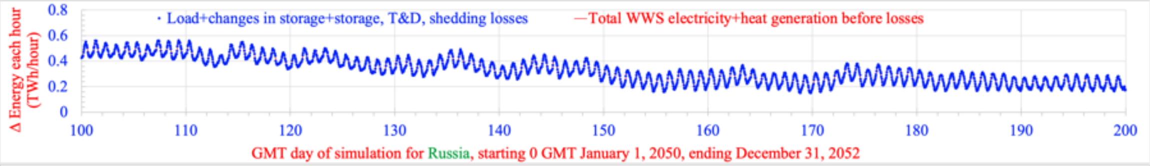


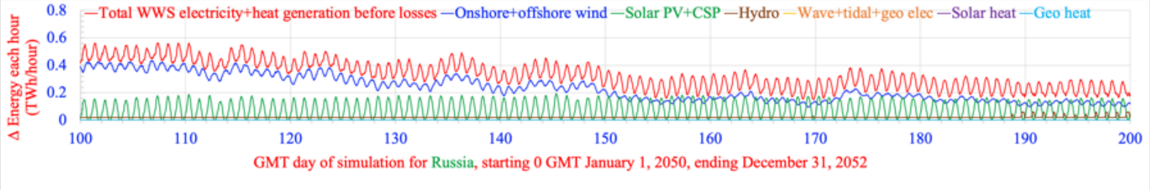


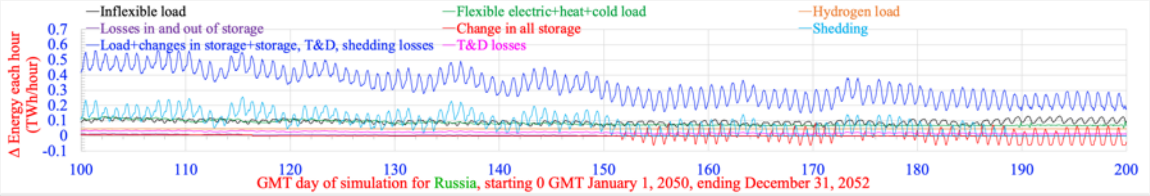


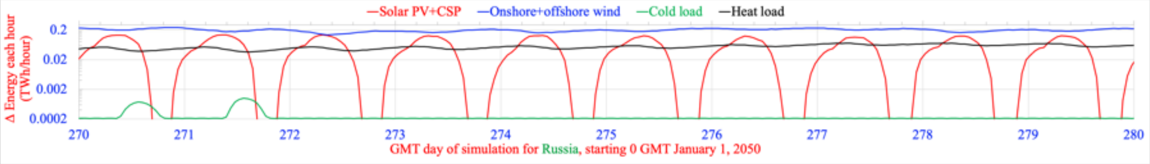
RUSSIA REGION

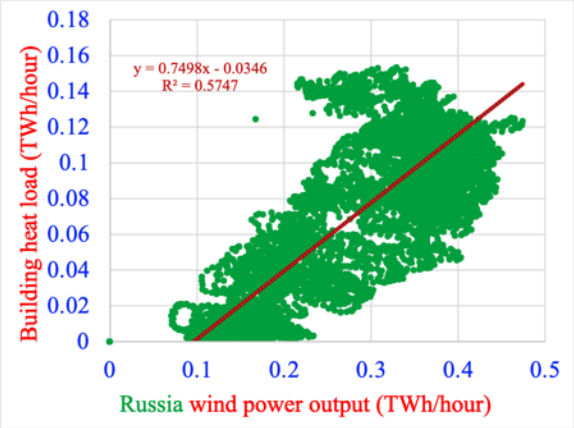


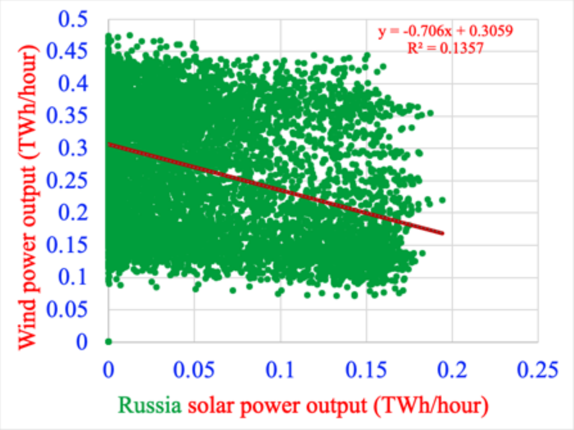




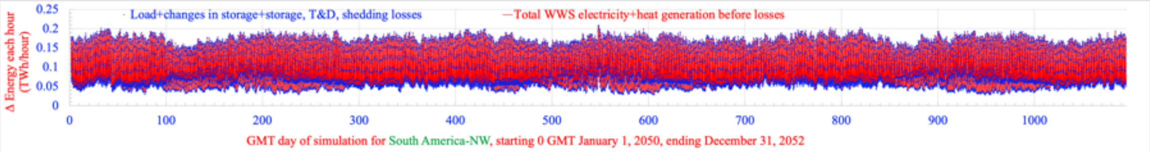


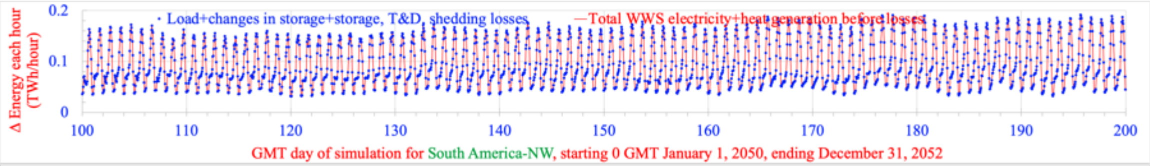


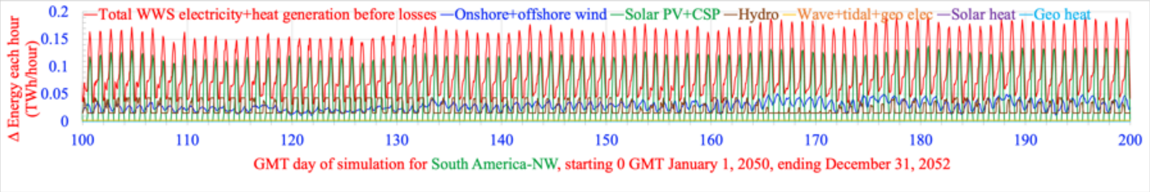


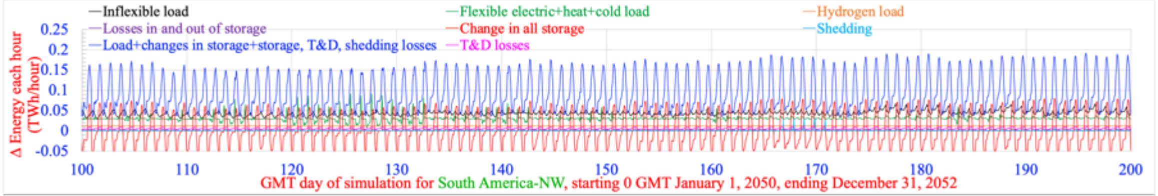


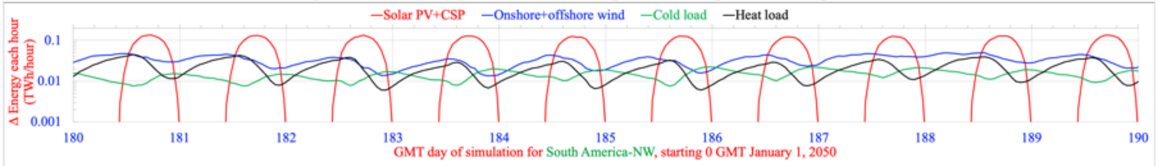
SOUTH AMERICA-NW

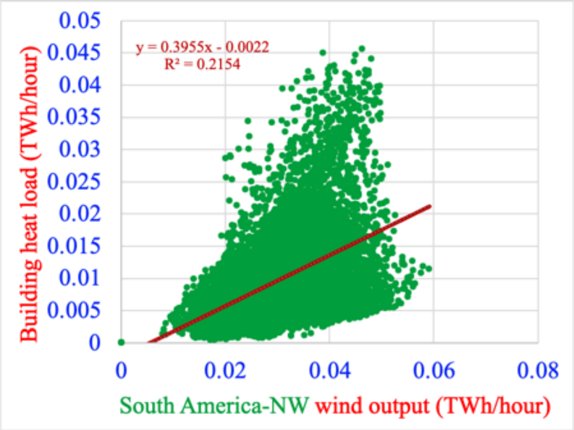


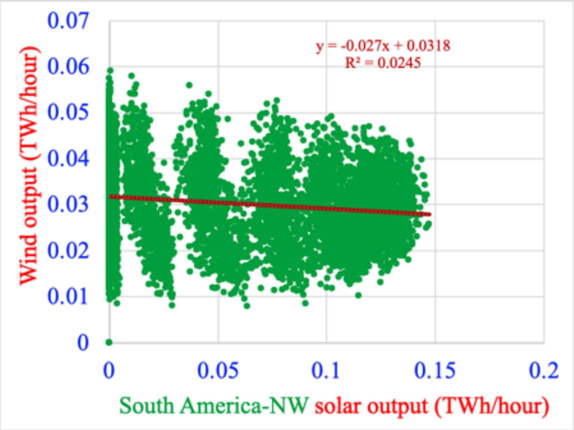




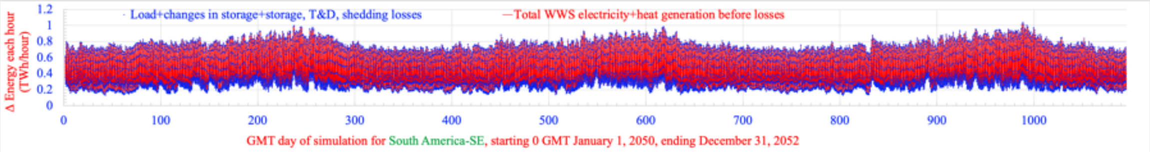


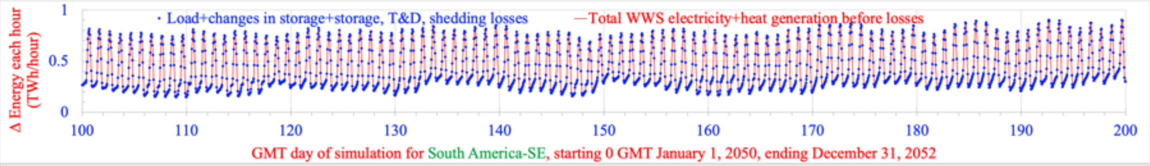


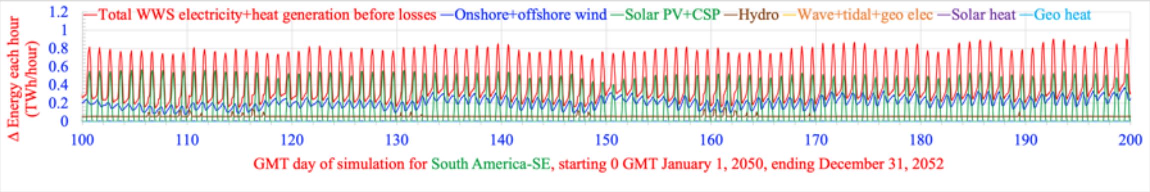


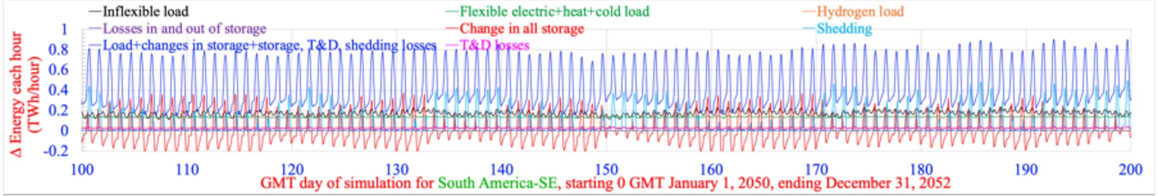


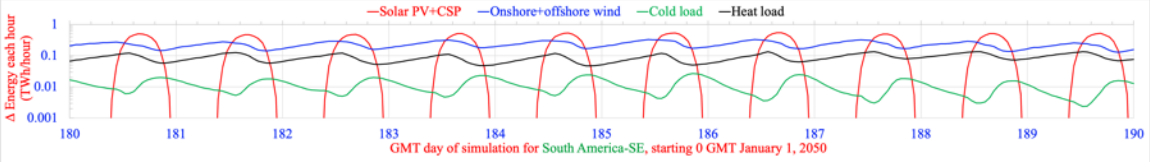
SOUTH AMERICA-SE

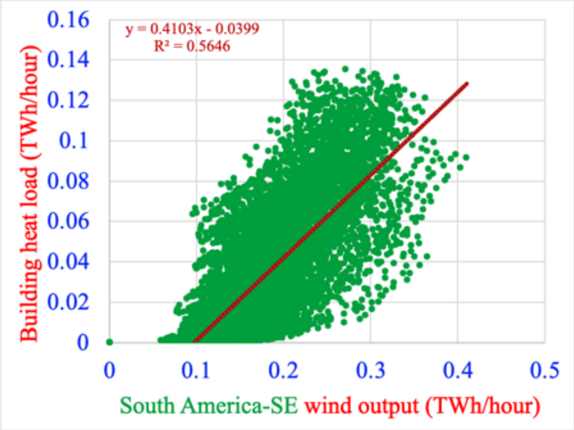


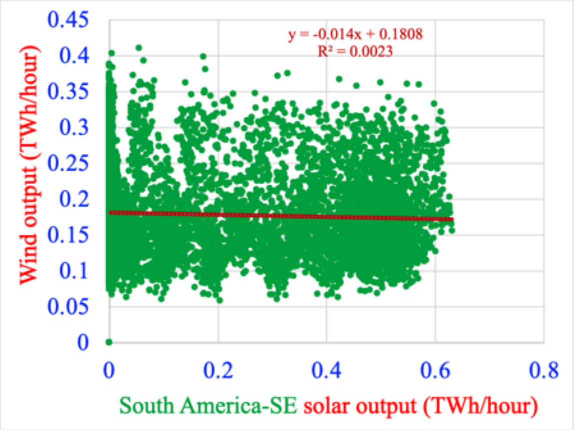




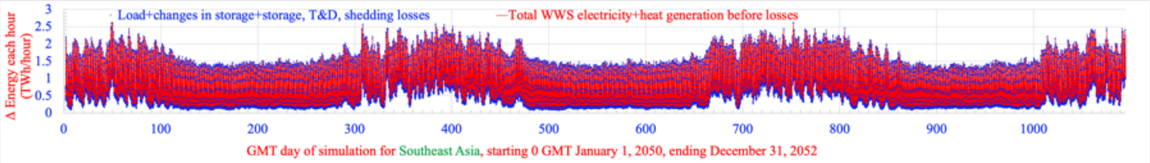


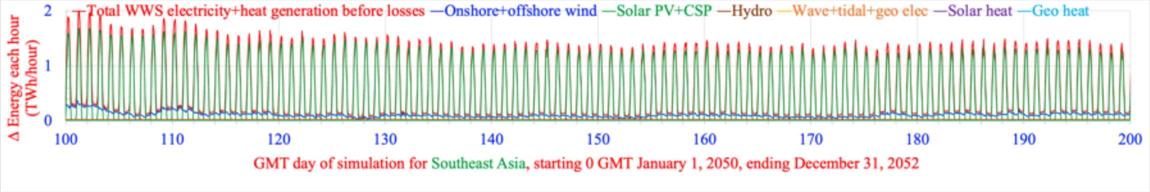


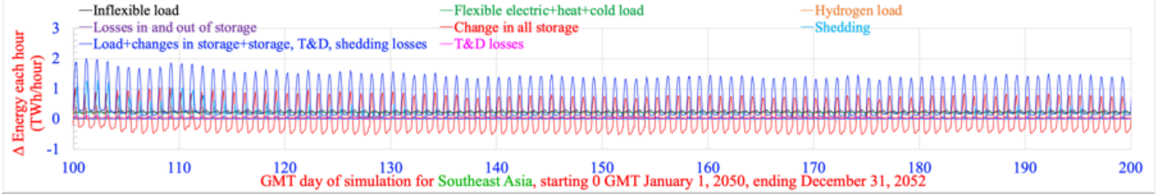


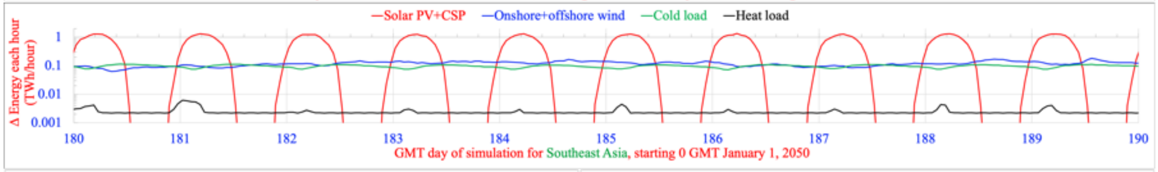


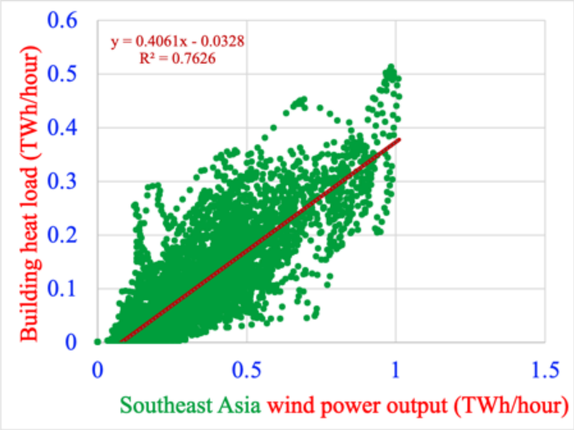
SOUTHEAST ASIA

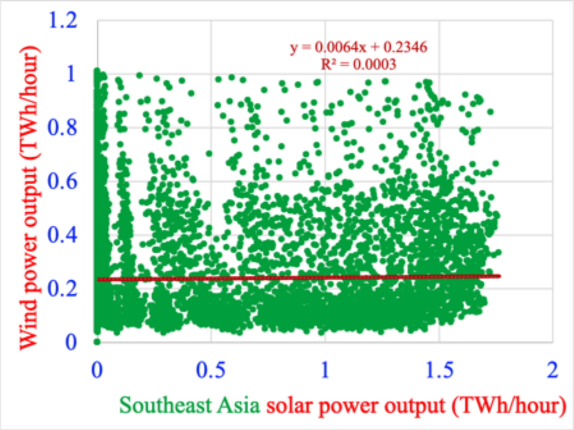




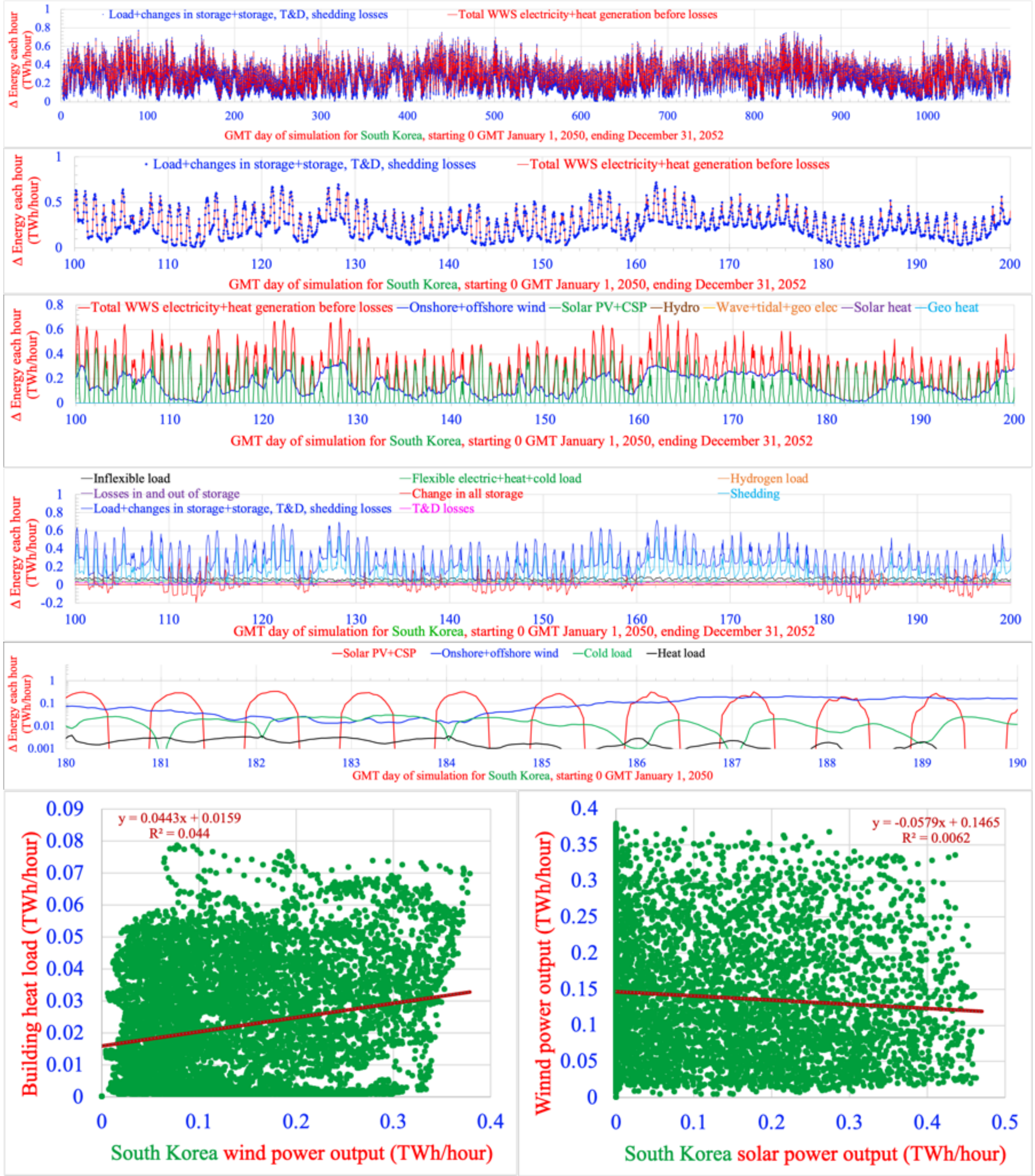






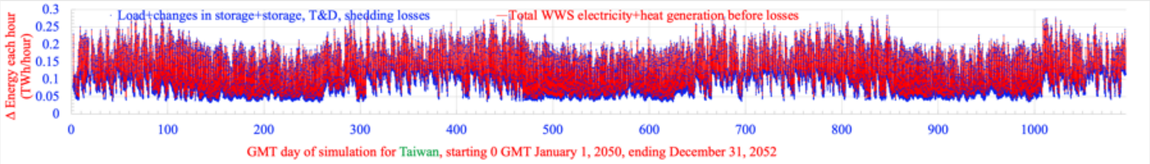


SOUTH KOREA

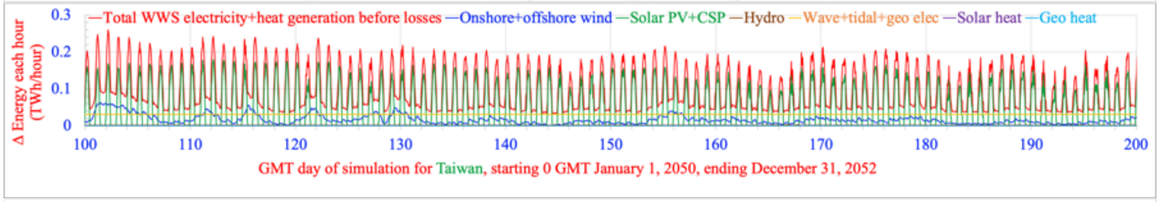


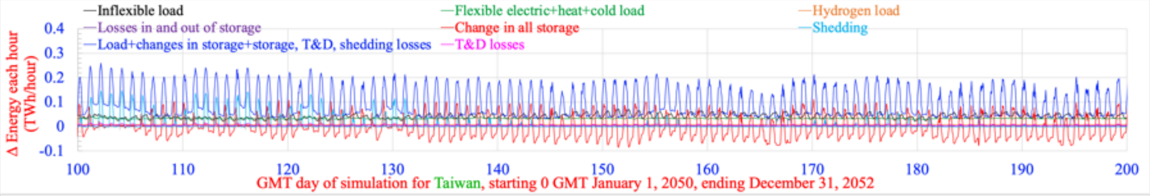
Load+changes in storage+storage, T&D, shedding losses
Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
GMT day of simulation for South Korea, starting 0 GMT January 1, 2050, ending December 31, 2052
Total WWS electricity+heat generation before losses
Onshore+offshore 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 South Korea, starting 0 GMT January 1, 2050
y = 0.0443x + 0.0159
R² = 0.044
Building heat load (TWh/hour)
South Korea wind power output (TWh/hour)
y = -0.0579x + 0.1465
R² = 0.0062
Winnd power output (TWh/hour)
South Korea solar power output (TWh/hour)

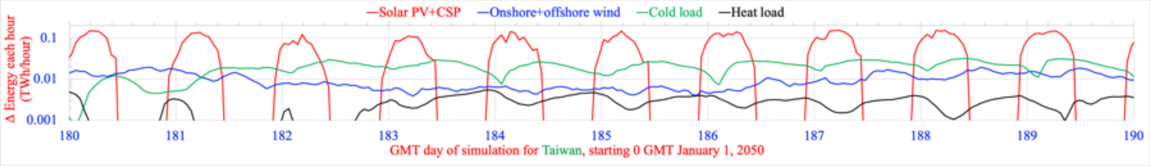
TAIWAN

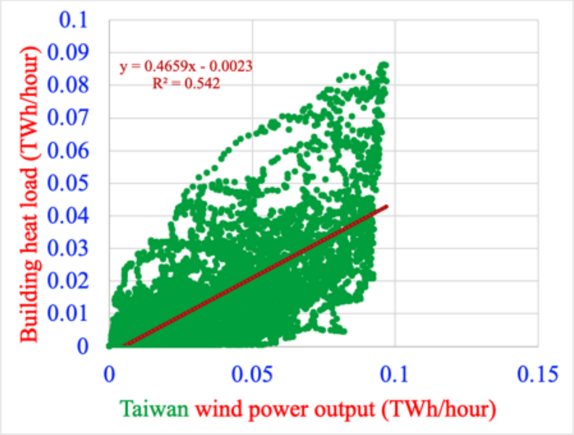

Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
100
200
300
400
500
600
700
800
900
1000
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052

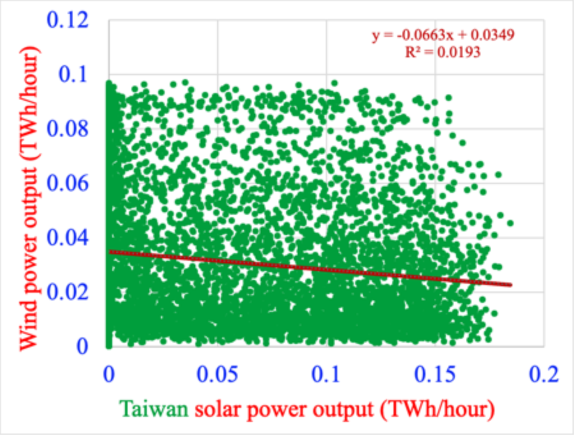

· Load+changes in storage+storage, T&D, shedding losses
—Total WWS electricity+heat generation before losses
Δ Energy each hour (TWh/hour)
0
0.1
0.2
0.3
100
110
120
130
140
150
160
170
180
190
200
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050, ending December 31, 2052


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

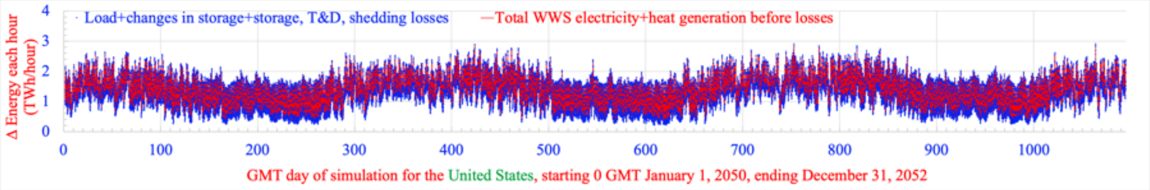

—Inflexible load
—Flexible electric+heat+cold load
—Hydrogen load
—Losses in and out of storage
—Change in all storage
—Shedding
—Load+changes in storage+storage, T&D, shedding losses
—T&D losses
Δ Energy each hour (TWh/hour)
-0.1
0
0.1
0.2
0.3
0.4
100
110
120
130
140
150
160
170
180
190
200
GMT day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

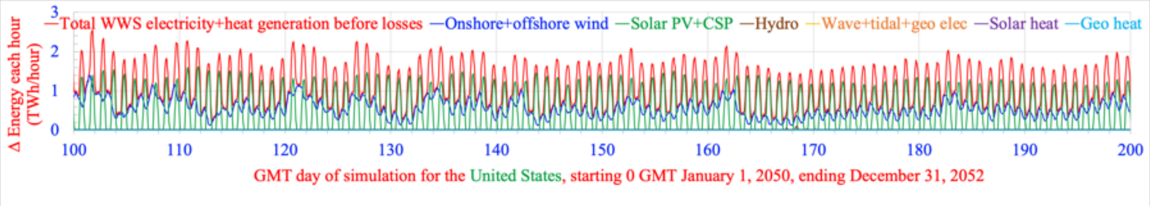

—Solar PV+CSP
—Onshore+offshore wind
—Cold load
—Heat load
Δ Energy each hour (TWh/hour)
0.001
0.01
0.1
180
181
182
183
184
185
186
187
188
189
190
GMT day of simulation for Taiwan, starting 0 GMT January 1, 2050

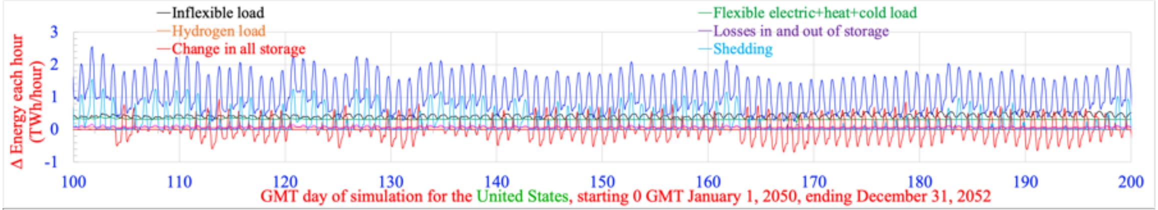

y = 0.4659x - 0.0023
R² = 0.542
Building heat load (TWh/hour)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.05
0.1
0.15
Taiwan wind power output (TWh/hour)

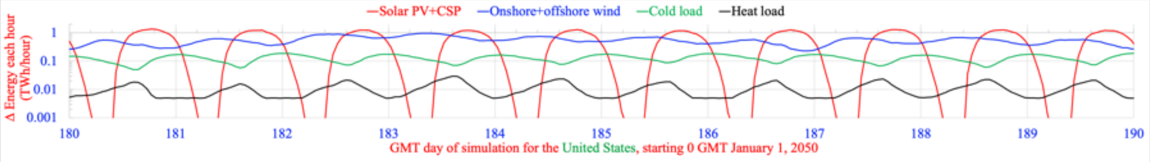

y = -0.0663x + 0.0349
R² = 0.0193
Wind power output (TWh/hour)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
0.05
0.1
0.15
0.2
Taiwan solar power output (TWh/hour)

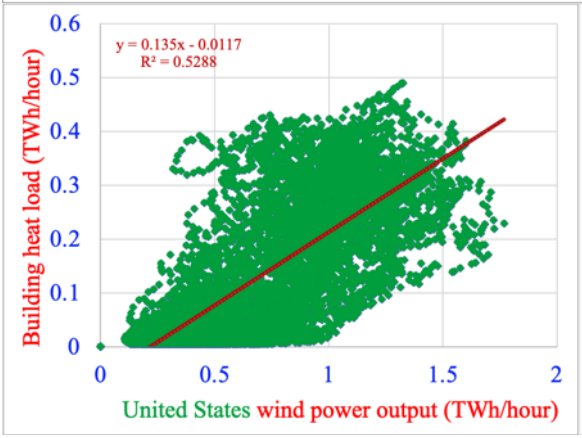
UNITED STATES

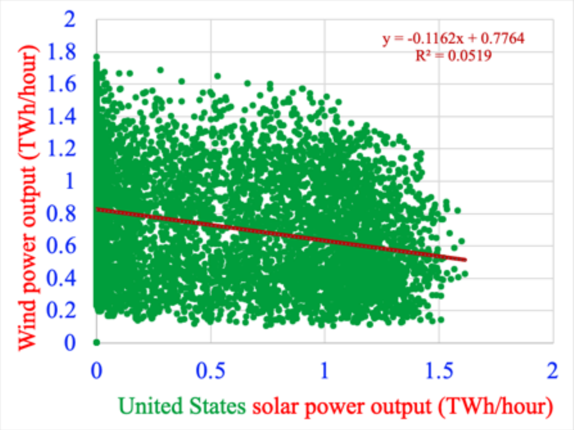












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