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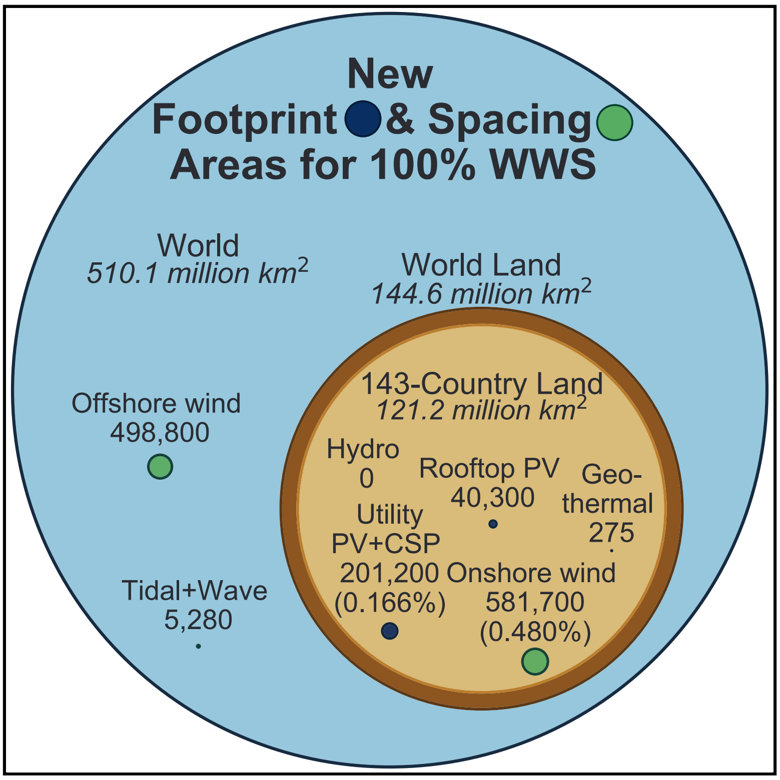
Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries

Graphical Abstract



Highlights

- Green New Deal all-sector energy roadmaps are developed for 143 countries
- WWS grid stability is analyzed, and cost metrics are developed for BAU versus WWS energy
- WWS energy reduces energy needs by 57.1%, energy costs by 61%, and social costs by 91%
- WWS energy costs $73 trillion upfront and creates 28.6 million more jobs than BAU energy

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In Brief

This paper evaluates Green New Deal solutions to global warming, air pollution, and energy insecurity for 143 countries. The solutions involve transitioning all energy to 100% clean, renewable wind-water-solar (WWS) energy, efficiency, and storage. WWS reduces global energy needs by 57.1%, energy costs by 61%, and social (private plus health plus climate) costs by 91% while avoiding blackouts, creating millions more jobs than lost and requiring little land. Thus, 100% WWS needs less energy, costs less, and creates more jobs than current energy.

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Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries

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SCIENCE FOR SOCIETY The Earth is approaching 1.5°C global warming, air pollution kills over 7 million people yearly, and limited fossil fuel resources portend social instability. Rapid solutions are needed. We provide Green New Deal roadmaps for all three problems for 143 countries, representing 99.7% of world's CO_2 emissions. The roadmaps call for countries to move all energy to 100% clean, renewable wind-water-solar (WWS) energy, efficiency, and storage no later than 2050 with at least 80% by 2030. We find that countries and regions avoid blackouts despite WWS variability. Worldwide, WWS reduces energy needs by 57.1%, energy costs from \$17.7 to \$6.8 trillion/year (61%), and social (private plus health plus climate) costs from \$76.1 to \$6.8 trillion/year (91%) at a capital cost of ~\$73 trillion. WWS creates 28.6 million more long-term, full-time jobs than are lost and needs only 0.17% and 0.48% of land for footprint and space, respectively. Thus, WWS needs less energy, costs less, and creates more jobs than current energy.

SUMMARY

Global warming, air pollution, and energy insecurity are three of the greatest problems facing humanity. To address these problems, we develop Green New Deal energy roadmaps for 143 countries. The roadmaps call for a 100% transition of all-purpose business-as-usual (BAU) energy to wind-water-solar (WWS) energy, efficiency, and storage by 2050 with at least 80% by 2030. Our studies on grid stability find that the countries, grouped into 24 regions, can match demand exactly from 2050 to 2052 with 100% WWS supply and storage. We also derive new cost metrics. Worldwide, WWS energy reduces end-use energy by 57.1%, aggregate private energy costs from \$17.7 to \$6.8 trillion/year (61%), and aggregate social (private plus health plus climate) costs from \$76.1 to \$6.8 trillion/year (91%) at a present value capital cost of ~\$73 trillion. WWS energy creates 28.6 million more long-term, full-time jobs than BAU energy and needs only ~0.17% and ~0.48% of land for new footprint and spacing, respectively. Thus, WWS requires less energy, costs less, and creates more jobs than does BAU.

INTRODUCTION

The world is beginning to transition to clean, renewable energy for all energy purposes. However, to avoid 1.5°C global warming, we must stop at least 80% of all energy and non-energy fossil fuels and biofuel emissions by 2030[1] and stop 100% no later than 2050.[1,2] Air pollution from these same sources kills 4–9 million people each year (Figure 1),[3] and this damage will continue unless the sources of air pollution are eliminated. Finally, if the use of fossil fuels is not curtailed rapidly, rising demand for increasingly scarce fossil energy will lead to economic, social, and political instability, enhancing international conflict.[3,4]

In an effort to solve these problems, studies among at least 11 independent research groups have found that transitioning to 100% renewable energy in one or all energy sectors, while keeping the electricity and/or heat grids stable at a reasonable cost, is possible.[1,5–26] The reviews of Brown et al.[27] and Diesendorf and Elliston[28] further find that critiques of 100% renewable systems are misplaced. The latter study, for example, concludes, "the main critiques published in scholarly articles and books contain factual errors, questionable assumptions, important omissions, internal inconsistencies, exaggerations of limitations and irrelevant arguments."

Among the studies that find that 100% renewable energy is cost effective, many have been of limited use to policy makers because they considered only private cost and not social cost, did not compare business-as-usual (BAU) with wind-water-solar

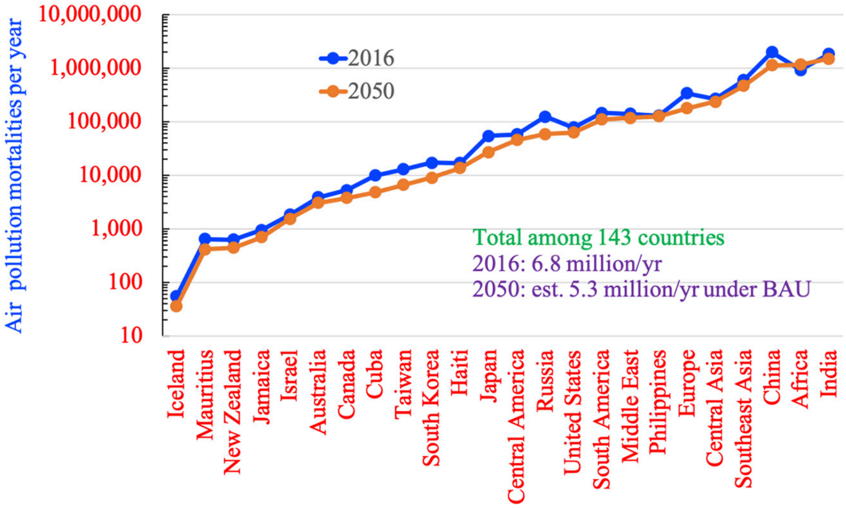


Figure 1. Estimated BAU Air-Pollution Mortalities in 2016 and 2050 by World Region

2016 and projected 2050 all-cause indoor plus outdoor air-pollution mortalities per year in 24 world regions encompassing 143 countries (see Table 1 for a list of countries in each region). We obtained 2016 data by multiplying country-specific indoor plus outdoor air-pollution deaths per 100,000 people from the World Health Organization[40] by 2016 country population. 2050 estimates were obtained with Equation S35 in Note S39. BAU energy is estimated to be responsible for 90% of the mortalities in this figure (most of the rest are from open biomass burning, wildfires, and dust). See Table S15 for a breakdown of 2016 world air-pollution deaths by cause.

(WWS) energy, and considered only cost per unit energy and not the aggregate (summed) cost over all end-use energy used.

First, social (economic) costs are private market costs plus external costs not accounted for in market costs or prices. In the present context, the most relevant external costs are those due to (1) air-pollution mortality, morbidity, and non-health damage and (2) global warming damage. A social-cost analysis is more useful to policy makers than is an analysis that considers only private costs because the former gives policy makers a more complete picture of the impacts of policies that affect climate change and air pollution than does the latter.

Second, many studies have not compared the cost of WWS energy with that of BAU energy. As such, determining the magnitude of the benefit of one over the other is difficult. Differences between WWS and BAU energy are masked even more when a private-cost analysis, which ignores health and climate costs, is performed instead of a social-cost analysis.

Third, most analyses look at the cost per unit energy rather than the aggregate energy cost per year. This problem is significant because a WWS system uses much less end-use energy than does a BAU system.

In 2009, Jacobson and Delucchi[5] calculated that transitioning the world's all-purpose energy to 100% WWS energy by 2030 could be technically and economically feasible, but for social and political reasons, a complete transition by 2030 was unlikely and could take up to a couple of decades longer. Subsequent roadmaps[1,4,15] proposed an 80% transition by 2030 and a 100% transition by no later than 2050 (e.g., Figure S1). The energy portion of the Green New Deal (GND) proposed in the US Congress[29] and earlier versions of it[30] adopted Jacobson and Delucchi's "technically and economically feasible" 2030 deadline and "100% clean, renewable, and zero-emission energy sources" goal.[30]

This paper provides GND energy roadmaps for transitioning 143 countries, representing more than 99.7% of global fossil fuel CO_2 emissions, to 100% WWS energy for all energy purposes (which include electricity, transportation, building heating and cooling, industry, agriculture, forestry, fishing, and the military; Note S28). The proposed transition timeline is no less than 80% WWS energy by 2030 and 100% by no later than 2050 (Figure S1) worldwide. The paper also provides analyses of grid stability for 24 world regions encompassing the 143 countries (Table 1). Because the 100% clean, renewable, and zero-emission energy goals of the present study are the same as those of the US GND, but with an adjusted timeline, the present study can help to evaluate the costs and feasibility of the energy component of not only the US GND but also the GNDs of 142 other countries. The US GND contains additional proposed legislation related to jobs, health care, education, and social justice.[29] The present study does not fully evaluate the costs or merits of these other components. However, because the energy transitions outlined here benefit air-pollution health, climate, and jobs, this work partly addresses some of these components. In this study, we evaluate results considering both private and social costs in terms of (1) the cost per unit end-use energy and (2) the cost aggregated over all end-use energy ("aggregate" cost). New cost metrics are provided. At the end, we discuss uncertainties and sensitivities as well as differences between the present study and two recent studies that argue that using 100% renewables for electricity is not feasible at low cost.

RESULTS AND DISCUSSION

We first projected 2016 end-use BAU energy in multiple energy sectors in 143 countries to 2050 (Note S3). 2050 BAU end-use energy loads were then electrified, the electricity for which was provided by WWS energy (Notes S4–S12). Table 2 and Figure S1 indicate that transitioning from BAU to WWS energy in 143 countries reduces 2050 annual average demand for end-use power (defined in Note S3) by 57.1% (case WWS-D in Table 2). Of this, 38.3 percentage points are due to the efficiency of using WWS electricity over combustion; 12.1 percentage points are due to eliminating energy in the mining, transporting, and refining of fossil fuels; and 6.6 percentage points are due to improvements in end-use energy efficiency and reduced energy use beyond those in the BAU case. Of the 38.3% reduction due to the efficiency advantage of WWS electricity, 21.7 percentage points are due to the efficiency advantage of WWS transportation, 3.4 percentage points are due to

Table 1. The 24 World Regions Composed of 143 Countries Treated in This Study

Region	Country or Countries within Each Region
Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of the Congo, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Libya, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, Tanzania, Togo, Tunisia, Zambia, Zimbabwe
Australia	Australia
Canada	Canada
Central America	Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
Central Asia	Kazakhstan, Kyrgyz Republic, Pakistan, Tajikistan, Turkmenistan, Uzbekistan
China	China, Hong Kong, Democratic Republic of Korea, Mongolia
Cuba	Cuba
Europe	Albania, Austria, Belarus, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Gibraltar, Greece, Hungary, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Moldova Republic, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
Haiti	Haiti, Dominican Republic
Iceland	Iceland
India	India, Nepal, Sri Lanka
Israel	Israel
Jamaica	Jamaica
Japan	Japan
Mauritius	Mauritius
Mideast	Armenia, Azerbaijan, Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
New Zealand	New Zealand
Philippines	Philippines
Russia	Georgia, Russia
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Curacao, Ecuador, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Southeast Asia	Bangladesh, Brunei Darussalam, Cambodia, Indonesia, Malaysia, Myanmar, Singapore, Thailand, Vietnam
South Korea	South Korea
Taiwan	Taiwan
United States	United States

the efficiency advantage of WWS electricity for industrial heat, and 13.2 percentage points are due to the efficiency advantage of heat pumps.

Initial estimates of nameplate capacities needed to meet annual average load were then derived for each of the 143 countries (Note S13). The 143 countries were subsequently grouped into 24 world regions (Table 1). LOADMATCH was next run from 2050 to 2052 with 30 s timesteps to match all-sector demand with supply in each region. For each region, the initial inputs were adjusted for each simulation until a zero-load-loss solution was found among all timesteps, typically within ten simulation attempts. After one successful simulation, we ran the model another 4–20 simulations, with further adjustments, to find additional lower-cost solutions. Thus, multiple zero-load loss solutions were obtained for each region, but only the lowest-cost solution is presented here. Tables S20 and S21 provide the final generator nameplate capacities and capacity factors, respectively, in each region. Table S11 provides the final storage characteristics.

Table 3 indicates that only 9% more generator nameplate capacity is needed, in the 143-country average, to meet time-dependent load than to meet annually averaged load. Storage is also needed to meet time-dependent load (Table S11).

Figure 2 shows the full 3-year time series of WWS power generation versus load plus losses plus changes in storage plus shedding for two world regions. Figure S4 shows the same but for all 24 world regions. Both figures also show a distribution of WWS power generation and of load plus losses plus changes in storage plus shedding for 100 days during each time series. The figures demonstrate no load loss at any time in any region.

The 2050–2052 WWS mean social cost per unit all-sector energy, when weighted by generation among all 24 regions, is 8.96 ¢/kWh-all-energy (USD 2013) (Figure 3A and Tables S22 and S23). However, Figure 3A shows that the individual regional averages range from 6.5 ¢/kWh-all-energy (Iceland) to 13.1 ¢/kWh-all-energy (Israel). The largest portion of cost is the cost of generation, which includes capital, operation, maintenance, and decommissioning costs (Table S14). In descending order, the next-largest costs are of transmission and distribution; electricity storage; hydrogen production, compression, and storage; and thermal energy storage.

Table 2. Reduced End-Use Demand upon a Transition from BAU to WWS Energy

		Percentage of Total						2050 Change in Demand			
Scenario	Total End-Use Demand	Residential	Commercial	Industrial	Transport	Agriculture, Forestry, and Fishing	Military and Other	Due to Higher WWS Work/Energy Ratio	Due to Eliminating Upstream Emissions with WWS	Due to Greater Efficiency with WWS Than with BAU	Total 2050 Change in Demand Due to Switching to WWS
BAU 2016	12,628 GW	21.1%	8.13%	38.4%	28.7%	2.1%	1.5%	–	–	–	–
BAU 2050	20,255 GW	19.1%	7.80%	37.4%	32.3%	1.9%	1.5%	–	–	–	–
WWS-A 2050[a]	15,932 GW	20.2%	8.50%	34.9%	32.6%	2.2%	1.6%	0%	−13.7%	−7.6%	−21.3%
WWS-B 2050[b]	11,968 GW	27.0%	11.3%	46.4%	11.8%	1.6%	1.9%	−21.7%	−12.4%	−6.8%	−40.9%
WWS-C 2050[c]	11,294 GW	28.6%	12.0%	43.2%	12.5%	1.7%	2.0%	−25.1%	−12.3%	−6.8%	−44.2%
WWS-D 2050[d]	8,693 GW	17.7%	10.5%	52.0%	16.2%	1.7%	1.8%	−38.3%	−12.1%	−6.6%	−57.1%

This table shows annually averaged end-use power demand for 2016 BAU, 2050 BAU, and 2050 100% WWS energy by sector, summed among the 143 countries in Table 1. The last column shows the total percent reduction in 2050 BAU end-use power demand due to switching from BAU to WWS energy, including the effects of reduced energy use caused by the higher work-output-to-energy-input ratio of electricity over combustion; eliminating energy used for mining, transporting, and/or refining coal, oil, natural gas, biofuels, bioenergy, and uranium; and assumed policy-driven increases in end-use energy efficiency beyond those in the BAU case. Four 2050 WWS cases are shown: WWS-A, WWS-B, WWS-C, and WWS-D. The result indicates that, of the 38.3% demand reduction due to the higher work-output-to-energy-input ratio of electricity over combustion, 21.7, 3.4, and 13.2 percentage points are due to the efficiency of WWS transportation, the efficiency of WWS electricity for industrial heat, and the efficiency of heat pumps, respectively. Table S2 shows rows “BAU 2050” and “WWS-D 2050” by country. Note S28 defines sectors.

[a] Case WWS-A eliminates the energy used for mining, transporting, and refining fossil fuels and uranium and increases energy efficiency beyond that of BAU energy (change all values for extra efficiency in Table S1 to current values from unity), but it does not change the work-output-to-energy-input ratio relative to that of BAU energy. It assumes that the efficiency of electrification is the same as that of fossil fuels (leave the electricity-to-fuel ratio = 1 for all fuels in all sectors in Table S1).

[b] Case WWS-B is the same as WWS-A, except that it includes the higher work-output-to-energy-input ratio of electric vehicles and hydrogen-fuel-cell vehicles powered by WWS energy over internal-combustion vehicles (reduce the electricity-to-fuel ratios from 1 to their current values for oil, natural gas, biofuels, and waste in the transportation sector and for oil in the agriculture, forestry, and fishing sector, military sector, and other sectors in Table S1).

[c] Case WWS-C is the same as WWS-B, except that it accounts for the higher work-output-to-energy-input ratio of high-temperature industrial processes with WWS energy (reduce the electricity-to-fuel ratios from 1 to their current values for oil, natural gas, coal, biofuels, and waste in the industrial sector in Table S1).

[d] Case WWS-D is the same as WWS-C, except that it accounts for the higher work-output-to-energy-input ratio of heat pumps over internal-combustion heating for low-temperature heat (reduce the electricity-to-fuel ratios from 1 to their current values for all remaining values below 1 in Table S1: namely, oil, natural gas, coal, biofuels, and waste in the residential and commercial sectors; heat for sale in all sectors; natural gas, coal, biofuels, and waste in the agriculture, forestry, and fishing sector, military sector, and other sectors).

Figure 3B indicates that the overall net present value of the capital cost of transitioning all energy sectors of 143 countries to 100% WWS energy while keeping the grid stable is about $72.8 trillion (USD 2013). Individual regional costs range from $2.6 billion for Iceland to $16.6 trillion for the China region. The cost for the US is about $7.8 trillion, and that for Europe is about $6.2 trillion. These capital costs pay themselves off over time by electricity and heat sales.

Figure 4 and Table 4 present results from our main cost metrics. Multiplying the private cost per unit energy in Figure 4A by the end-use energy consumed per year (or by the annual average power) in the WWS and BAU cases gives the aggregate annual private energy cost in each case, shown in Figure 4B. Among 143 countries, the aggregate annual private energy cost is $6.8 trillion/year in the WWS case and $17.7 trillion/year in the BAU case. The main (but not only) reason for this difference is the 57.1% lower end-use energy consumption in the WWS case (Tables 2 and 4).

What’s more, the aggregate annual social cost across all regions worldwide is $76.1 trillion/year in the BAU case but only $6.8 trillion/year in the WWS case (Table 4 and Figure 4B). Thus, the WWS-to-BAU aggregate annual social cost ratio is 9% (Table 4). In other words, the aggregate annual social cost (energy plus health plus climate costs) of WWS energy is only 9% that of a BAU system each year. Figure 4C shows the aggregate social cost ratio and its components for all 24 world regions. The ratio varies from 3.9% for the Philippines to 24.9% for Iceland. The smallest benefit of a transition occurs in Iceland simply because Iceland has already transitioned much of its energy, so its air pollution and climate emissions are already low. Thus, it sees less remaining benefit of converting than other regions.

Table 3. Nameplate Capacities Needed by Generator Type for 100% WWS Energy

Energy Technology	(A) Nameplate Capacity of One Plant or Device	(B) 2050 All-Purpose Annual Average Demand Met by Plant or Device	(C) Initial Nameplate Capacity: Existing plus New Plants or Devices to Meet Annual Average Demand	(D) Final Nameplate Capacity: Existing plus New Plants or Devices to Meet Time-Dependent Demand	(E) Percentage of Final Nameplate Capacity Already Installed by 2018	(F) Final Numbers of New Plants or Devices Needed for 143 Countries
Annual Average Power						
Onshore wind turbine	5 MW	30.50%	8,251 GW	11,976 GW	4.76%	2,281,019
Offshore wind turbine	5 MW	14.51%	3,841 GW	3,606 GW	0.68%	716,252
Wave device	0.75 MW	0.34%	156 GW	156 GW	0.0001%	208,313
Geothermal electricity	100 MW	0.92%	97 GW	97 GW	13.67%	837
Hydropower plant[a]	1,300 MW	5.72%	1,109 GW	1,109 GW	100.0%	0
Tidal turbine	1 MW	0.08%	31 GW	31 GW	1.76%	30,075
Residential rooftop PV	0.005 MW	11.14%	5,082 GW	2,776 GW	3.44%	536,080,000
Commercial or governmental rooftop PV[b]	0.1 MW	13.84%	6,705 GW	5,121 GW	1.87%	50,250,000
Utility PV plant[b]	50 MW	19.03%	8,234 GW	13,691 GW	2.09%	268,090
Utility CSP plant[b]	100 MW	3.93%	634 GW	1,262 GW	0.43%	12,565
Total for average power	–	100.00%	34,138 GW	39,842 GW	5.53%	610,045,000
For Peaking and Storage						
Additional CSP[c]	100 MW	2.36%	381 GW	0 GW	0%	0
Solar thermal heat[c]	50 MW	–	2,573 GW	632 GW	72.6%	3,468
Geothermal heat[c]	50 MW	–	70.3 GW	70.3 GW	100.00%	0
Total peaking and storage	–	2.36%	3,024 GW	702 GW	75.31%	3,468
Total All	–	–	37,163 GW	40,544 GW	6.74%	610,049,000

This table shows the estimated (C) initial nameplate capacities (meeting the annual average all-purpose end-use power demand) and final (D) nameplate capacities (meeting time-dependent demand) of WWS generators, summed among 143 countries in 24 regions, needed to supply 100% of all-purpose energy with WWS energy. Also shown are (B) the 143-country-averaged percent end-use demand estimated to be supplied by the initial nameplate capacity of each generator (values for individual countries are given in Table S5), (E) the percentage of final 2050 nameplate capacity of each generator already installed in 2018, and (F) the final numbers of new devices of specified sizes still needed. All values are summed over 143 countries in 24 regions. "Annual average power" is annual average all-purpose energy demand divided by the number of seconds per year. The nameplate capacity of each device (A) is assumed to be the same for all countries. The percentage of annual average power demand met by each device type (B) is a demand-weighted average among the mixes given for 143 countries in Table S5 before time-dependent demand calculations are performed with LOADMATCH. The "initial" nameplate capacity (C) is equal to the total end-use demand (B) multiplied by the percentage of demand satisfied by the device and then divided by the capacity factor of the device. This initial nameplate capacity (meeting average annual demand) for each grid region is used at the start of LOADMATCH simulations. The "For Peaking and Storage" section of (C) is the initial estimate of additional CSP installations and solar thermal heat generators for the start of the LOADMATCH simulations. Column (D) shows the 143-country final nameplate capacities needed to match load after the LOADMATCH simulations for each of the 24 grid regions. Table S20 gives the final nameplate capacities for each region. Columns (D) and (E) show the fraction of final nameplate capacity already installed as of the end of 2018 and the remaining number of devices of size specified in (A) still needed, respectively.

[a] No increase in the number of dams or in the peak discharge rate of hydropower is assumed.

[b] The solar PV panels used for this calculation were SunPower E20 panels. A CSP plant is assumed to have storage with a maximum charge-discharge rate (ratio of storage size to generator size) of 2.62:1. See the footnotes in Table S7 of Jacobson et al.[4] for more details.

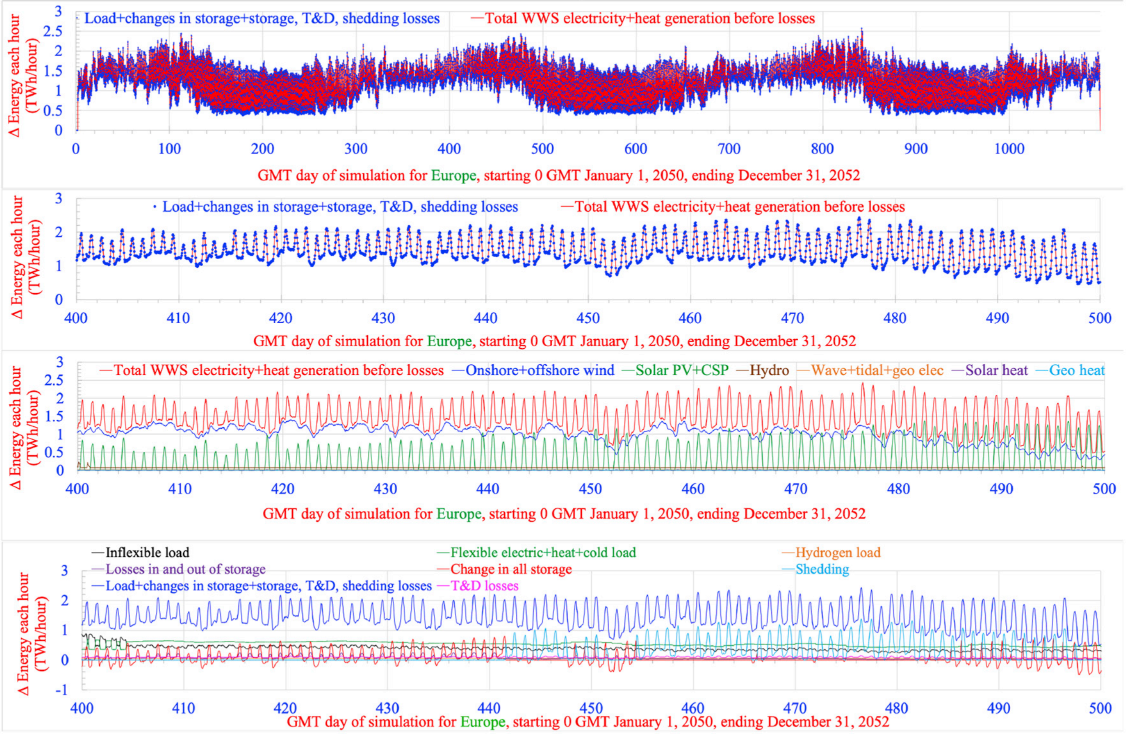
[c] Additional CSP is the estimated CSP plus storage beyond that for annual average power generation needed to provide peaking power to stabilize the grid. Additional solar thermal and existing geothermal heat are used for direct heat or heat storage in soil. "Geothermal heat" is existing geothermal heat, which is assumed not to change in the future (hence the same values in columns C and D).

Table 4 further indicates that the 143-country aggregate private cost ratio (Equation 9) is 39%, which means that, on average, the 100%-WWS-energy scenario cuts annual consumer energy bills by 61% worldwide. Finally, the social cost per unit energy (Equation 10) is 79% less in the WWS case than in the BAU case (Table 4).

We assumed here that the BAU cost per unit all energy equals the BAU cost per unit electricity given the lack of data on the BAU cost per unit non-electrical energy. Because the aggregate annual social and private costs in the WWS cases for all world regions are an order of magnitude lower than those in the BAU cases, we believe that assumption makes no difference to the conclusion found here, namely that WWS energy is much less expensive than BAU energy, given that the conclusion would still hold even if the assumption were off by a factor of, say, eight.

Figure 3A indicates that the 2050 cost of WWS energy per unit energy is relatively low for large regions (e.g., Canada, Russia, Africa, China, Europe, and the US) and for small countries with good WWS resources (e.g., Iceland and New Zealand). Larger land areas permit greater geographical dispersion of wind and

Europe



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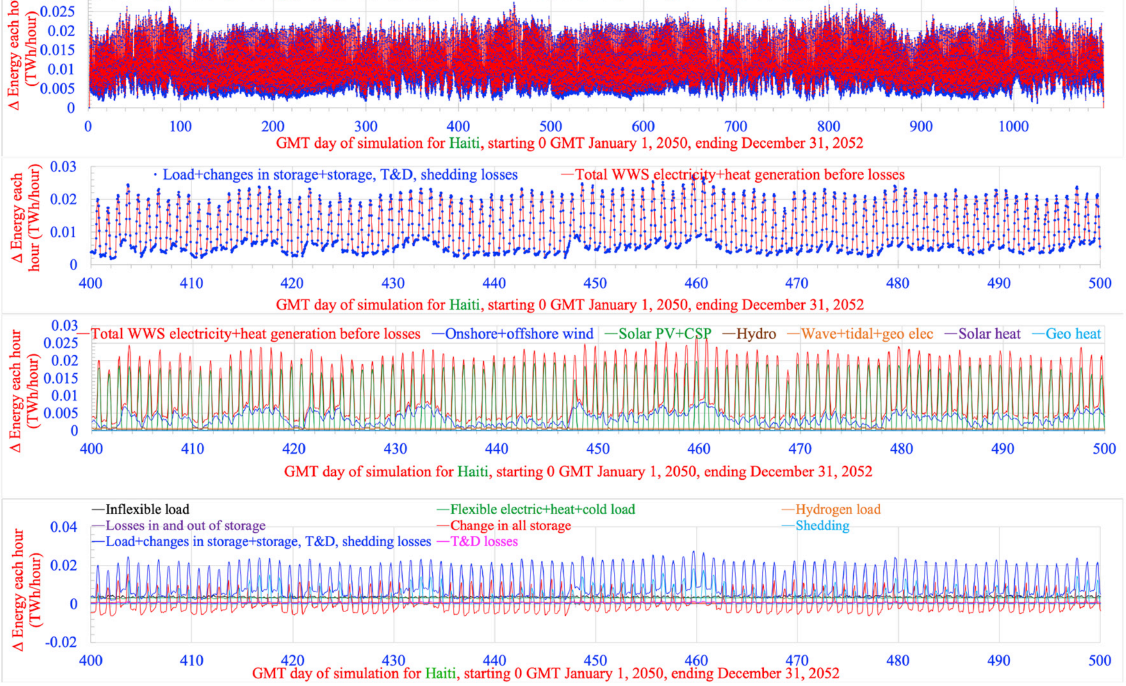

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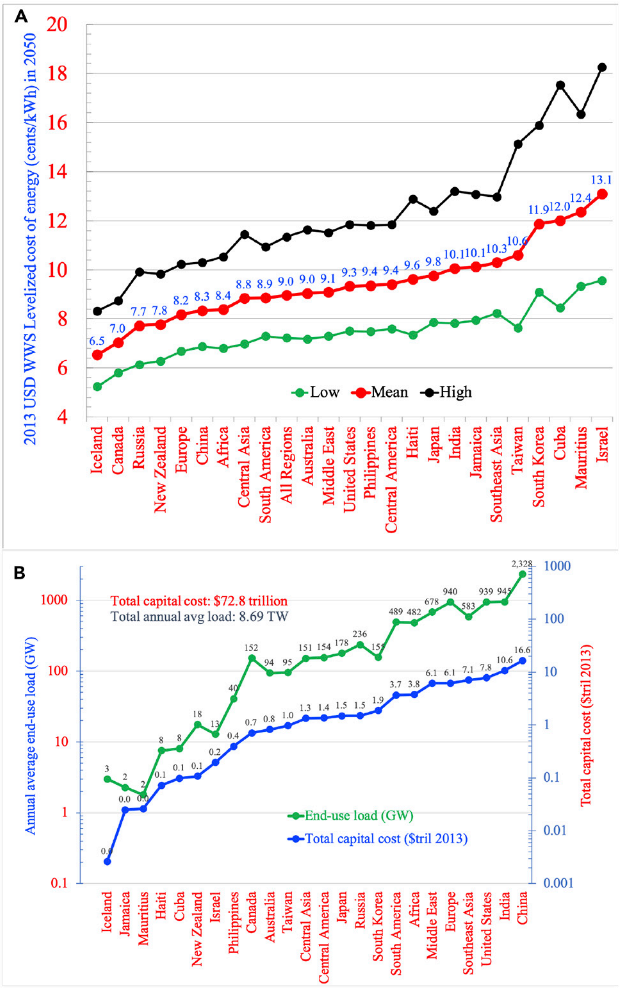

Figure 3. Energy Private Costs, Capital Costs, and Loads by World Region

(A) Low, mean, and high modeled levelized private costs (averaged between today and 2050 in 2013 USD) of converting 24 world regions encompassing 143 countries to 100% WWS energy for all energy purposes.

(B) Annual average all-purpose end-use loads and present values (2013 USD) of mean capital costs for a 100%-WWS-energy system. See Table S22 for low and high values of levelized cost.

solar energy. Connecting these dispersed resources via the regional grid reduces overall intermittency. These regions also have a good balance of solar and wind power, which are complementary in nature seasonally. Finally, the larger regions have some existing hydropower that can provide peaking power. Iceland has substantial hydropower, geothermal, and wind power.

Costs are highest in small countries with high population densities (Taiwan, Cuba, South Korea, Mauritius, and Israel). Nevertheless, the 2050 private cost of WWS energy per year in all five regions is 43%–65% that of BAU energy, indicating that a transition to WWS energy reduces costs even under the least favorable circumstances.

Land-use impacts are represented here by footprint and spacing areas required by WWS technologies. Footprint is the physical area on the top surface of soil or water needed for each energy device. New land footprint is created only for solar photovoltaic (PV) plants, concentrated solar power (CSP) plants, onshore wind turbines, geothermal plants, and solar thermal plants. Rooftop PV does not take up new land. 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 device with downstream devices. 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. The only spacing area over land needed in a 100% WWS world is between onshore wind turbines.

The total new land areas for footprint and spacing with 100% WWS energy are about 0.17% and 0.48%, respectively, for a total of 0.65% of the 143-country land area (Note S44, Table S26, and Figure S6). This is equivalent to about 1.85 times California's land area for virtually all world energy. In comparison, about 37.4% of the world's land was agricultural land in 2016, and 2.5% was urban area in 2010.[31] The footprint needed for WWS energy is almost all for utility PV and CSP plants. Some of the utility PV can fit on the spacing area that wind occupies, illustrating the dual use of the wind land.

Finally, a transition could increase the net number of long-term, full-time jobs. Such jobs arise as a result of energy generation, transmission, and storage. Note S45 describes how changes in jobs are determined. The calculation accounts for 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. Job changes due to changes in energy prices are not included. Changes in energy pricing could trigger changes in factor allocations among capital, energy input, and labor and thus changes in job numbers.

Results here indicate that a transition could create about 28.6 million more long-term, full-time jobs than lost among the 143

Figure 2. 3-Year LOADMATCH Results for Two World Regions

Time-series comparison, from 2050 to 2052 for two world regions, of modeled (first row) total WWS power generation versus total load plus losses plus changes in storage plus shedding; (second row) same as first row but for a window of days 400–500 during the 3-year period; (third row) a breakdown of WWS power generation by source during the window; and (fourth row) a breakdown showing inflexible load; flexible electricity, heat, and cold load; flexible hydrogen load; losses in and out of storage; transmission and distribution losses; changes in storage; and shedding. The model was run at 30-s resolution. Results are shown hourly. No load loss occurred during any 30-s interval. Figure S4 shows results for all 24 world regions.

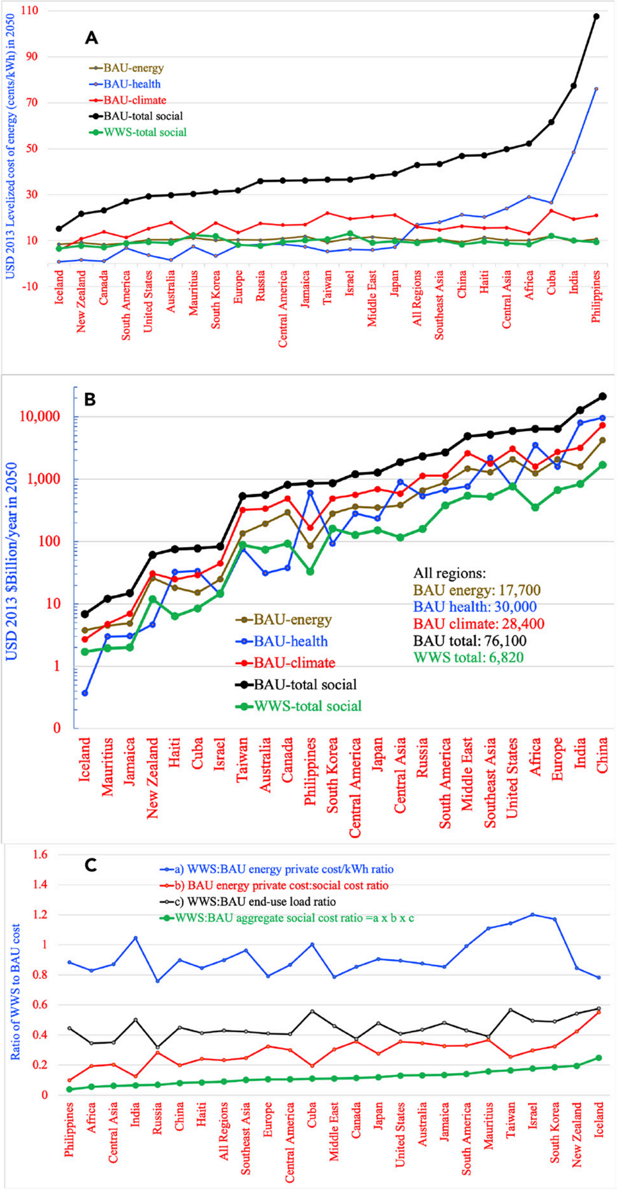

Figure 4. Summary of Private and Social Costs of WWS and BAU Energy

(A) Levelized private and social costs per kWh of energy produced by region in a BAU-energy world versus a WWS-energy world. BAU costs include energy, health, and climate costs. WWS costs include only energy costs because energy external costs are approximately zero. Energy costs are averaged between today and 2050 because the WWS-energy system will be built out during this period.

(B) Same as (A) but with the annual aggregate cost per year, obtained by multiplication of the cost per unit energy in (A) by the end-use energy consumption per year in the BAU or WWS case (from Table S2). See Table S22 for low and high annual aggregate costs of WWS energy per year.

(C) The WWS-to-BAU aggregate social cost ratio and its three component factors: the WWS-to-BAU ratio of cost per unit energy (obtained from A), the ratio of private cost of BAU energy to social cost (obtained from B), and the WWS-to-BAU ratio of end-use load (e.g., from Table S2 but for each region). 90% of all air-pollution mortalities are ascribed to BAU energy. Most of the rest are ascribed to open biomass burning, wildfires, and dust. The mean and range in aggregate health cost, summed over all regions, is $30 ($17.9–$52.7) trillion/year. That in aggregate climate costs is $28.4 ($16.0–$60.5) trillion/year. All costs are in 2013 USD.

countries (Table S28 and Note S45). Net job gains occurred in 21 out of 24 world regions. Net losses occurred in regions heavily dependent on fossil fuels, namely Canada, Russia, and parts of Africa. However, additional jobs in those and other regions could result from the need to build more electrical appliances, vehicles, and machines and to increase building energy efficiency, and these jobs were not considered here.

In the US, the estimated aggregate private and social costs of BAU energy are $2.1 and $5.9 trillion/year, respectively, whereas those of WWS energy are both $0.77 trillion/year. Thus, WWS energy decreases the aggregate private cost by 64% and aggregate social cost by 87%. The social-cost reduction arises from eliminating about 63,000 US air-pollution deaths per year (in 2050) and corresponding illnesses as well as eliminating the US energy contribution to global warming.

The US transition to 100% WWS energy is estimated to cost a mean of $7.8 trillion in net-present-value capital but create 3.1 million net long-term full-time US jobs (Table S28) and use only 0.22% of the country's land for footprint and 0.86% for spacing (Table S26). As such, a complete US transition, as also called for by the US GND,[29] will reduce aggregate energy costs each year, reduce health-care costs and mortality, reduce climate damage, and create jobs.

Uncertainties and Sensitivities

The results here contain uncertainties. Some include uncertainties arising from inconsistencies between load and resource datasets, the timing of generator and storage downtime, assuming perfect transmission, not modeling transmission congestion, not modeling frequency regulation, and projecting future energy use. Note S46 discusses these issues as well as several sensitivity tests performed here to examine uncertainties in more detail. These include cost sensitivities due to changes in the fraction of thermal loads subject to district heating and underground thermal energy storage, to changes in hydrogen storage, and to changes in demand response.

One particular concern is whether the simulations here captured the variability of energy demand and wind and solar supply, including during extreme weather events. However, GATOR-GCMOM (gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean model) accounts for extreme weather events because it models the variability of weather everywhere worldwide at a 30 s time resolution on the basis of physical principles. It also accounts for competition among wind turbines for available kinetic energy and the resulting feedback of such turbines to weather. Zero-load-loss results were found here every 30 s for 3 years, thus accounting for extreme weather events, in 24 vastly different world regions, each with different WWS supplies.

Another uncertainty arises from our assumption of a perfectly interconnected transmission system. Whereas the study accounts for transmission and distribution costs and losses, it assumes that electricity can flow to where it is needed without bottlenecks. This concern applies to only about half the regions examined given that 11 regions (Iceland, Cuba, Jamaica, Haiti

Table 4. Summary of Private and Social Costs over 143 Countries

Private and Social Costs	Value
(A) Private cost per unit BAU energy[a]	9.99 ¢/kWh
(B) Health cost per unit BAU energy	16.9 ¢/kWh
(C) Climate cost per unit BAU energy	16.0 ¢/kWh
(D) Social cost per unit BAU energy (A + B + C)	42.9 ¢/kWh
(E) Private and social cost per unit WWS energy[a]	8.96 ¢/kWh
(F) End-use power demand of BAU energy[b]	20,255 GW
(G) End-use power demand of WWS energy[b]	8,693 GW
(H) Aggregate annual private cost of BAU energy in the electricity sector (A × F)	$17.7 trillion/year
(I) Health cost of BAU energy (B × F)	$30.0 trillion/year
(J) Climate cost of BAU energy (C × F)	$28.4 trillion/year
(K) Social cost of BAU energy (D × F)	$76.1 trillion/year
(L) Private and social costs of WWS energy (E × G)	$6.82 trillion/year
(M) WWS-to-BAU ratio of private cost per kWh ($R_{WWS:BAU\text{-}E}$) (E/A)	0.90
(N) Ratio of private cost of BAU energy (kWh) to social cost of BAU energy (kWh) ($R_{BAU\text{-}S:E}$) (A/D)	0.23
(O) Ratio of WWS energy used (kWh) to BAU energy used (kWh) ($R_{WWS:BAU\text{-}C}$) (G/F)	0.43
WWS-to-BAU ratio of aggregate social cost (R_{ASC}) (M × N × O)	0.09
WWS-to-BAU ratio of aggregate private cost (R_{APC}) (M × O)	0.39
WWS-to-BAU ratio of social cost per unit energy (R_{SCE}) (M × N)	0.21

This table shows the 2050 mean social costs per unit WWS versus BAU energy for 143 countries (24 world regions), as well as the WWS-to-BAU ratio of aggregate social cost and the components of its derivation (Equation 5).

[a] This is the electricity-sector cost of BAU energy per unit energy. It is assumed to equal the all-energy cost of BAU energy per unit energy. The cost per unit WWS energy is for all energy, which is almost all electricity (plus a small amount of direct heat).

[b] Multiply GW by 8,760 h/year to obtain GWh/year.

and the Dominican Republic, Israel, Japan, Mauritius, New Zealand, the Philippines, South Korea, and Taiwan) have or could have, because of their small size, well-connected transmission and distribution systems. Stable, low-cost systems were found here for all those regions. As such, there is no reason to think that the US, for example, broken up into multiple isolated or moderately interconnected regions rather than one completely interconnected region can't also maintain a low-cost, stable 100% WWS grid. In fact, many of the dozens of earlier cited papers that have examined 100% renewable grids have treated transmission spatially and have found low-cost solutions. Aghahosseini et al.,[24] for example, found stable, low-cost, time-dependent electric grid solutions when North and South America were run on 100% renewables, and transmission flows were modeled explicitly among multiple lines. Although the present paper sacrifices spatial resolution needed to treat transmission explicitly, it treats time resolution (30 s) higher than other studies.

Finally, although the impact of transmission congestion on reliability is not modeled explicitly, Jacobson et al.[15] ran sensitivity tests (see their Figure S13) to check how different fractions of wind and solar power subject to long-distance transmission might affect cost. The result was that, if congestion is an issue at the baseline level of long-distance transmission, increasing the transmission capacity will relieve congestion with only a modest increase in cost.

Many remaining uncertainties are captured by the use of low, mean, and high costs of energy, air-pollution damage, and climate damage. Table S14, for example, shows low, mean, and high estimates of capital cost, operation and maintenance cost, decommissioning cost, energy generator lifetimes, and transmission, distribution, and downtime losses assumed here. Table S22 and Figure 3 provide the resulting low, mean, and high levelized private costs of energy per unit energy and private aggregate costs of energy for each world region. Table S18 provides the low, mean, and high estimated social costs of carbon, and Table S16 provides the parameters needed for calculating low, mean, and high air-pollution costs. Table S17 provides the resulting low, mean, and high air-pollution and climate costs per unit energy by country.

Comparison with Studies Critical of 100% Renewables

Two recent studies argue that 100% renewables is not a low-cost solution. One study[32] states that 80% of current US demand can be met by solar and wind power interconnected by either a US-wide transmission grid or 12 h of electrical storage but that more than 80% requires ‘‘costly’’ excess storage or solar or wind nameplate capacity. The present study and numerous papers among 11 independent research groups[4–28] contradict these findings.

First, the previous study[32] did not consider electrification of transportation, building heating, or industrial heat. Electrification of such loads not only reduces end-use demand substantially, as shown here, but also reduces the daily and seasonal variability of electric loads while creating more flexible loads that are subject to demand response. For example, current US electricity demand has a summer peak due to a high summer demand for air conditioning. Winter demand for building heating is currently provided mostly by natural gas and fuel oil, so it results in less winter electricity demand. Although replacing such heat with electric heat pumps increases winter electrical load (but by much less than the energy in the fuel it replaces as a result of the high coefficient of performance of heat pumps), the electrification of winter heating evens out seasonal (between summer and winter) electrical loads substantially as a result of the high summer electrical load.

On top of that, vehicles are used daily, so electrification of transportation results in a relatively even (throughout the year) distribution of additional electric load, further reducing the summer-winter electric-load imbalance. Because electric cars are charged mostly at night (particularly with tiered electrical rates that are lowest at night), such electrification also evens out day versus night electrical loads in comparison with the present grid.

Not only did this previous study[32] assume an unrealistic load distribution, but it also did not treat demand response, district heating, seasonal heat and cold storage, existing hydropower storage, or hydrogen production and storage for transportation. As a result, it shed excess wind and solar power instead of storing that energy in seasonal or daily thermal energy storage or hydrogen. In the present study, seasonal underground thermal energy storage is applied to the fraction of a region's thermal energy that is subject to district heating (Table S9). In addition, hydrogen is used for fuel cells for a portion of transportation, namely for long-distance heavy transport.

By not treating naturally rechargeable existing hydropower storage, the previous study[32] also limited its ability to fill in gaps in supply during key winter hours, when some of its shortfalls occurred.

The present study treats these processes and finds low-cost solutions with 100% WWS energy and storage not only in the US but also in 24 world regions.

A second study[33] used an optimization model that treats electricity from renewables, nuclear energy, natural gas with carbon capture, and biomass and battery storage in an effort to examine grid stability in two US regions. Simulations were run for 1 year with a 1-h time resolution. The model did not electrify transportation, building heating, or industrial heating; did not treat district heating or seasonal underground thermal energy storage; did not treat demand response or hydrogen production or storage; and did not treat concentrated solar power with storage, pumped hydropower storage, or hydropower storage. These processes are all treated here.

That study also did not consider the health or climate costs of the combustion sources, the delays between planning and operation of nuclear plants or plants using natural gas with carbon capture, or the resulting background-grid CO_2 and air-pollution emissions and costs due to such delays. It also assumed that carbon capture reduces 90% of CO_2 emissions, but that assumption ignores the upstream emissions from natural gas mining and transport and the fact that a natural gas plant with carbon-capture equipment requires 25%–50% more energy, and thus results in additional emissions, than the same plant without capture.[34] Thus, instead of reducing 90% of CO_2 emissions, carbon capture could result in a net emission reduction of only 10%–30% over a 20- to 100-year time frame.[35]

Moreover, that study substantially underestimated the private energy costs of nuclear power and natural gas with carbon capture. The nuclear capital cost in its mid-range case was 50% below the mean estimated nuclear capital cost from Lazard.[36] Its mid-range cost of natural gas with carbon capture was only $1,720/kW. However, the cost of the carbon-capture equipment alone for the only US power plant with carbon capture, the W.A. Thompson coal plant in Texas, was $1 billion or $4,200/kW.[35]

In sum, this previous study[33] not only biased nuclear and natural gas costs but also underestimated emissions and ignored many process that facilitate matching renewable supply with demand. Thus, its conclusion that "including nuclear power and natural gas plants that capture CO_2 consistently lower[s] the cost of decarbonizing electricity generation" was not shown. As calculated here, a transition to 100% WWS energy should reduce private and social costs substantially over those incurred by BAU energy without the need for nuclear power, fossil fuels with carbon capture, or bioenergy.

Finally, several additional studies have examined high penetrations of renewables. None of these studies examined scenarios with 100% renewables or disputed the possibility of using 100% renewables. One study[37] found that each region of the US could be powered with at least 90% renewable electricity and storage while matching power demand with supply hourly during a year. Renewable curtailment at 90% penetration was only 7%. The study did not examine 100% scenarios or scenarios in which all sectors were electrified. Two other studies similarly found that reducing US energy[38] or electricity[39] greenhouse gas emissions 80% below 1990 levels by 2050 is technically feasible and that multiple alternative pathways for achieving those reductions exist. Neither study examined 100% scenarios.

Conclusions

Here, we developed GND energy roadmaps for 143 individual countries to transition their all-purpose energy from BAU to 100% WWS, efficiency, and storage by no later than 2050 and with no less than an 80% transition by 2030. We then grouped the countries into 24 regions to study matching energy demand with 100% WWS supply plus efficiency and electricity, heat, cold, and hydrogen storage every 30 s from 2050 to 2052. Stable (no-load-loss) solutions were found in all world regions.

The cost of transitioning to 100% clean, renewable WWS, efficiency, and storage for all energy purposes while keeping the lights on can be viewed in terms of the private cost per unit energy, the aggregate private cost per year, the social cost per unit energy, and/or the aggregate social cost per year. Even more relevant is the comparative WWS versus BAU costs for these parameters. However, most studies to date have considered only private costs per unit energy, but this parameter shows only a modest difference between BAU and WWS energy. The WWS-to-BAU aggregate social cost ratio, on the other hand, indicates that the economic cost of transitioning to 100% WWS energy in 143 countries grouped into 24 regions is a mean of only 9%. In other words, 100% WWS energy reduces aggregate social costs by 91% in comparison with those incurred by BAU energy. The major reasons for this are much less end-use energy consumption, lower health and climate costs, and slightly lower private costs per unit energy with WWS energy than with BAU energy.

Further, transitioning 143 countries between today and 2050 requires only $6.8 trillion/year in annual private costs for WWS energy (accounting for electricity, heat, cold, hydrogen generation and storage, and transmission and distribution) versus $17.7 trillion/year for BAU energy. Thus, the aggregate private cost of WWS energy is 61% lower than that of BAU energy. What's more, the aggregate social cost of BAU energy is an astronomical $76.1 trillion/year.

The net present value of the capital cost of transitioning to WWS energy worldwide is ∼$72.8 trillion over all years of the transition between today and 2050. That for the US alone is about $7.8 trillion. This is the estimated net present value of the capital cost of energy in the US GND.

In the US, 100% WWS energy reduces aggregate private and social energy costs by 64% and 87%, respectively, reduces human mortality and morbidity, reduces climate-relevant emissions and impacts, and creates 3.1 million more long-term, full-time jobs than BAU energy.

The capital cost of WWS is not a cost that government needs to pay. It is a cost that pays itself off with electricity sales over the life of energy, storage, and transmission and distribution equipment. However, government assistance in a transition is helpful and necessary to speed the transition and is important given the rapid pace needed for a transition.

Uncertainties in this study arise mainly from inconsistencies between load and resource datasets, the timing of generator and storage downtime, assuming perfect transmission, not modeling transmission congestion, not modeling frequency regulation, and projecting future energy use. These uncertainties were discussed in this paper and in the Supplemental Information. Sensitivity tests and papers published by others suggest that these uncertainties should not affect costs more than marginally. Nevertheless, further work would help to verify this and quantify the impact of each uncertainty on cost in different world regions.

In sum, this study indicates that transitioning to 100% WWS energy in 143 countries decreases energy requirements and aggregate private and social costs while adding about 28.6 million more long-term, full-time jobs than are lost. A 100%-WWS-energy economy uses only about 0.65% of the 143-country land area, of which 0.17% is for footprint and 0.48% is for spacing. Thus, transitioning the world entirely from BAU energy to clean, renewable energy should substantially reduce energy needs, reduce costs, create jobs, reduce air-pollution mortality, and reduce global warming.

EXPERIMENTAL PROCEDURES

Method Components

This study consisted of the following steps:

1. Projecting the demand for BAU end-use energy to 2050 for seven fuel types in each of six energy-use sectors in each of 143 countries (Notes S2 and S3).
2. Estimating the 2050 demand reduction due to electrifying or providing direct heat for each fuel type in each sector in each country (Notes S4–S12).
3. Performing resource analyses and estimating a mix of WWS electricity and heat generators to meet the aggregate demand in each country in the annual average (Note S13).
4. Using a prognostic global weather-climate-air-pollution model (GATOR-GCMOM) that accounts for competition among wind turbines for available kinetic energy to estimate wind and solar-radiation fields country by country every 30 s for several years (Notes S14–S21).
5. Grouping the 143 countries into 24 world regions and using a model (LOADMATCH) that matches the variable supply of energy with variable demand, storage, and demand response to match demand with supply and storage every 30 s in each region from 2050 to 2052 (Notes S32–S35).
6. Evaluating energy, health, and climate costs (Note S36–S42) with new metrics (Note S43).
7. Calculating land-area requirements (Note S44).
8. Calculating changes in job numbers (Note S45).
9. Discussing and evaluating uncertainties (Note S46).

After estimating the nameplate capacities of energy generators, storage devices, and transmission lines needed for transitioning each of the 143 individual countries to 100% WWS energy in all sectors between now and 2050, we performed grid-stability analyses for the years 2050–2052 in 24 world regions encompassing the 143 countries. This process involved updating the nameplate capacities from those sufficient to meet annual average power demand to those ensuring that supply could match demand every 30 s during the 3 years in each region. We then calculated the average present value of the capital cost and the fully annualized cost of transitioning each region between today and 2050 to ensure such grid stability. We compared the resulting costs with those from a 2050 BAU scenario. We further estimated the changes in job numbers, health and climate cost savings, and land requirements of a transition.

Compared with a previous study,[1] this study uses updated energy data (2016 instead of 2012 data) for 143 (rather than 139) countries grouped into 24 (rather than 20) world regions and develops new cost metrics. It also treats each region as having a specified fraction of district heating for which seasonal and daily thermal energy storage can be used; uses new country-by-country mortality estimates[40] to project air-pollution damage costs of BAU energy; and updates estimates of country-specific population, urbanization fraction, carbon dioxide emissions, BAU fuel costs, job creation and loss, transmission and distribution efficiencies, resource potentials, rooftop areas, and land requirements, among other parameters. These updates are critical given that 61 countries have passed laws, as of the end of 2018, to transition to 100% renewable electric power and one (Denmark) has committed to transition all energy by different years between 2020 and 2050.[41] Countries that are committing to a transition could benefit from some guidance on at least one way to get there. The updated and more complete roadmaps and grid studies reported here provide such guidance for all energy sectors for 143 countries.

Cost Metrics

In this study, we present low, medium, and high estimates of external costs due to air pollution and climate change (Tables S16–S18) and then combine these external costs with estimates of private market costs to produce estimated total social costs. Social costs are evaluated in terms of both costs per unit energy and aggregate cost (Introduction).

Social-cost analyses are performed from the perspective of society rather than from the perspective of an individual or firm in the market and hence must use a social discount rate rather than a private-individual discount rate, even for the private-market-cost portion of the total social cost. To maintain consistency with the fact that our analysis is a social-cost analysis, we therefore use a social discount rate of 2% (1%–3%) for estimates of *all* our costs, both private and external, and for both WWS and BAU energy (Note S37).

The levelized private costs of BAU energy (P_{BAU}) and of WWS energy (P_{WWS}) are both defined here in units of \$/kWh-all-energy. All costs per unit energy herein for generation, storage, and transmission technologies are average values between today and 2050 but in 2013 USD. Average costs are used because the 2050 WWS energy infrastructure will be built out between today and 2050. We apply the average costs to the resulting 2050 nameplate capacities of WWS generators, storage, and transmission (determined herein) in order to estimate overall WWS costs for 143 countries grouped into 24 regions.

We estimate the average future cost of BAU electricity per unit energy in each country by weighting the cost of BAU electricity per unit energy averaged between today and 2050 for each BAU technology in each country by the current fraction of total BAU electricity consisting of each BAU technology (e.g., coal, natural gas, oil, biomass, nuclear power, and WWS).[4,42] Because we do not have data for the cost of BAU energy per unit energy outside of the electricity sector, for simplicity we assume that the cost per unit energy in other sectors (e.g., transportation, industry, etc.) equals that in the BAU electricity sector. As discussed in the Results and Discussion, this assumption makes no difference to the conclusions found here.

Additional cost-relevant parameters used here are the all-sector end-use annually averaged loads (GW or GWh-all-energy/year) of BAU energy (L_{BAU}) and WWS energy (L_{WWS}), the health cost of BAU energy per unit energy (H_{BAU}, \$/kWh-all-energy), and the climate cost of BAU energy per unit energy (C_{BAU}, \$/kWh-all-energy). The Supplemental Experimental Procedures detail how these parameters are calculated.

From these variables, social costs of BAU and WWS energy per unit energy (\$/kWh-all-energy) in 2050 are derived simply as follows:

$$S_{BAU} = P_{BAU} + H_{BAU} + C_{BAU} \qquad \text{(Equation 1)}$$

$$S_{WWS} = P_{WWS} \qquad \text{(Equation 2)}$$

Given that WWS energy eliminates virtually all health- and climate-relevant emissions from energy, including from the energy used for mining resources and building WWS equipment, a world powered by 100% WWS energy has little or no corresponding health or climate externality cost.

The one exception, if it is not controlled between today and 2050, is chemical CO_2 production during concrete and steel production, because building WWS equipment will require concrete and steel. Given that global chemical CO_2 emissions from concrete and steel amount to about 2% of total global CO_2 emissions and producing WWS energy equipment will consume only about 1% of the world's annually produced steel and 0.4% of the world's annually produced concrete, the net CO_2 emissions from producing WWS equipment will be only about 0.014% of current CO_2 emissions. It will go to zero if methods are developed to eliminate chemical CO_2 emissions from steel and concrete production. No air pollutants are emitted simultaneously during emissions of chemically produced CO_2 during concrete production if WWS electricity is used to provide heat and power for the production.

Nevertheless, other non-energy-related anthropogenic air pollutants and climate-affecting emissions will still occur in parallel with a 100%-WWS-energy system until they are stopped. Such emissions are due to biomass burning and human-caused wildfires; leaks of methane from landfills, feedlots, and rice paddies; halogen leaks; and nitrous oxide emissions from fertilizers. These emissions need to be mitigated simultaneously during a transition to WWS energy.

The aggregate annual social costs ($/year) for BAU and WWS energy are just the product of their social costs per unit energy and total end-use energy:

$$A_{BAU} = S_{BAU}L_{BAU} \quad \text{(Equation 3)}$$

$$A_{WWS} = S_{WWS}L_{WWS} \quad \text{(Equation 4)}$$

The ratio of these two aggregate social costs is a new metric, the WWS-to-BAU aggregate social cost ratio (R_{ASC}):

$$R_{ASC} = A_{WWS}/A_{BAU} = R_{WWS:BAU-E}\, R_{BAU-S:E}\, R_{WWS:BAU-C}, \quad \text{(Equation 5)}$$

where

$$R_{WWS:BAU-E} = P_{WWS}/P_{BAU}, \quad \text{(Equation 6)}$$

$$R_{BAU-S:E} = P_{BAU}/S_{BAU}, \quad \text{(Equation 7)}$$

and

$$R_{WWS:BAU-C} = L_{WWS}/L_{BAU} \quad \text{(Equation 8)}$$

are the WWS-to-BAU ratio of private cost of energy per kWh (dimensionless), the ratio of private cost of BAU energy per kWh to social cost of BAU energy per kWh (dimensionless), and the WWS-to-BAU ratio of end-use annual power demand (GW) (dimensionless), respectively.

A related new parameter is the WWS-to-BAU ratio of aggregate private cost:

$$R_{APC} = P_{WWS}L_{WWS}/(P_{BAU}L_{BAU}) = R_{WWS:BAU-E}R_{WWS:BAU-C}, \quad \text{(Equation 9)}$$

which gives an indication of the aggregate private energy cost per year in a region in a WWS versus BAU case. A third new metric is the WWS-to-BAU ratio of social cost per unit energy:

$$R_{SCE} = S_{WWS}/S_{BAU} = R_{WWS:BAU-E}R_{BAU-S:E}, \quad \text{(Equation 10)}$$

which gives an indication of the energy plus health plus climate cost per kWh in a WWS case versus BAU case.

Weather Model for Predicting Variable WWS Supply

This study uses a grid integration model, LOADMATCH, to simulate matching energy demand with supply and storage over time. LOADMATCH requires time-dependent intermittent WWS power generation as input. Time-dependent wind and solar generation are determined directly from a global weather-climate-air-pollution model, GATOR-GCMOM.[34,43–45] This model predicts time- and space-dependent solar thermal heat production and electricity production from onshore and offshore wind turbines, rooftop and utility-scale PV, and CSP plants. From the wind data, time-dependent fields of wave power are also derived. In general, the model simulates feedbacks 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 (see Note S14 for references).

GATOR-GCMOM accounts for the wind's reduced kinetic energy and speed due to the competition among wind turbines for available kinetic energy,[44] the temperature dependence of PV output,[45] and the loss of sunlight to buildings and the ground due to the conversion of radiation to electricity by solar devices. It also accounts for (1) changes in air and ground temperature due to power extraction by solar and wind devices and subsequent electricity use;[15] (2) impacts of time-dependent gas, aerosol, and cloud concentrations on solar radiation and wind fields;[34] (3) radiation to rooftop PV panels at a fixed optimal tilt at their location;[45] 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.[45] Notes S14–S20 describe the model in detail.

GATOR-GCMOM was run here on the global scale for 3 years (2050–2052) at 2° × 2.5° horizontal resolution. Modeled instantaneous power output from onshore and offshore wind turbines, solar rooftop PV, utility-scale PV, CSP plants, and solar thermal energy was written to a file every 30 s for the 3 years and aggregated over each country.

Model for Matching Supply with Demand and Storage

In general, three main types of computer models simulate the supply-demand balance, storage, and/or demand response on an electric power grid. These are power-flow (or load-flow) models, optimization models, and the trial-and-error simulation model. Notes S24–S26 describe each type of model.

LOADMATCH[1,15] is a trial-and-error simulation model (Note S26). This type of model works by running multiple simulations one at a time. Each simulation marches forward several years, one timestep at a time, just as the real world does. The main constraint during a simulation is that electricity, heat, cold, and hydrogen load, adjusted by demand response, must match energy supply and storage every timestep for an entire simulation period. If load is not met during any timestep, the simulation stops. Inputs (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 on the basis of an examination of what caused the load mismatch (hence the description "trial-and-error" model). Another simulation is then run from the beginning. New simulations are run until load is met every time step of the simulation period. After load is met once, additional simulations are performed with further-adjusted inputs on the basis of user intuition and experience to generate a set of solutions that match load every timestep. The lowest-cost solution in this set is then selected. Table S19 provides the final adjustment factors of nameplate capacities used here for each world region.

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, for example, only 55 s of computing time on a single 3.0 GHz computer processor to simulate 3.15 million 30-s timesteps (3 years). This is 1/500th to 1/100,000th of the computing time of an optimization model for the same number of timesteps. Results for the simulations shown here were calculated with a 30-s timestep. The disadvantage of a trial-and-error model compared with an optimization model is that the former does not necessarily 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 S6 summarizes many of the processes treated in the LOADMATCH simulations. Model inputs are as follows: (1) time-dependent electricity produced from onshore and offshore wind turbines, wave devices, tidal turbines, rooftop PV, utility PV, CSP plants, and geothermal plants; (2) a hydropower-plant peak discharge rate (nameplate capacity), which was set to the present-day nameplate capacity for this study, a hydropower-plant mean recharge rate (from rainfall), and a hydropower-plant annual average electricity output; (3) time-dependent geothermal and solar thermal heat-generation rates; (4) specifications of hot-water and chilled-water sensible-heat thermal energy storage (HW-STES and CW-STES) (peak charge rate, peak discharge rate, peak storage capacity, losses into storage, and losses out of storage); (5) specifications of underground thermal energy storage (UTES), including borehole, water pit, and aquifer storage; (6) specifications of ice storage (ICE); (7) specifications of electricity storage in pumped hydropower storage (PHS), phase-change materials coupled with CSP plants (CSP-PCM), batteries, etc.; (8) specifications of hydrogen (for use in transportation) electrolysis, compression, and storage equipment; (9) specifications of electric heat pumps for air and water heating and cooling; (10) specifications of a demand response system; (11) specifications of losses along short- and long-distance transmission and distribution lines; (12) time-dependent electricity, heat, cold, and hydrogen loads; and (13) scheduled and unscheduled maintenance downtimes for generators, storage, and transmission. Given the distributed nature of most generation and storage in this system, their downtimes are assumed to be spread evenly throughout a year (Note S46).

Note S33 describes the order of operations in LOADMATCH, including how the model treats excess generation over demand and excess demand over generation. 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.

Projecting BAU, WWS, Flexible, and Inflexible Loads

2050 BAU and WWS end-use loads are determined as follows. We start with 2016 BAU end-use loads from the International Energy Agency (IEA)[46] for seven fuel types in each of six sectors (residential; commercial and governmental; industrial; transport; agriculture, forestry, and fishing; and military or other) (Note S28). These end-use loads for each fuel type, sector, and country are projected to 2050 (Tables 2, S1, and S7).

The BAU projections are derived from *reference* scenario projections of the US Energy Information Administration (EIA)[47] for each fuel type in each sector in 16 world regions. The reference scenario is one of moderate economic growth and is described in detail by the EIA.[47] It accounts for policies in different countries, on population growth, on economic and energy growth, on the use of some renewable energy, on modest energy-efficiency measures, and on reduced energy use between 2016 and 2040. The EIA refers to their reference scenario as their BAU scenario. We adopt the EIA's BAU projections and extrapolate them from 2040 to 2050 by using a 10-year moving linear extrapolation for each fuel type in each sector in each world region. We then assume that the 2050 BAU end-use energy for each fuel type in each energy sector in each of 143 countries equals the corresponding 2016 end-use energy from the IEA[38] multiplied by the EIA 2050-to-2016 energy-consumption ratio, which is available after the extrapolation for each fuel type, energy sector, and EIA region.

Notes S4–S12 describe how 2050 BAU end-use energy for each fuel type in each energy sector in each country is then converted to electricity, electrolytic hydrogen for use in fuel cells for transportation, or heat, where the electricity and heat are provided by WWS energy. The notes also describe how to calculate the resulting change in end-use energy demand. They further delineate the five main reasons that demand for end-use energy decreases substantially in the WWS versus BAU scenario:

(1) Battery-electric vehicles and electrolytic hydrogen-fuel-cell vehicles are much more efficient than gasoline- and diesel-combustion vehicles for transportation.
(2) Electricity is more efficient than combustion for producing high-temperature industrial heat.
(3) Heat pumps are more efficient than combustion for providing low-temperature air and water heating.
(4) The WWS scenario eliminates the energy needed for mining, transporting, and processing fossil fuels, biofuels, bioenergy, and uranium.
(5) The WWS scenario includes slightly more energy-efficiency and demand-reduction measures than does the BAU scenario (Note S11), which is a moderate economic growth scenario that includes only moderate energy-efficiency and demand-reduction measures.[39]

Notes S28–S31 describe how annual average end-use WWS loads in each region from Table S7 for each sector are then separated into (1) electricity and heat loads needed for low-temperature heating, (2) electricity loads needed for cooling and refrigeration, (3) electricity loads needed for producing, compressing, and storing hydrogen for fuel cells used for transportation, and (4) all other electricity loads (including high-temperature industrial heat loads).

Each of these loads is further divided into flexible and inflexible loads. Flexible loads include electricity and heat loads that can be used for filling cold and low-temperature heat storage, all electricity used for producing hydrogen (given that all hydrogen can be stored), and the remaining electricity and heat loads subject to demand response. Inflexible loads are all loads that are not flexible. The flexible loads can be shifted forward in time with demand response. The inflexible loads must be met immediately. Table S10 summarizes the resulting inflexible and flexible loads in each of the 24 world regions given in Table 1. Annual loads are then distributed into time-dependent loads through the combination of contemporary electrical load profiles (hourly) with data on heating and cooling degree days for each country (Note S29).

Next, storage is sized (Tables S11 and S12), and storage, energy, and transmission and distribution cost parameters are determined (Tables S13 and S14). Model simulations are then run. In parallel, the mortality, morbidity, and non-health costs of BAU energy (Note S39, Figure 1, and Tables S15–S17) and the climate costs of BAU energy (Note S40 and Tables S17 and S18) are estimated.

DATA AND CODE AVAILABILITY

All spreadsheet derivations for the 143 country roadmaps are available online at http://web.stanford.edu/group/efmh/jacobson/Articles/I/143-countryWWS.xlsx. All data from this paper, including data going into all plots, and the LOADMATCH model are available upon request from jacobson@stanford.edu.

SUPPLEMENTAL INFORMATION

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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Update

One Earth

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One Earth

Correction

Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries

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In the originally published version of this article, Table S5 unfortunately contained incorrect values in the “2050 end-use demand (GW)” column for countries spanning from Curacao to the Syrian Arab Republic on pages 47 and 48. The values for these countries appeared correctly in Table S2. Table S5 has now been corrected in the Supplemental Information PDF online, and the authors apologize for any confusion the errors may have caused.