

A Solution to Global Warming, Air Pollution, and Energy Insecurity for 145 Countries

By Mark Z. Jacobson, Stanford University, October 25, 2021

This infographic summarizes results from simulations that demonstrate the ability of 145 countries within 24 regions (11 multi-country regions--Africa, Central America, Central Asia, China region, Europe, Haiti-Dominican Republic, India region, Mideast, Russia-Georgia, South America, and Southeast Asia--and 13 individual countries-- Australia, Canada, Cuba, Iceland, Israel, Jamaica, Japan, Mauritius, New Zealand, Philippines, South Korea, Taiwan, and United States), to match all-purpose energy demand with wind-water-solar (WWS) electricity and heat supply, storage, and demand response continuously every 30 seconds for three years (2050-2052) in each region. All-purpose energy is for electricity, transport, buildings, industry, agriculture/forestry/fishing, and the military. Results are shown for the sum of all countries, which emit 99.7% of world anthropogenic CO₂. The ideal transition timeline is 100% WWS by 2035; but results are shown for 2050-2052, after more population growth has occurred.

WWS electricity-generating technologies include onshore and offshore wind, solar photovoltaics (PV) on rooftops and in power plants, concentrated solar power (CSP), geothermal, hydro, tidal, and wave power. WWS heat-generating technologies include geothermal and solar thermal. WWS storage includes electricity, heat, cold, and hydrogen storage. WWS equipment includes electric and hydrogen fuel cell vehicles, heat pumps, induction cooktops, arc furnaces, induction furnaces, resistance furnaces, lawnmowers, etc. No fossil fuels, nuclear, bioenergy, carbon capture, direct air capture, or blue hydrogen is included.

The results are derived from the LOADMATCH grid model using 2018 business-as-usual (BAU) country load data by energy sector and fuel type (IEA, 2021), projected to 2050 then converted to load that is powered by wind-water-solar (WWS) electricity and heat. LOADMATCH also uses 30-second resolution 2050 WWS supply and building heating/cooling load data calculated from the GATOR-GCMOM weather-prediction model. The paper describing the model and results is

Jacobson, M.Z., A.-K. von Krauland, S.J. Coughlin, et al. (2022), A solution to global warming, air pollution, and energy insecurity for 145 countries, *Energy and Environmental Sciences*, 15, 3343-3359, doi:10.1039/d2ee00722c, 2022, <https://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-145-Countries.html>

Main results. Transitioning 145 countries to 100% WWS for all energy purposes...

- Keeps the grid stable 100% of the time. This is helped by the fact that, during cold storms, winds are stronger and wind/solar are complementary in nature;
- Saves 5.3 million lives from air pollution per year in 2050 in 145 countries;
- Eliminates 57 billion tonnes-CO₂e per year in 2050 in 145 countries;
- Reduces 2050 all-purpose, end-use energy requirements by 56.4%;
- Reduces 145-country 2050 annual energy costs by 62.7% (from \$17.8 to \$6.64 tril/y);
- Reduces annual energy, health, plus climate costs by 92.0% (from \$83.2 to \$6.64 tril/y);
- Costs ~\$61.5 trillion upfront. Upfront costs are paid back through energy sales. Costs are for WWS electricity, heat, and H₂ generation; electricity, heat, cold, and H₂ storage; heat pumps for district heating; all-distance transmission; and distribution;
- Requires 0.17% of the 145-country land area for footprint, 0.36% for spacing;
- Creates 28.4 million more long-term, full-time jobs than lost.

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Table 1. Reduced End-Use Demand (Load) Upon a Transition From BAU to WWS

1st row: 2018 annually-averaged end-use load (GW) and percentage of the load by sector. 2nd row: estimated 2050 total annually-averaged end-use load (GW) and percentage of the total load by sector if conventional fossil-fuel, nuclear, and biofuel use continues to 2050 under a BAU trajectory. 3rd row: estimated 2050 total end-use load (GW) and percentage of total load by sector if 100% of BAU end-use all-purpose delivered load in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU load due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity load (=all energy load) in the 2050 WWS case to the electricity load in the 2050 BAU case. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases, Column (k) shows that all energy decreases.

Scenario	(a) Total annual average end-use load (GW)	(b) Res- ident- ial % of total end- use load	(c) Com- mer- cial % of total end- use load	(d) Indus- try % of total end- use load	(e) Trans- port % of total end- use load	(f) Ag/for/ fish % of total end- use load	(g) Military / other % of total end-use load	(h) % change end- use load with WWS due to higher work: energy ratio	(i) % change end- use load with WWS due to elim- inating up- stream	(j) % change end- use load w/W WS due to effic- iency beyon d BAU	(k) Ove- rall % change in end- use load with WWS	(l) WWS: BAU elec- tricity load
145 countries												
BAU 2018	13,102.3	20.8	8.2	38.1	29.2	2.22	1.52					
BAU 2050	20,358.8	19.1	8	37.6	31.7	2.05	1.48					
WWS 2050	8,880.6	17.5	10.5	50.5	17.9	1.84	1.84	-38.4	-11.3	-6.6	-56.4	1.85

The reductions in Column (h) are due primarily to the efficiency of electric and hydrogen fuel cell vehicles over internal combustion engine vehicles, the efficiency of heat pumps for air and water heating over combustion and electric resistance heaters, and the efficiency of electricity rather than combustion for high-temperatures.

Table 2. 2050 WWS End-Use Demand by Sector

2050 annual average end-use electric plus heat load (GW) by sector in 145 countries after energy in all sectors has been converted to WWS. Instantaneous loads can be higher or lower than annual average loads. Values for a region equal the sum of values among all countries in the region.

Country or region	Total	Res- idential	Com- mercial	Trans- port	Industrial	Agricul- ture/fores- try/fishing	Military/ other
145 countries	8880.6	1555.7	928.5	4482.2	1587.0	163.52	163.84

Table 3. WWS End-Use Demand by Load Type

Annual average WWS all-sector inflexible and flexible loads (GW) for 2050 in 145 countries. “Total load” is the sum of “inflexible load” and “flexible load.” “Flexible load” is the sum of “cold load subject to storage,” “low-temperature heat load subject to storage,” “load for H₂” production, compression, and storage (accounting for leaks as well), and “all other loads subject to demand response (DR).” Annual average loads are distributed in time at 30-s resolution, as described in the text. Instantaneous loads, either flexible or inflexible, can be much higher or lower than annual average loads. Also shown is the annual hydrogen mass needed in each region, estimated as the H₂ load multiplied by 8,760 hr/yr and divided by 59.01 kWh/kg-H₂.

Country or region	Total end-use load (GW)	Inflex- ible load (GW)	Flex- ible load (GW)	Cold load subject to storage (GW)	Low-temp- erature heat load subject to storage (GW)	Load sub- ject to DR	Load for H ₂ (GW)	H ₂ needed (Tg- H ₂ /yr)
145 countries	8,880.6	4142.9	4,738.	95.6	570.1	605.6	3,467.	89.9

Table 4. Nameplate Capacities Needed by 2050 and Installed as of 2020

Final (from LOADMATCH) 2050 total (existing plus new) nameplate capacity (GW) of WWS generators needed to match power demand with supply, storage, and demand response continuously during 2050-2052 in 145 countries. Also given are nameplate capacities already installed as of 2020 end. Nameplate capacity equals the maximum possible instantaneous discharge rate.

Year	Onshore wind	Off-shore wind	Residential rooftop PV	Comm /govt rooftop PV	Utility PV	CSP with storage	Geothermal electricity	Hydro power	Wave	Tidal	Solar thermal	Geothermal heat
2020	712.7	35.50	141.2	141.2	423.6	6.47	14.01	1,164	.0006	0.53	456.4	107.7
2050	9,430	4,421	3,422	5,912	16,247	419.7	97.3	1,164	50.3	19.2	456.4	107.7

Table 5. Capacity Factors of WWS Generators

Simulation-averaged 2050-2052 capacity factors (percent of nameplate capacity produced as electricity before transmission, distribution or maintenance losses) in 145 countries. The mean capacity factors in this table equal the simulation-averaged power supplied by each generator in each region (Table 6) divided by the nameplate capacity of each generator in each region (Table 4).

Country or region	On-shore wind	Off-shore wind	Rooftop PV	Utility PV	CSP with storage	Geothermal electricity	Hydro power	Wave	Tidal	Solar thermal	Geothermal heat
145 countries	0.401	0.343	0.196	0.218	0.77	0.887	0.499	0.182	0.239	0.108	0.54

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). 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.

Table 6. Percent of Load Met by Different WWS Generators

Projected simulation-averaged 2050-2052 all-sector WWS energy supply before transmission and distribution losses, storage losses, or shedding losses, in 145 countries, and percent of supply met by each generator, based on LOADMATCH simulations. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/yr) divided by the number of hours of simulation. The percentages for each region add to 100%. Multiply each percentage by the 2050 total supply to obtain the GW supply by each generator. Divide the GW supply from each generator by its capacity factor (Table 5) to obtain the 2050 nameplate capacity of each generator needed to meet the supply (Table 4).

Country or region	Total WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with storage (%)	Geothermal electricity (%)	Hydro power (%)	Wave (%)	Tidal (%)	Solar thermal heat (%)	Geothermal heat (%)
145 countries	11,778	32.10	12.89	15.56	30.03	2.73	0.73	4.93	0.078	0.039	0.419	0.494

Table 7. Characteristics of Storage Resulting in Matching Demand With 100% WWS Supply

Maximum charge rates, discharge rate, storage capacity, and hours of storage at the maximum discharge rate of all electricity, cold and heat storage needed for supply plus storage to match demand in 145 countries.

Storage type	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Max storage time at max discharge rate (hr)
PHS	1,050	1,050	14.70	14
CSP-elec.	420	420	--	--
CSP-PCM	677	--	9.47	22.6
Batteries	21,129	21,129	84.51	4
Hydropower	521	1,164	4,567	3,925
CW-STES	38.3	38.3	0.536	14
ICE	57.4	57.4	0.803	14
HW-STES	2,046	2,046	14.43	7.1
UTES-heat	562	2,049	781.94	382
UTES-elec.	2,178	--	--	--

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

Pumped hydro storage for 2050 in a country or region is estimated as the existing (in 2020) nameplate capacity in the country or region multiplied by the ratio of existing plus pending capacity to existing capacity for 145 countries (from FERC, 2021). If a country has no existing hydro, a minimum is imposed to account for the addition of pumped hydro between 2021 and 2050.

Heat captured in a working fluid by a CSP solar collector can either be used immediately to produce electricity by evaporating water and running it through a steam turbine connected to a generator, stored in a phase-change material, or both. The maximum direct CSP electricity production rate (CSP-elec) equals the maximum electricity discharge rate, which equals the nameplate capacity of the generator. The maximum charge rate of CSP phase-change material storage (CSP-PCM) is set to 1.612 multiplied by the maximum electricity discharge rate, which allows more energy to be collected than discharged directly as electricity. Thus, since the high-temperature working fluid in the CSP plant can be used to produce electricity and charge storage at the same time, the maximum overall electricity production plus storage charge rate of energy is 2.612 multiplied by the maximum discharge rate. This ratio is also the ratio of the mirror size with storage versus without storage. This ratio can be up to 3.2 in existing CSP plants. The maximum energy storage capacity equals the maximum electricity discharge rate multiplied by the maximum number of hours of storage at full discharge, set to 22.6 hours, or 1.612 multiplied by the 14 hours required for CSP storage to charge when charging at its maximum rate.

Hydropower's maximum discharge rate in 2050 is its 2020 nameplate capacity. Hydropower can be recharged only naturally by rainfall and runoff, and its annual-average recharge rate approximately equals its 2020 annual energy output (TWh/yr) divided by the number of hours per year. Hydro is recharged each time step at this recharge rate. The maximum hydropower energy storage capacity available in all reservoirs is also assumed to equal hydro's 2020 annual energy output. Whereas the present table gives hydro's maximum storage capacity, its output from storage during a given time step is limited by the smallest among three factors: the current energy available in the reservoir, the peak hydro discharge rate multiplied by the time step, and the energy required.

The CW-STES peak discharge rate is set equal to 40% of the annual average cold load (for air conditioning and refrigeration) subject to storage. The ICE storage discharge rate is set to 60% of the same annual average cold load subject to storage. The peak charge rate is set equal to the peak discharge rate.

The HW-STES peak discharge rate is set equal to the maximum instantaneous heat load subject to storage during any 30-second period of the two-year simulation. The values have been converted to electricity assuming the electricity produces heat for heat pumps with a coefficient of performance of 4. Because they are based on maximum rather than the annual average loads, they are higher than the annual-average low-temperature heat loads subject to storage in Table 3. The peak charge rate is set equal to the peak discharge rate.

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

Table 8. Summary of Energy Budget Resulting in Grid Stability

Budget of simulation-averaged end-use power demand met, energy lost, WWS energy supplied, and changes in storage, summed over the three-year (26,291.4875 hour) simulations for all 24 world regions (145 countries). All units are GW averaged over the simulations and are derived from the data in Table 9 by dividing values from the 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.

Country or region	(a) Annual average end-use load (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Shedding losses (GW)	(e) End- use load+ losses =a+b+ c+d (GW)	(f) WWS supply before losses (GW)	(g) Changes in storage (GW)	(h) Supply+ch anges in storage =f+g (GW)
145 countries	8,880.5	771.2	279.4	1,861.4	11,793	11,778.4	14.1	11,793

Table 9. Details of Energy Budget Resulting in Grid Stability

Budget of total end-use energy demand met, energy lost, WWS energy supplied, and changes in storage, summed over the three-year (26,291.4875 hour) simulations for all 24 grid regions (encompassing 145 countries). 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 8 for key parameters.

	145 countries
A1. Total end use demand	233,482
Electricity for electricity inflexible demand	111,161
Electricity for electricity, heat, cold storage + DR	106,399
Electricity for H ₂ direct use + H ₂ storage	15,921
A2. Total end use demand	233,482
Electricity for direct use, electricity storage, + H ₂	218,616
Low-T heat load met by heat storage	14,397
Cold load met by cold storage	469
A3. Total end use demand	233,482
Electricity for direct use, electricity storage, DR	200,059
Electricity for H ₂ direct use + H ₂ storage	15,921
Electricity + heat for heat subject to storage	14,988
Electricity for cold load subject to storage	2,513
B. Total losses	76,560
Transmission, distribution, downtime losses	20,276
Losses CSP storage	50
Losses PHS storage	54
Losses battery storage	2,835
Losses CW-STES + ICE storage	85
Losses HW-STES storage	1,852
Losses UTES storage	2,471
Losses from shedding	48,938
Net end-use demand plus losses (A1 + B)	310,042
C. Total WWS supply before T&D losses	309,672
Onshore + offshore wind electricity	139,318
Rooftop + utility PV+ CSP electricity	149,616
Hydropower electricity	15,278
Wave electricity	241
Geothermal electricity	2,269
Tidal electricity	121

Solar heat	1,298
Geothermal heat	1,531
D. Net taken from (+) or added to (-) storage	370
CSP storage	3.4819
PHS storage	-0.9768
Battery storage	7.9036
CW-STES+ICE storage	0.1640
HW-STES storage	8.1379
UTES storage	288.0287
H ₂ storage	63.2392
Energy supplied plus taken from storage (C+D)	310,042

End-use demands in A1, A2, A3 should be identical. Generated electricity is shed when it exceeds the sum of electricity demand, cold storage capacity, heat storage capacity, and H₂ 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 m², 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 m² of mirrors and 2.17 km² 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 10. Breakdown of Energy Costs Required to Keep Grid Stable

Summary of 2050 WWS mean capital costs of new electricity plus heat generators; electricity, heat, cold, and hydrogen storage (including heat pumps to supply district heating and cooling), and all-distance transmission/distribution (\$ trillion in 2020 USD) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) summed or averaged over the simulations for all 24 world regions (encompassing 145 countries). Also shown is the energy consumed per year in each case and the resulting aggregate annual energy cost.

	145 countries
Capital cost new generators only (\$trillion)	45.697
Cap cost new generators + storage (\$trillion)	61.470
<i>Components of total LCOE (¢/kWh-all-energy)</i>	
Short-dist. transmission	1.050
Long-distance transmission	0.172
Distribution	2.375
Electricity generation	3.799
Additional hydro turbines	0
Geothermal + solar thermal heat generation	0.079
LI battery storage	0.554
CSP-PCM + PHS storage	0.027
CW-STES + ICE storage	0.002
HW-STES storage	0.013
UTES storage	0.092
Heat pumps for filling district heating/cooling	0.066
H ₂ production/compression/storage	0.310
Total LCOE (¢/kWh-all-energy)	8.538
LCOE (¢/kWh-replacing BAU electricity)	8.046
GW annual avg. end-use demand (Table 1)	8,880.6
TWh/y end-use demand (GW x 8,760 h/y)	77,794
Annual energy cost (\$billion/yr)	6,642.0

The LCOEs are derived from capital costs, annual O&M, and end-of-life decommissioning costs that vary by technology (and that are a function of lifetime 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 cost of generators-storage-H₂-HVDC (\$trillion) is the capital cost of new electricity and heat generators; electricity, heat, cold, and hydrogen storage; hydrogen electrolyzers and compressors; and long-distance (HVDC) transmission.

Since the total end-use load includes heat, cold, hydrogen, and electricity loads (all energy), the “electricity generator” cost, for example, is a cost per unit all energy rather than per unit electricity alone. The ‘Total LCOE’ gives the overall cost of energy, and the ‘Electricity LCOE’ gives the cost of energy for the electricity portion of load replacing BAU electricity end use. It is the total LCOE less the costs for UTES and HW-STES storage, H₂, and less the portion of long-distance transmission associated with H₂.

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), 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 11. Energy, Health, and Climate Costs of WWS Versus BAU

2050 145 countries annual-average end-use (a) BAU load and (b) WWS load; (c) percent difference between WWS and BAU load; (d) present value of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and all-distance transmission and distribution; mean levelized private costs of all (e) BAU and (f) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050); (g) mean WWS private (equals social) energy cost per year, (h) mean BAU private energy cost per year, (i) mean BAU health cost per year, (j) mean BAU climate cost per year, (k) BAU total social cost per year; (l) percent difference between WWS and BAU private energy cost; and (m) percent difference between WWS and BAU social energy cost. All costs are in 2020 USD. H=8,760 hours per year.

Country or region	(a) ¹ 2050 BAU Annual avg. end-use load (GW)	(b) ¹ 2050 WWS Annual avg. end-use load (GW)	(c) 2050 WWS minus BAU load = (b-a)/a (%)	(d) ² WWS mean total cap- ital 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 (%)
145 countries	20,359	8,880.6	-56.4	61.5	9.98	8.54	6,642.0	17,805	33,601	31,757	83,163	-62.7	-92.0

¹From Table 1.

²Capital cost of generators-storage-H₂-HVDC (\$trillion) is the capital cost of new electricity and heat generators; electricity, heat, cold, and hydrogen storage; hydrogen electrolyzers and compressors; and long-distance (HVDC) transmission.

³This is the BAU electricity-sector cost of energy per unit energy. It is assumed to equal the BAU all-energy cost of energy per unit energy.

⁴The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat)

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

⁶The 2050 annual BAU health cost equals the number of total air pollution mortalities per year in 2050 from Table 12, Column (a), multiplied by 90% (the estimated percent of total air pollution mortalities that are due to energy) and by a statistical cost of life of \$11.56 (\$7.21-\$17.03) million/mortality (2020 USD) and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts (Jacobson et al., 2019).

⁷The 2050 annual BAU climate cost equals the 2050 CO₂e emissions from Table 12, Column (b), multiplied by the social cost of carbon in 2050 of \$548 (\$315-\$1,188)/metric tonne-CO₂ (in 2020 USD), which is updated from values in Jacobson et al. (2019), which were in 2013 USD.

Table 12. Air Pollution Mortalities, Carbon Dioxide Emissions, and Associated Costs

145 countries (a) estimated air pollution mortalities per year in 2050-2052 due to anthropogenic sources (90% of which are energy); (b) carbon-equivalent emissions (CO₂e) in the BAU case; (c) cost per tonne-CO₂e of eliminating CO₂e with WWS; (d) BAU energy cost per tonne-CO₂e emitted; (e) BAU health cost per tonne-CO₂e emitted; (f) BAU climate cost per tonne-CO₂e emitted; (g) BAU total social cost per tonne-CO₂e emitted; (h) BAU health cost per unit all-BAU-energy produced; and (i) BAU climate cost per unit-all-BAU-energy produced.

Country or region	(a) ¹ 2050 BAU air pollution mortalities (Deaths/y)	(b) ² 2050 BAU CO ₂ e (Mtonne/y)	(c) ³ 2050 WWS (\$/ tonne- CO ₂ e- elim- inated)	(d) ⁴ 2050 BAU energy cost (\$/ tonne- CO ₂ e- emitted)	(e) ⁴ 2050 BAU health cost (\$/ tonne- CO ₂ e- emitted)	(f) ⁴ 2050 BAU climate cost (\$/ tonne- CO ₂ e- emitted)	(g) ⁴ 2050 BAU social cost = d+e+f (\$/ tonne- CO ₂ e- emitted)	(h) ⁵ 2050 BAU health cost (¢/kWh)	(i) ⁵ 2050 BAU climate cost (¢/kWh)
145 countries	5,292,576	56,873	116.79	313	591	558	1,462	18.8	17.8

¹2050 country BAU mortalities due to air pollution are extrapolated from 2016 values from WHO (2017) using the method described in Jacobson et al. (2019).

²CO₂e=CO₂-equivalent emissions. This accounts for the emissions of CO₂ plus the emissions of other greenhouse gases multiplied by their global warming potentials.

³Calculated as the WWS private energy and total social cost from Table 11, Column (g) divided by the CO₂e emissions from Column (b) of the present table.

⁴Columns (d)-(g) are calculated as the BAU private energy, health, climate, and total social costs from Table 11, Columns (h)-(k), respectively, each divided by the CO₂e emissions from Column (b) of the present table.

⁵Columns (h)-(i) are calculated as the BAU health and climate costs from Table 11, Columns (i)-(j), respectively, each divided by the BAU annual average end-use load from Table 11, Column (a) and by 8,760 hours per year.

Table 13. Land Areas Needed

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.

Country or region	Country or region land area (km ²)	Footprint Area (km ²)	Spacing area (km ²)	Footprint area as percentage of the country or region land area (%)	Spacing area as a percentage of the country or region land area (%)
145 countries	121,464,428	205,758	440,199	0.17	0.36

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. 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. Offshore wind, wave, and tidal are not included because they don't take up new land. Areas are given both as an absolute area and as a percentage of the country or regional 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 km², respectively.

Table 14. Changes in the Employment

Estimated long-term, full-time jobs created and lost due to transitioning from BAU energy to 100% WWS across all energy sectors in 145 countries. The job creation accounts for new jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including HVDC transmission) industries. It also accounts for the building of heat pumps to supply district heating and cooling. However it does not account for changes in jobs in the production of electric appliances, vehicles, and machines or in increasing building energy efficiency. Construction jobs are for new WWS devices only. Operation jobs are for new and existing devices. The losses are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, biofuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke, are retained. For transportation sectors, the jobs lost are those due to transporting fossil fuels (e.g., through truck, train, barge, ship, or pipeline); the jobs not lost are those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion appliances, including automobiles, ships, or industrial machines.

Country or region	Construction jobs produced	Operation jobs produced	Total jobs produced	Jobs lost	Net change in jobs
145 countries	25,374,575	30,185,558	55,560,134	27,190,159	28,369,975

References.

- FERC (Federal Regulatory Energy Commission) (2021). Pumped storage projects. <https://www.ferc.gov/industries-data/hydropower/licensing/pumped-storage-projects>.
- IEA (International Energy Agency) (2021), Data and Statistics for 2018, OECD Publishing, Paris. Retrieved October 5, 2021 from <https://www.iea.org/data-and-statistics>
- Jacobson, M.Z., Delucchi, M.A., Cameron, M.A., Coughlin, S.J., Hay, C., Manogaran, I.P., Shu, Y. and von Krauland, A.-K. (2019). Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. *One Earth* 1, 449-463.
- WHO (World Health Organization) (2017). Global health observatory data. Retrieved August 10, 2021, from, https://www.who.int/gho/phe/outdoor_air_pollution/en