A Solution to Global Warming, Air Pollution, and Energy Insecurity for 150 Countries

By Mark Z. Jacobson, Stanford University, October 17, 2025

This infographic summarizes results from simulations that demonstrate the ability of 150 countries within 29 regions [15 multi-country regions (Africa-East, Africa-North, Africa-South, Africa-West, Central America, Central Asia, China region, Europe, Haiti-Dominican Republic, India region, Mideast, Russia-Georgia, South America-NW, South America-SE, and Southeast Asia) and 14 individual countries (Australia, Canada, Cuba, Iceland, Israel, Jamaica, Japan, Madagascar, Mauritius, New Zealand, Philippines, South Korea, Taiwan, and United States)] to match all-purpose end-use energy demand with wind-water-solar (WWS) electricity and heat supply, storage, and demand response continuously every 30 seconds for three years (2050-2052). All-purpose energy is for residential and commercial/government buildings, transport, industry, agriculture/forestry/fishing, and the military. Results are shown for the sum of all countries, which emit >99.6% of world anthropogenic CO_2. The ideal transition timeline is 100% WWS by 2035; however, results are shown for 2050-2052, after additional population growth has occurred.

WWS electricity-generating technologies include onshore and offshore wind turbines, rooftop and utility solar photovoltaics (PV), concentrated solar power (CSP) plants, geothermal plants, hydro plants, tidal turbines, and wave devices. WWS heat-generating technologies include geothermal and solar thermal technologies. WWS storage includes electricity, heat, cold, and hydrogen storage. Electricity storage options include hydropower, pumped hydropower, batteries, CSP with storage, and hydrogen fuel cells. WWS equipment includes electric and hydrogen fuel cell vehicles, heat pumps, induction cooktops, arc furnaces, induction furnaces, resistance furnaces, etc. Green hydrogen is used for ammonia and steel manufacturing, long-distance transport, and grid electricity storage. No fossil fuels, nuclear, bioenergy, carbon capture, direct air capture, or blue hydrogen is included.

The results are derived from the LOADMATCH model using 2022 business-as-usual (BAU) country demand data by energy sector and fuel type (IEA, 2024), projected to 2050 then converted to demand powered by wind-water-solar (WWS) electricity and heat. LOADMATCH uses 30-s resolution 2050-2052 WWS supply and building heating/cooling demand data calculated from the GATOR-GCMOM weather-prediction model. Citation:

Jacobson, M.Z., D.J. Sambor, Y.F. Fan, A. Mühlbauer, and G.C. DiBari, The impact of enhanced geothermal systems on transitioning all energy sectors in 150 countries to 100% clean, renewable energy, 2025. https://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-150-Countries.html

Main results. Transitioning 150 countries to 100% WWS for all energy purposes…

Keeps the grid stable every 30 s for three years in every grid region;

Saves 5.6 million lives/y ($36.9 tril/y) from air pollution in 2050 among 150 countries;

Eliminates 56.1 bil tonnes-CO_2e/y ($32.5 tril/y in climate costs) 2050 among 150 countries;

Reduces 2050 all-purpose, end-use energy requirements by 54.2%;

Reduces 150-country 2050 annual energy costs by 60.6% (from $17.2 to $6.78 tril/y);

Reduces annual energy, health, plus climate costs by 92.2% (from $86.6 to $6.78 tril/y);

Costs ~$60.0 trillion upfront for WWS electricity, heat, and H_2 generation; electricity, heat, cold, and H_2 storage; heat pumps for district heating; all-distance transmission; and distribution. The payback time due to WWS annual energy cost savings vs. BAU is 5.8 years; that due to annual energy+health+climate cost savings is 0.75 years;

~9.6% of the WWS generator nameplate capacity needed has been installed;

New WWS requires 0.18% of the 150-country land for footprint, 0.39% for spacing;

Creates 28.0 million more long-term, full-time jobs than lost (not including increases in jobs in producing electric appliances, vehicles, machines).

Table of Contents

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

1st row: 2022 annually-averaged end-use demand (GW) and percentage of the demand by sector. 2nd row: projected 2050 annually-averaged end-use BAU demand (GW) and percentage of the total demand by sector. 3rd row: estimated 2050 total end-use demand (GW) and percentage of total demand by sector if 100% of end-use delivered BAU demand in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU demand due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity demand (=all energy demand) in the 2050 WWS case to the electricity demand in the 2050 BAU case. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases, Column (k) shows that all energy decreases.

Scenario	(a) Total annual-average end-use demand (GW)	(b) Resi-den-tial % of total	(c) Com-merci al % of total	(d) Indus-try % of total	(e) Trans-port % of total	(f) Ag-for-fish % of total	(g) Mil-itary-other % of total	(h) % change end-use deman d with WWS due to higher work: energy ratio	(i) % change end-use deman d with WWS due to elim-inating up-stream	(j) % change end-use deman d with WWS due to effic-iency beyon d BAU	(k) Over-all % change in end-use deman d with WWS	(l) WWS :BAU elec-tric-ity dem-and
150 countries												
BAU 2022	13,307.7	20	8	40.3	27.8	2.29	1.54					
BAU 2050	19,559.6	18.8	7.9	40.7	29.1	2.11	1.44					
WWS 2050	8,961.9	17.4	9.9	54.2	14.9	1.88	1.74	-37.03	-10.58	-6.57	-54.18	1.85

2022 BAU values are from IEA (2024). These values are projected to 2050 using U.S. Energy Information Administration (EIA, 2016) "reference scenario" projections, as described in the text. The EIA projections account for policies, population growth, modest economic and energy growth, some modest renewable energy additions, and modest energy efficiency measures and reduced energy use in each sector. The transportation demand includes, among other demands, energy produced in each country for aircraft and shipping. 2050 WWS values are estimated from 2050 BAU values assuming electrification of end-uses and effects of additional energy-efficiency measures beyond those in the BAU case, using the factors from Table S3. In the case of the industrial sector, the factors are applied after accounting for the change in energy between BAU and WWS during steel manufacturing due to purifying iron using green hydrogen in a shaft furnace instead of purifying it using coke in a blast furnace (Table S5), and during ammonia manufacturing due to using green hydrogen instead of gray hydrogen (Table S5). Multiply annual average demand (GW) by 8,760 hours per year to obtain annual energy per year (GWh/y) consumed. In 2022 and 2050, 23.11% and 22.99%, respectively, of the 150-country total BAU demand was for electricity.

Table 2. 2050 WWS End-Use Demand by Sector

2050 annual average end-use electric plus heat demand (GW) by sector after energy in all sectors has been converted to WWS. Instantaneous demands can be higher or lower than annual average demands. 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
150 countries	8,961.8	1,557.5	886.7	4,861.8	1,331.4	168.3	156.2

Table 3. WWS End-Use Demand by Demand Type

Annual average WWS all-sector inflexible and flexible demands (GW) for 2050. "Total demand" is the sum of columns (b) and (c). "Flexible demand" is the sum of columns (d)-(h). DR is demand-response. "Hight-temp industrial heat demand subject to firebrick storage" is demand for industrial heat that can be met by heat stored in firebricks that was produced by electric-resistance heating. "Demand for non-grid H_2" accounts for the production, compression, storage, and leakage of hydrogen. Annual average demands are distributed in time at 30-s resolution. Instantaneous demands, either flexible or inflexible, can be much higher or lower than annual average demands. Column (i) shows the annual hydrogen mass production rate needed for steel and ammonia manufacturing and long-distance transport, estimated as the H_2 demand multiplied by 8,760 h/y and divided by 47.01 kWh/kg-H_2.

				Flexible demands					
Region	(a) Total end-use demand (GW) =b+c	(b) Inflex-ible demand (GW)	(c) Flex-ible demand (GW) =d+e+f +g+h	(d) Cold demand subject to storage (GW)	(e) Low-temp-erature heat demand subject to storage (GW)	(f) Indus-trial process heat demand subject to fire-brick storage (GW)	(g) Dem-and sub-ject to DR	(h) Dem-and for non-grid H_2 (GW)	(i) Non-grid H_2 needed (Tg-H_2/y)
150 Countries	8,961.8	3,606	5,355.7	104.3	572.9	2,269	1,378	1,032	191.9

Table 4. Mass of Hydrogen Needed for Steel, Ammonia, and Long-Distance Transport

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

Region or country	(a) 2050 Tg-H_2/y needed to purify iron by hydrogen direct reduction	(b) 2050 Tg-H_2/y needed to make NH_3	(c) 2050 Tg-H_2/y needed for HFC vehicles	(d) 2050 Total Tg-H_2/y produced for steel, ammonia, and vehicles = a+b+c	(e) 2050 Power needed to produce and compress H_2 for steel and ammonia (GW)	(f) 2050 power needed to produce and compress H_2 for transport (GW)	(g) 2050 power needed to produce and compress H_2 for steel, ammonia, and transport (GW) = e+f
150 countries	78.72	31.70	81.49	191.91	593.72	438.17	1031.89

Table 5. Nameplate Capacities Needed by 2050 and Installed as of 2023

Final (from LOADMATCH) 2050-2052 total (existing plus new) nameplate capacities (GW) of WWS generators needed to match power demand with supply, storage, and demand response continuously from 2050 to 2052. Also given are nameplate capacities already installed as of 2023 end. A nameplate capacity equals the maximum possible instantaneous discharge rate of a generator.

Year	Onshore wind	Off-shore wind	Resi-dential roof-top PV	Comm /govt rooftop PV	Utility PV	CSP with stor-age	Geoth ermal -elec-tricity	Hydro power	Wave	Tidal	Solar therm al	Geoth ermal heat	Total
150 Countries													
2023	943.95	72.66	174.7	415.6	818.6	6.88	14.78	1,262	0.0006	0.53	490.9	107.7	4,308
2050	10,453	3,783	4,009	5,711	19,003	5.3	193.71	1,262	21.51	7.48	490.9	107.7	45,047

Table 6. Capacity Factors of WWS Generators

Simulation-averaged 2050-2052 capacity factors (percentage of nameplate capacity produced as electricity before transmission, distribution, maintenance, storage, or curtailment losses). The mean capacity factors in this table equal the simulation-averaged power output supplied by each generator from Table 7 divided by the final nameplate capacity of each generator from Table 5.

Country or region	On-shore wind	Off-shore wind	Rooftop PV	Utility PV	CSP with storage	Geo-thermal elec-tricity	Hydr opow er	Wave	Tidal	Solar therm al	Geo-thermal heat
150 countries	0.381	0.366	0.187	0.212	0.782	0.61	0.43	0.162	0.239	0.102	0.54

Capacity factors of offshore and onshore wind turbines account for array losses (extraction of kinetic energy by turbines). Capacity factors are determined before transmission, distribution, maintenance, storage, or curtailment losses, which are summarized for each region in Tables S18 and S19. T&D loss rates are given in Table S20. A zero indicates no installation of the technology. Roof PV panels are fixed-tilt at the optimal tilt angle of the country they reside in; utility PV panels are half fixed optimal tilt and half single-axis horizontal tracking (Jacobson and Jadhav, 2018).

Table 7. Percent of Demand Met by Different WWS Generators

LOADMATCH 2050-2052 simulation-averaged all-sector projected WWS end-use power supplied (which equals power consumed plus power lost during transmission, distribution, maintenance, and curtailment) and percentage of such supply met by each generator. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/simulation) divided by the number of hours of simulation. The percentages 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 6) to obtain the final 2050 nameplate capacity of each generator needed to meet the supply (Table 5).

Country or region	Annual-average WWS supply (GW)	On-shore wind (%)	Off-shore wind (%)	Roof PV (%)	Utility PV (%)	CSP with stor-age (%)	Geoth ermal elec-tricity (%)	Hydr opow er (%)	Wave (%)	Tidal (%)	Solar ther-mal heat (%)	Geo-ther-mal heat (%)
150 countries	11,994	33.19	11.53	15.16	33.63	0.035	0.986	0	4.522	0.029	0.015	0.416

Table 8. Characteristics of Storage Resulting in Matching Demand With 100% WWS Supply

Aggregate (among all 150 countries) of the maximum instantaneous charge rates, maximum instantaneous discharge rates, maximum energy storage capacities, hours of storage at the maximum discharge rate, and storage capacity factor, of the different types of electricity storage technologies treated here. Total hydropower values are split into baseload and peaking hydropower values. The maximum storage capacities are either of electricity (for the electricity storage options), or of thermal energy (for the heat and cold storage options). The storage capacity factor is the energy discharged from the storage medium over the entire simulation divided by the product of the maximum discharge rate and the number of hours of simulation.

Storage technology	Max charge rate (GW)	Max dis-charge rate (GW)	Max storage capacity (TWh)	Storage hours at max discharge rate	Storage capacity factor (%)
PHS	568	568	7.96	14.0	1.54
CSP-elec.	5	5	--	--	--
CSPS	9	--	0.12	22.6	13.36
Batteries	8,070	8,070	32.28	4.0	2.98
Hydropower	611	1,262	1,588	1,259	39.76
Base	523	523	822	1,570	92.50
Peaking	88	738	767	1,038	2.38
Grid H_2	1,456	1,456	0	0	0.87
CW-STES	42	42	0.58	14.0	19.71
ICE	63	63	0.88	14.0	19.71
HW-STES	2,027	2,238	5.59	2.5	11.58
UTES-heat	593	2,215	731.0	330.0	6.34
UTES-elec.	1,526	--	--	--	--
Firebricks	7,941	2,269	34.03	15.0	92.95

PHS=pumped hydropower storage; CSP=concentrated solar power; PCM=Phase-change materials; Batteries=battery storage (BS) for grid backup; Grid H_2 is green hydrogen storage (GSH) for grid backup; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; UTES=Underground thermal energy storage in soil or water pits; and firebricks are bricks used to store low- to high-temperature heat for industrial processes. The maximum storage capacity equals the maximum discharge rate multiplied by the number of hours of storage at that rate.

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

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

Hydropower's maximum discharge rate (GW) in 2050 is its 2023 nameplate capacity, and its annual energy output (TWh/y) in 2050 is close to that in 2023 in every region. Water released from a dam during hydropower production is replenished naturally with rainfall and runoff. Hydropower reservoirs contain water for energy and non-energy purposes. About 50-60% of the water in a reservoir is generally used for energy (IEA, 2021). The hydropower storage capacity available for energy in all reservoirs worldwide is estimated as ~1,470 TWh, broken down as follows: North America: 370 TWh; China: 250 TWh; Latin America: 245 TWh; Europe: 215 TWh; Eurasia: 130 TWh; Africa: 125 TWh; Asia Pacific: 120 TWh; Middle East: 15 TWh (IEA, 2021-Figure 4.8). The maximum hydropower storage capacity (TWh) in each country here is estimated by multiplying these regional storage capacities by the ratio of the 2023 estimated hydroelectric energy output of the country to that of the region the country falls in. The maximum storage capacity in each region is then calculated simply by summing the maximum storage capacities among all countries in the region. The maximum storage capacity and the total nameplate capacity of hydropower generators in each region are then distributed between baseload and peaking power uses by solving a set of six equations and six unknowns: (1) the sum of the maximum energy storage capacities (TWh) for baseload and peaking power equals the total maximum energy storage capacity of all reservoirs in each region, as just determined; (2) the sum of the instantaneous average charge rates (TW) of power for baseload and peaking power equals the total average charge rate of the reservoir, which equals the annual average hydropower power output (TW) of the reservoir in 2023 (which equals the 2023 energy output in TWh/y divided by 8,760 hours per year); (3) the sum of the maximum discharge rates (TW) for each baseload and peaking power equals the total nameplate capacity of all hydropower generators in the region; (4) the maximum discharge rate (TW) of baseload power from generators equals the instantaneous average charge rate of baseload power; (5) the maximum energy storage capacity (TWh) for peaking power equals the instantaneous average charge rate of peaking power (TW) multiplied by 8,760 hours per year (in other words, the peaking portion of the reservoir must be filled once per year); and (6) the maximum energy storage capacity (TWh) for baseload power equals the instantaneous average charge rate of baseload power (TW0 multiplied by a designated number of hours of storage of baseload energy. Since the maximum discharge rate of baseload hydropower is assumed to equal its instantaneous average charge rate, there should be no need for baseload storage. However, in reality, discharged water for baseload power is not replenished immediately. As such, sufficient storage capacity is assigned to baseload hydropower so that, if full, baseload can supply 60 days (1,440 hours) straight of hydroelectricity without any replenishment. For Iceland and South America, 5 and 15 days, respectively, are assumed instead of 60 days. In sum, whereas baseload power is produced and discharged continuously in the model every 30 s, peaking power is also produced every 30 s but discharged only when needed due to a lack of other WWS resources available. Whereas the present table gives hydropower's maximum energy storage capacity available for each baseload and storage, hydropower's output from baseload or peaking storage during a time step is limited by the smallest among three factors: the actual energy currently available in storage for baseload or peaking, the maximum hydro discharge rate for peaking or baseload multiplied by the time step, and (in the case of peaking) the energy needed during the time step to keep the grid stable. In addition, energy in the peaking portion of reservoirs is limited by the maximum storage capacity in that portion. Thus, if peaking energy is not used fast enough, it cannot accumulate due to rainfall and runoff to more than the maximum capacity.

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

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

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

Grid H_2. The storage capacity and storage duration of green hydrogen storage (GHS) for grid electricity storage are set to zero in this table because hydrogen production and storage for grid and non-grid purposes are merged in this study. In such a case, the storage time depends on the discharge rate of both grid and non-grid hydrogen. Table S17 provides the storage time of grid hydrogen as if it is the only hydrogen stored and discharged and the storage time of non-grid hydrogen as if it is the only hydrogen stored and discharged.

Firebricks are modeled after the RHB300 heat battery of from Rondo (2024). Each battery has a peak charge rate of 70 MW-AC-electricity, peak discharge rate of 20 MW-thermal, energy storage capacity of 300 MWh-thermal, storage time at the peak discharge rate of 15 h, round-trip efficiency of 98%, land a heat loss rate from storage of 1% per day. The cost is estimated by Rondo to be 1/10th that of battery electricity per kWh storage. The RHB300 provides heat output as hot air, nominally from 80ºC to 1,100ºC. This range is extended to 1,800ºC assuming low-cost direct resistance heating of firebricks (Forsberg and Stack, 2024; Electrified Thermal Solutions, 2024). Antora (2024) similarly produces low-grade carbon firebricks that store heat up to 2,400ºC.

Table 9. 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, during the three-year (26,291.4875 hour) simulations from 2050-2052 for all 150 countries, grouped into 29 world regions. All units are GW averaged over the simulation and are derived from the data in Table 10 by dividing values from that table in units of TWh per simulation by the number of hours of simulation.

Country or region	(a) Annual average end-use demand (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Shedding losses (GW)	**(e) End-use demand+ losses =a+b+ c+d (GW)**	(f) WWS supply before losses (GW)	(g) Changes in storage (GW)	**(h) Supply+ch anges in storage =f+g (GW)**
150 countries	8,961.8	788.4	278.9	1,986.4	**12,015**	11,996	18.871	**12,015**

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.

Table 10. Details of Energy Budget Resulting in Grid Stability

Budget of end-use energy demand met, energy lost, WWS energy supplied, and changes in storage, during the 26,291.4875-h (3 y) simulation from 2025-2052 for all 150 countries among all 29 regions. Units are TWh over the simulation. Divide by hours of simulation to obtain simulation-averaged power (TW) (Table 9 for key parameters).

	150 Countries
A1. Total end use demand	**235,618**
Electricity for electricity inflexible demand	100,947
Electricity for electricity, heat, cold storage + DR	107,538
Electricity for H_2 direct use + H_2 storage	27,133
A2. Total end use demand	**235,618**
Electricity for direct use, electricity storage, + H_2	167,112
Low-T heat demand met by heat storage	12,516
Cold demand met by cold storage	540
Hi-T heat demand met by firebrick storage	55,449
A3. Total end use demand	**235,618**
Electricity for direct use, electricity storage, DR	131,029
Electricity for H_2 direct use + H_2 storage	27,133
Electricity + heat for heat subject to storage	15,063
Electricity for cold demand subject to storage	2,741
Hi-T heat from electricity + firebrick storage	59,652
B. Total losses	**80,284**
Transmission, distribution, downtime losses	20,728
Losses CSP storage	0
Losses PHS storage	58
Losses battery storage	741
Losses grid H_2 storage	923
Losses CW-STES + ICE storage	98
Losses HW-STES storage	1,396
Losses UTES storage	2,752
Losses firebrick storage	1,365
Losses from curtailment	52,224
Net end-use demand plus losses (A1 + B)	***315,902***
C. Total WWS supply before T&D losses	**315,406**
Onshore + offshore wind electricity	141,049
Rooftop + utility PV+ CSP electricity	154,005
Hydropower electricity	14,261
Wave electricity	92
Geothermal electricity	3,109
Tidal electricity	47
Solar heat	1,312
Geothermal heat	1,531
D. Net taken from (+) or added to (-) storage	**496**
CSP storage	0.0259
PHS storage	0.7538
Battery storage	1.9357
Grid H_2 storage	0.0000
CW-STES+ICE storage	0.4035
HW-STES storage	4.1691
UTES storage	449.0843
Firebrick storage	18.3060
Non-grid H_2 storage	21.4775
Energy supplied plus taken from storage (C+D)	***315,902***

Table 11. Breakdown of Energy Costs Required to Keep Grid Stable

Summary of WWS mean capital costs ($ trillion in USD 2022) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) averaged over each simulation. Also shown is the energy consumed per year and the resulting aggregate annual energy cost. The last row is the percent increase in the total LCOE and the total annual energy cost if the baseline battery system cost is increased from the mean value in Table S22 ($60/kWh-electricity storage) to the high value ($90/kWh-electricity storage), or by a factor of 1.5. All costs are averages between 2022 and 2050. Values are the sum or average over all 150 countries.

	150 countries
Capital cost new generators only ($tril)	45.867
Cap cost generators-storage-H_2-HVDC ($tril)	**60.039**
Components of total LCOE (¢/kWh-all-energy)	
Short-distance transmission	1.050
Long-distance transmission	0.170
Distribution	2.375
Electricity generation	3.889
Additional hydro turbines	0
Geothermal + solar thermal heat generation	0.082
LI battery storage	0.210
Grid H_2 production/compression/storage/fuel cell	0.078
CSP-PCM + PHS storage	0.006
CW-STES + ICE storage	0.002
HW-STES storage	0.005
UTES storage	0.085
Heat pumps for filling district heating/cooling	0.055
Firebrick storage	0.013
Non-grid H_2 production/compression/storage	0.621
Total LCOE (¢/kWh-all-energy)	**8.64**
LCOE (¢/kWh-replacing BAU electricity)	7.841
GW annual avg. end-use demand	8,961.8
TWh/y end-use demand (GW x 8,760 h/y)	78,506
Annual energy cost ($billion/y)	**6,782.9**
% rise in LCOE & annual cost if 1.5x battery cost	1.21

LI=lithium ion; CSP=concentrated solar power; PCM=Phase-change materials; PHS=pumped hydropower storage; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; and UTES=Underground thermal energy storage in boreholes or water pits.

The LCOEs are derived from capital costs, annual O&M, and end-of-life decommissioning costs that vary by technology (Tables S20-S22) and that are a function of lifetime (Tables S20-S22) and a social discount rate for an intergenerational project of 2.0 (1-3)%, all divided by the total annualized end-use demand met, given in the present table. Capital costs are an average between 2022 and 2050, as are the LCOEs.

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

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

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

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

Long-distance transmission costs are $0.0089 (0.0042-0.010)/kWh (in USD 2022) (Jacobson et al., 2017, but brought up to USD 2022), which assumes 1,500 to 2,000 km HVDC lines, a capacity factor usage of the lines of ~50% and a capital cost of ~$400 (300-460)/MWtr-km. Table S15 gives the total HVDC line length and capacity and the fraction of all non-rooftop-PV and non-curtailed electricity generated that is subject to HVDC transmission by region.

Storage costs are derived from data in Table S22.

H_2 costs are broken down in Table S23.

Table 12. Energy, Health, and Climate Costs of WWS Versus BAU

2050 annual average end-use (a) BAU demand and (b) WWS demand; (c) percentage difference between WWS and BAU demand; (d) present value of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and all-distance transmission and distribution; mean levelized private costs of all (e) BAU and (f) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050); (g) mean WWS private (equals social) energy cost per year; (h) mean BAU private energy cost per year; (i) mean BAU health cost per year; (j) mean BAU climate cost per year; (k) BAU total social cost per year; (l) percentage difference between WWS and BAU private energy cost; and (m) percentage difference between WWS and BAU social energy cost. All costs are in USD 2022. H=8760 hours per year.

Country or region	(a)[1] 2050 BAU Annual avg. end-use demand (GW)	(b)[1] 2050 WWS Annual avg. end-use demand (GW)	(c) 2050 WWS minus BAU dem-and = (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/	(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 (%)
150 countries	19,560	8,962	-54.2	60.0	10.05	8.64	6,783	17,215	36,875	32,506	86,596	-60.6	-92.2

[1]From Table S4.

[2]The total capital cost includes the capital cost of new WWS electricity and heat generators; new equipment for electricity storage, low-temperature building heat storage, and hydrogen storage; hydrogen electrolyzers and compressors; ground- and air-source electric heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2022 and 2050.

[3]This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2022 and 2050.

[4]The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat). It is an average between 2022 and 2050.

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

[6]The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 from Table S26, Column (a), multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy – Jacobson et al., 2019) and by a value of statistical life (VOSL) calculated for each country and a multiplier of 1.15 for morbidity and another multiplier of 1.1 for non-health impacts (Jacobson et al., 2019). See Jacobson and Delucchi (2025) for values of VOSL in each country and Note S9 for a discussion.

[7]The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S26, Column (b), multiplied by the mean social cost of carbon in 2050 from Table S26, Column (f) (in USD 2022), which is updated from values in Jacobson et al. (2019), which were in 2013 USD. See Note S9 for a discussion.

Table 13. Air Pollution Mortalities, Carbon Dioxide Emissions, and Associated Costs

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

Country or region	(a)[1] 2050 BAU air pollution mortalities (Deaths/y)	(b)[2] 2050 BAU CO_2e (Mtonne/y)	(c)[3] 2050 WWS ($/ tonne-$CO_2e$-elim-inated)	(d)[4] 2050 BAU energy cost ($/ tonne-$CO_2e$-emitted)	(e)[4] 2050 BAU health cost ($/ tonne-$CO_2e$-emitted)	(f)[4] 2050 BAU climate cost ($/ tonne-$CO_2e$-emitted)	(g)[4] 2050 BAU social cost = d+e+f ($/ tonne-$CO_2e$-emitted)	(h)[5] 2050 BAU health cost (¢/kWh)	(i)[5] 2050 BAU climate cost (¢/kWh)
150 countries	5,632,472	56,082	120.95	307	658	580	1,544	21.5	19.0

[1]2050 BAU mortalities/y due to air pollution are calculated from 2019 indoor plus outdoor country-specific air pollution mortalities/y provided directly by WHO (2022a,b). WHO calculates 2019 mortalities/y by multiplying age-standardized mortality rates per unit population for each country for different air-pollution-related causes of death (lower respiratory tract illness; trachea, bronchus, and lung cancers; heart disease; stroke; and chronic obstructive pulmonary disease) by the 2019 population of the country. The 2019 values are then extrapolated to 2050 using Equation S35 from Jacobson et al. (2019). The extrapolation accounts for the projected 2050 population of each country, the fractional rate of change per year in each country in the air pollution death rate due to emission controls, and the estimated change in exposed population per unit change in population. It does not account for the change in age distribution with time. All components of the calculation for each country are given in Jacobson and Delucchi (2025). The result is a lower air pollution death rate in 2050 summed over all 150 countries (5.64 million/y in 2050 versus 7.19 million/y in 2019) and in most countries due to improved BAU emission-reduction technologies between 2019 and 2050.

[2]CO_2e=CO_2-equivalent emissions. This accounts for the emissions of CO_2 plus the emissions of other greenhouse gases multiplied by their global warming potentials. The emissions from these 150 countries represented 99.64% of world anthropogenic CO_2e emissions in 2023 (European Commission, 2024).

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

[4]Columns (d)-(g) are calculated as the BAU private energy cost, health cost, climate cost, and total social costs from Table S25, Columns (h)-(k), respectively, each divided by the CO_2e emissions from Column (b) of the present table.

[5]Columns (h)-(i) are calculated as the BAU health and climate costs from Table S25, Columns (i)-(j), respectively, each divided by the BAU end-use demand from Table S25, Column (a) and by 8,760 hours per year.

Table 14. 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 (% of region land area)	Spacing area (% of region land area)	Footprint plus spacing area as percentage of the country or region land area (%)
150 countries	122,484,753	0.182	0.392	0.574

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 km^2, respectively.

Table 15. 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. 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	Total jobs produced	Jobs lost	Net change in jobs
150 countries	55,363,864	27,363,621	28,000,243

References

Antora. 2024. Reliable, zero-emissions industrial heat and power. https://antoraenergy.com

EIA (Energy Information Administration). U.S. International Energy Outlook 2016. DOE/EIA-0484. 2016; http://www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf

IEA (International Energy Agency). Hydropower special market report. 2021; https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf

IEA (International Energy Agency) Energy Statistics Data Browser. OECD Publishing, Paris. 2024; https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?

Electrified Thermal Solutions. 2024. https://electrifiedthermal.com

European Commission, Edgar-emissions database for global atmospheric research, GHG emissions of all world countries, 2024, https://edgar.jrc.ec.europa.eu/report_2024

Forsberg C, Stack DC. 2024. Electrically Conductive Firebrick System, U.S. Patent: 11,877,376 B2. January 16, 2024. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11877376

Jacobson M.Z.; Delucchi, M.A.; Bauer, Z.A.F.; Goodman, S.C.; Chapman, W.E.; Cameron, M.A.; Bozonnat, C.; Chobadi, L.; Clonts, H.A.; Enevoldsen, P.; Erwin, J.R.; Fobi, S.N.; Goldstrom, O.K.; Hennessy, E.M.; Liu, J.; Lo, J.; Meyer, C.B.; Morris, S.B.; Moy, K.R.; O'Neill, P.L.; Petkov, I.; Redfern, S.; Schucker, R.; Sontag, M.A.; Wang, J.; Weiner, E.; Yachanin, A.S. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world. *Joule* **2017,** *1*, 108-121.

Jacobson, M.Z.; Jadhav, V. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy* **2018,** *169,* 55-66.

Jacobson M.Z.; Delucchi, M.A.; Cameron, M.A.; Coughlin, S.J.; Hay, C.; Manogaran, I.P.; Shu, Y.; von Krauland, A.-K. Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. *One Earth* **2019,** *1*, 449-463.

Jacobson, M.Z.; Fu, D.; Sambor, D.J.; Mühlbauer, A. Energy, health, and climate costs of carbon-capture and direct-air-capture versus 100%-wind-water-solar climate policies in 149 countries. *Environmental Science & Technology* **2025**, *59,* 3034-3045.

Jacobson, M.Z.; Delucchi, M.A. Spreadsheets for 150-country WWS study. 2025; http://web.stanford.edu/group/efmh/jacobson/Articles/I/150Country/150-Countries.xlsx

Rondo. 2024. The Rondo heat battery. https://rondo.com

WHO (World Health Organization). Household air pollution attributable deaths. 2022a; https://www.who.int/data/gho/data/indicators/indicator-details/GHO/household-air-pollution-attributable-deaths

WHO (World Health Organization). Ambient air pollution attributable deaths. 2022b; https://www.who.int/data/gho/data/indicators/indicator-details/GHO/ambient-air-pollution-attributable-deaths

Additional Background Material on 100% WWS

Jacobson, M.Z., *100% Clean, Renewable Energy and Storage for Everything*, Cambridge University Press, New York, 427 pp. (2020). https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html

Jacobson, M.Z., A.-K. von Krauland, K. Song, and A.N. Krull, Impacts of green hydrogen for steel, ammonia, and long-distance transport on the cost of meeting electricity, heat, cold, and hydrogen demand in 145 countries running on 100% wind-water-solar, *Smart Energy*, *11*, 100106, doi:10.1016/j.segy.2023.100106, 2023, https://web.stanford.edu/group/efmh/jacobson/Articles/Others/23-NonEnergyH2.pdf

Jacobson, M.Z., Batteries or hydrogen or both for grid electricity storage upon full electrification of 145 countries with wind-water solar? *iScience*, *27*, 108988, doi:10.1016/j.isci.2024.108988, 2024, https://web.stanford.edu/group/efmh/jacobson/Articles/Others/24-GridH2.pdf

Jacobson, M.Z., D.J. Sambor, Y.F. Fan, and A. Mühlbauer, Effects of firebricks for industrial process heat on the cost of matching all-sector energy demand with 100% wind-water-solar supply in 149 countries, *PNAS Nexus*, *3*, pgae274, doi:10.1093/pnasnexus/pgae274, 2024, https://academic.oup.com/pnasnexus/advance-article/doi/10.1093/pnasnexus/pgae274/7710221

Jacobson, M.Z., D. Fu, D.J. Sambor, and A. Mühlbauer, Energy, health, and climate costs of carbon-capture and direct-air-capture versus 100%-wind-water-solar climate policies in 149 countries, *Environmental Science & Technology, 59,* 3034-3045, doi:10.1021/acs.est.4c10686, 2025, https://web.stanford.edu/group/efmh/jacobson/Articles/I/149Country/149-Countries.pdf

Jacobson, M.Z., *Still No Miracles Needed: How Today's Technology can Save our Climate and Clean our Air*, Cambridge University Press, New York, (2026). https://web.stanford.edu/group/efmh/jacobson/WWSStillNMN/StillNMN.html