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

By Mark Z. Jacobson, Stanford University, January 4, 2024

This infographic summarizes results from simulations that demonstrate the ability of Cuba alone 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). All-purpose energy is for electricity, transportation, buildings, industry, agriculture/forestry/fishing, and the military. 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, lawnmowers, etc. Green hydrogen is used for ammonia and steel manufacturing, long-distance transport, and grid 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 2020 business-as-usual (BAU) country demand data by energy sector and fuel type (IEA, 2023), projected to 2050 then converted to demand powered by wind-water-solar (WWS) electricity and heat. LOADMATCH uses 30-s resolution 2050 WWS supply and building heating/cooling demand data calculated from the GATOR-GCMOM weather-prediction model. Citation:

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Main results. Transitioning Cuba to 100% WWS for all energy purposes…
Keeps the grid stable 100% of the time;

Saves 4,900 lives per year from air pollution in 2050 in Cuba;

Eliminates 43 million tonnes-CO_2e per year in 2050 in Cuba;

Reduces 2050 all-purpose, end-use energy requirements by 44.0%;

Reduces Cuba's 2050 annual energy costs by 55.1% (from $12.2 to $5.5 bil/y);

Reduces annual energy, health, plus climate costs by 92.6% (from $74 to $5.5 bil/y);

Costs ~$55 billion 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 8.2 years; that due to annual energy+health+climate cost savings is 0.8 years;

~0.9% of the WWS generator nameplate capacity needed has been installed;

New WWS requires 0.14% of Cuba's land for footprint, 0.29% for spacing;

Creates 45,300 more long-term, full-time jobs than lost (not including increases in jobs in producing electric appliances, vehicles, machines).

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

1st row: 2020 annually-averaged end-use demand (GW) and percentage of the demand by sector. 2nd row: projected 2050 annually-averaged end-use BAU demand (GW) and percentage of the total demand by sector. 3rd row: estimated 2050 total end-use demand (GW) and percentage of total demand by sector if 100% of end-use delivered BAU demand in 2050 is instead provided by WWS. Column (k) shows the percentage reductions in total 2050 BAU demand due to switching from BAU to WWS, including the effects of (h) energy use reduction due to the higher work to energy ratio of electricity over combustion, (i) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (j) policy-driven increases in end-use efficiency beyond those in the BAU case. Column (l) is the ratio of electricity demand (=all energy demand) in the 2050 WWS case to the electricity demand in the 2050 BAU case. Whereas Column (l) shows that electricity consumption increases in the WWS versus BAU cases, Column (k) shows that all energy decreases.

Scenario	(a) Total annual-average end-use demand (GW)	(b) Residential % of total	(c) Commercial % of total	(d) Industry % of total	(e) Transport % of total	(f) Ag-for-fish % of total	(g) Military-other % of total	(h) % change end-use demand with WWS due to higher work: energy ratio	(i) % change end-use demand with WWS due to eliminating upstream	(j) % change end-use demand with WWS due to efficiency beyond BAU	(k) Overall % change in end-use demand with WWS	(l) WWS:BAU electricity demand
Cuba												
BAU 2020	8.4	20.1	3.7	47.6	14.7	2.48	11.41					
BAU 2050	11.9	21.3	4.5	44.6	16.9	2.26	10.34					
WWS 2050	6.7	23.8	6	56.3	9	1.12	3.68	-32.69	-4.16	-7.13	-43.98	1.99

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 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	Residential	Commercial	Transport	Industrial	Agriculture/forestry/fishing	Military/other
Cuba	6.69	1.59	0.40	3.77	0.60	0.075	0.25

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)-(g). DR is demand-response. "Demand for non-grid H_2" accounts for the production, compression, storage, and leakage of hydrogen. Annual-average demands are distributed in time at 30-s resolution. Instantaneous demands, either flexible or inflexible, can be much higher or lower than annual-average demands. Column (h) shows the annual hydrogen mass production rate needed for steel and ammonia manufacturing and long-distance transport, estimated as the H_2 demand multiplied by 8,760 h/y and divided by 47.01 kWh/kg-H_2.

Country or region	(a) Total end-use demand (GW) =b+c	(b) Inflexible demand (GW)	(c) Flexible demand (GW) =d+e+f+g	(d) Cold demand subject to storage (GW)	(e) Low-temperature heat demand subject to storage (GW)	(f) Demand subject to DR	(g) Demand for non-grid H_2 (GW)	(h) Non-grid H_2 needed (Tg-H_2/y)
Cuba	6.7	3.3	3.4	0.3	0.4	2.5	0.28	0.05

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
Cuba	0	0	0.052	0.052	0	0.279	0.279

Table 5. Nameplate Capacities Needed by 2050 and Installed as of 2022

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. Also given are nameplate capacities already installed as of 2022 end. Nameplate capacity equals the maximum possible instantaneous discharge rate.

Year	Onshore wind	Off-shore wind	Residential roof-top PV	Comm /govt rooftop PV	Utility PV	CSP with storage	Geothermal -electricity	Hydro power	Wave	Tidal	Solar thermal	Geothermal heat	Total
2022	0.012	0	0.032	0.08	0.15	0	0	0.072	0	0	0	0	**0.34**
2050	6	1.8	3.9	12.3	12	0.01	0.000	0.07	0.019	0.031	0.00	0.00	**36.3**

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 in each region from Table 7 divided by the final nameplate capacity of each generator in each region from Table 5.

Country or region	On-shore wind	Off-shore wind	Rooftop PV	Utility PV	CSP with storage	Geo-thermal elec-tricity	Hydropower	Wave	Tidal	Solar thermal	Geo-thermal heat
Cuba	0.319	0.382	0.226	0.254	0.9	0	0.397	0.377	0.234	0	0

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. 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 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),, by region and percentage of such supply met by each generator. Simulation-average power supply (GW) equals the simulation total energy supply (GWh/simulation) divided by the number of hours of simulation. The percentages for each region add to 100%. Multiply each percentage by the 2050 total supply to obtain the GW supply by each generator. Divide the GW supply from each generator by its capacity factor (Table 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)	Onshore wind (%)	Offshore wind (%)	Roof PV (%)	Utility PV (%)	CSP with storage (%)	Geothermal electricity (%)	Hydropower (%)	Wave (%)	Tidal (%)	Solar thermal heat (%)	Geothermal heat (%)
Cuba	9.41	20.58	7.43	39.06	32.35	0.11	0	0.304	0.076	0.077	0.000	0.000

Table 8. 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.

Storage type	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Max storage time at max discharge rate (h)
PHS	3.00	3.00	0.042	14.0
CSP-elec.	0.012	0.012	--	--
CSP-PCM	0.019	--	0.000	22.6
Batteries	48	48	0.192	4.0
Hydropower	0.034	0.072	0.089	1,238
Base	0.029	0.029	0.041	1,439
Peaking	0.006	0.043	0.048	1,105
Grid H_2	0	0	0	0
CW-STES	0.108	0.108	.0015	14.0
ICE	0.163	0.163	.0023	14.0
HW-STES	1.18	1.18	0.009	8.0
UTES-heat	0	1.18	0.028	24.0
UTES-elec.	0.47	--	--	--

PHS=pumped hydropower storage; CSP=concentrated solar power; PCM=Phase-change materials; CW-STES=Chilled-water sensible heat thermal energy storage; ICE=ice storage; HW-STES=Hot water sensible heat thermal energy storage; and UTES=Underground thermal energy storage in soil. The maximum storage capacity equals the maximum discharge rate multiplied by the number of hours of storage at that rate.

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

CSP-PCM is the phase-change material storage associated with CSP. That storage is discharged for electricity production at the maximum discharge rate of CSP-elec. Thus, the maximum energy storage capacity of CSP-PCM 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. The maximum number of hours of storage at full discharge is 22.6 hours, or 1.612 multiplied by the 14 hours required for CSP storage to charge when charging at its maximum rate.

Hydropower's maximum discharge rate (GW) in 2050 is its 2022 nameplate capacity and its annual energy output (TWh/y) in 2050 is close to that in 2022 in every region. Water released from a dam during hydropower production is replenished naturally with rainfall and runoff. Hydropower reservoirs contain water for energy and non-energy purposes. About 50-60% of the water in a reservoir is generally used for energy (IEA, 2021). The hydropower storage capacity available for energy in all reservoirs worldwide is estimated as ~1,470 TWh, broken down as follows: North America: 370 TWh; China: 250 TWh; Latin

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

The CW-STES peak discharge rate is set equal to 40% of the annual-average cold demand (for air conditioning and refrigeration) subject to storage. The ICE storage discharge rate is set to 60% of the same annual-average cold demand subject to storage. The peak charge rate is set equal to the peak discharge rate. Heat pumps are used to produce both cold water and ice.

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. The peak charge rate is set equal to the peak discharge rate.

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

Grid H_2. Grid hydrogen storage capacity and storage times are set to zero in this table, but the peak charge and discharge rates are not. That is because hydrogen production and storage for grid and non-grid purposes are merged in this study. In such a case, the storage time depends on the discharge rate of both grid and non-grid hydrogen.

Figure 1. Keeping the Electric Grid Stable With 100% WWS + Storage + Demand Response

2050-2052 hourly time series showing the matching of all-energy demand with supply and storage. First row: modeled time-dependent total WWS power generation versus demand plus losses plus changes in storage plus shedding for the full three-year simulation period. Second row: same as first row, but for a window of 100 days during the simulation. Third row: a breakdown of WWS power generation by source during the window. Fourth row: a breakdown of inflexible demand; flexible electric, heat, and cold demands; flexible hydrogen demand; losses in and out of storage; transmission and distribution losses; changes in storage; and shedding. Fifth row: A breakdown of solar PV+CSP electricity production, onshore plus offshore wind electricity production, building total cold demand, and building total heat demand (as used in LOADMATCH), summed over the countries in each region for 10 days; Sixth row: correlation plots of building heat demand versus wind power output and wind power output versus solar power output, obtained from all hourly data during the simulation. Correlations are very strong for R=0.8-1 (R^2=0.64-1); strong for R=0.6-0.8 (R^2=0.36-0.64); moderate for R=0.4-0.6 (R^2=0.16-0.36); weak for 0.2-0.4 (R^2=0.04-0.16); and very weak for 0-0.2 (R^2=0-0.04) (Evans, 1996). The model was run at 30-s resolution. Results are shown hourly, so units are energy output (TWh) per hour increment, thus also in units of power (TW) averaged over the hour. No load loss occurred during any 30-s interval.

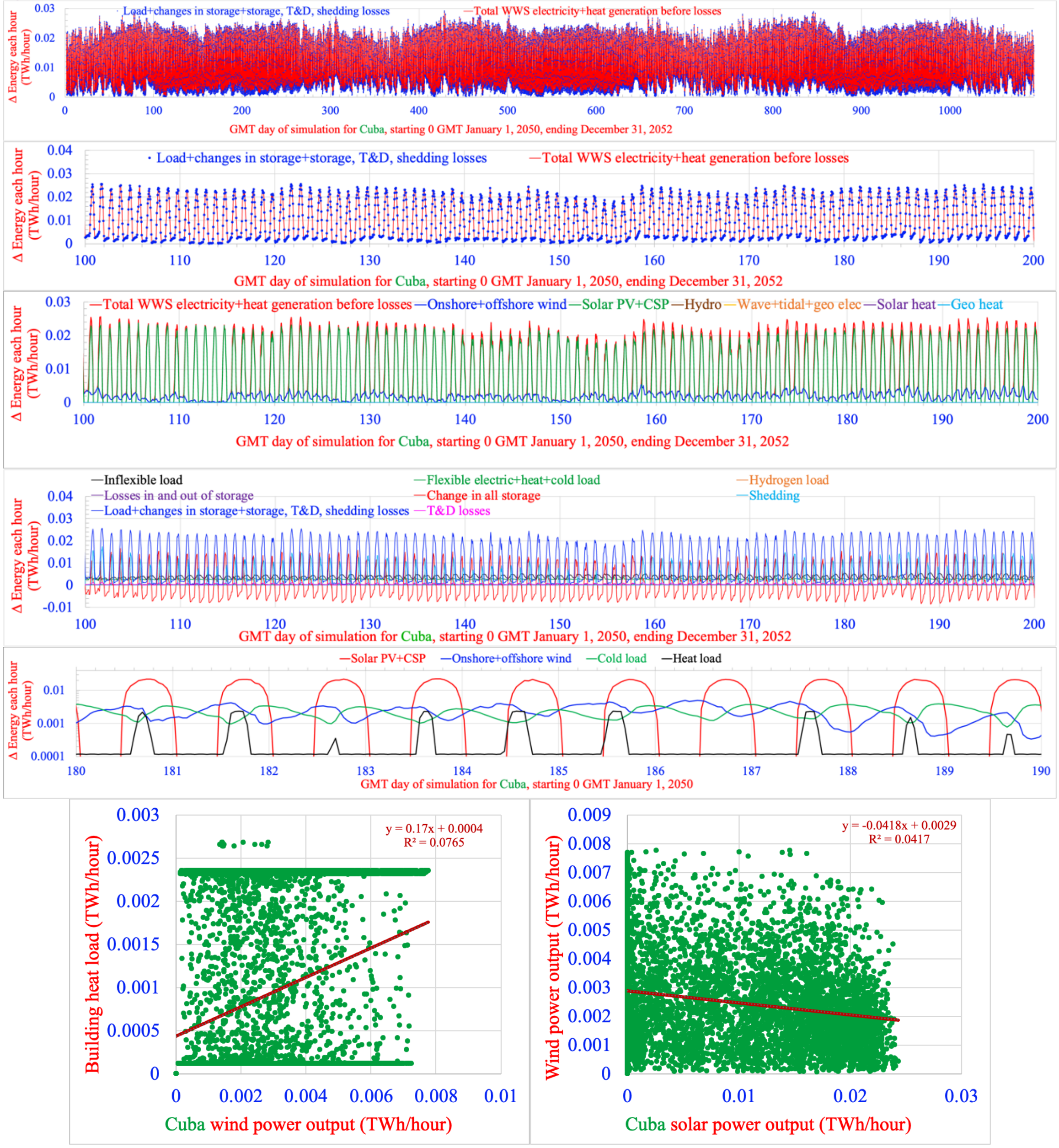

Table 9. Summary of Energy Budget Resulting in Grid Stability

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. All units are GW averaged over the 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 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+changes in storage =f+g (GW)**
Cuba	6.69	0.49	0.27	1.97	**9.41**	9.4	0.003	**9.41**

Table 10. 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, during the three-year (26,291.4875 hour) simulation. 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 9 for key parameters.

	Cuba
A1. Total end use demand	**176**
Electricity for electricity inflexible demand	95
Electricity for electricity, heat, cold storage + DR	74
Electricity for H_2 direct use + H_2 storage	7
A2. Total end use demand	**176**
Electricity for direct use, electricity storage, + H_2	170
Low-T heat demand met by heat storage	5
Cold demand met by cold storage	1.39
A3. Total end use demand	**176**
Electricity for direct use, electricity storage, DR	152
Electricity for H_2 direct use + H_2 storage	7
Electricity + heat for heat subject to storage	9
Electricity for cold demand subject to storage	7.12
B. Total losses	**72**
Transmission, distribution, downtime losses	13
Losses CSP storage	0.00
Losses PHS storage	0.0015
Losses battery storage	5.56
Losses grid H_2 storage	0
Losses CW-STES + ICE storage	0.25
Losses HW-STES storage	0.85
Losses UTES storage	0.54
Losses from curtailment	52
Net end-use demand plus losses (A1 + B)	***247***
C. Total WWS supply before T&D losses	**108**
Onshore + offshore wind electricity	15
Rooftop + utility PV+ CSP electricity	0
Hydropower electricity	37.2
Wave electricity	0.08
Geothermal electricity	21.6528
Tidal electricity	0.250
Solar heat	0
Geothermal heat	33.7242
D. Net taken from (+) or added to (-) storage	**-0.0016**
CSP storage	0
PHS storage	0
Battery storage	0
Grid H_2 storage	0
CW-STES+ICE storage	-0.0003
HW-STES storage	-0.0042
UTES storage	0
Non-grid H_2 storage	0.0029
Energy supplied plus taken from storage (C+D)	***108.1***

End-use demands in A1, A2, A3 should be identical. Electricity production is curtailed when it exceeds the sum of electricity demand, cold storage capacity, heat storage capacity, and H_2 storage capacity.

Table 11. 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) averaged over each simulation. Also shown is the energy consumed per year in each case and the resulting aggregate annual energy cost.

	Cuba
Capital cost new generators only ($tril)	0.042
Cap cost generators-storage-H_2-HVDC ($tril)	**0.055**
Components of total LCOE (¢/kWh-all-energy)	
Short-dist. transmission	1.050
Long-distance transmission	0.000
Distribution	2.375
Electricity generation	3.965
Additional hydro turbines	0
Geothermal + solar thermal heat generation	0.000
LI battery storage	1.671
Grid H_2 production/compression/storage/fuel cell	0.000
CSP-PCM + PHS storage	0.058
CW-STES + ICE storage	0.006
HW-STES storage	0.011
UTES storage	0.004
Heat pumps for filling district heating/cooling	0.034
Non-grid H_2 production/compression/storage	0.155
Total LCOE (¢/kWh-all-energy)	**9.33**
LCOE (¢/kWh-replacing BAU electricity)	9.125
GW annual avg. end-use demand	6.7
TWh/y end-use demand (GW x 8,760 h/y)	59
Annual energy cost ($billion/y)	**5.5**
% rise in LCOE & annual cost if 1.5x battery cost	9.0

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 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 costs are an average between 2020 and 2050, as are the LCOEs.

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

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

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

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

Long-distance transmission costs are $0.0089 (0.0042-0.010)/kWh (in USD 2020) assume 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 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 2020 USD. 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 (%)
Cuba	11.9	6.7	-44.0	0.055	11.65	9.33	5.5	12.2	37.5	24.0	74	-55.1	-92.6

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

[3] This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2020 and 2050.

[4] The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat). It is an average between 2020 and 2050.

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

[6] The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy) 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.

[7] The 2050 annual BAU climate cost equals the 2050 CO_2e emissions multiplied by the mean social cost of carbon in 2050 (in 2020 USD).

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)
Cuba	4,851	43	127.2	283	872	558	1,713	35.9	22.9

[1] 2050 country BAU mortalities due to air pollution are extrapolated from 2016 values from WHO (2017).

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

[3] Calculated as the WWS private energy and total social cost 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 respectively, each divided by the CO_2e emissions.

[5] Columns (h)-(i) are calculated as the BAU health and climate costs, respectively, each divided by the BAU end-use demand 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 (%)
Cuba	106,440	0.14	0.29	0.42

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
Cuba	64,169	18,916	45,253

References

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

IEA (International Energy Agency) Energy Statistics Data Browser. *OECD Publishing, Paris*. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser? (2023).

WHO (World Health Organization) (2017). Global health observatory data. Retrieved August 10, 2021, from, https://www.who.int/gho/phe/outdoor_air_pollution/en

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).

Jacobson, M.Z., von Krauland, A.-K., Coughlin, S.J., Dukas, E., Nelson, A.J.H., Palmer, F.C. & Rasmussen, K.R. Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. *Energy and Environmental Sciences* **15**, 3343-3359 (2022).

Jacobson, M.Z., *No Miracles Needed: How Today's Technology can Save our Climate and Clean our Air*, Cambridge University Press, New York, 437 pp. (2023).

Jacobson, M.Z., von Krauland, A.-K., Song, K. & Krull, A.N. 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 (2023).