A Low-Cost Solution to Global Warming, Air Pollution, and Energy Insecurity for Iceland Using Existing Hydro but No Nuclear, Fossil Fuels, Bioenergy, Batteries, or Fuel Cells for Grid Electricity

By Mark Z. Jacobson, Stanford University, August 11, 2023

This infographic summarizes results from simulations that demonstrate the ability of Iceland 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. Results are shown for Iceland with an isolated but well-interconnected grid. 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, 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 bioenergy, fossil fuels, carbon capture, nuclear energy, non-green hydrogen, or electro-fuels aside from green hydrogen is included. No batteries or hydrogen fuel cells are used or needed for grid electricity storage. Existing hydropower in Iceland is used for both baseload and peaking power to provide almost all (aside from a small amount of pumped hydropower) grid electricity storage. Heat and cold storage and non-grid hydrogen storage are included and tracked over time. Green hydrogen is used for steel and ammonia production and long-distance transport (including aviation and shipping) with fuel cells. All other transport is with battery-electric vehicles..

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. A paper describing the models and previous (but not the current) results and a book describing more details about transitioning to WWS are

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., *No Miracles Needed:* Cambridge Univ. Press, NY, 437 pp., 2023, https://web.stanford.edu/group/efmh/jacobson/WWSNoMN/NoMiracles.html

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

- **Keeps the grid stable 100% of the time (no blackouts);**
- **Saves ~36 lives from air pollution per year in 2050 in Iceland;**
- **Eliminates 5 million tonnes-CO_2e per year in 2050 in Iceland;**
- **Reduces 2050 all-purpose, end-use energy requirements by 42.9%;**
- **Reduces Iceland's 2050 annual energy costs by 47.1% (from $3.7 to $2.0 bil/y);**
- **Reduces annual energy, health, plus climate costs by 72.0% (from $7.0 to $2.0 bil/y);**
- **Costs ~$29 billion upfront. Costs paid back through energy sales. Costs are 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;**
- **Requires 0.006% of Iceland's land for footprint, 0.11% for spacing;**

Table of Contents

Table 1. Reduced End-Use Demand Upon a Transition From BAU to WWS
Table 2. 2050 WWS End-Use Demand by Sector
Table 3. WWS End-Use Demand by Load Type
Table 4. Nameplate Capacities Needed by 2050 and Installed as of 2020
Table 5. Capacity Factors of WWS Generators
Table 6. Percent of Load Met by Different WWS Generators
Table 7. Characteristics of Storage Resulting in Matching Demand With 100% WWS Supply
Figure 1. Keeping the Electric Grid Stable With 100% WWS + Storage + Demand Response
Table 8. Summary of Energy Budget Resulting in Grid Stability
Table 9. Details of Energy Budget Resulting in Grid Stability
Table 10. Breakdown of Energy Costs Required to Keep Grid Stable
Table 11. Energy, Health, and Climate Costs of WWS Versus BAU
Table 12. Air Pollution Mortalities, Carbon Dioxide Emissions, and Associated Costs
Table 13. Land Areas Needed
Table 14. Changes in Employment
References.

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) Residential % of total end-use load	(c) Commercial % of total end-use load	(d) Industry % of total end-use load	(e) Transport % 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 eliminating upstream	(j) % change end-use load w/WWS due to efficiency beyond BAU	(k) Overall % change in end-use load with WWS	(l) WWS: BAU electricity load
Iceland												
BAU 2018	5.0	13.5	13.7	42.1	23.0	7.43	0.27					
BAU 2050	5.6	14.4	14.6	41.5	22.2	7.01	0.26					
WWS 2050	3.2	9.1	13.5	62.6	10.8	3.90	0.11	-34.9	-2.1	-5.9	-43.0	1.21

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 Iceland 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	Residential	Commercial	Transport	Industrial	Agriculture/forestry/fishing	Military/other
Iceland	3.2	0.29	0.43	2.02	0.35	0.13	0.00

Table 3. WWS End-Use Demand by Load Type

Annual average WWS all-sector inflexible and flexible loads (GW) for 2050 in Iceland. “Total load” is the sum of columns (b) and (c). “Flexible load” is the sum of columns (d)-(g). DR is demand-response. “Load for non-grid H_2” accounts for the production, compression, storage, and leakage of hydrogen. Annual-average loads are distributed in time at 30-s resolution. Instantaneous loads, either flexible or inflexible, can be much higher or lower than annual-average loads. Column (h) shows the annual hydrogen mass production rate needed in each region, estimated as the H_2 load multiplied by 8,760 h/y and divided by 47.01 kWh/kg-H_2.

Country or region	(a) Total end-use load (GW) =b+c	(b) Inflexible load (GW)	(c) Flexible load (GW) =d+e +f+g	(d) Cold load subject to storage (GW)	(e) Low-temperature heat load subject to storage (GW)	(f) Load subject to DR	(g) Load for H_2 (GW)	(h) H_2 needed (Tg-H_2/yr)
Iceland	3.2	1.2	2.0	0.0	0.6	1.3	0.1	0.03

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 Iceland. 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	Resi-dential roof-top PV	Comm /govt rooftop PV	Utility PV	CSP with stor-age	Geothermal -elec-tricity	Hydro power	Wave	Tidal	Solar thermal	Geothermal heat
2020	0.002	0	0.001	0.001	0.004	0	0.756	2.086	0	0	0	2.373
2050	1.63	0	0	0	0	0	0.890	2.086	0.010	0.038	0	2.373

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 Iceland. 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	Geo-thermal elec-tricity	Hydropower	Wave	Tidal	Solar thermal	Geo-thermal heat
Iceland	0.573	0	0	0	0	0.925	0.551	0	0.253	0	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

Simulation-averaged 2050-2052 all-sector WWS energy supply before transmission, distribution, maintenance, storage, or curtailment losses, in Iceland, 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 sum to 100%. Multiply each percentage by the 2050 total supply to obtain the annual-average power (GW) supplied by each generator. Divide the GW supplied by 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 stor-age (%)	Geothermal elec-tricity (%)	Hydropower (%)	Wave (%)	Tidal (%)	Solar ther-mal heat (%)	Geo-ther-mal heat (%)
Iceland	4.20	22.21	0	0	0	0	19.62	27.39	0	0.227	0	30.56

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

Maximum charge rates, discharge rate, energy storage capacity (before losses), 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 Iceland.

Storage type	Max charge rate (GW)	Max discharge rate (GW)	Max storage capacity (TWh)	Max storage time at max discharge rate (hr)
PHS	0	0	0	0
CSP-elec.	0	0	--	--
CSP-PCM	0	--	0	0
Batteries	0	0	0	0
Hydropower	1.07	2.09	2.8	1,337
Baseload	0.76	0.76	0.1	120
Peaking	0.31	1.32	2.7	2,040
H_2-Fuel cells	0.0	0.0	0.0	0
CW-STES	0.018	0.018	.00025	14
ICE	0.027	0.027	.00037	14
HW-STES	1.05	1.05	0.0021	2
UTES-heat	0	0	0	0
UTES-elec.	0	--	--	--

PHS=pumped hydropower storage; PCM=Phase-change materials; CSP=concentrated solar power; 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 (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 is estimated as the existing (in 2020) nameplate capacity multiplied by 3.5, which is the approximate lower-end ratio of existing capacity plus pending permits to existing capacity in the United States (FERC, 2021). If a country has no existing pumped hydro, a minimum is imposed to account for the addition of pumped hydro between 2023 and 2050.

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 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 (GW) in 2050 is its 2020 nameplate capacity, and its annual energy output (TWh/y) in 2050 is close to that in 2020 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 2020 hydroelectric energy output of the country to that of the region the country falls in. The maximum storage capacity in each of the 24 regions in this study is then calculated simply by summing the maximum storage capacities among all countries in the region. The maximum storage capacity, total nameplate capacity, and natural recharge rate (assumed to equal 2020 hydropower output) 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 among 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 region's reservoirs, which equals the annual average hydropower power output (TW) of the reservoirs in 2020 (which equals the 2020 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 (TW 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. In sum, whereas baseload power is produced and discharged continuously in the model every 30 seconds, peaking power is also produced every 30 seconds 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 in each case: 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 two-year 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. 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. 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 demand subject to storage during any 30-s 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.

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 in Iceland. First row: modeled time-dependent total WWS power generation versus load plus losses plus changes in storage plus curtailment 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 load; flexible electric, heat, and cold load; flexible hydrogen load; losses in and out of storage; transmission and distribution losses; changes in storage; and curtailment. Fifth row: A breakdown of solar PV+CSP electricity production, onshore plus offshore wind electricity production, building total cold load, and building total heat load (as used in LOADMATCH), summed over each region; The model was run at 30-s resolution. Results are shown hourly, so units are energy output (TWh) per hour increment, thus also in units of power (TW) averaged over the hour. No load loss occurred during any 30-s interval. Raw GATOR-GCMOM results for solar, wind, heat load, and cold load were provided and fed into LOADMATCH at 30-s time increments. LOADMATCH modified the magnitudes, but not time series, of GATOR-GCMOM output, as described in the paper.

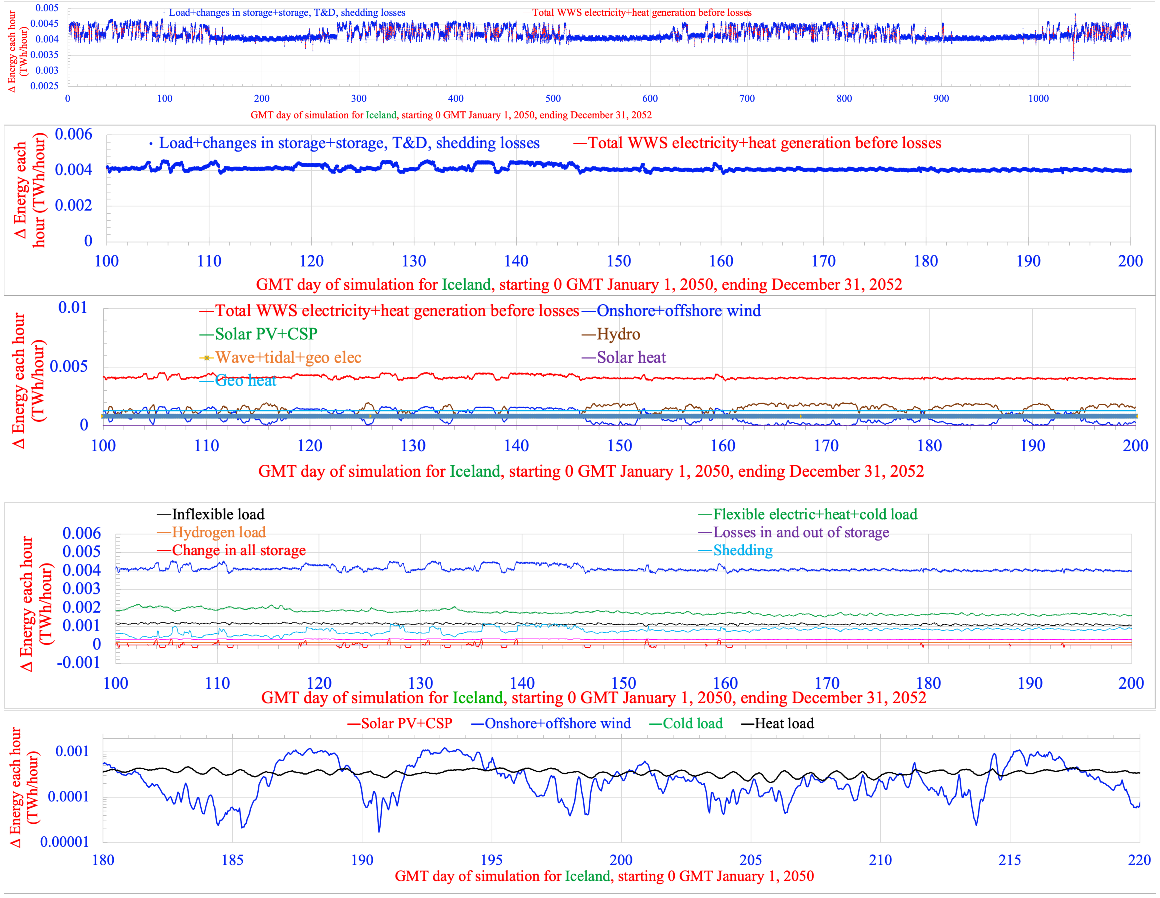

Table 8. Summary of Energy Budget Resulting in Grid Stability

Budget of simulation-averaged end-use power demand met, energy lost, WWS energy supplied, and changes in storage, during the three-year (26,291.4875 hour) simulation. All units are GW averaged over the simulation 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. Results are shown for Iceland.

Country or region	(a) Annual average end-use load (GW)	(b) TD&M losses (GW)	(c) Storage losses (GW)	(d) Curtail-ment 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+ changes in storage =f+g (GW)**
Iceland	3.17	0.31	0.00	0.71	**4.20**	4.20	0.000	**4.20**

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, 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 8 for key parameters. Results are shown for Iceland.

	Iceland
A1. Total end use demand	**83**
Electricity for electricity inflexible demand	31
Electricity for electricity, heat, cold storage + DR	49
Electricity for H_2 direct use + H_2 storage	4
A2. Total end use demand	**83**
Electricity for direct use, electricity storage, + H_2	69
Low-T heat load met by heat storage	15
Cold load met by cold storage	0.00
A3. Total end use demand	**83**
Electricity for direct use, electricity storage, DR	65
Electricity for H_2 direct use + H_2 storage	4
Electricity + heat for heat subject to storage	15
Electricity for cold load subject to storage	0.00
B. Total losses	**27**
Transmission, distribution, downtime losses	8
Losses CSP storage	0.00
Losses PHS storage	0.0000
Losses battery storage	0.00
Losses grid H_2 storage	0
Losses CW-STES + ICE storage	0.00
Losses HW-STES storage	0.00
Losses UTES storage	0.00
Losses from curtailment	18.7
Net end-use demand plus losses (A1 + B)	***110.4***
C. Total WWS supply before T&D losses	**110**
Onshore + offshore wind electricity	25

Rooftop + utility PV+ CSP electricity	0
Hydropower electricity	30.2
Wave electricity	0.00
Geothermal electricity	21.6528
Tidal electricity	0.250
Solar heat	0
Geothermal heat	33.7242
D. Net taken from (+) or added to (-) storage	**-0.0015**
CSP storage	0
PHS storage	0
Battery storage	0
Grid H_2 storage	0
CW-STES+ICE storage	-0.0003
HW-STES storage	-0.001
UTES storage	0
Non-grid H_2 storage	-0.0002
Energy supplied plus taken from storage (C+D)	***110.4***

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.

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

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

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

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

	Iceland
Capital cost new generators only ($trillion)	0.002
Cap cost new generators + storage ($trillion)	**0.0029**
Components of total LCOE (¢/kWh-all-energy)	
Short-dist. transmission	1.050
Long-distance transmission	0
Distribution	2.375
Electricity generation	1.777
Additional hydro turbines	0
Geothermal + solar thermal heat generation	1.679
LI battery storage	0
Grid H_2 production/compression/storage/fuel cell	0
CSP-PCM + PHS storage	0
CW-STES + ICE storage	0.002
HW-STES storage	0.005
UTES storage	0
Heat pumps for filling district heating/cooling	0.046
Non-grid H_2 production/compression/storage	0.137
Total LCOE (¢/kWh-all-energy)	**7.071**
LCOE (¢/kWh-replacing BAU electricity)	6.883
GW annual avg. end-use demand (Table 1)	3.2
TWh/y end-use demand (GW x 8,760 h/y)	28
Annual energy cost ($billion/yr)	**2.0**

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-H_2-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, 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), 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 Iceland 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/	(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 (%)
Iceland	5.6	3.2	-42.9	0.0029	7.51	7.07	2.0	3.7	0.4	2.9	7	-47.1	-72.0

[1] From Table 1.

[2] Capital cost of generators-storage-H_2-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.

[3] This 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.

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

[5] The 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.

[6] The 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).

[7] The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table 12, Column (b), multiplied by the social cost of carbon in 2050 of $548 ($315-$1,188)/metric tonne-$CO_2$ (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

Iceland (a) estimated air pollution mortalities per year in 2050-2052 due to anthropogenic sources (90% of which are energy); (b) carbon-equivalent emissions (CO_2e) in the BAU case; (c) cost per tonne-CO_2e of eliminating CO_2e with 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; (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)
Iceland	36	5	379.4	717	80	559	1,356	0.8	5.8

[1] 2050 country BAU mortalities due to air pollution are extrapolated from 2016 values from WHO (2017) using the method described in Jacobson et al. (2019).

[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.

[3] Calculated as the WWS private energy and total social cost from Table 11, Column (g) divided by the CO_2e emissions from Column (b) of the present table.

[4] Columns (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 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 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 (%)
Iceland	100,250	0	82	0.0004	0.082

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 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 Iceland. 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
Iceland	1,744	5,758	7,503	4,635	2,868

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