Simulation Matching Demand With 100% Wind, Water, and Solar Supply Plus Storage Across all Energy Sectors in ICELAND With NO Added Hydropower Turbines

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Figure 1. Five-year (60-month, 2050-2054) time-series comparison for Iceland of computer modeled (a) monthly-averaged total wind-water-solar (WWS) power generation versus the sum of load met across all energy sectors (electricity, transportation, heating/cooling, industry, agriculture/forestry fishing) plus losses plus changes in storage plus shedding, (b) breakdown of load plus losses plus changes in storage plus shedding into individual components, and (c) breakdown of WWS power generation by generation technology.

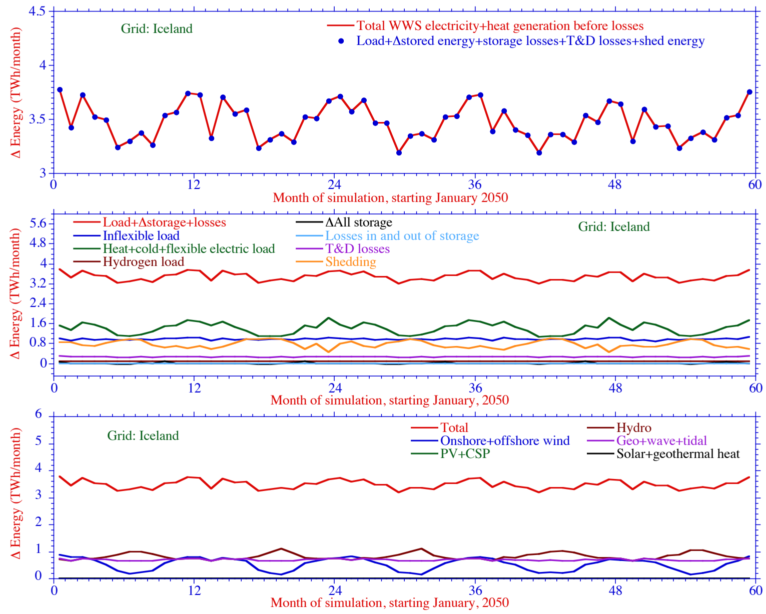
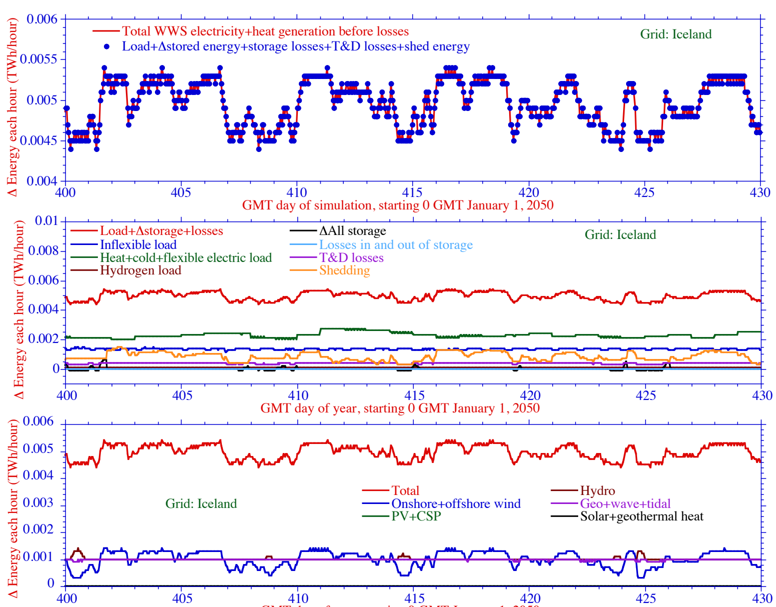


Figure 2. Same as Fig. 1, but with hourly results for a 30-day period during the 5-year simulation.



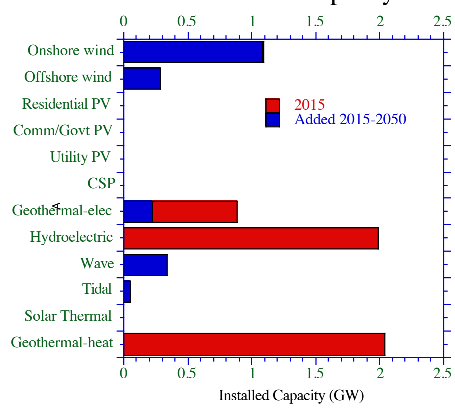
The model used was the LOADMATCH grid integration model (Jacobson et al., PNAS 112, 15,060-15,065, 2015). It used a 30-second time step. Supply matched demand every 30 s for all 5 years, accounting for the intermittency of WWS and extreme weather events. Results here are shown in the monthly average and hourly average. Total annual average load met in 2050 with 100% WWS in Iceland was 3.36 GW, a reduction of ~24.7% from the business-as-usual (BAU) case due to (a) the higher work out to energy in ratio of electricity over combustion (12.0%), (b) eliminating energy in the mining, transporting, and refining of fossil fuels and uranium (6.89%), and (c) additional end use efficiency improvements and reductions in energy use beyond BAU (5.85%). Table 1 gives the installed capacity and storage requirements for the system. No hydropower turbines beyond those installed in 2015 were assumed.

Table 1. (a) 2015 and proposed 2050 installed capacity for WWS generators to power 100% of all energy sectors in region. Figure 3 graphs these results. (b) Maximum charge rates, discharge rate, and storage capacity of all electricity, cold and heat storage needed for supply + storage to match demand in the region.

(a) WWS Generator	2015 (GW)	2050 (GW)	(b) Storage type	Max charge rate (GW)	Max discharge rate (GW)	Storage (TWh)
Onshore wind	0.003	1.09	CSP	0	0	0
Offshore wind	0	0.283	PHS	0	0	0
Residential PV	0	0	Batteries	0	0	0
Comm./govt. PV	0	0	Hydropower	0.944	1.99	8.27
Utility PV	0	0	CW+ice	0.037	0.037	0.00052
CSP	0	0	HW	2.08	2.08	0.0167
Geothermal-elec.	0.665	0.89	UTES-heat	0	0	0
Hydropower	1.99	1.99	UTES-elec	0	--	--
Wave	0	0.335				
Tidal	0	0.056				
Solar thermal	0	0				
Geothermal-heat	2.04	2.04				

CSP = concentrated solar power; PHS=pumped hydropower storage; CW+ice= chilled water storage plus ice storage; HW=hot water storage; UTES-heat=underground thermal energy storage in rocks, where heat is obtained from solar thermal collectors; UTES-elec=UTES storage in rocks, where heat is obtained from excess WWS electricity. In addition, hydrogen was produced (0.0167 Tg-H_2/yr) and stored (0.0015 Tg-H_2 tanks) for use only in transportation. Battery electric vehicles were also used in transportation.

Figure 3. 2015 and proposed 2015-2050 additions of installed capacity of WWS generators for Iceland.



The cost of energy replacing retail electricity was 4.90 (4.37-5.65) ¢/kWh in 2013 USD. **The cost of all energy was 5.14 (4.50-6.03) ¢/kWh.** The system capital cost was $0.0055 (0.0039-0.0071) trillion. Costs include electricity generation; heat, cold, electricity, and hydrogen storage; hydrogen electrolysis and compression; and short- and long-distance transmission; and distribution.

Citations:

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.V, Mathiesen, Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes, Renewable Energy, https://doi.org/10.1016/j.renene.2018.02.009, 2018, https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html

Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule, 1*, 108-121, doi:10.1016/j.joule.2017.07.005, 2017, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html