

Simulation Matching Demand With 100% Wind, Water, and Solar Supply Plus Storage Across all Energy Sectors in the UNITED STATES plus CANADA With NO Added Hydropower Turbines (Thus, Near-Current Hydro Max Discharge Rate)

Mark Z. Jacobson, October 28, 2017

Figure 1. Five-year (60-month, 2050-2054) time-series comparison for the United States plus Canada 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.

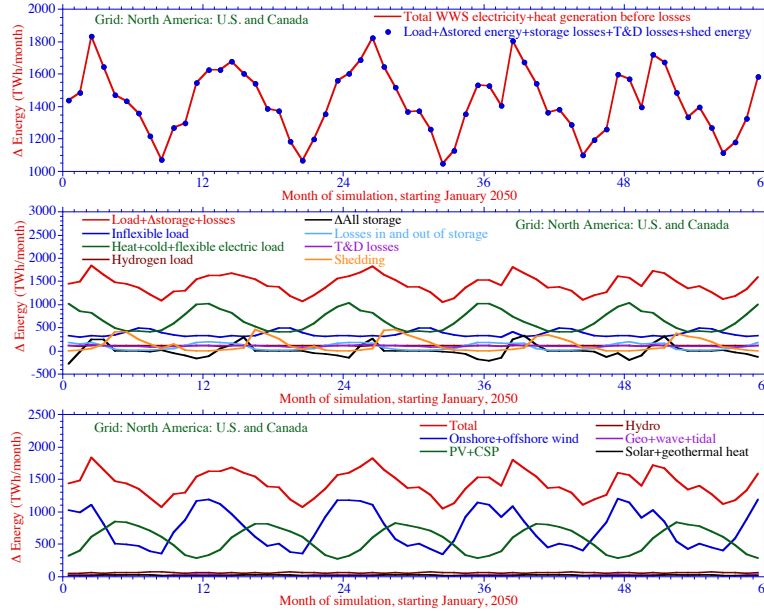
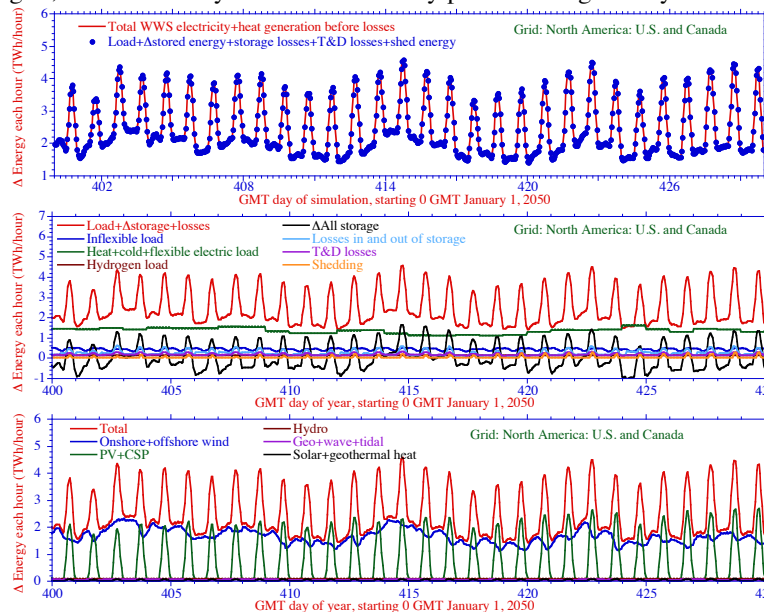


Figure 2. Same as Fig. 1, but with hourly results for a 30-day period during the 5-year simulation.



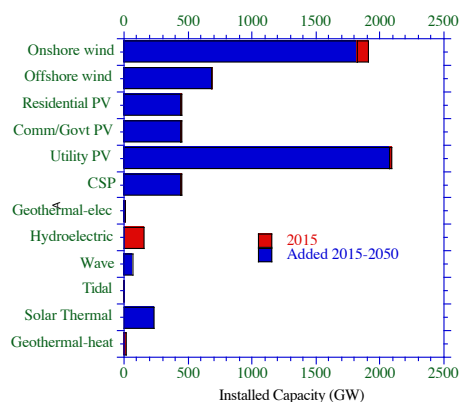
The model used was the LOADMATCH grid integration model (Jacobson et al., PNAS 112, 15,060-15,065, 2015). It used a 30-second time step. Supply matched demand every 30 s for all 5 years, accounting for the intermittency of WWS and extreme weather events. Results here are shown in the monthly average and hourly average. Total annual average load met in 2050 with 100% WWS in the United States plus Canada was 1532 GW, a reduction of ~45.3% from the business-as-usual (BAU) case due to (a) the higher work out to energy in ratio of electricity over combustion (27.6%), (b) eliminating energy in the mining, transporting, and refining of fossil fuels and uranium (10.9%), and (c) additional end use efficiency improvements and reductions in energy use beyond BAU (6.8%). 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	85.7	1910	CSP	721.9	447.7	10.1
Offshore wind	0	688	PHS	125.4	125.4	1.76
Residential PV	6.08	451	Batteries	880	880	1.71
Comm./govt. PV	7.58	449	Hydropower	71.0	158.3	622.3
Utility PV	14.5	2092	CW+ice	99.82	99.82	1.40
CSP	1.83	448	HW	1309	1309	18.3
Geothermal- elec.	3.45	11.5	UTES-heat	236.8	1309	597.1
Hydropower	158.3	158.3	UTES-elec	2619	--	--
Wave	0	71.1				
Tidal	0	2.35				
Solar thermal	0	237				
Geothermal- heat	18.9	18.9				

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 (21.3 Tg-H₂/yr) and stored (1.34 Tg-H₂ 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 the United States plus Canada.



The cost of energy replacing retail electricity was 9.72 (7.8-12.4) ¢/kWh in 2013 USD. The cost of all energy was 10.5 (8.1-13.9) ¢/kWh. The system capital cost was \$15.3 (12.5-18.1) 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>