

# Simulation Demonstrating a 100% Stable Grid With 100% Wind, Water, and Solar in all Energy Sectors Across the UNITED STATES plus CANADA, With NO Added Hydropower Turbines (Thus, Near-Current Hydro Max Discharge Rate)

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Five-year (60-month) time-series comparison for the United States plus Canada of modeled (a) monthly-averaged total wind-water-solar (WWS) power generation versus the sum of load 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. 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. Results here are shown in the monthly average. For this simulation zero additional hydropower turbines were added (only near-current turbine capacity was used). Total hydro installed turbine capacity (U.S. plus Canada) was 158.34 GW, and the hydro capacity factor was 48.1%. . Other installed capacities were: Onshore wind, 1,852 GW; Offshore wind, 688.4 GW; Residential rooftop PV, 451.5 GW; Commercial/government rooftop PV, 449.0 GW; Utility PV, 2056 GW; CSP, 447.7 GW; Geothermal, 11.5 GW; Wave, 71.1 GW; Tidal, 2.35 GW; Solar thermal heat, 426.2 GW; and Geothermal heat, 18.9 GW. Other electricity storage included CSP with storage (10.11 TWh; 721.9 TW max charge rate; 447.7 GW max discharge rate), pumped-hydro storage (1.76 TWh; 125.42 GW max charge and discharge rates), and batteries (1.94 TWh; 1 TW max charge and discharge rates). Heat storage included underground thermal energy storage (439.95 TWh; 426.2 GW max charge rate from heat; 2,619 GW max charge rate from electricity; 1309 GW max discharge rate), hot water storage (18.3 TWh; 1309 GW max charge and discharge rates), cold water and ice storage (1.4 TWh; 99.8 max charge and discharge rates), and hydrogen storage. Hydrogen was used for part of transportation only. The cost of energy replacing retail electricity was 9.8 (7.9-12.5) ¢/kWh in 2013 USD. **The cost of all energy was 10.4 (8.1-13.7) ¢/kWh, which compares with 10.3 (8.0-13.5) ¢/kWh for the same simulation of the U.S. plus Canada, but increasing the discharge rate of hydropower and accounting for the estimated cost of additional hydropower turbines plus pipes while using less CSP and no batteries.** Costs include generation; heat, cold, electricity, and hydrogen storage; short- and long-distance transmission; and distribution.

