It Is Impossible to Obtain Firm Power from Renewable Sources

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***Abstract*—Storage requirements to obtain firm power from renewable sources were computed using generation data from California, New York, Texas, USA as a whole, Denmark, Germany, and EU as a whole. American utilities define *firm power* to be available 99.97% of the time – about two hours and forty minutes per year without power. The analyses here show that to obtain firm power, 900–1,500 watt hours of storage are required per watt of average demand, depending upon location – about 2,125,000 GWe-hours for USA. These quantities of storage are not physically realizable, and if they were they would not be economically possible.**

Keywords: Renewable energy, storage requirements, batteries, pumped storage, towed storage

I. INTRODUCTION

In *Grid-Scale Storage of Renewable Energy: The Impossible Dream* [1], Euan Mearns used one year of generation data with one hour resolution for all of England and Scotland to calculate that to avoid outages, 390 watt hours of storage would be needed per watt of average demand. In *Is 100 Percent Renewable Energy Possible?* [2], Norman Rogers used one year of generation data from Texas with one hour resolution to calculate that storage capacity of 400 watt hours is needed per watt of average wind and solar generation. In *Geophysical constraints on the reliability of solar and wind power in the United States* [3], Shaner et al used 36 years of geophysical data for all of North America with one hour resolution to calculate that 400-800 watt hours of storage are needed per watt of average solar and wind generation, depending upon location and the mix of solar and wind.

I obtained generation data from the California Independent System Operator [4] with hourly resolution from 1 January 2011 until 30 November 2020, and five minute resolution thereafter, data from the Electric Reliability Council of Texas with hourly resolution from 2 July 2018 onward by way of the US Energy Information Agency (EIA) Hourly Electric Grid Monitor [5], data from the New York Independent System Operator [6] with five minute resolution from 9 December 2015 onward, nationwide data from the EIA Hourly Electric Grid Monitor [5] with one hour resolution from 1 July 2018 onward, and data from EU for Denmark, Germany, and EU as a whole with hourly resolution from 1 January 2015 until 30 September 2020.

California provides separate generation data for geothermal, biomass, biogas, small hydro, large hydro, wind, solar photovoltaic, solar thermal, nuclear, natural gas, and coal. Others provide less detailed data. In these analyses, renewable sources are considered to be all sources other than coal, gas, nuclear, and petroleum.

II. METHOD OF ANALYSIS

To compute the amount of energy that would have been accumulated into (or discharged from) storage in an hypothetical all-renewable energy system at any particular instant, by extrapolating from historical data, start by computing the difference $\delta(t)$ between what instantaneous power production would have been if renewables were the only source, and instantaneous demand, both in watts per watt of average demand.

The amount of energy in storage at time t since the beginning of the analysis, in watt hours per watt of average demand, is then obtained by accumulating the instantaneous power surplus (or deficit) $\delta(t)$ in each measurement interval, multiplied by the interval length (energy = power × time), i.e., by computing the integral:

$$S(t) = \int_0^t \mathrm{d}\tau\, \delta(\tau) \approx \sum_{n=1}^{N} \delta(t_n)\, \Delta t_n \,, \qquad (1)$$

where $\delta(t)$ has units of watts of surplus (or deficit) of generation compared to demand per watt of average demand, N is the number of measurement instants, Δt_n (the duration of the n^{th} measurement interval) has units

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of hours, and $S(t)$ has units of watt hours in storage per watt of average demand.

Rectangular quadrature is justified by the fine resolution of measurements – Δt_n was one hour for California from 1 January 2011 until 30 November 2020, and five minutes thereafter, five minutes for New York from 9 December 2015 onward, and one hour for the other data.

To use historical data to compute what $\delta(t)$ would have been if all sources were renewable sources, increase measured renewables' average production to match average demand. Let $\overline{R}$ be current average renewables' production, and $M\overline{W}$ be the additional average renewables' production needed to match average total demand $\overline{T}$, where $\overline{W}$ is a weighted average of renewables' production, and M is a magnification factor. Then

$$\overline{R} + M\overline{W} = \overline{T}, \text{ or } M = \frac{\overline{T} - \overline{R}}{\overline{W}} . \tag{2}$$

To compute the relationship of $S(t)$ to average total demand, that is, how much storage capacity is needed per watt of average demand, we need

$$\delta(t) = \frac{R(t) + GMW(t)}{\overline{T}} - \frac{T(t)}{\overline{T}} , \tag{3}$$

where G is a general growth factor that allows to increase the weighted average of renewables' production above average demand, $T(t)$ is instantaneous total demand, $R(t)$ is instantaneous renewables' output, and $W(t)$ is a weighted average of instantaneous renewables output, given by

$$\begin{gathered} R(t) = \sum_{i=1}^{N} R_i(t),\, W(t) = \sum_{i=1}^{N} g_i(t) R_i(t) , \\ \text{and } \sum_{i=1}^{N} g_i(t) = 1 . \end{gathered} \tag{4}$$

The instantaneous magnifications $g_i(t)$ were computed as $1 + r_i / \sum |r_i|$, where r_i is the rate of change of each renewable's generating method, and then normalized as in Equation (4), separately in each year for California and once using a projection for nationwide generation. Therefore, for California, the proportions by which different methods are increased are different each year, and the accumulated surplus (or deficit) of energy in storage is computed as if the generation capacities had been magnified, during that year, to be sufficient to meet average demand. The relationships of rates of change in California have not significantly changed since about 2012, when solar photovoltaic capacity began increasing rapidly, and construction of new wind capacity stopped. If all $g_i(t)$ were equal and constant, this method would assume that all renewable sources can be magnified by the same amount M to increase their total average output to total average demand. This is not going to happen. For example, environmentalists want to remove dams, not build more of them. In the initial analysis $G = 1$. Later, we examine the effect of larger G.

Because neither average demand nor average renewables' production are constant, the "instantaneous" average demand and production were computed using least-squares fits [7] to cubic splines [8] having second-order continuity,[1] with slope (m_i) constraints at the ends of the interval given by least-squares fits to straight lines, $\overline{R}_i(t) \simeq m_i t + b_i$. The slope constraints are necessary because the interval of analysis does not necessarily begin or end at the end of a year. Without it, the "instantaneous" average near the beginning or end of the interval would be anomalously small or large compared to a similar instant in the middle of the interval.

III. RESULTS OF ANALYSES

Many advocates for all-renewable energy systems claim that fewer than twelve watt hours of storage per watt of average demand are sufficient because demand during nights is generally less than demands during days. But when the effects of prolonged changes in generating and demand conditions are analysed, it becomes clear that far more is needed.

The amounts of storage needed are equal to the difference between the maximum surplus and the deepest deficit that results if individual categories of renewable generators' average outputs are magnified according to their growth rates, and their aggregate is magnified to be equal to average demand, that is, $\sup(S) - \inf(S)$. Othwerwise, either blackouts would occur when demand exceeds supply because storage is empty, or power would be dumped when supply exceeds demand because storage is fully charged. The results are shown in Table I.

The result of analysis for California, $S(t)$ above, is illustrated in Figure 1. Figures for other analyses have similar appearance. Notice that yearly variation and variation similar to the Sun's eleven-year cycle are apparent and far greater than daily variation.

Analyses were repeated with the total average output of renewable generators increased to 1.25 × average

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[1] A *spline* is a curve consisting of segments. Cubic splines are composed of cubic polynomials. Second-order continuity means "continuous through the second derivative," so cubic splines have continuous values, continuous slopes, and continuous curvatures.

TABLE I
STORAGE REQUIREMENTS FOR FIRM POWER

Region	Deepest Deepest	Largest Surplus	Storage Requirement
California	-496 Wh/W	688 Wh/W	1,184 Wh/W
New York	-455 Wh/W	459 Wh/W	914 Wh/W
Texas	-483 Wh/W	1,004 Wh/W	1,488 Wh/W
USA	-1,784 Wh/W	395 Wh/W	2,179 Wh/W
EU	-598 Wh/W	355 Wh/W	953 Wh/W

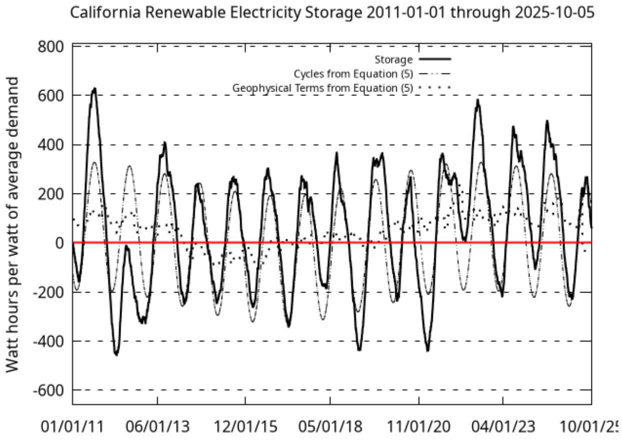

Fig. 1. Renewable Energy in Storage

demand (i.e., $G = 1.25$) , and storage limited to 100 watt hours per watt of average demand. In California, there would have been outages 19% of the time, and 44% of total ~~generated~~ consumed output would have been dumped.

Analyses were repeated with the total average output of renewable generators increased to three × average demand, and storage limited to twelve watt hours per watt of average demand, as many advocates for renewable energy sources, such as Jacobson, advocate. In California, there would have been outages 3.4% of the time, and 355% of total ~~generated~~ consumed output would have been dumped.

IV. WHAT CAUSES THE VARIABILITY

The variability of California storage requirements was analyzed by least-squares [7] fitting to

$$S(t) \simeq \sum_{i=1}^{3} r_i \sin(\omega_i\, t + \phi_i) + \sum_{j=1}^{n} g_j\, x_j(t)\,, \qquad (5)$$

where t is in hours, $\omega_1 = \frac{2\pi}{24}$ (daily variation), $\omega_2 = \frac{2\pi}{24\times 365.2422}$ (yearly variation), $\omega_3 = \frac{2\pi}{24\times 365.2422\times 11}$ (variation according to the Sun's eleven-year cycle), and x_j are indices of geophysical phenomena, most having monthly resolution. The solutions for the phases with respect to the beginning of the analysis at midnight on 1 January 2011 are ϕ_1 = 15.4 hours, ϕ_2 = 234 days, and ϕ_3 = 2.85 years. Fitting only to the cycles (i.e., $n = 0$) accounted for 52.9% of the variation. Including the Pacific Decadal Oscillation index, the Tropical North Atlantic Oscillation index, California Air Resources Board estimates of 2.5μm particles and aerosols, and the volcanic explosivity index, accounted for 58.3% of the variation. Including estimates of 10μm particles had essentially no effect. Although including sulfur dioxide data from the California Air Resources Board reduced the overall variation of the residual, the data have several enormous outliers that confound the analysis. Significant unexplained deviations from the fitted result in 2012 and 2022 account for most of the remaining variation. The cyclic and geophysical terms from Equation (5) are shown in Figure 1.

V. STORAGE METHODS AND COSTS

Estimates of average electric power required for an all-electric USA vary. In 2015, Jacobson et al estimated 1,593 GWe [9]. We use 1,700 GWe here, but in light of projections of increased requirements for data centers, this is probably an under-estimate. In detail, the analysis for USA as a whole did not appear to be reasonable. There was an enormous unexplained deficit during the 2024-2025 winter, so the smaller value of 1,250 Wh/W, about 52 days' storage, is used here. The storage requirement for USA would be 1,700 GWe × 1,250 Wh/W = 2,125,000 GWh.

A. Batteries

The May 2023 overnight capital cost for utility-scale batteries batteries was \$500/kWh [10, p. 19]. The purchase cost for batteries for USA would be \$1.06 quadrillion, or about 35 times total USA 2024 GDP of \$30 trillion. Batteries last about ten years, so the annual cost would be only about 3.5 times total USA GDP. Retaining them in service for longer durations reduces their capacity, resulting in blackouts and dumping, or increased label capacity requirements. This cost estimate does not include capital amortization, transportation, installation, operation, maintenance, safety, decommissioning, destruction, recycling, transportation again, and landfilling. If 85% charge-discharge efficiency and 5-7% transmission losses are included, the storage requirement is increased. The total cost would be substantially more than three times total USA GDP — every year — forever. Battery prices fluctuate somewhat but there never was, and never will be, an exponential "Moore's Law" decrease in battery prices.

In *The Mining of Minerals and the Limits to Growth* [11], Professor Simon Michaux (Adelaide and Geologian Tutkimuskeskus) tabulated the amounts of metals needed for lithium ion batteries. Their density is about 230 watt hours per kilogram. Batteries for grid storage alone for USA alone (not counting electric vehicles) would weigh about 9.24 billion tonnes, about 3.3 times more than Professor Michaux's estimate of 2.779 billion tonnes for the total amount of storage needed worldwide. Being a mining engineer, he also tabulated known reserves of the relevant materials. His analyses are summarized in Table II.

TABLE II
MATERIALS NEEDED FOR LITHIUM ION BATTERIES

Material	Proportion in batteries (%)	Mass in 2.779 billion tonnes of batteries
Copper	17.0%	498
Aluminum	8.5%	236
Nickel	15.19%	422
Cobalt	2.79%	67.5
Lithium	2.17%	60.3
Graphite	22.0%	611

Material	Global Reserves (2018)	Required ÷ Reserves
Copper	880.0	1.69
Aluminum	32,000	0.022
Nickel	95.0	14.1
Cobalt	6.9	33.5
Lithium	22	13.0
Graphite	320.0	5.51

Other than aluminum, the Earth does not contain enough metals to make the first generation of necessary batteries for the United States alone! Batteries are not completely recyclable. Even if the first generation could be built, where would the second generation come from?

A common objection to this analysis is that the requirement for storage is reduced by increasing generation capacity, but this simply moves the materials requirements from batteries to generators and transmission systems, while increasing land use and environmental degradation.

Presented with these quantities, activists propose other storage methods.

B. Pumped storage

The potential energy, in joules (watt-seconds), of a mass m (kilograms) lifted to a height h (meters) in a gravitational field with acceleration g (9.8 meters per second squared at the surface of the Earth) is mgh.

The *Snowy 2* project in Australia is planned to connect two reservoirs with capacity of 254,099 million liters = 254,099 million kilograms, separated by an elevation of 680 meters. Water is to be pumped between the reservoirs in 27 kilometers of tunnels. One of the three tunnel boring machines, called "Florence," was stopped by a cave-in less than a kilometer from the start, and has not been recovered or restarted (geologists warned of this before the project was started). If the energy storage capacity of Snowy 2 were calculated as above, the result would be 470 GWe-hours. The advertised efficiencies are 67-76% depending on output of 1,000–2,000 MWe, or 315–357 GWe-hours [12].

The current budget for Snowy 2 is \$AU 4.8 billion = \$US 3.26 billion, but many expect the project's cost to exceed \$AU 20 billion = \$US 13.6 billion. The project is scheduled to be completed in 2029, but many believe it will not be completed. The United States would need almost 6,000 such systems. There are currently 1,450 conventional hydroelectric power plants, and 40 pumped storage plants, in the United States. Using Australia's optimistic official estimates, the total cost for 6,000 such projects in the United States would be \$81 trillion – almost three times USA 2024 GDP —if we could find places for them and water to use them.

California consumes about 7.3% of total USA primary energy. Using that ratio, an all-electric California energy economy would have appetite for about about 123.6 GWe, and a storage requirement of about 123.6 GWe$\times$1250 Wh/W = 154.6 trillion watt hours.

California's Oroville Dam at 771 feet or 235 meters is the highest dam in the country. The area of Yosemite Valley is 6 square miles, or about 15 square kilometers. Assuming it's flat (which it isn't), building a 235 meter dam across the entrance could impound 3.535 trillion liters = 3.535 trillion kilograms of water. The mouth of the valley is 1,200 meters above sea level, so the top of the full reservoir would be 1,435 meters above sea level. Assuming a power plant at sea level, not at the base of the dam, the water in such a reservoir would have potential energy of about $3.535 \times 10^{12} \times 1,435 \times 9.8/3,600 = 13.8$ trillion watt hours. Although the Betz limit for the efficiency of an open turbine is 59.3% [13], it does not apply to ducted turbines, which can achieve efficiencies approaching 90% — but the maximum efficiency expected for Snowy 2 is 76%. Using that value, California would need at least 154.6 trillion / (0.76×13.8 trillion) = 15 of these reservoirs. If the power plant were at the mouth of the valley instead of at sea level, about 90 would be required. The nation as a whole would need almost 950 pumped-storage systems, each with 235 meter head and two reservoirs the size of Yosemite valley. All of this assumes optimal conditions and unrealistically large efficiency, in particular, no loss to friction or turbulence in the tunnels, so in reality much more would be required.

Opportunities for reservoirs the size of Yosemite Valley, especially pairs of adhacent ones, are limited.

Total rainfall in a particular river's watershed is cyclical. Although Lake Mead (impounded by the 221 meter Hoover Dam) has a capacity of about 36 trillion liters, it was almost empty in 2022. Texas has a more difficult problem than California, with water in the East but no mountains, and mountains 1,000 miles to the West but no water. A statistical analysis of data from the Shuttle Radar Topography Mission showed that Kansas is indeed as flat as a pancake.

C. *Towing weights*

The next proposal is towing weights up mountains or old mine shafts. How many are required? The storage requirement is 2,125,000 GWe-hours × 3600 seconds/hour = 7.65 quintillion watt seconds, or joules. Assuming 100% efficiency, a ten tonne weight, and a one kilometer lift, the result is "only" 74 million such devices. Where would these be put? How much would they cost, per year and per kWh, taking into account capital, amortization, transportation, operations, safety, maintenance, replacement, decommissioning, environmental effects, and disposal or recycling?

Other schemes such as flywheels and ultracapacitors are equally unworkable.

VI. CONCLUSIONS

It is not possible to construct a reliable energy supply for the Unites States using renewable sources alone plus storage. Data from Europe indicate the same difficulty. The problem is almost certainly a worldwide problem. There are more details in my book [14], and on my web page about this topic [15].

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