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From Fossil to Renewable: Calculating the Path to a Wind, Water, and Solar-Powered United States

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Abstract. As global development increases energy consumption and pollution, transitioning to a more sustainable, healthier, and more secure energy future through renewable sources like wind, water, and solar (WWS) becomes increasingly crucial. This shift towards renewable energy reduces environmental harm and ensures long-term energy stability. Countries such as the United States, can transition to a 100% clean energy system powered by WWS technologies. This research identifies the resources and infrastructure needed in the US to make this shift. By calculation, it is estimated a total U.S. final energy demand of 7,970.9 TWh/yr for a WWS system, excluding non-energy uses. To meet this demand, the transition necessitates approximately 3.04 billion solar photovoltaic (PV) panels, 1,421 concentrated solar power (CSP) plants, 400,000–500,000 wind turbines, 20 GW of hydropower, and 26 GW of geothermal capacity. Land use requirements include 3.5 million acres for ground-mounted PV, 2.0 million acres for CSP, and 404,000 km² of spacing for wind farms, with a minimal permanent footprint of 3,500 km². Geothermal energy requires less than 500 km². By leveraging scalable solar and wind resources, strategic siting, and multi-use land practices, this analysis demonstrates that the U.S. has sufficient land and rooftop space to support a 100% WWS energy system.

Keywords: Sustainability, Clean Energy, Renewable Energy

1. Introduction

The transition of the United States to 100% clean energy is both a necessity and an opportunity. Climate change and air pollution cost trillions of dollars in damages annually, along with leading to hundreds of thousands of premature deaths. The urgency of decarbonizing the U.S. energy system has led to detailed studies, most prominently by Mark Z. Jacobson and collaborators, showing that a shift to wind, water, and solar (WWS) power is technically feasible [1-3].

Several assessments provide the basis for estimating renewable energy deployment. NREL's Annual Technology Baseline provides representative performance values (capacity factors) for solar photovoltaics and concentrating solar power (CSP), while its Rooftop Solar Photovoltaic Technical Potential study quantifies the maximum generation possible from U.S. rooftops [4]. Lawrence Berkeley National Laboratory (LBNL) updated the empirical Land Requirements for Utility-Scale PV, while NREL's Land-Use Requirements for Solar and Land-Use Requirements of Modern Wind Plants describe energy-per-acre values for CSP and wind respectively [5,6]. The USDA Economic

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Research Service reports that most wind development in the U.S. occurs on cropland and pasture, demonstrating the land-use compatibility of wind [7]. Finally, the U.S. Energy Information Administration (EIA) provides authoritative explanations of geothermal use and limitations [8].

This research focuses on the physical requirements of such a transition for the United States. Specifically, it calculates how much energy needs to be produced, how many solar panels and wind turbines that are required, how much land area is needed for PV and CSP solar, wind, and geothermal, and whether the land and rooftop space available in the U.S. is sufficient.

2. Research methods

To assess the transition of the U.S. energy system to a WWS framework, this study quantifies the total energy demand, determines the optimal energy mix, calculates required generation capacities, estimates device counts, and evaluates land use requirements. The methodology integrates data from authoritative sources such as the National Renewable Energy Laboratory (NREL), the International Energy Agency (IEA), and the U.S. Energy Information Administration (EIA). Energy demand was first established, followed by the allocation of energy sources based on technical potential and resource availability. Capacity calculations utilized technology-specific capacity factors, while device counts, and land use estimates were derived using standardized metrics for each technology. Key assumptions, such as prioritizing rooftop solar and siting constraints for certain technologies, were incorporated to ensure realistic deployment scenarios.

2.1. Energy use baseline

The total U.S. final energy demand for a WWS system was estimated at 7,970.9 TWh/yr, excluding non-energy uses. The energy mix comprises 47% solar, 45% wind, 5% hydropower, and 3% geothermal, determined based on U.S. technical potential and key assumptions. Solar and wind were prioritized due to their scalability, widespread resource availability, and complementary diurnal and seasonal patterns. Hydropower expansion was constrained by environmental considerations, while geothermal was limited to a 3% share due to its geographic restriction to western states.

2.2. Conversion to capacity

Generation capacities were calculated using the formula:

$$C(GW) = E(TWh/yr) \div (CF \times 8.76) \tag{1}$$

where C represents the required capacity in gigawatts, E is the annual energy demand in terawatt-hours, and CF is the technology-specific capacity factor. Capacity factors were sourced from NREL's Annual Technology Baseline (ATB) 2024: 0.25 for photovoltaic (PV), 0.59 for concentrating solar power (CSP), 0.35 for wind, 0.45 for hydropower, and 0.90 for geothermal.

2.3. Device counts

To estimate the device counts required for a U.S. transition to a wind, water, and solar (WWS) energy system, this study employed specific methodologies for photovoltaic (PV) panels, concentrating solar power (CSP) plants, and wind turbines.

For PV panels, calculations were based on 450 W modules, as specified by IEA PVPS (2024), with the number of panels determined using the formula:

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$$N(panels) = C(GW) \div (Ppanel(W) \div 1,000,000,000) \tag{2}$$

where C represents the required capacity in gigawatts and Ppanel is the panel wattage.

For CSP plants, the analysis used the NREL ATB's 102 MW net reference power tower with 10 hours of storage, calculating the number of plants with the formula:

$$N(plants) = (C(GW) \times 1,000) \div PlantSize(MW) \tag{3}$$

where PlantSize is the capacity of a single plant in megawatts.

For wind turbines, modern 2–3 MW turbines were assumed, and the number of turbines was derived using the formula:

$$N(turbines) = C(MW) \div Prated(MW/turbine) \tag{4}$$

where Prated is the rated power of a single turbine in megawatts.

2.4. Land requirements

To assess the land requirements for a U.S. transition to a WWS energy system, this study calculated the land needed for ground-mounted photovoltaic (PV) systems, concentrating solar power (CSP) plants, wind turbines, and geothermal facilities.

For PV systems, land use was estimated using the Lawrence Berkeley National Laboratory's (LBNL) median value of 447 MWh/acre-yr, with the formula:

$$AcresPV = E(GWh/yr) \div 0.447(GWh/acre - yr) \tag{5}$$

where E is the annual energy output in gigawatt-hours.

For CSP plants, land requirements were based on NREL's (2013) average of 2.7 acres/GWh-yr, calculated as using the formula:

$$AcresCSP = E(GWh/yr) \times 2.7(acres/GWh - yr) \tag{6}$$

For wind turbines, land use was determined using NREL's (2009) estimates, with a direct footprint of 0.3 ha/MW (0.74 acres/MW) and spacing requirements of 34.5 ha/MW (85 acres/MW), using the formulas:

$$AcresDirect = C(MW) \times 0.74(acres/MW) \tag{7}$$

and

$$AcresSpacing = C(MW) \times 85(acres/MW) \tag{8}$$

where C is the capacity in megawatts.

Geothermal facilities were assumed to have negligible additional land use beyond plant footprints, with siting limited to western states as per EIA (2024) data.

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2.5. Research hypothesis

This study assumes that rooftop photovoltaic (PV) systems, with an estimated potential of 1,432 TWh/yr, are prioritized to reduce the land requirements for ground-mounted PV installations. Wind farms are primarily located on cropland or pasture, consistent with data from USDA ERS (2024). Concentrating solar power (CSP) deployment is confined to desert states with high direct normal irradiance (DNI), specifically California, Arizona, Nevada, New Mexico, and Utah. Geothermal development is restricted to resource-rich western states.

3. Results

3.1. Device counts

The analysis quantifies the equipment needed for a U.S. transition to a WWS energy system. For solar photovoltaic (PV), approximately 3.04 billion 450 W panels are required to meet the necessary capacity. Concentrating solar power (CSP) demands about 1,421 plants, each with a 102 MW net capacity and 10 hours of storage, based on the NREL Annual Technology Baseline (ATB) 2024 reference design. Wind power, requiring a total capacity of roughly 1,170 GW, necessitates approximately 400,000 to 500,000 modern wind turbines, each rated at 2–3 MW. Hydropower needs an additional 20 GW of capacity, achieved primarily through upgrades at non-powered dams and efficiency improvements at existing facilities. Geothermal energy requires an additional 26 GW, mainly through the development of Enhanced Geothermal Systems (EGS).

3.2. Land area requirements

The land requirements for a U.S. wind, water, and solar (WWS) energy system are estimated as follows. Ground-mounted solar photovoltaic (PV) systems require approximately 3.5 million acres, after accounting for contributions from rooftop PV. Concentrating solar power (CSP) installations need about 2.0 million acres. Wind farms necessitate a total spacing area of roughly 404,000 km^2 (40.4 million hectares), though over 95% of this land remains available for agriculture or grazing, with a permanent footprint of approximately 3,500 km^2. Geothermal facilities require less than 500 km^2, limited by plant footprints and resource availability in western states.

Table 1 below summarizes the number of devices needed and the land area required.

Table 1. Device counts and land area requirement

Category	Device Count	Land Area Requirement
Solar Photovoltaic (PV)	~3.04 billion 450 W panels	~3.5 million acres (ground-mounted, after accounting for rooftop PV contributions)
Concentrating Solar Power (CSP)	~1,421 plants (102 MW net capacity each, with 10 hours of storage)	~2.0 million acres
Wind	~400,000–500,000 turbines (2–3 MW each, for 1,170 GW total capacity)	~404,000 km^2 (40.4 million ha) total spacing, with ~3,500 km^2 permanent footprint
Hydropower	Additional 20 GW via upgrades at non-powered dams and efficiency improvements	minimal additional land use
Geothermal	Additional 26 GW via Enhanced Geothermal Systems (EGS)	<500 km^2, limited by plant footprints and resource availability in western states

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These results demonstrate the feasibility of meeting U.S. energy demand with WWS technologies, leveraging scalable solar and wind resources while minimizing land use impacts through strategic siting and multi-use land practices [9].

4. Conclusion

The transition of the U.S. energy system to a WWS framework is both technically feasible and strategically viable. This is also demonstrated by this analysis of energy demand, generation capacity, device counts, and land requirements.

Meeting the estimated annual energy demand of 7,970.9 TWh/yr requires a balanced mix of 47% solar, 45% wind, 5% hydropower, and 3% geothermal, leveraging the scalability and complementary patterns of solar and wind resources. The infrastructure demands are significant, including approximately 3.04 billion solar PV panels, 1,421 CSP plants, 400,000–500,000 wind turbines, 20 GW of additional hydropower, and 26 GW of geothermal capacity. Land use, while substantial at 3.5 million acres for ground-mounted PV, 2.0 million acres for CSP, and 404,000 km² for wind farm spacing, is mitigated by prioritizing rooftop PV, utilizing multi-use land for wind farms (with a permanent footprint of only 3,500 km²), and limiting geothermal development to less than 500 km² in resource-rich western states. Strategic siting, such as placing CSP in high-DNI desert regions and wind farms on cropland or pasture, further optimizes land use.

These findings underscore the potential for a WWS-based energy system to meet U.S. energy needs sustainably, provided that deployment is supported by robust policy, technological innovation, and careful land management to minimize environmental impacts while maximizing resource efficiency.

There are a few limitations for this study. This study relies on current technological efficiencies and cost estimates, which may not account for future advancements or unforeseen challenges in scaling WWS technologies. The analysis assumes stable energy demand and does not fully address variability in weather patterns, grid integration challenges, or the economic and social costs of transitioning, such as workforce retraining or supply chain constraints for critical materials like rare earth metals. Additionally, land use estimates may oversimplify ecological and community impacts, particularly for large-scale wind and solar projects, and the feasibility of widespread rooftop PV adoption may be limited by urban infrastructure or economic barriers.

Further studies should explore dynamic energy demand scenarios, incorporating potential changes in consumption patterns due to electrification or population growth. Research into advanced grid storage solutions, such as next-generation batteries or hydrogen systems, is needed to address intermittency issues in solar and wind generation. Additionally, investigations into the socio-economic impacts of the transition, including job creation, community displacement, and material supply chains, would provide a more holistic view. Finally, detailed environmental impact assessments for large-scale WWS deployments and innovations in low-impact technologies, such as floating wind turbines or agrivoltaics, could enhance the sustainability of the transition.

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