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Geophysical constraints on the reliability of solar and wind power in the United States†

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We analyze 36 years of global, hourly weather data (1980–2015) to quantify the covariability of solar and wind resources as a function of time and location, over multi-decadal time scales and up to continental length scales. Assuming minimal excess generation, lossless transmission, and no other generation sources, the analysis indicates that wind-heavy or solar-heavy U.S.-scale power generation portfolios could in principle provide ~80% of recent total annual U.S. electricity demand. However, to reliably meet 100% of total annual electricity demand, seasonal cycles and unpredictable weather events require several weeks' worth of energy storage and/or the installation of much more capacity of solar and wind power than is routinely necessary to meet peak demand. To obtain ~80% reliability, solar-heavy wind/solar generation mixes require sufficient energy storage to overcome the daily solar cycle, whereas wind-heavy wind/solar generation mixes require continental-scale transmission to exploit the geographic diversity of wind. Policy and planning aimed at providing a reliable electricity supply must therefore rigorously consider constraints associated with the geophysical variability of the solar and wind resource—even over continental scales.

Broader context

Many plans to decarbonize the electricity sector call for >80% of future electricity to be supplied by solar and wind power. However, the extent to which solar and wind can contribute to the generation mix will be constrained by the temporal and spatial variability of solar and wind resources, along with the timing and location of electricity demand and other features of the electricity system (*e.g.*, transmission grid, energy storage, demand management, dispatchable power, reliability requirements, *etc.*). Here, we analyze 36 years of global, hourly weather data to assess the geophysical resource characteristics of solar and wind power over the United States. We find that achieving ~80% of demand met by solar and wind requires a US-wide transmission grid or 12 hours worth of energy storage (~5.4 TW h). Beyond 80%, the required amount of energy storage or excess solar/wind generating capacity needed to overcome seasonal and weather-driven variabilities increases rapidly. Today this would be very costly. The availability of relatively low cost, dispatchable, low-CO_2 emission power would obviate the need for this extra solar and wind or energy storage capacity while meeting reliability requirements over a multi-decadal timescale.

Many proposed low-carbon electricity systems assume primarily wind and solar energy to generate electricity,[1–14] but the variable and uncertain nature of these resources raise concerns about system reliability. The current North American Electricity Reliability Corporation (NERC) reliability standard specifies a loss of load expectation of 0.1 days per year (99.97% reliability).[15] Hence, for energy systems that extensively use wind and solar generation, a statistically robust evaluation of long-term reliability, especially given the 40–50 year useful life of deployed energy infrastructure, requires evaluation of the co-variability of the solar and wind resource over a multi-decadal time scale.

Studies of wind energy for 1 year for 60 European stations;[16] 1 year for 17 wind farms in Denmark;[17] 5 years for 11 stations on the U.S. East Coast;[18] or 45 years for 117 stations across Canada,[13] have shown that after removal of diurnal cycles and seasonal trends, the variability of wind energy on hourly time scales decreases exponentially with distance, with a characteristic correlation length of 200–500 km. Analysis of 44 years of 6 hour-averaged wind energy data derived from a weather model yielded a correlation length of 400–600 km over Europe.[19] Anemometer data from nine tall-tower sites spanning the contiguous U.S. have been used to estimate the occurrence of low-wind-power events over large areas.[20]

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Solar and wind co-variability studies of relatively small geographic regions (*e.g.*, the United Kingdom, California, the Iberian Peninsula) over timescales of months to a few years have indicated that the combination of solar and wind resources can decrease the variability intrinsic to either resource alone.[2,12,21] Energy system models that include a range of generation sources and embedded assumptions about the relative costs of different generation technologies as well as transmission and storage have been constructed to obtain cost-optimized solutions for specific deployment scenarios that include various penetrations of carbon-free generation in the electricity mix.[1,5,8,9,22,23] Examples include an economic optimization of solar, wind and natural gas generator deployment along with grid construction using 3 years of solar and wind over the contiguous US,[22] an assessment of US and global wind power availability using 5 years of reanalysis data[24] and computationally expensive capacity planning and dispatch algorithms that restrict analysis to representative hours, days and weeks for the US[8,14,23] or Europe.[25] Electricity decarbonization scenarios, primarily consisting of solar and wind, have been presented over a range of areas spanning individual US states to whole continents.[3,4,10,11,13,26–30]

We use herein a simple, transparent model, that is independent of detailed economic or technological assumptions, to assess the geophysical constraints imposed by wind and solar resources over the continental U.S. "reanalysis" products, which assimilate a wide array of observational data to deliver an internally consistent historical representation of weather, facilitate assessment of multi-decadal solar and wind resource (co)-variability.[26] Accordingly, we have used a reanalysis data set[31] covering 1980 to 2015 with hourly solar and wind resource data to evaluate the spatiotemporal variability of the solar and wind resources over the continental U.S. and the ability of these resources to satisfy U.S. electricity demand, instantaneously and in aggregate, as a function of (1) the amount and spatial extent of installed solar and wind capacity, and (2) various amounts and temporal qualities of energy storage—but with no other generation sources utilized. Our results thus describe the geophysically based variability of energy production from solar and wind resources and identify the constraints that this variability places on reliably meeting U.S. electricity demand in this limiting case. Further, we quantify the duration and magnitude of residual "gaps" when electricity generation fails to meet demand that are a consequence of the geophysical variability of these resources even over continental scale.

The details of our analytic approach, and the sources of data, are described in the Methods section. First, global, hourly surface solar fluxes and wind speeds (50 m height) from a long-term (36 year) reanalysis data set (MERRA-2) were used to estimate the resources available each hour at a spatial resolution of $0.5^\circ \times 0.625^\circ$. Higher temporally and spatially resolved wind resource data do not span as long a time series and/or encompass comparably large geographic areas.[1,8,22,23,29,30] The MERRA-2 data set is therefore well-suited to investigate correlations of the wind resource and co-variability with the solar resource over long length and time scales, without emphasis on rapid variability on sub-hourly timescales. Second, hourly solar and wind power production profiles over areas of interest were calculated simply using an area-weighted average of each resource, as opposed to assuming specific cost-optimized locations or regions for either solar or wind energy production.[8,22,32] The installed local nameplate generation capacity was estimated using representative real-world capacity factors. These separate power production profiles were then combined considering various mixes and amounts of solar and wind generation. Finally, to assess the resulting energy system reliability over the time period of interest, the energy produced was compared to the energy demanded in each hour, as a function of the assumed energy storage capacity. One year of actual U.S. electricity demand, from July 2015–July 2016, was compared to all 36 years of resource data (see SOM for complete details).

Perfect transmission and energy storage, with no losses or constraints, was assumed, yielding a best-case scenario for realizing the benefits of geographic anti-correlation of the resources and to allow isolation of the limitations associated purely with geophysical characteristics of wind and solar energy resources. Specific transmission constraints,[8,32] higher-resolution resource data,[22] energy storage inefficiencies,[7] optimization of the choice of generation locations to minimize their mutual correlation as opposed to maximization of local energy production, and operational limits and market dynamics, among other practical considerations, will play important roles in determining the details of system- and site-specific design and operation of an actual electricity system of this magnitude.

Resource and demand variability

Fig. 1a shows the seasonal variability of the solar and wind resources when aggregated over the contiguous U.S. (referred to as CONUS) normalized by the 36 year mean. For each day, the median and range across the 36 years is shown. The solar resource reaches a maximum during summer (June–July) that is 3.7 times the winter minimum (December–January; yellow curve in Fig. 1a). In contrast, the wind resource peaks in spring (Mar–Apr) and decreases to by up to a factor of 3.5 during the summer months (July–August; purple curve in Fig. 1a). For comparison, recent electricity demand (July 2015–July 2016) is greatest during the summer (July–August) and decreases by a factor of 1.8 to its minimum in spring (March–early May; orange curve in Fig. 1a). As can be seen by the shading in Fig. 1a, the wind resource has much greater daily variability about its median than the solar resource, particularly in the winter and spring when the median daily wind resources are largest. The wind resource also exhibits greater variability than the solar resource on the time scale of days to weeks.

The seasonal variability depicted in Fig. 1a indicates some fundamental trade-offs when electricity demand is to be met with large quantities of solar and wind generation aggregated over the CONUS. Combining solar and wind generation can alleviate some of the seasonal deficiencies of each, but the generation complementarity is limited by the large variability in the wind resource on a wide range of time scales, as well as by

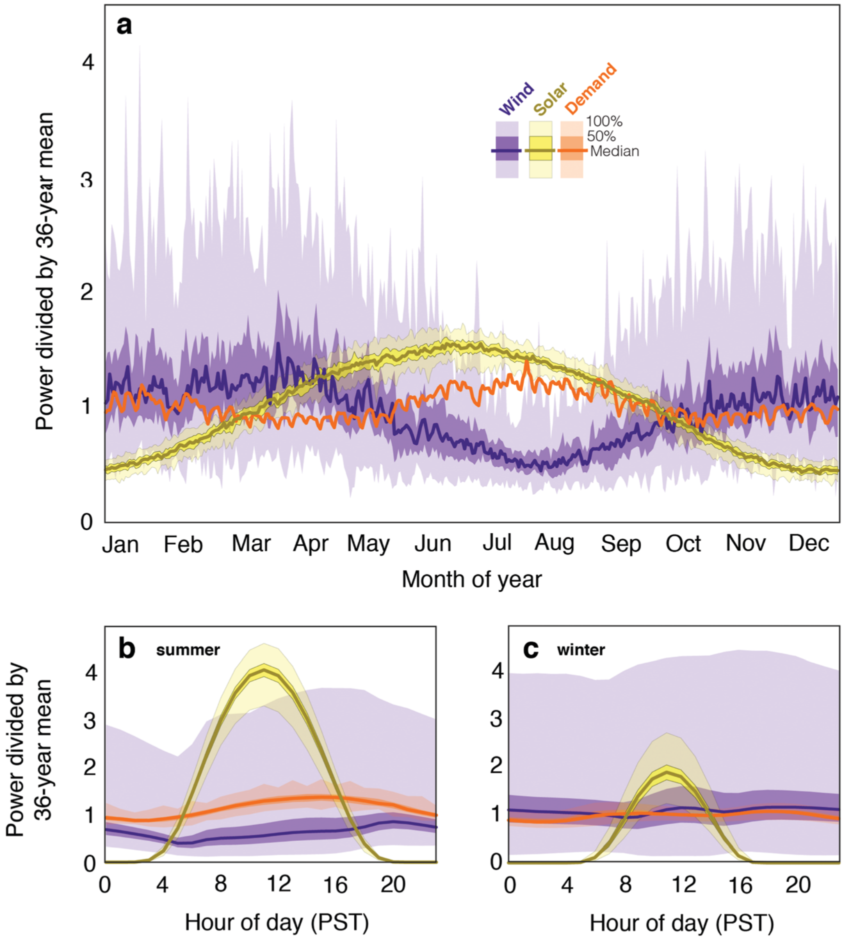

Fig. 1 Temporal variability of solar and wind resources and electricity demand. Climatological variability of the area-weighted median power from wind (purple) and sun (yellow) resources over the contiguous U.S. during the 36 year period 1980–2015: (a) Daily and seasonal; (b) hourly summer for June, July, August; (c) hourly winter for December, January, and February. The lines represent the median, the dark shading represents the inner 50% of observations (25th to 75th percentile) and the light shading represents the outer 50% of observations (0th to 100th percentile). Orange curves in each panel represent U.S. electricity demand for a single year from July 2015–July 2016. Because the time of day shown is Pacific Standard Time (PST), the solar maximum is prior to noon. The solar, wind, and demand data are each normalized by their respective 36 year mean value. The daily average variability is shown to indicate the seasonal variability, the amplitude of the daily variability, and to guide the eye through the hourly data over the course of a year.

the substantial difference in the amplitude and seasonal cycles of the solar resource relative to either wind or electricity demand.

Fig. 1b and c show the daily variability of the solar and wind resource and electricity demand during the summer (June, July, August) and winter (December, January, February), respectively. Unlike the solar resource, in aggregate, the wind resource and electricity demand have relatively small daily cycles and never reach zero (Fig. 1b and c). However, at hourly time scales the wind resource is much more variable than either the solar resource or demand (Fig. 1b and c). Without energy storage, the extreme daily cycle of the solar resource also places a substantial constraint on reliability, requiring high ramp rates of additional generation in the morning and evening hours.

Area-dependence and resource mix

Throughout, we evaluate two levels of installed combined solar and wind capacity: installations sufficient to generate the total integrated electricity demanded in the U.S. July 2015–July 2016 according to mean annual resources over our 36 year record, and installations sufficient to generate 150% of total U.S. electricity over that period. We refer to these as 1× and 1.5× (read "1.5 times") generation, and use them to gauge the reliability benefits of deploying excess generation capacity. Similarly, we discuss energy storage in units of time of mean demand. For example, in the U.S., total mean power demand is 450 GW, so 12 h of storage equals 5.4 TW h of energy capacity.

The temporal correlation of the wind resource decreases as a function of distance and declines more rapidly in the east–west (longitudinal) direction than in the north–south (meridional) direction.[22] Generating wind energy over larger "aggregation areas" is most effective at reducing the hourly and daily energy production variability. Long distance, high-voltage transmission is a proposed technical approach to aggregate these temporally de-correlated resources.[14,22]

The temporal correlation of the solar resource for the contiguous U.S. decreases relatively weakly with distance (There are only four hourly time zones in the CONUS). Energy storage, demand management, and/or separate carbon-neutral, flexible generators are necessary to overcome the daily solar cycle (generation values >100% of peak capacity do not help when production is zero (dark hours)), while energy storage, demand management, separate carbon-neutral, flexible generators and/or installation of excess name-plate solar and wind capacity (generation of >1×) are needed to overcome the seasonal resource cycles.

Fig. 2 shows the total annual electricity demand that can be met (*i.e.*, reliability) by using solely solar and wind resources, as a function of the mix of solar and wind energy generation contribution (vertical axes in each panel) as well as the area over which the resources are aggregated (horizontal axes in each panel). Without storage and with 1× generation, the highest reliability is obtained from wind-heavy generation mixes (*e.g.*, 60–75% wind), with an increase from <60% reliability when the resources are aggregated over city-sized areas (10^3–10^4 km^2) up to >75% reliability when the resources are aggregated at CONUS scale (10^7 km^2; Fig. 2a). The overall patterns are similar with 1.5× generation and no storage, but reliability increases by 10–12%; the effect on reliability is larger when the resource is aggregated over larger areas (Fig. 2c).

Wind and solar resources could in principle provide an arbitrarily high percentage of electricity generation with high reliability (at some cost penalty) if the resulting intermittency were fully compensated by dispatchable power such as natural gas plants, pumped hydroelectricity, demand management, and/or for example rampable nuclear power. To focus on the reliability gaps associated with utilization solely of wind and solar resources, we consider herein systems that fill the resulting unmet demand solely with energy storage. Fig. 2b and d display the effects of energy storage equal to 12 hours of mean demand (*e.g.*, batteries, pumped hydroelectric reservoirs, power-to-gas-to-power, compressed-air energy storage, thermal storage, *etc.*) on system reliability for various mixes of wind and solar generation. The availability of 12 hours of energy storage shifts the optimal generation mix towards a solar-heavy system; in this scenario mixes comprising energy generation contributions of 70–75% from solar, with the balance from wind, produce the highest reliability (Fig. 2b and d). This change in the optimal generation mix results from storage smoothing out the daily solar cycle such that seasonality becomes the main limit on increasing reliability. In the absence of storage, no amount of solar capacity can overcome the daily cycle, hence supporting technologies are obviously needed to meet nighttime demand. The availability of storage also substantially decreases the importance of the resource aggregation area in this deployment scenario. For example, the highest reliability for solar and wind generation mixes aggregated over an area the size of New Hampshire ($\sim 2 \times 10^4$ km^2) increases from 65% to 85% with the addition of 12 h of storage (Fig. 2a and b). The presence of 1.5× generation again increases reliability by ~10%. When generation is aggregated over areas >10^6 km^2, the combination of 1.5× generation and storage allow solar and wind resources to

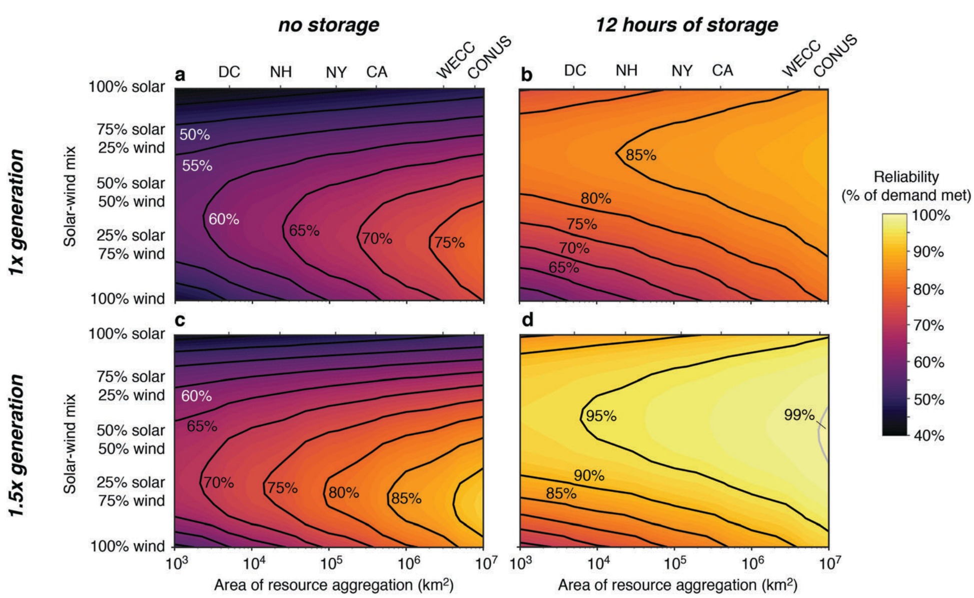

Fig. 2 Reliability of solar and wind generation as a function of area and resource mix. Contours and shading in each panel represent the average calculated reliability (% of total annual electrical demand met) by a mix of solar and wind resources ranging from 100% solar to 100% wind (*y*-axes) and aggregated over progressively larger areas of the contiguous U.S. (on *x*-axes compared to size of states (DC, NH, NY, CA) and regions (Western Electricity Coordinating Council, CONUS)). Storage and generation quantities are varied in each panel: (a) 1× generation, no storage; (b) 1× generation, 12 hours of storage; (c) 1.5× generation, no storage; (d) 1.5× generation, 12 hours of storage. These plots were generated by running each scenario for all 50 states, 8 NERC regions, and the contiguous U.S., respectively. For each resource mix simulated, the results were regressed ($y = \log(x) + b$) and plotted as the shown heat maps. Thus, the plots represent the average area-dependence and effect of resource mix on ability to meet the total annual electricity demand in the contiguous U.S.; specific regions will be more, or less, reliable.

meet >95% of total annual electricity demand with relatively little sensitivity to the resource generation mix (Fig. 2d).

Storage and generation

Storage is critical for solar-heavy wind/solar mixes to approach meeting 80% of total annual electricity demand, with a decreasing marginal return on additional storage after the daily cycle is smoothed (∼12 hours of mean demand storage capacity). In contrast, relatively small quantities (<3 hour of mean demand) of energy storage are beneficial to further decreasing the variability of geographically diverse wind resources. In both cases, meeting the last ∼20% of total annual electricity demand with only wind and solar generation requires substantial increases in the quantities of installed capacity and/or storage. The marginal return on this additional capacity is low, and the marginal benefit on reliability decreases further as the reliability increases (Fig. 3 and Fig. S7 and S8, ESI†).

Fig. 3 further illuminates the relationships among the reliability of solar and wind power generation in meeting total annual electricity demand, the availability of energy storage, and the generation quantity when the resources are aggregated across the CONUS. Fig. 3a and b focus on satisfying the first ∼80% and last ∼20% of total annual electricity demand using linear and logarithmic *x*-axes, respectively. From top to bottom in Fig. 3a and b, the generation mix shifts from solar to wind, with the lines in each plot representing scenarios having different capacities of energy storage (0 and 12 hours, and 4 and 32 days are shown). The capacities of storage are again based on the mean annual energy demand, and the generation is similarly the total energy generated divided by the total energy demanded over the 36 year period (the horizontal red line indicates a generation of 1×, *i.e.* the total energy generated equals the total energy demand).

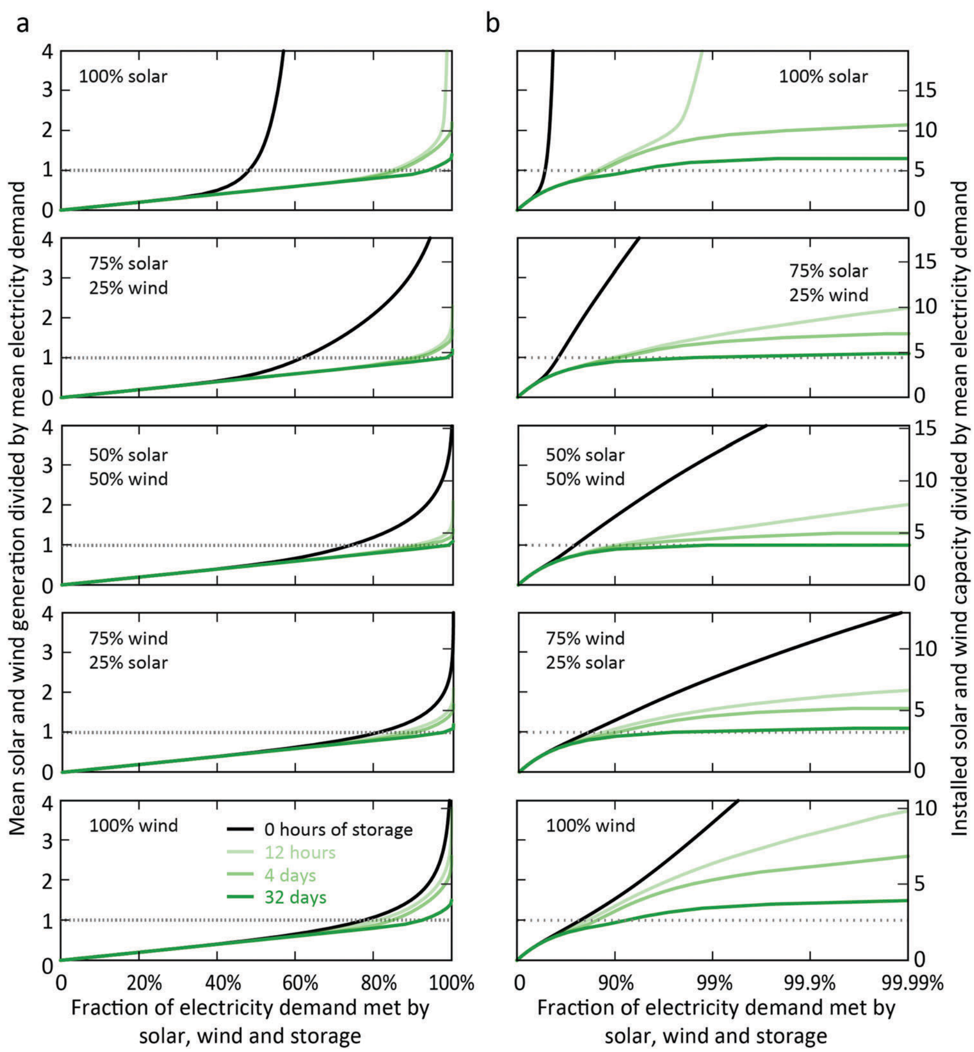

Fig. 3 Changes in reliability as a function of energy storage capacity (0–32 days) and generation. Lines in each panel show the reliability (% of demand met; *x*-axes, (a) linear scale, (b) log scale) of a mix of solar and wind resources aggregated over the contiguous U.S. and ranging from 100% solar (top panel) to 100% wind (bottom panel) as the installed generation quantity (left *y*-axis) or capacities (right *y*-axis) increase and the energy storage available increases (lines). Energy storage capacities of 0 and 12 hours, and 4 and 32 days are shown. In each case, the horizontal dashed line indicates the capacity at which total energy production and electricity demand over the 36 year period are equal (*i.e.* 1× generation).

Consistent with prior studies over smaller length and/or time scales,[22] with 1× generation and no storage, the MERRA 2 reanalysis data indicate that CONUS-scale wind power could in principle meet 78% of total annual electricity demand (*i.e.* intersection of dashed 1× generation line and 0 hours of storage scenario line, Fig. 3a). For comparison, solar power generation equal to annual mean demand could meet 48% total hourly electricity demand without any energy storage; with 12 hours of storage, this amount of solar power could meet 85% of hourly demand (Fig. 3a). Beyond this level of storage with only solar generation, the benefits on reliability diminish substantially (clustering of lines for 100% solar in Fig. 3a; flattening of yellow curves in Fig. S12 and S13, ESI†). In contrast, the addition of energy storage produces only modest increases in reliability for aggregated wind resources, with diminishing benefits beyond ∼3 hours of storage due to the relatively high variability of wind power in conjunction with the lack of a strong daily cycle in the wind resource (Fig. 3a and Fig. S9, ESI†). Several weeks' worth of energy storage or high amounts of overbuild would be needed to produce high reliability from a wind-only system, even if aggregated to >3000 km length scales (Fig. 3).

The amount of additional installed solar and wind capacity (generation >1×) needed to produce an increase in reliability is indicated by the slope of each line in Fig. 3a (see also, Fig. S7 and S8, ESI†). In under-generation cases (below the dashed line), the increase in reliability is constant as the installed capacity increases (*i.e.* slopes are constant), except for cases that include solar with <12 hours of energy storage, for which the benefits of increased reliability diminish at lower levels of storage. When generation is >1× (above the dashed line), additional installed capacity results in diminishing returns as the reliability increases (*i.e.* slopes are increasing).

Regardless of the wind/solar resource mix, meeting the final ∼20% of total annual electricity demand with only solar and wind resources—even when aggregated at continental scale—will require generation quantities ≫1× and/or substantial amounts of energy storage (Fig. 3b and Fig. S7 and S8, ESI†). Fig. 3b demonstrates the technical feasibility of meeting up to 99.99% of demand with wind, solar and storage.[15] Meeting 99.97% of total annual electricity demand with a mix of 25% solar–75% wind or 75% solar–25% wind with 12 hours of storage requires 2× or 2.2× generation, respectively. Increasing the energy storage capacity to 32 days reduces the generation need to 1.1× for these generation mixes.

Unmet demand

In the absence of ≫1× generation and/or storage, the largest and most persistent periods when daily demand cannot be met during the 36 year period analyzed herein coincide with the seasonal minima of the dominant resource used (solar or wind). Even in scenarios with high annual mean reliability, <70% of daily demand is satisfied for many days in the 36 year record, suggesting that a large backup capacity and/or large quantities of demand management would be needed; instantaneously (one-hour period) many hours occur when <40% of demand can otherwise be met. Moreover, the relatively high variability of the wind resource results in sporadic periods, at times not coincident with the seasonal minimum of wind resource, when demand cannot be met. For all mixes evaluated, the dark hours, with no consequent solar energy production, are the most difficult time to meet demand.

Fig. 4 shows the temporal characteristics and extent of satisfied daily demand in 4 different infrastructure scenarios throughout the 36 year period, again assuming that the resources are aggregated over the CONUS (the full suite of infrastructure cases are explored in Fig. S2–S11, ESI†). In a wind-heavy mix with 1× generation and no storage, 81% of total annual electricity demand over the 36 years is met. As little as 28% of daily demand is met on the day with the highest unmet demand in the 36 year period, while instantaneous (one-hour period) periods of the highest unmet demand in the 36 years satisfy as little as 12% of demand, concentrated after dark during summer months (Fig. 4a and b). Adding 0.5× generation (total of 1.5×) and 12 hours of storage to the wind-heavy mix greatly improves the overall reliability (98.3% of total annual electricity demand is met), but substantial gaps in meeting demand nevertheless occur on summer days (days occur with only 48% of demand met), when the wind resources are low and demand is high (Fig. 4c, d and 1a).

For a solar-dominated mix with 1× generation and no storage, 62% of total annual electricity demand is met. In this scenario, every month contains nighttime hours with unsatisfied demand – days occur with as little as 34% of demand met, while one-hour periods occur with as little as 4% of demand satisfied (Fig. 4e and f). The addition of 0.5× generation (total of 1.5×) and 12 hours of storage to this solar-heavy mix substantially increases the total annual electricity demand met to 98.3%. However, there are still days where only 51% of demand is met and hours when as little as 7% of demand is satisfied, typically occurring during winter periods when solar energy production is low and when wind has failed to charge storage, due to weather-driven intermittency (Fig. 4g and h). Better storage management can increase minimum fractions of instantaneous and possibly daily demand satisfied at the expense of decreasing the fraction of instantaneous and daily demand satisfied at other times; however such an approach will not impact the total annual electricity demand satisfied. With accurate forecasts of solar and wind energy and electricity demand, in conjunction with improved demand management, decision makers might be able to discharge storage more slowly to reduce the overall backup capacity that would be required to satisfy instantaneous demand.

Discussion

The amplitude and timing of the daily and seasonal cycles of the solar and wind resources and electricity demand, as well as the inherent variability of these cycles, present challenges for deep decarbonization systems that are heavily reliant on solar

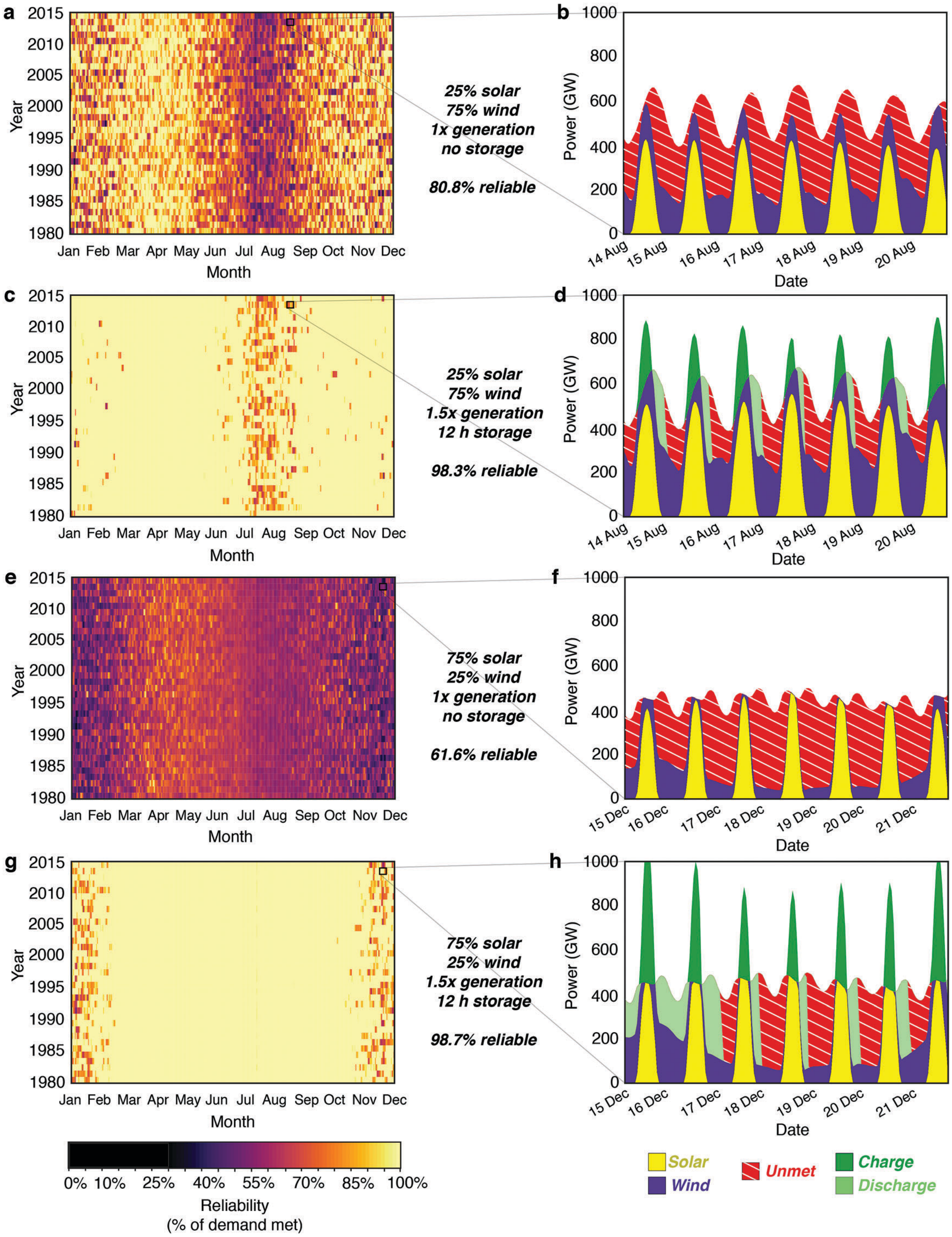

Fig. 4 Daily demand met as a function of resource mix, generation and energy storage. Temporal characterization of daily demand met by solar, wind and energy storage (if present) for every day in the simulation period and aggregated over the contiguous U.S. under four different scenarios: (a and b) 25% solar–75% wind resource mix, 1× generation and no energy storage; (c and d) 25% solar–75% wind resource mix, 1.5× generation and 12 hours of energy storage; (e and f) 75% solar–25% wind resource mix, 1× generation and no energy storage; (g and h) 75% solar–25% wind resource mix, 1.5× generation and 12 hours of energy storage. In each scenario, the left panel shows the magnitude of demand met for each day throughout the 36 year period, and the right panel details the energy profile over a weeklong period when meeting demand is particularly difficult. A more comprehensive set of these results is shown in Fig. S2–S11 in the ESI.†

and wind energy generation without any substantial source of dispatchable power. Satisfying the first ∼80% of total annual electricity demand entails overcoming the daily solar cycle and the less predictable hourly and daily wind variability ("total annual electricity" demand is distinct from "instantaneous" hourly averaged power demand, which is discussed later). Meeting the last ∼20% of total annual electricity demand requires overcoming the seasonal cycles of the solar and wind resources as well extreme weather-related events.

With an infinite amount of idealized energy storage, in principle, variable electricity demand could be met with 100% reliability using wind and solar generation with no overbuild. For modest amounts of overbuild, several weeks' worth of electricity storage would be required to produce a reliable electricity system using only these primary energy sources. However, as discussed below, current costs of storage would need to decrease by an order of magnitude or more to constitute an economically feasible solution.

The results presented in Fig. 3 have been normalized to enable scaling to scenarios with different levels of (net) demand, in the absence of changes to the spatial and/or temporal character of demand and/or solar and wind resources. For example, if the power generation mix included baseload generation, the results presented in Fig. 3 would apply only to the portion of demand being met by solar and wind (*e.g.* total demand net of baseload supply). The effect of baseload generation on reliability depends on the correlation between baseload variability and solar and wind variability. If increased levels of baseload generation capacity are available and can be cost-effectively dispatched, the total system reliability would increase, provided that the ratio of solar and wind capacity to net (total – baseload) demand met is constant in both cases.

Climate change is expected to alter the spatial and temporal distribution of solar and wind resources and to affect demand through climate's effect on human behavior. The effect of such changes on reliability depends on the correlation of the changes with existing demand and energy resources, and reliability gaps would be exacerbated by further increases in the variability of the wind resource. A quantitative assessment of the magnitude of these changes in reliability requires a detailed analysis within a specific climate and energy supply and demand scenario. Further simulations could be performed based on the model presented here to consider the influence of factors such as the availability of baseload generation, climate change, adoption of electric vehicles, demand management, *etc.*, but such analyses are beyond the scope of this study – which aims to highlight the interactions among wind, solar, natural gas, and electricity storage in the context of historical weather and demand data. Some scenarios moreover involve large-scale adoption of electric vehicles. Direct charging of battery electric vehicles could produce changes in demand profiles as well as absolute demand levels, and would thus result in different reliability depending on the strategy for implementation of the technology. However, further complexity is introduced if vehicles are also used as energy storage devices for the grid-enabling smoothing of some variability. Additional simulations of such scenarios are thus needed to quantify the impact on reliability and total and marginal costs. If large increases in battery electric vehicles affect only the magnitude of demand (no spatial or temporal change), the effect on reliability and total and marginal costs (see discussion below) would remain unchanged relative to that described herein. If large numbers of hydrogen vehicles are adopted, hydrogen could, in principle, be made through electrolysis and stored for later refueling, providing a buffer between electricity and refueling demands. Such a system could be used to increase reliability by varying the demand profile to better match that of solar and wind generation. In either case, we note that the ability of vehicle-based storage to buffer gaps between supply and demand is limited, because for example discharging 10% of the stored energy in 150 million light duty vehicles in the U.S., each with a total battery storage capacity of 100 kW h, would provide 1.5 TW h of stored energy, sufficient to provide ∼3 h of mean power demand in the U.S., and hence clearly insufficient to address the majority of the gaps between supply and demand on daily, weekly, or seasonal timescales that affect reliability as evaluated herein. Low-carbon renewables such as biogas and/or bioelectricity, as well as pumped hydroelectricity or geothermal energy could thus prove to be preferable approaches to improving reliability on these timescales relative to vehicle-based or stationary batteries.

Each of these configurations represents a distinct combination of infrastructure and future investments, and it may be unnecessary (and economically inefficient) to extensively pursue both large-scale storage and long-distance transmission. In wind-heavy energy generation scenarios, efficient long-distance transmission enables access to wind resources that are often de-correlated from each other, with east–west linkages being especially beneficial.[22] Moreover, these wind resources generally have a higher capacity factor than solar resources, resulting in a lower total installed capacity and potentially less investment, depending on the capital cost differences between solar and wind generation systems. One proposed, and modeled, U.S.-wide transmission system consists of an estimated 34 000 km (21 000 miles; 7 lengths of the US from Los Angeles, CA to Portland, Maine) of line with a capacity of up to 12 GW.[22] An installed cost of \$1 MM GW^{-1} km^{-1} implies a capital expenditure on the order of \$410 billion, as compared to >\$1 trillion that would be required to install 12 hours of storage in the US (mean demand is ∼450 GW) assuming an installed cost at present of \$200 per kW h (pumped hydro; most other systems (*e.g.* batteries, flywheels, *etc.*) have current costs in excess of \$500 per kW h).[33]

Our analysis moreover highlights the geophysically based limits on reliability, and the consequent magnitude and frequency of gaps between supply and demand that would occur if solely wind and solar generation were used in an idealized, lossless continental-scale transmission scenario. In the case of the solar-dominated system, storage would enable smoothing of the daily cycle. At present, energy-storage technologies are limited by high costs and/or a lack of geographically suitable sites (pumped hydro, compressed air).[33] As an extreme example, we consider a scenario in which only wind and solar generation is deployed and only storage is used to increase reliability. For context, storage totaling 12 hours of U.S. mean demand, 5.4 TW h of energy capacity, is ∼150 years of the annual production capacity of the Tesla Gigafactory (35 GW h) or a ~20× increase in the pumped hydro capacity of the U.S. (260 GW h, or 22 GW with ~12 hours of discharge). Cost targets for energy storage systems are ~\$100 per kW h, but current costs for systems that are not geographically constrained are ~\$500 per kW h or higher.[33,34] At \$100 per kW h and \$500 per kW h, the total capital investment would be \$540 billion and \$2.7 trillion, respectively. With a 10 year service life, one cycle per day, a linear capacity decline to 80% of rated capacity at the end of storage system life, 92% charge/discharge energy storage efficiency, a 10% discount rate, and no operating costs, a currently representative cost of \$500 kW h for a fully installed secondary Li-ion battery system yields a leveled cost of energy storage (LCES) of ~\$0.25 per kW h.[33,34] Achieving 99.97% reliability with a system consisting solely of solar and wind generation in conjunction with energy storage would require a storage capacity equivalent to several weeks of average demand (Fig. 3b), and the low capacity factor would lead to a LCES of >\$0.25 per kW h. Three weeks of storage (227 TW h) at the cost target of \$100 per kW h results in a capital expenditure of \$23 trillion and either ~6500 years of the annual Tesla Gigafactory production capacity or a ~900× increase in the pumped hydro capacity of the U.S.

A mix of 75% solar and 25% wind (by total energy generation contribution) with 3.4× generation and no storage would have approximately the same reliability (90%) as that same solar-wind mix with 1× generation and 12 hours of storage (Fig. 3). At \$1.50 per W (for both solar and wind) and capacity factors of 20% and 38% for solar and wind, respectively, the additional 2.4× generation would cost an additional ~\$7.1 trillion.[35] A 25% solar–75% wind mix with 1.2× generation and no storage would have approximately the same reliability (87%) as that same solar-wind mix that had instead 1× generation and 12 hours of storage (Fig. 3). At \$1.50 per W (for both solar and wind) and capacity factors of 20% and 38% for solar and wind, respectively, the additional 0.2× generation would cost an additional ~\$250 billion, but would require long-distance transmission. The trade-offs between generation quantities and hours of storage capacity are thus complex, being dependent on the resource mix and cost trajectories.

Approximately a capacity doubling for the 75% solar-25% wind scenario and a capacity quadrupling for the 25% solar-75% wind scenario would be required to achieve 99.97% reliability without storage. With a lifetime of >25 years at \$2 per W and a 35% capacity factor, a doubling or quadrupling of generation capacity from 1× generation to 2× or 4× generation would cost additional ~\$2.5 trillion or ~\$7.5 trillion, respectively. The costs associated with storage, absent a radically new and low-cost solution, are likely to exceed most other options for overcoming the seasonal challenge. Thus, excess capacity installation (>1× generation), where beneficial, could be a substantially less expensive option for both solar and wind systems, especially for meeting the seasonal challenge.

Some previous studies[36] have indicated that 100% of U.S. energy generation could physically be met with a combination of solar and wind, ~1× generation and ~3–4 weeks of storage capacity, and concluded that such an energy system can be affordable, with however the assumption of a storage capital cost of \$1 per kW h. Our analysis, in accord with other studies over more limited geographic scales and time scales, indicates however that costs rise sharply if more than ~80% of total annual U.S. electricity demand is met using solely wind and solar generation in conjunction with storage and transmission, given storage capital cost assumptions (>\$100 per kW h) that are consistent with current and near-term projected costs.[22] The difference in conclusions with respect to electricity costs has its origin in the physical characteristics of solar and wind resources that cause the marginal improvements in reliability from additional storage and generation to decrease substantially as reliability increases (Fig. 3), as well as the low capacity factors for storage used infrequently to compensate for the intermittency of the solar and wind resources over long time scales of unmet demand.

Conclusions

CONUS-scale aggregation of solar and wind power is not sufficient to provide a highly reliable energy system without large quantities of supporting technologies (energy storage, separate carbon-neutral, flexible generators, demand management, *etc.*). This conclusion stems directly from an analysis of the physical characteristics of solar and wind resources and does not depend on any detailed modeling assumptions. The system architecture required to produce high reliability using primarily solar and wind generation is driven almost entirely by the need to overcome seasonal and weather-driven variability in the solar and wind resources. Achieving high reliability with solar and wind generation contributing >80% of total annual electricity demand will require a strategic combination of energy storage, long-distance transmission, overbuilding of capacity, flexible generation, and demand management. In particular, our results highlight the need for cheap energy storage and/or dispatchable electricity generation. Determination of the most cost-effective strategic combination depends on future costs that are not well-characterized at present. Regardless of the levelized cost of electricity from solar or wind power alone or in combination, our examination of 36 years of weather variability indicates that the primary challenge is to cost-effectively satisfy electricity demand when the sun is not shining and the wind is not blowing anywhere in the U.S.

Methods

Time-averaged hourly resource data was taken from the NASA developed MERRA-2 reanalysis product, which spans 36 years (1980–2015) and has a resolution of 0.5° latitude by 0.625° longitude.[31,37] We used the surface incoming shortwave flux [W m^{-2}] (variable name: SWGDN) and eastward wind and northward wind at 50 m [m s^{-1}] (variable names: U50M, V50M). Wind data at 50 m are a raw output of the MERRA2 data set, whereas use of other hub heights would introduce extrapolation errors from the available raw data set. Wind speed magnitudes at each grid point were found using the Pythagorean theorem.

Each raw data point (an hourly energy density (solar) or wind speed (wind) value at a specific location and time) was converted into a capacity factor based on a pre-determined power capacity rating for solar and wind generators. The capacity factor describes the actual energy output as compared to the systems' rated energy output (power capacity multiplied by one hour). For solar, the raw data were divided by 1000 W m^{-2}, which is the industry standard used to rate current solar cells and modules. The wind capacity factor calculation employed a piecewise function consisting of four parts: (i) below a cut-in speed (u_{ci}) of 3 m s^{-1} the capacity factor is zero, (ii) between the cut-in speed of 3 m s^{-1} and rated speed (u_r) of 15 m s^{-1} the capacity factor is ${u_{c1}}^3/{u_r}^3$, (iii) between the rated speed of 15 m s^{-1} and the cut-out speed (u_{co}) of 25 m s^{-1} the capacity factor is 1.0 and (iv) above the cut-out speed of 25 m s^{-1} the capacity factor is zero.[38]

An area-weighted mean hourly energy generation profile was created for the solar and wind resources individually for a region of interest. The native MERRA-2 projection was used to calculate the area ratios, although because the units are non-standard, a different method was used for calculating the absolute areas in square kilometers. For Fig. 2, two methods were used to calculate the area of the regions; for states and the contiguous U.S., the actual values were tabulated and used, while for the NERC regions, the MERRA-2 grid was re-projected from the native WGS84 (EPSG: 4326) coordinate system to the Northern American Lambert Conformal Conic (ESRI: 102009) coordinate system. The size of the NERC regions required a relatively large projection area and thus the accuracy of the area calculations was off by $\sim$10%. The values were systematically low, so each calculated area was corrected by dividing by 0.9.

The installed solar and wind capacities were calculated based on a specified resource mix (X% of energy generated is from solar, $(100 - X)$% of energy generated is from wind), the hourly resource data and the generation value. The generation value is defined as the energy produced by solar and wind divided by the total energy demand over all 36 years, and is shown as a multiplier (*e.g.* 1$\times$ generation means energy generated over the 36 year period is equal to energy demanded). Capacity factors derived from reanalysis data are known to differ from real-world systems, and thus these calculated capacities were used only as scaling values to produce the desired amount of generation.[4,39] Accordingly, the reanalysis data were used herein only for the temporal and spatial characteristics, which have been shown to be in good agreement with observational data (wind speeds).[4] The normalized capacity values shown in Fig. 3, and other related supplementary results, were calculated using real-world capacity factors for solar and wind systems (CF_{solar} = 20%, CF_{wind} = 38%) and the generation values.

Hourly NERC-wide (includes small contributions from some Canadian and Mexican regions) electricity demand data were taken from EIA for July 4, 2015–July 3, 2016.[40] These dates were chosen because they produced a smooth transition from July 3, 2016 to July 4, 2015. The data were ordered from Jan 1 to Dec 31 irrespective of year, and were joined together 36 times to form a 36 year record consistent with the resource data. Some errors existed in the data set, and the most gross errors were corrected (see ESI† for full log of corrections). A single year of demand data was used because a self-consistent continuous gapless time series of U.S.-wide hourly electricity demand is not readily available for the long time periods over which the reanalysis data allows extraction of geophysical information on the solar and wind resource. Correlation analysis between the solar and wind resource and the year of available demand data (2015) demonstrates that this year is not an outlier among all other analyzed years (see SOM), indicating that our use of a single year of demand data should not substantially affect our analysis of geophysical reliability over the multi-decadal period.

Given the resource data, installed capacities and electricity demand, a forward running simulation was performed to track solar and wind generation, charging or discharging of storage, if present, and the ability of wind, solar and energy storage to meet demand in every hour (a flow diagram of the algorithm is shown in Fig. S14, ESI†). Storage was charged with excess solar and wind generation, if available, until the storage was full, after which solar and wind generation was curtailed. The storage was discharged until empty, if demand exceeded solar and wind generation. The decision to discharge was based solely on the current hour, and completely filled the difference between demand and solar and wind generation, provided that sufficient energy was present in the storage system. The ability to forecast future solar and wind generation and demand may allow dispatch of storage in a more uniform fashion, thereby minimizing the need for other backup capacity and/or demand management. When storage was assumed to be available, the initial state was set to empty, but the simulation looped back at the end of the 36 year period, preserving the end-storage state as the initial state, and running forward from the beginning until no change in storage state was detected as compared to the previous loop. This method ensured that the initial condition did not affect the results. Perfect storage (100% efficient and no charge/discharge rate limits) and perfect transmission (area over which resource was aggregated had no transmission constraints or losses, *i.e.* copper plate assumption) were assumed.

Permutations were run for different storage capacities, generation values, areas of resource aggregation and resource mixes. The NERC-wide demand data were used for all simulation runs, although for smaller areas this demand profile may deviate from the local demand profile.

The Python code used for this study can be found in the ESI.†

Conflicts of interest

There are no conflicts to declare.

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