Caiazza Personal Comment on Renewable Energy Resource Availability

Summary

This comment explains why an accurate and detailed evaluation of renewable energy resource availability is crucial to determine the generation and energy storage requirements of the future New York electrical system. I describe the history of blackouts in New York and specific lessons from Texas that must be incorporated into New York planning to prevent a similar problem in New York. I explain that in order to ensure electric system reliability for an energy system that depends on renewable generators and energy storage, the resources available during periods of low wind and solar energy production must be known. To date, many studies do not consider the importance of worst-case conditions on reliability planning and I believe that the Draft Scoping Plan also fails to address this issue. I show that there is a viable approach that addresses could robustly quantify the worst-case renewable energy resources and provide the information necessary for adequate planning. I recommend that such a study be commissioned as soon as possible to determine if the existing estimates of New York's electrical energy renewable resources are adequate.

Blackouts

There is a long history of blackouts in New York City (NYC) that show why this issue is so important for New York. After a blackout in July 2019, AMNY published a brief history of blackouts in New York City. In 1959 and 1961 surges in electrical use caused blackouts and "The outage spurred changes to better protect the city's power grid from future blackouts". The 1965 blackout was the first regional blackout and was caused by a transmission problem in Ontario causing a wave of disruptions in the transmission system. Over 30 million people and 80,000 square miles in Ontario, New York, Connecticut, Massachusetts, New Hampshire, New Jersey, Pennsylvania, Rhode Island, and Vermont were left without power for up to 13 hours. As part of the response to that event New York set up a power pool to manage electricity generation and transmission. There was another blackout in 1977 that was limited to NYC. This one was caused by storms cutting off transmission into the City and in-City generation being unable to quickly replace the load. When generating units or transmission lines trip off, the system is unbalanced and protective devices turn off overloaded lines and transformers to prevent damage. Those shutoffs cascade down to the distribution system cutting off power to consumers and this led to the blackout. As a result, reliability constraints were implemented to ensure that when storms threaten transmission into the City that sufficient in-City generation is available to prevent a re-occurrence. Other associated issues were identified and additional constraints implemented. In 2003 there was another regional blackout caused by a computer software problem. Grid operators identified the cause and then developed procedures to prevent it from happening again. In 2012 tropical storm Sandy caused blackouts exacerbated by flood protection weaknesses. Since then, there have been massive investments to strengthen the infrastructure to prevent a reoccurrence. Note that after every blackout the electric system owners and operators developed strategies to prevent a reoccurrence of the problems that caused the blackouts. Keep in mind, however, that they did not anticipate the conditions that caused the blackouts.

I believe that, despite the best efforts of those responsible for the reliability of the electric grid, the transition to an electric power system that relies on intermittent wind and solar resources introduces so many changes that it will be impossible to anticipate them all. As a result, grid resilience will decrease and blackouts are inevitable. For example, consider that a team of researchers from the University of Nottingham recently addressed the effect of renewable energy resources on power grid stability. The abstract from the paper states with my highlights added:

> Contemporary proliferation of renewable power generation is causing an overhaul in the topology, composition, and dynamics of electrical grids. These low-output, intermittent generators are widely distributed throughout the grid, including at the household level. It is critical for the function of modern power infrastructure to understand how this increasingly distributed layout affects network stability and resilience. This paper uses dynamical models, household power consumption, and photovoltaic generation data to show how these characteristics vary with the level of distribution. **It is shown that resilience exhibits daily oscillations as the grid's effective structure and the power demand fluctuate. This can lead to a substantial decrease in grid resilience, explained by periods of highly clustered generator output. Moreover, the addition of batteries, while enabling consumer self-sufficiency, fails to ameliorate these problems.** The methodology identifies a grid's susceptibility to disruption resulting from its network structure and modes of operation.

Texas Blackout Lessons to Consider

In February 2021 the Texas electric system suffered major blackouts. In brief, the ultimate cause of the blackouts and resulting problems in Texas was due to poor planning. The weather in Texas during the storm was extreme but not unprecedented. Similar cold snaps occurred in 2011, 1991, 1990, 1989, 1983, 1963, and 1961 and there were electrical outages in 2011. Because there is no apparent trend in low daily maximum temperatures, climate change was not a factor. This was a weather event.

While there have been reports that dozens of deaths are tied to the storm in Texas, experts say the death toll is likely far larger. In addition, the blackouts cost the state economy upward of $130 billion in damages and losses, and some people who did have power saw their bills spike by thousands of dollars. Grid operators say that the situation could actually have been a lot worse, with the system minutes away from a months-long blackout.

Chuck DeVore explains that poor planning led to two problems that caused the blackouts but policy failures over many years were the root cause. He states that "had every Texas generator powered by natural gas, coal, nuclear and hydro operated at full output during the height of the storm's demand, Texas still would have experienced planned blackouts". The policy failure that led to this situation is that "Federal and state tax policy have encouraged the overbuilding of wind, and to a lesser extent, solar power, resulting in cheap, subsidized power flooding the Texas grid" and that in turn has discouraged building new natural gas power plants and keeping existing coal and gas plants on-line. Clearly the extremely cold weather did reduce wind turbine output and it also affected fossil and nuclear output. The more worrisome problem for me is that as ERCOT struggled to keep the lights on, "the grid became unstable, tripping additional power plants offline to protect their massive generators from destructive interaction with a fluctuating line frequency". This appears to have been largely caused by large fluctuations in wind output. "As ERCOT issued the order to start load shedding – rotating blackouts – some of the darkened circuits included vital oil and gas infrastructure. This uncoordinated move starved natural gas power plants of their fuel – leading to a further loss of power and the widespread and incorrect rumor that wellhead and pipeline freeze off contributed to the disaster." I am very confident that the NY electric system is resilient to current extreme weather conditions but I worry about major changes to the electric generating mix away from current and recent levels of dispatchable nuclear and fossil-fired generation.

Clearly the Texas electricity market failed to provide adequate resiliency for these conditions. I agree with Becky Klein, former commissioner and chairman of the Public Utility Commission of Texas who writes that the questions that need to be considered now are:

- Are we prepared to pay more for electricity and water to ensure higher levels of reliability?
- And if so, how much more?
- How can we be better prepared for "outlier" events, regardless of their probability?

The Climate Action Council has not confronted these questions.

The Renewable Energy Resource Availability Problem

I believe that there are two problems with the Draft Scoping Plan that have to be addressed as New York transitions its electric system to one dependent upon renewables. The first is inadequate recognition how peak load considerations must be the primary driver of reliability planning. The second is the focus of this comment. In the future, the availability of renewable energy resources must be known accurately in order to have any hope to plan for the worst-case conditions.

New York has very stringent reliability standards that include a parameter called loss of load expectation (LOLE). LOLE is generally defined as the expected (weighted average) number of days in a given period (e.g., one study year) when for at least one hour from that day the hourly demand is projected to exceed the zonal resources (event day). Within a day, if the zonal demand exceeds the resources in at least one hour of that day, this will be counted as one event day. The New York criterion is that the LOLE not exceed one day in 10 years, or LOLE < 0.1 days/year.

I think there is a serious disconnect between many aspects of the Draft Scoping Plan and most academic studies of electric resiliency that are relevant to New York reliability planning. In order to accurately estimate the one in ten-year limit a long evaluation period is needed to develop an accurate and robust estimate of the worst-case conditions. The Draft Scoping Plan relies on an electrification strategy using intermittent wind and solar. The strategy includes elements that have been proposed as viable components without adequately taking the worst-case availability situation. For example, micro grids consisting of a solar array and battery system have been proposed that are claimed to boost self-sufficiency. From what I can see micro grid proponents claim that they are viable solutions using inadequate average or annual total generation and load profiles. In the paper that claimed microgrids boost self-sufficiency, demand and generation profiles were based on a 36-month data set and 17-month data set. It is very likely that energy storage sized to work based on those data periods will be inadequate over a longer time period. As a result, the grid will have to pick up the slack complicating worst-case grid resiliency planning.

The focus of this comment is what is an adequate analysis of renewable resource availability. Fortunately, the NYISO Climate Change Impact and Resilience Study ("Resilience Study") lays the foundation to start to address this question in New York. While it is a start, I maintain that further work is necessary.

New York Reliability Planning

According to the 2020 NYISO Reliability Needs Assessment: "The New York system is deemed to have sufficient resources if the probability of an unplanned disconnection of firm load (loss of load expectation, or "LOLE") is equal to or less than the standard of once in every 10 years or 0.1 events per year." Note that the Texas data indicate that conditions similar to those that caused the blackouts exceed this standard. As a result, the New York energy planning process should evaluate renewable resources based on the LOLE standard.

A primary concern of the Power Generation Advisory panel should be how to maintain the current levels of reliability during the transition to a zero-emissions electric grid. I believe that diversity, redundancy, flexibility, dependability, and resiliency are key components of a reliable and affordable system. The Draft New York State Energy Plan and Draft Environmental Impact Statement dated December 2001 sets the bar: "Greater diversity in the types of fuel used for energy production could benefit all market participants, ensuring adequate fuel supplies and dampening price volatility."

Unfortunately, the New York trends for all components of reliability are towards increasing risk. Fuel diversity in New York has already been reduced. In 2001, New York electricity was generated 16% by coal, 27% by natural gas, 11% by oil, 16% by hydro, 28% by nuclear, 0% by wind and solar and 2% by other sources. In 2019, New York electricity was generated 38% by natural gas, 23% by hydro, 33% by nuclear, 3% by wind and solar and 2% by other sources. One key aspect of redundancy and resiliency is the ability to store fuel on-site so the facility can run for weeks. That is a feature of coal, oil, hydro and nuclear but those resources are used much less than in 2001. It is also important to be able to transport and deliver fuel in different ways which is another feature of coal and oil that has disappeared. Although activists claim that wind and solar are flexible - I disagree. Wind and solar power are utterly dependent upon the vagaries of weather so cannot be called flexible. They certainly are not dependable without additional energy storage and grid support services that markedly increase the cost. The claim that wind and solar are more resilient to massive outages is absurd given that every night with calm winds causes an outage of both of these generating resources. Furthermore, solar panels and wind turbines are more fragile to extreme weather and thus less resilient.

Description of the Problem

Both E3 in their presentation to the Power Generation Advisory Panel on September 16 and the Analysis Group in their September 10, 2020 presentation to NYISO described what I maintain is the ultimate problem. They explained that in order to meet the CLCPA emissions reduction goals that a resource category that provides firm, dispatchable and zero-emissions generation is needed. The Analysis Group labels these resources as dispatchable and emissions-free resources ("DE Resources") but gives no specific examples. On the other hand, E3 gives examples such as "such as bioenergy, synthesized fuels such as hydrogen, hydropower, carbon capture and sequestration, and nuclear generation". The International Energy Agency (IEA) recently published "Special Report on Clean Energy Innovation" that classified the technology readiness level of the technologies that could possibly be both dispatchable without GHG emissions. The bottom line is that none of the E3 examples of firm, dispatchable and zero-emissions technologies are close to being ready for adoption except nuclear and hydro which I believe are unlikely to provide any meaningful additional support for New York.

The Resilience Study does a good job outlining the difficulties of the challenge of this problem. They explained the criteria used to "establish a system that; (1) has demand consistent with the Climate Change Phase I Study, (2) has a set of resources that comply with the requirements of the CLCPA, and (3) that meets electricity demand in every hour all year." They went on to explain the uncertainties for these initial "starting point" resources:

- The New York power system is currently heavily dependent on natural gas fired generating units to provide energy, to be available during high load hours, to provide critical reserves on the system, and to be able to ramp up and downs on timescales of seconds, minutes, hours, and days to manage net load variability. At least as currently configured and fueled, these resources cannot operate in 2040;
- Even retaining existing low-carbon (nuclear, hydro) resources, there is an enormous amount of energy and capacity needed to meet projected demand in 2040;
- Currently-available and reasonably economic resources available to make up the zonal and system-wide energy deficits include solar and wind resources, yet their availability is uncertain and somewhat unpredictable. In fact, data reviewed for this report reveal that there would be long (multi-day) "lulls" in production from these resources. This means that almost no quantity of nameplate capacity from these resources is sufficient to meet demand in all hours of the year;
- Energy storage resources that are currently and expected to be available can fill part, but not all of the gap needed to maintain system reliability;
- There is a void that will need to be filled with technologies and/or fuels that - at the scales that would be required - are currently neither proven nor economic; and
- There is no doubt a major amount of technological change that will happen over the next twenty years, rendering it very difficult to forecast a future resource set with reasonable confidence.

On October 8, 2020 Kevin DePugh, Senior Manager for NYISO Reliability Planning, made a presentation to the Executive Committee of the New York State Reliability Council that gave an overview of the Reliability Study and emphasizes the results in the context of reliability planning. He listed the following characteristics of the DE resource:

- Large quantity of DE Resource generation is needed in a small number of hours;
- DE Resource has low capacity factor (~12%) during the winter;
- DE Resource has only a 3.7% capacity factor in the summer;
- DE Resource is not needed at all during spring and fall;
- Substantial quantity of DE Resource capacity is needed, the energy need is minimal;

- DE Resource must be able to come on line quickly, and be flexible enough to meet rapid, steep ramping need;
- On an average day, storage can meet evening peaks, but the DE Resource must generate if storage is depleted and renewable generation is low; and
- In the Winter CLCPA scenario, the DE Resource output across the state must increase from 362 MW (1.1% of DE Resource nameplate capacity) to27,434 MW (85.4% of name plate capacity) in six hours of the most stressed day.

To sum up this section, these are the resources that are necessary to prevent a New York blackout similar to the Texas blackout of 2021. The International Energy Agency (IEA) recently published "Special Report on Clean Energy Innovation" that classified the technology readiness level of the technologies that could possibly be both dispatchable without GHG emissions. The bottom line is that there is nothing close to being ready for adoption that fulfills those requirements. If the Climate Action Council scoping plan does not develop a plan to ensure that these resources will be available as needed, then blackouts will occur.

There is a fundamental issue related to this resource. Even if the technology is available a robust estimate of renewable energy resource availability in the worst case is needed to determine how much of this resource as well as wind, solar and energy storage will be needed. I have submitted comments (described here and here) as a party to the Department of Public Services (DPS) resource adequacy matters proceeding, docket Case 19-E-0530, arguing that a more comprehensive assessment of resource availability needs to be completed. I also raised the issue in comments to Power Generation Advisory Panel last year. In brief, I believe that it is imperative to do an analysis of the availability of wind and solar resources in New York based on long-term meteorological data sets.

Wind and Solar Drought Climatology

The critical consideration is the frequency, duration, and severity of periods when wind and solar resources are in "droughts" or low resource availability. There have been several recent applicable papers describing analyses to estimate the frequency and duration of periods with those conditions. The references section includes extracts from each of the papers described below.

Two recent papers looked just at wind resources. Ohlendorf and Schill (2020) analyzed the frequency and duration of low-wind-power events in Germany using 40 years of reanalysis data. They found that "low-wind-power events are less frequent in winter than in summer, but the maximum duration is distributed more evenly between months. While short events are frequent, very long events are much rarer." Leahy and McKeogh (2012) looked at wind variability in Ireland using a shorter period of meteorological observation data. They found that "Sustained 20-day periods corresponding to extremely low levels of wind generation are found to have return periods of around ten years in coastal areas." However, they also noted that "Persistent, widespread low wind speed conditions across the entire country are found to occur only rarely."

Other studies have looked at both wind and solar resources. Juasz et al., 2021 used 40 years of meteorological reanalysis data in Poland. They found that "that the probability of 'resource droughts' (periods when cumulative generation was less than arbitrary threshold) lasting one day is 11.5% for solar resources, 21.3% for wind resources and only 6.2% if both resources are considered in a joint resource evaluation." Otero, et. al., 2021 (submitted manuscript) used meteorological reanalysis data for a 40-year period covering Europe. They showed that "moderate winter energy droughts of both low renewable production and high residual load occur every half a year, while summer events occur every 3.6 and 2.4 years (on average)." They went on to note that: "As expected, the occurrence of energy droughts tends to decrease with the degree of the severity of the energy drought, and moderate and extreme energy droughts showed longer return period for most countries."

Finally, (Brown et al., 2021) used a meteorological reanalysis database that covers 71 years from 1950 to 2020 to compare estimated weekly solar and wind availability against cooling and heating degree days as a proxy for electrical load over that entire period for the western United States. In a personal communication, Dr. Brown used that database to look at daily data in the Eastern Interconnect region to illustrate the expected return time for wind droughts. Figure 1 illustrates a potential product. It shows that a ten-day drought at the load level in the second column would have a return period of 3,653 days or once in ten years.

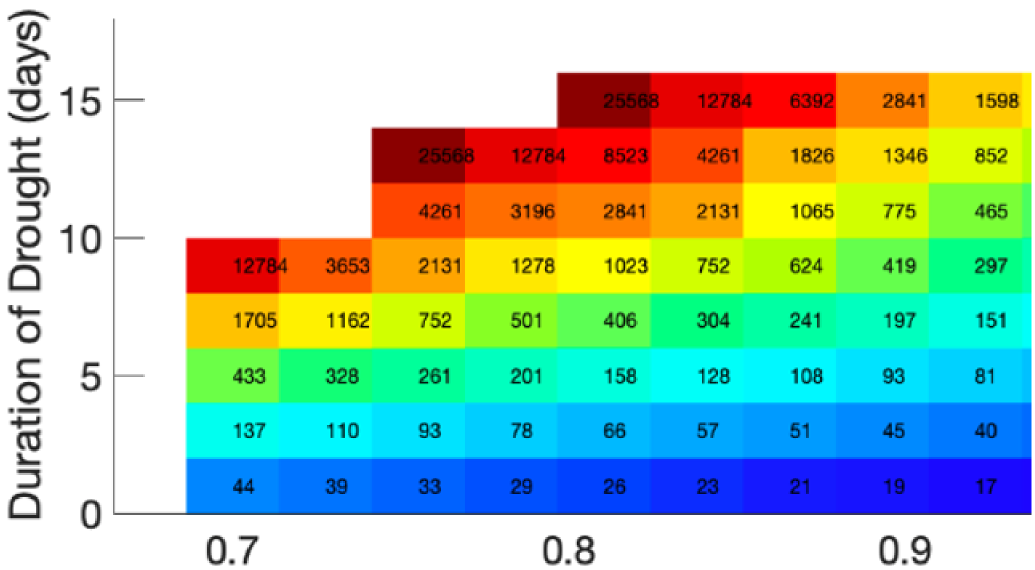

Figure 1: Wind Generation Drought Frequency (Expressed as Return Period in Days). X-Axis is the intensity of the daily electrical energy generation drought. Excerpt at the lower end of the range shown for clarity.

Recommendation

In order to provide a robust estimate of the wind and solar availability during worst case conditions it is necessary to analyze as long a time period of historical meteorological data as possible. Fortunately, meteorological reanalysis descriptive data generated by modern weather forecast models but using original data from decades ago is available for this application. The ERA5 global reanalysis data base provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. As shown by the papers described above, these data can be used to estimate wind and solar resource availability.

I strongly recommend an analysis in New York using the complete (1950 to present) ERA5 meteorological database to determine the frequency and duration of renewable resource droughts in order to estimate the appropriate worst case. The goal of the project would be three-fold:

- Determine historical intensity, frequency, duration and seasonality of wind and solar droughts in New York.
- Identify co-occurrence of wind and solar droughts with high demand periods (heating/cooling degree days)
- Interpret the droughts and high demand periods: seasonal, weather regimes, interannual variability (e.g. El Niño-Southern Oscillation), multi-decadal climate regimes, and trend associated with global warming

I have looked into projects to get this critically needed work done. I have corresponded with Brown and his team about doing work centered on New York. However, his schedule in 2022 precludes him from doing the work so he is not an option. I asked Dr. Judith Curry at Climate Forecast Applications Network (CFAN) if she would be interested and she has stated she is willing to do an analysis to determine the frequency and duration of wind and solar droughts in New York.

The CFAN approach would be similar to the recent studies cited above. The New York reliability needs experts need to define criteria of interest (e.g., daily wind speeds less than 10 mph). CFAN would then search the reanalysis record for the frequency and duration of those conditions and assess the meteorologic conditions associated with the wind and solar droughts and anomalously high demand for electricity. The actual scope of the project must be determined by New York reliability needs experts. In my discussions we agreed on the following for a proposed New York analysis:

- Use ERA wind, solar radiation, and temperature data from 1950 to present (19-mile horizontal resolution)
    - Define relevant thresholds for extreme events: wind - e.g. 2%, 5%, 10% of capacity; 4 m/s cut in speed; above 80th percentile for heat/cold events
    - Evaluate intensity, duration (2-10 days), frequency and event seasonality
    - Spatial correlations in the targeted regions for extreme events
- Region: NY ISO (plus ISO-NE, PJM, NPCC?)

Conclusion

It is critically important to accurately determine the availability of wind and solar resources for New York and surrounding areas that may be called on to provide renewable energy to the state. That analysis must use as long a period as possible and consider wind and solar resources simultaneously. The Draft Scoping Plan assessment does not meet these criteria and studies by the NYISO have not used a reanalysis data base that extends the evaluation period by decades.

I have done enough research on the feasibility of the analysis that I am confident that a more appropriate estimate of worst-case resources is possible and I strongly recommend doing an analysis that uses date for as long a period as possible.

I prepared this comment because I believe that an analysis of the availability of wind and solar resources in New York based on long-term meteorological data sets is necessary for reliability planning. I am a retired meteorologist who started working for Niagara Mohawk in 1981 and have continued to work in the New York electric generating industry continuously since then. I have written extensively on implementation of the Climate Act because I believe the ambitions for a zero-emissions economy outstrip available renewable technology such that it will adversely affect reliability and affordability, risk safety, affect lifestyles, will have worse impacts on the environment than the purported effects of climate change in New York, and cannot measurably affect global warming when implemented. The opinions expressed in this document do not reflect the position of any of my previous employers or any other company I have been associated with, these comments are mine alone.

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References (Available Upon Request)

Brown. P, D.J. Farnham, and K Caldeira, 2021: Meteorology and climatology of historical weekly wind and solar power resource droughts over western North America in ERA5. SN Applied Sciences (2021) 3:814, https://doi.org/10.1007/s42452-021-04794-z

Abstract: Wind and solar electricity generation is projected to expand substantially over the next several decades due both to rapid cost declines as well as regulation designed to achieve climate targets. With increasing reliance on wind and solar generation, future energy systems may be vulnerable to previously underappreciated synoptic-scale variations characterized by low wind and/or surface solar radiation. Here we use western North America as a case study region to investigate the historical meteorology of weekly-scale "droughts" in potential wind power, potential solar power and their compound occurrence. We also investigate the covariability between wind and solar droughts with potential stresses on energy demand due to temperature deviations away human comfort levels. We find that wind power drought weeks tend to occur in late summer and are characterized by a mid-level atmospheric ridge centered over British Columbia and high sea level pressure on the lee side of the Rockies. Solar power drought weeks tend to occur near winter solstice when the seasonal minimum in incoming solar radiation co-occurs with the tendency for mid-level troughs and low pressure systems over the U.S. southwest. Compound wind and solar power drought weeks consist of the aforementioned synoptic pattern associated with wind droughts occurring near winter solstice when the solar resource is at its seasonal minimum. We find that wind drought weeks are associated with high solar power (and vice versa) both seasonally and in terms of synoptic meteorology, which supports the notion that wind and solar power generation can play complementary roles in a diversified energy portfolio at synoptic spatiotemporal scales over western North America.

Jurasz, J.; Mikulik, J.; Da˛bek, P.B.; Guezgouz, M.; Ka´zmierczak, and B. Complementarity, 2021: 'Resource Droughts' of Solar and Wind Energy in Poland: An ERA5-Based Analysis. Energies 2021, 14, 1118.
https://doi.org/10.3390/en14041118

Abstract: In recent years, Poland has experienced a significant increase in the installed capacity of solar and wind power plants. Renewables are gaining increasing interest not only because of Poland's obligations to European Union policies, but also because they are becoming cheaper. Wind and solar energy are fairly-well investigated technologies in Poland and new reports are quite frequently added to the existing research works documenting their potential and the issues related to their use. In this article, we analyze the spatial and temporal behavior of solar and wind resources based on reanalysis datasets from ERA5. This reanalysis has been selected because it has appropriate spatial and temporal resolution and fits the field measurements well. The presented analysis focuses only on the availability of energy potential/resources, so characteristics intrinsic to energy conversion (like wind turbine power curve) were not considered. The analysis considered the last 40 years (1980–2019) of available data. The Spearman coefficient of correlation was considered as a complementarity metric, and the Mann–Kendal test was used to assess the statistical significance of trends. The results revealed that: The temporal complementarity between solar and wind resources exists mostly on a seasonal scale and is almost negligible for daily and hourly observations. Moreover, solar and wind resources in joint operation exhibit a smoother availability pattern (assessed based on coefficient of variation). Further findings show that the probability of 'resource droughts' (periods when cumulative generation was less than arbitrary threshold) lasting one day is 11.5% for solar resources, 21.3% for wind resources and only 6.2% if both resources are considered in a joint resource evaluation. This situation strongly favors the growth of local hybrid systems, as their combined power output would exhibit lower variability and intermittency, thus decreasing storage demand and/or smoothing power system operation.

Leahy, P. and McKeogh, E. (2012) 'Persistence of low wind speed conditions and implications for wind power variability'. Wind Energy, http://dx.doi.org/10.1002/we.1509

Abstract: As the penetration of wind generation increases on power systems throughout the world, the effects of wind variability on power systems are of increasing concern. This study focuses on sustained occurrences of low wind speeds over durations ranging from one hour to twenty days. Such events have major implications for the variability of energy yields from wind farms. This in turn influences the accuracy of wind resource assessment. The frequency analysis techniques commonly used to study wind variability cannot represent the autocorrelation properties of wind speeds and thus provide no information on the probabilities of occurrence of such sustained, low wind events. We present two complementary methods for assessing wind variability, runs analysis and intensity-duration frequency analysis, both with emphasis on characterising the occurrence of continuous, extended periods (up to several days) of low wind speeds. Multi-annual time series of hourly wind speeds from meteorological stations in Ireland are analysed with both techniques. Sustained 20-day periods corresponding to extremely low levels of wind generation are found to have return periods of around ten years in coastal areas.

Persistent, widespread low wind speed conditions across the entire country are found to occur only rarely.

Long term records of hourly surface wind speeds and directions from fourteen geographically dispersed stations in the Republic of Ireland were studied, starting from 1980.

Long periods of low wind speeds in the preprocessed, vertically extrapolated series were identified in the records through the technique of runs analysis. In order to perform the runs analysis, a threshold wind speed, *vt*, has to be selected first. Then the entire record is compared against the threshold. Values falling before the threshold are identified, and the durations of periods of sustained below-threshold speeds are recorded. The cumulative percentage frequency of wind speed remaining consistently below the threshold may then be calculated for any duration of interest [17].

Complementary to the runs analysis, intensity-duration-frequency methods allow return periods to be calculated for events of specific magnitude and duration from long series of measured values. Return periods are calculated for low wind speed events by means of intensity-duration-frequency analysis. The goal is to produce a relationship describing the magnitude of an occurrence of prolonged low wind speeds as a function of the event duration *D* and the recurrence interval or return period *Tr*.

Ohlendorf, N. and W. Schill, 2020: Frequency and duration of low-wind-power events in Germany. Environ. Res. Lett. 15 (2020) 08404,5 https://doi.org/10.1088/1748-9326/ab91e9

Abstract: In the transition to a renewable energy system, the occurrence of low-wind-power events receives increasing attention. We analyze the frequency and duration of such events for onshore wind power in Germany, based on 40 years of reanalysis data and open software. We find that low-wind-power events are less frequent in winter than in summer, but the maximum duration is distributed more evenly between months. While short events are frequent, very long events are much rarer. Every year, a period of around five consecutive days with an average wind capacity factor below 10% occurs, and every ten years a respective period of nearly eight days. These durations decrease if only winter months are considered. The longest event in the data lasts nearly ten days. We conclude that public concerns about low-wind-power events in winter may be overrated, but recommend that modeling studies consider multiple weather years to properly account for such events.

Based on wind speeds and power curves, we derive an hourly aggregated time series of capacity factors for wind power in Germany. First, we take wind speeds at 50 m above surface from the MERRA-2 reanalysis dataset, which covers 40 years from 1980 to 2019, and extrapolate to hub heights[2]. Second, capacity factors of each MERRA-2 grid cell are calculated based on power curves of recently installed wind turbines. Third, we spatially aggregate these capacity factors using a weighting scheme that considers the current spatial distribution of onshore wind power capacity in Germany. Finally, we investigate the resulting time series of hourly aggregated capacity factors by applying a narrower and a wider definition of LWP events.

Otero, N., O. Martius, S. Allen, H. Bloomfield, and B. Schaefli, 2021: A copula-based assessment of renewable energy droughts across Europe, Manuscript has been submitted for publication in Renewable Energy (December 1, 2021).

Abstract: Meeting carbon-reduction targets will require thorough consideration of climate variability and climate change due to the increasing share of climate sensitive renewable energy sources (RES). One of the main concerns arises from situations of low renewable production and high demand, which can hinder the power system. We analysed energy droughts, defined as periods of low energy production (wind plus solar generation) or high residual load (demand minus production), in terms of two main properties: duration and severity. We estimated the joint return periods associated with energy droughts of residual load and power production. We showed that moderate winter energy droughts of both low renewable production and high residual load occur every half a year, while summer events occur every 3.6 and 2.4 years (on average). As expected, the occurrence of energy droughts tends to decrease with the degree of the severity of the energy drought, and moderate and extreme energy droughts showed longer return period for most countries. In general, we found a large variability across Europe in summer, with some countries (e.g. Italy) being more sensitive to energy droughts. Our results highlight the relevance of sharing RES during prolonged periods of low production and high demand.

We use daily time series of hourly European electricity demand, solar and wind power at country level for 27 countries (Table S1). The data sets created by Bloomfield et al. (2019b) are a reconstruction of energy indicators (i.e. en ergy demand, wind and solar power), based on the ERA5 reanalysis product (Hersbach, 2018) that covers the period 1979-2019.

The electricity demand was reconstructed based on a multiple linear regression model trained with observed national demand, in giga (10^9) watts (GW), corresponding to two complete years (2016-2017), extracted from the ENTSOe transparency platform (ENTSOE, 2019). The regression model uses both weather-dependent and human-behaviour-dependent predictors (e.g. the day-of-the-week and long-term socioeconomic trends, Bloomfield et al., 2019b). The weather-dependent model parameters are heating-degree days (HDDs) and cooling-degree days (CDDs).

Wind power capacity factors were obtained from a physical model that uses bias-adjusted wind speeds (using the Global Wind Atlas as the ’truth’) at an altitude of 100 m above ground from the ERA5 reanalysis (Bloomfield et al., 2019a). Calibrated wind speeds are then passed through a power-curve to convert to wind power capacity factors. Different power-curves are used for different grid cells of the underlying climate data set: three turbine classes are retained, Class 1, 2 and 3. The choice of the turbine class per grid cell is dependent on the long-term average wind power generation. The three different turbine curves 135 allow the maximum potential to be extracted from each grid-cells wind speeds. Country-level wind power generation is calculated by weighting each grid box by the amount of wind power installed there (in the reference year 2017).

Solar power capacity factors were modelled following the empirical formulation of Evans and Florschuetz (1977), using 2m temperature and incoming surface solar radiation as inputs. The solar power capacity factors were created at each grid point and then aggregated to national level assuming a uniform distribution of solar panels across the country (as at the time of model creation there was not available data on panel locations). Both wind and solar power datasets captured the overall behaviour of the national wind and solar power generation well (see Bloomfield et al. (2019a) and references therein for further details).

The capacity factors (expressed in %) obtained from both wind and solar power models were used to calculate the daily national wind and solar power production, for which we used as the baseline the installed capacity of wind and solar corresponding to 2017 (for each country) (Bloomfield et al., 2019a, 2020).

Energy droughts: event definition

We begin our analysis by defining ED events using a threshold-level based approach. An ED of low production is identified as an episode or period of time during which the energy production of renewable sources (i.e. wind and solar) is below the 10th percentile of the total generation (e.g. production of wind plus solar, which will be referred to as LWS) over the period of study 1979-2019. Similarly, an ED of the residual load (i.e. demand minus wind and solar production, referred to as RL) occurs when the 90th percentile of the distribution of RL is exceeded the 90th percentile of the distribution of RL.