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An Assessment of Resource Drought Events as Indicators for Long-Duration Energy Storage Needs

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- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
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LIST OF ABBREVIATIONS

AEMO	Australian Energy Market Operator
BE	Belgium
CAISO	California Independent System Operator
DE	Denmark
DK	Germany
ERCOT	Electric Reliability Council of Texas
EU	European Union
GB	Great Britain
IEA	International Energy Agency
ISO	independent system operator
ISO-NE	Independent System Operator of New England
LDES	long-duration energy storage
MISO	Midcontinent Independent System Operator
NEM	Australian National Electricity Market
NL	Netherlands
NSW	New South Wales
PJM	PJM Interconnection
PV	photovoltaic
QLD	Queensland
SA	South Australia
RTO	regional transmission organization
TAS	Tasmania
VIC	Victoria
VRE	variable renewable energy

EXECUTIVE SUMMARY

Variable renewable energy sources (VRE) like wind and solar are being rapidly deployed by many countries around the world to help meet their respective clean energy goals. Given the increased reliance on VRE resources, there is broad consensus amongst policymakers, regulators, system operators and electricity market participants that resources enabling increased flexibility in the delivery of energy will be a critical enabler in achieving energy sector decarbonisation goals.

Along with short-term variability and intermittency, VRE resources are prone to weather-driven lows in generation – *resource droughts* – over extended periods of time, ranging from multiple days to weeks. Such resource droughts are not a new phenomenon in the context of the power system. For instance, hydrological droughts have impacted hydropower generation on a seasonal, annual, or even multi-year basis for decades. Historically, other flexible resources have been able to help compensate for these gaps. The dispatchable thermal generation fleet, typically fuelled by natural gas or coal, along with stored energy in reservoirs and pumped storage facilities in adjacent regions, have generally been able to mitigate these shortfalls and provide flexibility to the system. However, as the conventional generation fleet is decommissioned to meet decarbonization goals, clean and dispatchable capacity will be needed to support system operations and to reliably meet electricity demand on a continuous basis across all time scales ranging from milli-seconds to years. Short-duration energy storage technologies are already being deployed alongside VRE resources, particularly solar, to balance short-term variability. However, as a larger share of the energy generation fleet is composed of VRE, long-duration energy storage (LDES) technologies, along with extended transmission networks, will play an important role, especially for managing the VRE resource droughts.

Presently, there are no established metrics or indicators for LDES requirements. The frequency, duration, and magnitude of VRE resource droughts will inform resource adequacy and reliability needs, and hence, can be important indicators of the potential need for LDES because they demonstrate a mismatch between VRE generation and system demand over extended periods of time. In this report, we used historical observations of VRE production spanning 2016—2023 to analyse metrics for the frequency, magnitude, and duration of VRE resource droughts in multiple regions, including parts of the United States, Europe, Australia, and Canada. We used the statistics describing VRE drought periods in these regions as approximate indicators of LDES needs, which could be met by hydropower and other flexible resources. To provide a relevant comparison across many power systems and geographies, a similar set of analyses were undertaken using consistent definitions in each region. We then compared the findings across different geographical domains and investigated how aggregation of VRE resources affects the energy deficits due to VRE resource droughts. We also studied the complementarity of wind and solar resources, particularly, the ability of solar generation to meet energy deficits during periods of wind resource droughts.

We defined a VRE resource drought as a period wherein energy production falls below a fraction of past production in a reference period for a minimum duration. For identification of wind droughts, we adopted a threshold of 10% of historical annual production sustained for a minimum of 4 hours. For solar droughts, we adopted a threshold of 30% of historical annual production for at least 1 day. However, we only consider periods of at least 8 consecutive hours of wind generation below 10% of the historical annual generation as indicators for the need of LDES. The solar resource drought definition, by default, accounts for at least 8 hours of generation below 30% of the annual average.

Tables ES-1 and ES-2 show the results of the analysis identifying historical droughts and impact metrics for onshore wind and solar, respectively. The study results show that more than 10 wind drought events per year can be expected in North America, while more than 50 wind drought events can be expected in various regions of Australia on average annually.

Table ES-1. Onshore wind energy drought metrics across North America, Europe, and Australia

	Historical Baseline	# of Events	Average Duration of Event (# of Hours)	Average Energy Deficit (% of load)	Duration of Longest Event (# of Hours)	Energy Deficit of Longest Event (MWh)
ERCOT	2018-2022	82	8	25%	15	145,853
CAISO	2018-2022	167	9	8%	42	71,849
Québec	2019-2022	192	10	6%	34	44,280
Spain	2016-2020	38	6	18%	12	66,100
Portugal	2016-2020	234	9	23%	42	60,100
Spain + Portugal	2016-2020	27	6	18%	11	69,515
Victoria	2018-2023	303	10	17%	41	44,000
Tasmania	2018-2023	340	10	14%	55	7,000
South Australia	2018-2023	325	9	65%	31	21,000
Queensland	2018-2023	411	9	2%	60	4,000
New South Wales	2018-2023	247	7	7%	17	11,000

Table ES-2. Solar energy drought metrics across North America, Europe, and Australia

	Historical Baseline	# of Events	Average Duration of Event (# of Days)	Average Energy Deficit (% of load)	Duration of Longest Event (# of Days)	Energy Deficit of Longest Event (MWh)
ERCOT	2018-2022	52	1	2%	5	169,842
CAISO	2018-2022	22	1	12%	2	130,406
Spain	2016-2020	75	2	4%	6	212,709
Portugal	2016-2020	65	1	1%	4	10,514
Spain + Portugal	2016-2020	69	2	4%	4	120,440
Victoria	2018-2023	41	2	2%	2	725,272
South Australia	2018-2023	31	2	4%	3	362,141
Queensland	2018-2023	13	1	5%	3	152,717
New South Wales	2018-2023	17	1	4%	3	253,915

We identified five key observations and insights from this study:

1) **Variable renewable energy resources are prone to extended periods of low generation output:** Wind and solar display extended periods of low or no generation output. These resources are uniquely vulnerable to extreme weather conditions (e.g., water droughts, heatwaves, cold snaps, etc.), but the extent of impact differs between resource type and location. These resource droughts can create energy deficits over an extended period, which can stress localized power systems and cause cascading impacts to neighbouring power systems. Historical resource drought events can provide indications for future need for LDES. At present, the existing thermal and hydropower generation resources provide sufficient backup during VRE resource drought events. Additional local transmission and/or interconnections with other regions will likely be needed in addition to LDES and shorter-duration storage. The correct mix of storage and transmission will depend on the region and the available set of generation technologies and energy resources.

2) **Standardized definitions of a resource drought event do not currently exist:** Resource drought events can be defined differently using various metrics and it should be noted that there is a general lack of consensus on the definition of a resource drought. This study adopted consistent metrics in an effort to synthesize drought impacts across regions and resources. While this study defined a wind drought event as at least 4 consecutive hours with production less than 10% of expected wind generation, and for

solar at least one day with production less than 30% of expected, the results are difficult to compare across regions due to geographically localized resource availability. Standardized metrics provide a common footing for comparison but must come with the acknowledgement of the impacts of resource and geographic diversity.

3) **Solar generation cannot always overcome the energy deficit during wind drought events:** While we primarily quantified and compared the indicators for wind and solar generation separately, we also did a preliminary analysis of the complementarity of these resources, i.e., the ability of one resource type (solar) to fill the gap created during a resource drought for the other (wind). We observed that solar is not an ideal complement to wind and hence, overbuilding of solar alone will not be adequate to overcome the energy deficits created by wind resources. The converse was not fully explored in the current study because it will require methodological advancements.

4) **Aggregation across geographic regions can reduce the intensity and frequency of drought events:** The aggregation of wind – onshore and offshore – can reduce the number of reported wind drought events by an order of magnitude, the average energy deficit by a quarter, and the average duration of events by a half. However, aggregation and access to extra-regional resources will require additional transmission buildout, as well as regulatory and market mechanisms to enable the trade.

5) **The requirements for LDES will vary by regions:** The drought threshold values adopted in this analysis of 10% for wind and 30% for solar are not likely to be universally applicable for defining a resource drought, which in turn will define the estimated need for LDES. Instead, the requirements may also need to be parameterized to account for the composition of stored energy and flexibility resources, as well as the availability of existing and new transmission and interconnections. The longest wind drought event observed in the USA ERCOT region lasted 15 hours, creating an energy deficit of ~140 GWh. This deficit is the equivalent of 10 hypothetical thermal power plants, each with rated capacity of 1 GW, generating continuously for 14 hours, or an LDES resource capable of discharging 10 GW for 14 consecutive hours. Actual requirements for LDES can only be ascertained based on detailed planning studies which consider policy goals, regulatory pathways, and available market mechanisms, as well as other available options such as transmission expansion and interconnection with other regions. The need for LDES will increasingly need to consider the impacts of changing climate and extreme weather, which affects not just the demand for energy but also the availability of wind, solar, and hydropower generation capacities.

The analysis in the report shows a growing number of resource drought events across multiple regions driven by increased reliance on weather-dependent power generation. Historical resource droughts are a strong indicator for the need for LDES, however the metrics that summarize the impacts of these events fall short in translating to procurement targets. More work is needed to bridge resource drought events with LDES procurement recommendations to avert reliability impacts to the power system. Existing resource adequacy metrics are designed to specify procurement targets for fossil fuel-based generation. These metrics will need to evolve to clarify the system need for both power capacity (as with current metrics) and energy capacity. With improvements in resource adequacy metrics in place, new regulatory and market mechanisms can be developed to support the investment in LDES.

Future work on resource drought identification and resource adequacy metrics should address the following:

1) **Drought identification parameters should be defined to resolve the events most impactful to a specific region:** Changing the parameter values to identify a resource drought will impact the duration, magnitude, and frequency of events, but not proportionally. For instance, changing the threshold for a wind drought event from 10% to 20% will likely increase the number of events that are detected but may not directly translate to an increase in energy deficit per event. This threshold change will select for longer duration droughts which will naturally increase the energy deficit, but this increase in energy deficit will not be different for hours that were already identified by a 10% threshold. The actual definition of a resource drought used in a region will have a material impact on the implications for the attributes of LDES.

2) **The impact of growing reliance on renewables will need to be clarified:** We used historical data to quantify the frequency and duration of wind and solar resource droughts. Since all analysis conducted herein is based on historical observations, any potential indicators of LDES requirements also need to consider the growing reliance on both wind and solar generation with the concomitant reduction in thermal generation. The energy systems around the world are undergoing a significant transition and this change will likely require much more storage than identified with historical data.

3) **New mechanisms for commensurate accreditation and valuation of LDES will need to be designed**: The growing penetration of renewables is creating longer-term energy deficits, which will require the replacement capacity to be available over longer periods of time. However, current capacity market constructs around the world are mostly designed to ensure enough generation is deployed to meet peak capacity requirements, rather than available capacity over longer periods, such as stored energy in an LDES device or facility. New mechanisms will be required to create incentives to attract and maintain the energy capacity required to manage these emerging and growing risks alongside existing power capacity requirements. There are examples of emerging market constructs, such as in the PJM capacity market (FERC 2024), that have created value differentiation for storage based on duration, primarily resulting from exposing a primary risk driver based on winter performance as opposed to summer. This has sent the signal to value resources that can help manage these longer periods of risk. More work needs to be done to identify the true value of LDES and to design market mechanisms that provide market signals commensurate with that value.

INTRODUCTION

There is broad consensus amongst policymakers, regulators, system operators and electricity market participants that increased flexibility will be a critical enabler in achieving energy sector decarbonisation goals. The renewable energy technologies that are being deployed most rapidly, wind and solar, by nature have variable and uncertain energy outputs. Clean and dispatchable capacity therefore will be needed to support system operation and to reliably meet electricity demand (or “load”) on a continuous basis. Battery energy storage is already being deployed alongside these technologies, particularly solar, to balance short-term variability. However, as a larger share of the energy generation fleet is composed of variable renewable energy (VRE) resources, the impact of longer, low VRE generation periods will increase. Deep energy storage will be increasingly required to help fill these gaps.

Such resource droughts are not a new phenomenon in the context of the power system. Hydrological droughts have impacted hydropower generation on a seasonal, annual, or even multi-year basis for decades. Historically, other flexible resources have been able to help compensate for these gaps. The dispatchable thermal generation fleet, typically fuelled by natural gas or coal, has generally been able to mitigate these shortfalls and provide flexibility to the system. While this required flexibility has provided both the necessary energy capacity through sustained delivery (GWh) and power capacity through instantaneous delivery (GW), the traditional system planning paradigm has historically focused on power capacity as the driving design criterion to match generation to peak demand. As an increasing portion of the generation fleet becomes less dispatchable and subject to energy resource availability constraints, attention will shift toward energy capacity requirements. While the generation fleet has adequate power capacity to meet peak demand, it may struggle to deliver this power for the required duration.

During the ongoing energy transition, the driving system design criterion will need to shift from providing peaking power capacity during high demand times toward supplying energy capacity to compensate for times of low VRE generation. Moreover, to support decarbonisation, the existing thermal generation fleet will ultimately need to be largely or fully retired; other resources will be required to supply this flexibility. Long-duration energy storage (LDES)[1] technologies can play an important role in managing the gap between electricity demand and an increasingly variable supply.

Extended periods of low VRE output can be characterized as “VRE resource droughts”. The frequency and duration of these droughts are important indicators of the potential need for LDES because they demonstrate a mismatch between VRE generation and demand that would be very costly to mitigate through over-building of VRE generation alone. No amount of additional wind power capacity will help meet system demand in an economically efficient

[1] In this report, we define LDES to be energy storage assets with a duration longer than 10 hours (i.e., the amount of energy storage is sufficiently large to generate at full power capacity for at least 10 hours, thus translating to energy capacity of rated power times 10 hours). This is in line with the USA DOE’s LDES Shot (https://www.energy.gov/eere/long-duration-storage-shot)

manner if the wind availability is very low across the entire power system area. In regions where VRE resource droughts occur for periods of days to weeks, short-duration energy storage will not be sufficient to help bridge these gaps.

In this report, we use historical data to analyse metrics for the frequency, magnitude, and duration of VRE resource droughts in multiple regions, including parts of the United States, Europe, Australia, and Canada (Hydro Québec). In turn, we use the quantitative estimates of these shortage events to identify the potential need for LDES. We compare the findings across different geographical domains and investigate how aggregation of VRE resources affects the energy drought metrics. We use the results to identify “flexibility requirements” in these regions as approximate indicators of LDES needs, which could be met by hydropower and other flexible resources. The benefits of this approach are threefold: (1) we clarify the historical VRE droughts; (2) we translate these VRE droughts to system flexibility needs with emphasis on LDES; and (3) we provide insight into the utility of current drought evaluation metrics for system flexibility needs. Altogether, this approach aims to ensure robust evaluation of drought indicators for effective system planning in the transition to cleaner electricity systems.

1 BACKGROUND

1.1 Metrics and Indicators for Energy Droughts in the Literature

As the amount of VRE has grown rapidly in most regions of the world in the last decade, the existence of longer periods of low VRE availability is getting increasing attention from the perspective of the power grid. As an example, the German term “dunkelflaute” (loosely translating to "the dark doldrums") has become a universally adopted term to describe periods in which there is severely reduced energy availability from wind and solar, such as prolonged periods of substantial cloud coverage paired with limited wind. This term helps to contextualise the challenges of balancing supply and demand under these weather conditions.

In the research literature, low wind speed events have received attention for quite a while, although there is little agreement on definitions or thresholds for defining “low wind speed”. This means that while each paper has individual merit, it can be difficult to compare the literature. For instance, Leahy and McKeough (2013) studied the persistence of low wind speed events and conducted an empirical analysis using historical data from meteorological stations in Ireland. The authors used different wind speed thresholds and durations in defining low wind speed events and estimated probabilities of occurrence accordingly.

In a similar line of work, Patlakas et al. (2017) studied low wind speed events and developed intensity-duration-frequency curves for such events in the North Sea. They found that the duration of these events tends to be longer close to shore than in the open sea. Engeland et al. (2017) conducted a comprehensive review of the space-time variability of renewable electricity production, including wind, solar, and hydropower, but without focusing specifically on extreme events.

More recent literature includes studies of the power outputs from VRE rather than weather variables. For instance, Raynaud et al. (2018) assessed the characteristics of “energy droughts” for wind, solar, and run-of-river hydropower in Europe. They estimated daily power outputs for such facilities using a large-scale hydro-meteorological dataset (30 years) and standard weather-to-energy conversion models. An energy drought was defined to occur when the daily output from a VRE resource falls below a certain threshold, defined as a fraction of the average output over the entire dataset horizon. An alternative metric considers the difference between supply and demand with results presented for 12 European countries. Ohlendorf and Schill (2020) took a similar approach for their analysis of low-wind-power events in Germany. They used 40 years of reanalysis data to estimate outputs from wind power in Germany. The analysis was conducted with hourly data and power capacity factors thresholds of 2%, 5%, and 10% were used to define low-wind-power events, using either individual hourly consecutive observations or a moving average, where the latter is a wider definition that identifies more events. Li et al. (2021) investigated low-VRE output events in Europe using 32 years of simulated power production data from the publicly available database renewables.ninja.[1] They

[1] www.renewables.ninja is an open-source wind and solar power model that converts reanalysis meteorological data into power (Pfenninger and Staffel 2016, Staffel and Pfenninger 2016).

also used reanalysis data to identify the types of meteorological conditions under which such events tend to occur. Their definition of a drought event was based on power capacity factors, where they defined “dunkelflaute” as an event where both wind and solar power capacity factors drop below 20% for at least 24 hours. The authors found that these events happen almost exclusively in November, December, and January in Europe and that the frequency of such events drops from 3–9% for individual countries to 3.5% for the combined region. These findings demonstrate the impact of regional aggregation on event detection, which is explored later in this work.

Mayer et al. (2023) used machine learning to estimate future patterns for VRE generation in Hungary. Using the generated hourly time series data for VRE generation as well as historical observations, they identified the timing and frequency of dunkelflaute events, finding that they typically occur in the summer nights. Their definition of dunkelflaute is also based on power capacity factor thresholds for wind and solar power, using 1%, 5%, and 10% thresholds, respectively. This finding is the opposite of Li et al. which found that the events almost exclusively occurred in winter. However, Mayer et al. used a different temporal definition and different magnitude thresholds, showing the importance of consistent terminology.

Most of the research on low-VRE events comes from Europe. Outside of this region there have been analyses in the United States, Australia, and Japan. In the United States, Bhatnagar et al. (2022) evaluated wind drought events over a 3 year period from 2018 through 2020 for several balancing areas, including the Electric Reliability Council of Texas (ERCOT), Independent System Operator of New England (ISO-NE), Midcontinent Independent System Operator (MISO), and PJM Interconnection LLC (PJM). They defined wind droughts as a continuous period during which the average hourly output is less than 10% of the average hourly output during that calendar month. The study looked at 8-, 12-, 24-, 48- and 72-hour events across each of these operational footprints. Bracken et al. (2024) analysed compound wind and solar droughts with synthetic power production within all balancing authorities in the United States. They adopted a standardized renewable energy production index to identify periods when production fell below 10% of the average for three reference periods – all years of the data, the week of the year, and the hour of the day. Gilmore et al. (2022) conducted a similar analysis to Bhatnagar et al. for the Australian National Electricity Market (NEM). Throughout the paper, the authors emphasized that "VRE drought risks may have been overstated.” This was largely based on a previously stated concern about needing to find an alternative supply for 80-90% of the grid over a period of seven days. This is revised down to around 45% - but the presented timeline is still seven days, showing a strong need for large and long duration energy storage. Ohba et al. (2023) investigate the effects of low-VRE events on residual loads in Japan.

Table 1 summarizes and compares the methodologies used to estimate VRE droughts in the relevant literature outlined above with the approach used in this paper, which is further elaborated in the next section.

Table 1. Overview of approaches used in selected quantitative studies of variable renewable energy droughts

Study	Data	Temporal Resolution	Threshold	Evaluation Window	Minimum Duration	Variable Renewable Energy (VRE) Type	Geographical Resolution
Raynaud et al. (2018)	Modelled power production	Daily	Fraction of the average output over the full time horizon	Daily	24 hours	Wind, solar and run-of-river hydro	National (Europe)
Ohlendorf and Schill (2020)	Modelled power production	Hourly	Power capacity factors of 2%, 5% and 10%	Individual hourly observations or a moving average	5 hours	Wind	National (Germany)
Li et al. (2021)	Modelled power production	Hourly	Power capacity factor of 20%	Hourly and daily	24 hours	Wind and solar	National and multinational (Europe)
Bhatnagar et al. (2022)	Historical measurements	Hourly	10% of the average output over a 30-day period	Moving, eight-hour average	8 hours	Wind	Regional (United States)
Gilmore et al. (2023)	Modelled power production	Hourly	% of average and expected over running period	1 to 60 days	1 day	Wind and solar	National (Australia)
Mayer et al. (2023)	Modelled future power production and historical measurements	Hourly	Power capacity factors of 1%, 5% and 10%	Hourly	1 hour	Wind and solar	National (Hungary)
Bracken et al. (2024)	Modelled historical power production	Hourly	10% of output averaged over all years, week of year, and hour of day	1-hour, 4-hour, 12-hour, 1-day, 2-day, 3-day, 5-day	1 hour	Wind, solar, and load	National (United States)

This study	Historical measurements	Hourly	10%/30% of the average output over a 30-day period for wind/solar	Four hour (wind)/daily (solar and combined wind/solar)	4 hours (wind)/1 day (solar and combined wind/solar)	Wind and solar	Regional/National (United States, Europe, Australia)

2 METHODOLOGY: DROUGHT INDICATORS USED IN THIS STUDY

In this study, we explored three different drought conditions: wind droughts, solar droughts and periods of combined wind and solar droughts. We developed a methodology for quantifying each of these drought conditions using measured hourly wind and solar output data. The purpose is to investigate the usefulness of these types of drought metrics as indicators for LDES needs and to understand what historical operational data can reveal about future system needs. The next sections describe how each of these drought events are calculated, followed by a discussion of some of the key attributes of these indicators.

2.1 Wind Droughts

The wind drought calculation extends upon the methodology described in Bhatnagar et al. (2022). In the mathematical formulation for a wind drought used here, a period of *n* hours *(n_{hours})* is said to contribute to a wind drought if the mean wind output over that n-hour period is less than a certain threshold percentage *($T_{\%}$)* of the mean wind output over a span of time *(t),* given in days. For this work, $T_{\%}$ = 10% was used as the criterion to define a wind drought. This criterion is defined mathematically in (1).

$$\frac{\sum_{i=1}^{n_{hours}} P_{wind,i}}{n_{hours}} < T_{\%} \tag{1}$$

$$where\ T\% = \frac{\sum_{j=1}^{t*24} P_{wind,j}}{t*24}$$

where $P_{wind,i}$ is the average wind output within each hour, and $P_{wind,j}$ is the daily wind output over the reference period *t*.

A wind drought is defined as a consecutive span of time *($l_{drought}$)* during which the hourly average wind output within a rolling period of n_{hours} is below a threshold *T* (defined in the the above criterion) and where that span of time $l_{drought}$ is longer than a defined minimum number of hours *(n_{min})*. This is illustrated in Figure 1. In this example, the rolling period n_{hours} is 4 hours, the minimum number of hours n_{min} is 4 hours, and the actual length of the wind drought, $l_{drought}$, is 5 hours.

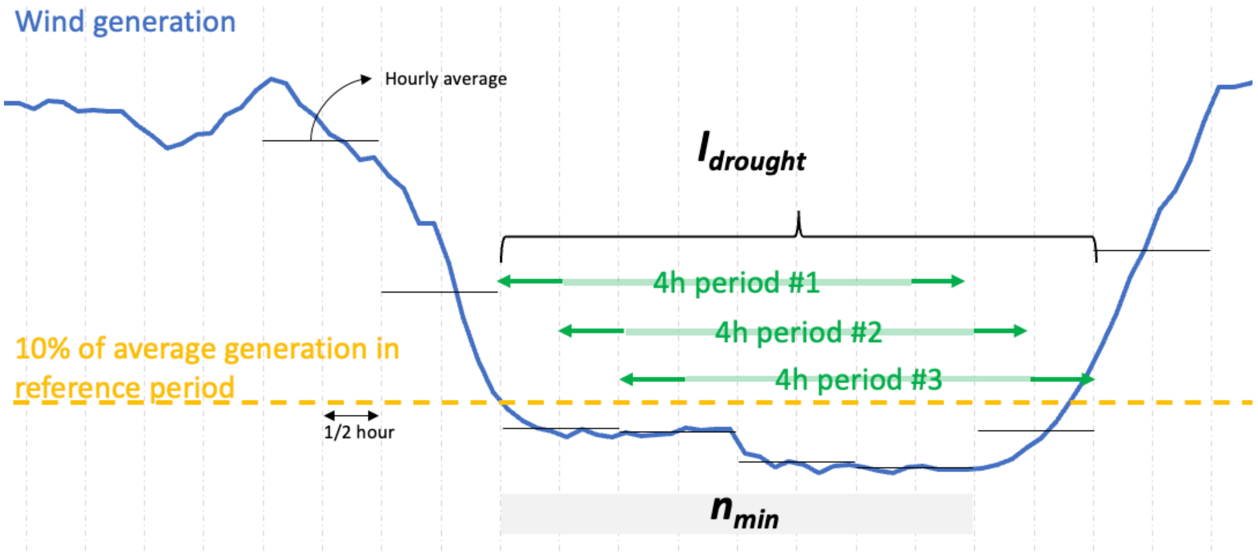


Figure 1. Graphical example illustrating a hypothetical wind drought scenario. The rolling period to evaluate the wind drought, n_{hours}, is 4 hours, the minimum duration to qualify as a wind drought, n_{min}, is 4 hours, and the length of the drought period, $l_{drought}$, is 5 hours.

2.2 Solar Droughts

The solar drought calculation is similar to the wind drought calculation in many respects except that, because of the diurnal nature of solar production, the smallest window of time considered, n_{min}, is a 24-hour period. The average output over a 24-hour period, P_{solar}, is compared to the average daily output of solar within the benchmark span of time, t (for example, 15 days before and 15 days after the 24-hour period in question). If the average output over that 24-hour period is less than the prescribed percentage threshold of the benchmark, $T_{\%}$, then that 24-hour period meets the drought condition as given in (2). For this work, $T_{\%}$ = 30% was used as the criterion to define a solar drought. One or more consecutive 24-hour periods meeting this condition would constitute a solar drought.

$$\frac{\sum_{i=1}^{n_{days}} P_{solar,i}}{n_{days}} < T_{\%} \tag{2}$$

$$where\ T\% = \frac{\sum_{j=1}^{t} P_{solar,j}}{t}$$

where $P_{solar,i}$ is the average hourly solar output within each day, and $P_{solar,j}$ is the daily solar output over the reference period t.

2.3 Drought Energy Deficit

The energy deficit associated with a drought period ($l_{drought}$) in this work is defined as the difference between the typical amount of energy produced by the resource in question and the actual production during the drought period. More specifically, define the amount of energy over the number of hours in the drought during the reference period ($E_{typical}$) and the amount of energy produced by the resource in question during the drought period ($E_{drought}$).

Then, for example, if a wind drought were 5 hours in duration and the period used for benchmarking were the 30 days surrounding that 5 hour event, $E_{typical}$ would be the average hourly wind output for that 30 day period multiplied by 5 hours. $E_{drought}$ would be the average wind output during the 5 hour drought event and the energy deficit, $E_{deficit}$, would be the difference between the $E_{typical}$ and $E_{drought}$. These are represented in (3), (4), and (4).

$$E_{typical} = \frac{\sum_{j=1}^{t*24} P_{wind,j}}{t*24} l_{drought} \quad (3)$$

$$E_{drought} = \sum_{j=1}^{l_{drought}} P_{wind,j} \quad (4)$$

$$E_{deficit} = E_{typical} - E_{drought} \quad (5)$$

2.4 Attributes of the Indicators

Inherent to this methodology is the selection of several parameters and attributes that shape the analysis. Different choices on these parameters will impact how severe a resource deficit needs to be to qualify as a drought and making different assumptions will yield different types of insight. Table 1 summarizes how key assumptions used in this study compare to other recent studies on renewables droughts. The impacts of parameter choice for threshold, window size, and length of reference period are further discussed below.

2.4.1 Threshold

The most basic parameter assumption is the threshold, *T%*, used to evaluate whether the average resource output over a consecutive number of hours qualifies as a drought period. For the analysis presented in this report, a 10% threshold was used for wind and a 30% threshold was used for solar because the intention was to capture droughts that represent periods of notably reduced VRE electricity generation. Using higher thresholds would in general mean that more periods would qualify as droughts, possibly leading to results that show longer and more frequent periods of resource droughts. Because these periods likely would be longer with a less conservative threshold, they could actually represent periods of greater energy deficit, which might yield different insight into LDES or flexibility needs. Although our assumptions used for wind and solar thresholds are largely in line with other studies (Table 1), the choice of this parameter should be explored in more detail in future research. The choice entails whether to identify the more extreme events or also events that occur with higher frequency. LDES and other flexible assets can assist under both types of events.

2.4.2 Window Size

When the wind drought results are calculated, there is a rolling window (labelled n_{hours} in Figure 1) over which power output is averaged to determine whether a period meets the drought condition. This window must be equal to or shorter than the minimum drought length, and the shorter the rolling window size, the more conservative the drought definition is. For example, a one-hour window size would mean that every hour of power output would need to fall below the selected threshold. However, with an eight-hour sliding window, some hours within those eight hours could be above the threshold and still have that period qualify as a drought if the average over that eight-hour period falls below the threshold. In general, a larger rolling window is likely to result in longer droughts in the analysis results. For this study, a four-hour starting window was used for the wind results, and a 24-hour period was used for the evaluation of the solar and combined results due to the daily cycle of solar. The duration of the drought period is identified by increasing the window size by one hour with each pass through the time series for wind, and by 24 hours for the evaluation of solar and combined wind plus solar. This is shown in Figure 1 with two 4-hour periods which result in a drought duration of five hours.

2.4.3 Length of the Reference Period

When evaluating a period to determine whether it meets the drought condition, the resource output must be compared to some "typical" output to determine whether it is below the determined threshold. The choice of the reference period must consider multiple and possibly contradictory criteria, such as providing a robust benchmark generation level that avoids natural (e.g., seasonal) variations and avoid being impacted by changes in installed capacity during the analysis period, all while still capturing energy droughts. In principle, the benchmark for generation could be the capacity of the installed VRE resource or some calculated "typical" output. Different approaches have been taken in terms of reference period length (Table 1). For this study, average resource output over the reference period was selected as the basis for comparison, as it considers the typical performance of the resource and facilitates comparison across different regions independent of resource quality, capacity factor, or changes in installed VRE capacity.

When calculating this benchmark, the length of the reference period considered will have an influence on what qualifies as a resource drought, and this will be more important if there is significant seasonal variability in resource output. For this analysis, a period of one year was used as the benchmark length of the reference period. This longer reference period allows for smoothing of the results to account for skewing of data by factors not directly pertaining to weather, such as prolonged transmission or generation outages or constraints causing resource curtailments. Selection of an annual reference period can, however, obscure sub-seasonal dependencies of droughts. For example, if there were a 3-week period of very low wind output, that might reduce the 30-day average enough so that the period would not fall below a 10% threshold when the reference period is 30 days. However, if that same 3-week period were compared to the average wind output over the course of the full year, it might fall below that 10% threshold and be classified as a drought. This parameter therefore has the potential to shape the types of insights that the resulting drought metric can provide. An annual reference might be more appropriate when considering longer (i.e., several days to weeks) or seasonal type droughts, while a shorter reference period, such as 30 days, might be more targeted at shorter, but less seasonally driven drought periods. Additionally, since this analysis is based on actual historical output data, the longer the reference period used for comparison, the more likely it is that the installed capacity of the resource in the region will change over the course of that period. In many places, the share of wind and solar resources on the grid continues to grow rapidly. To explore the quantitative impact of the choice of reference period length, we compare how the results change for a 30-day vs. annual reference period in one of the sensitivity cases below.

3 RESULTS: ANALYSIS OF HISTORICAL SYSTEM DATA

The results from analysis of wind and solar drought events are presented in this section. The analysis was conducted using the methodology described above applied to observed hourly dispatch data from 2018–2022 for the USA (CAISO and ERCOT), 2019—2022 for Canada (Hydro Québec), 2016—2020 for the EU (Portugal, Spain, Germany, Denmark, UK, and the Netherlands), and 2018—2023 for Australia.

All drought events were identified with an annual reference period. Wind droughts were identified as periods when production fell below 10% of the reference for a minimum window of 4 hours. Solar droughts were identified periods when production fell below 30% of the reference for a minimum window of 1 day.

In addition to the drought results for each resource in each region, additional analyses are presented to look at the impact of resource complementarity during events and regional support through interconnections. The analysis for the USA looks at the complementarity of wind and solar and presents the joint resource drought of the two. The analysis for the EU looks at the aggregation of single resource types across multiple regions.

3.1 United States (USA)

3.1.1 Wind Droughts

The results on wind droughts will be presented in this section for the two ISO/RTO regions in the USA – CAISO and ERCOT. These two regions are highlighted due to their high penetration of wind power in their resource portfolios. CAISO's wind capacity accounts for the majority of the inventory in the western interconnection in the USA and ERCOT operates as an electrically islanded region.

3.1.1.1 California Independent System Operator (CAISO)

CAISO is an independent system operator (ISO) managing the wholesale market and a regional transmission operator (RTO) managing long-term transmission planning in a footprint roughly spanning the state of California in the western half of the country. The CAISO region has a total installed generation capacity of ~75,000 MW, of which 43% is in the form of natural gas while wind and solar resources account for over 30% (Figure 2; EIA 2023). The region also has close to 5,000 MW (~6%) of batteries installed as of 2022, comprised mostly of 4–6 hours of energy storage. As of early 2024, that number has already risen to 8,000 MW installed, with another 4,600 MW under construction (EIA 2024).

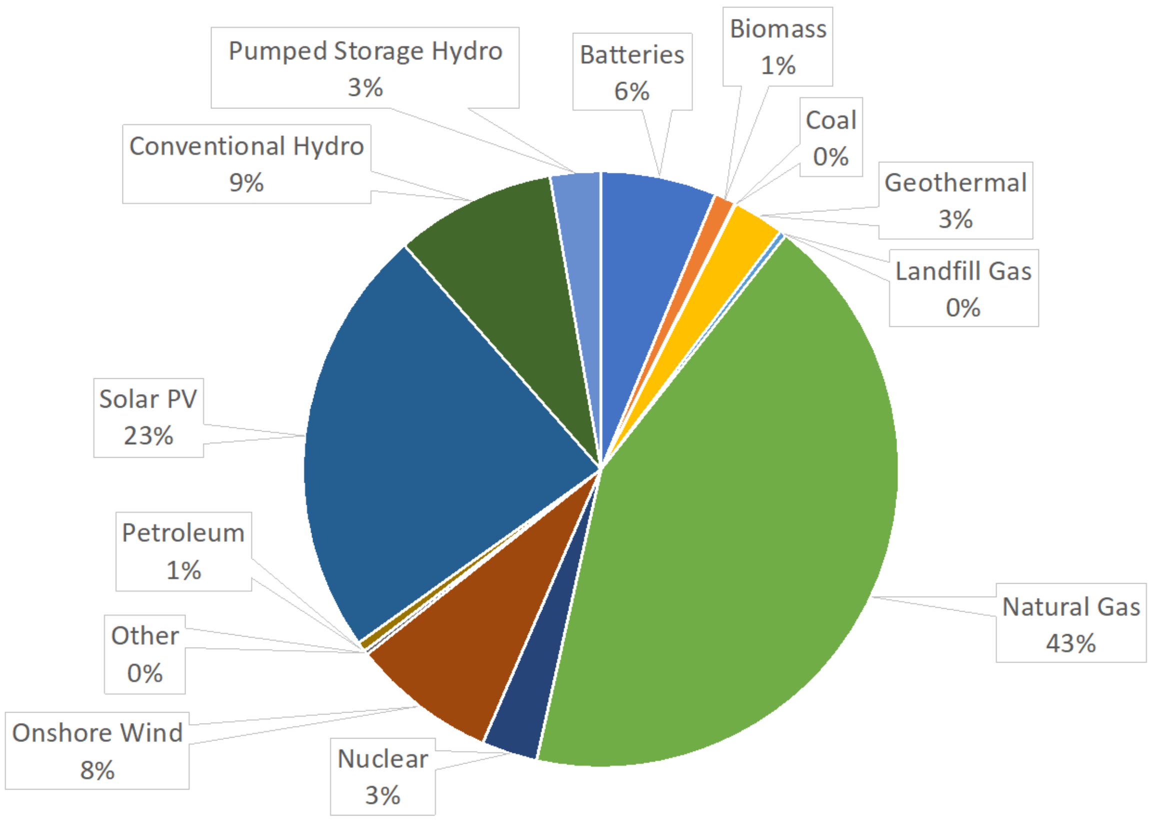


Figure 2. Wind and solar resources in California Independent System Operator account for roughly 30% of the generation inventory

Description of Wind Drought Events in CAISO: Table 2 shows the total number of wind drought events for each of the analysis year. Except for the year 2021, the total number of drought events has remained relatively steady although the count by duration of events differs slightly. Figure 3 (left) shows that most wind drought events in CAISO span 4–16 hours, with roughly the same number of events for 4–8 and 8–16 consecutive hours in total duration. Events spanning 16 hours or longer have also been observed, but those account for less than 10% of all events. The average duration of wind drought events across the years was observed to be ~8 hours, and the longest event, which lasted 42 consecutive hours, was observed in 2019. These drought durations become relevant when considering necessary LDES requirements, as an 8-hour wind drought would exhaust the capacity of most batteries.

The average percent of load that is met by wind during normal conditions is roughly 8%, however this drops by a factor of eight to 1% of system load during wind drought events (demonstrated in Figure 4). As expected, the largest energy deficits occurred during the longest wind droughts, i.e. those spanning more than 16 hours in total duration.

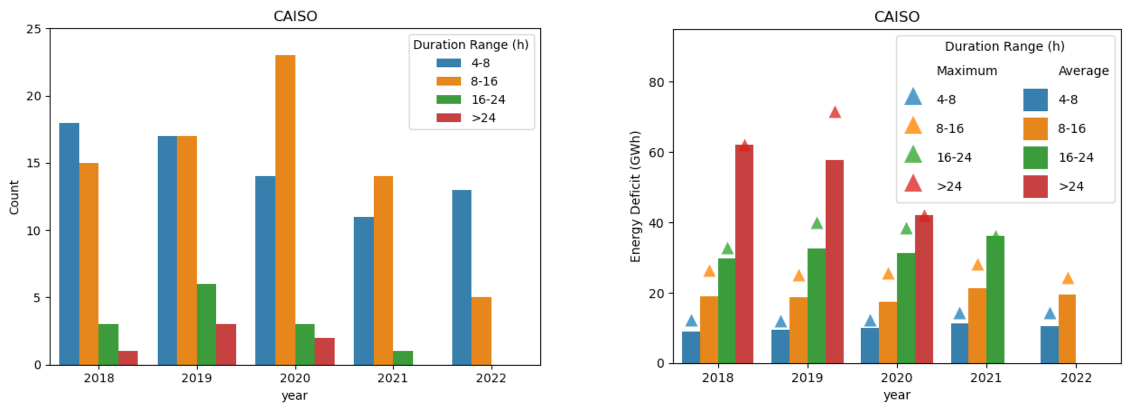


Figure 3. Solar drought frequency (left) and energy deficit by duration (right) in CAISO.

<u>Potential Implications for LDES in CAISO:</u> Estimation of the energy and power capacity needs for LDES can look to the maximum wind deficit and the average deficit. We can estimate the maximum capacity need for LDES by sizing the resource to serve the largest wind deficit event, i.e. the event lasting 42 consecutive hours in 2019 (Table 2). Given the associated energy deficit of ~72 GWh, the LDES resource would need to be sized at ~1,700 MW capable of continuously discharging for 42 hours. The average energy capacity needs are shown in Figure 4. Wind drought events last for roughly 8 hours in this region, amounting to an average energy deficit of 15 GWh (Figure 4, right). If designed to serve average energy deficits, LDES resources would need to be sized at 1,875 MW capable of discharging continuously for 8 hours. As a point of comparison, there is 4,822 MW/16,625 MWh of energy storage currently operating in the CAISO region as of 2022 (EIA 2023). In reality, a combination of storage assets of different durations as well as other dispatchable resources will likely provide the flexibility needed to address the range of wind drought events.

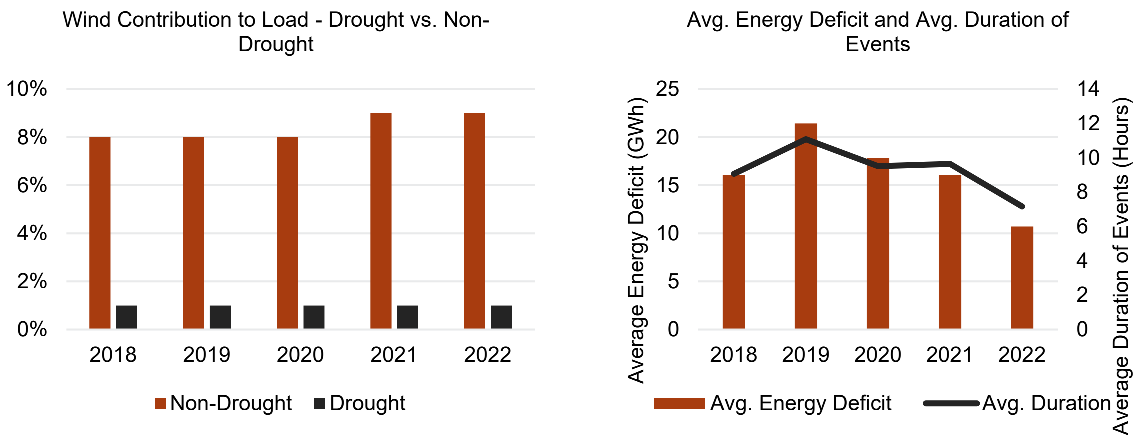


Figure 4. Wind supports load in CAISO more during non-drought events by a factor of eight (left). Average wind energy deficit is 15 GWh providing supply for 8 hours (right).

Table 2. Number of wind drought events, duration of longest event, and energy deficit of longest event in California Independent System Operator

Parameter	2018	2019	2020	2021	2022
Number of Events	37	41	41	26	18*
Duration of Longest Event (h)	35	42	26	18	12
Energy Deficit - Longest Event (GWh)	62	72	44	36	25

*Data for 2022 were only available for half of the year

Sensitivity of Results to Reference Period Aggregation: The number of reported wind drought events was observed to increase significantly in CAISO when using the annual average as reference instead of the 30-day period used throughout this report (Figure 5). The number of drought events was observed to increase by at least 20% in every category, except for the 4–8-hour events. The associated amount of energy deficit also increased significantly when using the annual average. The corresponding change in energy deficit, relative to total system, also increased slightly from 6% to 7%. The maximum power output needed to resolve the deficit remains the same between the two scenarios at ~1,700 MW. However, given that the duration of the longest event with annual average (42 consecutive hours) is significantly greater than the longest duration with 30-day average (17 consecutive hours), the upper bound storage size of the LDES resource would have to be significantly greater. Similarly, there is a noticeable difference in the LDES resources serving the average amount of energy deficit. An LDES resource sized using 30-day average would be rated at 1,600 MW, capable of discharging continuously for 7 hours, as opposed to 1,875 MW for 8 hours for the case of annual averages.

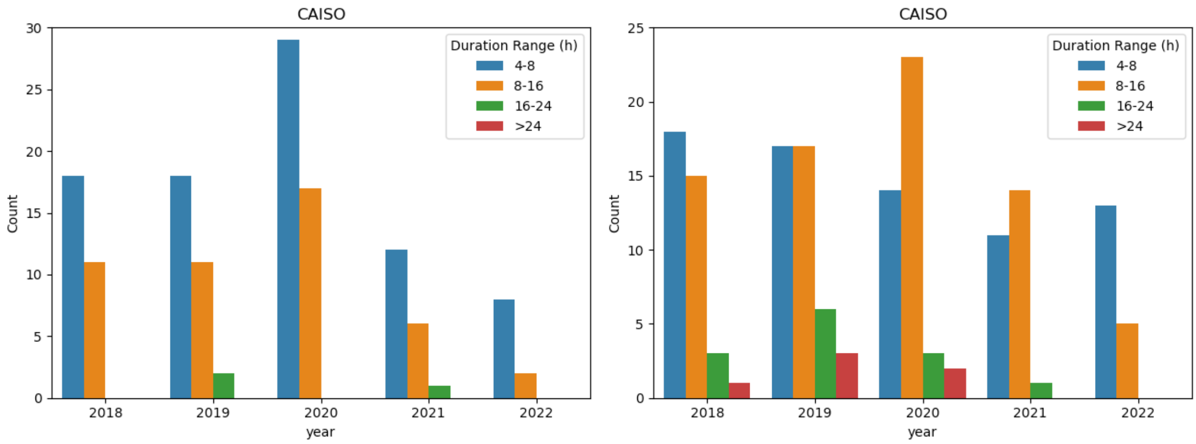


Figure 5. Wind drought frequency identified by comparing with 30-day average (left) and with annual average (right) in CAISO.

3.1.1.2 Electric Reliability Council of Texas

The ERCOT is the ISO and RTO for the region of the USA roughly covering the geographical footprint of Texas. ERCOT manages ~135,000 MW of installed generation capacity with 48% coming from natural gas, 26% from wind, and 8% from solar (Figure 6). ERCOT currently has 2,000 MW (2%) of batteries in operation. Of these, 70% offer less than 2 hours of power and only one provides 4 hours of power with sustained dispatch.

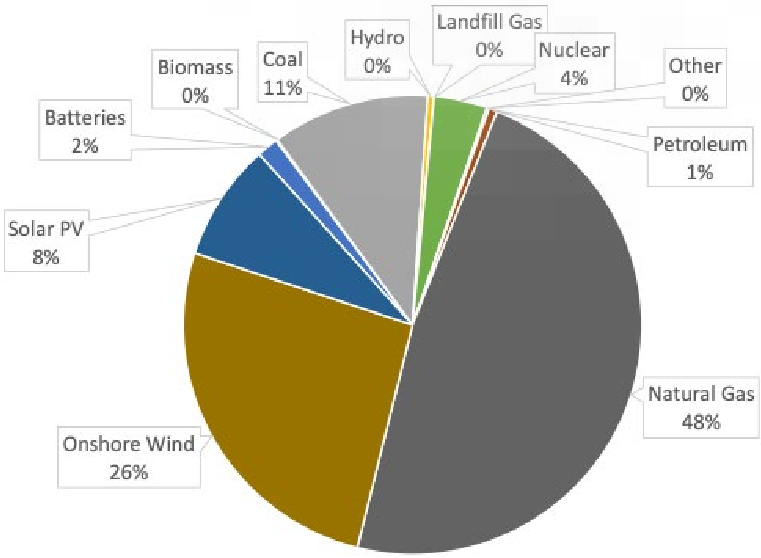


Figure 6. Electric Reliability Council of Texas is dominated by natural gas and onshore wind with marginal support by storage.

Description of wind drought events in ERCOT: Between 2018 and 2022, there was an increase in 8–16-hour wind drought event frequency (Figure 7). In 2019 and 2021, most events spanned 4–8 hours. Events spanning 16 hours or longer were not observed. The average duration of wind drought events was observed to be ~8 hours (Figure 8, right), and the longest event was observed in 2020, lasting 15 consecutive hours (Table 3). The average energy deficit from wind drought events was observed to be in the range of 20–25% of the total system load during the event hours (Figure 8, left). The largest energy deficits occur, as expected, during the longest wind droughts, i.e., those spanning more than 8 hours in total duration.

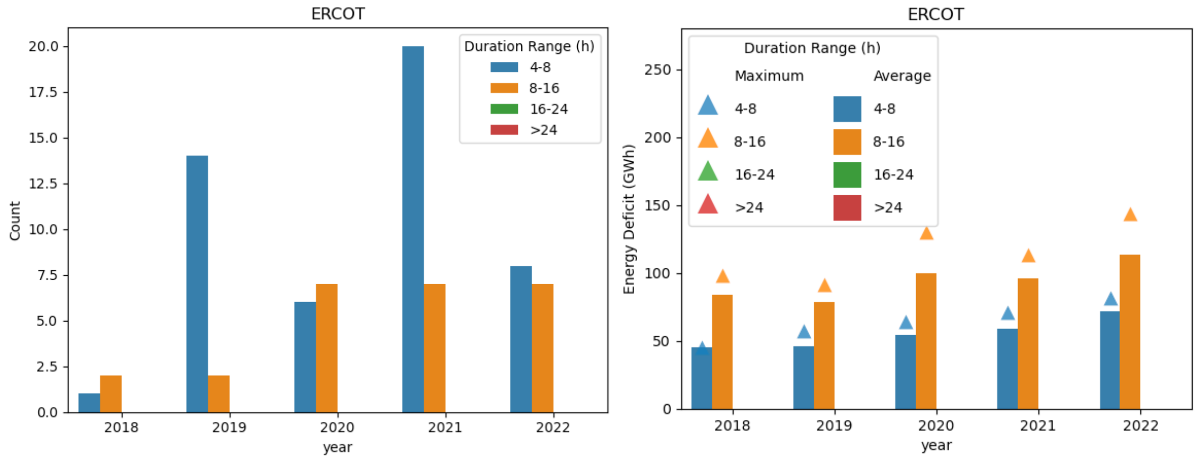


Figure 7. Solar drought frequency (left) and energy deficit by duration (right) in ERCOT.

Potential implications for LDES in ERCOT: The need for LDES can be estimated using the largest energy deficit event and the average event. The largest event lasted 15 consecutive hours in 2020 (Table 3). Given the associated energy deficit of ~146 GWh, the LDES resource would be sized at ~9,700 MW capable of continuously discharging for 15 hours. The average wind drought event lasted 8 hours with an average energy deficit of 80 GWh (Figure 8, right). With LDES resources designed to serve average energy deficits, their capacity would need to be sized at 10,000 MW capable of discharging continuously for 8 hours. With only 10 MW of 4-hour energy storage operating in ERCOT as of 2022, these historical events have largely been addressed through other flexible resources in the ERCOT system (EIA 2023). Recent deployments of storage bring this capacity up to 2.7 GW (Potomac Economics 2023).

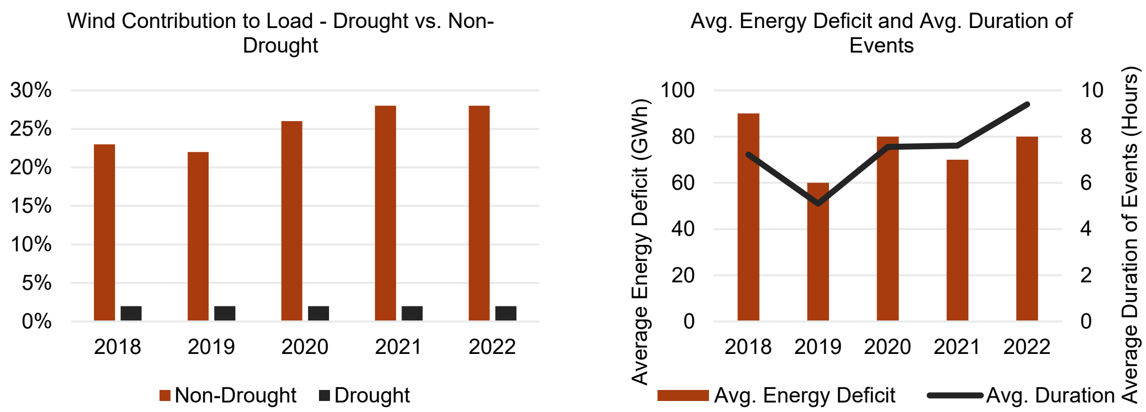


Figure 8. Wind power generation contribution to the load (left), and average deficit (right) in ERCOT.

Table 3. Number of wind drought events, duration of longest event, and energy deficit of longest event in Electric Reliability Council of Texas

Parameter	2018	2019	2020	2021	2022
Number of Events	3	16	13	27	15
Duration of Longest Event (h)	13	11	15	11	12
Energy Deficit - Longest Event (GWh)	100	93	146	120	151

3.1.2 Solar Droughts

3.1.2.1 California Independent System Operator

Description of Solar Drought Events in CAISO: Most solar drought events in CAISO lasted 1 day[1] (Figure 9, left), with some years also including droughts over two successive days. The average energy deficit from solar drought events was observed to be in the range of 12–18% of total system load during the event hours (Figure 10, left). The energy deficits from solar droughts in CAISO were observed to be much greater than wind drought events and showed an increasing trend over the years. This is not surprising, given that solar PV provides a larger share of load than wind in CAISO.

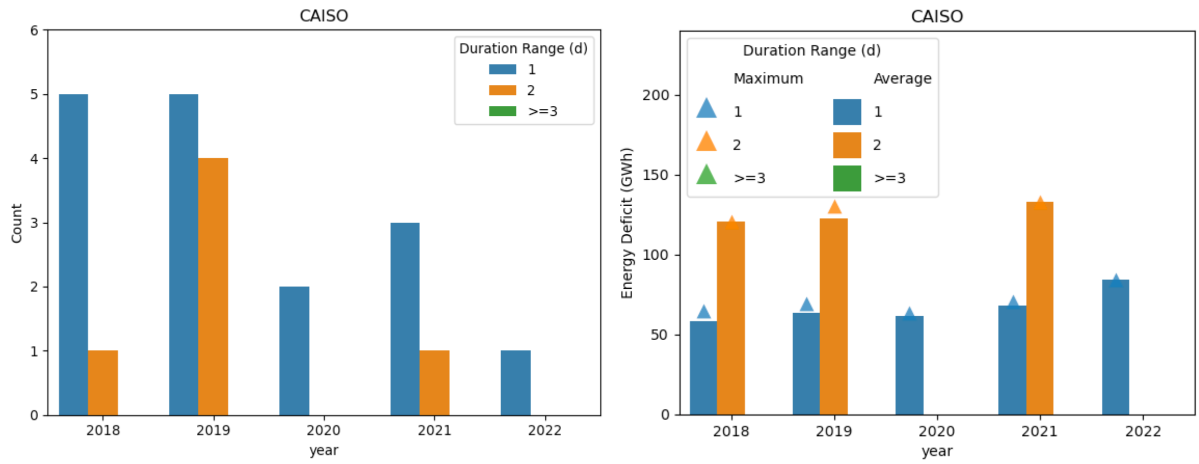
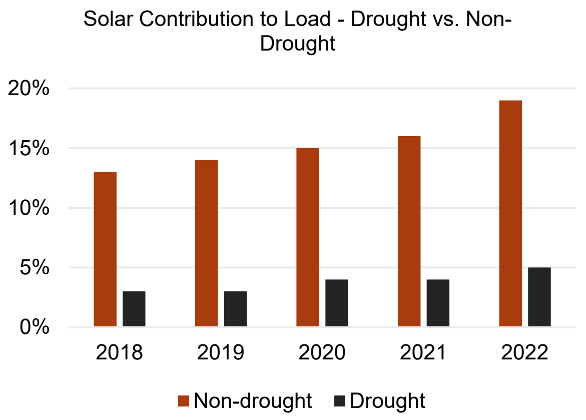


Figure 9. Solar drought frequency (left) and energy deficit (right) by duration in CAISO.

Potential implications for LDES in CAISO: Estimation of the biggest LDES source sized to serve the largest solar deficit event would need to manage the event lasting 2 days (or about 20 hours across two days) in 2021. Given the associated energy deficit of ~140 GWh, the LDES resource would be sized at ~7,000 MW capable of continuously discharging for 20 hours over two days. On average, solar drought events lasted for 1 day (or about 10 consecutive hours) amounting to an average energy deficit of 80 GWh. LDES resources designed to serve average energy deficits would need to be sized at 8,000 MW capable of discharging continuously for 10 hours. There is 3,600 MW of 4-6-hour duration of energy

[1] A one-day period realistically equates to 8–12 consecutive hours of solar drought, depending on the time of a year. This analysis assumes 10 hours of continuous LDES discharge are needed to support solar droughts.

storage currently deployed in the CAISO region and 2 MW of storage capable of dispatching at full power for longer than 10 hours (EIA 2023). As with wind droughts observed in ERCOT, other resources are primarily used to balance the system during these events.



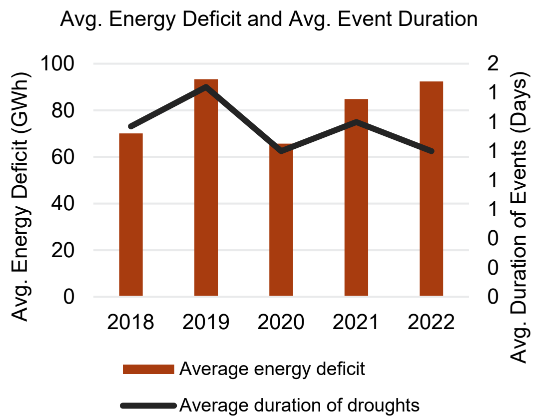


Figure 10. Solar power generation contribution to load (left), and average deficit (right) in CAISO.

Table 4. Number of solar drought events, duration of longest event, and energy deficit of longest event in California Independent System Operator

Parameter	2018	2019	2020	2021	2022
Number of Events	6	9	2	5	1
Duration of Longest Event (days)	2	2	1	2	1
Energy Deficit - Longest Event (GWh)	123	136	67	140	92

3.1.2.2 Electric Reliability Council of Texas

Description of solar drought events in ERCOT: Most solar drought events in ERCOT were observed to last for 1 day, with some years also including droughts occurring over 2, 3, and 5 successive days (Figure 11, left). The average energy deficit from solar drought events was observed to be in the range of 1–5% of total system load during the event hours (Figure 12, left), which is considerably lower than the energy deficit events during the wind drought events in ERCOT. This is because solar PV currently contributes much less than wind to meet load in ERCOT.

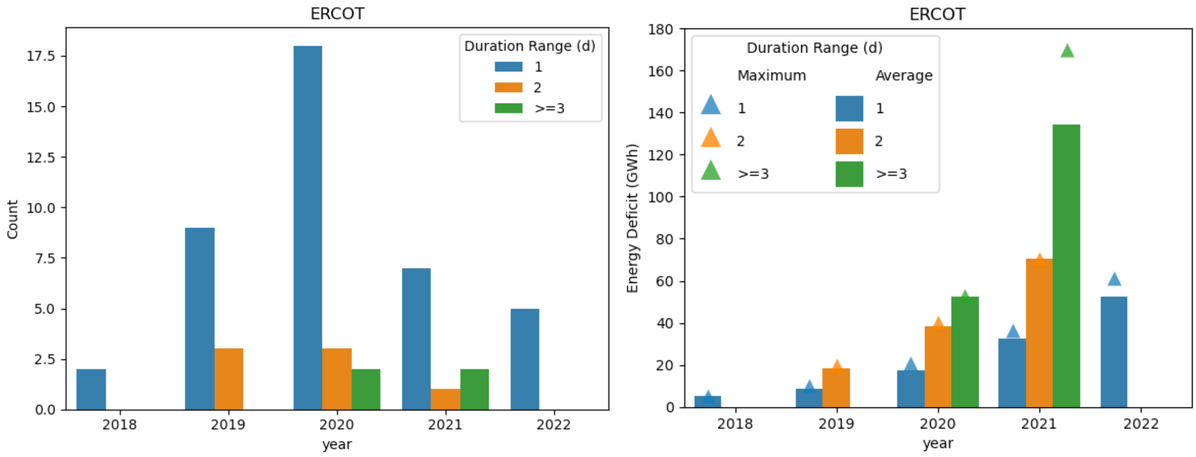


Figure 11. Solar drought frequency (left) and energy deficit (right) by duration in ERCOT.

<u>Potential implications for LDES in ERCOT:</u> Estimation of the largest LDES source can size to serve the largest solar deficit event, i.e. the event lasting 5 days (or ~50 hours) in 2021. Given the associated energy deficit of ~190 GWh, the LDES resource would be sized at ~3,800 MW capable of continuously discharging for about 50 hours over 5 days. On average, solar drought events lasted for 2 days (or about 20 hours) amounting to an average energy deficit of 60 GWh. LDES resources designed to serve average energy deficits would need to be sized at 3,000 MW capable of discharging across 20 hours. As of 2022, there are 10 MW of 4–6-hour energy storage resources operational in ERCOT, with a total installed capacity of 2.7 GW of storage (EIA 2023; Potomac Economics 2023).

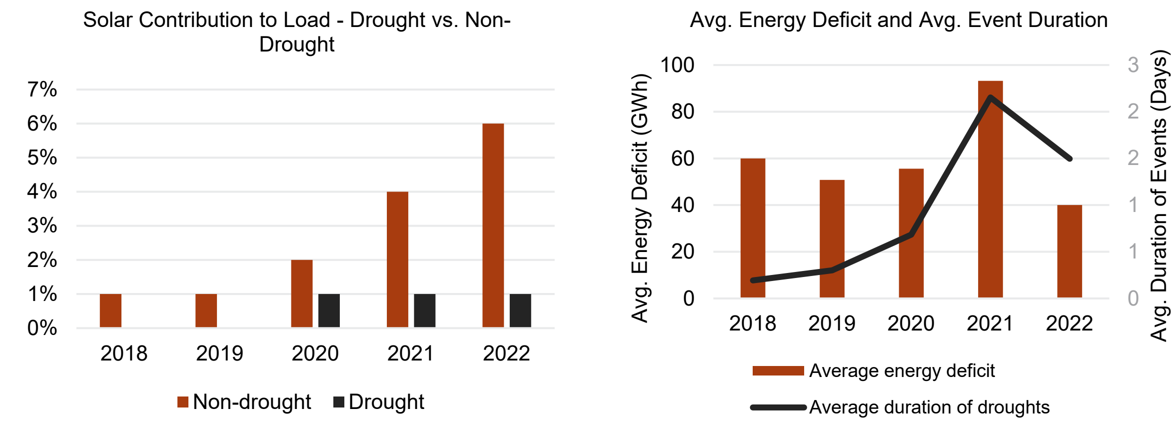


Figure 12. Solar power generation contribution to load (left), and average deficit (right) in ERCOT.

Table 5. Number of solar drought events, duration of longest event, and energy deficit of longest event in Electric Reliability Council of Texas

Parameter	2018	2019	2020	2021	2022
Number of Events	2	11	18	6	3
Duration of Longest Event (days)	2	2	3	5	1
Energy Deficit - Longest Event (GWh)	10	21	57	189	67

3.1.3 Complementarity of Wind and Solar

While the dearth of anticipated power from any individual resource carries real consequences for system balance of load, coincident droughts across multiple resources will compound this impact. To address this, the complementarity between wind and solar generation was analysed by calculating the expected vs. actual wind generation during the solar drought events. The expected amount of wind generation was calculated using the same methodology that was used for determination of wind drought events. If the actual amount of wind generation is greater than the expected amount during a solar drought event, then it may be concluded that the additional wind generation can serve some of the energy deficit created by solar drought. For both CAISO and ERCOT, it was observed that, on average, the actual wind generation was a lot less than the expected amount during the solar drought events. Hence, it may be concluded that, on average, wind generation added to the energy deficit during solar drought events. This observation varies across years and is more significant in CAISO than ERCOT. Further investigation of combined shortages of wind and solar (e.g., dunkelflaute events) should be explored in future work to characterise their compounded stress to the system.

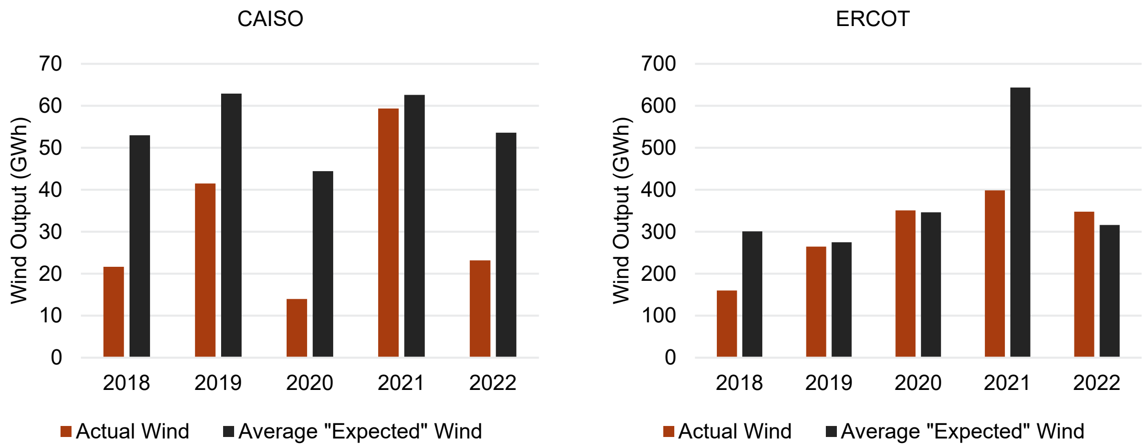


Figure 13. Actual and expected wind production in CAISU (left) and ERCOT (right) during solar drought events.

3.2 Québec

Québec is a province of Canada, in which most of the power generation comes from hydropower generating stations operated by state-owned Hydro Québec, which has a total of about 40 GW of installed capacity (Figure 14; Hydro Québec 2024). Starting from the 2000s, wind generation has been regularly added to the generation portfolio to support load growth. There is currently more than 3.7 GW of installed wind generation in Québec, mostly along the Saint-Laurent River. Note that the solar installed capacity in Québec is currently too limited to allow for a comparable data analysis.

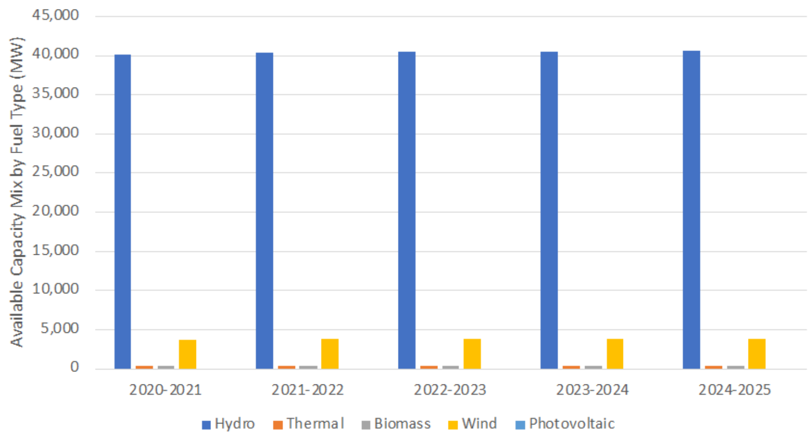


Figure 14. Generation inventory by fuel type and year in Québec

3.2.1 Wind Droughts

The input data for this analysis were wind generation data from 2019 to 2021 in Québec. The installed capacity throughout this period was stable at roughly 3.9 GW. The average wind drought event, i.e. during which wind output was constantly below 10% of long-term average, is 10 hours (Table 6). This is similar to values reported for other regions in this report such as the USA (e.g., ERCOT, CAISO were each about 8 hours), Europe, and Australia (10 hours).

Table 6. Number of wind drought events, average and maximum duration of longest event and energy deficit of longest event in Québec

Parameter	2019	2020	2021	2022
Number of Events	45	50	51	46
Average deficit (GWh)	12.4	12.3	12.6	12.7
Average duration of droughts (hours)	10	10	11	11
Maximum deficit (GWh)	44.3	36.3	37.8	32.1
Maximum duration of droughts (h)	34	28	32	26

Figure 15 (left) shows that wind droughts longer than 16 hours are much less common than those lasting between 4 and 16 hours. This conclusion is consistent from one year to another throughout the available dataset.

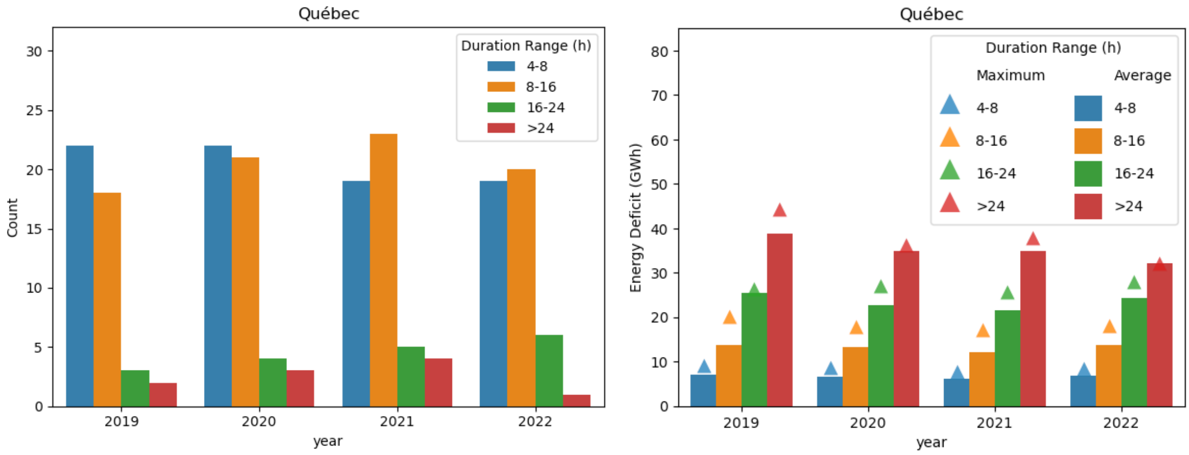


Figure 15. Wind drought frequency (left) and energy deficit (right) in Québec by year

Figure 16 (left) shows that wind contributes roughly 6–7% to load during non-drought conditions and less than 0.5% in drought conditions. Whereas in CAISO the contribution from wind to load drops 8% between non-drought and drought events, in Hydro Québec this drops by roughly 13%, underlining the criticality of LDES to the region especially under future grid conditions where the region's firming hydropower services may be needed to support surrounding regions.

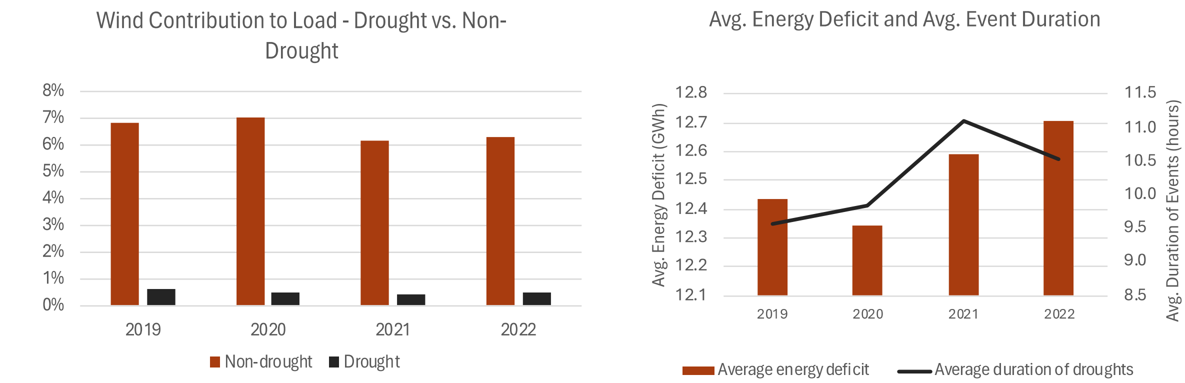


Figure 16. Wind contribution to load during drought and non-drought conditions (left), and average deficit (right) in Québec

Potential implications for LDES: Wind droughts described above last on average 10.3 hours, with an average deficit of 12.5 GWh (Table 6). Therefore, an LDES resource able to support average energy deficits would need to be roughly 1,200 MW size able to provide sustained discharge at this power capacity for 10.3 hours. If the LDES resource was designed to meet the longest deficit (34 hours/44 GWh), it would need to be sized at 1,300 MW with 34 hour discharge duration.

Solutions to manage wind droughts are likely to involve a combination of different tools. Interconnections and demand-side management are two potential contributors; Hydro

Québec currently has 15 interconnections with neighbouring regions.[1] In addition, Hydro Québec owns and operates a maximum amount of hydropower storage of about 175 TWh.[2] This storage capacity plays various roles such as hedging against sustained hydrological droughts that can last over months or years. However, in an almost 100% hydropower region like Hydro Québec, hydro storage is also used to manage shorter term variations of load and wind generation.

3.3 European Union (EU)

The composition of capacity mix in Europe varies greatly across countries (see Figure 17; **Eurostat 2019**). For instance, wind accounts for around 41% of Denmark's total installed capacity, but only 12% in the Netherlands. Average wind capacity throughout Europe was around 18% in 2019. Similarly in solar capacity, Germany and the Netherlands have around 20% solar capacity while Portugal has 4%. The average is around 13%.

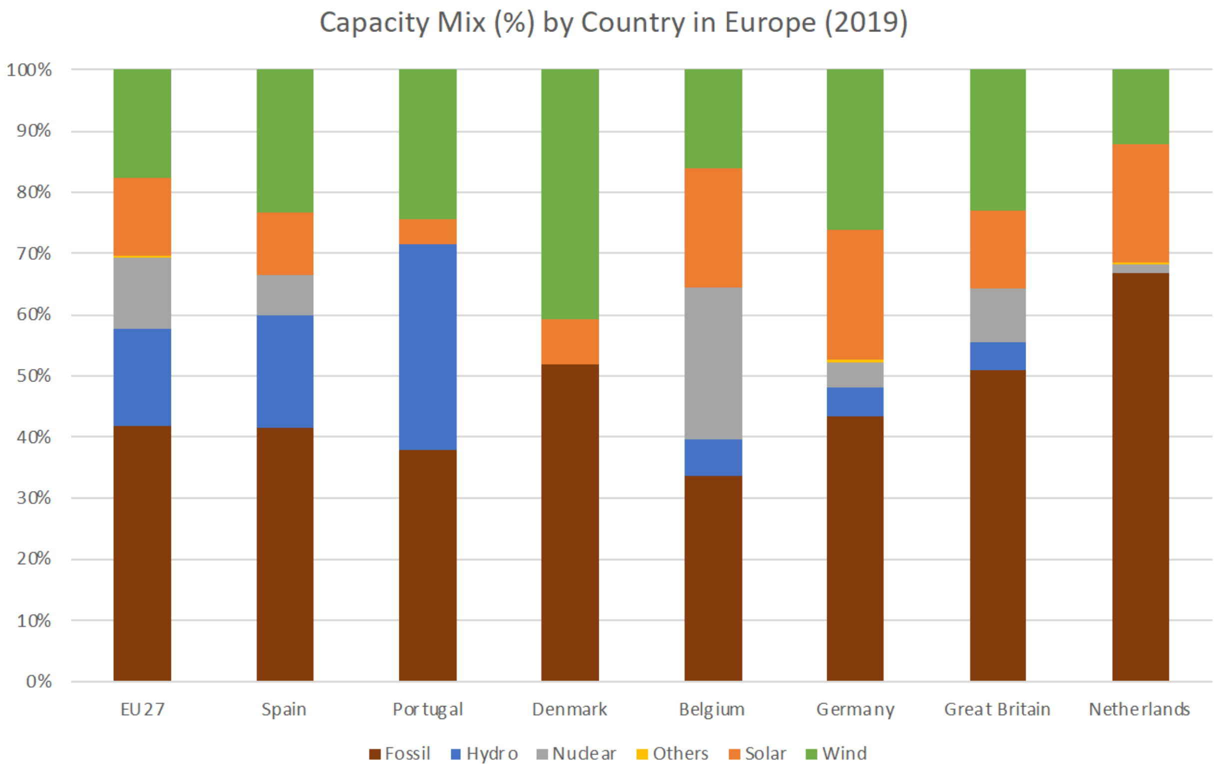


Figure 17. Capacity mix in Europe categorized by country, 2019

European countries have had an uneven pace of renewable energy adoption. As shown in Figure 18 (left, green dots), Denmark has the highest average wind power generation, while Spain and Great Britain are second and third, respectively, based on the data between 2016 and 2020.[3] Compared to the load, countries like Denmark, Ireland, Portugal, Germany, and

[1] https://www.hydroquebec.com/transenergie/en/

[2] https://www.regie-energie.qc.ca/fr/participants/dossiers/R-4210-2022/doc/R-4210-2022-B-0011-Demande-Piece-2022_11_01.pdf see Table 4.5

[3] Open Power System Data. 2020. Data Package Time series. Version 2020-10-06. https://doi.org/10.25832/time_series/2020-10-06. (Primary data from various sources, for a complete list see URL).

Spain have more than 20% of their load met by wind power (not shown). The wind power generation to load ratio averaged over these regions is 11.1%. The quality of wind power generation varies as well in terms of wind droughts counts and duration. Figure 18 (left, blue bars) shows the wind drought count by each country.[1] Germany, Spain, and Great Britain have relatively less frequent wind drought while simultaneously having very high amounts of wind generation. Figure 18 (right, green dots) shows the wind drought average duration by country. Most of the countries have average drought durations ranging between 5 to 15 hours.

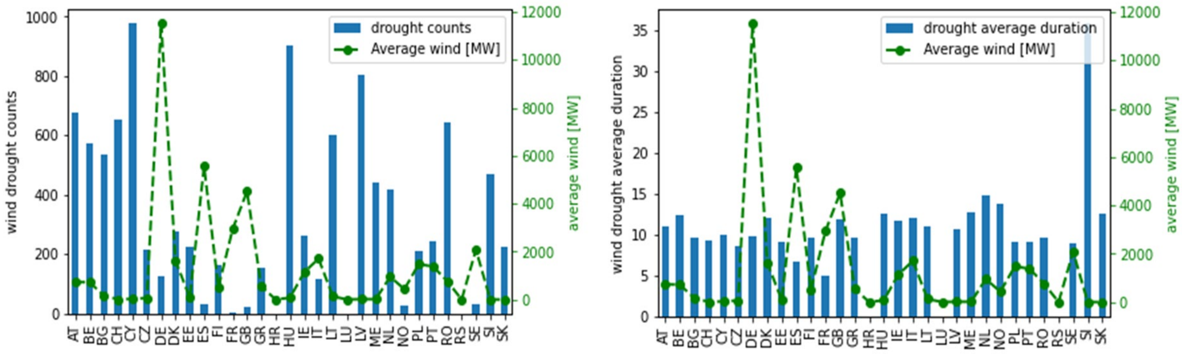


Figure 18. Wind drought frequency (left) and average duration (right) with energy deficit by duration in European Union countries by year (blue) superimposed over average annual wind production between 2016–2020 (green)[2]

In this study, we will take a closer look at (1) wind and solar generation in Spain and the aggregation of Spain and Portugal; and (2) offshore wind generation in countries around the North Sea.

The rationale for choosing Spain, Portugal, and Spain + Portugal is grounded in several key factors. First, Spain and Portugal must contend with geographically imposed transmission capacity limitations with the rest of Europe. Second, there exists a noteworthy interconnection between the grids of Spain and Portugal and the capacity of this interconnection is increasing. Third, both Spain and Portugal have a significant installation of wind power in comparison to their total generation capacity, which makes them strategic choices for further exploration and analysis in this study.

The decision to concentrate on the North Sea countries (e.g., Belgium, Denmark, Germany, Great Britain, and Netherlands) for offshore wind analysis is grounded in a twofold rationale. First, these nations exhibit a notable correlation in offshore wind generation, indicating a potential shared energy landscape. This correlation offers insights into the interconnected

[1] The counts and duration are sensitive to wind capacity. The counts and duration for countries with small capacity could be randomly high or low, e.g. Cyprus or Hungary.
[2] Countries listed are: Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Cyprus (CY), Czechia (CZ), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Great Britain (GB), Greece (GR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Montenegro (ME), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Serbia (RS), Sweden (SE), Slovenia (SI), Slovakia (SK)

dynamics of offshore wind power in the North Sea region. Second, the North Sea has become a focal point for extensive interest and growing capacity in offshore wind power. This strategic focus enables a comprehensive examination of the evolving dynamics and interconnected nature of offshore wind in the North Sea countries.

3.3.1 Wind Droughts

3.3.1.1 Spain

Description of wind drought events in Spain: All wind drought events between 2016 and 2020 in Spain lasted less than 16 hours (Figure 19, left). Seventy-five percent of drought events span less than 8 hours. The average duration of wind drought events across the years was observed to be roughly 6 hours (Figure 20, right), and the longest event, observed in 2019, lasted 12 consecutive hours (Table 7). The average energy deficit from wind drought events is in the range of 18–20% of total system load during the event hours (Figure 20, left). The largest energy deficits occur, as expected, during the longest wind droughts, i.e., those spanning more than 12 hours in total duration.

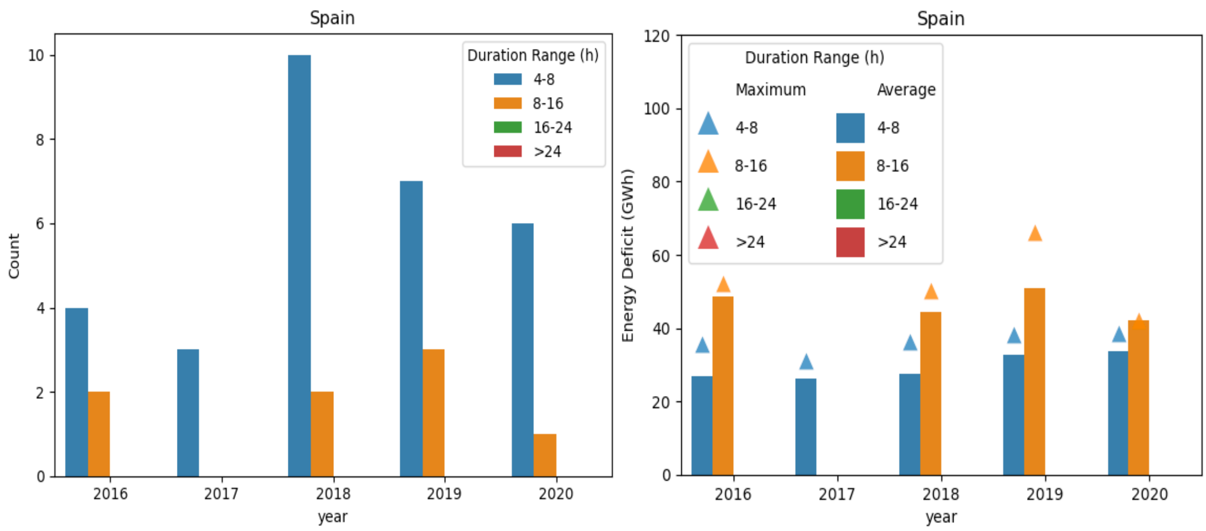


Figure 19. Spain wind drought frequency (left) and energy deficit by duration and year (right, triangle markers indicate the deficit of the maximum deficit event)

Potential implications for LDES in Spain: An upper bound to the LDES sizing needs would need to account for the largest wind deficit event, i.e., the event lasting 12 consecutive hours in 2019 (Table 7). Given the associated energy deficit of ~66 GWh, the LDES resource would be sized at ~5,500 MW capable of continuously discharging for 12 hours. On average, though, wind drought events last for 8 hours amounting to an average energy deficit of 35 GWh. Hence, LDES resources, designed to serve average energy deficits, would need to be sized at 4,400 MW capable of discharging continuously for 8 hours. As a point of comparison, there is 8,300 MW of energy storage currently deployed in Spain, inclusive of hydropower.

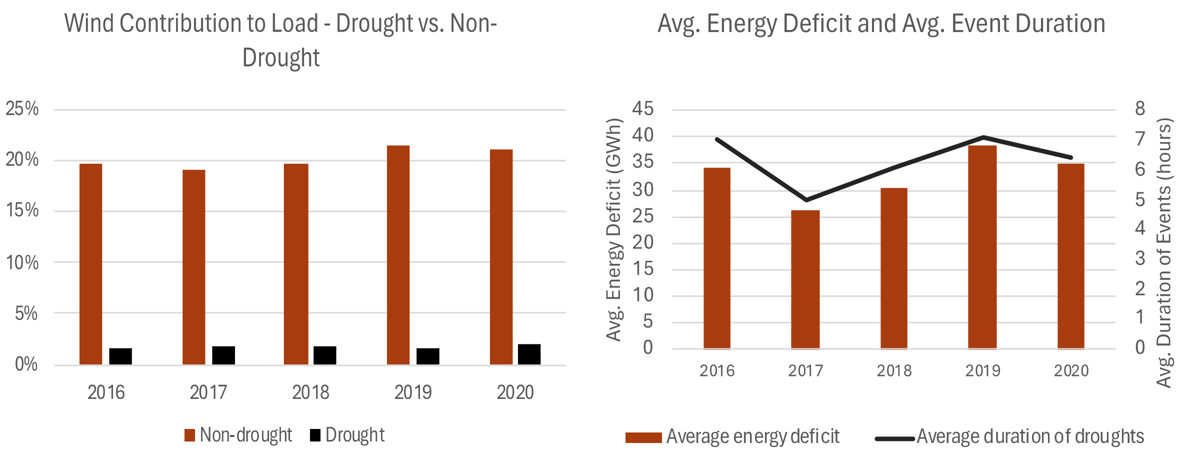


Figure 20. Spain wind power generation contribution to the load (left), and average deficit (right) in Spain.

Table 7. Duration and energy deficit from the longest wind drought event in Spain

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (h)	10	6	10	12	8
Energy Deficit – Longest Event (GWh)	52.1	31.1	50.4	66.1	42.0
Number of Events	6	3	12	10	7

3.3.1.2 Portugal

Description of wind drought events in Portugal: Of the observed wind drought events in Portugal, 57.6% spanned less than 8 hours while only 8% of events lasted longer than 16 hours (Figure 24, left). The average duration of wind drought events across the years was observed to be ~8 hours (Figure 25, right), and the longest event was observed in September 2020, which lasted 42 consecutive hours (Table 9). The average energy deficit from wind drought events is in the range of 21–27% of total system load during the event hours (Figure 25, left). The largest energy deficits occur, as expected, during the longest wind droughts, i.e., those spanning more than 42 hours in total duration.

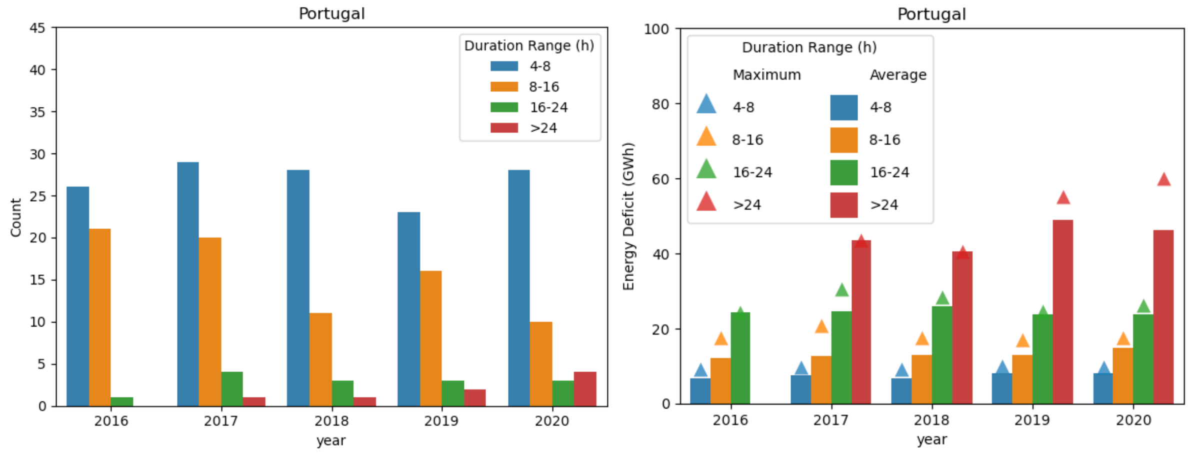


Figure 21. Wind drought frequency (left) and energy deficit by duration by year in Portugal (right, triangle markers indicate the deficit of the max deficit event)

<u>Potential implications for LDES in Portugal:</u> Assuming that the entire amount of energy deficit will be served by LDES resources, the biggest LDES source would need to be sized to serve the largest wind deficit event, i.e., the event lasting 42 consecutive hours in 2020. Given the associated energy deficit of ~60 GWh, the LDES resource would be sized at ~1,570 MW capable of continuously discharging for 42 hours. On average, though, wind drought events lasted for 8 hours amounting to an average energy deficit of 17.4 GWh. Hence, LDES resources, designed to serve average energy deficits, would need to be sized at 2,200 MW capable of discharging continuously for 8 hours. As a point of comparison, there is 2,900 MW[1] of energy storage currently deployed in the Portugal region.

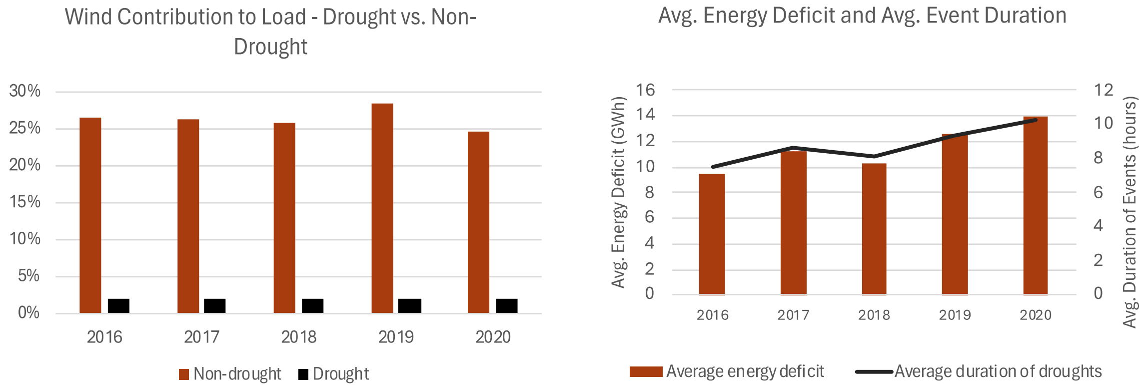


Figure 22. Wind power generation contribution to the load (left) and average deficit in Portugal (right)

[1] https://www.energyglobal.com/energy-storage/28012022/iberdrola-develops-giga-battery-in-portugal/

Table 8. Duration and energy deficit from the longest wind drought event in Portugal

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (h)	19	31	33	40	42
Energy Deficit – Longest Event (GWh)	24.3	43.4	40.5	55.2	60.1
Number of Events	48	54	43	44	45

3.3.1.3 Aggregated Resources from Spain and Portugal

Description of wind drought events: The number of reported wind drought events across Spain and Portugal was slightly less than the number of events within Spain alone and much less than the number of events within Portugal alone. This observed decrease is more significant for events lasting greater than 8 hours (Figure 28). The associated energy deficits slightly increase when compared to that of each country individually since the installed wind capacity is much larger in the aggregated system. The average duration of events is similar. The corresponding change in energy deficit, relative to total system, increases slightly from 18% to 20%.

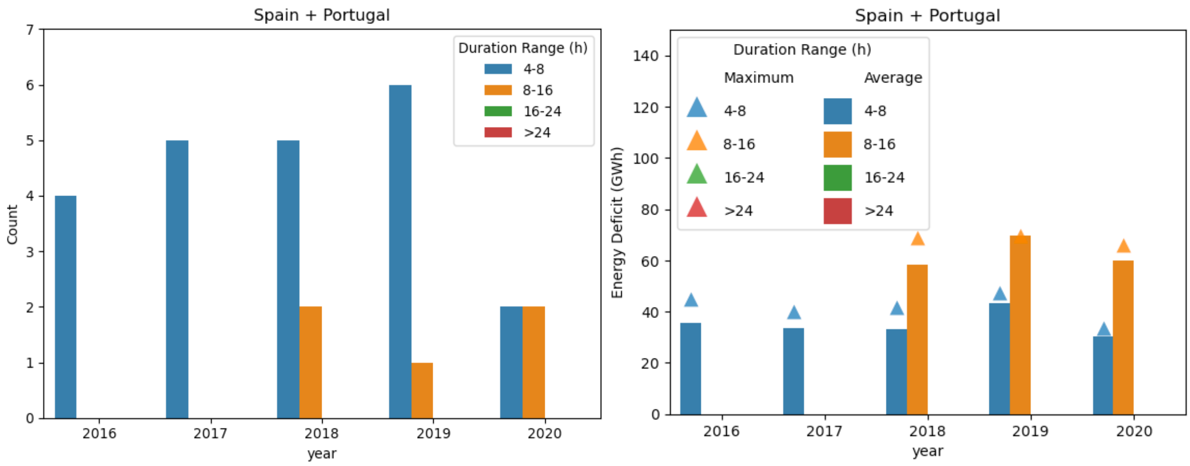


Figure 23. Spain + Portugal wind drought frequency (left) and energy deficit by duration by year (right, triangle markers indicate the deficit of the maximum deficit event)

Implications for LDES in Spain and Portugal: Assuming that the entire amount of wind energy deficit will be served by LDES resources, the duration of the longest event in Spain and Portugal together is slightly less than that of Spain individually and the energy deficit of the longest event is slightly more than that of Spain (Table 11). However, in terms of total LDES required, this represents a smaller requirement than considering the sum of the energy deficit for the two countries separately.

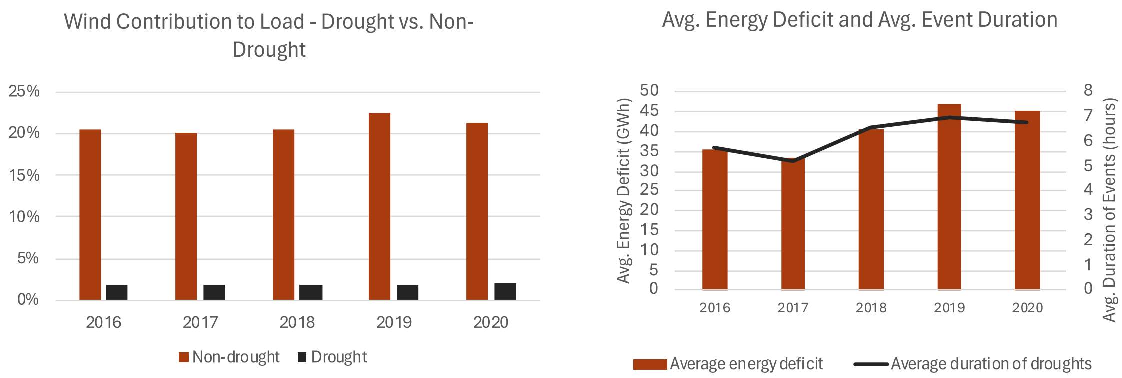


Figure 24. Wind power generation contribution to load and average deficit across Spain + Portugal together

Table 9. Duration and energy deficit from the longest wind drought event across Spain and Portugal

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (h)	7	6	11	10	10
Energy Deficit – Longest Event (GWh)	45.0	40.0	69.1	69.5	66.2
Number of Events	4	5	7	7	4

3.3.2 Solar Droughts

3.3.2.1 Spain

Description of solar drought events in Spain: Most solar drought events in Spain lasted 1 day, with some years also including droughts over two successive days (Figure 21, left). The average energy deficit from solar drought events was observed to be in the range of 4–8% of total system load during the event hours (Figure 22, left). The largest energy deficits from solar droughts were observed to be greater than the largest wind drought events, showing an increasing trend, particularly in 2020 (Table 8).

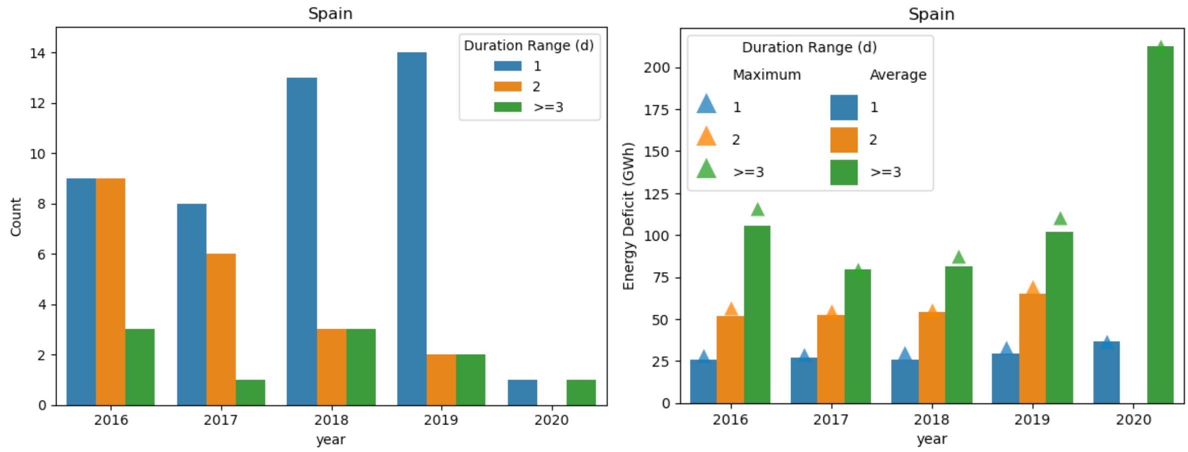


Figure 25. Spain solar drought frequency (left) and energy deficit by duration and year (right, triangle markers indicate the deficit of the maximum deficit event)

<u>Potential implications for LDES in Spain:</u> Assuming that the entire amount of energy deficit would need to be served by LDES resources, the biggest LDES source would need to be sized to serve the largest solar deficit event, i.e., the event lasting 6 days (or about 60 hours) in 2020 (Table 8). Given the associated energy deficit of roughly 212 GWh, the LDES resource would need to be sized at 3,500 MW capable of continuously discharging for 60 hours over six days. On average though, solar drought events lasted for 1 day (or 10 consecutive hours) amounting to an average energy deficit of 25 GWh. Hence, LDES resources, designed to serve average energy deficits, would need to be sized at 2,500 MW capable of discharging continuously for 10 hours. Recalling that there is 8,300 MW operational of energy storage currently Spain including hydropower, the installed capacity would be sufficient to absorb droughts from solar based solely on nameplate power.

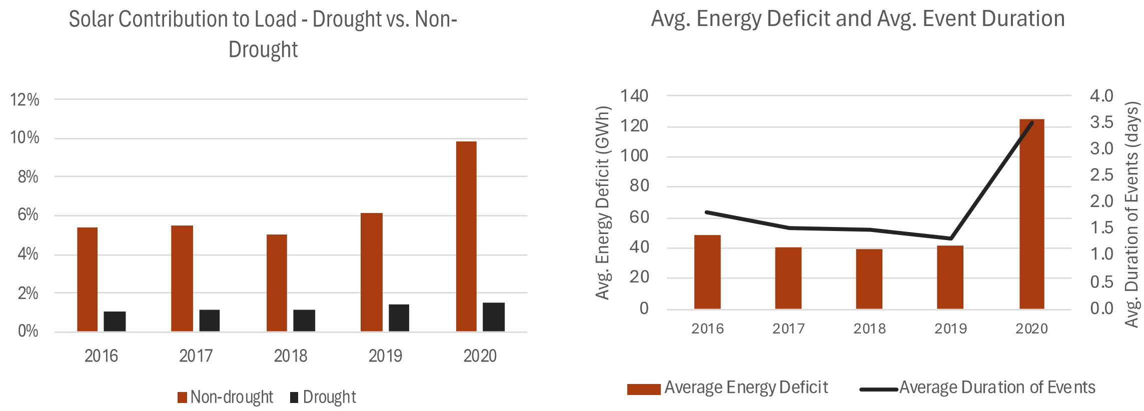


Figure 26. Solar power generation contribution to load (left) and average deficit (right) in Spain.

Table 10. Duration and energy deficit from the longest solar drought event in Spain

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (Day)	4	3	3	3	6
Energy Deficit – Longest Event (GWh)	115.5	79.5	87.3	110.6	212.7
Number of Events	21	15	19	18	2

3.3.2.2 Portugal

Description of solar drought events in Portugal: Given that installed solar capacity is roughly 20% that of wind capacity in Portugal (Figure 17), the impact of solar droughts on this grid is less significant compared with wind droughts. Most solar drought events in Portugal lasted 1 day, with some years also including droughts over two to three successive days (Figure 26, left). The average energy deficit from solar drought events was observed to be in the range of 0.3–0.45% of total system load during the event hours (Figure 27, left).

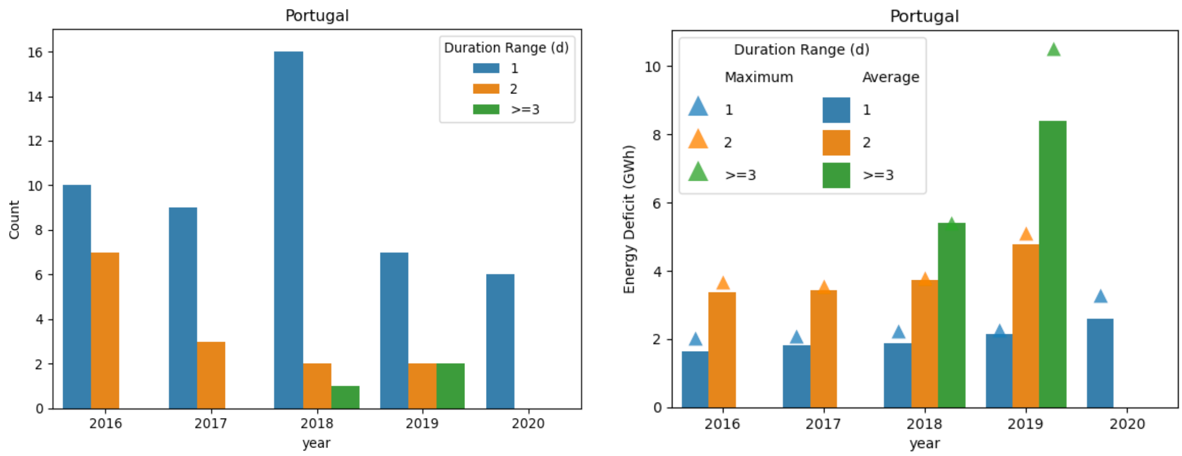


Figure 27. Solar drought frequency (left) and energy deficit by duration by year in Portugal (right, triangle markers indicate the deficit of the max deficit event).

Potential implications for LDES in Portugal: Assuming that the entire amount of energy deficit would be served by LDES resources, the biggest LDES source would need to be sized to serve the largest solar deficit event, i.e., the event lasting 4 days (or about 40 hours) in 2019 (Table 10). Given the associated energy deficit of ~10.5 GWh, the LDES resource would be sized at ~260 MW capable of continuously discharging for 40 hours over four days. On average though, solar drought events lasted for 1 day (or 10 consecutive hours) amounting to average energy deficit of 2.5 GWh. Hence, LDES resources, designed to serve average energy deficits, would need to be sized at 250 MW capable of discharging continuously for 10 hours. As a point of comparison, there is 2,900 MW of energy storage currently deployed in the Portugal region.

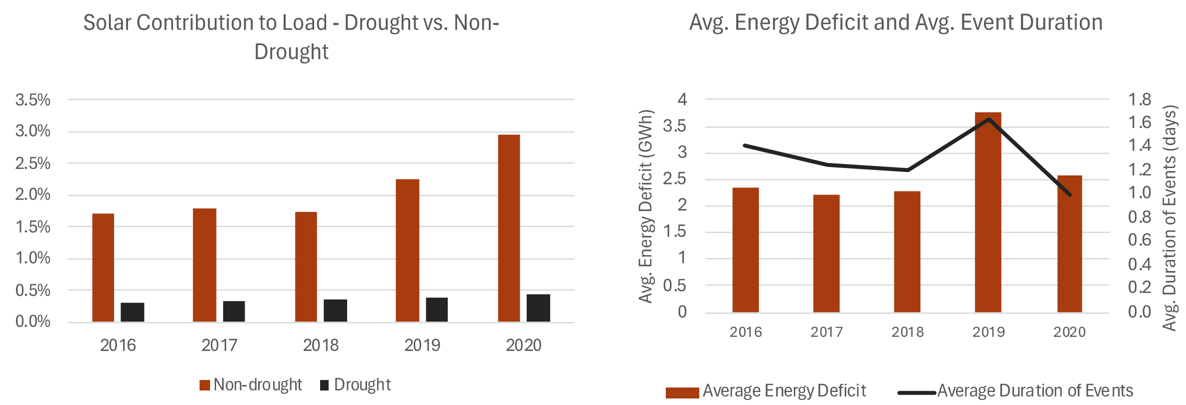


Figure 28. Solar power generation contribution to load (left) and average deficit (right) in Portugal.

Table 11. Duration and energy deficit from the longest solar drought event in Portugal

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (Day)	2	2	3	4	1
Energy Deficit – Longest Event (GWh)	3.67	3.55	5.40	10.51	3.27
Number of Events	17	12	19	11	6

3.3.2.3 Aggregated Resource from Spain and Portugal

Description of Solar Drought Events: The number of reported solar drought events was observed to decrease slightly from 89 to 81 in total when we consider the solar generation from Spain and Portugal together, compared to the number if Spain is considered alone. The associated amount of energy deficit also decreased from 54,525 MWh to 48,337 MWh on average (Figure 30). The average duration of events also decreases from 1.82 days to 1.57 days. The corresponding change in energy deficit, relative to total system, decreases slightly from 5% to 4.4% (Figure 31).

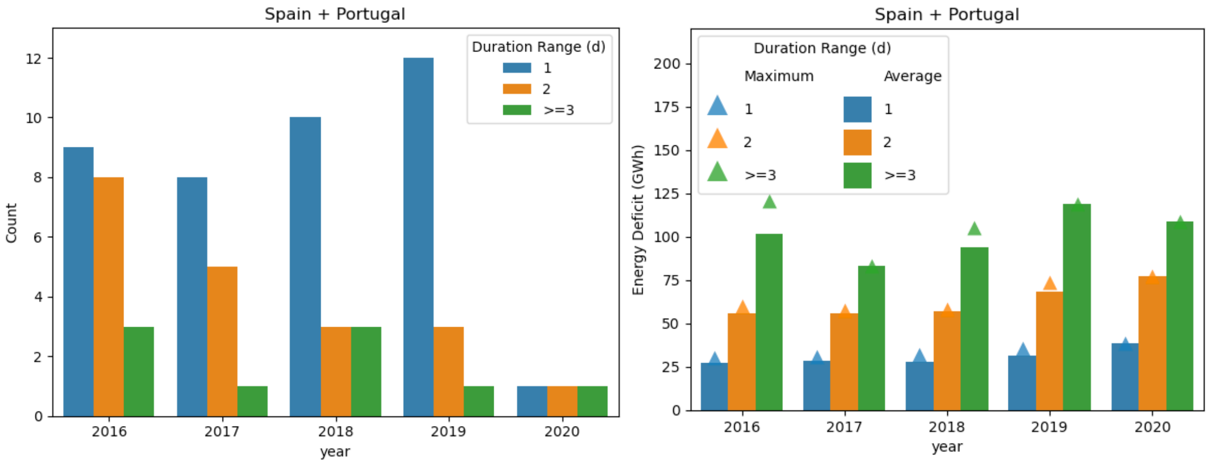


Figure 29. Spain + Portugal solar drought frequency (left) and energy deficit duration by year (right, triangle markers indicate the deficit of the maximum deficit event)

Implications for LDES in Spain and Portugal: Assuming that the entire amount of energy deficit will be served by LDES resources, there would be a decreased need for LDES in terms of both duration and capacity when solar generation from Spain and Portugal is aggregated together, compared to the total requirement in the case when each country is treated independently (Table 12).

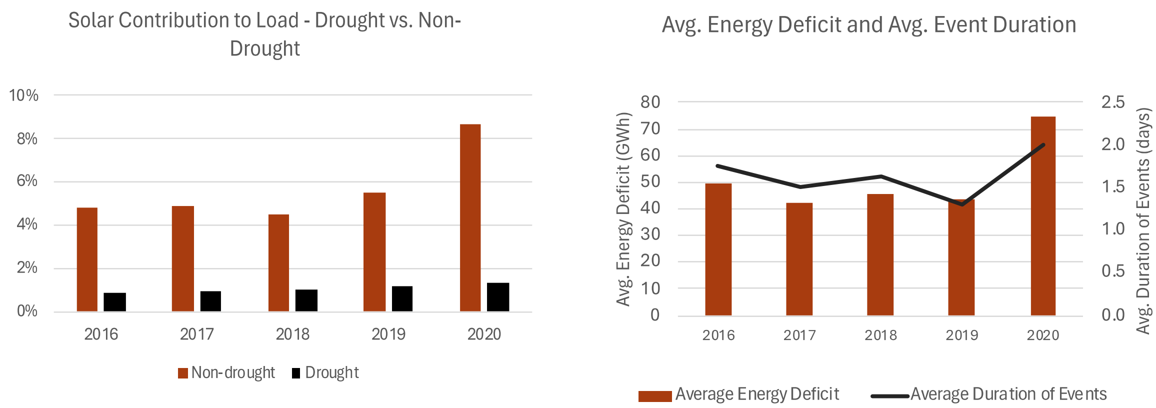


Figure 30. Solar power generation contribution to load (left) and average deficit (right) across Spain + Portugal together

However, given that not all storage qualifies as long duration, the existing units may not be able to sustain output sufficiently. Moreover, due to the integrated nature of the European grid, the storage may well be efficiently shared with neighbouring grids (such as France) which could complicate the analysis. Finally, introducing more solar to further decarbonise the grid will increase the need for LDES.

Table 12. Duration and energy deficit from the longest solar drought event across Spain and Portugal

Parameter	2016	2017	2018	2019	2020
Duration of Longest Event (days)	4	3	4	3	3
Energy Deficit – Longest Event (GWh)	120.4	83.4	105.5	118.7	108.6
Number of Events	20	14	16	16	3

3.3.3 Offshore Wind Droughts

Around the North Sea, there are five countries with significant offshore wind generation during the analysis period: Belgium (BE), Denmark (DE), Germany (DK), Great Britain (GB), and the Netherlands (NL). The wind drought analysis was based on the actual offshore wind production from individual countries and the aggregate of them. Offshore wind production from Belgium is excluded as the drought events from this country do not pass the threshold defined in Section 3.4.1.

Description of Wind Drought Events: The number of reported offshore wind drought events was observed to decrease significantly in total when considering the aggregate offshore wind generation from North Sea countries, compared to the results where each country is considered individually (Figures 31 and 32). The associated amount of average energy deficit also slightly decreased for most of the years (except for in 2020 when there was a significant installed capacity increase in GB and DE). The average duration of events is also decreased. In addition, the duration and energy deficit of the longest drought events in the aggregated North Sea countries are reduced compared to those from the individual countries.

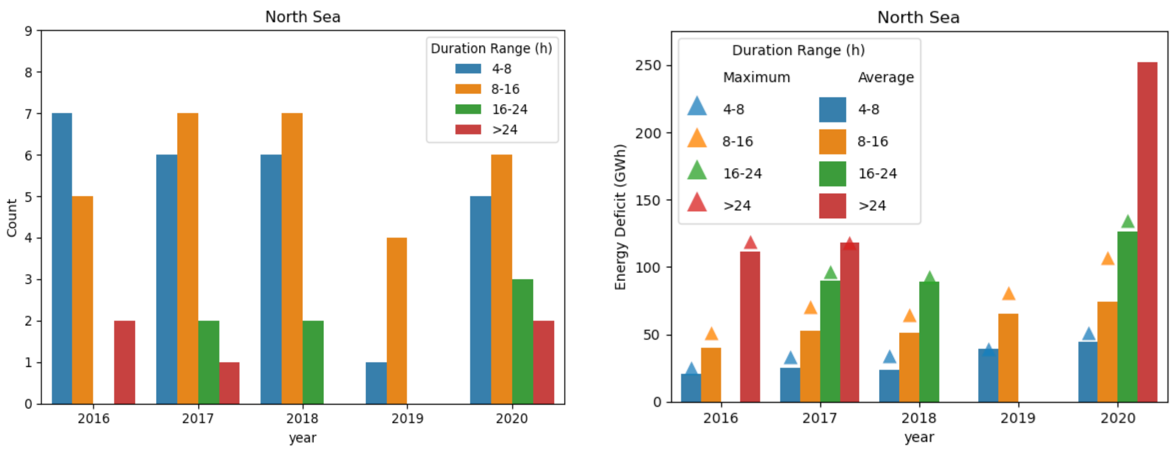


Figure 31. Aggregated North Sea countries wind drought frequency (left) and energy deficit by duration by year (right)

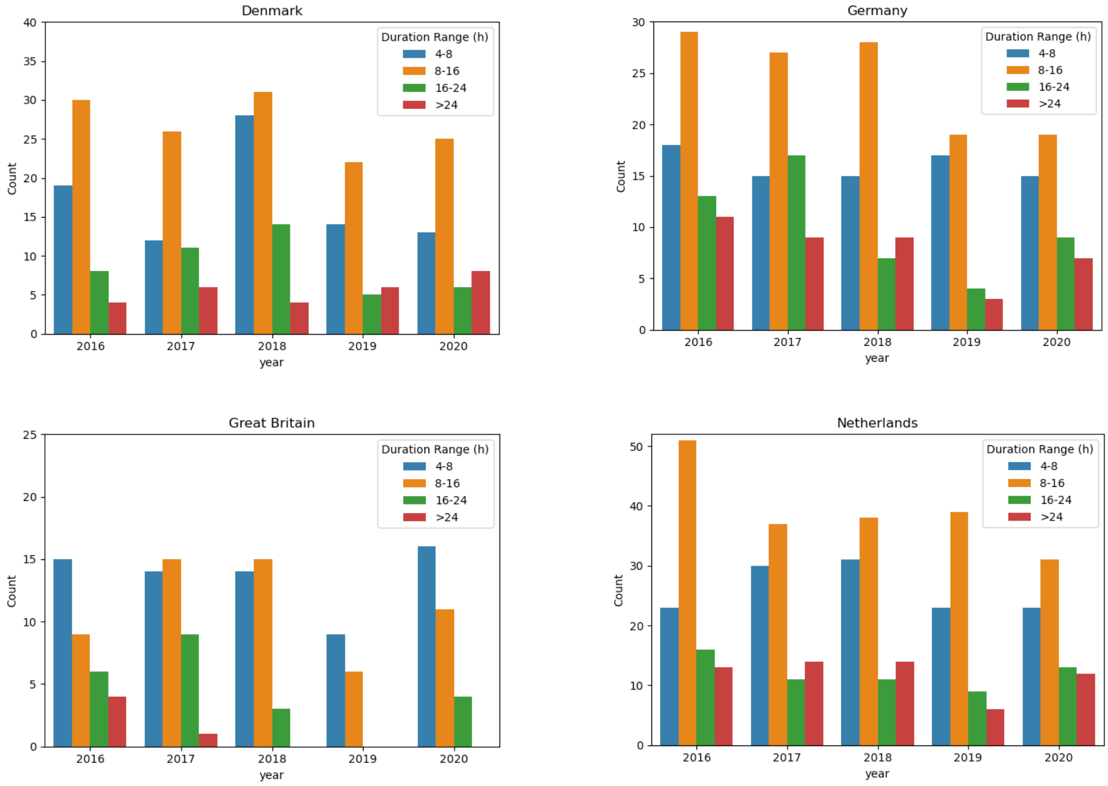


Figure 32. North Sea countries wind drought frequency (by individual country)

<u>Implications for LDES in North Sea countries</u>: Assuming that the entire amount of energy deficit will be served by LDES resources, there would be decreased need for storage in terms of both duration and capacity if the offshore wind generation from all North Sea countries is aggregated. Specifically, given the largest wind deficit event, i.e., the event lasting 39 consecutive hours in 2020 and its associated energy deficit of ~285 GWh, the LDES resource would need to be sized at ~7,300 MW capable of continuously discharging for 39 hours (Table 14). On average, though, wind drought events last for 13.5 hours amounting to average energy deficit of 97 GWh (Figure 33). Designed to serve average energy deficits, LDES resources would need to be sized at around 7,200 MW capable of discharging continuously for 13.5 hours.

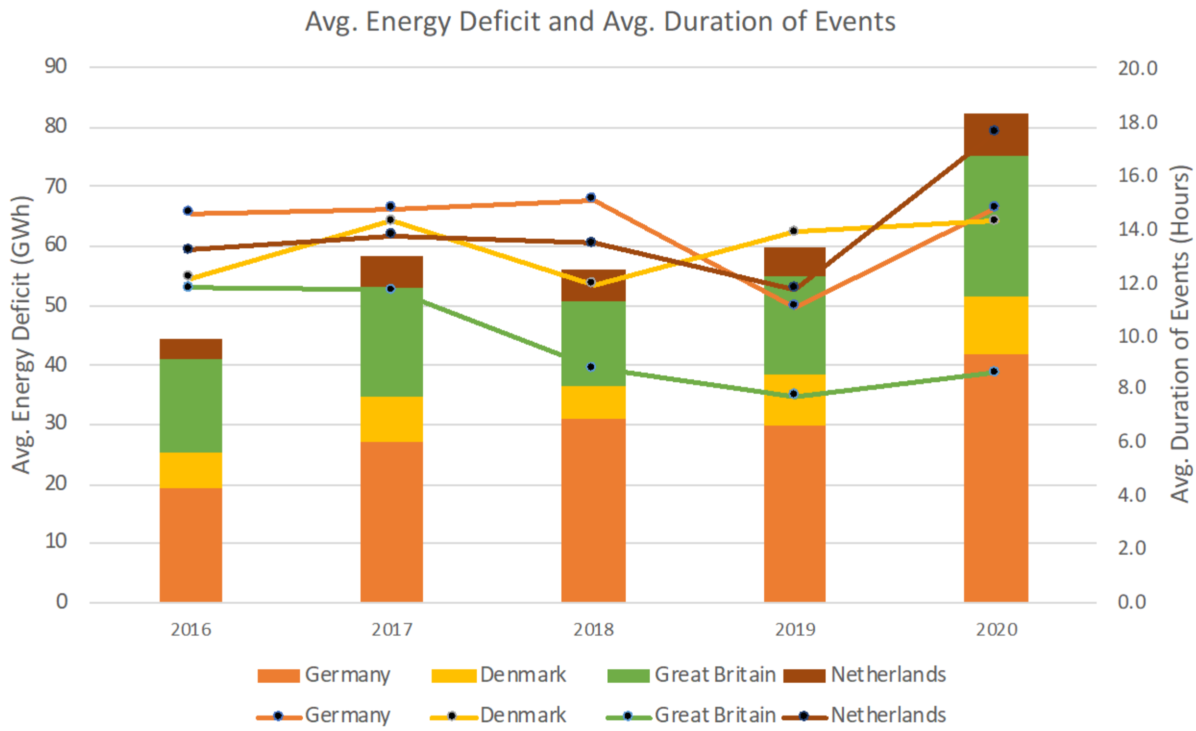


Figure 33. North Sea countries average duration of wind drought event and energy deficit by individual country

Figure 34 shows that even aggregating wind farms across all the North Sea (the most significant offshore wind zone in the world) there are still substantial wind droughts in terms of both energy deficit and duration. As more reliance is placed on offshore wind each year, the energy deficits during a wind drought grow yet the average duration of wind droughts is barely diminishing. Contrary to the perspective that offshore wind provides a consistent supply, the evidence from this figure and Table 14 shows that increasing offshore wind energy will have a marked increase in the need for long duration energy storage.

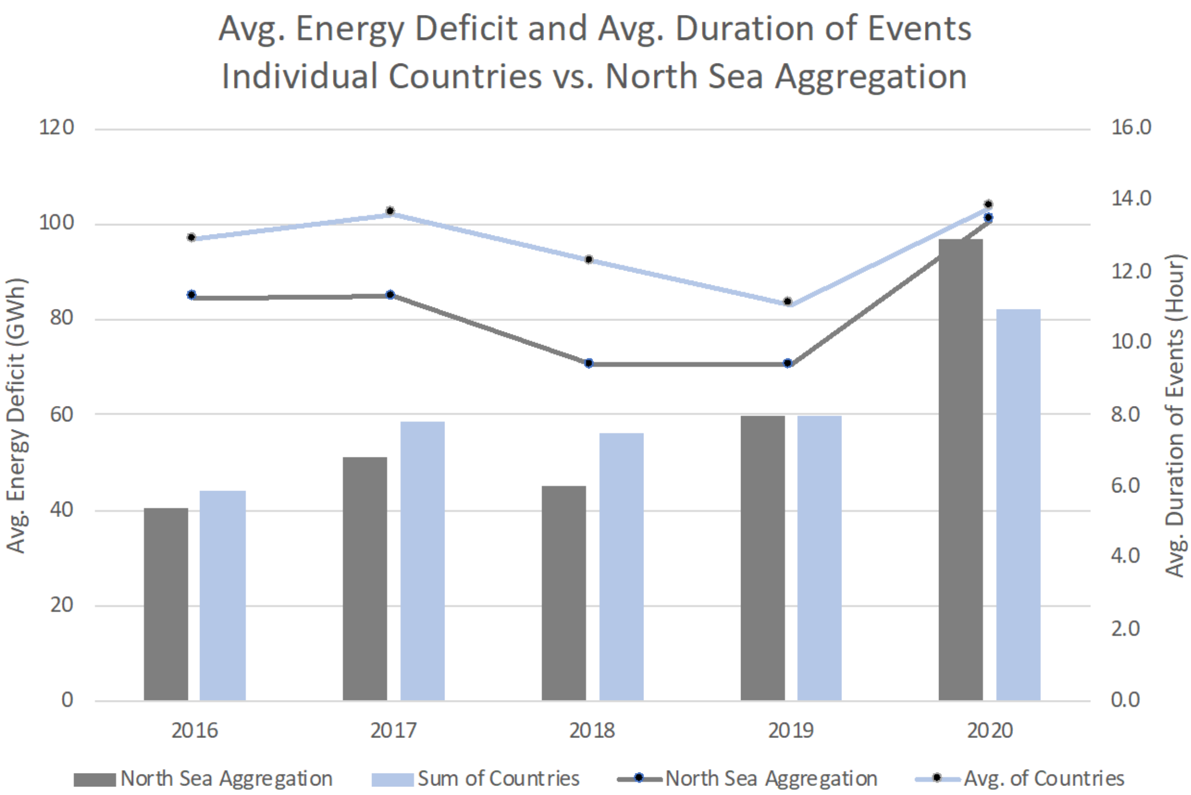


Figure 34. North Sea countries average duration of wind drought event and energy deficit (Individual country vs. Aggregated)

Table 13. Duration and energy deficit from the longest wind drought event for each country in the North Sea

Country	Parameter	2016	2017	2018	2019	2020
Denmark	Duration of Longest Event (h)	73	45	87	27	45
	Energy Deficit – Longest Event (GWh)	96.3	84.6	184.5	74.2	130.3
	Number of Events	71	68	59	43	50
Germany	Duration of Longest Event (h)	50	57	56	66	67
	Energy Deficit – Longest Event (GWh)	23.8	31.2	27.1	43.2	46.6
	Number of Events	61	55	77	47	52
Great Britain	Duration of Longest Event (h)	31	43	22	13	21
	Energy Deficit – Longest Event (GWh)	43.0	72.6	36.0	31.0	58.7
	Number of Events	34	39	32	15	31
The Netherlands	Duration of Longest Event (h)	45	59	47	45	198
	Energy Deficit – Longest Event (GWh)	13.8	23.7	18.3	18.5	78.0
	Number of Events	103	92	94	77	79
Aggregated	Duration of Longest Event (h)	33	25	19	12	39
	Energy Deficit – Longest Event (GWh)	119.0	118.1	93.0	80.7	285.4

	Number of Events	14	16	15	5	16

3.4 Australia

The Australian National Electricity Market (NEM) comprises five states: New South Wales (NSW); Queensland (QLD); South Australia (SA); Tasmania (TAS); and Victoria (VIC). Spanning roughly 2,900 km (~1,800 miles) from north to south, the distance between Port Douglas in far northern QLD and Hobart in the south of TAS is roughly equivalent to distances between Toronto (Canada) and Kingston (Jamaica); Barcelona (Spain) and Moscow (Russia); and that between Bangkok (Thailand) and Beijing (China). This makes the NEM one of the largest single interconnected power systems in the world, characterised by numerous key load centres with varying levels of interconnection between them.

Each region is unique, with a variety of generation sources, quality of renewable resource, differing levels of interconnection with neighbouring regions (typically considered fairly low due to large distances and low population), and demand profiles. Adding to this natural complexity is the governance complexity of the energy system. Strictly speaking, energy policy is the direct responsibility of each NEM state and territories separately, but this is overlaid by national market structures and federal government policy.

The composition of Australia's generation mix can vary greatly between regions (see Figure 35). For instance, wind accounts for ~40% of SA's installed capacity, but only 6% of capacity in QLD. Average demand profiles range from ~7,600 MW in NSW to ~1,100 MW in the hydro-rich island state of TAS (see Figure 36). The "peakiness" of the load is also highly variable ranging from SA with a peak load 111% larger than the average down to TAS with a peak load only 48% larger than average. All other states range from ~65% to 75%.

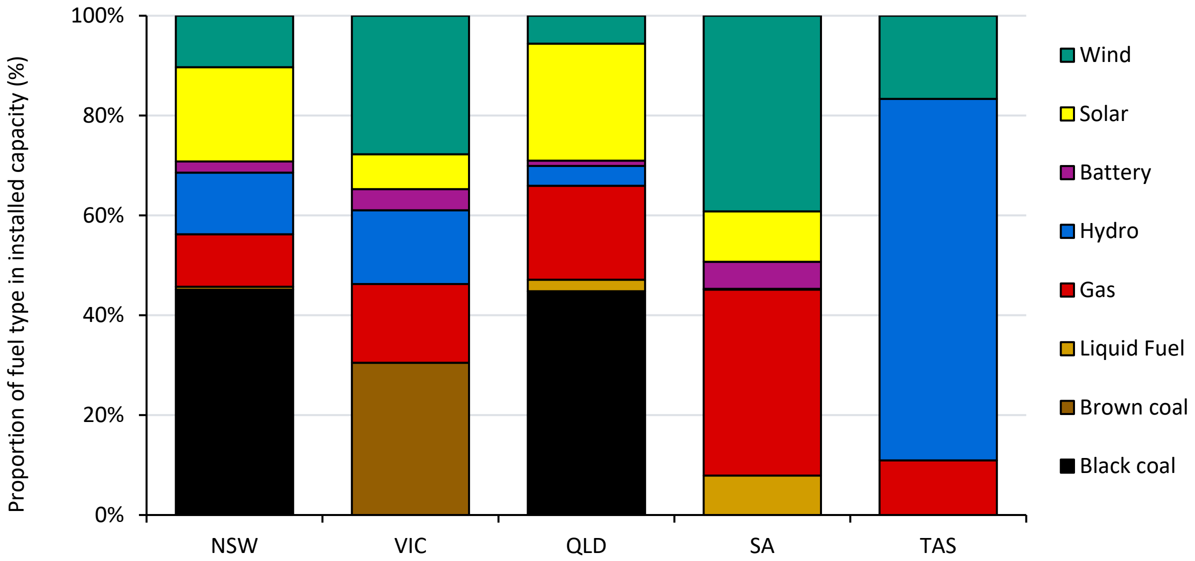


Figure 35. Proportion of fuel by installed capacity for each region in Australia (New South Wales = NSW; Queensland = QLD; South Australia = SA; Tasmania = TAS; and Victoria = VIC)

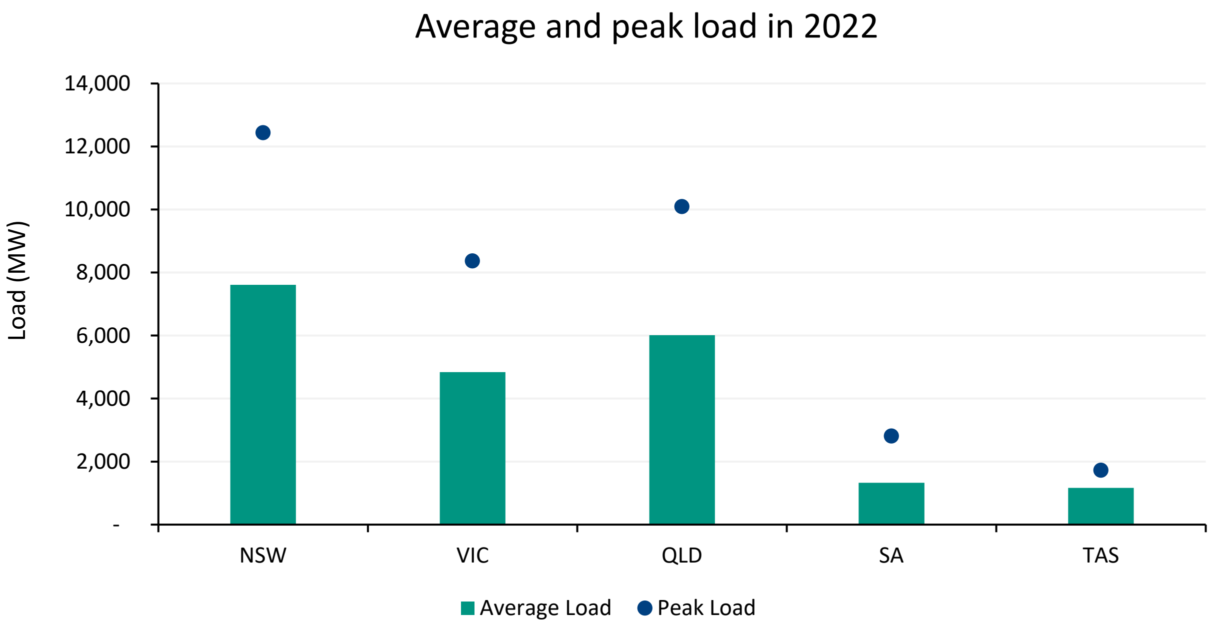


Figure 36. Average and peak load in Australian National Electricity Market regions in 2022 (New South Wales = NSW; Queensland = QLD; South Australia = SA; Tasmania = TAS; and Victoria = VIC)

To acknowledge the varying characteristics of regions across the NEM, modelling has been carried out for each state individually rather than on a system-wide basis. This is particularly important given the relatively low levels of interconnection between key load centres, limiting the freedom of full resource sharing.

3.4.1 Wind Droughts

For this study, we analysed NEM wind output between March 2018 and May 2023. On average, NEM wind drought events lasted around 9 hours (not shown). In 2022, the number of wind droughts was broadly consistent across the different NEM regions, with 50–70 drought events of 4+ hours occurring in all regions. Wind droughts spanning 4–16 hours were most common, accounting for 82% to 98% of all drought events.

As shown in Figure 37, the average load served by wind varies greatly among regions. In SA, the average amount of system demand supplied by wind was ~60% in non-drought periods, but only ~10% in NSW.[1]

[1] QLD has even less wind, but due to a small number of windfarms, the dataset is insufficient to draw statistical insights.

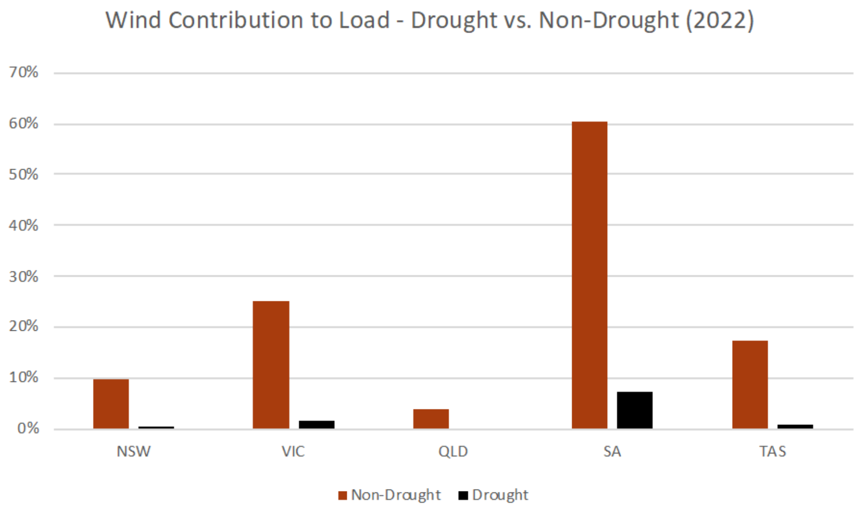


Figure 37. Wind power contribution to load in Australia during drought and non-drought events in 2022 (New South Wales = NSW; Victoria = VIC; Queensland = QLD; South Australia = SA; and Tasmania = TAS)

For longer wind drought events (16+ hours), there were 170 events during the study period (an average of 1.7 per month). Approximately 30% of these events occurred in VIC, which has the second highest penetration of wind in the NEM. We take a closer look at the impact of wind droughts in VIC in the next section.

3.4.1.1 Victoria

Description of Wind Drought Events in Victoria: Most wind drought events in VIC span 8–16 hours (43% of all events), with the second most frequent in the 4-8 hour range (38% of all events; see Figure 38). Events spanning 16 hours or longer accounted for 18% of events – a notable proportion especially given the definition of 90% lower than typical production. The average duration of wind droughts was ~10.5 hours, and the longest event, which lasted 41 consecutive hours, occurred in 2022 (Table 14). The average energy deficit observed from wind droughts has increased from 9% to 23% of load between 2018 and 2023 as further wind generation capacity has been deployed (Figure 39, right). The largest energy deficits occurred during the longest wind droughts.

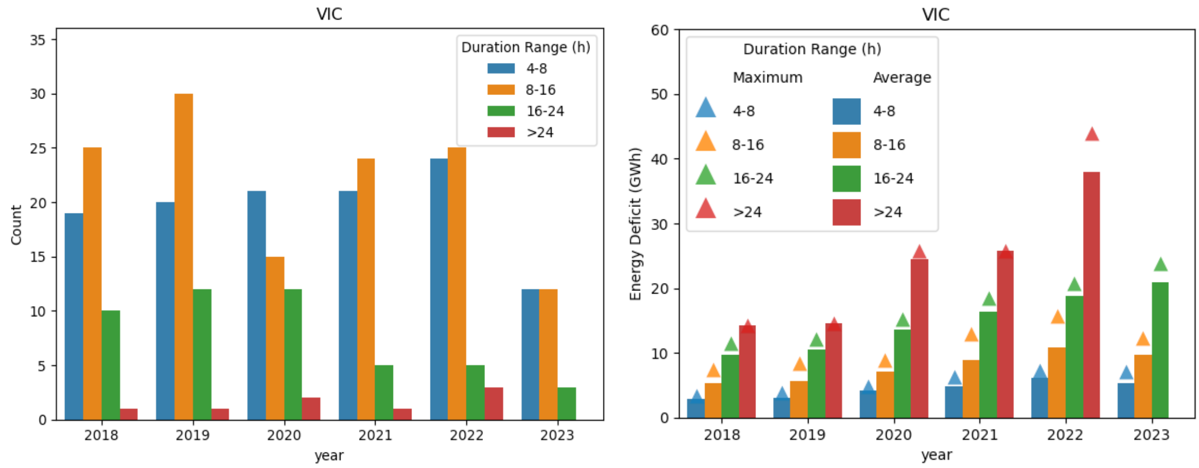


Figure 38. Wind drought frequency (left) and energy deficit by duration (right) in Victoria (VIC).

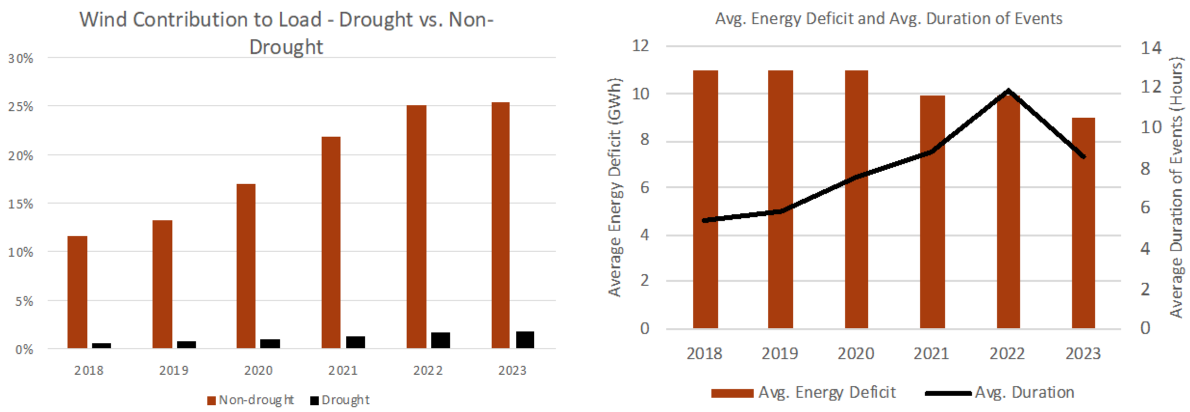


Figure 39. Wind power generation contribution to load (left), and average deficit (right) in Victoria (VIC).

Table 14. Number of wind drought events, duration of longest event, and energy deficit of longest event in Victoria

Parameter	2018	2019	2020	2021	2022	2023 (to May)
Number of Events	55	63	50	51	57	27
Energy Deficit – Longest Event (GWh)	14.3	14.6	25.7	25.7	43.9	23.9
Duration of Longest Event (hours)	29	26	37	28	41	23

Potential implications for LDES in Victoria: On average, wind drought events last for 10.5 hours amounting to an average energy deficit of 7.8 GWh. Hence, LDES resources designed to serve average energy deficits would need to be sized at 744 MW capable of discharging continuously for 10.5 hours. As a point of comparison, there is 530 MW of battery energy storage currently deployed in VIC ranging from 1 to 2 hours of storage (around 10% of the energy storage requirement) (AEMO n.d.).

Assuming that the entire amount of energy deficit will be served by LDES resources, the biggest LDES source would need to be sized to serve the largest wind deficit event, i.e., the event lasting 41 consecutive hours on 8 to 9 August 2022. Figure 40 shows this period with very little renewable energy generation over a period of days followed by a period with much stronger supply, particularly from wind. Given the associated energy deficit of 44 GWh in this period, the LDES resource would need to be sized at ~1,070 MW capable of continuously discharging for 41 hours. In Australia, the optimal approach to address energy deficits in the future will likely involve some combination of LDES, traditional hydropower, increased interconnection across regions, demand-side response, and potentially gas peaking generation.

Historically, this power system has relied on a large stable baseload supply from brown coal generation. This baseload is supplemented by hydropower, gas generation, and imports through interconnections to balance the grid throughout morning and evening peak events. This is demonstrated in Figure 40, where coal provides the majority of baseload generation, supplemented by gas, hydropower, and small amounts of solar and imports during peak hours.

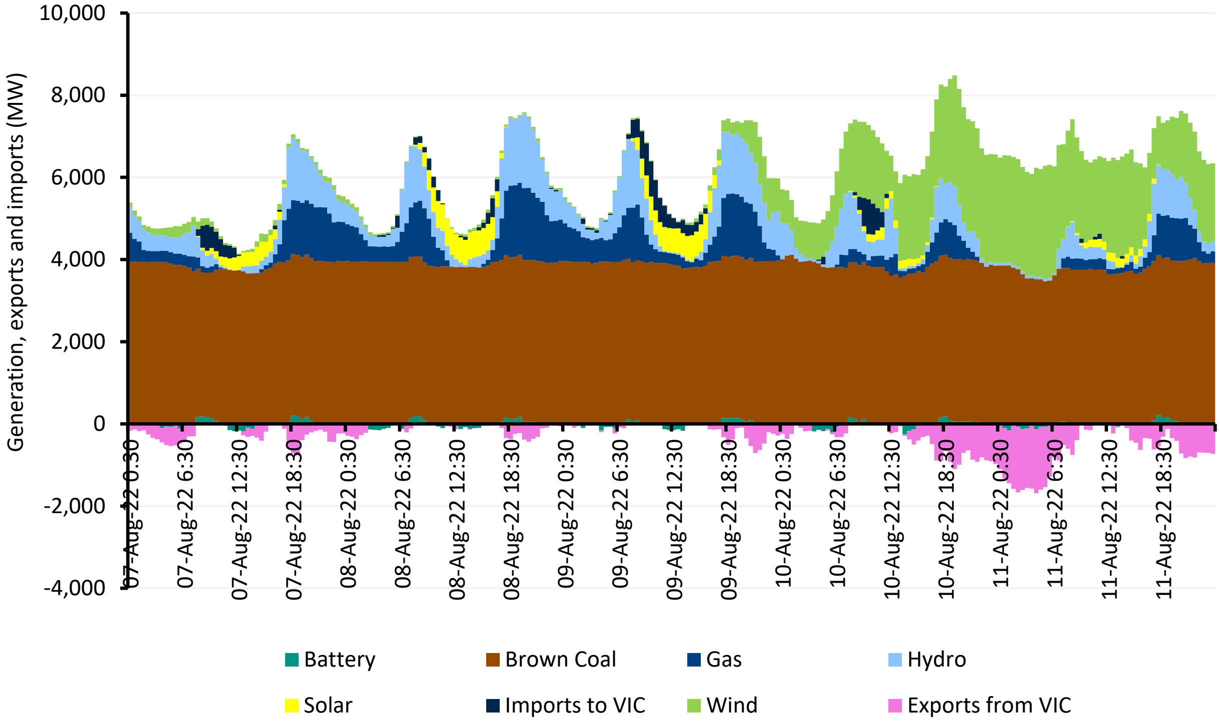


Figure 40. Victoria (VIC) generation mix throughout an extended wind drought spanning 8 August 2022 through 9 August 2022

Potential Implications in Future Scenarios: There are three main changes in VIC's energy market that will increase the impact of wind droughts:

- The Victorian and Federal Government's commitment to decarbonisation through a rapid uptake of renewable energy, supported by various policies and mechanisms
- The retirement of VIC's three major brown coal generators (the highest emitting generation assets in the NEM)

- Ongoing availability of natural gas while Victoria's active gas wells continue to deplete

The VIC Government has strong policy ambitions to decarbonise their power system by driving a deeper integration of renewables into their power system. The Victorian Renewable Energy Target (or "VRET") is targeting 40% renewables by 2025, 65% by 2030, and 95% by 2035 (Victoria State Government 2024). This will be supported by the iterative roll-out of various Renewable Energy Zones (or "REZs"), augmenting and expanding Victoria's transmission network to facilitate further renewables deployment.

Concurrently, Victoria's three major brown coal generation assets (Yallourn, Loy Yang A, and Loy Yang B) are expected to gradually retire, the first of which (1,450 MW Yallourn power station) is scheduled to retire in 2028. Further renewables deployment will depress spot market prices, particularly through the middle of the day during peak solar PV generation, making it increasingly unviable for brown coal generators to operate at a profit and may force earlier retirements than currently anticipated.

The changing energy dynamics in the VIC power system necessitates a careful consideration of risks to supply reliability moving forward. LDES located in VIC (or across regional borders with sufficient interconnection) can play a significant role in supporting VIC's renewables ambition.

3.4.2 Solar Droughts

As a nation with abundant solar energy, Australia has one of the highest shares of rooftop solar PV installations globally. The Australian Energy Market Operator (AEMO) notes that roughly 30% of detached residential homes in Australia have rooftop solar PV installed, contributing approximately 15 GW of capacity to the grid (AEMO 2022). For this study, the findings of Australian solar droughts reported below were limited to observed outputs from large-scale, grid-connected solar farms only. For context, this represents about one-third of the solar energy in the NEM with the remaining two-thirds being rooftop PV. Across the NEM, the daily volatility of both rooftop and utility PV are roughly similar, although the hourly traces vary substantially.

The median length of solar drought events between 2018 and May 2023 in the NEM was 1 day, with very few events spanning more than 2 days. In 2022, there was far more diversity in solar drought events across the regions than wind droughts, with only 4 events occurring in QLD, compared to 18 in SA (not shown in figures).

Figure 41 shows the contribution to load from solar during drought and non-drought events. The average amount of load served during these periods is substantially lower than that of wind droughts (Figure 37).

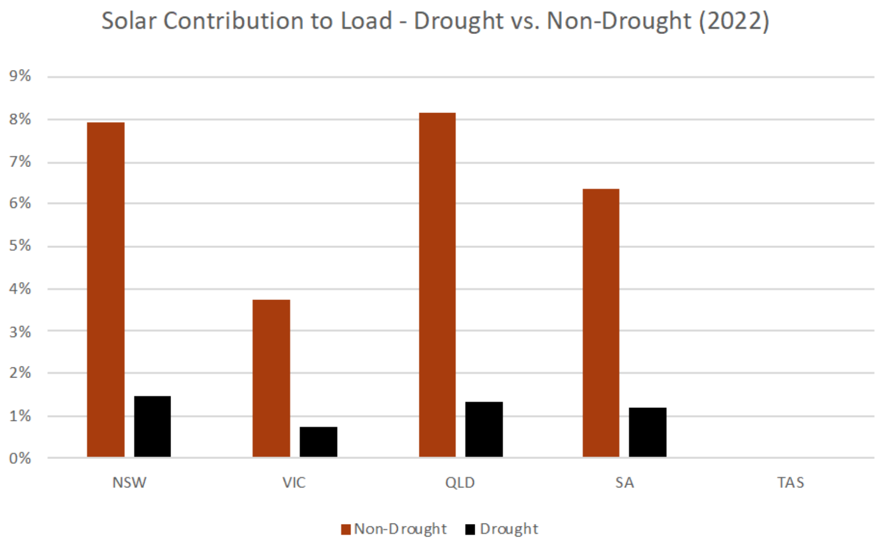


Figure 41. Solar power contribution to load in Australia in 2022 (New South Wales = NSW; Victoria = VIC; Queensland = QLD; and South Australia = SA; no large-scale solar farms in Tasmania, TAS)

3.4.2.1 New South Wales

<u>Description of Solar Drought Events in New South Wales:</u> Most solar drought events in NSW lasted 1 day, although 2022 had a drought lasting over two successive days (Figure 42). The average contribution of solar to total system load was in the range of 0–2% during drought periods compared to 1–9% during non-drought periods (Figure 43, left). The share of non-drought load served by solar generation has increased since 2018 as more solar plants enter the grid.

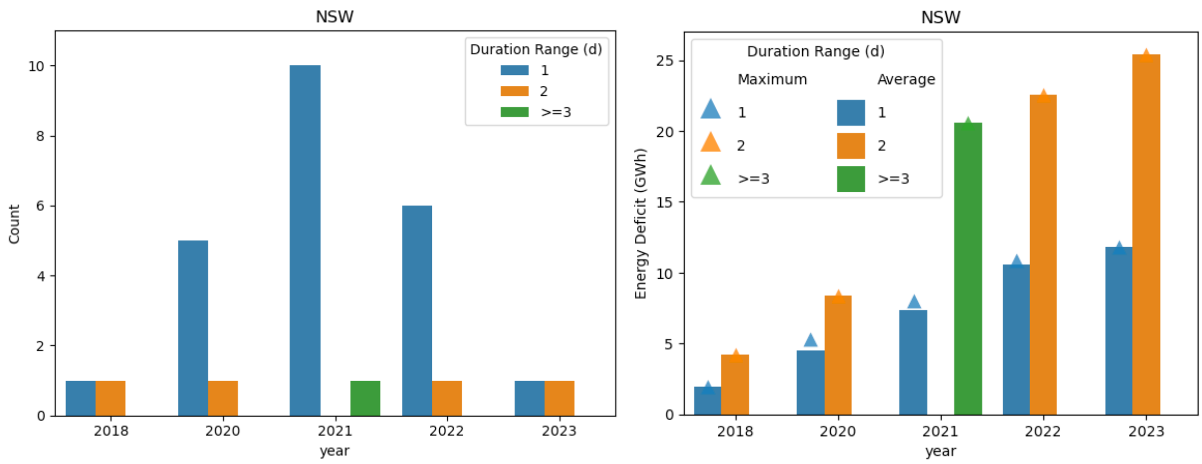


Figure 42. Solar drought frequency (left) and energy deficit by duration (right) in New South Wales (NSW).

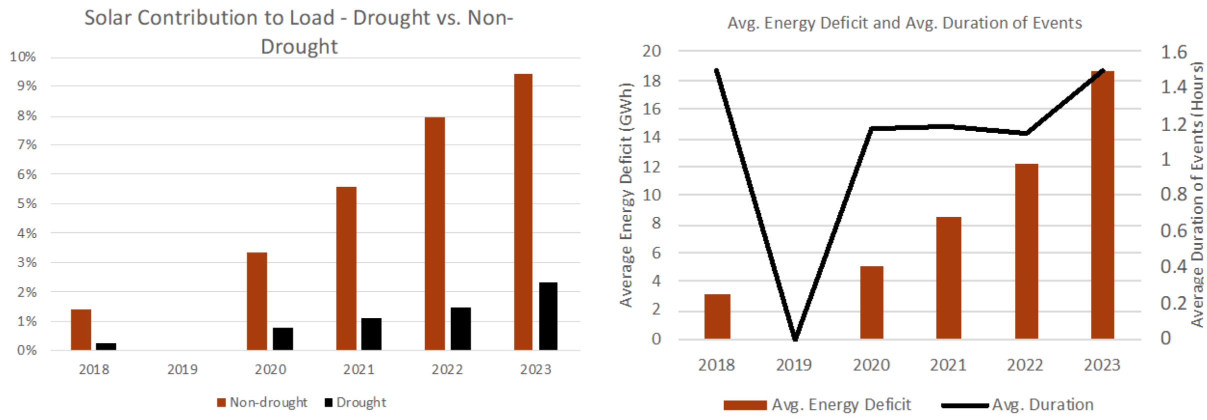


Figure 43. Solar power generation contribution to load (left), and average deficit (right) in New South Wales (NSW).

<u>Potential Implications for LDES in New South Wales:</u> Assuming that only LDES is used to address solar droughts and can charge during the non-solar periods, the largest LDES would need to be sized to cover the largest solar deficit event lasting 3 days in 2021 (Table 15). Given the associated energy deficit of ~21 GWh, the LDES resource would need to be sized at ~687 MW. On average, solar drought events lasted for one day (or 10 consecutive hours) with an average energy deficit of 9.1 GWh. Hence, LDES resources designed to serve average energy deficits would need to be sized at 910 MW. As a point of comparison, 310 MW of battery storage is currently deployed in NSW ranging from 1.5 hours to 2 hours in duration (AEMO 2023). NSW also has two pumped hydro generators: Shoalhaven (240 MW, 24 hours storage; Hydropower & Dams 2022) and TUMUT3 (1,800 MW, 33 hours storage; NSW Government 2023). As noted, however, this analysis only captures grid-scale solar – and most of NSW's solar resource is provided by rooftop PV, likely increasing the size of the challenge substantially.

Table 15. Number of solar drought events, duration of longest event, and energy deficit of longest event in New South Wales

Parameter	2018	2019	2020	2021	2022	2023 (to May)
Number of Events	2	0	6	11	7	2
Duration of Longest Event (days)	2	0	2	3	2	2
Energy Deficit – Longest Event (GWh)	4.2	0	8.4	20.6	22.5	25.4

<u>Potential Implications in Future Scenarios:</u> There are three main changes to NSW's energy market:

- The retirement of black coal generators in the near future (currently making up 45% of NSW's total generation capacity) including Eraring (3,056 MW) which is due to retire in 2025
- The draft 2023 Infrastructure Investment Objectives report published by the NSW Consumer Trustee sets out the State's ambition to deliver 33,600 GWh of new renewable electricity and 2 GW of long-duration energy storage by 2030 (AEMO 2023)

- The development of Snowy 2.0 project – a 2 GW pumped storage hydro project due to be completed by December 2029.

Solar currently makes up 19% of NSW's installed capacity and this figure is likely to increase significantly with the retirement of coal generators and new solar entrants. The NSW government's commitment to coordinating storage, growth of VRE and coal retirements is aimed at maintaining reliable supply amidst the energy transition. This is particularly relevant for NSW, which is interconnected with VIC, QLD and soon SA as well.

4 DISCUSSION

4.1 Summary and Key Findings

We used historical data to quantify the frequency and duration of extreme wind and solar resource droughts in the United States, Europe, Canada (Hydro Québec), and Australia. We used these findings to estimate flexibility requirements in these regions and as potential indicators of long-duration storage needs moving forward. It is important to note that less stringent definitions of resource droughts may result in more occurrences, longer durations, and therefore larger energy deficits. Moreover, since all analysis conducted herein is based on historical observations, any potential indicators of long-duration energy storage requirements also need to consider the growing reliance on both wind and solar generation. The energy systems around the world are undergoing a significant transition and this change will likely require much more storage than identified with historical data.

To provide a relevant comparison across many power systems and geographies, a similar set of analyses were undertaken using consistent definitions. We compared the findings across different geographical domains and investigated how aggregation of VRE resources affects the energy drought indicators. Additionally, while we primarily quantified and compared the indicators for wind and solar generation separately, we also did a preliminary analysis of the complementarity of these resources, i.e., the ability of one resource type (wind) to fill the gap created during a resource drought for the other (solar). The key findings from the study can be summarized as follows:

- Characteristics of Wind and Solar Drought Events: Even with a strict definition of a fairly extreme resource drought, there are still a significant number of VRE drought events lasting longer than 8 hours for each resource type, in all the areas of study.
  - The longest duration drought event was observed to be a wind drought in the North Sea region lasting almost 200 hours (see Table 13, Netherlands) – even the aggregated wind from the entire region had resource droughts lasting 40 hours. All regions (except Spain and ERCOT) experienced wind droughts lasting at least 30 hours, most with a maximum wind drought slightly over 40 hours.
  - Spain experienced a solar drought lasting for six days and ERCOT experienced one lasting for five days. All regions experienced solar droughts that lasted at least two days, with most lasting twice that long.
- Indication of Long-Duration Energy Storage Needs: The energy deficit analysis based on extreme VRE droughts can be used to help guide assessments on the need for LDES. Quantitative comparisons between different power systems provide little insight owing to the stark differences in system topology, generation inventory, and meteorological potential. A GWh in Australia will have notably different impact compared with a GWh in Germany. This is influenced by the size of the system, the strength of interconnection with neighbouring systems, the reliance on VRE, and the other energy sources in the grid (including access to low-cost energy to charge storages). Each of these influences may change over time and need to be considered in more detail when assessing the need for LDES in a system. The exact need for LDES in future systems will vary between different regions, and the actual needs can only be addressed by performing detailed engineering and economic studies considering the full range of potential flexibility providers to a system.

- Impact of Renewables in Different Systems: As expected, regions with greater penetration of a renewable resource are more impacted by the times when the resource is not producing.
  - Solar drought events in regions with large penetration, such as CAISO, were observed to have the characteristic of large energy deficits with less frequency compared with other regions (e.g., ERCOT). A plausible explanation is that regions with larger solar penetration see more geographic resource aggregation and less variability in total outputs. Similar findings are observed in Australia as well. Allowing full resource sharing across states reduces the variation, but not to the extent that the strictly defined resource droughts disappeared.
  - Wind drought events in regions with large penetration, such as ERCOT, were shown to have shorter duration compared with other regions (e.g., CAISO). This may be attributed to a better wind resource over a larger geographic area. However, this conclusion is somewhat mitigated by observations in the North Sea, a region with an excellent wind resource over a large area and a large amount of generation; wind drought events are reasonably frequent and of a longer duration. The local weather conditions play a substantial factor.
- Complementarity Between Renewables During Droughts: A preliminary analysis based on the USA data revealed that during solar drought events, wind power tended to perform below the expected level in CAISO while close to the expected level in ERCOT. However, more work is needed to investigate the complementarities between different VRE resources and to develop metrics for droughts to allow comparison of system impacts across resource types.
- Impact of Geographic Aggregation on Energy Droughts in the EU:
  - Onshore Wind and Solar Generation: The aggregation of wind generation across the Spain and Portugal would slightly reduce the number of reported wind drought events in the region, compared to the number if Spain is considered alone. This reduction in wind drought frequency is more pronounced when compared with the number of events in Portugal alone. The reduction in frequency of events is more significant for events greater than 8 hours. The associated amount of energy deficit is slightly larger when compared to that of each country individually, since the installed wind capacity is much larger in the aggregated system.

    The aggregation of solar generation across these two countries reduces the number of reported solar drought events, compared to the frequency if Spain is considered alone. The associated average energy deficit is reduced from 54,525 MWh to 48,337 MWh and the average duration of events is reduced from 1.82 days to 1.57 days.
  - Offshore Wind: The number of reported offshore wind drought events decreased significantly when the offshore wind generation from the North Sea countries was considered in aggregate, compared with each country considered individually. The associated average energy deficit slightly decreased for most of the years[1] along with the average duration of events. The duration and energy deficit of the longest drought events in the aggregated North Sea countries is reduced compared to that from the individual countries.
- Definition of Drought Events Reference Period:

[1] Excepting 2020, when there was a significant increase in installed capacity in GB and DE.

30-day vs. Annual Average: The frequency and intensity (associated energy deficit) of reported wind drought events was observed to increase significantly when using an annual average as reference due to a higher annual average production compared with seasonal low wind. The average duration of events increased slightly from 7 to 8 hours when using the annual average. The use of a “30 day” or “annual average” depends on the specific applications. The annual average captures droughts driven by the seasonality of VRE, while the shorter reference period captures acute drought phenomena. A “30 day” reference period is likely to result in larger drought deficits during the high wind season and lower deficits during the low wind season, as the amount of energy deficit is tied to the amount that a system needs to recover in operations. The annual average reference period provides insight best suited to the impact of resource droughts and energy deficits for use in capacity planning.

4.2 Future Work

- Exploration of Future Indicators: In this study, we analysed the wind and solar drought events separately for all regions, excepting a brief analysis of the complementarity of the resources in CAISO and ERCOT. However, to understand the true complementarity of wind and solar resources, we will need to adapt the methodology and drought metrics to consistently account for the diurnal nature of solar availability. Future work should also explore the seasonal availability of many hydropower resources, especially those with no or small amounts of available storage capacities.
- Further Analysis of Indicator Attributes: The indicators in this study used strict temporal, spatial, and quantity thresholds (e.g., 10% threshold and 4-hour windows for a wind drought event). Future analysis will explore the use of softer limits in the definition of such drought events. It will be important to fully investigate the impact of changing the values of these attributes, especially as they relate to overall attributes of the system under study.
- Impacts of Higher Variable Renewable Energy Penetration: The impact of further additions in VRE resources on the frequency, extent, and timing of future VRE droughts was not considered in this study and needs to be investigated, especially in the context of climate change. Changing weather patterns may affect VRE resource availability as well as the frequency and duration of VRE droughts. Understanding future VRE resource availability is an important area for future research that should be factored into power planning studies.
- Translation of Indicators to System Planning: Finally, future work should also entail the translation of these indicators into information that can be used for system operations and planning of future investments. The indicators for wind and solar droughts only describe the temporal nature of individual VRE resources. They can give initial indications of flexibility and LDES needs in specific systems and enable comparison of VRE resources between systems. Future work should consider if and how such indicators can feed into a more comprehensive technical and economic analysis of flexibility and LDES needs to ensure resource adequacy and energy security of future clean power systems.

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