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OCCURRENCE OF VARIABLE RENEWABLE ENERGY SYSTEM GENERATION LULLS IN A FUTURE EUROPEAN CAPACITY SCENARIO

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ABSTRACT

In order to effectively develop a future European energy system based on variable renewable energy systems (VRES), the probabilistically-occurring low generation periods from wind and PV generators must be better understood. However, little explicit information on these VRES lulls is currently available in relation to: how long these VRES lulls could last, how often they could occur, and how these qualities vary between differing regional contexts. This work, therefore, addresses these issues for wind and PV generation in the context of an exemplary future European energy system. To accomplish this, future-oriented wind and PV generation is recreated at high spatial and temporal resolution from the basis of a literature-derived European energy system scenario in 2050. The occurrence of VRES lulls are then observed in the resulting generation profiles over a 37 year time frame for the whole of Europe and several nations. The likelihood of observing a lull spanning X hours at least once in a randomly selected year is then found. Results of this work can be used by energy system planners and researchers to estimate minimal backup and storage needs in future VRES-prominent European energy systems.

Keywords: renewable energy, renewable energy intermittency, power generation, energy system design

1. INTRODUCTION

Following current trends, future European energy systems will increasingly rely on renewable energy sources in their generation mix [1]. Of these sources, variable renewable energy systems (VRES), most notable on and offshore wind as well as solar photovoltaic (PV), will play a large role due to their rapidly decreasing costs [2]. Nevertheless, before VRES generators can be reliably incorporated at large scales into future European energy system development plans, several issues must be addressed in greater detail than is currently available in the scientific literature. One such issue concerns the occurrence of low generation lull periods, VRES lulls, wherein the available electricity generation from VRES sources is below a desired threshold. These lulls, which arise probabilistically as a result of weather-driven intermittency, have been previously estimated to last for weeks at a time [3], and to span both national and European contexts [4].

As the Earth's climate system and stochastic weather phenomena are highly complex, the causes of VRES lulls are widespread. For small scale phenomena (relative to the European energy system) it is commonly speculated that their impact on VRES generation can be averaged out over a large enough area [5], [6]. Conversely, larger synaptic scale developments, such as North Atlantic Oscillations (NAO) [7], can also be observed that directly impact VRES generation on a continental scale [8]. As a result of NAOs and other anomalous synaptic scale events, many researchers have concluded that VRES lulls would certainly be observed across a European scope [9]–[11]. In turn, this is expected to impact the storage and backup needs in future energy systems reliant on VRES generation [12].

Previous studies have touched on topics relating to VRES lulls in Europe, and addressed questions such as the rate of lull occurrence and the average time spans spent within a single lull event. Weber et al. [4], for example, modeled wind turbine generation and, assuming a copper-plate across Europe, found that about one in 100 lulls would last at between 14 to 25 days; depending on the selected weather source. Another example is that of Raynaud et al. [9], who find the average number and average length of lulls for numerous European countries. In general, they find that countries can observe between 5 and 60 lull events per year which each last between 1.5 and 15 days depending on the country and VRES technology.

However, previous studies on this topic tend to share several qualities which leave room for improvement. For instance, many studies have not been performed in enough detail to capture the impact of many small and short scale weather phenomena. Furthermore, these studies also tend to investigate uniform distributions of contemporary wind and PV generators across the European context, and additionally tend to use simplified VRES simulation schemes, all of which will not capture a realistic generation profile from these technologies in a future energy system. Lastly, presentations of lull occurrence results are typically not provided in a way which suggest clear actions to policy makers and regional stakeholders who participate in the design of future energy systems.

In the current work the occurrence of VRES lulls will be investigated in a manner which incorporates: higher spatially and temporally resolved wind turbine and PV module simulation, a spatial distribution of VRES generators which follows a literature-derived future scenario for 2050, and finally probabilistic VRES lull occurrence results for Europe and several other national contexts. As the nature of this work concerns the VRES lulls originating from the generation profiles themselves, issues such as correlation between VRES generation and electricity demand, grid limitations, availability of back-up generators, or large scale storage will not be addressed.

2. METHODOLOGY

2.1 Scenario Design

In order to investigate the future occurrence of VRES lulls in Europe, the scenarios developed in line with the European Commission's E-Highway 2050 project [13] are selected for replication here on account of their relatively highly detailed regionalization of Europe, as well as projections of renewable and non-renewable generator capacities to 2050 [14]. Furthermore, of the 5 contrasting scenarios developed in the E-Highway 2050 project, the "100% RES" scenario is specifically selected as this scenario has the highest proportional reliance on VRES sources, and thus should be the most susceptible to the occurrence of VRES lulls. Figure 1 provides an overview of the installed wind and PV capacities in the E-Highway 2050's "100% RES" scenario.

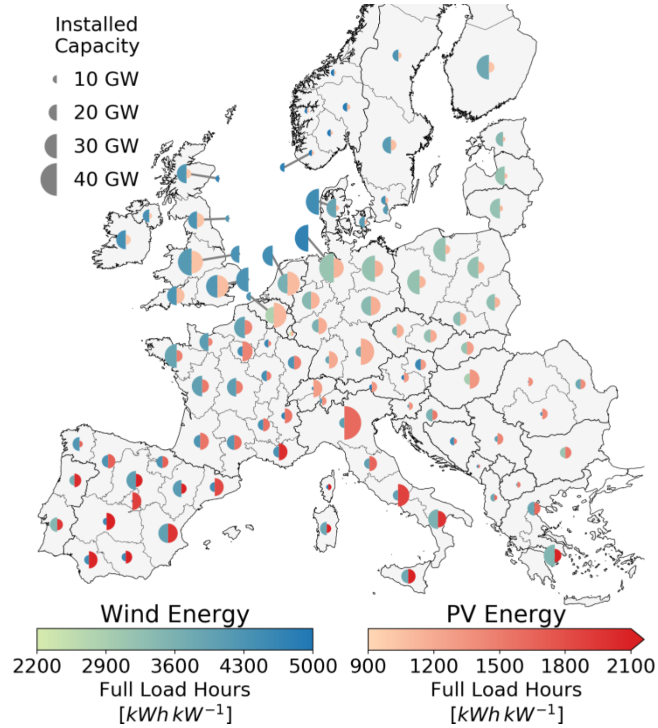

Fig 1: Wind and PV capacity [14] and full load hours in 2050 calculated for this work

2.2 Wind and PV Generation Profiles

Figure 1 also shows the calculated average full load hours (FLH) for the wind and PV generators within each of the E-Highway regions. These FLHs correspond to the resulting FLH from hourly wind turbine and PV park simulations over a 37 year (1980 until 2016) time frame. As the simulation schemes used to produce these generation profiles have previously been discussed by Ryberg et al. [15] for onshore wind, Caglayan et al. [16] for offshore wind, and finally Ryberg [17] for PV, this issue will only be summarized here. The key aspects are:

- Independent land eligibility analyses are performed for onshore wind [18], offshore wind [16], and open-field PV [17].
- Placement algorithms identify all possible turbine and park locations within the eligible zones [17].
- Rooftop PV systems are assumed to be spread across each region in proportion to population.
- Futuristic turbine [15] and PV system [17] designs are tailored to each potential location.
- MERRA2 weather data [19] from 1980 until 2016 is used to simulate each potential turbine and PV system location over the full 37 year time frame.
- Levelized cost of electricity (LCOE) is estimated for each onshore wind, offshore wind, open-field PV,

and rooftop PV location; which are then sorted from least to most expensive.

- Within each region the top *X* turbines/parks are selected, where *X* corresponds to the installed regional capacity prescribed in E-Highway's "100% RES" scenario. A 50/50 share is assumed between rooftop and open-field PV.
- The calculated hourly generation profiles of the selected locations are summed together to form an hourly profile for each of onshore wind, offshore wind, and PV generators for each region and for each of the 37 weather years.

2.3 *Lull Event Identification*

Identification of VRES lulls is performed by selecting a technology set, a regional context, and a relative VRES lull threshold. The technology set can be a single VRES technology, such as only onshore wind, or else a combination of technologies, such as onshore wind and offshore wind. The regional context can be a single E-Highway region, or else can be a combination of E-Highway regions, such as those that constitute a country. Finally the lull threshold refers to a constant percentage of the multi-annual average hourly generation for the technologies and regional context in question, which determines the point at which a lull event is initiated. Once these items are defined, the following procedure is taken:

1. For each weather year, the generation profiles from the selected technologies in the selected E-Highway regions are summed together to form 37 hourly generation profiles each spanning 8760 hours. A copper plate is assumed within each context.
2. Individual lull events are identified according to the diagram in Figure 2. Note that a single lull event begins when the hourly generation falls below the lull threshold, and continues until the deficient generation is offset by super-threshold generation.

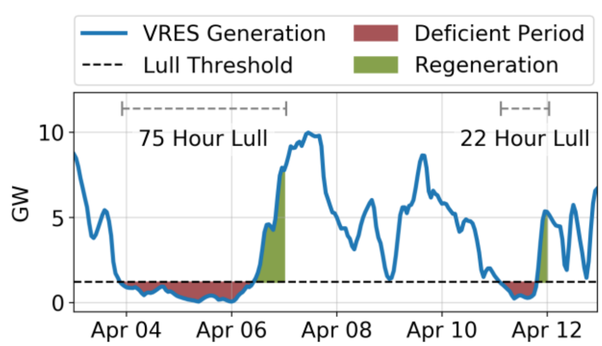

Fig 2: Exemplary diagram showing lull identification

3. Finally, the probability of the selected region to observe at least one lull spanning *S* or more hours in a randomly selected year is found; where *S* refers to any time span between 1 and 8760 hours.

Besides applying this procedure to the whole of Europe (defined by the regions of Figure 1), the following national contexts are also investigated on account of their high shares of VRES capacity in the E-Highway scenario: France, the United Kingdom, Spain, Italy, and Germany.

Regarding lull thresholds, two set-ups will be investigated. First, a constant lull threshold equal to 25% of the average VRES generation is chosen, and the full trend of lull span observance probabilities will be found for the previously mentioned regional contexts. This lull threshold is chosen to exemplify lull occurrence for a reasonable level of a desired base VRES generation. Afterwards, the effect of varying the lull threshold between 0 and 100% of the average generation is determined in respect to three quantities: (1) lull spans which are guaranteed to be observed at least once in any weather year, (2) lull spans that should correspond to an observance rate of once in ten years, and finally (3) the longest lull span observed from all 37 weather years.

3. RESULTS

3.1 *25% Lull Threshold*

With a lull threshold held at 25% of the average generation, the lull observation trends seen in Figure 3 are found. These results show a broad spread of lull span probabilities depending on both the region and technology in question. Nationally, the United Kingdom

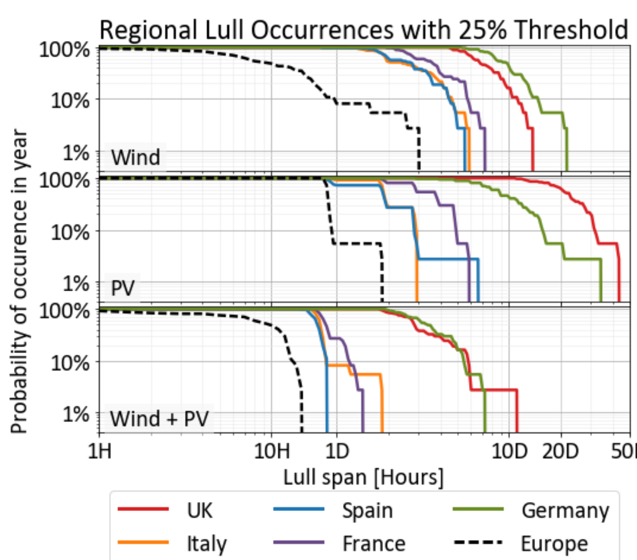

Fig 3: Lull occurrence trends

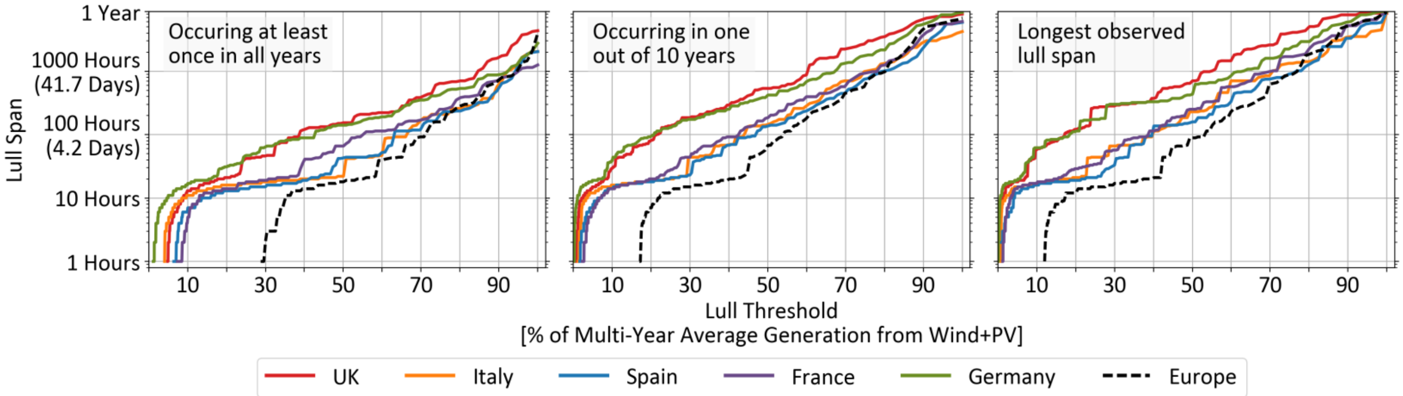

Fig 4 Lull span occurrence probabilities as a function of the selected lull threshold.

and Germany tend to observe the longest lulls, while Spain and Italy tend to observe the shortest. Of all displayed regional contexts, however, the European scope experiences the shortest lulls due to the larger spatial area.

Comparing technologies, with the exception of Germany and the United Kingdom, PV generation appears to be far less prone to long lull spans than wind generation. When combining wind and PV generation, however, lull occurrences are reduced by a factor of three or four (depending on the regional scope) compared to either independent technology.

3.2 *Variable Lull Threshold*

Figure 4 displays the effect of varying the lull threshold from 0 to 100% of the multi-annual average combined wind and PV generation for each regional scope. Unsurprisingly, it is seen that the chosen lull threshold has a large influence on the lull spans that will be observed. These trends also indicate the threshold which is required to observe a VRES lull. Across the European context, for instance, it is seen that below a 28% threshold, it is possible for some weather years to not observe any VRES lull events. Similarly, with a 17% threshold only one in ten years observe a VRES lull, while with an 11% threshold no lull events are observed in any weather year across the European scope. Conversely, the national scopes are much more susceptible to VRES lulls; especially in the case of Germany and the United Kingdom. Moreover, unlike over the whole of Europe, no country is seen to be capable of generating a base load from wind and PV alone.

3.3 *Comparison to literature*

Weber et al. [4] performed an analysis similar to this study for onshore wind energy in Europe and Germany, and thus their study offers comparable results. Their set-up is most comparable to a 50% lull threshold of this study, although they only provide relative occurrence frequencies of individual lull spans; and thus cannot comment on how likely a lull is to occur in any given year. Since these occurrences are given in high-detail, however, they can be recreated with the results generated in this work. Finally, note that Weber et al. do not consider a regeneration period when searching for lull events. The comparisons from this point on were adjusted to match Weber et al.'s context, and so are disconnected from Figures 3 and 4.

Ultimately, Weber et al. predict a higher proportion of shorter onshore wind lull events across Europe compared to this work. This can be seen by their prediction that 90% of lulls should last less than roughly 90 hours, while in the present work finds 140 hours. Both studies agree, however, that 99% of European onshore wind lull events should last less than 400 hours. The earlier disagreement is thought to arise from Weber et al.'s use of the EURO-CORDEX weather datasets, which possess significantly higher spatial resolution than the MERRA2 dataset used in this work. This likely leads to more spatial mixing of the onshore wind generation profiles across Europe and thus a decreased likelihood for extended lull periods.

Conversely, for Germany, this work and Weber et al. agree that 90% of onshore wind lull events should last less than roughly 120 hours, however they disagree on the length of the rarest lulls. In this case, Weber et al. predict that 99% of onshore wind lulls in Germany should last less than 390 hours, while this work finds 262 hours. In this case the difference is thought to arise from Weber et al.'s use of a uniform spatial distribution compared to the explicit selection of well-performing installation sites used in this work; which should lead to higher FLHs. Another difference is Weber et al.'s use of 6-hourly wind speed data, compared to the hourly data employed here which can allow for longer uninterrupted periods of generation below the lull threshold.

4. CONCLUSIONS

This work shows that the occurrence of VRES lulls is highly sensitive to the region, technology, and definition of what constitutes a lull. Some countries, such as Germany and the United Kingdom, appear to be more susceptible to VRES lulls than others and thus may be more reliant on storage solutions in a future VRES-based energy system. PV generally appears to be more reliable than wind energy when considering the occurrence of long lull spans, but the combination of wind and PV is clearly superior to either independent technology. This suggests that a future VRES-based energy system should always rely on a mixed generation portfolio. Lastly, when combining wind and PV generation across the European scope, a base generation is found to be possible equaling to 11% of the average hourly generation.

The outcomes of this work tied to the selected E-Highway scenario and, therefore, follow-up works should investigate alternative capacity and VRES design scenarios. Furthermore, temporally-resolved electricity demand, grid limitations as well as the availability of back-up generation and storage options, should also be included. Nevertheless, the occurrence probability results of this work can assist policy makers and energy systems planners when making risk-informed decisions regarding how much VRES generation should be relied upon in their local regions, and by extension how much storage or backup capacity they may additionally require.

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