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Potential contributions of wind power to a stable and highly renewable Swiss power supply

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HIGHLIGHTS

- Correlation as a function of distance is lower than in non-complex terrain.
- Sustained low wind power intervals are less likely in winter and at higher elevations.
- Despite lower air density, wind power production increases with elevation.
- The seasonal pattern of (alpine) wind power is complementary to hydropower and PV.
- At higher elevations, this complementarity increases.

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ABSTRACT

Using data from two measurement networks, we analyse the following aspects of wind speeds over Switzerland to assess the possibility of high wind power penetration: spatial correlation, persistent low wind power conditions and the diurnal and seasonal wind speed patterns. We show that correlation amongst speeds as a function of distance is significantly lower compared to values found in literature. This can be attributed to the complex terrain of the Alps, which has a profound influence on meteorological parameters. Secondly, using extreme value analysis we calculate return levels for low wind power periods. Large differences are found, with return levels ranging from 29 to 1017 h of no power production for a return period of 10 years. No clear spatial pattern was found that can account for these values. However, the length of no-production periods decreases with increasing elevation. Next, we investigate diurnal and seasonal wind speed patterns and show how the different patterns and their intra-annual variation can be explained by local topography. We also find that with increasing elevation mean wind speeds and power production increase, even when accounting for lower air density. Wind speeds are on average higher in winter, and at elevation the relative increase in winter compared to summer is higher. Notable exceptions are explained from topography and carry implications for wind power development. In view of Switzerland's electricity shortage in winter, these findings make a strong claim for wind power development, especially at higher elevations.

1. Introduction

In 2011, following the Fukushima Daiichi nuclear disaster, the Swiss Federal council and Parliament decided on the phase out of Switzerlands five nuclear energy plants [1]. As nuclear energy is responsible for 37.9% of Switzerlands annual (2014) electricity supply [2], this phase out implies a major overhaul of the Swiss electricity supply. To this end, the Federal council has developed the Energy Strategy 2050, which - amongst others - encompasses an expansion of electricity production from renewable sources (wind, solar, hydro and geothermal).

Rapid expansion of weather dependent renewable electricity sources can however lead to undesired side effects. In Germany, where solar and wind power have seen a significant increase over the last decade, negative prices and high consumer costs are amongst such effects [3,4]. With a high share of wind power (15% of total German electricity consumption in 2015) [5], the ability to dampen fluctuations in production is also reduced. In extreme cases neighbouring countries are called upon to help

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smoothen out spikes in power production, as happened during a storm in March 2015, when the German TSO requested neighbouring countries to absorb German wind electricity in order to stabilise the German transmission grid [6]. While in this case the neighbouring countries were able to assist, in a future, highly renewable Europe where all countries have a large share of weather dependent renewables, such balancing from neighbours cannot be guaranteed, since there is a strong correlation between wind speeds on those geographic scales [7]. Recently, much research has therefore focussed on the integration of renewables into the grid (see for example [8–10]) and the associated costs [11,12]. Switzerland differs from the general European case due to the presence of large amounts of hydropower,[1] which has been shown to increase the market value of wind energy [13], as hydropower allows for the compensation of short-term mismatches [14].

With current wind power penetration levels in Switzerland (0.14% of 2014 power production/ 0.17% of consumption) [15,2] it appears most economical to locate the capacity based on maximum annual yield, ignoring the temporal generation profile, since the installed capacity is relatively small. Imports can be called upon when no wind power is delivered and demand is high. However as both Switzerland and the EU are expected to increase their wind capacity in the coming decade,[2] the temporal generation profiles and their correlation will become increasingly important. The case of Germany exemplifies that placing capacity based on maximum annual yield can become harmful to the system once penetration rates of renewables reach certain levels. Although it makes sense from an individual investor's perspective to locate capacity based on maximum annual yield (especially given current feed in tariffs), for the system as a whole it may be beneficial to consider other spatio-temporal statistics when allocating renewable sources.

The purpose of this work therefore is to explore those wind speed statistics over Switzerland that are relevant in case of high penetration rates of wind power. Specifically three elements are investigated: Firstly, we look into the correlation between wind speeds throughout the country, because this is related to the ability to smoothen overall wind power production. Secondly, using extreme value analysis, we examine the occurrence of long periods where wind speeds are outside the turbine's operating range (i.e. either too high or too low). Such a probabilistic assessment sheds light on the worst case scenarios that are to be expected. Lastly, we investigate the diurnal wind speed patterns across the country, and look into their seasonal variation. Given that demand for electricity is subject to significant diurnal and seasonal fluctuation, in a future Swiss power system with large shares of renewables, the temporal production patterns of non-dispatchable renewable sources are crucial to minimise mismatch between (residual) demand and supply. For all three aspects mentioned above, we try to assess the influence of the highly complex topography on the results. In so far as these themes have been researched, most studies have considered non-complex terrain. Given the profound influence of topography on meteorological parameters, there is little reason to assume the results of these studies could apply to complex terrain as well.

The correlation ρ between wind speeds as a function of distance d is typically related to a decay parameter D, which determines how fast the correlation decays with distance [7]. Giebel [7] finds a decay parameter of $D = 723$ km for correlation between wind stations across Europe. Holttinen [17] finds a value of $D = 500$ km for Scandinavian countries, and Katzenstein et al. [18] estimate $D = 350$ km for Texan wind power time series. Villanueva et al. describe a linear relation between correlation and distance, and compare correlations in both complex and non-complex terrain. They conclude that a linear relation between correlation and distance is a decent approximation in both cases. Reducing output variation therefore typically requires combining wind farms over distances in these orders of magnitude, where the relative variability of wind power decreases as the area considered as an interconnected system increases [19]. However, the terrain in these studies is relatively flat. Given the aforementioned influence of topography on meteorological parameters, it is unlikely that the values found in these studies apply to more complex topography (such as that of Switzerland [20]). So far, no comparison between correlation of wind speeds in complex terrain with these existing studies has been made. With this study we aim to fill that gap.

Next, we examine the occurrence of long periods where wind speeds are outside of the turbine's operating range and consequently, no power can be produced. While short term fluctuations (in the order of minutes to hours) may be balanced by hydropower production [14], sustained periods with low wind speeds have a strong impact on power systems that are highly dependent on wind power production. Often, wind speed persistence is investigated using the autocorrelation function, conditional probability or speed duration curves [21–23], but also runs analysis and intensity-duration analysis [24]. Recently, Telesca et al. [25] investigated the temporal structure of high frequency wind series in Switzerland, and found cyclic components of 24, 12, and sometimes 8 or 6 h, that they relate to temperature and pressure variations. We will use extreme value analysis (EVA) to make inferences about long periods of low wind power conditions, because EVA allows for estimates beyond the length of the observed dataseries. Extreme value analysis is often used to describe extremes of processes in nature such as snowfall [26–28], rainfall [29], and wind speeds [30], but also financial processes and value at risk [31]. Its basic premise is to separately model the tail of a distribution. Although the magnitude of extreme wind speeds in Switzerland and elsewhere has been investigated before [32–35], to our knowledge no effort has been undertaken to map the extremes of low-wind persistence in Switzerland, or relate these to power production.

Lastly, we examine the seasonal and diurnal evolution of wind speeds across Switzerland as well as elevational trends. Given the varied and complex terrain found across the country, it is possible that the (evolution of) wind speeds will be affected by this. For example, Chow [36] describes diurnal mountain wind systems or thermally driven winds: Due to the heating and cooling of the lower atmosphere, winds form that are driven by buoyancy. Mainly during stable summer weather, daytime heating in valleys will produce an up-valley flow. Nighttime cooling in its turn, will produce downwind flows, as cooler, heavier air flows downslope. In Section 3.3, we will investigate the evolution of the diurnal wind speed patterns over Switzerland, and infer implications for wind power production.

Apart from a diurnal evolution, there is also a seasonal pattern to the Swiss electricity demand that is mainly associated with an increase in lighting and heating in winter [37]. Combined with reduced hydropower production in winter due to the characteristics of the hydrological cycle, this leads to a power deficit in winter [38]. We will therefore also investigate the seasonal evolution of diurnal cycles, and see to what extent wind power is able to meet this demand. This is especially relevant given the fact that solar power declines significantly in winter due to the earth's inclination, and as such is unable to complement hydropower in its seasonal cycle. Mean wind speeds in Europe, on the contrary, are

[1] 56.4% of annual (2014) electricity supply, 31.7% of which consists of storage hydropower [2].

[2] The European Wind Energy Agency estimates installed wind capacity in the EU to reach between 251 and 391GW in 2030 (between 19 and 33% of the EU's 2030 demand) [16]. In Switzerland, wind power is projected to produce between 500 and 1700 GWh in 2035, when demand for electricity will be in the range of 55 to 60 TWh (0.8–3%) [15].