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

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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 hours 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.

Keywords: Wind energy, Correlation, Extreme value analysis, Persistence, Valley winds, Wind power integration

1. Introduction

In 2011, following the Fukushima Daiichi nuclear disaster, the Swiss Federal council and Parliament decided on the phase out of Switzerland's five nuclear energy plants [5]. As nuclear energy is responsible for 37.9% of Switzerland's annual (2014) electricity supply [13], 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 [29, 43]. With a high share of wind power (15% of total German electricity consumption in 2015) [1], the ability to dampen fluctuations in production is also reduced. In extreme cases neighbouring countries are called upon to help 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 [58]. 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 [33]. Recently, much research has therefore focussed on the integration of renewables into the grid (see for example [10, 51, 66]) and the associated costs [11, 12]. Switzerland differs from the general European case due to the presence of large amounts of hydropower¹, which has been shown to increase the market value of wind energy [38], as hydropower allows for the compensation of short-term mismatches [25].

With current wind power penetration levels in Switzerland (0.14% of 2014 power production / 0.17% of consumption) [56, 13] 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 decade², the temporal generation profiles and their correlation will become increasingly important. The case of Germany exempli-

¹56.4% of annual (2014) electricity supply, 31.7% of which consists of storage hydropower [13]

²The European Wind Energy Agency estimates installed wind capacity in the EU to reach between 251 and 391 GW in 2030 (between 19 and 33% of the EU's 2030 demand) [22]. 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 to 3%) [56]

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fies 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 [68], 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 [33]. Giebel [33] finds a decay parameter of $D=723$ km for correlation between wind stations across Europe. Holttinen [39] finds a value of $D=500$ km for Scandinavian countries, and Katzenstein et al. [42] estimate $D=350$ km for Texan wind power time series. Villanueva et al. [68] 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 [32]. 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 [69]). 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 [25], 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 [15] [44] [45], but also runs analysis and intensity-duration analysis [48]. Recently, Telesca et al. [64] investigated the temporal structure of high frequency wind series in Switzerland, and found cyclic components of 24, 12, and sometimes 8 or 6 hours, 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 data series. Extreme value analysis is often used to describe extremes of processes in nature such as snowfall [8][7][6], rainfall [65], and wind speeds [59], but also financial processes and value at risk [61]. 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 [17, 28, 47, 55], 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 [18] 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 down-slope. 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 [3]. Combined with reduced hydropower production in winter due to the characteristics of the hydrological cycle, this leads to a power deficit in winter [63]. 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 reported to increase in winter [37]. We will investigate if this also holds for the complex terrain in the Alps.

The paper is structured as follows: In the next section we describe the two main datasets that were used as well as the data processing that was done and the methods to calculate correlation, return levels and diurnal patterns. Next, in section 3 we discuss the results. We analyse some of the sensitive parameters with regards to the calculation of return levels in section 4. In section 5 we present our conclusions.

2. Data and Methods

2.1. Measurement stations

The Swiss weather service MeteoSwiss deploys a network of roughly 160 automated measuring stations across Switzerland, called SwissMetNet (from here on SMN) [52]. We've manually selected the stations with long measurement series (minimum of 35 years) of hourly wind speeds, which gives us a dataset of 42 stations. These stations are located throughout Switzerland, at altitudes ranging from 273 (Lugano) to 3302 m.a.s.l. (Piz Corvatsch). A second dataset is formed by the IMIS station network [50, 60]. This network, consisting of 198 stations around the Alps and Jura mountains, is operated by the Swiss Institute for Snow and Avalanche Research SLF. These stations are located in pairs with a wind station at an exposed location and a snow station at a less exposed location, which is generally also at slightly lower elevation. All stations measure temperature, humidity and wind speed. Data are averaged over 30 minutes. For our purposes, we use the wind stations and only use the snow stations to interpolate missing data in the wind stations (see next section). These wind stations are located at elevations from 1936 (Amden - Mattstock) to 3345 (Zermatt - Plattthorn) m.a.s.l. In total this gives us 62 of these stations, of which we use the 57 that have data sets longer than 5 years. Figure 1 shows both the IMIS and SMN stations in Switzerland.

Figure 1: The SMN and IMIS stations

2.2. Missing Data

Most wind speed time series contain missing data, for example due to icing of the anemometers [34]. Since the continuity of the time series is important to infer results about persistence, we want to work with continuous data as much as possible. For the IMIS stations, the presence of a second station (snow station) close to the wind station provides a useful set to base our estimates of missing data on. Here, missing values are imputed with the Amelia package in R [40][41]. This package estimates missing values based on an Expectation-Maximization with

Bootstrapping (EMB) algorithm. To this end, for each IMIS wind station, the overlapping periods with the IMIS snow station, as well as the neighbouring SMN station (based on smallest distance) are synchronised and fed into the Amelia algorithm to impute the missing values. As there are periods where both the corresponding snow station and the nearest SMN station are also without data, not all missing values have been resolved. Initially the average missing data per series was 8.9 % (with a median and max of 7.6% and 23.4% resp.). After imputation, these percentages are 0.4, 0.3 and 2.3% respectively. We then average the IMIS values over the hour, so that both datasets have hourly resolution and can be easily combined. For the calculation of correlation coefficients and the calculation of diurnal wind patterns, we use this dataset and ignore the entries with missing values. For the calculation of return levels, the remaining missing values are replaced with the mean, because leaving them as zero or missing would distort the calculation as they would be regarded as being below the cut-in speed, and this could falsely introduce long periods of no wind power.

2.3. Correlation

Cross-correlation between measurement stations describes the degree to which two time series change in the same direction and magnitude. It is usually quantified using Pearson's correlation coefficient. Several authors have fitted an exponentially decaying function to describe correlation between wind speeds as a function of distance [33], [39], [42]. These functions have mainly been of the form

$$\rho = e^{-d/D}, \quad (1)$$

where ρ is the correlation coefficient, d is the distance and D the decay parameter that describes how fast the correlation decreases with distance. The latter is usually determined by fitting equation 1 to the data.

2.4. Turbine choice

The power a wind turbine produces at a certain speed is described by a turbine's power curve, which is specific for each turbine. In this work, we use the Enercon E82 turbine with a capacity of 2MW, the cut-in speed at which the turbine starts to produce electricity, and the cut-out speed, at which the turbine is shut down to prevent damage. This turbine is widely used in Switzerland (a full list of current installations can be found on-line at [53]). It has a relatively low cut in speed of 2.5 m/s, which is thought to be favourable in low(er) wind conditions such as Switzerland. Using the same turbine for all locations arguably leads to sub-optimal results, since a higher power yield could be achieved by optimising the turbine selection for the wind characteristics of each location. As the selection of a turbine for a specific site is not straightforward however, this is beyond the scope of the present work. Since the goal is to compare locations rather than find the optimal yields, using one turbine seems plausible.

2.5. Height transformation

The wind data is recorded at 10m, whereas most turbines are in the height range of 75-100 meters. Therefore a transformation has to be made to make these speeds comparable. The vertical wind profile is often represented as following a logarithmic or power law [23] [26], the latter being given by

$$v_{hh} = v_{10} \left(\frac{hh}{10} \right)^\alpha \quad (2)$$

with v_{hh} the speed at hub height hh , v_{10} the speed measured at a height of 10 meter and α the wind shear coefficient. For neutral stability, a rule of thumb is to use a value of 0.143 or 1/7 for α , although it is acknowledged that this may underestimate energy yield [46] (and references therein), as α is neither constant over height nor over time. Indeed, a range of (average) values for α have been reported, from 0.1 in a mountain pass in Switzerland [19] to 0.36 for a Mediterranean island [30]. When intra-annual values of α are considered, it becomes clear that great variation during the year takes place. Kubik et al. [46] finds values ranging from -0.5 to 0.5, with a mean of 0.119, as well as a clear diurnal pattern, where night time shear values are almost twice the daily values. Clifton et al. [19] find negative values for south-easterly winds at a pass location, and Farrugia [30] reports higher shear exponents during night-time and during winter. Furthermore, Bunse and Mellinshoff [14] show that the distribution for α is broader in flat terrain than it is in complex terrain, and concludes no general trend towards lower values of α in complex terrain. Lastly, it has been noted by several authors that in complex terrain, the vertical wind profile does not always follow a logarithmic- or power law [16] [24] and that this may lead to errors in power estimates of up to 50% [31]. In absence of a clear parametrisation of α , we stick to the common-yet-disputable value of 0.14. Rather than transforming the entire wind speed time series from 10 m to hub height, we transform the turbine's power curve (and thus the cut-in and cut-out speed) down to 10m, for an assumed hub height of 80m. This is done solely for computational purposes, as transforming these two is less time consuming than transforming all multi-year time series. This then gives us a direct translation from measured wind speeds at 10m to power output of a hypothetical wind turbine with a hub height of 80m.

2.6. Extreme Value Analysis

Extreme value analysis deals with the statistical behaviour of the extremes of a distribution of random variables [35]. For a sequence of independent and identically distributed random variables $X_1, X_2, \dots, X_n$ the maximum is given by $Z_n = \max(X_1, \dots, X_n)$. Given that n is large enough, the probability that Z_n does not exceed a level z is given by the Generalised Extreme Value (GEV) distribution, whose cumulative distribution function is given by

$$G(z; \mu, \sigma, \xi) = \begin{cases} \exp \left[- \left(1 + \xi \frac{z - \mu}{\sigma} \right)^{-\frac{1}{\xi}} \right] & \text{for } 1 + \xi \frac{z - \mu}{\sigma} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where μ , σ and ξ are the location, scale and shape parameter, respectively. The sign of the shape parameter ξ tells us whether the distribution is bounded ($\xi < 0$), in which case the value of X is limited and theoretically no value above an upper bound can be observed. When the distribution is light tailed (i.e. $\xi = 0$), extreme values are possible albeit not very likely. Lastly, in the case of a heavy tailed distribution ($\xi > 0$), extreme values are more likely to occur. These three cases of the GEV distribution are also known as the Weibull-, the Gumbel and the Frechet distribution respectively. For a visual representation of the GEV parameters, see [7]. Two main methods exist for dealing with maxima. Traditionally, the data is separated into blocks (e.g. months) and the GEV distribution is fitted to the monthly maxima. Hence this method is referred to as the block maxima method. The obvious downside here is that a lot of extremal data is discarded. The so-called peaks-over-threshold (POT) method on the other hand, takes into account all values above a certain threshold u . Given that the threshold is sufficiently high, the distribution of threshold exceedances can either be described by a generalised Pareto distribution (GPD), or by a Poisson Point (PP) Process. The latter has the advantage that by rescaling the intensity function of the Poisson process, the parameters can be made identical to those of the GEV. (For details see [20] or [21]). This allows for the computation of the return level z_p , a value that is exceeded on average once every return period $1/p$. As such, a return level represents the $(1-p)$ th quantile of the GEV distribution. By inverting equation 3 we can obtain its value:

$$z_p = \begin{cases} \mu - \frac{\sigma}{\xi} \left[1 - \{-\log(1-p)\}^{-\xi} \right] & \text{for } \xi \neq 0 \\ \mu - \sigma \log - \log(1-p) & \text{for } \xi = 0 \end{cases} \quad (4)$$

Of relevance to power production are the periods when no power is produced because the wind speed is either below the cut-in speed, or because the wind speed is above cut out speed. To assess these, we record the length of the intervals where the wind speed is outside of the turbine's operating range (i.e. below cut-in or above cut-out). With the distribution of these interval lengths, a Poisson point process is fitted to the exceedances over a threshold, for which the 90th percentile is used. Since we are modelling the interval length rather than wind speed, these data are independent. An important issue is the role of declustering in these series. Is the end of a no-power interval defined by one hour of power production, or do we need several consecutive hours of power production before a no-power interval is over? The consequences for the power system of a single hour of power production in between large intervals of no power can be argued to be insignificant. Therefore the declustering is run with a declustering parameter [62] of 3 hours. This means that wind speeds will have to be above the cut-in threshold (or below cut-out) for a minimum of 3 hours in order to separate no-power production intervals. Increasing this parameter leads to larger clusters of no-power events and as such will have a profound impact on the results. (see figure 2. The parameter choice is thus an important one, although there is no obvious choice. (For now we keep the decluster-

Figure 2: The Return level (in hours) as a function of the declustering parameter k . Shown here for the location Chasseral, in the Bernese Jura region of Switzerland.

Figure 3: Cross-correlation between wind speeds in Switzerland. Also shown are the fitted functions, as well as the other values found in literature describing this relation [33, 39, 42].

ing parameter $k \ll \text{threshold } u$). No power production due to forced downtime is not considered here. The return periods for no production because of low or high winds are difficult to compare to production losses because of turbine service or material damages. However, most turbines require on the order of days of service time with a yearly return period [36] but - more importantly - not all turbines of a farm will be off production at the same time. Therefore, we neglect the service and repair production losses in our analysis. Although it is acknowledged that in highly turbulent environments, fatigue loads may be higher [9], which could lead to shorter turbine life or increased downtime, the magnitude of such effects is highly site-specific.

2.7. Diurnal wind speed patterns

To investigate the diurnal wind patterns at different stations, data were processed as follows. Hourly time series for both station networks were averaged by hour of the day to produce annual averaged diurnal profiles. Secondly, the averaging was done per month and per hour of the day, so that intra-annual difference could be explored.

3. Results and Discussion

3.1. Correlation

Figure 3 shows the cross-correlation coefficients as a function of the distance for 99 wind measurement stations from both the IMIS and SMN network in Switzerland. Also shown are some of the functions found in literature describing the relation between wind speed (or power) correlation and distance as discussed in the introduction.

Upon a first glance at the data in figure 3, fitting an exponential curve does not appear very obvious. And indeed, when we do, although we find a decay parameter D of 44km, the R^2 value of -0.65 tells us this is a worse fit than a horizontal line. A linear fit is hardly better with an R^2 of 0.04. From a visual assessment we can conclude that the correlations between wind speeds as a function of distance are significantly

lower in Switzerland when compared to the values found in literature. What is furthermore noteworthy, is the fact that a significant number of negative correlations are found, indicating anti-correlation. This finding is interesting in view of combining wind farms to reduce overall output variability. It should be noted that because of the non-linear relation between wind speed and power output, correlation between power production is not (exactly) the same as correlations amongst wind speeds. Generally, correlations between power are lower (in the case of Giebel [33] $D=723$ for speed and 641 for power). However, even with this remark, the above conclusion that correlations in Switzerland are lower still holds.

3.2. Return levels

Figure 4 shows the return levels for return periods of 10 and 50 years, in hours of no power production. This can be interpreted as the level being exceeded once every 10 (50) years. It ranges from 29 to 1017 hours (roughly 6 weeks) for a return period of 10 years. For the return period of 50 years, the range spans from 34 hours to 1964 hours (figure 4). The highest 10 year return level is found in Disentis/Sedrun (1197 m.a.s.l.), in the central part of Switzerland, whereas the lowest return level was found at Sidelhorn, a summit close to the Grimsel pass on the border of the cantons of Bern and Valais. At a first glance, no clear spatial pattern seems apparent. A investigation into the relation between altitude and the parameters of the fitted Poisson Point process is shown in figure 6. It can be seen that there is a correlation between a station's elevation and the parameters of the fit, which leads to a correlation between the 10 year return level and elevation. We can also see that the majority of stations have an unbound distribution, indicated by the positive value of ξ . For a couple of stations the parameter ξ is negative, indicating a bound distribution. If we closer examine the 14 stations with a significant negative ξ parameter ($\xi < 0.01$), we find that these are mainly stations above 2200 m.a.s.l, except for two stations in the (far) western part of Switzerland at lower elevations (the only two SMN stations in the lower right panel

(a) 10 year return level

(b) 50 year return level

Figure 4: Return levels for no power intervals. These represent the no-power production intervals that are to be expected once every 10 (50) years.

of figure 6). These two stations are both located at a hill with a long upwind fetch amidst relatively flat terrain, which may contribute to their above average wind speeds.

3.3. Seasonal decomposition

Switzerland's electricity consumption is higher in winter due to increased heating and lighting demand [3]. Combined with the characteristics of the hydrological cycle, this leads to a power deficit in winter [63]. It is therefore insightful to look at the return levels for sustained no-power events in the summer and winter periods separately. To this end, the dataset is split into summer and winter. This creates yearly interruptions in the dataset, whereby the average interval length is shortened. As such, these results cannot be directly compared to the overall return levels, but only side by side. This is done in figure 5, where we see distinctly lower return levels during winter, when compared to the summer periods. This implies that no-power

Figure 5: Ratio of return levels in summer vs winter. A value above 1 indicates higher return levels in summer. The series were split into summer and winter, where summer was defined as consisting of the months May to October, and winter as November through April.

periods are -on average- shorter during the winter months.

3.4. Diurnal patterns

Figure 7 shows diurnal wind speed profiles for the stations in the SMN network (left) and IMIS network (right). There appear to be two distinct types of profiles, characterised either by an increase in wind speed during the afternoon, or a decrease. The majority of the stations belong to the latter, which can be explained by the diurnal evolution of the boundary layer. The other distinct pattern we see is wind speeds increasing during the afternoon. This occurs mainly at stations in the SMN network (compare fig a and b). In the IMIS network, only two stations display this behaviour. Both are situated at mountain ridges near the upper end of long valleys (Sidelhorn in the Rhone valley and Cho d'Valetta (Bever) at the Inn valley respectively). Long valleys are known to produce so called valley winds, when thermally induced pressure differences cause up-valley flows [18]. Specifically in the Inn valley, pressure differences of up to 5hPa have been reported [67]. The SMN dataset includes more valley stations, and here the afternoon peak in speeds is more common (see fig 7(a)).

3.4.1. Seasonal decomposition of diurnal patterns.

The majority of Switzerland's power comes from hydropower, which has a distinct annual cycle, with production peaking in mid-summer, although demand peaks in winter [3]. In a future renewable Swiss power system, high emphasis will be placed on compatibility with this annual hydropower cycle. Although photovoltaic power generation is assumed to play a big role in Switzerland's future electricity supply [56], it also suffers from an annual cycle that is not complementary to that of hydro [3]. Wind power could provide a balancing component to the power supply. We therefore look at the monthly variations in diurnal patterns, by calculating the average diurnal

Figure 6: The 10 year return level (upper left), and the parameters of the GEV distribution, plotted as a function of altitude.

Figure 7: Diurnal wind speed profiles for the a) SMN stations. b) the IMIS stations. The SMN dataset contains stations at lower elevations, and as such has more stations that display a typical valley wind pattern with wind speeds increasing in the afternoon. In The IMIS dataset with higher elevation stations this behaviour is less common. Times are in UTC (+1 hr for Swiss wintertime, +2 for summertime.)

Figure 8: monthly diurnal patterns for the locations Chasseral, Gütsch, Bever Visp, Simplon and Chur. The black dashed line indicates the annual average, the coloured lines represent the months. Times are in UTC (+1 hr for Swiss wintertime, +2 for summertime.)

Figure 9: Relative increase in mean speeds in winter compared to summer, as a function of elevation. Higher altitude locations seem -on average- to have relatively higher wind speeds in winter.

Figure 10: Simulated electricity production as a function of elevation. Higher altitude locations seem -on average- to have relatively higher yield, despite lower air density.

cycle per month. Figure 8 displays such monthly decompositions for 6 selected stations. What is clear in all cases, is that there is significant variation from the annual average diurnal cycle, displayed by a dashed black line. Examining the stations at Gütsch, Bever, Chur and Visp, we see that the increase during the afternoon that is associated with a thermally induced valley wind, mainly occurs in the summer months when irradiance is high. During winter the peak is significantly less pronounced at these locations. Similarly for the stations without thermally driven winds (Chasseral, and Simplon) we also see a decrease in intra-daily variation during winter, as profiles become flatter.

3.5. Elevation

Mean wind speeds in Europe are reported to be higher in winter [37], which based on our data we can confirm for Switzerland: On average, mean wind speeds in the winter months (November through April) are 20,2% higher than the mean speeds in summer. However, 11 out of the 99 locations do not have a higher mean speed in winter. These 'summer-high' stations all display a clear signature of thermally induced winds, which explains the high summer means. Plotting the relative difference in seasonal mean speed as a function of elevation, we see an interesting pattern depicted in figure 9. The relative increase in winter compared to summer increases with elevation.

Higher winter wind speeds could imply favourable conditions for wind farms at higher elevations, although at the same time air density decreases with elevation, leading to lower power output. To investigate this we have simulated the power production for each location, including a correction for reduced yield due to air density. The methodology is described in Appendix A. When we plot the power production (corrected for air density) as a function of elevation, we see that there is a clear increase in power production at higher elevations (figure 10). The negative effect that lower air density has on power production seems to be more than offset by higher wind speeds. Also included in this plot is a sensitivity analysis of the effect

of the wind shear parameter α on the results. The calculation was performed several times with values of α between -0.07 and 0.42. The resulting spread in the results is indicated with vertical bars. The fit and R values are for an α of 0.14.

4. Sensitivity and Outlook

In this section we investigate some of the assumptions and uncertainties that may influence the results. A large factor of uncertainty is introduced by the vertical translation of wind speeds. Although it is acknowledged that the value of the wind shear coefficient α varies significantly (see section 2.5 and references therein), no suitable parametrisation has been found. Since the vertical translation is done for the cut-in and cut-out speeds of the turbine, the choice of α will have a direct effect on the value of the (translated) cut-in speed and thus on the length of the intervals outside of the turbine's operating range (and hence the calculated return levels). Similarly, the cut-in and cut-out speeds themselves influence the interval length and return levels. The choice of turbine will therefore also have an effect on the results. Both effects can be captured by varying the cut-in speed and recording the effect on the 10 year return level of sustained no-power periods. The spread of the results is depicted in figure 11, where the most sensitive location (max) and the least sensitive location (min) are shown alongside the average effect. A similar graph (not shown) for the sensitivity to cut-out speeds showed very low sensitivity to cut-out speed variation.

Figure 11: Sensitivity of calculated return levels to cut in speeds.

5. Conclusion

Using hourly wind speed data from two measurement networks across Switzerland, we have shown that cross-correlations as a function of distance between stations are significantly lower in Switzerland than values reported in literature for Europe and the US. The discrepancy with previously reported values can easily be understood from the complex terrain that makes up much of Switzerland's surface. This influences wind speed characteristics significantly, as can also be seen in other results. The implications for wind power production may however be positive: Smoothing the output from combinations of wind farms can in Switzerland be achieved over much shorter distances than those commonly reported in literature. This holds for any country with complex terrain influencing the wind climate. Furthermore, capacity credit - the ability to displace conventional generating capacity - increases with increased smoothing of the combined wind power output [27]. Because of this, the capacity credit of wind power will be higher with lower correlation.

We have analysed the length of periods where the wind speed is outside the operating range of the Enercon E82 turbine for 99 wind stations across Switzerland. An extreme value distribution was fitted to each of these length records, to allow for the calculation of return levels for return periods of 10 and 50 years. These return levels show great spatial variability, yet return levels clearly decrease as the elevation of the stations increases (figure 6), which implies that wind farms that are located at higher elevation are less likely to suffer long periods without power production. A decomposition of the return levels for summer and winter periods showed significantly lower return levels in winter, indicating that the likelihood of persistent periods where no wind power can be produced are lower for almost all locations in winter. This is beneficial for Switzerland, since it has an electricity deficit in winter, and a future renewables-based power system is likely to be under the greatest stress during the winter months, as is the current system.

We have confirmed that wind speeds are on average indeed higher in winter, although we have also been able to show that there are notable exceptions, with implications for wind power

generation. While many of the measurement locations at mountain ridges are exposed to rather free tropospheric wind conditions during night and much of the day, the developing thermal up-slope and up-valley winds are able to create a local boundary layer. This boundary layer prevents the penetration of high wind speeds to ground level. Hence the majority of the measurement stations display a decrease in wind speed during the afternoon. Contrarily, long valleys experience rather low wind speeds during night time and most of the day. With strong solar irradiation however, thermally induced pressure differences can cause up-valley winds. As the temperature increases during the day, wind speeds increase with a peak between 3 p.m. and 8 p.m. These peaks are more pronounced during the summer months when solar irradiation is higher, whereas in winter they can be virtually non-existent. For the 88 of the 99 stations in our dataset, the mean wind speed is higher in winter. The few stations that have higher mean wind speed in summer are all found at the bottom of valleys, where the strong radiative heating in summer creates the afore-described increase in wind speed.

The usefulness of these valley stations for wind electricity production is limited since their pronounced peak mainly occurs during summer, when the demand for electricity is lower and hydropower is abundantly available. Moreover, as electricity production from PV is projected to increase both in Switzerland and in the neighbouring countries, in a future, highly renewable Europe there will likely be a surplus of power at daytime during summer.

For all but these few valley stations, not only is the mean wind speed higher in winter, but the relative difference between winter and summer is also more pronounced with increasing elevation (figure 9). Moreover, power production also appears to increase with elevation (figure 10), despite the negative effects of lower air density on electricity yield.

5.1. Implications and Outlook

Given Switzerland's power deficit in winter and its intended nuclear phase-out, electricity sources that are either dispatchable or have a seasonal pattern to complement this deficit are called for. However apart from biomass, all currently feasible dispatchable technologies are fossil based and as such are questionable in view of climate change. Amongst the currently mature renewable technologies, wind power has a highly favourable seasonal profile. We've been able to show that this seasonal pattern appears more pronounced at altitude, and that wind power in long valleys subject to thermally induced wind speed-up has an unfavourable seasonal profile. Annual average wind speeds can mask such important dynamics, which can become important as renewables penetrate the electricity market. Feed-in tariffs, which currently allow profitable power production from such valley wind farms will eventually be abolished as wind power reaches grid parity, at which point market prices reflecting demand will determine the profitability. Given our results it is highly debatable whether wind farms that mainly produce during periods of low (residual) demand should be subsidised in this way, especially as we have shown that high elevation locations are able to provide power at times of high

demand. In shaping Switzerland's energy transition, accounting for these dynamics may prevent costly mishaps. The results here underline the need for further research into seasonal dependent feed-in tariffs for wind power.

There are still a lot of open questions however. For one, the wind climate in alpine terrain is extremely hard to map. Where in flat terrain correlations are relatively strong over long distances, facilitating extrapolation of measurements and models in the complex terrain of the Alps this is challenging. Attaining an accurate overview of the wind climate in the Alps would require either a drastic (and possibly unrealistic) increase in measurement stations, or huge advances in computational power as the resolution required to accurately model the flow in this terrain should be high enough to capture all relevant terrain features. Perhaps a hybrid approach, where high resolution modelling of specific locations can provide an estimate of the Alpine potential by extrapolation to similar features, is the first step to take.

Another aspect that has not been taken into consideration here is the performance of wind turbines in Alpine environments. Extreme temperatures can influence the material properties of various components [4], while surface roughness has been linked to an increase in fatigue loads [49], and icing of the rotor blades can cause energy losses of ca 2% [2]. Although an algorithm to estimate icing frequencies in Switzerland has been developed, the authors acknowledge that model resolution is too low to capture local terrain features in the Alps that determine icing frequencies [34]. Combining all these elements to attain insight into the failure probabilities of wind turbines in alpine terrain, will therefore be an important next step on the road to extensive wind power deployment in the Swiss Alps.

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7. References

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Appendix A. air density and altitude

With increasing altitude, air density decreases and as such, the momentum that can be extracted from the air by a turbine is lower. The energy produced at similar wind speeds is therefore lower at altitude, and for a country such as Switzerland, this could be significant. To investigate this effect on power production, we calculate a correction factor to account for the differences in air density at a certain altitude.

The power that can be extracted from the wind is given by

$$P = \frac{1}{2} \rho A v^3 \quad (\text{A.1})$$

where ρ is the air density, A is the rotor swept area, and v the wind speed. The air density ρ in its turn is a function of pressure p , Temperature T (and humidity):

$$\rho = \frac{pM}{RT} \quad (\text{A.2})$$

with M the molar mass and R the ideal gas constant. Both pressure and temperature can be expressed as a function of altitude h [54]

$$p = p_0 \left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RL}} \quad (\text{A.3})$$

$$T = T_0 - Lh \quad (\text{A.4})$$

where p_0, T_0 are the pressure and temperature at sea level, respectively; L is an average constant representing the temperature lapse rate (0.0065 K/m), and g , the gravitational constant (9.80665 m/s²). Combining A.5, A.3 and A.4 we obtain an approximate correction factor for the power production at altitude h compared to sea level:

$$\frac{\rho(h)}{\rho_0} = \left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RL} - 1} \quad (\text{A.5})$$

As temperature varies during the course of the day, the air density is not constant [57]. However, here we neglect diurnal fluctuations in air density.