



Final Report: 31 January 2020

WindVar

Spatial-temporal variability of wind energy potential in Switzerland and neighbouring countries

Räumliche und zeitliche Variabilität der Windkraft in der Schweiz und Nachbarländern



Quelle: Bernhard Mühr, www.wolkenatlas.de



Datum: 31 Januar 2020

Ort: Bern

Subventionsgeberin:

Bundesamt für Energie BFE
Sektion Energieforschung und Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subventionsempfänger/innen:

ETH Zürich, Climate Policy Group
Universitätstrasse 16, 8092 Zürich
<https://www.cp.ethz.ch/>

Autor/in:

Bryn Pickering, ETH Zürich, brynmor.pickering@usys.ethz.ch
Stefan Pfenninger, ETH Zürich, stefan.pfenninger@usys.ethz.ch

BFE-Projektbegleitung:

Katja Maus, katja.maus@bfe.admin.ch
Lionel Perret, lionel.perret@bfe.admin.ch

BFE-Vertragsnummer: SI/501768-01

Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.



Zusammenfassung

Kann ein besseres Verständnis der kleinräumigen Variabilitätsmuster der schweizerischen Winderzeugung dazu beitragen, die mögliche Rolle der Windkraft für das Land zu klären? Das ist die Frage, die in diesem Projekt beantwortet wird.

Zunächst beurteilen wir die Fähigkeit zur genauen Modellierung des Windkraftpotenzials in komplexem Gelände auf der Grundlage mehrerer meteorologischer Reanalysen. Wir stellen fest, dass die regionale Reanalyse COSMO-REA2 mit einer räumlichen Auflösung von 2 km in der Lage ist, einige der Windphänomene an Messstandorten im ganzen Land zu reproduzieren. Darunter fallen z.B. die tageszeitliche Variabilität, die durch die Brisen in den Gebirgstälern und die kanalisierenden Föhn- und Bise-Ströme verursacht werden. Wir kommen daher zu dem Schluss, dass die Verwendung von COSMO-REA2 für weitere Analysen gerechtfertigt ist.

Unsere gesamtschweizerische Analyse mit COSMO-REA2 zeigt erstens dass kleinräumige Geländemerkmale in der Schweiz zu kleinräumigen Gebieten führen, die sich in Bezug auf die Variabilität der Windkraft anders verhalten als ihre Umgebung. Zweitens sehen wir dass es in ausgewählten Schweizer Subregionen klare Muster der Windkraftvariabilität gibt, die mit europaweiten Wetterregimes korrelieren. So weisen einige der Subregionen auf der Zeitskala von Tagen bis Wochen mögliche Muster der Windstromerzeugung auf, die sich fast vollständig von denen in benachbarten, weniger gebirgigen Gebieten unterscheiden.

Schliesslich erstellen wir ein Optimierungsmodell des europäischen Stromsystems, in dem die Schweiz als einzelne Kantone modelliert wird und die zuvor identifizierten Subregionen innerhalb dieser separat modelliert werden. Anhand dieses Modells entwerfen wir zunächst ein optimales Stromsystem für ganz Europa einschließlich der Schweiz. Dieses erste Szenario setzt auf internationale Übertragungsleitungen um die Variabilität der erneuerbaren Energien in Europa ausgleichen. In diesem Szenario wird in der Schweiz im kostenoptimalen Fall keine Windkapazität installiert. Wir testen zwei Szenarien im Optimierungsmodell wo das Modell eine Minimalabdeckung von 10% bzw. 20% des Winterstrombedarfs erreichen muss. Das Modell zeigt dass beide Fälle für die Schweiz wirtschaftlich günstiger sind als das europäische Optimum, basierend auf tieferen Stromgestehungskosten. In beiden Fällen würde sich die Kapazität auf die Jurakämme konzentrieren, mit nur geringer zusätzlicher Kapazität auf den Alpenkämmen und im Kanton Tessin.

Resumé

Le but de ce projet est d'étudier si une meilleure compréhension de la variabilité à petite échelle de la production éolienne suisse pourrait aider à clarifier le rôle possible de l'énergie éolienne pour le pays.

Tout d'abord, nous évaluons la capacité à modéliser avec précision le potentiel éolien en terrain complexe en nous basant sur plusieurs réanalyses météorologiques. Nous constatons que les données COSMO-REA2, avec une résolution spatiale de 2 km, permettent de reproduire certains des phénomènes éoliens de tout le pays, par exemple la variabilité diurne causée par les brises de vallée de montagne, et les flux de canalisation du Föhn et de la Bise..

Sur la base de cette analyse avec COSMO-REA2, nous constatons premièrement que les caractéristiques du terrain à petite échelle en Suisse conduisent à des zones de petite taille qui se comportent différemment de leurs régions environnantes en ce qui concerne la variabilité de l'énergie éolienne. Deuxièmement, nous constatons qu'il existe des schémas clairs de variabilité de l'énergie éolienne dans certaines sous-régions suisses qui sont en corrélation avec les régimes météorologiques européens. Ainsi, sur une échelle de temps



allant de quelques jours à quelques semaines, certaines sous-régions présentent des schémas de production d'électricité éolienne possibles presque totalement opposés à ceux des régions voisines moins montagneuses.

Finalement, construisons un modèle d'optimisation du système électrique européen dans lequel la Suisse est modélisée en tant que cantons individuels, et les sous-régions identifiées auparavant sont modélisées séparément au sein de ceux-ci. À l'aide de ce modèle, nous concevons d'abord un système électrique optimal pour toute l'Europe, y compris la Suisse. Dans ce scénario, qui repose sur des connexions internationales équilibrant la variabilité des énergies renouvelables à travers l'Europe, aucune capacité éolienne n'est installée en Suisse dans un cas de coût optimal. Ensuite, nous relançons le modèle d'optimisation avec une capacité de production éolienne suisse minimale requise équivalente à la couverture de 10 % et 20 % de la demande d'électricité en hiver. Ces deux derniers cas sont plus favorables à la Suisse sur le plan économique que l'optimum européen basé sur le coût actualisé de l'électricité en Suisse, qui est plus faible. Dans les deux cas, la capacité installée serait concentrée sur les crêtes du Jura, avec seulement une petite capacité supplémentaire sur les crêtes alpines et dans le canton du Tessin.

Riepilogo

L'obiettivo di questo progetto è di verificare se una migliore comprensione dei modelli di variabilità su scala ridotta della produzione di energia eolica in Svizzera, possa contribuire a chiarire il possibile ruolo dell'energia eolica per il Paese.

In primo luogo, valutiamo la capacità di modellare accuratamente il potenziale dell'energia eolica in terreni complessi sulla base di diverse rianalisi meteorologiche. Scopriamo che COSMO-REA2, con una risoluzione spaziale di 2 km, è in grado di riprodurre alcuni fenomeni del vento nei siti di misurazione in tutto il paese. Tra cui ad esempio la variabilità diurna causata dalle brezze delle valli di montagna e i flussi di canalizzazione di Föhn e Bise. Concludiamo quindi che l'utilizzo di COSMO-REA2 per ulteriori analisi è giustificato.

Sulla base di tali analisi con COSMO-REA2, troviamo che le caratteristiche del terreno su piccola scala in Svizzera portano a zone di piccole dimensioni che si comportano in modo diverso rispetto alle regioni circostanti per quanto riguarda la variabilità dell'energia eolica. In secondo luogo, e cosa ancora più importante, vediamo che ci sono chiari modelli di variabilità dell'energia eolica in selezionate sottoregioni svizzere che sono in correlazione con i regimi meteorologici a livello europeo. Così, nella scala temporale da giorni a settimane, alcune delle sottoregioni presentano possibili modelli di produzione di energia eolica quasi completamente opposti a quelli delle zone limitrofe, meno montagnose.

Infine, costruiamo un modello di ottimizzazione del sistema energetico europeo all'interno del quale la Svizzera viene modellata come singoli cantoni e le sottoregioni identificate in precedenza vengono modellate separatamente al loro interno. Con questo modello progettiamo prima di tutto un sistema energetico ottimale per tutta l'Europa, Svizzera compresa. In questo scenario, che si basa su collegamenti internazionali che bilanciano la variabilità delle rinnovabili in tutta Europa, in un caso di ottimizzazione dei costi, non viene installata alcuna capacità eolica in Svizzera. Poi, riproponiamo il modello di ottimizzazione con una capacità di generazione eolica minima richiesta in Svizzera equivalente a coprire il 10% e il 20% del fabbisogno di energia elettrica invernale. Entrambi i casi sono più favorevoli alla Svizzera dal punto di vista economico rispetto all'optimum europeo, questo in base al fatto che il costo dell'elettricità livellato in Svizzera è inferiore. In entrambi i casi, la capacità si concentra sulle creste del Giura, con solo una piccola capacità aggiuntiva sulle creste alpine e nel Canton Ticino.

Summary



The aim of this project is to investigate whether an improved understanding of smaller-scale variability patterns of Swiss wind generation could help clarify the possible role of wind power for the country.

First, we assess the ability to accurately model wind power potential in complex terrain based on several meteorological reanalyses. We find that COSMO-REA2, with a 2 km spatial resolution, is able to reproduce some of the wind phenomena at measurement sites across the country, for example, diurnal variability caused by mountain-valley breezes, and the Föhn and Bise channelling flows. We thus conclude that using COSMO-REA2 for further analyses is justified.

Based on such analysis with COSMO-REA2, we find that smaller-scale terrain features in Switzerland lead to small-scale areas that behave differently than their surrounding regions with respect to wind power variability. Second, and more importantly, we see that there are clear patterns of wind power variability in selected Swiss subregions which correlate with Europe-wide weather regimes. Thus, at the time scale of days to weeks, some of the subregions exhibit possible wind electricity generation patterns almost completely opposite to that in neighbouring, less mountainous areas.

Finally, we build an optimisation model of the European power system within which Switzerland is modelled as individual cantons, and the subregions identified before are separately modelled within them. Using this model, we first design an optimal power system for all of Europe including Switzerland. In this scenario, which relies on international connections balancing renewable variability across Europe, no wind capacity is installed in Switzerland in a cost-optimal case. Then, we re-run the optimisation model with a minimum required Swiss wind generation capacity equivalent to covering 10% and 20% of winter electricity demand. Both cases are more economically favourable to Switzerland than the European optimum based on the Swiss levelised cost of electricity being lower. In either case, capacity would be concentrated on Jura crests, with only small additional capacity on alpine crests and in the canton of Ticino.



Take-home messages

- COSMO-REA2 is able to depict some of the wind patterns in Switzerland's complex terrain that less highly resolved models cannot.
- The complex terrain of Switzerland leads to areas that behave differently to their surrounding regions with respect to wind power variability.
- In different European weather regimes, which can span days to weeks, some Swiss subregions noticeably anticorrelate with neighbouring, less mountainous countries in their potential wind electricity generation.
- Wind power anticorrelation leads to the low average capacity factor region of Lake Geneva being chosen as one of three Swiss subregions in which wind capacity deployment would be economically favourable.
- There is no Swiss wind capacity within a cost-optimal European power system, but capacity could increase to meet 20% or more of winter electricity demand when focussing on economic favourability for Switzerland alone.



Contents

1. Introduction	9
1.1. Background	9
1.2. Motivation	10
1.3. Project goals	10
2. Methods	11
2.1. Wind power model	11
2.2. Validation	12
2.3. European weather regimes	13
2.4. Swiss subregions of interest	14
2.5. Swiss and European power system modelling	16
3. Results	17
3.1. Assessing the ability to model wind power in complex terrain	17
3.2. Variability in Swiss subregions modelled with COSMO-REA2	21
3.3. Value of Swiss wind power	24
4. Conclusions	27
5. Outlook and implementation	27
6. National and international collaboration	28
7. Publications	28
8. References	28
9. Appendices	29



Abbreviations

COSMO	Consortium for Small-scale Modelling
COSMO- REA2	2km horizontal resolution regional reanalysis based on the COSMO NWP model
COSMO- REA6	6km horizontal resolution regional reanalysis based on the COSMO NWP model
CF	Capacity factor
LCOE	Levelised cost of electricity
NWP	Numerical weather prediction
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
VWF	Virtual wind farm



1. Introduction

1.1. Background

The European and Swiss energy systems will have to undergo a rapid and deep transformation in order to successfully mitigate climate change (Fragkos et al., 2017). Clean electricity through renewable generation has emerged as one of the most promising ways to build the backbone of this new energy system. While wind power has grown rapidly across Europe, this growth has been concentrated largely in the North Sea region (Staffell and Pfenninger, 2016). Previous work has shown that this concentration of generation leads to fluctuation in wind power output across Europe on the time scale of days to weeks, and that this fluctuation can be explained by weather regimes: large-scale meteorological patterns that affect the entire European continent simultaneously (Grams et al., 2017). Grams et al. (2017) showed that an understanding of how weather regimes affect continental patterns of wind generation makes it possible to propose a more balanced deployment of wind generation across Europe with greater wind turbine deployment in southern parts and far northern regions reducing the overall variability.

These Europe-wide results raise the question of whether patterns of correlation or anticorrelation over different time scales also exist at much smaller spatial scales, in a country with complex topography like Switzerland, and whether they could lead to higher value for wind deployment in certain regions by virtue of anticorrelation with other sites. Grams et al. (2017) only looked at nationally aggregated wind power generation, thus entirely ignoring complex terrain and variability of wind power within a specific country. Here, we want to understand whether in Switzerland specifically, an improved understanding of smaller-scale variability patterns could lead to a revised understanding of the role of wind power for the country.

Such work relies on a crucial tool in renewable energy system modelling: meteorological reanalysis. Meteorological reanalysis is a method to combine historical weather measurements with state-of-the-art weather forecast models to generate consistent, historical time series of weather conditions, either globally (global reanalysis) or regionally (regional reanalysis). Most studies on renewable energy in Europe, including Grams et al. (2017), are based on global meteorological reanalyses. The quasi-standard dataset often used is MERRA-2, with a ~55 km horizontal resolution (Staffell and Pfenninger, 2016), slowly being replaced by ERA-5, which has a similar spatial resolution as MERRA-2. In order to understand whether what we see at the European scale also happens at much smaller spatial scales within Switzerland, it is necessary to move to datasets with a much finer spatial resolution, which is therefore a necessary component of work to address the question posed above. Here, we use the COSMO reanalyses operated by the German Weather Service DWD, which exist in two versions: COSMO-REA6, at 6km resolution covering all of Europe, and COSMO-REA2, at 2km resolution, covering only Germany and neighbouring countries, which includes Switzerland.

Studies with higher spatial resolution have shown that wind power output varies considerably across the complex terrain in Switzerland (Jafari et al., 2012; Krut et al., 2017). These studies show that the alpine range, Jura range, and the Swiss plateau all exhibit site-specific wind speed strengthening and suppression at time scales ranging from diurnal to seasonal. Valleys experience an increase in wind speed in the mid-afternoon, while crests experience the inverse: an increase in wind speed overnight followed by a decrease in the afternoon - referred to as mountain-valley breezes. On slightly larger spatial scales, complex orography favours channelling flows that persist for several hours to a few days. Well-known examples are (1) the easterly Bise when low-level winds are enhanced in the Swiss Plateau region due to channelling between the Jura range and the Alps and (2) the north-south oriented Föhn flow extending from specific alpine valleys into the foot hills and beyond (Federal Office for



Meteorology and Climatology, 2015). These local spatio-temporal patterns could represent both barriers and opportunities for wind farm deployment. For example, high afternoon output from valley-deployed turbines could exacerbate line loading in alpine regions, when hydroelectric power output is particularly strong (Singh et al., 2014).

1.2. Motivation

In order to address the issues laid out above, this project proposed to answer two research questions:

1. How does wind power output in different parts of Switzerland vary across time scales from multiple days to seasons?
2. How does the variability of wind in neighbouring countries compare?

Answering these questions permits us to understand the possible value of Swiss wind power. This is a relevant question from two separate perspectives. The first perspective is that of the European power system as a whole. Here, we can assume that Swiss wind power, owing to the fact that Switzerland is just a small component of the overall system, does not have the potential to contribute substantially to balancing the Europe-wide power system. The second perspective is that of Switzerland, in two respects. On the one hand, the planning of a highly renewable power system in Switzerland will benefit from a better understanding of wind power variability across the country. On the other hand, as European power markets evolve to value stability of renewable generation, investors into Swiss wind projects could benefit from knowing the patterns by which potential Swiss wind power sites correlate or anti-correlate with wind output from neighbouring countries.

Finally, the improved understanding of modelling wind power gained in this project has applicability beyond the immediate use case presented in this report. First, it advances the understanding of wind power modelling in complex terrain, which has applications worldwide. Second, it gives a clear indication of where currently available meteorological reanalyses fail to work in the case of Switzerland, due to even more local wind phenomena requiring even higher model resolution.

1.3. Project goals

The specific project goals in order to address the research questions laid out above are threefold:

1. Understand and quantify the extent to which high-resolution regional meteorological reanalysis data can accurately depict wind power patterns in complex terrain such as Switzerland, as a necessary basis for all following work.
2. Understand the output variability of wind power at high spatial resolution across Switzerland.
3. Quantify the value of Swiss wind power over the medium to long term future as both Switzerland and Europe as a whole decarbonize their electricity systems.

After presenting a summary of the methods used, the results section below will detail the findings with respect to these three points.



2. Methods

2.1. Wind power model

We use the COSMO reanalyses as a source of wind speeds on a consistent spatial grid to simulate hypothetical wind farms in Switzerland (see Table 1 for more details). Although the COSMO reanalyses have a high spatial resolution, they have been shown to only represent wind phenomena at six to eight times coarser spatial resolutions (i.e. their ‘effective resolution’) (Wahl et al., 2016). We thus expect wind systems of a scale of 14km to be resolved with COSMO-REA2. For Switzerland this involves the channelling in the Swiss Plateau region between the alpine and Jura ranges, Föhn flows in major alpine valley outlets and perhaps even mountain-valley breezes in the broad Rhone valley. Despite the caveat of the effective resolution, we expect both COSMO reanalyses to better describe wind speed variability in Switzerland than global reanalyses. Since COSMO-REA6 covers a greater spatio-temporal extent than COSMO-REA2, it has the potential to be a more useful data source.

Table 1: Key characteristics of regional COSMO reanalyses and global reanalysis MERRA-2. Effective resolution is the resolution of meteorological phenomena that a given model can accurately depict, and is larger than the size of the model’s grid size. Effective resolution for COSMO reanalyses from (Wahl et al., 2016). We have no source for the effective resolution of MERRA-2, but a working assumption in meteorology is that effective resolution is normally 2-4 times higher than the model resolution.

	Spatial		Temporal Effective resolution		
	Extent	Resolution		Extent	Resolution
COSMO-REA2	AT, BE, DK, DE, LI, LU, NL, SI, CH	2 km	14 km	7 years (2007 - 2013)	1 hour
COSMO-REA6	Europe	6 km	48 km	23 years (1995 - 2017)	1 hour
MERRA-2	Global	~55 km (0.5° x 0.625°)	-	38 years (1980 - 2018)	1 hour

Hypothetical wind farms are simulated using the open-source Virtual Wind Farm (VWF) model from Renewables.ninja (Staffell and Pfenninger, 2016). We perform detailed validation, but due to insufficient measured data for that purpose, we do not perform a systematic bias correction for the COSMO reanalyses. To understand the scale of any improvements provided by the COSMO reanalyses in simulating wind turbine electricity generation in complex terrain, the VWF model is also run with wind speeds derived from the global reanalysis model MERRA-2; i.e. the output currently available when simulating wind farms using the Renewables.ninja platform. When comparing simulation results to specific wind farm sites, the turbine model and hub height of the wind turbine(s) at the site are used. Only wind farm sites for which the VWF has pre-existing power curves are considered in the comparisons, ignoring some uncommon and no longer available models.



2.2. Validation

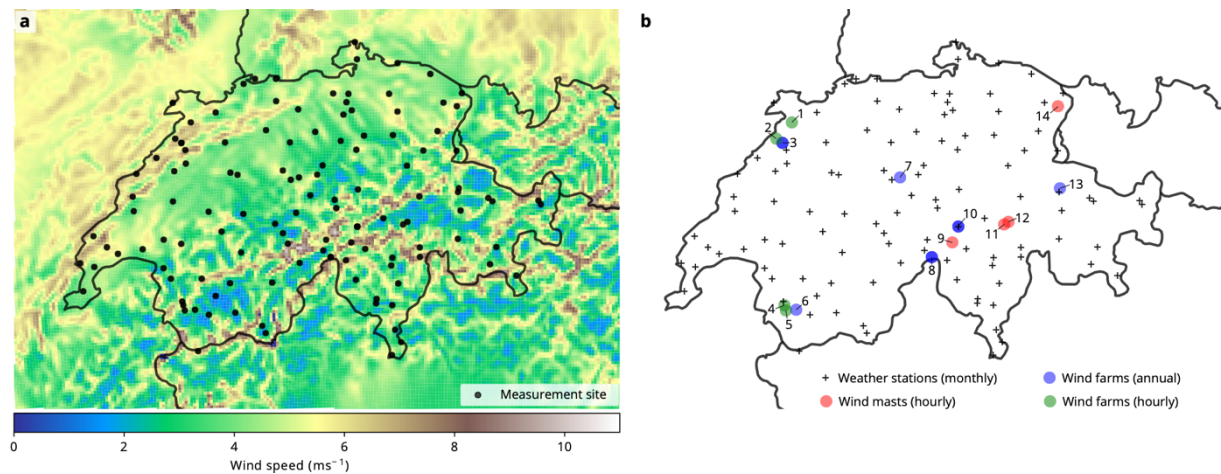


Figure 1: Geographic location of available measured data points used to validate COSMO reanalysis simulations. Locations are overlaid on 100m vertical height wind speed in (a), as given by COSMO-REA2. Data types of each location are specified in (b), as well as the site number. Country borders are outlined in black

To validate simulated wind speeds and turbine electricity generation, three primary sources of data are used: weather station 10m vertical height wind speed, hub-height wind speed, wind farm electricity generation. The geographic location of these sources can be seen in Figure 1; key information on wind turbines and hub-height anemometers is given in Table 2. Monthly wind speed data from 10 m vertical height anemometers at 109 weather stations have been acquired from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). This data is compared to direct 10m vertical height data from both COSMO-REA2 and -REA6 (i.e. no log-law interpolation is required). Anemometer readings have also been provided by multiple private sources, to compare measured and simulated wind speeds at vertical heights ranging from 40 m to 100 m. In total, readings at six sites are used, three of which are sited directly on existing turbines. The other three sites are under consideration for wind farms, hence the existence of the masts. Where multiple height measurements are made, simulations are compared at each of these heights, but the results are communicated as an average across all heights at a site. Alongside the anemometer readings, the three wind turbine sites are used to compare hourly wind turbine electricity generation over several years.

As well as hourly wind turbine data, annual turbine electricity production data exists for each of the 40 wind farms in Switzerland. Only 10 of these wind farms are simulated with the virtual wind farm (VWF) model, since power curves were available only for the turbines at those sites. These are also the sites with the most substantial installed capacity, constituting 97% of the 2018 Swiss installed capacity of 75.43 MW.



Table 2: Validation data sources for wind speed and electricity generation. Wind farm and mast numbers correspond to the numbering given in

Figure 1.

Wind speed					
Site			Temporal resolution ^a	Timeseries overlap	Measurement height
Number	Name	Location (lat, lon)			
N/A	MeteoSwiss stations	Various (109)	M	84 ^b	10
1	St. Brais	47.3, 7.1	H	33,730	78
4	Collonges	46.16, 7.04	H	55,115	100
5	Martigny	46.13, 7.05	H	23,324	99
9	Gotthard	46.56, 8.56	H	933 - 982	42,79,80
11	Vrin (Cavel)	46.67, 9.03	H	7,561 - 7,641	40,80,82
12	Vrin (Scharls)	46.68, 9.07	H	7,715 - 7,949	40,80,82

Wind electricity generation					
Site			Temporal resolution ^a	Timeseries overlap	Measurement height
Number	Name	Location (lat, lon)			
1	St. Brais	47.3, 7.1	H / Y	8,379 / 4	78 (1)
2	Peuchapatte	47.2, 6.96	H / Y	0 / 3	108 (3)
3	Mt. Crosin	47.18, 7.02	Y	2	90 (12), 112 (4)
4	Collonges	46.16, 7.04	H / Y	15,456 / 7	100 (1)
5	Martigny	46.13, 7.05	H / Y	6,623 / 5	99 (1)
6	Charrat Vs Adonis	46.13, 7.14	Y	1	99 (1)
7	Lutersarni	46.96, 8.09	Y	0	78 (1)
8	Gries	46.46, 8.37	Y	2	85 (4) ^c
10	Guetsch	46.65, 8.62	Y	5	46 (1), 55 (3)
13	Haldenstein	46.89, 9.54	Y	0	119 (1)

^a Timeseries overlap is given in hours (H) / months (M) / years (Y), depending on the temporal resolution.

^b Some weather stations have missing data. 81% of sites have over 80 months of overlap in the study years 2007–2013.

^c Two turbine models with the same hub height are sited at Gries. Three of one model and one of the other model are installed.

2.3. European weather regimes

Seven distinct weather regimes can be identified which affect the European continent (Grams et al., 2017). Regimes are identified by variability in weather for time periods of more than five days, and on a spatial scale of about 1,000km. Low- pressure systems dominate three of the seven regimes and imposing windy and mild conditions for wide parts of Europe (“cyclonic regimes”): Atlantic trough (AT), zonal (ZO), Scandinavian trough (ScTr). High pressure dominates the remaining four regimes, often with concomitant calmer weather (“blocked” regimes): Atlantic ridge (AR), European blocking (EuBL), Scandinavian blocking (ScBL), Greenland blocking (GL). With this classification, Grams et al (2017) identified the impact of large-scale meteorological phenomena on subseasonal European wind electricity generation potential. For Switzerland higher than average wind electricity generation is expected during AT and ScTr, whereas EuBL and ScBL reduces it.



Intra- and inter-regime variability may be identifiable at a sub-national scale, particularly when the terrain is complex. We study this variability using regime classification at a six-hour resolution for subregions of Switzerland which exhibit other meteorological phenomena of interest, as described further below. Areas of interest are particularly those with large summer CF diurnal variation and higher than average simulated wind farm CFs.

2.4. Swiss subregions of interest

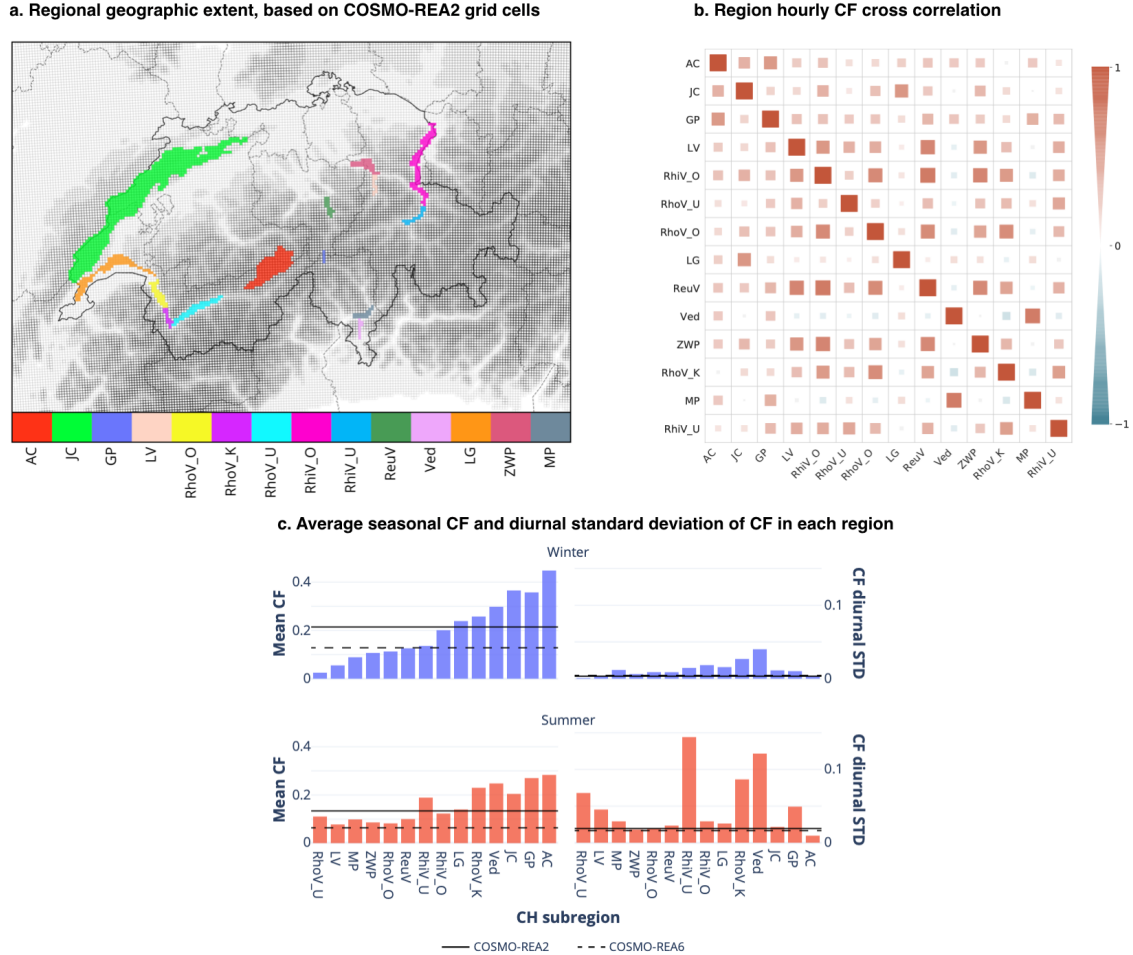


Figure 2: Characteristics of selected Swiss regions. Orography is depicted by the line weight and opacity of each COSMO-REA2 grid cell in (a). (b) shows the cross correlation of hourly CF in each region, for all hours in the period 2007 – 2013. (c) shows the average seasonal CF and diurnal CF standard deviation in each region, alongside the average Swiss CF in the same time periods, from both COSMO-REA2 and COSMO-REA6. Diurnal CF standard deviation depicts the CF variation between the hours of the day across all days in a season, and is an indicator of the strength of mountain-valley breezes in a region.

The complex terrain of Switzerland leads to meteorological phenomena which influence wind speed (see Box 1). On smaller scales, these are mountain-valley breezes due to terrain forcing and thermal forcing (Jafari et al., 2012). On intermediate scales, these are channelling flows like the Föhn or Bise, caused by the alpine and Jura mountain ranges (Federal Office for Meteorology and Climatology, 2015). On larger scales, these are the subseasonal weather regimes described in section 2.2.

Following the assessment of COSMO reanalyses with respect to measured data, we concentrate on analysing spatio-temporal wind variability in selected regions of Switzerland. We select fourteen regions of interest in Switzerland that we expect to be impacted by



mountain-valley breezes, Bise flows, Föhn flows, or the separation of weather systems on either side of the Alps (Figure 2). Details on these regions is available in Table 3.

Box 1: Swiss weather systems

The alpine range creates an orographic barrier between the north and south of Switzerland. During specific large-scale meteorological conditions this leads to the so-called “Föhn” flow: a circulation across or around the alpine range which often causes high wind speeds in North- South elongated alpine valleys, but also in the respective foothills. The Föhn flow is a direct consequence of the North-South pressure gradient and occurs on both sides of the Alps, but with a higher occurrence frequency on the Northern slope (Federal Office for Meteorology and Climatology, 2015). When high pressure prevails north of Switzerland low-level flow from northern and eastern Europe is channelled through the Swiss Plateau between the alpine range and the Jura mountains (the “Bise” flow). This flow is further compressed between the northern pre-Alps and the Jura mountain range until Lake Geneva, where the channelled wind speed usually reaches its maximum.

The complex terrain in Switzerland leads to a wide variation in wind conditions. Higher altitude regions (AC, GP, JC) have the highest mean CF in winter, but three further regions have greater CF than the Swiss average: Ved, RhoV_K, and LG (Figure 2c). These regions might benefit from flow channelling. In the case of Ved and RhoV_K, this may be caused by strong inversion, in which cold air laying in either the lowlands or valleys might cause channelled density currents in the valley floor.

Diurnal variation in summer has a particularly strong impact in RhiV_U, RhoV_K, and Ved, as seen in Figure 2c. The strength of diurnal flows leads to a positive correlation between RhiV_U and RhoV_K, although they are on opposite ends of the country. Indeed, Figure 2b shows that regions with similar dominant meteorological phenomena positively correlate, even when they are geographically separated. There is also a positive correlation between northern alpine valley outlets (RhiV_O, ReuV, LV, ZWP, RhoV_O) and the crest regions (AC, GP, JC). South of the Alps, Ved and MP correlate well. Hourly CF in these two regions also correlate poorly with all other regions in the country.

Table 3: Key characteristics of selected Swiss subregions. Number of grid cells and altitude data is based on COSMO-REA2.

	Name	Cells	Classification	Altitude		
				Min	Mean	Max
GP	Gotthard pass	5	Alpine pass	1812	2083	2318
LG	Lake Geneva northern shore	86	Channeling plain	386	517	766
ZWP	Zurichsee to Walensee plain	30	Channeling plain	363	458	679
MP	Magadino plain	18	Channeling plain	292	488	860
JC	Jura crests	577	Crests	798	1059	1524
AC	Alpine crests	125	Crests	2500	2927	3491
RhoV_U	Upper Rhone valley	47	Northern alpine valley	432	757	1349
RhoV_K	Rhone valley knee	13	Northern alpine valley	615	866	1114
RhiV_U	Upper Rhine valley	17	Northern alpine valley	620	787	1000
LV	Linth valley outlet	12	Northern alpine valley outlet	495	828	1129
RhiV_O	Rhine valley outlet	85	Northern alpine valley outlet	390	583	1199
RhoV_O	Rhone valley outlet	30	Northern alpine valley outlet	323	437	617
ReuV	Reuss valley outlet	16	Northern alpine valley outlet	537	702	1007
Ved	Vedeggio river valley	10	Southern alpine valley	368	614	784



2.5. Swiss and European power system modelling

To understand the value of wind energy in Switzerland, it is necessary to consider it within the context of a wider European electricity system, since it is the anticorrelation of weather systems with neighbouring countries that may prove economically advantageous. The resulting energy system model is shown spatially in Figure 3. All countries other than Switzerland have been simplified to single nodes. The resulting transmission system connects all countries with their direct neighbours. Data on demand, renewable energy potential, and conventional technology capacities have been aggregated at this national level. Switzerland is modelled at a regional level, with regions corresponding to the 26 Swiss cantons and 14 selected subregions (see Section 2.4).

The energy system model is optimised to minimise total system cost in the context of a zero carbon European electricity system using the Euro-Calliope model (see Appendix 2), a 2030 model year, and a 2012 weather year. The model year sets the technology costs and some technology capacity limits (e.g. nuclear maximum, renewable technology minimums), while the weather year sets both the renewable technology potential and the electricity demand. Initially, a pan-European optimisation is undertaken, in which all technology capacities across Europe are to be decided by the model; Switzerland is also nationally aggregated in this model. The result of this optimisation is used to fix the technology capacities in all countries other than Switzerland.

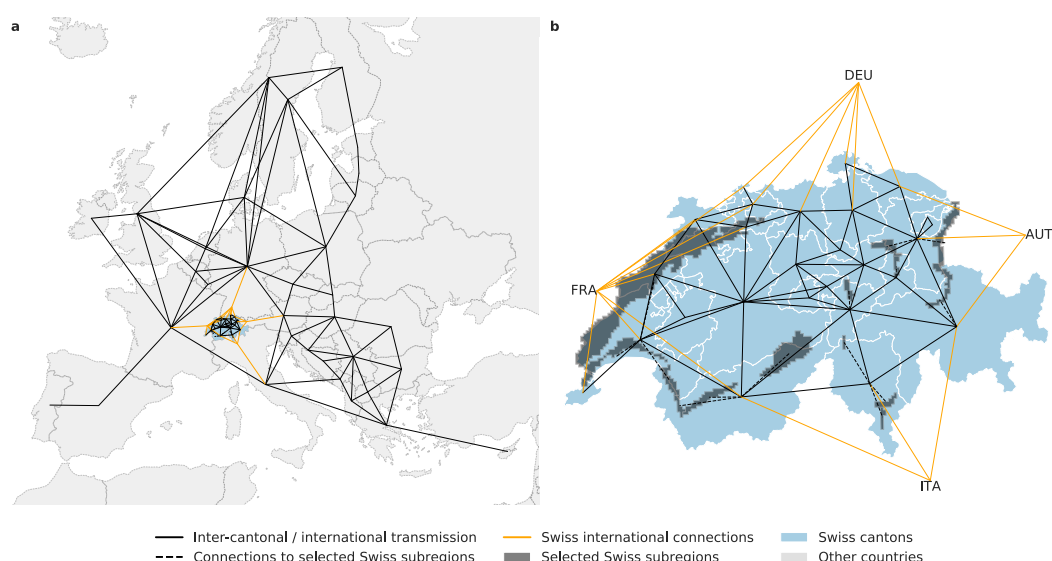


Figure 3: Spatial configuration of energy system model. (a) shows the European transmission system, wherein European countries are nationally aggregated and Switzerland is regionally aggregated. (b) shows a closeup of the Swiss modelled transmission network. All internal transmission connections have a fixed net transfer capacity; line losses are assumed to be negligible within Switzerland, but not on international connections.

Following the fixing of all non-Swiss countries in the model, the optimisation is re-implemented to again minimise total European costs, but now under different Swiss scenarios (Table 4). As a result, the only investment decisions being made are those for Switzerland. In each of these scenarios, COSMO-REA2 data is used to inform the wind turbine capacity factors in each of the regions shown in Figure 3b. These scenarios assess the impact on system costs of (a) varying Swiss electricity independence and (b) reliance on wind electricity generation. We intend on using these scenarios to understand the value of wind power in Switzerland, and the reliance that value has on the ability to export that power.



Table 4: Model capacity scenarios in which (right) net transfer capacities (NTCs) between Switzerland and its neighbours is progressively increased relative to ENTSOE 2027 and 2020 scenarios and (left) installed wind capacity is progressively increased from no wind to maximum technically feasible capacity.

NTC scenarios	Swiss import / export NTCs (GW)	Wind capacity scenarios	Capacity (GW)
NTC2027	12 / 14	No wind	0
2 x NTC2020	17 / 22	Capacity to meet 10% winter demand	3.15
4 x NTC2020	35 / 44	Capacity to meet 20% winter demand	6.3
		Maximum technically feasible capacity	54.6

3. Results

3.1. Assessing the ability to model wind power in complex terrain

First, we need to assess the ability to accurately model wind power potential in complex terrain with the different reanalyses we examine. This is a first and important outcome as it expands the state of knowledge with respect to wind power modelling not just in Switzerland but more generically for complex terrain. We find that COSMO-REA6 performs overall no better than MERRA-2, despite its substantially higher spatial resolution, in Switzerland's mountainous terrain, but that COSMO-REA2, while still suffering from numerous weaknesses, is able to reproduce some of the measured wind phenomena. We thus conclude that using COSMO-REA2 for further analyses is justified. The rest of this section details the work leading to this conclusion.

We begin validation of the COSMO reanalyses by comparison with available observed wind speeds. At a 10m vertical height, Figure 4 shows that measured and simulated/reanalysis mean wind speeds correlate better using COSMO-REA2 than using COSMO-REA6 ($\rho = 0.5$ compared to $\rho = 0.2$). However, neither is particularly well correlated when compared to studies on flatter terrain, which found $\rho > 0.8$ in most cases (Borsche et al., 2016; Ramirez Camargo et al., 2019). COSMO-REA2 tends to overestimate the wind speed, while a sizable number of measurements are under-predicted by COSMO-REA6.

COSMO-REA6 also under-predicts hourly measured hub-height data, but with a greater overall correlation than with weather station measurements (Figure 4). Since crests are smoothed out by the COSMO-REA6 grid cell size, higher wind speeds are lost; very few wind speeds above 5ms^{-1} are simulated. Performance as a function of height above surface cannot be readily compared, since the spatial and temporal distribution of the measurement sites are sufficiently different.

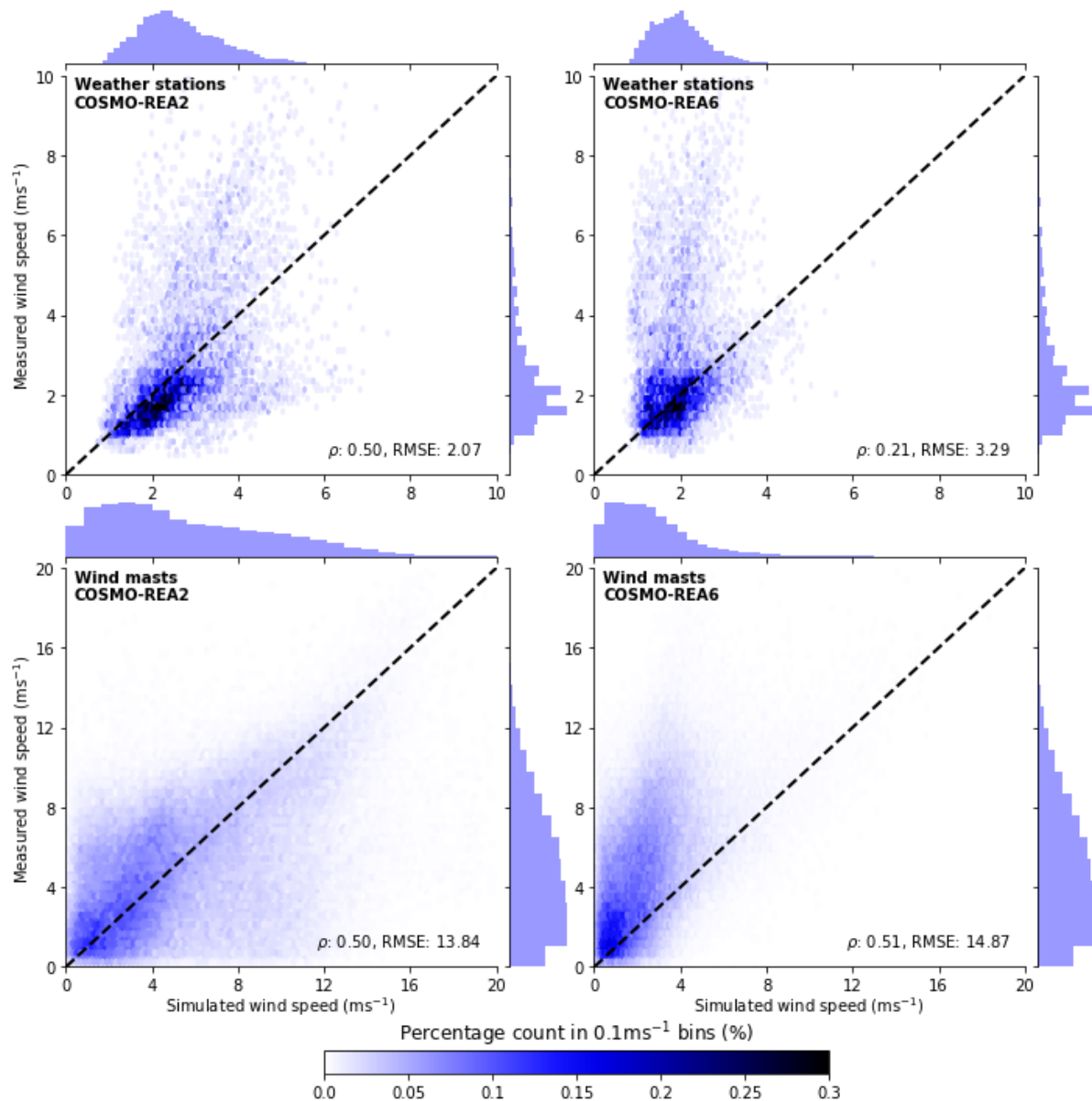


Figure 4: Heatmap comparison of simulated and measured wind speed according to anemometers at weather stations, wind masts, and wind turbines. Comparison is made for data in the period 2007–2013, with the number of data points given in Table 2. Weather station anemometers are situated 10m above surface and record data at a monthly resolution. Wind mast and wind turbine anemometers are at heights above surface which vary between 40m and 100m and record data at an hourly resolution. In all cases, simulation data is compared at the height of each anemometer. Pearson correlation (ρ) and root-mean-square error (RMSE) is given in the bottom-right of each.

Reanalysis wind speed data consistently leads to an under-prediction of wind farm electricity generation.

Figure 5 compares the performance of COSMO-REA2 and COSMO-REA6 with the global reanalysis MERRA-2 (as is currently available on the Renewables.ninja platform). The MERRA-2 simulations were run with and without bias correction, which is available following a systematic global assessment of wind electricity generation (Staffell and Pfenninger, 2016).

When CF is under-predicted, COSMO-REA2 performs better than the other reanalyses. However, more often than not, COSMO-REA2 over-predicts annual CF. In the Jura mountain



range sites (Mt. Crosin, St. Brais, and Peuchapatte), the relative performance of the reanalyses is somewhat reversed: MERRA-2 outperforms COSMO-REA6. At Peuchapatte, MERRA-2 even outperforms COSMO-REA2; uncorrected MERRA-2 results perform particularly well.

Across all sites, COSMO-REA2 is the best dataset to predict CF. In fact, COSMO-REA6 has a negative correlation between measured and simulated CF. Although COSMO-REA2 does relatively well, its simulations still have a low correlation coefficient of approximately 0.5.

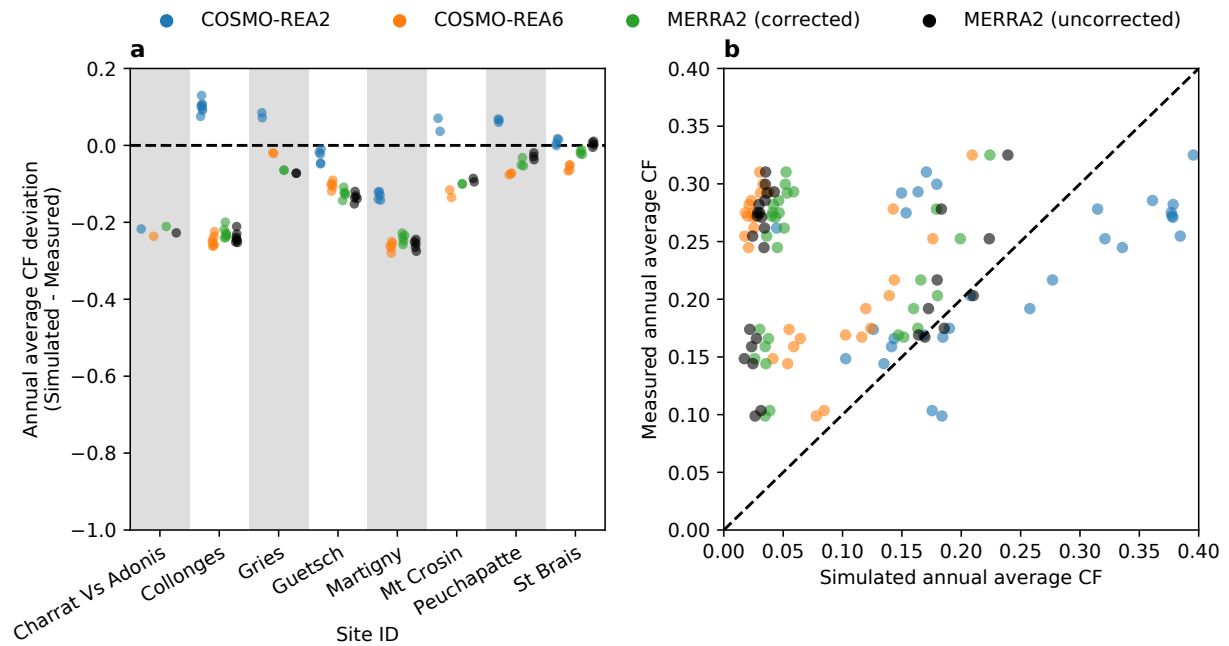


Figure 5: Performance of wind electricity generation simulations compared to measured annual wind farm data, for simulations derived from the VWF model using COSMO-REA2, COSMO-REA6 and MERRA-2 reanalyses. (a) shows the deviation in CF at each site, while (b) shows the match between simulated and measured data for all sites. Simulations are undertaken at an hourly level, then averaged over each year. Only data points for the years 2007-2013 (the extent of COSMO-REA2) have been considered. 'corrected' and 'uncorrected' MERRA-2 data refers to the use (or not) of bias correction in the VWF model, when simulating wind electricity generation.

The comparative advantage of COSMO-REA2 is also pronounced when considering hourly data.

Figure 6 shows the load duration curve (LDC) of the turbine sites. The LDC orders the hourly CF across the entire time series from greatest to smallest, scaled to one year. This allows us to assess the hourly variability of the data independently of exactly when in a year the variability occurs.

In the two Rhone Valley sites (Martigny and Collonges), there is considerable under-prediction of the shape of the LDC. Although COSMO-REA2 does not match the measured load duration curves, in these valleys it is a markedly better fit to the measured LDC than the other reanalyses. The significant under-performance of wind farms predicted by COSMO-REA6 and MERRA-2 at the two valley sites can be explained by their inability to resolve mountain-valley breezes.

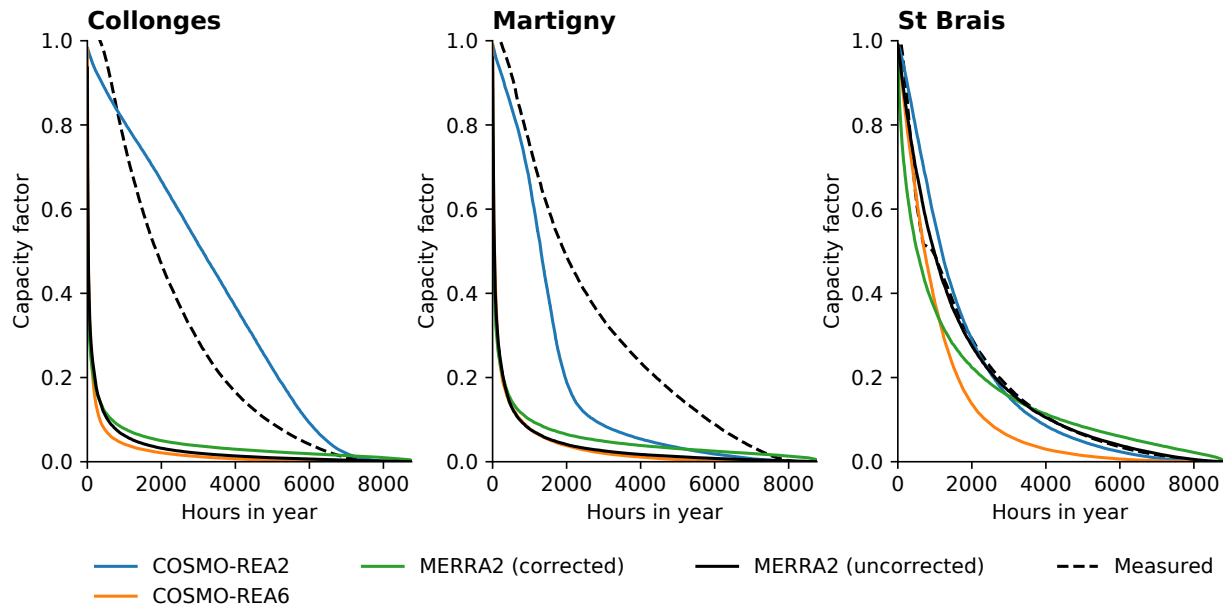


Figure 6: Load duration curve of three Swiss wind farms, based on measured and simulated data. Both measured and simulation data is restricted to hourly data in the period 2007-2013 (the extent of COSMO-REA2), and only in hours for which there is measured data. 'Corrected' and 'uncorrected' MERRA-2 data refers to the use (or not) of bias correction in the VWF model, when simulating wind electricity generation. Although several years are represented in the load duration curves, they have all been scaled to a single year (8760 hours) on the x-axis.

Summer diurnal variation in wind speed, and consequently electricity generation, is evident in the measured data shown in

Figure 7. The pronounced diurnal variation is captured by COSMO-REA2, albeit with a slightly different peak time and magnitude. However, COSMO-REA6 and MERRA-2 completely miss this; they predict that the summer electricity generation at these valley sites will not increase much above 20% CF at any time during the day, whereas the measured data shows between a third and a half of hours are above 20% CF at each site. The increased overnight wind speeds in summer on the Jura crests is also captured by COSMO-REA2, but only an afternoon peak is shown at these sites in COSMO-REA6 and MERRA-2. In the winter, COSMO-REA2 predicts the variation in wind farm electricity generation well on the Jura crests. However, it under-predicts output in Martigny and over-predicts in Collonges. This can also be seen in the load duration curves given in

Figure 6. The systematic, and significant under-prediction of electricity generation at all sites is evident in the COSMO-REA6 and MERRA-2 results.

Overall, we conclude that none of the reanalyses reproduce reported electricity generation accurately under all circumstances, but COSMO-REA2 clearly outperforms the other reanalyses in complex orography.

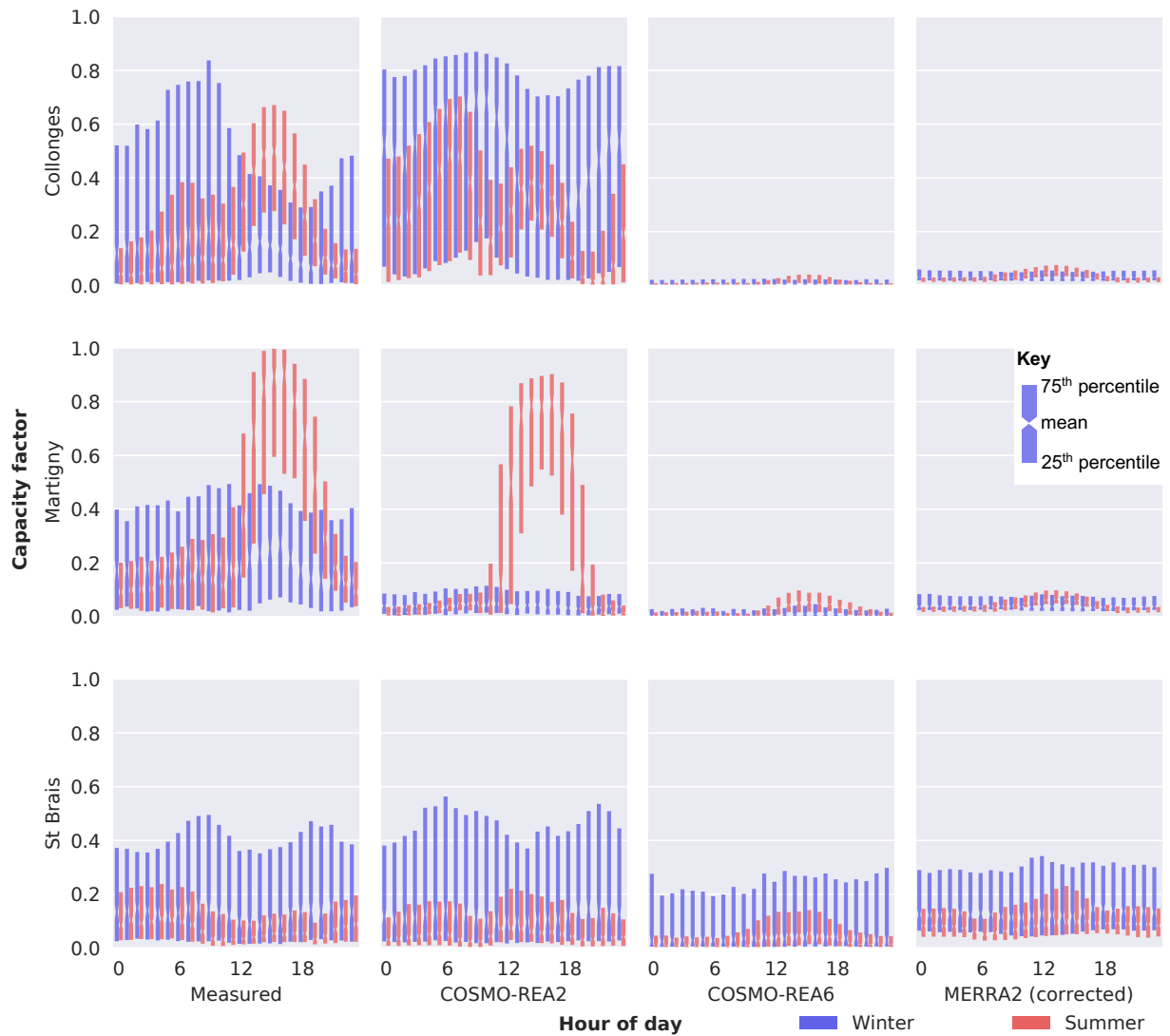


Figure 7: Diurnal variation at three wind farm sites in Switzerland, based on measured and simulated data. Each bar shows the interquartile range of wind electricity generation in a given hour, based on all days in each season. Both measured and simulation data is restricted to hours in the winter and summer periods of 2007-2013 (the extent of COSMO-REA2), and only for hours in which there is measured data. ‘Corrected’ and ‘uncorrected’ MERRA-2 data refers to the use (or not) of bias correction in the VWF model, when simulating wind electricity generation.

3.2. Variability in Swiss subregions modelled with COSMO-REA2

Based on the above assessment, we conclude that we can use COSMO-REA2 to investigate wind variability in the subregions selected in section 2.4. We arrive at two main findings. First, it is clear that Switzerland and thus Swiss wind power spans across a meteorological divide caused by the Alps, and furthermore, that smaller-scale terrain features in Switzerland lead to small-scale areas that behave differently than their surrounding regions with respect to wind power variability (Figure 8). Second, and more importantly, there are clear patterns of wind power variability in the Swiss subregions correlated with weather regimes. Thus, at the time scale of days to weeks, some of the subregions show behaviours almost completely opposite to that in neighbouring, less mountainous areas (Figure 9).

The meteorological divide created by the Alps is evident in Figure 8. In summer, the most and least performant regimes are inverted in the south compared to the north of the Alps. In winter, it is not a direct inversion, but different regimes are still more, or less, dominant in the



two parts of the country. Figure 8 inset 1 shows that blocking regimes (AR and EuBL) dominate along the northern shore of Lake Geneva, so this region behaves differently to the rest of Switzerland. This is not unexpected, as the Bise flow should be particularly strong in these regimes, whereby wind is channelled along the northern Alps, reaching peak flow velocity around the Lake Geneva area.

Inset 2 in Figure 8 emphasises the ability of COSMO-REA2 to handle the complex terrain in Switzerland. It shows the impact of ridges north of Zurich on wind CF. To the west of these five ridge lines there are small areas in which there is very low CF in the ZO regime. This is an expected impact of elevated areas in otherwise flat, and low lying, terrain in the ZO regime: with westerly ZO flow, low lying cold air dams ahead of the hills and hinders mixing. Thus, near surface flow is decoupled from the stronger westerly flow which is apparent above the inversion. The same effect can be seen to the south of the Jura mountain range.

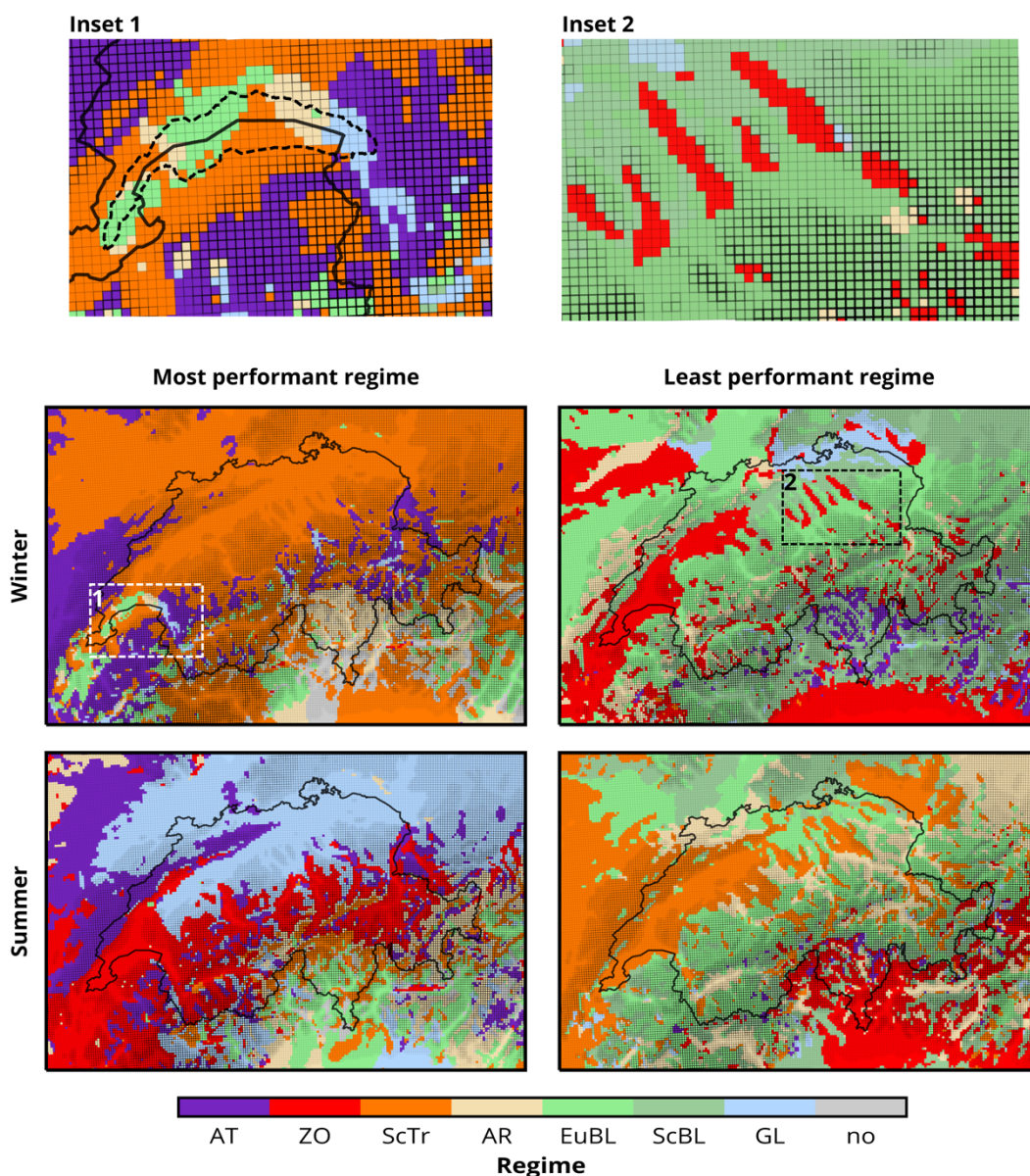


Figure 8: Most and least performant regimes in each COSMO-REA2 grid cell in Switzerland. The highest performance regime in any grid cell is that with the greatest average CF, calculated across all hours in a season classified by that regime (and vice-versa for the lowest performance regime). Switzerland is outlined in black and altitude is represented by grid cell outline shading, whereby a darker outline signifies a higher altitude.



Figure 9 compares seven of our selected Swiss regions with country-level aggregated data for Switzerland and its neighbouring countries. Compared to the Swiss average output, the Lake Geneva region shows a clear anticorrelation with all neighbouring countries in the AR and EuBL regimes. Similarly, the Rhone Valley knee region shows anticorrelation with neighbouring countries in the ScBL and GL regimes. In summer, Swiss wind power output is particularly strong in the ZO regime, which anticorrelates with all neighbours except France. This performance is driven by the Upper Rhine Valley, Lake Geneva, and Rhone Valley Knee regions. South of the Alps, the Vedeggio valley region matches Italy in its relatively high ScTr performance, but unlike Italy as a whole, also does well in the AR regime and when there is no discernible regime. Such patterns suggest revenue possibilities for Swiss wind power within a highly renewable European power system, based on their ability to produce above average when neighbouring regions produce relatively less.



Figure 9: CF deviation in select subregions of Switzerland, compared to that of neighbouring countries. CF deviation = $(CF_{region,regime} - CF_{region,season})$, where 'region' denotes a Swiss subregion or an entire country, 'regime' denotes a CF average across the weather regime of interest, and 'season' denotes a CF average across the entire season. Deviation is relative to the seasonal average CF, which is given by the grey bars. Neighbouring country data is taken from Renewables.ninja and is based on simulations using 'longterm-future' wind farm deployment predictions and the MERRA-2 global reanalysis. Swiss subregion data is based on COSMO-REA2 simulations.

Winter (December, January, February) is of particular interest due to the low productivity of solar power and the high demand for (increasingly electrified) heating. In winter, the most



productive Swiss regions are on par with or even exceed the average wind productivity in neighbouring countries. The Jura Crests region has a relatively high average CF for Switzerland, its performant regimes generally match French and, to a lesser extent, German performant regimes. Hence, there is likely less potential for for Jura Crests wind farms to capitalise on variations in the European electricity market. Jura Crests is the region with highest mean CF, thus initially, the most attractive region for investment into Swiss wind power. Other less regions with on average substantially lower productivity, such as Lake Geneva, are more productive during regimes when the Jura Crests underperform (EuBL and ScBL). Thus, if wind power is to increasingly play a role in the Swiss power system, and to contribute not just to average electricity production but also to the system's stability, investment in other parts of the country appears justified even in face of lower average generation potential.

3.3. Value of Swiss wind power

In Section 3.2, we showed that wind turbine capacity factor varies both temporally and spatially within Switzerland. Anticorrelation with neighbouring countries is evident at the sub-seasonal scale, but this is not captured with existing representations of Switzerland in the context of a European electricity system. In this section we present the results of modelling the energy system initially presented in Section 2.5. We focus on the value of Swiss wind under a range of scenarios in which wind turbine capacity and Swiss international net transfer capacity are constrained according to Table 4. We conclude that there is value for wind capacity in Switzerland, at levels high enough to meet 20% or more of current Swiss winter electricity demand. This capacity could increase to levels reaching the maximum technical potential of wind energy in Switzerland without a perceptible increase in Swiss levelised cost of electricity (LCOE), provided that greater interconnection with the European electricity system is prioritised.

The optimal wind turbine capacity in a Europe-wide model that contains a regionalised representation of Switzerland depends on the expected capacity of all variable renewable generation. If a minimum rooftop PV capacity is not set, then 3.1GW of wind capacity would be optimal, alongside no PV capacity (i.e. a decrease in PV capacity compared to today). This corresponds to wind turbines meeting 10% of current Swiss winter electricity demand. If PV capacity is set instead to that expected around 2030 (5.6GW), then no Swiss wind capacity is present in an optimal European energy system. The remainder of this section builds upon the more realistic scenario: there will be a sizeable PV capacity in Switzerland, building on the existing 2.17 GW capacity. Consequently, the baseline scenario has 60 MW of wind capacity. At 0.25% of the total installed capacity in Switzerland, it is a negligible quantity of installed capacity.

No wind capacity is the optimum in Switzerland when minimising the cost of operating the full European electricity system. Our scenario analysis shows that there is value in greater Swiss wind capacity, if considering the levelised cost of electricity in Switzerland independently of the rest of Europe. At a capacity of 6.3 GW, enough to meet 20% of current Swiss winter electricity demand, Figure 10 shows that Swiss LCOE would fall by approximately 4% compared to that given by a capacity of 0 GW. Swiss LCOE would also be lower with capacity sufficient to meet 10% of winter demand, and higher if capacity is 54.6GW (the maximum technical potential). The value of wind varies very little as a function of net transfer capacity (NTC) with neighbouring countries; only wind capacity at its maximum technical potential benefits from increased NTC. Indeed, if NTC were to increase four-fold from 2020 values, Swiss LCOE would only be 1.8% above optimal, due to the revenue gained from the export of wind electricity generation (Figure 11). At 3 – 6 GW of capacity, Figure 11 shows that there is no strong correlation between wind electricity generation and the operation of other technologies in Switzerland. This suggests that the development of wind capacity would not adversely impact the system stability, or require increasing capacity of specific technologies elsewhere in the system to manage wind electricity generation.



Given the spatially explicit nature of our model, consisting of 40 Swiss subregions, we can see where in Switzerland wind capacity would be best deployed. Figure 12 indicates that two selected subregions and one cantonal region are most favourable: Jura crests (up to 4.75 GW), Alpine crests (up to 0.32 GW), and Ticino (up to 1.13 GW). In the remainder of the country, negligible capacity is deployed in both the 10% and 20% winter electricity demand scenarios. Both the Jura crests and Alpine crests have high average CF, explaining the preference for deployment in both locations. Ticino has a lower CF than several other selected subregions, but strongly anticorrelates with Germany and France in particular weather regimes (Figure 9). This result indicates that the prevalence of anticorrelation is playing a part in the value of Swiss wind power. In the scenario where no PV capacity is installed, wind capacity deployment is slightly different, favouring deployment on the northern shore of Lake Geneva over Ticino.

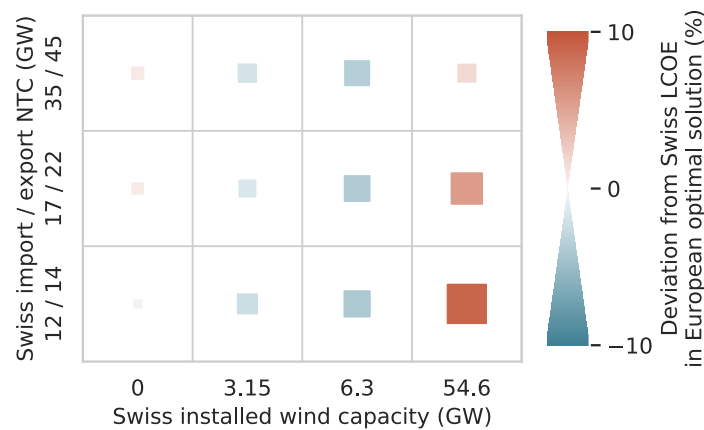


Figure 10: Percentage deviation of Swiss levelised cost of electricity (LCOE) under scenarios in which the Swiss international transmission net transfer capacity (NTC) and Swiss installed wind capacity are varied. The baseline LCOE is calculated for Switzerland using a pan-european optimisation model, wherein the optimal wind capacity is 0 GW and the NTC is fixed to ENTSOE 2027 projections. LCOE is calculated as: $(\text{Total Swiss costs} + \text{net electricity import costs}) / (\text{total Swiss electricity production} - \text{net electricity export})$, where net electricity import is priced at the European average LCOE. NTC and wind turbine capacities vary according to the scenarios detailed in Section 0.

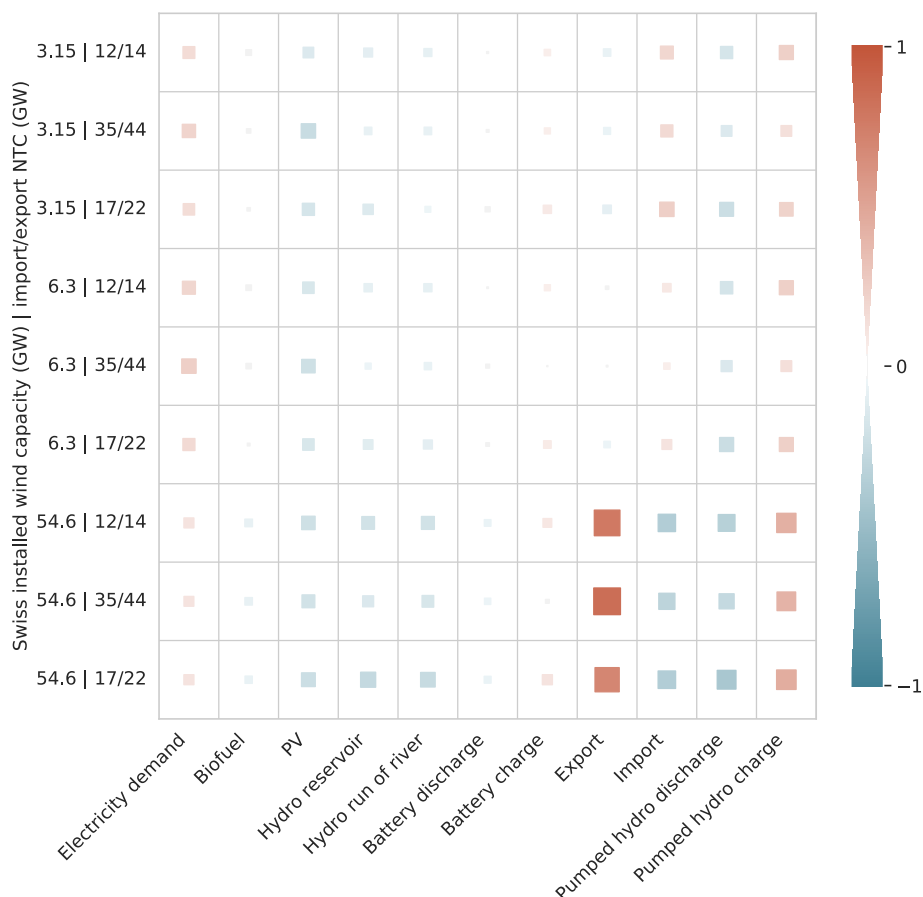


Figure 11: Hourly timeseries. cross correlation of Swiss wind electricity generation to the operation of other installed technologies in Switzerland, across various NTC and wind turbine capacity scenarios. Correlation is calculated as the Pearson correlation coefficient, which varies between 1 (full correlation) and -1 (full anticorrelation).

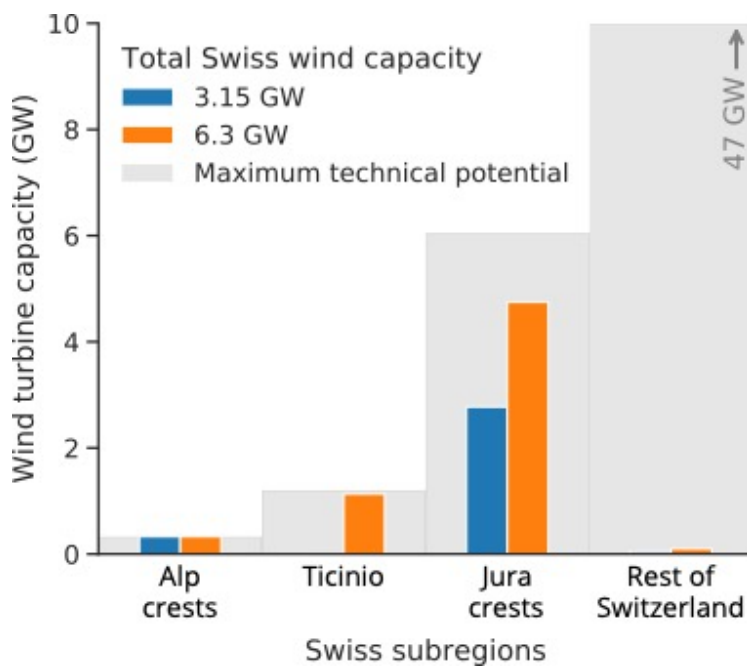


Figure 12: Spatial distribution of optimal Swiss wind capacity in different wind capacity scenarios. Almost all capacity is concentrated in the Swiss subregions of AC and JC, and within the canton of Ticino. Transmission net transfer capacity is fixed to NTC2027 scenario in the results of this figure.



4. Conclusions

We compared wind power simulations based on the MERRA-2 global reanalysis and the high-resolution regional reanalyses COSMO-REA6 and COSMO-REA2 to investigate wind electricity generation variability in the complex terrain of Switzerland, with a focus on mountain-valley breezes, orographic channelling, and large-scale variability imposed by weather regimes. We find that COSMO-REA2 is the only of these to represent very local weather patterns, for example, the diurnal wind patterns in the Rhone Valley. Thus, a 2 km grid (COSMO-REA2) resolves some aspects of the complex terrain in Switzerland, while a 6km grid (COSMO-REA6) is insufficient to do so; it is only marginally better than one with almost ten times worse resolution (MERRA-2). However, one needs to pay a price for this accuracy in the spatial dimension: there is limited coverage in time — COSMO-REA2 covers only the years 2007 - 2013. This means that it is insufficient to cover the full climatological variability of likely wind conditions, which would require several decades of historical conditions.

Using COSMO-REA2 based wind power simulations, we can investigate wind patterns across distinct subregions of Switzerland. We see that the northern alpine valleys anti-correlate with regions south of the Alps (Föhn flow) and see high wind speeds across Lake Geneva during blocking weather regimes (Bise flow). We find that electricity generation from wind turbines in specific regions of Switzerland anti-correlates with that in the flat terrain of neighbouring countries. These patterns of anti-correlation we see should aid in balancing wind electricity generation and other variable renewable generation within Switzerland itself. However, the subregions we investigate are small, with overall limited potential for wind generation. For instance, the maximum theoretical wind turbine capacity along the northern shore of Lake Geneva is 2.75GW based on our Lake Geneva region size of 344km² (derived from the COSMO-REA2 grid) and a wind turbine power density of 8MW/km² (European Environment Agency, 2009). This is less than the onshore capacity added by Germany in 2018 alone (Komusanac et al., 2019) and is reduced further to 0.27 GW when considering only the land on which it is technically feasible to install wind capacity (Tröndle et al., 2019). Thus, it is unlikely that the anticorrelation patterns between these Swiss regions and neighbouring countries would be of substantial value to the wider European power system. However, these patterns of variability may still provide the economic incentive to kick-start wind turbine deployment in locations where average capacity factors would initially suggest unfavourable conditions. Indeed, our European energy system model with a focus on Switzerland indicates that it is these Swiss subregions in which wind capacity is best deployed, namely in the Jura crests, the Alpine crests, and the Lake Geneva region.

The economic incentive suggested by the analysis of wind variability is reinforced by our analysis of Switzerland within a European energy system. No wind electricity generation would exist in Switzerland in a pan-European optimal energy system. When focusing on only the economic benefit to Switzerland, a lower cost system would be achieved by increasing wind capacity to meet 10%, or even 20% of Swiss winter electricity demand (3.15 and 6.3 GW, respectively). In fact, combined with increased net transfer capacities with neighbouring countries, a wind capacity of 54 GW could still be economically viable. It is a high spatial and temporal resolution model of Swiss wind energy that has allowed us to identify such a capacity potential.

5. Outlook and implementation

The immediate next step for further implementation of the results is releasing the COSMO-REA2 Swiss wind power dataset we developed, alongside the publication of the first of the two peer-reviewed papers coming out of this work, through our web platform



www.renewables.ninja under an open license, for further use and analysis by third parties in Switzerland and beyond.

In addition, the wind power modelling developed in this project will be used in at least two further studies. First, in a detailed study of the economy-wide elimination of emissions in Switzerland on a time plan between 2040 and 2050, to be conducted by our research group in 2020, and funded through the ETH Foundation. Second, in further investigating the use of COSMO-REA2 and COSMO-REA6 data for wind power applications beyond Switzerland.

We have seen that at specific sites in Switzerland, the variability of hourly measured wind speeds and electricity generation are not accurately reproduced by any of the reanalyses we investigate, so there is clear room for further improvement with even higher resolution simulations. Despite the new detail in local wind patterns revealed by COSMO-REA2, we have not studied smaller scale wind variability, which is unlikely to be accurately captured by COSMO-REA2 at all. Improved reanalysis products or other methods, such as operational forecast models or WRF downscaling to get to finer spatial detail, are still necessary for this. However, such efforts will be even more limited in their spatial and especially temporal coverage, so there is clear value to working with COSMO-REA2.

The original project goal had foreseen a comparison with ERA-5 based wind power simulations, rather than the MERRA-2 simulations ultimately used. Initial work clearly showed that ERA-5 simulations would be no better at the spatial scales considered for this project (the spatial resolution of ERA-5 is similarly coarse as that of MERRA-2), so it was decided to continue using the already well validated MERRA-2 simulation. Nevertheless, ERA-5 simulations of Switzerland will be completed and made available through www.renewables.ninja later in 2020.

6. National and international collaboration

Nationally, the wind power data developed in this project will see further use within the SCCER-SoE and the SoE/CREST joint activity “IDEA”, which investigates the future need for Swiss hydropower and deep geothermal energy within a highly renewable European energy system.

As laid out in the original project plan, a key component of this project involved international collaboration with the meteorology group of Christian Grams at KIT Karlsruhe.

7. Publications

Bryn Pickering, Christian Grams, and Stefan Pfenninger (2020). Sub-national variability of wind power generation in complex terrain and its correlation with large-scale meteorology. *Environmental Research Letters (ERL)*. Accepted manuscript URL: <http://iopscience.iop.org/article/10.1088/1748-9326/ab70bd>

8. References

Borsche, M., Kaiser-Weiss, A.K., Kaspar, F., 2016. Wind speed variability between 10 and 116 m height from the regional reanalysis COSMO-REA6 compared to wind mast measurements over Northern Germany and the Netherlands, in: *Advances in Science and Research*. Presented at the 15th EMS Annual Meeting & 12th European Conference on Applications of Meteorology (ECAM) -, Copernicus GmbH, pp. 151–161. <https://doi.org/10.5194/asr-13-151-2016>



- European Environment Agency, 2009. Europe's onshore and offshore wind energy potential (Technical report No. 6/2009). European Environment Agency, Luxembourg.
- Federal Office for Meteorology and Climatology, 2015. Typische Wetterlagen im Alpenraum. Zurich, Switzerland.
- Fragkos, P., Tasios, N., Paroussos, L., Capros, P., Tsani, S., 2017. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy* 100, 216–226. <https://doi.org/10.1016/j.enpol.2016.10.023>
- Grams, C.M., Beerli, R., Pfenninger, S., Staffell, I., Wernli, H., 2017. Balancing Europe's wind-power output through spatial deployment informed by weather regimes. *Nature Climate Change* 7, 557–562. <https://doi.org/10.1038/nclimate3338>
- Jafari, S., Sommer, T., Chokani, N., Abhari, R.S., 2012. Wind Resource Assessment Using a Mesoscale Model: The Effect of Horizontal Resolution. Presented at the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, American Society of Mechanical Engineers, pp. 987–995. <https://doi.org/10.1115/GT2012-69712>
- Komusanac, I., Fraile, D., Brindley, G., 2019. Wind energy in Europe in 2018. *Wind Europe*.
- Kruyt, B., Lehning, M., Kahl, A., 2017. Potential contributions of wind power to a stable and highly renewable Swiss power supply. *Applied Energy* 192, 1–11. <https://doi.org/10.1016/j.apenergy.2017.01.085>
- Ramirez Camargo, L., Gruber, K., Nitsch, F., 2019. Assessing variables of regional reanalysis data sets relevant for modelling small-scale renewable energy systems. *Renewable Energy* 133, 1468–1478. <https://doi.org/10.1016/j.renene.2018.09.015>
- Singh, A., Willi, D., Chokani, N., Abhari, R.S., 2014. Optimal power flow analysis of a Switzerland's transmission system for long-term capacity planning. *Renewable and Sustainable Energy Reviews* 34, 596–607. <https://doi.org/10.1016/j.rser.2014.03.044>
- Staffell, I., Pfenninger, S., 2016. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* 114, 1224–1239. <https://doi.org/10.1016/j.energy.2016.08.068>
- Tröndle, T., Pfenninger, S., Lilliestam, J., 2019. Home-made or imported: On the possibility for renewable electricity autarky on all scales in Europe. *Energy Strategy Reviews* 26, 100388. <https://doi.org/10.1016/j.esr.2019.100388>
- Wahl, S., Bollmeyer, C., Crewell, S., Figura, C., Friederichs, P., Hense, A., Keller, J., Ohlwein, C., 2016. A novel convective-scale regional reanalyses COSMO-REA2: Improving the representation of precipitation. *Meteorologische Zeitschrift* 26. <https://doi.org/10.1127/metz/2017/0824>

9. Appendices

Appendix 1: Paper accepted in *Environmental Research Letters* (should be publicly available in February 2020)

Appendix 2: Calliope model description