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Critical weather situations for renewable energies – Part A: Cyclone detection for wind power

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ABSTRACT

A constantly increasing share of weather dependent renewable energies in Germany's power mix poses new challenges concerning grid management and security of energy supply. An evaluation of the three year period from 2012 to 2014 reveals, that 60% of days with largest errors in the day-ahead wind power forecasts for Germany are linked to cyclones and troughs traversing the North Sea, the Baltic Sea or Germany. A cyclone detection algorithm has been developed to automatically indicate these critical weather situations. The algorithm is based on Numerical Weather Prediction model forecasts of mean sea level pressure. The cyclone detection is used to design an automated weather information tool for end-users such as Transmission System Operators (TSOs). For 2014, it identified a critical weather development in 38% of all days. The root mean square error of day-ahead wind power forecasts increased by 1% of installed capacity during these periods. A real time application of the tool is being implemented in order to support a sustainable and save integration of the increasing wind power production. It will then be provided to, and will be tested by, three German TSOs with the purpose of an operative usage to guarantee the security of supply.

1. Introduction

The share of renewable energies in the German power mix is constantly increasing. In 2015, 35% of the country's net electricity production was provided by solar-, wind-, hydro-power and biomass, whereof the largest contribution was due to wind power with 15.1% [1]. The total installed net capacity of wind power is 43.7 GW and during favorable weather conditions it supplies more than half of the country's total energy production [2]. By nature, wind energy is strongly variable and highly weather-dependent. For an accurate detection of these strong fluctuations, transmission system operators (TSOs) need precise wind power forecasts to guarantee system stability. These, in turn, depend also on the quality of the underlying Numerical Weather Prediction (NWP) models. Weather and power forecasts are, however, afflicted with forecast errors. Certain weather situations are particularly hard to forecast and thus are challenging for TSOs.

In the mid-latitudes, day to day weather is fundamentally influenced by extra-tropical cyclones [3]. Within a cyclone, air masses circulate around a center of low air pressure and thus cyclones are also called low pressure systems or lows. On the northern hemisphere, this rotation is counter-clockwise. In the process of cyclone development, well-defined frontal systems are formed, which represent the borders between low-energy (cold) and high-energy (warm) air masses. These fronts are attached to the cyclone and especially to its movement. The presence of intense low pressure systems not only causes rather unstable, wet and windy weather conditions but also amplifies the wind power production. The associated frontal systems can cause fast changes in wind speed as well as in wind direction and may lead to critical, sharp ramps in the wind power production. Fronts with strong wind speeds in Northern Germany are even regarded as critical events concerning the net stability [4]. Large amounts of wind energy are then produced in the North of the country and need to

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be transported towards the South. Such a scenario, especially in combination with low temperatures and consequently a high energy demand, stresses the power grid and poses a challenge to the TSOs. This paper addresses day-ahead wind power forecast errors, identifies cyclones and fronts as problematic weather situations and presents an automated tool to recognize such challenging weather elements.

As low pressure systems strongly govern our weather conditions, the ability of atmospheric models to predict cyclones is intensively studied by meteorologists and climatologists. A comprehensive overview of previous extra-tropical cyclone predictability studies focusing on short to medium-range forecasts is given by Ref. [5]. Nine global ensemble prediction systems (EPS) and their ability to forecast cyclones for a 6-month period was investigated in Ref. [6]. EPS produce multiple weather forecasts, which represent a sample of possible future atmospheric states. In accordance with previous findings [7] it is shown that global deterministic models forecast the position of a cyclone with a higher accuracy than the cyclone intensity. EPS instead can add valuable information to the latter, as they show a higher skill in forecasting the strength of a cyclone. In most of the 14 reviewed global forecast systems cyclones also tend to propagate too slowly. With respect to seasonal forecasts, Ref. [8] investigated wintertime extra-tropical cyclones using the European Centre for Medium-Range Weather Forecast (ECMWF) model and concluded that higher model resolution leads to better simulation of extra-tropical cyclones. Furthermore, there is strong interest on past and future changes in cyclone intensity, frequency and changes in cyclone tracks. The latter have also a special implication on future wind resource assessments as they introduce substantial uncertainty (see Ref. [9]). Ref. [10] gives a review of mid-latitude cyclone climatologies with focus on the present climate and possible changes in the future. In Europe, special interest lies on cyclone tracks over the Mediterranean (e.g. Refs. [11,12]). Their future changes as simulated by regional climate models is addressed, e.g., in Refs. [13,14].

All the above mentioned studies rely on automated cyclone identification and tracking algorithms in order to be able to produce statistics over many cyclone cases. Depending on the intended application, many different cyclone detection and tracking methods have been developed. Most of them follow a Lagrangian point of view, which means that they identify a cyclone as a cyclonic (counter-clockwise) atmospheric circulation around a low pressure center and follow the cyclone as it moves through space and time. Commonly used for the identification of cyclones is the mean sea level pressure (MSLP) field, which represents the atmospheric pressure at sea level. In meteorology, it is also conventional to analyze the (geopotential) height of different vertical levels with constant air pressure. Within both representations of the atmospheric state, cyclones can be identified as local minima, as implemented e.g. in Ref. [15] for the MSLP field or in Ref. [16] or [17] for the 1000 hPa or 700 hPa field, respectively. Instead of looking for local minima, some cyclone detection algorithms compute the Laplacian of the MSLP field. Therein, cyclones coincide with local maxima, as used, e.g., in Refs. [18,19]. Low pressure systems are also marked by high values of relative vorticity, which is a measure for the rotation in a fluid. The 850 hPa relative vorticity field is used e.g. in Ref. [20] to identify cyclones. Other concepts include the analysis of wind fields (e.g. Refs. [21,22]). Ref. [23] even use a variety of meteorological fields at multiple levels as input for the cyclone detection and tracking algorithm from Ref. [24] and combine the information to investigate northern hemisphere winter storm tracks. Ref. [25] also use a hybrid of local minima in the 1000 hPa field and maxima in the vorticity field. Furthermore, their objective identification method comprises the complete life-cycle of cyclonic features, including fronts. An extensive overview of the many different cyclone detection algorithms is given, for example, in Refs. [26,10] or [27]. The latter publication summarizes results of the project *Intercomparison of Mid Latitude Storm Diagnostics* (IMILAST). Therein, 15 detection and tracking algorithms for extra-tropical cyclones have been applied to the same reanalysis dataset and their results are compared in order to assess the method related uncertainty. The cyclone detection algorithms greatly differ in the way they preprocess data. Depending on the resolution of the input fields, an interpolation or a smoothing and up-scaling step may be applied. Furthermore, various threshold settings may be chosen appropriately. Amongst others, Ref. [27] point out, that even though all approaches share a common physical understanding of cyclones, they differ greatly in its implementation and thus all have their individual strengths and weaknesses. Depending on the intended application, a cyclone detection or tracking algorithm has to be chosen and tuned carefully.

In the following, an automated tool is presented that gives an apriori-indication of weather situations which are shown to be critical for German TSOs. Therefore, a cyclone detection algorithm is developed on the basis of the valuable experiences and results of all the afore mentioned studies. The developed algorithm is based on day-ahead forecasts of the NWP-model COSMO-EU [28] from the German Weather Service (DWD) and it is optimized and carefully tuned for the needs of German TSOs. Thus, the focus of the cyclone detection lies on Northern Europe and concentrates on scales which influence the Germany-wide wind energy production and prediction. By evaluating the location and movement of identified cyclones and troughs, critical weather situations are identified and an automated warning is produced. Until now, no such product is available to the German TSOs.

In section 2, the paper gives an overview of the wind power capacity in Germany and the German TSOs. Also introduced is the used wind power forecast and production data. In section 3, day ahead wind power forecast errors for 2012–2014 are evaluated in more detail and their connection to the underlying weather situation is investigated. The method of the developed cyclone detection algorithm is explained in section 4. The results are summarized in section 5, in which also the performance of a derived, automated weather information tool is presented. The conclusions of the paper can be found in section 6.

2. Wind power data

The presented work focuses on wind energy production in Germany and the corresponding day-ahead forecast errors. The installed wind energy in Germany is unequally distributed, with most wind power installed in the northern lowlands. Fig. 1(a) shows the spatial distribution of installed onshore wind energy in 2014 (from Ref. [29], therein Figure 12) and in Fig. 1(b) the control areas of the four German TSOs Amprion, TransnetBW, TenneT and 50 Hertz are depicted. In the area of TransnetBW, the least amount of wind energy production capacity is installed. The TSO's focus lies on balancing demand and supply as accurately as possible. All arising discrepancies need to be compensated. In order to compute day-ahead wind power forecast errors, the so-called Meta-forecasts (best possible forecast of the four German TSOs) are used. These forecasts provide the basis for the day-ahead processes (system operation and marketing) and are published on the TSO's web pages ([30–33]) together with an estimation of the actual power production. The power forecast and production values have a temporal resolution of 15 min and are the basis for all further investigations. The time period between 2012 and 2014 is considered.