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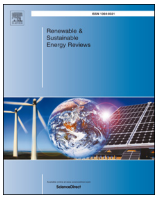

Vulnerability of European intermittent renewable energy supply to climate change and climate variability

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ABSTRACT

The impact of both climate change and climate variability on the supply of intermittent renewable energy sources (I-RES) in Europe are assessed based on global climate model simulations. The main driver of climate variability over Europe is the North Atlantic Oscillation (NAO) in winter and its equivalent in summer (sNAO) which determine to a large extent the atmospheric circulation in Europe. Four climate scenarios are constructed distinguished by a moderate and strong increase of the average global surface temperature, and a positive and negative phase of the atmospheric variability over the North Atlantic and Europe. This spans a framework which combines the effects of both climate change and climate variability. Using a 2050 distribution of PV panels and wind turbines, we found that although climate change is likely to have significant impact on future I-RES output in Europe, its effects, especially for wind power, are outweighed by the high and strongly variable impact of the NAO/sNAO phases. Variability in the large-scale atmospheric circulation is able to induce median I-RES yield differences of 20–30% for high wind potential regions. Due to the NAO variability also months were identified with persistent calm conditions over Europe linked to the inflow of frigid arctic air resulting in some regions in a decrease in wind power of up to 75%a accompanied with an increase in heating degree days of up to 30%. The results of the study imply that if requirements for the power system including back up capacity take into account the weather variability, the power system can also cope with the climate change impacts.

1. Introduction

Intermittent renewable energy sources (I-RES), such as wind and solar power, need to contribute significantly to the reduction of greenhouse gas emissions [1]. However, the dependency of I-RES on local weather conditions renders power output from I-RES vulnerable to climate change and natural climate variability. Earlier studies [2–6] investigating the relation between climate change and I-RES, found a relatively small impact of climate change on wind and solar power generation, with regional differences in these trends over Europe. Using the latest EURO-CORDEX regional climate models in combination with newly developed capacity scenarios [7–10], a small decrease was found in annual wind power for southern Europe with more stable wind power production in northern Europe [10] in combination with a decrease in irradiation in northern Europe and an increase in southern Europe [8].

Natural climate variability is caused by variations in large-scale atmospheric circulation patterns which strongly modulate the temperature, wind, and irradiation for large parts of Europe. The North Atlantic Oscillation (NAO) is the most important mode of atmospheric variability over the North Atlantic sector in the winter, and plays a major role in weather and climate variation over eastern North America, the North Atlantic, and the Eurasian continent [11]. The NAO can be in a positive or a negative phase, relating to the sign of the NAO index, which is the normalized atmospheric pressure differences between the Azores and Iceland (and is one way of quantifying the variations in pressure difference between the subtropics and the subpolar regions). When the pressure difference in the NAO is higher or lower than average, it is in its positive or negative phase, respectively. In the winter, a positive NAO generally leads to windy conditions in northern Europe, with a south-westerly wind bringing mild, cloudy and rainy weather, while southern Europe enjoys relatively sunny and dry conditions. With a negative NAO, the storm track over the North Atlantic ocean is located much more to the south, bringing cloudy and windy conditions to the southern part of Europe while northern Europe generally has calm, cool and dry weather [12]. The equivalent of NAO in the summer season, the so-called summer North Atlantic Oscillation (sNAO), is characterised by a more northerly location of the high- and low-pressure areas over the North Atlantic and a smaller spatial scale than its winter counterpart [13]. While the sNAO is the dominant mode

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of atmospheric variability in the summer, it explains less the prevailing weather patterns than the NAO.

Note that the NAO is only one mode of atmospheric variability and many systems are in use to characterize the variability of the atmosphere of the North Atlantic/European sector in terms of recurring patterns. An overview of these patterns for Europe and their impact on temperature is provided by e.g. [14].

A strong relation is found between the NAO phases and I-RES output. Brayshaw et al. [15] further analysed this relation and concluded that the NAO has a significant impact on the hourly-, daily- and monthly-mean power output distributions of the turbines in wind farms. For the Iberian Peninsula the negative NAO phase enhances the wind speed (10–20%) and reduces the irradiation (10–20%) [16]. Results with similar magnitudes were found for northern regions in Europe [17] while for the Mediterranean region year-to-year variations of over 20% in winter I-RES output was found [18]. While the climate change effect on I-RES output is relevant, the impact of natural climate variability like the (s)NAO, is shown to have a strong impact on I-RES as well, in combination with the observation that the (s)NAO is variable and difficult – if not impossible – to predict. This points to the necessity of considering climate change and climate variability in combination rather than as separate drivers of I-RES trends and variations. Insights into the combined impact on I-RES can guide policy makers, transmission system operators, distribution system operators, and electricity producers, with designing their strategies (e.g. investments in generation, storage and backup capacity, and interconnections). The aim of this study is, therefore, to provide such a combined evaluation of the impact of future weather on I-RES output. This study focusses on Western Europe and evaluates the impacts for the year 2050. For this purpose, historical weather data from observations and future weather data from a climate model with high spatial resolutions are combined with distributions of onshore and offshore wind turbines and photovoltaic systems (PV). Other sources of I-RES, like hydropower, are not considered. Furthermore, possible negative effects of climate change such as icing, corrosion, and abrasion due to airborne particles, are neglected. Finally, this research is limited to analysis of I-RES output in the winter and summer, as in these seasons the dominant modes of climate variability are well-defined in the (s)NAO processes.

2. Methods

With the climate model, EC-Earth (Section 2.1) four scenarios of future weather data were created to span the spectra of climate change and climate variability (Section 2.2). Next, the results of these four scenarios were combined with spatial distributions of I-RES (Section 2.3) to calculate the I-RES generation across Europe (Section 2.4). Finally, the resulting generation profiles were compared with generation profiles based on observational weather data.

2.1. Climate model

The climate model used is the EC-Earth model [19] which is a state-of-the-art global coupled earth system model, consisting of the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF) as the atmosphere component and the Nucleus for European Modelling of the Ocean (NEMO) developed by Institute Pierre Simon Laplace (IPSL) as the ocean component. We use EC-Earth version 2.3 employing IFS cycle 31R1, which has been modified in order to meet the requirements for climate research. For our study we use a horizontal spectral resolution of T159 in the dynamical core of IFS and a corresponding N80 reduced Gaussian grid ($\sim 1.125^\circ \times 1.125^\circ$) for the computation of physical processes. In the vertical there are 62 hybrid model levels extending up to about 5 h Pa (~ 37 km). The time stepping is done using a semi-Lagrangian advection scheme, permitting a time step as large as 1 h in T159. The EC-Earth model has shown to successfully model large scale circulation above the Atlantic and Europe [19] and compares to the median of the CMIP5 suite of climate models.

2.2. Climate scenarios and data sets

With EC-Earth an ensemble of 16 simulations for the period 1950–2100 is made assuming a RCP 8.5 emission pathway. Each simulation is initialized differently, aiming to span the full spectrum of internal climate variability and provides an equally probable and realistic estimate of day-to-day weather consistent with the emission pathway.

The ensemble was divided into four scenarios based on two parameters: global temperature, and atmospheric circulation, represented by the (s)NAO index. Since the relation between global temperature and greenhouse gas is well-understood and linear, data from the 2051 to 2065 period are taken to represent climatic conditions with a strong global warming while data from the 2036–2050 period represent climatic conditions with a moderate warming. The impact of atmospheric variability is captured by labelling each winter and summer season by the phase of the NAO and sNAO, respectively. This division in moderate (M) and high (H) warming and positive (≥ 0) and negative (<0) (s)NAO index resulted in the four scenarios: M+, M-, H+ and H-, where e.g. M+ represents a moderate global warming with a dominantly positive (s) NAO index.

The terminology to refer to ‘M’ and ‘H’ scenario's relates to approach of the climate scenario's issued by the Royal Netherlands Meteorological Institute [20]. The principal reason for using this terminology is that the KNMI’14 scenario's are defined for two time horizons: 2050 and 2085. For the moderate (M) scenario's, the 2050 time horizon corresponds to a global mean temperature increase of 1 °C (and 1.5 °C for 2085). The high (H) scenario's relate to a global mean temperature increase of 2 °C in 2050 (and 3.5 °C in 2085). These values are relative to the 1981–2010 climatic mean.

The 16 simulations of the EC-Earth climate simulations thus resulted in approximately 120 winter and 120 summer variants per scenario (15 years times 16 simulations of which about half with a positive and the other with a negative (s)NAO index). The 480 variants can be considered as many different projections of potential weather in 2050 and are not long time series of successive years. The relevant output parameters of the EC-Earth climate model for this research are presented in Table 1.

The General Circulation Models (GCMs) that provide climate simulations usually suffer from biases in their output. This bias needs correction. The standard procedure to quantify the biases by comparing the model climatology for the current climate with that of observations. In this study, the model climatology is simply adjusted by subtracting this bias. The motivation of this approach is that a climate model may

Table 1
Types of output of the EC-Earth model relevant for this research.

Type of data	Unit
Daily average Radiation Surface Downward Short wave (RSDS) (includes direct and diffuse irradiation)	W/m^2
Daily average wind speed at 10 m height (AWS)	m/s
6 hourly wind speed at 80 m height (V)	m/s
6 hourly wind speed at 100 m height (V)	m/s
6 hourly wind speed at 120 m height (V)	m/s
6 hourly wind speed at 150 m height (V)	m/s
Average daily temperature at 2 m height (T_{AVG})	°C
Daily maximum temperature at 2 m height (T_{MAX})	°C