



# The impact of climate change on the levelised cost of wind energy



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## ARTICLE INFO

### Article history:

Received 14 March 2016  
Received in revised form  
29 June 2016  
Accepted 3 September 2016

### Keywords:

Climate change  
Wind energy  
Wind resource  
Levelised cost  
LCOE  
GIS

## ABSTRACT

Society's dependence on weather systems has broadened to include electricity generation from wind turbines. Climate change is altering energy flows in the atmosphere, which will affect the economic potential of wind power. Changes to wind resources and their upstream impacts on the energy industry have received limited academic attention, despite their risks earning interest from investors.

We propose a framework for assessing the impact of climate change on the cost of wind energy, going from the change in hourly wind speed distributions from radiative forcing through to energy output and levelised cost of electricity (LCOE) from wind farms. The paper outlines the proof of concept for this framework, exploring the limitations of global climate models for assessing wind resources, and a novel Weibull transfer function to characterise the climate signal.

The framework is demonstrated by considering the UK's wind resources to 2100. Results are mixed: capacity factors increase in some regions and decrease in others, while the year-to-year variation generally increases. This highlights important financial and risk impacts which can be adopted into policy to enhance energy system resilience to the impacts of climate change. We call for greater emphasis to be placed on modelling wind resources in climate science.

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## 1. Introduction

Energy policy has always been impacted by uncertainty in future resource availability and cost; the volatility of gas prices (early 2000s) and oil prices (mid-2010s) only reinforce this critical link. Understanding how the cost of energy infrastructure as a whole may change over time can allow policy to be directed to redress pervasive aspects of the market. Issues pertaining to renewable energy infrastructure should not be immune from this critique, including stranded assets [1].

Of the many effects that climate change will have on Earth's weather systems, its impacts on wind resources and the wind energy industry have received limited attention. Traditionally the primary focus of climate models has been temperature and precipitation; however our dependence on the weather for energy supply is strengthening in the wake of COP21 as the international community redoubles its efforts in mitigating climate change. Some 3% of global electricity and 7% in Europe is harvested from atmospheric motion [2], so the need to assess this resource in this nuanced context is gaining traction.

Climate change is expected to modify the spatial and temporal characteristic of current wind speeds: turbulence (changeability), direction (prevalence), extreme events, frequency, density and temperature [3,4]. Climate model projections show wind speeds changing heterogeneously [5,6] with wind resource potentials increasing in some areas whilst reducing in others [7]. As wind energy scales with the cube of its speed, slight changes in these characteristics are magnified in the extractable energy output [8].

Wind energy economics are characterised by relatively high capital expenditure (capex) and low operational expenditure (opex). The average cost of energy from wind, known as the levelised cost of electricity (LCOE), scales with a 1:1 inverse relationship to the amount of wind available when all other variables remain constant. Changes in the wind's availability will therefore have a significant impact on the cost of electricity from wind power.

Investment in wind power is mired with uncertainty, from energy policy and financial subsidies to forecasting its variability. Measures that can reduce associated risks and their costs will therefore improve the deployment of this climate change mitigation measure. Wind farms must compete with conventional fossil fuels on the electricity market [9]. A framework is proposed in this paper to assist in the future-proofing of wind farm portfolios and lay the foundations for a tool to provide a due diligence mechanism to statistically represent investment risk when siting assets. Such a

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### List of abbreviations

AEP	annual energy production
BADC	British Atmospheric Data Centre
CMIP5	Coupled Model Inter-comparison Project 5
Capex	capital expenditure
CF	capacity factor
IPCC	Intergovernmental Panel on Climate Change
LCOE	levelised cost of electricity
MERRA	modern era retrospective-analysis for research and applications
ESM2G (NOAA GFDL)	National Oceanic and Atmospheric Association: Geophysical Fluids Dynamics Laboratory – Earth System Model 2
Opex	operational expenditure
RCP	representative concentration pathways
RMS	root mean square

tool could ultimately influence the cost of capital and enhance sustainable investments [10,11].

Academics are increasingly using interdisciplinary approaches towards these issues around wind energy, scoping more stakeholders in their studies [12]. Very few have considered the entire research-chain that is required to assess the impact of climate change on the cost of wind energy; which encompasses climate science, engineering, energy economics and policy disciplines [13].

Increased wind energy potentials may not directly lead to greater energy revenues or a stronger impetus to invest [14]. This non-linear response is due to the complex nature of electricity markets [15]. Incorporating this into the evaluation of how wind resources may vary under different climate scenarios enables better scope of what interdisciplinary boundaries exist between different stakeholders and experts, primarily between power engineers and climate scientists.

There are two aims of this paper. Firstly to identify and highlight knowledge gaps that exist across the interdisciplinary spectrum of climate science and energy systems research. To this end, Section 2 reviews the current state of knowledge across these disciplines, and Section 3 presents a framework to resolve the information gaps via coupling climate model outputs with a techno economic model. The second aim is to investigate whether climate change will alter the UK's wind resource and the economic implications this may have for wind power in the future. This paper goes on to demonstrate this framework using publicly available data from a single run of a climate model. Sections 4 and 5 determine whether there is a difference between observed and projected probability distributions of wind profiles at specific sites within the research area under different scenarios; and evaluate the economic feasibility of using the wind resource under different scenario conditions.

## 2. Background

### 2.1. Wind resources

#### 2.1.1. The UK's wind resource

The UK has substantial wind resources compared to other European nations [16], which it intends to increasingly utilise for low carbon electricity [17]. The UK's location at the crossroads for many mid-latitude air currents provides a variety of non-extreme weather phenomena [18]. It is buffeted by the thermally

moderating nature of the Atlantic Ocean and its Gulf Stream (west), the European continental landmass (east) and Arctic air masses (north) [19].

Within the UK and its exclusive economic zone (EEZ), the northern regions (Scottish Islands and North Atlantic) are significantly windier than the south. Coastal and offshore areas also experience higher mean wind speeds than inland, primarily due to impact of topography and its thermal properties causing pressure heterogeneities which induce winds [18]. This is reflected in the distribution of wind farms across the UK (Fig. 1), which are predominantly in the central belt of Scotland and off the east coast of England.

Due to the UK's mid-latitude position, the seasons impact on wind resources by changing how energy is delivered and redistributed. A primary mechanism is extratropical cyclone formation, where low pressure storm systems form in the mid-Atlantic and travel towards the UK along a storm track [20]. As this mechanism is enhanced due to the increased temperature gradient in winter, average wind speeds are 50% higher in winter than summer, at 9.2 cf. 6.2 m/s [21,22]. Speeds are higher during the day than at night, which is exacerbated in summer due to fewer low pressure systems and a greater difference between day and night temperature gradients [18].

Due to both external climate forcing and internal chaotic atmospheric phenomena there has been natural variation in the UK's wind resource over past centuries [16]. The North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and long-term persistence (LTP) can skew wind speeds within their natural variable range due

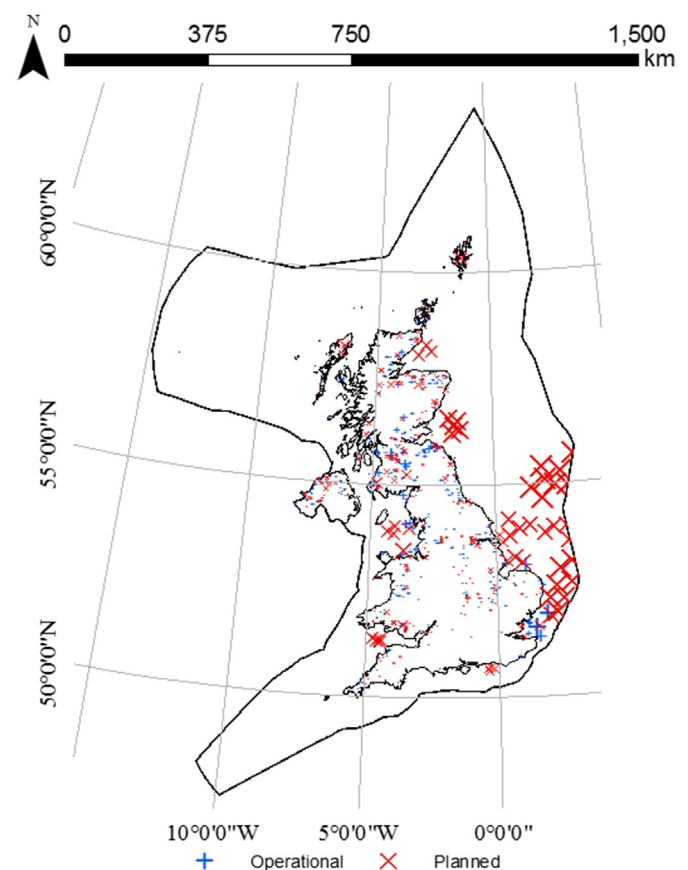


Fig. 1. The location of current and planned wind farms in the UK. Cross size is proportional to farm capacity, and the thick line shows the UK's exclusive economic zone (EEZ).

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