Technology Review

Predicting the effects of climate change on wind energy facilities and infrastructure

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Andrew Clifton

Climate change will affect wind energy in many different ways. How can we predict those effects?

This document provides a short perspective on our understanding of the effects of climate change on wind energy, and how this can be quantified for use in wind farm planning or the assessment of climate-related risks.

For more information, or to have this customised to your needs, please contact us.

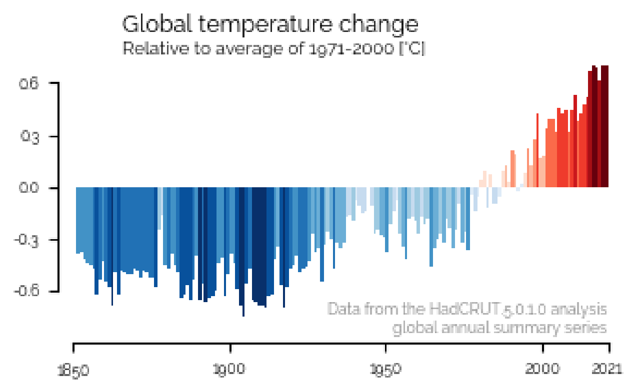

Figure 1: The evolution of the global mean temperature compared to the period 1971-2000. Red colours are above the average for that period, blue colours are below average. Illustration produced by enviConnect using the HadCRUT.5.0.1.0 analysis global annual summary series.

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Disclaimer

The presence of a person's name or an organisation's name in this document should not be taken to imply that a named person (or their employer), or a named organisation agrees with any opinions set out here.

1 What is it?

The climate is the average weather in a place over many years. Climate change is a shift in those conditions from a combination of natural processes and human activities. Since the industrial revolution in the 1800s, **climate change has been accelerated by human activities,** primarily due to burning fossil fuels, deforestation, and farming livestock.

Climate change has already resulted in an increase of the global mean air temperature of around 1 °C above long-term means (Figure 1). This has led to loss of glaciers and seasonal sea ice, warming of ocean waters, changes in ocean acidity, changes in land surface cover, modifications to weather patterns, and increases in the severity and frequency of extreme weather events. **These changes will continue while humanity burns fossil fuels, cuts down forests, and farms livestock.**

2 Why is it important?

Climate change could affect wind energy facilities in many ways (Table 1). It could change wind resources for better or worse [see e.g., 1, 2], or lead to significant changes in operating conditions over the lifespan of a plant, resulting in more or less energy production than predicted. It could affect operating costs. And, it could reduce the power a wind farm can export. These may impact the financial performance of a wind farm. Thus, **climate change introduces uncertainty and adds risk to investments**.

However, many of the potential impacts of climate change can be mitigated during the design phase of a wind farm if the wind farm designer is aware of them. For example, it is much easier to specify larger stormwater drainage, larger cooling units, or enhanced lightning protection during the design process, than it is to retrofit a plant once it is built. **It therefore can make sound financial sense to plan ahead for the effects of climate change**.

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Table 1: Some of the ways climate change could impact an onshore wind farm. These are linked to wind conditions (wind icon), changes in weather patterns (weather icon), increased temperatures (thermometer icon), lightning risk (lightning icon), extreme events (storm icon), or wildfires (fire icon).

Possible impacts	LCOE impact
Site prospecting	
different future wind climate compared to past wind climates reduces the usefulness of historical data for predicting future wind resources	increased development costs
Wind resource assessment	
damage to measurement equipment during extreme events	increased development costs
uncertainty in future wind resource	increased financing costs
Turbine design	
extreme conditions are more frequent	turbine designs may need to change
more, and more energetic lightning strikes	—"—
increased temperatures require increased turbine cooling	—"—
Site design	
need to plan for possible change of soil properties around foundations and roads during the operational life of the plant	increased development costs
need to plan for increased maximum operating temperatures or degree-days → extra cooling capacity for equipment	increased equipment costs
need to increase dimensions of drains, culverts, and stormwater management for extreme rainfall or thawing events	increased construction costs
Energy yield analysis	
increased uncertainty in wind resources → uncertainty in energy yield	increased financing costs
unknown increases to the wind farm's own energy use for cooling, leading to uncertainty in energy yield	—"—
Construction	
changes to construction season due to changes in weather patterns	increased *or* decreased construction costs
need for contingency plans for extreme weather events during construction	increased construction costs
reduced lifting windows due to more severe and more frequent extreme weather events	—"—
Operations	
increased risk of unexpected wind droughts	reduced energy production
increased energy use in turbines or on site for cooling	—"—
increased frequency of lightning strikes due to higher temperatures [3]	
... potentially leading to turbine blade or infrastructure damage	increased O&M costs
reduced working hours in hot climates or areas affected by seasonal storms, leading to slower maintenance and reduced turbine availability	reduced energy production
potentially reduced operating lifespan due to extreme weather damage	reduced operating life; less opportunity for lifetime extension
Grid connection	
reduced export capacity to reduce transmission line sag [4]	reduced energy production
loss of grid connection / transmission line damage in extreme events	—"—

Levelized Cost of Energy (LCOE)

The LCOE of a wind farm is the average cost of building and operating it, per unit of electricity generated over the planned lifetime of the wind farm. It is effectively the average minimum price for energy required in order for the farm to offset all costs over it's lifetime. LCOE is calculated from the net present value (NPV) of the costs and the net energy produced:

$$\text{LCOE} = \frac{\text{NPV of all costs over lifetime}}{\text{NPV of all net energy}}$$

The costs for a wind farm include development, financing, equipment (including the turbines and balance of plant), construction, operations and maintenance, disposal (less scrap value), land reinstatement, and other costs.

3 How can it be planned for?

Quantifying climate changes and the associated effects on a wind farm requires accurate and reliable models of the future climate at a wind farm.

The future path of global warming is highly dependent on the policies put in place to limit it, how economies and societies respond to those policies, technological developments, and many other factors. These are captured in scenarios that model these developments over several decades. Information from these scenarios is then used to model the climate at different times along that pathway. Because there are many different ways to model the climate, climate modelling results in a range of projections* for each scenario, as shown in Fig. 2. This means that we cannot make deterministic predictions of climate change, but **must anticipate a range of possible outcomes**.

***Predictions* are estimates of future state based on well-known boundary conditions and well-known processes. *Projections* are an

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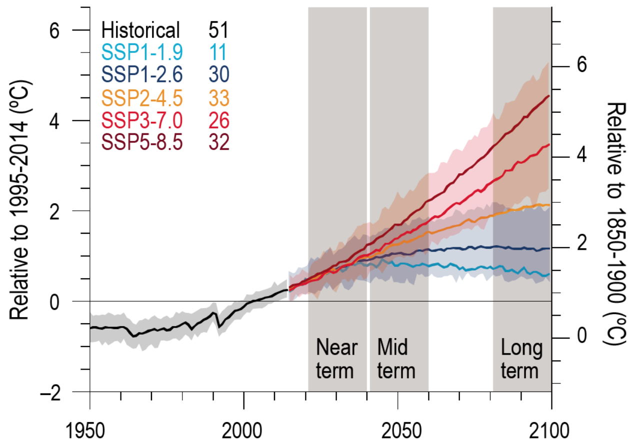

Figure 2: Predictions of future global surface air temperature changes under different emission scenarios (SSP..) relative to the 1995–2014 average (left axis) and relative to the 1850–1900 average (right axis). From [5].

Climate models typically have coarser temporal and spatial resolution (typically 50-100 km and 30 minutes) than weather models (1-5 km, 10-30 min.), and so cannot reliably predict conditions at a wind farm. To obtain local data, outputs from climate models are used as inputs to other models that simulate conditions at the wind farm. This process is called downscaling and can take many forms.

Because it is not clear which emissions scenario will occur, this downscaling process should be carried out for multiple climate scenarios, using results from different climate models. This gives a range of projected values for each scenario at the wind farm location.

Once the potential physical effects of climate change are known, these can be used to estimate effects on plant performance and costs using wind farm energy models (Fig. 3). Some effects are difficult to quantify, and so a qualitative risk assessment may be required. The result of this is an **assessment of the range of effects of climate change** at a wind farm.

As a result of these steps, **climate change becomes a risk that can be anticipated, quantified, and potentially mitigated in the planning phase** of a wind farm.

4 How mature is the technology?

There is no doubt in the global scientific community that climate change exists and that recent short term change is driven by human activities following well-described physical principles. There is overwhelming evidence for this, summarised in the IPCC's[‡] *Sixth Assessment Report* from 2021 [6]. Climate change will continue if emissions follow current trends; in 2018 the IPCC stated, "Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate." [§A1 in 7]

The future emissions scenarios are based on extensive research and are considered realistic by the scientific community [see e.g. 8]. The climate models that project future climates based on the emissions scenarios have been extensively validated against historical observations. Results from the most recent Coupled Model Intercomparison Project [CMIP6; see 9] suggest that some models are more accurate than others, and that a careful model ensemble selection is essential for realistic climate projections [10].

As with most scientific disciplines, there is ongoing scientific debate about climate change, for example about the mechanisms, impact, or magnitude of the effects. However **there is no doubt that climate change is driven by human activities, will continue, and will cause more observable changes by 2050.**

Downscaling from climate models to a location such as a town is also a well-established process and the climate data is considered accurate enough to be actionable by municipalities [e.g., 11].

Predicting the *effect* of climate change on facilities is harder. Although it can be done qualitatively (Table 1) and often quantified (e.g., number of days with temperatures above 0 °C or above a safe working limit, or where precipitation occurs, etc.), turning this data into an impact on the value of the investment requires understanding the link between weather and income or costs at all stages of the facility lifespan.

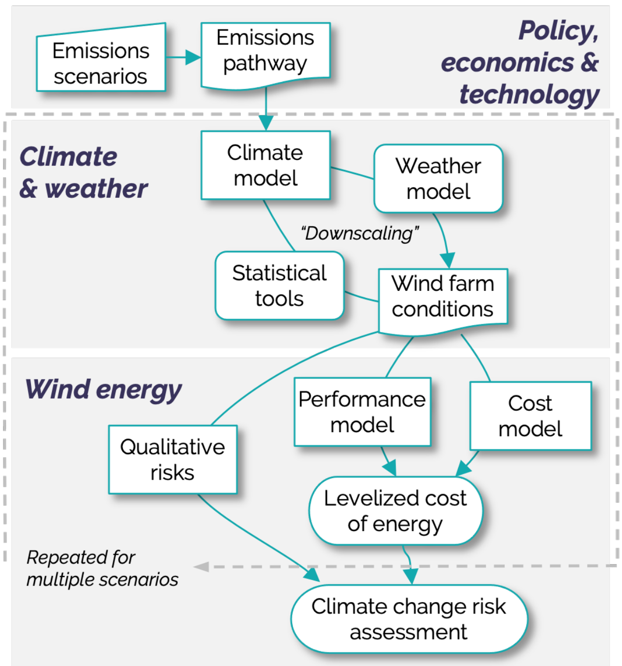

Figure 3: Modeling the effect of climate change on a wind farm requires linked simulations in several disciplines

estimate of future state for a given set of boundary conditions.

[‡]The Intergovernmental Panel on Climate Change (IPCC) is a body of the United Nations responsible for advancing knowledge on human-induced climate change.

5 What standards exist?

Different parts of the process of predicting the effects of climate change on wind energy facilities and infrastructure have different approaches to standards.

1. The emissions scenarios are standardized in that they are publically available, well documented and agreed by the climate modeling community.
2. The climate models themselves are not standardised, but go through rigorous version control and update cycles which ensures tracability. There is also a coordinated movement to identify a well-performing core group of models.
3. There are no universally accepted approaches or methodologies to evaluate climate models but CMIP provides a framework for this.
4. The IPCC recommends of steps to derive regional information from climate models (and all other available information), but processes used to downscale model ensembles to specific locations are not standardised.
5. Results can be compared to publicly-operated weather stations.
6. The processes used to evaluate the impacts of climate change on wind energy are commercially sensitive and are not standardised.
7. Frameworks exist for reporting climate-related risks (see next).

6 Is it *required*?

In 2014 the European Union introduced requirements for businesses in the EU with more than 500 employees to report non-financial risks (the Non-Financial Reporting Directive ↗), with the goal of prompting businesses to address risks. The EU published guidelines for reporting climate-related risks in 2019.

This directive is backed up by other measures. In 2020 the European Central Bank announced supervisory expectations on risk management and disclosure for climate-related and environmental risks for around 1,000 financial institutions in Europe [12]. These institutions are starting to examine climate- and environmental risks in large investments, such as energy facilities.

There have also been international efforts to require businesses to report their exposure to climate-related risks. The Task Force for Climate-related Financial Disclosures (TCFD) was created in 2015 as an initiative from the G20 group of nations. In 2017 it published recommendations for more effective climate-related financial disclosures as part of existing reporting [13]. More than 2,600 organisations worldwide – managing $194 Trillion in assets – have signed up to the TCFD [14]. Although these disclosures are voluntary, **many countries are moving towards mandatory reporting** aligned with the TCFD's recommendations.

7 What are the challenges with it?

There are several main challenges associated with predicting the effect of climate change on wind energy facilities and infrastructure:

1. Uncertainty about which climate change scenarios will actually occur
2. Difficulty of accurately projecting changes in climate variables – e.g. temperature, rain or snowfall – at a wind farm's location.
3. Difficulty in converting projected changes in climate variables into effects on a wind farm's design, building, operations and maintenance, and financial performance.
4. Results are not deterministic but instead offer a range of outcomes for different scenarios.

These **challenges can be offset by first working with an experienced service provider, and then building internal capabilities**.

8 What's coming next?

Evaluating, managing, and reporting the risks from climate change **will become an essential business activity** in the wind energy sector. This may be driven by legislation, company policy, or shareholders.

More companies will be required to disclose climate-related risks. The EU's 2021 Sustainable Finance Package included the Corporate Sustainability Reporting Directive, which would require all listed companies to provide reporting on climate-related risks (CSRD ↗). This directive might be adopted by 2024 (↗). The U.S. Securities and Exchange Commission (SEC) proposed similar requirements for listed companies in the U.S. in March 2022, to be phased in over 3-5 years (↗).

Some larger energy companies already convert climate change information into actionable risk assessments for oil and gas facilities or other infrastructure. We expect large wind energy developers and owner-operators to develop their internal capabilities.

As a result of reporting requirements we expect to see third-party climate change risk assessments being carried out as wind farms are bought and sold, especially if listed companies or larger financial organisations (such as a bank or pension fund) are involved.

It seems likely that climate modeling and downscaling to a wind farm location will continue to be provided by specialist third parties because of the expertise required. We anticipate it becoming cheaper and faster as demand and competition increases.

We expect smaller or privately-held companies to use external climate modeling and risk assessment service providers as part of their normal processes for managing the risks associated with building, owning, and operating wind farms. **Such information - particularly if mitigating steps have been taken - could potentially increase the value of those facilities.**

9 Getting started

We suggest initially working with third party experts to make a climate-related risk assessment on a facility.

10 Suppliers

The following organisations are known to offer asset-level climate modeling as a commercial service:

- **Climate scale**
- **Jupiter**
- **Meteodyn**
- **RMS**

Some national weather services may provide such services.

Inclusion in this list is not an endorsement. It is not complete, and we welcome suggestions.

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Feedback and updates

Please send any feedback to info@enviconnect.de. Check for new versions of this document here.

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