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# Climate Change Impacts on Wind Energy

Exploring the Effects of Climate Change on Clean Energy Sources

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# The Climate Change Impact

**Renewables Resource Changes**

Gradual shifts in wind speed and direction, as well as in temperature, pressure and humidity patterns, affect renewable resource availability and energy production.

**Extreme Temperature Events**

Cold spells and heatwaves are becoming more frequent, increasing risks such as turbine icing, overheating and mechanical stress on wind energy assets.

**Storms and Lightning Risks**

The increasing frequency of severe storms and lightning poses a threat to wind farm reliability and safety by causing damage to blades and electrical systems.

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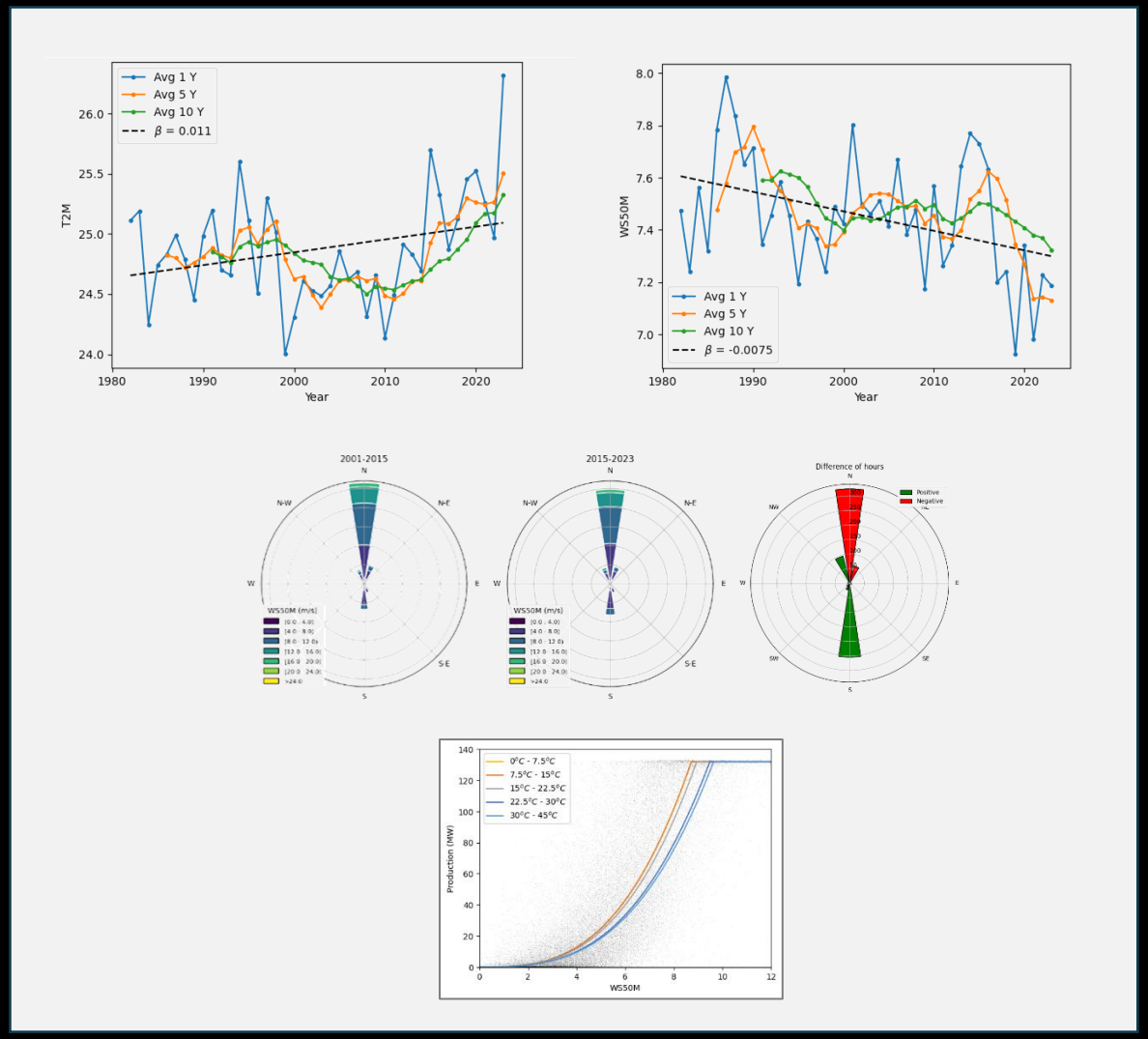
# The Climate Change Impact on Renewable Resources

Climate change is altering global patterns of temperature, rainfall, humidity, and wind speed, while also increasing the frequency and intensity of extreme weather events.

Wind generation potential is affected by these changes, particularly through variations in wind speed, air density, wind direction, pressure and temperature. Understanding these effects is therefore essential.

Climate model projections indicate that these changes will not be uniform across the planet; in most regions, the impact is expected to be negative.

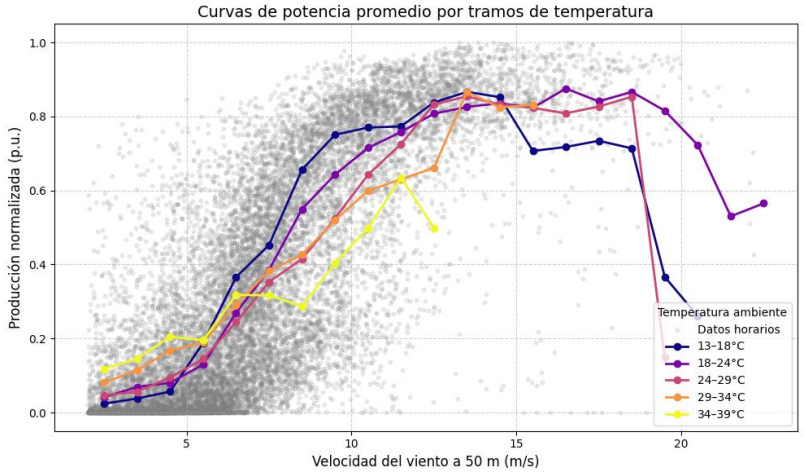
**Given the sensitivity of the wind resource to the variables above, the future evolution of resource availability and energy production across different locations is assessed under the SSP1-2.6 to SSP5-8.5 scenarios (Source: IPCC AR6 SYR, 2024. Synthesis Report of the IPCC Sixth Assessment Report (AR6), Longer Report).**




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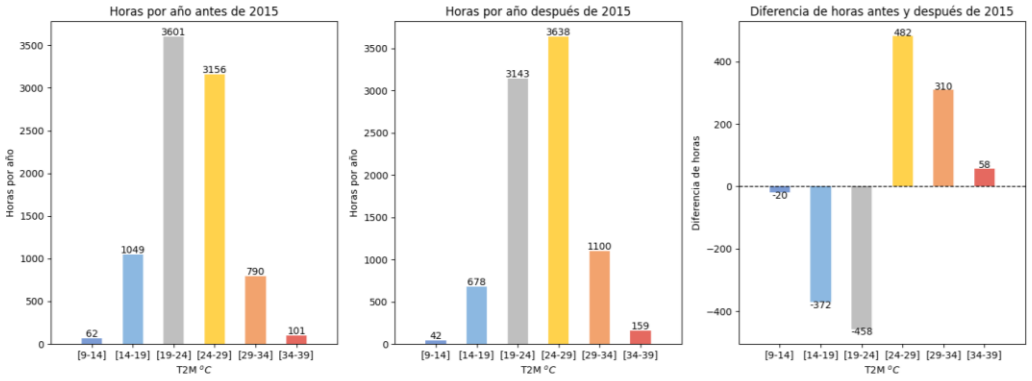
# Assessment of the impact of climate change on wind projects

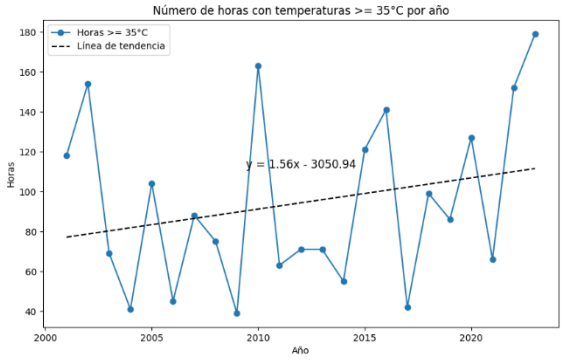
## Wind farm installation (example)




The power curves of the wind farm turbines have been assessed. The highest power output is obtained between 13 and 18°C, the lowest temperature range recorded at the site.

As expected, under the hottest conditions the power curve does not reach the levels achieved in other temperature ranges, owing to changes in air density: the higher the temperature, the lower the density and the less energy extracted by the blades.



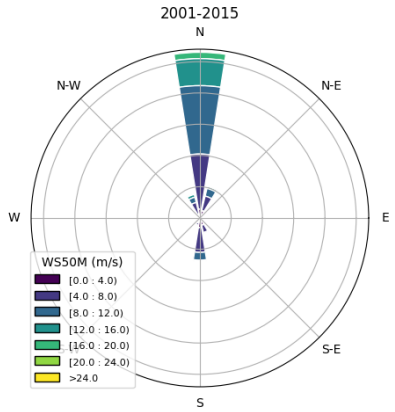

- The number of hours per year in which site temperatures exceeded 35°C shows an upward trend.
- Hours per year with temperatures between 9 and 24°C fell by 850.
- These hours have shifted to the remaining temperature bands, where energy yield is lower because air density decreases as temperature rises.

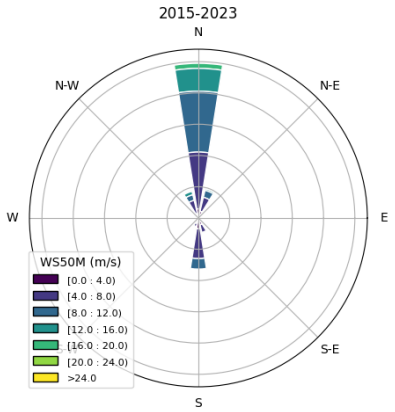
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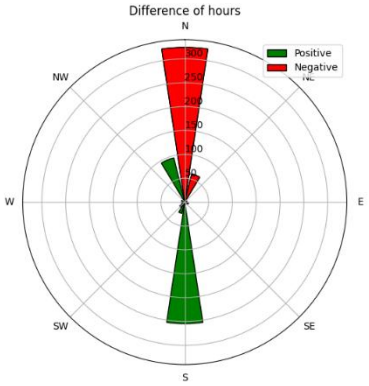
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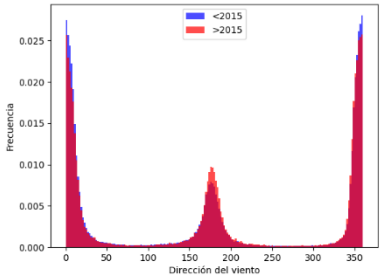
## Wind farm installation (example)

Historical data from 2001 to 2023 on the evolution of wind direction at the site has been compiled. Mixed trends are observed in the frequency of the prevailing direction (N), with a clear decline in recent years.




- The historical data identifies North as the prevailing wind direction at this site.
- The directional profile has changed between the 2001-2014 and 2015-2023 periods.

  These changes represent a decrease of around 324 hours per year in the prevailing direction (N) and an increase of 255 hours in the southerly direction.

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# Sensitivity of resource availability to meteorological variables

## Sensitivity of wind speed to other meteorological variables

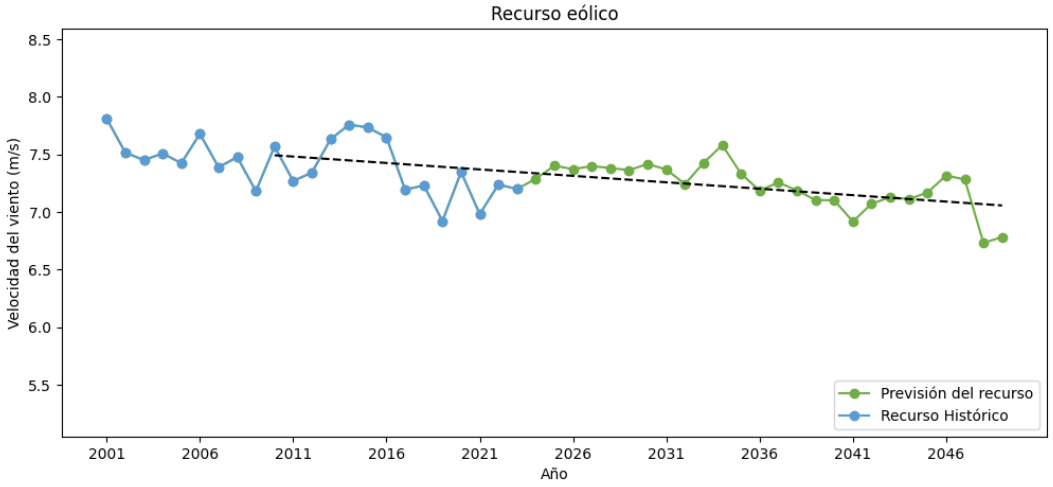
| Dependent variable | Independent variable | Causality | Significance | Slope | Impact |
|---|---|---|---|---|---|
| Wind Speed 50m (WS50M) | Dew Temperature (T2MDEW) | Yes (100%) | Yes (100%) | -0,6287 | For each 1°C increase in dew point temperature, wind speed decreases by 0.63 m/s. ↓ |
| Wind Speed 50m (WS50M) | Air temperature (T2M) | Yes (100%) | Yes (100%) | -0,5854 | For each 1°C increase in air temperature, wind speed decreases by 0.59 m/s. ↓ |
| Wind Speed 50m (WS50M) | Relative humidity (RH2M) | Yes (100%) | Yes (98%) | -0,0261 | For each 1% increase in relative humidity, wind speed decreases by 0.03 m/s. ↓ |
| Wind Speed 50m (WS50M) | Precipitation (PRECTOTCORR) | Yes (100%) | Yes (100%) | -0,3399 | For each additional mm of precipitation, wind speed decreases by 0.34 m/s. ↓ |
| Wind Speed 50m (WS50M) | Atmospheric Pressure (PS) | Yes (99.59%) | Yes (100%) | 8,6880 | For each unit increase in surface pressure, wind speed increases by 8.69 m/s. ↑ |
| Wind Speed 50m (WS50M) | Wind Direction (WD50M) | Yes (100%) | Yes (100%) | 0,1044 | For each unit increase in cosWD50M, wind speed increases by 0.10 m/s. ↑ |

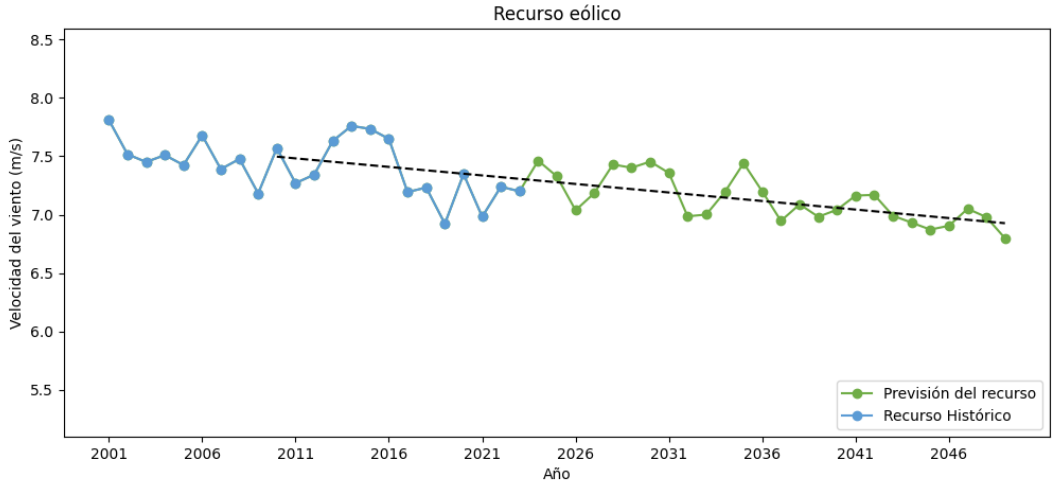
Further details of these analyses are provided in the annex to this document.

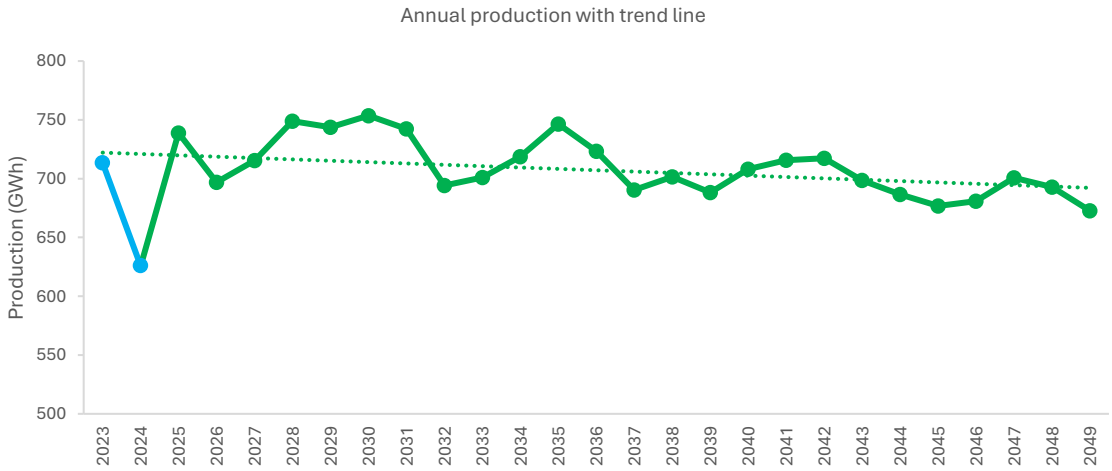
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# Sensitivity of resource availability to meteorological variables

## Wind Resource Evolution Forecast: SSP2-4.5 and SSP3-7.0




| Period | 2038-2040 | 2023-2025 |
|---|---|---|
| Average Wprod (GWh) | 710.34 | 747.56 |
| **Δ (%)** | | **-4.98%** |

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# Impacts of Extreme Weather Conditions on Wind Generation Assets



The frequency of extreme temperature conditions, both cold and hot, is increasing in certain locations.

**Effects of Extreme Cold**

Icing on turbine blades reduces efficiency and increases structural loads, causing safety shutdowns and mechanical stress.

**Consequences of Extreme Heat**

High temperatures lower air density, reduce power output and increase thermal stress on critical turbine components.

**Operational and Maintenance Challenges**

Extreme temperatures increase maintenance requirements, degrade materials and cause more frequent shutdowns and failures.

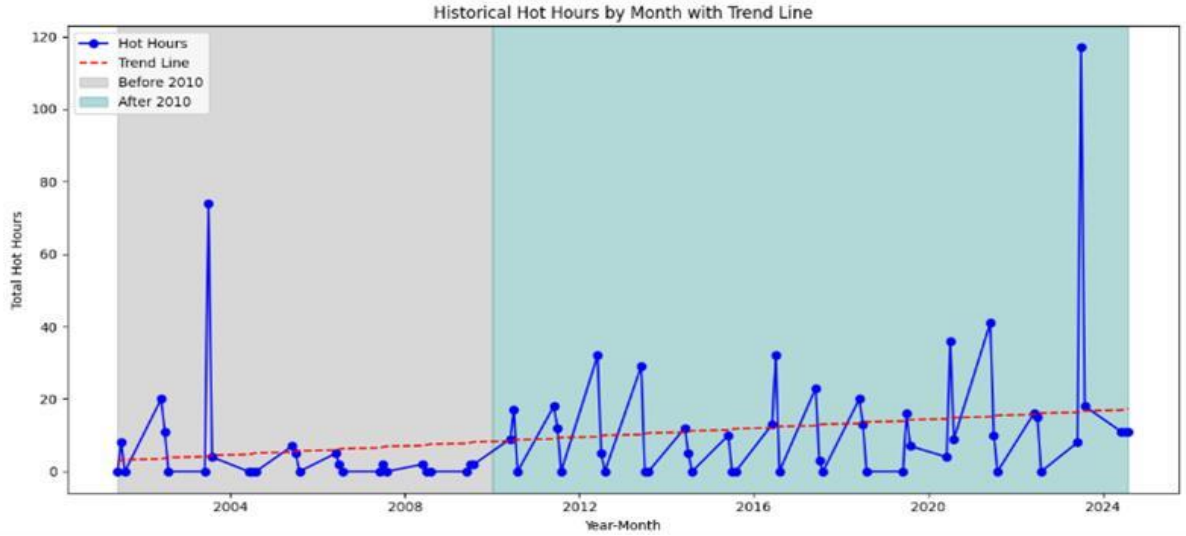
**Need for Adaptation**

A changing climate demands technical and operational adaptation to ensure turbine safety and reliable performance.

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# Extreme cold and heat events and climate change

## Extreme weather impact on the wind energy business (examples)




Wind Farm A

Hot hours per month (>35°C).

Before 2010: 1 month with more than 25 hours.

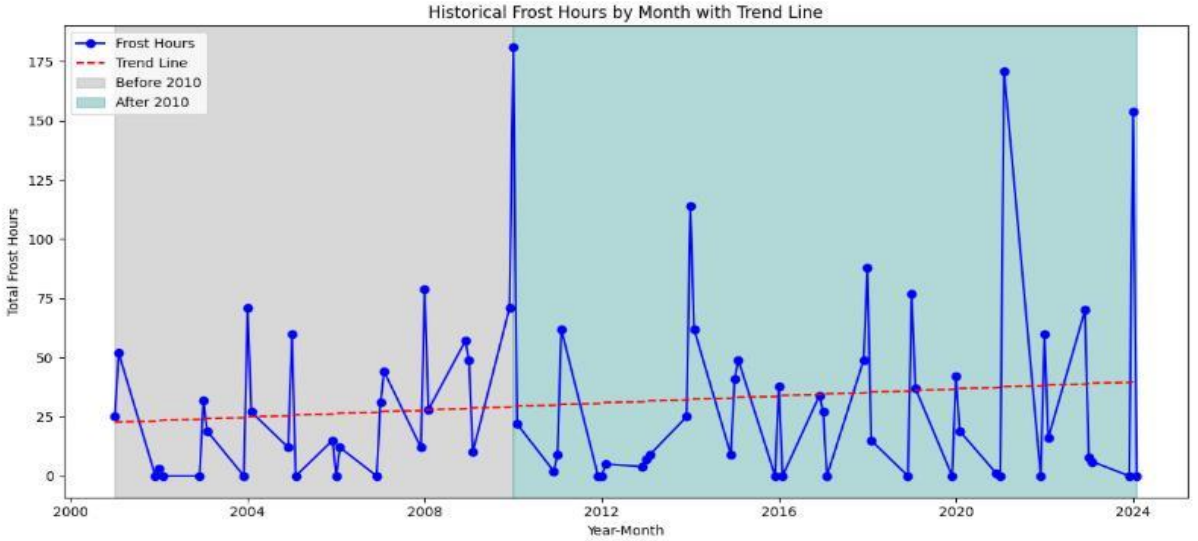
After 2010: 6 months with more than 25 hours.

Wind Farm B

Frost hours per month (<-15°C).

Before 2010: 1 month with more than 80 hours.

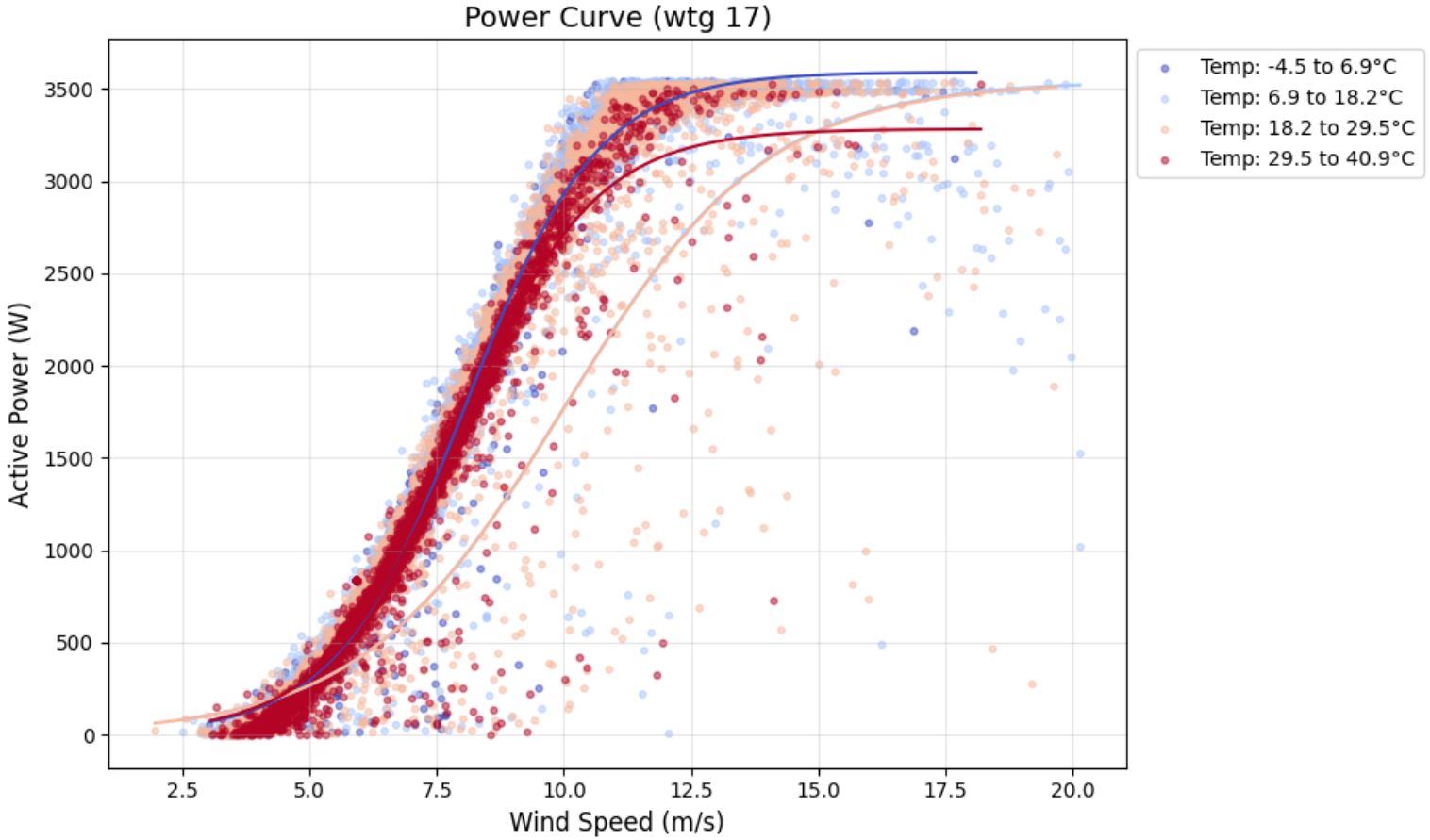
After 2010: 5 months with more than 80 hours.




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# The impact of extreme weather events on the wind energy business

## Impact on energy production (example)




Wind farm data has been analysed to evaluate power curves (power vs. wind speed) across different temperature ranges.

At high temperatures (29-40°C), turbines struggle to reach maximum power, as expected given the reduction in air density and de-rating.

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# MAIN CONSEQUENCES OF CLIMATE CHANGE FOR THE RENEWABLE ENERGY BUSINESS



**Wind Resource Degradation**

Declining wind speeds reduce energy output, an effect amplified by the cubic relationship between power and wind speed.

**Impact of Rising Temperatures**

Higher temperatures decrease air density and solar panel efficiency, stressing wind turbines and reducing output.

**Changing Wind Patterns**

Shifts in wind direction and seasonality cause turbine misalignment and increased wake losses, reducing efficiency.

**Extreme Weather Challenges**

More frequent severe weather events increase maintenance costs, downtime and operational risk across renewable energy portfolios.

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# IMPACTS ON RENEWABLE RESOURCE AVAILABILITY AND PRODUCTION



**Declining Wind Resource Availability**

Rising temperatures and declining wind speeds are reducing wind power potential in many locations worldwide.

**Temperature Effects on Wind Turbines**

Higher temperatures lower air density and trigger turbine de-rating, reducing production particularly during summer peaks.

**Wind Direction Shifts**

Shifts in wind direction reduce turbine efficiency by increasing wake effects and limiting productive hours from the prevailing wind sectors.

**Solar PV Temperature Impact**

Rising temperatures reduce solar panel efficiency, partially offset by changes in solar irradiance and cloud patterns.

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# IMPACTS OF STORMS AND LIGHTNING ON WIND FARMS



**Lightning Vulnerability of Turbines**

Wind turbines are vulnerable to lightning due to their height, exposed locations, and sensitive electronic systems.

**Damage to Turbine Components**

Lightning can cause severe damage to rotor blades and electrical systems, with a risk of fire and structural damage.

**Storm Effects Beyond Lightning**

Strong winds, heavy rain and hail place additional stress on turbine structures, causing downtime and added cost.

**Mitigation and Monitoring**

Robust lightning protection, atmospheric monitoring and proactive maintenance reduce storm-related outages and damage.

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# MITIGATION STRATEGIES AND ADAPTATION MEASURES



**Cooling Systems for Heat Management**

Enhanced cooling and ventilation prevent overheating and extend the service life of turbine components as temperatures rise.

**Cold Climate Anti-Icing Solutions**

Blade coatings, heating systems and ice detection sensors reduce icing risk and maintain turbine efficiency in cold weather.

**Lightning and Fire Risk Mitigation**

Lightning protection, grounding and fire suppression systems reduce damage during storms and safeguard operational safety.

**Infrastructure and Strategic Planning**

Reinforced grid assets and climate risk assessments improve resilience and long-term management of renewable energy sites.

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# FINAL CONCLUSIONS AND STRATEGIC OUTLOOK



**Impact of Climate Change**

Climate change is reducing wind resources and placing additional stress on renewable energy equipment, increasing operational risk and disruption.

**Challenges for Wind Power**

Wind power faces efficiency losses from lower wind speeds and rising temperatures, exposing the limits of current turbine designs.

**Mitigation Strategies**

Technical upgrades and improved monitoring reduce vulnerability, supporting asset longevity and grid reliability in a changing climate.

**Strategic Adaptation Opportunity**

Proactive climate adaptation builds resilience, protecting asset value and supporting the global energy transition.

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