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Climate Change impact on the Wind Energy Business

Assessment Approach

May 2023

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The Climate Change and the Wind Energy

The climate change and the wind energy

Background

BBC Sign in Home News Sport Reel Worklife

NEWS

Texas weather: Are frozen wind turbines to blame for power cuts?

Critics of green energy in the United States have blamed the failure of wind turbines for the power shortages in Texas during the recent freezing conditions there.

"The windmills failed like the silly fashion accessories they are, and people in Texas died," said Fox News's Tucker Carlson.

The power grid was clearly overwhelmed, but to what extent was a loss of wind power to blame?

Was wind-power failure the problem?

Texas has promoted the development of wind energy over the past 15 years, and some of these turbines certainly froze in the recent bitingly cold conditions

Climate Change is modifying the temperature, rainfall, humidity and wind speed patterns along the world, and increases extreme weather events.

Of the many effects that climate change will have on Earth's weather systems, its impacts on wind resources and the wind energy should be taken into account. Climate Change is expected to modify the spatial and temporal characteristic of current wind speeds: turbulence, direction, frequency, density and temperature. Climate model projections show wind speeds changing heterogeneously with wind resource potentials increasing in some areas whilst reducing in others. As wind energy scales with the cube of its speed, slight changes in these characteristics are magnified in the extractable energy output.

Wind energy economics are characterized by relatively high capital expenditure and low operational expenditure. The average cost of energy from wind has an 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.

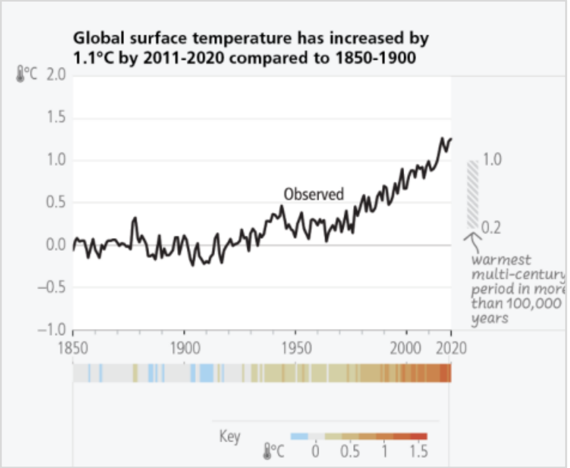
These risks and their costs should be identified and evaluated, identifying the affordable measures to mitigate them.

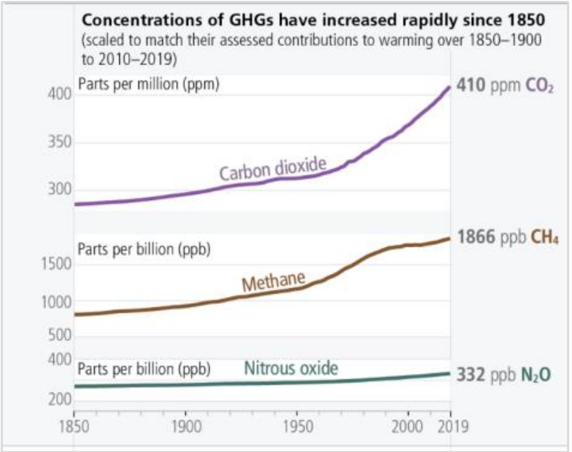
The Climate Change and the wind energy

The IPCC Sixth Assessment Report, AR6

- Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 (1.3% yr^{-1}) was lower than that between 2000 and 2009 (2.1% yr^{-1}).
- Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09°C [0.95°C–1.20°C]), with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88°C [0.68°C–1.01°C]). Observed warming is human-caused, with warming from greenhouse gases, dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling.

  It is certain that hot extremes (including heatwaves) have become more frequent and intense across most land regions since the 1950s, resulting in warmer summers and milder winters. However, some studies show that Climate Change can also result in periods of extreme cold in northern-midlatitudes.
- The frequency and intensity of heavy precipitation events have increased since the 1950s over most regions, increasing exposure to extreme river flows and flooding.
- Global mean sea level increased by 0.20 [0.15–0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] yr^{-1} between 2006 and 2018.
- Wind patterns has changed, increasing the proportion of peak wind speed and the intensity of tropical cyclones.



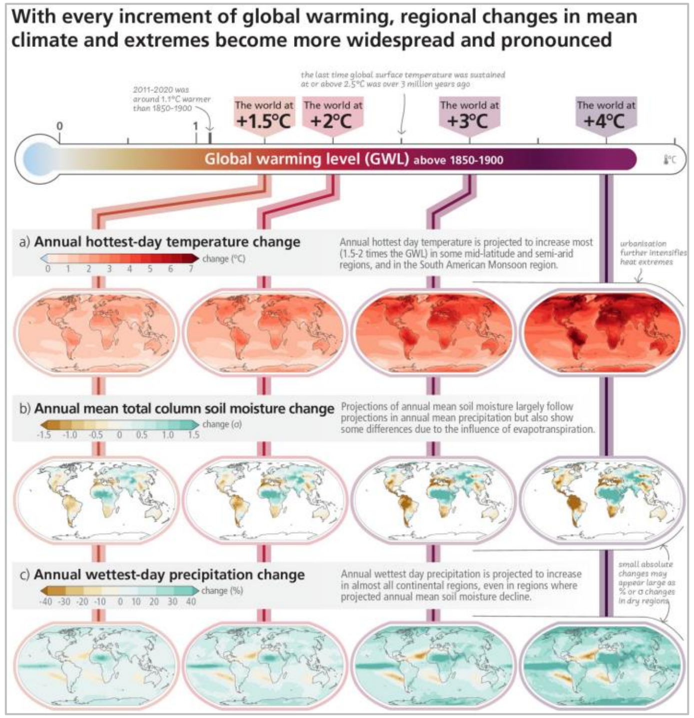


Source: IPCC AR6 SYR, 2023. Synthesis report of the IPCC Sixth Assessment report (AR6). Longer Report.

The Climate Change and the wind energy

Wind energy related variables affected by Climate Change

Variable	Changes effects and their impacts
Temperature	The main temperature is expected to increase globally, as a direct consequence of global warming. Intensity and frequency of hot extremes will also increase. Compound heatwaves and droughts are becoming more frequent, as well as aridity conditions and fire weather.
	• High temperatures reduce the air density: lower production. Power de-rating above certain temperatures • Cases of extreme cold will produce ice accretion: impact on production and/or damage in the equipment.
Wind	Wind energy (mean power density) is dependant on temperature and will be affected by Climate Change. Frequency of wind extreme conditions will increase.
	In some areas like Western and Central Europe and North America, a well-spread drop of ~15% in wind power density is expected. In other areas (e.g. Eastern Europe), the impact will be the opposite and wind power density will increase. Extreme events reduce the production and damage the equipment.
Humidity	The general warming effect and the increase in the mean temperature, combined with frequent droughts, will reduce the humidity, increasing air density (higher wind energy resource). On the other hand, during periods with intense precipitation, humidity can reach higher levels than usual.
	A humidity reduction will have a positive impact on the production and the useful life of the equipment (lower corrosion). However, in periods of intensive precipitation and high humidity, corrosion can be dangerous for some materials.
Flooding	At 1.5°C global warming, heavy precipitation and flooding events are projected to intensify and become more frequent in most regions in Africa, Asia, North America and Europe. At 2°C or above, these changes expand to more regions and/or become more significant.
	Damage in the equipment and difficulties to access the facility.
Rainfall and storms	Some projected regional changes include intensification of tropical cyclones and/or extratropical storms, which can compromise the safety of wind energy farms.
	Extreme events reduce the production and damage the equipment.



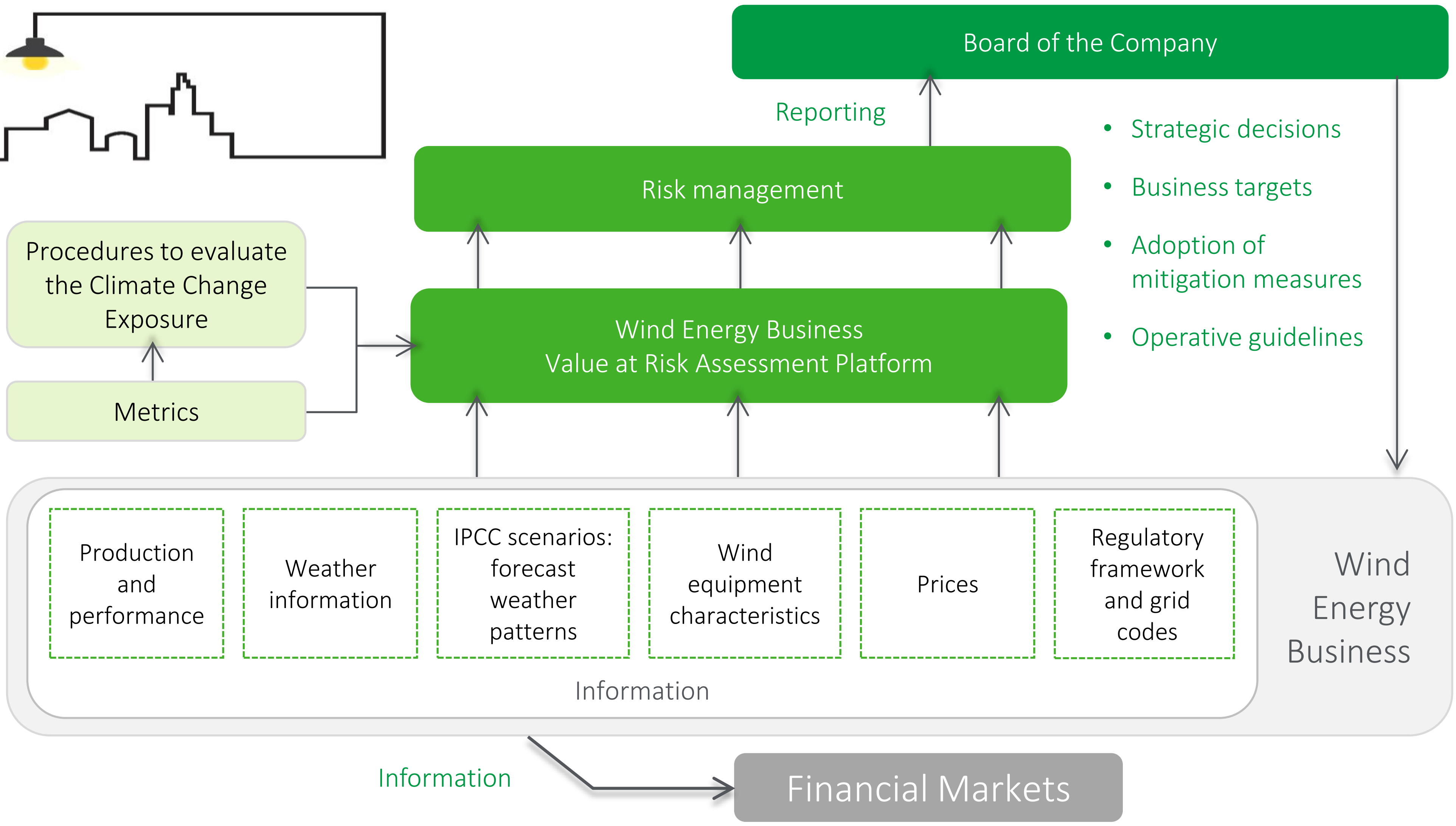
Source: IPCC AR6 SYR, 2023. Synthesis report of the IPCC Sixth Assessment report (AR6). Longer Report.

The Climate Change and the wind energy

Objective of the impact assessment model, consistent with TCFD[1] approach

Building an information model to identify and evaluate the risks and opportunities due to the Climate Change to anticipate them and adopt smart business decisions, and provide accurate information to the financial market.

The model is based on an intensive use of the data (internal and external) and the application of the analytical models.



[1] TCFD: Task Force on Climate-related Financial Disclosures.

02

Climate Change impact: technical assessment methodology

Assessment methodology

Components of the assessment model, consistent with TCFD[1] approach

- IPCC scenarios: weather patterns forecast
- Impact and performance metrics
- Climate-Related Risks and Opportunities: Exposure
- Climate-Related Risks and Opportunities: Evaluation process
- Risk assessment controlling process
- Governance

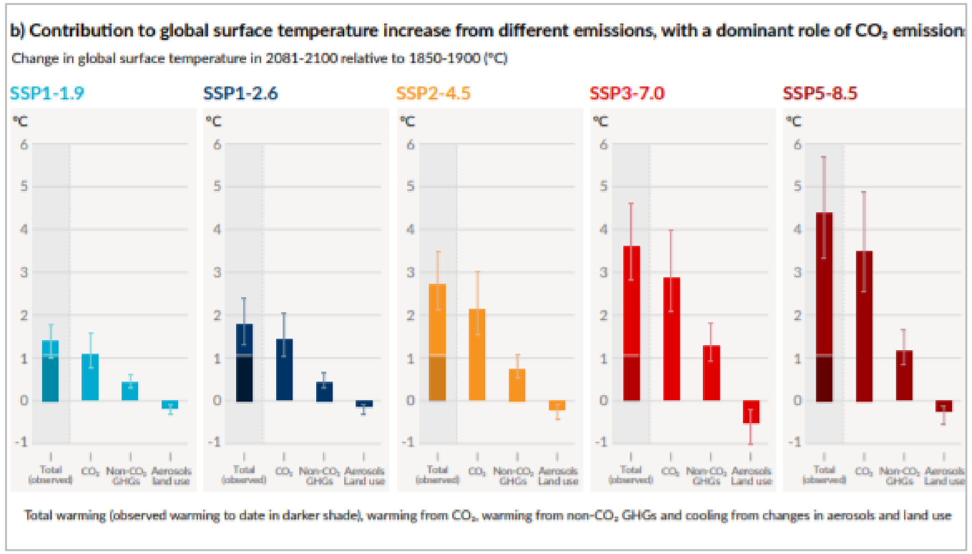
[1] TCFD: Task Force on Climate-related Financial Disclosures.

Assessment methodology

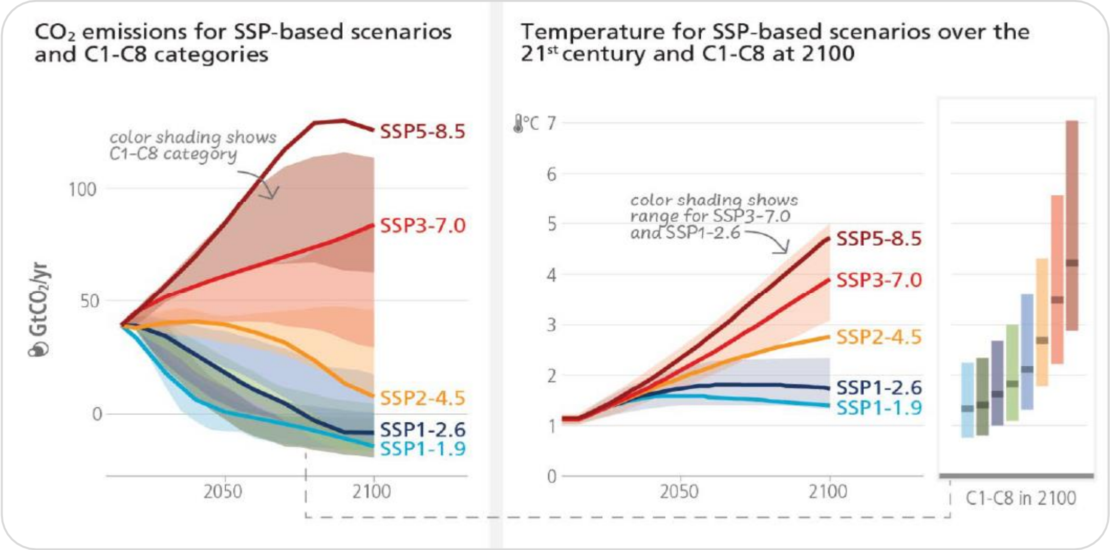
IPCC scenarios: forecast weather patterns

The risk assessment requires to establish Climate Change impact scenarios for the weather patterns evolution in different locations.

IPCC has established reference scenarios, that consist on the Shared Socioeconomic Pathways (SSP) on which they are based (SSP1-SSP5), combined with the expected level of radiative forcing in the year 2100 (1.9 to 8.5 W/m^2). Deloitte recommends to use pathways SSP2-4.5 and SSP5-8.5 to evaluate the risk exposure.



Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

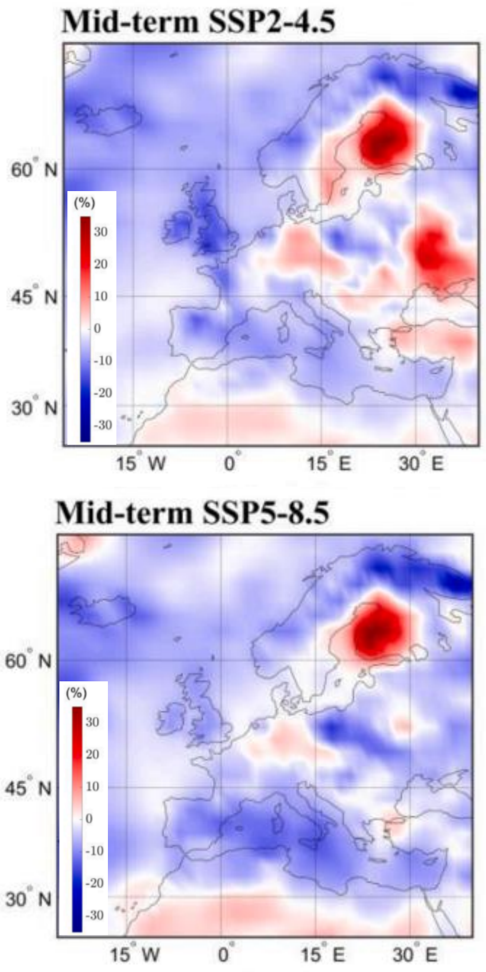


Source: IPCC AR6 SYR, 2023. Synthesis report of the IPCC Sixth Assessment report (AR6). Longer Report.

Additional scenarios can be established according to the needs of the company.

Assessment methodology

IPCC scenarios: forecast wind energy evolution in Europe (example)



Change (%) of the mean power density in the mid-term future

Overall, the SSP5-8.5 predicts a general decrease in wind power density of approximately 15% in the long-term future, which is equivalent to roughly 0.2% annually.

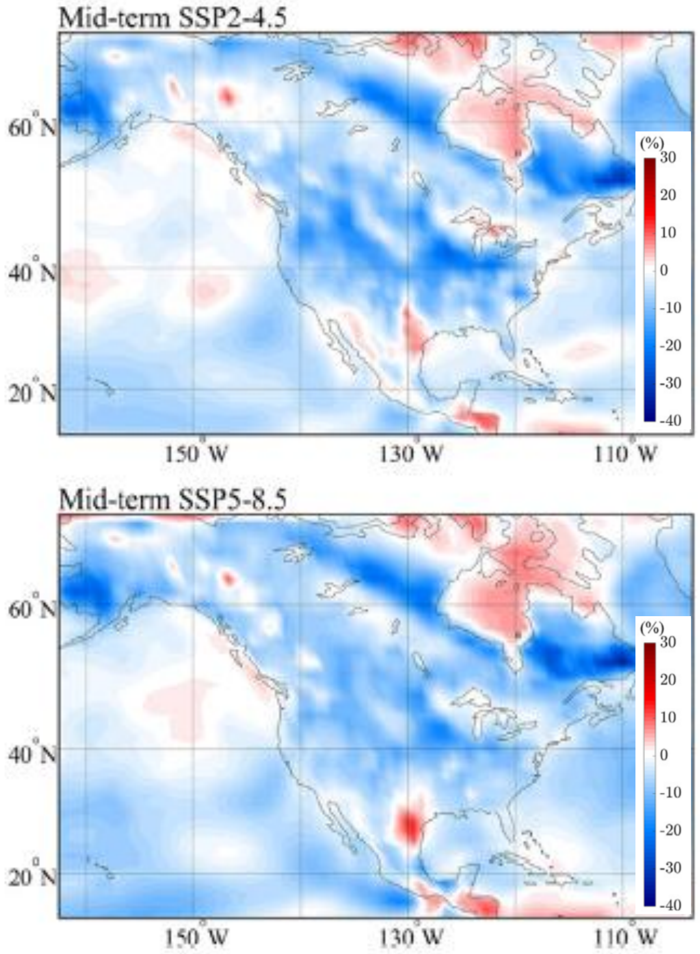
In the intermediate Climate Change scenario, SSP2-4.5, a general trend that would hold generally for the entire continent cannot be discerned. Instead, the evolution of the resource presents regional differences. Significant decreases in wind power density are projected for Ireland, Britain, the Mediterranean Sea and the northernmost regions of the continent (in the range of 10–30%). Some discrepancies are observed between the projections in different Climate Change scenarios, including in some cases even opposite trends at regional level. This is the case, most notably, of Central Europe and parts of Western Europe (France, Germany, Czech Republic), where the SSP2-4.5 scenario predicts a rise of up to 15% in wind power density, while the SSP5-8.5 scenario projects slight reductions.

These discrepancies indicate that some regions are highly sensitive to the Climate Change scenario, which may well be the reason behind the discrepancies found in the literature on the evolution of wind energy in Central Europe.

Source: A. Martinez, G. Iglesias (2021). Wind resource evolution in Europe under different scenarios of Climate Change characterized by the novel Shared Socioeconomic Pathways. Energy Conversion and Management, Volume 234, 2021. 113961. ISSN 0196-8904.

Assessment methodology

IPCC scenarios: forecast wind energy evolution in North America (example)



Change (%) of the mean power density in the mid-term future

Both Climate Change scenarios anticipate important changes in wind power density in the mid-term future (in the range of ±20%) and the long-term future (up to ±40%). The trends detected in the mid-term future in a particular area, whether positive or negative, are typically expanded in the long term.

The Climate Change scenario with intensive GHG emissions (SSP5-8.5) leads to the greatest changes in wind power density, in the range –40% to +30% in the long-term future. Climate projections in this scenario present a well-spread drop of ~15% in wind power density in the United States and Canada. Greater reductions in mean wind power density (~40%) are projected for Quebec and Nunavut, in Canada, and the US state of Alaska.

Substantial increases in wind power density are predicted in the same Climate Change scenario (SSP5-8.5) for certain regions: the state of Texas and north-eastern Mexico (>10%), Hudson Bay (~30%) and the regions of southern Mexico and Central America (up to 40%).

In climate change scenario SSP2-4.5 smaller changes relative to the baseline may be expected.

Source: A. Martinez, G. Iglesias (2022). Climate change impacts on wind energy resources in North America based on the CMIP6 projections, Science of The Total Environment, Volume 806, Part 2, 150580, ISSN 0048-9697.

Assessment methodology

IPCC scenarios: forecast temperature patterns

Table SPM.1

Changes in global Surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global Surface temperature of the prior 1850-1900 are reported in ºC.

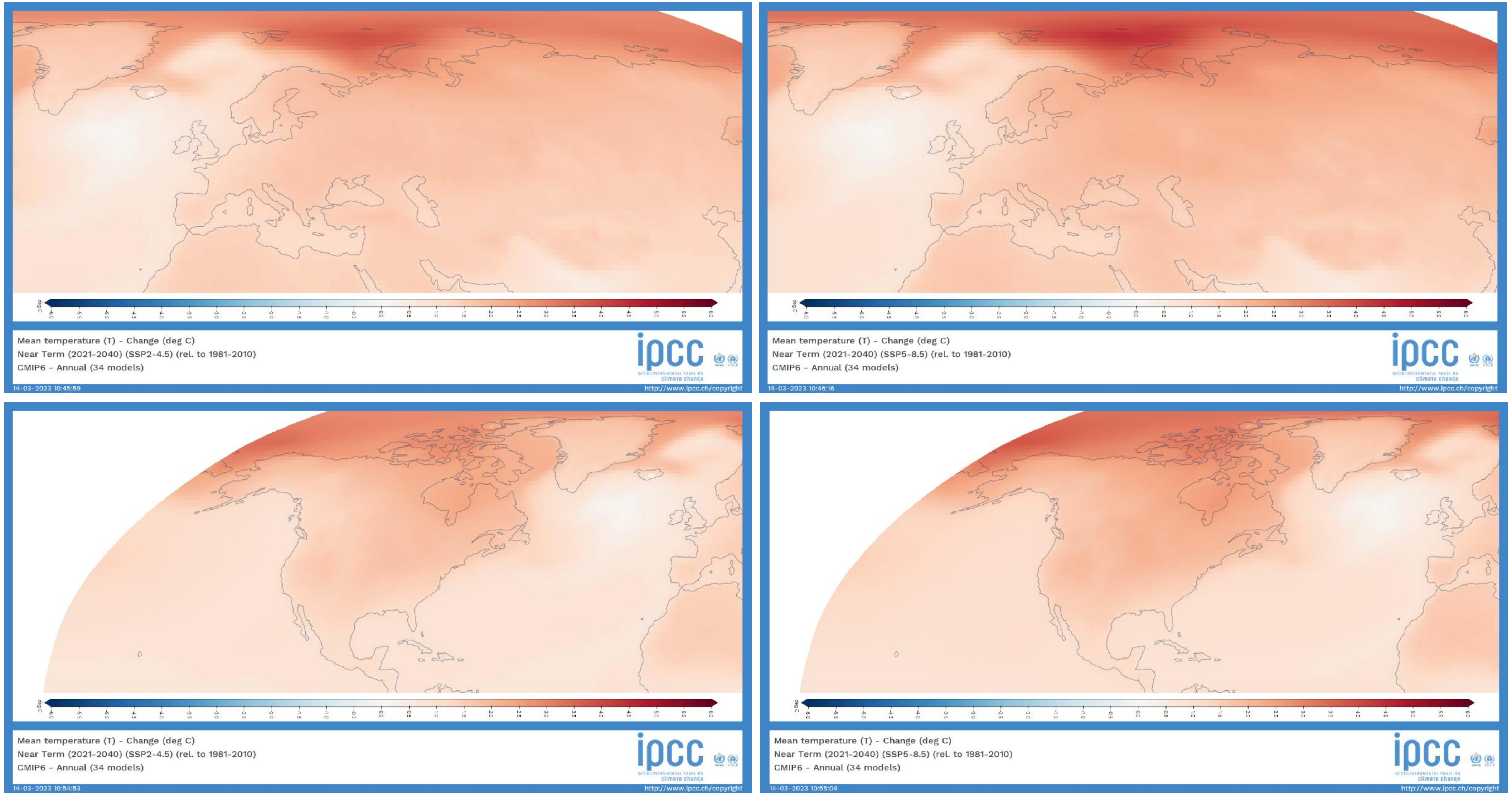
This includes the revised assessment of observed historical warming for the AR5 reference period 1986-2005, which in AR6 is higher by 0.08 [-0.01 to 0.12] ºC than in the AR5. Changes relative to the recent reference period 1995-2014 may be calculated approximately by subtracting 0.85 ºC, the best estimate of the observed warming from 1850-1900 to 1995-2014.

	Near term, 2021-2040		Mid-term, 2041-260		Long term, 2081-2100	
Scenario	Best estimate (ºC)	Very likely range (ºC)	Best estimate (ºC)	Very likely range (ºC)	Best estimate (ºC)	Very likely range (ºC)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.5	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.

Assessment methodology

IPCC scenarios: temperature evolution in Europe and America (example)



Source: IPCC WGI Interactive Atlas.

Assessment methodology

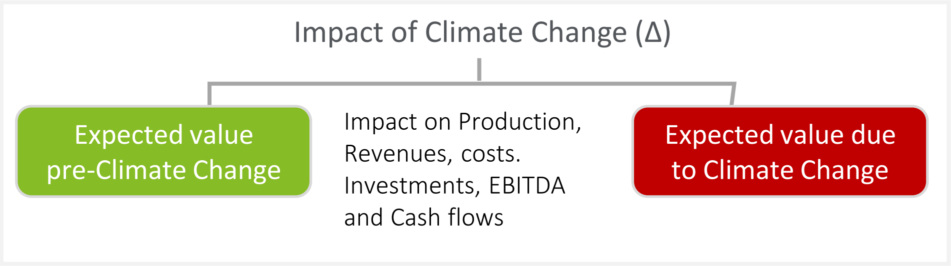
Impact and performance metrics

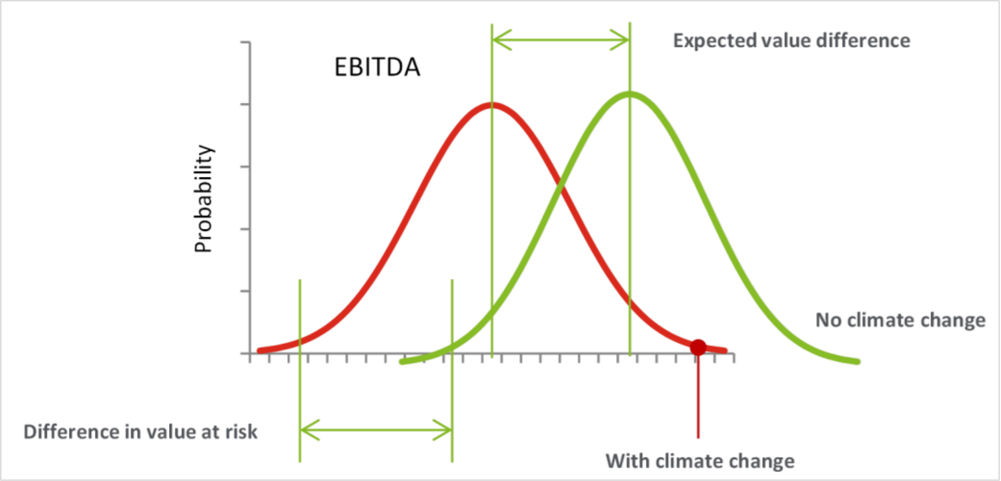
The metrics are analysed by comparing the business scenarios expected by the company with those derived from the forecasts of the impact of Climate Change.

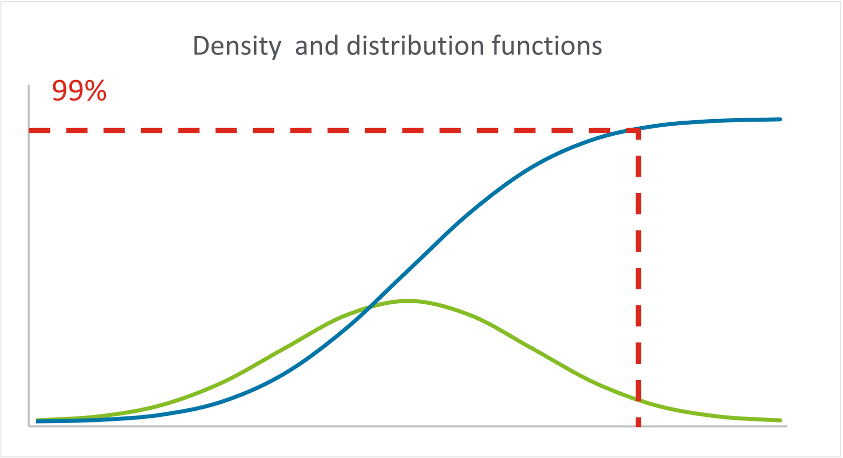
The scenarios are elaborated from hypotheses regarding the evolution of the weather and regulatory conditions.

The proposed model allows to evaluate for each wind farm of the company the impact of the different risk factors derived from Climate Change using the following indicators:

- Production and production per capacity unit, and availability.
- Revenues and/or costs.
- Expected EBITDA, cash flows, NPV and IRR with and without considering the variability caused by Climate Change.
- Standard deviation of each risk.
- VaR (Value at Risk), EBITDA and cash flows calculated for confidence level of 90%, 95% and 99%.
- Stress scenarios.







Assessment methodology

Impact and performance metrics

The integration of the risks is carried out based on their correlations.

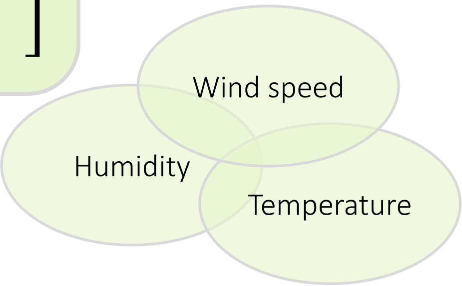
Measure of the maximum potential change in value of a portfolio with a given probability over a pre-set horizon.
VaR answers the question: how much can the company lose with x% probability over a given time horizon?

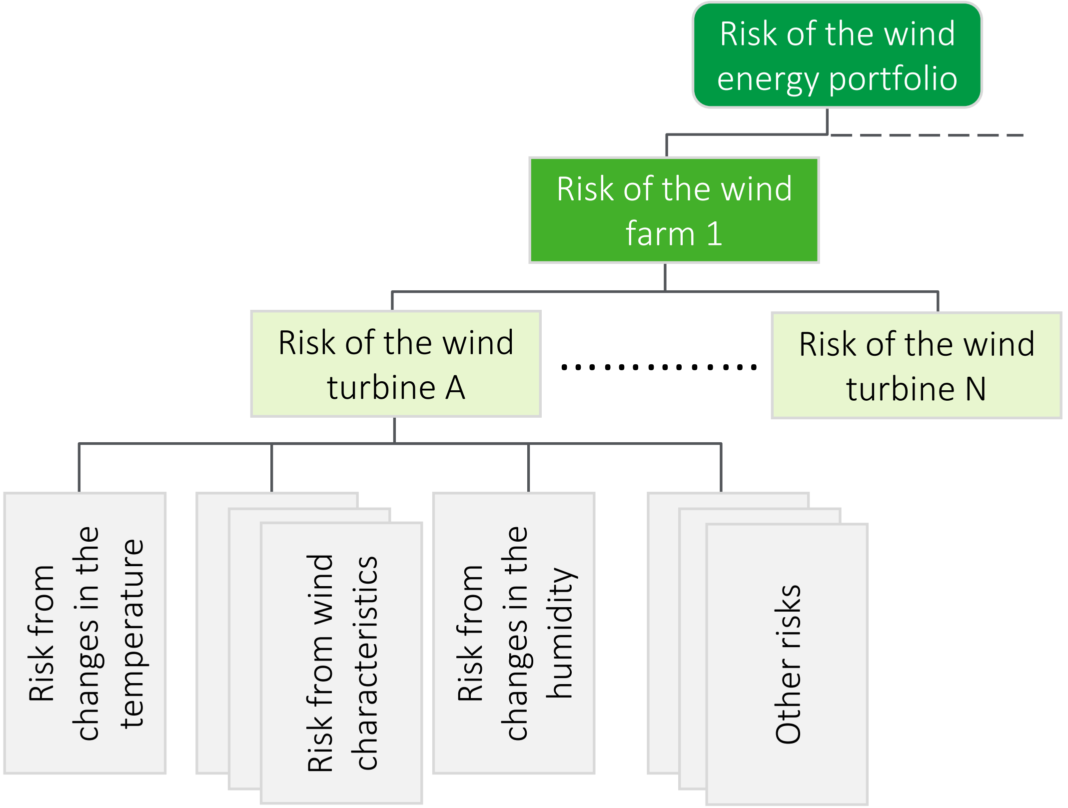
VaR can be estimated for every asset and risk exposure, and it is aggregated at different levels based on the correlation among the risk variables.

$$VaR = \sqrt{VRV^T}$$

V: VaR vector of the wind turbine/wind farm/wind farm portfolio.

$$R = \begin{bmatrix} 1 & \rho_{2,1} & \rho_{3,1} & \rho_{4,1} \\ \rho_{1,2} & 1 & \rho_{3,2} & \rho_{4,2} \\ \rho_{1,3} & \rho_{2,3} & 1 & \rho_{4,3} \\ \rho_{1,4} & \rho_{2,4} & \rho_{3,4} & 1 \end{bmatrix}$$



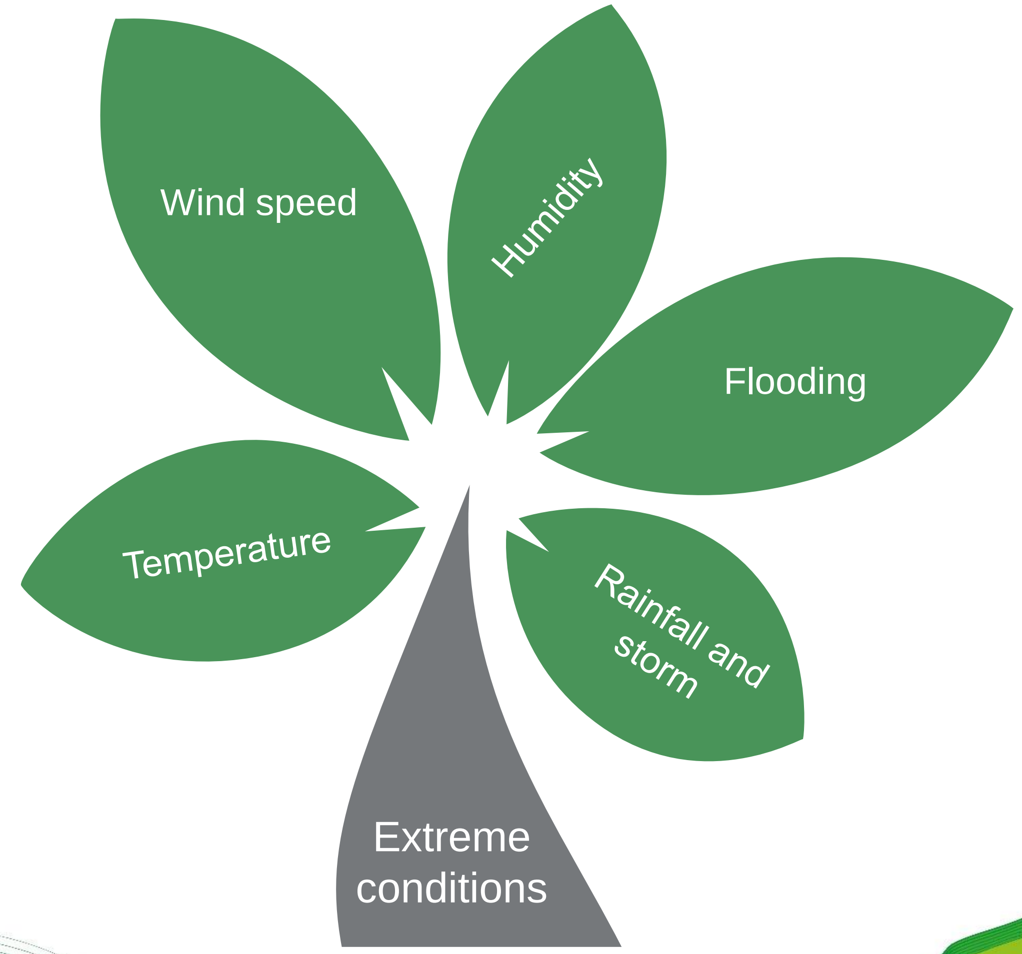


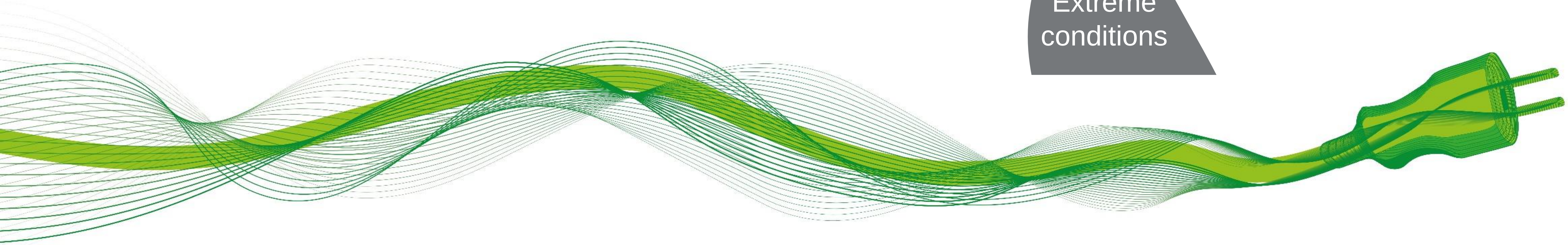
Assessment methodology

Climate Change risk exposure

Climate Change affects the wind energy business due to the evolution of the following variables: wind speed, temperature (heat and cold), humidity, extreme conditions, rainfall/storms and sea level elevation.

This phenomena affects wind turbines and farms in different ways, modifying the previous operation patterns and, therefore, causing risk.





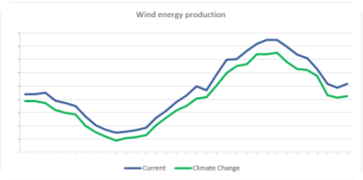
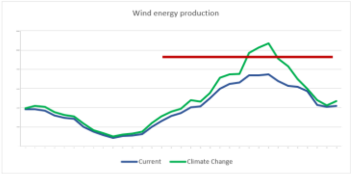
Assessment methodology

Climate Change risk exposure

Component	Risks				
	Temperature	Wind speed	Humidity	Flooding	Rainfall & storm
Generator		●			
Gearbox		●	●		
Rotor		●			
Blade	●	●			●
Pitch		●			
Tower		●			
Converters	●		●		
Transformers	●				
Other: electrical components, facility, access, workers, O&M…	●			●	●

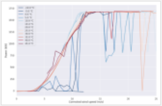
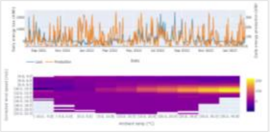
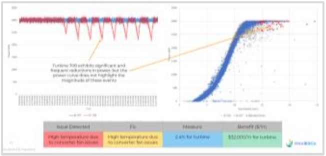
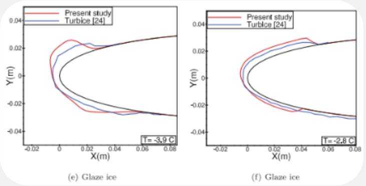
Assessment methodology

Climate Change risk exposure

Risk	Impact	Assessment	Mitigation measures
Changes in the wind resource: reduction in the wind power density	• Decrease of the production 	• Current production • Impact on the production • IPCC scenarios per regions • Electricity price	
Changes in the wind resource: increase in the wind power density	• Increase in the production • Drop the performance • Damage in the equipment due to more activity: e.g. rotor and tower	• Current production • Impact on the production • IPCC scenarios per regions • Electricity price	• Selection of the most adequate wind turbine (long term) • Adapt the maintenance criteria (short term) • Performance and reliability assessments (short term)
Changes in the wind resource: extreme conditions	• Reduction in the production • Higher seasonality • Damage in the equipment due to more activity: e.g. rotor and tower 	• Frequency and level of extreme conditions • Comparison between extreme wind energy speed and the cutoff speed • Stress evaluation	

Assessment methodology

Climate Change risk exposure

Risk	Impact	Assessment	Mitigation measures
Higher average ambient temperatures and extreme heat waves  	• Decrease of the production: – De-rating of power with high temperatures – The knee of the power curve decreases – Change in air density  • Problems in the transformers and converters with high ambient temperatures: equipment damage	• Current production • IPCC scenarios per regions • Historical temperatures • Regression to evaluate the sensibility between the heat and the production • Electricity price • Maintenance costs/cost of the equipment • Stress evaluation	• Selection of the most adequate wind turbine and components (long term) • Improvement of the cooling system (medium term) • Adapt the maintenance criteria (short term) • Performance and reliability assessments (short term)
More extreme temperatures: extreme cold  	• Ice accretion on the blades and rotor: mechanical damage • Ice on the blades can cause poorer aerodynamic functioning • Ice can cause vibrations in the tower • Damage to the people and the facilities due to ice throws	• Frequency and level of extreme cold waves • Comparison between extreme cold level and the characteristics of the equipment • Losses in production during the cold waves • Stress evaluation for the production • Stress evaluation for damages in the people and the facilities	• Reinforce anti-icing equipment (medium term) • Install blade heating systems (medium term) • Measures to avoid damages and awareness of the technicians (short term)

Assessment methodology

Climate Change risk exposure – Temperature Risk

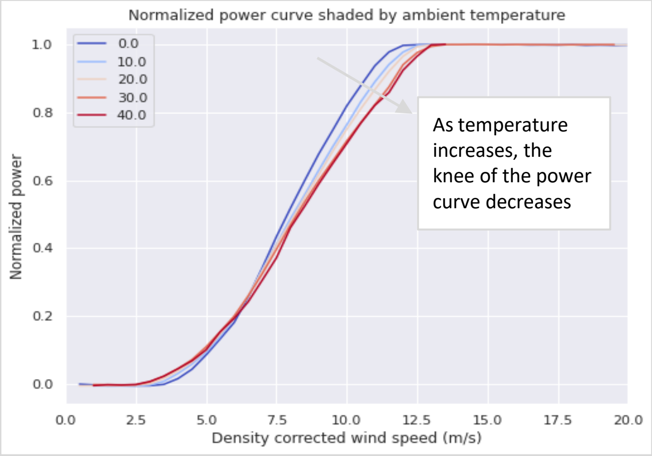
Example:

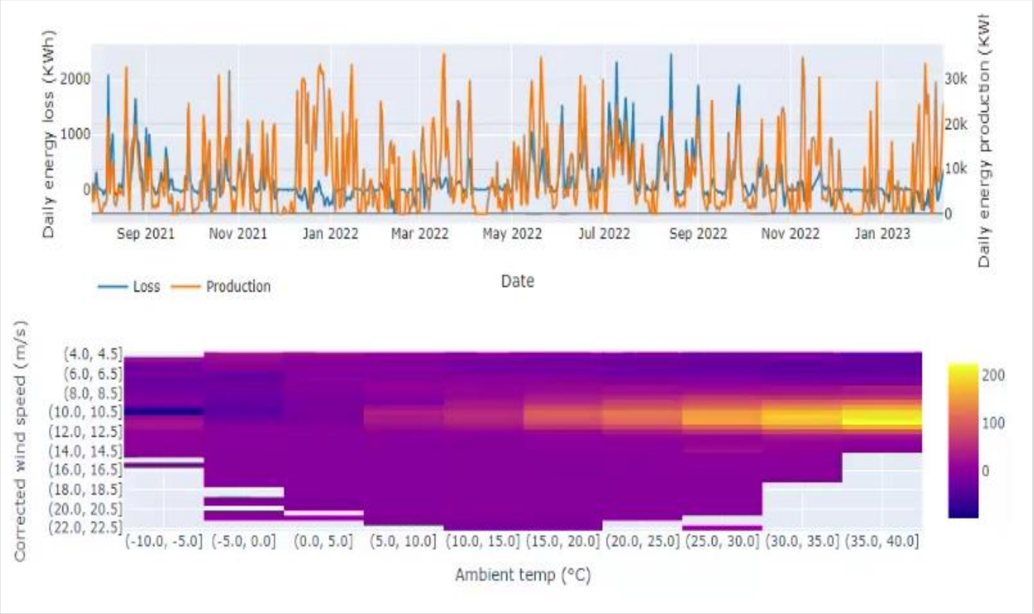
- With low temperatures, there is a weak correlation between wind speed and production.
- With temperatures between 15ºC and 30ºC there is a strong correlation between wind speed and production.
- For the same wind speed, production becomes lower as temperature increases.

Due to the impact on the temperature of Climate Change, the frequency of the different cases explained above will change. Therefore, the curve map will change: this impact must be included in the assessment.

This picture introduces the relationship between the energy production and the ambient temperature: summer is the period with higher production losses.

Climate Change will modify the frequency of these patterns





Source: Windesco

Assessment methodology

Climate Change risk exposure

Risk	Impact	Assessment	Mitigation measures
Humidity Climate Change in most of the cases will reduce the humidity	• Less humidity will increase the air density, boosting wind energy production $\rho = \frac{n \cdot m_w}{V} \rightarrow P_{wind} = \frac{C_p \rho_h A u^3}{2}$ • Less humidity will extend the useful life of the converters	• Current production • IPCC scenarios per regions • Historical weather variables: humidity and wind speed • Regression to evaluate the sensibility between the humidity and the production • Electricity price • Maintenance costs/cost of the equipment	In case of a humidity level increase: • Protect the converters and mechanic component: isolation (medium term) • Adapt the maintenance activities to prevent/avoid corrosion (short term)
Rainfall and storms	• Rain-induced leading-edge erosion of wind turbine blades	• IPCC scenarios per regions • Maintenance or equipment costs • Stress evaluation • Historical weather variables: precipitations and wind speed	• Adapt the maintenance activities to prevent pluvial erosion

Assessment methodology

Climate Change risk exposure

Risk	Impact	Assessment	Mitigation measures
Flooding of the facilities	• Damage in the electric and mechanic equipment • Difficulties in the access to the facilities	• Location of the wind farm • Potential situations of flooding: near by rivers • IPCC scenarios per regions	• Design of contingency plans to avoid the impact of flooding (short term) • Developing activities in the future will have to consider the flooding probability

One of the main Climate Change effects will be the increase in extreme weather events, such as cyclones, hurricanes or tornados. The main impacts and mitigations measures of these phenomena are those previously described for extreme wind conditions.

Assessment methodology

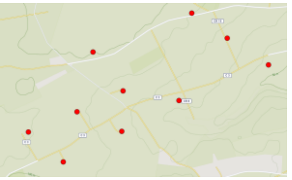
Climate Change risk exposure: impact evaluation, Swarm simulations

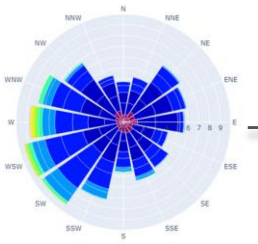
As Climate Change occurs, certain wind plants will be subject to adverse production changes due to shifts in the prevailing wind and atmospheric conditions.

The Swarm simulations examine the production benefit of Swarm-enabled collective control. However, the Swarm Simulations can also be used to quantify production risk due to different Climate Change scenarios and the benefits of Swarm mitigation.

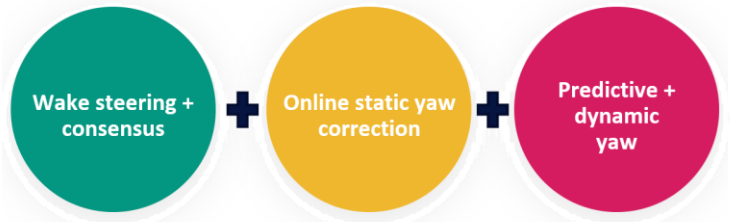
Swarm simulations for risk evaluation

Simulation Input





Simulation Models



Simulation Output

	Swarm Application	Predicted Plant IAEP (%)	Predicted IAEP (MWh)	Predicted Increase in Revenue (€)*
1	Wake Steering + Consensus	1.5	681	55,482
2	Online Static Yaw Correction	0.3	137	11,234
3	Predictive + Dynamic Yaw	0.2-0.5	197	8,072-20,181
	Estimated Cumulative AEP Benefit:	2.0-2.3	1015	74,788- 86,897

Climate Change Scenarios

ΔWS
ΔWD
ΔT

Changes in Extremes (e.g., wind ramps)

Assessment Output

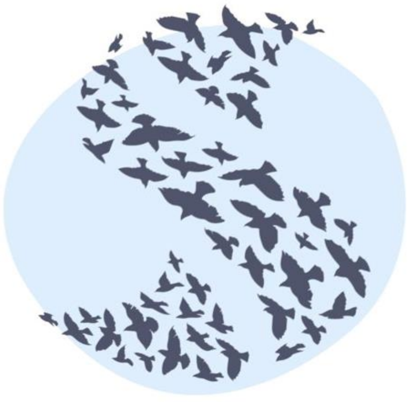
- Production Risk Assessment
- Production Risk Mitigation Assessment
- Extreme Event Risk Mitigation Assessment

Assessment methodology

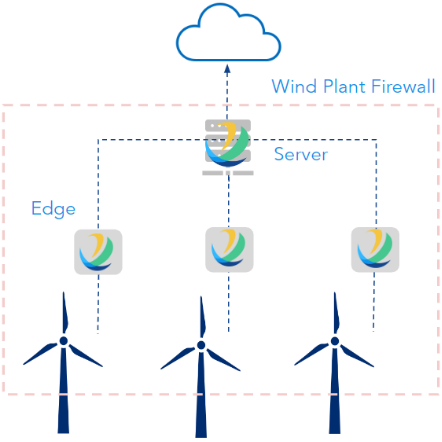
Climate Change risk exposure: mitigation, Swarm IoT

Windesco Swarm IoT Solution

Solution for collective control of wind turbines. Combining advanced analytics, model-in-the-loop control and Industrial Internet of Things, Swarm accomplishes what the industry has failed to achieve to date, a significant increase in AEP collective control strategies without adversely impacting loads.

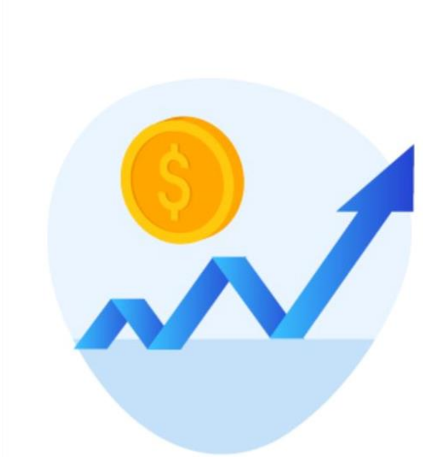


Inspired by nature, Swarm allows turbines to adapt and learn from each other.



Working cooperatively, Swarm increases plant output and turbine lifetime while improving wind plant resilience.

Utilizes multiple applications including wake steering, yaw by consensus, predictive and dynamic yaw, and online static yaw misalignment correction.



SaaS and hardware model ensures continued optimization through a growing list of applications and benefits.

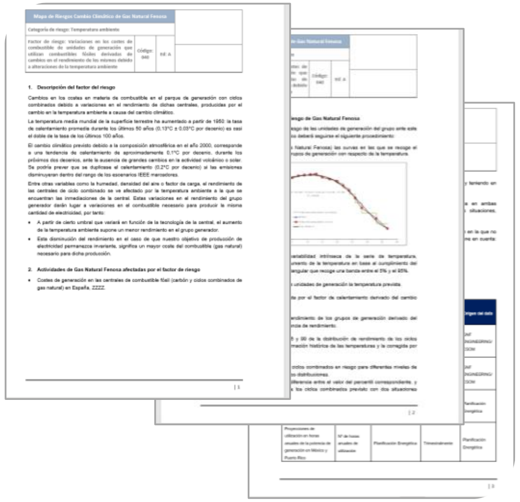
Assessment methodology

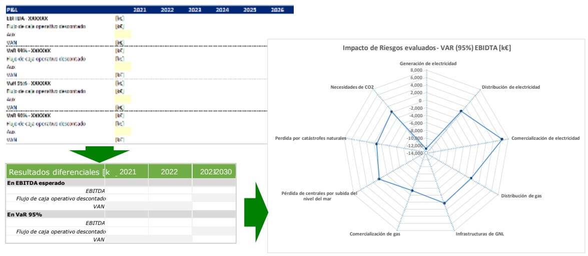
Evaluation process

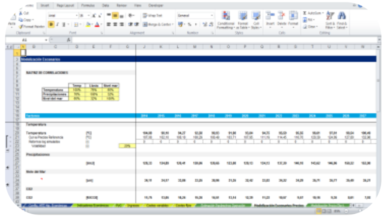
A protocol to evaluate the exposure of each risk will be carried out with the following content:

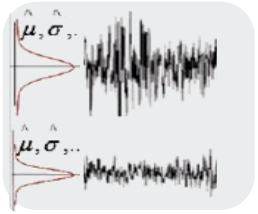
- Description of the risk: causes, variables that impact the asset/activity, impacts on the equipment and the production, affected components, time scope, etc.
- Locations where the Company operates that could be exposed to the different risks.
- Risk variable range to evaluate according to IPCC forecast or company criteria.
- Necessary data and information to evaluate the risk exposure and the procedure to collect them.
- Analytic model to assess the risk exposure due to Climate Change (technical and economic evaluation).
- Stress cases to take into consideration.
- Mitigation measures that could be adopted to reduce the risk exposure: description and economic impact.

A tool to support the quantitative assessment and to integrate the risks exposure of the Company wind farms will be implemented.





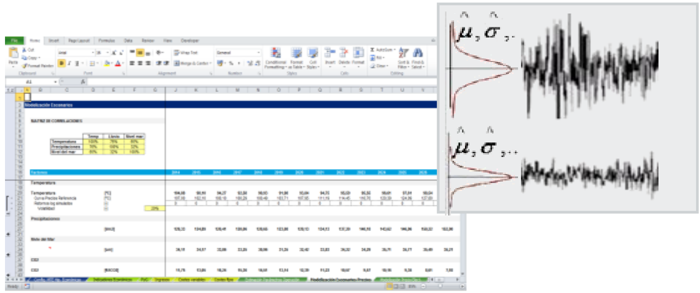




Assessment methodology

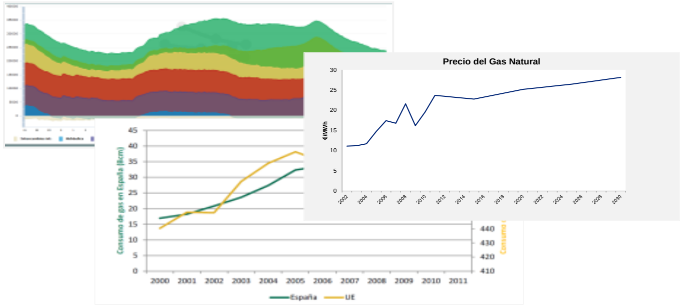
Evaluation process: the tool

Modelling Risk Factors



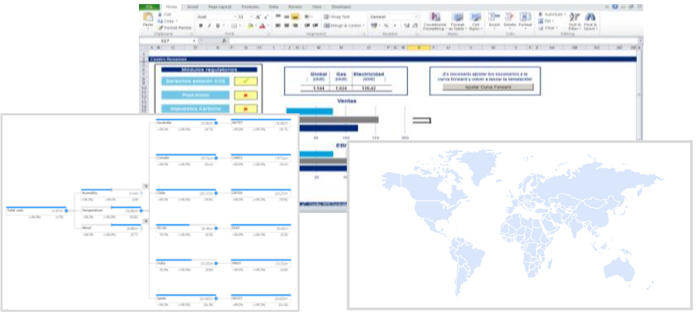
- Modelling the behaviour of key Climate Change variables.
- Development of stochastic behaviour models of risk factors.
- Volatility and correlation.

Impact of factors on every business



- Impacts of risk factors on key business: production, availability, etc.
- Impact on economic KPIs.
- Analysis under different scenarios.
- Stress cases.

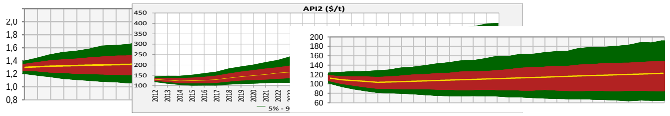
Summary table with economic impacts



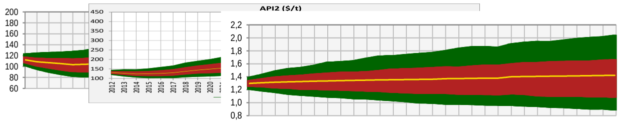
- Obtaining measurement at risk from the main indicators of the company.
  - Global indicators.
  - Indicators by business, country, turbine manufacturer, etc.
  - Indicators by country.

Results

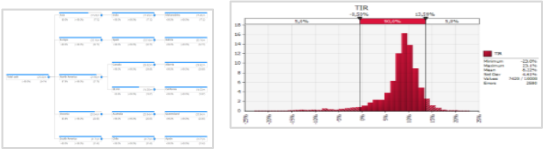
Risk factor scenarios



Business magnitudes at risk



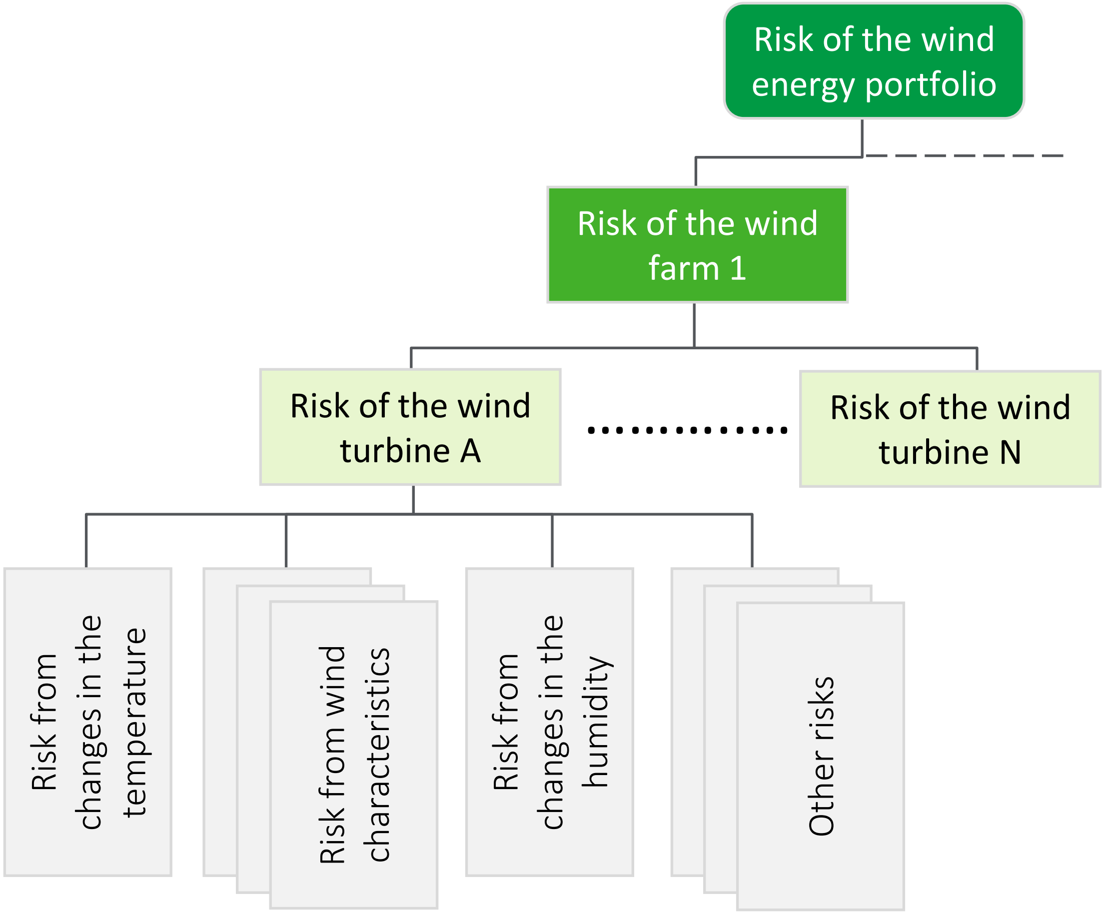
EBITDA/CF at Risk



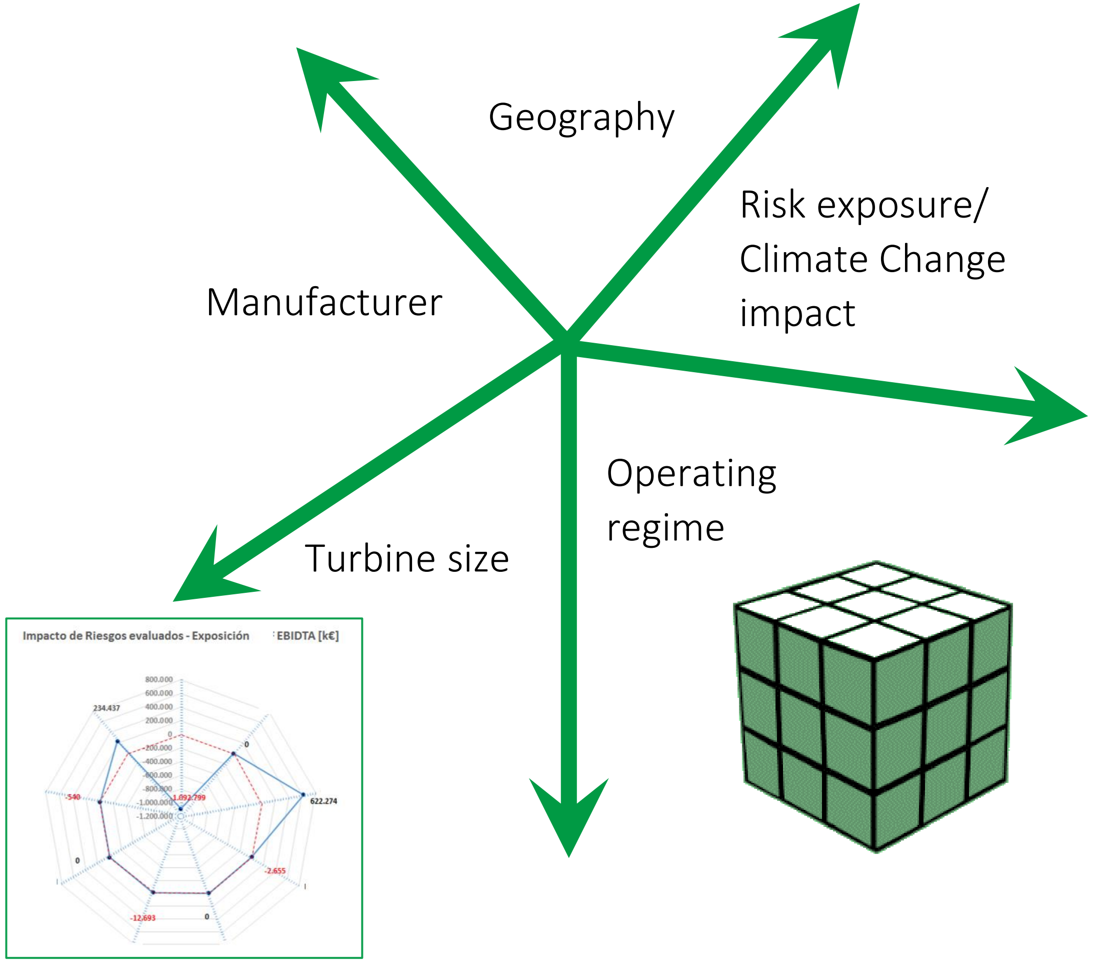
Assessment methodology

Risk assessment controlling process

Technical and business KPIs: production, availability, EBITDA, Cash flows, revenue and costs, etc.



Activity control based on different business criteria regarding Climate Change impact



Assessment methodology

Governance

Governance

- Disclose the organization's governance around climate related risks and opportunities.
- Develop board's oversight of climate-related risks and opportunities.
- Define management's role in assessing and managing climate-related risks and opportunities.
- Establish clear responsibilities regarding Climate Change management.
- Financial reports should include risk exposure regarding Climate Change.

Strategy

- Disclose the actual and potential impacts of climate-related risks and opportunities on the organization's businesses, strategy, and financial planning.
- Identification of climate-related risks and opportunities (short, medium, and long term).
- Impact evaluation of climate related risks and opportunities on the organization's businesses, strategy, and financial planning.
- Integration of risk exposure in the strategic planning: establish the Climate Change strategy and targets.

03

Route map

Route map

Chronogram

	Tasks	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Climate Change Impact on the Wind Energy Business Model: Building	Establish the guideline to develop the Impact of Climate Change on the Wind Energy Business Model	■														
	Select the scenarios to evaluate the Climate Change impact on the Wind Energy business	■	■													
	Select the metrics to evaluate the Climate Change impact on the Wind Energy business	■	■													
	Identify and evaluate the risk due to the Climate Change that affects the Wind Energy business	■	■	■	■	■	■	■	■							
	Build the tool to evaluate and integrate the risks due to the Climate Change		■	■	■	■	■	■	■	■						
	Carry out a pilot with five wind farms in different regions				■	■	■	■	■	■	■	■	■			
	Gather the data and information				□	□	□	□	□	□	□	□				
	Elaborate the models				□	□	□	□	□	□	□	□	□			
	Implement the model in the tool					□	□	□	□	□	□	□	□			
	Analyse the results											□	□			
Climate Change Impact on the Wind Energy Business Model: Operation	Implementation of the model in the rest of Company Wind farms													■	■	■
	Maintenance of the Climate Change Impact on the Wind Energy Business Model													■	■	■