Wind farm revenues in Western Europe in present and future climate

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Project team and structure

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FONDATION TUCK The Future of Energy

E4C INTERDISCIPLINARY CENTER

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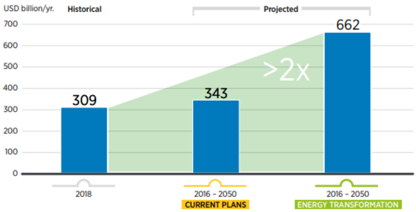
Context and motivation

Investment into wind energy is hampered by the uncertainty of future revenues of wind power producers, arising from:



Global RE invesment needs for NDC of Paris Agreement. Source: IRENA

- natural variability of the wind resource;
- evolution of regulatory policies;
- climate change impact on wind energy production, energy demand and electricity prices.

A more precise understanding of the uncertainties is needed:

- for private sector to have a better view of risks/opportunities of wind energy;
- for public authorities to quantify the level of support;
- for financial industry to develop suitable funding instruments.

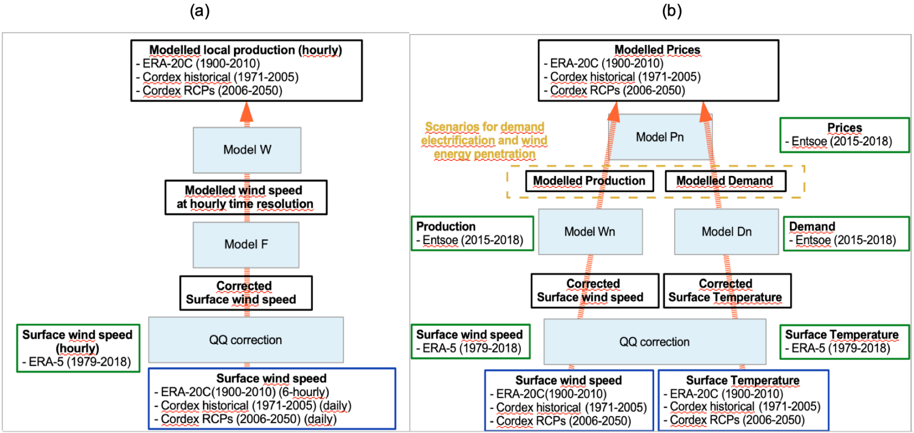
Research questions

- Quantify the uncertainty of the NPV of wind power plants in European countries under present climate;
- Quantify the support level needed to guarantee profitability of wind farms under future climate / economic scenarios.

Present climate: methodology

- We use historical climate time series from 1900 to 2010, and models to simulate a long time series of synthetic local production at each grid point and synthetic national day ahead prices
- We define 81 virtual wind farm projects at each gridpoint starting on the 1^{st} of January of each year from 1900 to 1981 and lasting 30 years
- For each grid point we analyse the distribution of NPV (over 81 projects)
- The computations are done (i) without subsidies, (ii) with a feed-in premium and (iii) with a feed-in tariff

Present climate: modeling approach



Model for local production

Model F :

Generates hourly wind speed from 6-hourly wind speed statistically consistent with hourly wind speed from ERA-5 reanalysis.

Assume $X_t = \log(V_t)$ follows an Ornstein-Uhlenbeck process :

$$X_s = X_0 e^{-ks} + \theta(1 - e^{-ks}) + \sigma \int_0^s e^{-k(s-r)} dW_r$$

with stationnary law :

$$N\left(\theta, \frac{\sigma^2}{2k}\right),$$

and autocorrelation $\rho(s,t) = e^{-k(t-s)}$.

The model parameters σ, k and θ are estimated from the mean, variance, and autocorrelation of the log-wind time series.

Model for local production

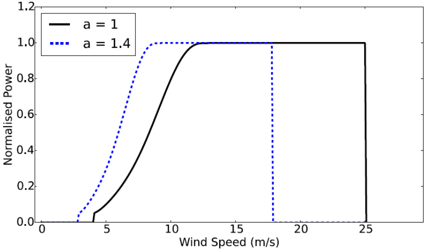
Model W :

Generates hourly local capacity factor from hourly 10m wind speed F_{10m}.

- Wind speed extrapolation to $100m$ height using power law with $\alpha = \frac{1}{7}$:

$$F_{100m} = F_{10m} \times \left(\frac{100}{10m}\right)^{\alpha}$$

- Apply power curve to obtain capacity factor, with $a_{onshore} = 1.28$ ($\overline{CF} = 25\%$) and $a_{offshore} = 0.82$ ($\overline{CF} = 35\%$).



Model for Prices

Model W_n : Generates daily national production W_n timeseries from daily 10m wind speed

- Apply power curve with $a = 1.0$ to F_{100m} (extrapolated) at each gridpoint to obtain $W_{t,i}$, and compute : $W^0_{n,t} : \frac{1}{N}\sum_{i=1}^{N} W_{t,i} \times C_{installed}$
- correct bias with linear regression fitted with ENTSOE observed national production : $W_{n,t} = aW^0_{n,t} + b$

Model D_n : Generates daily national electricity demand D_n timeseries from daily 2m temperature

$$D_{n,t} = f^w(T_t, T_h, T_c)1_{t\in W} + f^o(T_t, T_h, T_c)1_{t\in O} + \epsilon_t$$

with T_h (hot) and T_c (cold) the thresholds temperatures for which the demand becomes dependent with T. The function f is expressed as follows :

$$f^{wo}(T_t, T_h, T_c) = a^{wo}_0 - a^{wo}_h(T_t - T_h)^+ + a^{wo}_c(T_c - T_t)^+$$

Model for Prices

Model P_n : Generates hourly price time series from previously obtained $W_{n,t}$ and $D_{n,t}$.

Denote hourly price as $P_{j,h}$ and the daily price as P_j, and $\Delta(P_{j,h}) = P_{j,h} - P_j$.

Decompose $\Delta(P^w_{j,h})$ (week) and $\Delta(P^o_{j,h})$ (off) using PCA :

$$\Delta(P^{wo}_{j,h}) = \overline{E^{wo}_h} + \sum_{p=1}^{N} E^{wo}_{p,h} Z^{wo}_{p,j} + \epsilon$$

Introduce the vectors (with $N = 3$)

$$X^{wo}_j = \begin{pmatrix} P^{wo}_j \\ Z^{wo}_{1,j} \\ \vdots \\ Z^{wo}_{N,j} \end{pmatrix}$$

Model for Prices

The dynamics of each vector (X_j^w, X_j^o) is described by an AR model involving $D_{n,j}$, $W_{n,j}$, seasonal and AR components.

$$X_j^{wo} = a^{wo} D_j + b^{wo} D_j^2 + \sum_{i=1}^{L=3} l_i^{wo} D_{j-i} + c^{wo} W_j$$
$$+ \alpha_{sin}^{wo} \sin(\frac{2\pi j}{365}) + \alpha_{cos}^{wo} \cos(\frac{2\pi j}{365}) + \beta^{wo} X^{wo}{}_{j-1} + \epsilon_j^{wo}.$$

The full model for the price process can then be written :

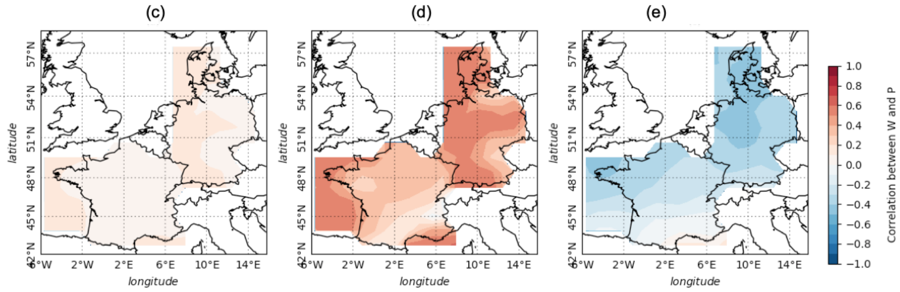
$$P_{j,h} = 1_{j \in W} \left(P_j^w + \sum_{p=1}^{N} E_{p,h}^w Z_{p,j}^w \right) + 1_{j \in O} \left(P_j^o + \sum_{p=1}^{N} E_{p,h}^o Z_{p,j}^o \right),$$

Present climate: datasets

(a) Simulated synthetic local production at the spatial resolution of 1.125° and hourly time resolution, for the period from 1900 to 2010 (obtained using wind speeds from reanalysis datasets);

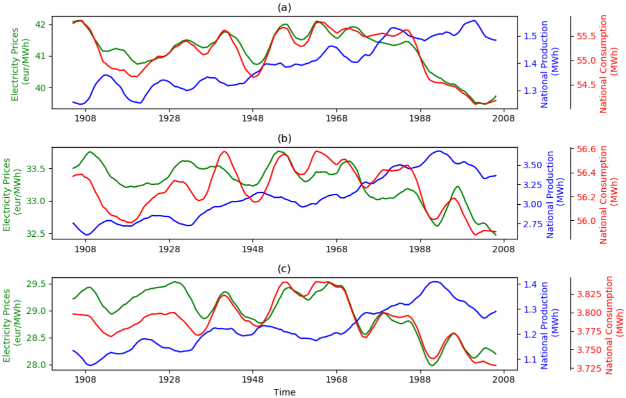
(b) Simulated synthetic day-ahead prices (as well as demand and national wind energy production) in France, Germany and Denmark for the period from 1900 to 2010, at the hourly time resolution (using the model for price and demand estimated on recent data).

Price-production correlation



Correlation between synthetic intraday price and production at hourly (a), monthly (b) and yearly (c) time scale.

Long-term trends



Long-term trends in synthetic price, production and demand in France (a), Germany (b) and Denmark (c).

Net present value and revenues of a wind farm

The net present value of the wind farm is calculated as follows:

$$NPV = \sum_{t=1}^{T} (C_t^{in} - C_t^{out})(1+r)^{-t}$$

where T is the duration of the project (in years), C_t^{in} denotes the revenues and C_t^{out} the cost during year t, where

$$C_t^{out} = Capex_t + Opex_t \quad \text{and} \quad R_t = \sum_{n=1}^{N} W_n f_t(P_n)$$

where N is the length of the considered time period (in hours), W_n is the production for hour n in MWh, P_n is the day-ahead price for hour n in €/MWh, f_t takes into account the subsidy, and r is the discount rate (5% in this study).

Subsidies

- Under feed-in tariff (FiT), used in France until 2016, the revenue per MW is given by

$$f_t^{FiT} = 82€/\text{MWh}_{0\leq t<10} + \left(82 - 54\frac{(t-10)^+}{5}\right)€/\text{MWh}_{10\leq t<15} + P_{t_{t>15}}$$

- Under feed-in premium (FiP), used in Denmark, the revenue per MW is given by

$$f_t^{FiP} = (P_t + 33€/\text{MWh})_{P_t<45€/\text{MWh}} + P_{t_{P_t\geq 45€/\text{MWh}}})$$

- Germany used a FiT mechanism similar to the French one until 2012 and now uses a FiP similar to the Danish one. We use the same mechanisms for onshore and offshore wind farms.

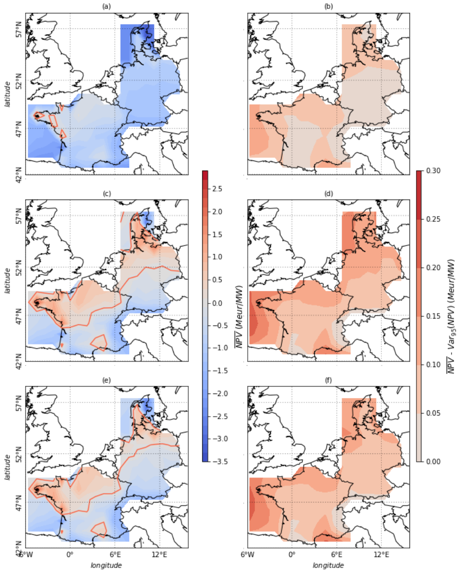
Costs

The investment costs for onshore and offshore wind turbines in Europe range from 1.2M€/MW to 2.0M€/MW for onshore wind turbines and from 3.0M€/MW to 4.4M€/MW for offshore turbines.

The annual fixed OPEX are around 1.5% and 2.0% of the CAPEX for onshore and offshore wind turbines respectively.

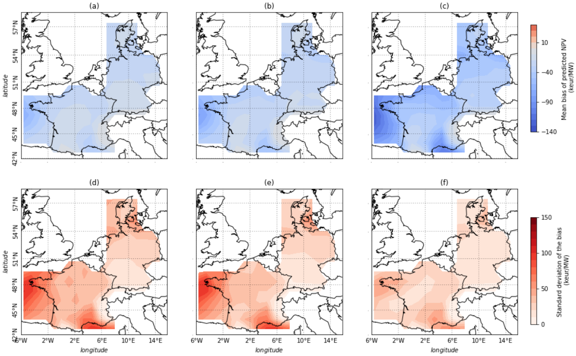
Costs	Onshore	Offshore	Source
Capex	1350 k€/MW	3000 k€/MW	Turbine, grid connection
Fixed Opex	20 k€/MW/yr	60 k€/MW/yr	O&M, balancing costs

Present climate: results



Mean NPV (left) and difference between mean and 95^{th} quantile of NPV (right), over the 81 wind farm projects and after 30 years of lifetime for wind farms operating without a subsidy (a,b), with FiT subsidy (c,d), and with FiP subsidy (e,f). The red contour line on left panels displays the line of NPV=0.

Present climate: evaluation errors



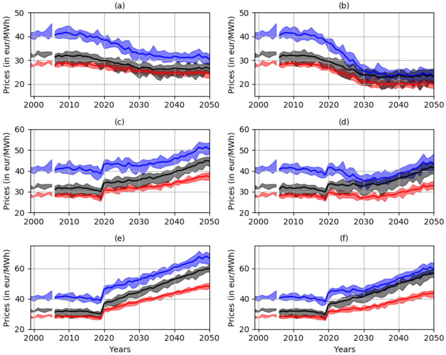
Mean (a,b,c) and standard deviation (d,e,f) of the bias calculated between the NPV at the end of a project and the projected NPV based on (a,d) the past 5 years (b,e) the past 10 years (c,f) the past 30 years.

Future climate: datasets

(a) Synthetic simulated local production at the spatial resolution of 0.44° for the period from 2006 to 2050, at the hourly time resolution, under the RCP-4.5 and the RCP-8.5, for 5 different climate models (CORDEX)

(b) Synthetic simulated day-ahead prices, demand and national wind energy production in France, Germany and Denmark for the period from 2006 to 2050, at the hourly time resolution, under the RCP-4.5 and the RCP-8.5, for 5 different climate models and under 3 scenarios of demand (no electrification, medium electrification, high electrification) and 2 scenarios of wind energy penetration (low and high).
Demand scenarios are from IMAGE 3.0 model and wind energy penetration scenarios are from `windeurope.org`.

Yearly mean price projections



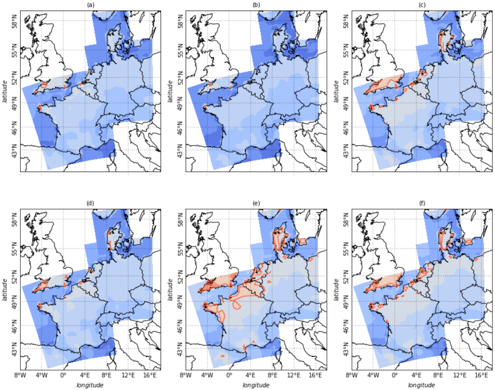
Yearly mean price projections for France (blue), Germany (black) and Denmark (red). Shaded area: minimum and maximum yearly mean prices among the 10 simulations (5 models and 2 RCPs). Left: low penetration, right: high penetration. Top: no demand trend, middle: medium demand trend, bottom: high demand trend.

Future climate: methodology

We compute the NPV for wind farm projects operating from January 1st, 2021 to December 31st, 2050, averaged over 2 RCPs and 5 models.

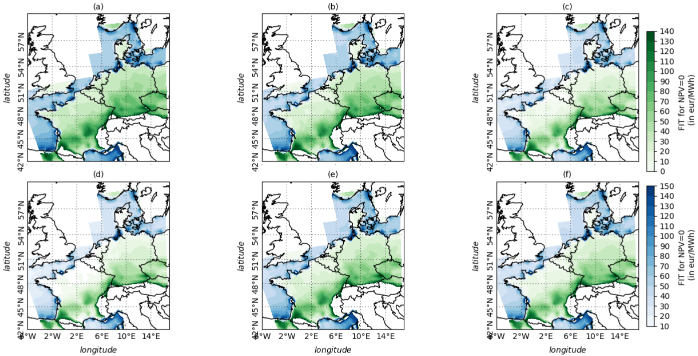
We evaluate the profitability (zero NPV for 90% of the fleet) of wind plants operating without subsidies, and the subsidy level (for 15 years) needed to make the plant profitable

Future climate: results without subsidies



Net present value, averaged over the 10 CORDEX simulations (5 models and 2 RCPs), for the 6 prices scenarios. (a), (b): no demand trend; (c), (d): medium demand trend; (e), (f): high demand trend. (a), (c), (e): high wind penetration; (b), (d), (f): low wind penetration.

Future climate: subsidy level required to ensure profitability



Bonus level to guarantee wind farm profitability under the 6 scenarios considered. (a), (b): no demand trend; (c), (d): medium demand trend; (e), (f): high demand trend. (a), (c), (e): high wind penetration; (b), (d), (f): low wind penetration.

Future climate: total cost of ensuring profitability

1: No demand trend, low wind penetration;

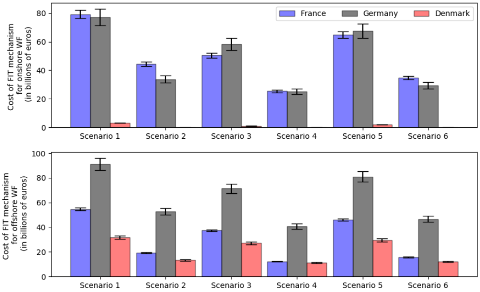
2: No trend, high penetration;

3: Medium trend, low penetration;

4: Medium trend, high penetration;

5: High trend, low penetration;

6: High trend, high penetration.



Cost for supporting future onshore (top panel) and offshore (bottom panel) wind farm installations for 15 years; profitability (NPV =0) is guaranteed for 90% of the new wind farms installed. The bars level display the mean cost over the 5 models and 2 RCPs used ; the uncertainties displayed represent 2 standard deviations.

Conclusions and outlook

Main contribution: combine information on the wind resource from reanalysis and climate scenarios with information on energy prices from a realistic model of electricity consumption based on climate data and economic scenarios.

Further research:

- Evolution of capital and operational costs of wind energy;
- More realistic model for electricity prices including e.g., fuel costs;
- More realistic wind farm economics;
- Sensitivity analysis of the choice of IAM scenarios.

A demonstrator of the model is being developed in the framework of the E4C Datahub.