Developments in simulating VRE time series for power and energy system studies

WinGrid power system operation workshop

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16 June 2021

Agenda

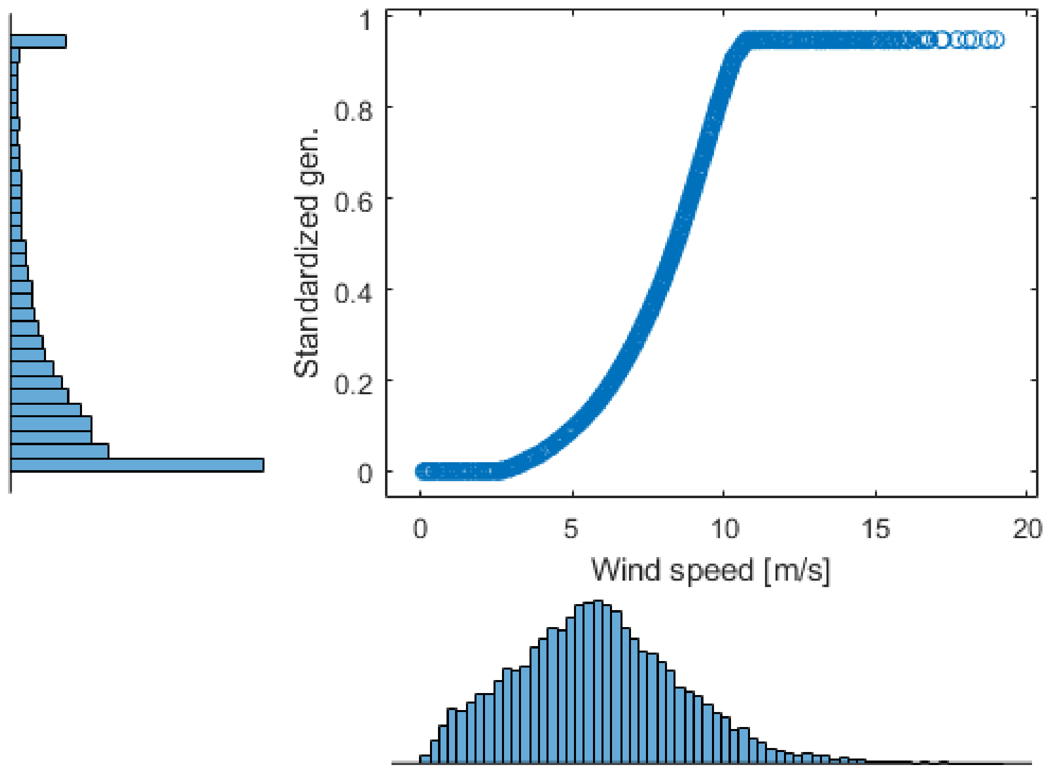
- **What is VRE generation?**
  - And why should we simulate VRE time series?
- **Developments in simulating VRE time series**
  - Use of reanalysis data
  - How to achieve higher spatial and temporal resolution
  - Including analysis of forecast errors
- **Applications and recent projects**

What is VRE and why time series matter?

What is VRE generation?

- **Variable renewable energy (VRE)**
  1. It’s renewable
  2. **It’s variable due to being weather dependent**

- **Mainly wind and solar photovoltaic (PV) generation**
- Also (but not considered in this presentation):
  - Concentrated solar power (CSP)
  - Run-of-river hydro power

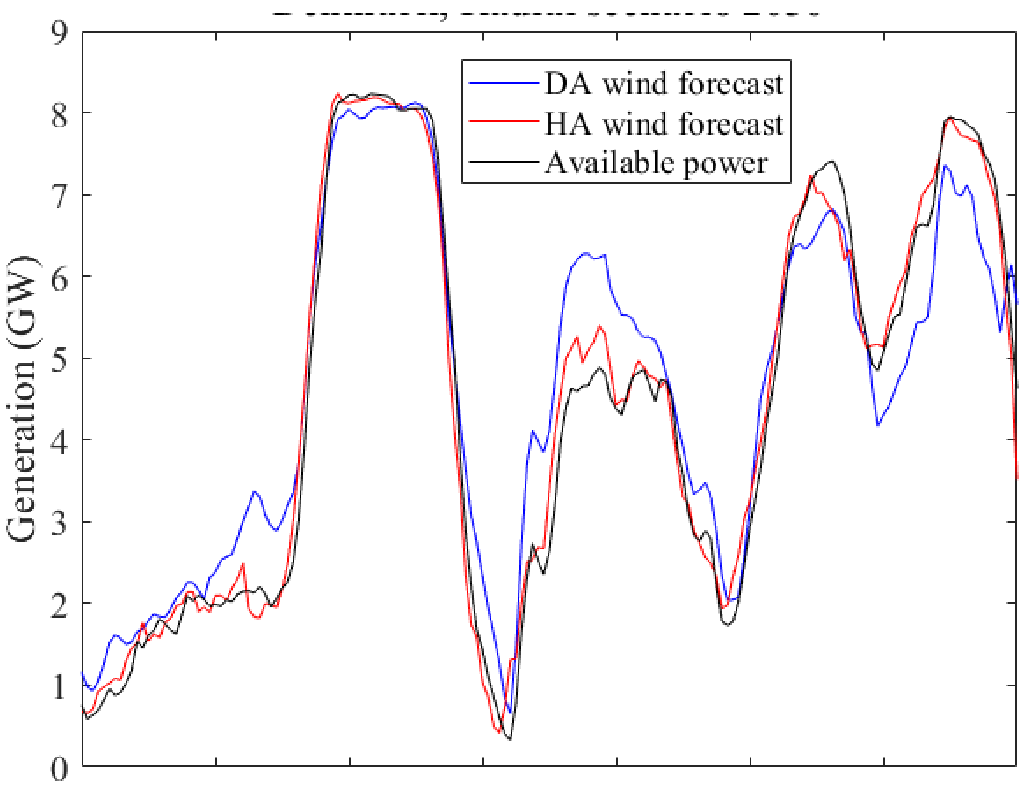


Variability in wind speed translates to variability in generation

Variability and forecast uncertainty

- **Variability**
  - inherent in weather-dependent generation
  - Affected by technology (e.g., power curve shape)
  - Cannot be removed

- **Forecast uncertainty**
  - Caused by forecast errors
  - Can be reduced by more accurate forecasts



Variation in available power is **variability**.

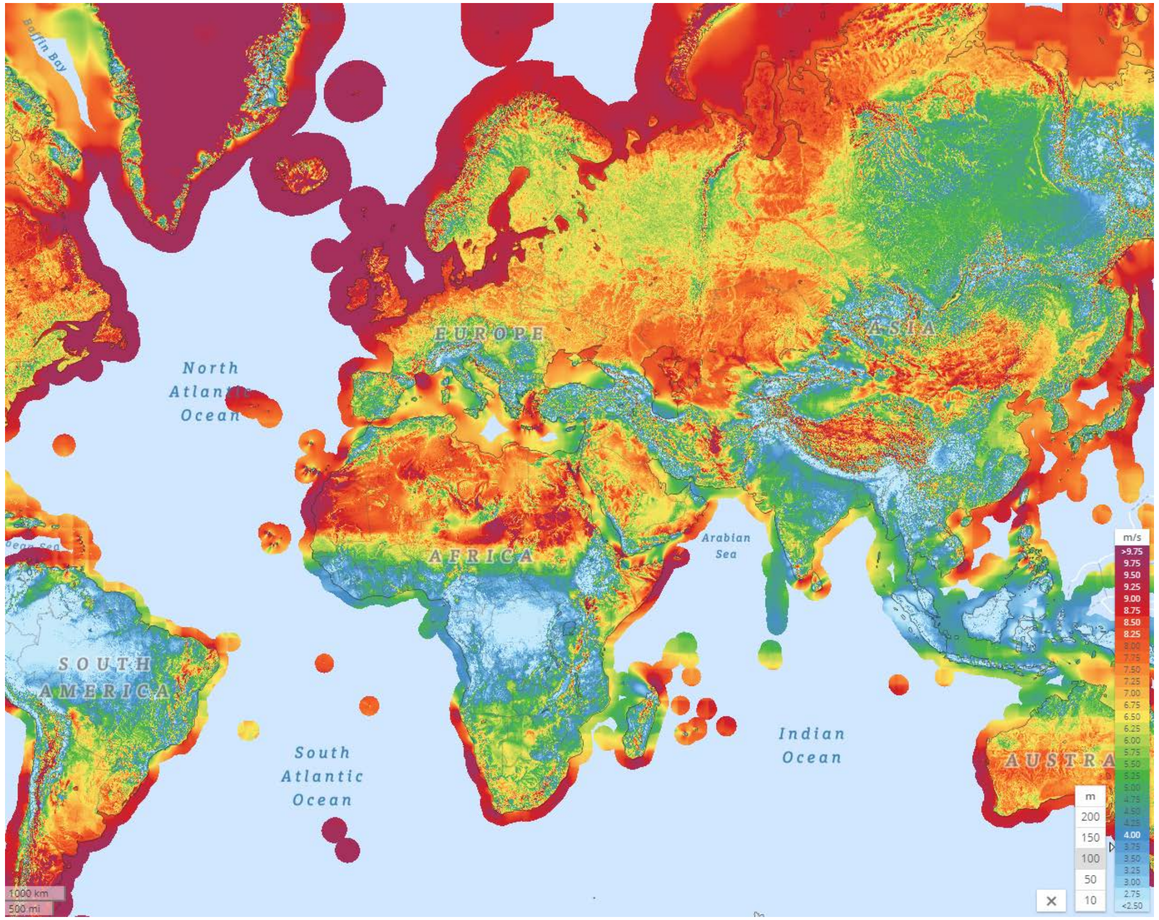
Difference between available power and HA forecast (or DA forecast) reflects **forecast uncertainty**.

DA = day-ahead; HA = hour-ahead

Why do we care about VRE time series?

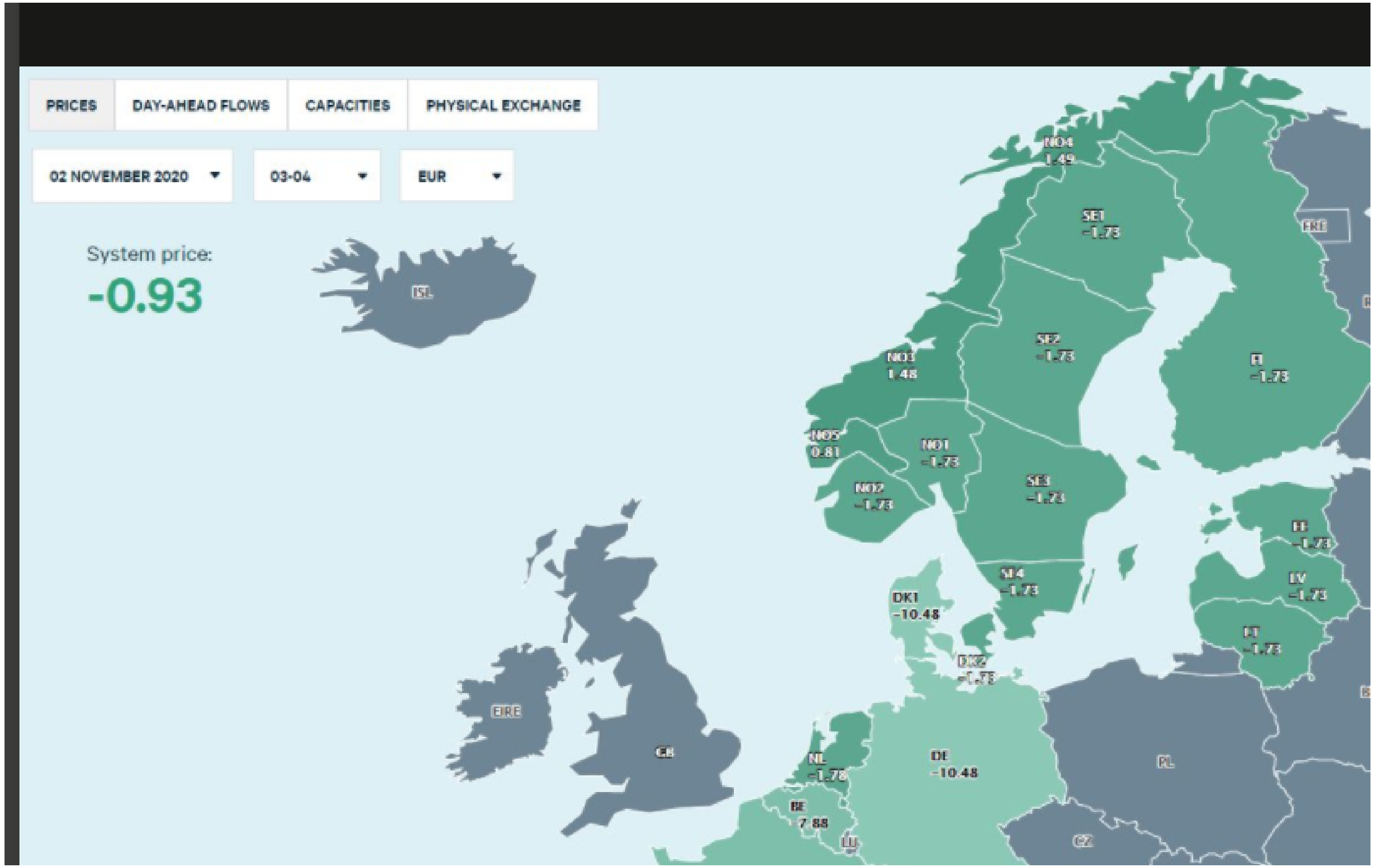
- **Wind atlases:**
  - Mean wind speed
  - Wind speed distribution
  - **Focus on annual energy generation**

- However:
  1. **Electricity markets operate on hourly (or higher) resolution**
  2. **The power system needs to be in balance at all times**



Wind resource map from Global Wind Atlas (https://globalwindatlas.info/)

Impacts already seen on electricity prices: Sometimes low (or even negative)



Negative European Day-ahead Prices and Nordic System Price this morning.

Day-ahead prices turned negative across Europe in the early hours of Monday 2nd November. Only western and northern Norway managed to keep prices at positive levels.

The negative prices were largely driven by the following:
- Above-normal temperatures reduced the need for heating, coupled with a general low consumption during night hours
- Significant wind power production in the Nordics and on the continent: at 03:00 tonight, wind power stood for around 63% of Germany's load
- Considerable precipitation, especially during Sunday 1st November, leading to ample hydro power supply.

This also impacted the Nordic System Price, which turned negative during three consecutive hours. Power production in Norway adjusted to the oversupply in the system and decreased substantially compared to previous days, but that was not enough to keep the

LinkedIn post from Nord Pool AS, Nov 2020 (www.linkedin.com/company/nord-pool/)

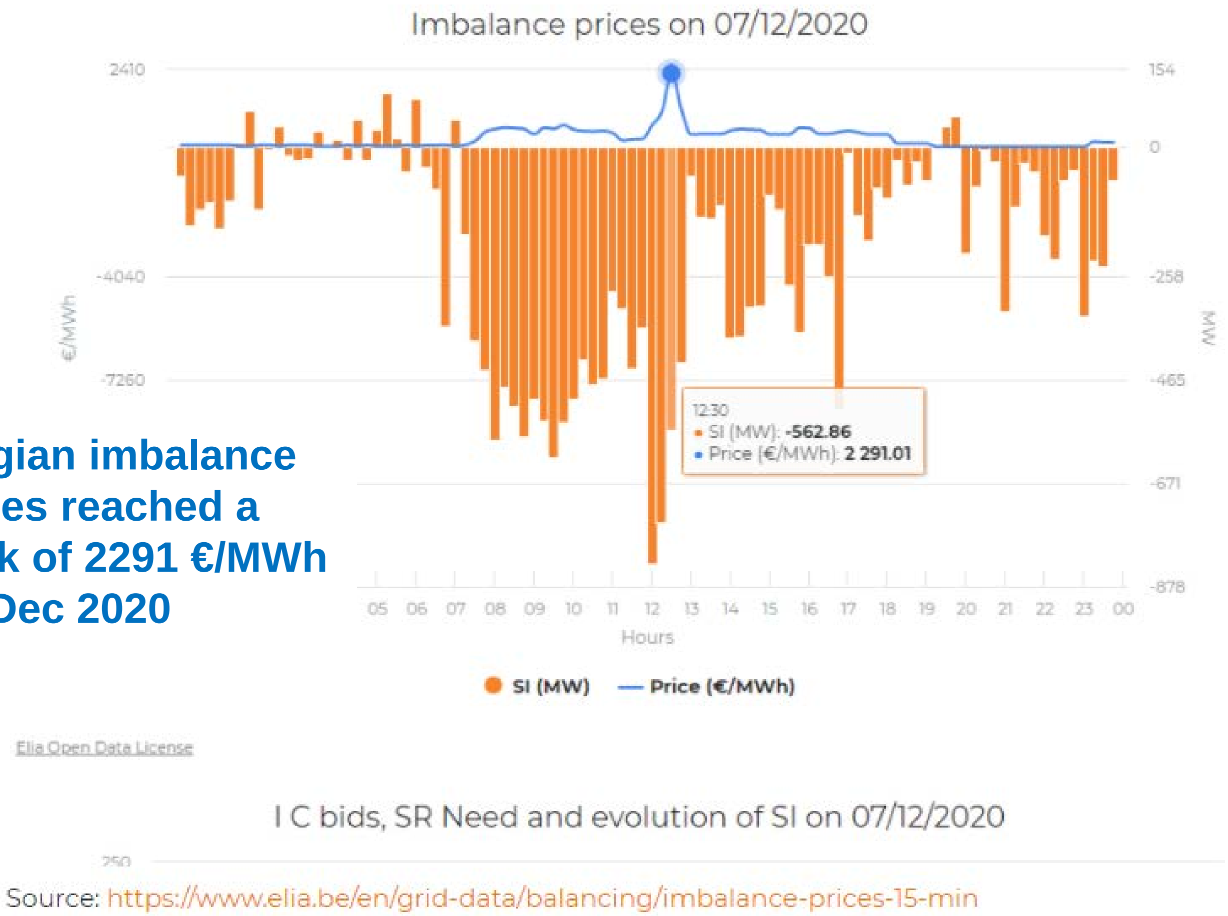
Impacts already seen on electricity prices: Sometimes very high

Power prices spike to £720/MWh as low winds continue to stretch grid

Image: Andy Beecroft.

https://www.current-news.co.uk/news/power-prices-spike-to-720-mwh-as-low-winds-continue-to-stretch-grid

Impacts already seen on electricity prices: Balancing market prices can also be high



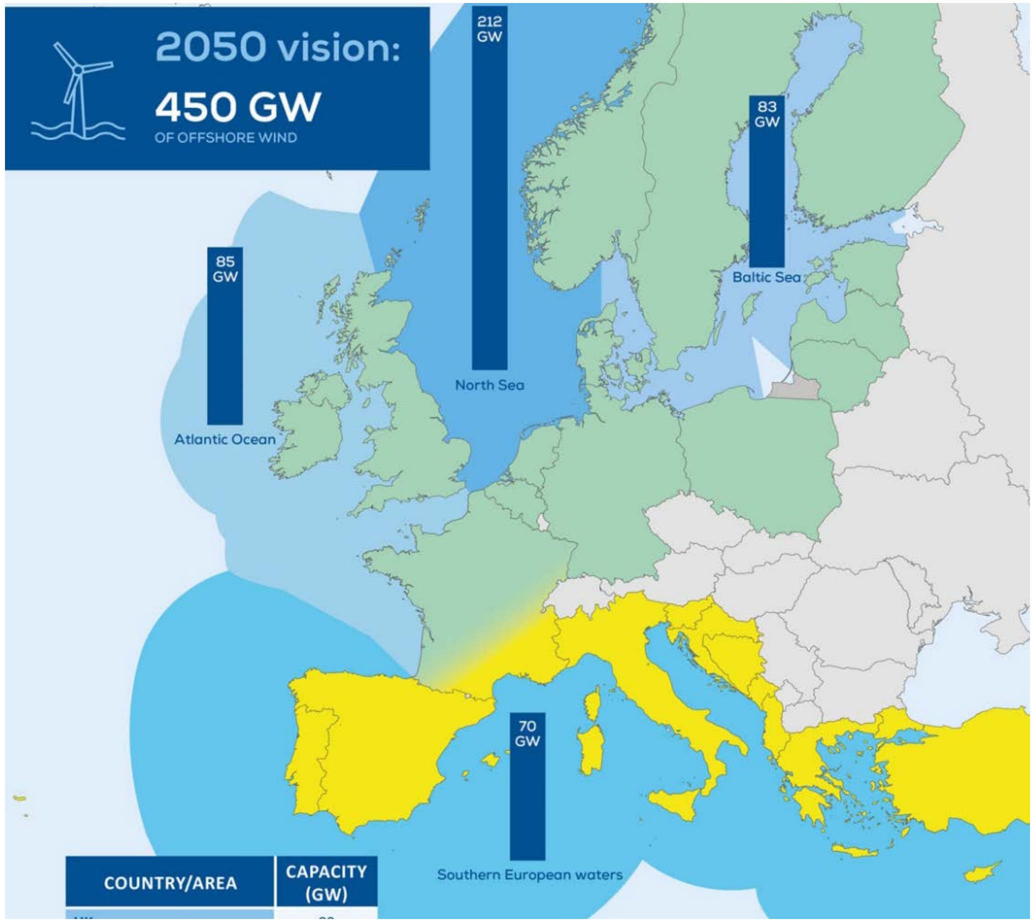
Belgian imbalance prices reached a peak of 2291 €/MWh on Dec 2020

https://www.egssis.com/its-time-to-become-a-balancing-service-provider/

Why not just use historical VRE data?

- **Measurements cover a limited time range**
  - May not include extreme cases (e.g., storms, low wind events)
- **Measurements cover existing VRE fleet**
  - New installations may have different technology
  - And different geographical distribution

- **Simulations allow:**
  – Using tens of years of meteorological data
  – Changing VRE technology
  – Changing VRE installation locations

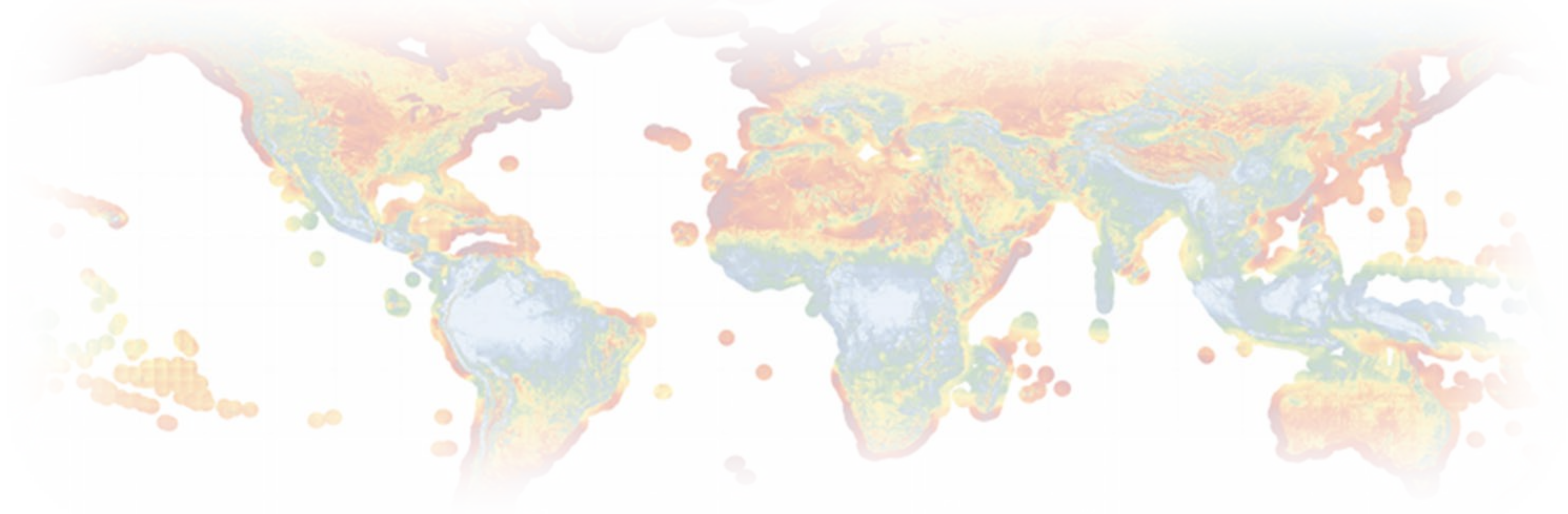


Wind Europe “Our energy, our future“, 2019, https://windeurope.org/about-wind/reports/our-energy-our-future/

Developments in simulating VRE time series

CorRES:
Correlations in Renewable Energy Sources

- Time series simulation tool for variable renewable energy (VRE) generation:
    1. **VRE variability**
    2. **VRE forecast uncertainty**
- Globally via ERA5 reanalysis and Global Wind Atlas microscale data
- Developed at DTU Wind Energy



CorRES:
The two key parts of the model chain

Meteorological data

- ERA5
- ERA5-Land
- Global Wind Atlas

→

Conversion to power generation

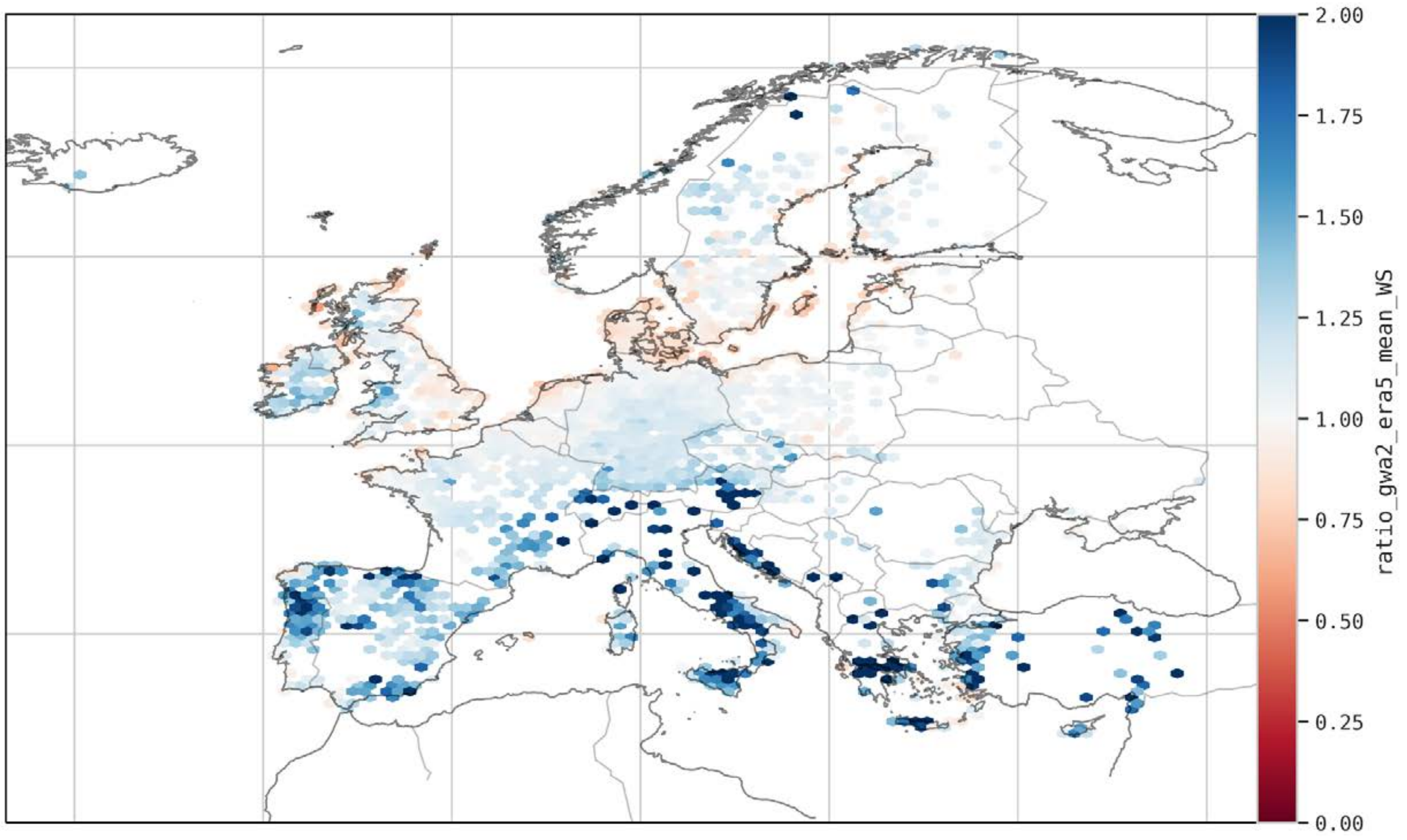
- Wakes using PyWake
- Storm shutdown model
- PVLib for solar PV

- Turbine data
- Wind power plant (WPP) data

→

VRE time series

CorRES:
Reanalysis time series + Global Wind Atlas

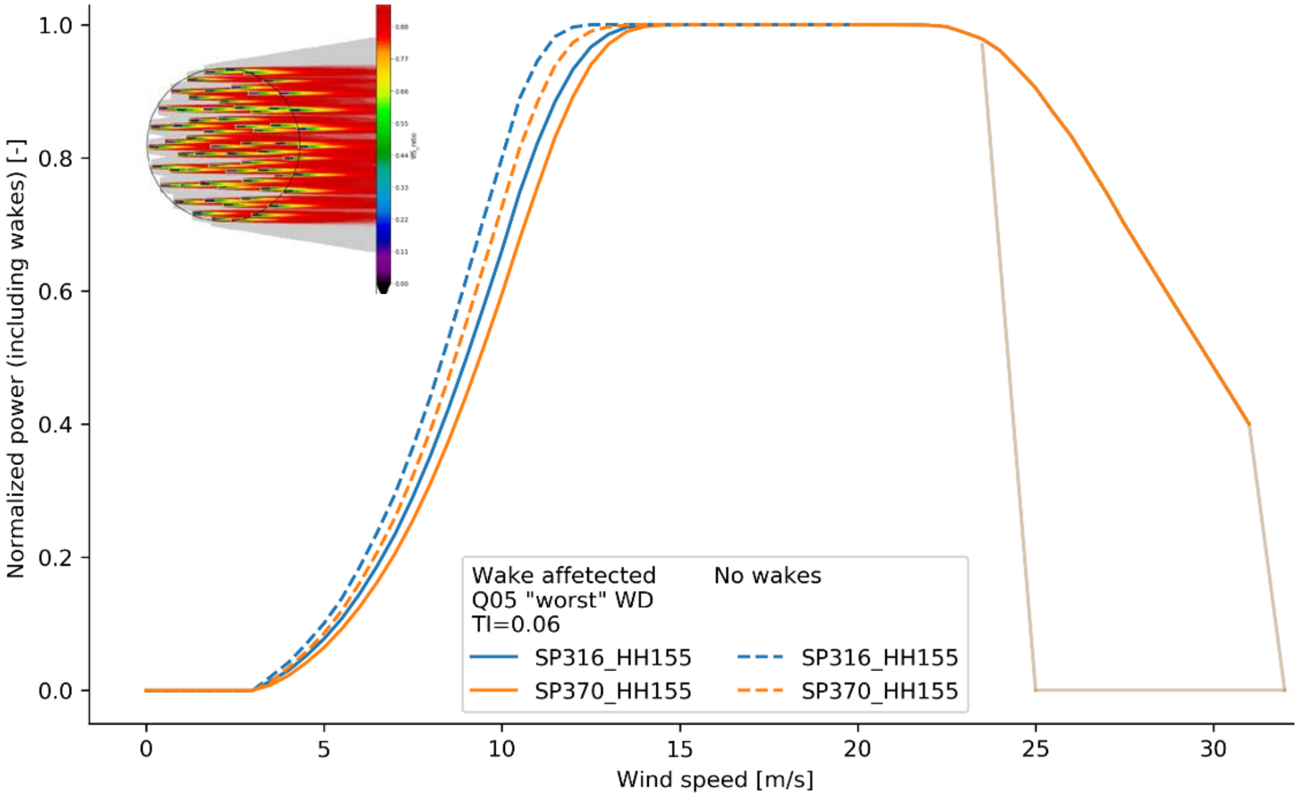


- Reanalysis datasets use low-resolution terrain and land-use data
  - ERA5 output on 30 km resolution
- Global Wind Atlas (GWA):
  - Microscale modelling using WAsP
  - Up to 250 m resolution
- **CorRES applies scaling to match the GWA mean wind speeds[1]**

[1] M. Koivisto, et al., "Application of microscale wind and detailed wind power plant data in large-scale wind generation simulations", *Electric Power Systems Research*, 2021

CorRES:
Wind conversion to power generation

- **Wakes**
  - Using PyWake[1]
  - Also farm-to-farm wakes[1]
  - Machine learning (ML) used to handle thousands of WPPs
- **Storm shutdown**
  - Plant-level model based on turbine-level specs[1]
- **Turbine database**
  - Hundreds of turbine types
- **WPP database**
  - Thousands of WPPs



[1] J. P. Murcia Leon et al., "Power Fluctuations In High Installation Density Offshore Wind Fleets", *Wind Energy Science*, 2021

CorRES:
Includes also solar PV variability model chain

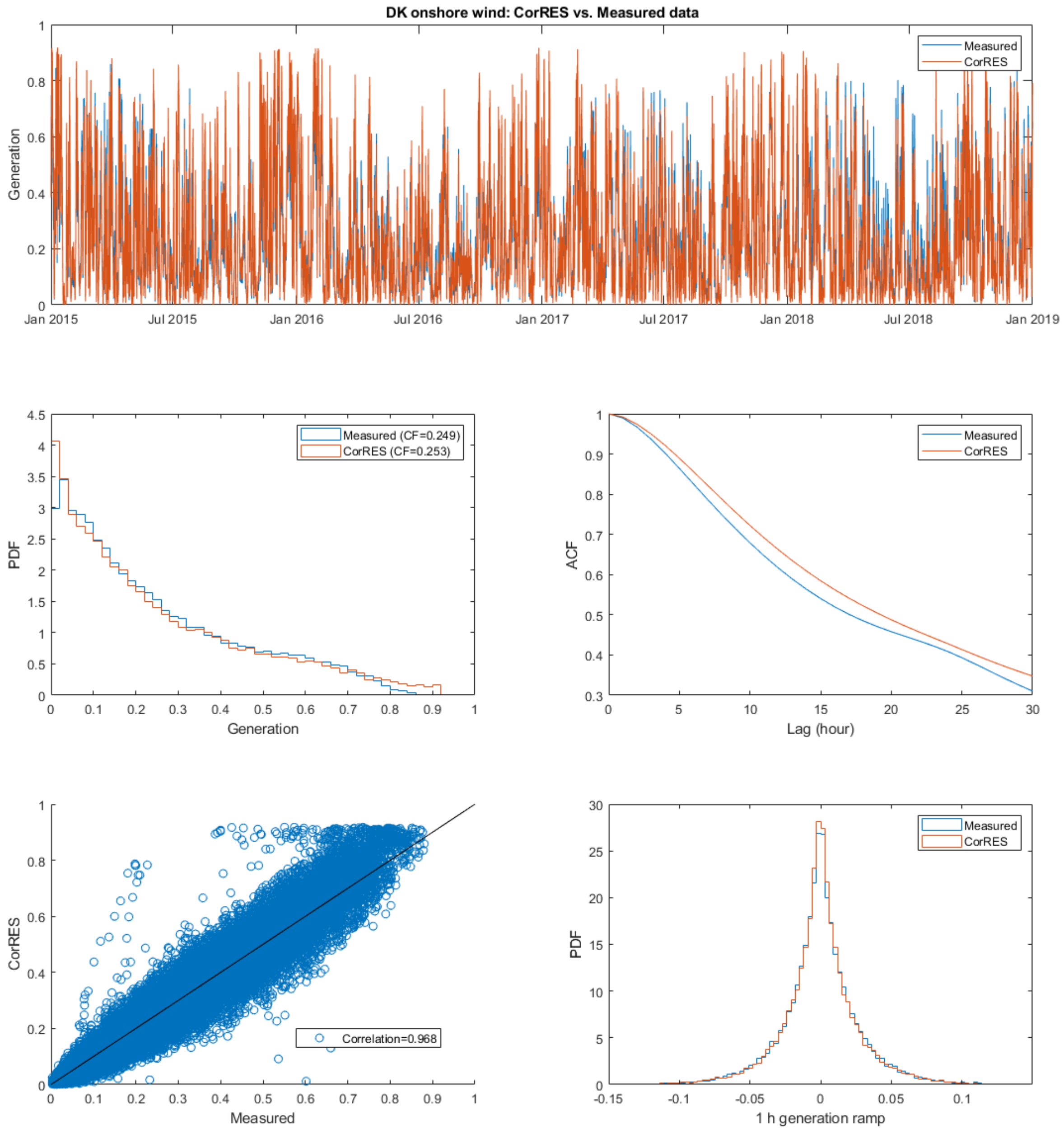
- **Weather data**
  - ERA5-Land for global irradiance
  - 9 km resolution, hourly
  - PVLib is used to get from global irradiance data to direct and diffuse components
- **Conversion to power generation**
  - Using PVLIb
  - Generic solar PV & inverter model

PVLib: https://pvlib-python.readthedocs.io/en/latest/

Validation

CorRES validation: DK onshore wind

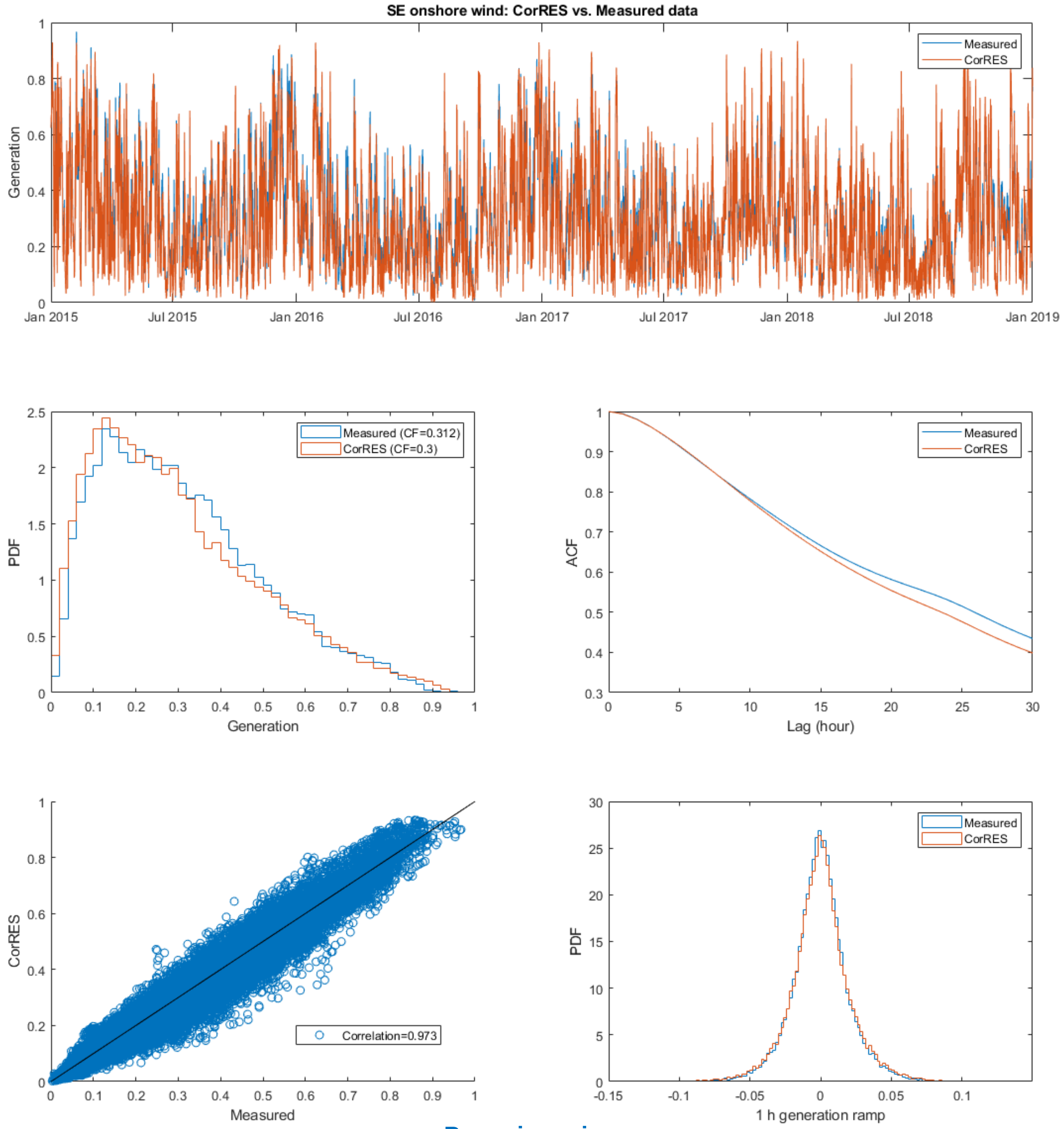
- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



Paper in review

CorRES validation: SE onshore wind

- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



Paper in review

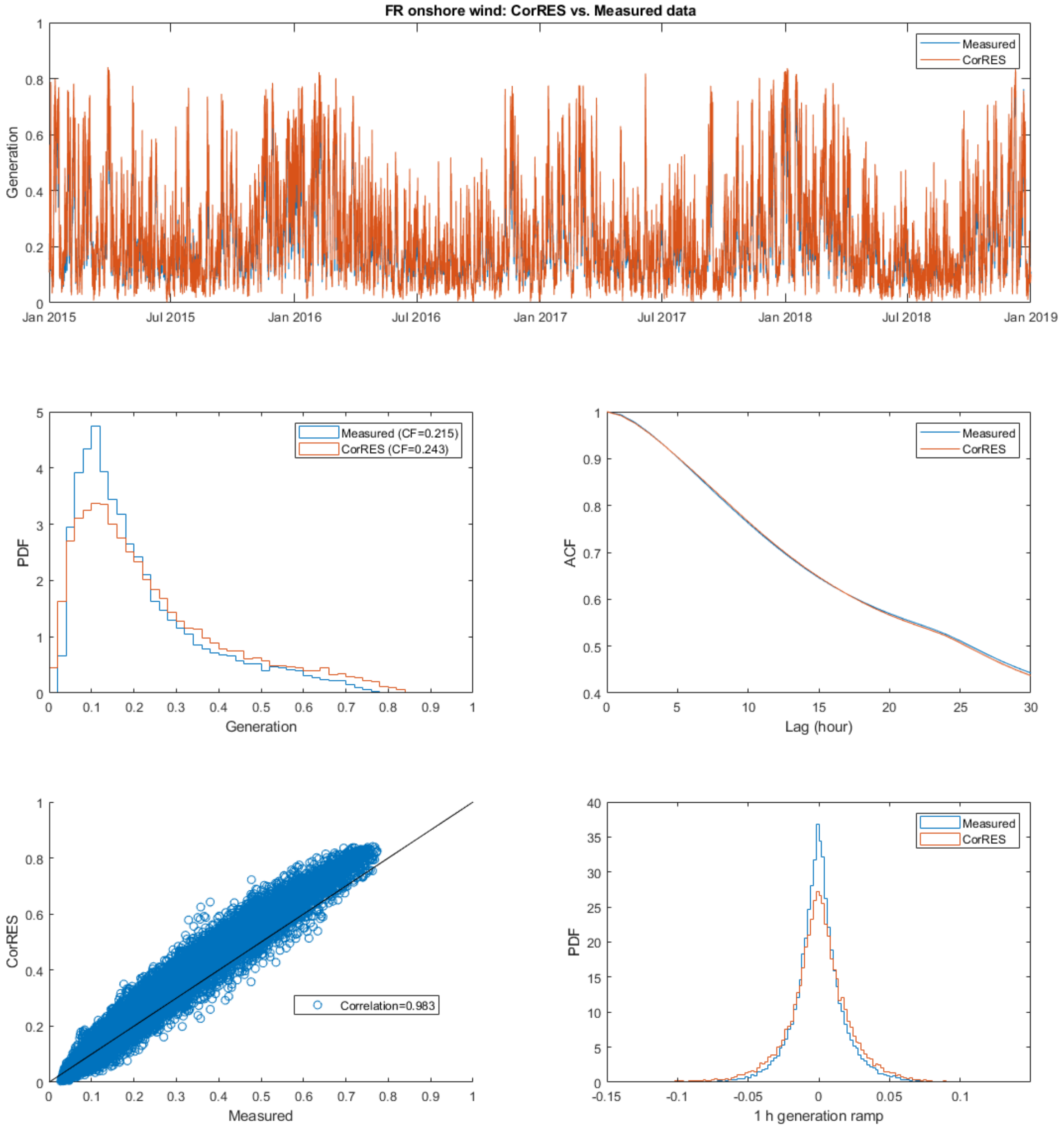
CorRES validation: FR onshore wind

- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA

Note: Uncertainty in the historical French onshore wind capacity factor (CF), as differences between sources:

0.20 (ENTSO-E annual generation & installed capacity)

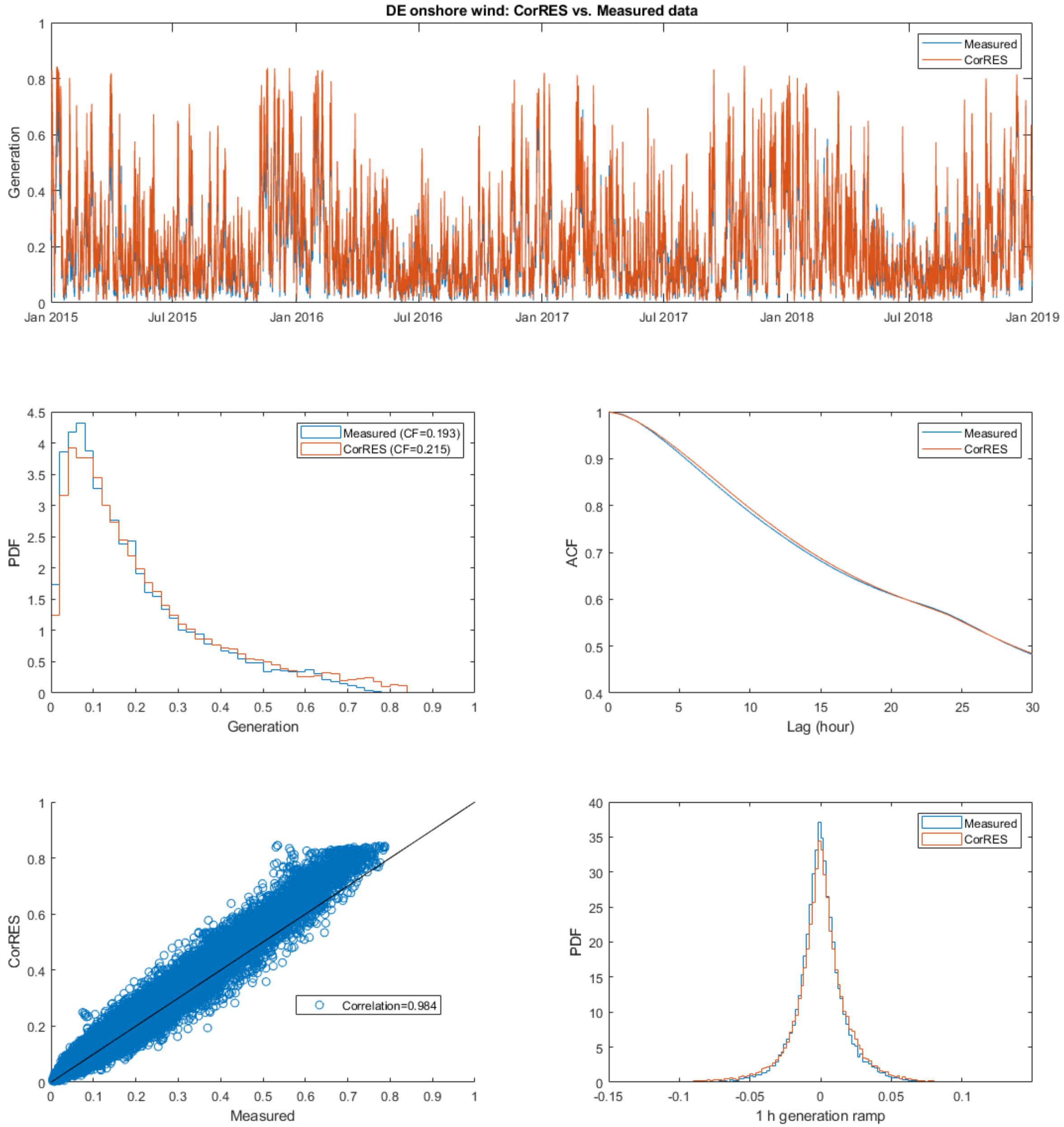
0.23 (IRENA annual generation & installed capacity)



Paper in review

CorRES validation: DE onshore wind

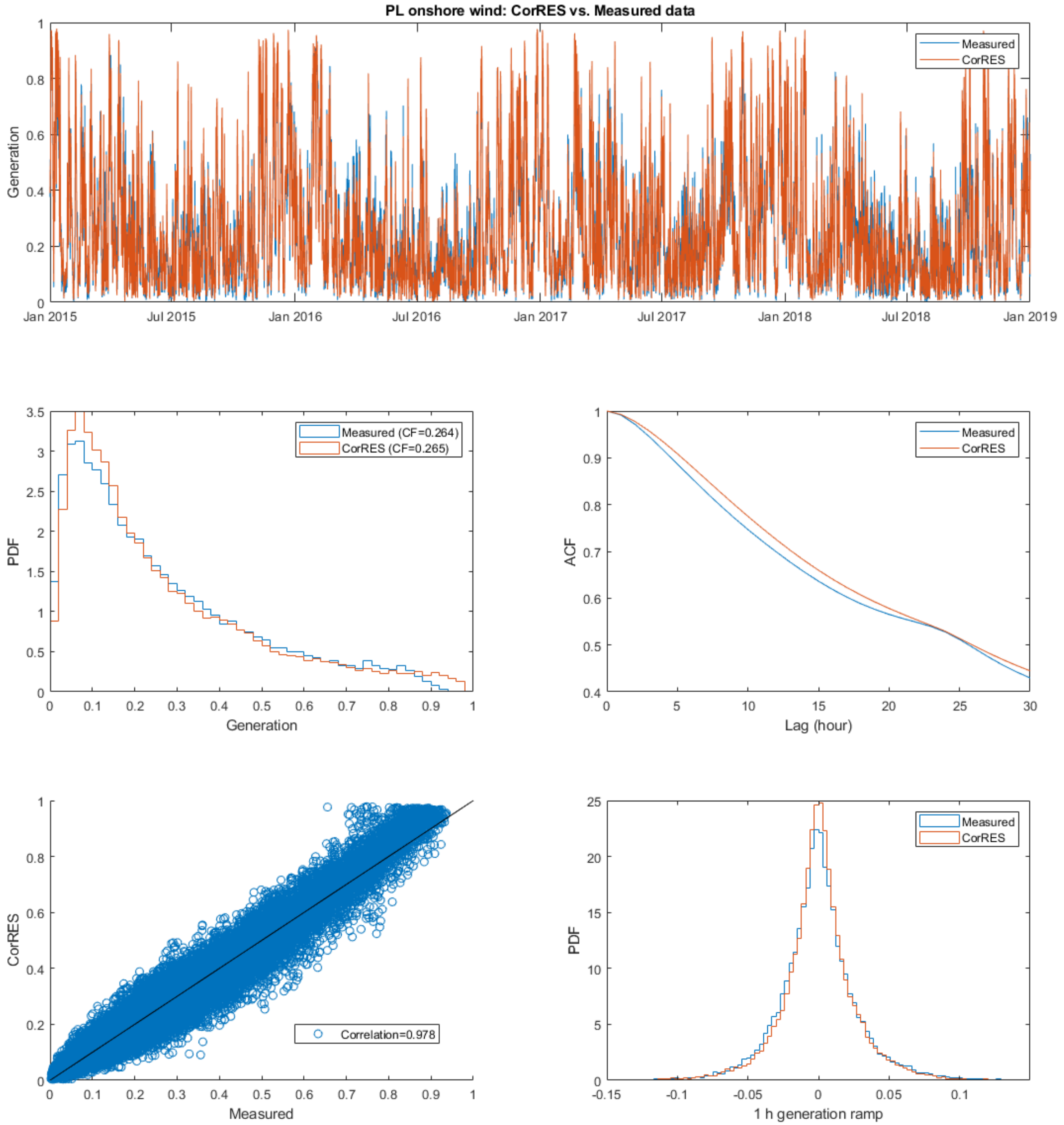
- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



Paper in review

CorRES validation: PL onshore wind

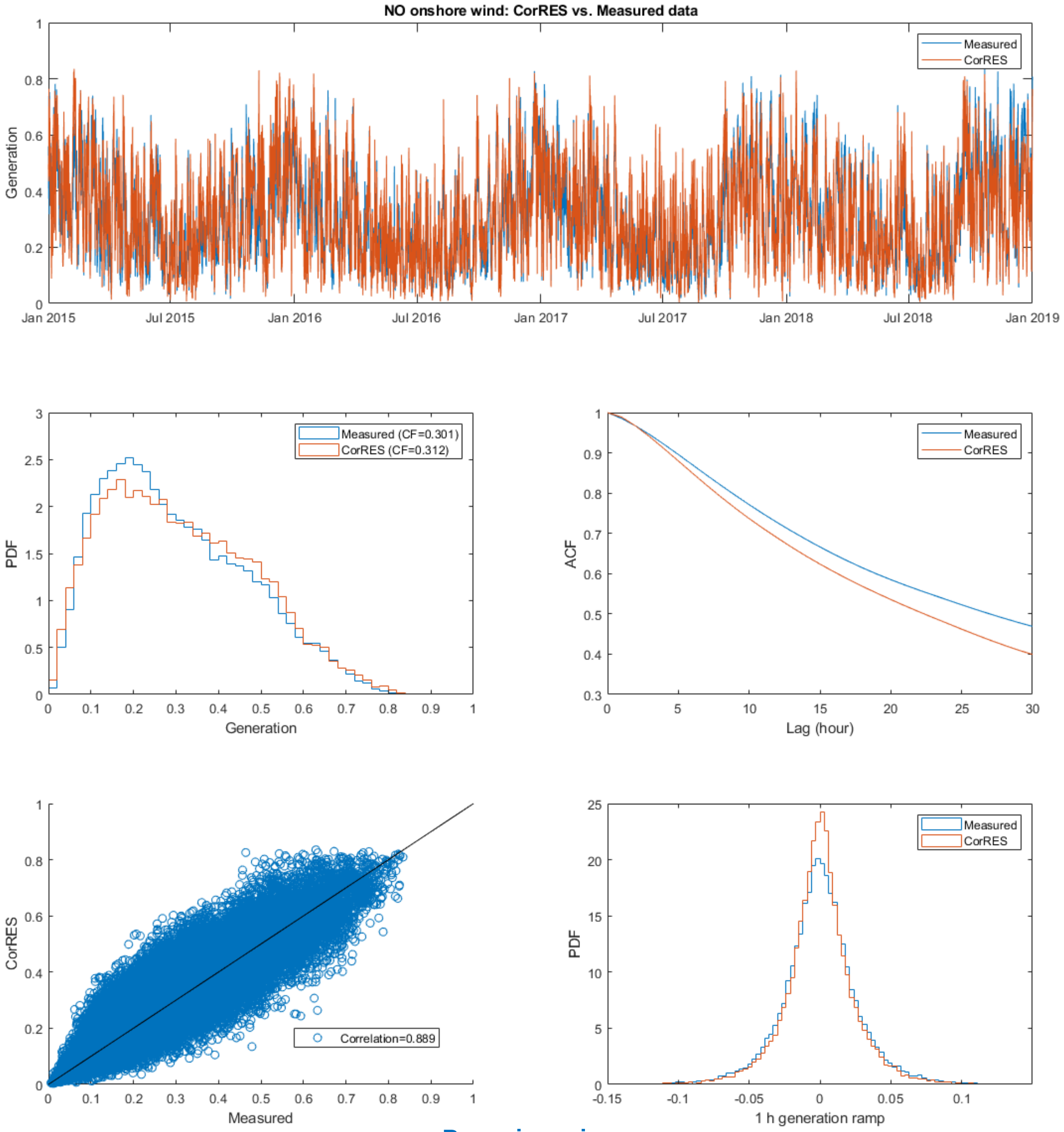
- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



Paper in review

CorRES validation: NO onshore wind

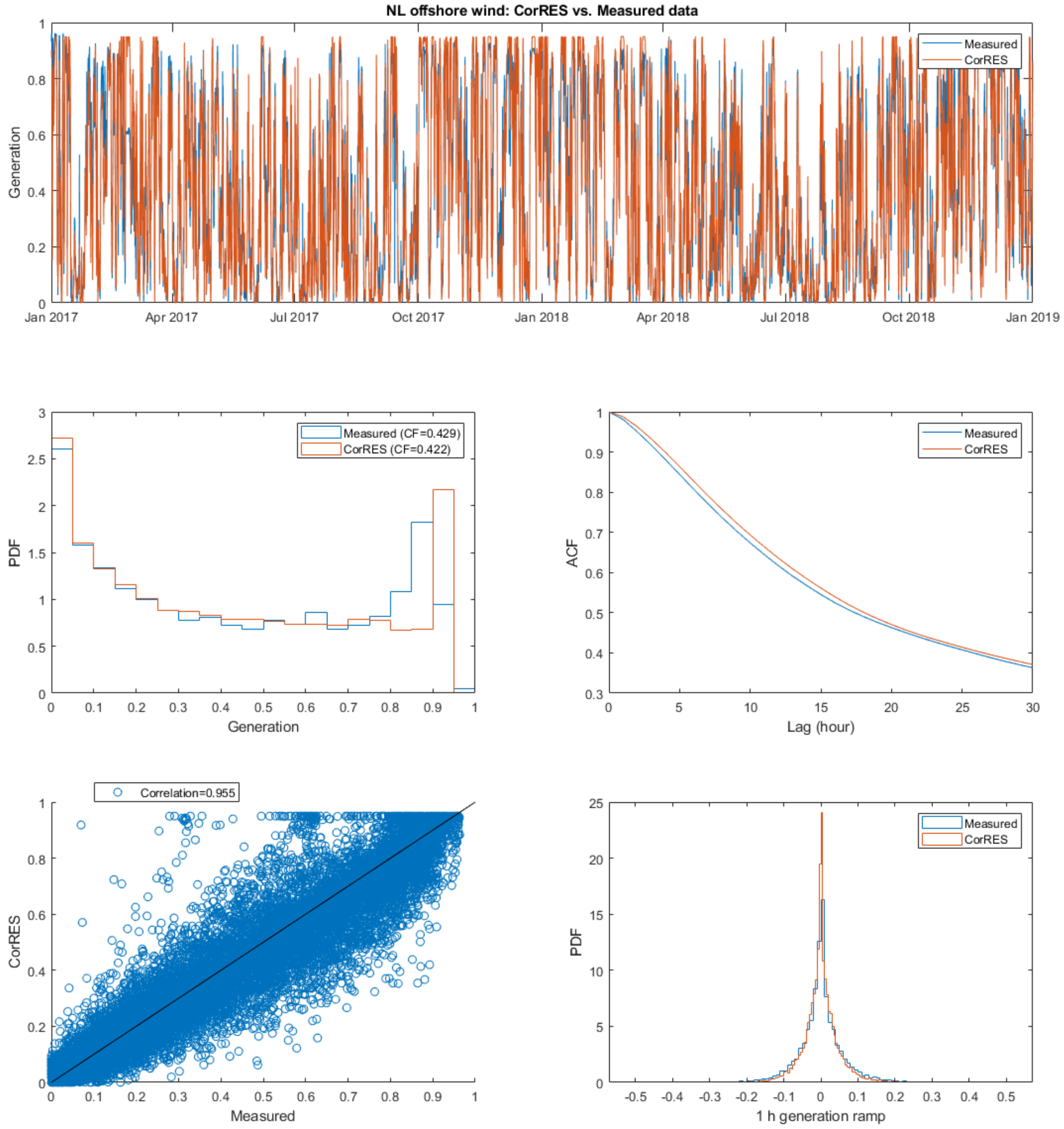
- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



Paper in review

CorRES validation: NL offshore wind

- Measured generation data
  - https://open-power-system-data.org/
  - Based on ENTSO-E Transparency Platform
- Installed capacity data
  - IRENA



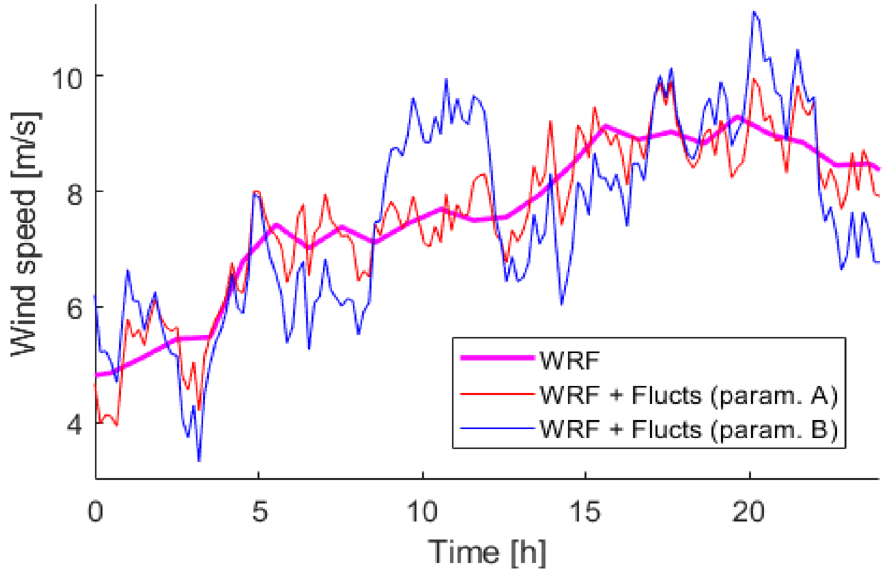
Paper in review

Sub-hourly data and forecast errors: Via stochastic simulation

CorRES: Sub-hourly fluctuations

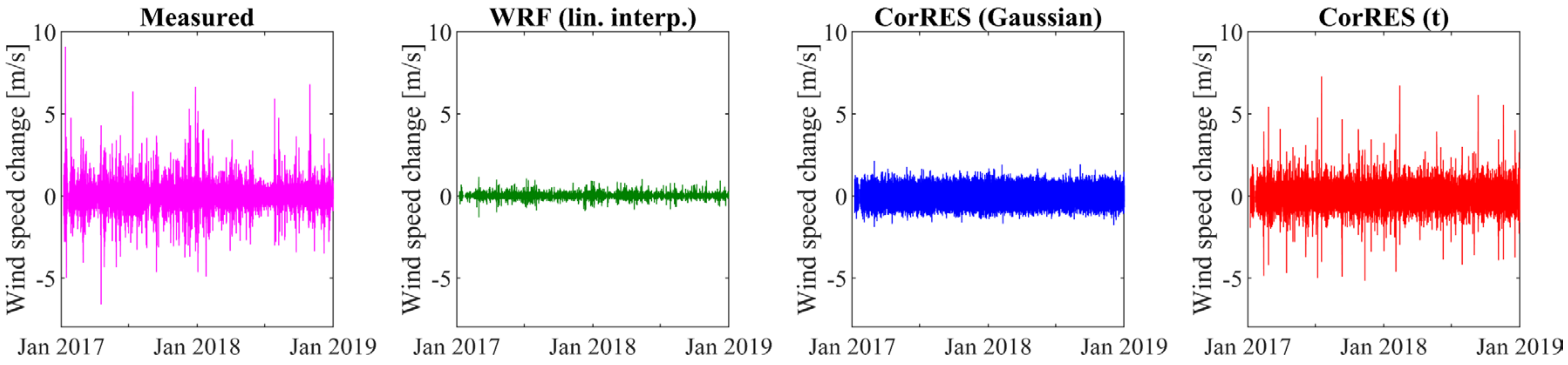
- **The reanalysis wind speeds do not include all high frequency information**
  - Caused by smoothening effects in the models
  - The resulting power time series do not model ramp rates accurately

- Stochastic simulation is used to add the missing variability to the reanalysis data in CorRES
  - **Allows sub-hourly simulation resolution**
  - Currently available for wind
  - In development for solar



M. Koivisto et al., "Combination of meteorological reanalysis data and stochastic simulation for modelling wind generation variability", *Renewable Energy*, 2020

CorRES:
Sub-hourly fluctuations



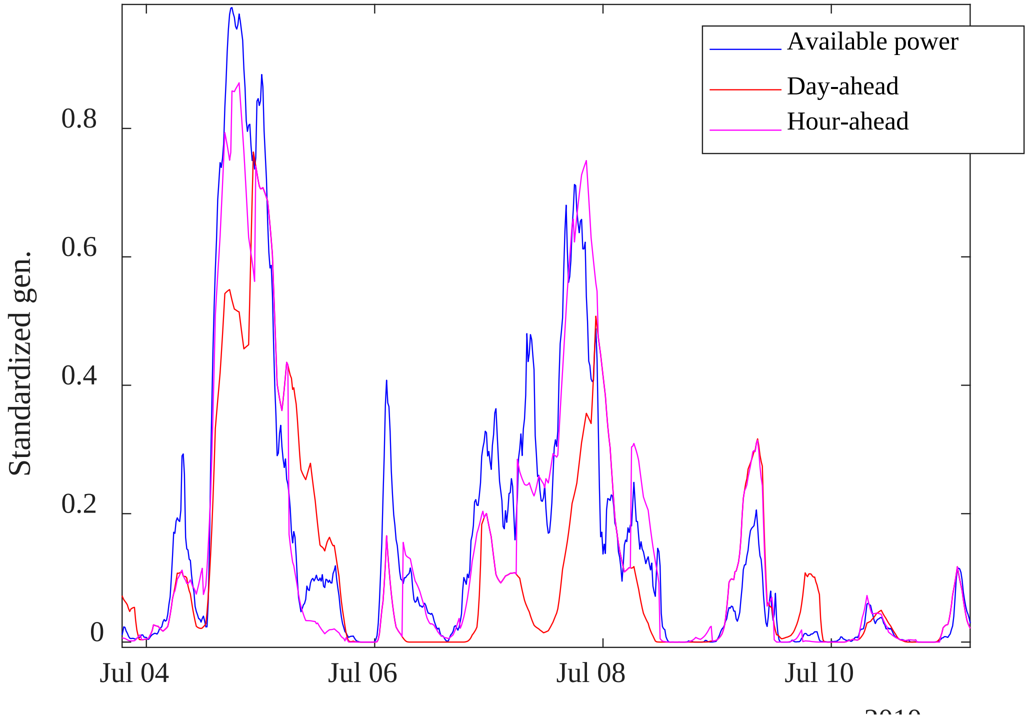
- **Stochastic fluctuation model**
  - Stochastic model (like the turbulence models) captures autocorrelations at each plant
  - And cross-correlations between fluctuations in multiple locations
  - Gaussian or t-student distributed fluctuations

J. P. Murcia Leon et al., "Power Fluctuations In High Installation Density Offshore Wind Fleets", *Wind Energy Science*, 2021

CorRES:
Modelling VRE forecast uncertainty

- **Simulation of VRE forecast errors**
  - For analysing forecast errors in the long term (expected behaviour)
  - Not for forecasting tomorrow
  - Based on stochastic time series simulation

- For wind and solar PV generation
- **For different forecast horizons**
  - E.g., day-ahead, hour-ahead
- Example applications:
  - **Estimating balancing costs**
  - **System balancing needs**



Simulated offshore wind generation for and example region:
Day-ahead, hour-ahead and available power

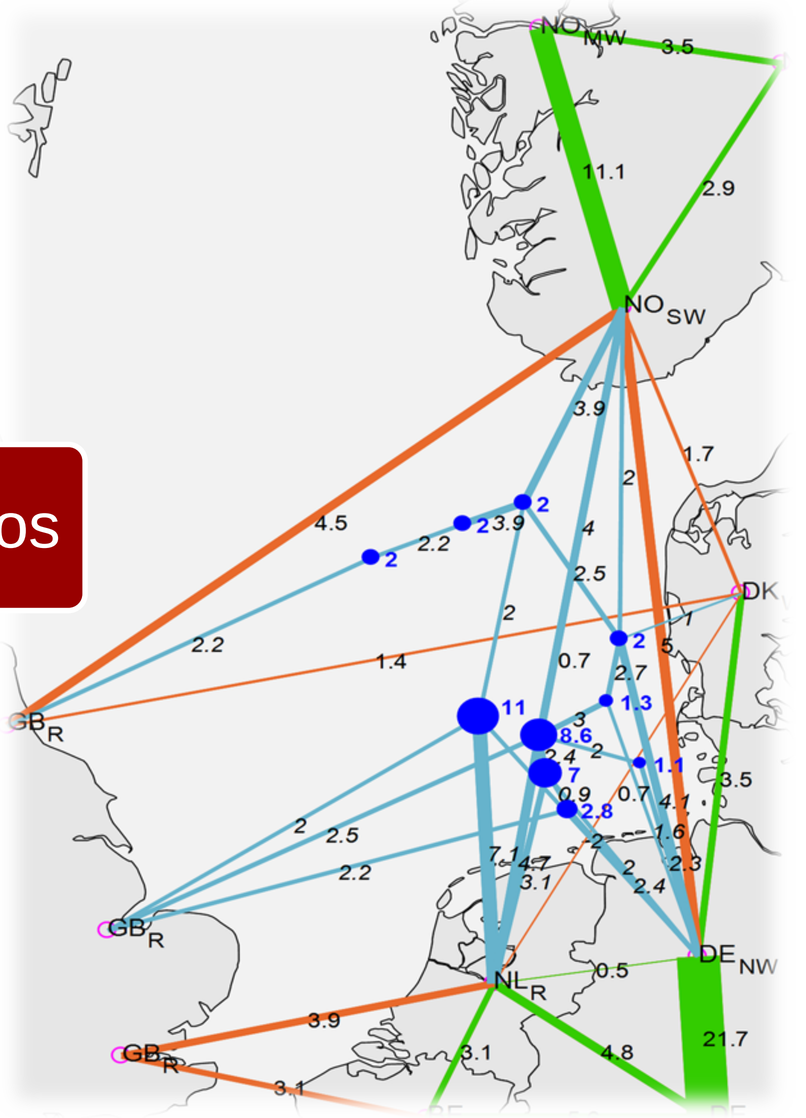
E. Nuño et al, "On the simulation of aggregated solar PV forecast errors", *IEEE Transactions on Sustainable Energy*, 2018

Applications and recent projects

Energy system investment studies

CorRES → Balmorel → Scenarios

- For example for studying:
  - **Offshore energy hubs & meshed grids**
  - **Impact of sector coupling**

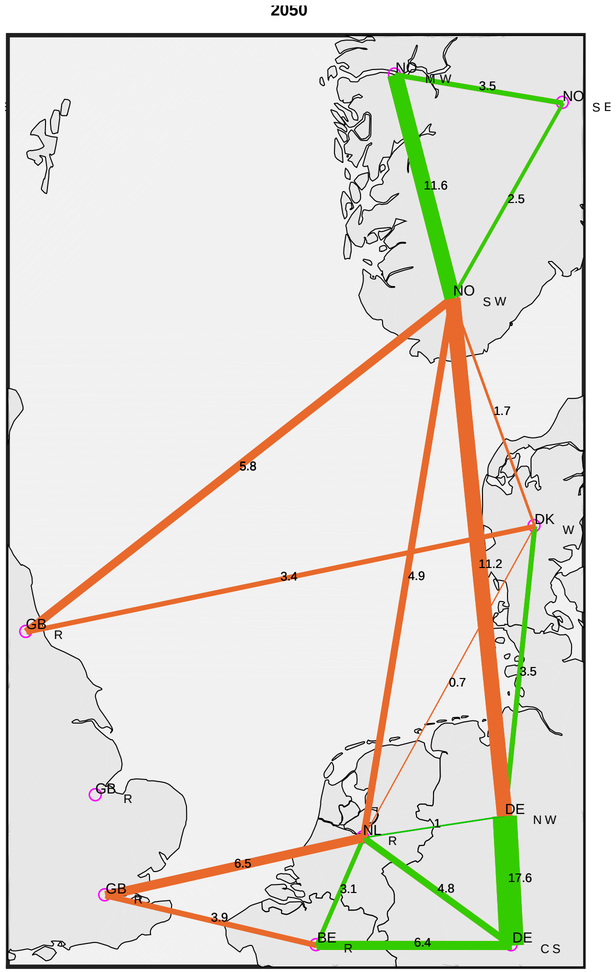


J. Gea-Bermúdez et al., “Optimal generation and transmission development of the North Sea region: impact of grid architecture and planning horizon”, *Energy*, 2020 (https://doi.org/10.1016/j.energy.2019.116512)

M. Koivisto et al., “North Sea region energy system towards 2050: integrated offshore grid and sector coupling drive offshore wind installations”, *Wind Energy Science*, 2020 (https://doi.org/10.5194/wes-2020-60).

Is a meshed offshore grid beneficial?

Baseline: No North Sea offshore grid



VRE type	Starting point [GW]	2030 [GW]	2050 [GW]
Offshore wind	22	64	**92**
Onshore wind	76	106	114
Solar PV	70	126	182

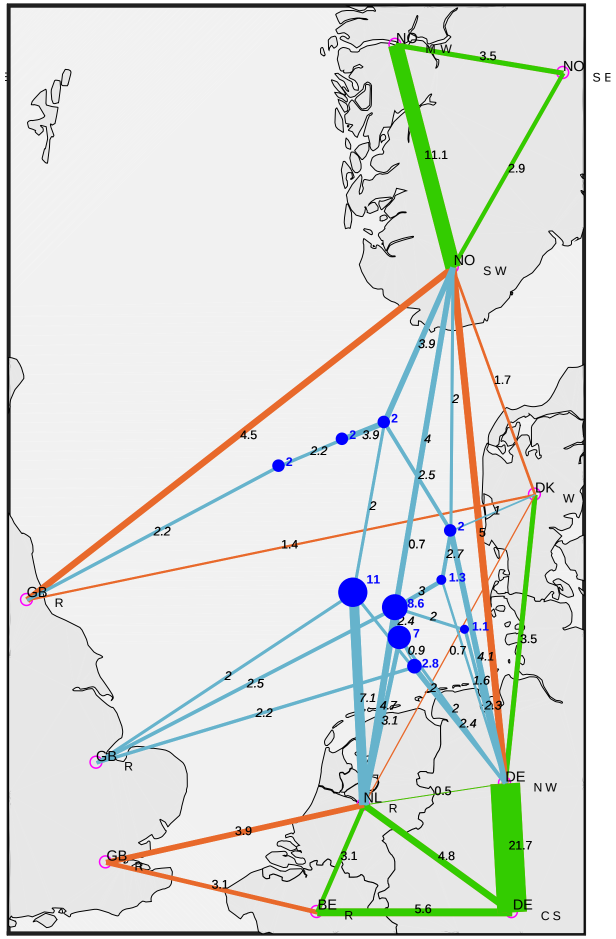
Generation share	Starting point	2030	2050
VRE	28%	55%	**70%**
Renewable	46%	75%	**88%**

M. Koivisto et al., “North Sea offshore Grid development: Combined optimization of grid and generation investments towards 2050”, *IET Renewable Power Generation*, vol. 14, no. 8, pp. 1259-1267, June 2020 (https://doi.org/10.1049/iet-rpg.2019.0693)

Is a meshed offshore grid beneficial?

Offshore grid is built in the optimised system

2050



VRE type	Starting point [GW]	2030 [GW]	2050 [GW]
Offshore wind	22	69 (30%)	**102** (39%)
Onshore wind	76	101	106
Solar PV	70	120	176

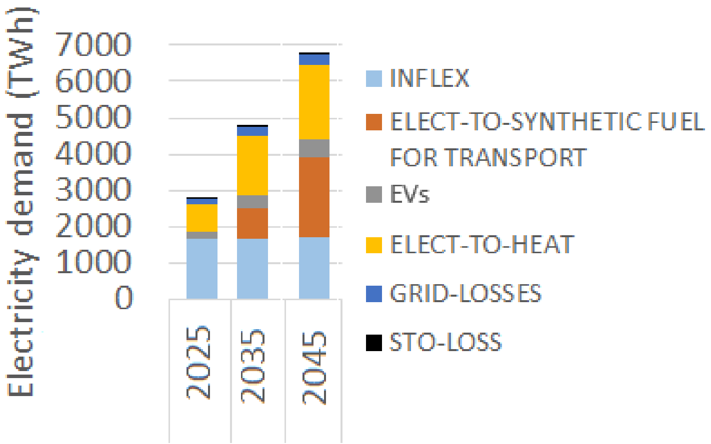
Percentages show hub-connected offshore wind shares

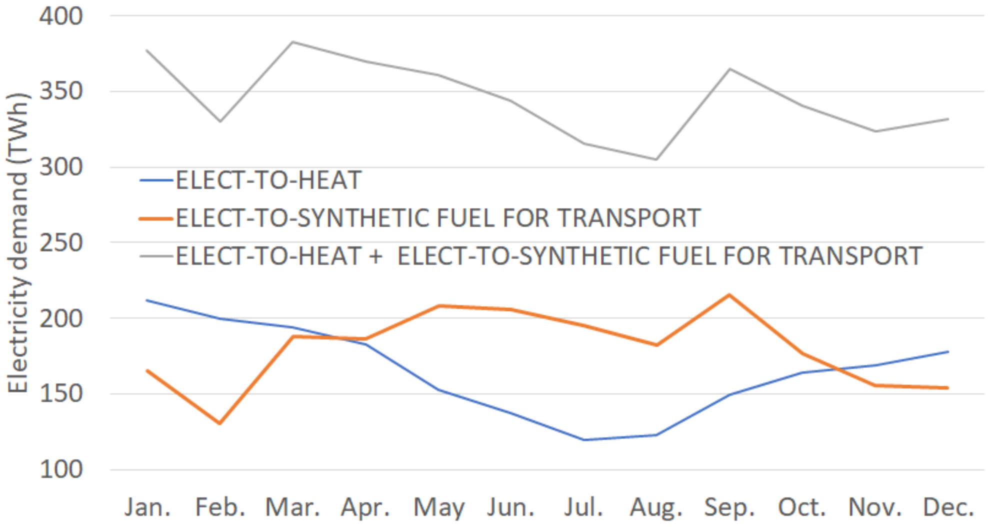
Generation share	Starting point	2030	2050
VRE	28%	56%	**72%**
Renewable	46%	76%	**89%**

M. Koivisto et al., “North Sea offshore Grid development: Combined optimization of grid and generation investments towards 2050”, *IET Renewable Power Generation*, vol. 14, no. 8, pp. 1259-1267, June 2020 (https://doi.org/10.1049/iet-rpg.2019.0693)

Sector coupling impacts

- **A change of paradigm** takes place due to sector coupling:
  - The system moves from generation adapting to demand, to **demand adapting to generation**
- **The installed electricity capacity by 2050 roughly triples compared to 2025**
  - When power-to-heat (P2H) investments and transport demand (also hydrogen) are considered
- P2H is the preferred option to decarbonize the heat sector
  - **P2H provides flexibility to the system**





2045

J. Gea-Bermúdez, et al., "The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050", *Applied Energy*, 2021

Sector coupling drives the development of offshore meshed gird

- **The higher the level of sector coupling, the higher the value of offshore grids**

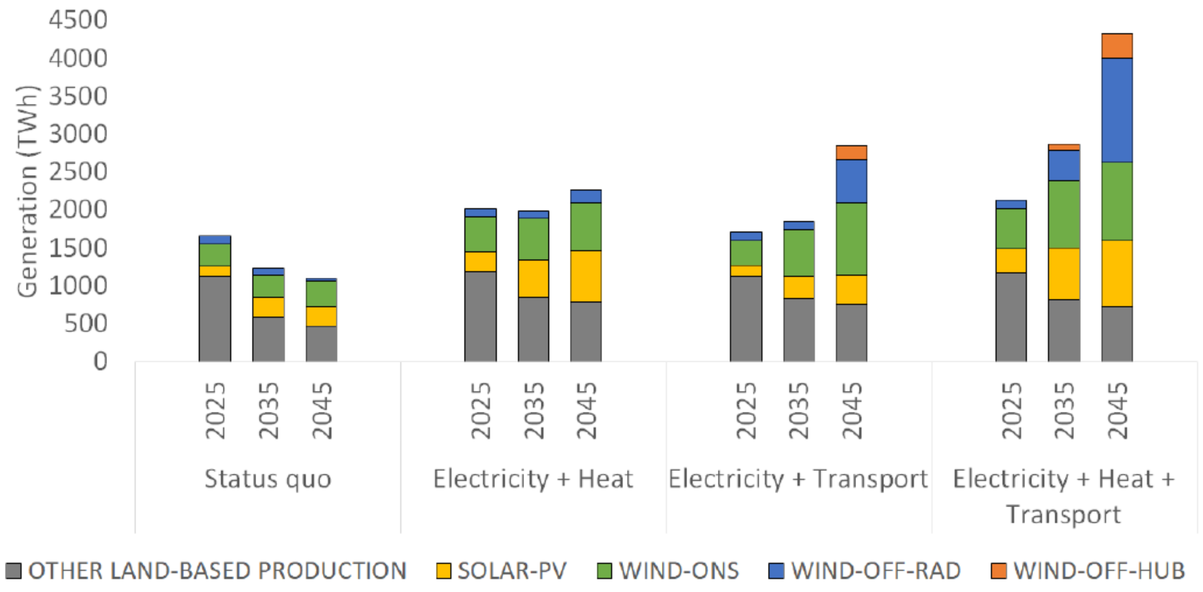
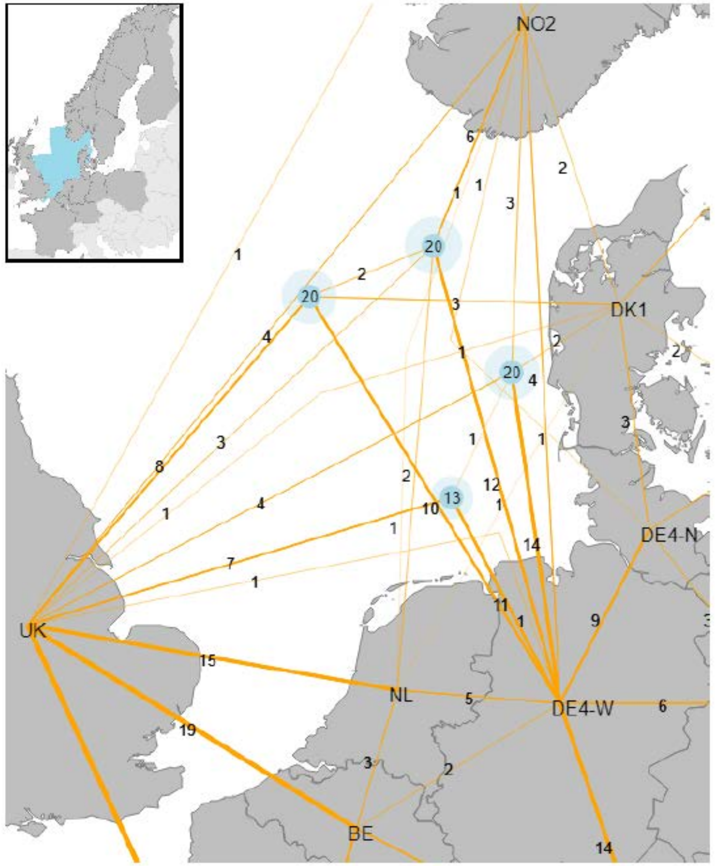


Figure 3: Electricity generation per scenario, year, and aggregated technology type in all the studied countries (TWh).

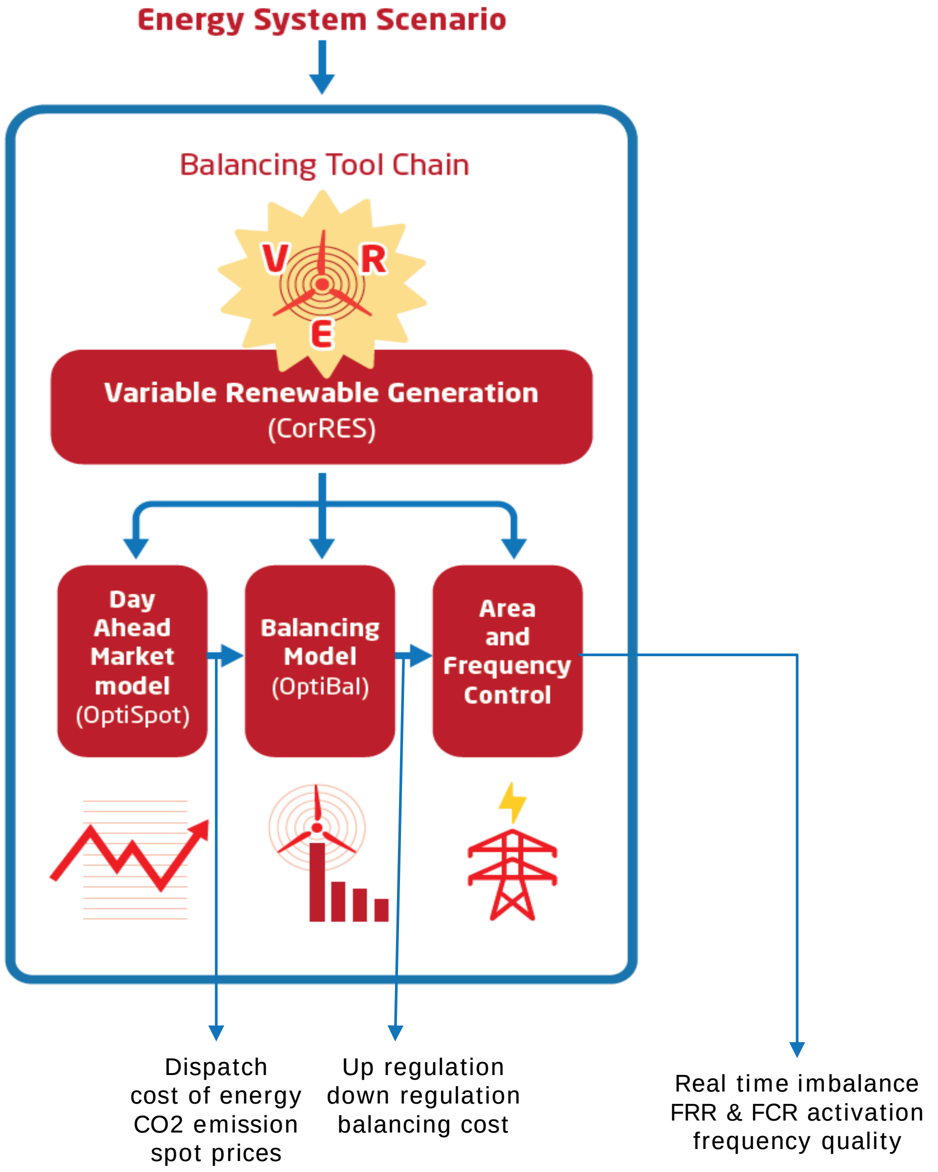


J. Gea-Bermúdez et al., "The value of sector coupling for the development of offshore power grids", *Pre-print, TechRxiv*, 2021

Balancing Tool Chain

- **On top of Balmorel investment runs**
    - Or other scenarios

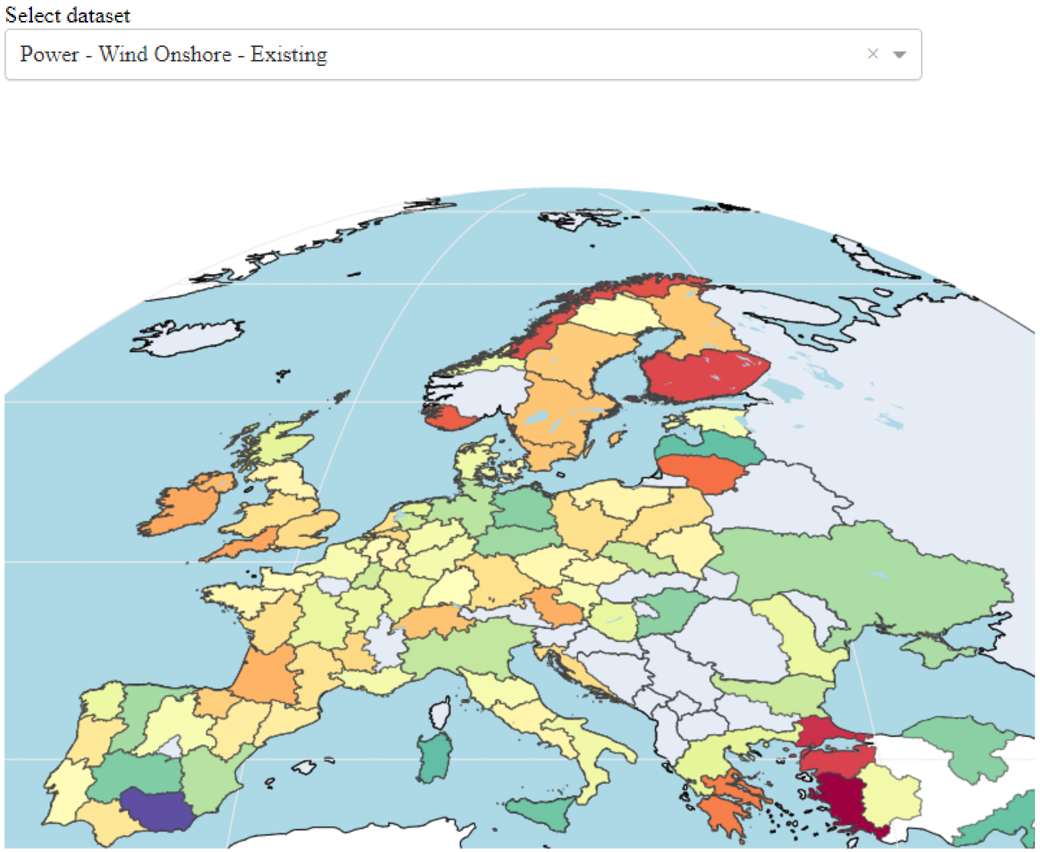
- Unit commitment and dispatch (spot market)
- Society cost of energy
- Balancing volume and costs (balancing model)
- **Real time imbalance**
- **Frequency quality**



VRE simulations for ENTSO-E

- **Pan-European climate database (PECD):**
  - Database of weather driven time series
  - DTU Wind Energy does wind & solar
  - Hourly resolution, 35+ years

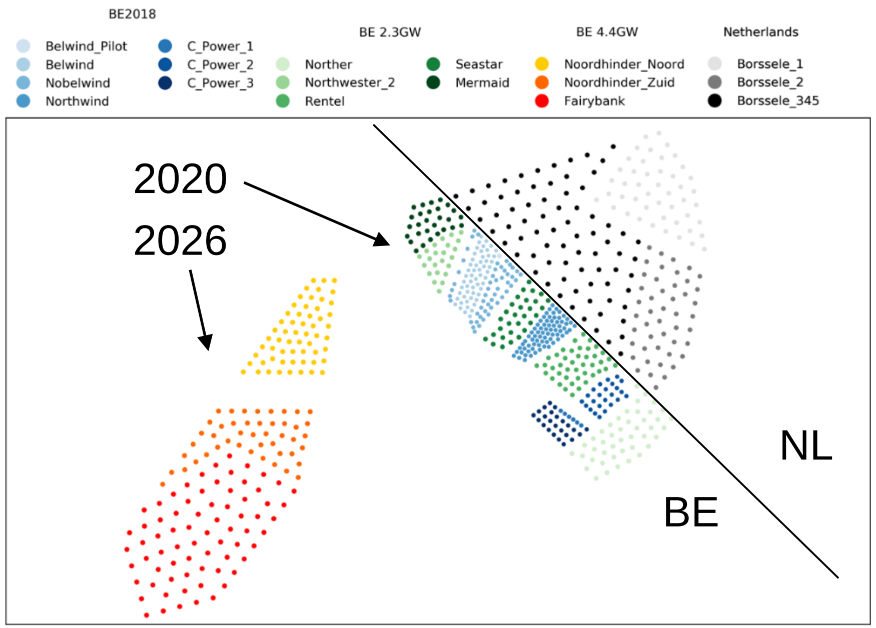
- DTU Wind Energy and ENTSO-E entered into a Long-term Cooperation Agreement for 2018-2023
- Update of PECD data in Spring 2021
  - **Including large range of wind technologies for scenario building needs**



Web based access in development

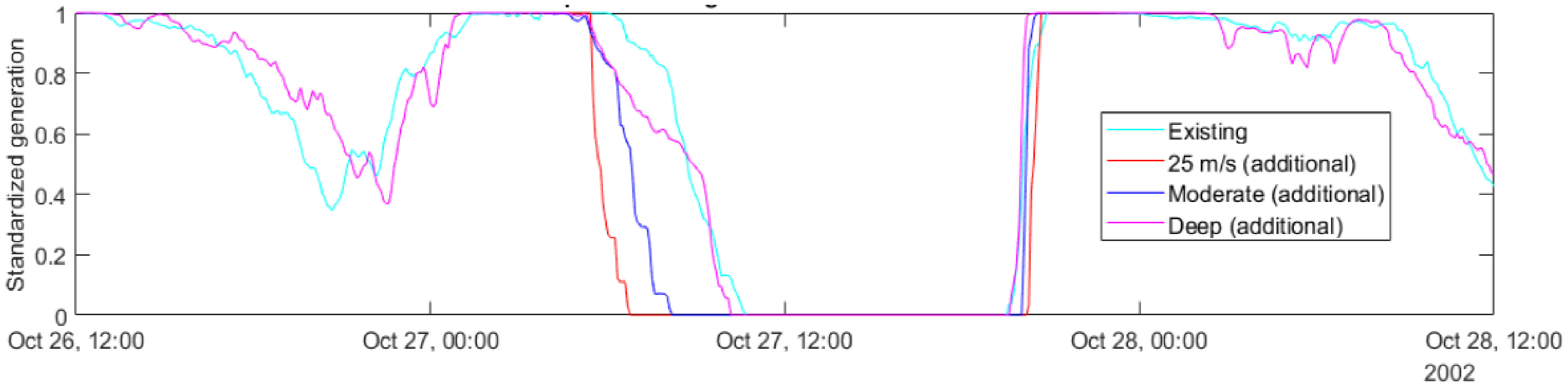
4.4 GW offshore wind integration study for Elia: Impacts on power systems

- 4.4 GW offshore wind integration study for the Belgian TSO Elia
- Very dense offshore wind installations
  - Wake modelling important
  - **Including farm-to-farm wakes**
  - Multiple plants may experience simultaneous storm shutdown
- Impacts on:
  - **Ramp rates**
  - **Fleet-level storm shutdowns**
  - **Expected forecast errors**



DTU Wind Energy, "Report for Elia: MOG II System Integration: Public version", 2020 (https://orbit.dtu.dk/en/publications/elia-mog-ii-system-integration-public-version).

4.4 GW offshore wind integration study for Elia: Impacts of storm shutdown technology



Impact of different storm shutdown technologies in an example storm case.

Significant difference on how quick power ramps down

DTU Wind Energy, "Report for Elia: MOG II System Integration: Public version", 2020 (https://orbit.dtu.dk/en/publications/elia-mog-ii-system-integration-public-version).

Modelling offshore wind in North Sea energy hubs

- Contracted research by the North Sea Wind Power Hub (NSWPH)
  - NSWPH is a consortium of Energinet, Gasunie and TenneT
  - https://northseawindpowerhub.eu/
- DTU Wind Energy supports the study of offshore energy hubs and their energy system impacts
  - https://northseawindpowerhub.eu/nspwh-contracts-research-partners-for-extensive-energy-system-study/
  - Simulation of all VRE time series

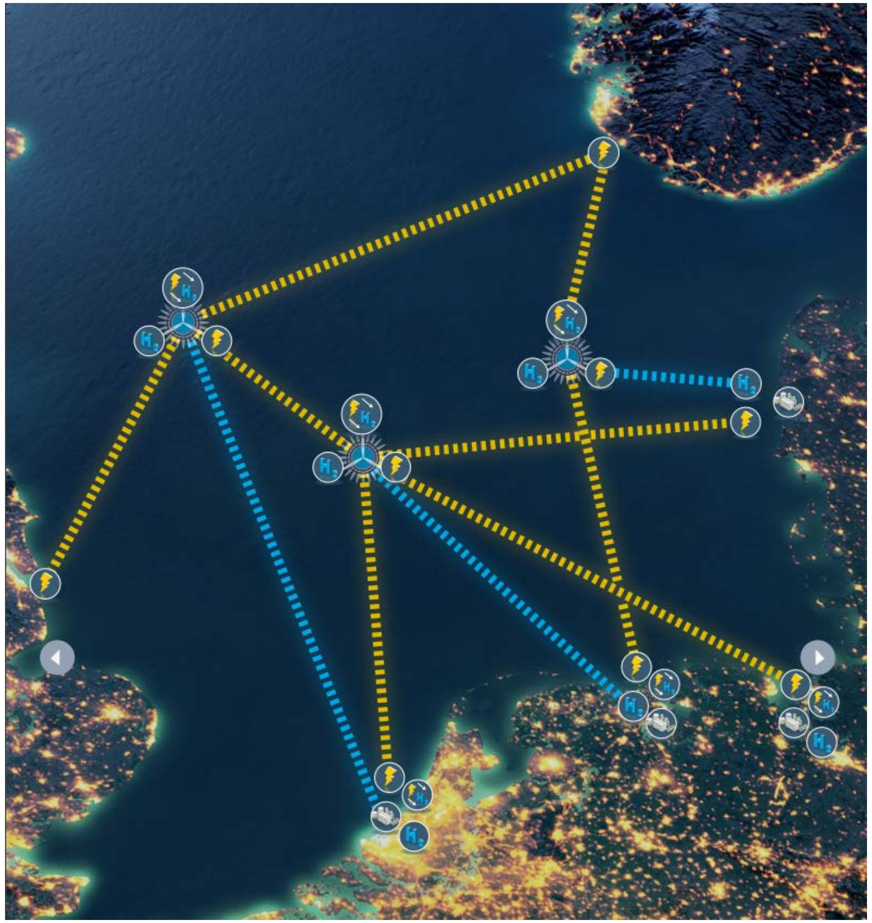


Figure from: https://northseawindpowerhub.eu/wp-content/uploads/2019/11/NSWPH-Drieluik-Herdruk_v01.pdf

Other

- NSON-DK: Impacts of offshore wind on the Danish system
- OffshoreWake: Farm-to-farm wakes
- PSfuture: Future systems & climate change
- BaltHub: Offshore energy hubs & P2X in the Baltic Sea

- Funding for the different projects presented in this presentation:
    - La Cour Fellowship, DTU Wind Energy
    - EUDP, Danish Energy Agency
    - Nordic Energy Research
    - Commissioned works for ENTSO-E and Elia