Paving the Way for Wind Farm Control in Industry

Task 3.3: Summary of activities and WESC mini-symposium

Final Report

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1 Introduction and motivation

Wind Farm Control (WFC) is a technology that aims at mitigating the wakes emitted by operating wind turbines, in order to increase the overall farm power production and reduce turbine loading. Consequently, the vast majority of the studies led regarding this subject were primarily focused on the operating phase of a wind project, when the turbines are built and the operator aims to optimize the performance of his asset.

However, when WFC is available at a large scale, additional benefits can be achieved already in the design phase (or pre-construction phase) of a wind project, when the farm is being developed and financed. Indeed, knowing that WFC will be applied later on during the operation phase can strongly influence several key design parameters, such as the farm layout, the turbine size and load envelope, or the electrical infrastructure. Furthermore, accounting for the extra energy production provided by WFC can lead to an increase in the predicted P50 and P90 of the farm (the energy production that the farm has respectively 50% and 90% chance to exceed), which are the quantities typically considered for the bankability a wind project. Therefore WFC can contribute to make the projects more competitive for the tenders and reduce their cost of financing, leading thus to a reduction in the levelized cost of wind energy.

Since it is a relatively new field in WFC research, it was decided to dedicate a complete task within the FarmConners project about this subject, in Work Package 3: Electricity Market Integration. The objective was to introduce these issues to the wind energy community, so that they could stimulate more research in the future and be analyzed in further details. This present report summarizes the activities held within the Task 3.3 “Design Phase” of the project.

2 Setup of the mini-symposium

The Task 3.3 on Design Phase benefits was first introduced during workshop “Today’s Market Challenges for wind energy and added value of WFC” held in KU Leuven at the beginning of February 2020. The main objectives of the task were presented at this occasion, and also a certain number of ideas were gathered for the organization of the mini-symposium at the Wind Energy Science Conference (WESC) 2021. Among those ideas, the following topics were finally selected during the Autumn 2020 for further discussion at the conference :

- Combined Layout and WFC optimization: The fact that wind farm control is available in the operating phase of a project can influence the layout of a wind farm. Indeed, as wake effects can be mitigated via WFC, it is possible to keep the same level of wake losses while reducing the spacing between the turbines to densify the wind farm, i.e. decreasing the area required for a wind farm or allowing more power for the same available area.
- Grid Integration: Regulations are changing to comply with the higher share of renewable energy in the grid. New constraints are likely to be applied to wind farms to have them behave like conventional generators. WFC can help fulfill these new regulatory constraints, however it is needed to study how WFC can interact with classical power electronics to achieve these objectives.
- Bankability of WFC: When financing a wind project, an energy yield assessment (EYA) is generally realized to evaluate the future annual energy production (AEP) of the farm, with the lowest uncertainties possible. Since WFC is expected to provide an increase in the AEP, it is critical that this AEP is evaluated with a high confidence so that it can be trusted by investors and become a bankable technology.
- Loads reduction and lifetime extension: Another potential benefit of WFC is load mitigation. By decreasing the mechanical fatigue exerted on a wind turbine, its lifetime can be extended leading to a longer period of energy production which can influence both the farm design and the project financing. Therefore, the influence of WFC on the turbine loading must be modeled accurately and reliably to make sure the predicted gains will truly be achieved.

3 WESC 2021 mini-symposium

Four speakers, all coming from institutions related to the FarmConners project (either project members or part of the advisory board) kindly accepted to give a presentation corresponding to one of the subjects listed above. The title of the presentations and name of the presenters are indicated in the table below.

Topic	Institution	Presenter	Title of the presentation
Combined Layout and WFC optimization	NREL	Christopher Bay	Increasing Turbine Density for Wind Plants Through Combined Layout and Yaw Optimization
Grid integration	SINTEF	Til Kristian Vrana	Electrical design and control for grid code compliance
Bankability of WFC	DNV	Lars Landberg	Bankability of wind farm control
Loads reduction / lifetime extension	CENER	Elena Cantero	Wind farm performance optimization from design phase

Due to the Covid-19 pandemic, WESC 2021 was held as an online event between May 25th and May 28th 2021. The mini-symposium on “Design Phase” was organized on May 27th, between 13:40 and 15:20 in the session called “Wind Farm Control (II)”. It gathered in average 55 to 60 attendees for the different talks, with a peak at 68 people in the middle of session. A quick summary of the presentations is given in the subsections below.

3.1 Talk #1: Increasing Turbine Density for Wind Plants Through Combined Layout and Yaw Optimization

Turbine layouts in wind plants are often designed to minimize wake interactions between turbines to increase energy production. Wake steering is the control strategy in which a turbine is yawed away from the incoming wind direction to induce a deflection on its wake downstream. This deflection can steer the wake away from downstream turbines resulting in an overall increase in energy production for the plant. Accounting for the applicability of a wake steering directly in the design phase of a project provides more flexibility to handle environmental constraint. Furthermore higher production can be expected by optimizing jointly layout and wake steering rather than successively. This presentation investigates how the open-source library FLORIS developed by the NREL and TU Delft can be used to perform such an optimization, and densify a wind farm by reducing the distance between turbines while maintaining the AEP at a constant level.

Simulations realized with the Gauss-Curl Hybrid (GCH) model of FLORIS for a two turbine setup show that a 22% reduction in distance can be achieved using wake steering. The distance reduction can raise up to 47% for a 5 turbine setup. Two extra turbines could be installed in the newly available space, leading to a 27% increase in power for the same space. Similar trends are obtained by considering a 2-dimensional turbine array, confirming the potential of combined layout and wake steering optimization for increasing power density within wind farms.

3.2 Talk #2: Electrical design and control for grid code compliance

The design of the wind power plant control is mostly determined by the main control objective, which has historically been the maximum power tracking to supply energy to an ideal grid (wind-determined wind power plant control). To enable operation with far-from-ideal grids, so-called grid forming converter control has evolved. With this approach, the output frequency becomes an internal state of the converter control, in contrary to classical PLL-based approaches that measure the grid frequency as external input parameter. While solving many problems on the grid side, this control approach causes new challenges within the turbine; the grid-frequency-dependent power output fluctuations affect the turbine and disturb rotor speed.

The solution can only be to move away from master-slave concepts towards a more cooperative approach where both converters on turbine and grid side take part in the responsibility of DC voltage control (i.e. power balancing). With such a control approach both converter sides affect each other. The energy storage between the converters effectively decouples them, giving them the possibility to both behave master-like, but only for time scales where the storage can handle the resulting power imbalances. All possibilities for providing this energy storage, dedicated system, rotor inertia or turbine deloading have their economical downside. The final solution will likely be a combination of all, and distributed in-turbine-storage to monitor this issue might well be a new aspect for wind farm control.

3.3 Talk #3: Bankability of wind farm control

A method/process/procedure is defined as bankable when there is an acceptance in an entire industry (amongst banks, investors, insurance, manufacturers, consultants, certification bodies, etc.) that it is robust and well-defined, with a proven track record, effects known and uncertainties understood to such a level that loans and investments can be safely employed. Three stages of progression are proposed for Wind Farm Control to go from being experimental to bankable: pre-qualified, qualified and commercially proven. Each stage comes with its own requirements that need to be fulfilled.

In the pre-qualified stage, the WFC technology supplier must show robust and reproducible modelling techniques, simulate the impact on energy and loads with a methodology accepted by at least one independent third party, and demonstrate feasibility and practical plans for implementation on a range of projects under different conditions. In the qualified stage, it is also required to demonstrate the reliable operation of the technology by means of validation studies, to ensure that all contractual and commercial obligations can be met, and to provide assurance from a certification body that it may work at least under generic conditions considered in the corresponding certificate. Finally, in the last commercially proven stage, the calculation methodologies used to simulate the WFC outcome must be independently verified, reliable and reproducible under a range a conditions, and the technology supplier must be able to provide evidence of substantial track records by means of site-specific design assessment (SSDA) or project certificate.

3.4 Talk #4: Wind farm performance optimization from design phase

In the design and development phase of a wind farm, a site suitability assessment of each wind turbine must be carried out according to the IEC 61400-1 standard. In particular, it is checked whether the turbulence intensity (TI) at each turbine location remains within the limits given by the turbine class. TI depends not only on the site wind and terrain (orography, roughness, …) conditions but also on the wind farm layout, since due to wake added turbulence. In some cases it is necessary to shut down the turbines to reduce wake-emitted TI; this strategy, generally referred as Wind Sector Management (WSM), can lead to a significant energy loss. In this talk CePO is presented, which is an optimization tool allowing to minimize the energy losses of the farm while ensuring that constraints of the standard are still fulfilled.

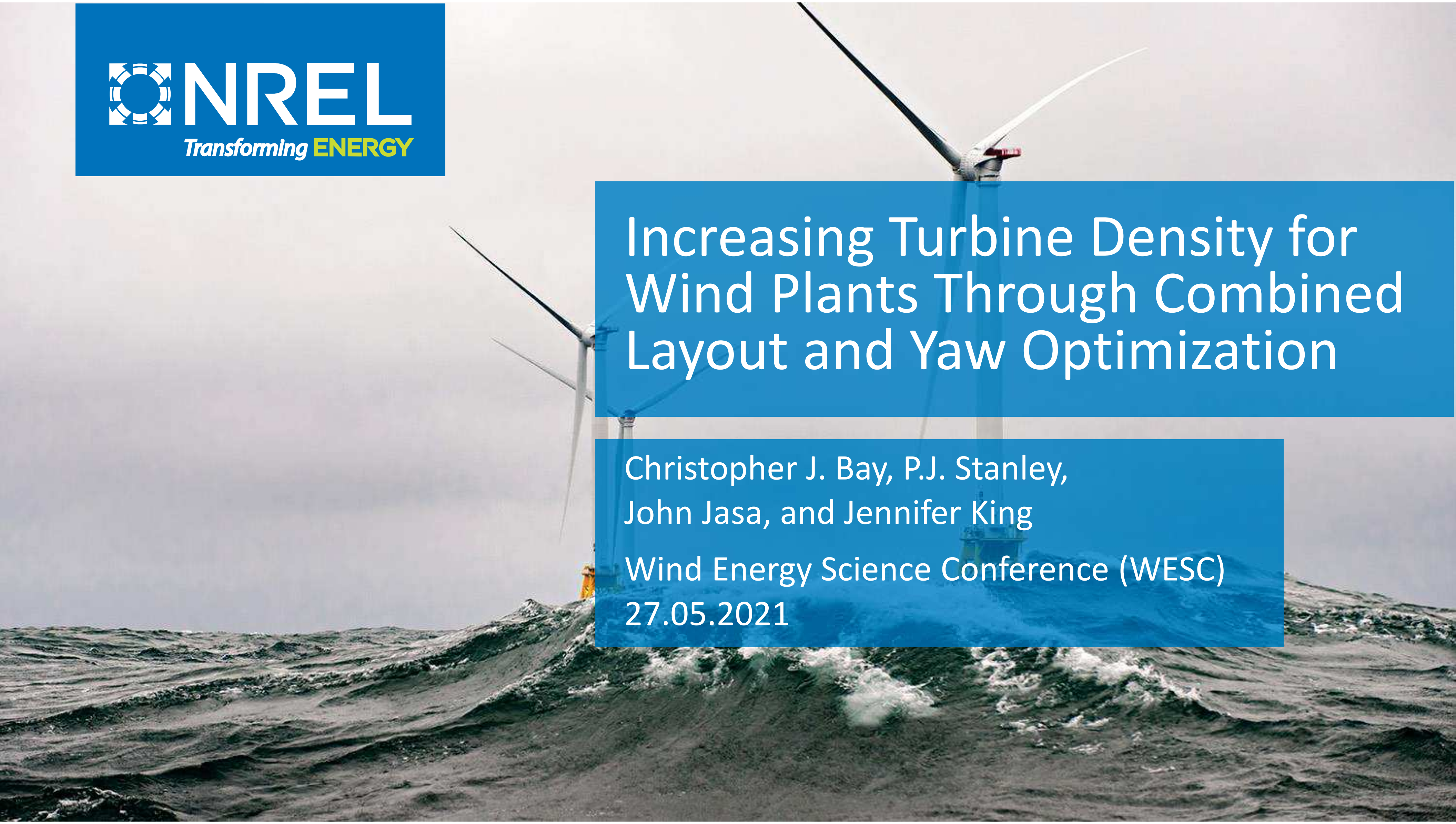
As a study case, the tool is applied on Sole du Moulin Vieux (SMV) wind farm. In this example, the SMV5 wind turbine is affected by the wake emitted by the upstream turbine SMV6, which causes exceedances of the acceptable threshold between 9 and 14 m/s. Through CePO, the performance of the wind farm can be optimized by choosing the WSM strategy leading to a lower loss of the available energy. In the CePO v.0, only shut downs of turbines are considered, but in the new version v.1, currently in development, derating will also be considered, leading to a better wind farm control optimization for power and loads.

4 Conclusion

The benefits of Wind Farm Control in the design phase of wind project were studied within the Task 3.3 of the FarmConners projects. A mini-symposium at the Wind Energy Science Conference 2021 was organized to introduce several topics related to this issue: combined layout and WFC optimization, grid integration, bankability of WFC, and loading reduction. This is one of the first times the topic has been presented and discussed in detail within the wind energy community. It is hoped that thanks to this initiative and the further development of WFC, more research can be realized in the future regarding this subject, and lead to an enhanced deployment of this technology.

5 Appendices

The presentations from the four speakers in the WESC mini-symposium are attached in the following pages.



Increasing Turbine Density for Wind Plants Through Combined Layout and Yaw Optimization

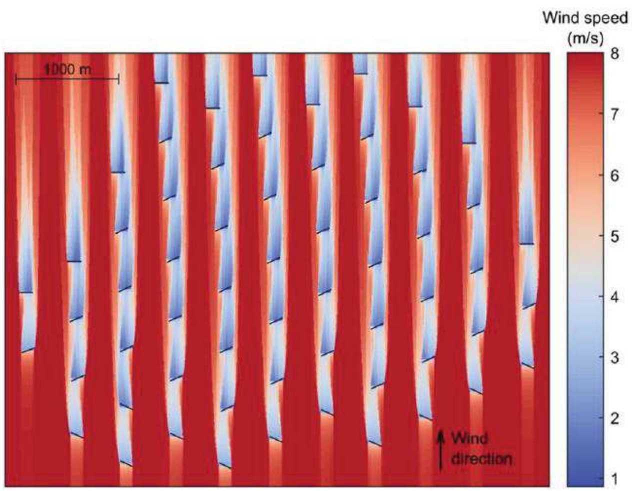
Christopher J. Bay, P.J. Stanley,
John Jasa, and Jennifer King

Wind Energy Science Conference (WESC)
27.05.2021

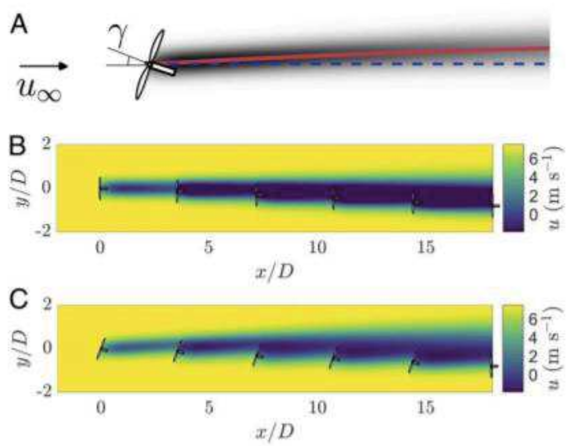
Overview of Wake Steering

- Wake deflection can be used in wind turbine arrays/farms to increase AEP
- Gain in downstream turbines can outweigh loss in upstream turbines
- Wake steering is more powerful in low-TI conditions
- Active research into wake steering over recent years

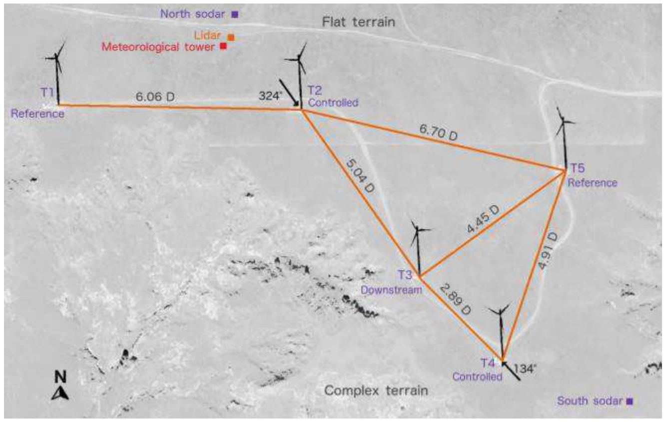
*Not a complete list



(Fleming, et. al., 2016)



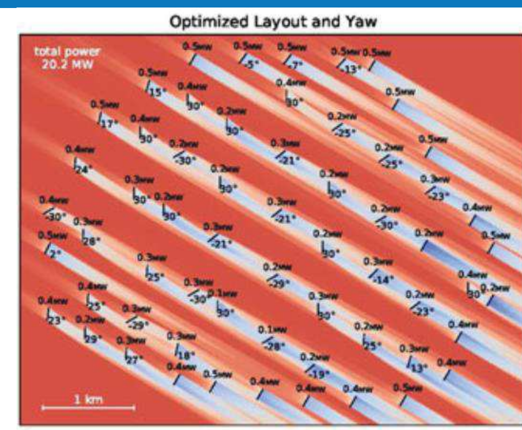
(Howland, et. al., 2018)



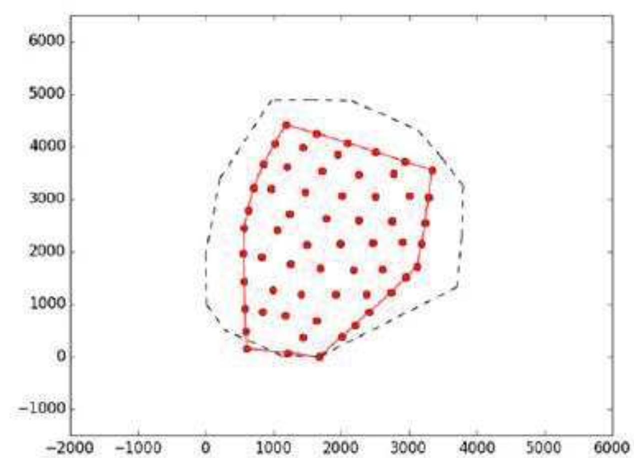
(Fleming, et. al., 2019)

Combined Layout and Yaw Optimization

- Limited previous work of wake steering + layout has been completed in literature
- Increases the design flexibility to handle environmental constraints
- More opportunity for co-design optimizations, tying together controls, layout, cabling, lease area, loads, etc.
- Full optimizations require a lot of computational resources
- Simplified methods that achieve most of the performance gains are beneficial



(Gebraad, et. al., 2016)



(Fleming, et. al., 2016)

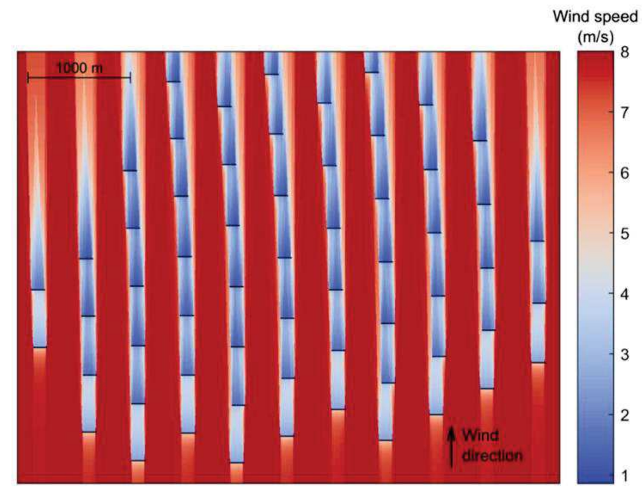
FLORIS: Controls-Oriented Wind Farm Model

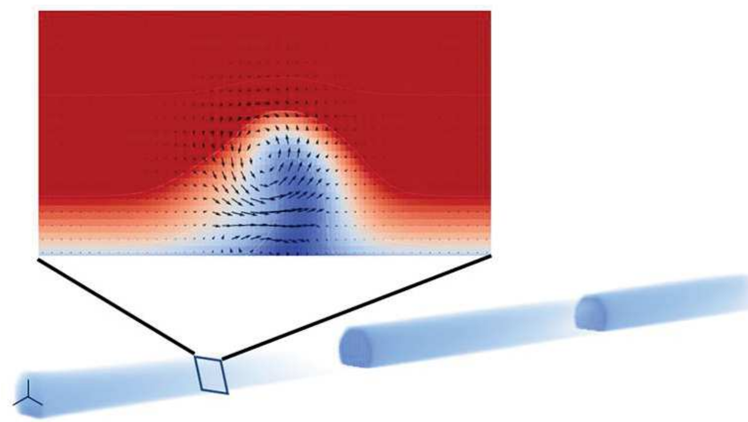
FLORIS framework provides a computationally inexpensive, controls-oriented modeling tool for steady-state characteristics in wind farms.

Available on github (https://github.com/NREL/floris) with several examples.

Models currently implemented:

- Jensen model for velocity deficit
- Jimenez model for wake deflection
- Gauss model for deflection and velocity deficit
- Curl model for deflection and velocity deficit
- **Gauss Curl Hybrid (GCH)** model for deflection and velocity deficit





1D Problem Setup

- Minimizing length of 1D array
- Apply the same spacing between turbines
- Each turbine's yaw angle can be changed
- Constrained to produce the same power as the initial spacing
- Optimized for one wind direction/speed

$$\min_{x_{spc},\gamma} J = \frac{Dist(x_{spc})}{Dist_{init}}$$

$$\text{s.t. } AEP(\gamma) \geq AEP_{init}$$

$$\gamma_{min} \leq \gamma \leq \gamma_{max}$$

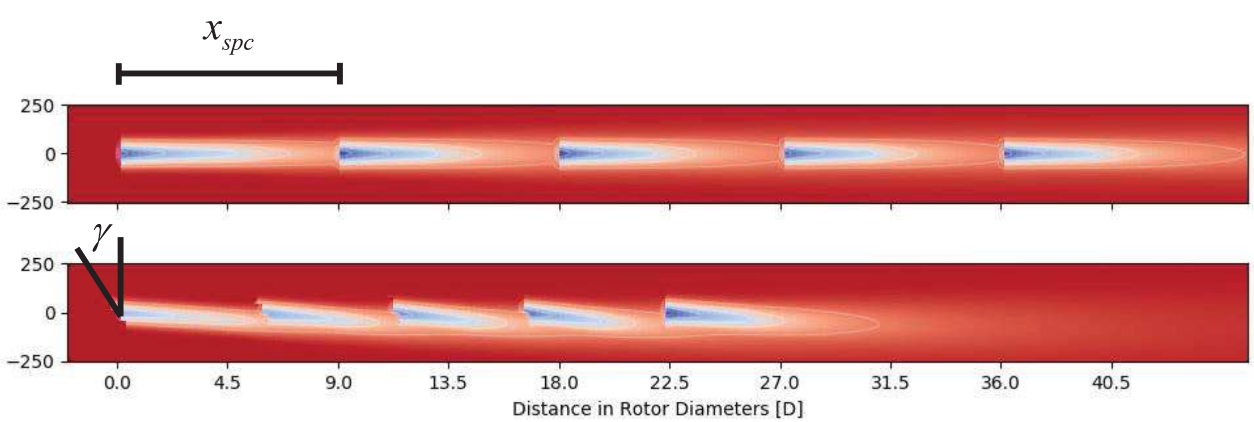
$$S_{ij} \geq 3D$$

$$Dist = \max(layout_x) - \min(layout_x)$$

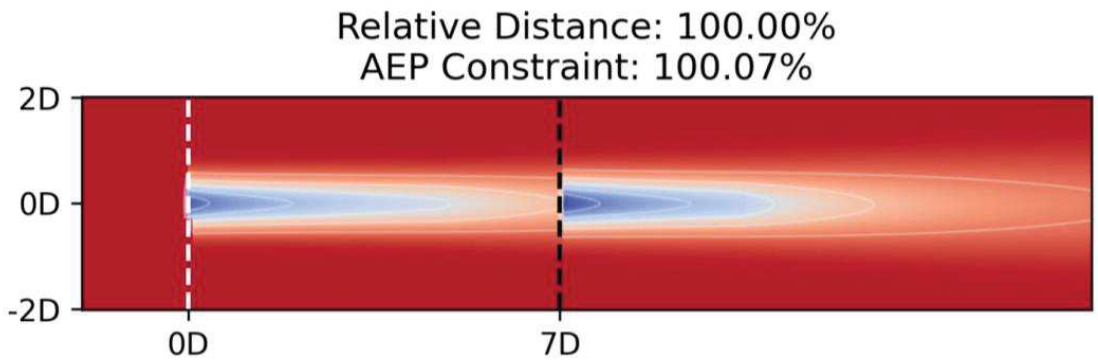
$$layout_x = [i \cdot x_{spc} \text{ for } i \text{ in range}(nturbs_x)]$$

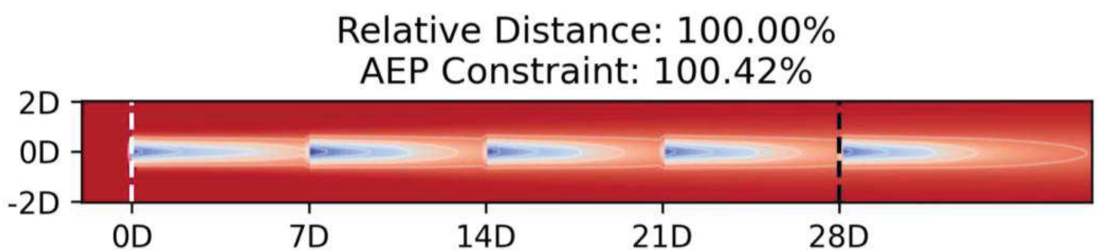
$$x_{spc} = \text{turbine spacing in the x-coordinate}$$

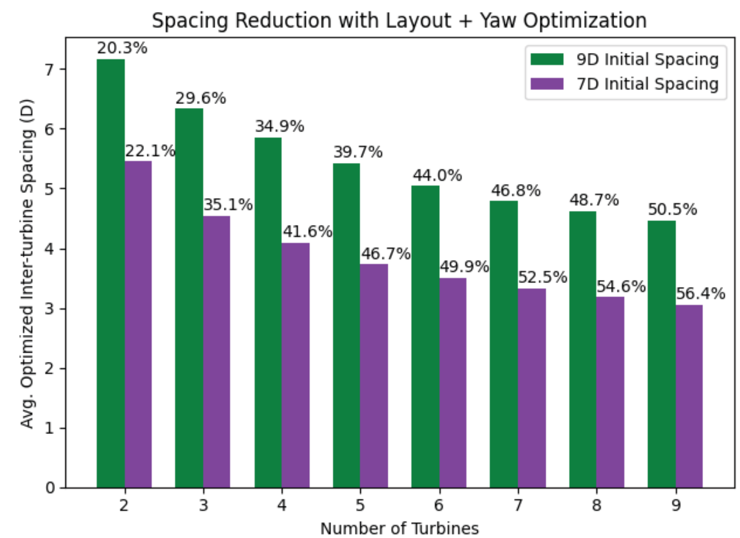
$$\gamma = \text{array of turbine yaw angles}$$

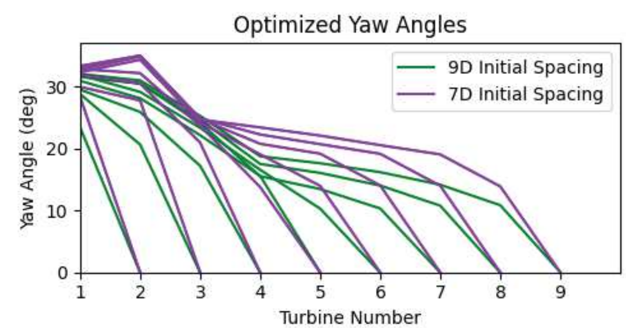


1D Optimization Results





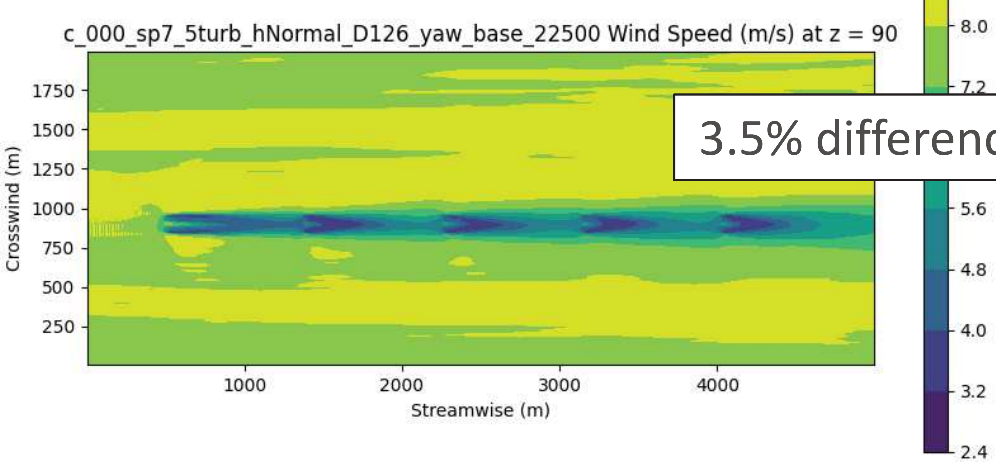




1D SOWFA Validation

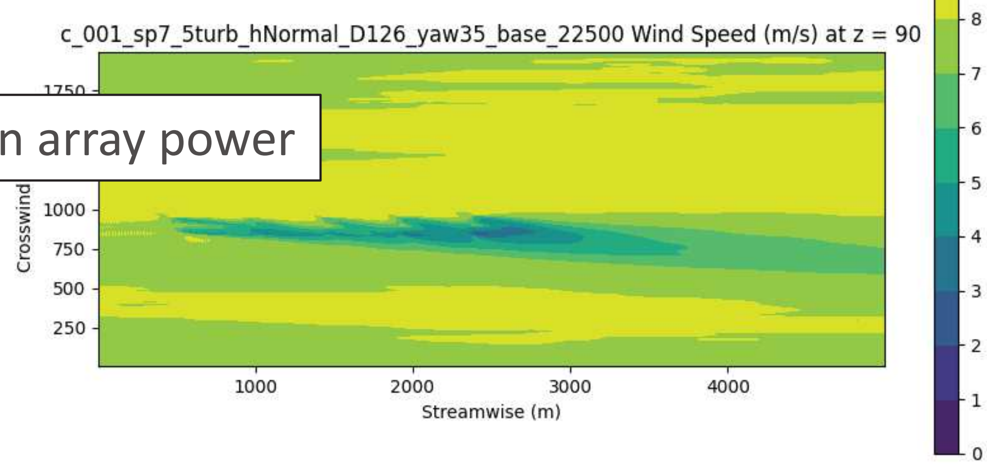
- Ran SOWFA simulations for the baseline 5 turbine array as well as the optimized locations and yaw angles
- Small difference in power can be attributed to FLORIS' current capabilities of capturing deep array effects, as well as tuning/averaged values of SOWFA

Initial Aligned Case



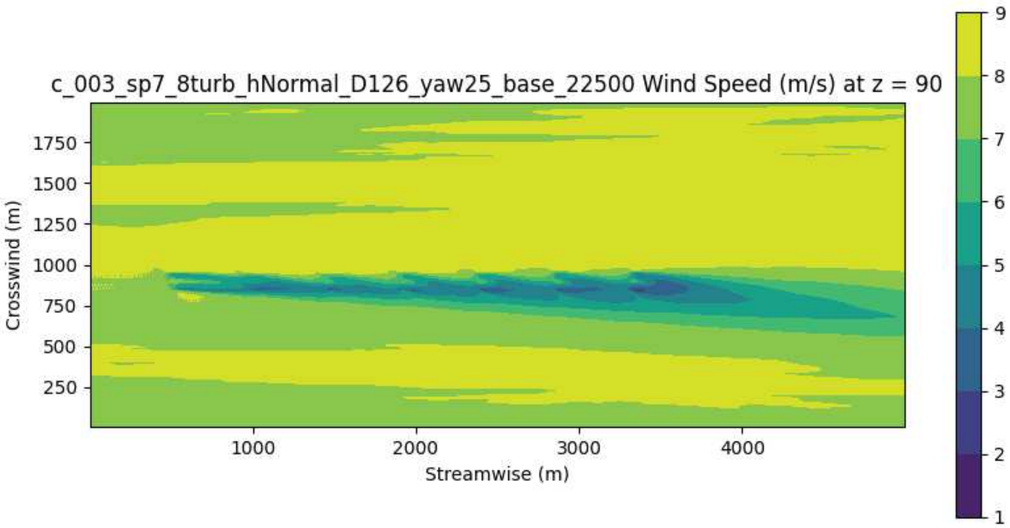
3.5% difference in array power

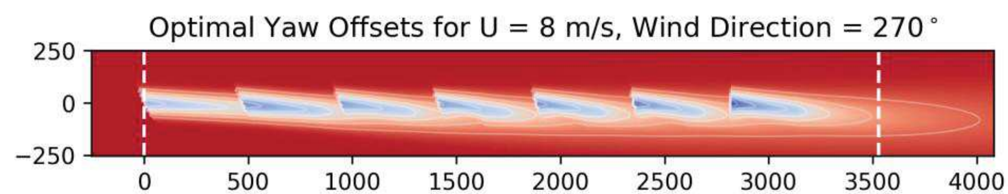
Optimized Layout + Yaw



Adding Turbines to Newly Available Space

- Can increase energy production by placing turbines in newly free space
- Assuming same spacing as determined from the first optimization, fill the array within the original spacing footprint
- Re-optimizing yaw angles on new layout shows power increase of ~27% for same wind condition in SOWFA (with the objective of increasing AEP)





2D Problem Setup

- Minimizing area of 2D array
- Apply the same spacing spanwise and streamwise between turbines
- Each turbine's yaw angle is optimized for each wind direction/speed combination
- Constrained to produce the same power as the initial spacing

$$\min_{x_{spc},\gamma} J = \frac{Area(x_{spc})}{Area_{init}}$$

$$\text{s.t. } AEP(\gamma) \geq AEP_{init}$$

$$\gamma_{min} \leq \gamma \leq \gamma_{max}$$

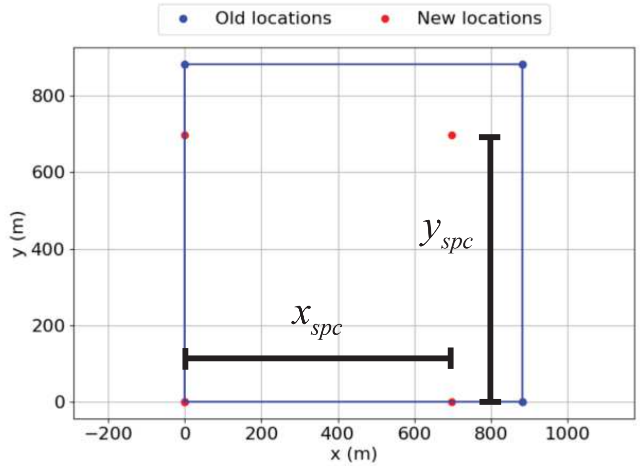
$$S_{ij} \geq 3D$$

$Area =$ area of the convex hull of turbine coordinates

$x_{spc} =$ turbine spacing in the x-coordinate

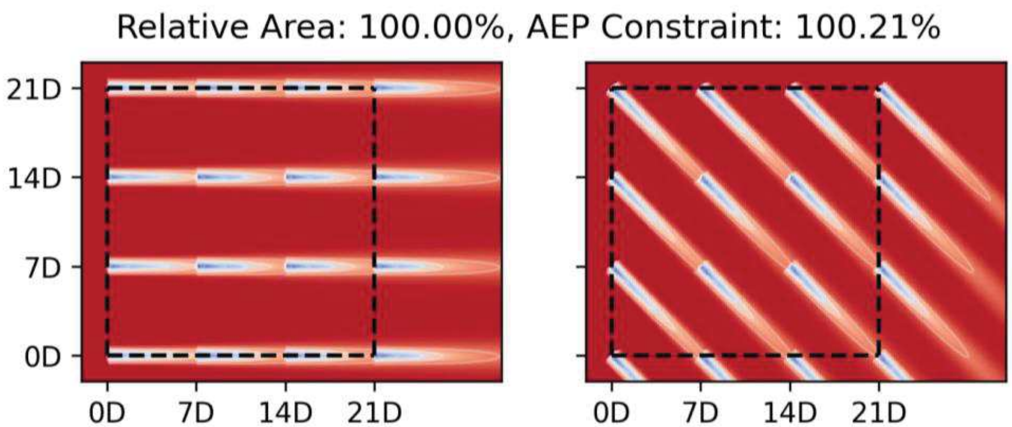
$y_{spc} = x_{spc}$

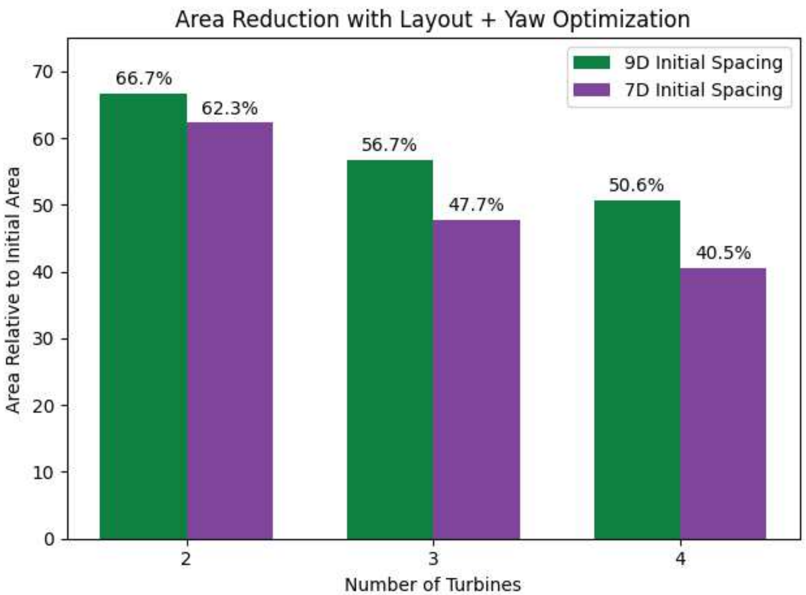
$\gamma =$ array of turbine yaw angles



2D Optimization Results

- Similar trend as 1D optimization, with leading turbines yawing to recover power production
- Table shows that using just 2 wind directions doesn't result in significant AEP differences vs a more complete wind rose





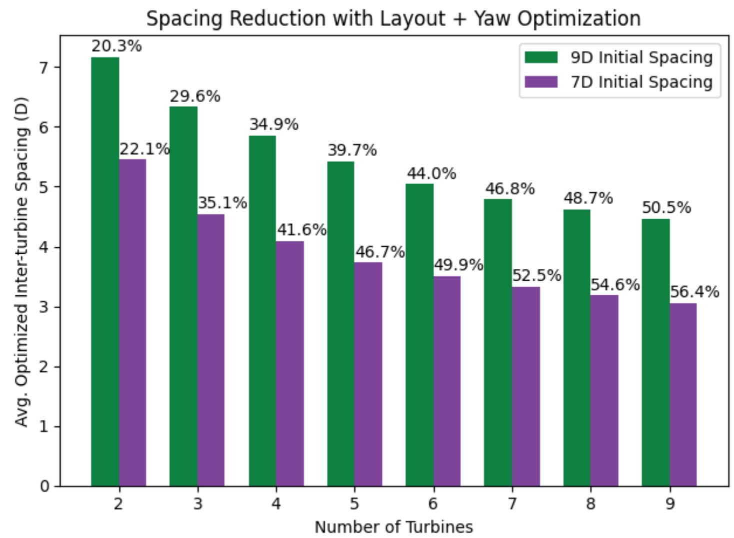
Layout	Baseline AEP	Optimized AEP	Difference
2x2	56.70 GWh	56.29 GWh	0.72%
3x3	123.87 GWh	120.43 GWh	2.78%

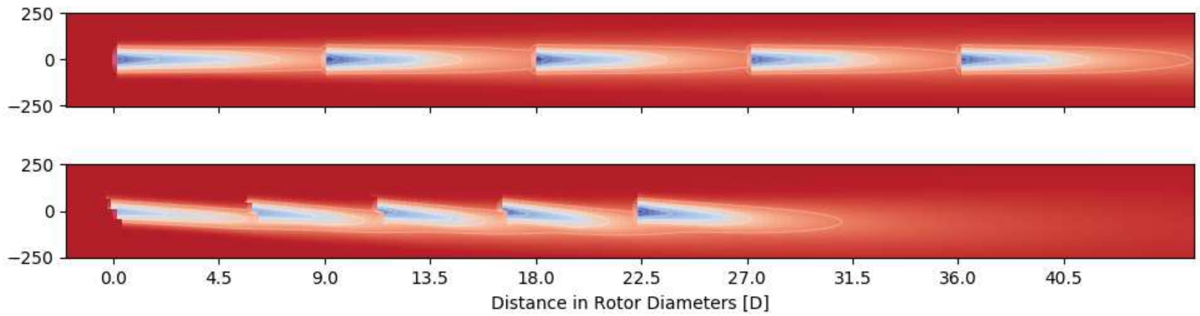
Future Work

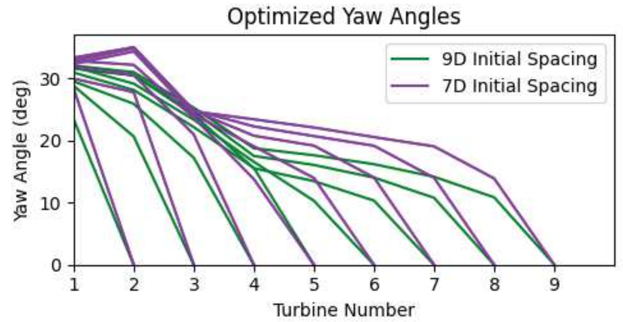
- More complex optimizations:
  - Environmental constraints/exclusion zones
  - Non-fixed number of turbines
  - Non-grid layouts
  - Co-design (cabling, loads, etc.) under different objective functions (cost, revenue)
  - Optimization under uncertainty
- Develop ways to simplify optimizations
- Further investigate differences between coupled and step-wise optimizations of layout and yaw

Summary

- Layout + yaw optimizations enable increased power density within wind farms
- Initial LES validation shows FLORIS can be used to accurately predict increases in performance
- Coupling of layout and yaw in the design phase enables increased design flexibility







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NREL Transforming ENERGY

Electrical design and control for grid code compliance and system service provision

Til Kristian Vrana
SINTEF Energi
Trondheim, Norway

Outline

- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
- Compromise-determined grid-forming control

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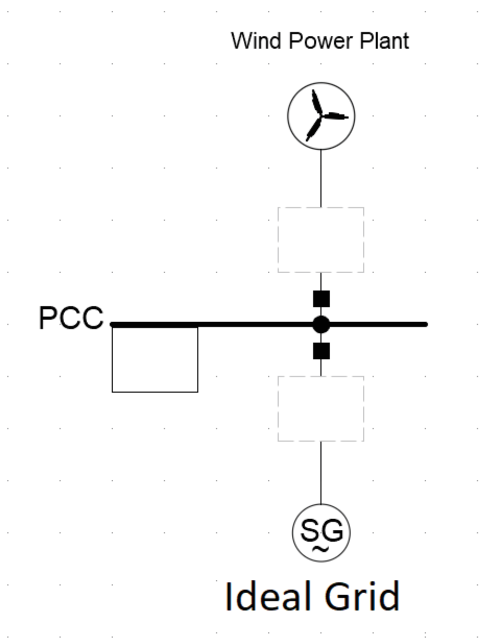
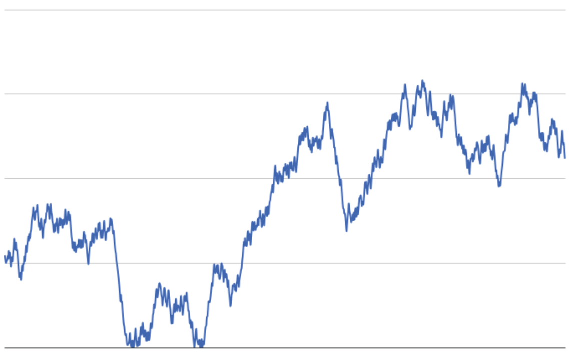
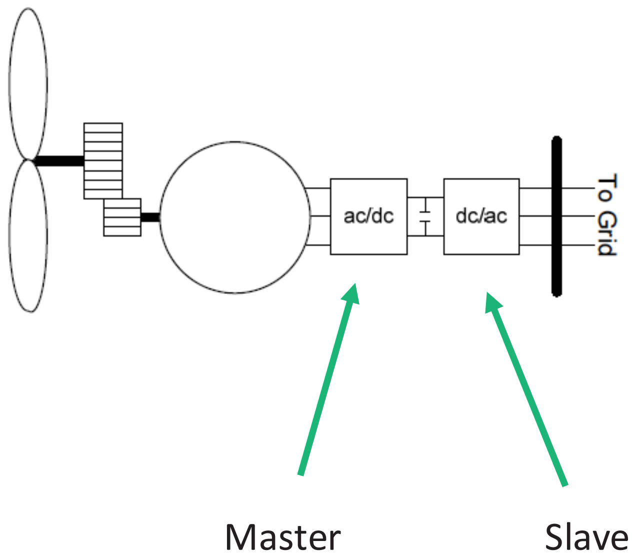
Turbine-determined grid-following control

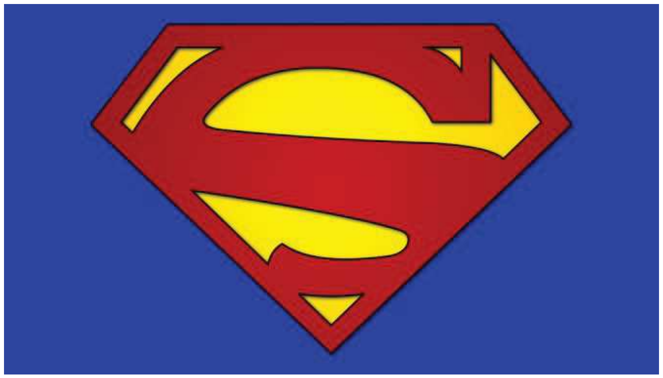


- Grid side active power is determined by the turbine and the wind
- Grid is ideal and just accepting the incomming power, whatever it may be

Turbine-determined grid-following control







Outline

- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
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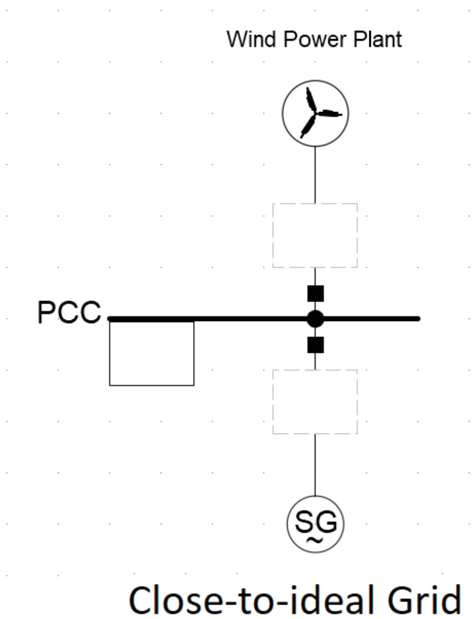
Turbine-determined grid-supporting control



- Grid side active power is determined by the turbine and the wind most of the time
- Grid is close to ideal and just accepting the incomming power most of the time
- System services (e.g. FRT, FFR,…) provided by the wind power plant when needed

Outline

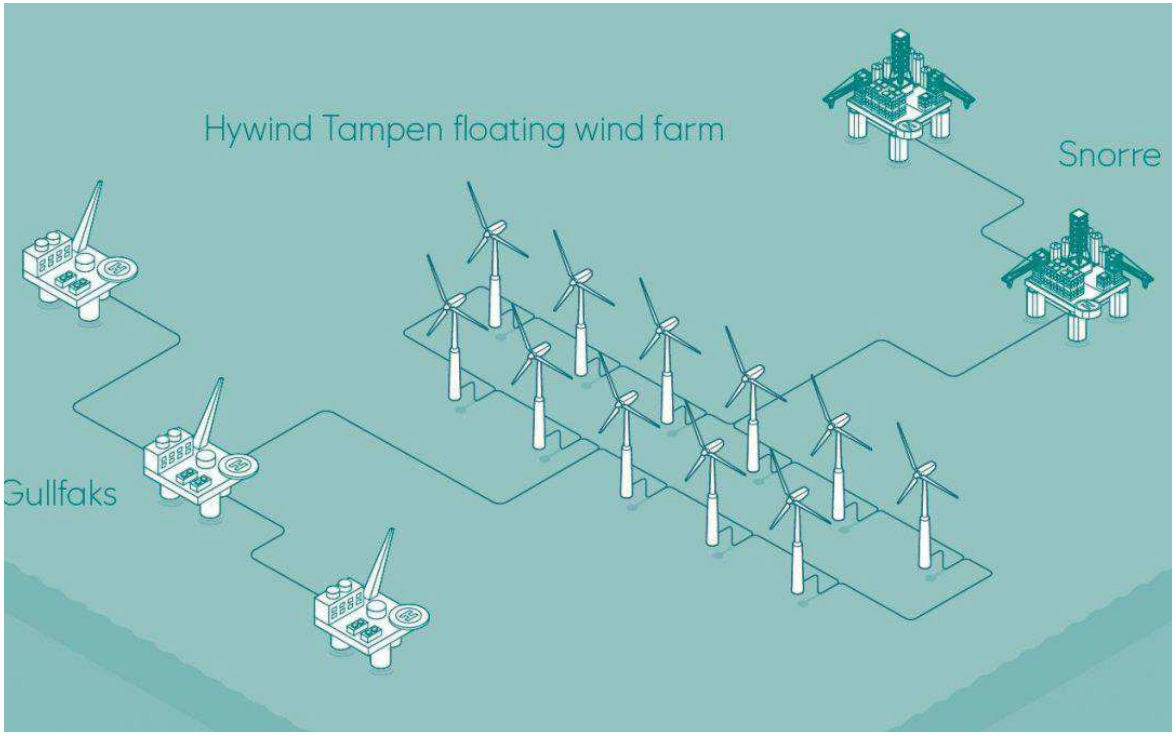
- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
- Compromise-determined grid-forming control

Outline

- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
- Compromise-determined grid-forming control

Grid-determined grid-forming control
Offgrid electricity supply

Grid-determined grid-forming control
Hywind Tampen



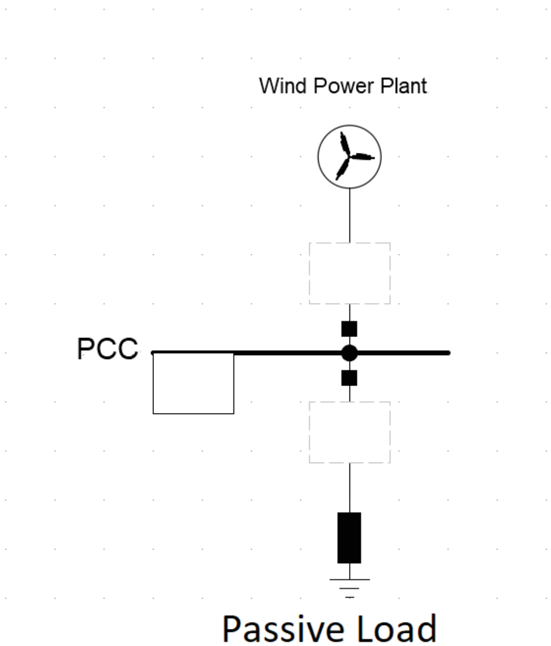
Grid-determined grid-forming control

- There is a parallel source of electricity
  - based on fossile fuel
  - doing all the hard work (forming the grid voltage, keeping the power balance)
- Wind turbine is standard booring grid-following

wouldn't it be nice if the wind turbine could do it alone?

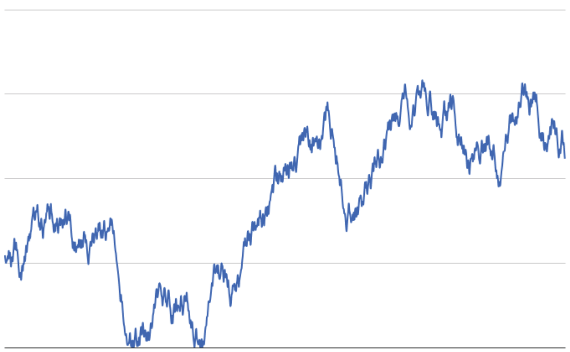
not with the control principles as we use them today...

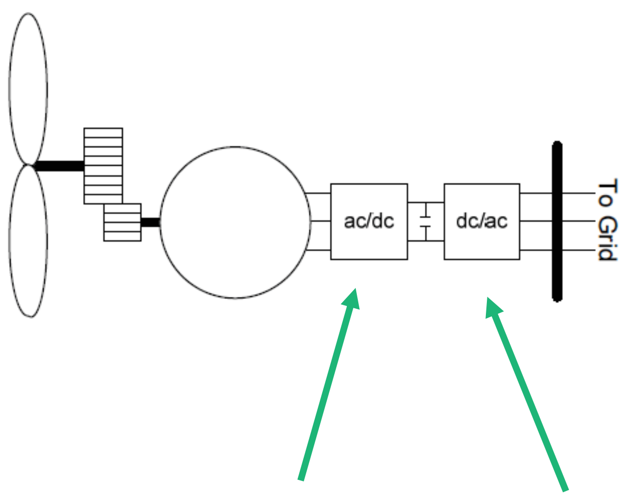
Grid-determined grid-forming control
The other extreme



- Grid side active power is determined by the load (grid impedance)
- The turbine has to deliver, whatever it may be

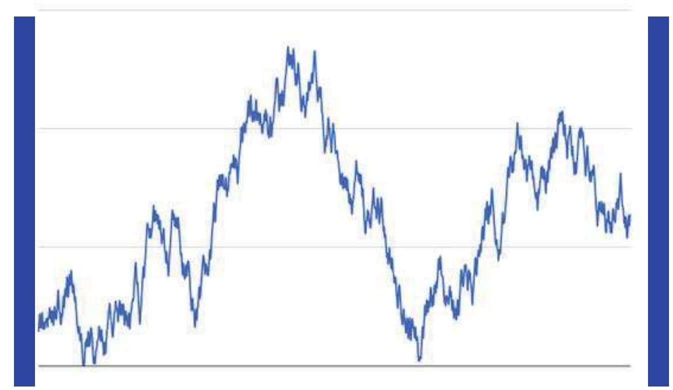
Grid-determined grid-forming control
The other extreme





Master

Slave



Turbine vs grid determined

Turbine determined control

- Active power is determined by the turbine
- Grid is accepting the incomming power

- Example: Wind Turbine today

Grid determined control

- Active power is determined by the electrical loads
- Turbine delivers the exact amount demanded

- Example: UPS

Grid following vs forming?

Grid following (supporting)

- Current source
- Measures grid voltage and frequency
- No stand-alone operation
- Not future-proof

Grid forming

- Voltage source
- Has its own voltage and frequency
- Stand-alone operation
- Future proof

Outline

- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
- Compromise-determined grid-forming control

Outline

- Turbine-determined grid-following control
- Turbine-determined grid-supporting control
- Grid-determined grid-forming control
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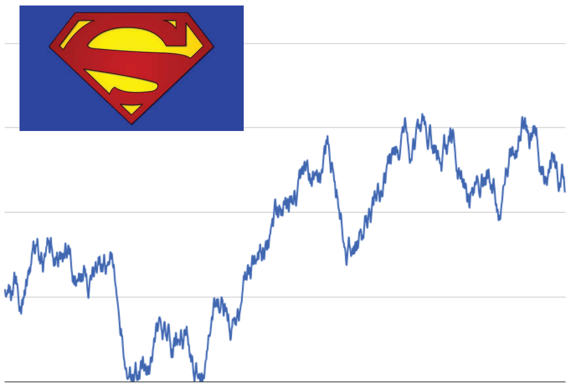
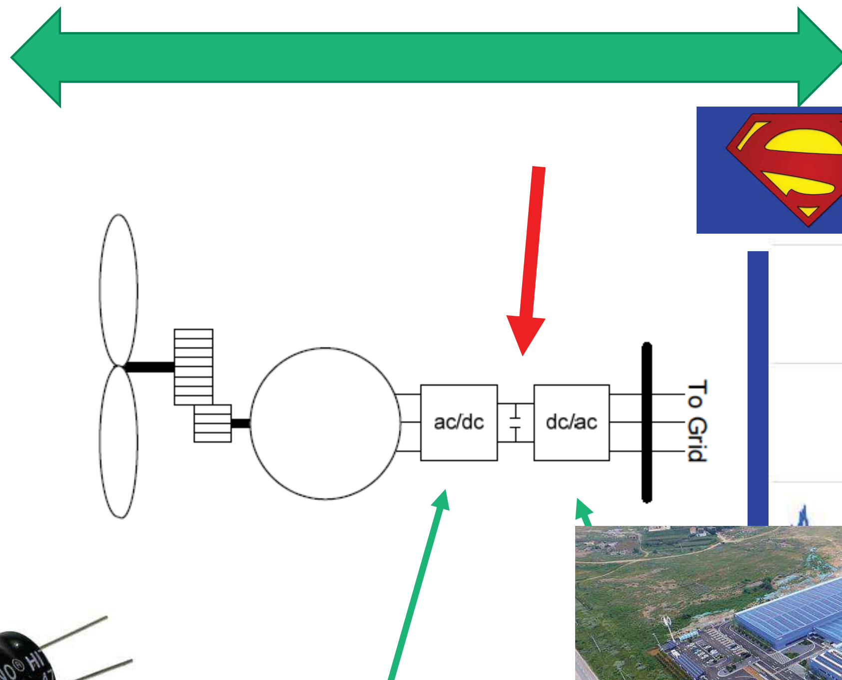
Compromise-determined grid-forming control



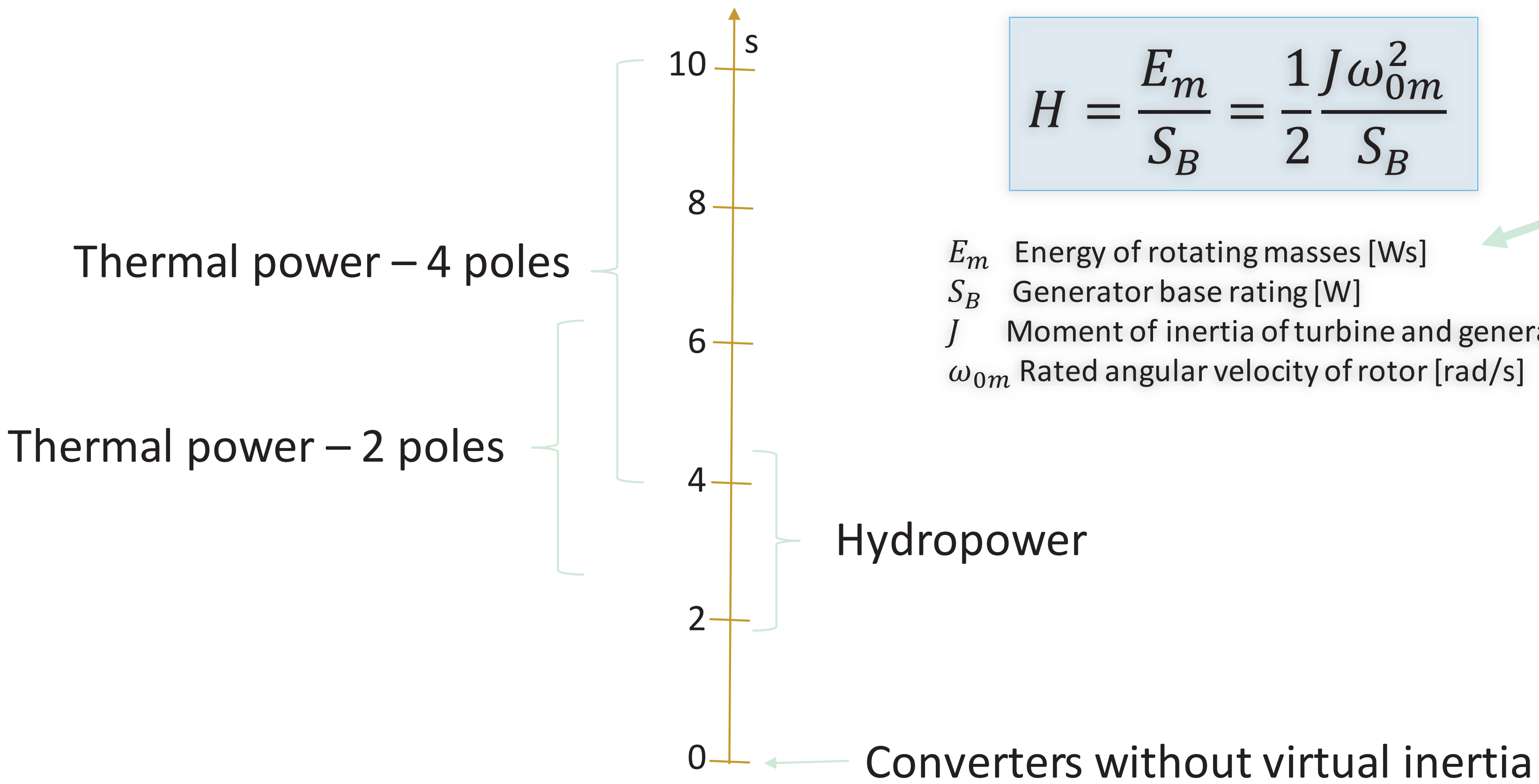


Master

Compromise-determined grid-forming control
Inertia

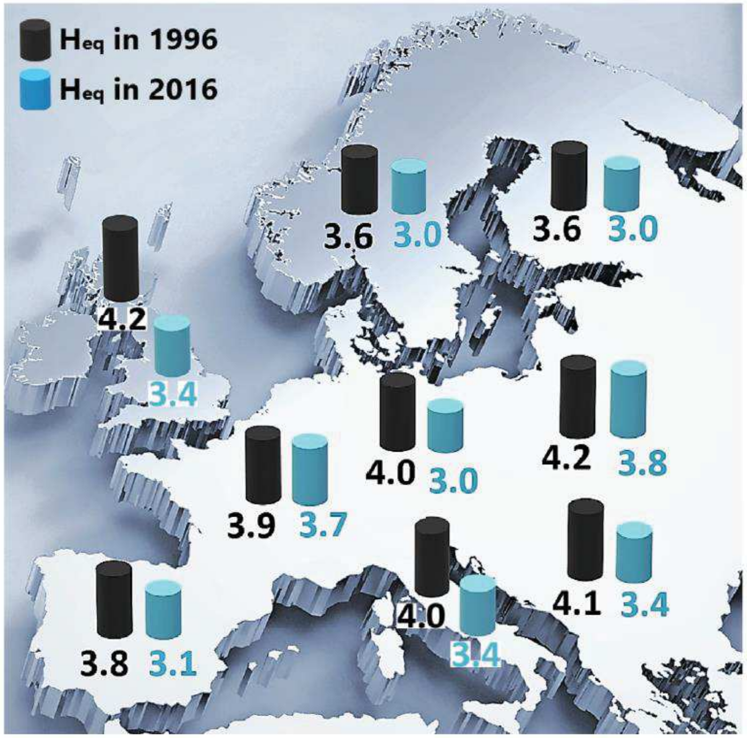
$$H = \frac{E_m}{S_B} = \frac{1}{2}\frac{J\omega_{0m}^2}{S_B}$$

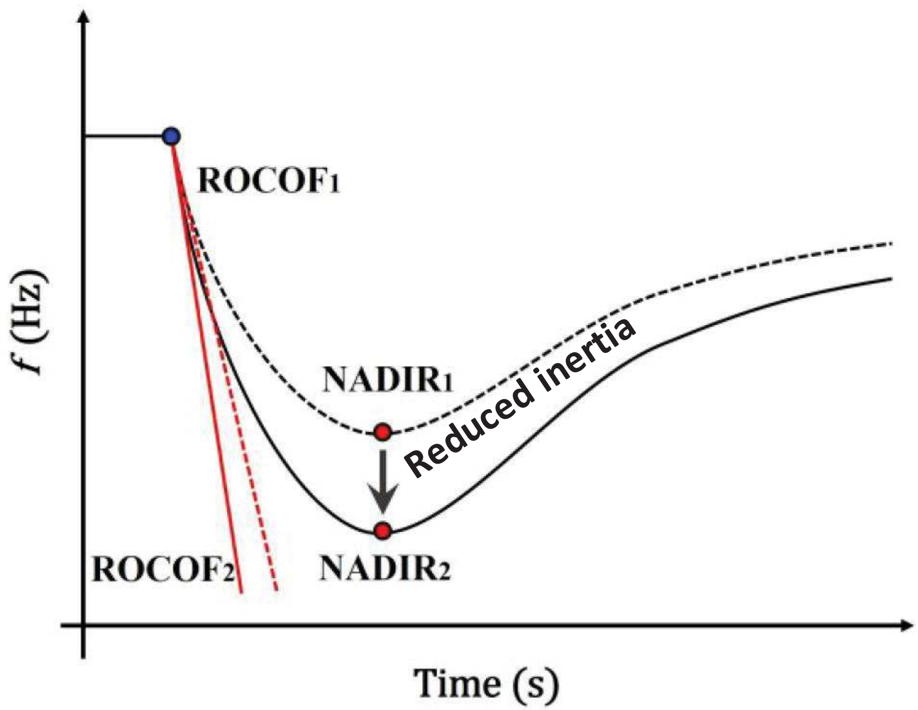
E_m Energy of rotating masses [Ws]
S_B Generator base rating [W]
J Moment of inertia of turbine and generator [kgm^2]
ω_{0m} Rated angular velocity of rotor [rad/s]



Takk Tor Inge Reigstad for denne foljen

Compromise-determined grid-forming control
Inertia





Compromise-determined grid-forming control
Where to get the energy from?

- Dedicated storage
  - Buying that storage costs a lot of money…
- Inertia of the rotor
  - Seriously messing with turbine control
    - increasing mechanical loads
    - reducing energy capture
      - costs a lot of money…
- Deloading the turbine
  - Wasting a lot of energy
    - costs a lot of money…

-> A combination of the above…

Compromise-determined grid-forming control "Fourier tranformation"

Fast components of the response

- Storage
  - Small size sufficient
  - Ability to be really fast
- Wind Turbine
  - Ugly mechanical load changes
  - Pitch speed very limited

Slower components of the response

- Storage
  - Expensive large storage
  - Fast speed not needed
- Wind Turbine
  - Less mechanical loads
  - Suitable response speed

Conclusion

- Turbine control will become less turbine-determined than today
- Grid events could influence wind farm flow
- Virtual inertia provision requires some output flexibility
  - Either energy from dedicated storage
  - Or from the turbine itself
- Best solution likely a combination of both
- Modular expandable storage for future-proofness?
- Distributed in-turbine-storage will be a new aspect for wind farm control

Thank you for your attention

Danke fürs Zuhören

Takk for merksemda

WHEN TRUST MATTERS

Bankability of Wind Farm Control

Lars Landberg, Ervin Bossanyi, Renzo Ruisi, Nicholas Skeen, Giuseppe Ferraro, Matthew Harrison, Stefanie Bourne, Keir Harman, Andreas Manjock, Nikolai Hille, Anja Neubert, Mattia Boccolini, Axel Dombrowski, Tom Levick, Tony Mercer

27 May 2021

How did we get here?

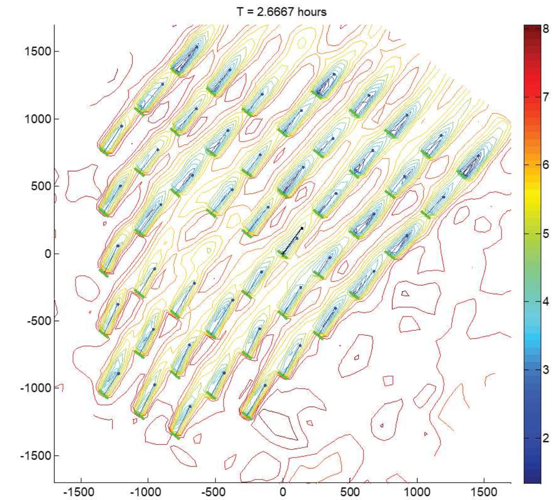
- R&D in academia and industry (including DNV)
- Funded research projects, like Farmconners, TotalControl, CL-Windcon, OWP control etc
- First moving developers, owners and manufacturers

Today’s menu

- What is WFC?
- What is Bankability?
- Why is Bankability important?
- Who are the stakeholders?
- The steps towards bankability
- Where are we today?
- What about certification?
- JIP!

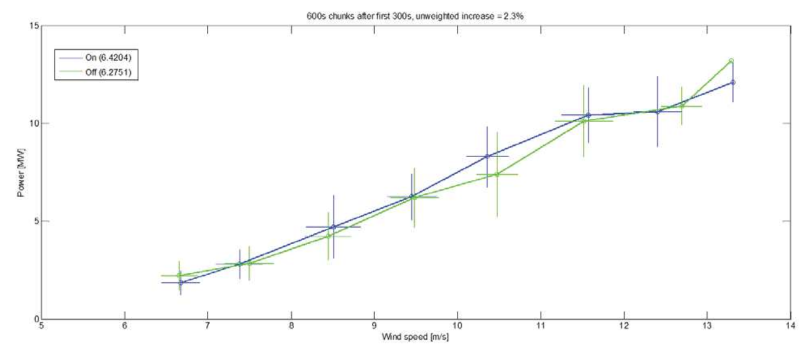
DNV

Wind Farm Control



What[1]

- Wake steering
- Induction control



Why

- Increased revenue from generation
- Reduction in operational turbine loading
- Extension of the life of the wind turbines

[1] Wind farm control, Group Research & Development white paper 2018 https://www.dnvgl.com/publications/wind-farm-control-133013

Bankability

Bankability can broadly be defined as the **willingness of an established financial institution to finance a project at a reasonable interest rate**. The decision to invest in a given technology will typically be taken once a certain level of confidence is reached, proven track record is observed, and suitable contractual risk coverage is in place.

Not *for DNV to assign bankability to any given project*

Steps towards bankability

- DNV framework:
  - pre-qualified
  - qualified
  - commercially proven

“Dimensions” of WFC

- Retrofit
- New wind farms

Pre-qualified

A technology shall enter pre-qualified stage when:

- The technology supplier is able to **simulate** the implementation and impact in terms of energy and loading of wind farm control and the methodology should be accepted by at least one established independent party
- **Robust and repeatable** modelling techniques are demonstrated by the supplier
- A specific technology supplier has demonstrated feasibility and practical plans for implementation on **a range** of projects under different conditions and a related study has been checked by an established independent party

Qualified

As for pre-qualified and also:

- The technology supplier must be able to demonstrate reliable operation in a range of conditions by means of **validation studies**, which should be reviewed and accepted by an established independent party
- The technology supplier must **demonstrate** all contractual and commercial obligations can be met
- The technology supplier must be able to **provide assurance** from the certification body that this technology may work at least under generic conditions considered in the type certificate.

Commercially proven

As for qualified and also:

- The technology supplier demonstrates that the calculation methodologies to simulate and calculate the wind farm control outcome **are independently verified, reliable and repeatable** under a range of conditions
- There is **substantial track record** for the specific wind farm control implementation, with several operational applications supported by measurements
- The technology supplier must be able to provide evidence of track record by means of **site-specific design assessment or project certificate** on multiple projects featuring the specific implementation of wind farm control being considered.

WFC Bankability main players

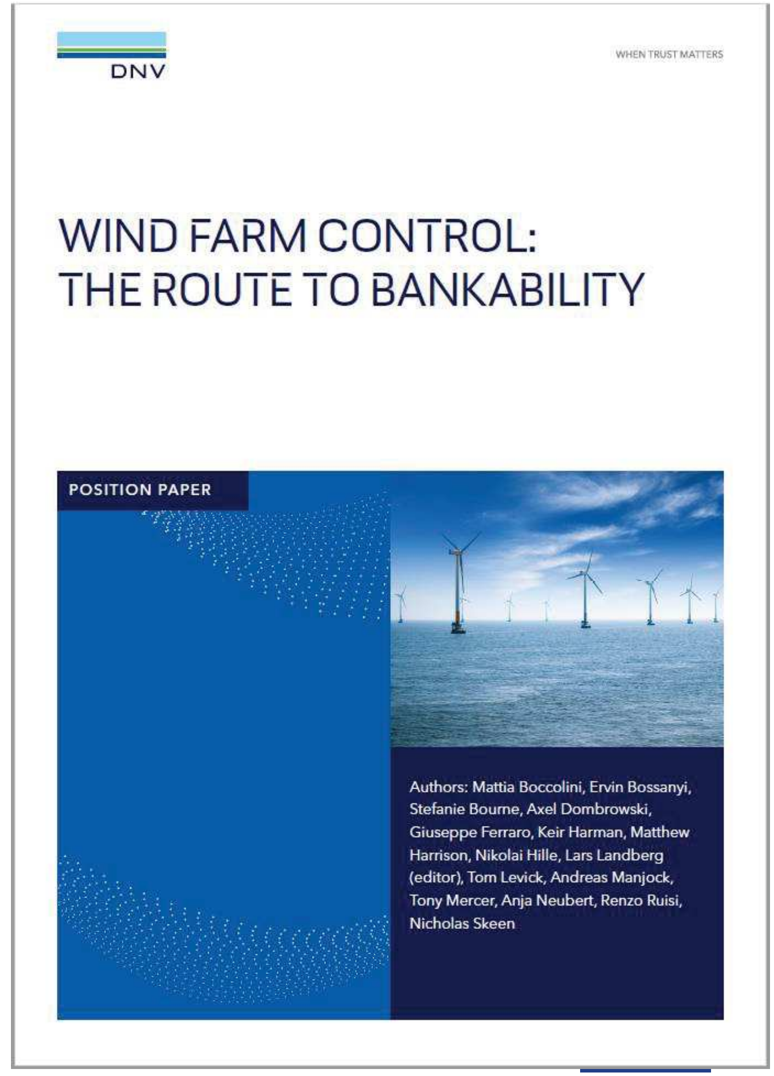
- Banks and other financial institutions
- Investors
- Developers
- Owners
- Operators
- Manufacturers
- Insurers
- Certifying bodies
- Consultants

Certification

- Currently, no designated design standard for wind farm control exists prescribing detailed requirements for certification
- However, certification approaches such as measurement-based assessment or risk-based assessment exist and can be applied for wind farm control certification to achieve comparable safety levels to usual standards

Position paper just out!

https://www.dnv.com/Publications/wind-farm-control-198162


DNV

WHEN TRUST MATTERS

WIND FARM CONTROL:
THE ROUTE TO BANKABILITY

POSITION PAPER

Authors: Mattia Boccolini, Ervin Bossanyi, Stefanie Bourne, Axel Dombrowski, Giuseppe Ferraro, Keir Harman, Matthew Harrison, Nikolai Hille, Lars Landberg (editor), Tom Levick, Andreas Manjock, Tony Mercer, Anja Neubert, Renzo Ruisi, Nicholas Skeen

JIP

- Duration: 1-1½ years
- No of partners: >10
- Set-up: work packages (can be confidential)
- Output: report

Starting soon!

Validation: Toggle test

Hard (impossible!) to find two identical wind farms in identical conditions to test the WFC

So..

Do a toggle test, ie toggle between

WFC ON

WFC OFF (baseline)

Toggle interval eg 35 mins up to 5 h, depending on the case

Summary & Conclusion

- What is WFC?
- What is Bankability?
- Why is Bankability important?
- Who are the stakeholders?
- The steps towards bankability
- Where are we today?
- What about certification?
- JIP!

WHEN TRUST MATTERS

Questions?

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WIND FARM PERFORMANCE OPTIMIZATION FROM DESIGN PHASE

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Wind Farm Design Phase

Wind Farm Design ①

Site conditions, layout, turbine distances.

Site Suitability ②

IEC 61400-1> Turbulence intensity.

Wind Sector Management ③

Turbulence intensity reduction → Energy production reduction

④ Best strategy?

Minimizes turbulence intensity,
Maximizes energy production,
Minimizes time dedication,
Traceable and systematic.

⑤ Optimization

Genetic algorithms,
Local method.

⑥ CePO

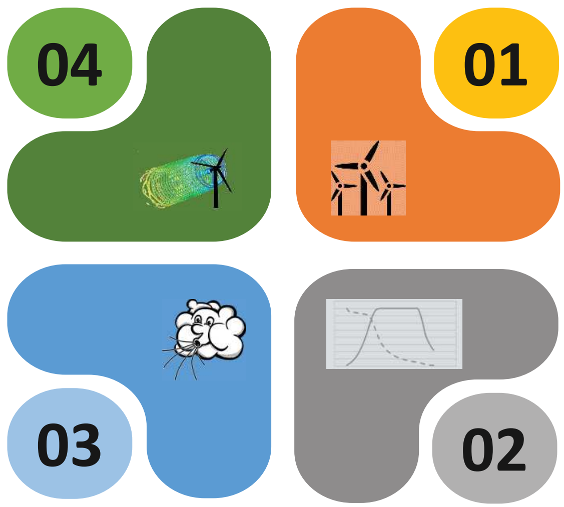
CENER Production Optimizer,
Automated WSM strategy definition.

CePO v0: Define the Wind Sector Management (WSM) that maximizes production and minimizes effective turbulence intensity

What does CePO do?

Turbulence restrictions
For each wind turbine the maximum turbulence intensity in each wind speed

Wind Farm data
Coordinates, turbine model, diameter,…



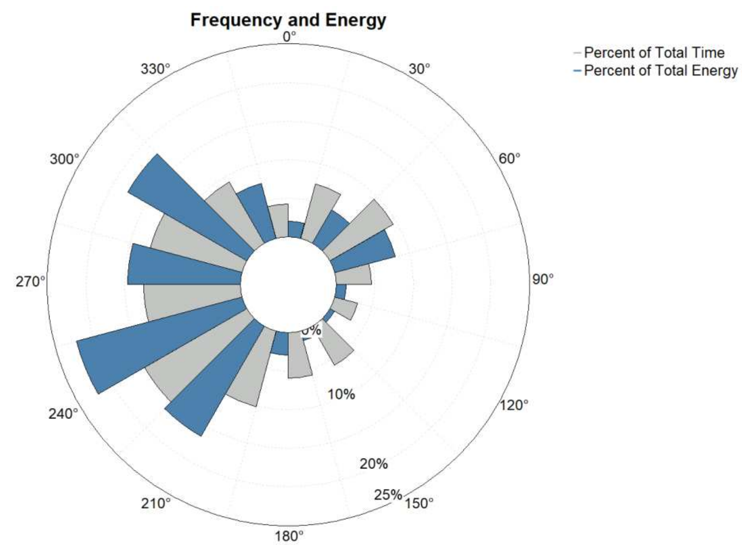
Free wind in each turbine (IEC 61400-1)
Time series (10’) with mean wind, standard deviation and wind direction

Thrust and Power curve
For each turbine and density

Wind farm Sole du Moulin Vieux (ENGIE Green))

CePO V0: Inputs

- Wind data:
  - ➢ Time period: 1st April 2011 to 1st April 2012
  - ➢ Mean wind speed and standard deviation at 81m height
  - ➢ Wind direction at 60 m height
  - ➢ V81=6.13 m/s



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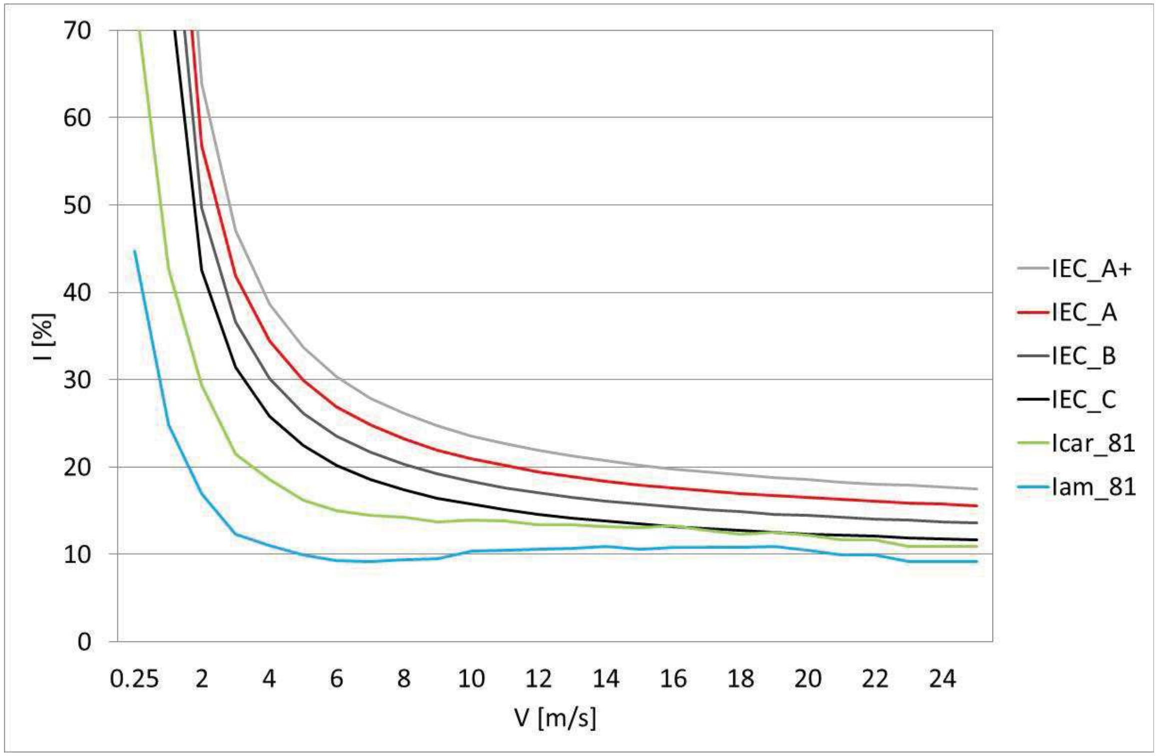
CePO V0: Inputs

- Control turbulence intensity:



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Gobierno de Navarra
Nafarroako Gobernua

CePO V0: Inputs

- Wind Farm data:

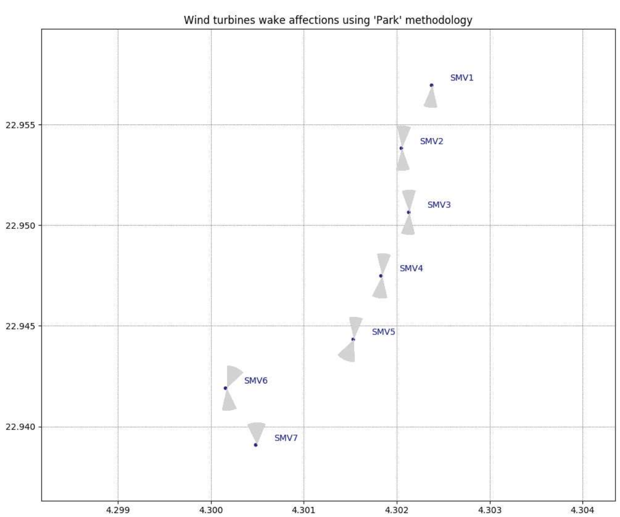
ID	X_UTM	Y_UTM	D	Wind Turbine	Vg	Sg	Wind Data	Turbulence
SMV1	633519	2539349	82	MM82.txt	1.011	1	Mast.txt	Ed3_A
SMV2	633489	2539000	82	MM82.txt	1.011	1	Mast.txt	Ed3_A
SMV3	633500	2538650	82	MM82.txt	1.009	1	Mast.txt	Ed3_A
SMV4	633473	2538300	82	MM82.txt	1.006	1	Mast.txt	Ed3_A
SMV5	633445	2537950	82	MM82.txt	1.006	1	Mast.txt	Ed3_A
SMV6	633307	2537680	82	MM82.txt	1.006	1	Mast.txt	Ed3_A
SMV7	633343	2537367	82	MM82.txt	1.003	1	Mast.txt	Ed3_A

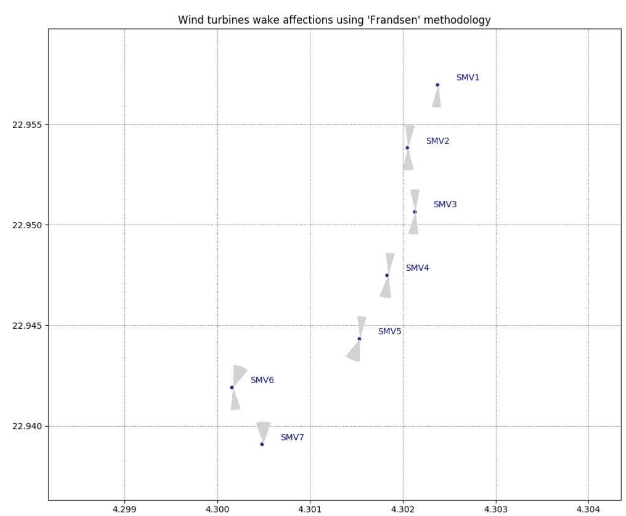
CePO V0. Configuration

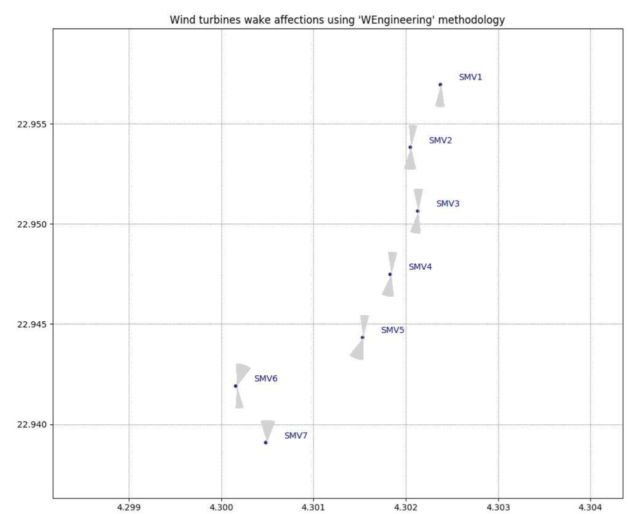
- **Angle of affection (Frandsen)**
- Global or sector calculation (Global)
- IEC 61400-1 edition (Ed3)
- WSM configuration:
  - ➢ Speed range (operation range)
  - ➢ Optimizable or not (all optimizable)
  - ➢ Max. nº of stops (without limit)
  - ➢ The wake decay constant, only for Park angle affection (0.075)
  - ➢ Wöhler parameter (m=10)

CePO V0. Configuration

- **Angle of affection:**
  - Park, f(**k**, D, d)
  - Frandsen, f(D, d)
  - EWEC 2009, cte

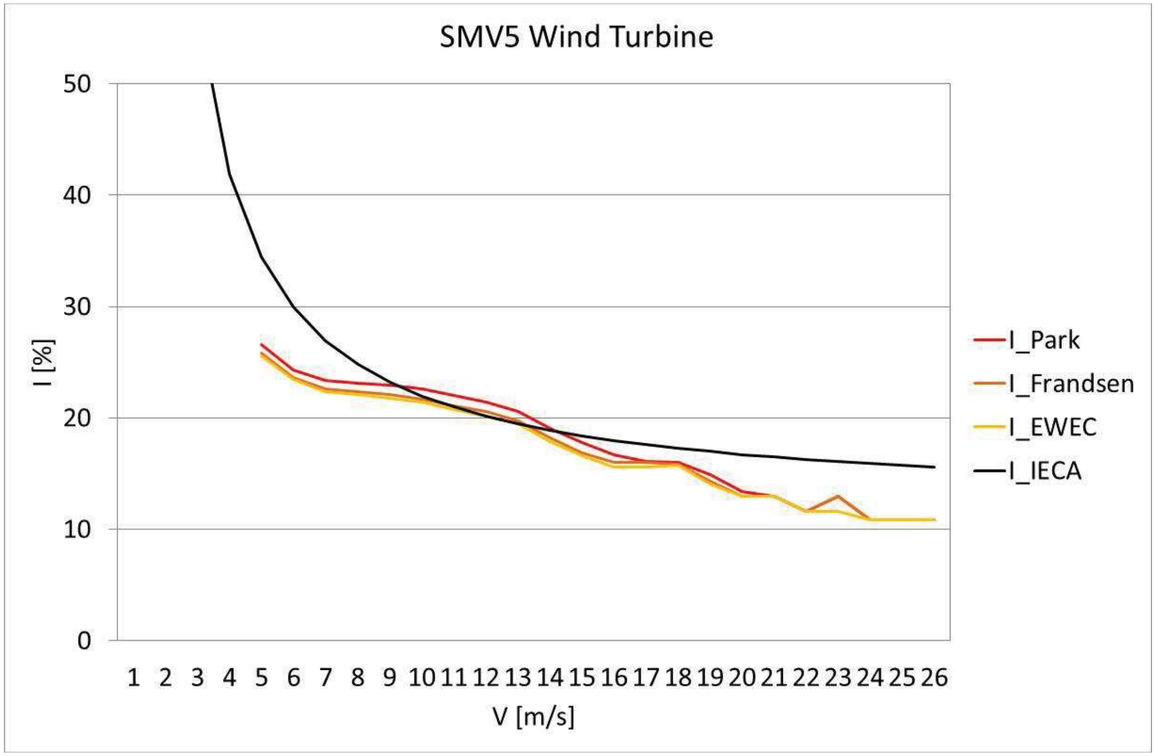






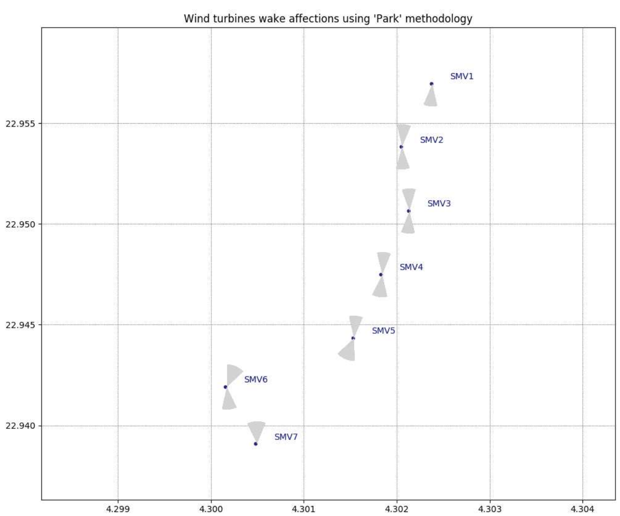
CePO V0. Configuration

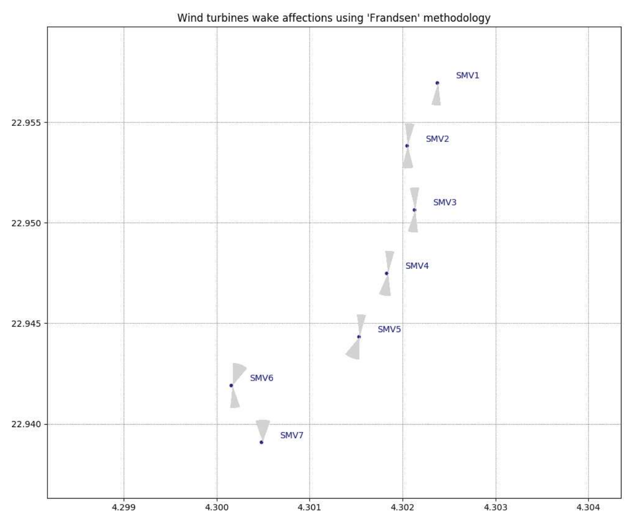
- Angle of affection:

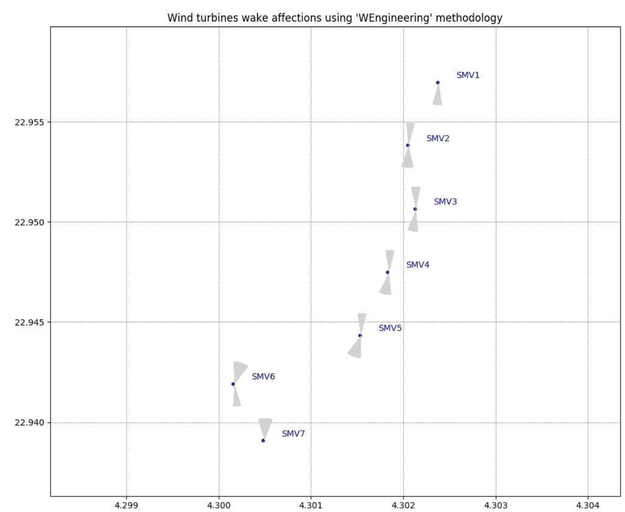


CePO V0. Configuration

- Angle of affection:
  - **Park, f(k, D, d)**
  - Frandsen, f(D, d)
  - EWEC 2009, cte

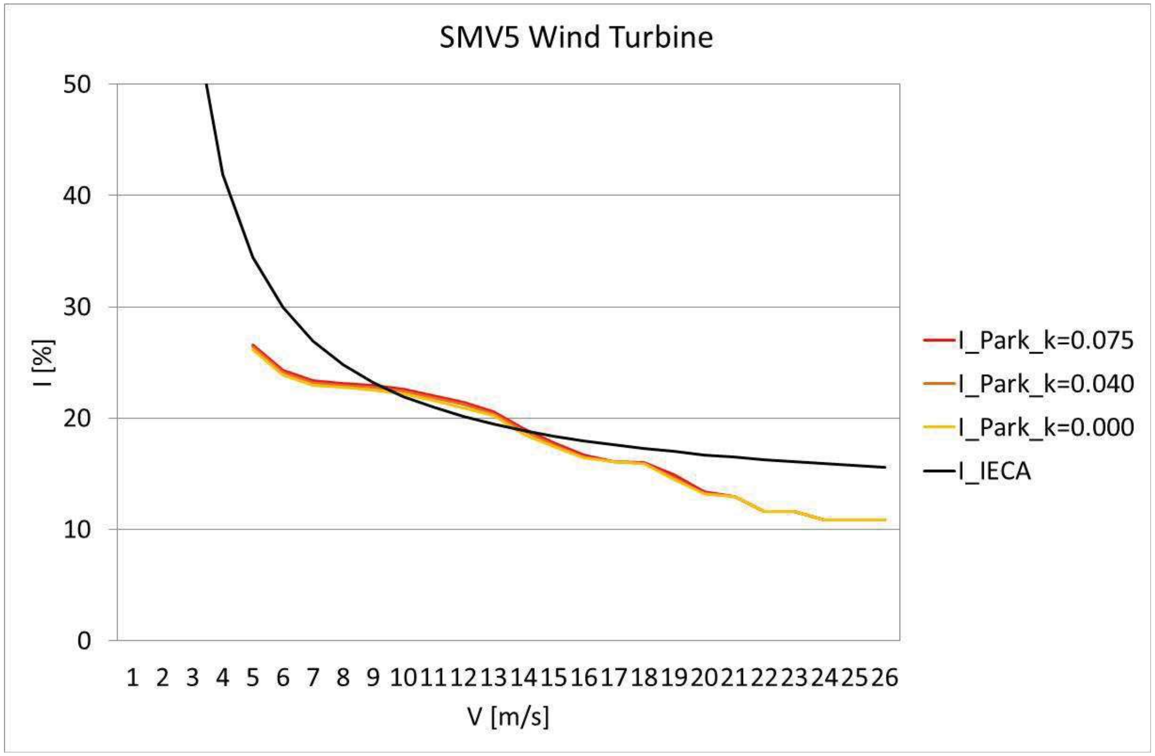






CePO V0. Configuration

- Angle of affection:
  - **Park, f(k, D, d)**

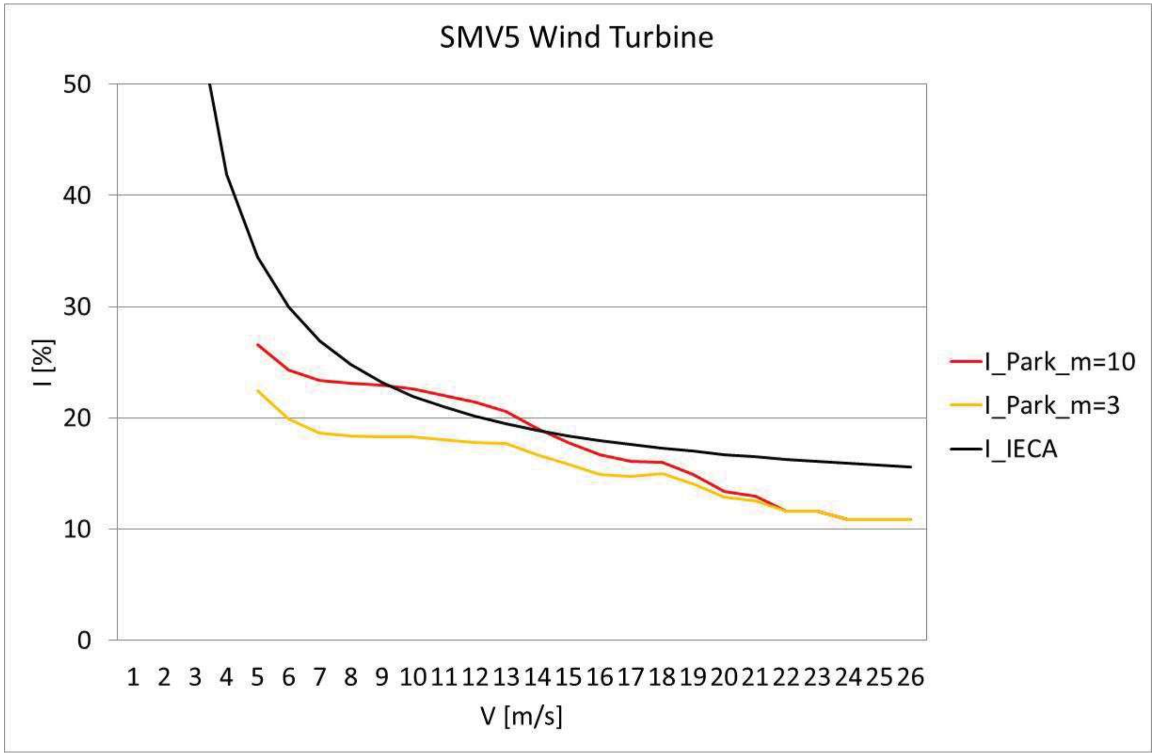


CePO V0. Configuration

- Angle of affection (Frandsen)
- Global or sector calculation (Global)
- IEC 61400-1 edition (Ed4)
- WSM configuration:
  - Speed range (operation range)
  - Optimizable or not (all optimizable)
  - Max. nº of stops (without limit)
  - The wake decay constant, only for Park angle affection (0.075)
  - **Wöhler parameter (m=10)**

CePO V0. Configuration

- **Wöhler parameter:**
  - Ieff, f(m)
    - (3, 5) steel;
    - (10-12) fiberglass

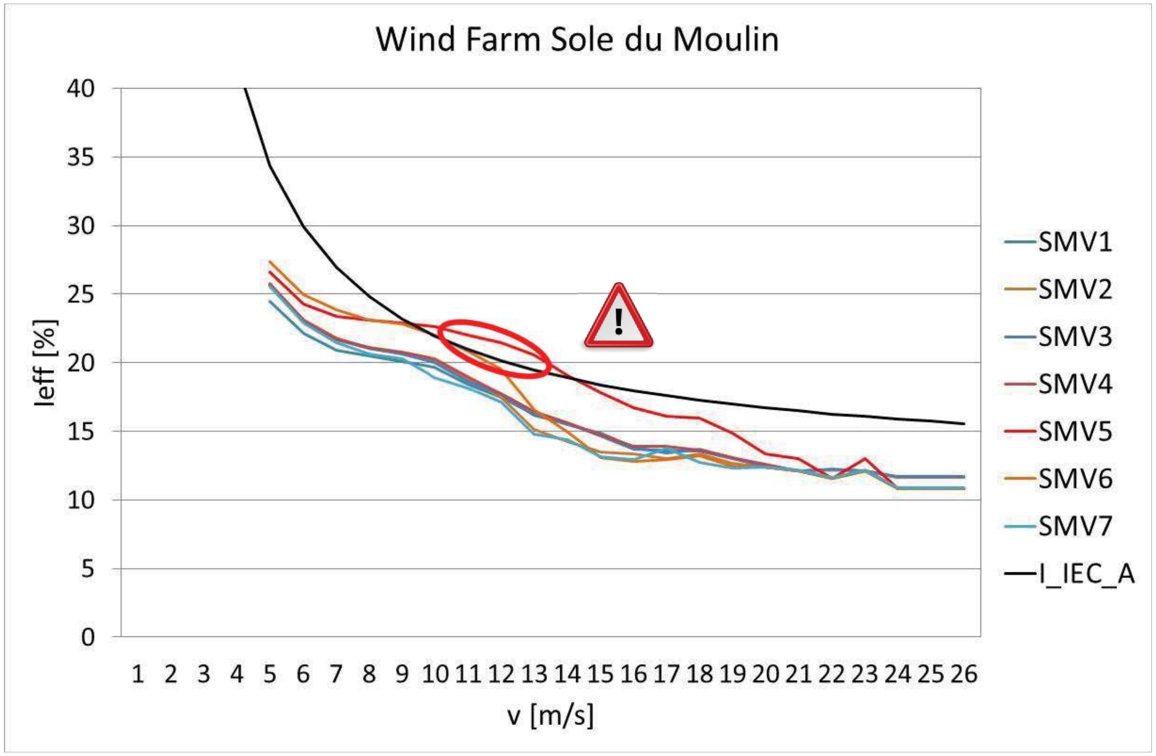


CePO V0. Configuration

- Others parameters:
  - Minimum turbine distance, (1.5D)
  - Distance for fixed stops, (3D)
  - Maximum turbine distance, (20D)
  - Minimum number of data, (50)

CePO V0. Optimization

- Effective turbulence intensity:

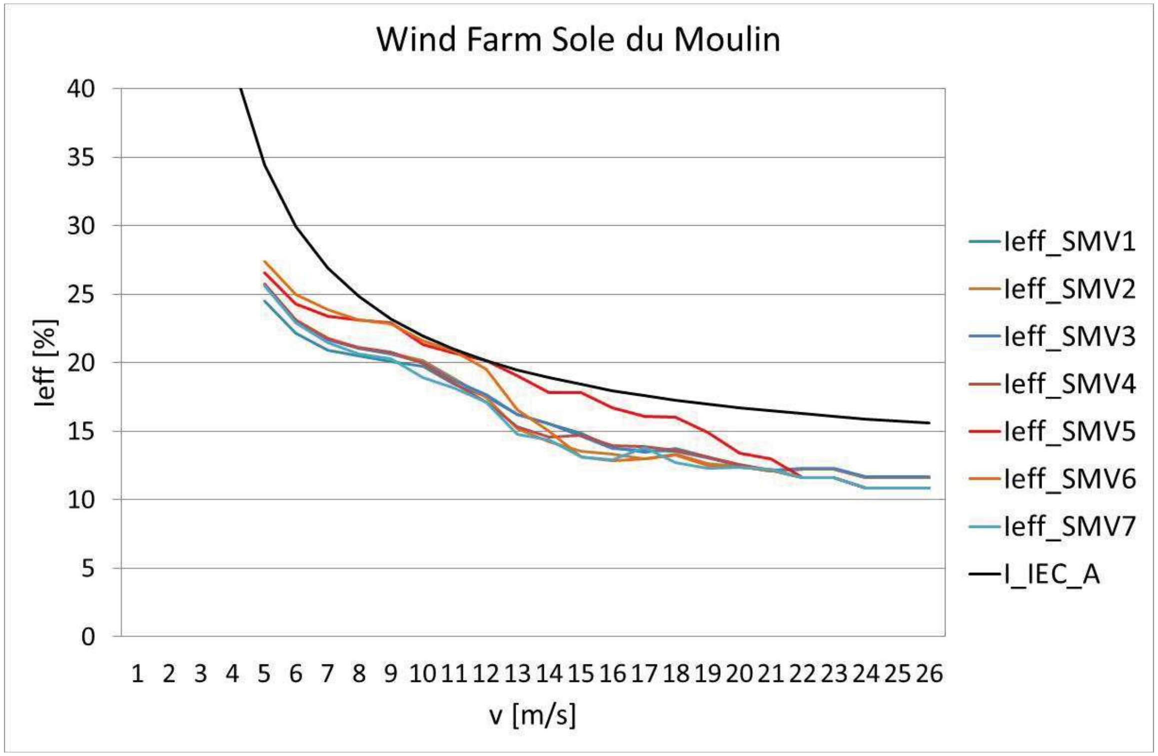


CePO V0. Optimization

- Wind farm analysis:

CePO V0. Optimization

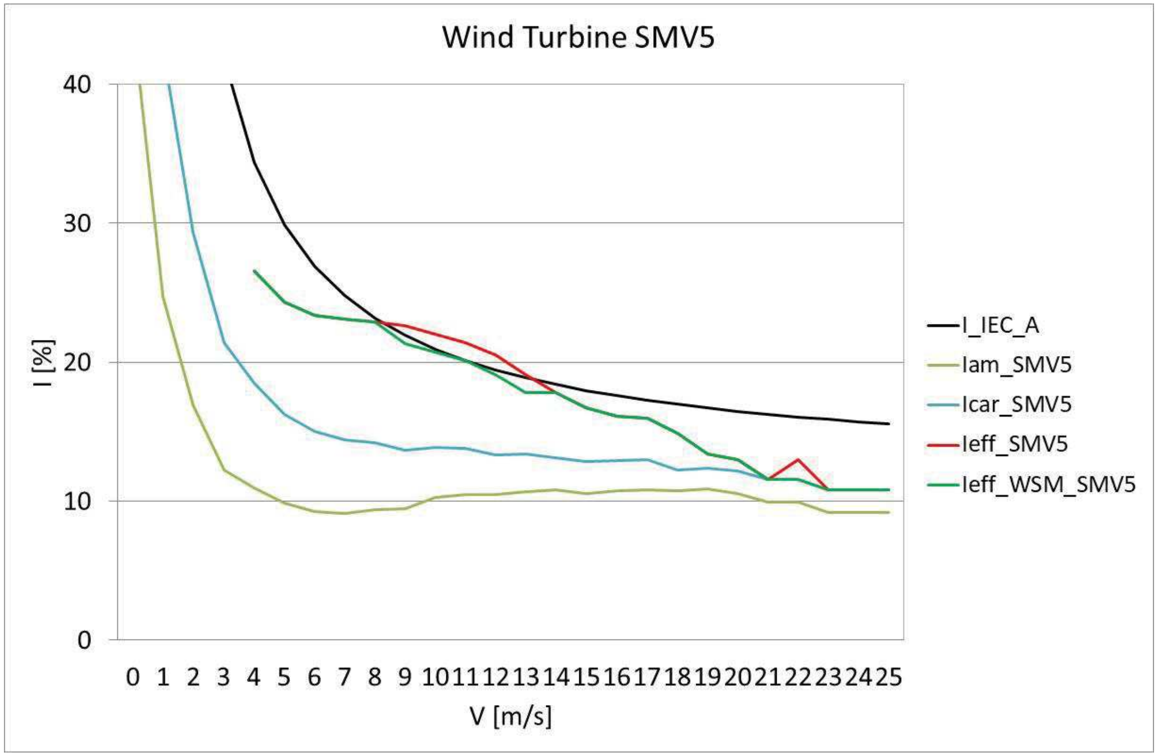
- Optimized WSM



ID	Amin	Amax	Vmin	Vmax	%Gross Energy
SMV5	21	33	9	9	0.23
SMV5	195	219	9	13	1.86
Wind Farm					**0.29**

CePO V0. Optimization

- Turbine SMV5



CePO V0. Conclusions

- CePO V0:
  - Variety of functionalities available for detailed analysis of effective turbulence intensity condition.
  - CePO minimizes the losses associated with usual WSM strategies, reduces the time to obtain results and assures repeatability and optimum finding.
  - Fast and reliable option to obtain an estimate of the losses associated with a WSM strategy.

CePO. On-going New Version

- CePO V1:
  - ➢ Defines a strategy (WSM and/or derating) that maximizes production and minimizes effective turbulence intensity:
    - Inputs (changes):
      - Thrust and power curve → Several for each turbine according to different turbine modes (derating)
    - Optimization (changes)
      - New optimization function

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Thank You Very Much!

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