An investigation into the effect of low induction rotors on the levelised cost of electricity for a 1GW offshore wind farm

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- *Goal*
- Context
  - Low Induction Rotors (LIR’s)
  - Wind Farm Power Density
- Methodology
  - Target wind farm
  - Target turbines
  - Modelling: Wake effects, electrical infrastructure, turbine costs
- Results

Goal:

To optimise the LCOE of Low Induction Rotors versus Conventional Rotors for a 1GW off-shore wind farm with different values of Wind Farm Power Density using state of the art wake modelling, electrical modelling and cost modelling

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Introduction

Classical Approach versus Low Induction

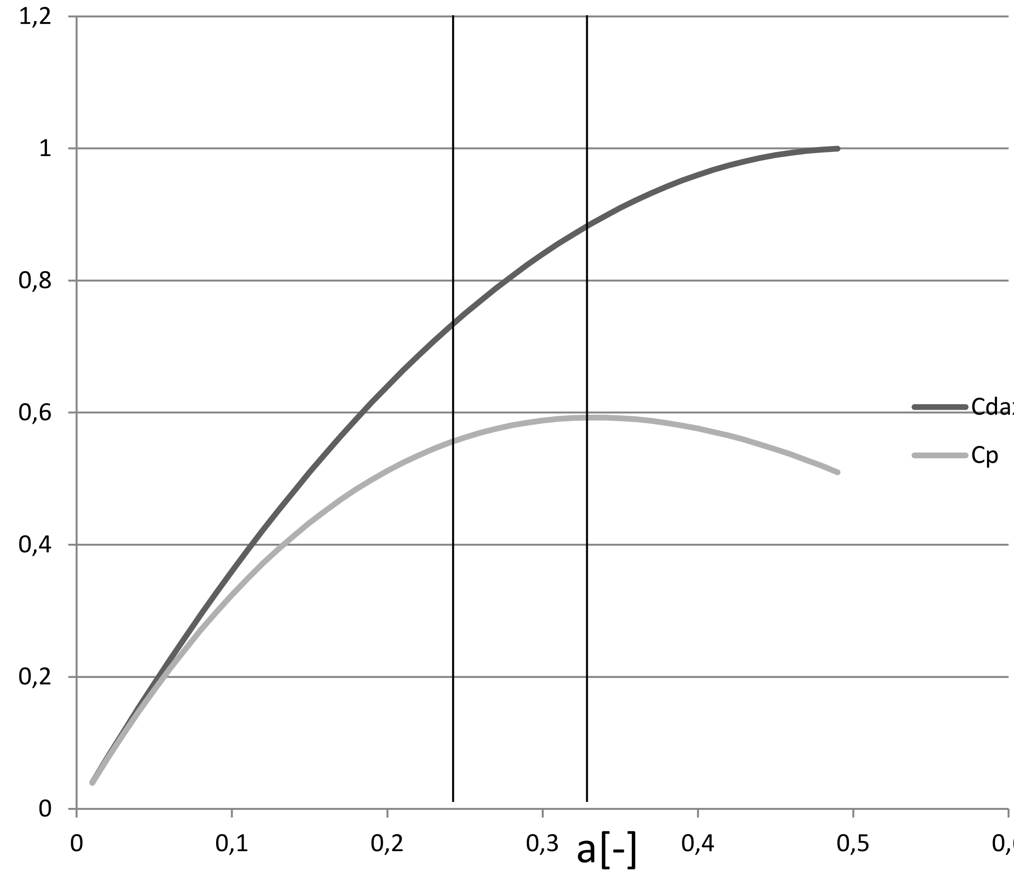
- Power Coefficient flat around Betz maximum (a = 1/3)

$$C_P = \frac{P}{\frac{1}{2}\rho A U_\infty^{\ 3}} = 4a(1-a)^2$$

- Aerodynamic load coefficient strongly dependant on a

$$C_{D.ax} = \frac{D.ax}{\frac{1}{2}\rho A U_\infty^{\ 2}} = 4a(1-a)$$

- Increase diameter→ maintain aerodynamic loads→ increase power



Introduction

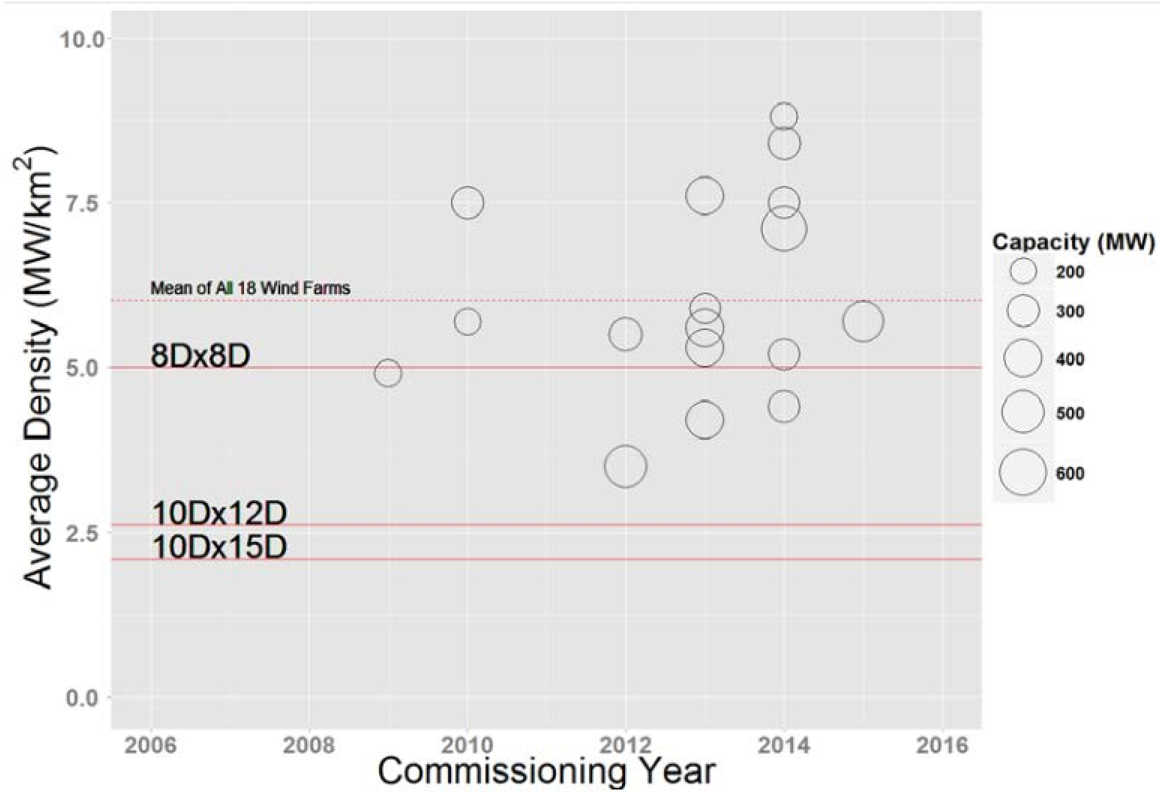
Low Induction Rotors

- Low induction Rotors (LIR's) are sometimes seen as an option to reduce LCOE
- Literature finds justification for LIR's for isolated operation, e.g. [1])
- Wake effects are known to depend on C_{Dax} (induction)
- LIR's are expected to reduce the wake effects

[1]) Chaviaropoulos, Beurskens & Voutsinas 2013

Introduction

No clear trend on Wind Farm Power Density (WFPD)



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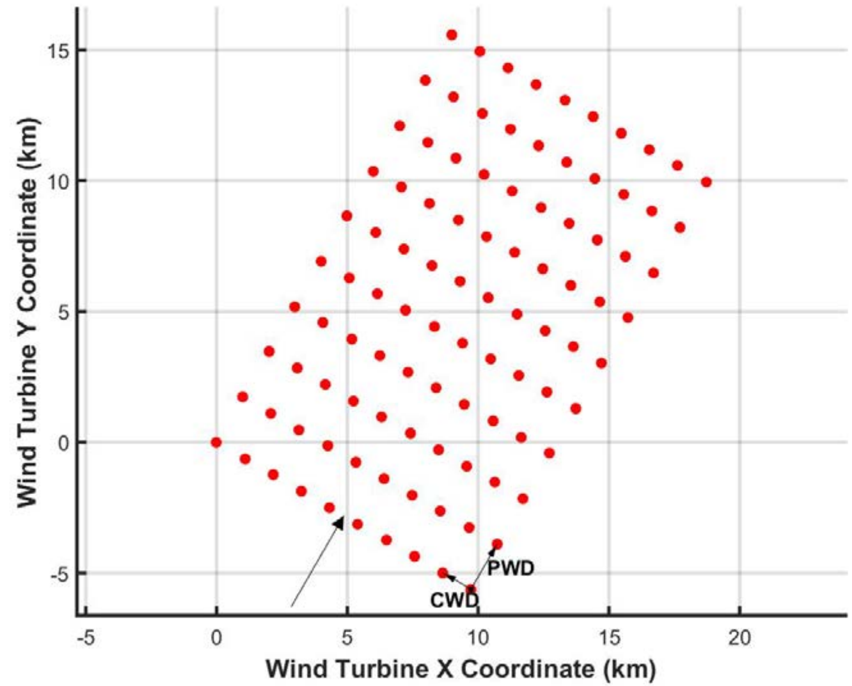
Methodology

The Approach

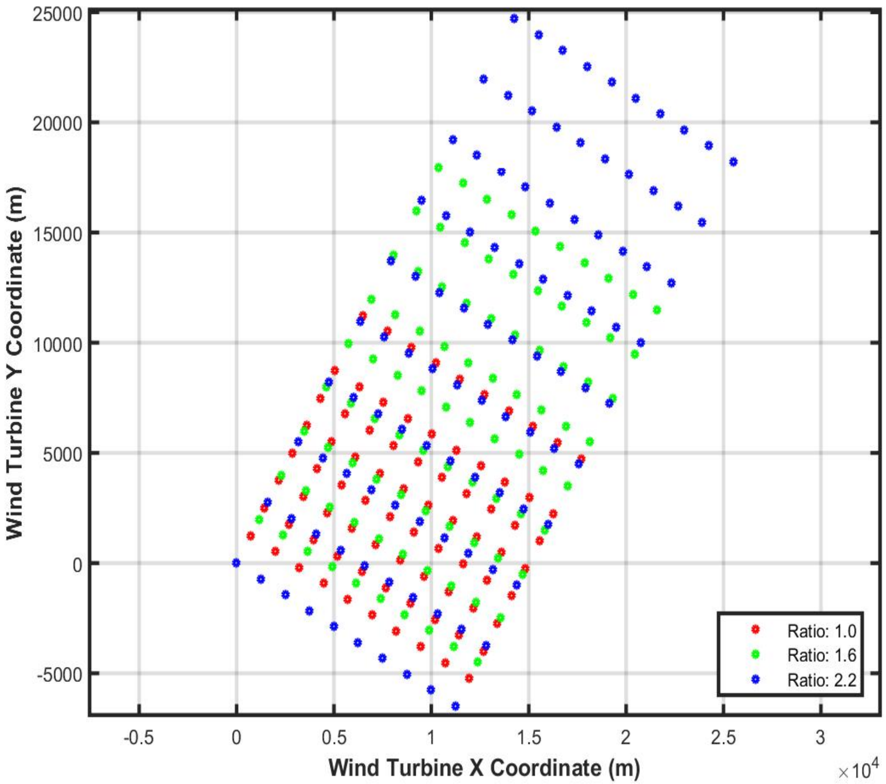
- Theoretical 1GW wind farm (10x10 grid)
- Range of Turbine Spacings
  - Fixed spacing ratios (PWD/CWD)
  - Range of CWDs



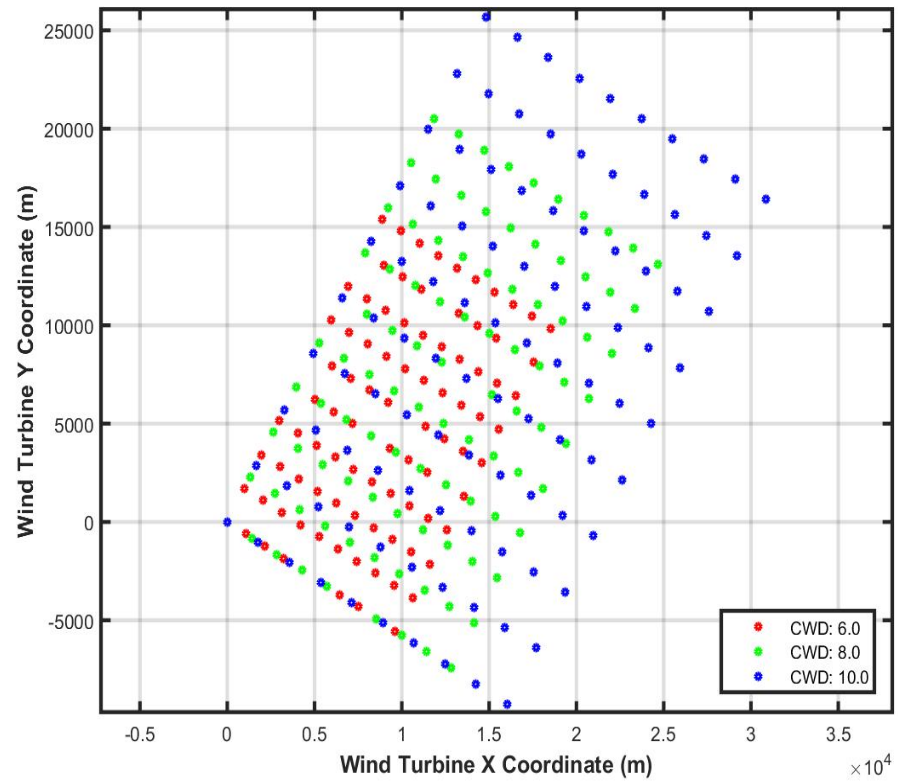
Methodology

The Approach

Fixed CWD



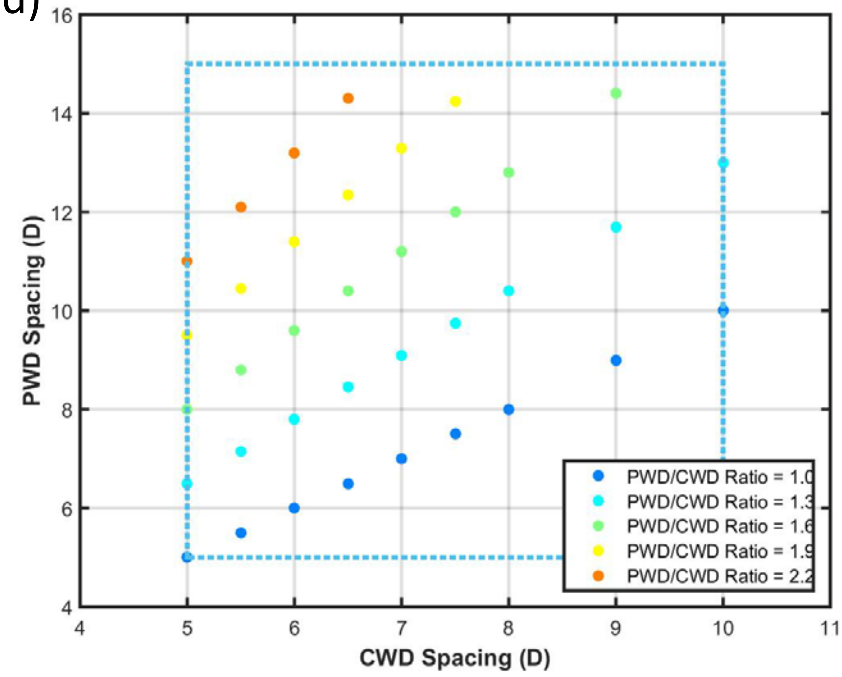
Fixed Ratio



Methodology

The Approach

- Theoretical 1GW wind farm (10x10 grid)
- Range of Turbine Spacings
  - Fixed spacing ratios (PWD/CWD)
  - Range of CWDs
- Either conventional or LIR turbines



INNWIND.EU and AVATAR RWT *)

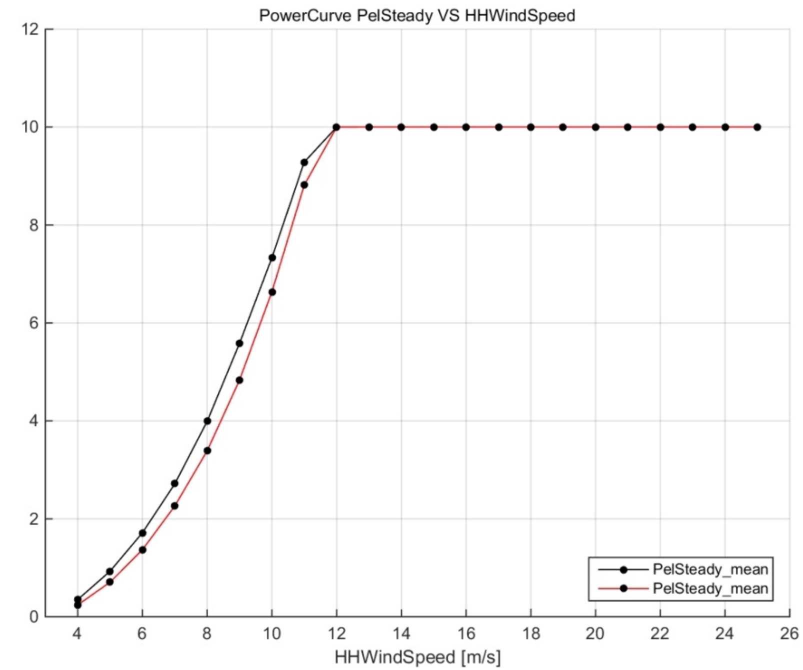
	INNWIND.EU	AVATAR (AdVanced Aerodynamic Tools for lArge Rotors)
Power:	10 MW	10 MW
Rotor diameter:	178.3m	205.8m
WTPD:	400 W/m^2	300 W/m^2
Axial induction:	0.3	0.24
RPM→ Tip speed	9.8rpm→ 90m/s	9.8 rpm→ 103.4 m/s
Hub height:	119m	132.7m

www.innwind.eu and http://www.eera-avatar.eu/

AVATAR RWT vs. INNWIND.EU RWT

http://www.eera-avatar.eu/publications-results-and-links/

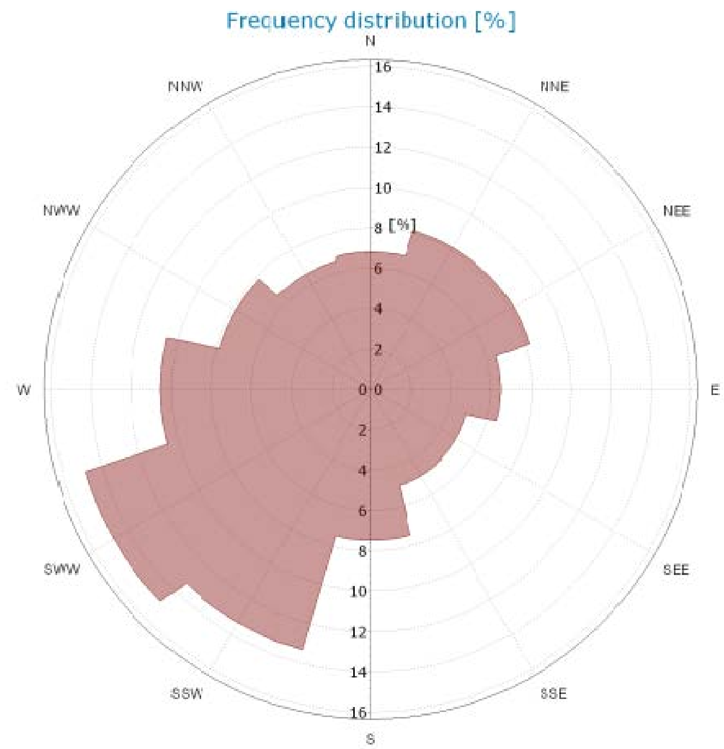
- 5% Increase in energy production due to larger diameter
- Key rotor load levels are maintained but:
  - Non-rotor loads and mass slightly exceeded
  - Use of carbon fibre
    →
  - Does increased AEP compensate increased costs?



Methodology

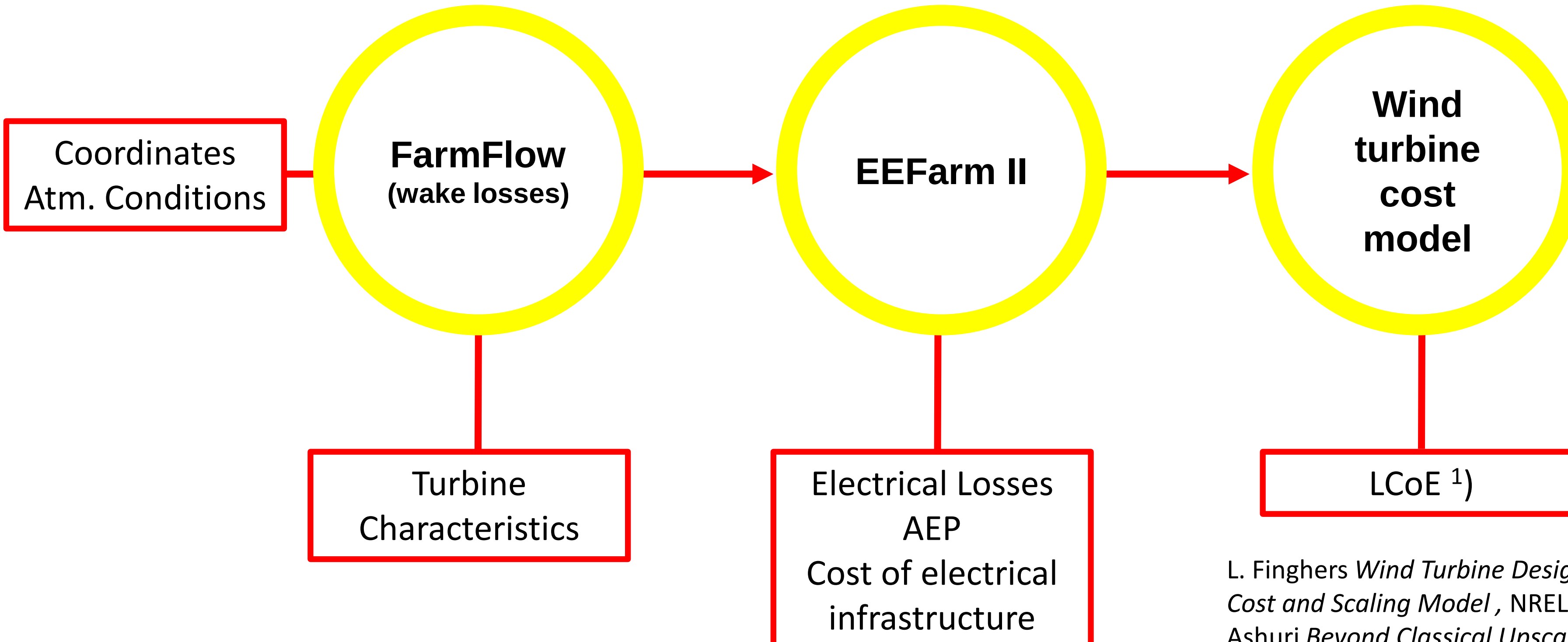
The Approach

- Theoretical 1GW wind farm (10x10 grid)
- Range of Turbine Spacings
  - Fixed spacing ratios (PWD/CWD)
  - Range of CWDs
- Either conventional or LIR turbines
- Typical North Sea wind climate

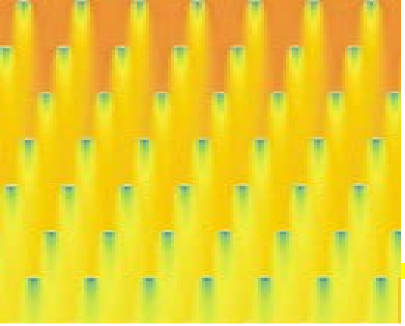


Methodology

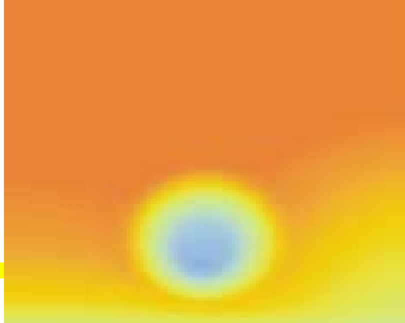
Process



L. Finghers *Wind Turbine Design Cost and Scaling Model* , NREL, 2006
Ashuri *Beyond Classical Upscaling* TUDelft 2014



What is FARMFLOW?

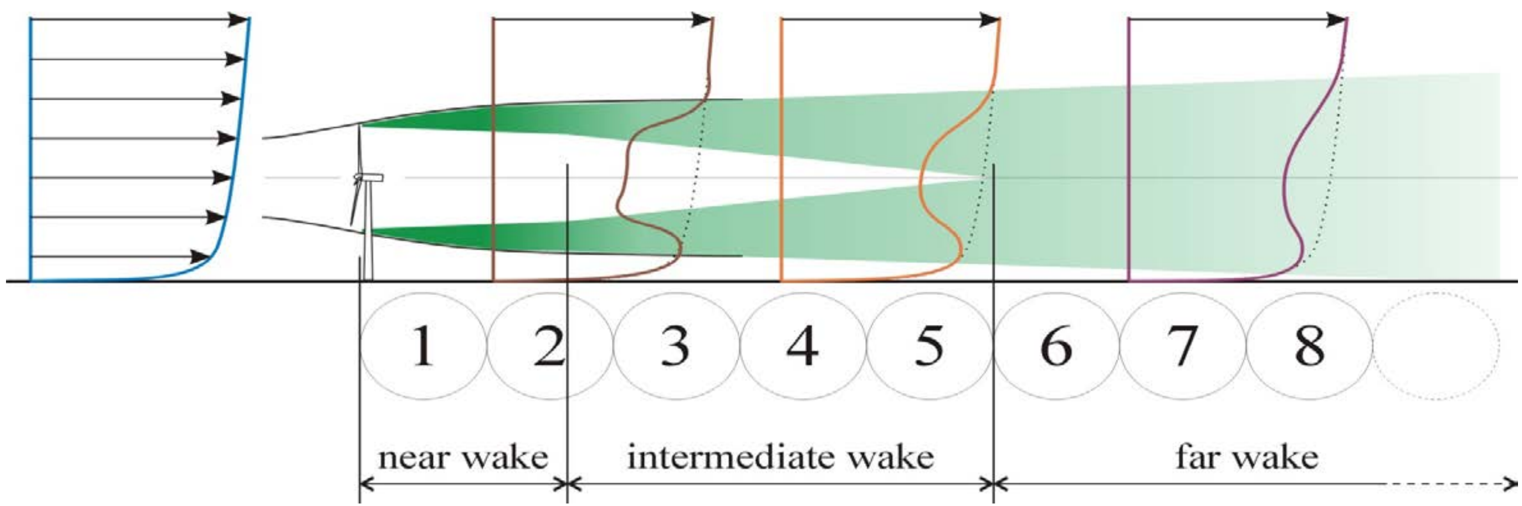


- Calculates:
  - Losses and added turbulence due to wakes
  - Annual energy production (AEP)
- The model is based on UPMWAKE [1])/WAKEFARM/FARMFLOW
  - Modified by ECN since 1993
  - Extensively validated with results from ECN's research farms and measurements from EU projects (e.g. ENDOW, Upwind, EERA-DTOC)

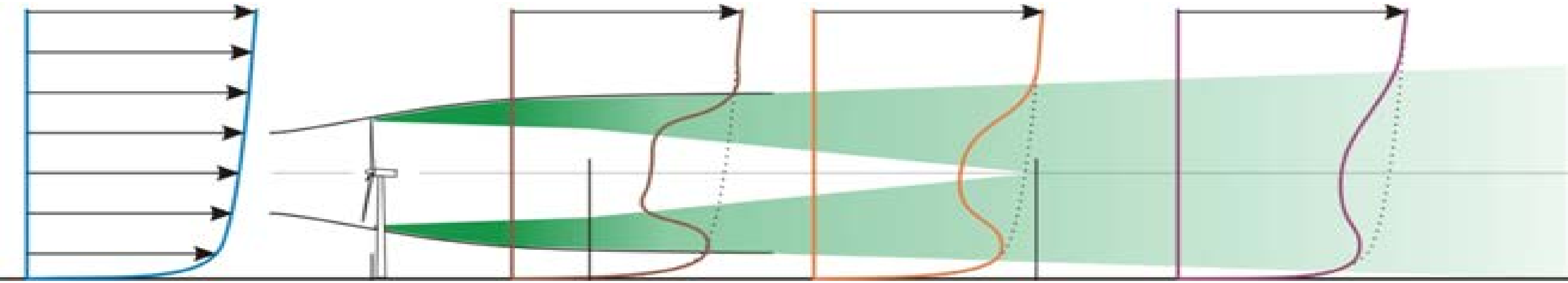
[1]) Crespo et al. 1988

FARMFLOW: Theory and model description

- Solves the Parabolized Navier-Stokes equation
- Turbines modelled as actuator disc, prescribed by C_{Dax}
- Wake modelled with a k-ε turbulence model



FARMFLOW: Advanced Model

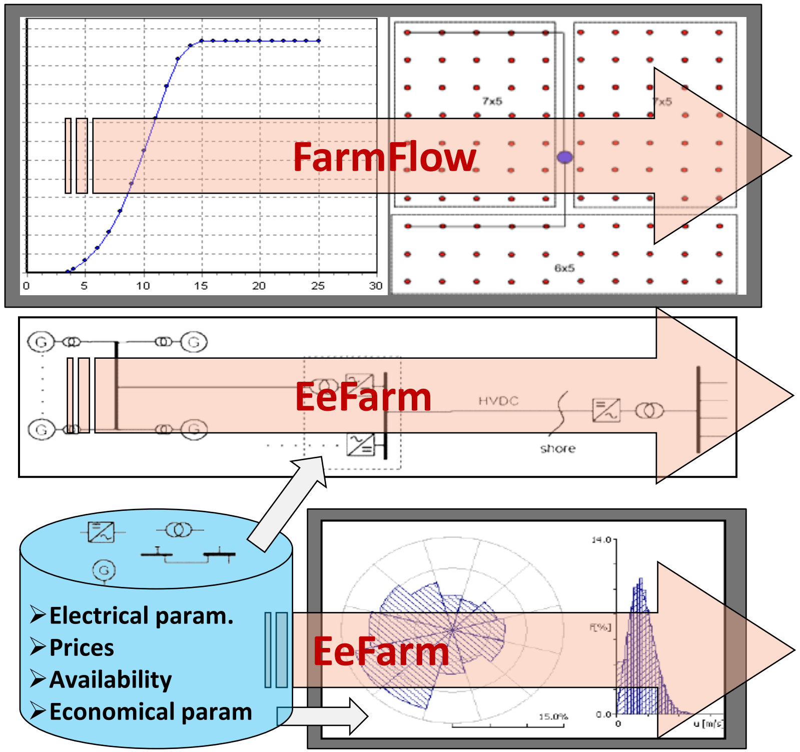


- Parabolisation: Fast, but how to solve the near wake where axial pressure gradients are significant?
- Solution:
  - Prescribe axial pressure gradients from free vortex wake method!
  - Fast database approach
- Adjusted k-ε turbulence model parameters in near wake based on:
  - Measurements from ECN’s research farms and Horns Rev farm
  - Detailed wake measurements in TUDelft wind tunnel

What is EEFARM?

- Program to study and optimise the electrical performance of wind farms.
- Program is used to determine the:
  - Energy production,
  - Electrical losses,
  - Component failure losses
  - Price of the produced electric power

EeFarm-II linked to FarmFlow!



Aerodynamic power:

$P_{WT1} \ldots P_{WTN} = f\,(Vw, Vdir)$

Investments
P_{loss}
P_{fail}
} per component

LCOE

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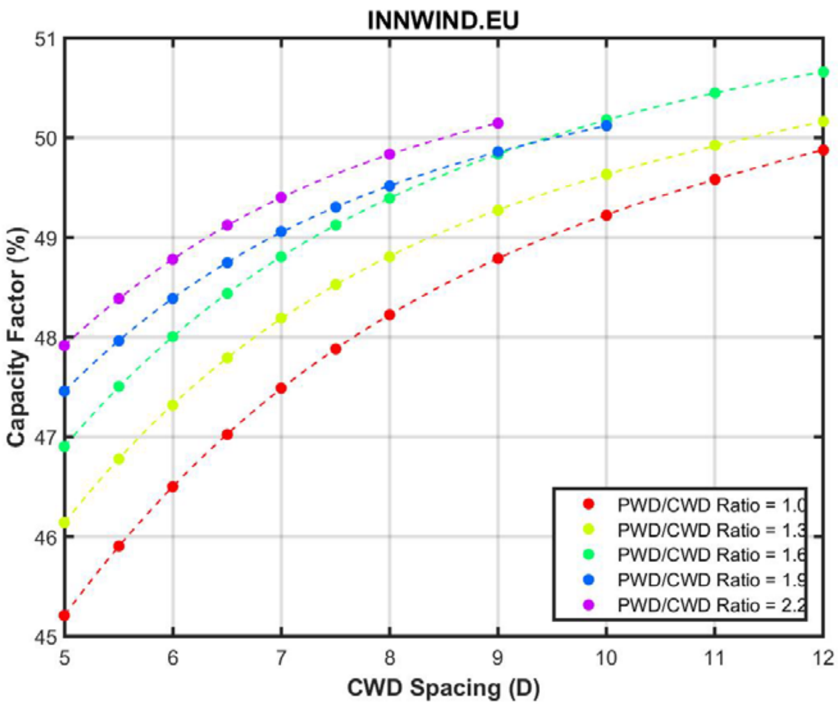
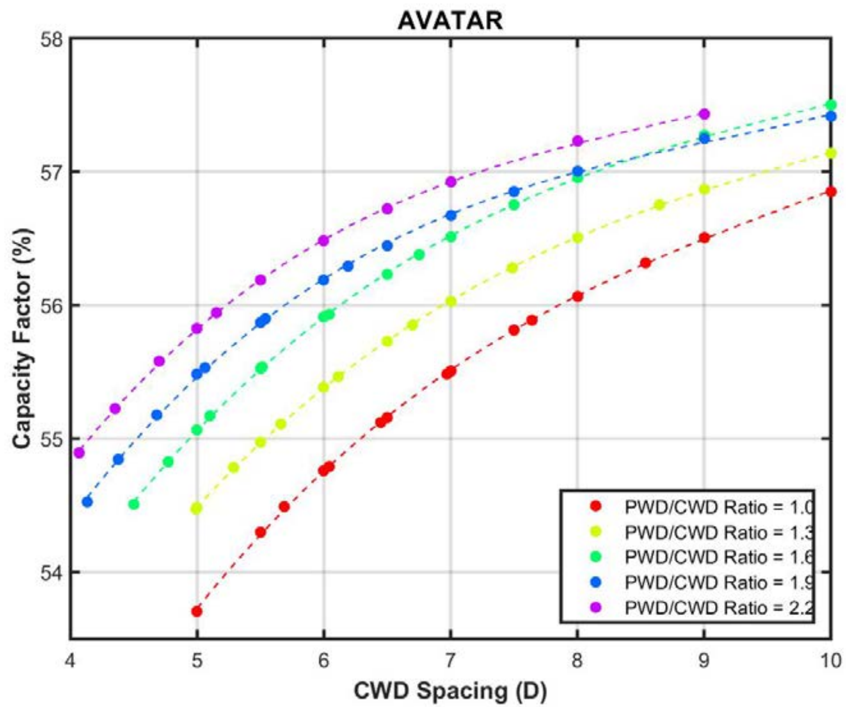
Results

Capacity Factor

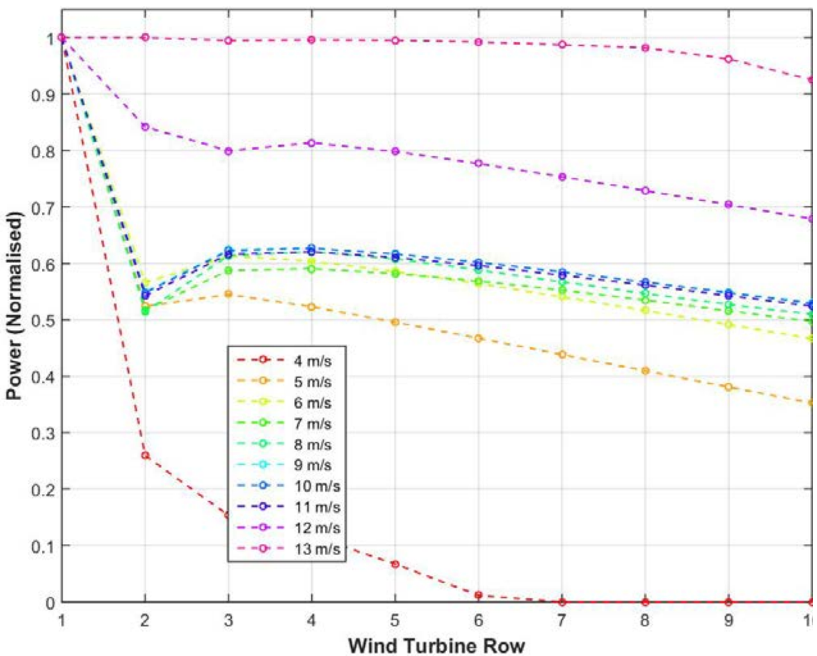




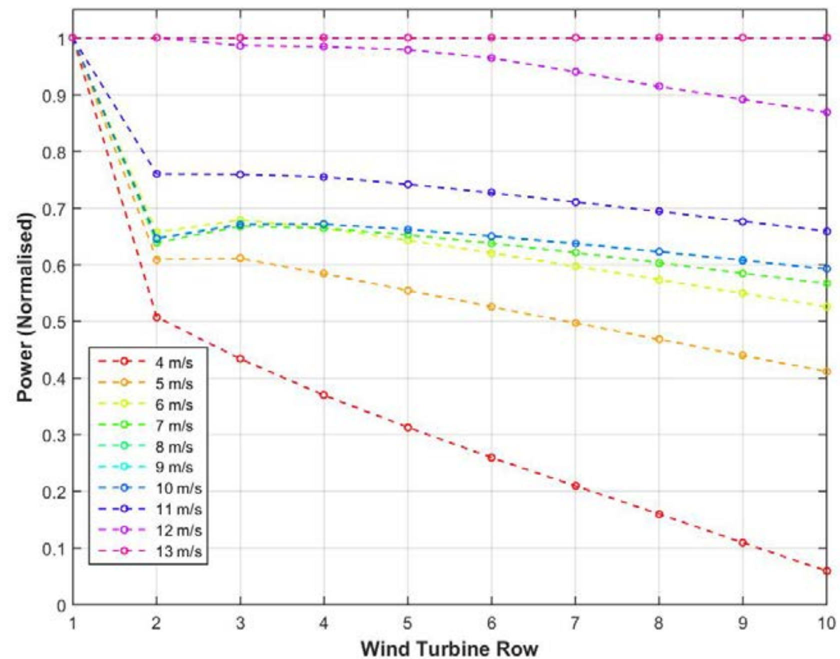
Results

Power Performance (7Dx11.2D)

INNWIND.EU

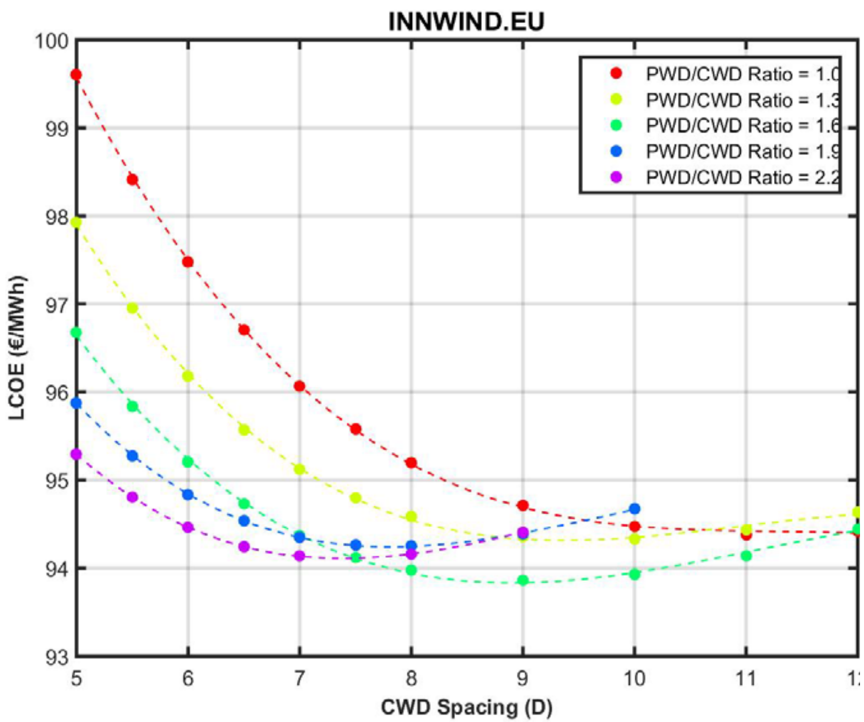


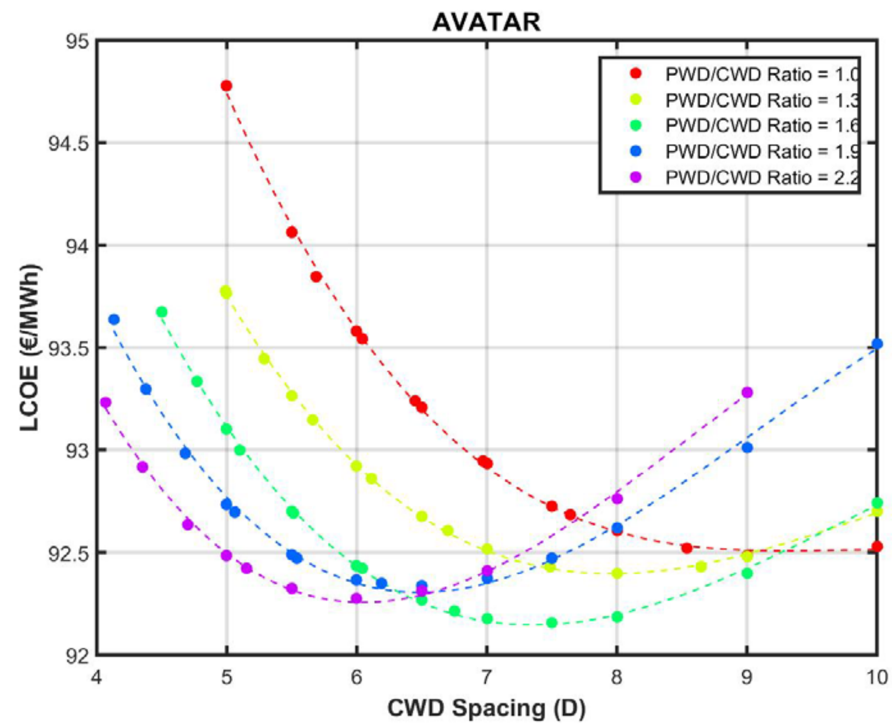
AVATAR



Results

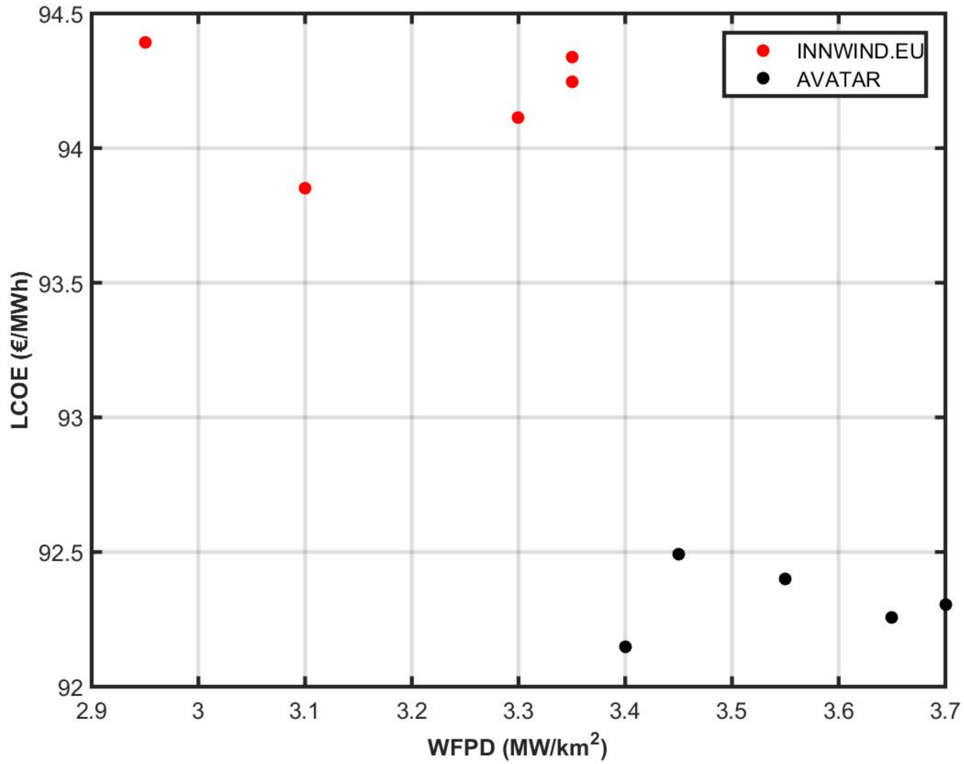
LCoE





Results

LCoE



Conclusions

- LIR could offer a lower LCoE than conventional turbines
  - Sensitive to cost model
  - Sensitive to atmospheric conditions
  - How representative is AVATAR LIR?
- LIR requires less area than conventional turbine for optimum LCoE
  - Indicates LIR turbines offer more efficient use of sea area
- Alternative layouts (not in presentation, but in paper)
  - Staggered offered no improvement
  - Aligned offered marginal cost reduction

Questions?