Effect of wind direction on wind park performance using Actuator Surface Modelling (ASM) approach

Balram Panjwani and Jon Samseth

SINTEF, Norway

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Outline

- Introduction
- H2020 project: UPWARDS
- Theoretical background of Actuator surface model
- Model verification
  - Power curve
  - Wake deficits
  - Park
- Effect of wind direction on power
- Conclusions and future work

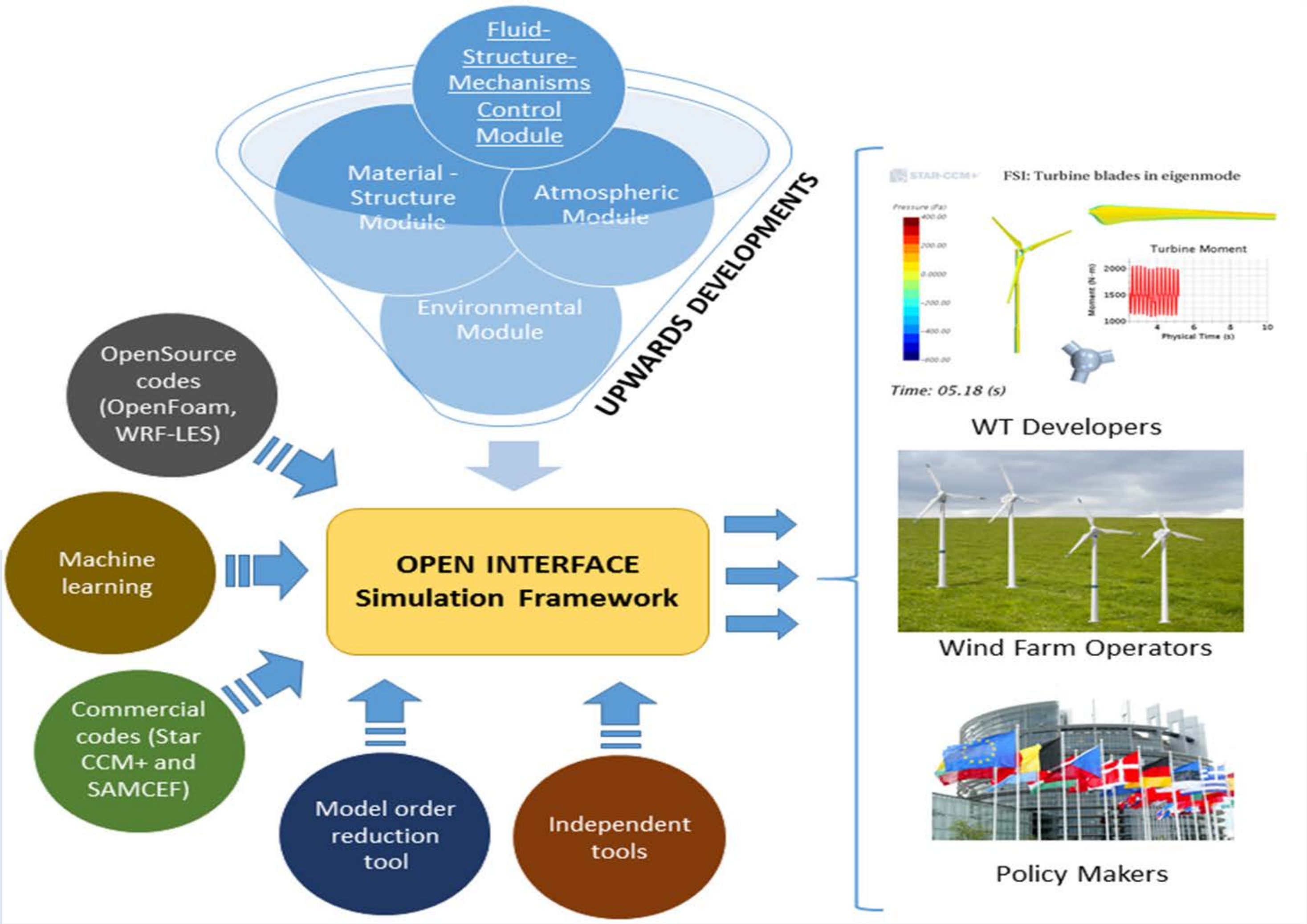
Introduction

- A full CFD method (resolving wind turbines on the grid scales)
- Virtual turbine methods
  - Actuator Disk model (ADM)
  - Actuator Line model (ALM)
  - Actuator Surface Model (ASM)
- Actuator disk assume turbine as a porous disk and forces are estimated using thrust coefficient
- ALM method assume each blade as line and forces are estimated from lift and drag coefficient of the blades

Challenges with ALM

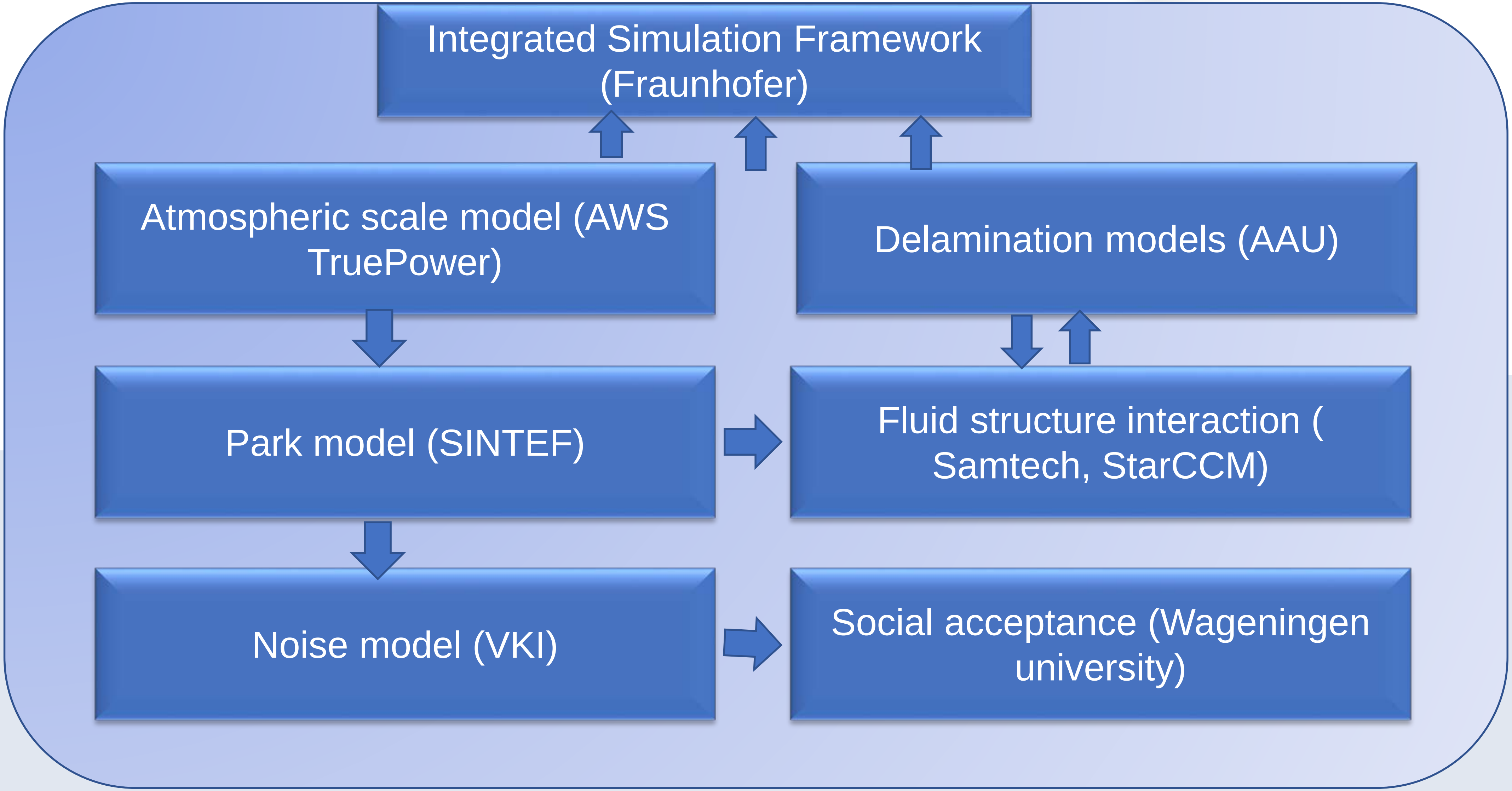
- The actuator line model can incorporate rotational effects, tip loses, 3D stall effects, and the effect of non-uniform force distribution in the azimuthal direction.
- The ALM is unable to resolve the detailed geometrical features of turbine blades on a mesh.
- There are two major limitations with the standard ALM:
  1) The lack of an effective nacelle model
  2) A finer mesh (i.e. Large Eddy Simulation) cannot resolve more geometrical features of the turbine blade.
- Need of ASM

Brief description of UPWARDS project



UPWARDS: H2020 project

15 MW virtual wind turbine
(Siemens Gamesa)



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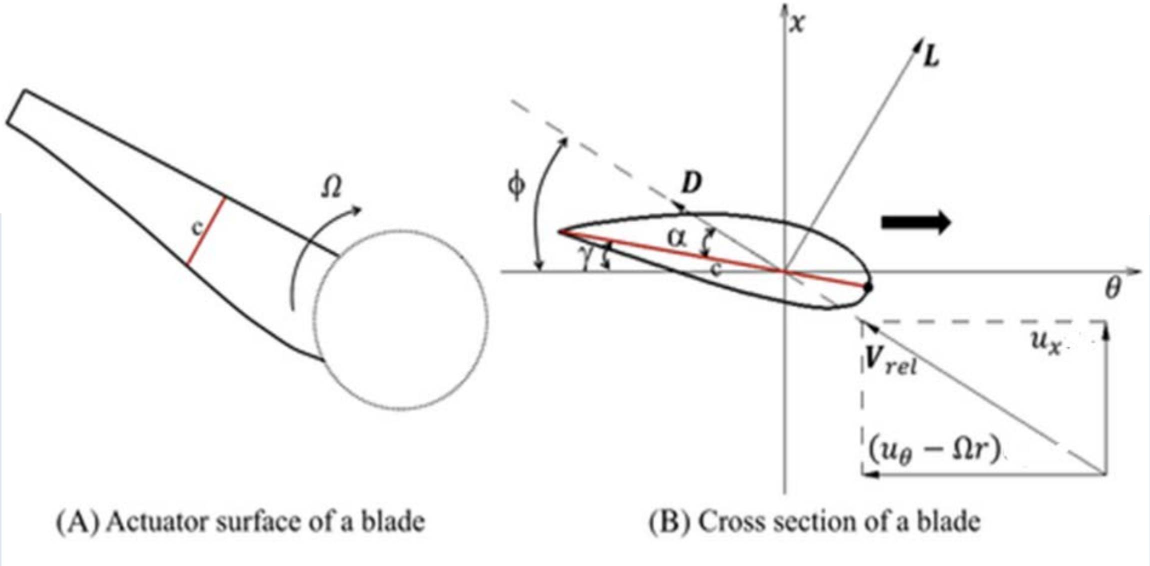
ASM Model: Theory and model description

- The turbines are modelled as a sink term in momentum equation and this is described by following generalized N-S equation.
- $\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \, \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}_i}{\partial x_i} + \frac{\partial \tau_i}{\partial x_j} + S$
- $\alpha = tan^{-1}\left(\frac{u_x}{u_t}\right) - \gamma$

$$\boldsymbol{L = \frac{1}{2} C_l(\alpha) \rho V_{rel}^2 c}$$

$$\boldsymbol{D = \frac{1}{2} C_D(\alpha) \rho V_{rel}^2 c}$$



schematic of the actuator surface model for blade. The lift and drag forces calculated using the blade element method are distributed over the actuator surface formed by chord lines of a blade[1].

[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,

Theory

- Estimate average local blade velocities over the blade surface (chord wise)
- $u_x = \frac{1}{c}\int_c u(X)ds$
- $u_\theta = \frac{1}{c}\int_c u(X)ds$
- Transform volume velocities onto blade surface
- $u(X) = \sum_{x \in gx} u(x)\delta_h(x - X)V(x)$
- smoothed four-point cosine function

$$\delta_h(\mathbf{x} - \mathbf{X}) = \frac{1}{V}\phi\left(\frac{x-X}{h_x}\right)\phi\left(\frac{y-Y}{h_y}\right)\phi\left(\frac{z-Z}{h_z}\right)$$

$$\phi(r) = \begin{cases} \frac{1}{4} + \frac{\sin(\pi(2|r|+1)/4)}{2\pi} - \frac{\sin(\pi(2|r|-1)/4)}{2\pi}, & |r| \leq 1.5, \\ \frac{5}{8} - \frac{|r|}{4} - \frac{\sin(\pi(2|r|-1)/4)}{2\pi}, & 1.5 \leq |r| \leq 2.5, \\ 0, & 2.5 \leq |r|, \end{cases}$$

[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,

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Implementation of 3D stall and Nacelle model

- Stall delay phenomena of the blade increase the lift coefficients and decrease the drag coefficients as compared with the corresponding two-dimensional airfoil data.
- Model developed by Du and Selig*

$$C_{L,3D} = C_{L,2D} + f_L \left(C_{L,p} - C_{L,2D} \right),$$

$$f_L = \frac{1}{2\pi} \left(\frac{1.6(c/r)a - (c/r)^{\frac{d}{\Lambda}\frac{R}{r}}}{0.1267b + (c/r)^{\frac{d}{\Lambda}\frac{R}{r}}} - 1 \right),$$

$$C_{D,3D} = C_{D,2D} - f_D \left(C_{D,2D} - C_{D,0} \right),$$

$$f_D = \frac{1}{2\pi} \left(\frac{1.6(c/r)a - (c/r)^{\frac{d}{2\Lambda}\frac{R}{r}}}{0.1267b + (c/r)^{\frac{d}{2\Lambda}\frac{R}{r}}} - 1 \right),$$

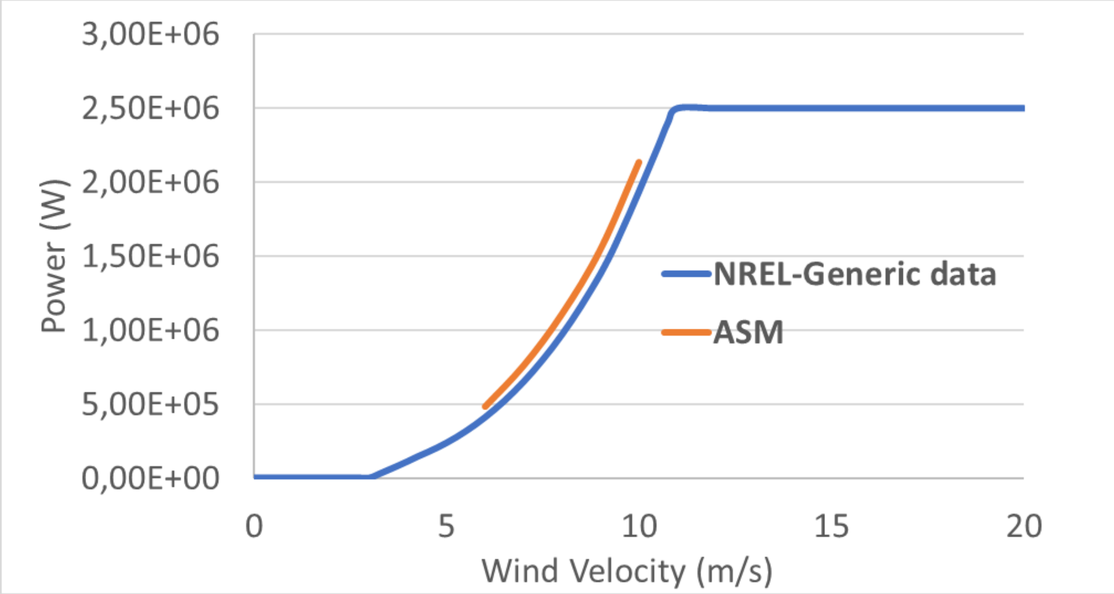
- Nacelle Model is a simplified model based on drag coefficient
  - Point forces are transferred into a volume mesh using Gaussian functions

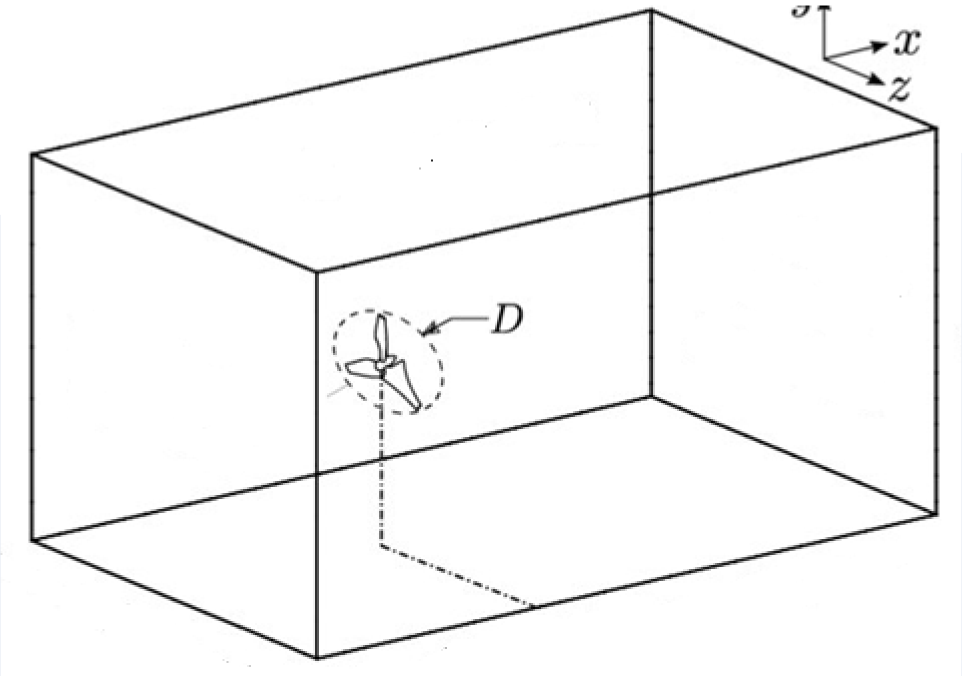
[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,

*Du Z, Selig MS. A 3-d stall-delay model for horizontal axis wind turbine performance prediction. AIAA Paper 1998; 21.

Model verification for power curve

- The model was verified with a single turbine placed in a computational domain
- The turbine was the generic 2.3 MW# siemens wind turbine.
- The aerodynamic data of generic wind turbine was produced by NREL

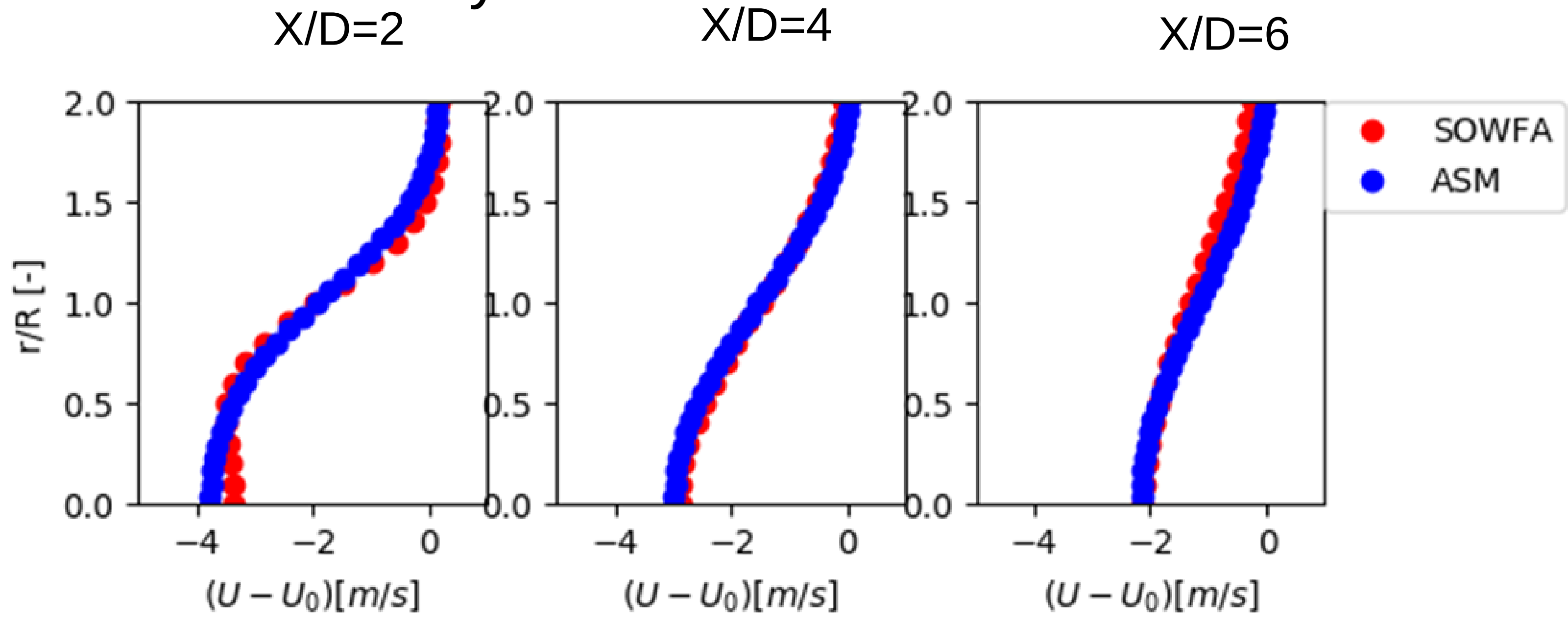


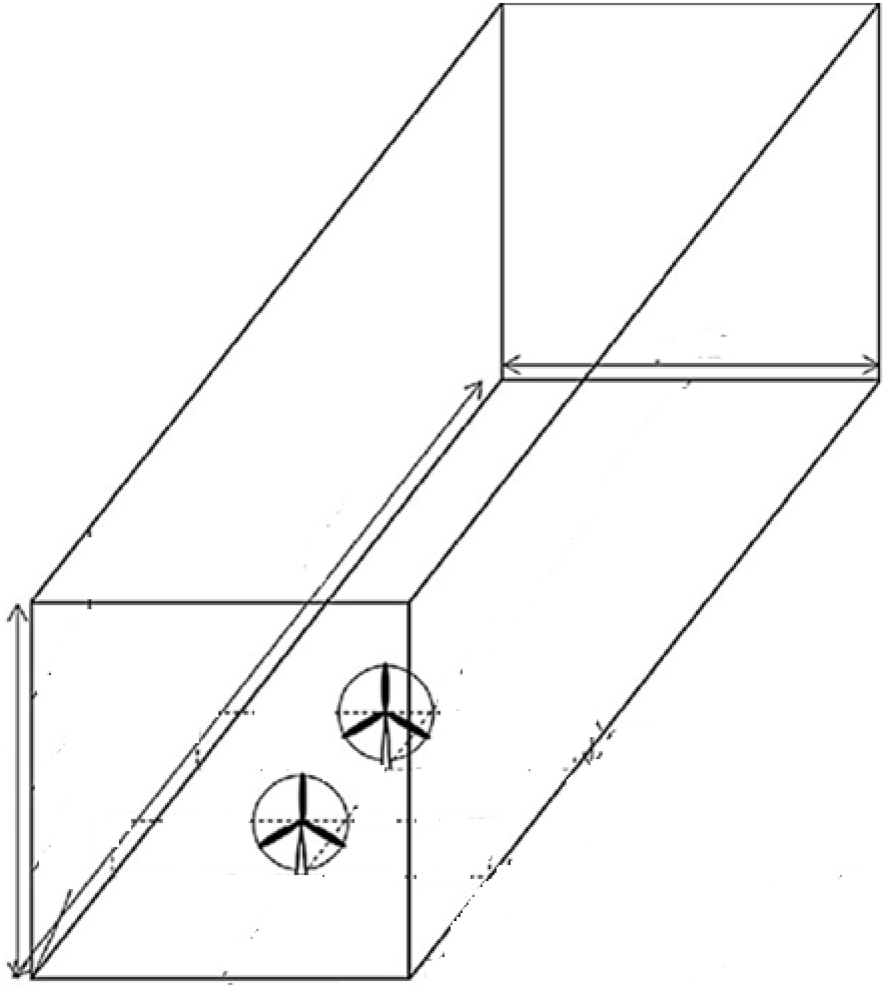


#Matthew J. Churchfield, Generic Siemens SWT-2.3-93 Specifications, NREL 2013

Verification studies

- Verification studies were performed with two NREL 5WM turbines.
- The results are compared with SOWFA*
- A distance between these two turbine was 8 m/
- Wind velocity 8 m/s and TI 6%





*Jonkman et al. Validation of FAST.Farm Against Large-Eddy Simulations, The Science of Making Torque from Wind (TORQUE 2018)

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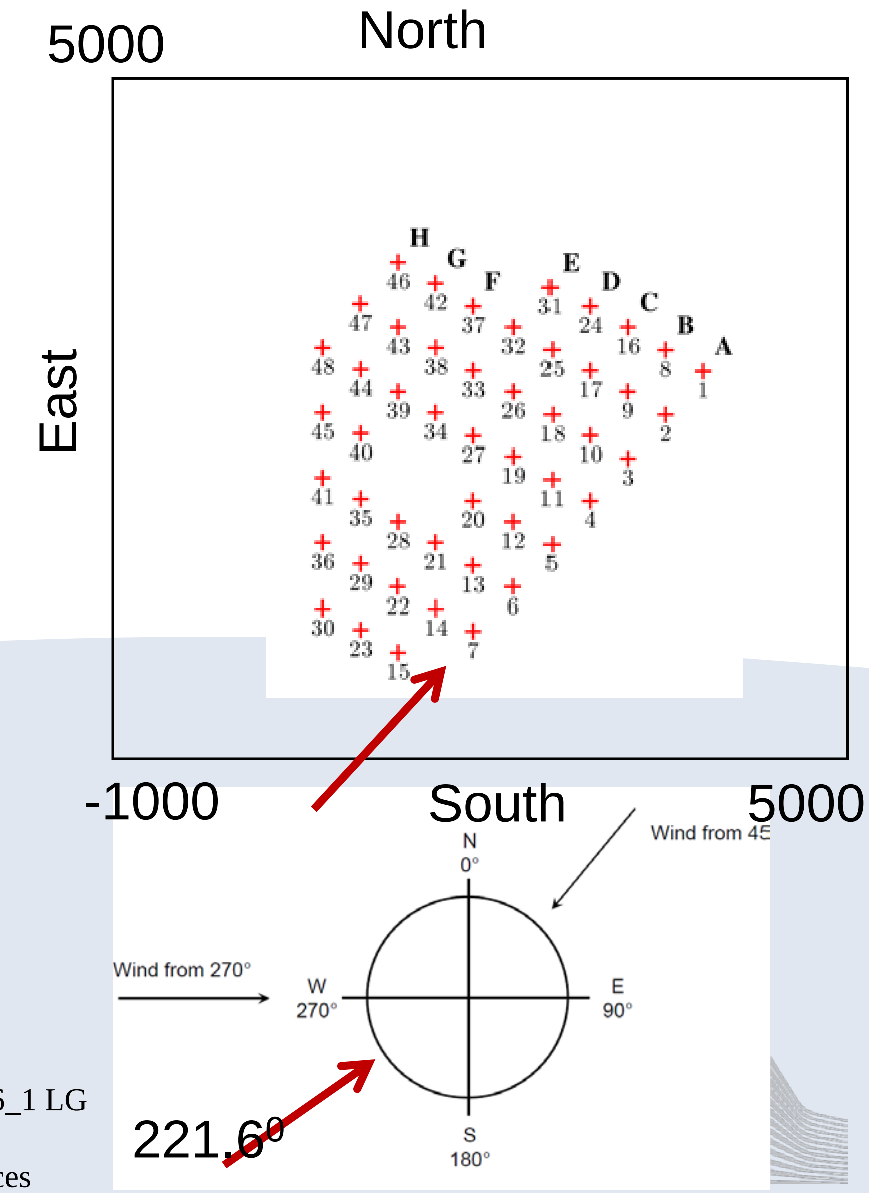
Park verification

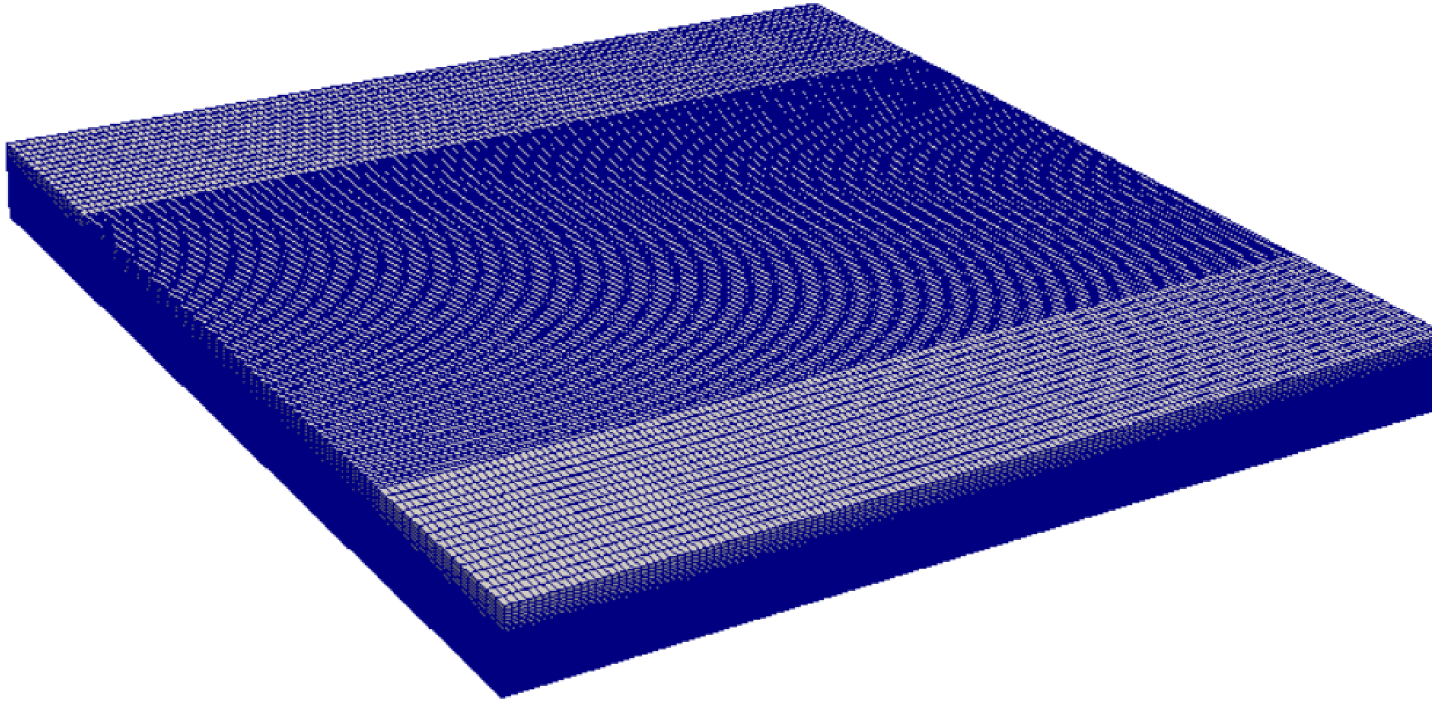
- The wind plant simulated in this study is the Lillgrund offshore facility operated by Vattenfall Vindkraft AB#.
- Boundary conditions
  - Top : Free slip wall boundary
  - Bottom : No slip wall boundary
  - East : Inflow
  - West : Outflow
- Present ASM: URANS with 5 million cells on 24 processors
- Mesh is refined at the turbine location
- SOWFA: LES using 300 million cells on 4100 processors. These simulations were performed by NREL##

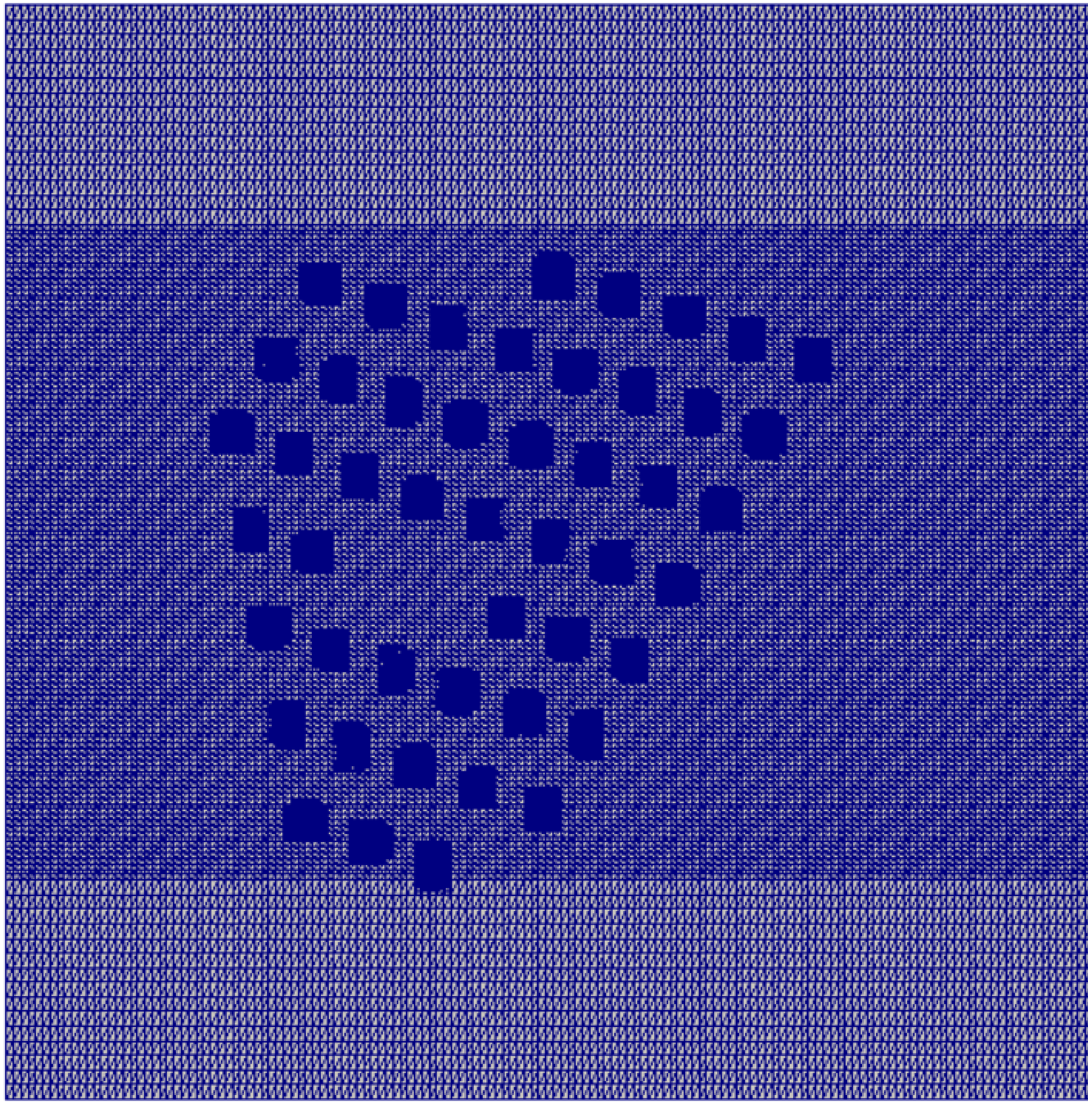


#Dahlberg J-Å (2009) Assessment of the Lillgrund Wind Farm: Power Performance Wake Effects. Vattenfall Vindkraft AB, 6_1 LG Pilot Report, September 2009

##Matthew J. Churchfield et al (2012) A Large-Eddy Simulation of Wind-Plant Aerodynamics, 50th AIAA Aerospace Sciences Meeting Nashville, Tennessee

Mesh





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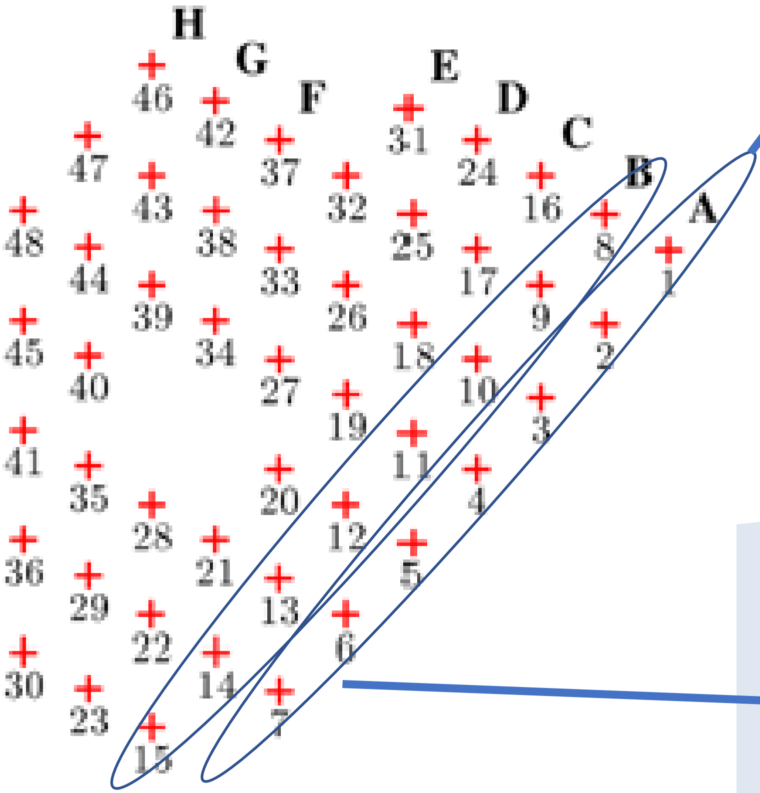
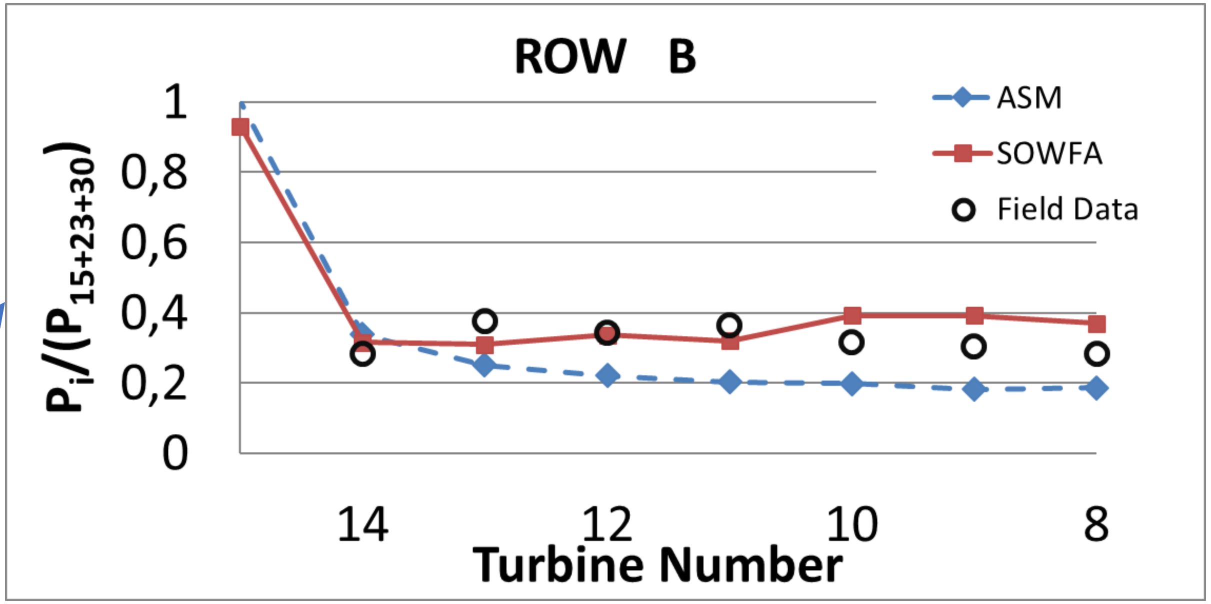
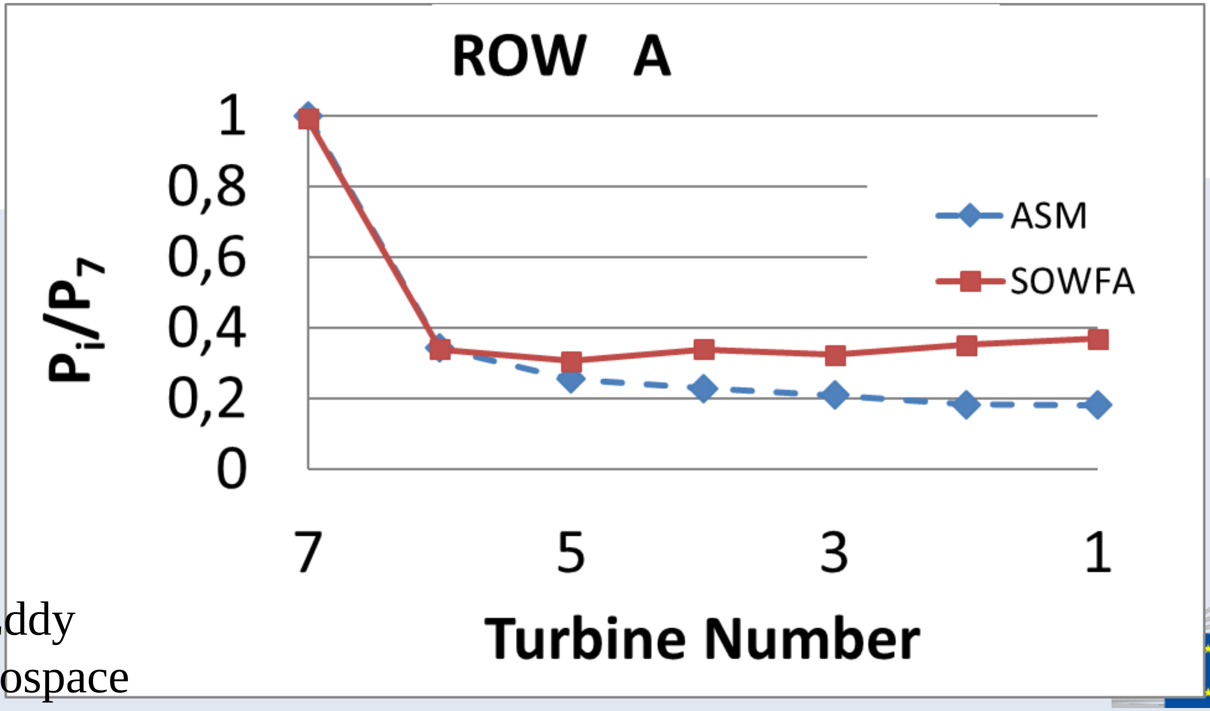
Results

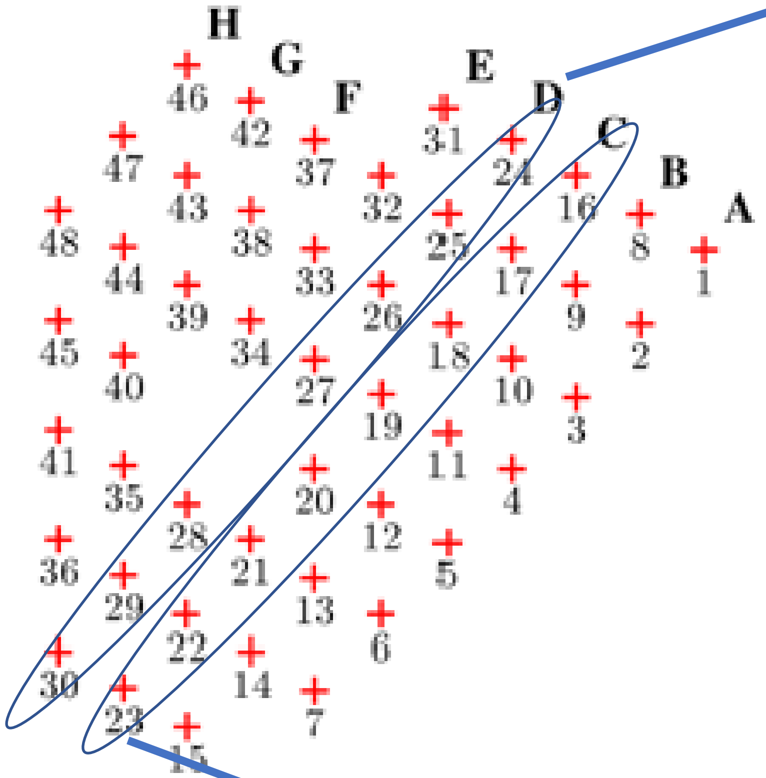


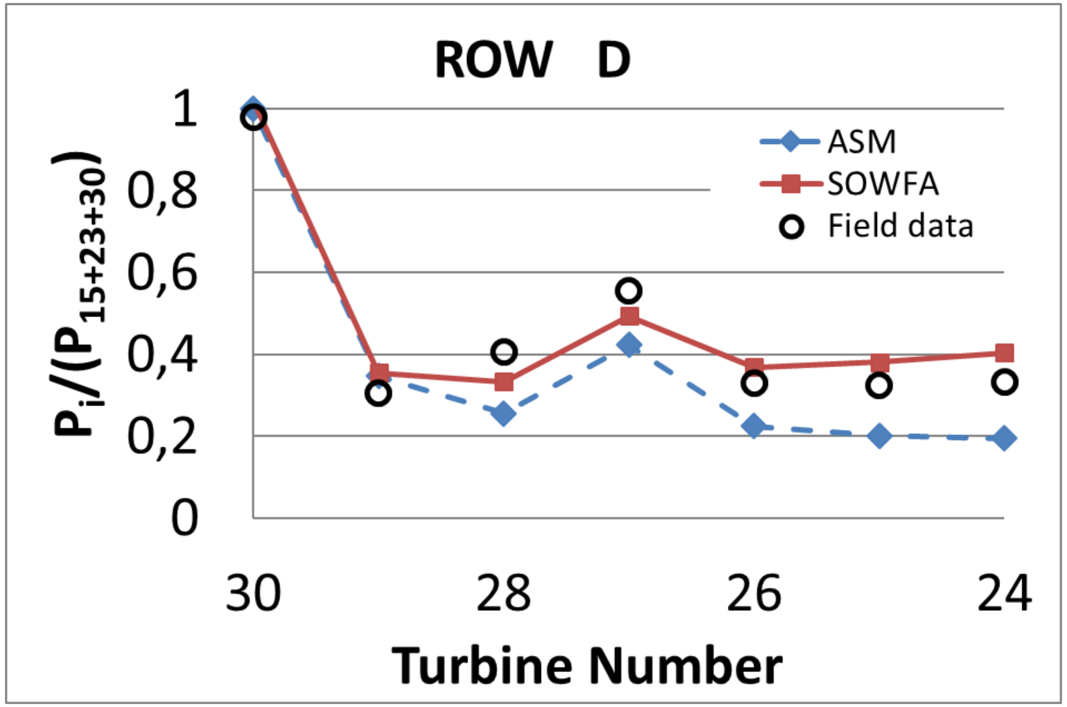


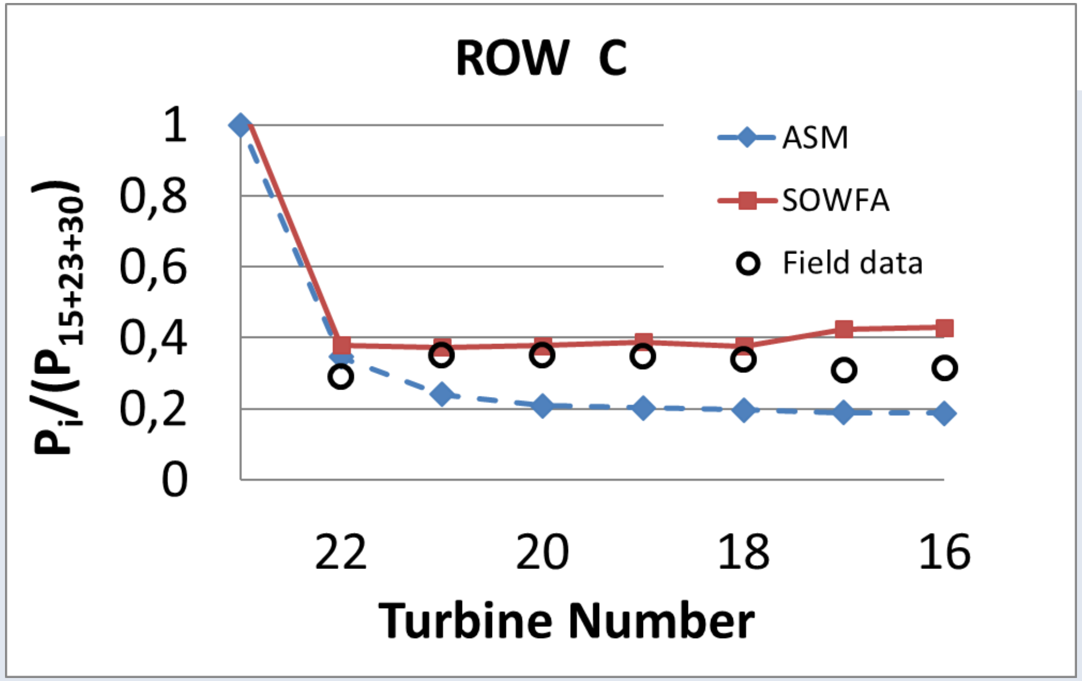


SOWFA from: Matthew J. Churchfield et al (2012) A Large-Eddy Simulation of Wind-Plant Aerodynamics, 50th AIAA Aerospace Sciences Meeting Nashville, Tennessee

Results







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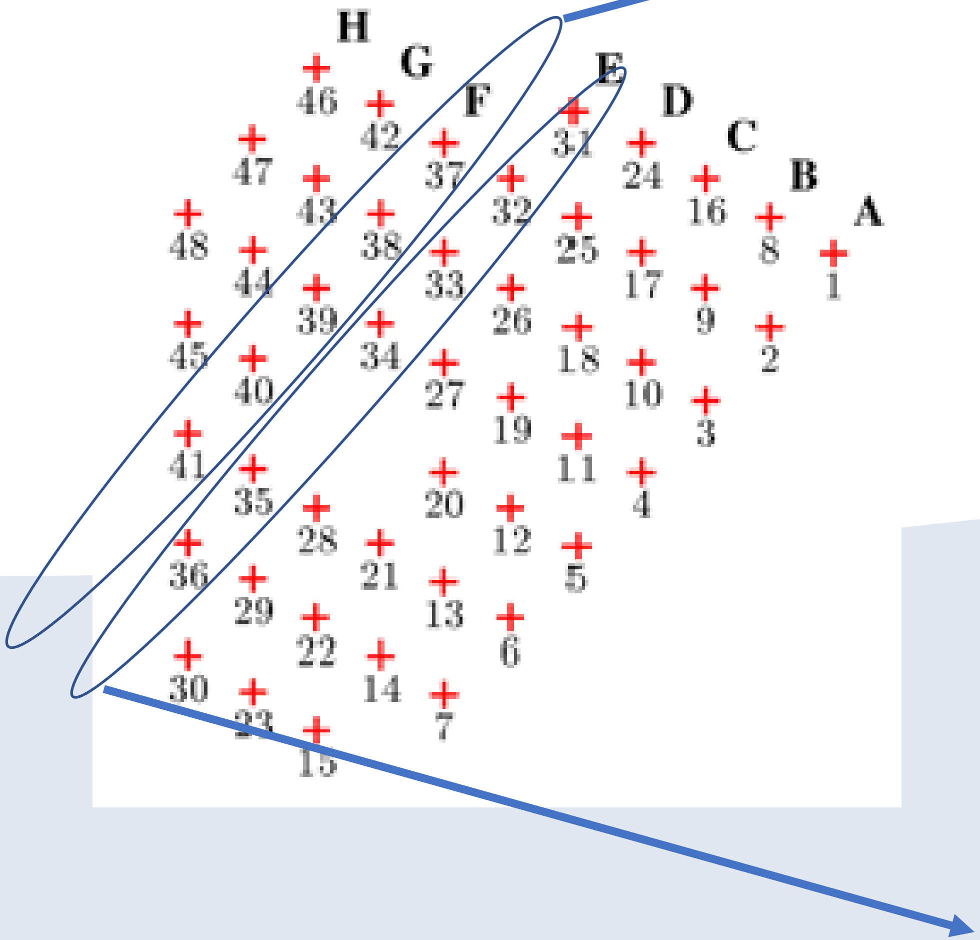
Results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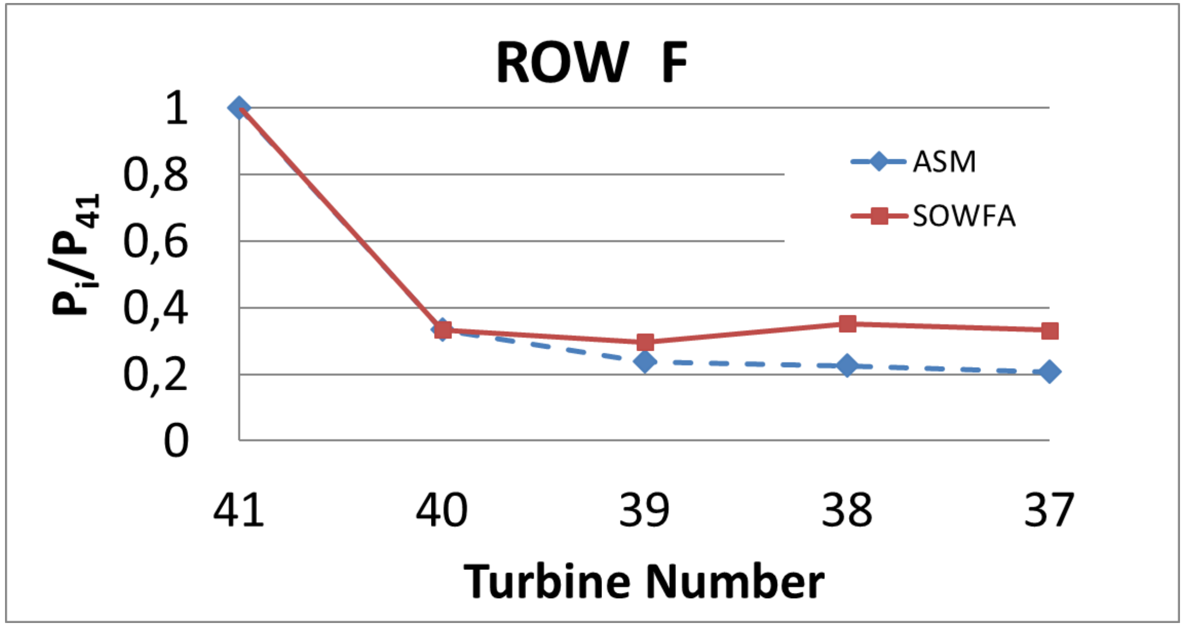
ROW F
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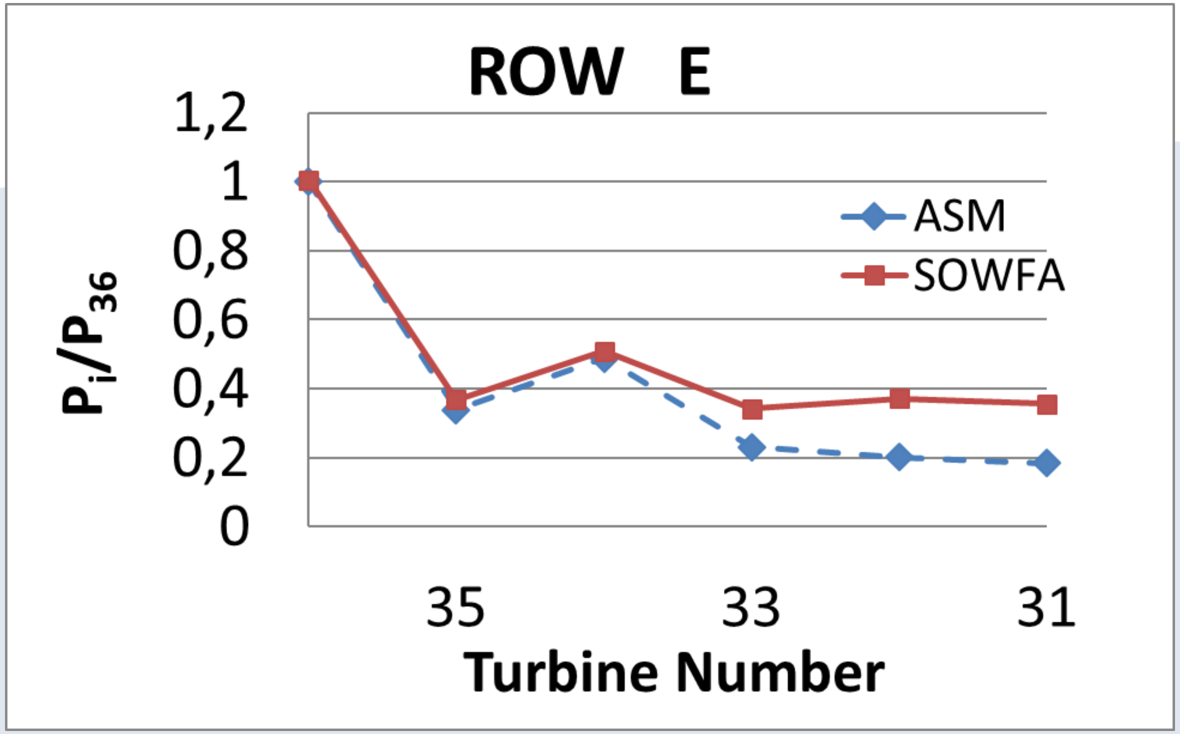
0,6
0,4
0,2
0
ASM
SOWFA
41
40
39
38
37
Turbine Number


ROW E
P_i/P_{36}
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1
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0,6
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ASM
SOWFA
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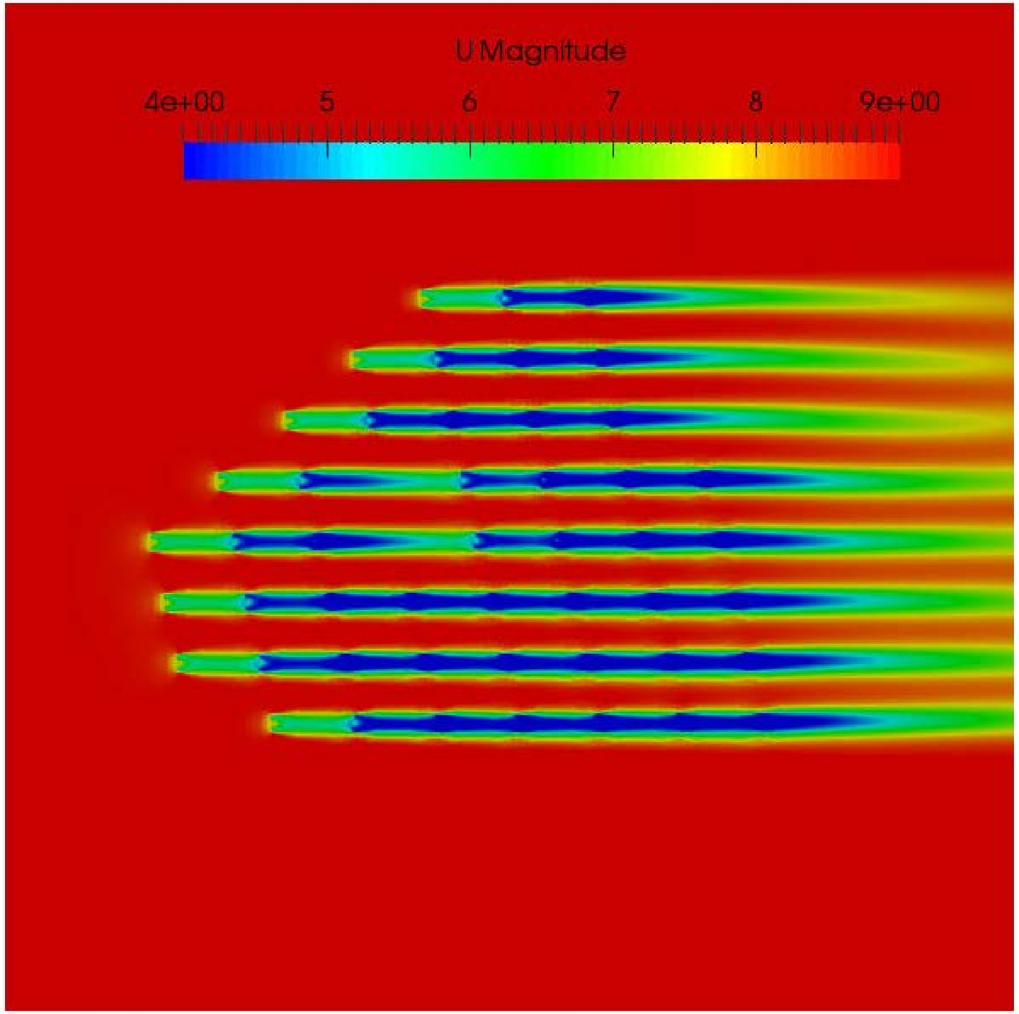
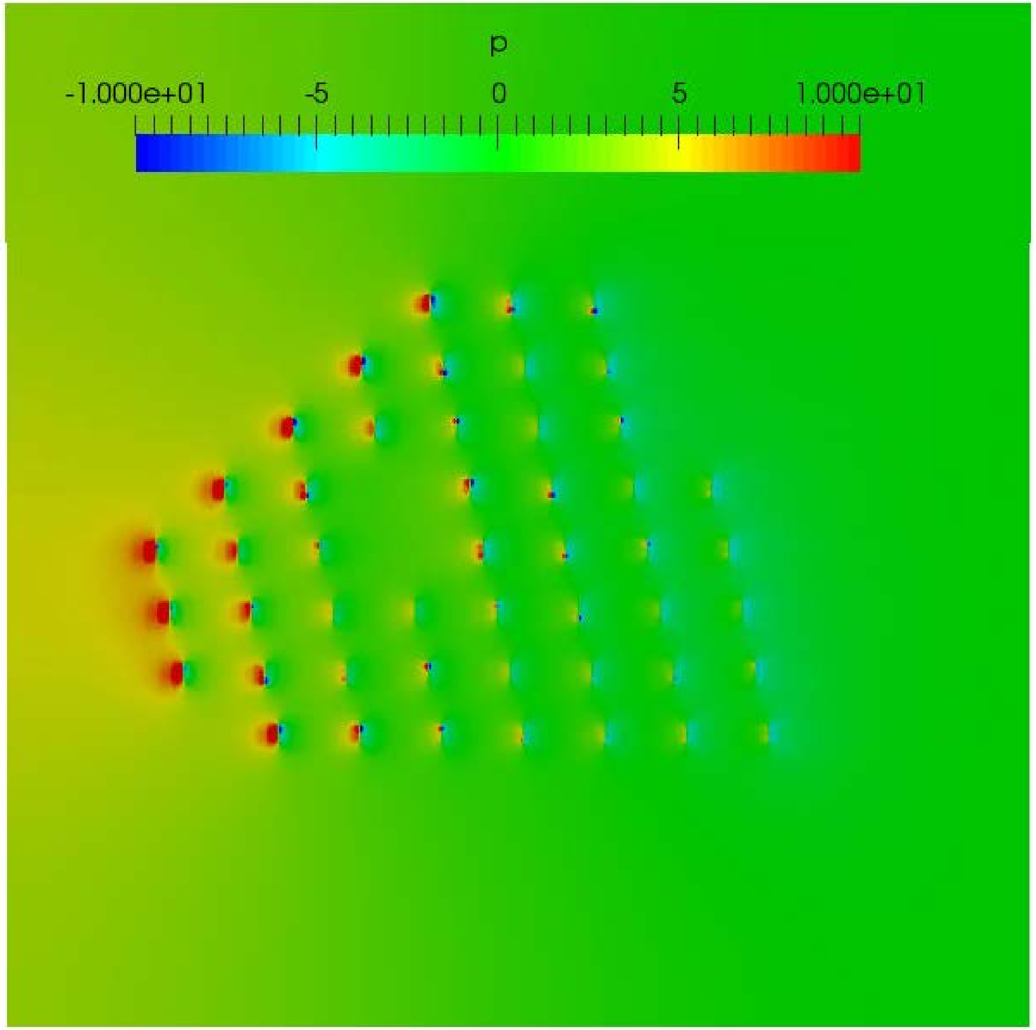
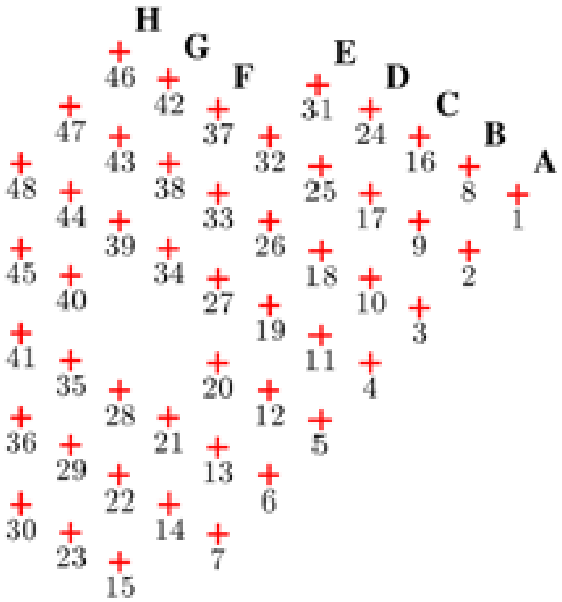
Turbine Number

Velocity and pressure distribution (WD=221)

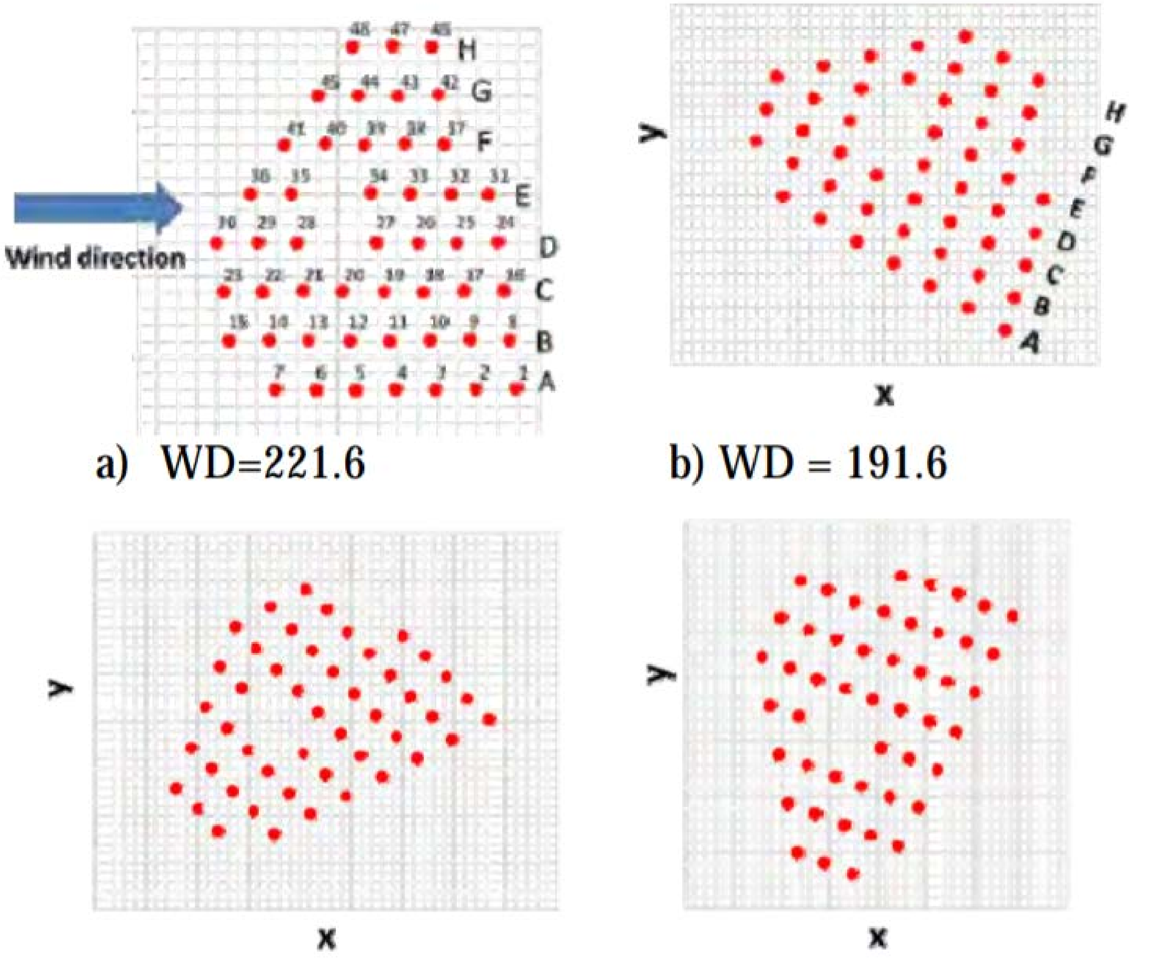




Orientation of the wind farm relative to different wind velocities.



Original wind park Layout



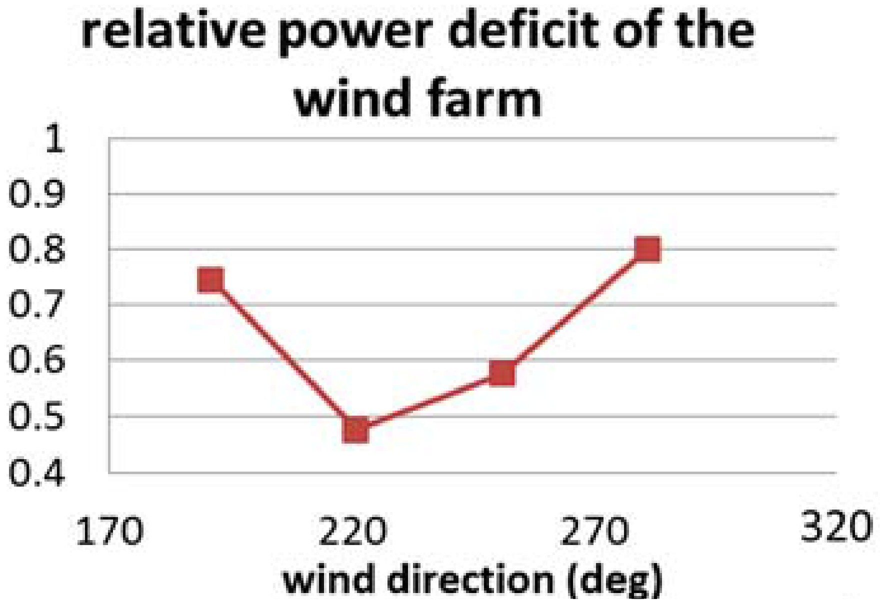
a) WD=221.6

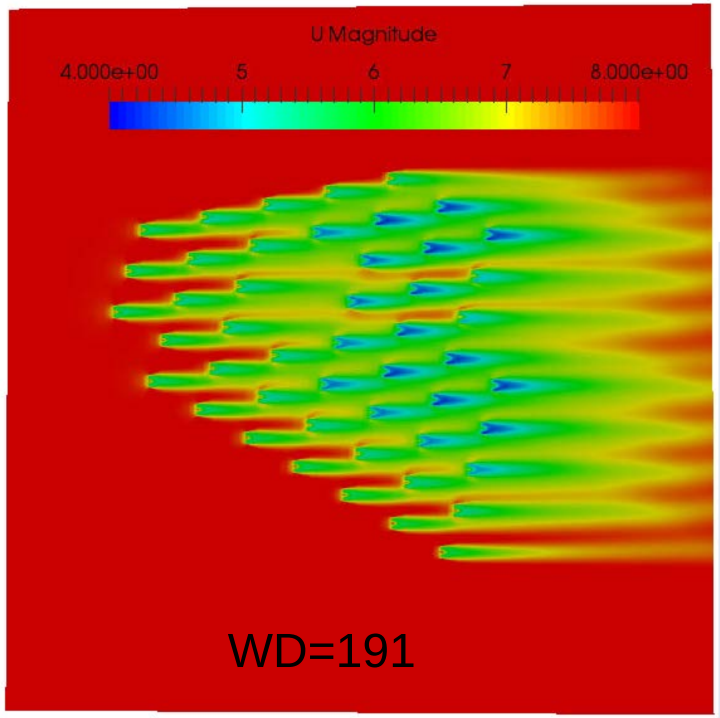
b) WD = 191.6

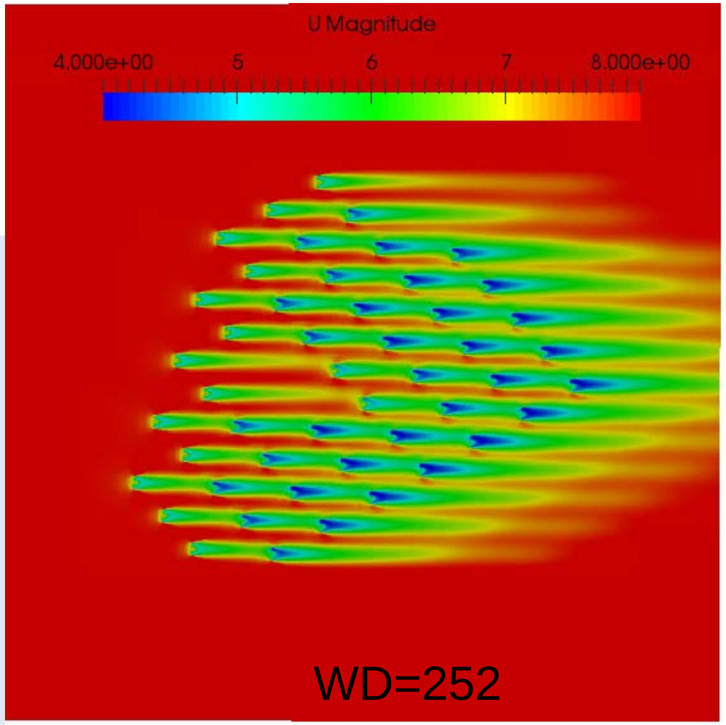
c) WD=251

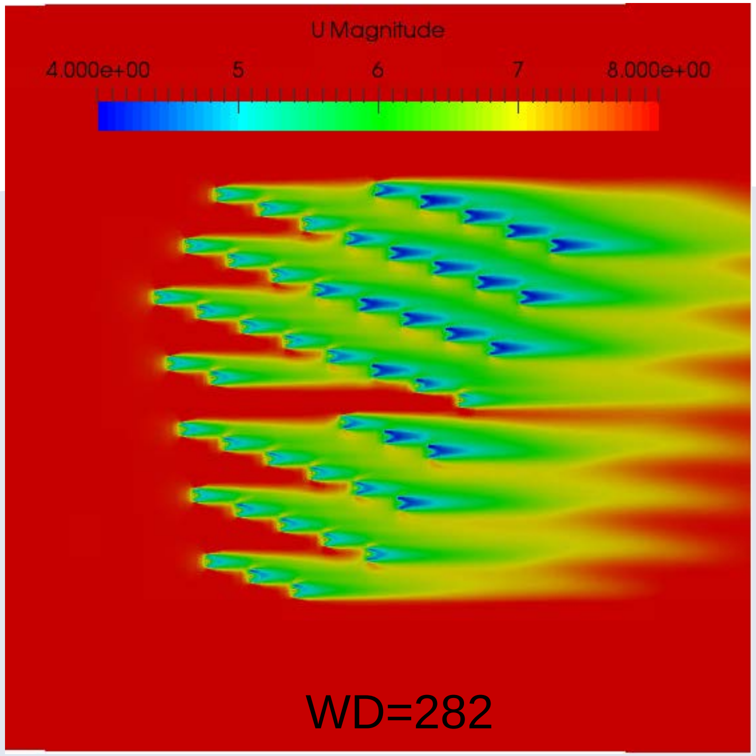
d) WD=281

Effect of wind direction









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Conclusions and future studies

- ASM is implemented in OpenFoam
- A preliminary verification of the models is completed
- The implemented ASM underpredicts power compared to the field data for turbines which are in multiple wakes
  - Cross check the implementation to find out bugs
  - Further refine the mesh (Mesh sensitivity studies)
  - Modify turbulence models
- Turbulence models need to updated by adding source term in k and ε equations
- Our group has developed Filter-based unsteady RANS turbulence model
- Validation of ASM for other wind farm.

Acknowledgement

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