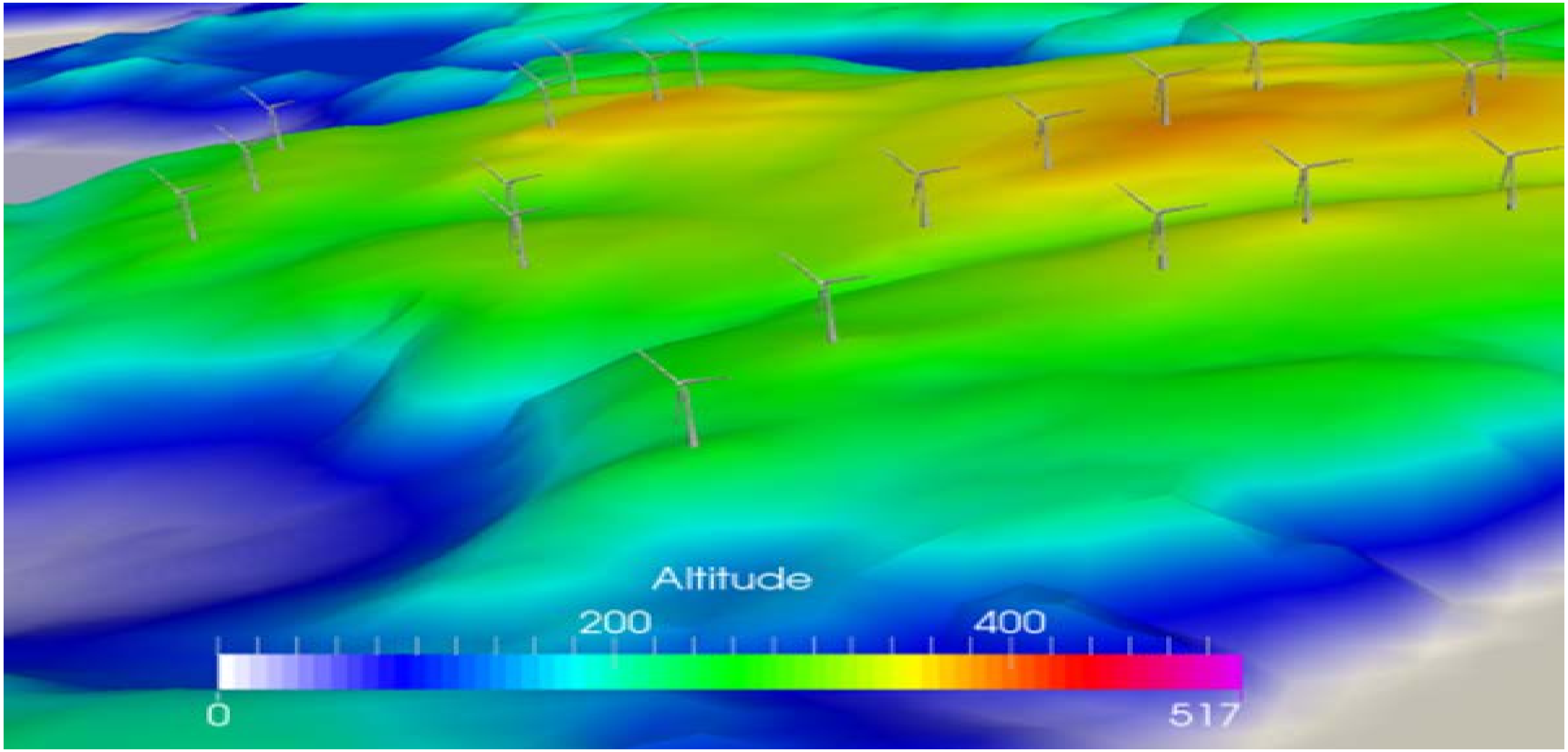

INVESTIGATION OF THE IMPACT OF WAKES AND STRATIFICATION ON THE PERFORMANCE OF AN ONSHORE WIND FARM

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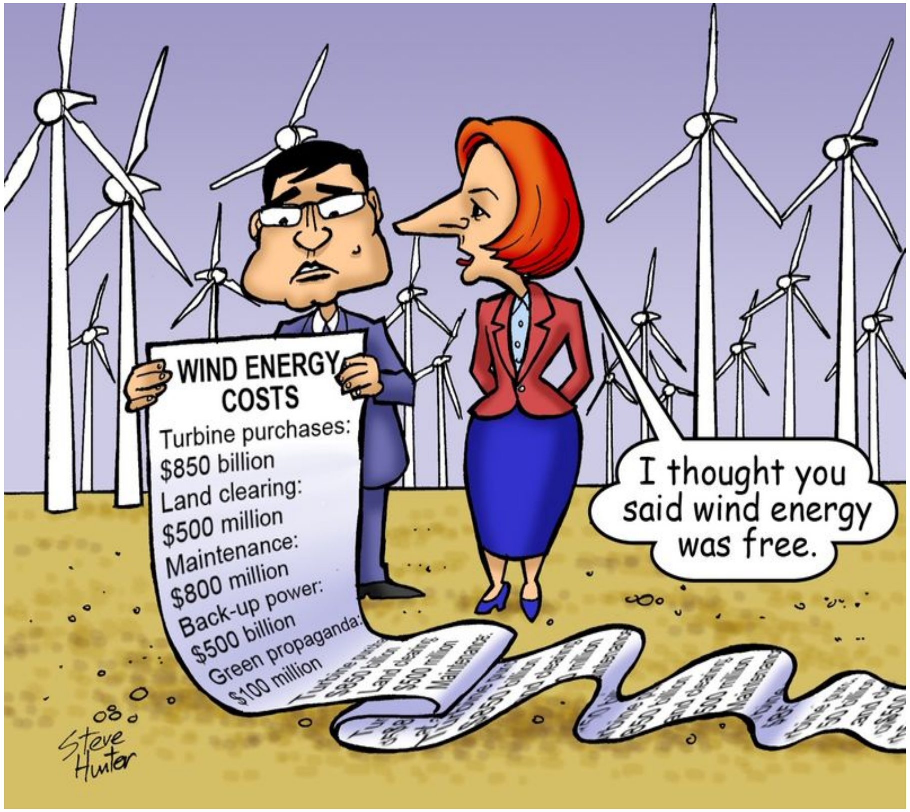
12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015, Trondheim, 6th February 2015

CONTENTS OF PRESENTATION

- MOTIVATION
- STATUS
- OBJECTIVE
- MODEL APPLICATION ON BESSAKER WIND FARM
- RESULTS
- CONCLUSION

MOTIVATION

- Reducing Cost of Energy (CoE)

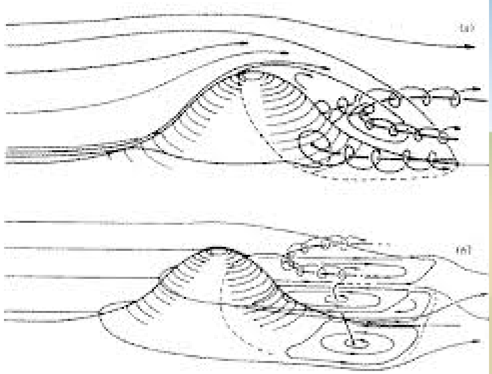


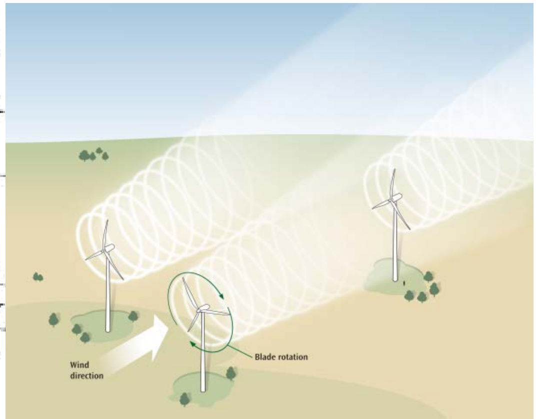
Cartoon Source : forthewind.wordpress.com

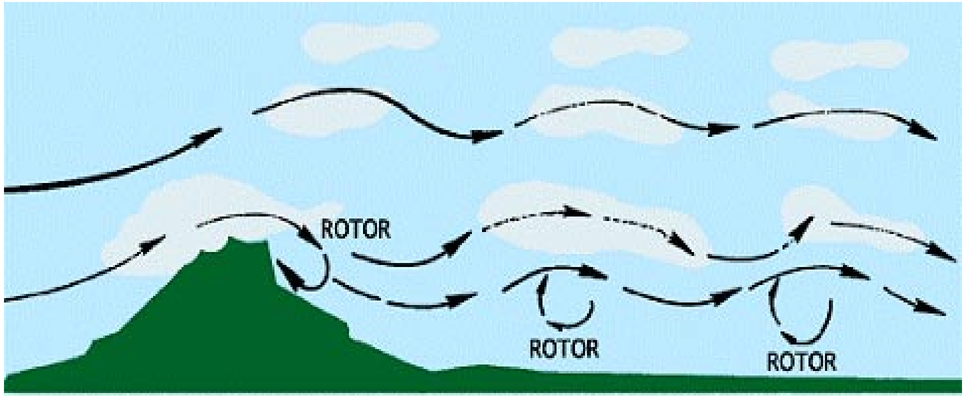
APPROACH TOWARDS COE REDUCTION

- Accurate estimation of wind resource and power production at a wind farm location will help in CoE reduction.

- Influenced by :
  - terrain conditions
  - wake effects
  - atmospheric stratification (Neutral, Stable, Unstable)







Schematic cross section of a mountain wave. Note also the rotary circulation below the wave crests.

CURRENT STATUS : NUMERICAL MODELLING TO ESTIMATE POWER AND WIND RESOURCE

- Most numerical wind models simplify actual physics in atleast one of these three ways :

  (a) Ignoring complex terrain geometry : simplification involves using a roughness factor.

  (b) Ignoring stratified conditions : simplification involves assuming neutral conditions in its place.

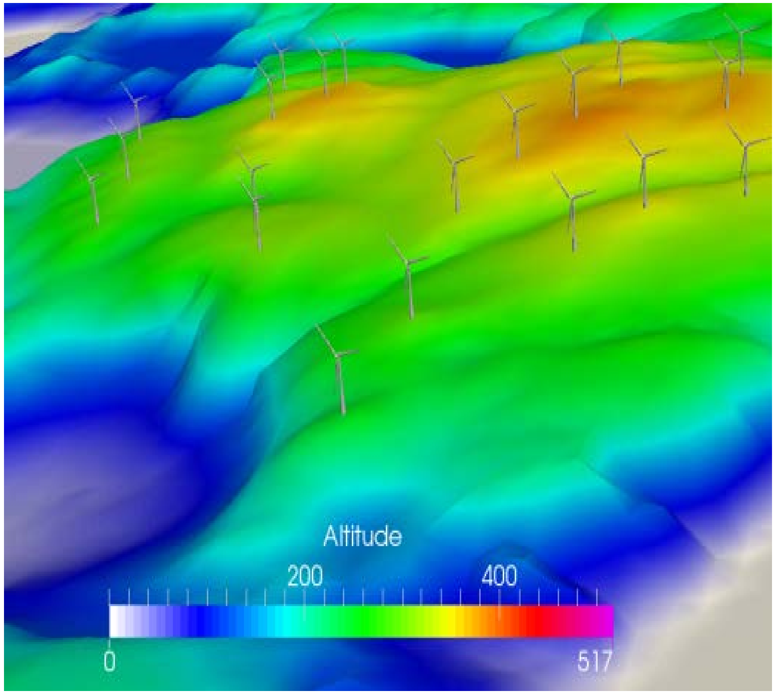
  (c) Ignoring wake effects or using simplified wake models.

- Hardly any model that combines these three effects simultaneously without resorting to over-simplification.

OBJECTIVE

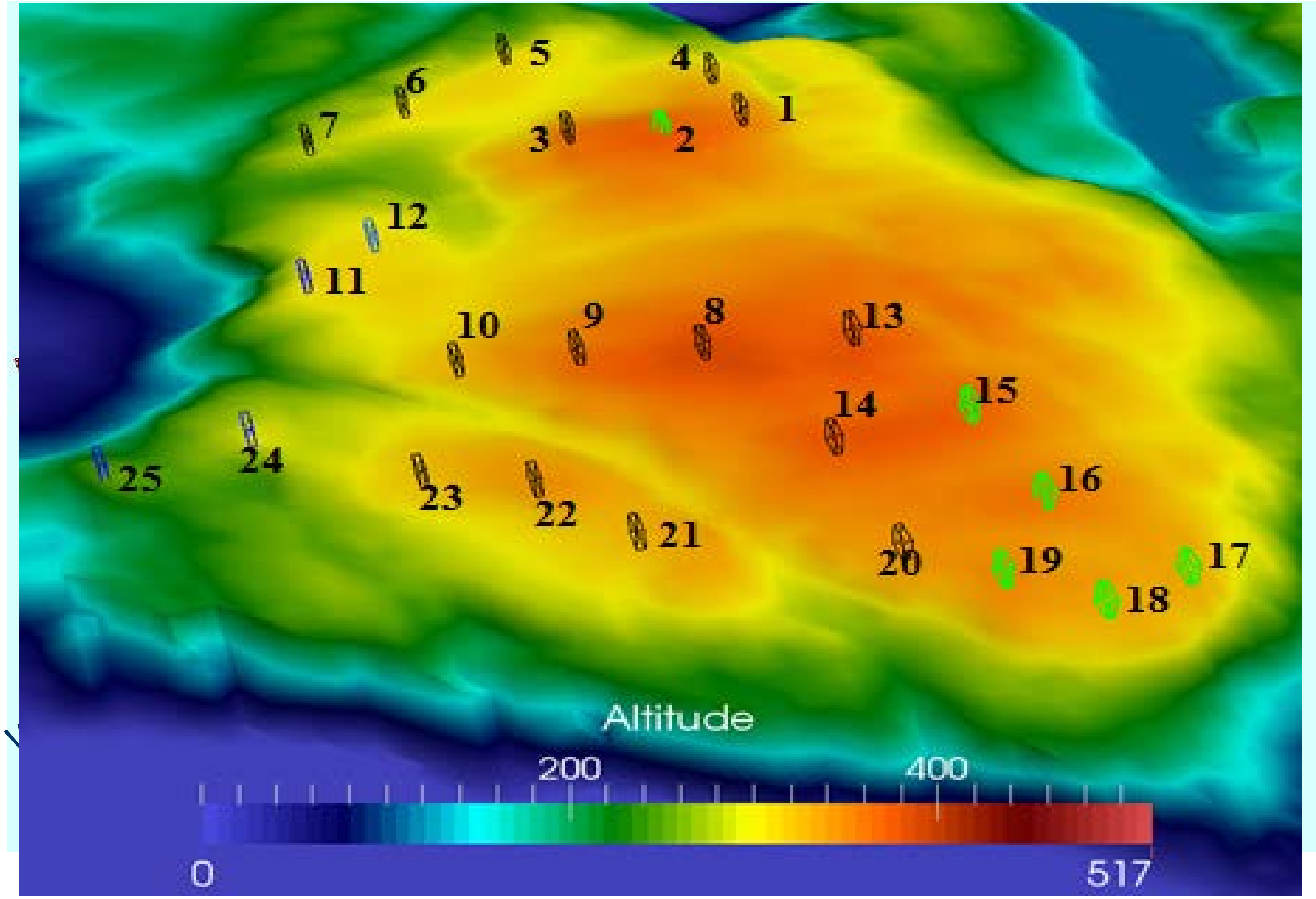
- To develop an advanced numerical model that accounts for these three effects simultaneously.
- To study the influence of these physics on wind field and power production.
- To apply this model on a realistic industrial wind farm.
- To encourage usage of such models for industrial wind farms

APPLICATION : BESSAKER WIND FARM



It is a 25 Turbine farm located in a complex terrain in mid-Norway near Trondheim, and is operated by Trønder Energi. Each Turbine- Rated Power 2.3 MW, 71 m diameter.

CFD Solution Methodology



Domain: 6.8 Km x 4.5 Km x 1.5 Km. Westerly Wind Direction considered.
Grid Size **13 Million**. Finest grid size is 6 m in wind farm region. Both Neutral and Stable Atmospheric Stratification considered.

EQUATIONS SOLVED

$$\nabla.(\rho_s \boldsymbol{u})=0$$

(1) CONTINUITY EQUATION

$$\frac{D\boldsymbol{u}}{Dt} = -\nabla\left(\frac{p_d}{\rho_s}\right) + \boldsymbol{g}\left(\frac{\theta_d}{\theta_s}\right) + \frac{1}{\rho_s}\nabla.(\boldsymbol{R}) + \boldsymbol{f}$$

(2) MOMENTUM EQUATION

$$\frac{D\theta}{Dt} = \nabla.(\gamma_T \nabla\theta) + q$$

(3) POTENTIAL TEMPERATURE EQUATION

$$\frac{DK}{Dt} = \nabla.(v_T \nabla K) + P_k + G_\theta - \varepsilon$$

(4) TURBULENT KINETIC EQUATION

$$\frac{D\varepsilon}{Dt} = \nabla.\left(\frac{v_T}{\sigma_e}\nabla\varepsilon\right) + (C_1 P_k + C_3 G_\theta)\frac{\varepsilon}{k} - C_2\frac{\varepsilon^2}{k}$$

(5) EDDY DISSIPATION RATE

(6)

$$R_{ij} = v_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}$$

(6) REYNOLD STRESS

$$P_k = v_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}, \quad G_\theta = -\frac{g}{\theta}\frac{v_T}{\sigma_T}\frac{\partial\theta}{\partial z}$$

(7) TKE Production by Shear, TKE Production by Buoyancy.

ACTUATOR LINE MODEL

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

$$D = \frac{1}{2} C_D(\alpha)\rho V_{rel}^2\, c.$$ (2) DRAG FORCE

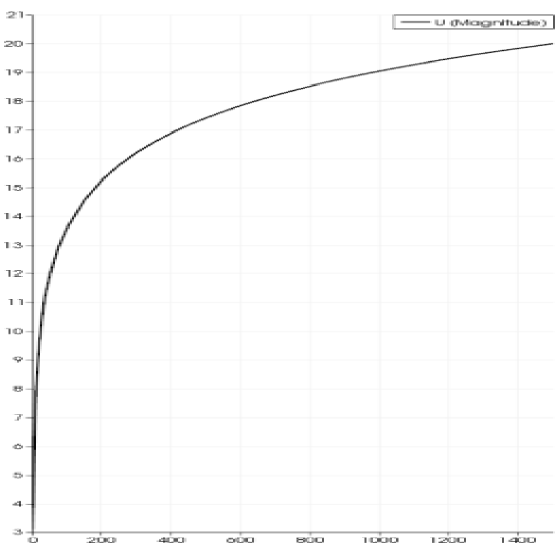
$$F_i^T(x,y,z,t) = -\sum_{j=1}^{N} f_i^T(x_j,y_j,z_j,t)\frac{1}{\epsilon^3\, \pi^{3/2}} exp\left[-\frac{{r_j}^2}{\epsilon}\right]$$ (3) FORCE PROJECTION

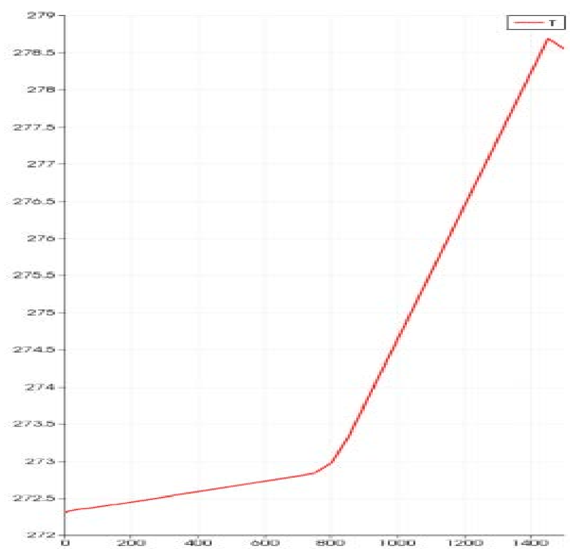
Output from the model is : Forces , Torque , Thrust on the turbine blades and Power produced by each turbine. (6)

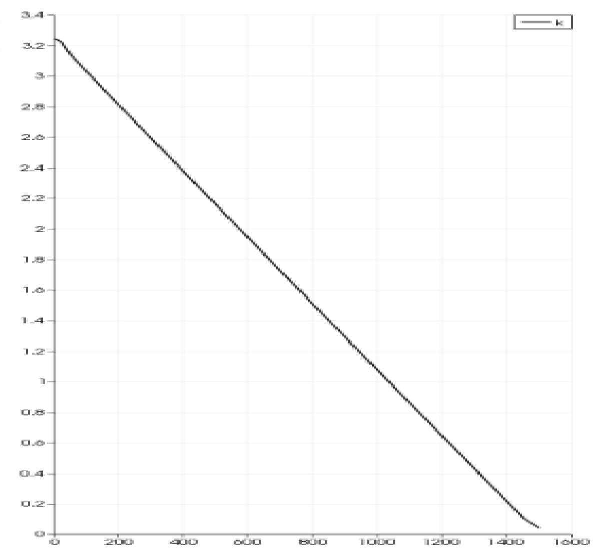
OpenFOAM was used in this work. Parts of model from SOWFA (ALC) have been used and rest additional terms like buoyancy induced turbulence; complex terrain model incorporated by us .

INLET PROFILES USED IN SIMULATIONS

VELOCITY TEMPERATURE TKE





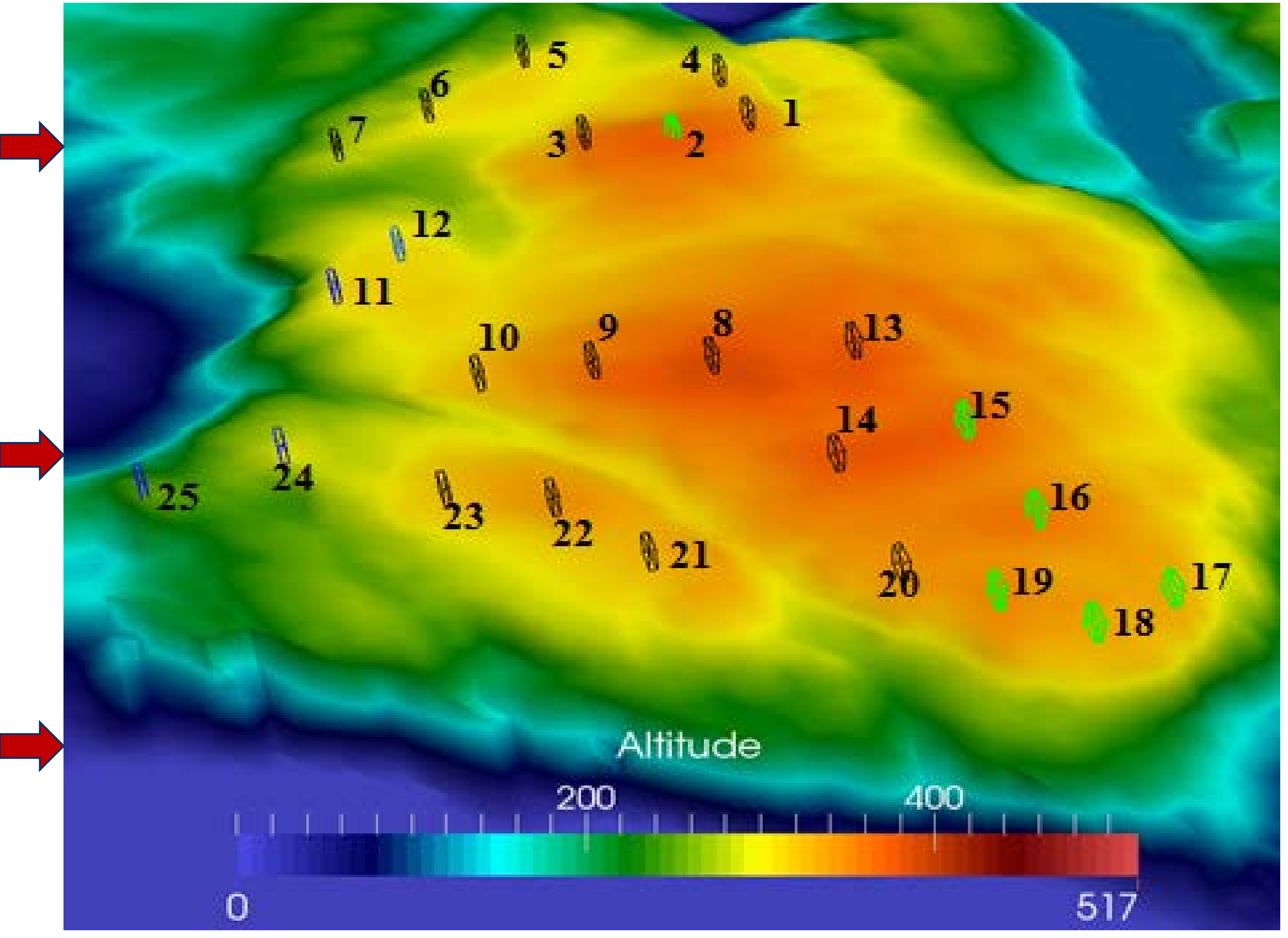


X AXIS : HEIGHT, VERTICAL DISTANCE FROM GROUND

TWO RUNS CONDUCTED : ONE WITH NEUTRAL CONDITION AND ONE WITH STABLE STRATIFICATION. STABLE CASE USES THE TEMPERATURE PROFILE USED ABOVE.

RESULTS

RESULTS : TURBINE PERFORMANCE FOR BOTH NEUTRAL AND STABLE SCENARIO.

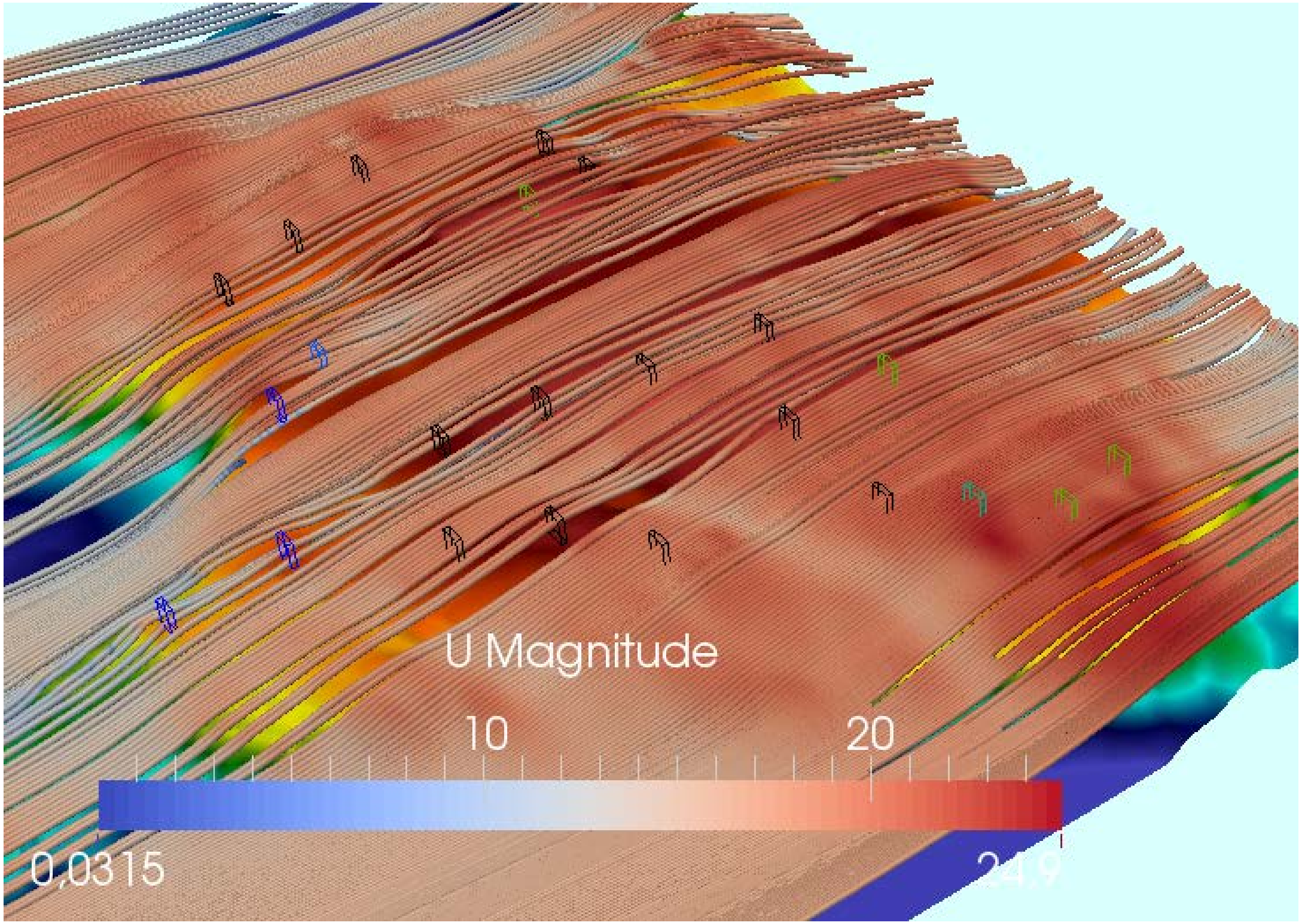


Green : High performing turbines.

Blue : Low Performing Turbines.

Black : Medium Performance.

STREAMLINES TO SHOW REASONS FOR POWER PRODUCTION

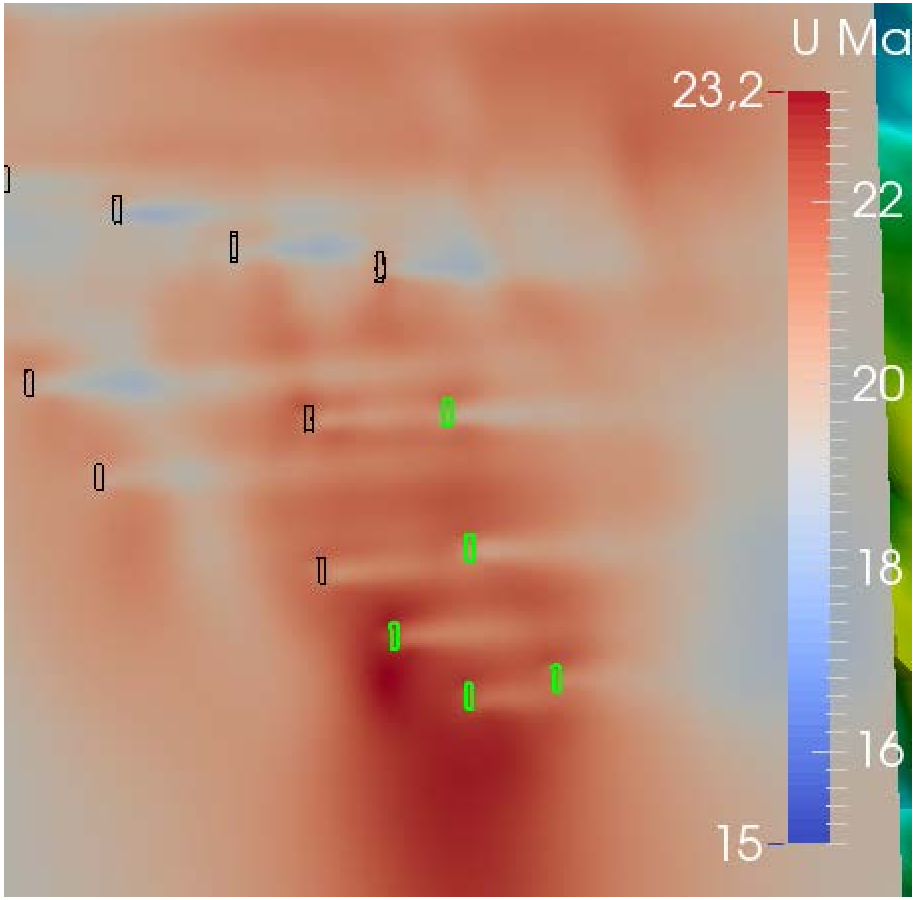


POWER PRODUCTION : NEUTRAL Vs STABLE CASE

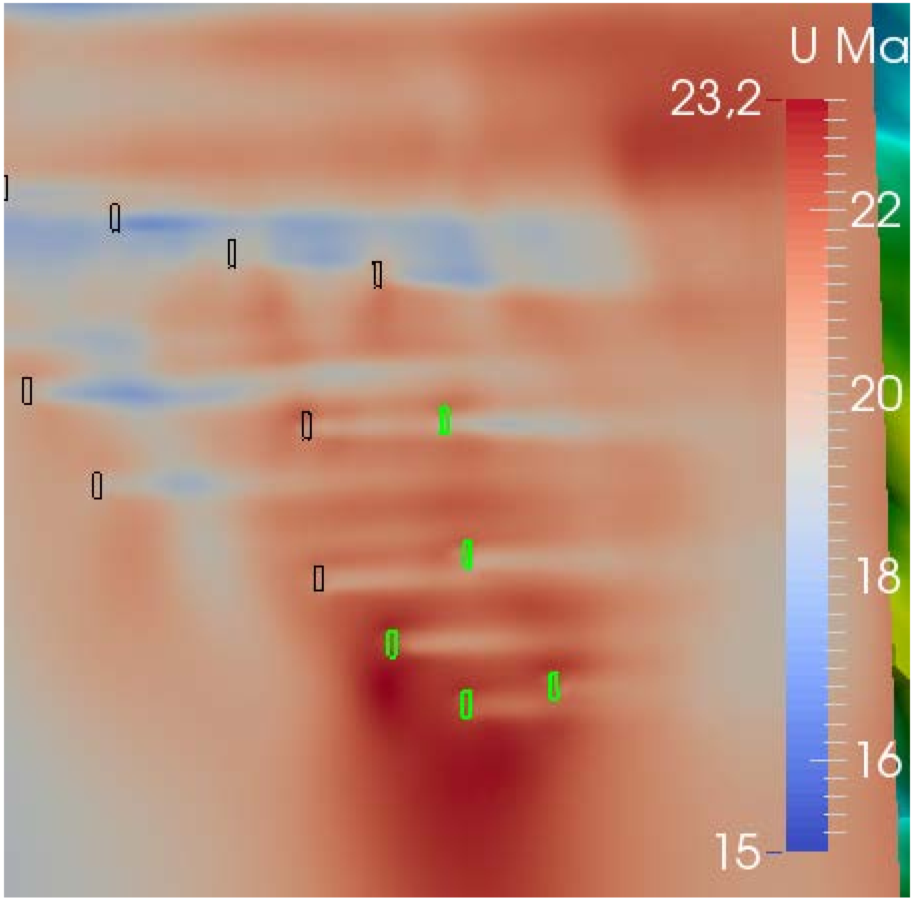
- **In this particular case, the power produced during stratification was lower by 2% as compared to the neutral case.**
- Stable stratification in a terrain : channelling and/or delayed wake decay owing to low turbulence, both of which **may** cause lower production.
- However, for present thermal stratification condition, the reduction seems due to delayed wake effect and not due to channelling. This is expected as the Froude number higher than one (nearly 5) so wind moves over the hills and not sideways.

WAKE VELOCITY DEFICIT : NEUTRAL VS STABLE

Contour of Velocity : Wake Velocity Deficit Region is more in Stable case resulting in lower power production.



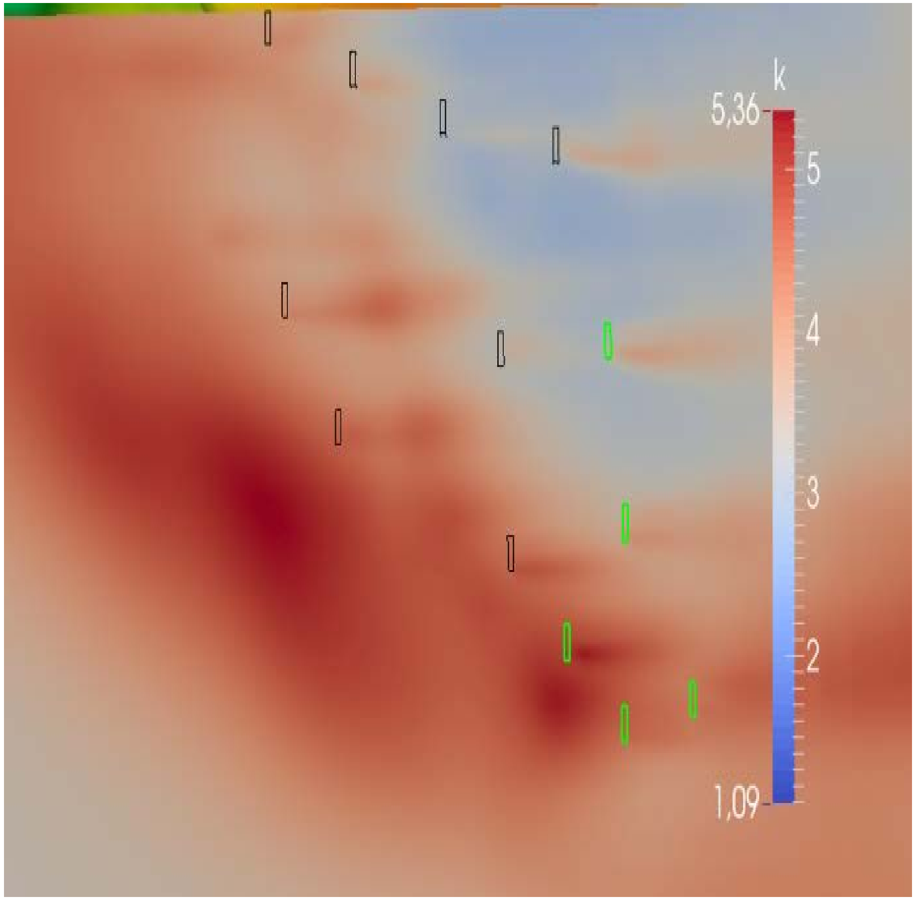
Neutral



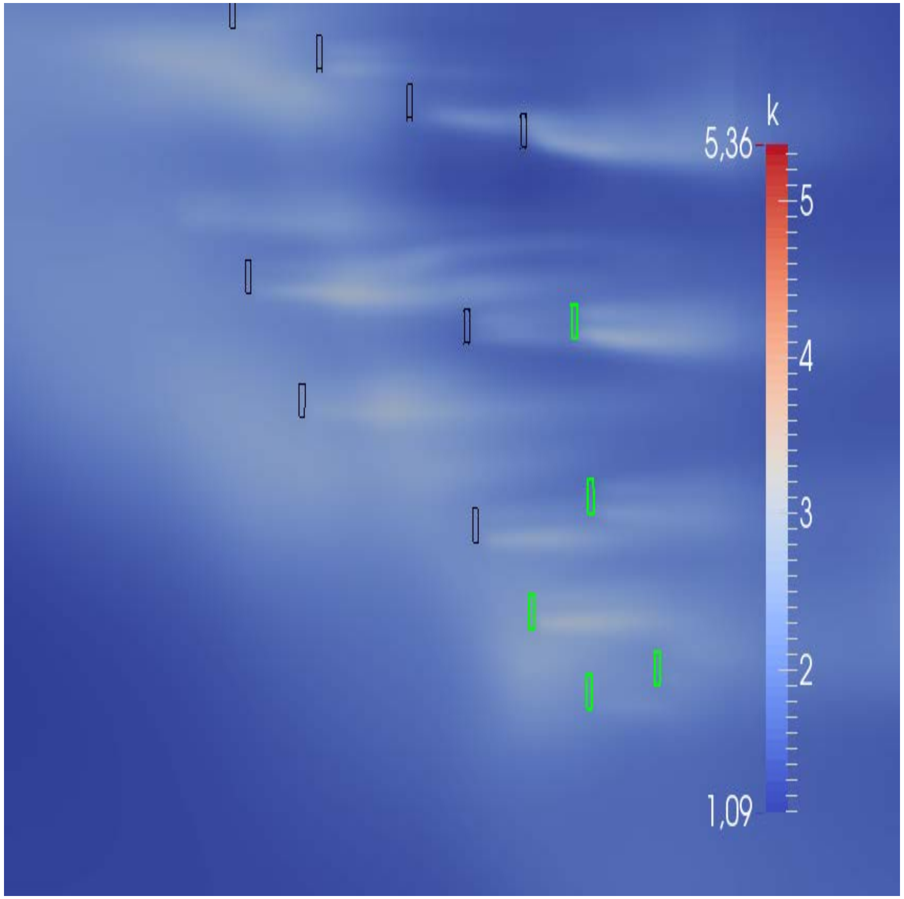
Stable

TURBULENT KINETIC ENERGY : NEUTRAL VS STABLE.

Higher TKE in Neutral case. Low TKE causes delayed wake decay in stable case.



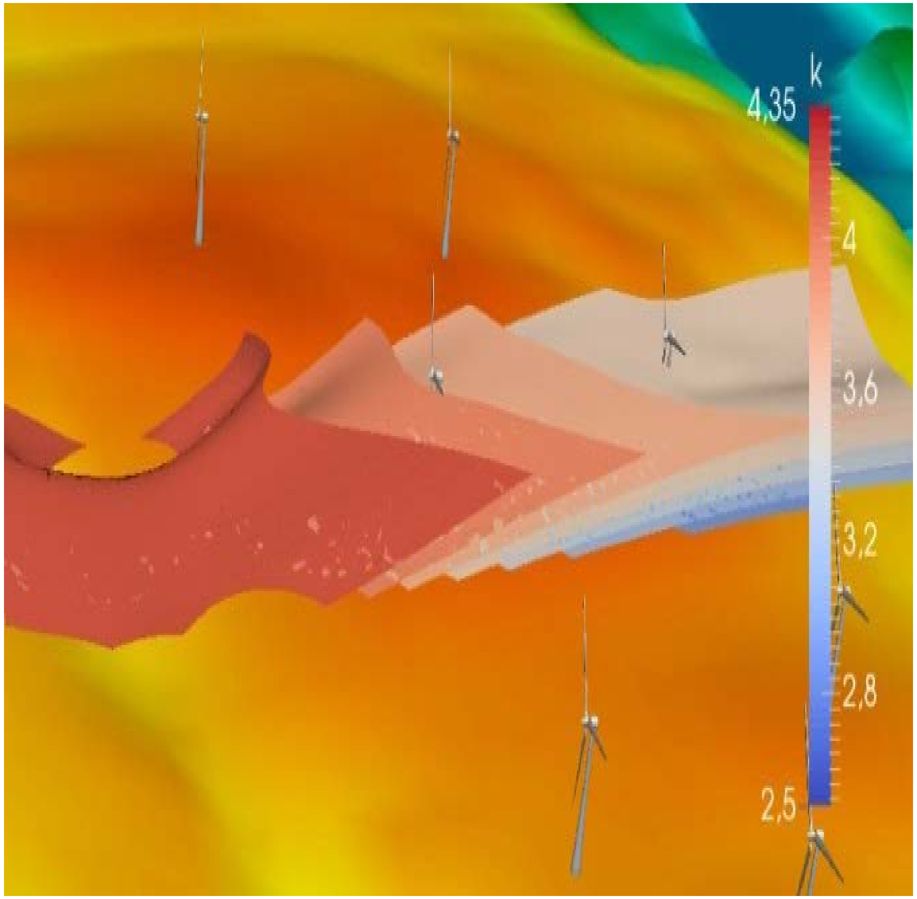
Neutral



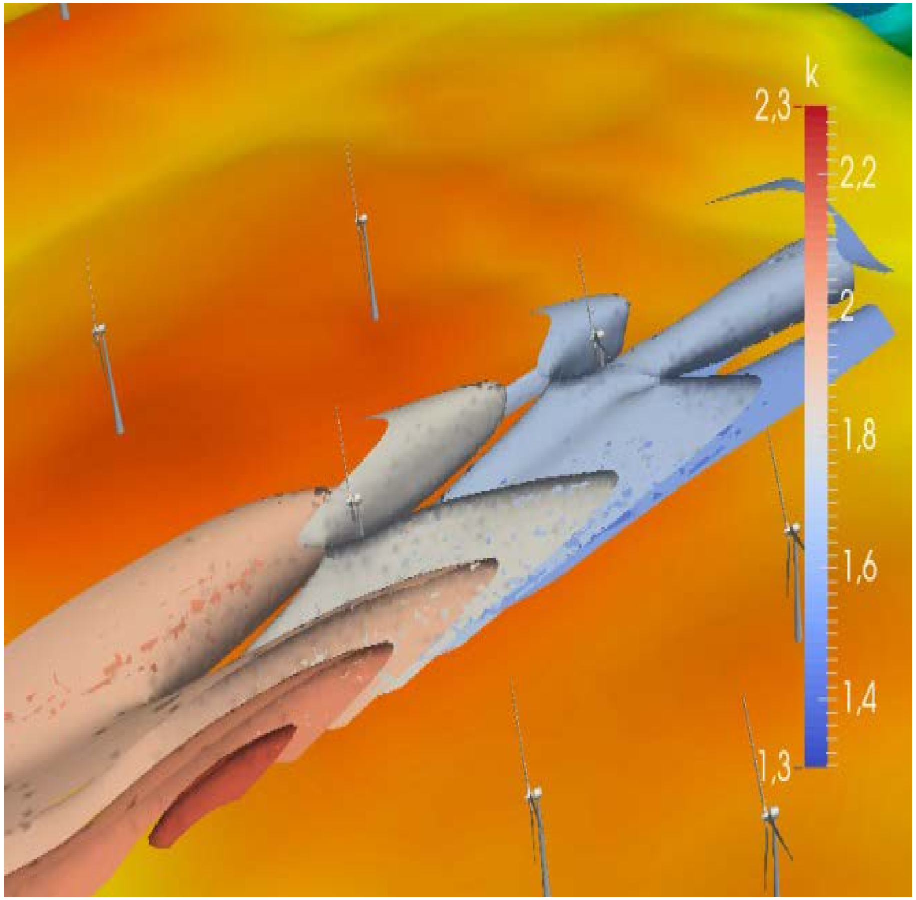
Stable

WAKES : NEUTRAL VS STABLE

Wake structure intact in stable case and extends from one turbine to another.



Neutral



Stable

CONCLUSION AND FUTURE WORK

- A model accounting for complex terrain, wake effects and thermal stratification is developed.
- Effect of stratification on wake decay is captured.
- This gives insights about the reduced power scenario in stratified condition as compared to neutral conditions.
  - The inter-turbine distance of 4 rotor turbine diameter might lead to reduced power during stratified condition as wake decay is delayed owing to lower atmospheric turbulence in stratified case.

- Future studies : Different wind directions, Domain effect, clubbing meso-scale model, LES.

ACKNOWLEDGEMENTS

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  www.fsi-wt.no

  (Fluid-Structure Interaction for Wind Turbine)

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THANK YOU