A fast reduced order method for assessment of wind farm layouts

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Why is there a need for a fast and accurate method?

- There are many possible applications:
  - Assessment of layout
  - Long term energy yield estimation
  - Short term production forecasting

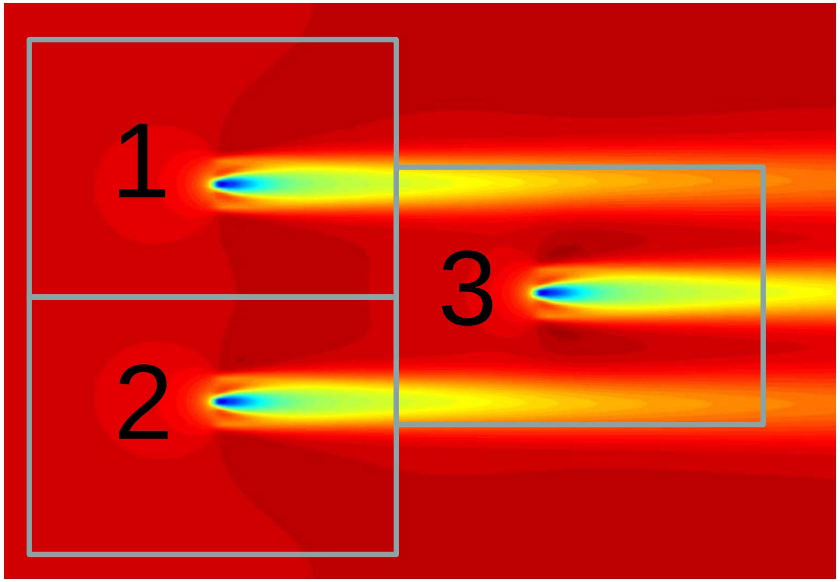
- But it is hard! The flow field in wind farms is complex due to interacting wakes
  - Wake losses depend on wind conditions and turbine positions

- Computational Fluid Dynamics (CFD) can be used, but is too slow for interactive assessment of different layouts

- Other computationally fast methods simplify the governing equations
  - Simplified models of turbine wakes (e.g. Jensen model)
  - FUGA: linearization of the flow equations

Model reduction

- Our proposed alternative fast technique
- Reduction of the solution space, while including the nonlinear RANS equations
- The solutions space is constructed from a set of steady state CFD simulations using the RANS equations
- The solution time is reduced from hours to seconds

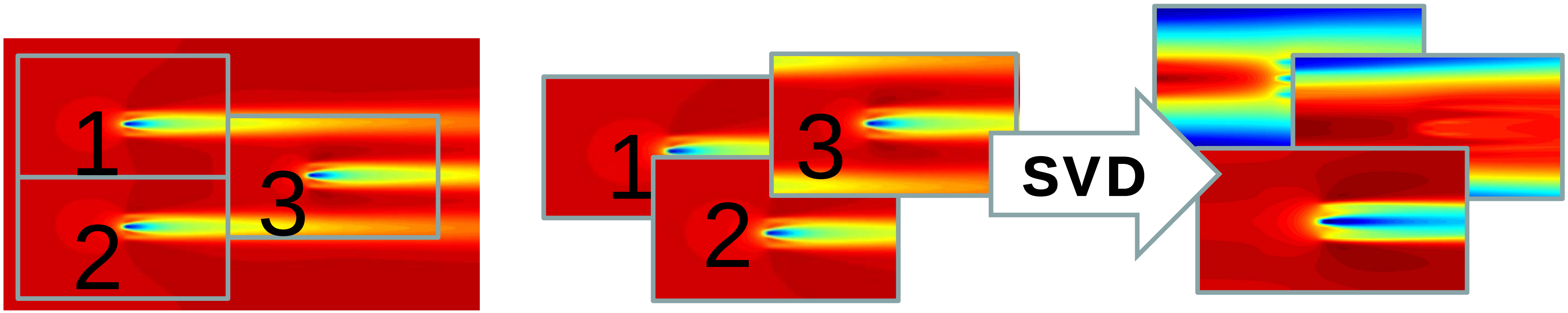


Construction of the reduced space

- Run multiple CFD simulations for varying setups
  - Different turbine positions
  - Different wind conditions
- Use the simulations to produce a low dimensional space of basis modes

Example:

One CFD simulation　　Three snapshots　　Orthogonal basis modes



The solution in the reduced space

- The solution space is represented by a matrix of basis modes/vectors

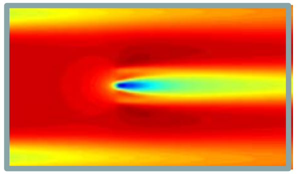
$$B = [\varphi_1, \varphi_2, \dots, \varphi_M]$$

- Any solution for a tile is written as a coefficient vector

$$a = [a_1, a_2, \dots, a_M]$$

- This reduced space solution represents the reconstructed full-space solution

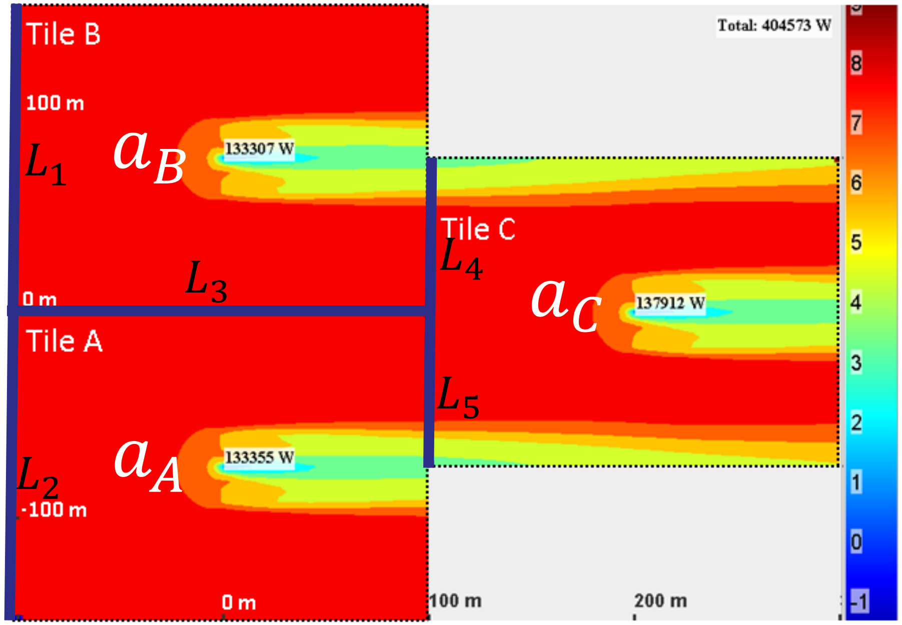
$$u = Ba$$



$$\xleftarrow{\quad B \quad} [a_1, a_2, \dots, a_M]$$

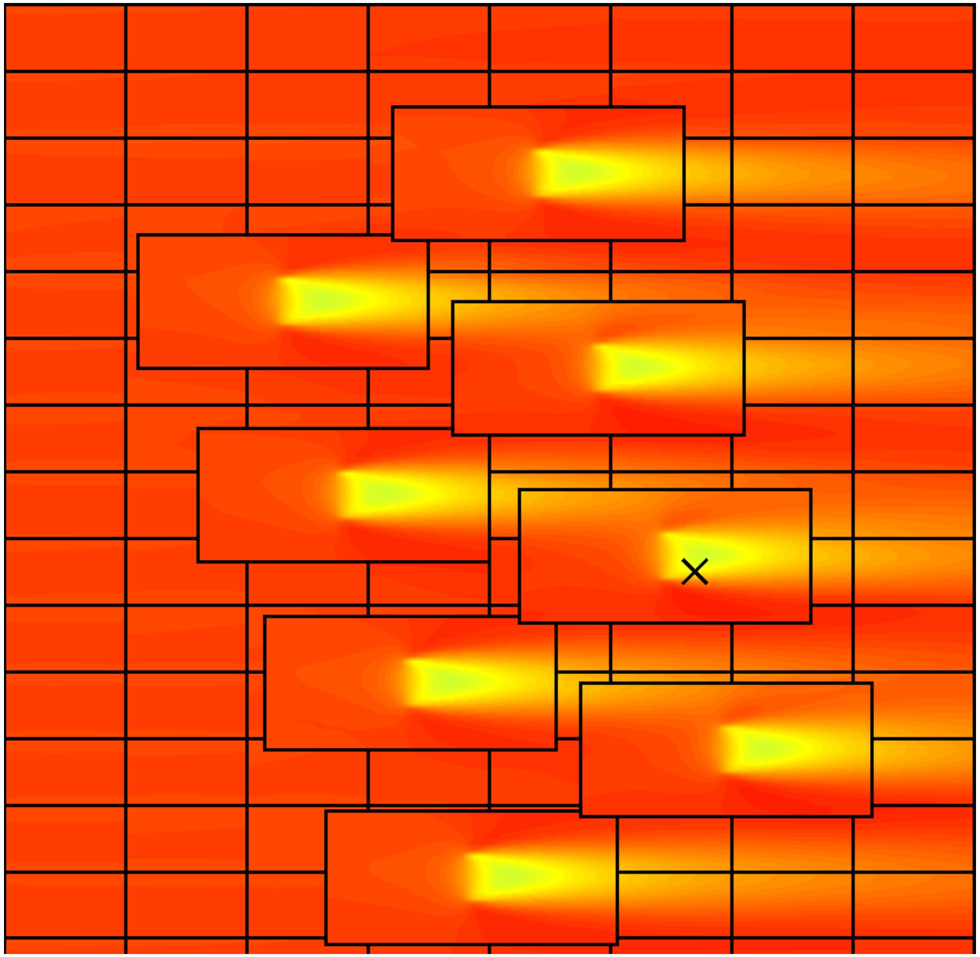
Tile coupling and fitting to RANS equations

- Minimize the sum of boundary discrepancies in the full space (least squares fitting)
- At the same time the reconstructed full space solution should satisfy the RANS equations as well as possible
- The weighting between tile coupling and fitting to RANS equations is controlled through a parameter α
  - $\alpha = 0$: All weight to tile coupling
  - $\alpha = 1$: All weight to RANS



Find $[a_A^T, a_B^T, a_C^T]$ so that $L_1 + L_2 + L_3 + L_4 + L_5$ is minimized

Empty tiles and the background grid

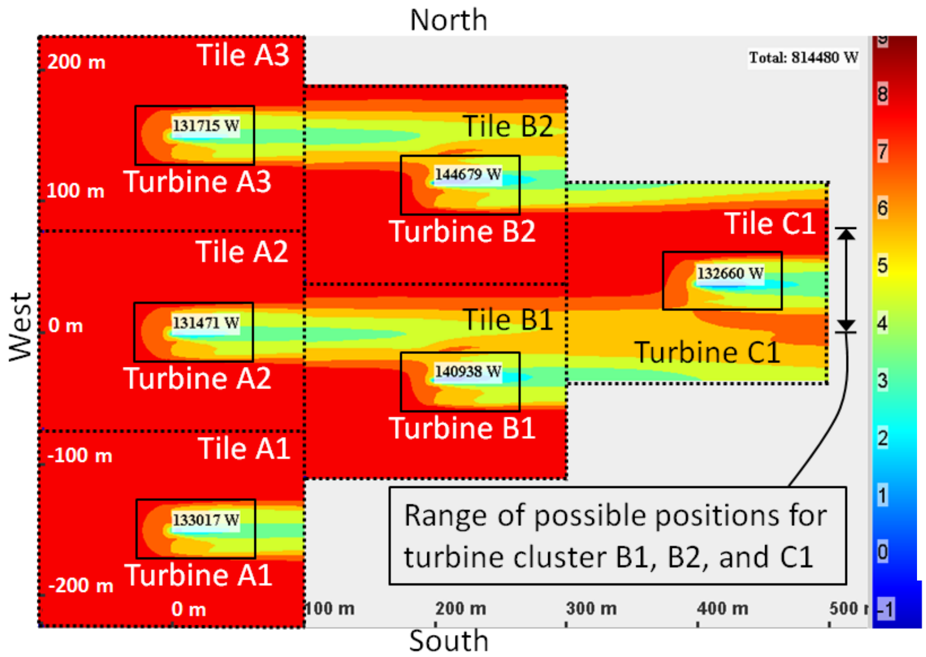


- We have added “empty tiles” to propagate the flow field between non-overlapping turbine tiles
  - Empty tiles have a different basis than turbine tiles
  - Turbine tiles are placed on top of a grid of empty tiles
- The physical dimension of empty tiles is smaller than turbine tiles
  - Gives more flexibility when extracting snapshots for empty tiles

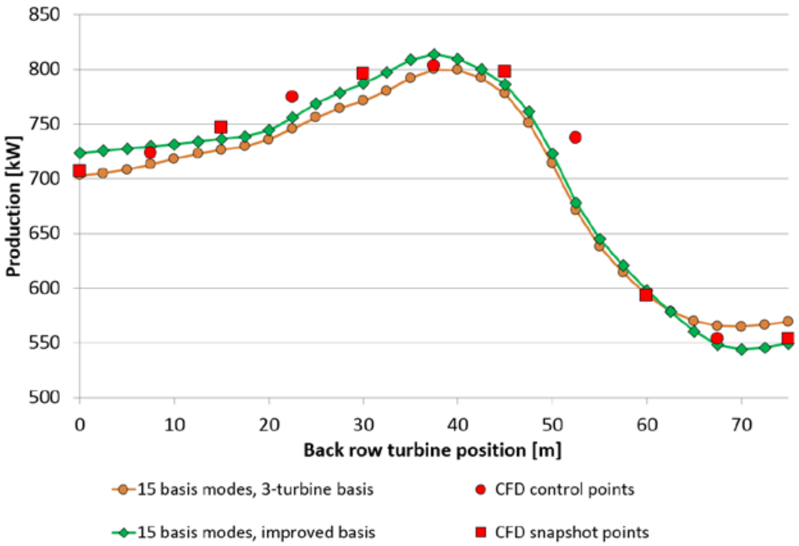
Results

- Movement of turbines in the cross-stream direction
- Multiple wake effect, turbines in line
- Varying wind speed

Cross stream movement of turbines



Solution of the x-component of the flow field at hub-height.



Production estimates for the wind farm for different positions of the three downstream turbines. The value 0 m refers to a center position of the cluster in a cross stream direction.

Heggelund Y, Skaar IM, and Jarvis C, 2012, Interactive design of wind farm layout using CFD and model reduction of the steady state RANS equation, 11th World Wind Energy Conference, Bonn, Germany. 3-5 July 2012.

Multiple wakes

- Ten turbines in a row with a uniformly varying distance between the turbines
- A solution basis was created from CFD simulations with turbine distances of 5 and 9 rotor diameters
- An equal number of snapshots were used from the 5 and 9 diameter cases

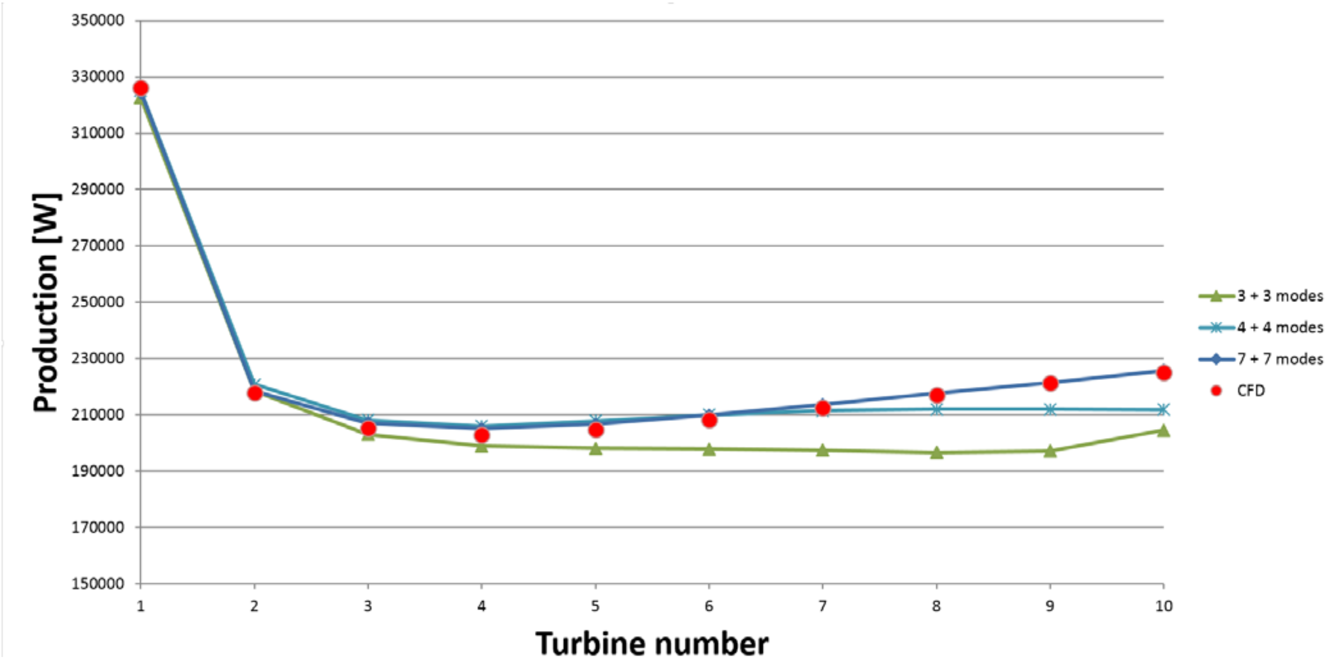
5 rotor diameters

Multiple wakes (cont.)

- The total deviation of the power production is less than 3.3% when using 4+4 or more modes.

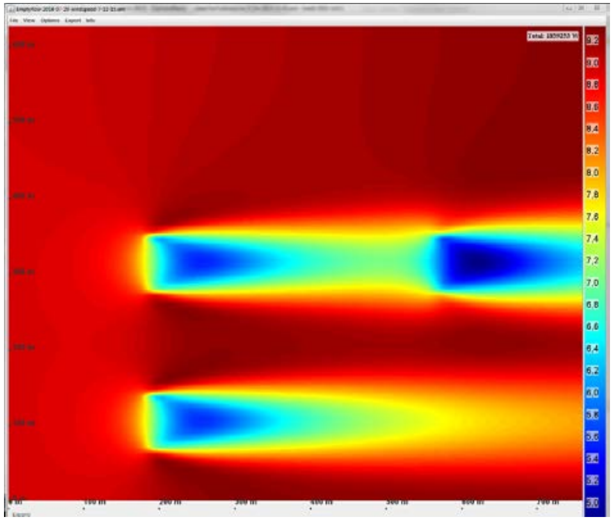
Heggelund Y., Khalil M., Jarvis C., Interactive design of wind farm layouts using CFD and model reduction, EWEA 2014, Barcelona, Spain, 10-13 March 2014.

Seven rotor diameters



Varying wind speed

- Fixed turbine positions
- Wind speed between 7 m/s and 15 m/s at hub height



Basis construction

Basis name	CFD simulation		
	7 m/s	11 m/s	15 m/s
Basis 7-15	✓		✓
Basis 7-11-15	✓	✓	✓

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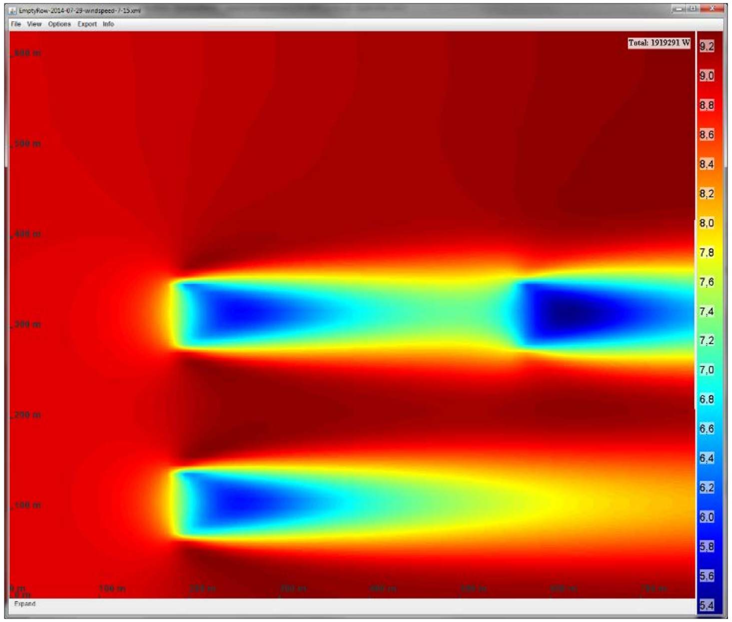
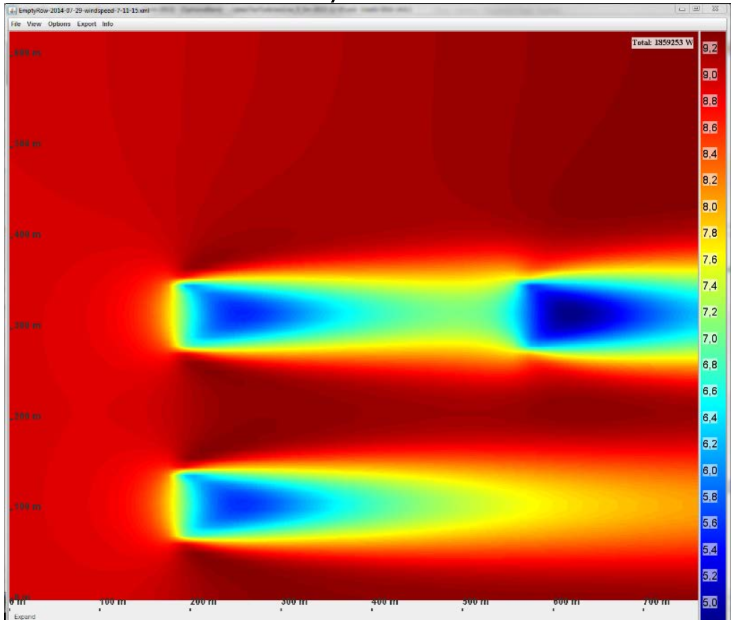
Varying wind speed (cont.)

Reproduction of the flow field for 9 m/s

Basis 7-15, $\alpha = 0.5$



Basis 7-11-15, $\alpha = 0.5$

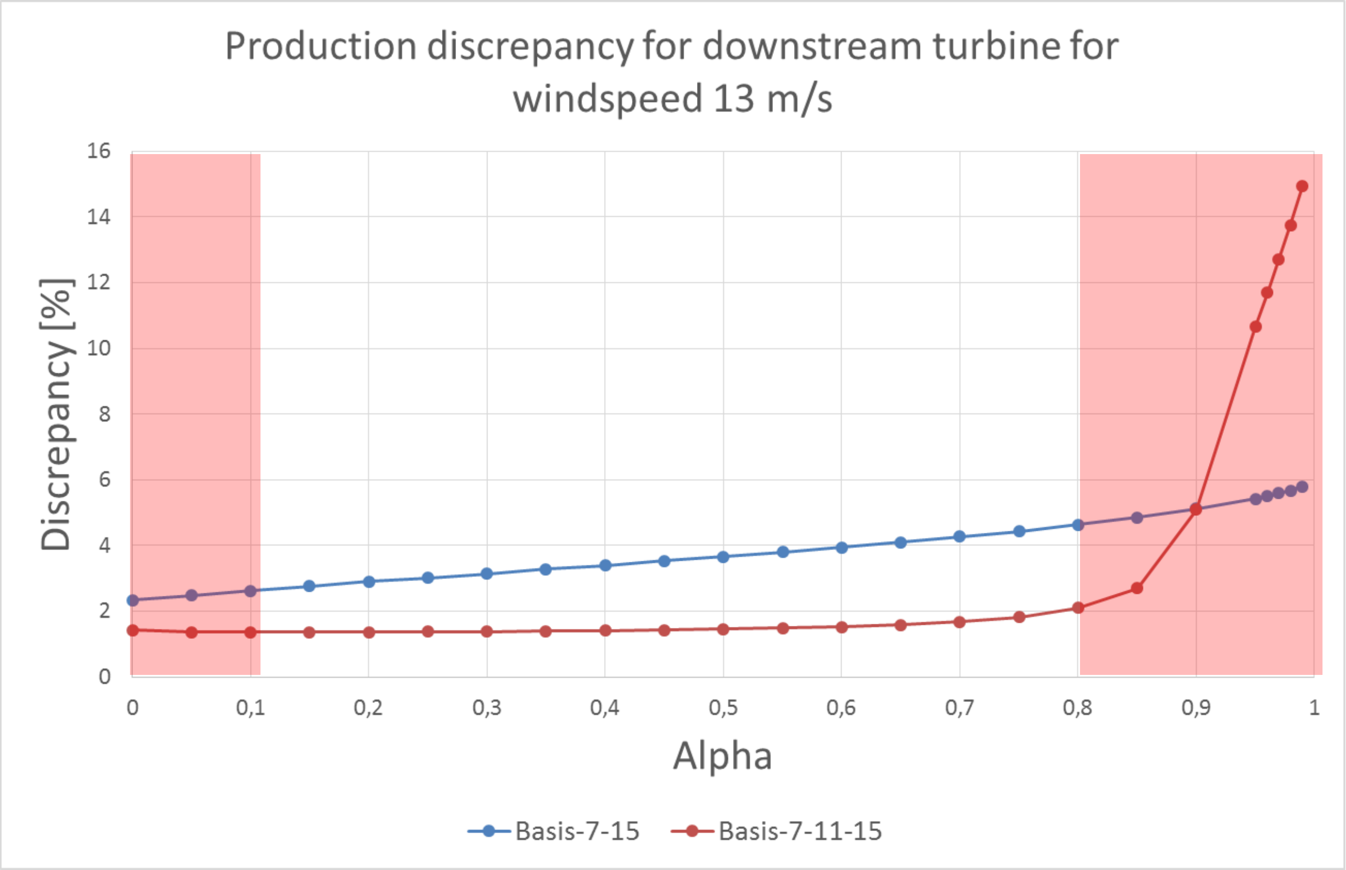


Production discrepancy compared to CFD, $\alpha = 0.5$

Basis name	Verification case		
	9 m/s	11 m/s	13 m/s
Basis 7-15	2.3 %	2.4%	1.2%
Basis 7-11-15	0.9%	0.3%	0.4%

Varying wind speed (cont.)

- Sensitivity to the α-parameter



Technical status

Concluding remarks, and future perspectives

- The technique builds on CFD
  - The accuracy is controlled by the representativeness of the CFD simulations used to build the basis
  - Improvements to the CFD simulator can easily be transferred to the model reduction framework

- The model reduction technique saves significant computing time compared to CFD
  - All cases reported here takes less than one second to compute

- Verification against CFD
  - Plans for verification with larger setups
  - In the future we will validate against real production data

- Development plans
  - Include atmospheric stability