# Experimental study on power curtailment of three in-line wind turbines

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## Background

- Show up the potential of wind farm power optimization through tip speed ratio control
- Provide a well-defined experimental dataset for verification of computational models

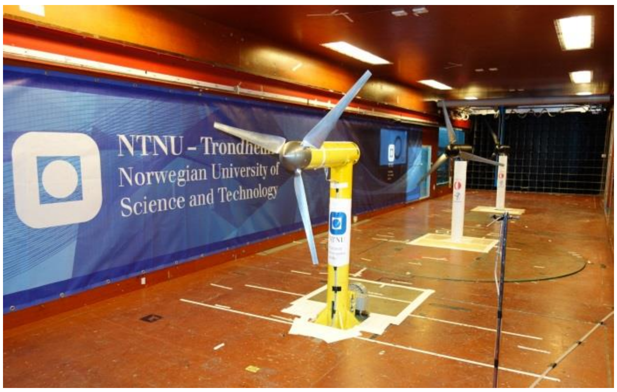

**Figure 1** Experimental setup of three model wind turbines in the large wind tunnel at NTNU

## Experimental setup

- Wind tunnel at NTNU, test section of 1.9 x 2.7 x 12.0 m
- Three model turbines with a rotor diameter of $D_{rotor}$ = 0.944 m
- Rotor based on NREL S826 airfoil
- Rated tip speed ratio $\lambda_{T1} = \lambda_{T2} = \lambda_{T3} = 6.0$
- Inter-turbine spacing of x/D=3
- Uniform inflow at $u_{ref}$ = 11.5 m/s
- Inflow of low turbulence intensity at $TI_{T1}$=0.23% (at first turbine pos.)

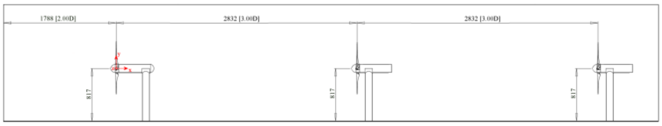

**Figure 2** Experimental setup of three model wind turbines in the large wind tunnel at NTNU

- In-nacelle torque- and RPM-sensors
- Wake flow measurements by Laser-Doppler-Anemometer (LDA)
- Scanning turbine power in steps of $\Delta\lambda_{T1}$= 0.5 and $\Delta\lambda_{T2}=\Delta\lambda_{T3}$=0.2

## Reference case

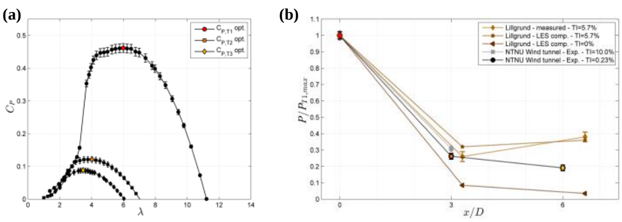

**Figure 3** (a) $C_P$-λ-curves of the three aligned turbines, all referred to $u_{ref}$=11.5m/s
(b) relative power of test cases compared to full-scale data from Lillgrund windfarm

[Nilsson et al. Large-eddy simulations of the Lillgrund wind farm. *Wind Energy 2015*;18:449–467]

## 1st turbine curtailment

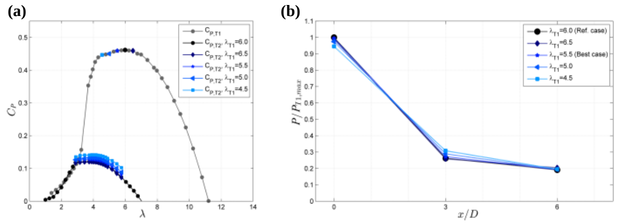

**Figure 4** (a) $C_P$-λ-curves of the second turbine T2 depending on different tip speed ratios of T1
(b) relative power for T1, T2 and T3 for a curtailed first row turbine T1

## 2nd turbine curtailment

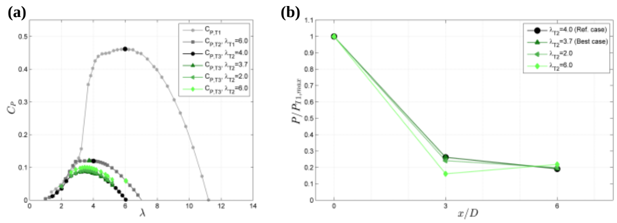

**Figure 5** (a) $C_P$-λ-curves of the third turbine T3 depending on different tip speed ratios of T2
(b) relative power for T1, T2 and T3 for a curtailed second row turbine T2

## Wake flow analysis

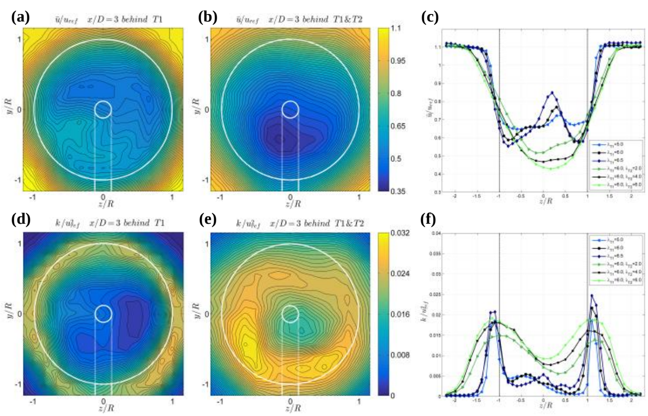

**Figure 6 (a,b,c)** Normalized mean velocity and **(d,e,f)** Normalized turbulent kinetic energy
**(a,d)** behind T1 operated at $\lambda_{T1}$=6; **(b,e)** behind T1 operated at $\lambda_{T1}$=6 and T2 operated at $\lambda_{T2}$=4 (reference case);
**(c,f)** behind T1 operated at $\lambda_{T1}$=5,6,7 (blue) resp. T1 and T2 operated at $\lambda_{T2}$=2,4,6 (green) (curtailed cases)

## Conclusions

- Power measurements show good agreement with full-scale data from Lillgrund
- Considerably bigger power drop from T1 to T2 (74%) than from T2 to T3 (27%)
- Higher mean velocity loss in the wake behind T2 than in the wake behind T1
- More spread out distribution of turbulent kinetic energy behind T2 than behind T1
- Only insignificant total power gains ($P_{T1}+P_{T2}+P_{T3}$) of less than 1% achieved by T1 curtailment; (T1 curtailment more effective than T2 curtailment)
- Best combined efficiencies achieved for slightly lower than rated tip speed ratios
- Small potential of curtailment for wind farm power optimization, but effective method for load distribution between turbine rows at constant power?

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