Potential and costs for wind power of providing system services to the electricity grid

Salur Basbug & Anders Wickström

Renewable Energy Systems

RISE Research Institutes of Sweden

financed by Swedish Energy Agency

Energimyndigheten

Anders Wickström

- Wind turbine design engineer at different private companies
- Independent consultant at Scandinavian Wind
- Researcher and project leader at RISE since 2018

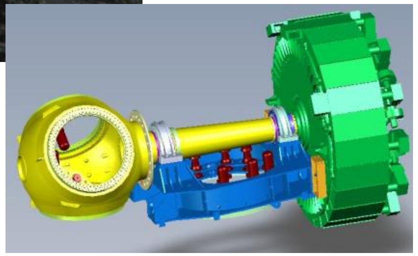
Chalmers forskningsturbin
på Björkö med trätorn

GE Offshore-113 4.1 MW
”Big Glenn”

Näsudden II på Gotland
Diameter 80 m, 3 MW

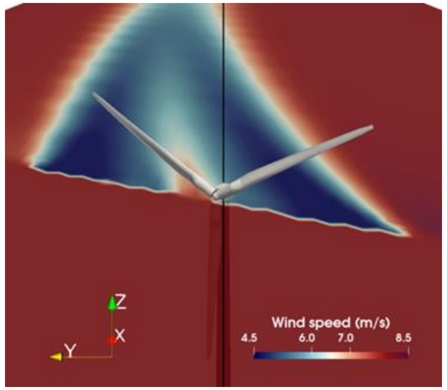
ScanWind Demo I
Nord Trönderlag
Diameter 80 m, 2.5 MW

ScanWind SW3.5-90 Diameter
90 m, 3.5 MW

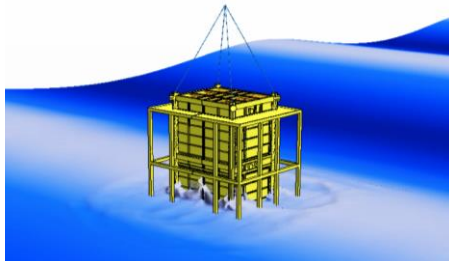


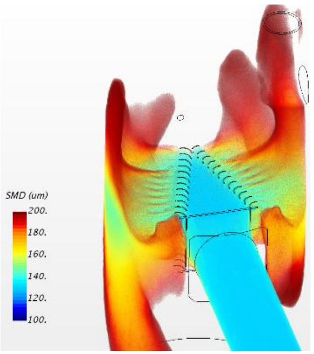
Salur Basbug, PhD

- **Research Institutes of Sweden,** the unit **”Renewable Energy Systems”**
  - Aero-elastic wind turbine and windfarm simulations
  - CFD & turbine control simulations

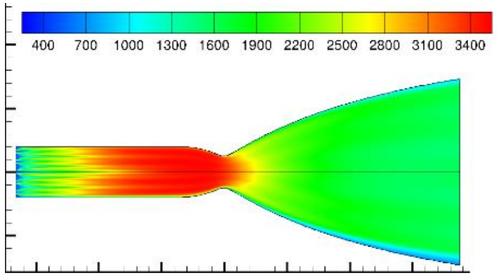


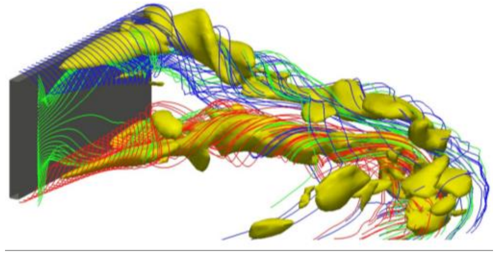
- Aker Solutions, *Offshore Oil & Gas (2018 – 2020)*

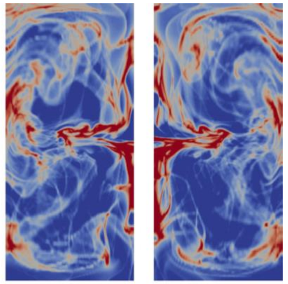




- PhD at Imperial College London, *Turbulent Mixing (2013 – 2017)*
- MSc thesis at Airbus, *Combustion in Rocket Engines*



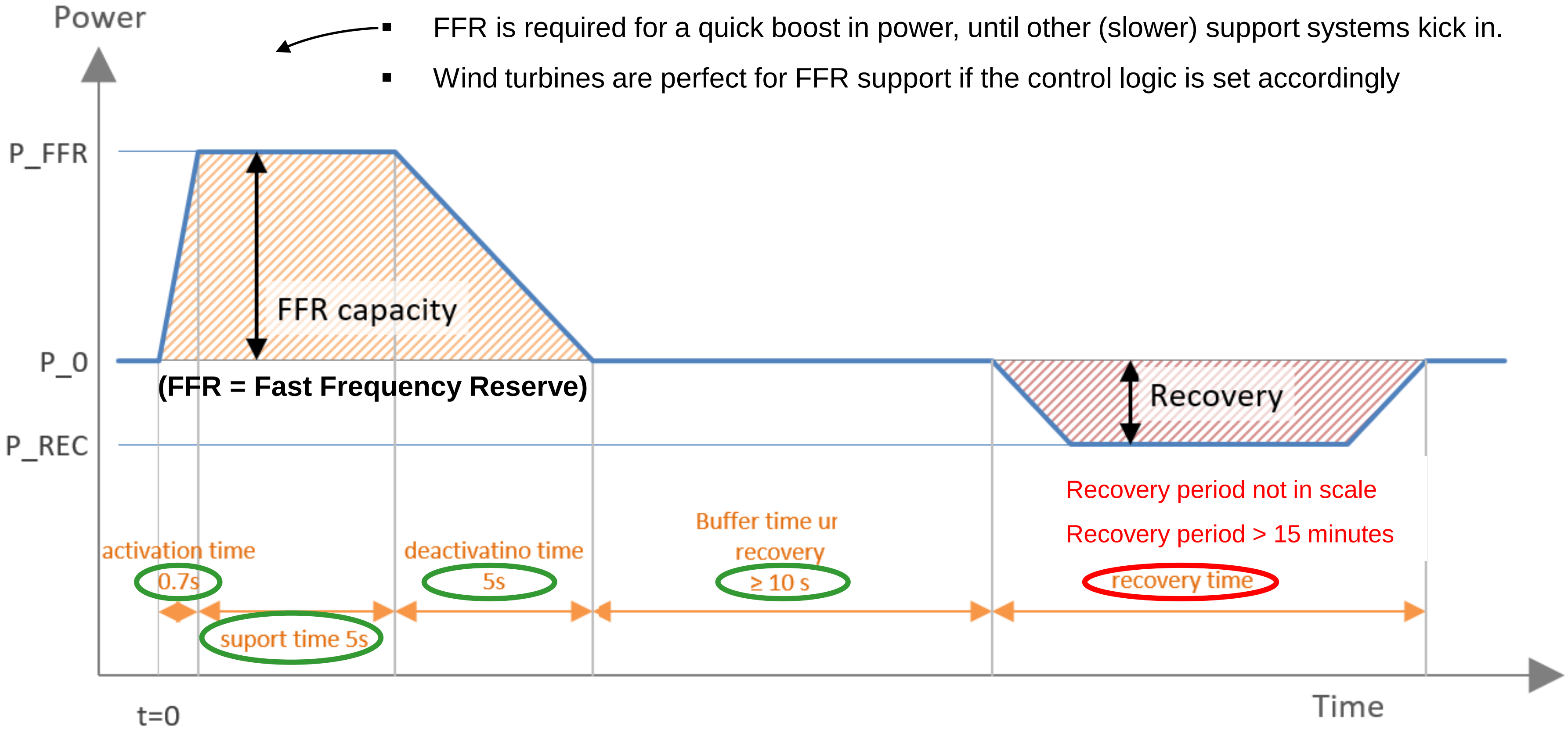




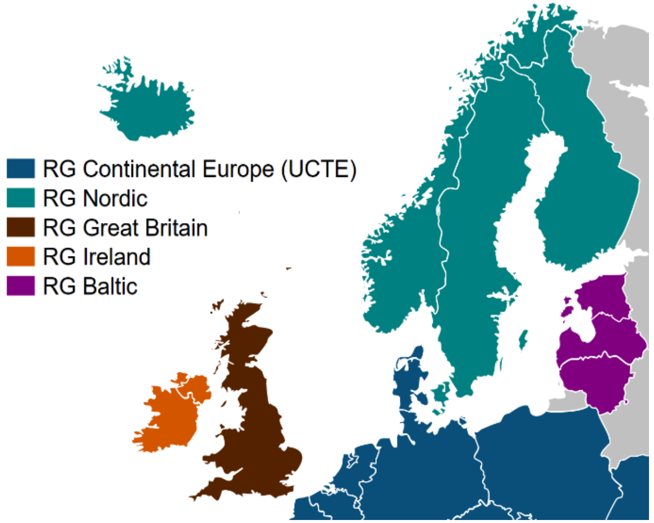
Technical requirements for Fast Frequency Reserve defined by ENTSO-E

= European Network of
Transmission System Operators
for Electricity

- When the demand on the power exceeds the supply, AC grid frequency drops below 50 Hz
- The inertia of synchronized turbines and a range of system services support the grid stability
- FFR is required for a quick boost in power, until other (slower) support systems kick in.
- Wind turbines are perfect for FFR support if the control logic is set accordingly



Synchronous grid areas of Europe



Instantaneous minimum grid frequency simulated by ENTSO-E

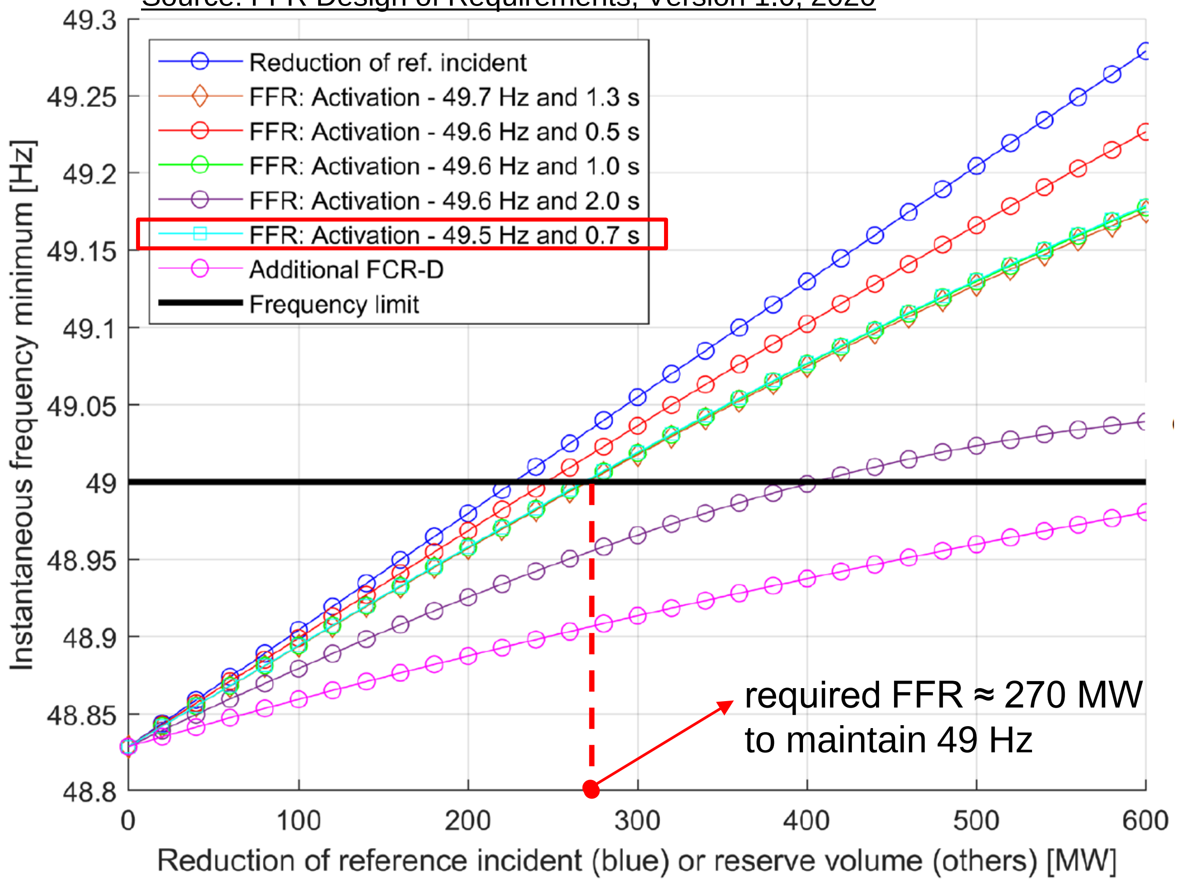


Figure 3: Simulation results of different FFR activation options, for an inertia level of 100 GWs, compared to 1) the reduction of reference incident (1450 MW) and 2) additional FCR-D volume of typical performance and stability settings.

- Many scenarios are simulated to see power grid's reaction if 1.45 GW of supply is instantly lost
- A kinetic energy of 100 GWs is assumed to be the lowest value in the Nordic system (inertia of hydro turbines etc.)
- Equal amount of Frequency Containment Reserve (FCR-D) activated (50% in 5s, 100% in 30s)
- Our project assumes, FFR is activated at 49.5 Hz, within 0.7s
- That would require ca. 270 MW FFR, to maintain min. 49 Hz
- If 1500 turbine participate => in average 180 kW / turbine sufficient
- 4000+ turbines already installed in Sweden
- FFR is booked & paid by *Svenska Kraftnät* (regardless of activation)

Energy storage by wind turbine inertia

- A rotating wind turbine has a certain amount of energy (E) stored in the inertia (J) of the turbine.
- This energy storage is depending on the angular velocity (ω).
- By decreasing the angular velocity, i.e., the rotor speed, this energy can be transformed into mechanical power (P).

$$E = \frac{1}{2} J \omega^2$$

$$\frac{\delta E}{\delta t} = J \omega \frac{\delta \omega}{\delta t} \Rightarrow P_{FFR}$$

Stored energy from wind turbine rotational inertia		
Total number of turbines	4120	
Total capacity	9061	MW
Average capacity	2.2	MW
Average turbine inertia	1.0E+07	kgm2
Average angular velocity	1.0	rad/s
Average rotating energy	5.0E+06	J
Total rotating energy	**2.1E+10**	**J**

- This is almost 10 % of the existing inertia in Sweden.
- However, it is not connected to the grid by “stiff” synchronous generators.
- Turbine control is needed to utilize it.

IEA 3.4 – 130 wind turbine model in FAST and VIDYN

- Within the project, we have created a model of the public IEA 3.4 MW – 130 m wind turbine in the aeroelastic codes OpenFAST and VIDYN
- The turbine control is based on the NREL DISCON concept.

IEA Wind Task 37 on Systems Engineering in Wind Energy
WP2.1 Reference Wind Turbines

Pietro Bortolotti[1], Helena Canet Tarrés[2], Katherine Dykes[1], Karl Merz[3], Latha Sethuraman[1], David Verelst[4], and Frederik Zahle[4]

[1]National Renewable Energy Laboratory, Golden CO, USA
[2]Wind Energy Institute, Technische Universität München, Germany
[3]SINTEF Energy Research AS, Trondheim, Norway
[4]Wind Energy Department, Technical University of Denmark, Roskilde, Denmark

May 23, 2019

Abstract

This report describes two wind turbine models developed within the second work package (WP2) of IEA Wind Task 37 on Wind Energy Systems Engineering: Integrated RD&D. The wind turbine models can be used as references for future research projects on wind energy, representing a modern land-based wind turbine and a latest generation offshore wind turbine. The land-based design is a class IIIA geared configuration with a rated electrical power of 3.4-MW, a rotor diameter of 130 m, and a hub height of 110 m. The offshore design is a class IA configuration with a rated electrical power of 10.0 MW, a rotor diameter of 198 m, and a hub height of 119 m. The offshore turbine employs a direct-drive generator.

4 3.4-MW Land-Based Wind Turbine

Cp-Max was the tool mostly used in the development activities of the land-based wind turbine. Here, the design work aimed at developing a class 3A land-based wind turbine model with a rated electrical power of 3.37 MW, a rated aerodynamic power of 3.6 MW, a rotor diameter of 130 m and a hub height of 110 m. These values were selected by the project partners with the expectation that they will establish as standards within the land-based wind energy market. The optimization was run for minimum COE, estimated by a cost model developed at NREL [29].

4.1 Design Process

The wind turbine was designed against a set of critical design load cases (DLCs), selected to be run within the structural optimization loop of Cp-Max, including standard operating conditions in normal turbulence (1.1), operation under extreme turbulence (1.3), shut down cases in turbulent wind (2.1), and steady wind with gusts (2.3), as well as storm conditions (6.1, 6.2, 6.3) [17]. DLC 1.1 and DLC 1.3 were realized with three turbulent seeds, while the others with one, for a total of 151 dynamic simulations.

The aerodynamic design included 24 optimization variables describing twist at eight stations, chord at nine stations, and the position of the seven airfoils along blade span. The structural design was based on 50 variables parameterizing the skin, the two spar caps, the two webs, and the leading-edge (LE) and trailing-edge (TE) reinforcements at nine stations along blade span, as well as the diameter and wall thickness of ten tower sectors. In this reference design, the mechanical properties of the composites were kept fixed, while sweep curvature, angles in the composite fibers, and offset in the spar cap positions were all set to zero. After a total computational time of approximately 100 hours running on a workstation equipped with 56 logical processors, Cp-Max converged to the solution that is presented here.

The main wind turbine characteristics are summarized in Table 2. Notably, the table reports the values of initial capital cost (ICC) and COE that drove the optimization. The next section presents all the details of the design in terms of rotor aerodynamics, rotor structure, hub, drivetrain, nacelle, tower, and controller.

Table 2: Summary of the configuration of the land-based wind turbine.

Data	Value	Data	Value
Wind class	IEC 3A	Rated electrical power	3.37 MW
Rated aerodynamic power	3.60 MW	DT & Gen. efficiency	93.6%
Hub height	110.0 m	Rotor diameter	130.0 m
Cut-in	4 m/s	Cut-out	25 m/s
Rotor cone angle	3.0 deg	Nacelle uptilt angle	5.0 deg
Rotor solidity	4.09%	Max V_{tip}	80.0 m/s
Blade mass	16,441 kg	Tower mass	553 ton
Blade cost	120.9 k$	Tower cost	829.7 k$
Aerodynamic AEP	14.99 GWh	Electrical AEP	13.94 GWh
ICC	4,142.1 k$	COE	44.18 $/MWh

May 2019

IEA Wind TCP Task 37

Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines

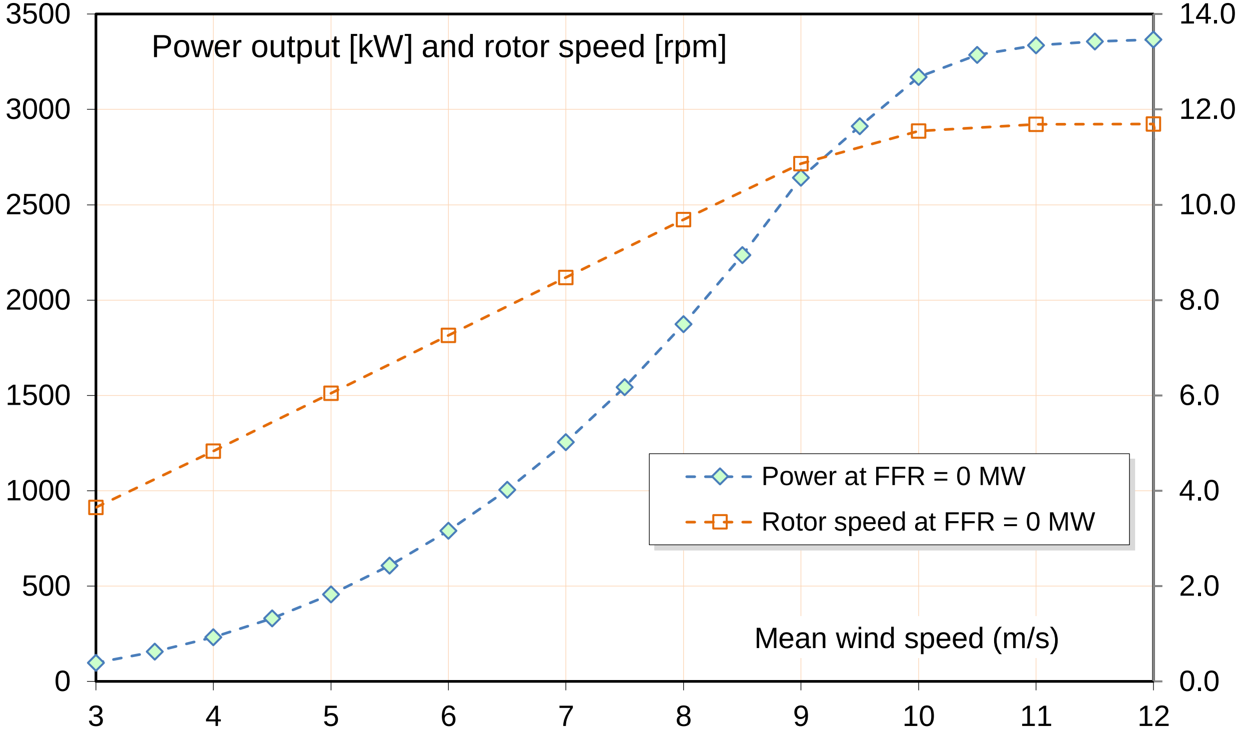
Technical Report

iea wind

Calculation of power curve for operation at optimal rotor speed

Optimal rotor speed, the corresponding power curve, and calculation of AEP

This is how the turbine is designed to operate, FFR-reserve = 0

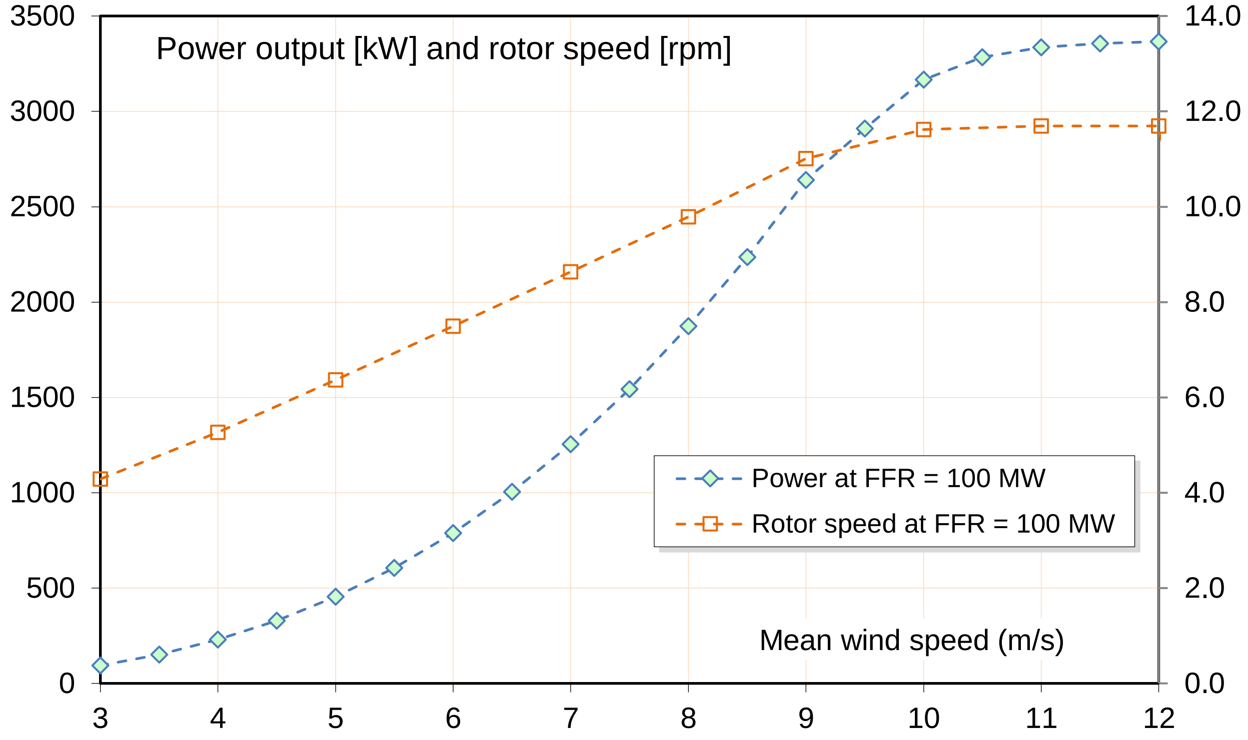


Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.882**	**GWh/år**
Capacity factor	43.3%	

Power curve for increased rotor speed

Increased rotor speed to have a FFR reserve of **100 kW**

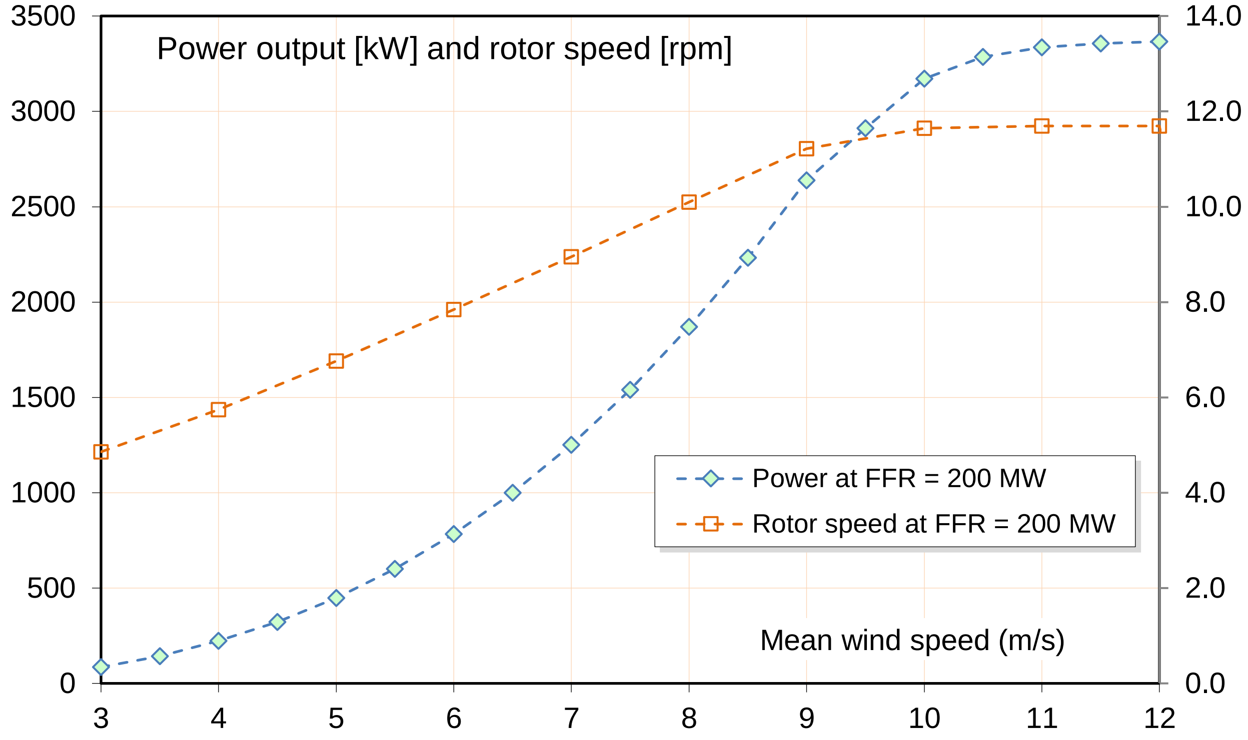


Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.875**	**GWh/år**
Capacity factor	43.2%	

Power curve for increased rotor speed

Increased rotor speed to have a FFR reserve of **200 kW**

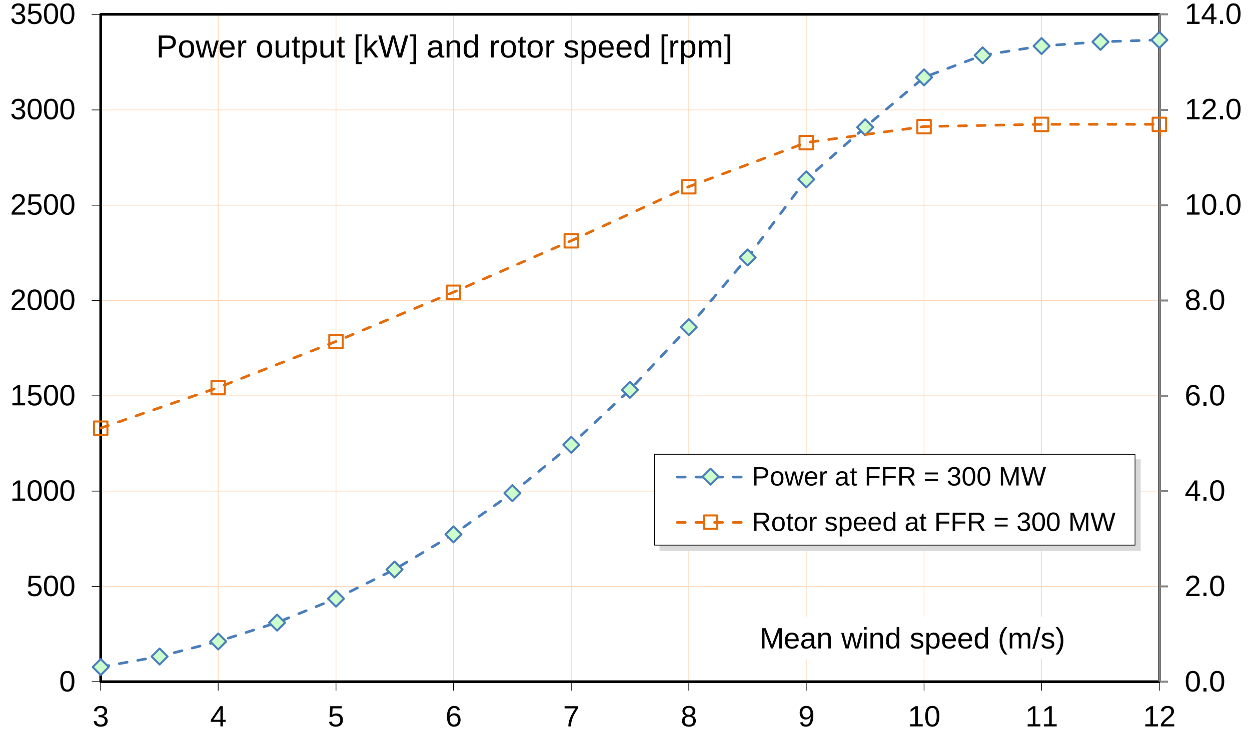


Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.850**	**GWh/år**
Capacity factor	43.1%	

Power curve for increased rotor speed

Increased rotor speed to have a FFR reserve of **300 kW**



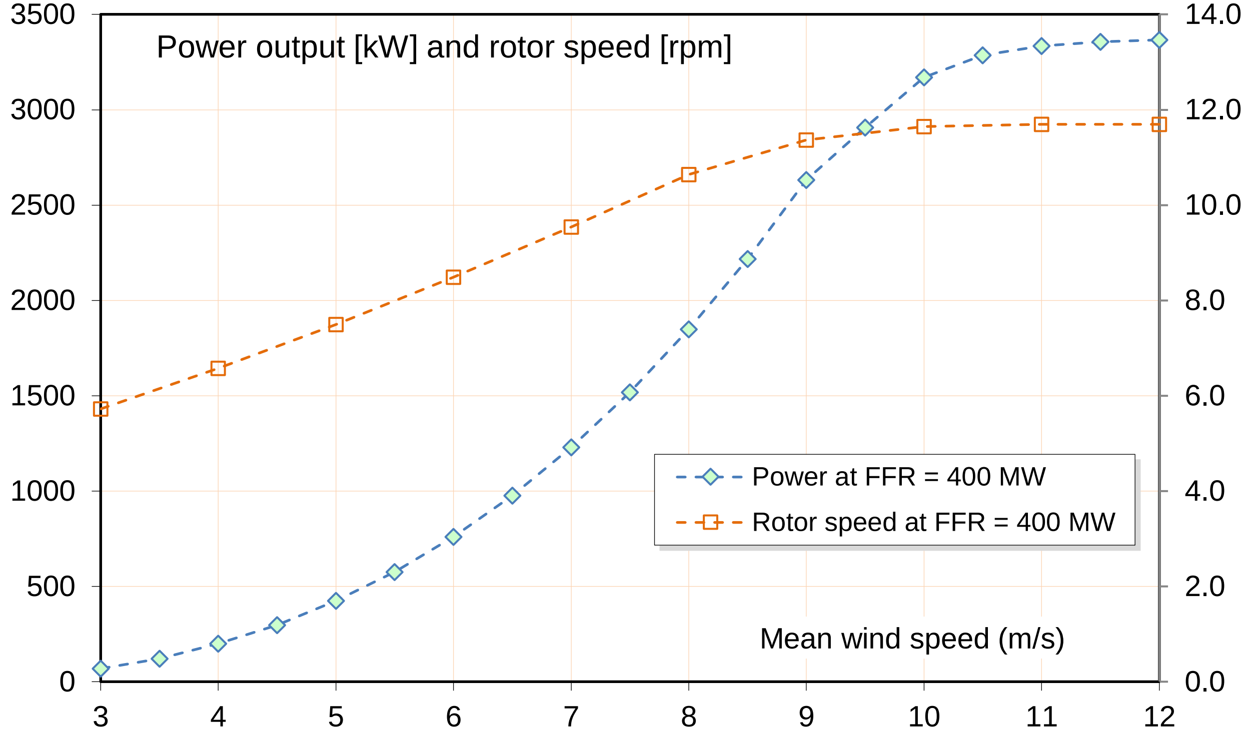
Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.806**	**GWh/år**
Capacity factor	43.0%	

Power curve for increased rotor speed

Increased rotor speed to have a FFR reserve of **400 kW**

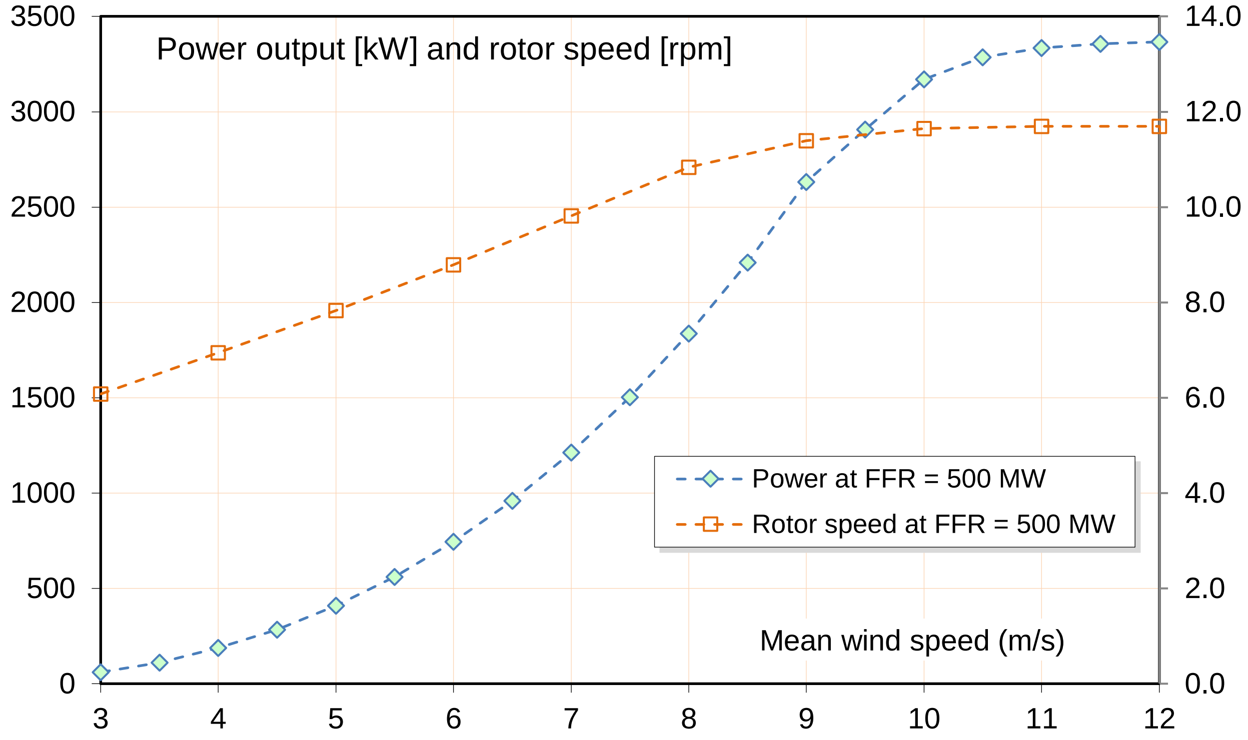
Input wind conditions		
Average wind speed	7.5	m/s



Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.749**	**GWh/år**
Capacity factor	42.8%	

Power curve for increased rotor speed

Increased rotor speed to have a FFR reserve of **500 kW**



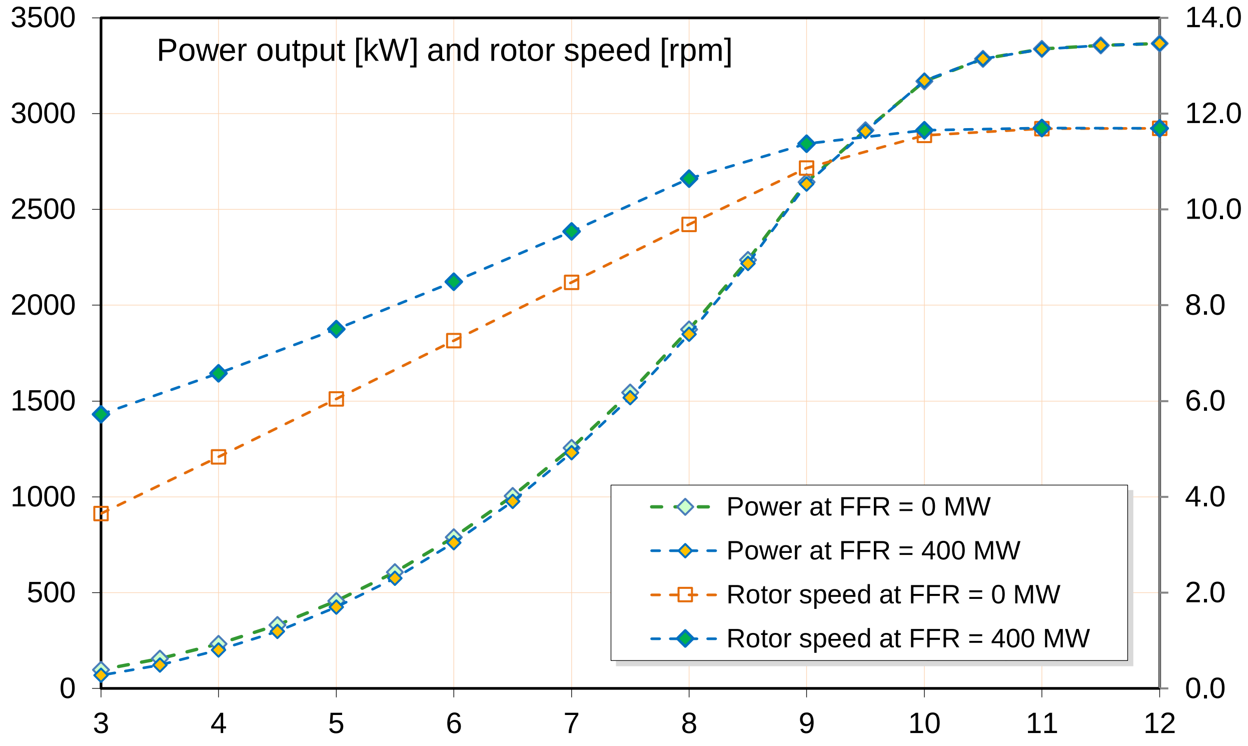
Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.690**	**GWh/år**
Capacity factor	42.6%	

Power curve comparison between optimal operation vs. high rotor speed

Comparison of AEP between operation at optimal rotor speed

vs. operation with **400 kW** power reserve using high rotor speed



Power reserve via rotor speed ⇨ AEP is 99.0% of optimal rotor speed

Input wind conditions		
Average wind speed	7.5	m/s

Optimal operation

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.882**	**GWh/år**
Capacity factor	43.3%	

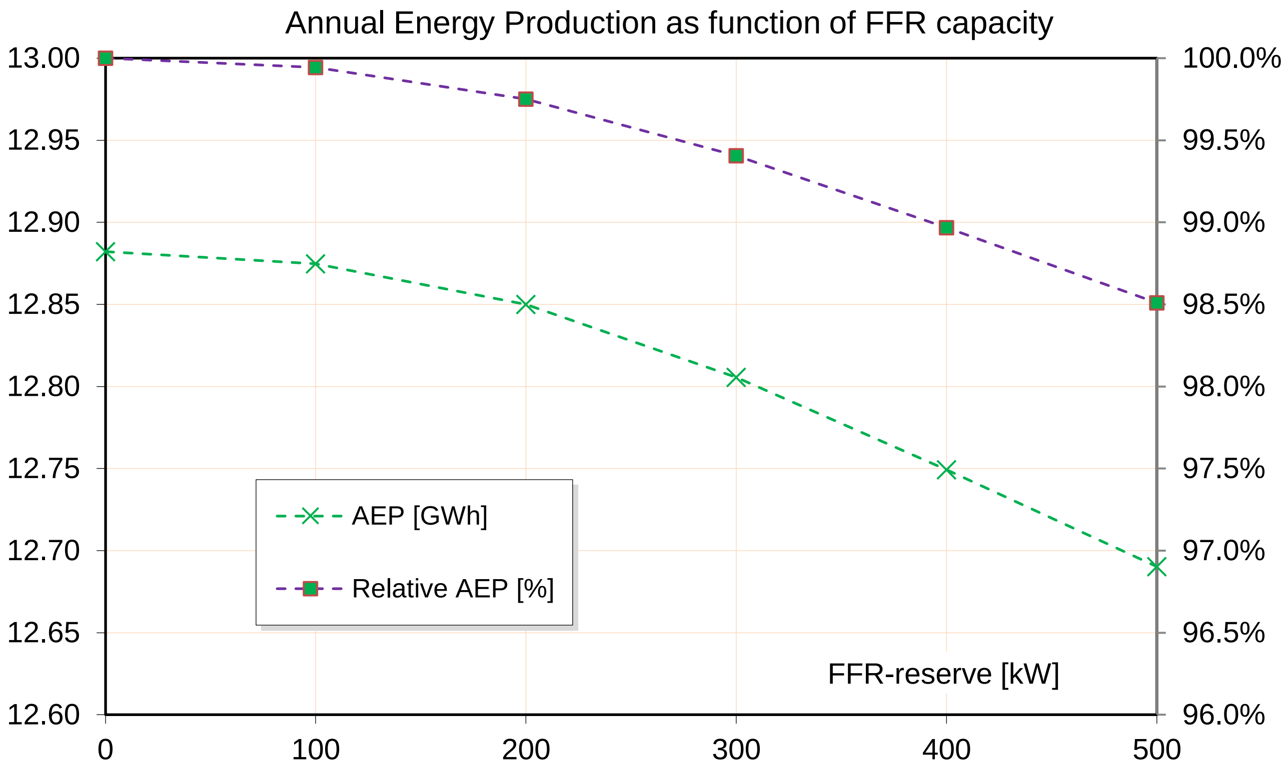
Power reserve of 400 kW rotor speed

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.749**	**GWh/år**
Capacity factor	42.8%	

Annual energy production depending on rotor speed concept

By plotting the actual and normalized AEP, the impact of the increased rotor speed is illustrated.

This is the cost to pay for to get the FFR reserve:

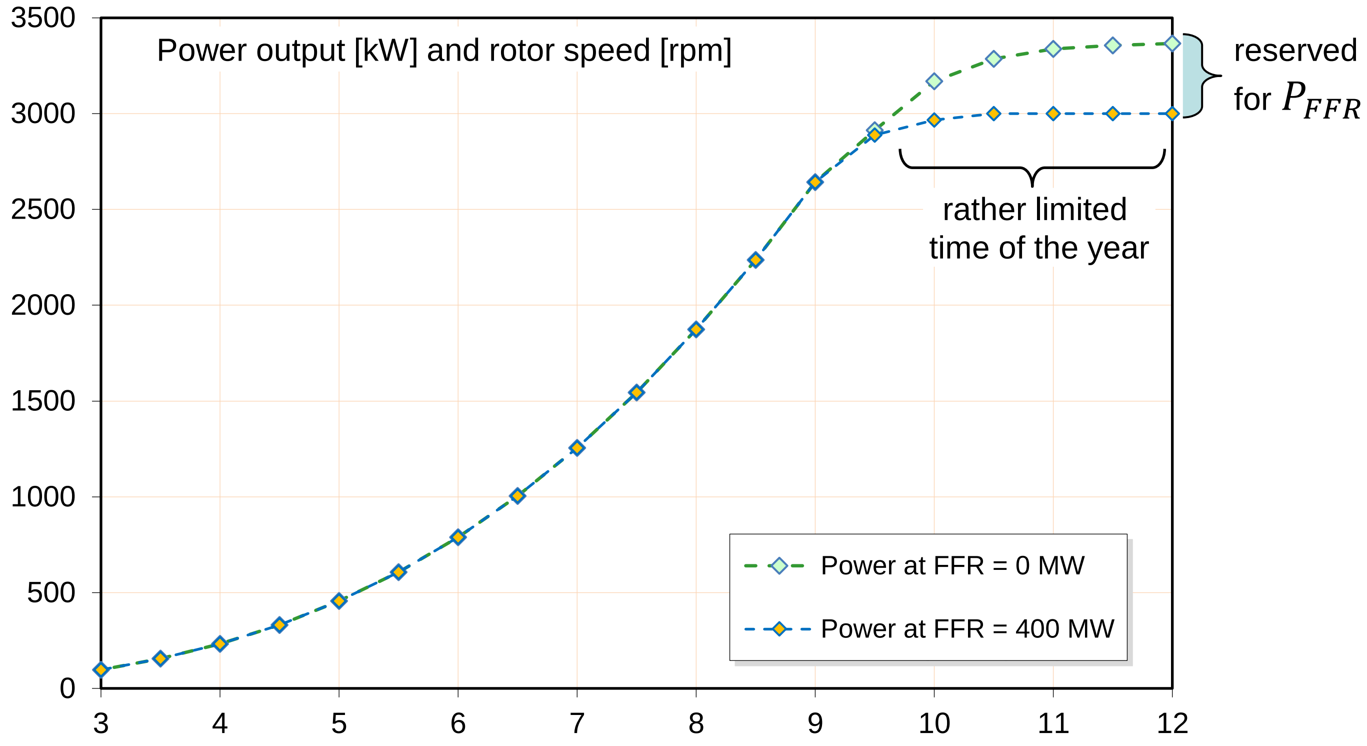


Summary of reduced production caused by FFR capacity		
FFR [kW]	AEP [GWh]	Relative AEP [%]
0	12.882	100.0%
100	12.875	99.9%
200	12.850	99.8%
300	12.806	99.4%
400	12.749	99.0%
500	12.690	98.5%

Power curve comparison between optimal operation vs. power curtailment

Comparison of AEP between operation at optimal power

vs. operation with **400 kW** power reserve using power curtailment (lower rated power)



Power reserve via rating ⟹ AEP is 94.4 % of optimal operation

Input wind conditions		
Average wind speed	7.5	m/s

Optimal operation

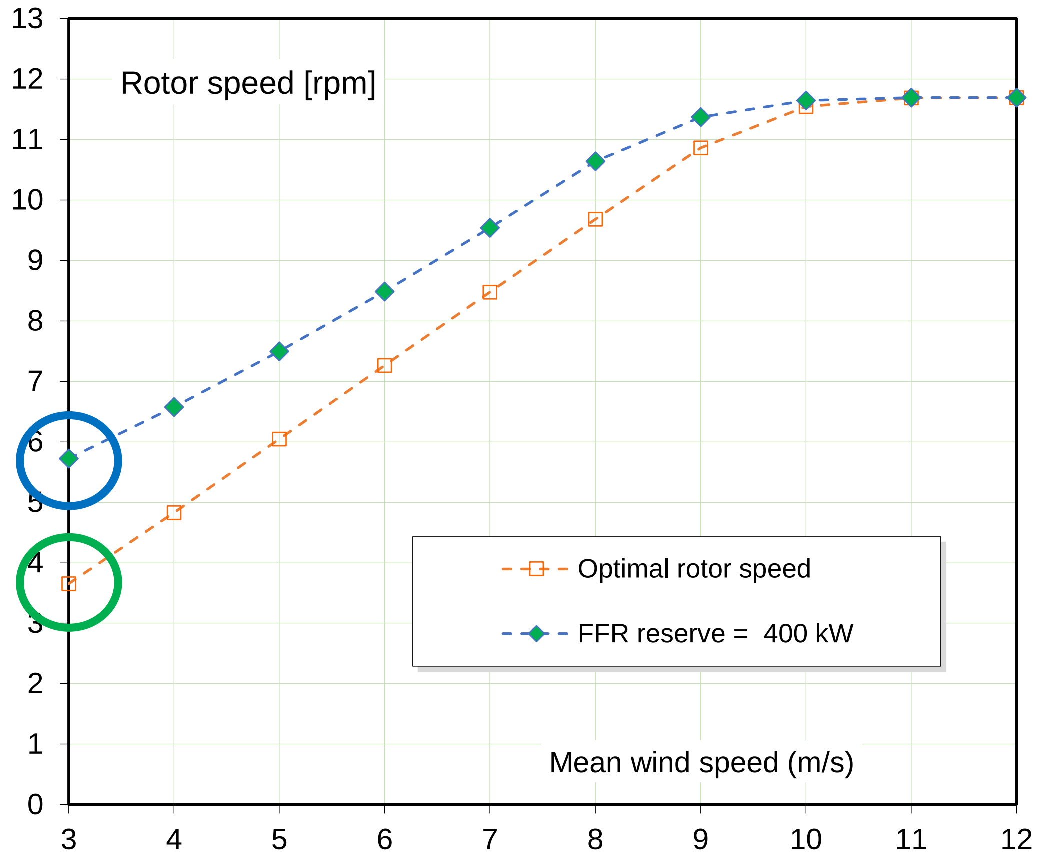
Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.882**	**GWh/år**
Capacity factor	43.3%	

Power reserve of 400 kW via curtailment

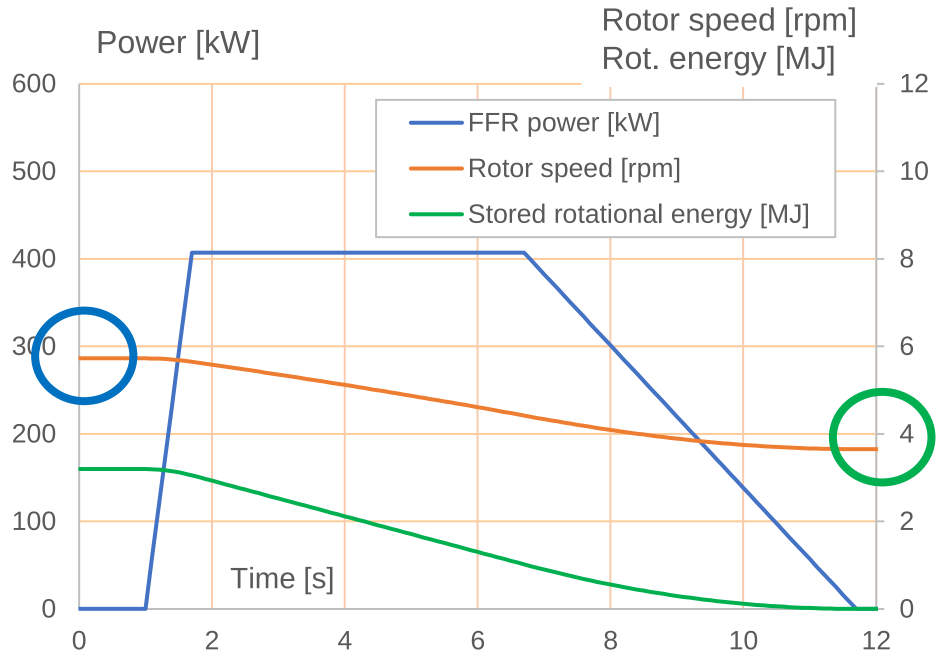
Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.00	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.166**	**GWh/år**
Capacity factor	46.3%	

Example of FFR power reserve of 400 kW at mean wind speed 3 m/s

FFR capacity of 400 kW at 3 m/s, from 5.7 rpm to optimal 3.7 rpm

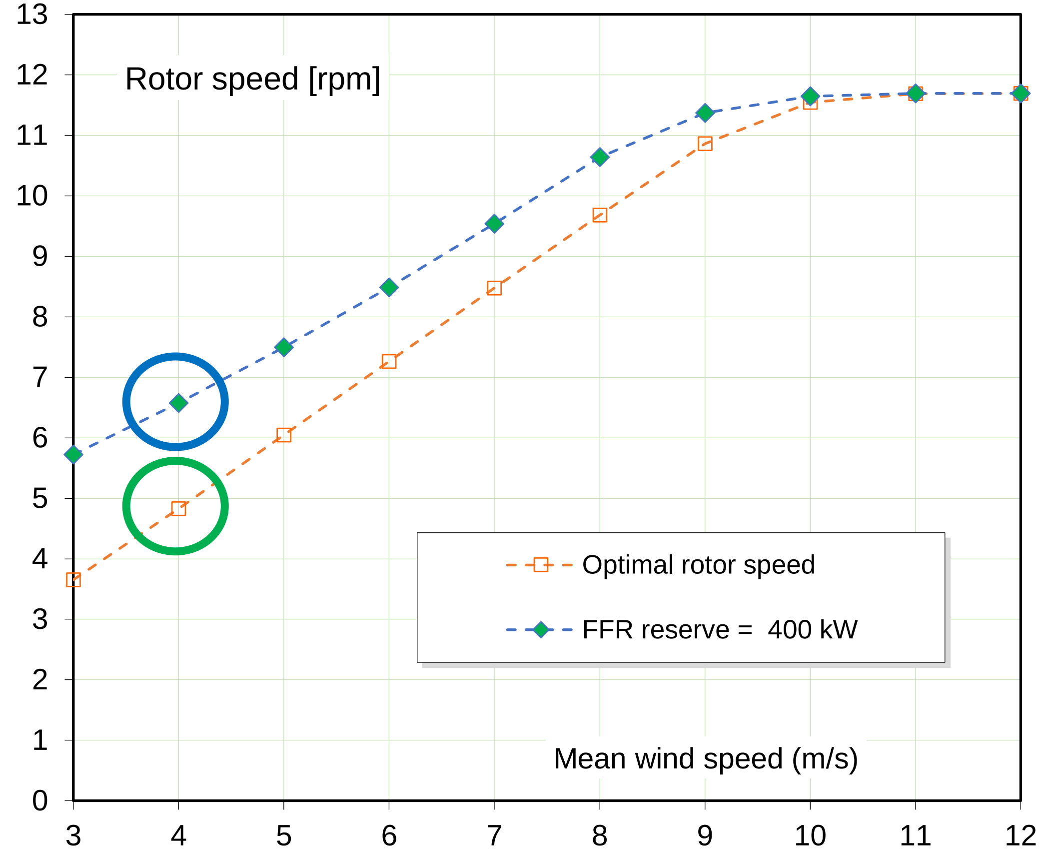


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.599	rad/s
Rotating energy at start	5.39E+06	J
Angular velocity at end	0.382	rad/s
Rotating energy at end	2.19E+06	J
Extracted energy	3.20E+06	J
FFR capacity	**407**	**kW**

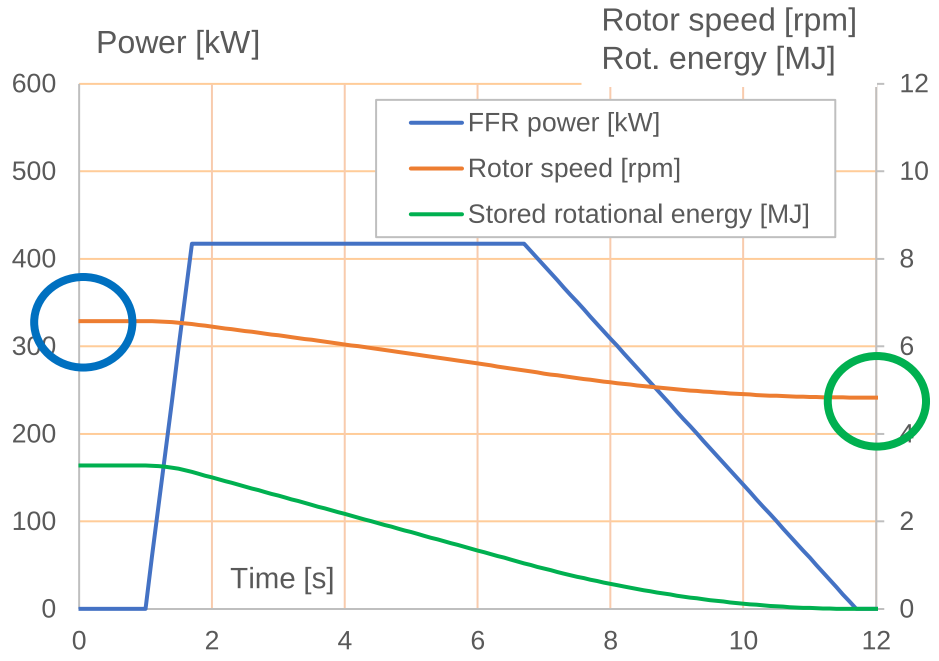


Example of FFR power reserve of 400 kW at mean wind speed 4 m/s

FFR capacity of 400 kW at 4 m/s, from 6.6 rpm to optimal 4.8 rpm

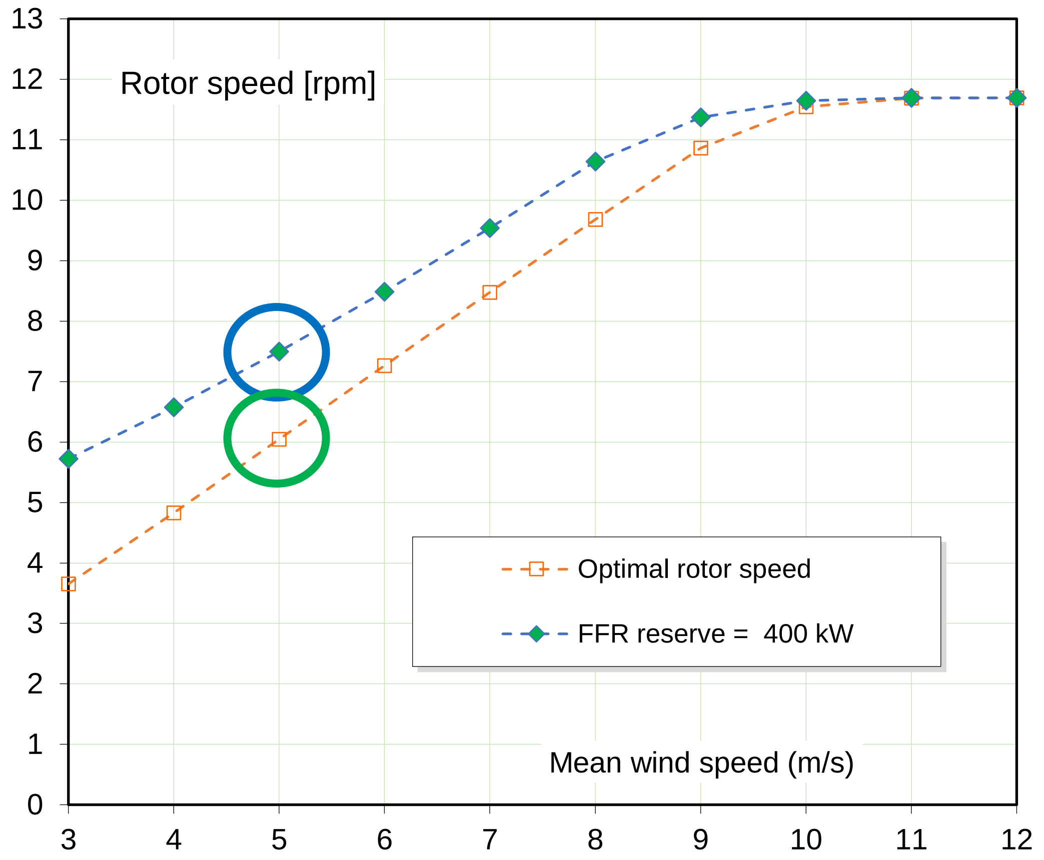


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.689	rad/s
Rotating energy at start	7.12E+06	J
Angular velocity at end	0.506	rad/s
Rotating energy at end	3.84E+06	J
Extracted energy	3.28E+06	J
FFR capacity	**417**	**kW**

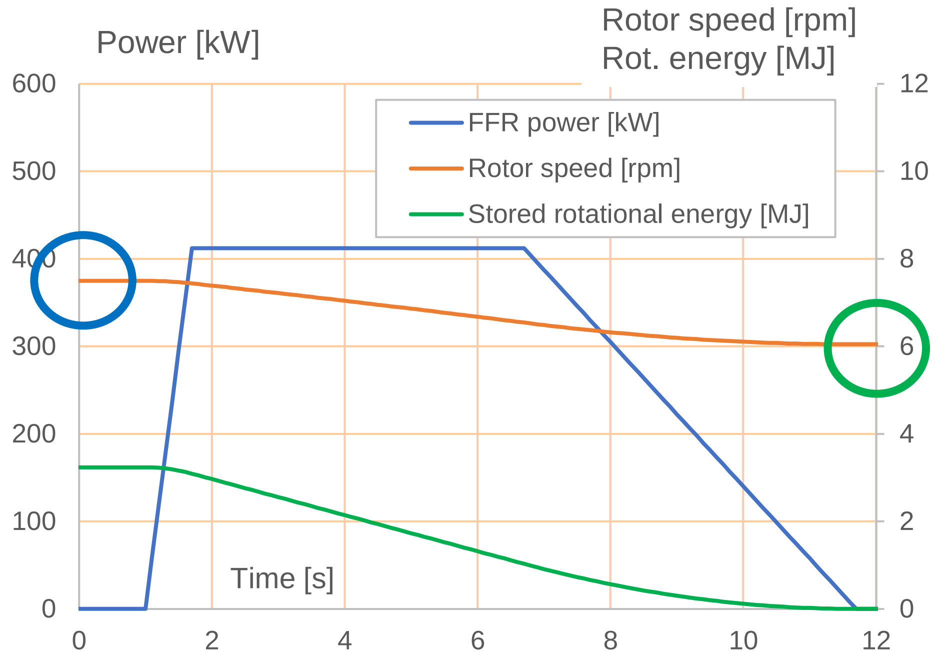


Example of FFR power reserve of 400 kW at mean wind speed 5 m/s

FFR capacity of 400 kW at 5 m/s, from 7.5 rpm to optimal 6.0 rpm

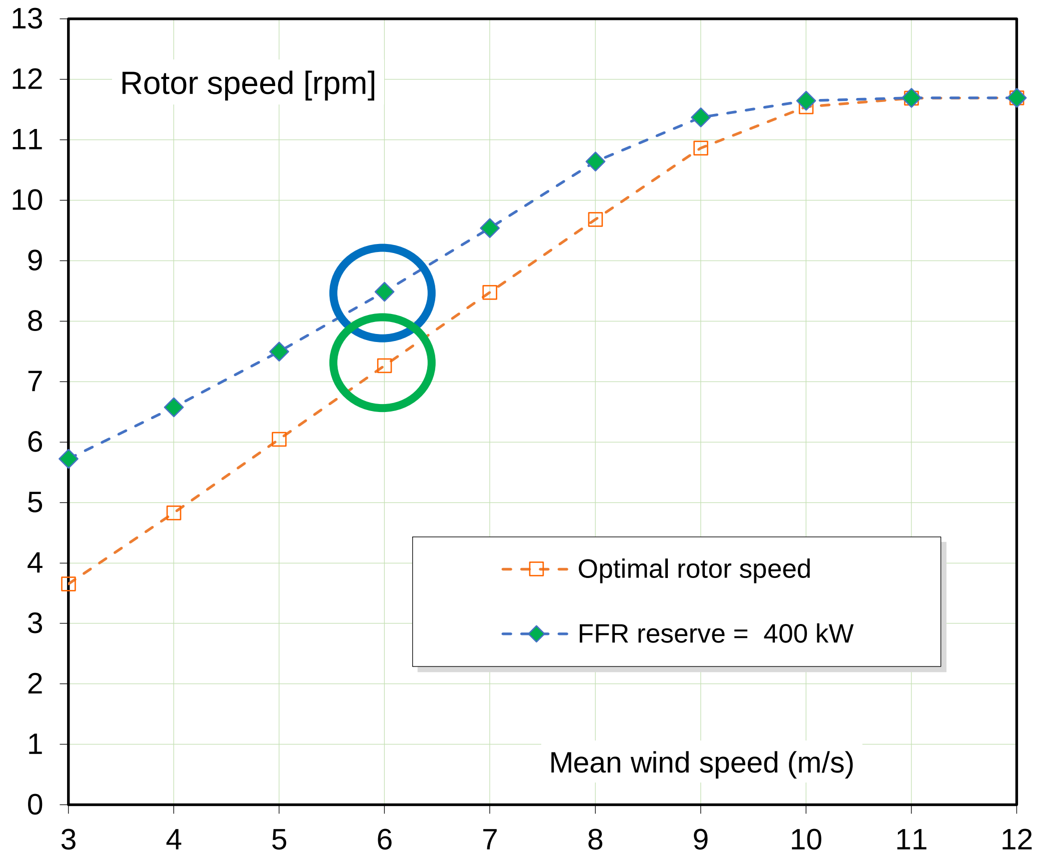


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.785	rad/s
Rotating energy at start	9.25E+06	J
Angular velocity at end	0.633	rad/s
Rotating energy at end	6.01E+06	J
Extracted energy	3.23E+06	J
FFR capacity	**412**	**kW**

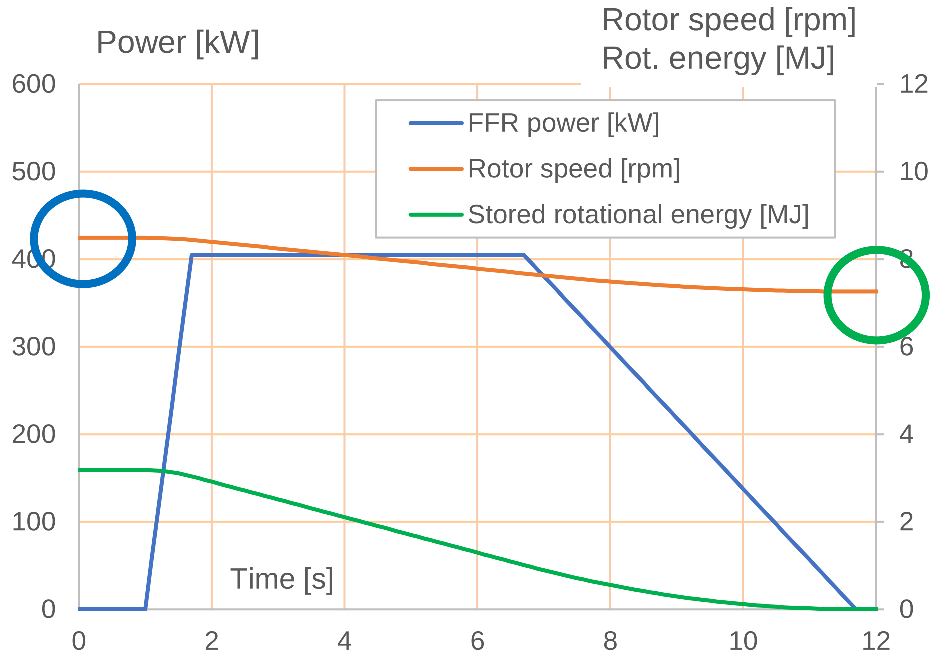


Example of FFR power reserve of 400 kW at mean wind speed 6 m/s

FFR capacity of 400 kW at 6 m/s, from 8.5 rpm to optimal 7.3 rpm

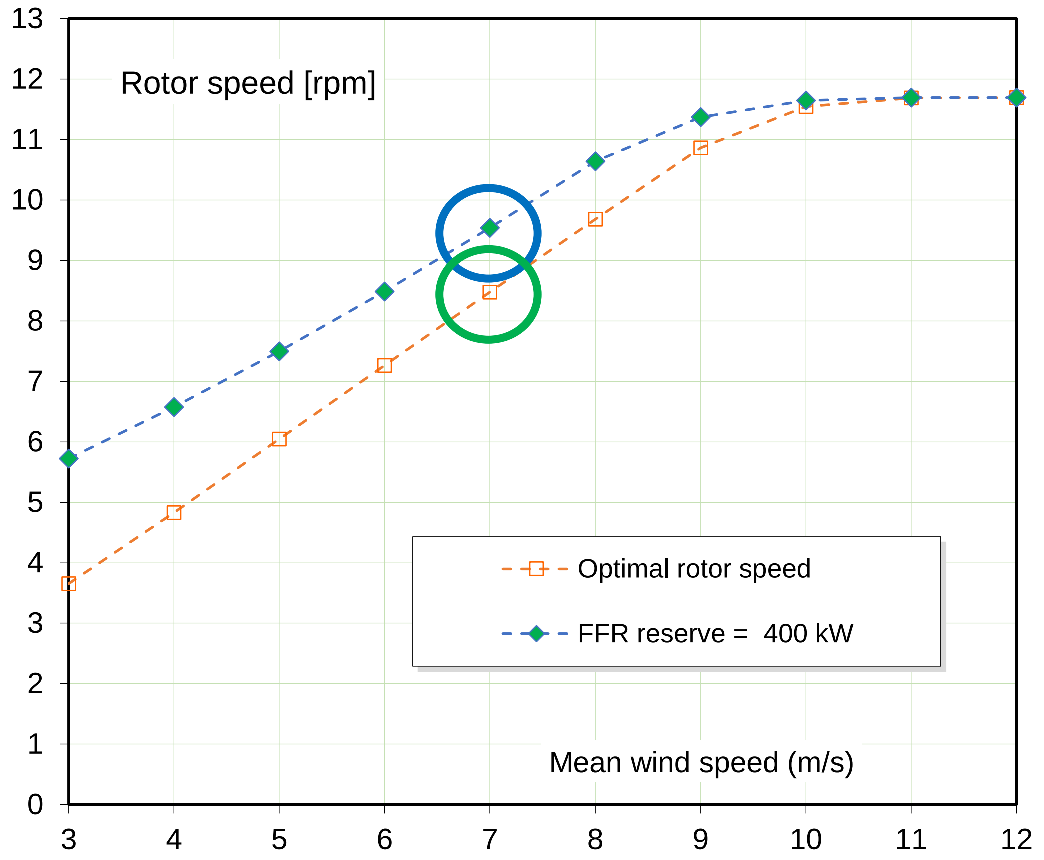


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.889	rad/s
Rotating energy at start	1.19E+07	J
Angular velocity at end	0.760	rad/s
Rotating energy at end	8.67E+06	J
Extracted energy	3.18E+06	J
FFR capacity	**405**	**kW**

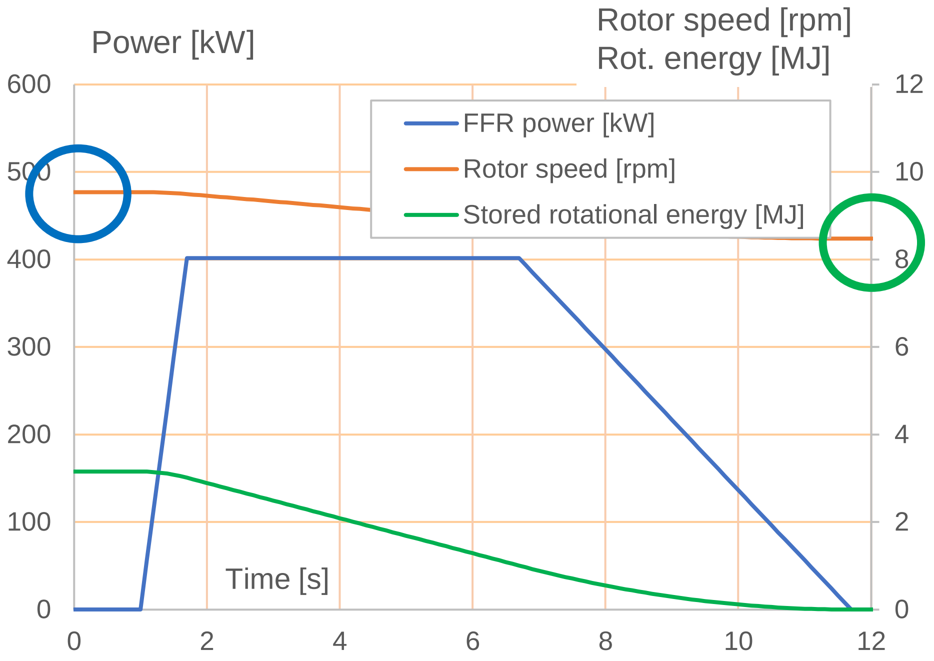


Example of FFR power reserve of 400 kW at mean wind speed 7 m/s

FFR capacity of 400 kW at 7 m/s, from 9.5 rpm to optimal 8.5 rpm

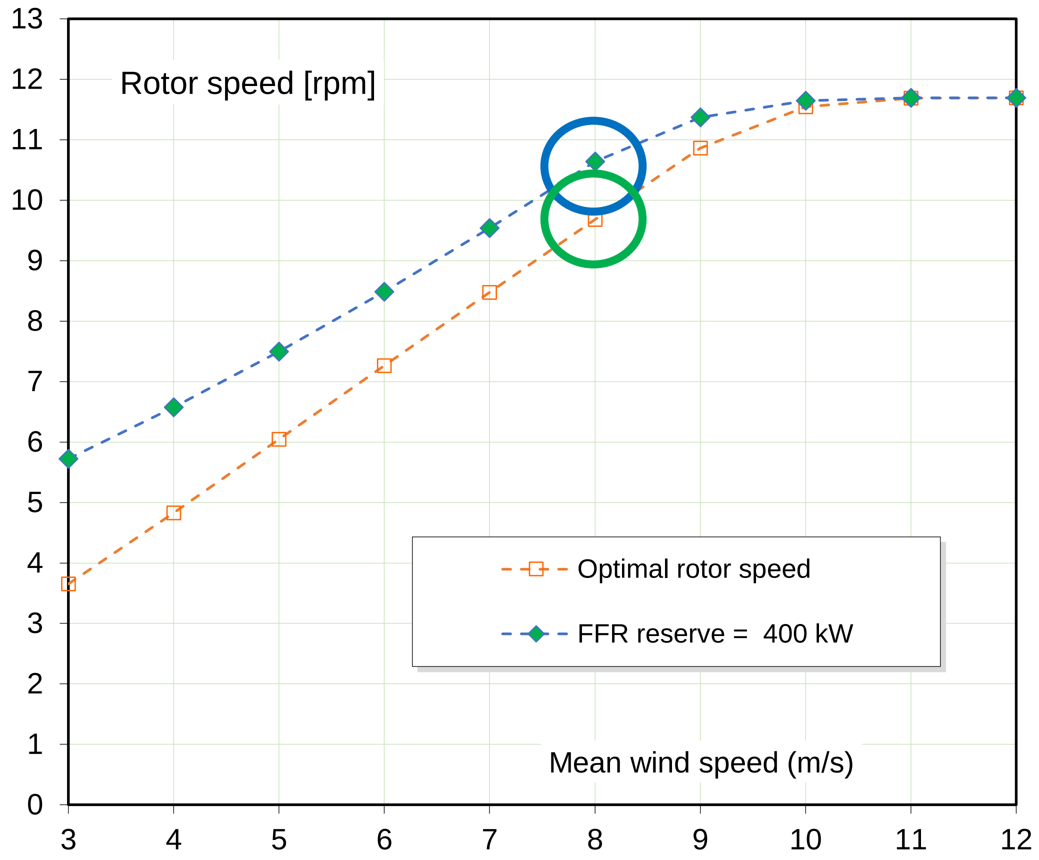


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.999	rad/s
Rotating energy at start	1.50E+07	J
Angular velocity at end	0.888	rad/s
Rotating energy at end	1.18E+07	J
Extracted energy	3.15E+06	J
FFR capacity	**402**	**kW**

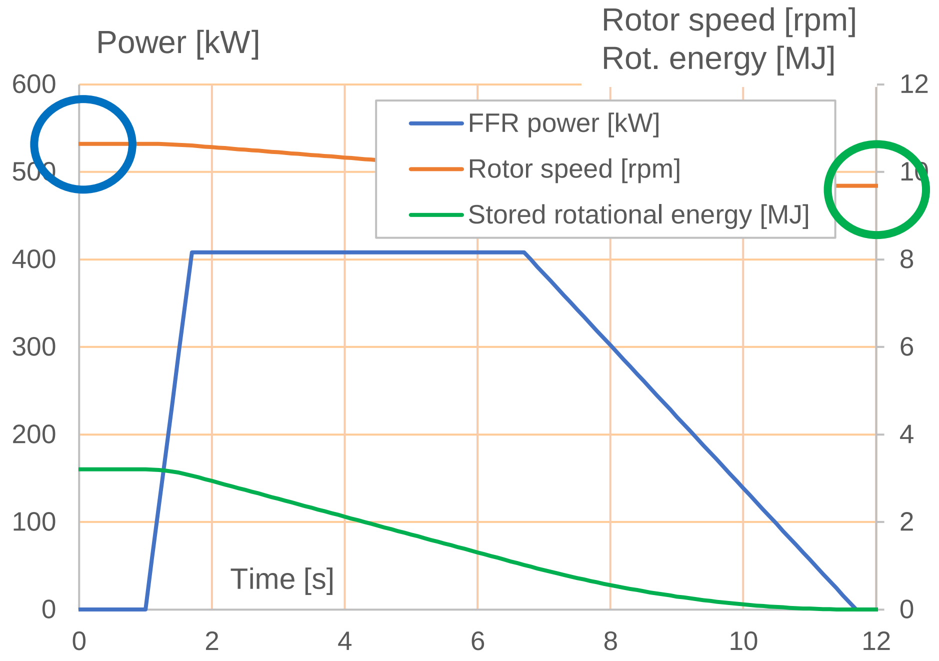


Example of FFR power reserve of 400 kW at mean wind speed 8 m/s

FFR capacity of 400 kW at 8 m/s, from 10.6 rpm to optimal 9.7 rpm

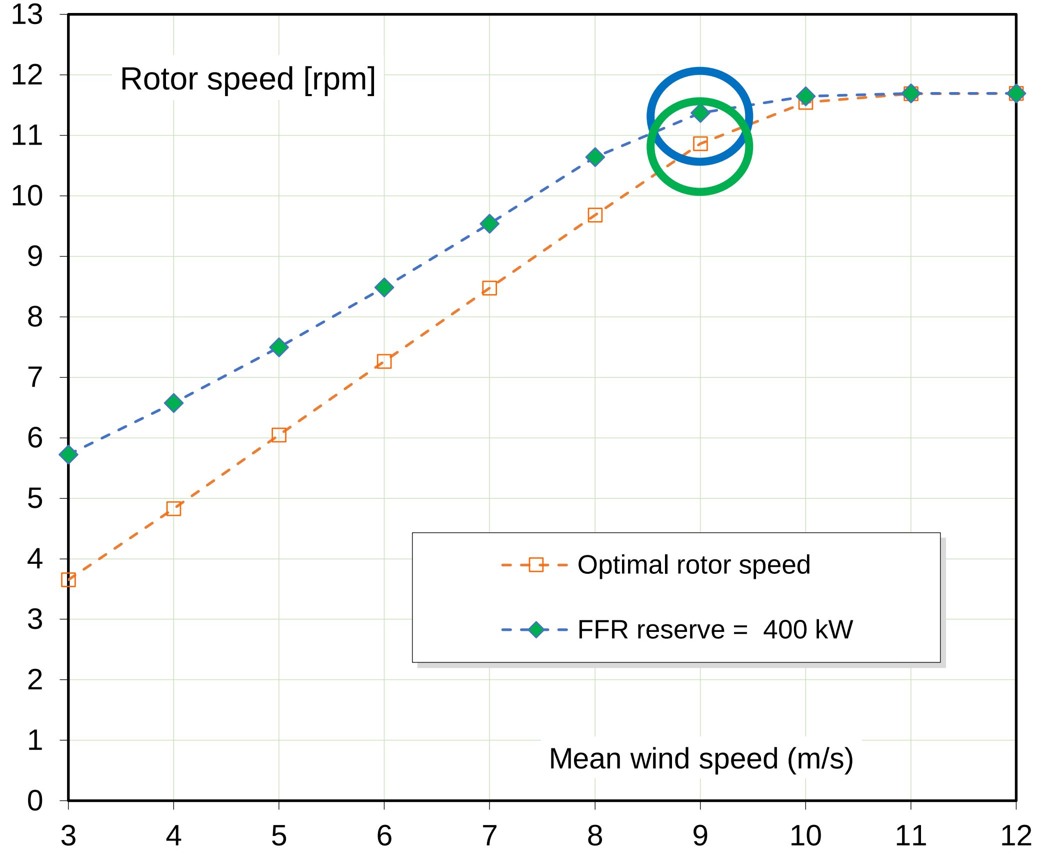


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	1.115	rad/s
Rotating energy at start	1.86E+07	J
Angular velocity at end	1.014	rad/s
Rotating energy at end	1.54E+07	J
Extracted energy	3.20E+06	J
FFR capacity	**408**	**kW**

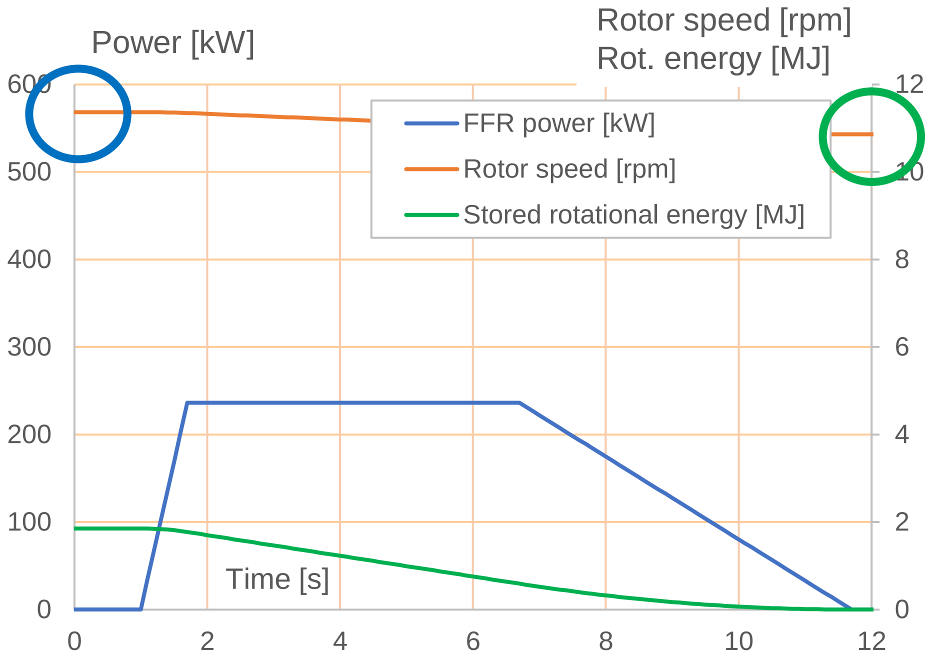


Example of FFR power reserve at mean wind speed 9 m/s

At 9 m/s, the FFR capacity is less than 400 kW
if no power curtailment is implemented

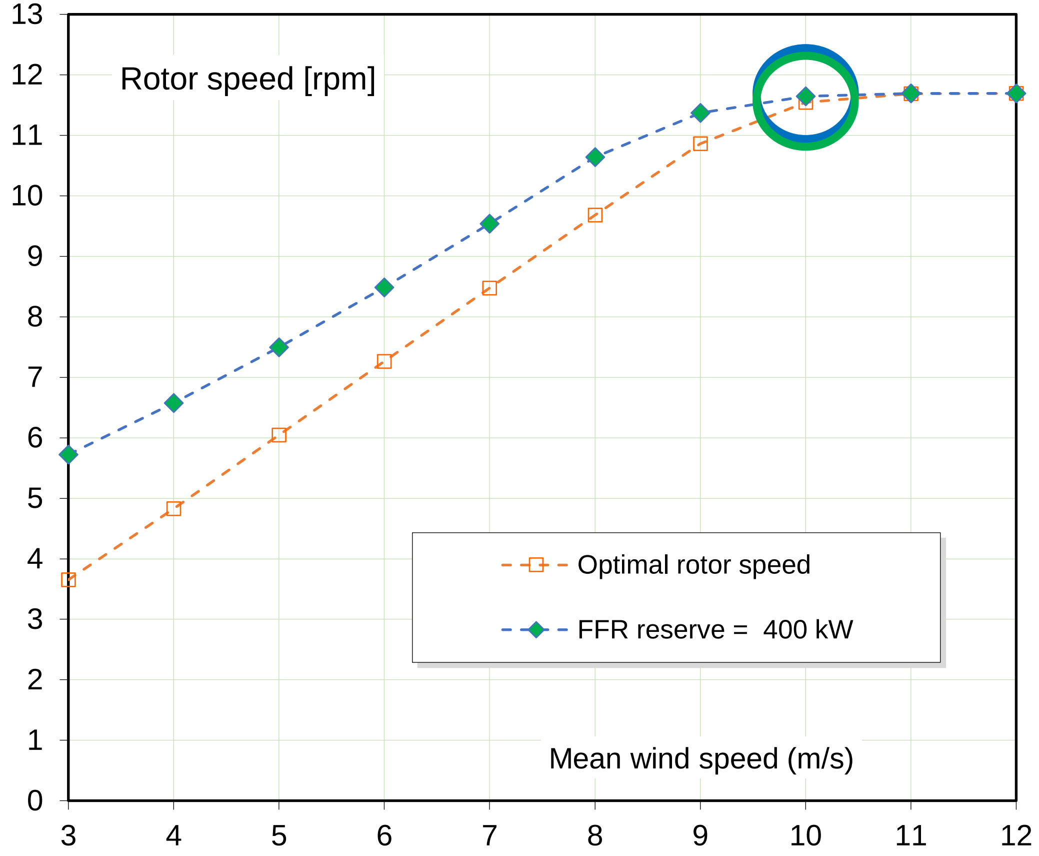


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	1.191	rad/s
Rotating energy at start	2.13E+07	J
Angular velocity at end	1.137	rad/s
Rotating energy at end	1.94E+07	J
Extracted energy	1.85E+06	J
FFR capacity	**236**	**kW**

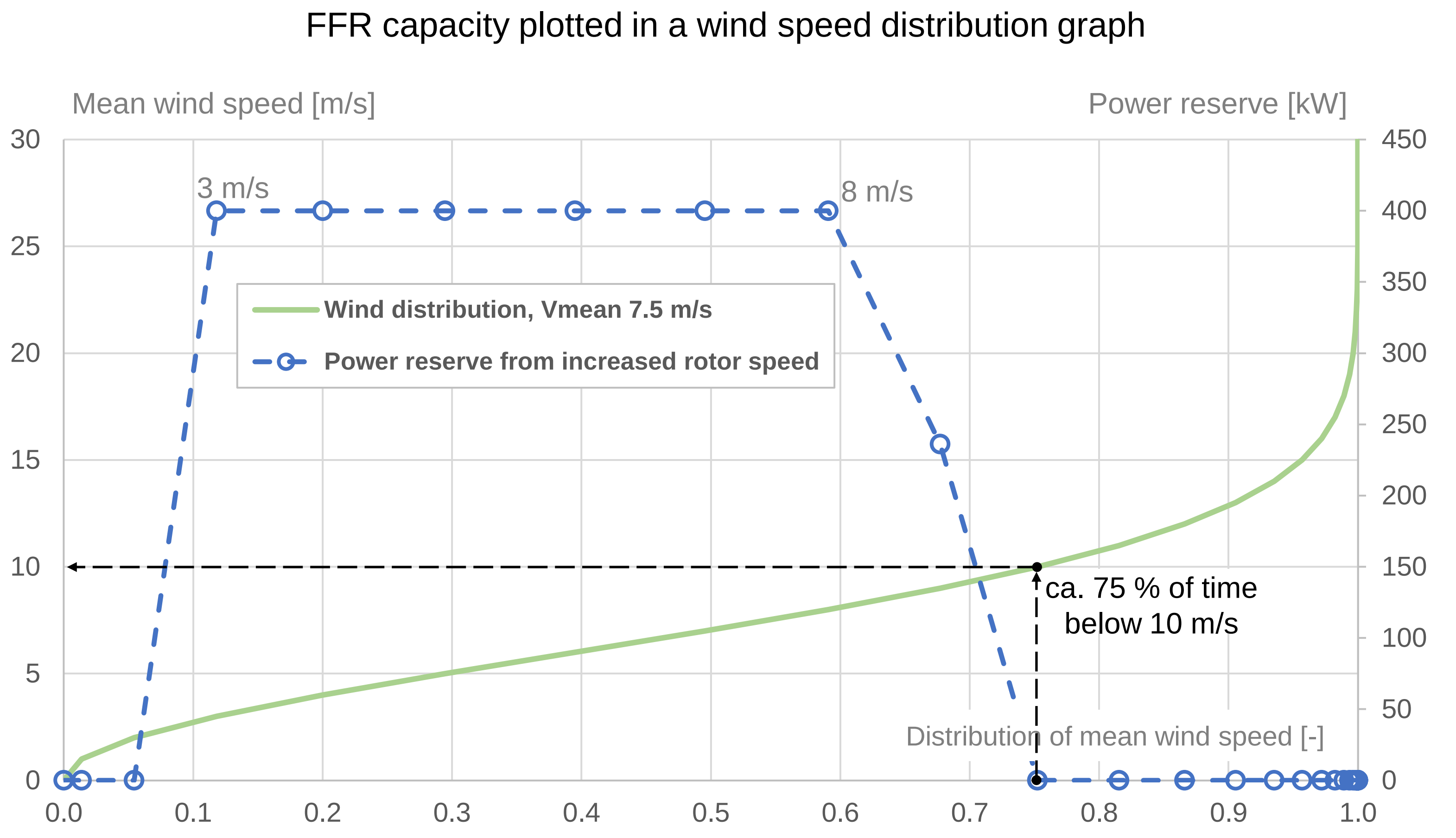


No FFR power reserve at mean wind speed 10 m/s without curtailment

At 10+ m/s, there is no FFR capacity
if no power curtailment is implemented as the rated rotor speed is reached.



Correlation between wind speed distribution and FFR power reserve



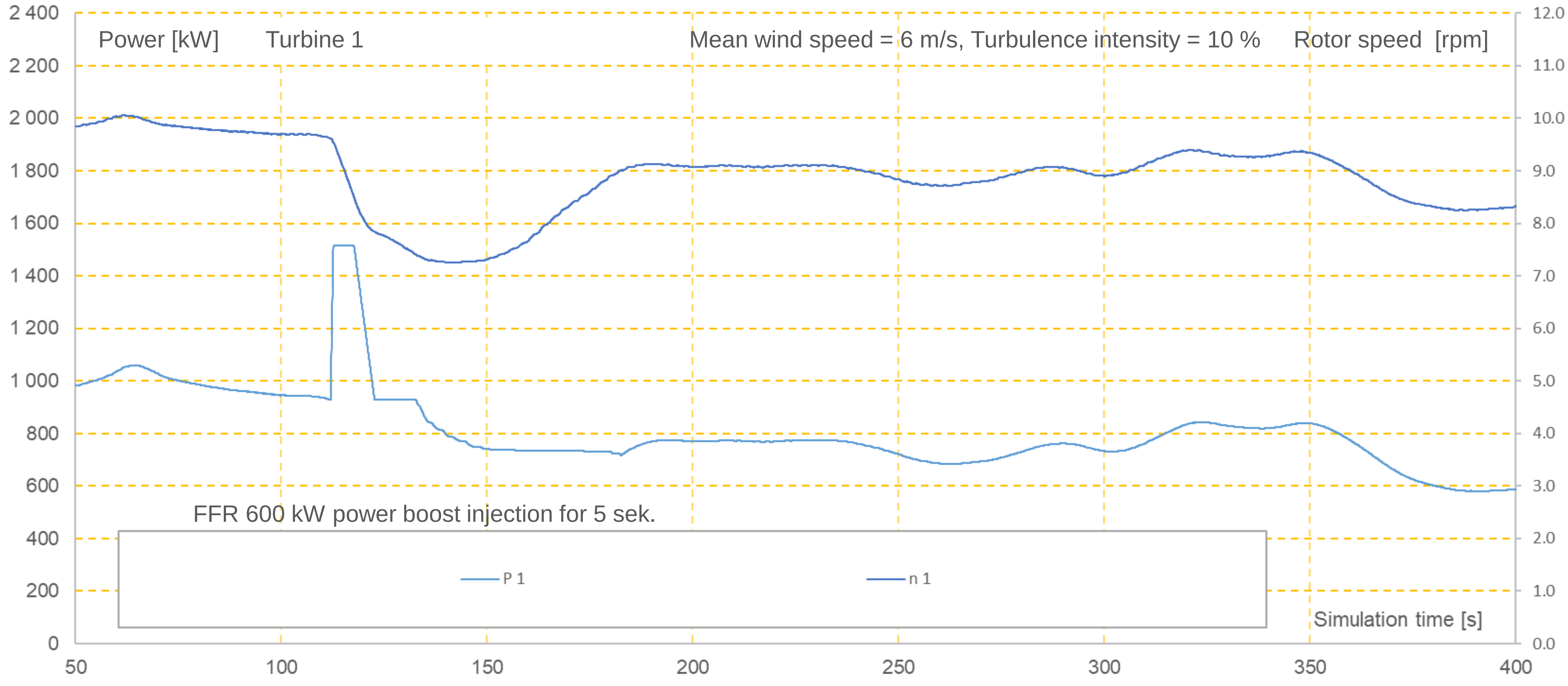
Annual average FFR reserve per turbine

$$\int_0^1 (\text{Power reserve})\ \delta\phi \ = \ 240 \text{ kW}$$

An FFR capacity of 240 kW per turbine is enough for the worst-case scenario.
The cost for this rapid reserve is a power production decreased of 1.0 %.

Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



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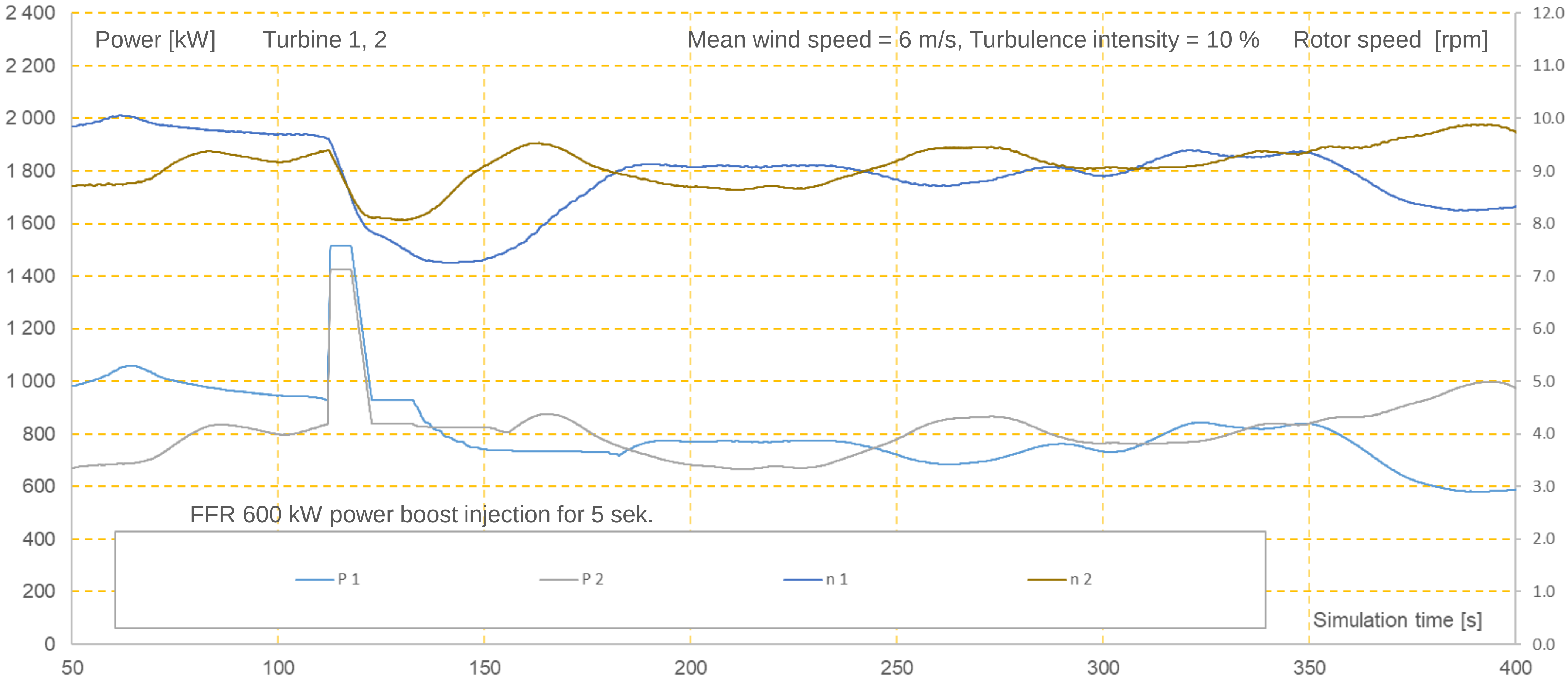

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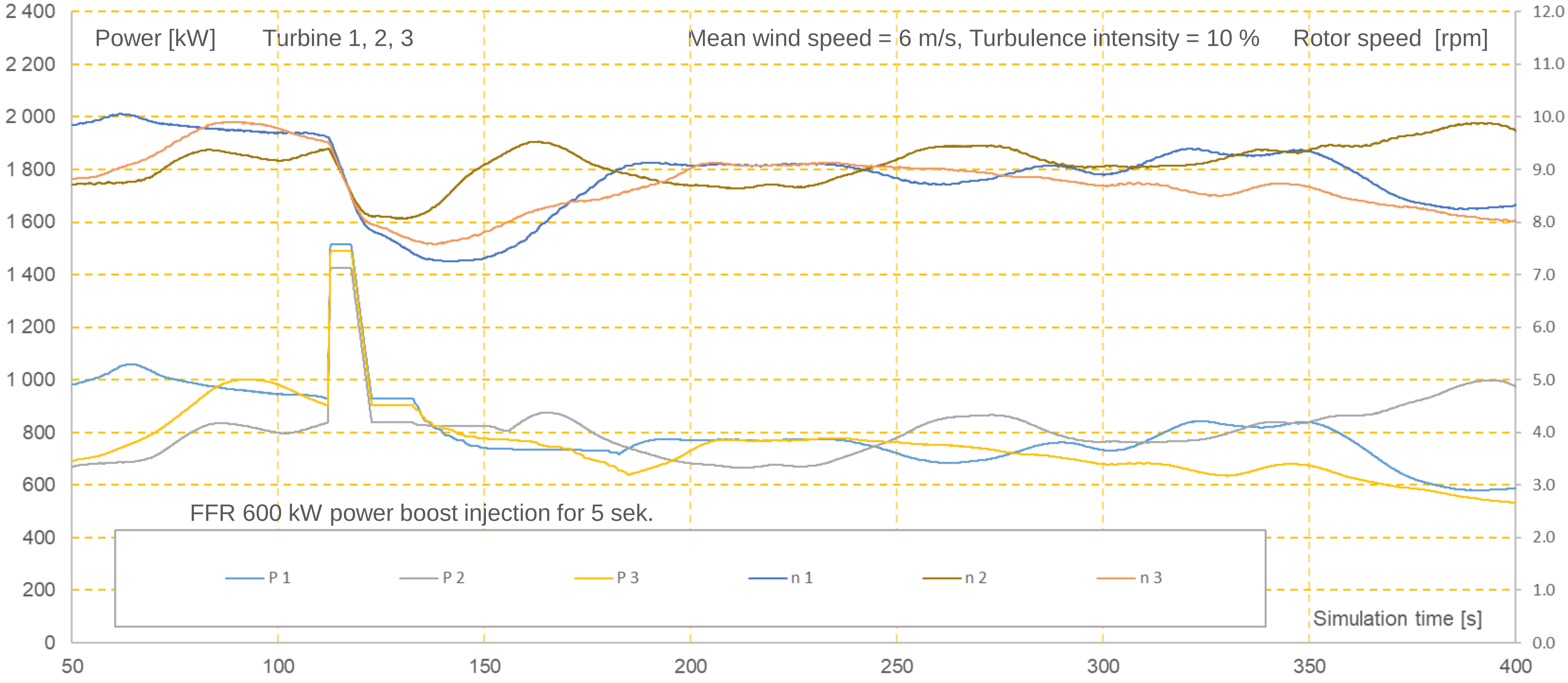

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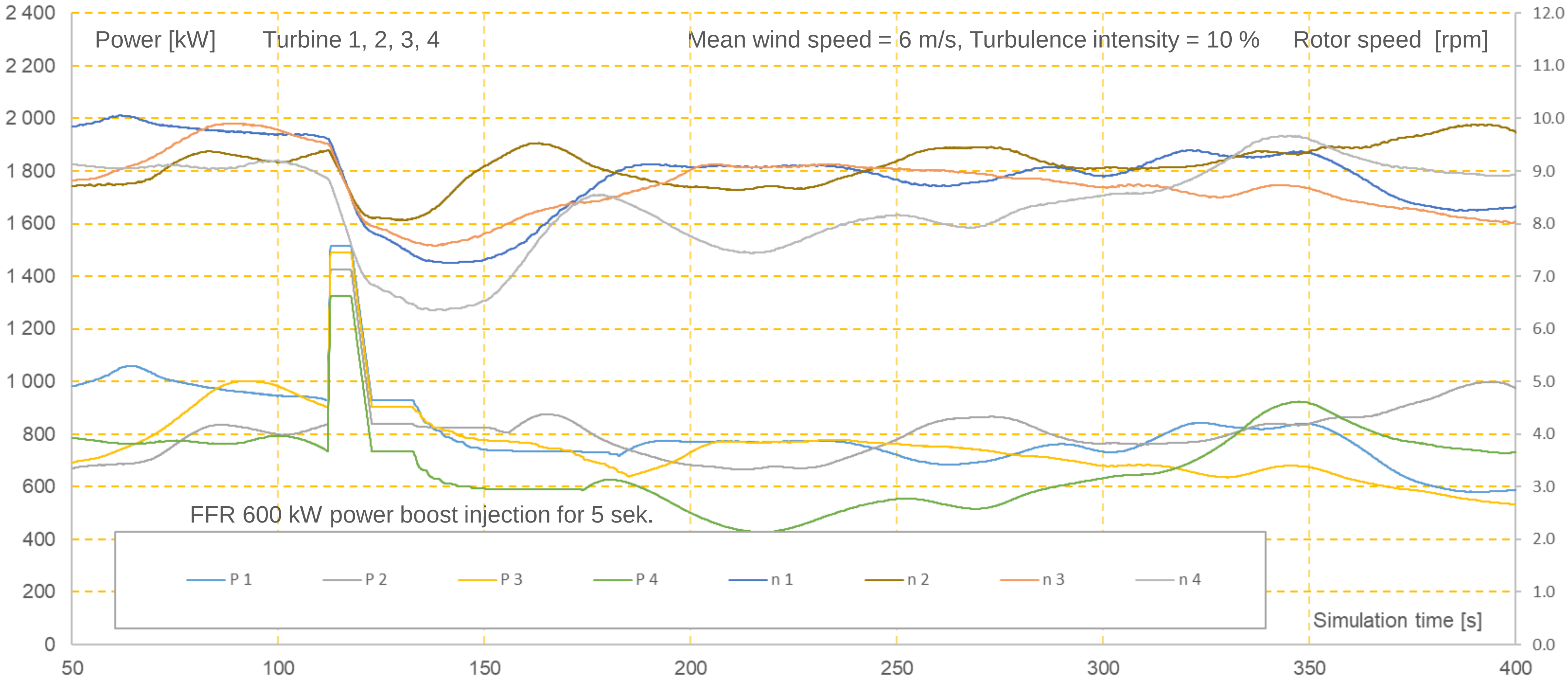

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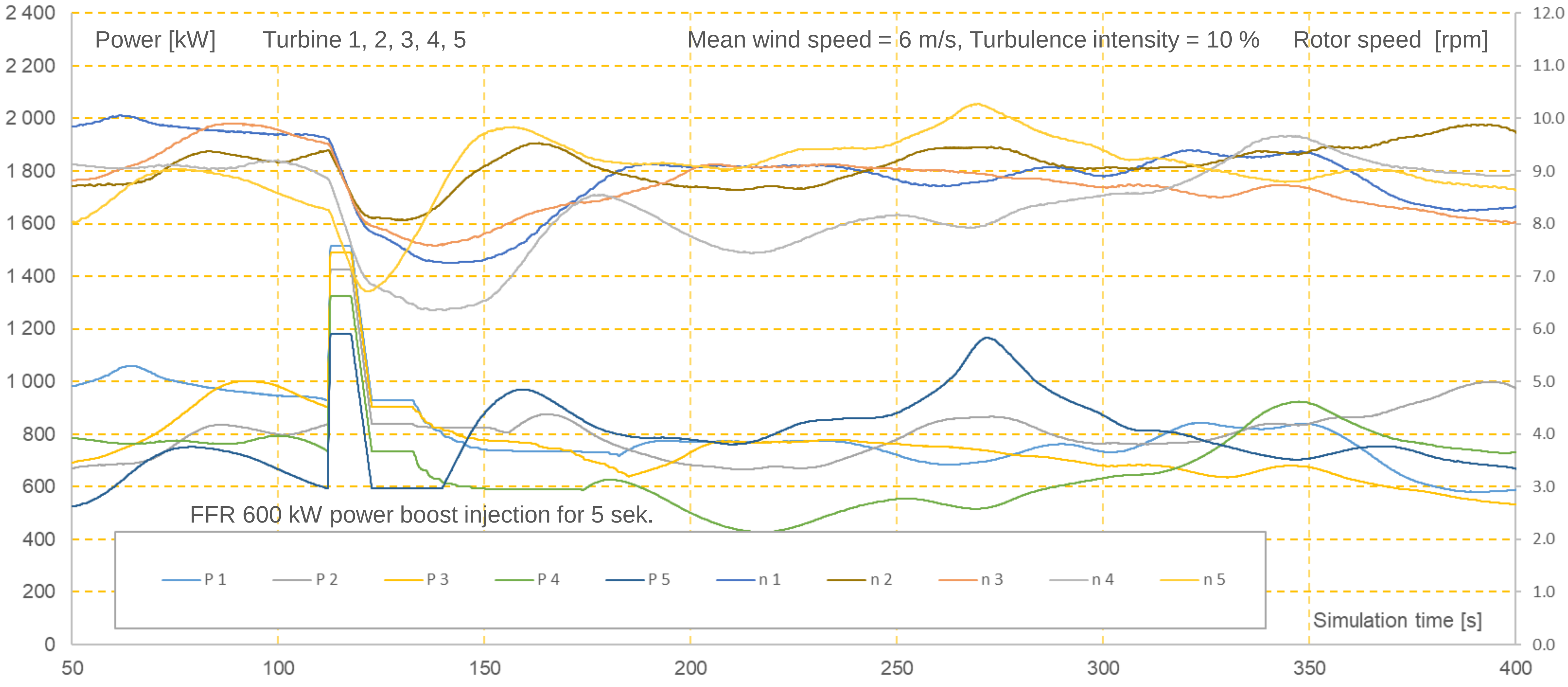

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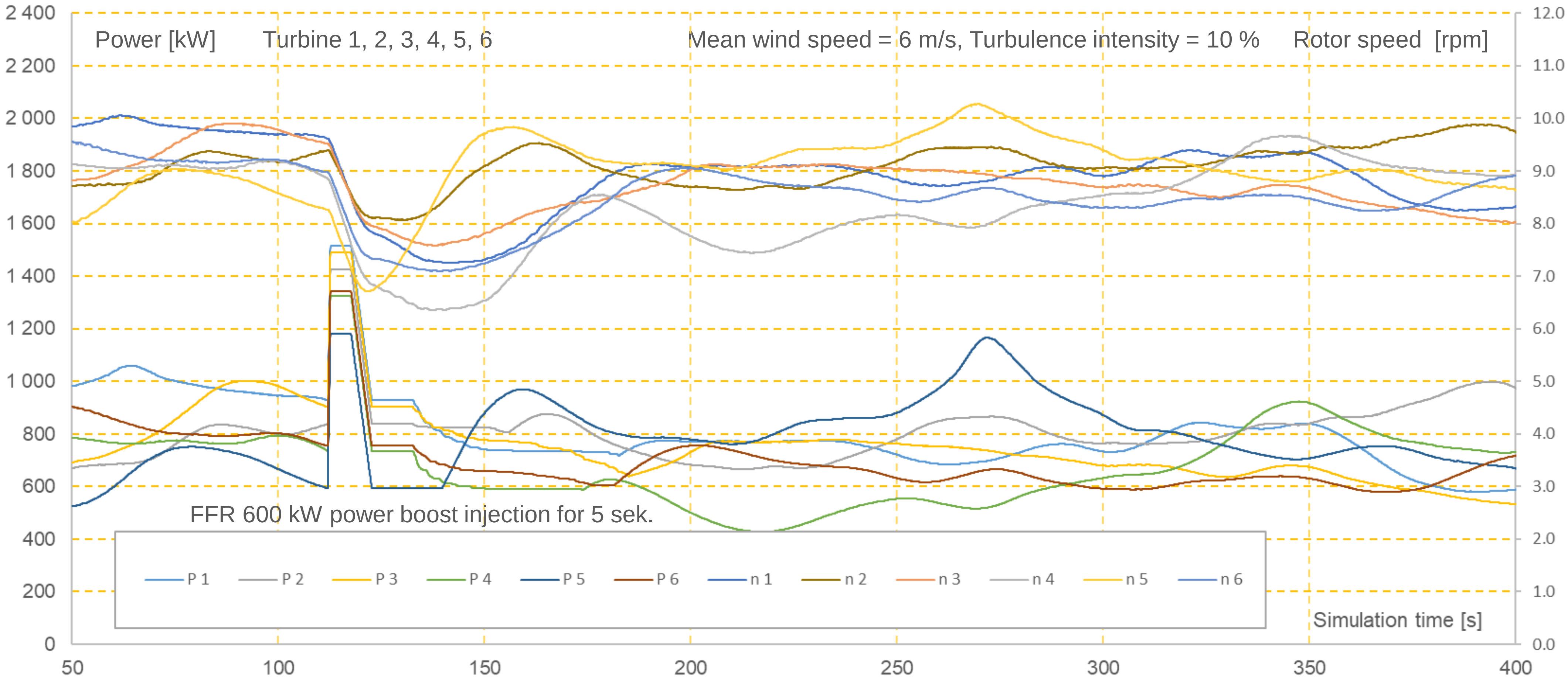

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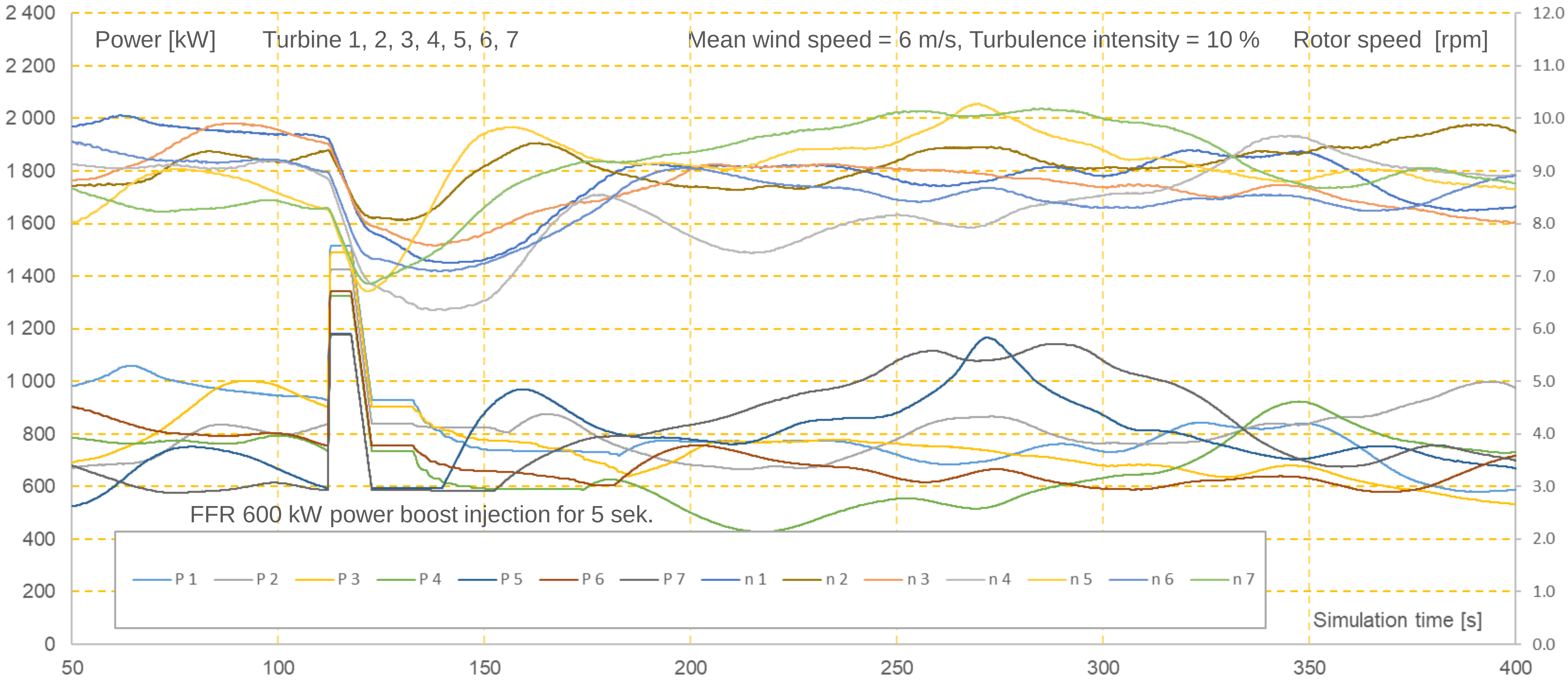

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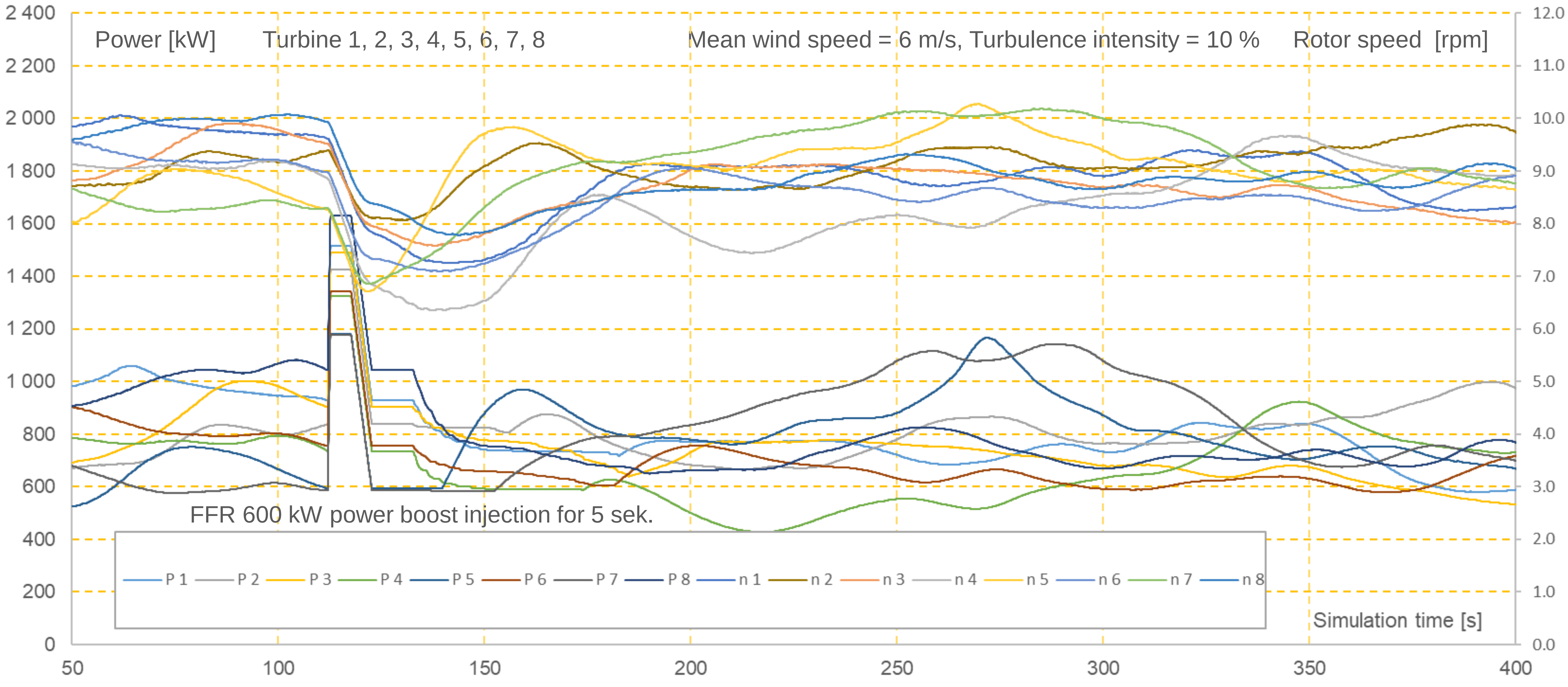

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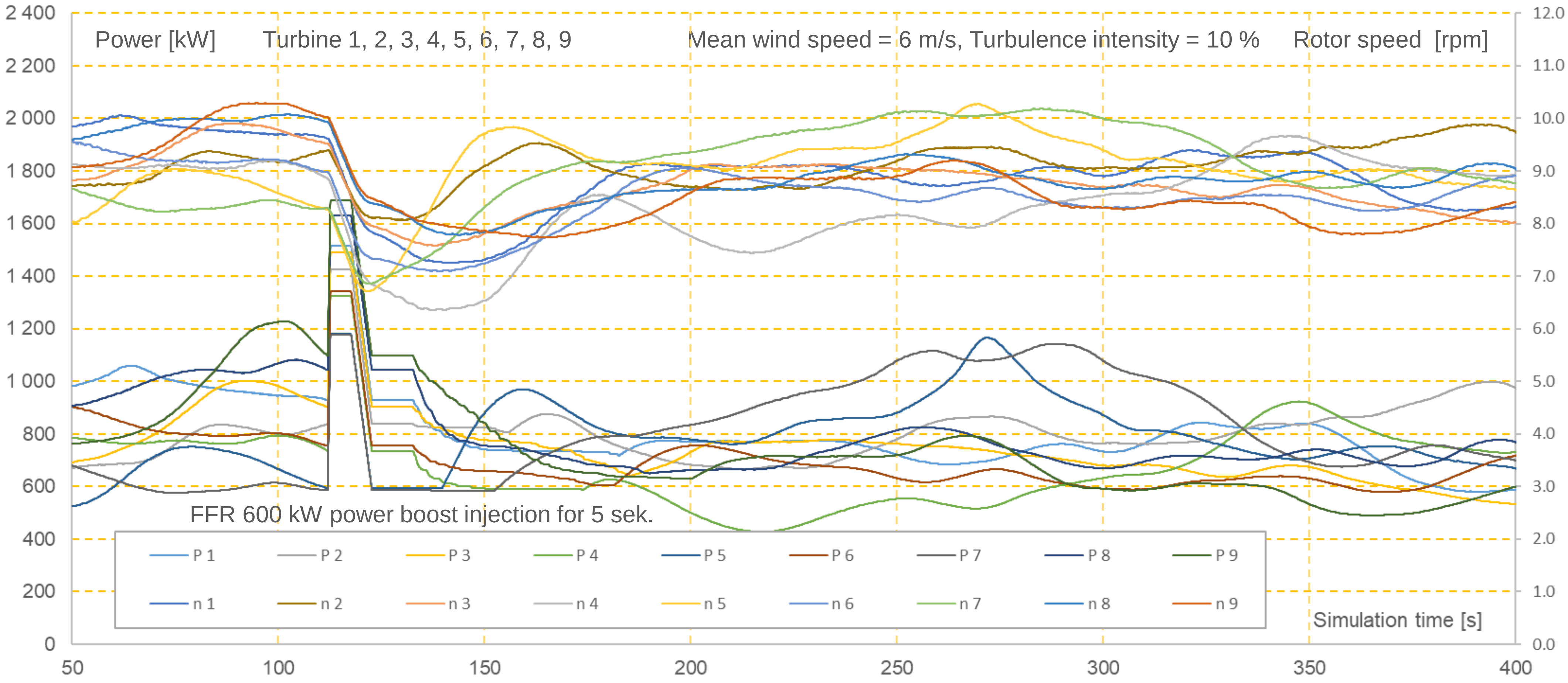

Power and rotor speed during FFR 600 kW power boost

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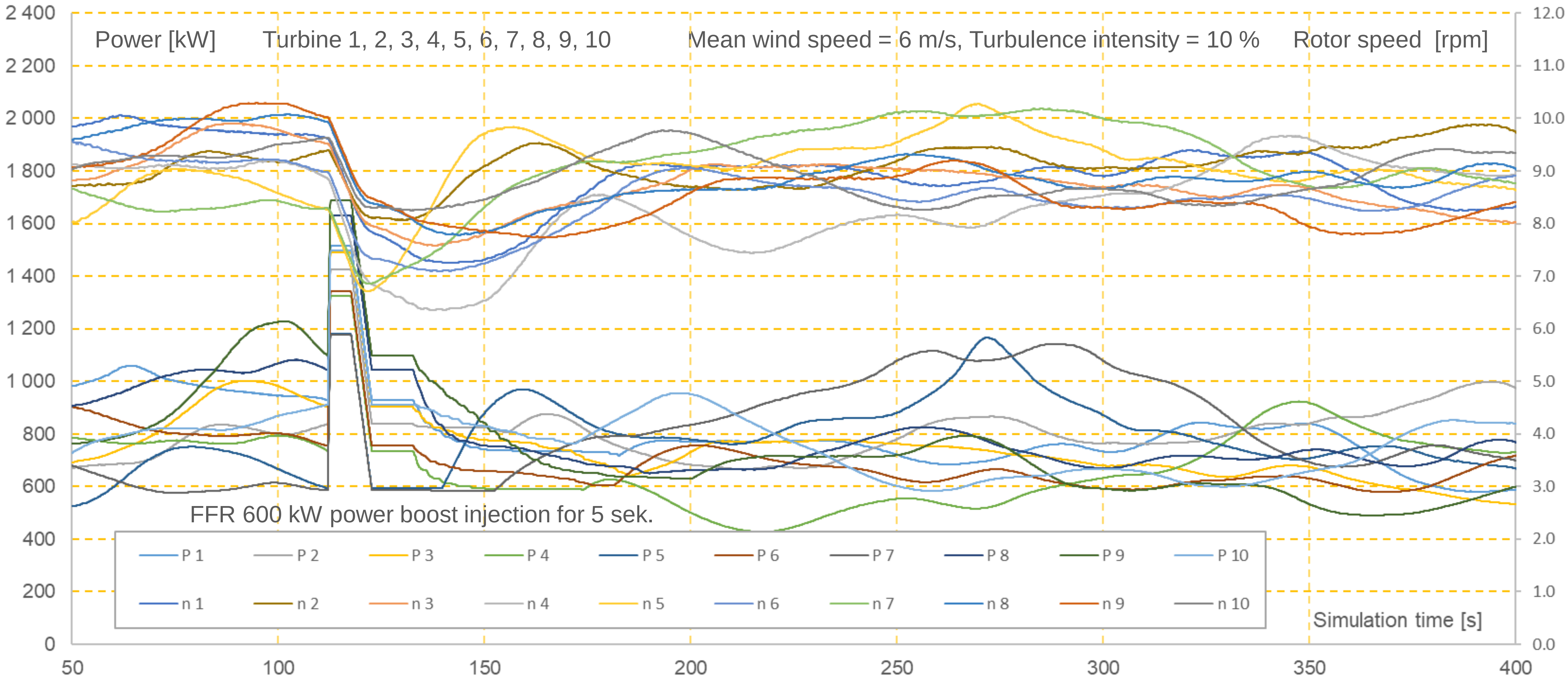

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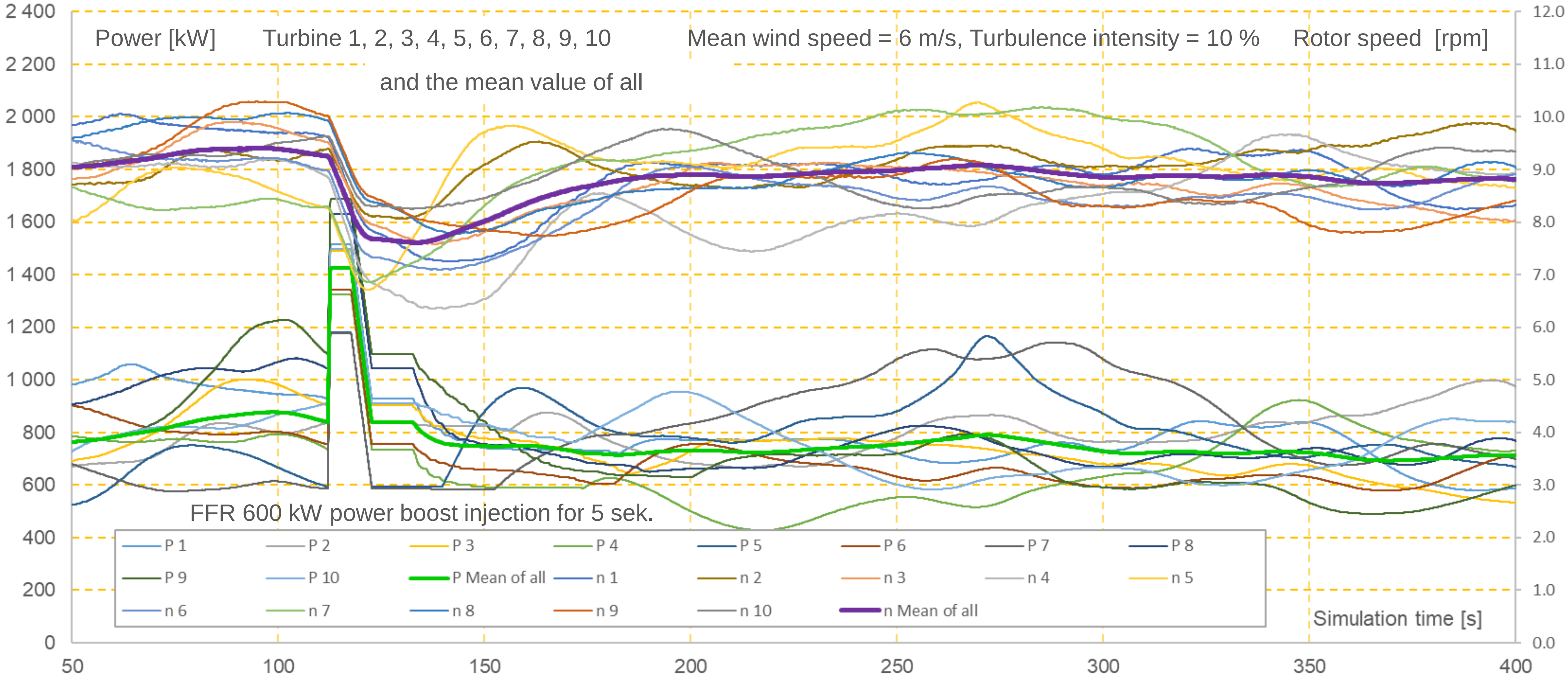

Power and rotor speed during FFR 600 kW power boost

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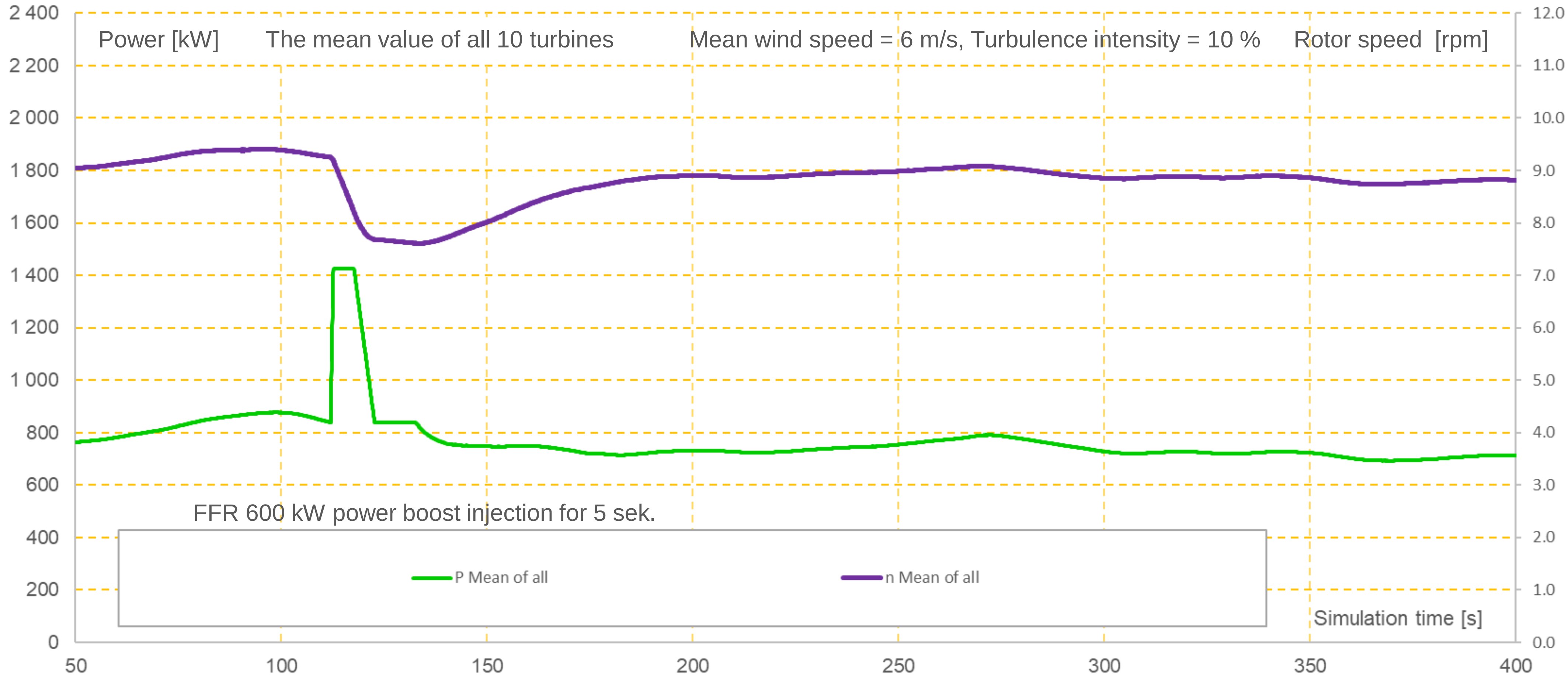


Using several scattered turbines, it is possible to keep the total wind power constant

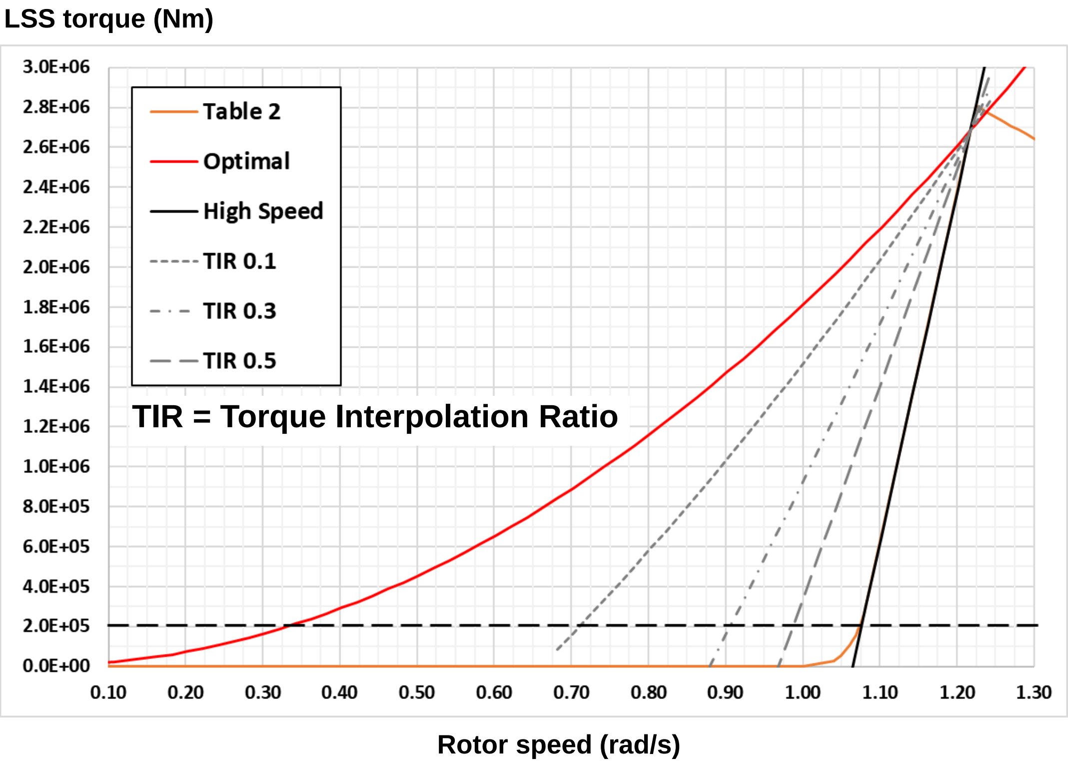
Key take-aways

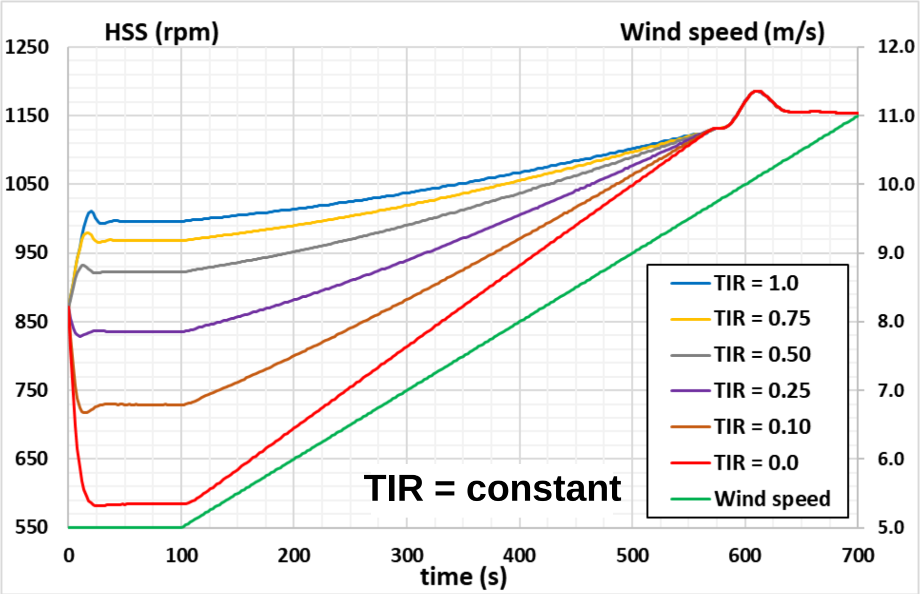
- Fast Frequency Response (FFR) is required to maintain the balance in the power grid
- Wind turbines can provide FFR with a minor change in the control system
- The required energy can be stored in the kinetic energy of the rotor via an increased rpm
- …and released upon the drop in the grip AC frequency
- The corresponding losses in efficiency is minimal (1% of AEP)
- Installed wind capacity in Sweden is more than sufficient to provide the total need for FFR in Nordic grid
- Next step: incorporation of the price signal into the control system (price of energy vs compensation for FFR)

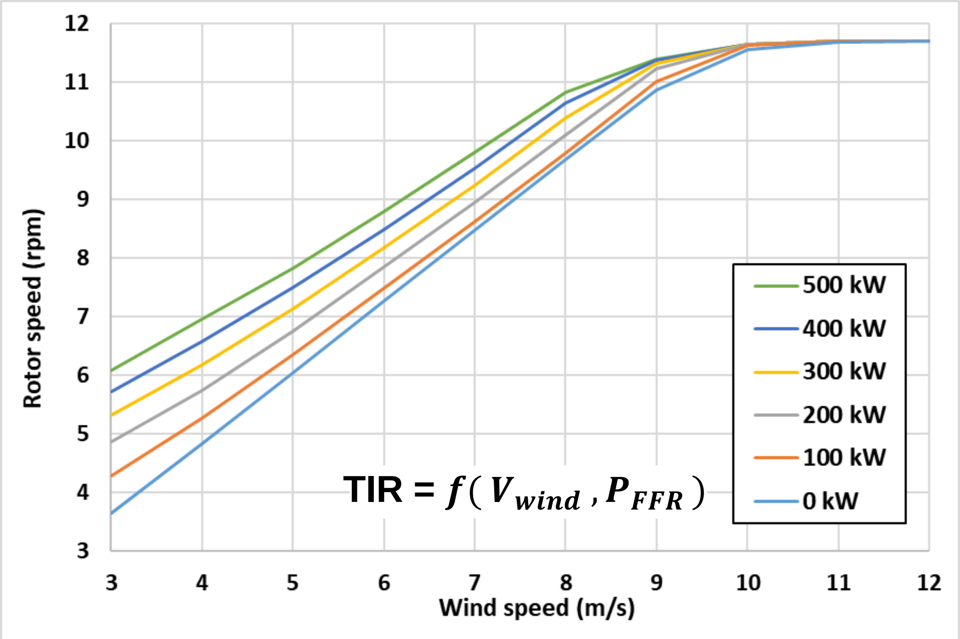
  => Control logic decides how to maximize the revenue from that turbine

Thanks! Questions?

Backup slide: Control System

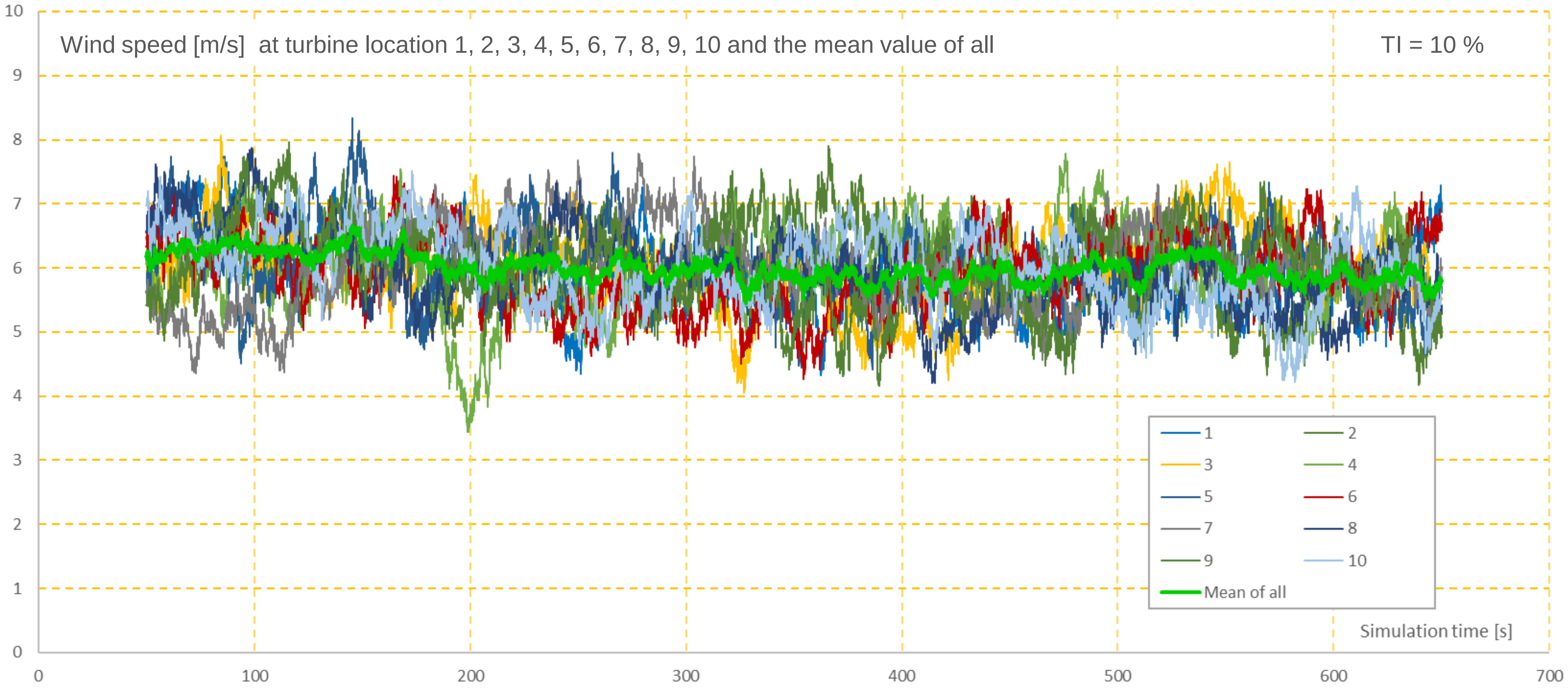






Backup slide: Wind speed signal at mean wind speed 6 m/s

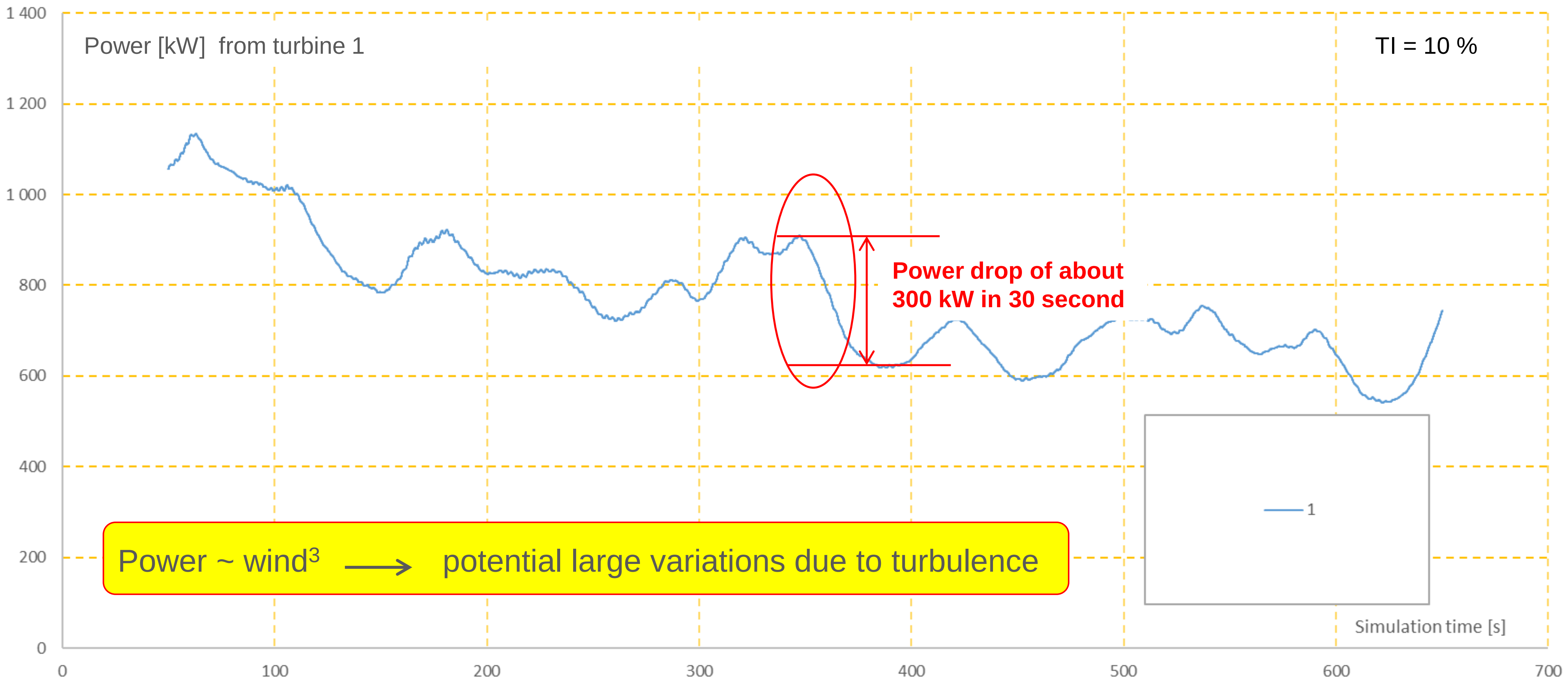
Results from generation of stochastic turbulent wind for 10 minutes



Looking at the mean value, the variations are significant smaller

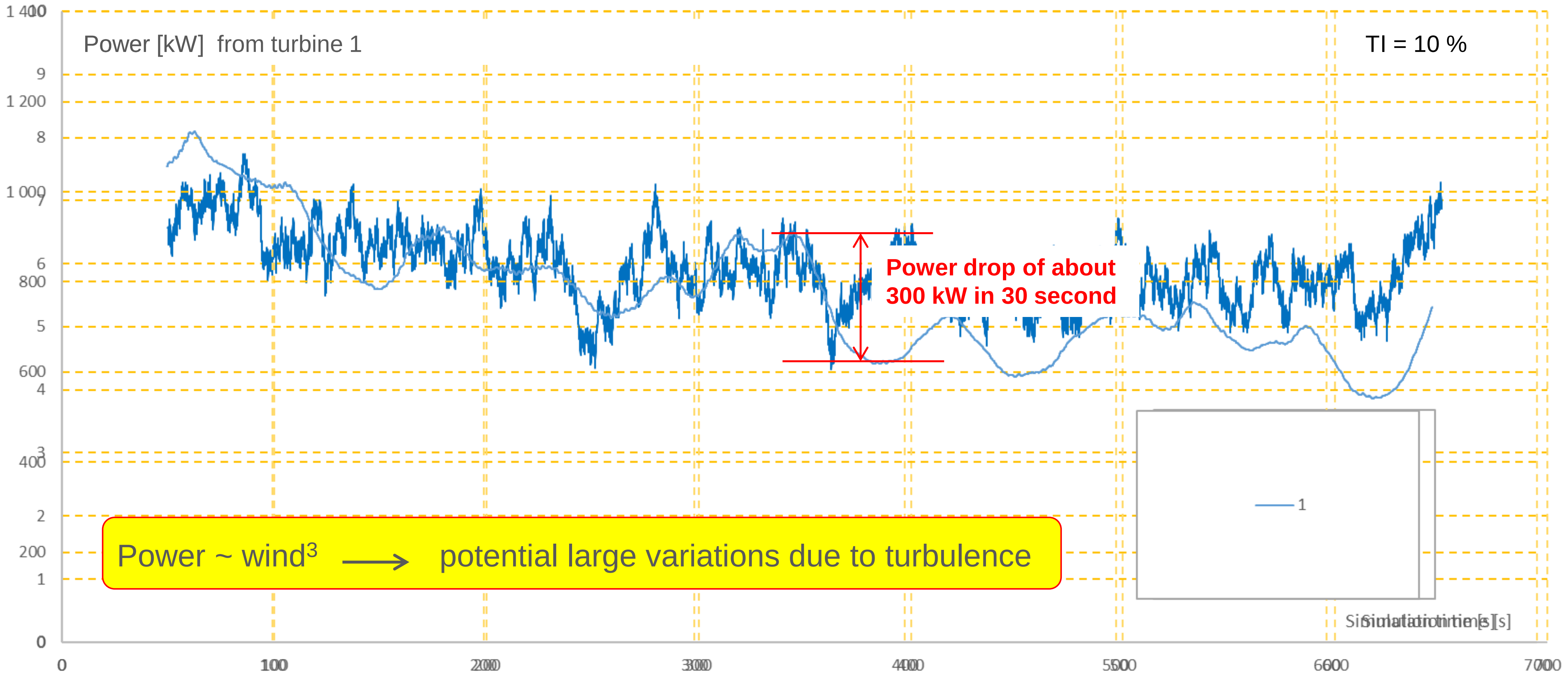
Backup slide: Power output in mean wind speed 6 m/s

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 10 minutes in turbulent wind



Backup slide: Power output in mean wind speed 6 m/s

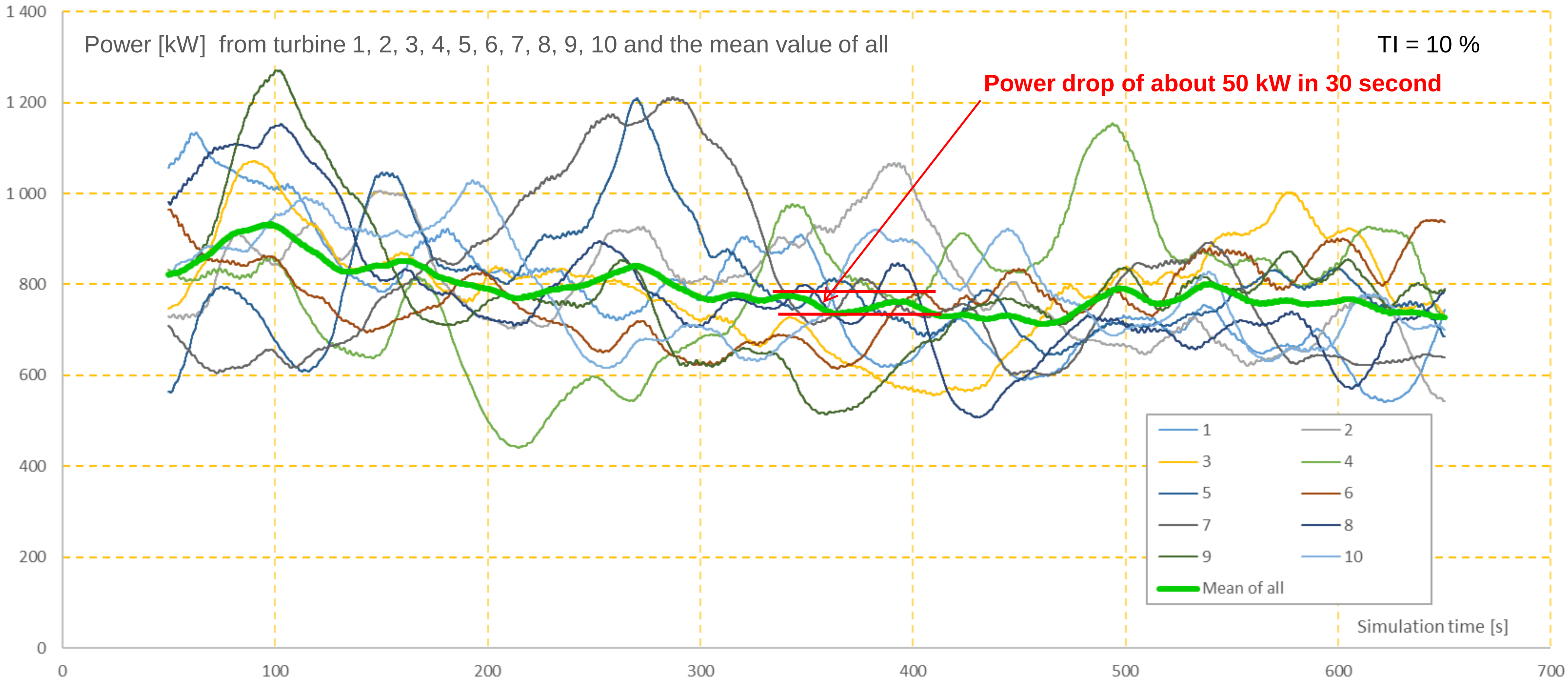
Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 10 minutes in turbulent wind



It is not possible to run a turbine at constant power for longer times in low wind speeds

Backup slide: Power output in mean wind speed 6 m/s

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 10 minutes in turbulent wind

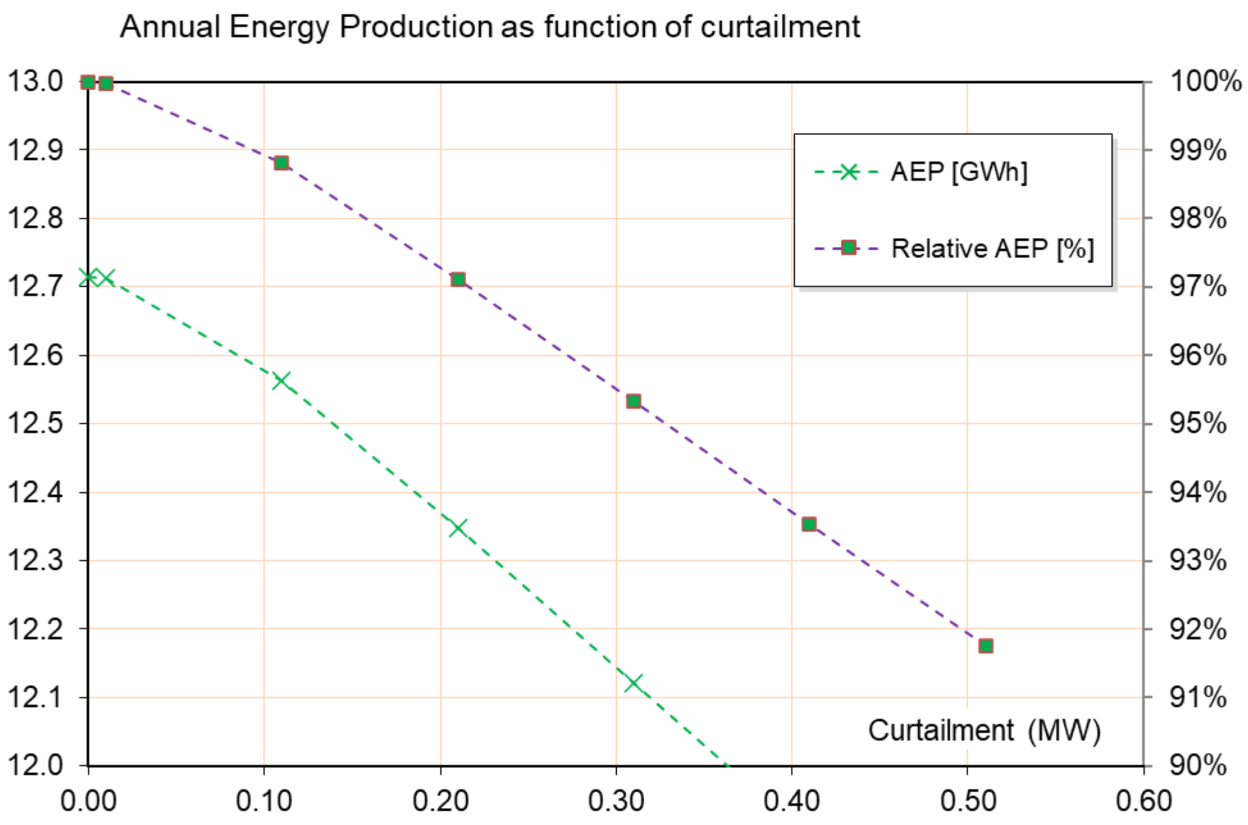


Using several scattered turbines, it is possible to keep turbine power relatively constant

Backup slide: Annual energy production depending on power curtailment

By plotting the actual and normalized power production, the impact of the power curtailment is shown.

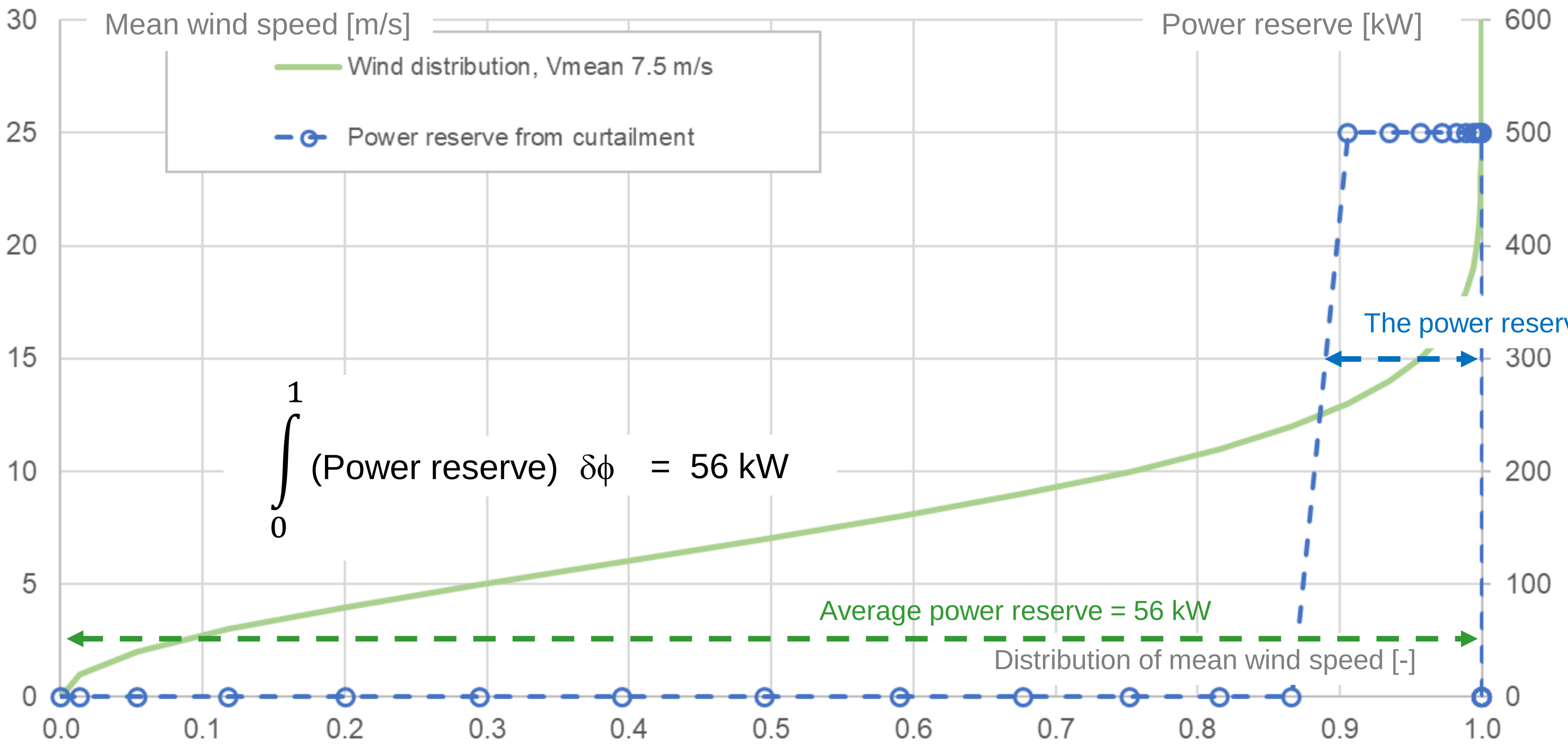
This is the cost to pay for to get the FFR reserve!



Reduced production caused by curtailment		
Curtailment	**AEP [GWh]**	**Relative AEP [%]**
0.00	12.716	100.00%
0.01	12.712	99.97%
0.11	12.564	98.81%
0.21	12.348	97.11%
0.31	12.121	95.33%
0.41	11.894	93.54%
0.51	11.667	91.76%

Backup slide: Correlation between wind speed distribution and P_rating

The calculated FFR capacity plotted in a wind speed distribution graph



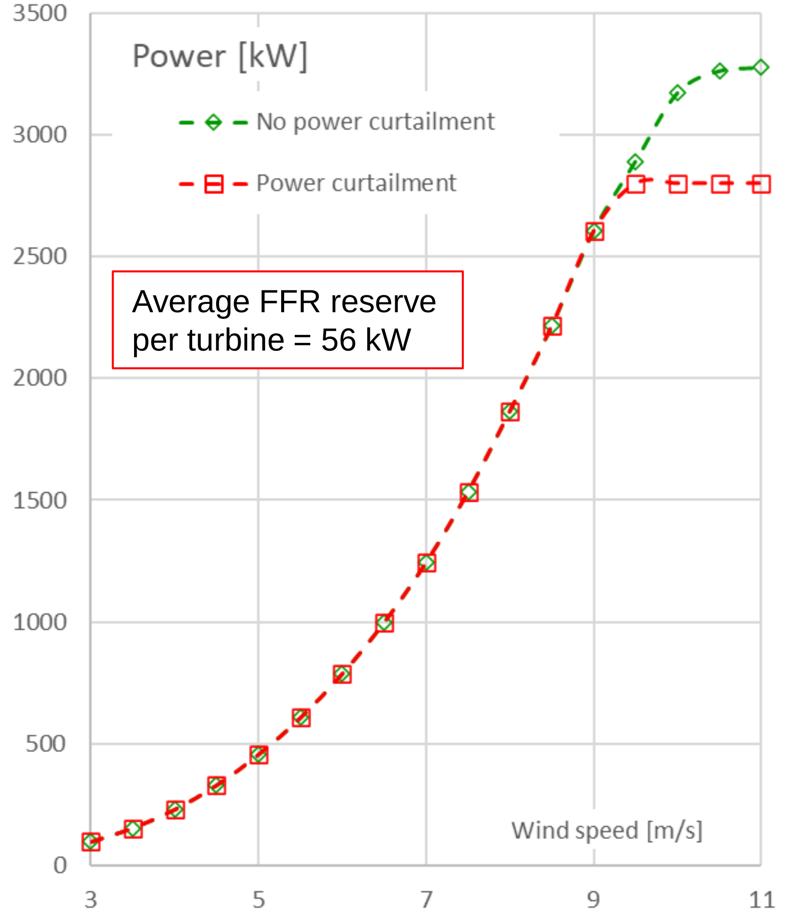
Summarized power reserve		
Total wind power production	20	TWh
Curtailment per turbine	500	kW
Production per turbine	11.67	MWh
Number of turbines	1573	
Production reduction	1.05	MWh
Production reduction	8.24	%
Average reserve per turbine	56	kW
Total power reserve	**88**	**MW**

An FFR capacity of 56 kW per turbine is not enough for the worst-case scenario. The cost for this rapid reserve is a power production decreased of 8.2 %.

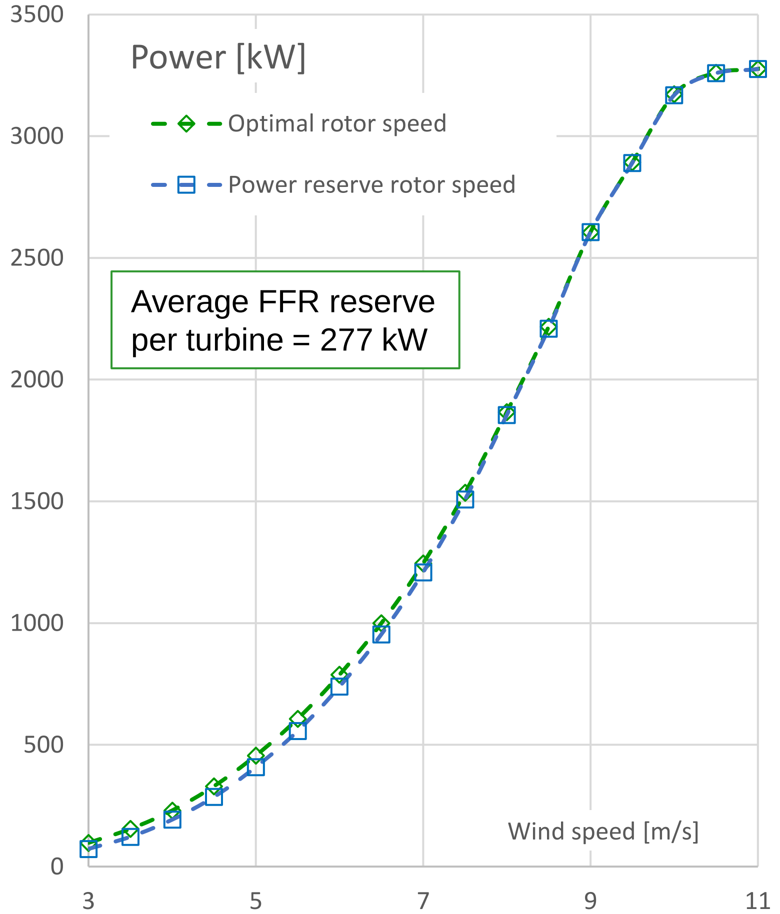
However, this power reserve might act for longer than 5 – 10 seconds

Backup slide: Conclusion

Comparison of AEP between operation at optimal rotor speed vs. power reserve speed



Power reserve by curtailment ⟹ 92 % of AEP



Power reserve by rotor speed ⟹ 99 % of AEP

FFR by rotor speed provides 5 times higher power reserve compared to curtailment.

The cost (AEP reduction) for FFR by rotor speed is only 1/6 compared to curtailment .