Parameterized turbine performance

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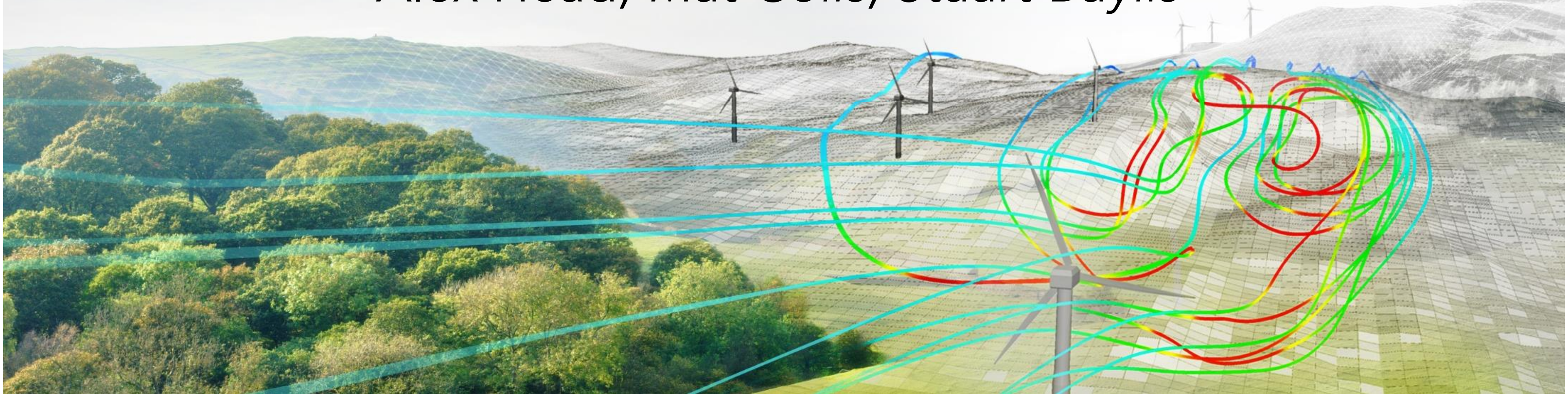

About Prevailing

Å Wind farm analysis specialists

Å 500 wind farms analysed in 18 countries

Å Developer, Lender and Acquisitions roles

Å Pre-construction and operational

Å US office in Portland, OR

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Site specific performance

Å A calculated power curve is calculated in a particular set of conditions (shear, turbulence etc.).

Å We can ask two questions:

1. In matching conditions, do measurements agree?

2. How does performance change outside these conditions?

Å Today we will focus on answering the second question.

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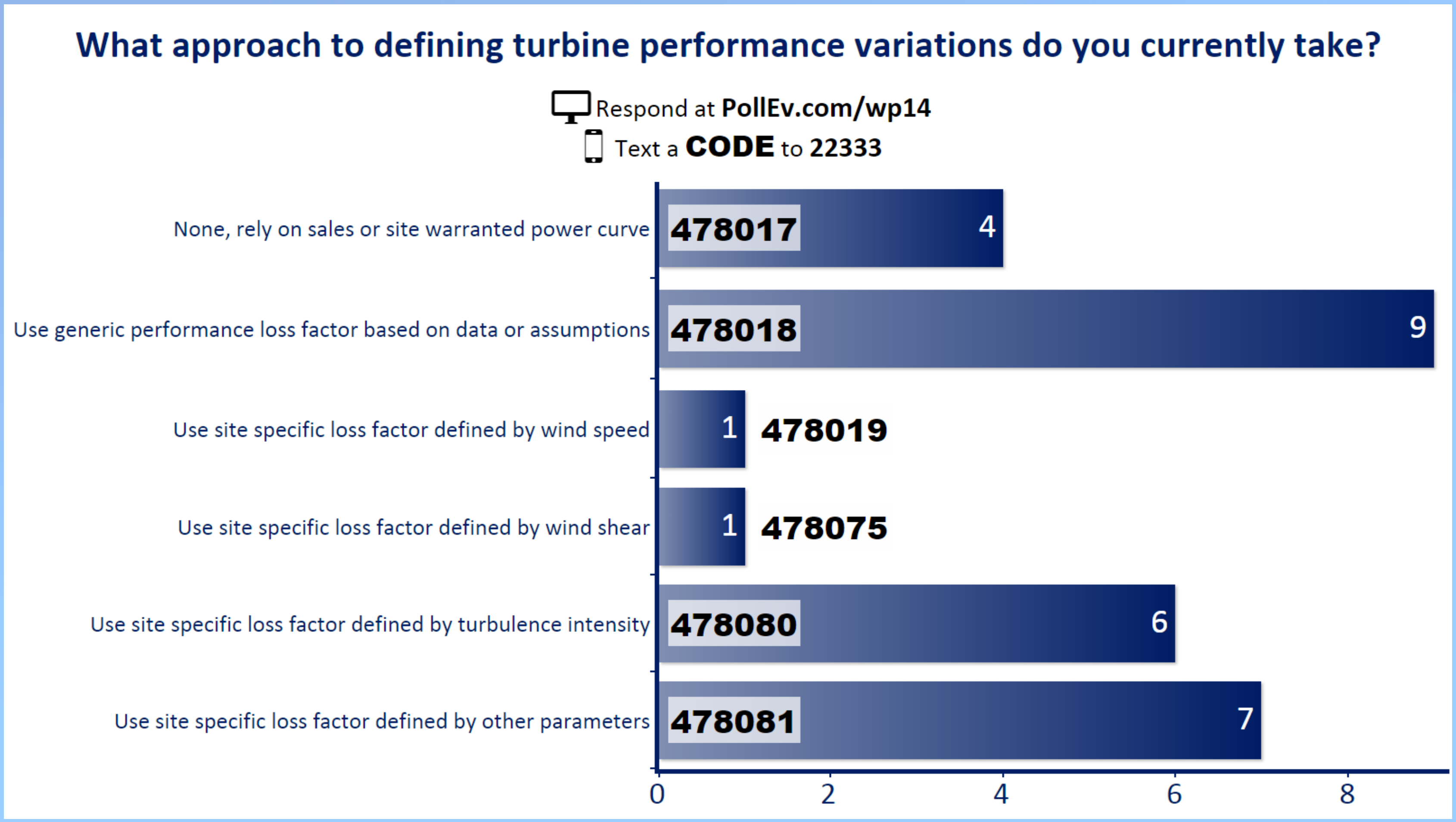
Aim

- To aggregate turbine performance data into a parameterized model:
  - A single model applicable globally
  - Spanning variations in geometry of turbines
  - Across all site conditions
- Parameters must capture physical drivers of performance variation
  - Rotor aerodynamics
  - Controller influence
- To be used to predict turbine performance with pre-construction mast data.

What do you do?



If you combine parameters respond "Other"

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Current practice

- Various methods in use
- Theoretical or data-derived
- Often parameterized
  - Fixed adjustment
  - Shear
  - Turbulence
  - Wind speed
  - Geometry
  - Turbine type
  - Geography
  - Density
- 2D binning misses significant performance variation

(data for illustrative purposes)

Wind speed/turbulence

	4		6		8		10		12	
24%	120%	112%	108%	106%	102%	102%	99%			
	116%	109%	106%	104%	104%	102%	101%	100%	96%	97%
16%	111%	105%	101%	101%	101%	102%	101%	100%	99%	99%
	99%	96%	96%	98%	99%	101%	101%	101%	100%	100%
8%	82%	88%	8[illegible]%	92%	95%	98%	100%	101%	102%	101%
	75%	82%	8[illegible]%	87%	88%	93%	97%	99%	101%	100%
0%	62%	70%	7[illegible]%	78%	81%	84%	88%	94%	100%	101%

Shear/turbulence at 6 m/s

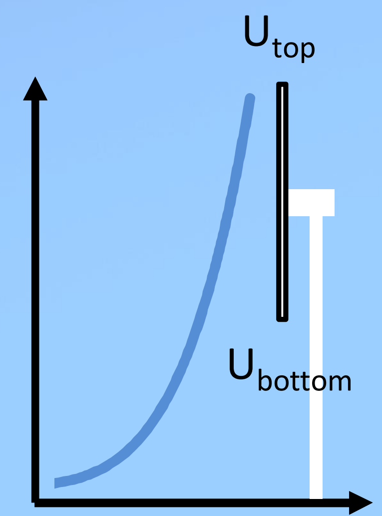
	-0.2		0[illegible]0		0.2		0.4			0.6
24%	92%	100%	[illegible]	112%	109%	102%				
	89%	98%	110%	106%	110%	97%	96%	95%		
16%	94%	95%	103%	101%	102%	101%	99%	89%		
		83%	101%	99%	96%	99%	99%	91%	89%	84%
8%		80%	95%	93%	95%	91%	90%	91%	91%	85%
			90%	88%	86%	90%	90%	87%	80%	82%
0%					75%	69%	74%	74%	75%	73%

Aerodynamic performance variation

Å Blade “lift to drag ratio”(LDR) is a good measure of aerodynamic efficiency

Å For any blade, LDR is sensitive to:
- ï Turbulence
- ï Relative wind speed
- ï Angle of attack variation

RWSR = U_{top}/U_{bottom}

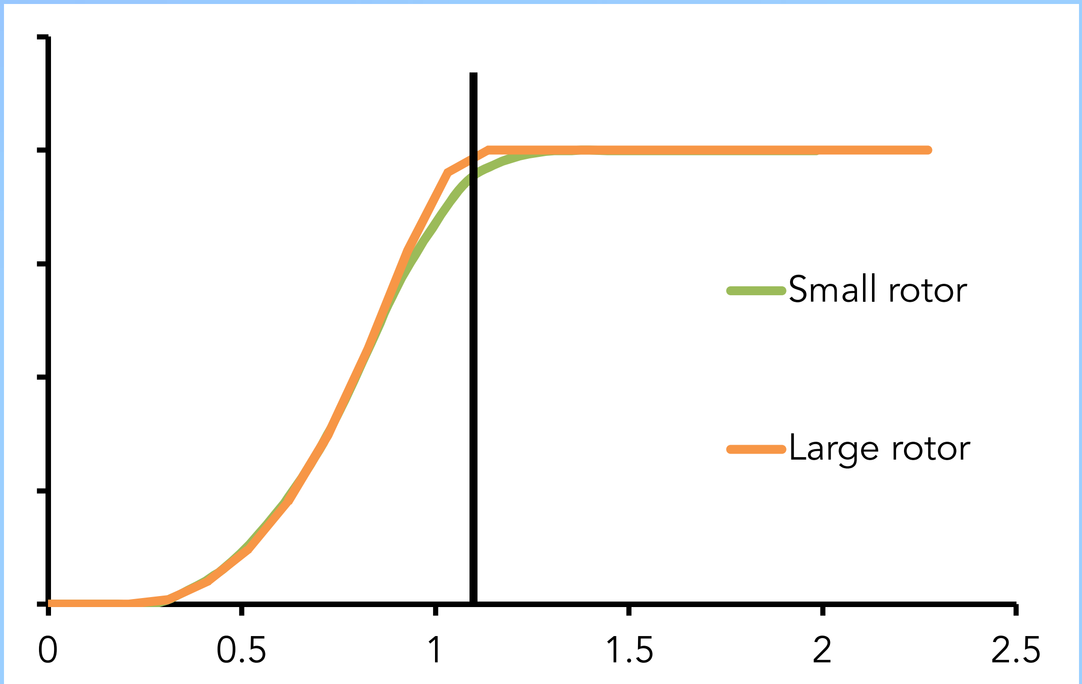


Å To capture rotor performance, the solution is to aggregate on:
- ï Turbulence
- ï Wind speed
- ï Rotor Wind Speed Ratio

Å This captures turbulence, shear and rotor geometry influences on rotor aerodynamic performance

Controller effects

Å Distinct cubic and rated power curve phases
Å Wind speed alone doesn't allow comparison
Å Normalize by zero turbulence rated wind speed (from IEC proposed standard)



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Resulting parameter set

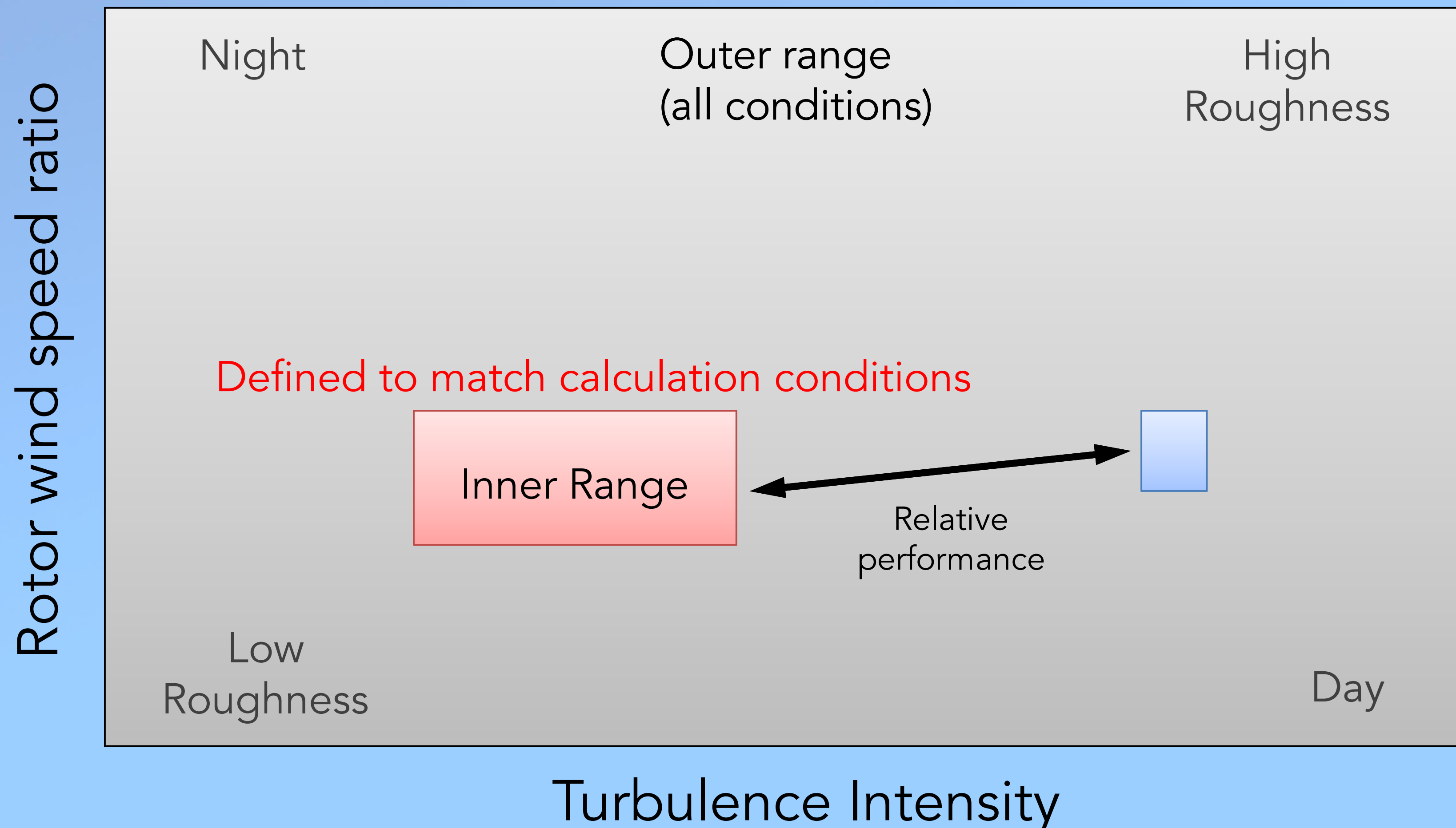
Å Turbulence
- ï A factor in blade Lift to Drag performance

Å Rotor wind speed ratio
- ï Correlates with angle of attack variation across rotor
- ï Captures impact of diameter, hub height and shear

Å Normalised wind speed
- ï Wind speed affects blade Lift to Drag performance
- ï Normalised by the zero TI rated speed to align controller modes across turbine types.

Inner and outer range

For any normalised wind speed:



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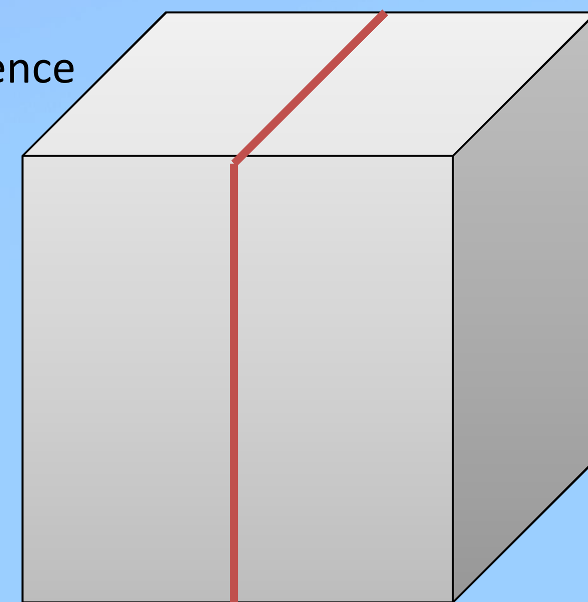
Data set

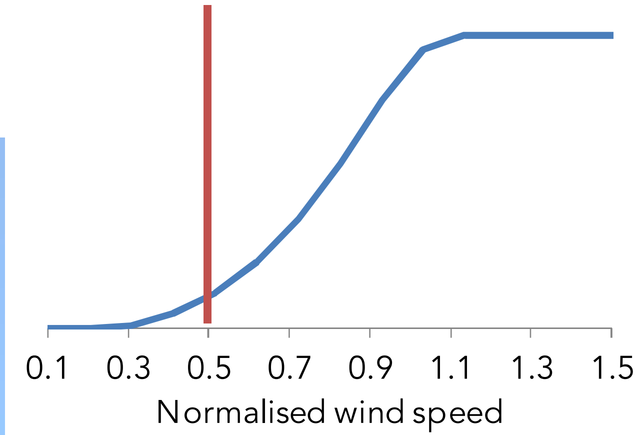
Å 47 turbines
Å 8 turbine types
Å 4 Manufacturers

Å Data from USA, Europe, Asia

Å Applicable to a broad range of site conditions.



$U_{norm} = 0.5$



Rotor wind speed ratio ↓

Turbulence intensity →

	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%
1.7	72%	73%	75%	79%	79%	80%	82%	71%				
1.6	71%	75%	78%	79%	81%	83%	82%	85%	78%			
1.5	72%	76%	78%	82%	85%	85%	84%	85%	86%	83%	95%	
1.4	72%	75%	81%	85%	85%	84%	84%	89%	90%	92%	94%	95%
1.3	75%	76%	80%	84%	86%	85%	90%	92%	92%	98%	98%	108%
1.2	73%	77%	84%	87%	89%	92%	95%	100%	105%	105%	108%	114%
1.1	73%	78%	86%	[illegible]	[illegible]	[illegible]	[illegible]	109%	110%	112%	114%	117%
1.0	73%	80%	87%	91%	101%	101%	103%	108%	110%	[illegible]	118%	124%
0.9		72%	85%	89%		91%	92%	91%	97%	101%	100%	107%
0.8							88%	87%	82%	89%	91%	97%
0.7							85%	84%	82%	84%	87%	

Night

Inner Range

Day

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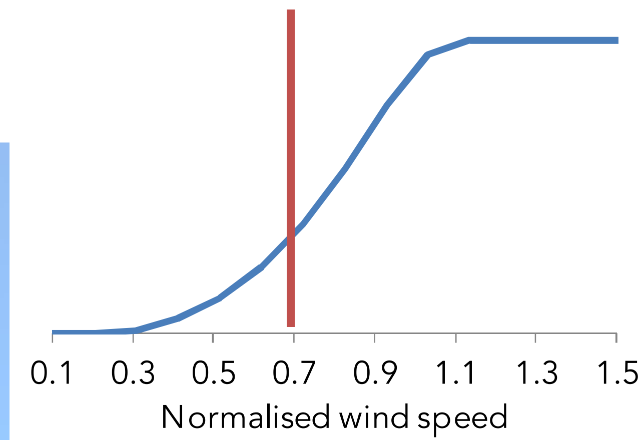
$U_{norm} = 0.7$



Rotor wind speed ratio ↓

Turbulence intensity →

	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%
1.7	79%	78%	83%	[illegible]	[illegible]	[illegible]						
1.6	79%	82%	85%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
1.5	79%	84%	87%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
1.4	80%	86%	88%	91%	94%	96%	96%	96%	95%	99%		
1.3	81%	85%	89%	91%	95%	98%	98%	97%	100%	100%	102%	95%
1.2	81%	88%	90%	92%	96%	98%	100%	100%	102%	104%	103%	106%
1.1	77%	87%	91%	94%	[illegible]	[illegible]	[illegible]	103%	105%	107%	107%	109%
1.0		89%	93%	96%	98%	100%	101%	104%	105%	105%	111%	103%
0.9							94%	95%	95%	96%	102%	
0.8							90%	93%	92%	95%	97%	
0.7							88%	89%	92%	90%	94%	

Performance varies with both rotor wind speed ratio and turbulence intensity

s, larger rotors
her shear

Inner Range

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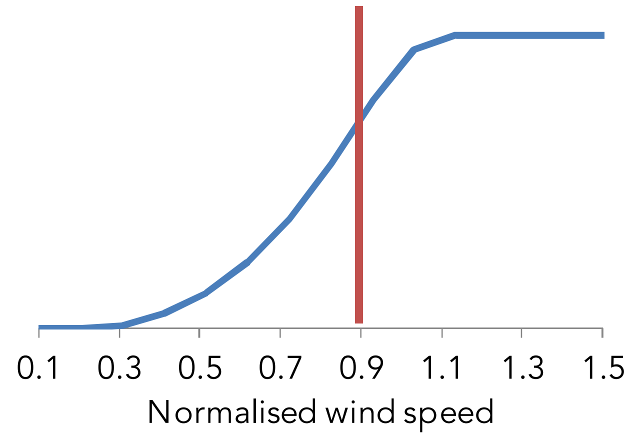
$U_{norm} = 0.9$



Rotor wind speed ratio ↓

Turbulence intensity →

	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%
1.7	85%	88%	87%	92%								
1.6	84%	92%	99%	92%	97%							
1.5	85%	93%	96%	95%	94%	102%	98%					
1.4	86%	94%	96%	97%	99%	100%	100%	101%	105%	105%		
1.3	87%	94%	95%	98%	99%	101%	101%	102%	102%	102%	102%	
1.2		95%	96%	98%	99%	101%	102%	102%	102%	103%	102%	101%
1.1	98%	95%	93%	98[illegible]	[illegible]	[illegible]	[illegible]	102%	102%	103%	103%	
1.0				97%	101%	101%	102%	102%	103%	105%		
0.9					96%	100%	100%	97%	92%	93%		
0.8					94%	96%	94%	96%	89%			
0.7							94%	90%	86%			

Inner Range

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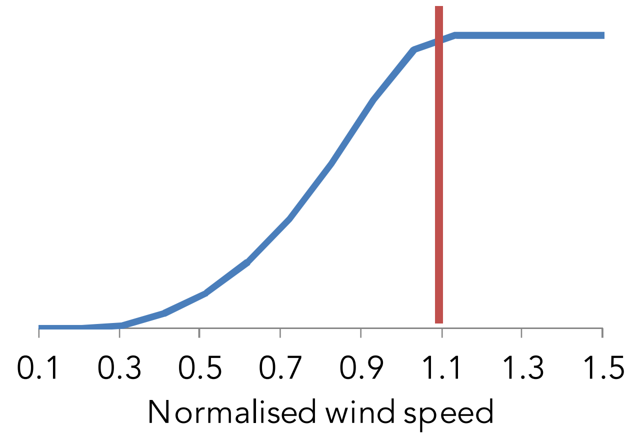
$U_{norm} = 1.1$



Rotor wind speed ratio ↓

Turbulence intensity →

	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%
1.7	91%	90%										
1.6	91%	102%										
1.5	95%	100%	103%									
1.4	99%	100%	102%	100%	100%	101%	101%	98%				
1.3	101%	99%	102%	102%	102%	102%	101%	99%	100%			
1.2	105%		102%	102%	102%	102%	101%	101%	101%	99%	98%	
1.1	106%			[illegible]	[illegible]	[illegible]	[illegible]	100%	100%	101%		
1.0				101%	99%	100%	103%					
0.9					100%	98%						
0.8												
0.7												

Less performance variation at higher wind speeds

Inner Range

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Outcome

- Data shows that Turbulence Intensity, Rotor Wind Speed Ratio and Normalised Wind Speed can be used to define a single universal turbine performance model.
- The results show good consistency, across turbine types, geometries and geographies – model captures physical drivers of turbine performance variations.
- It can be easily applied to normal pre-construction data to predict expected turbine performance levels for any given site.
- It allows higher confidence predictions for new diameters, hub heights and climates.

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Next steps

Several refinements are in progress:

Å Expansion of the source data and conditions ranges.

Å Further investigation of variation *within* bins:
  ï Turbine type (blade geometry, pitch strategy etc)
  ï Constrained operation
  ï Up- and cross-flow
  ï Directional veer
  ï Non-constant shear

Å Link to CFD

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Thank you

- Thanks to data contributors

- Send us your PPT data!
  - Operators, we’ll send you free results in exchange for your data.
  - Manufacturers, we’d welcome engagement.

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