Presentation of Power Curve Uncertainty to PCWG

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[29 April 2015, Frank Ormel, Certification and Operatinal Readiness]

Presentation Outline

- A quick reminder: Informative vs. Normative
- Overview of key updates (proposed) to IEC61400-12-1 standard:
    - New wind speed definition, New power curve definition, Normative Uncertainty Annex
- Shear/Veer/TI assumed distributions, modelled AEP results; further issues to be addressed
- Shear/Veer/TI assumed distributions, modelled AEP results; further issues to be addressed
- Treatment of power curve uncertainty
- Multiple turbine testing
- Uncertainty Analysis Tools

Quick Reminder: Informative vs Normative

A quick reminder on terminology

- **Informative Annex:** methodology defined for information only or information supporting/explaining normative sections of standard i.e. **it does not have to be followed in order to comply with the standard**

- **Normative Annex:** methodology is defined as an essential component of the standard i.e. **it must to be followed in order to comply with the standard**

Overview of key changes (proposed) to IEC61400-12-1 standard

The new version of the IEC 61400-12-1 contains the following key changes*:

- **New wind speed definition**
  - Rotor Equivalent Wind Speed & HubHeight wind speed
- **New power curve definition:**
  - Power curved defined using new wind speed definition (Shear / Veer Treatment)
  - Turbulence Intensity treatment
- **Normative Uncertainty Calculations**
  - More guidance; missing uncertainty components added

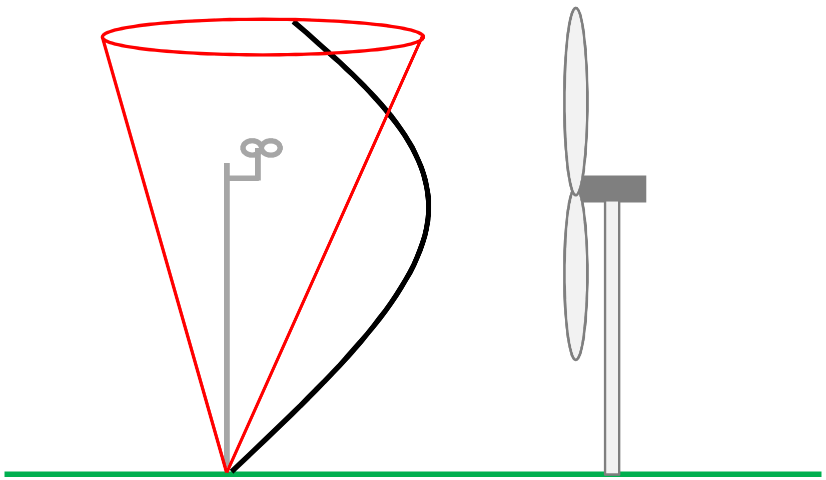
**This is an overview of ongoing work in the IEC 61400-12-1 maintenance team and therefore subject to change. Expectation is a CDV summer 2015, FDIS early 2016 and IS summer 2016.*

Key Updates: New Wind Speed Definition

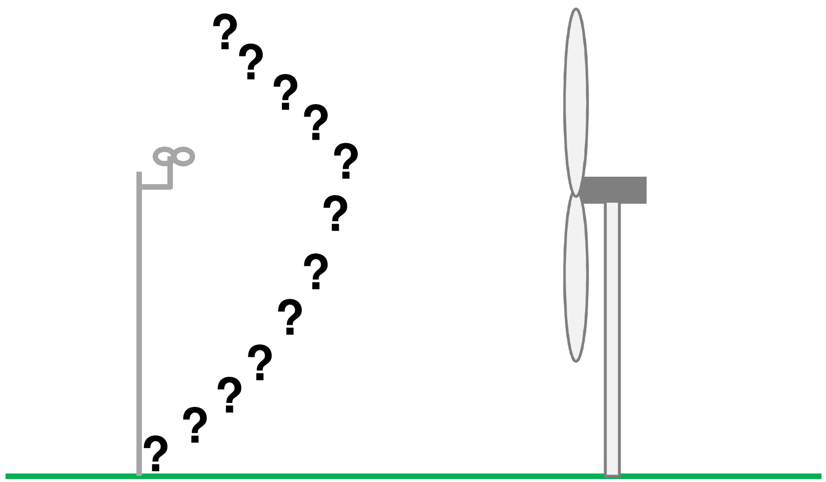
The new draft standard defines an energy equivalent wind speed

$$V_{eq} = \left(\frac{1}{A}\int_i (V_i \cos(\varphi_i - \varphi_{hub}))^3 \, dA_i\right)^{1/3}$$

If vertical wind shear and veer are not measured over the full height of the rotor there is added uncertainty in the equivalent wind speed.



Rotor Measurements



Hub Measurement

Key Updates: New Power Curve Definition

The power curve is dependent on:

- The **hardware** of the turbine
- The **software** of the turbine
- The **climatic conditions** experienced by the turbine:
    - Wind Speed/Density
    - Shear (vertical wind speed variation)
    - Veer (vertical wind direction variation)
    - Turbulence Intensity

The power curve in the new standard is defined using the new wind speed definition (energy equivalent wind speed)

$$V_{eq} = \left(\frac{1}{A}\int_i (V_i \cos(\varphi_i - \varphi_{hub}))^3 dA_i\right)^{1/3}$$

New Wind Speed Definition

The new standard also incorporates a treatment for turbulence intensity (Annex M)

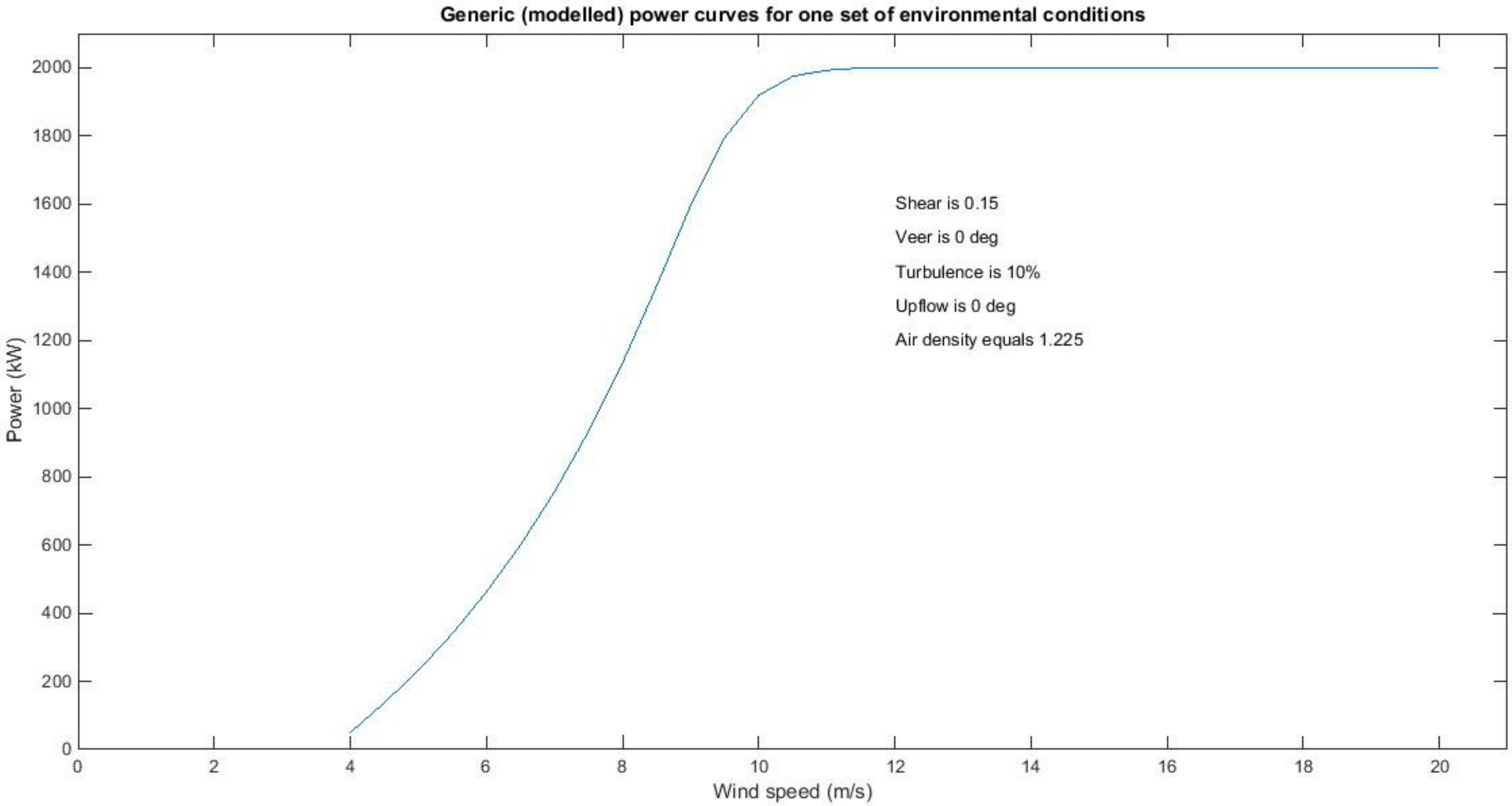
Overview of Climate Specific Power Curve

The power curve (according to the draft standard) is a climate specific power curve where:

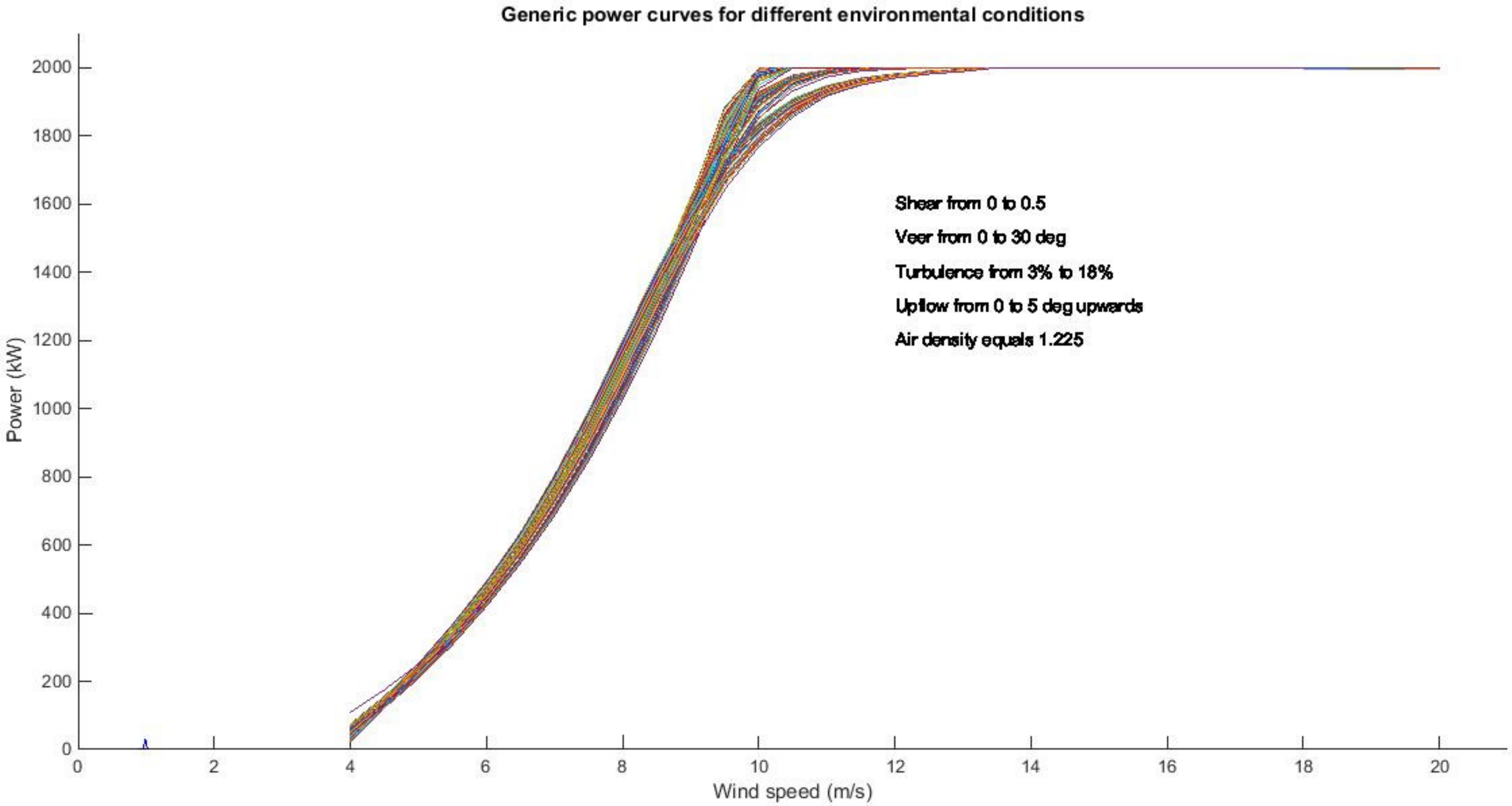
- The wind speed of the power curve is defined as the equivalent wind speed.
- Air density is measured at hub height and the power curve is normalized to the site average density during the measurement period.
- Turbulence is measured at hub height and the power curve is presented without a turbulence normalization.
- The power curve can be normalised to a broader range of climatic conditions (e.g. specific air density, turbulence intensity, vertical shear and veer)*.

* The power curve normalization is only valid for limited ranges of the climatic conditions from the actual site conditions.

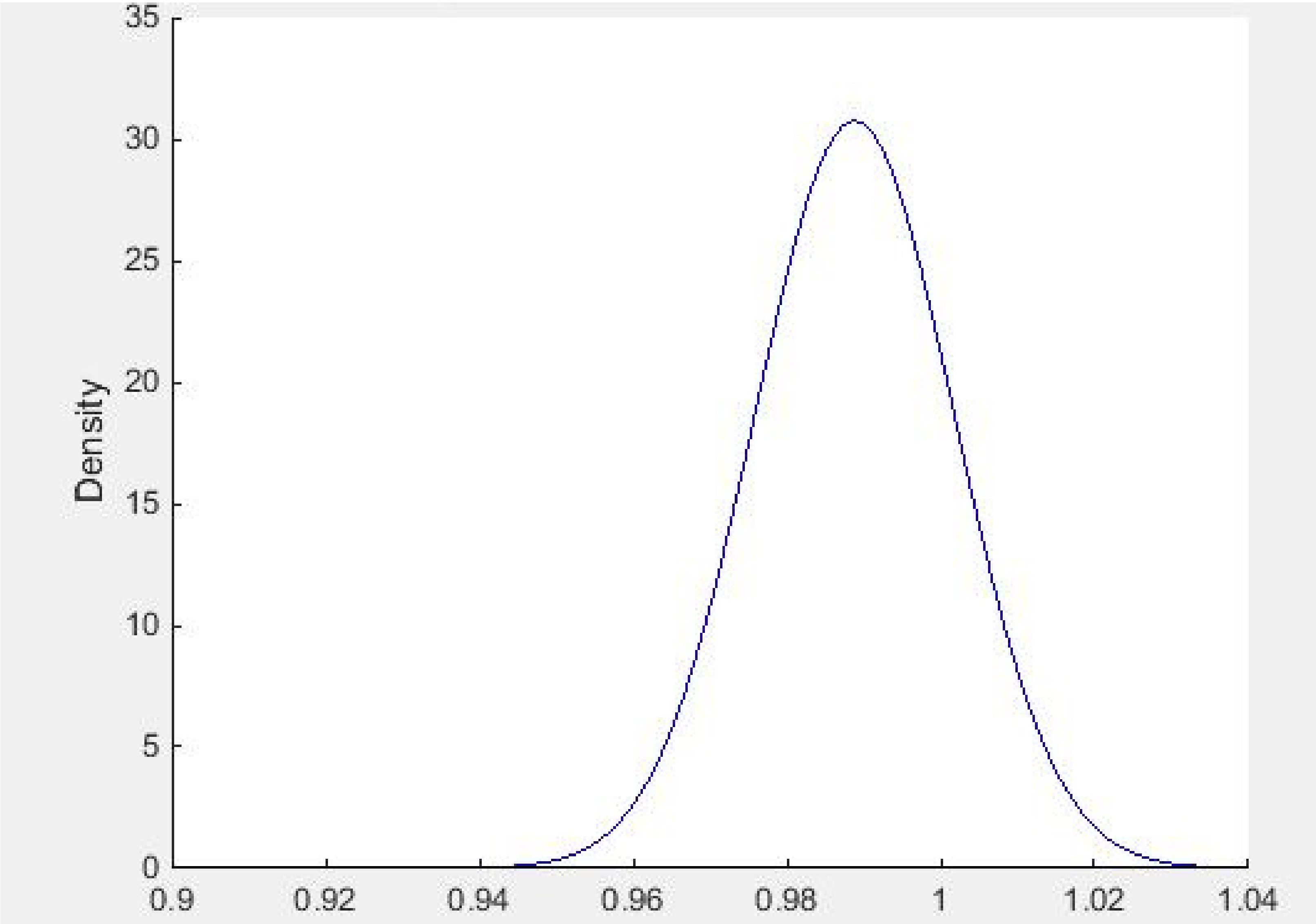
Power Curve definition (new)



Power Curve definition (new)



Power Curve definition (new)



Modelled results

Current assumptions used to derive default magnitude of uncertainty terms for turbulence, shear, veer and upflow:

	Min	Mean	Max
Turbulence	3%	10%	18%
Shear	0	0.1	0.5
Veer	0	10 deg	30 deg
Upflow	0	2 deg	5 deg

Some Issues:

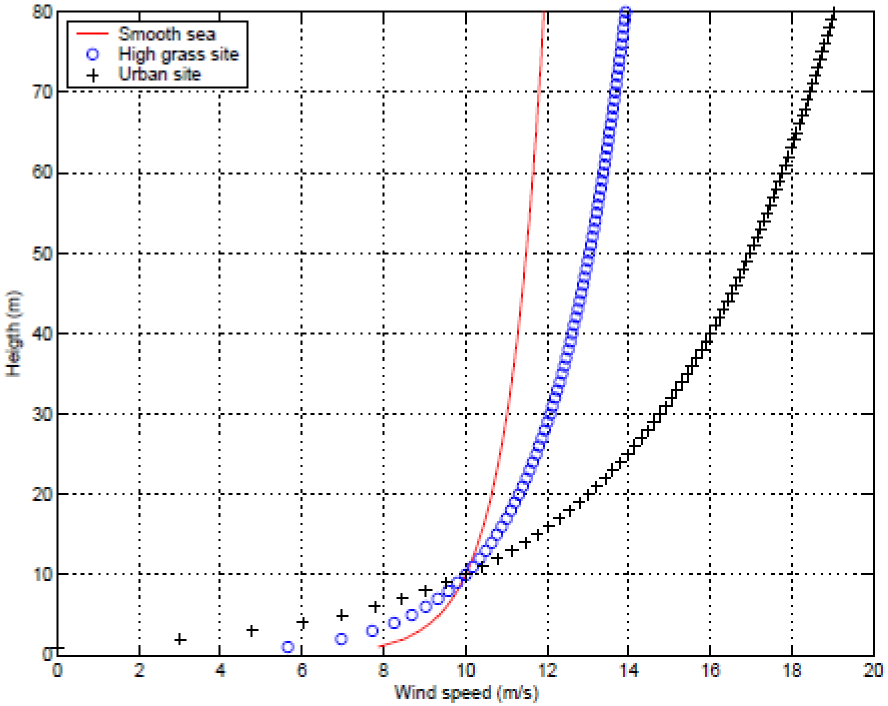
- Correlation between turbulence and shear/veer
- Pitch/yaw time constant to be included in the definition of turbulence (de-trending)
- Non roughness shear often does not follow power law (stability, low level jets, katabatic winds

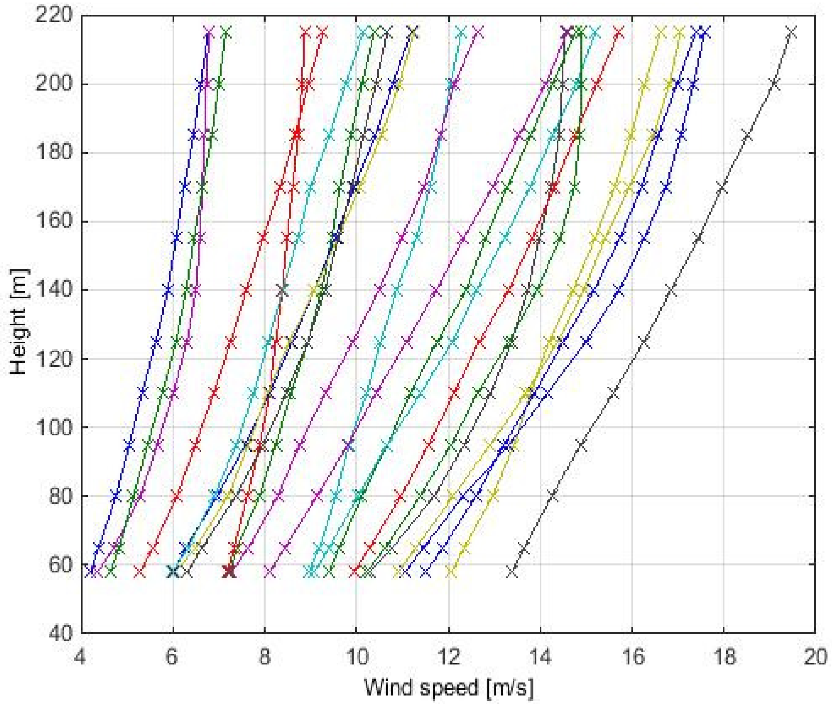
What is the AEP Impact of the Climate Variables?

AEP change (generic turbine model values)	Shear	Veer	TI	Upflow
0.0% (baseline)	Baseline	Baseline	Baseline	Baseline
0.1%	Baseline	Baseline	Baseline	Specific
0.1%	Baseline	Baseline	Specific	Baseline
2.1%	Baseline	Specific	Baseline	Baseline
0.1%	Baseline	Baseline	Specific	Specific
2.1%	Baseline	Specific	Specific	Baseline
2.5%	Specific	Specific	Baseline	Baseline
2.3%	Baseline	Specific	Baseline	Specific
2.6%	Specific	Specific	Specific	Baseline
2.9%	Specific	Specific	Baseline	Specific
2.3%	Baseline	Specific	Specific	Specific
2.9%	Specific	Specific	Specific	Specific

Up to 2.9% change in AEP due to climatic variables

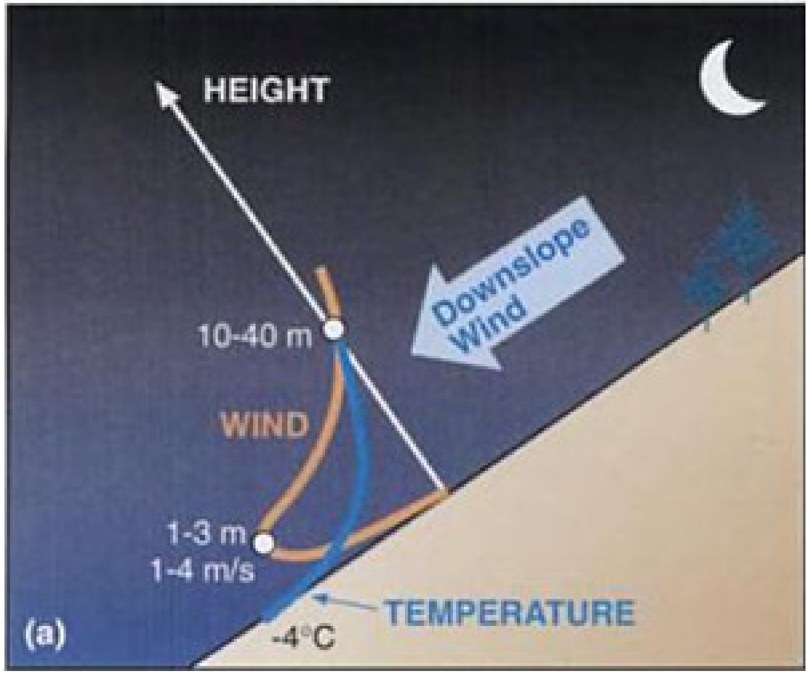
Shear

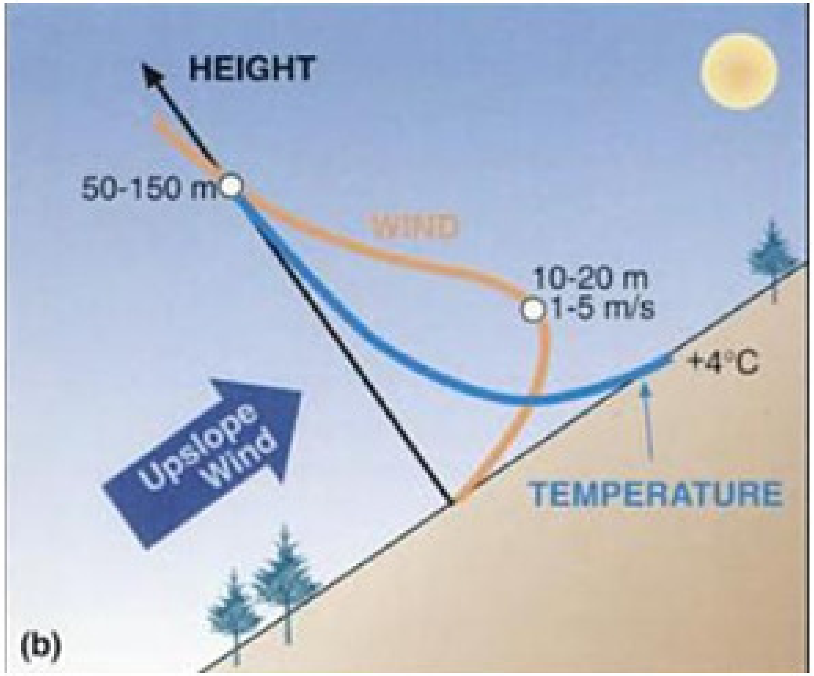




Wind Shear (Variation of Wind Speed with Height)

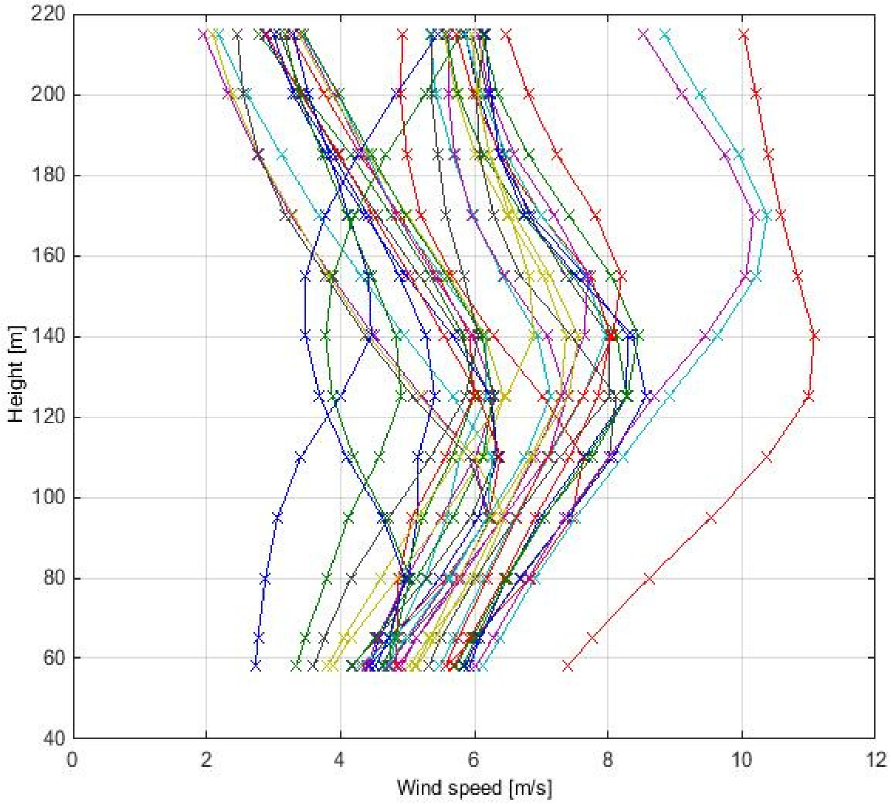
Power curve in complex flow

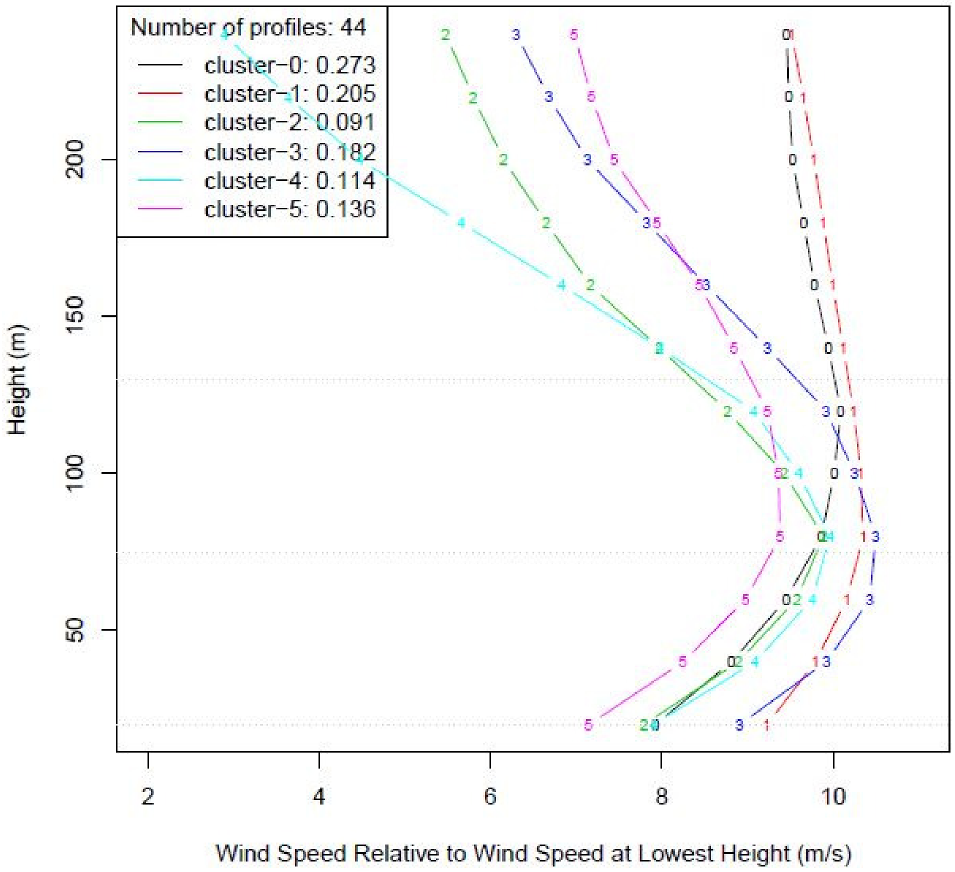




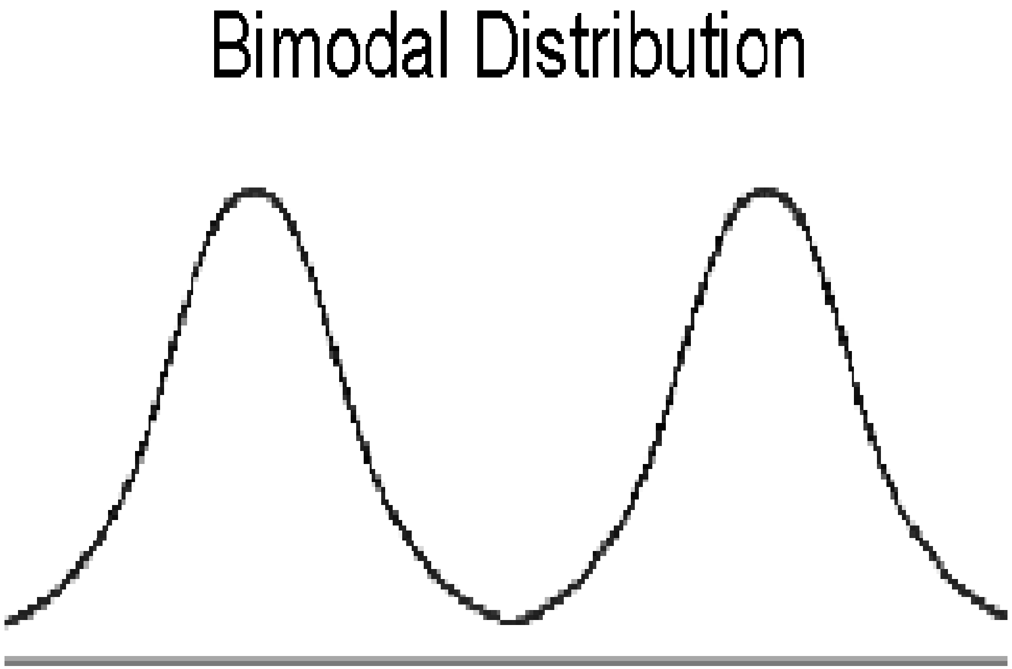
- Wind direction turns 180 degrees between day/night
- Not due to ‘standard’ low level jets (atmosperic stability)
- Very low / no mesoscale winds
- If peak flow reaches hub height, our turbines produce 27% less energy
- High turbine to turbinevariability expected due to terrain complexity / ridges

Complex shear

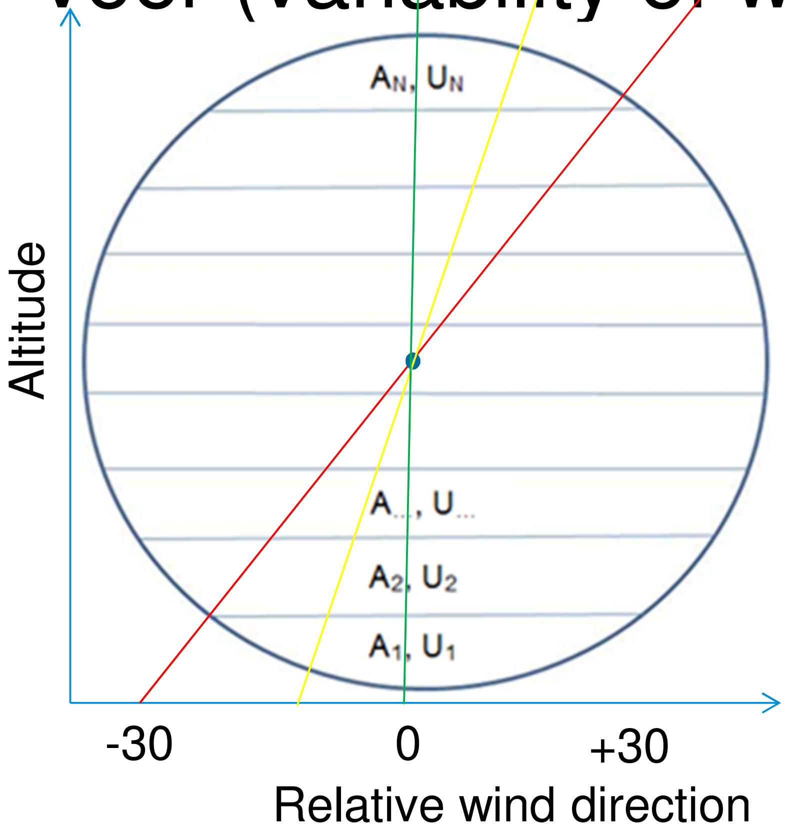


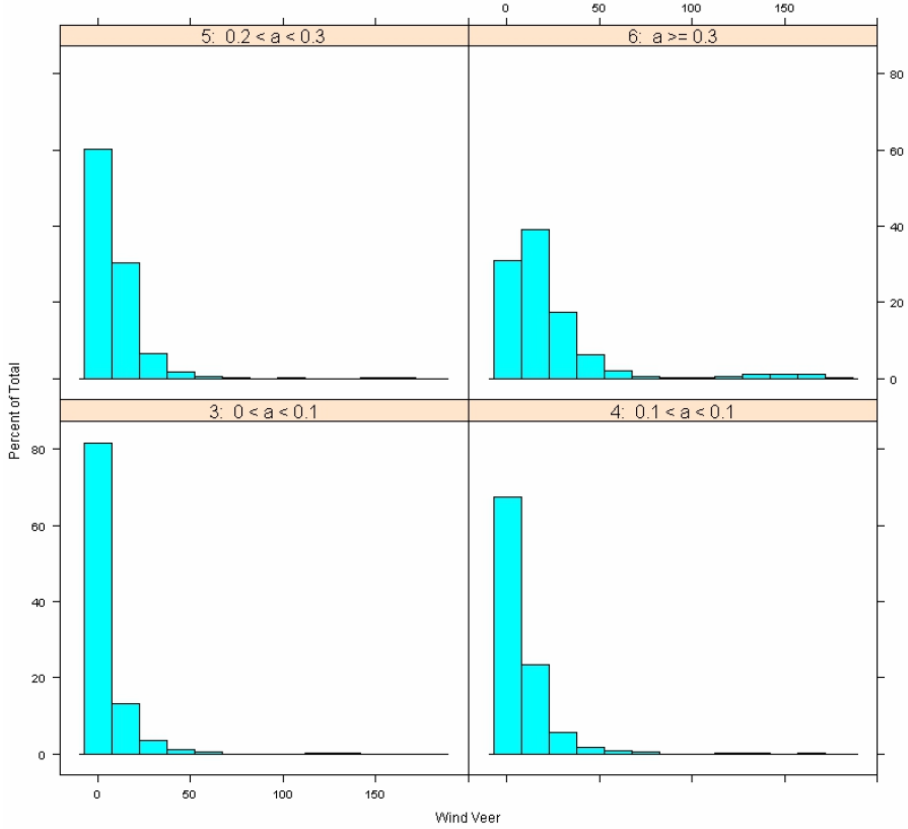


Shear distribution

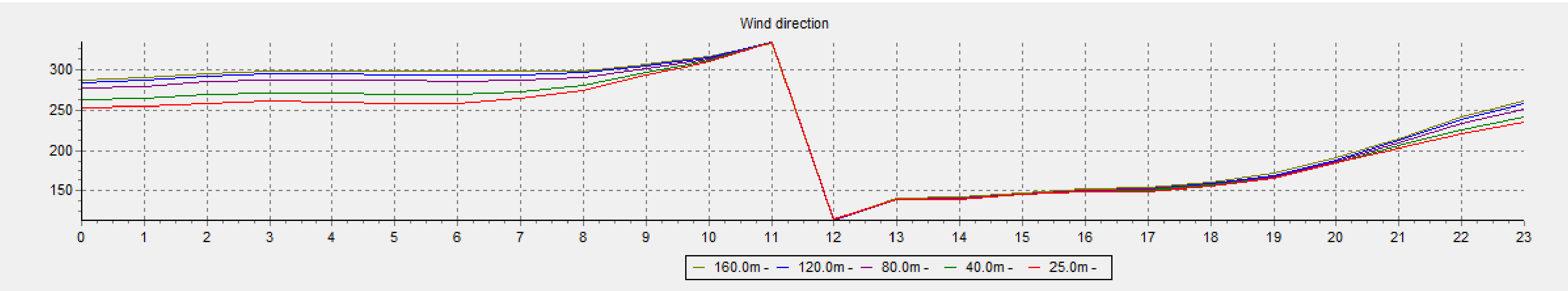


Veer (variability of wind direction with height)





Barlovento data



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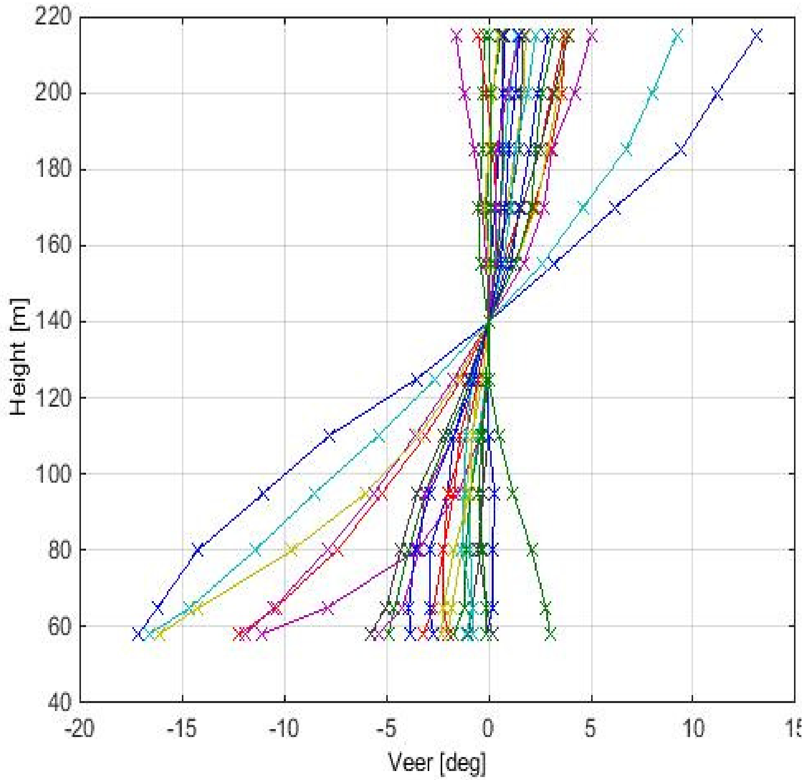
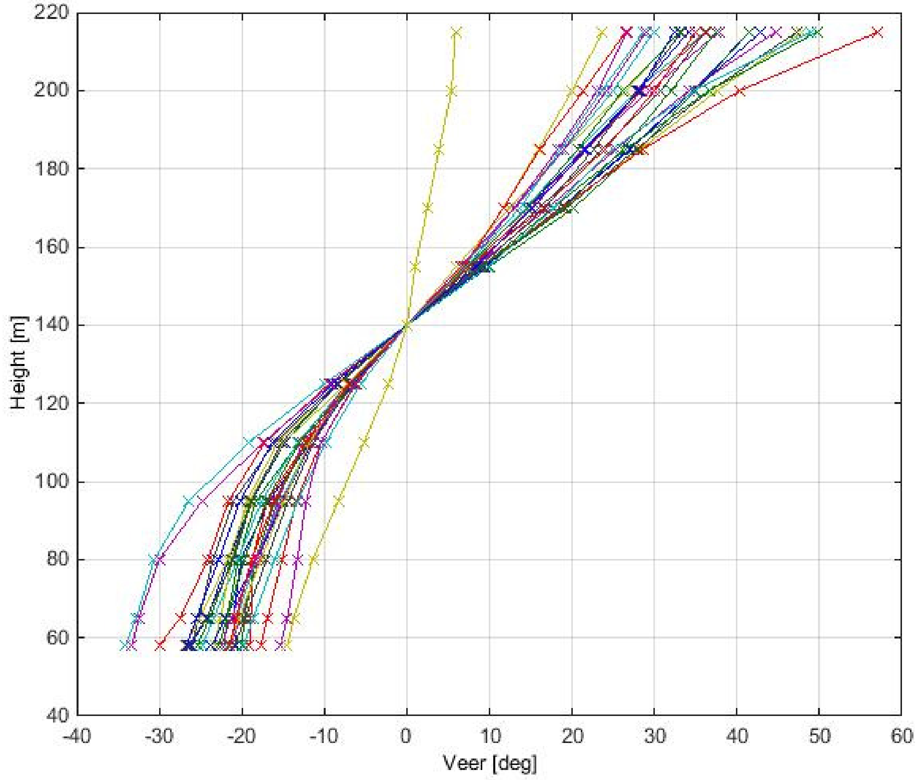
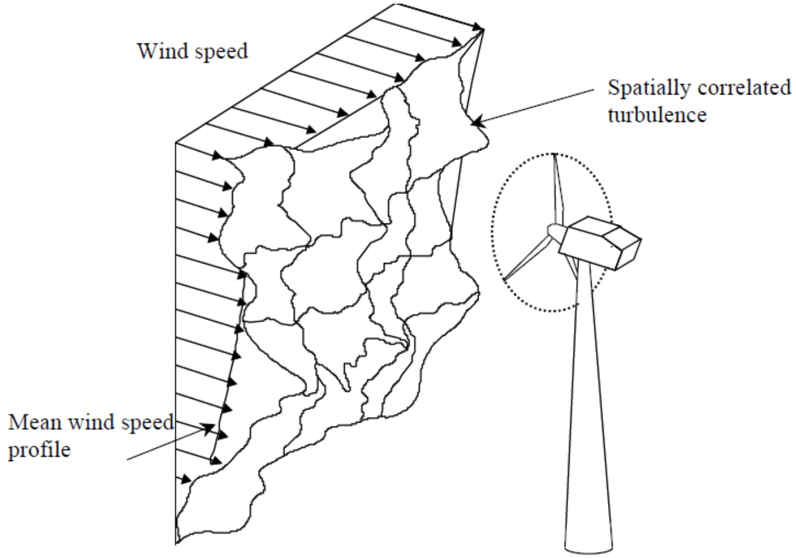
Measured Veer

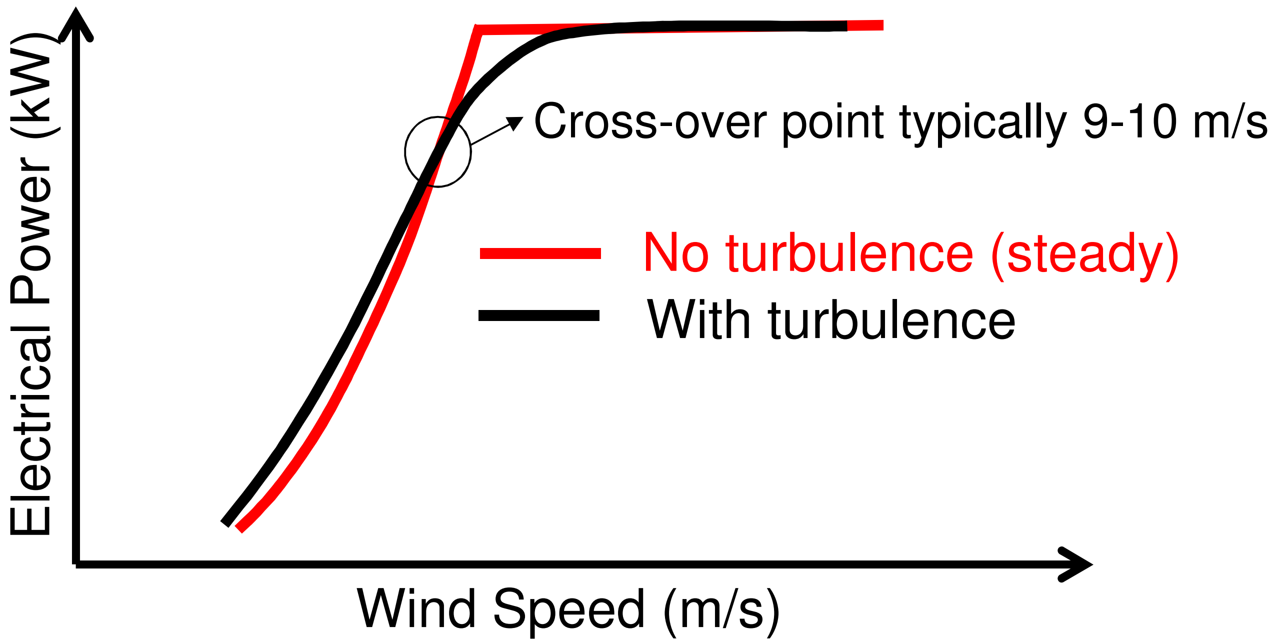




Turbulence



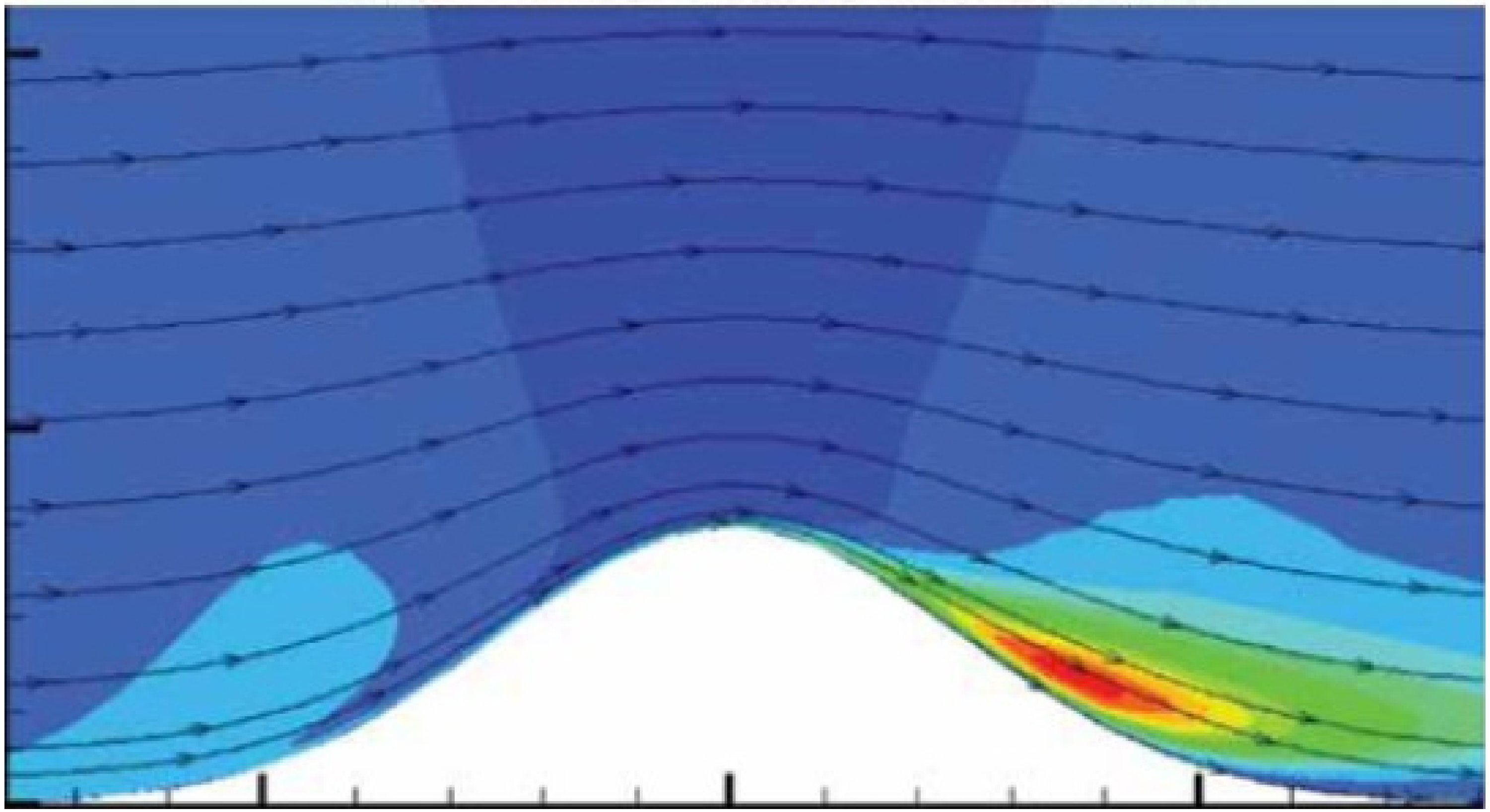
- The turbulence effect is largely due to the 10 min averaging required by the standard...
- ...but there is a ‘real’ effect in that the turbine cannot achieve its optimal setpoint before the wind speed has changed again.



Upflow

Upflow is the vertical component of the wind vector. As a rule of thumb this is 2/3 of the terrain slope right in front of the turbine.

- **Wind Speed:** The influence of the upflow on the wind speed measurement is convered by the classification of the anemometer.



Informative uncertainty annex (Annex E)

Key Principles

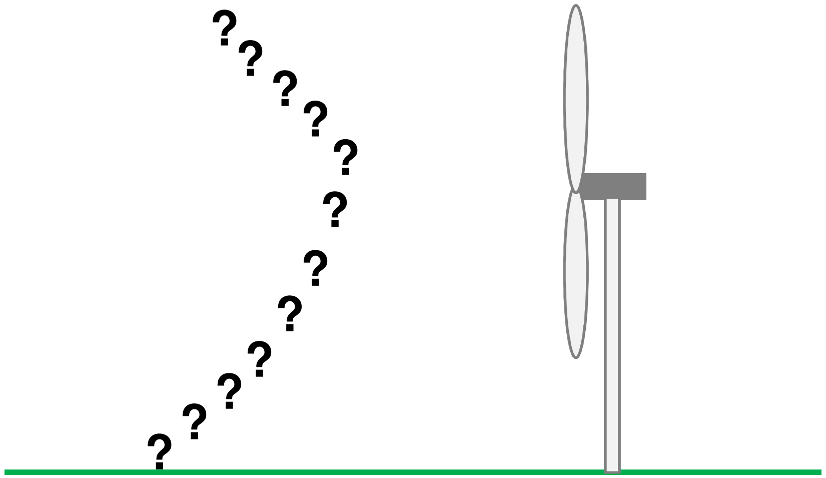
- All uncertainty components have a default range defined
- If further data is available, this may be used instead of the default values
- Influence of shear/veer/TI included
- New power curve and wind speed definition included
- Missing uncertainty components added (dynamic power measurement, seasonal variation)

Uncertainty in Wind Conditions in Swept Area: Shear

- Uncertainty due to **limited number** of wind speed measurements in swept area.

or

- Uncertainty due to wind shear in the **absence** of a wind shear measurement



Heights	Magnitude [%]
2 (lower shear only)	2.9%
3	1.2%
5	1.8%
7	1.3%

(default magnitudes)

H [m]	D [m]	Magnitude [%]
60	60	3.0%
60	80	3.9%
100	80	2.4%
120	80	2.0%
100	120	3.5%
150	120	2.4%

(default magnitudes)

Uncertainty in Wind Conditions in Swept Area: Veer

- Uncertainty due to **limited number** of wind direction measurements in swept area.

or

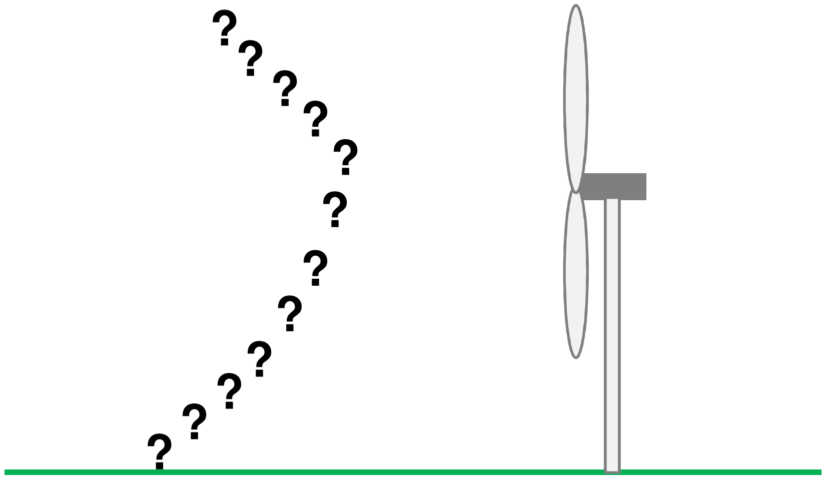
- Uncertainty due to wind veer in the **absence** of a wind direction measurement

Heights	Magnitude [%]
3	1.5%
5	1.25%
7	0.9%

(default magnitudes)

D [m]	Magnitude [%]
20	0.04%
40	0.1%
60	0.3%
80	0.6%
100	0.9%
…	…
200	3.2%

(default magnitudes)



Uncertainty: Turbulence Measurement

- Apply turbulence correction (Annex M) and calculate uncertainty in correction.

or

- Calculate uncertainty in absence of turbulence correction (see Annex M)

or

- Assume uncertainty

Heights	Magnitude [%]
0 (no accurate TI due to RSD)	2.0%
1 (hub height only)	1.75%
2 (lower rotor)	1.65%
3	1.51%
5	1.25%
7	0.9%
9	None

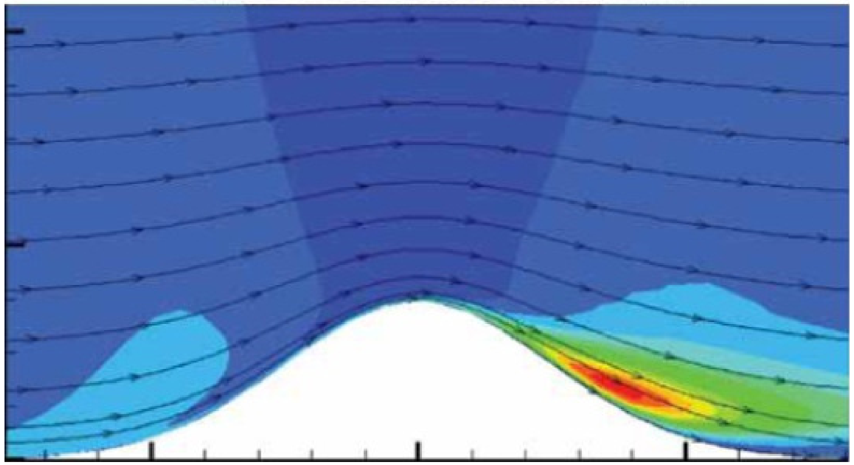
Uncertainty in Wind Conditions in Swept Area: Upflow Measurement

Upflow is the wind vector including the vertical component. As a rule of thumb this is 2/3 of the terrain slope right in front of the turbine.

- **Wind Speed:** The influence of the upflow on the wind speed measurement is convered by the classification of the anemometer.

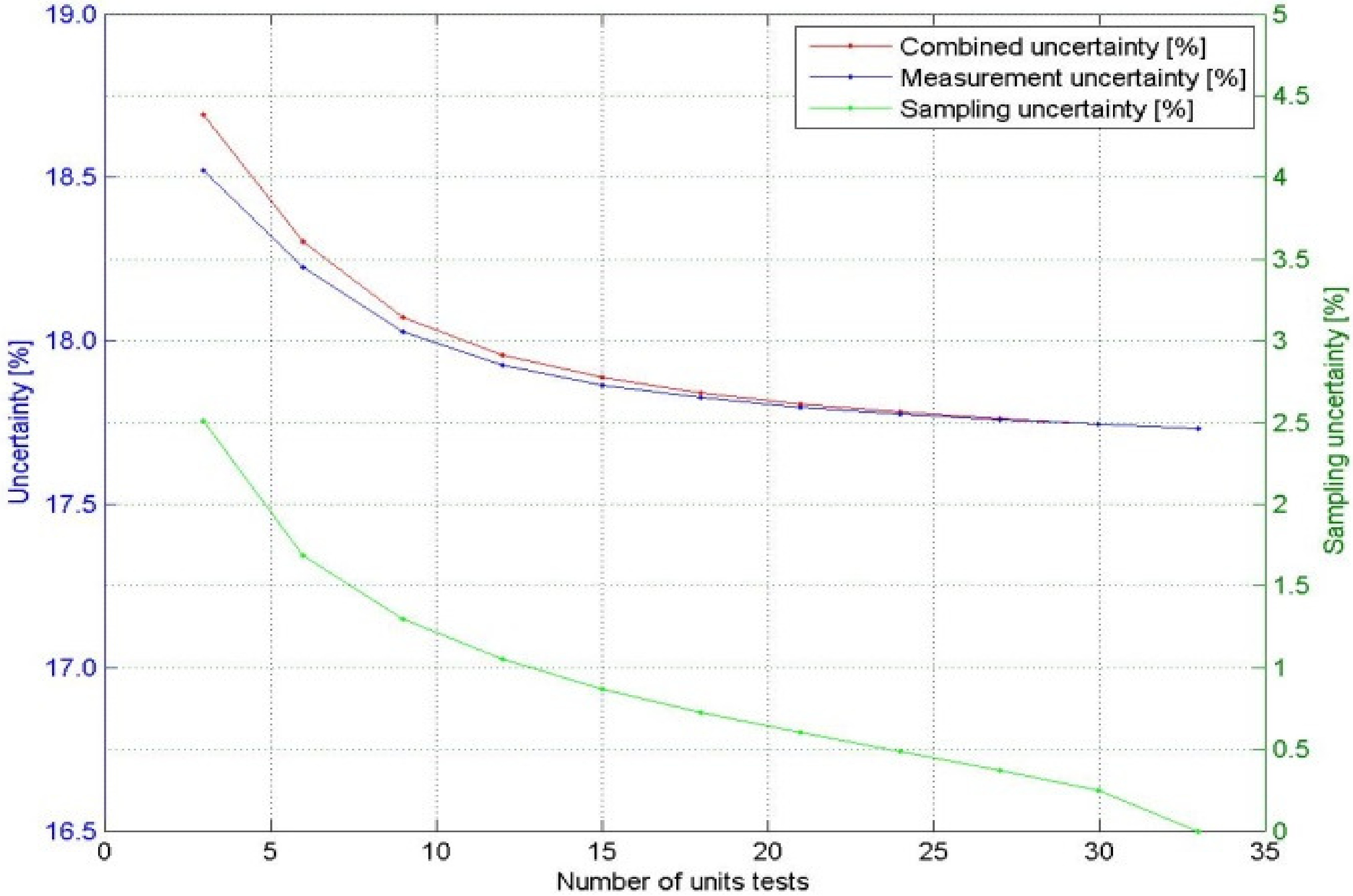
- **Wind Turbine**: The influence of upflow at the wind turbine is defined by the following uncertainties:

Heights	Magnitude [%]
0 (no measurement)	2.35%
1 (hub height only)	1.75%
2 (lower rotor)	1.65%
3	1.5%
5	1.25%
7	0.9%

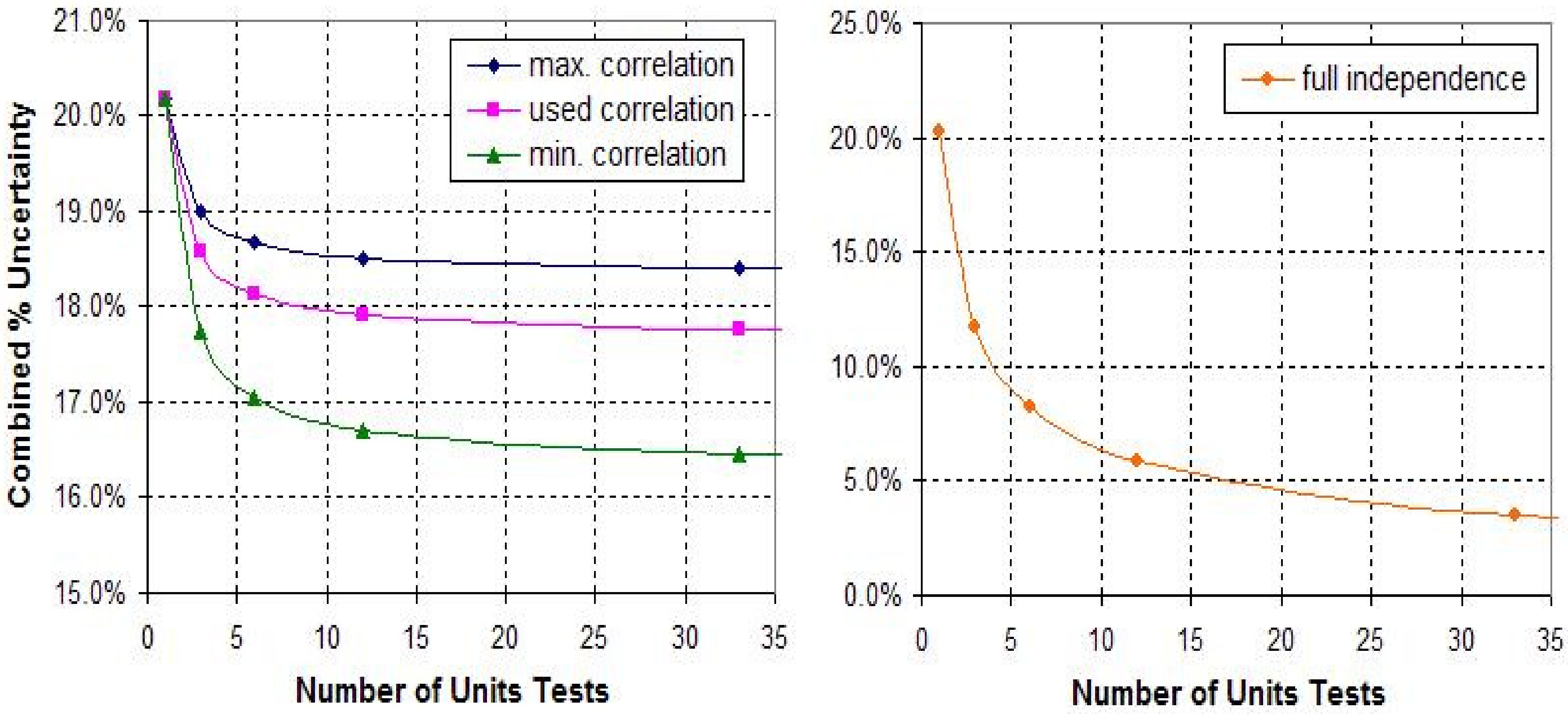


Remember that the turbine influences the upwind flow, including off-axis flow.

Multiple turbine testing – Annex R

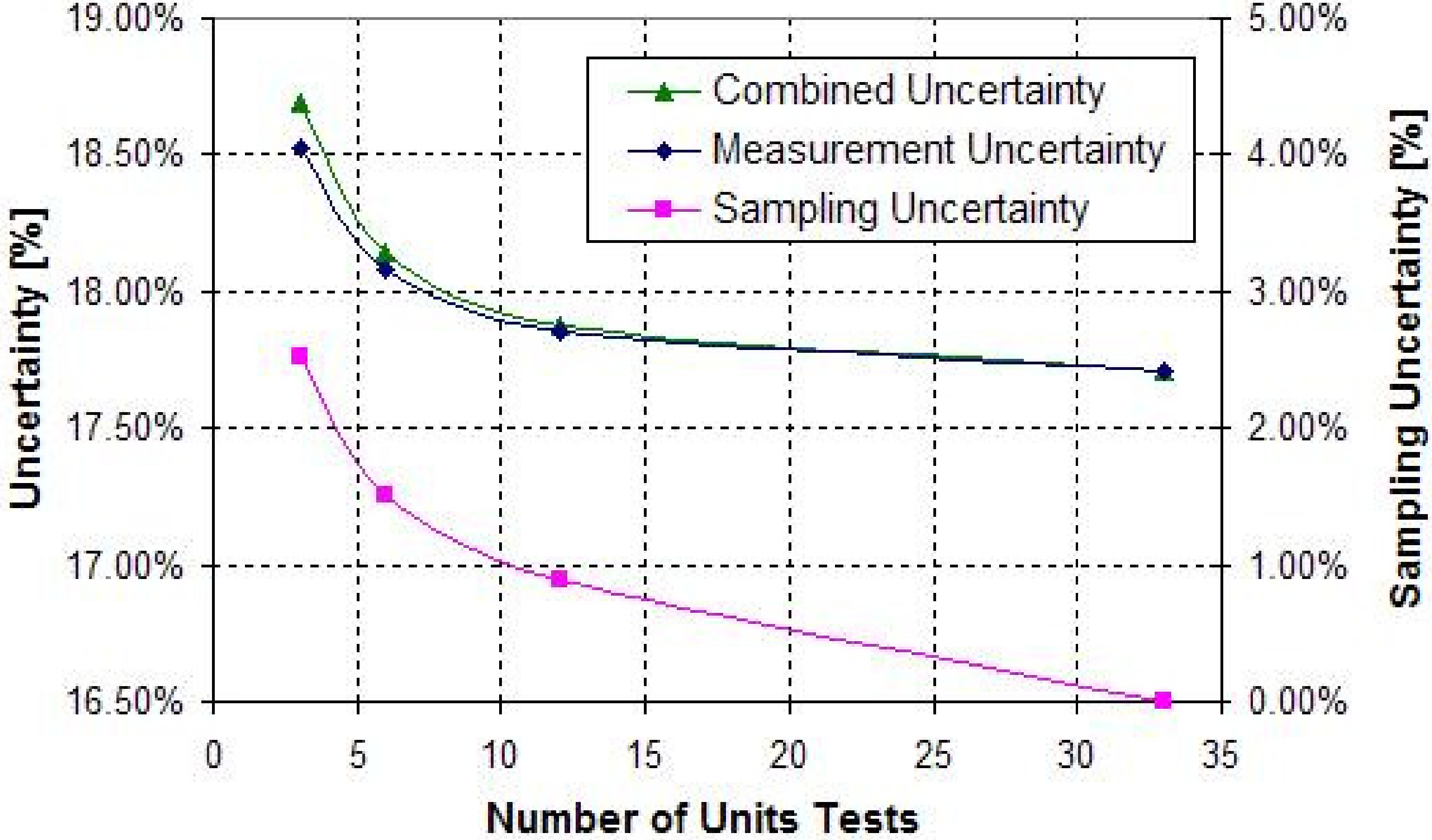


Multiple turbine testing (-12-2)



Min corr = 93%; mean corr = 96%; max corr = 96.5%

Multiple turbine testing (-12-2)



Climatic Variables: Work left to do!

- (As stated previously) the power curve is dependent on the following climatic variables:

  - Shear & veer
  - Turbulence.

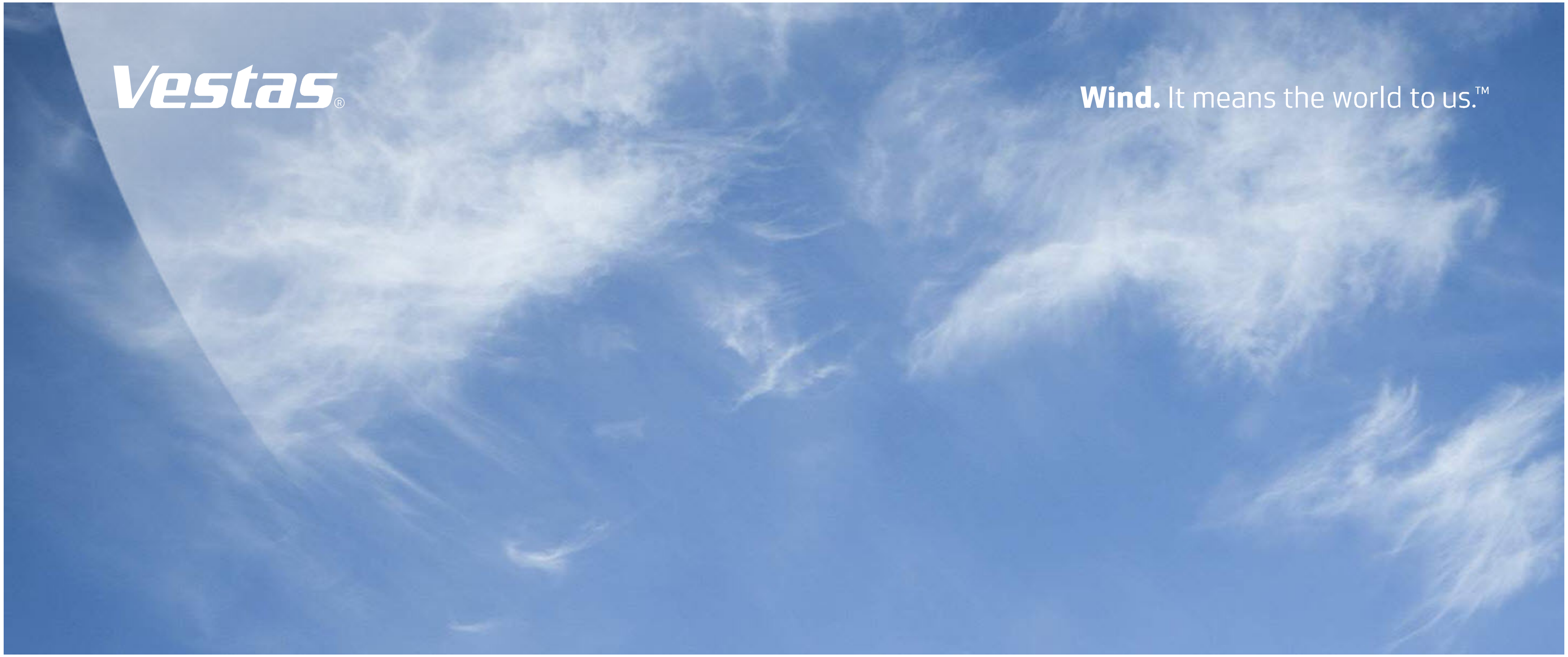
- Further issues to be address include:
  - **Better tools to characterise these variables in the field**
  - **Establish 'default' distributions for these variables**
  - **Match field data and power curve models**
  - **Agree on AEP influences for classes of these variables**

  Current work is ongoing (including through the PCWG).

Uncertainty Tools

- A spreadsheet implementation of the uncertainty methodology defined in the standard has been developed

- The PCWG have committed to implementing the uncertainty methodology defined in the standard in the PCWG Open Source code base for power performance.



Thank you for your attention

Quick Reminder: Category A vs Category B

A quick reminder on terminology

- **Category A Uncertainty:** The magnitude of uncertainty can be determined from measurements.

- **Category B Uncertainty :** The magnitude of uncertainty is determined from other means.

Terminology from ISO/IEC Guide 98-3:2008,
“Uncertainty of Measurement – Part 3”.

Normative Uncertainty Annex II: List of Components (1)

	Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude
	Power output		$u_{P,i}$	$c_{P,i} = 1$	
	Current transformers	a	$u_{P,CT,i}$		0.75%
	Voltage transformers	a	$u_{P,VT,i}$		0.5%
	Power transducer or power measurement device	a	$u_{P,PT,i}$		0.5%
	Dynamic power measurement	d	$u_{P,dyn,i}$		0.1%
	DAQ**	d	$u_{dP,i}$		0.1%
	Wind speed		$u_{V,i}$		
	Wind speed (cup or sonic)		$u_{VS,i}$		
	Calibration	b	$u_{VS,precal,i}$	$c_{V,i} \approx \left\lvert \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right\rvert$	0.07 m/s
measurement	Post calibration / In situ	b	$u_{VS,postcal,i}$		0.1 m/s
	Classification	c	$u_{VS,class,i}$	For last bin use: $c_{V,i} \approx \frac{P_i - P_{i-1}}{V_i - V_{i-1}}$	1.0%
	Mounting effects				
	Standard mounting	d	$u_{VS,mnt,std,i}$		1.0%
	Alternative mounting	d	$u_{VS,mnt,alt,i}$		1.2%
	Side mounted	d	$u_{VS,mnt,side,i}$		1.5%
	Lightning final	d	$u_{VS,lgt,i}$		1.0%
	Mast Flow Distortion Correction	d	$u_{VS,MFDC,i}$		0.1%
	DAQ**				

Normative Uncertainty Annex II: List of Components (2)

	Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude	Source of Magnitude
measurement	**Wind speed RSD**	g	$u_{VR,i}$	$c_{V,i}$ (see above)		
	Verification	cb	$u_{VRvrf,i}$		0.2 m/s	guestimation
	Classification	c	$u_{VRcls,i}$		1.0%	guestimation
	Mounting	g	$u_{VRmnt,i}$		1.0%	guestimation (current standard)
	Flow variation in different probe volumes at same height	c	$u_{VRflw,i}$		1°,-1°	guestimation
	Monitoring test	c	$u_{VRmon,i}$		-	
	DAQ**	c	$u_{dVR,i}$		0.1%	guestimation (current standard)
	Wind direction Vane	g	$u_{WV,i}$			
	Calibration	b	$u_{WVcal,i}$			
	Orientation (of boom)	c	$u_{WVor,i}$			
	Operation (influence of mast)	d	$u_{WVop,i}$			
	Mounting (north mark setting)	c	$u_{WVmnt,i}$			
	magnetic declination angle	c	$u_{WVmag,i}$			
	DAQ**	c	$u_{dWV,i}$			
	Wind direction RSD	g	$u_{WR,i}$			
	Verification	ab	$u_{WRvrf,i}$			
	Classification	c	$u_{WRcls,i}$			
	Monitoring test	c	$u_{WRmon,i}$			
	Flow variation in different probe volumes at same height	c	$u_{WRflw,i}$			
	Mounting	d	$u_{WRmnt,i}$			
	magnatic declination angle	c	$u_{WRmag,i}$			
	DAQ**	c	$u_{dRW,i}$			

Normative Uncertainty Annex II: List of Components (3)

	Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude	Source of Magnitude
	Air density					
	Temperature		$u_{T,i}$	$c_{T,i} \approx \frac{P_i}{288{,}15\text{K}}$		guestimation (current standard)
	Temperature sensor	ab	$u_{Tsen,i}$		0.5K	
	Radiation shielding	cd	$u_{Tshld,i}$	$c_{B,i} \approx \frac{P_i}{1013\,\text{hPa}}$	2 K	
	Mounting effects	cd	$u_{Tmnt,i}$		0.33K	
	DAQ**	c	$u_{dT,i} u_{B,i}$		0.1%	
	Air pressure			$c_{RH,i} \approx \frac{P_i}{100\%}$		guestimation (current standard)
	Pressure sensor	ab	$u_{Bsen,i}$		3 hPa	
	Mounting effects	a	$u_{Bmnt,i}$		-	
	DAQ**	c	$u_{dB,i}$		0.1%	
	Relative Humidity		$u_{RH,i}$			
	Humidity sensor	ab	$u_{RHsen,i}$		0.02	guestimation
	Mounting effects	cd	$u_{RHmnt,i}$		0.1	
	DAQ**	c	$u_{dRH,i}$		0.1%	
	Data acquisition system		$u_{d,i}$	Sensitivity factor is derived from actual uncertainty parameter	0.1%	guestimation (current standard)
	Signal transmission	b	$u_{d1,i}$			
	System accuracy	cd	$u_{d2,i}$			
	Signal conditioning	b	$u_{d3,i}$			
	Category B: Terrain					
	Flow distortion due to terrain with site calibration	c	$u_{VTerrSC,i}$	$c_{V,i}$ (see above)	-	
	Flow distortion due to terrain without site calibration	d	$u_{VTerr,i}$		2%,3%	guestimation (current standard)

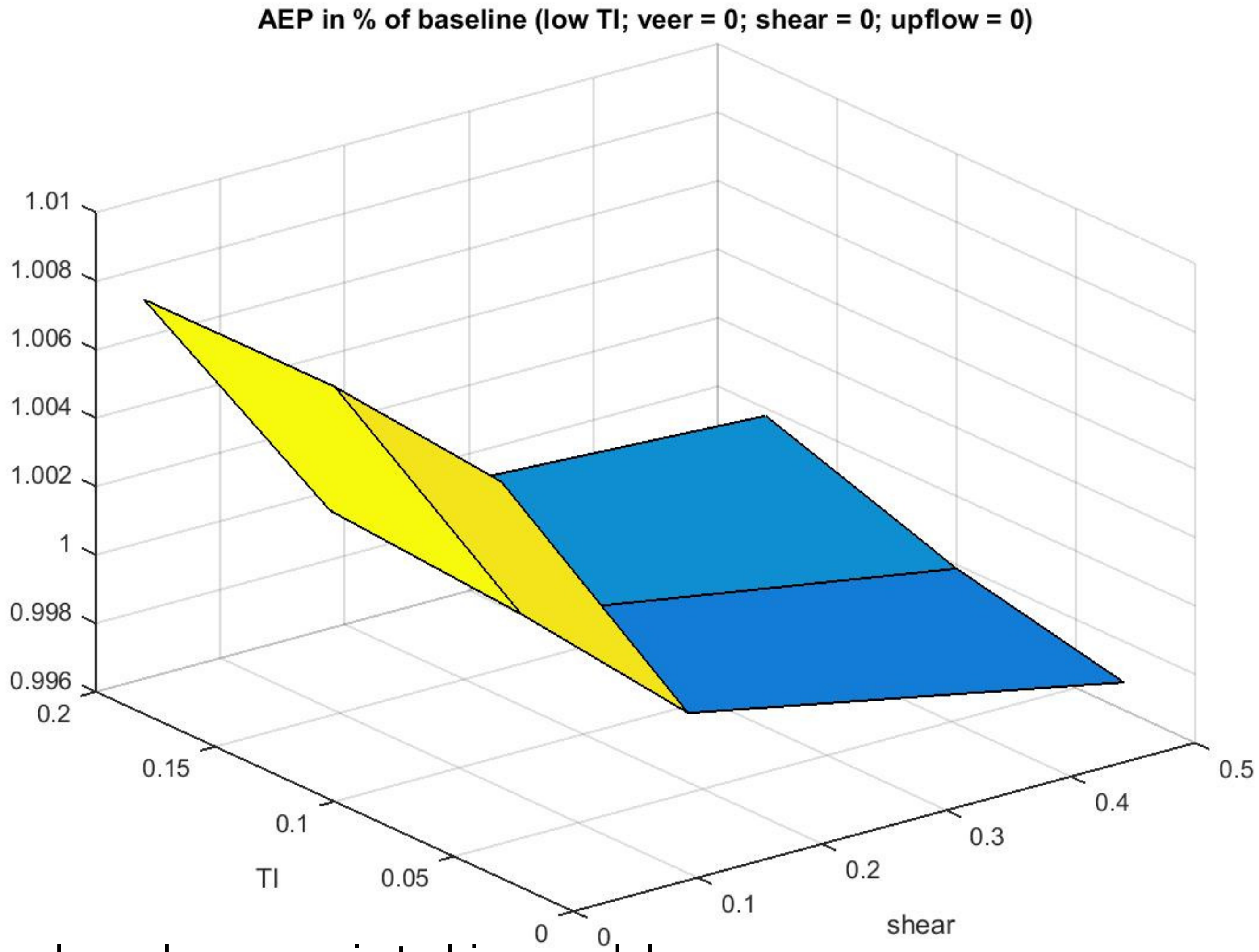
Normative Uncertainty Annex II: List of Components (4)

	Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude	Source of Magnitude
	Category B: Wind conditions in swept area					
	shear measurement veer measurement upflow measurement turbulence measurement	cd cd cd cd	$u_{WCshr,i}$ $u_{WCvr,i}$ $u_{WCupflw,i}$ $u_{WCtl,i}$	$c_{V,i}$ (see above)	see tables in E.5.9	guestimation
	Category B: Method					
	Method Air density correction mast flow distortion seasonal effects Turbulence Normalisation (or lack of turbulence normalisation) shear normalisation (or lack of shear normalisation) cold climate Covergence check Correlation check for linear regression Change of correction (adjacent wind direction bins) Removal of wind direction sensor between site calibration and power curve measurement different seasons	 cd cd cd cd cd cd cf cf cf cf cf	$u_{M,i}$ $u_{Mden,i}$ $u_{Mmfd,i}$ $u_{Msfx,i}$ $u_{Mtl,norm,i}$ ($u_{Mtl,i}$) $u_{Mshr,norm,i}$ ($u_{Mshr,i}$) $u_{Mcc,i}$ $u_{MSCcc,i}$ $u_{MSCcorr,i}$ $u_{MSCcoc,i}$ $u_{MSCrmv,i}$ $u_{MSCds,i}$	$c_{Mden,i}$ = 1 $c_{V,i}$ (see above) $c_{V,i}$ (see above) $c_{Mtl,i}$ = 1 $c_{Mshr,i}$ = 1 Sensitivity factor is derived from actual uncertainty parameter	- ? ? - - ? 0 0 - - -	

Normative Uncertainty Annex II: List of Components (5)

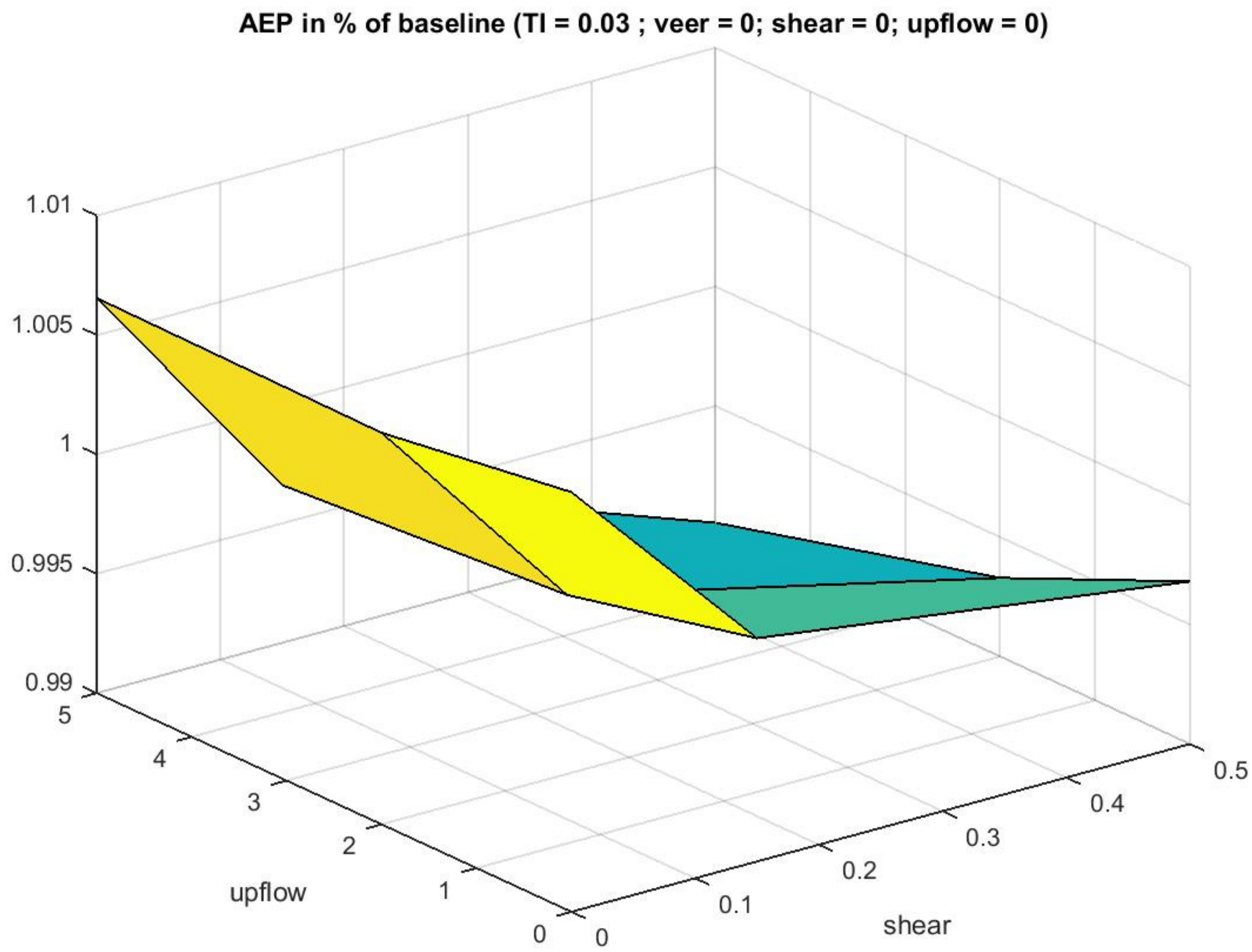
	Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude	Source of Magnitude
	Category A: Statistical					
	Electric power	e	$s_{P,i}$	$c_{P,i} = 1$		
	Climatic variations	e	s_{CV}		1%	guestimation
	Site Calibration	e	s_{sc}	$c_{V,i}$ (see above)	0.05 m/s	guestimation

Climate influence – shear vs TI



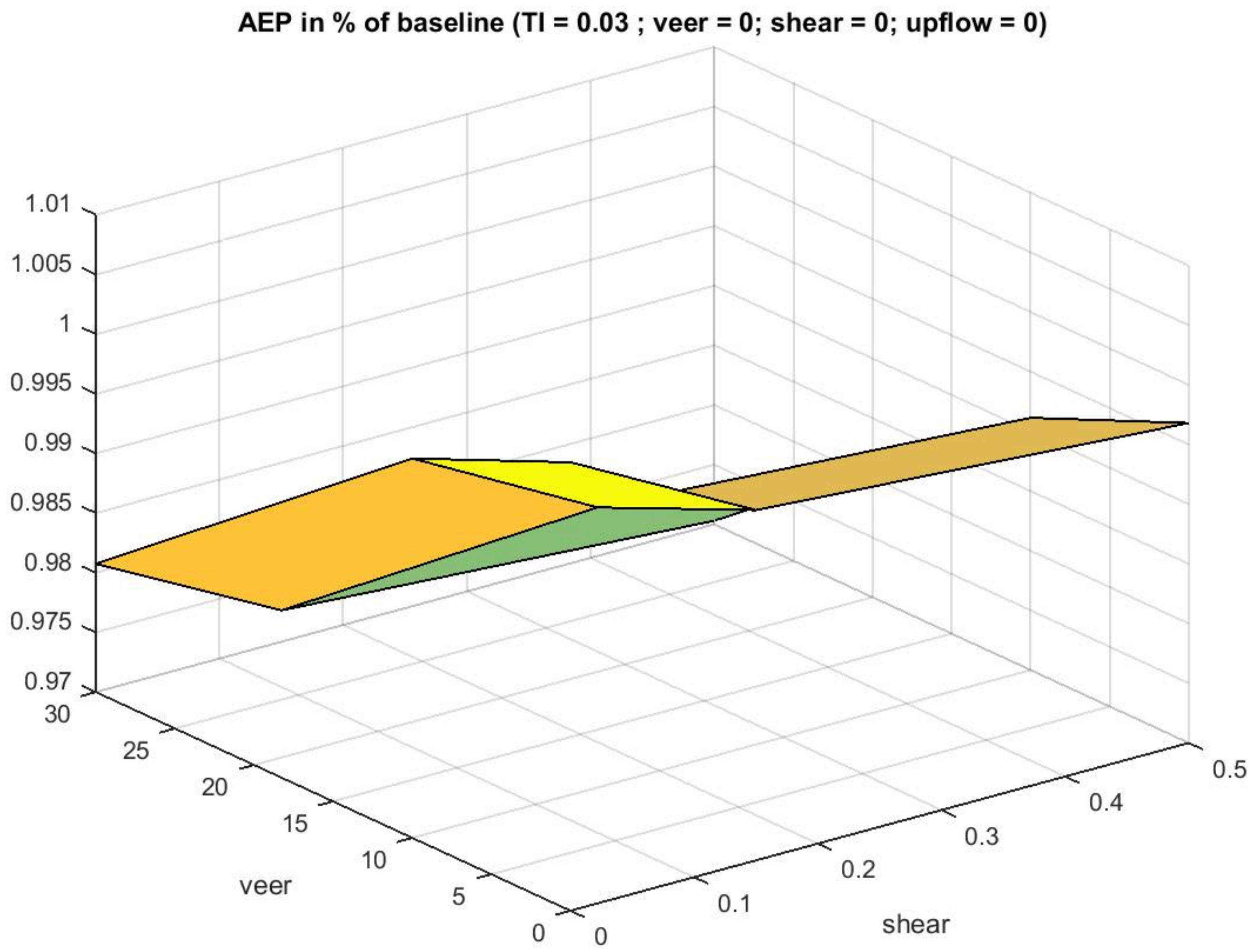
Values based on generic turbine model

Climate influence – shear vs upflow



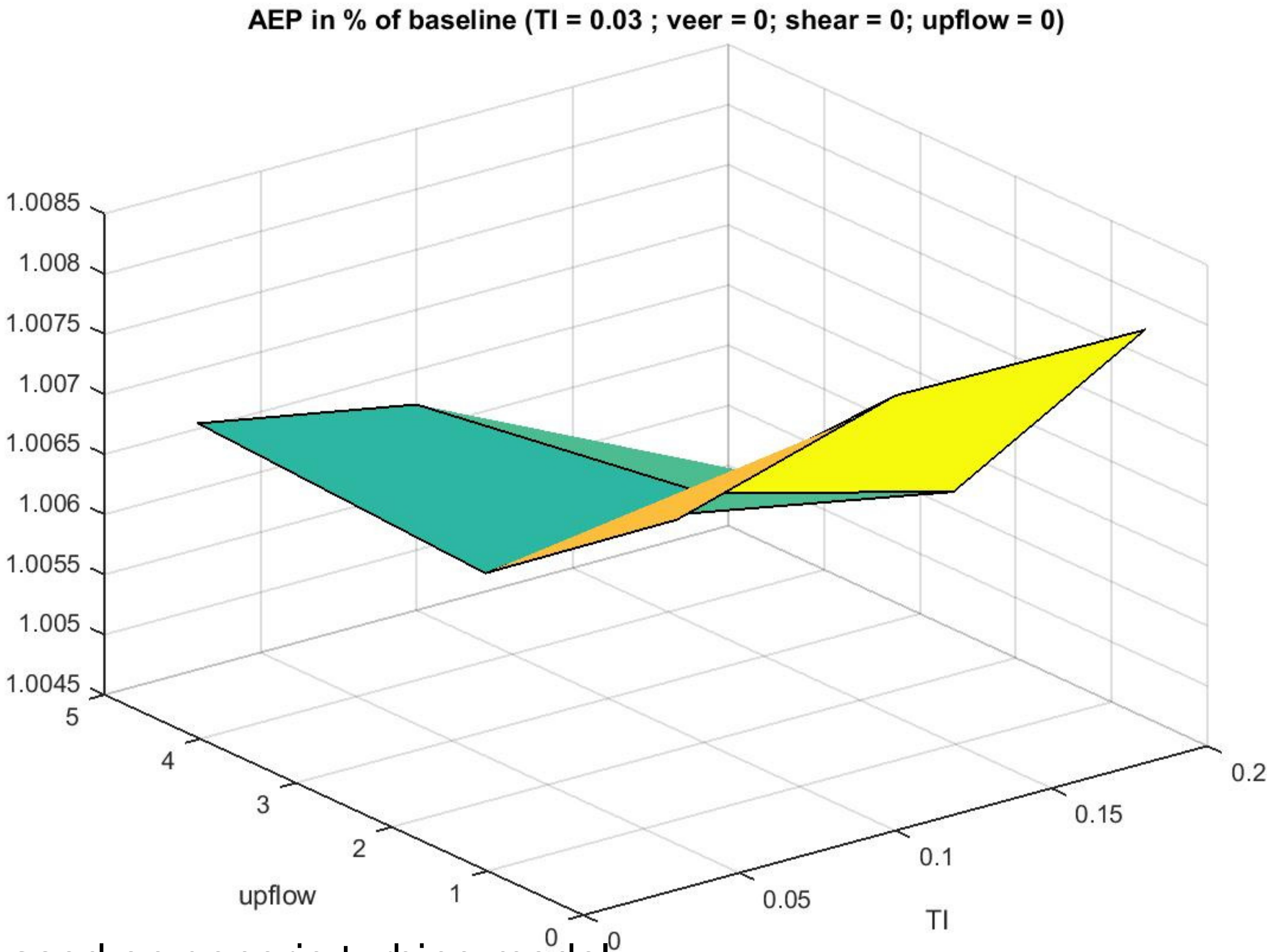
Values based on generic turbine model

Climate influence – shear vs veer



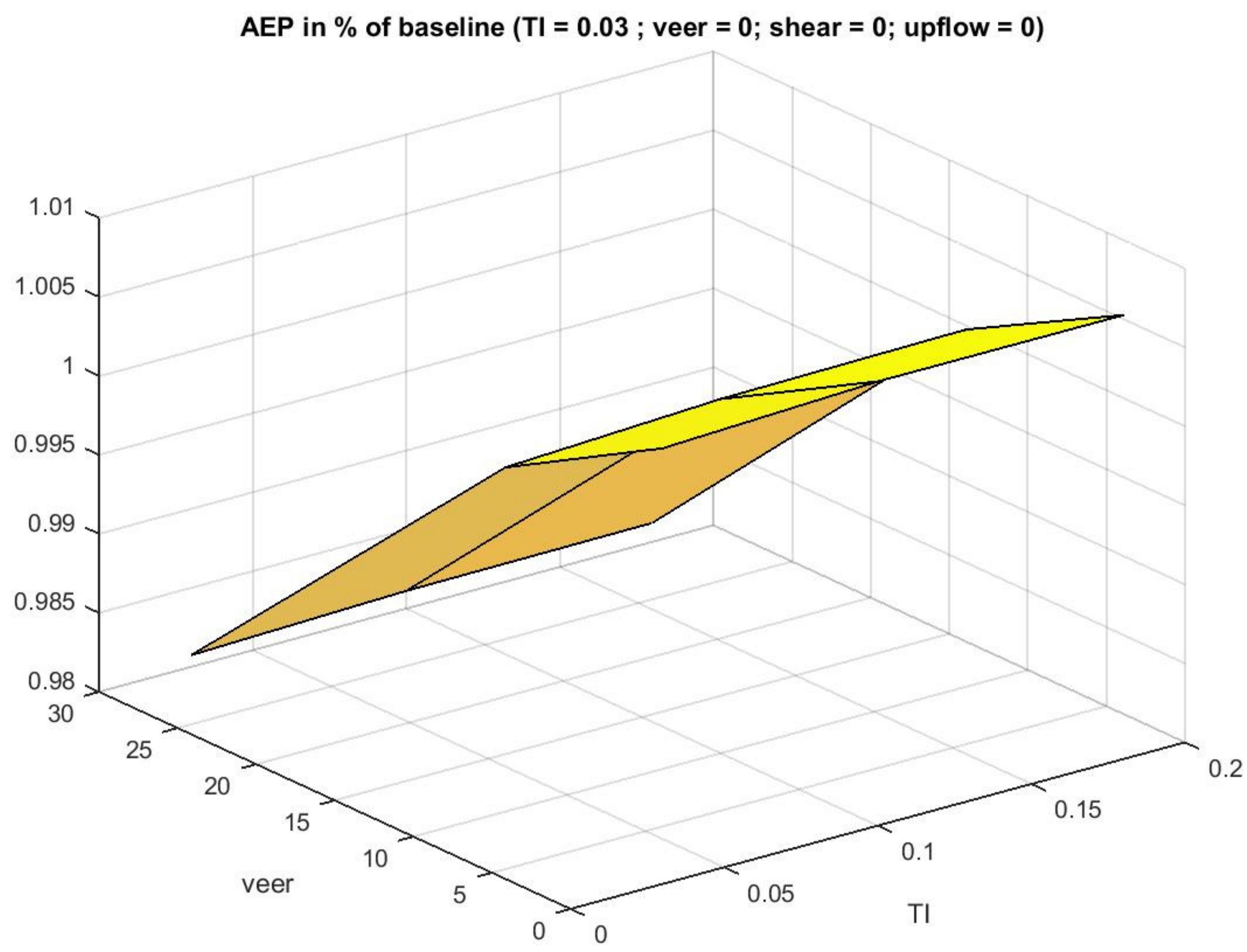
Values based on generic turbine model

Climate influence – upflow vs TI



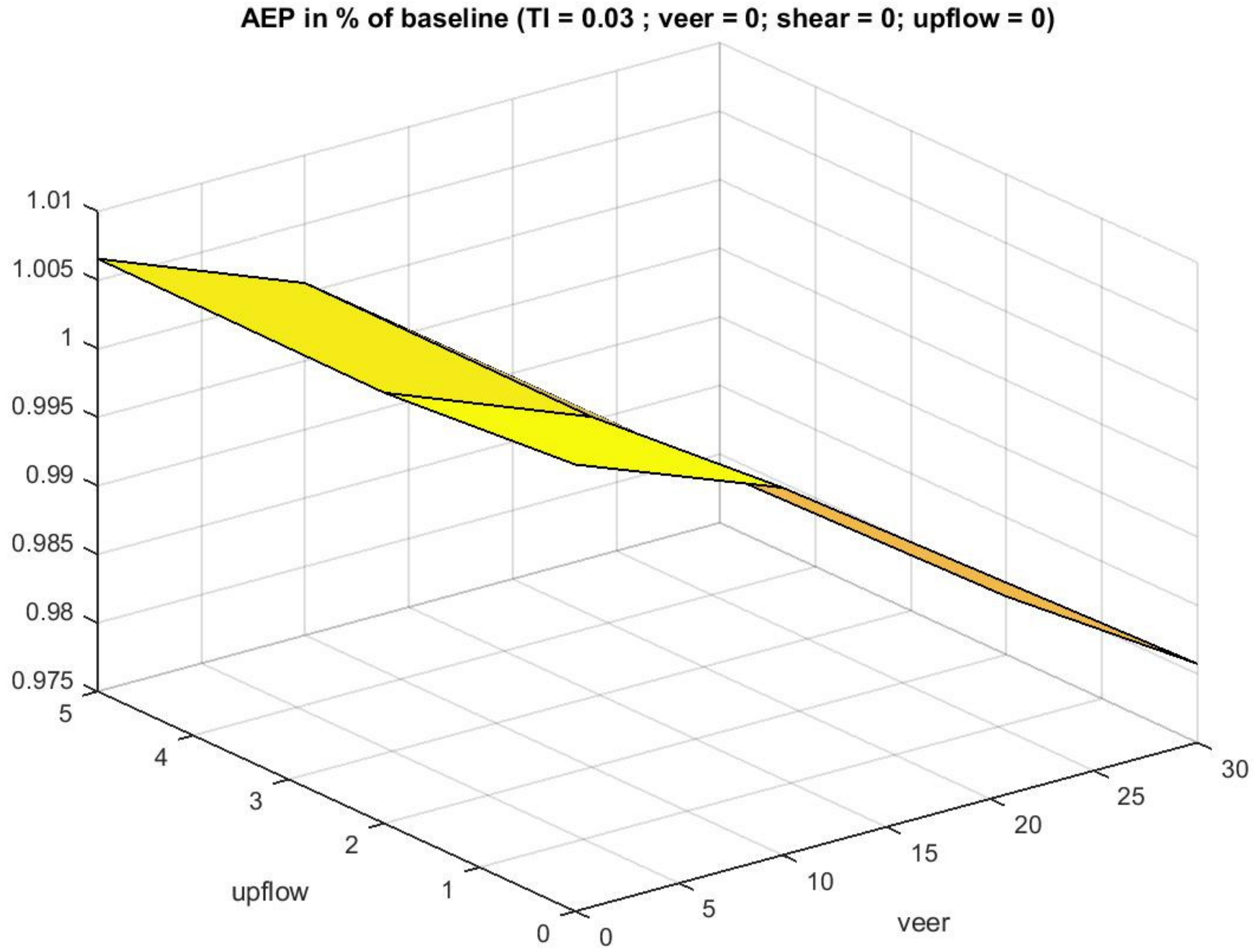
Values based on generic turbine model

Climate influence – veer vs TI



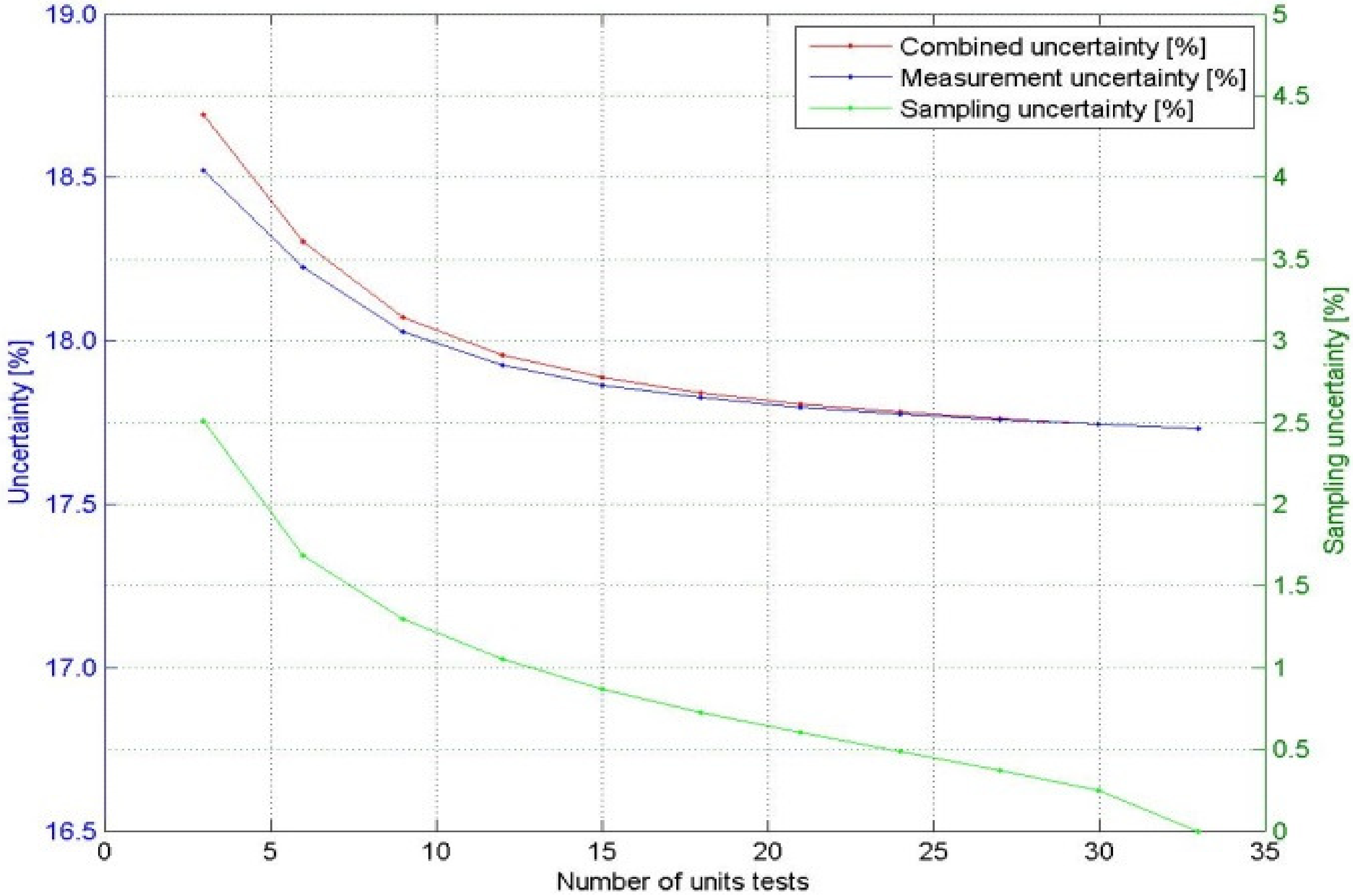
Values based on generic turbine model

Climate influence – upflow vs veer

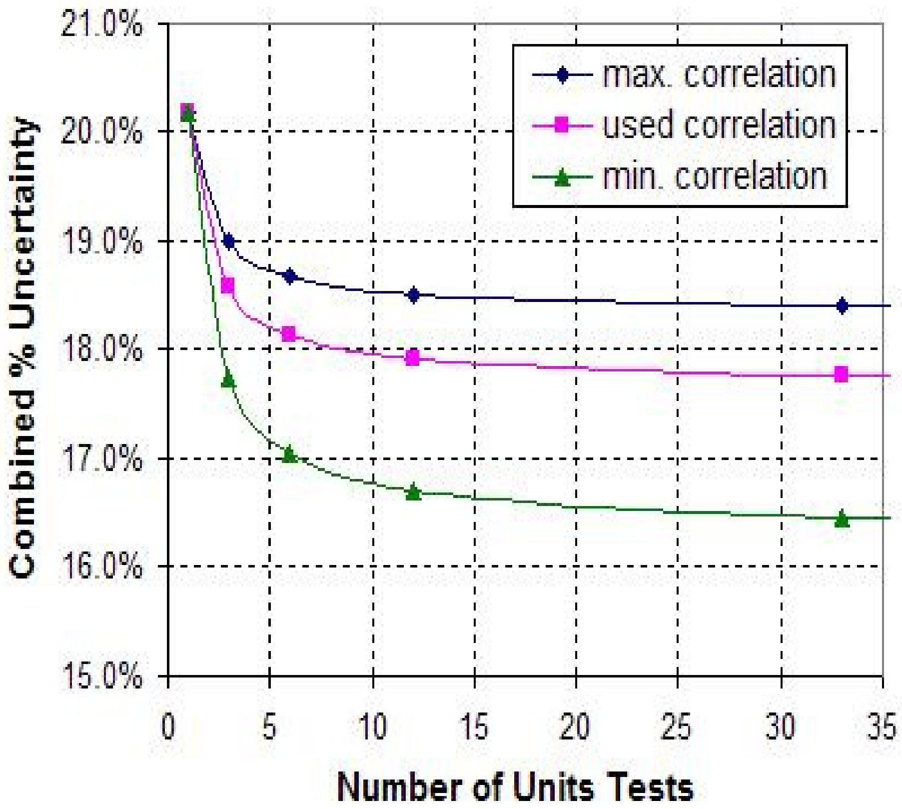


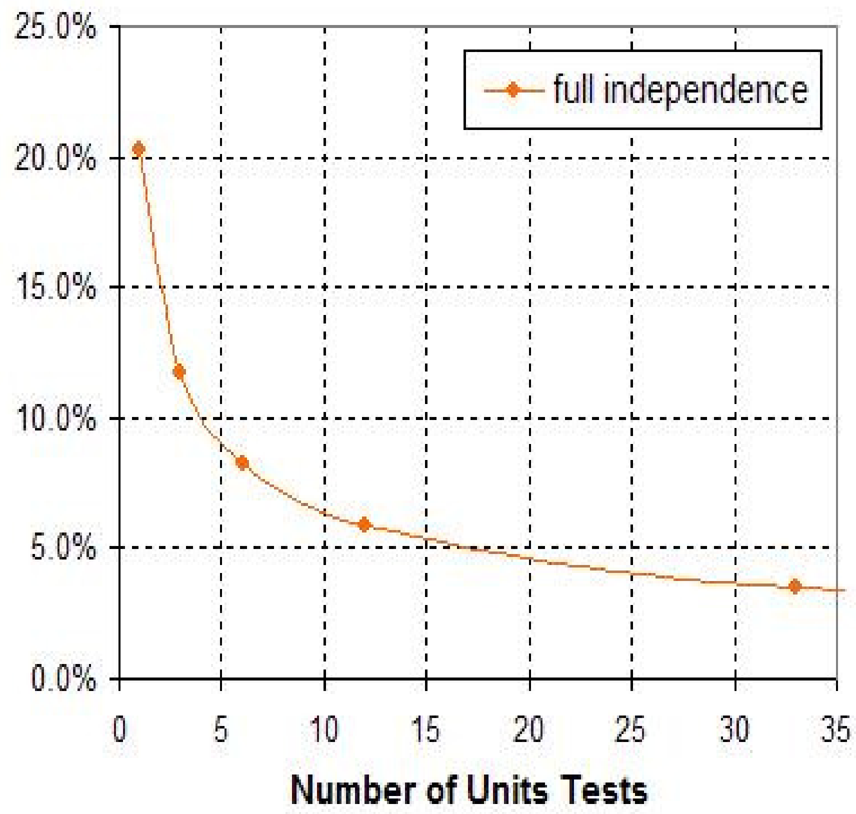
Values based on generic turbine model

Multiple turbine testing



Multiple turbine testing (-12-2)





Min corr = 93%; mean corr = 96%; max corr = 96.5%

Multiple turbine testing (-12-2)