



The PowerMatrix format

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Introduction

Modern wind turbines have developed drastically in recent decades. Rotor size has grown exponentially and turbines have become 'intelligent' by use of advanced control and operation strategies. Such special operation modes include e.g. noise or load reduction, power boost, high wind or high temperature operation. Meanwhile, the power curve format has changed little and standard power curve corrections are typically invalid for special operation modes. We therefore propose the PowerMatrix format as an improved wind turbine data format:

- to prevent the need to manually copy-paste data from extensive pdf-files or Excel sheets
- to address the needs which arise because modern wind turbines...
 - sample a larger part of the atmospheric boundary layer
 - are operated using advanced operation and control strategies

Outline of PowerMatrix format

A PowerMatrix is a single zip-file (.powermatrix), which defines a turbine model's power, thrust and noise data¹ for several operation modes as functions of the relevant climate variables. The zip-file contains several files:

- An **XML-file** describing the turbine model, its operation modes and relevant climate variables
- Multiple **Mat-files** with a matrix of power (kW), thrust (Ct) or noise (dBA) for each operation mode

The basic idea of the PowerMatrix is to fully define the turbine data for each operation mode and the mode's dependence on the relevant climate variables. Hence, a PowerMatrix 'includes' power curve corrections.

The XML-file

XML-files are structured, human readable and can be viewed in a browser. The XML-file in a PowerMatrix zip-file contains the basic ID and specs of the turbine model, its operation modes and the relevant climate variables. It also defines the **reference power curve** via a **reference operation mode** and a set of **reference climate conditions**. The main purpose of the XML-file is to define the link between each operation mode and the files with the corresponding data matrices (Mat-files) containing: the power data, the Ct data and the source noise data¹. The XML-file also defines the n climate variables and their discrete values, which represent the dimensions and the indices along each dimension of the data matrices. The supported climate variables are:

{WindSpeed, AirDensity, TurbulenceIntensity, WindShearPowerLawExponent, VerticalInflowAngle, Veer}.²

[Link to simple example XML-file](#)

The Mat-files

The Mat-files are binary data files³ each containing a single data matrix. For each operation mode there at least two Mat-files, one with the Power data and one with Ct data. Mat files with noise data¹ and TipSpeedRatio are optional. For Power, Ct and TipSpeedRatio the n-dimensional data matrices contain e.g. power (in kW) for the discrete values of each combination of the n climate variables. The climate dimensions are typically n=2 or 3, with wind speed, air density and possibly turbulence, but may include wind shear exponent or wind veer². The mat-files can contain NaN values as mat-files for different modes share the wind speeds, and some wind speeds might be outside operation for one of the modes. The Noise data matrix contains A-weighted source noise in decibels (dBA) as a function of two dimensions, wind speed and frequency (1/3-octave data).

[Link to simple example Mat-file \(Power\)](#)

[Link to simple example Mat-file \(Noise\)](#)

¹ Noise data are optional. Noise values must always be A-weighted decibels (dBA).

² Wind Veer is defined as a normalized quantity $\delta\theta$ in °/m. Full rotor veer is $RD*\delta\theta$, evenly distributed with 0 veer at HH.

³ Level 5 Mat file format, supported by Matlab, Python or R. www.mathworks.com/help/pdf_doc/matlab/matfile_format.pdf

A basic example of a PowerMatrix

A basic standard example of a PowerMatrix is a turbine model with four different operation modes. A standard 'mode 0' (the reference mode) and three noise-reduced modes, i.e. modes {0,1,2,3}. This example has just two climate dimensions for Power and Ct, wind speed and air density. Wind speeds range from 2.5m/s to 23.0m/s in steps of 0.5m/s. Air densities range from 0.950 to 1.275 in steps of 0.025 kg/m³. The source noise is given for wind speeds from 3m/s to 22m/s in steps of 1m/s for each standard 1/3-octave frequency from 10Hz to 10kHz.

The resulting PowerMatrix contains three Mat-files for each of the four operation modes, 12 files in total. The Power and Ct matrices give the variation as a function of the two climate dimensions and has 42 values along the first dimension (wind speed) and 14 values along the second dimension (air density). The source noise Mat-file has 19 entries along the first dimension (wind speeds) and 31 along the second (1/3-octave frequencies).

The **reference operation mode** is 'mode 0', and the **reference climate condition** is AirDensity = 1.225 kg/m³. Together this defines the **reference power curve** (= reference mode + reference climate conditions).

[Link to example PowerMatrix zip-file](#)

How to use a PowerMatrix – 100% reproducibility

Because a PowerMatrix includes the variation of power and Ct as functions of the relevant climate variables, only simple mathematics is needed when using it. Values shall be extracted from the data matrix using multi-linear interpolation⁴. In the example above with just two climate variables, wind speed and air density, this simplifies to bi-linear interpolation⁵. For 100% reproducibility, the order of interpolation must follow the order of the climate variables defined above in the 'The XML-file' section. Extrapolation of the data-matrices is not allowed; extreme data shall be truncated at the edges. **Cut-in** is defined by a first wind speed with zero power. If there is no zero power value, it is assumed 0.5 m/s before the first wind speed with a power value⁶. **Cut-out** is defined as the last power value - either the last entry or the last numeric value followed by only NaN values.

PowerMatrix in windPRO and optional security

The PowerMatrix format is supported from windPRO 3.2 as an alternative way to define turbine data in windCAT. For maximum benefit, we recommend turbine manufacturers to provide PowerMatrix data for general use by all windPRO users via the windCAT⁷. However, for project specific use where turbine data area adjusted locally and subject to legal constraints, windPRO allows **additional measures of security** for PowerMatrix data. These measures are optional and may be applied to the raw PowerMatrix files directly by the windPRO user using a simple tool from within windPRO. In addition to the basic security that a manufacturer decides with whom to share the PowerMatrix file, the additional security options in windPRO are encryption and license control of the PowerMatrix file. With these security measures the zip-file will be encrypted and access to use the file in windPRO will be restricted to the license numbers specified upon encryption.

Noise data considerations

It is optional but recommended to include source noise data in a PowerMatrix. Source noise data requirements are complicated and vary from country to country. In PowerMatrix the noise data matrix (Mat-file) contains source noise as a function of two dimensions: 1) hub height wind speed and 2) frequency. A complete set of such source noise data, covering all relevant wind speeds and all relevant 1/3-octave frequencies, will cover the current source noise requirement of any country's national noise code. The wind speeds and frequencies for the noise data are defined separately in the XML-file as, typically, wind speeds are coarser sampled for noise as opposed to power. The complete set of 1/3 octave data is spanning from 10Hz to 10kHz (see appendix III).

⁴ See e.g.: <https://docs.scipy.org/doc/scipy-0.16.1/reference/generated/scipy.interpolate.RegularGridInterpolator.html>

⁵ See e.g.: https://en.wikipedia.org/wiki/Bilinear_interpolation

⁶ Following the IEC61400-12-1 ed. 2 standard for AEP calculation, see p. 44.

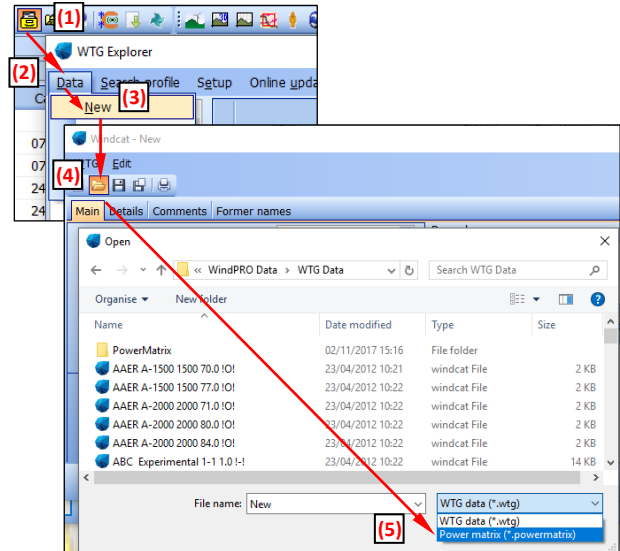
⁷ To add publicly available turbine data/models to windCAT contact: mm@emd.dk.

Appendix I – PowerMatrix in windPRO

This appendix describes how the PowerMatrix format can be loaded in windPRO.

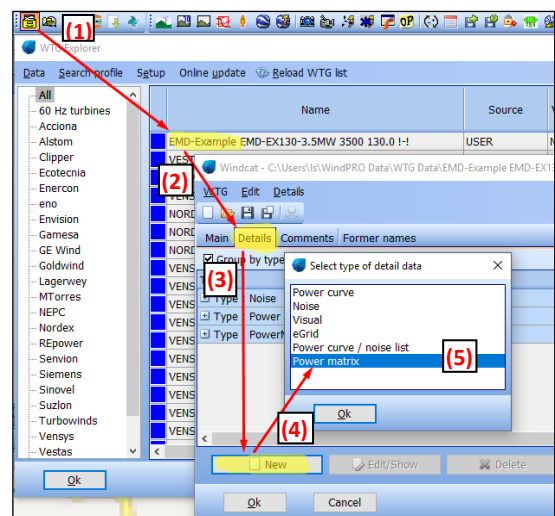
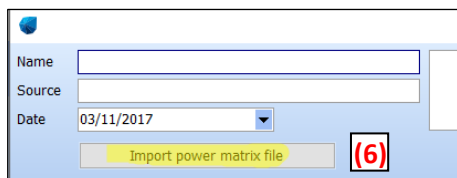
Load PowerMatrix to define a new wind turbine in windCAT

- Open windCAT, select 'Data' and then 'New' (1+2+3)
- In the 'New' window click 'Open WTG' icon (4)
- In file browser change type to '*.powermatrix'... and select the PowerMatrix file (5)



Load PowerMatrix in an existing windCAT file/turbine

- Open windCAT and open turbine file (1+2)
- Select 'Details', click 'New' (3+4)
- Select type 'Power matrix' and click OK (5)
- Click 'Import power matrix file' (6)
- Select the PowerMatrix file in the file browser.

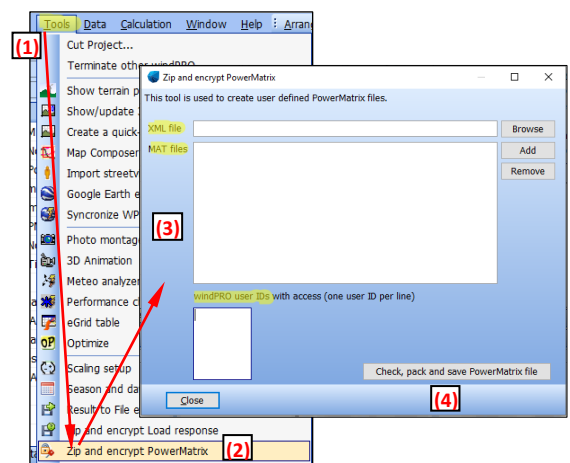


Extra security option for PowerMatrix data

A PowerMatrix can be encrypted and license protected for project specific use. In windPRO:

- Open 'Tools' menu (1)
- Select 'Zip and encrypt PowerMatrix' (2).
- Finally, select the xml-file + mat-files and type the windPRO user IDs (license numbers) who will be allowed to read the file (3)
- Click 'Check, pack and save PowerMatrix' (4).

This .powermatrix can now only be loaded and used by the defined windPRO license IDs.



Appendix II – Mat-file contents

Example visualization of a Mat-file with power data from the simple example described in the main text.

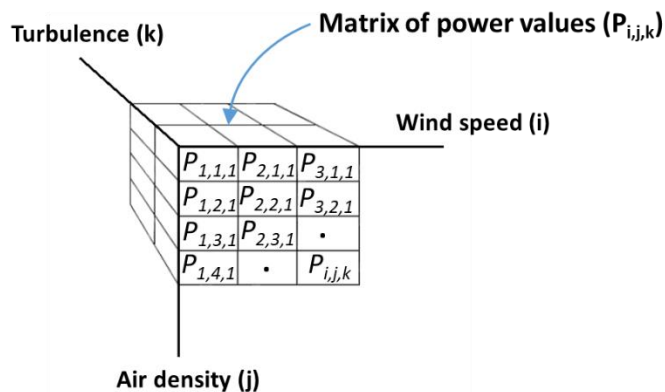
This example has four operations modes and for each mode there is one Mat-file for Power, one for Ct and one for Noise, 12 Mat-files in total. The Power and Ct files both contain two-dimensional data matrices with the climate dimensions: wind speed and air density as defined in the XML-file (see Appendix II). The noise Mat-files also contain a data matrix with two dimensions: wind speed and frequency.

Example Mat-file/data matrix for power for Mode 0 (in kW):

		AirDensity:											
		0.950	0.975	1.000	1.025	1.050	1.075	1.100	1.125	.	.	.	ρ_j
WindSpeed:	2.5	0	0	0	0	0	0	0	0	.	.	.	$P_{1,j}$
	3.0	14	15	17	18	20	21	23	24				
	3.5	67	70	73	76	80	83	86	89				
	4.0	136	141	146	151	156	161	165	171				
	4.5	217	225	232	239	246	253	260	267				
	5.0	315	325	334	344	353	363	372	382				
	5.5	432	445	458	471	483	495	508	521				
	6.0	574	591	607	624	640	657	672	689				
	6.5	741	762	783	804	824	845	865	887				
	7.0	938	964	990	1015	1042	1067	1092	1118				
	7.5	1161	1193	1225	1256	1288	1319	1350	1381				
	8.0	1417	1454	1492	1529	1568	1605	1642	1680				
	8.5	1703	1748	1792	1837	1882	1925	1970	2013				
	9.0	2022	2073	2125	2177	2229	2280	2330	2381				
	9.5	2367	2426	2485	2544	2604	2659	2714	2769				
	10.0	2730	2792	2852	2913	2975	3023	3072	3119				
	10.5	3062	3111	3161	3209	3259	3290	3321	3352				
11.0	3288	3320	3353	3384	3417	3431	3445	3459					
11.5	3423	3436	3451	3466	3481	3484	3488	3493					
12.0	3476	3481	3486	3490	3496	3497	3498	3499					
12.5	3493	3495	3496	3498	3499	3499	3500	3500					
13.0	3498	3498	3499	3499	3500	3500	3500	3500					
13.5	3499	3499	3499	3500	3500	3500	3500	3500					
14.0	3500	3500	3500	3500	3500	3500	3500	3500					
.	.												
.	.												
.	.												
u_i												$P_{i,j}$	

Note: In this case, with two climate dimensions, the rows represent wind speed and columns air density. Hence, the variation of power values across rows and columns, represent the power variation with wind speed and air density, respectively. Zero values of power are included in the data matrix to define cut-in.

Alternative example of data matrix for power, with three climate dimensions:





Appendix III – XML-file contents

Example contents of the XML-file for the simple example described in the main text.

```
<XMLFormatSpec>
  <XMLFormatVersion>1.0</XMLFormatVersion>
  <Source>EMD</Source>
  <CreateDate>18-09-2017</CreateDate>
  <EditDate>18-09-2017</EditDate>
</XMLFormatSpec>
<TurbineSpec>
  <Manufacturer>EMD-Example</Manufacturer>
  <TurbineUID>EMD-EX 130-3.5MW</TurbineUID>
  <HubHeight>130</HubHeight>
  <RatedPower>3500</RatedPower>
  <RotorDiameter>130</RotorDiameter>
  <Reference>
    <ReferenceMode>Mode 0</ReferenceMode>
    <ReferenceAirDensity>1.225</ReferenceAirDensity>
    <ReferenceTurbulenceIntensity/>
    <ReferenceWindShearPowerLawExponent/>
    <ReferenceVerticalInflowAngle/>
    <ReferenceVeer/>
  </Reference>
  <Comment>This is an example of the XML file in the power matrix format</Comment>
</TurbineSpec>
<OperationalModes>
  <OperationalItem ModeName="Mode 0">
    <PowerMatrix_FileName>PowerMode0.mat</PowerMatrix_FileName>
    <CtMatrix_FileName>CtMode0.mat</CtMatrix_FileName>
    <SourceNoiseMatrix_FileName>OctaveNoiseMode0.mat</SourceNoiseMatrix_FileName>
  </OperationalItem>
  <OperationalItem ModeName="Mode 1">
    <PowerMatrix_FileName>PowerMode1.mat</PowerMatrix_FileName>
    <CtMatrix_FileName>CtMode1.mat</CtMatrix_FileName>
    <SourceNoiseMatrix_FileName>OctaveNoiseMode1.mat</SourceNoiseMatrix_FileName>
  </OperationalItem>
  <OperationalItem ModeName="Mode 2">
    <PowerMatrix_FileName>PowerMode2.mat</PowerMatrix_FileName>
    <CtMatrix_FileName>CtMode2.mat</CtMatrix_FileName>
    <SourceNoiseMatrix_FileName>OctaveNoiseMode2.mat</SourceNoiseMatrix_FileName>
  </OperationalItem>
  <OperationalItem ModeName="Mode 3">
    <PowerMatrix_FileName>PowerMode3.mat</PowerMatrix_FileName>
    <CtMatrix_FileName>CtMode3.mat</CtMatrix_FileName>
    <SourceNoiseMatrix_FileName>OctaveNoiseMode3.mat</SourceNoiseMatrix_FileName>
  </OperationalItem>
</OperationalModes>
```

(continued on next page)



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<ClimateDimensions>
  <MeanWindSpeeds>
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    <Value>23.0</Value>
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  <AirDensity>
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    <Value>0.975</Value>
    <Value>1.000</Value>
    <Value>1.025</Value>
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    <Value>1.125</Value>
    <Value>1.150</Value>
    <Value>1.175</Value>
    <Value>1.200</Value>
    <Value>1.225</Value>
    <Value>1.250</Value>
    <Value>1.275</Value>
  </AirDensity>
</ClimateDimensions>
```

(continued on next page)



```
<NoiseDimensions>
  <MeanWindSpeeds>
    <Value>3</Value>
    <Value>4</Value>
    <Value>5</Value>
    <Value>6</Value>
    <Value>7</Value>
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    <Value>8000</Value>
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  </Frequency>
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</PowerMatrix>
```