




**Further Developing Europe's Power Market
for Large Scale Integration of Wind Power**

WP2.6 – Equivalent Wind Power Curves

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A	23/04/07	Original Release	J R McLean
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1 INTRODUCTION

As part of the Tradewind project, Garrad Hassan and Partners (GH) has been asked to produce an equivalent wind power curve (EPC), as detailed in WP2.6, in order to convert wind data to power data for wind farms across each region. The hub height wind speed time series (H_{WS}) described in WP2.4 [1] will be combined with the EPC to estimate the power time series for each region. Future developments in wind turbine design and the implications for the EPC are considered up to the year 2030.

As detailed in [2] the EPC will include factors such as array losses, topographic losses, electrical losses, availability and similar, and will take into account possible future developments in wind turbine power curves and hub heights.

2 APPROACH

GH has undertaken the following steps:

- Define wind farm classifications to be considered
- Investigate typical power curves for turbines currently in use
- Investigate how wake, topographic and high wind speed cut out effects modify the power curve over a number of turbines/wind farms
- Take account of typical availability and electrical losses for each wind farm classification
- Produce power curve models based on predictions for 2030

The above stages are described below in more detail.

2.1 Wind farm classifications

The terrain in which a wind farm is located has a significant effect on the local wind speeds as well as the wind farm and turbine design. For the purpose of this study GH considers commercial wind farms can be categorised into three broad groups based on the terrain where the wind farm is located. The three categories are;

- Lowland (up to 400 m above sea level)
- Upland (over 400 m above sea level)
- Offshore

The wind farm classifications correspond to the site classifications in [1].

2.2 Turbine power curve modelling

The wind farm power curve is to be used to derive power output from the wind farms based on the wind speeds derived through [1]. Turbine power curves have been compared, selecting a range of turbines used in various terrain types. Characteristics such as the shape of the power curve, the wind speed at which rated power is reached and cut out speed were investigated. For the purposes of this study GH has assumed that when normalised, present day turbine power curves are broadly similar for the three wind farm classifications.

A wind turbine power curve has been produced using a numerical model of a representative multi-megawatt wind turbine in the GH software Bladed. This has been used to produce a prediction of power as a function of wind speed at the turbine output terminals. This has been undertaken with assumed nominal (14 m/s) settings for rated wind speed, as shown in Table 2.1 and Figure 2.1. The wind turbine power curves have been normalised to their rated power.

Stall regulated turbines make up a significant proportion of the installed capacity within some countries in Europe. For this reason a present day equivalent power curve model for stall regulated turbines has been created based on typical existing stall regulated turbine power curves. The stall regulated turbine power curve is presented in Table 2.1 and in Figure 2.1. The equivalent power curve model for stall regulated turbines in lowland sites is shown in Table 2.2 and Figure 2.2.

2.3 Equivalent power curve modelling

GH has considered the variation of the following parameters for each wind farm classification and their impact on the equivalent power curve:

- Array efficiency
- High wind speed cut out
- Topographic effect
- Spatial averaging
- Availability
- Electrical losses

Array efficiency (i.e. the effect of reduction in wind speed due to the wakes of upstream wind turbines) is heavily dependent on the layout of the wind farm, wind regime and type of terrain. GH considers it appropriate to assume the following array efficiencies for each wind farm classification, as detailed in the table below. A higher wake loss is assumed for Offshore wind farms due to the large arrays of wind turbines in Offshore projects currently planned.

Wind farm classification	Array efficiency [%]
Lowland	92.5
Upland	92.5
Offshore	85.0

The array efficiency has been applied to the wind turbine power curve up to the rated wind speed to represent the effect of wakes on the turbine power curve.

The turbine controller causes the turbine to cut out during high wind speed periods, resulting in reduced production. Within a wind farm, individual wind turbines will experience slightly different wind speeds, and therefore a small change in wind speed around the cut out wind speed will not result in all turbines shutting down or starting up. For the purposes of the Tradewind project, GH has ramped the production of the turbine power curve down to zero for high wind speeds to represent this effect.

The effect of topography is such that at any time the wind speeds experienced by one turbine will differ from others in the same wind farm. For this reason the shape of the power curve for a whole wind farm will be made up of a number of individual turbine power curves at a range of wind speeds. To represent this GH have averaged the power from a range of power curves at different wind speeds. The effect of topography is higher in Upland wind farms, and therefore the wind speed variation across wind turbines and wind farms is greater than is found in Lowland sites. To account for this GH has averaged over a wider wind speed range for Upland sites and a lower wind speed range for Offshore sites.

There is also a variation of wind speeds experienced by wind farms across a region ('spatial averaging') and GH has applied an averaging method similar to that described above to the wind farm power curves to produce an equivalent regional power curve for each wind farm classification.

GH has assumed the following availability for each wind farm classification. A lower figure is assumed for Offshore wind farms due to increased difficulty in access.

Wind farm classification	Availability [%]
Lowland	97
Upland	97
Offshore	92

Electrical efficiency for both Onshore and Offshore sites are assumed to be 97 %. The availability and electrical efficiency have been applied to the power curve for all wind speeds.

The resulting Equivalent Power Curves for each wind farm classification are shown in Table 2.2 and Figure 2.2.

It can be seen from Figure 2.2 that the EPC for stall-regulated turbines has no significant difference from the EPC for pitch-regulated turbines in the other categories. This is because the spatial averaging effect smooths the discontinuities in the turbine power curves (Figure 2.1), so that the differences between the stall-regulated and pitch-regulated power curves are effectively lost. Stall-regulated turbines currently make up a significant proportion of the installed wind capacity only in Germany and Denmark. In Denmark, the stall-regulated capacity is currently 1449 MW out of a total of 3136 MW, i.e. under 50%. The stall-regulated capacity is expected to fall to 1200 MW by 2015, as turbines reach the end of their lives, and more rapidly to almost zero by 2020. Equivalent figures for Germany are not readily available, but a similar picture is expected. For these reasons, it is concluded that there is no benefit in considering stall-regulated turbines separately in the Tradewind project.

2.4 Future trends

By considering how each of the characteristics might change as we approach the year 2030, GH has produced future power curve models for each wind farm classification.

It is anticipated that the saturation of high wind speed sites and the development of more low wind speed sites will promote the development of turbines that reach rated power at a lower wind speed. Currently, rated power is reached at approximately 13 m/s for turbines in all wind farm classification types, but it is thought that a more likely rated wind speed for onshore turbines by 2030 is 12 m/s. No change in rated wind speed is anticipated for offshore turbines.

Advances in turbine design and improvements in turbine control systems are not likely to cause any significant improvement in turbine power performance, as turbine technology has largely reached maturity, and therefore GH has not considered any improvement in power performance in the future. However improvements in turbine controllers and understanding of structural loads are likely to allow higher cut out wind speeds for turbines in the future. To account for this, the future power curve models for all wind farm classifications have a cut out wind speed of 30 m/s.

No future changes are considered appropriate for wake losses, topography effects, availability or electrical losses in the 2030 power curve models. Future trends for increasing hub height are discussed in [1].

As detailed in Section 2.2, GH software Bladed has been used to produce a prediction of power as a function of wind speed at the turbine with assumed nominal (12m/s) settings for rated wind speed, as shown in Table 2.1 and Figure 2.1. All power curves have been extended to a cut out wind speed of 30 m/s.

Regional power curve models have been created using the methodology, described in Section 2.3, for the three wind farm classifications. Tables 2.2 and 2.3 show the

normalised power curve models for the present day and for the year 2030 respectively and plots of the present day and 2030 equivalent power curve models are shown in Figures 2.2 and 2.3 respectively. It is considered that the proportion of installed capacity from stall regulated turbines will not be significant in 2030.

3 APPLICATION OF EQUIVALENT POWER CURVES

The equivalent power curve models are used in conjunction with the wind speed time series R_{WS} developed in [1] as follows. See [1] for explanation of correction factors.

For any geographical region, target year and scenario:

For each timestep:

1. Look up R_{WS} (i.e. Reanalysis wind speed data allocated to that region)
2. For Lowland category:
 - 2.1 Calculate site windspeed $S_{WS} = R_{WS} \cdot T_F \cdot C_F$
($T_F = 1.00$, C_F from Section 2.5 of [1])
 - 2.2 Calculate hubheight windspeed $H_{WS} = S_{WS} \cdot H_F$ ($H_F = 1.00$) (**Note 1**)
 - 2.3 Look up Lowland power curve in Table 2.2 (for years 2005 to 2020) or Table 2.3 (for year 2030)
 - 2.4 Multiply by Lowland wind capacity for that region (MW)
 - 2.5 Result is the output (MW) from all wind turbines in Lowland category in that region.
3. For Upland category:
 - 3.1 Calculate site windspeed $S_{WS} = R_{WS} \cdot T_F \cdot C_F$
($T_F = 1.20$, C_F from Section 2.5 of [1])
 - 3.2 Calculate hubheight windspeed $H_{WS} = S_{WS} \cdot H_F$ ($H_F = 1.00$)
 - 3.3 Look up Upland power curve in Table 2.2 (for years 2005 to 2020) or Table 2.3 (for year 2030)
 - 3.4 Multiply by Upland wind capacity for that region (MW)
 - 3.5 Result is the output (MW) from all wind turbines in Upland category in that region.
4. For Offshore category:
 - 4.1 Calculate site windspeed $S_{WS} = R_{WS} \cdot T_F$ ($T_F = 1.30$)
 - 4.2 Calculate hubheight windspeed $H_{WS} = S_{WS} \cdot H_F$ ($H_F = 1.00$)
 - 4.3 Look up Offshore power curve in Table 2.2 (for years 2005 to 2020) or Table 2.3 (for year 2030)
 - 4.4 Multiply by Offshore wind capacity for that region (MW)
 - 4.5 Result is the output (MW) from all wind turbines in Offshore category in that region.
5. Summate output (MW) for Lowland, Upland and Offshore categories. Result is the total output (MW) of all wind generation in that region.

Repeat for next timestep.

Note 1: For the Lowland terrain case only, the effect of increased hub heights in later years can be investigated by using other values of H_F , as described in [1].

TABLES

Wind speed [m/s]	Current Pitch Regulated	Current Stall Regulated	Future Onshore	Future Offshore
0	0%	0%	0%	0%
1	0%	0%	0%	0%
2	0%	0%	0%	0%
3	0%	1%	0%	0%
4	2%	3%	3%	2%
5	5%	8%	8%	5%
6	11%	14%	14%	11%
7	17%	21%	23%	17%
8	26%	33%	34%	26%
9	38%	46%	51%	38%
10	53%	59%	70%	53%
11	69%	71%	96%	69%
12	87%	82%	100%	87%
13	96%	90%	100%	96%
14	100%	95%	100%	100%
15	100%	98%	100%	100%
16	100%	100%	100%	100%
17	100%	100%	100%	100%
18	100%	97%	100%	100%
19	100%	94%	100%	100%
20	100%	90%	100%	100%
21	80%	70%	100%	100%
22	60%	50%	100%	100%
23	40%	30%	100%	100%
24	20%	10%	100%	100%
25	0%	0%	100%	100%
26	0%	0%	80%	80%
27	0%	0%	60%	60%
28	0%	0%	40%	40%
29	0%	0%	20%	20%
30	0%	0%	0%	0%
31	0%	0%	0%	0%
32	0%	0%	0%	0%
33	0%	0%	0%	0%
34	0%	0%	0%	0%
35	0%	0%	0%	0%

Table 2.1 Normalised turbine power curves

Wind speed (H _{ws}) [m/s]	Offshore	Lowland	Lowland Stall Regulated	Upland
0	0%	0%	0%	0%
1	0%	0%	0%	1%
2	0%	0%	1%	2%
3	1%	1%	2%	3%
4	2%	3%	4%	6%
5	5%	6%	8%	10%
6	8%	11%	14%	15%
7	14%	17%	21%	21%
8	20%	25%	30%	30%
9	29%	35%	40%	39%
10	40%	47%	51%	49%
11	53%	60%	61%	58%
12	64%	72%	69%	67%
13	76%	81%	76%	75%
14	84%	88%	82%	82%
15	89%	92%	87%	87%
16	89%	94%	89%	91%
17	89%	94%	90%	91%
18	89%	94%	90%	88%
19	89%	90%	85%	82%
20	83%	83%	75%	73%
21	71%	72%	63%	63%
22	54%	56%	47%	52%
23	36%	38%	30%	42%
24	18%	23%	17%	31%
25	6%	11%	8%	21%
26	0%	4%	2%	13%
27	0%	0%	0%	6%
28	0%	0%	0%	2%
29	0%	0%	0%	0%
30	0%	0%	0%	0%

Table 2.2 Present day regional normalised power curve models

Wind speed (H _{ws}) [m/s]	Offshore	Lowland	Upland
0	0%	0%	0%
1	0%	0%	1%
2	0%	1%	2%
3	1%	2%	5%
4	2%	4%	8%
5	5%	8%	13%
6	8%	14%	20%
7	14%	22%	29%
8	20%	33%	39%
9	29%	48%	49%
10	40%	62%	59%
11	53%	75%	68%
12	64%	85%	77%
13	76%	92%	84%
14	84%	94%	89%
15	89%	94%	93%
16	89%	94%	94%
17	89%	94%	94%
18	89%	94%	94%
19	89%	94%	94%
20	89%	94%	94%
21	89%	94%	94%
22	89%	94%	92%
23	89%	94%	88%
24	89%	90%	82%
25	83%	83%	73%
26	71%	72%	63%
27	54%	56%	52%
28	36%	38%	42%
29	18%	23%	31%
30	6%	11%	21%
31	0%	4%	13%
32	0%	0%	6%
33	0%	0%	2%
34	0%	0%	0%
35	0%	0%	0%

Table 2.3 Future regional normalised power curve models for 2030

FIGURES

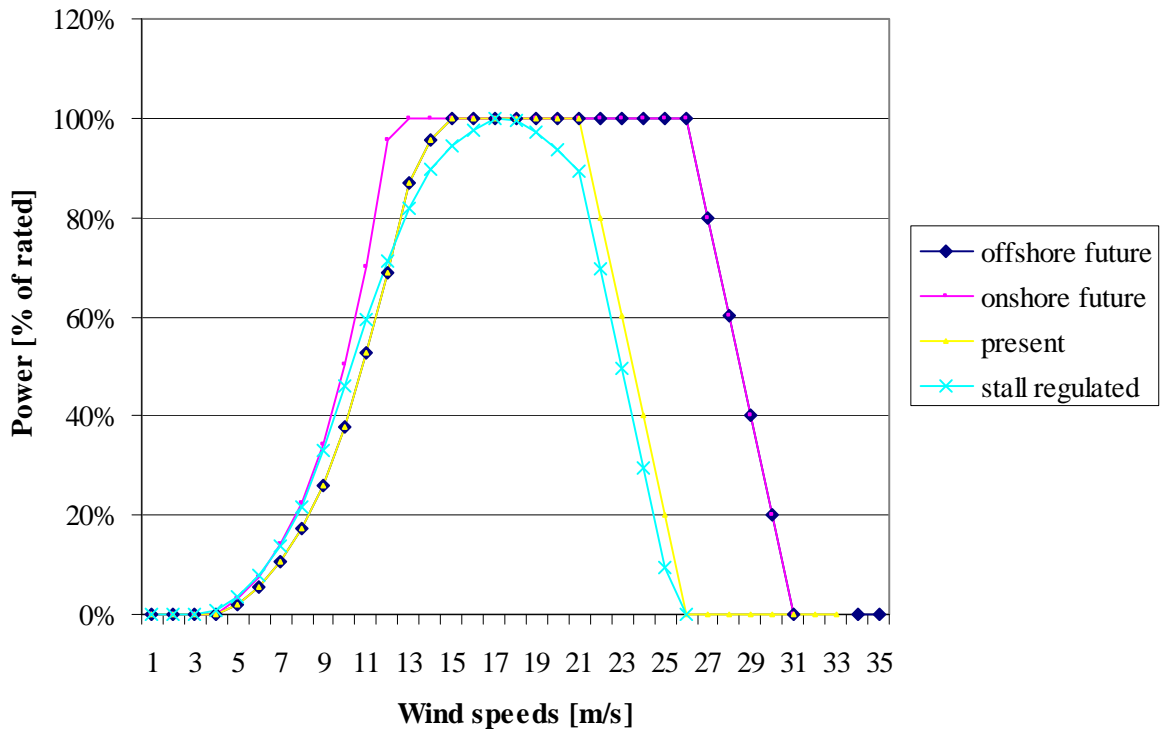


Figure 2.1 Turbine power curve models as created with GH Bladed

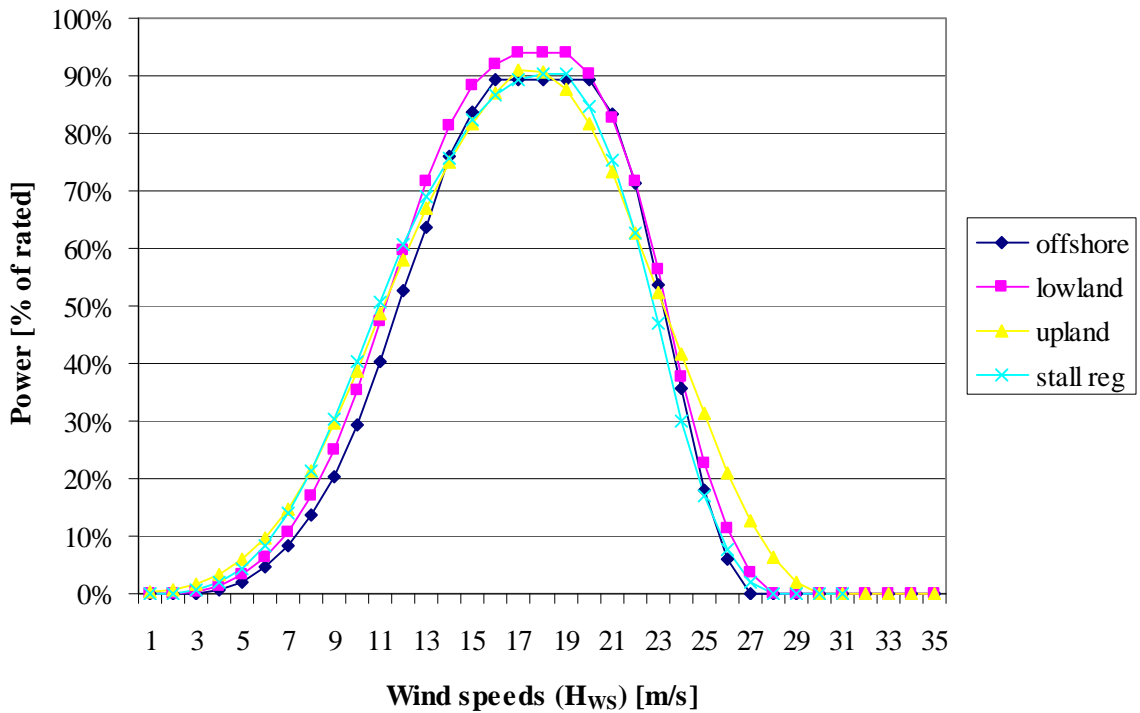


Figure 2.2 Equivalent regional power curve models for present day

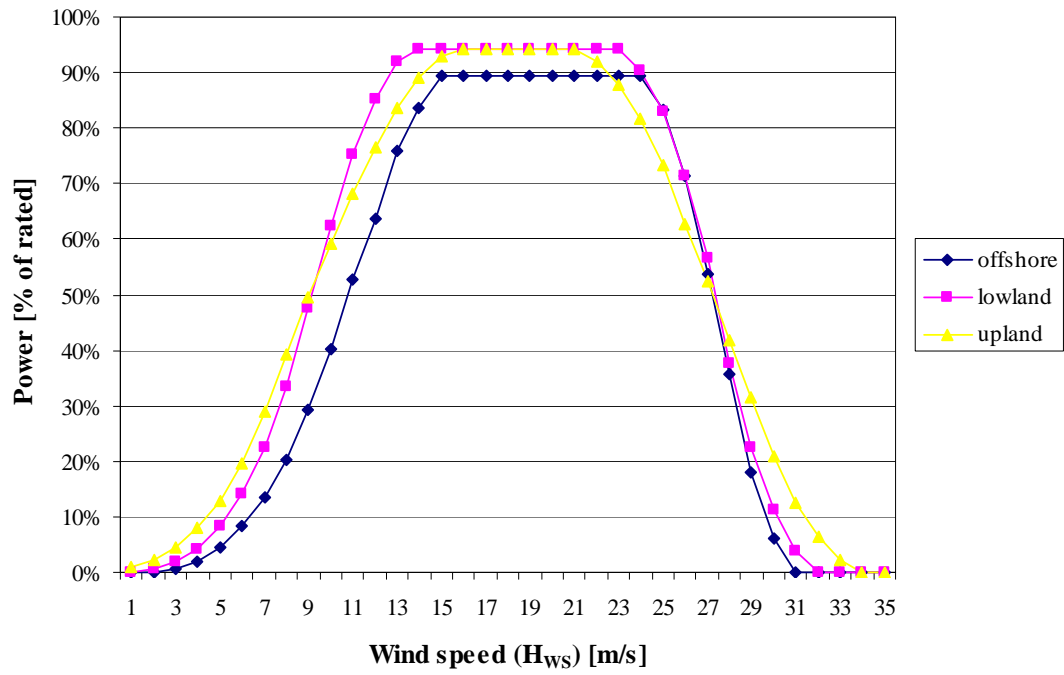


Figure 2.3 Equivalent regional power curve models for 2030

REFERENCES

- [1] Garrad Hassan document 11914/BT/01B. *Tradewind project, WP2.4 – Characteristic wind speed time series*
- [2] Intelligent Energy Europe (IEE), Annex 1 – Description of Action, Agreement no. EIE/06/022/SI2.442659