UNCERTAINTY OF VERTICAL WIND SPEED EXTRAPOLATION

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ABSTRACT

The vertical extrapolation of wind speed or production data is connected with an uncertainty. As a rule of thumb 1% uncertainty of the wind speed per 10m vertical extrapolation is often assumed, independent of siting conditions. However, this number lacks validation and might be site dependent.

We used 410 pairs of wind speeds at different heights from masts equipped with cup anemometry in various climatic and topographic conditions to quantify the prediction error using WAsP. The sites have been split depending on the actual site conditions into four categories:

- Non-complex without forest
- Non-complex with forest
- Complex without forest
- Complex with forest

For all four categories, the prediction errors have been analysed and suggestions are made to describe the uncertainty. With the exception of one scenario, the rule thumb (1% per 10m) does not reflect reality. Also the uncertainty advised by [1], which is supposed to find entry in the IEC61400-15 cannot be aligned with the findings of this analysis. In addition to an uncertainty, in some cases, a bias has been identified. The result of this analysis is a much more comprehensive uncertainty description.

Keywords: *flow modelling, WAsP, uncertainty, vertical extrapolation, prediction error.*

OBJECTIVE

Hub height measurements of wind speeds performed with traditional masts are rare, particularly in Europe. The estimate of wind resources and AEP in these cases consequently require vertical extrapolation from measurement height to hub height. Similarly, vertical extrapolation also becomes necessary, when production data from existing WTGs are used for estimating the AEP for future WTGs, typically with higher hub heights.

The vertical wind speed profile depends on site conditions via the local meteorology and the physical properties of the surface, topography and roughness. In flat, forested terrain a large change of wind speed with height is expected, while complex, steep terrain is normally associated with smaller changes of wind speed with height. The work presented here shows that the prediction error depends on the site conditions. In addition to the uncertainty, a bias has been identified for some scenarios.

Consequently, a more sophisticated approach to estimate the uncertainty and bias of vertical wind speed extrapolation is possible and is being demonstrated here.

METHODOLOGY

Cup anemometry measurements at several heights above ground level (a.g.l.) from a total of more than 100 sites in various climatic conditions form the basis of the analysis. The vertical wind speed changes were predicted using WAsP and compared with actual measured wind speeds. The stability settings within WAsP were adjusted relative to the local conditions, if found necessary. Also, displacement heights were introduced if required. Both parameters were judged based on the site setting and the model fit to the observed wind speed profile.

To reflect realistic conditions, the predictor heights (the measurement height which is used to predict the wind speed at greater height) have been filtered to match typical measurement heights. Two different scenarios have been considered: predictor heights between 40 and 75m (scenario 1 – reflecting situations with a low measurement mast) and predictor heights between 60 and 80m (scenario 2 – reflecting situations with a taller measurement mast). As target height, typical wind turbine hub heights have been specified between 85 and 130m. The maximum vertical distance between predictor and target height is therefore limited to a difference of 60m in the first scenario and 50m in the second scenario. A minimum of 8 months concurrent data on all measurement heights has been used to ensure sufficient data for Weibull fitting. After this rigorous filtering 410 measurement pairs of different measurement heights remained in the database for the first scenario and 260 for the second scenario, with a smaller range of predictor heights. The data have been sorted into four categories:

- Non-complex without forest
- Non-complex with forest
- Complex without forest
- Complex with forest

RESULTS

The results are presented in two ways: First as the prediction error of the wind speed versus vertical distance, and secondly as the prediction error of the wind speed versus the natural logarithm of the ratio between predictor and target height. The latter has been chosen to accommodate for the different steepness' on the logarithmic profile with height above ground level. The negative part of the y-axis reflects under-prediction of the vertically extrapolated wind speed, the positive part over-prediction. Results are marked as dots for each individual measurement pair. The trend line is marked as a dotted line. The 1% uncertainty per 10m vertical difference rule of thumb is indicated as shadow in the plots of the prediction error versus vertical distance. In case of the logarithmic presentation the uncertainty following [1] has been indicated, which is an empirically determined uncertainty description. Box-whisker plots show the median and the 25% and 75% quantile, respectively, where the graph is sufficiently populated. The following observation are made:
Figure 1 and Figure 2 show the prediction error in non-complex and non-forested terrain. A significant difference of the prediction error is visible between the scenario with low predictor heights between 40 and 75m (scenario 1) and scenario 2 with higher predictor heights between 60 and 80m. The uncertainty is significantly reduced. Clearly the assumption of 1% uncertainty per 10m vertical extrapolation would be conservative if the mast was sufficiently tall. The uncertainty

following [1] is clearly underestimated. A marginal bias is visible, but more data is necessary to evaluate the statistical significance.

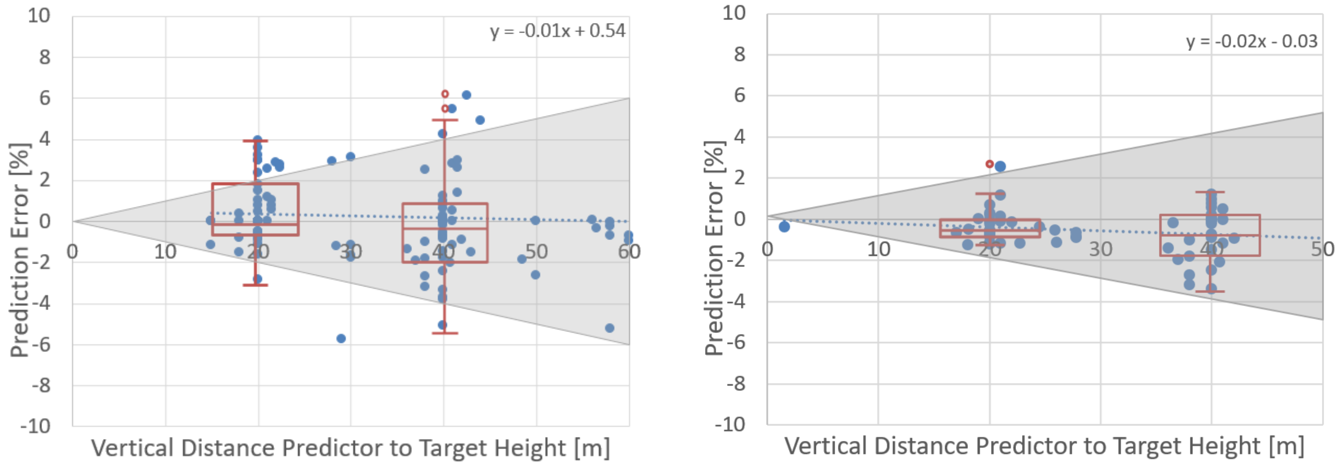

Figure 1: Vertical prediction error versus vertical distance for non-complex, non-forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) - right

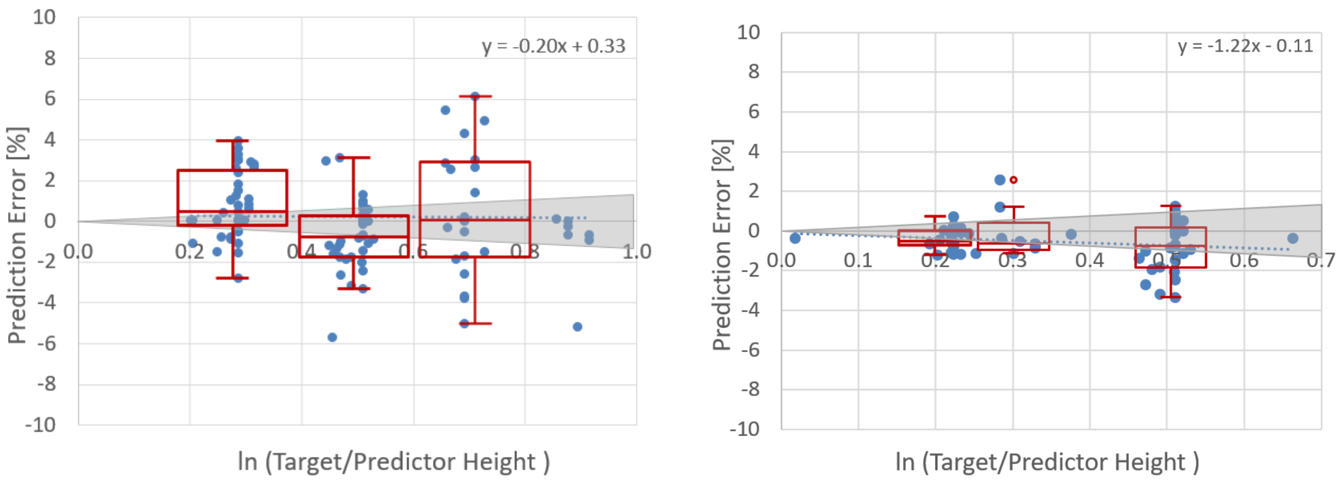

Figure 2: Vertical prediction error versus logarithm vertical distance for non-complex, non-forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) - right

In complex, not forested terrain (Figure 3 and Figure 4) unfortunately there is not enough data to make a qualified statement about the impact of the measurement height on the prediction error. However, there is an indication that the vertical extrapolation error is independent of the vertical distance that needs to be bridged, as the median stays near zero and the whiskers do not grow with increasing vertical distance. The errors seem to be less than 1% per 10m. The uncertainty in the logarithmic presentation following [1] is clearly underestimated. No bias can be detected.

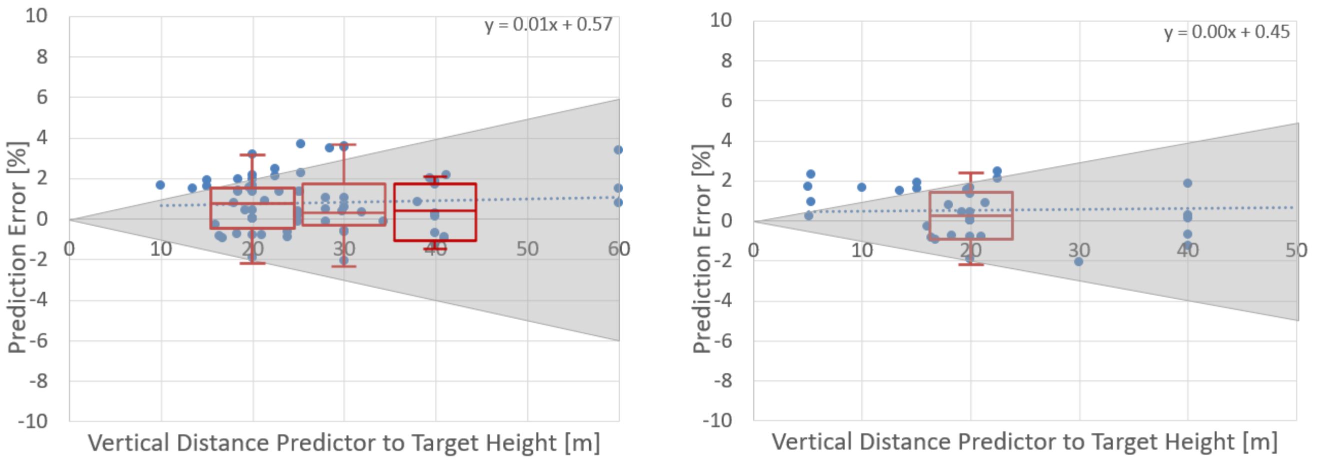

Figure 3: Vertical prediction error versus vertical distance for complex, non-forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) – right

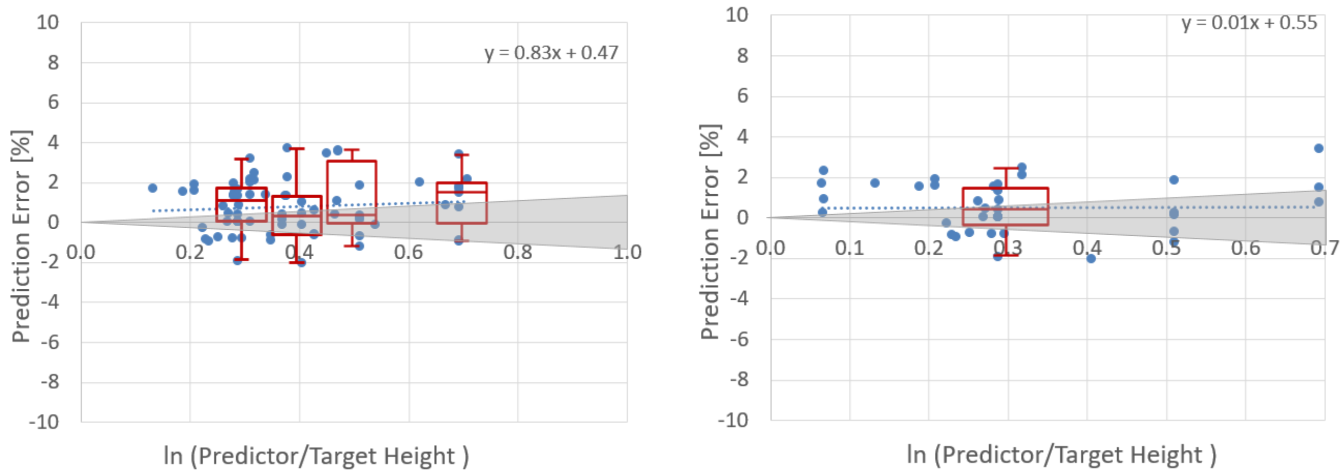

Figure 4: Vertical prediction error versus logarithm distance for complex, non-forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) - right

In non-complex but forested terrain (Figure 5 and Figure 6) it seems that the measurement height on average has no impact on the prediction error. However, the uncertainty seems to be reduced for scenario 2. In contrast to the non-forested scenarios (Figure 1 and Figure 4) a bias can be observed, such that the vertically extrapolated wind speed is systematically under-predicted. This finding ties up qualitatively with practical experience [2]. Despite the presence of a bias, the uncertainty (scatter) is smaller than 1% per 10m vertical extrapolation. The uncertainty in the logarithmic presentation following [1] is clearly underestimated.

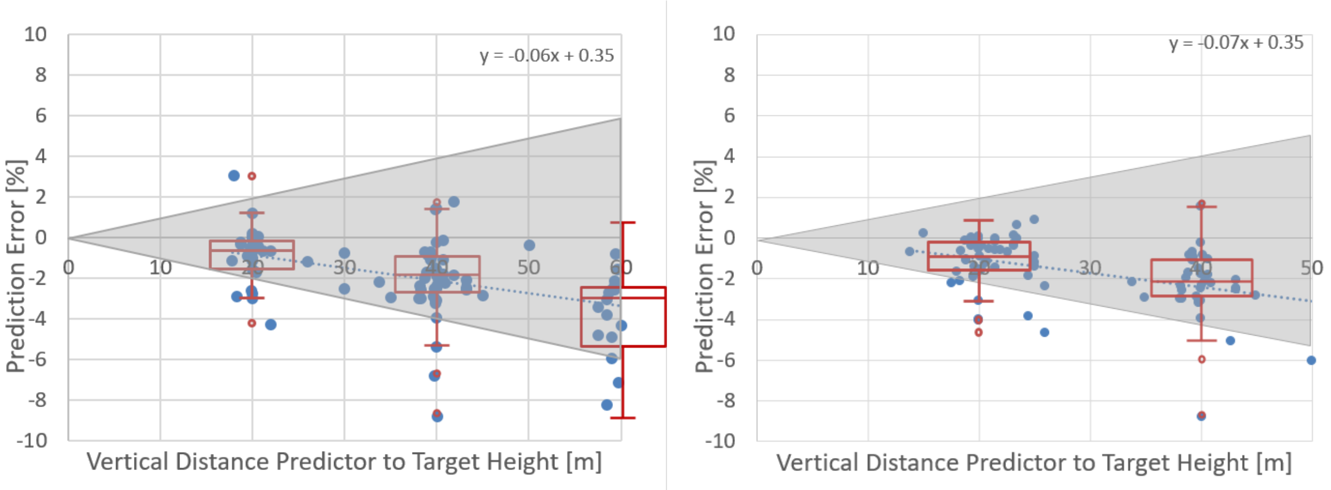

Figure 5: Vertical prediction error versus vertical distance for non-complex, forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) – right

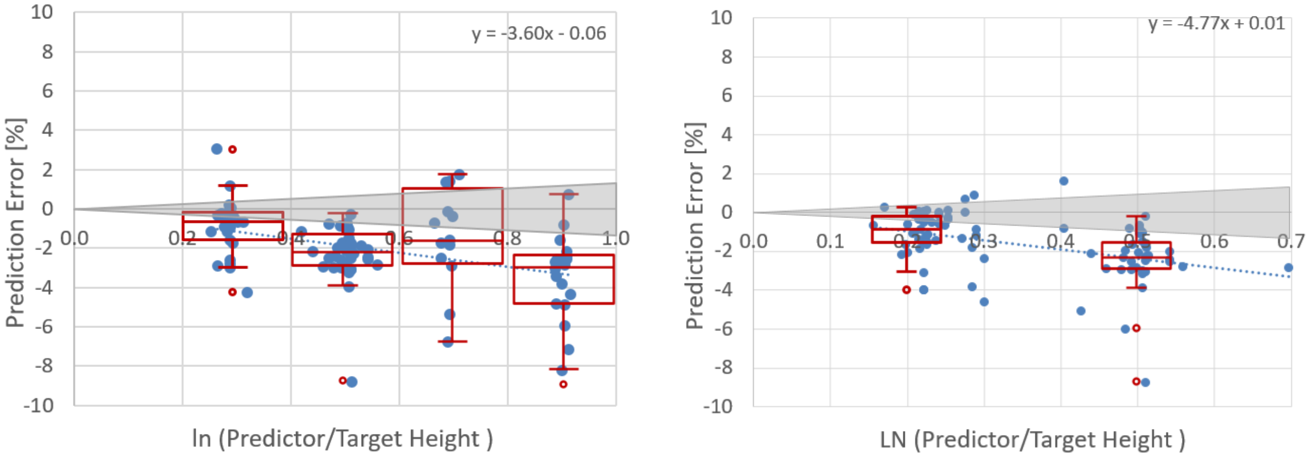

Figure 6: Vertical prediction error versus logarithm vertical distance for non-complex, forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) – right

In complex and forested terrain, low measurement masts seem to lead to a systematic under-prediction (Figure 7 and Figure 8 – left side). This bias is no longer visible when the measurement height increases (right side of the graphs).

A possible explanation could be that a measurement height of 60m is no longer in the roughness sublayer created by the forest. As a rule of thumb, it is frequently assumed that the trees impact is measurable up to 3 times the tree height. Assuming a tree height of 20m, this would result in a roughness sublayer with a height of 60m. However, this effect should also have been visible in flat forested terrain, but here the bias remains also for measurement heights above 60m. However, in complex terrain a second effect, the increased speed-up, might be counter-acting the roughness sublayer.

From all scenarios evaluated in this analysis, the uncertainty (scatter) is clearly largest in case of complex forested sites, as expected, and exceeds 1% per 10m vertical extrapolation.

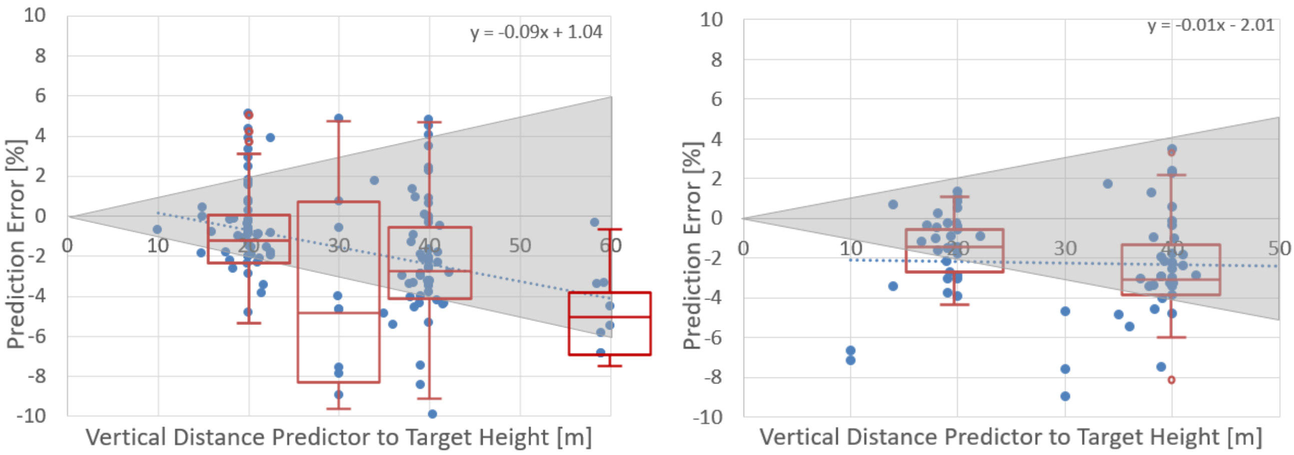

Figure 7: Vertical prediction error versus vertical distance for complex, forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) – right

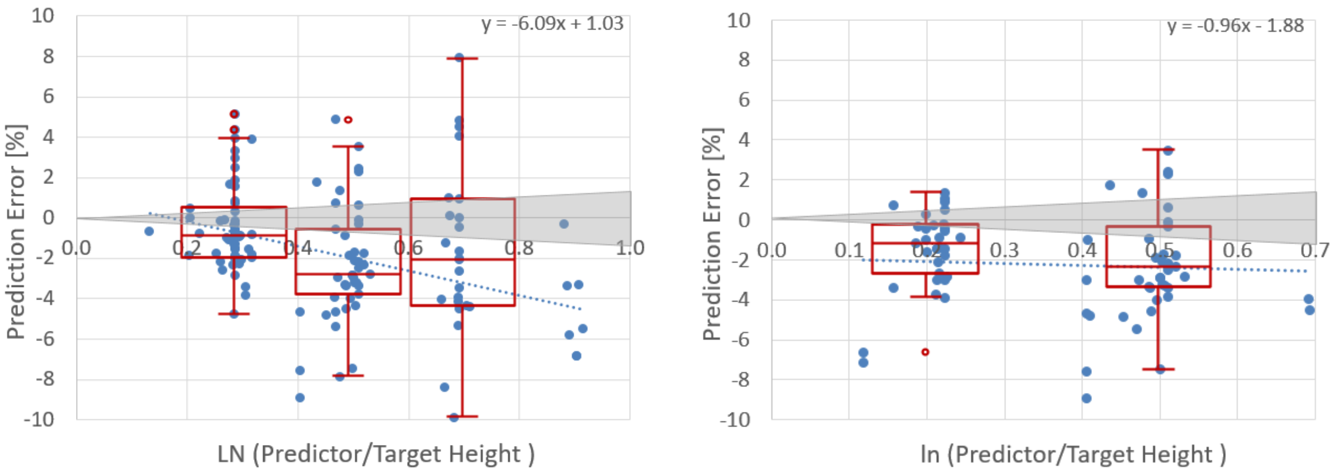

Figure 8: Vertical prediction error versus logarithm vertical distance for complex, forest situations: Scenario 1 (shorter masts) - left, Scenario 2 (taller masts) – right

CONCLUSION

We have shown that a more sophisticated approach is possible when estimating the uncertainty related to vertical extrapolation.

For measurement masts exceeding 60m height 1% per 10m vertical extrapolation seems to be conservative for most types of terrain. Only in complex, forested terrain the uncertainty reaches this magnitude, and might even exceed it. However, more data is necessary for a quantification.

Also, the uncertainty description in the logarithmic presentation following [1], which is meant to find entrance in the upcoming IEC 61400-15, is not reflecting reality and is underestimating the uncertainty.

For non-forested terrain, both flat and complex, the uncertainty seems to be nearly independent of the vertical distance.

In flat forested conditions a bias has to be taken into account, since the wind speed is systematically underpredicted.

The uncertainty in non-forested complex terrain is smallest, but highest in the presence of forest. Clearly, in complex forested terrain it is advisable to measure as high as possible to avoid a combination of high uncertainty and a significant bias.

REFERENCES

[1] M. Kelly: Uncertainty in vertical extrapolation of wind statistics: shear-exponent and WAsP/EWA methods, 2016, DTU Wind Energy. (DTU Wind Energy E; No. 0121)

[2] P. Nielsen: Danish Wind Turbine Performance, EWEA Workshop Analysis of Operating Wind Farms, Malmø 2014

BIOGRAPHIES

Wiebke Langreder – was born in 1969 in Germany. She holds an engineering degree for Applied Physics (1993) and a M.Sc. for Renewable Systems Technology from CRES, Loughborough Technical University, UK (1996). In her current position, she is heading the Wind Energy Consulting department at EMD International A/S and is leading a team of 6 wind energy consultants.

During her 20 years of professional work in the international wind industry she worked for a number of different wind turbine manufacturers and has therefore expert knowledge in site suitability and IEC site classification. Furthermore, she has an in-depth knowledge of uncertainty analysis and long-term corrections.

Madalina Marilena Jogararu – was born in 1989 in Romania. She holds a degree for Electrical Engineering and Management (2012) from Romania and a M.Sc. for Sustainable Energy Planning and Management from Aalborg University, DK (2014). In her current position, she is a Wind Energy Consultant at EMD International A/S.

In her professional work in the international wind industry she worked on a number of projects from earlier planning stages to bankable energy assessments across the world. She also gives training courses in working with WindPRO software and is aiding in uncertainty analysis and long-term correction.

Sérgio Augusto Costa was born in 1979 in the city of Curitiba, Paraná state, Brasil, and has earned his undergraduate degree in Mechanical Engineering from the Federal University of Santa Catarina, Brasil, in 2002. In his current position, he is the managing director of EMD Brasil Ltda. With more than 14 years of experience in the Brazilian energy sector, specifically in the energy generation business, he worked in several engineering and consultancy companies, hydro turbine manufacturer and utility company. He is the founder and managing director of VILCO Engenharia e Consultoria Ltda., which he is the responsible for the overall coordination of activities and specialized services in consulting and engineering projects of power generation by renewable energy sources (wind farms, solar plants, hydroelectric and biomass plants). He has experience in development of more than 3.5 GW of wind power projects in Southern and Northeast of Brasil. His key professional interests are within wind, power, renewable energy, energy planning, energy trading, finance, capital markets, asset evaluation and project management. At the moment, he is studying MBA in Mergers & Acquisitions, Asset Evaluation, Finance, Capital Markets, and Risk Analysis.

Mr. Costa is a member of the Brazilian Federal Council of Engineering and Agronomy.