SI-2b

A Short Approximation Method

to Pre-estimate the Electric Yield of Wind Farms

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Abstract

Amongst the Renewable Energy Sources (RES) contributing to the worldwide electricity production, wind energy became very important. Germany and several other countries own significant wind potentials. 2% of a country's area can be used for wind farms, thus Germany could produce easily up to 200 TWh_{el} yearly just onshore. However, often legal and especially financial aspects decide about the speed of development. Careful project preparation guaranteed by professional management is obligatory. Beside factors such as (i) rights to the property and (ii) electric grid connection, (iii) the sufficiency of the wind and peripheral conditions need to be known. A proper wind forecast and yield prognoses are important items. To solve these tasks, professional programs are sold on the markets. To offer a convenient alternative, authors will present software based on Excel named as WindCalc 1.5, which is still under development.

1 Introduction

Within the last decades, a significant growing of the wind energy branch had been observed. Whereas amongst the Renewable Energy Sources (RES) in terms of global electricity still the hydropower rules - contributing around 20% of the worldwide electricity production - starting from the early 90s, the wind energy became the second important RES technology after the hydropower. However, by the end of 2019 Germany operated wind fields with a total capacity of 53.9 GW_{el} onshore and 7.5 GW_{el} offshore [1]. Thus, the yearly electricity production was estimated to have reached 132 TWh_{el} in 2019 [1], which covered nearly 25% of the annual electricity net consumption in Germany. For comparison, according to the former German Ministry for Environment BMU reported in 2013, in 2012 onshore/offshore still only 49.9/0.72 TWh_{el} had been produced from wind energy [2].

Around 2000, Germany reached the point of equivalence at 4 GW_{el} with Denmark, traditionally the wind energy pioneer. Within the following years Spain came up to be one of the first European nations, later than firstly USA and finally China won the leadership in the markets. Whereas the entire installed capacity amounted to 369.6 GW_{el} worldwide in 2014 [3], by the end of 2019 this grew up towards 650.6 GW_{el} (reported by the German Wind Association BWE and Global Wind Energy Council GWEC, [1] - 36% of it in China. However, also smaller countries in transition are already developing the wind power successfully. For instance, since 2010 the Turkey passed the magical 1-GW_{el}-border [4]. At the end of 2011 Turkey operated an in-

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stalled wind capacity of nearly 1.7 GW_{el} aiming at 5 GW_{el} in 2015 and under optimistic assumptions maybe more than 20 GW_{el} in 2025 [4]. This examples may show, that

1. wind energy is a strong Renewable Energy Source, and
2. countries in transition easily can develop own domestic wind energy application.

For Germany, today serious estimations including (i) expanding the onshore installation, (ii) repowering old onshore wind farms by modern systems, and (iii) further developing the off-shore area show that it might be feasible to develop the wind energy in Germany to contribute finally more than 30-40% of the national net electricity demand.

2 Wind Basics and Wind-turbine Yield Simulation

Basics on wind, wind energy and wind technology can be found in [5], [6] or [7]. However, this chapter 2 is foreseen firstly to give basic information on how wind regimes work and especially how electric yields generated from them can be predicted, and secondly, to prepare how to manage computational simulation, comparing (briefly) professional but often expensive software tools with a simple but forceful new Excel based program code named as WindCalc 1.5 in chapter 3.

2.1 Basics on Wind Performance – Input to the Simulation Models

In order to simulate electric yield from wind energy systems, due to the compatibility of the input some transformations are necessary. As well, some background theory is needed [8], [9]: Wind often is measured close to surface, standardized at 10 m above the ground. If measurements had been taken at higher levels, it will be remarked in wind speed maps or data will be reduced down to a reference level. Long-term observations result in statistical averages. This data are fundament of the calculation.

First point of interest is the long-term average (= mean) of the wind speed at reference level, in order to obtain afterwards a statistical distribution in hub elevation. There are three steps to obtain this:

1. Evaluation of data and calculation of long-term ground wind-speed average
 - a. Data can be collected or measured
2. Height correction and evaluation of long-term hub wind-speed average which must be expected
 - a. The height formula is one opportunity to simulate the wind speed profile, thus minimum the roughness z_0 as function of the landscape typ is required
3. Calculation of the wind-speed distribution by Weibull or Rayleigh theory
 - a. In terms of Weibull theory, the so-called shape factor C is needed, a property of the landscape typ and altitude

To complete the technical calculation, machine parameters and mechanical calculations finally are needed. In order to prepare a wind field, also further information due to air temperature, airpressure and humidity functions during the season will be collected and evaluated. To solve the question how to adjust the wind-farm shape, further investigations and evaluation on the direction distribution will be done (wind-rose). However, this can be respected later to estimate the farm factor.

2.2 Estimating the Mean of Wind Speed at Hub Elevation

Formula (1) shows the height formula to calculate wind-speed average in hub elevation according to a logarithmic model, formula (2) is the Hellmann formula [8], [9].

Height formula

$$v_2 = v_1 \frac{\ln\left(\frac{h_2 - d}{z_0}\right)}{\ln\left(\frac{h_1 - d}{z_0}\right)} \quad (1)$$

with

v_2 : Wind speed on the upper level h_2 (e.g. hub) (in m/s)

v_1 : Wind speed on the lower level h_1 (e.g. measurement) (in m/s)

z_0 : Roughness (in m)

d : Shift (in m)

Hellmann formula

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^\alpha \quad (2)$$

with

v_2 : Wind speed on the upper level h_2 (e.g. hub) (in m/s)

v_1 : Wind speed on the lower level h_1 (e.g. measurement) (in m/s)

α : Hellmann exponent (—); starting $\alpha = 0.10$

In table 1 the landscape types, roughness factors z_0 and other properties can be found. Wind speed data estimated from the calculation according to formula (1) and (2) can be compared with results of mast-based long-term anemometer measurements in different levels, respectively.

Table 1: Landscape types, roughness (according to European Wind Atlas) and other properties [8] [9] [10]

Class of Roughness	Roughness z_0 (m)	Energy Index (%)	Typ of Landscape
0	0.0002	100	Ocean
0.5	0.0024	73	Flat land, greenland, coastal land
1	0.03	52	Open agricultural land
1.5	0.055	45	Wide agricultural land
2	0.1	39	Medium agricultural land
2.5	0.2	31	Narrow agricultural land
3	0.4	24	Settlements, forest etc.
3.5	0.8	18	Cities with high buildings
4	1.6	13	Big cities

2.3 Calculating the Wind Speed Distribution Using Statistical Methods

Formula (3) shows the statistics by the Rayleigh distribution, formula (4) shows the mother function, the Weibull distribution. If the shape factor C of Weibull is set = 2, it results in the simplified so-called Rayleigh distribution [8], [9].

Rayleigh distribution

$$f(v_i) = \frac{\pi}{2} \frac{v_i}{v_m^2} e^{-\frac{\pi}{4} \left(\frac{v_i}{v_m} \right)^2} \quad (3)$$

Weibull distribution

$$f(v_i) = \frac{C}{A} \left(\frac{v_i}{A} \right)^{C-1} e^{-\left(\frac{v_i}{A} \right)^C} \quad (4)$$

with

C : Shape factor = form factor (—)

A : Scale factor (m/s)

$$A = \frac{2}{\sqrt{\pi}} * v_m$$

Figure 1 (a) shows as an example of a Rayleigh probability distribution of the wind-speed v at hub elevation of 100 m a.s.l. as $f(v)$ in the nearshore in Germany (Northern Sea), calculated with the program Excel.

Figure 1: (a) Example of Rayleigh distribution of wind-speed, (b) Scheme of the ideal energy flow at the hub

Figure 1 (b) shows idealized energy flow scheme at the hub of a wind energy turbine. In the early 20th century Albert Betz postulated the so-called Betz-theorem, which defines the maximum efficiency of an aerodynamic updraft system (Albert Betz in 1923) not to exceed 0.5926 [11].

3 Numerical Simulation with WindCalc 1.5 – Forecasting the Yearly Electrical Yield

In order to get input data for the calculation mentioned above, (i) to estimate the local wind potential in form of wind speed distribution or mean data, wind direction etc., the following sources and/or tools usually are used:

1. Weather forecast service authorities (long-term statistics)
2. In Europe: Regional and European wind atlas
3. Wind simulation programs
 - a. WindPRO 3.4 (EMD) [12]
 - b. WindCalc 1.5 (authors, [13])
 - c. Others
4. On-site-measurement surveys
5. Expertise without measurement

3.1 Calculating the Rated Power and Estimating the Yearly Electrical Yield

The formulas (5) and (6) explain the flow of kinetic energy in the wind, the extractable electric power respecting technical efficiencies and finally the total yield (refer to figure 1 (b)).

Physics of the wind and the machinery

$$P_{el}(v_i) = 0.5 c_{p, anl}(v_i) A \rho v_i^3 \quad (5)$$

and

$$W_{el, a} = \sum_{i=1}^n (P_{el}[v_i] t[v_i]) = \sum_{i=1}^n (0.5 c_{p, anl}[v_i] A \rho v_i^3 t[v_i]) \quad (6)$$

with

$$\begin{aligned} E_{kin} &= 0.5 * m * v^2 \quad | \quad d/dt \\ dE_{kin}/dt &= P_{kin} = 0.5 * dm/dt * v^2 \\ V &= A * x \quad | \quad d/dt \\ dV/dt &= A * v \\ m &= V * \rho \quad | \quad d/dt \\ dm/dt &= dV/dt * \rho = A * \rho * v \\ P_{kin} &= 0.5 * dm/dt * v^2 \\ P_{kin} &= 0.5 * A * \rho * v^3 \\ P_{el} &= 0.5 [c_{p, Betz} * \Pi_j \eta_j] * A * \rho * v^3 \\ c_{p, anl} &= c_{p, Betz} * \Pi_j \eta_j = c_{p, Betz} * \eta_{rotor} * \eta_{bearing} * \eta_{gearbox} * \eta_{generator} \end{aligned}$$

As an object of an own former investigation, the wind farm Rüdersdorf near Berlin had been examined. Task was to investigate whether (i) the 20 years old field can be repowered by modern technology, under the limitation (ii) that the nine wind turbines are to be replaced only by one new system, (iii) taking into account the same electric yield.

It could be shown, that the tool was sufficient to solve such technical questions in a quick and financially convenient way. Indeed, it proved one new wind energy system can substitute more than 5 machines from the 90ies. Results of this former simulation of the wind farm Rüdersdorf near Berlin using the Enercon E-101 are presented below (see Figure 2).

Figure 2: Results for simulation scenario taken from WindCalc 1.5 (repowering of the Rüdersdorf wind farm, nearby Berlin, [13])

3.1.1 Resume

The Excel based program code WindCalc had been established as an alternative calculation tool to professional simulation programs such as WindPRO. Their advantage is to cover several of the needs of professional work in the field of developing wind farm project often on high level, so noise emission and shading analysis, computer flow simulation and so on. On the other hand, in the field of science and education often such tools simply are too expensive to be applied.

4 Conclusions

This paper had been targeted (i) to report about development and state of the art of the wind energy to contribute clean electricity for the future, (ii) to show the importance to support and develop the further application while there are significant potentials in several countries, (iii) to demonstrate that wind energy is an environmentally friendly and clean technology in order (iv) to provide a certain portion of the domestic electricity at a feasible price.

On one hand, in countries such as Germany during the last decades wind energy grew fast and properly to contribute nowadays around 25% of the net electricity consumption. On the other hand, still electricity (hereby mainly the coal power) contributes nearly 40% of the national CO₂ emission in Germany, around 290 Mill. tons per year from power plants in 2018 [14].

Several countries own significant wind potentials. 2% of a country's area can be used for wind farms, thus Germany could produce easily up to 200 TWh_{el} yearly just onshore. However, often legal (or political) and especially financial aspects decide about the speed of development, so the German EEG [15]. Careful project preparation guaranteed by professional management is obligatory. Beside (i) rights to the property and (ii) electric grid connection, (iii) the sufficien-

cy of the wind plus peripheral conditions need be known. A proper wind forecast and yield prognoses are important items.

To solve these tasks, professional programs are sold on the markets, such as the WindPRO issued by the Danish software producer EMD. To offer a convenient alternative for students and researchers as well as project developers, authors presented the software based on Excel named as WindCalc 1.5 which is still under development.

5 References

- [1] BWE [Bundesverband Windenergie], <https://www.wind-energie.de/themen/zahlen-und-fakten/>, 2020.
- [2] BMU [German Federal Ministry for Environment, Nature Conservation and Nuclear Safety], „Erneuerbare Energien in Zahlen - nationale und internationale Entwicklung“, [brochure], 112 p., 2013.
- [3] GWEC [Global Wind Energy Council], „Global Wind Statistics 2014“, <https://gwec.net/publications/global-wind-report-2>, 2015.
- [4] R. Ata, “The Current Situation of Wind Energy in Turkey”, *Journal of Energy*, vol. 2013, [8 p.], 2013, Art. 794095.
- [5] R. Gasch, J. Tvele [ed], “Wind Power Plants – Fundamentals, Design, Construction and Operation”, (2nd ed.), Springer, Heidelberg, 2012.
- [6] V. Quaschnig, “Renewable Energy and Climate Change”, (2nd ed.), Wiley IEEE, London, 2019.
- [7] S. Heier, „Nutzung der Windenergie“, (7th Ed. [in German]), Fraunhofer IRB, Stuttgart, 2016.
- [8] BWE [Bundesverband Windenergie], „Online Skript Windenergietechnik“, <http://www.wind-energie.de/de/technik>, 2009.
- [9] B. Schmidt, D. Schmidt, „Grundkurs Windenergie“, Solarinitiative Mecklenburg-Vorpommern e.V., 69 p., 2002.
- [10] I. Troen, E. Lundtang Petersen, „Europäischer Windatlas“, *Roskilde Risø National Laboratory*, 1990.
- [11] A. Betz, „Das Maximum der theoretisch möglichen Ausnützung des Windes durch Windmotoren“, *Zeitschrift für das gesamte Turbinenwesen*, vol. 26, 1920.
- [12] EMD [International A/S], WindPRO 3.4, <http://www.emd.dk/windpro/>, 2020.
- [13] L.B. Giese, S. Fürkus, A. Eltez, S. Rolle, “Simulating the Electric Yield of Wind Farms – A Short Introduction into how to Develop Wind Projects Supported by an Excel Based Program Code”, *Proc. 3rd Anatolian Energy Symposium (AES) Muğla/Turkey*, 10 p., 2015.
- [14] BMWi [German Federal Ministry for Economics and Technology], “Energiedaten - nationale und internationale Entwicklung”, EXCEL file, (internet update 2020/03/31 download: www.bmwi.de), 44 sheets, (2020).
- [15] Deutscher Bundestag, „Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG 2017)“, https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl#_bgbl_%2F%2F%5B%40attr_id%3D%27bgbl116s2258.pdf%27%5D1592139475498, 2020.