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Modelling of cost indicators for wind turbines of multimegawatt class in various sizes

V Podhurenko¹, Yu Kutsan² and V Terekhov²

¹ Admiral Makarov National University of Shipbuilding, 9 Prospect of Heroes of Ukraine, Nikolayev 54025, Ukraine

² G.E. Pukhov Institute of Problems Modeling in Energetics NAS of Ukraine, 15 General Naumov Street, Kyiv 02000, Ukraine

E-mail: vl.terekhov86@gmail.com

Abstract. The choice of wind turbines to fit various specific wind conditions for the purpose of ensuring maximum generation of electric power at least investment expenditures is among the wind power sector overarching challenges. Solving this task involves the evaluation of cost indices for wind turbines of various sizes. A well-known and rather popular with investigators model, made by the National Renewable Energy Laboratory (USA) has been improved for the first time with the aim of determining the cost of wind turbines of various sizes on the basis of their main parameters (rated power, rotor diameter, hub height) for current conditions of application. The established correlation relationships between the cost of wind turbine and its main parameters made possible the transformation of a well-known complex model into a model with linear equations and minimization of computations. Based on the research studies of the evolution of wind turbines main parameters and an average (global) cost of 1 MW of their power, the authors have suggested the first-ever original linear mathematical models that enable evaluating the wind turbine cost for any year of research. In illustration of application of the first ever developed technique, we have made the assessment of operating efficiency of the US wind farms from 2010 to 2019. The results obtained convincingly indicate the high quality of the developed model.

1. Introduction

One of the vital tasks of the wind power industry consists in choosing a suitable wind turbine (WT) for specific wind conditions to ensure maximum energy production with minimum investment expenditures. For attaining maximum operation efficiency, selection of proper site for wind farm (WF) construction is the most important scientific-and-technical problem. When choosing the site, many factors should be taken into account, including climatic pattern.

The problem of site selection is so much complex and extremely important that many specialists came to the conclusion that it is possible to obtain maximum efficiency only by developing WT design for a specific locality [1 – 4].

The solution of this task assumes determination of a number of indices, which include the cost of wind turbine of specified size.

No information regarding wind turbine cost is available to the public. Wind turbine manufacturers restrict any access to them through commercial databases [5].



Therefore, no wonder that in a number of papers by various authors [6, 7], the estimated cost values for WT's are not in line with current statistical data.

A way out of escaping from this difficult situation can be an independent calculation of wind turbine cost, the more so because the mathematical model that allows to accomplish it is known [8].

Since late 2005, the investigators from the National Renewable Energy Laboratory NREL (USA) have been hard at work on developing a reliable tool for evaluating the cost of both onshore and offshore WT's known as "NREL Wind Turbine Design Cost and Scaling Model" (hereinafter referred to as "NREL CSM"). The said model provides prediction of expenses for wind power using WT's of various sizes. But the said model is not intended for prediction of WT "price formation", which is a function of varying and uncertain market forces that are outside of the purview of NREL investigators. The estimate of expenses is predicted based on the following input data: rated power (P , kW), rotor diameter (D , m), hub height (H , m).

NREL CSM model is based on mathematical modeling of the cost of WT basic components (more than 15), i.e., on the element-by-element analysis, and determination of some of their costs necessitates additional time-consuming calculations of weight parameters.

Despite 15 years of age, this model continues to be popular with investigators [9 – 13], as it is the only tool that enables calculation of WT cost on the basis of its main parameters. The model was developed based on the data obtained in 2002 – 2003, therefore for today the results of modeling require adequate correction.

NREL specialists are constantly engaged in checking the cost of wind electric energy production [14 – 20], yet mathematical models of calculation thereof, as presented, for example, in publication [9], are not available therein.

In view of the above, the only way out is to adjust the calculations of NREL CSM, but the information about the cost of WT's in particular sizes is not freely available, which fact makes it difficult to estimate it. The idea to tie up the results of NREL CSM modeling with current cost statistics is not new. Mark Bolinger and Ryan Wiser [13] corrected the results of modeling with regard for change of producer price index (PPI), which reflects the level of change in prices for raw material, materials, energy sources etc. Regretfully, a stepwise algorithm, coefficients and mathematical models that are not available in the publication make it impossible to independently repeat similar adjustment.

2. Technique and Model development

In 2012 C. Levandowski [10] within the framework of the study on wind turbine towers construction technology, on the basis of NREL CSM calculated the costs C_L of WT's in various sizes for the year of 2012. Let us compare the costs calculations made by Levandowski with the results of NREL CSM modeling C_{N02} (index 02 corresponds to the year of 2002) (Table 1).

Table 1. Wind turbine indices.

No.	P (MW)	D (m)	H (m)	C_L (\$ mln)	C_{N02} (\$ mln)	C_L / C_{N02}
1	1.5	77	80	1.731	1.369	1.26
2	2.5	100	80	3.048	2.426	1.26
3	1.5	110	100	2.163	2.410	0.89
4	2.5	90	100	3.322	2.251	1.48
5	3.6	104	100	4.622	3.423	1.35
6	2.5	112	120	3.793	3.116	1.22
7	3	117	120	4.454	3.626	1.23
8	3	122	140	4.880	4.022	1.21
9	5	129	140	8.027	6.294	1.28

We can observe from the Table 1 that for the period of 2002 – 2012, the cost of WT's (except for line 3) increased by more than 1.2 times. However, according to the data [21, 22], over the period of 2000 – 2002 the WT cost amounted to \$700/kW, and in 2012 – \$1300 – 1400/kW, i.e., it increased by

a factor of 1.86 – 2, which is evidently in variance with the ratios given in Table 1 and indicates that Levandowski took into consideration some other indices in his recalculations.

The indicated [21, 22] statistical information reflects year-wise average costs of the most commonly available WT's in selected year, which can be presented as WT's with annual mean averaged parameters. But these parameters increase year in year out, and to compare the costs of WT's with identical parameters but of different years of publication (as is shown in the Table 1) on the basis of these statistic data is not quite correct.

Let's determine what average parameters for 2002 the WT possessed, the cost c_{02} being equal to \$700/kW.

The works [23, 24] contain rated powers of the WT's installed in Germany over the years of 1988 – 2001 (Table 2).

Table 2. Average values of rated power of the WT's installed in Germany.

Years	<i>P</i> (kW)		
	As per [23]	As per [24]	Average values
1997	628.9	623	626.0
1998	785.6	783	784.3
1999	935.5	919	927.3
2000	1114	1101	1107.5
2001	1278	1281	1279.5

Table values are excellently described with the aid of the linear regression equation with determination factor $R^2 = 0.9983$: $P = 163.03 \cdot Y - 324952$, where Y – year.

By using extrapolation of the data in the last five years, the WT's average rated power was determined in 2002 at the level of 1434 kW.

According to NREL 2012 report [25], the average parameters of WT's over the period of 2000 – 2005 were: $P = 1500$ kW, $D = 70$ m, $H = 70$ m.

Javier Serrano-González [26] dealt with the problem of WT sizes historical evolution. His research covers the span of time soon after 2002 (2005 – 2012 (2014)). According to the published data for Europe and North America, excluding Asia and the rest of the world, the numerical average values of WT's parameters (Table 3) and respective linear relationships were defined.

Table 3. Wind turbine parameters evolution

Year	<i>P</i> (MW)	<i>D</i> (m)	<i>H</i> (m)
2005	1.5	72	72
2006	1.6	74	78
2007	1.7	77	82
2008	1.8	78	79
2009	1.9	81	83
2010	1.9	83	85
2011	2.1	86	87
2012	2.1	90	91
2013	2.2	91	
2014	2.3	96	

Based on the table data, the linear regression equations were determined (Fig. 1):

$$P = 0.0806 \cdot Y - 160.1 \quad (1)$$

$$D = 2.5515 \cdot Y - 5044.7 \quad (2)$$

$$H = 2.2798 \cdot Y - 4497.1 \quad (3)$$

where Y – year.

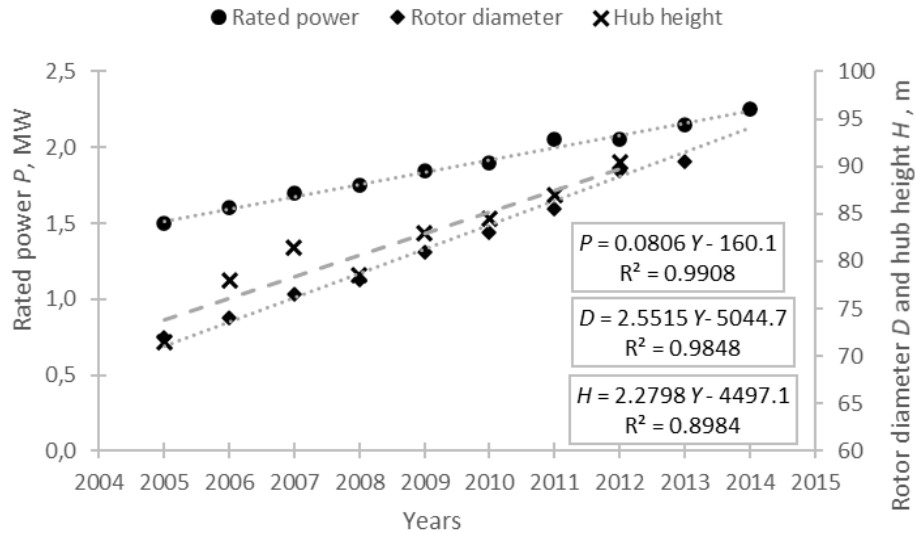


Fig. 1. WT parameters evolution.

As a result of extrapolation of the dependencies obtained for 2002, the following WT parameters were determined: $P_{02} = 1261$ kW, $D_{02} = 63$ m, $H_{02} = 67$ m. Having taken these parameters as yearly average ones, we will determine the cost of the reference WT on the basis of NREL CSM model [8]. Its cost amounted to \$982 600 or \$779/kW, which approximates the IRENA data [21] (\$700/kW).

Having taken as an average cost AC_{02} , which is equal to \$779/kW (\$ 0.779 mln/MW), we will determine how the cost of other WTs changes, depending upon their parameters. For this purpose, based on NREL CSM model, we will calculate the costs of WTs of various sizes by world manufacturers and analyze deviations of their costs from AC_{02} using as an example the parameter k_{02} that defines by how much the cost of the selected WT differs from AC_{02} (Table 4).

Table 4. Cost comparison of WTs of various sizes.

No.	Manufacturer, WT model*	P (MW)	D (m)	H (m)	C_{N02} (\$ mln)	c_{N02} (\$ mln/MW)	$k_{02} = c_{N02} / AC_{02}$ (units)
1	Reference ₀₂	1.261	63	67	0.983	0.779	1.000
2	Enercon E58	1	58	59	0.789	0.789	1.013
3	Siemens SWT 1.3	1.3	62	68	0.987	0.759	0.975
4	GE 1,5 sl	1.5	70	65	1.168	0.779	1.000
5	GE 1.6	1.6	82.5	80	1.530	0.956	1.228
6	GE 1.7	1.7	100	96	2.129	1.252	1.608
7	Enercon E66	1.8	70	86	1.386	0.770	0.988
8	Vestas V90	2	90	95	1.968	0.984	1.263
9	Siemens SWT 2.3	2.3	93	80	2.121	0.922	1.184
10	Fuhrlander FL 2.5	2.5	100	100	2.548	1.019	1.308
11	GE 2.75	2.75	100	98.3	2.683	0.976	1.252
12	Enercon E115	3	115	122	3.557	1.186	1.522
13	Nordex N100	3.3	100	100	3.059	0.927	1.190
14	Enercon E126	3.5	127	135	4.583	1.309	1.681

Note: * – WT parameters are taken from [27].

It is necessary to define correlation relationship between parameters P , D , H and k_{02} . For this purpose, we will use the tool "Correlation" from the "Data Analysis" of MS Excel program (Table 5).

Table 5. Correlation Matrix.

	P	D	H	k_{02}
P	1			
D	0.899178	1		
H	0.887323	0.947408	1	
k	0.646873	0.902691	0.861513	1

We can observe from Table 5 that parameter k_{02} is strongly influenced both by the size of rotor D (0.903 – strong correlation) and by hub height H (0.861 – strong correlation), and, to a lesser degree, by rated power P (0.646 – moderate correlation).

Let us determine the following linear regression equation: $k_{02} = a_0 + a_1P + a_2D + a_3H$.

For this purpose, we will use the tool "Regression" from the "Data Analysis" of MS Excel program.

As a result, we obtain the following mathematical model:

$$k_{02} = 0.08379 - 0.27505 \cdot P + 0.01542 \cdot D + 0.00414 \cdot H \quad (4)$$

The obtained model (4) has a high coefficient of multiple correlation R (0.98530), high coefficient of determination R^2 (0.97082), relatively small standard error (0.04582). The model is significant as a whole according to Fisher and Student, that is, it has no visible limitations.

On defining the parameter k_{02} from the equation (4), we can calculate the cost of WT from the equations:

$$c = k \cdot AC, \quad [\$ \text{ mln/MW}] \quad (5)$$

or

$$C = k \cdot P \cdot AC. \quad [\$ \text{ mln}] \quad (6)$$

If there is no need in determination of WT units cost, the equations (4) – (6) fully release the investigator from the necessity of making calculations according to NREL CSM model that includes around 30 equations, which fact essentially saves time and efforts.

Based on the statistics [21, 22] let us define the regression equation that will enable to determine WT AC depending on the selected year (Table 6).

Table 6. World average cost (AC) of WT.

Year	AC (\$ mln/MW)		
	As per [21]	As per [22]	Average values of AC
2002	0.700		0.700
2004	1.180		1.180
2005	1.360		1.360
2006	1.345		1.345
2007	1.465		1.465
2008	1.570	1.560	1.565
2009	1.720	1.840	1.780
2010	1.485	1.515	1.500
2011	1.400	1.350	1.375
2012		1.300	1.300
2013		1.235	1.235
2014		1.265	1.265
2015		1.200	1.200
2016		1.130	1.130
2017		1.025	1.025

The data of Table 8 on the time spans of 2002 – 2009, 2010 – 2017 are fairly well described by the linear regression equations with determination coefficients $R^2 = 0.93$:

$$AC = 0.1365 \cdot Y - 272.41 \quad (7)$$

For the years Y of 2002 – 2009 and for the years Y of 2010 – 2017 and further:

$$AC = -0.0574 \cdot Y + 116.79 \quad (8)$$

On the basis of equation (4), let us define what fold the cost of WTs under investigation is higher (or lower) relative to the WTs with average parameters for any year under investigation, by using the following formula:

$$k = 1 - 0.27505 \cdot (P - P_Y) + 0.01542 \cdot (D - D_Y) + 0.00414 \cdot (H - H_Y), \quad (9)$$

where: P_Y, D_Y, H_Y – WT parameters for the year under investigation.

With the first developed mathematical models at our command aimed at calculation of the costs of WTs of various sizes in multimewatt class, we will change over to defining the cost of the electrical power generated by them.

3. Comparison of actual and calculated indicators on the example of US wind farms

The COE is the most comprehensive technical-and-economic criterion that enables to assess a wind power project from the standpoint of its investment attractiveness. The up-to-date industrial WF's are commercial projects, with this in mind all the technical indices of WTs should be considered chiefly from the standpoint of their economic expediency. The COE is calculated from the formula [28]:

$$COE = ((FCR \cdot CapEX) + OpEX) / AEP \quad (10)$$

Where: FCR – fixed charge rate of fees – annual expenses for covering capital and other fixed expenses. According to [19], actual average FCR for onshore WF in 2018 was 7.5%;

CapEx – initial capital expenditures for construction of WF. It is known that WT cost of the CapEx value amounts to 60 – 70% [13], 70 – 80 % [29], 64 – 84% [21] or 75.6 [30]. For further calculations, let us assume that:

$$CapEX = C / 0.75 \quad (11)$$

OpEx (or O&M) – annual operational expenditures; AEP – WT annual energy production.

From the NREL reports, the dynamics of the averaged technical and economic indicators (TPI) of the US reference wind turbines for a ten-year period is known [14 - 20]. Taking from it the initial data, for example, for 2010: $P = 1.5$ MW; $D = 82.5$ m; $H = 80.0$ m; $FRC = 0.095$, $OpEX = \$34/\text{kW}$, $AEP = 5017.5$ MW·h, we calculate by the first proposed models of their TPI in the same year: $P_{10} = 1.9$ MW; $D_{10} = 83.8$ m; $H_{10} = 85.3$ m; $AC_{10} = \$1.416$ mln/MW; $k_{10} = 1.068$; $c_{10} = \$1.512$ mln/MW; $C_{10} = \$2.268$ mln; $CapEX_{10} = \$3.024$ mln and the COE generated by US wind farms in 2010 by (10): $COE = (0.095 \cdot 3.024 \cdot 10^6 + 34 \cdot 1.5 \cdot 10^3) / 5017.5 = \$67.4/\text{MW} \cdot \text{h}$.

The COE for other analyzed years is determined in a similar way (Table 7).

Table 7. Comparison of estimated and factual cost indices.

Years	Cost of WT (\$ mln)			CapEx (CE) (\$ mln)			Cost of energy (\$/MW·h)		
	C	C_Y	$ C - C_Y / C, \%$	CE	CE_Y	$ CE - CE_Y / CE, \%$	COE	COE_Y	$ COE - COE_Y / COE, \%$
2010	2.180	2.268	4.0	3.233	3.024	6.5	71.0	67.4	5.1
2013	2.548	2.606	2.3	3.300	3.476	5.3	66.0	69.1	4.7
2014	2.656	2.545	4.1	3.317	3.395	2.4	65.0	66.7	2.6
2015	2.714	2.496	8.0	3.380	3.328	1.5	61.0	60.3	1.1
2017	2.914	2.730	6.3	3.735	3.640	2.5	47.0	46.1	1.9
2018	2.786	2.680	3.8	3.528	3.573	1.3	42.0	42.6	1.4
2019	2.959	2.704	8.6	3.945	3.605	8.6	37	35.7	3.5
Average relative error			5.3			4.0			2.9

The results of Table 7 clearly indicate that the highest accuracy of mathematical modeling was achieved based on the results of calculations of the COE and CapEx, slightly less – when calculating the cost of wind turbines.

4. Conclusions

In the conditions of restricted access to the information relating to the cost of wind turbines, it is for the first time that the technique of cost parameters estimation for WT of specific size has been suggested on the basis of the statistical data available to the public.

For the purpose of investigating the influence of size of wind turbine upon its cost, the authors employed a well-known and quite popular mathematical model of WT costs by the National Renewable Energy Laboratory (NREL), USA. As a result of the research investigation, a cumbersome (complex) original model was simplified by replacing it with a linear regression equation of the cost deviation of the wind turbine under consideration from statistically average one and was improved and brought up to date with regard for developed linear equations of averaged cost behavior and parameters evolution of wind turbine.

The first-ever developed linear mathematical models basically present the unique solution that allows to determine the cost of wind turbines based on their main parameters (rated power, rotor diameter and hub height) for any year of research.

The developed technique makes it possible to determine the optimal WT parameters as early as at the wind farm design stage by setting the cost of the energy produced by WT in the form of optimization function in compliance with available sizes of WTs in the world market.

References

- [1] El-Ahmar M, Abou-Hashema M and Hemeida A 2017 Evaluation of factors affecting wind turbine output power Proc. 2017 Nineteenth International Middle East Power Systems Conference (MEPCON) pp 1471 – 1476
- [2] Khalfallah M and Koliub A 2007 Suggestions for improving wind turbines power curves Proc. the Ninth Arab Intern. Conf. on Solar Energy (AICSE-9) 221 – 229.
- [3] Salih S, Taha M and Alawsaj M 2012 Performance analysis of wind turbine systems under different parameters effect International Journal of Energy and Environment (IJEE) **3** 895–904
- [4] Bencherif M, Brahmi B and Chikhhaoui A 2014 Optimum selection of wind turbines Science J. of Energy Eng. **2**(4) 36–46
- [5] Saint-Drenan Y-M, Besseau R, Jansen M, Staffell I, Troccoli A, Dubus L, Schmidt J, Gruber K, Simões S and Heier S 2020 A parametric model for wind turbine power curves incorporating environmental conditions Renewable Energy **157** 754–768 doi: 10.1016/j.renene.2020.04.123.
- [6] Soulouknga M, Oyedepo S, Doka S and Kofane T 2020 Evaluation of the cost of producing wind-generated electricity in Chad International J. of Energy and Environmental Engineering **11** 275 – 287. 10.1007/s40095-019-00335-y.
- [7] Charabi Y and Abdul-Wahab S 2020 Wind turbine performance analysis for energy cost minimization Renewables: Wind, Water, and Solar **7** 11 p 10.1186/s40807-020-00062-7.
- [8] Fingersh L, Hand M and Laxson A 2006 Wind turbine design cost and scaling model (United States) p 38
- [9] Longfu L, Xiaofeng Z, Song D, Weiyi T, Li L and Xiaoyu T 2019 Minimizing the energy cost of offshore wind farms by simultaneously optimizing wind turbines and their layout Applied Sciences **19** doi:10.3390/app9050835.
- [10] Levandowski C 2015 Evaluating tall wind turbine towers in the field. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1116&context=undergradresearch_symposium

- [11] Ning A and Dykes K 2014 Understanding the benefits and limitations of increasing maximum rotor tip speed for utility-scale wind turbines (United States)
- [12] Karczewski M, Domagalski P, Wingerde A, Stoevesandt B, Jamieson P and Sætran L 2020 Potential of load and O&M costs reductions of multi rotor system for the south Baltic Sea Wind Energ. Sci. Discuss. (preprint) doi:10.5194/wes-2020-23.
- [13] Bolinger M and Wiser R 2011 Understanding trends in wind turbine prices over the past decade DOI:10.2172/1051290 <https://www.osti.gov/biblio/974157>
- [14] Tegen S, Hand M, Maples B, Lantz E, Schwabe P and Smith A 2012 2010 Cost of wind energy review (Technical report NREL/TP-5000-52920) (Golden CO: NREL) 111 p <https://www.nrel.gov/docs/fy12osti/52920.pdf>.
- [15] Moné C, Smith A, Maples B and Hand M 2015 2013 Cost of Wind Energy Review (Technical Report NREL/TP-5000-63267) (Golden CO: NREL) p 97 <http://www.nrel.gov/docs/fy15osti/63267.pdf>.
- [16] Moné C, Stehly T, Maples B and Settle E 2015 2014 Cost of Wind Energy Review (Technical report NREL/TP-6A20-64281) (Golden CO: NREL) p 85
- [17] Moné C, Hand M, Bolinger M, Rand J, Heimiller D and Ho J 2017 2015 Cost of Wind Energy Review (Technical Report NREL/TP-6A20-66861) (Golden CO: NREL) p 91
- [18] Stehly T, Beiter Ph, Heimiller D and Scott G 2018 2017 Cost of Wind Energy Review (Technical Report NREL/TP-6A20-72167) (Golden CO: NREL) p 46
- [19] Tyler S and Beiter Ph 2020 2018 Cost of Wind Energy Review (Technical Report NREL/TP-5000-74598) p 71
- [20] Stehly T, Beiter P and Duffy P 2020 2019 Cost of wind Energy review (Technical report NREL/TP-5000-78471)(Golden CO: NREL) p 86
- [21] IRENA 2012 Renewable energy technologies: cost analysis series 1(5/5) 64
- [22] Bloomberg NEF 2018 2H 2017 Wind turbine price index. <https://about.bnef.com/blog/2h-2017-wind-turbine-price-index>
- [23] Ackermann T and Soder L 2002 An overview of wind energy-status 2002 Renewable and Sustainable Energy Reviews **6** 67–127. doi:10.1016/S1364-0321(02)00008-4.
- [24] EWEA 2003 Wind Force 12 report. <http://archivo-es.greenpeace.org>
- [25] Lantz E, Wiser R and Hand M et al 2012 IEA Wind task 26: the past and future cost of wind energy Work Package 2 Technical Report NREL/TP-6A20-53510. [http://www.etiea.cn/data/attachment/WP2_task26\(1\).pdf](http://www.etiea.cn/data/attachment/WP2_task26(1).pdf)
- [26] Serrano-González J and Lacal-Arántegui R 2016 Technological evolution of onshore wind turbines a market-based analysis Wind Energ **19** 2171– 2187
- [27] Wind turbines 2021 <https://en.wind-turbine-models.com/turbines>
- [28] Han Y, Jin C and Xiaoping P 2018 Wind Turbine Optimization for Minimum Cost of Energy in Low Wind Speed Areas Considering Blade Length and Hub Height Applied Sciences **8** 1202
- [29] Bolinger M and Wiser R 2009 Wind Power Price Trends in the United States Preprint of article published in Modern Energy Review (Lawrence Berkeley National Laboratory)
- [30] WindFacts 2021 <https://www.wind-energy-the-facts.org/index-43.html>