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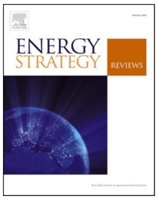

The efficiency of wind power companies in electricity generation

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ABSTRACT

This study analyses the assessment of the relative efficiency of electricity generation of 78 wind power companies in 12 selected European countries. The basic purpose is to identify the factors that improve the efficiency of wind power companies as important producers of renewable electricity. The Data Envelopment Analysis method was applied (input-oriented BCC model). Considering the required average improvements in input variables, different projection amounts aiming to move individual factors to the efficiency frontier, ranging from 3.6% to 10.2%. This is the first study to analyse the comprehensive performance of wind power companies including their economic and technical characteristics, which is a major divergence from previous studies and makes a significant contribution to the development of wind energy.

1. Introduction

World research point to the importance and the need to study the restructured electricity sector with the aim of improving individual activities of the sector. In this view, electricity generation is the key segment in the process of electricity supply to consumers, and in the realization of possible multiplicative effects on the economy, but also negative externalities, primarily ecological ones. Renewable energy sources preserve the environment and are considered suitable solutions in electricity generation demands. Presently, renewable energy sources have become extremely attractive worldwide due to their significant ability to participate in electricity markets [1]. Wind power companies are specific in production of electricity primarily because they do not cause the cost of energy resource or fuel and require a minimal (or not at all) labour force in electricity generation from wind power. As a significant and prospective form of renewable energy sources in electricity generation, wind energy is an important in highly developed countries. For example, Denmark targets to integrate 50% of electricity from wind energy by 2020 [2].

Nowadays, one of the most important companies' issues is performance evaluation. Efficient and smooth performance is crucial for successful business. Evaluation methods of companies' performance can help decision makers to gain an insight into the current situation and position of the company on the market and achievement of the desired objectives. One of the relatively new methods (Charnes, Cooper and Rhodes introduced it in 1978), while being flexible and informative in many ways, that can be used to measure company performance is Data Envelopment Analysis (DEA), which is used in this paper.

Hence, evaluation of performance efficiency is the main subject of this research. The objective of the paper is the assessment of the relative efficiency of wind power companies from selected countries of the European community. Moreover, by using DEA methodology, the basic purpose is to identify the factors that will improve the efficiency of wind power companies as important producers of electricity from renewable energy sources. In addition to the relative efficiency results of each wind power company, by means of projections on the efficiency frontier, sources and amounts of relative inefficiency were determined, which represent potential improvements for all inefficient wind power companies.

The relevance of this paper can be found in the fact that for the first time it evaluates the relative efficiency of 78 wind power companies throughout Europe, i.e., from eleven selected EU countries and one non-EU country. To the best of authors' knowledge, so far there has not been any research that includes such a huge number of wind power units across Europe. Additionally, this is the first research that analyses the comprehensive performance of wind power companies including their economic and technical characteristics, in which sense it represents a huge divergence from existing studies, a qualitative step forward and a significant contribution of the paper to this area of research.

Accordingly, the basic hypothesis of the research is set as follows: With the scientifically based knowledge on the specifics of electricity generation from renewable sources using wind energy, and considering the existing degree of efficiency of wind power companies in European countries, it is possible to extract factors that impact the efficiency of

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wind power companies in the electricity generation. Furthermore, this research confirms the importance of managing companies' overall resources (economic and technical aspects of wind power companies) since the obtained data have a direct impact on the efficiency of wind power companies in the observed European countries.

2. Theoretical basis and literature review

As a starting point for the theoretic basis of the production processes, in this paper we employ the most commonly used functional form of the production function which is the Cobb-Douglas production function [3]. Since the initial empirical work in 1928, many studies have tended to support the hypothesis that production processes are well described by a linear homogeneous function [4]. The Cobb-Douglas production function represents the relationship between two or more inputs, which are typically physical labour and capital, and the number of outputs that can be produced by those inputs. As it will be shown below, a modified form of the Cobb-Douglas production function is presented in this paper.

Regarding to the fact that wind power industry is very highly technologically automatized, instead of the labour and capital as inputs, in this research we apply capital and fuel expressed in different units. These inputs are transforming to outputs, i.e., annual electricity production (GWh) and EBITDA (EUR), which are included in the model of the research. Along with the corresponding inputs and outputs, the Cobb-Douglas production function may also contain a constant which is referred as technological progress or total factor productivity (TFP). It measures the change in output that is not the result of the inputs. Typically, this change in TFP can be the result of an improvement in efficiency or technology. Given the above-mentioned, it is important to emphasize that the relative efficiency, as a measure of performance evaluation, does not imply technological progress. So, in this research it is assumed (ceteris paribus) that technology is given, i.e., the constant level of technological development.

In the early 1980s, the application of the DEA methodology was recorded in the power sector. The first authors who used the DEA method in the electricity generation were Färe, Grosskopf and Logan [5] who evaluated the relative efficiency of electric power companies in the American state of Illinois between 1975 and 1979 and found that only a few companies were technically efficient in comparison with other companies. Since then, a huge number of studies have been conducted in evaluating relative efficiency of energy sector by using DEA methodology (e.g. Refs. [6,7]). To the best of authors' knowledge, in the literature can be found only two studies measuring the relative efficiency of wind farms and wind turbines by using DEA method, and one study assessing the performance of wind farms by using stochastic frontier models.

Iglesias, Castellanos, Seijas [8] measure the productive efficiency of 57 Spanish wind farms located in the region of Galicia during the period 2001–2004 using the frontier methods Data Envelopment Analysis and Stochastic Frontier Analysis (SFA). Some of the results indicate that the average technical efficiency is high, exceeding 75% in both DEA and SFA models, i.e., that the average SFA efficiency of 0.8192 is higher than the CCR averages and inferior to the BCC averages. Moreover, the results do not show significant changes in the annual efficiency scores for each wind farm. However, the results must be considered with caution given the limited number of wind farms and years studied.

Ertek, Tunç, Kurtaraner, Kebude [9] present a data-centric analysis of 74 commercial on-shore wind turbines of leading manufacturers in the world. They provide multidimensional benchmarking through DEA, visual data analysis by using scatter plots, surface plots and graph visualization, and statistical hypothesis testing. Evaluating the relative efficiency, two DEA models were constructed depending of the wind speed. The first model resulted in 4 relative efficient wind turbines among the 74 included, while the second model resulted in 5 relative efficient wind turbines among the 32 included.

Pestana Barros and Sequeira Antunes [10] analyse the technical efficiency of 65 Portuguese wind farms during the period 2004–2008 by using SFA models regarding to ownership and unobserved managerial ability as factors affecting the performance of wind farms. The results of the research reveal that the Portuguese wind farms are heterogeneous, and that managerial practices, ownership by an energy companies and firm size all have a positive impact on the efficiency of wind farms.

Unlike the existing studies that focused on a multi-year period and the so-called "DEA window analysis", the study in this paper focuses on a one-year period. Furthermore, this paper covers a very wide geographical area (almost half of the EU countries and one non-EU country), in comparison to previous studies focusing only on one country.

Additionally, in the literature can be found numerous wind energy studies analysing their dynamic behavior throughout the year. As presented in some research studies [11], increased interest in wind turbines to generate electrical power entails studying and modeling the steady state and dynamic behavior of the wind turbine in laboratory conditions to prevent possible problems during installation and later use. A novel sensorless-based modeling for wind energy system is developed by using a torque-controlled squirrel-cage induction motors as the wind turbine simulator. Another study investigates the dynamic behavior of a three-dimensional model of one-stage straight bevel gear system (mechanical gear transmission) used in vertical axis wind turbine in transient regime. It is found that the rotational speed of the rotor shaft has a significant effect on the aerodynamic torque performance [12]. Moreover, Asareh [13] assesses the dynamic behavior of wind turbine structure under different operational states when subjected to simultaneous wind and earthquake loading. Similar research study of dynamic behavior of wind power structures develops an aeroelastic simulation tool for horizontal axis wind turbine. The novelty of this study is to create a general simulation tool for wind turbine applications and not to model a particular turbine (Danwin 180 kW) [14]. It is clear that trend in modern wind turbine design process is development of bigger, lighter and more flexible rotors. However, the issue raised is what happens in ultimate and fatigue loads, at extreme weather conditions, for example. Totsuka, Imamura, Yde [15] analyse the vibration problem under 50-year storm conditions while rotor is parked and blades are feathered. Also, in the design of a wind farm it is important to consider wake effects (downstream wind which leave the turbine and has a lower energy content than the wind upstream of the turbine) in order to maximize the energy output and lifetime of the wind turbines. Evaluating the impact of the wake effect on both the steady-state operation and dynamic behavior of a wind farm, results indicate the importance of wind turbine spacing and the directionality of wind speeds [16]. Although the mentioned aspects of the dynamic behavior of wind energy are very interesting and also deserve appropriate research space, this paper does not enter into the described phenomena, but provides some other relevant insights presented below.

On the other hand, there are studies that are dealing with the issues of climate change and its impact on the wind turbine performance. Examine the impact of climate change on the dynamic behavior and future safety of an offshore wind turbine, founded in clay incorporating dynamic soil–structure interaction, shows that changes in design of offshore wind turbines are really necessary [17]. Due to climate change, it is estimated that wind power potential will increase substantially by 2100, so that it will be a perfect substitute for the lost electricity generated from hydroelectric plants [18,19]. Climate change are often the reason to make an investment into sustainable technologies, such as wind energy technologies, and to integrate large scale wind power into an electricity grid [20]. Finally, it can be found various studies dealing with renewable energy technologies, such as their economic viability [21], their positive and negative economic effects [22], or (in the broader sense) their advantages and disadvantages in general, without considering any individual type of renewables [23].

3. Research methodology

Data Envelopment Analysis is one of the methodologies that is widely used to calculate relative efficiency of numerous Decision Making Units (DMUs) operating in similar conditions. It is a type of non-parametric, comparative, performance analysis, which assumes that there are *n* DMUs to evaluate where not all DMUs are efficient. These DMUs convert multiple inputs into multiple outputs and therefore devising a functional form, relationship between them is not possible (or is unknown to us), but requires verification of the positive correlation between inputs and outputs. DEA is based on mathematical programming and evaluates the efficiency of a DMU relative to a set of comparable DMUs. DEA forms an efficient frontier using efficient units as a standard of best-achieved performance. DMUs that are not relatively efficient are below the efficiency frontier, and DEA then measures the amount of inefficiency (distance from efficiency frontier) of inefficient units whilst making comparisons with the best practice units. DEA also provides a way for inefficient DMUs to achieve an efficient frontier due to projections such as potential changes of inputs or outputs. Evaluating the relative efficiency by using DEA method, it can be assumed an input or output-oriented DEA model. Therefore, efficiency can indicate of a certain/fixed level of outputs with minimum level of inputs or maximizing output with existing level of inputs. The methodology can be valuable, especially in complex situations where numerous DMUs are operating with multiple outputs and inputs, and which cannot be analysed using other techniques that may be too complicated for management decision making purposes. Due to DEA method limitation, it is important to emphasize that the minimum number of DMUs should be three times greater than or equal to the sum of the number of inputs and outputs.

One of the basic DEA models is the Charnes-Cooper-Rhodes model (CCR model) based on the constant returns to scale (CRS) assumption and efficiency defined as the ratio of output to input [24]. The Banker-Charnes-Cooper model (BCC model) is another commonly used DEA model based on the assumption of variable returns to scale (VRS) with piecewise linear efficiency frontier [25].

Model represents an input-oriented BCC model that obtains optimal slack values in order to achieve the piecewise linear efficiency frontier. Due to different efficiency frontiers, and compared to the CCR model, BCC efficiency scores for all DMUs under evaluation are better or at least the same as CCR efficiency scores. That is why it is very important to take into account the type of returns to scale before evaluating DMUs. In the following section it would be explained the reason for applying the BCC model, instead of the CCR model.

Model BCC

$$\text{Min}\quad \theta - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right) \tag{3.1}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta x_{io}\ (\mathrm{i} = 1,\dots,\ \mathrm{m}) \tag{3.2}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro}\ (\mathrm{r} = 1,\dots,\mathrm{s}) \tag{3.3}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{3.4}$$

$$\lambda_j \geq 0\ (\mathrm{j} = 1,\dots,\mathrm{n}) \tag{3.5}$$

$$s_i^- \geq 0 \tag{3.6}$$

$$s_r^+ \geq 0 \tag{3.7}$$

The definition for BCC efficiency [26] says that if the optimal solution of the BCC model $(\theta_B^*, \lambda^*, s^{-*}, s^{+*})$ satisfies $\theta_B^* = 1$ and $s^{-*} = 0, s^{+*} = 0$, the DMU_o is BCC efficient and lies on the efficient frontier, otherwise the BCC is inefficient and lies below the efficient frontier. As in the case of the CCR model, the projections for all inefficient DMUs can be calculated as follows.

Inputs:

$$\widehat{x}_{io} = \theta^* x_{io} - s_i^{-*}\ (\mathrm{i}\ \ = 1.,\ .\mathrm{m}) \tag{3.8}$$

Outputs:

$$\widehat{y}_{ro} = y_{ro} + s_i^{+*}\ ((\mathrm{r}\ \ =\ \ 1,\dots,\mathrm{s})) \tag{3.9}$$

4. Description of variables and the model

Out of approximately two hundred wind power companies, this research includes and analyses 78 wind power companies from selected countries of Europe, and namely from Bulgaria (number of wind power companies (n) in the sample = 2), Croatia (n = 2), Germany (n = 4), Greece (n = 1), Ireland (n = 2), Italy (n = 3), Poland (n = 1), Portugal (n = 1), Romania (n = 5), Spain (n = 12), Sweden (n = 39) and the United Kingdom of Great Britain and Northern Ireland (n = 6). Considering the above information, it is important to present the percentage of wind energy in the energy matrix of these countries, to get an impression of their contribution in total electricity generation. With regard to the fact that the observing year in this research is 2014, the share of electricity production from wind for selected countries in 2014 was the following [27]: Bulgaria 2.84%, Croatia 5.43%, Germany 9.41%, Greece 7.33%, Ireland 19.92%, Italy 5.47%, Poland 4.85%, Portugal 23.31%, Romania 9.51%, Spain 18.92%, Sweden 7.32% and the United Kingdom of Great Britain and Northern Ireland 9.53%. From 2014 to 2020, according to the data, Ireland achieved the highest improvement in electricity generation from wind energy (35.13% in 2020), while Portugal had the lowest percentage change (23.69% in 2020).

While forming the research sample by using two relevant databases ("Amadeus" [28] and "The Wind Power" [29])[1], firstly, the wind power companies were selected out of all companies which produce electric energy in the European Union countries and other countries in European territory. Out of the total number of wind power companies (several thousands of them); two hundred of them were selected according to the availability of the number of employee factor, as a generally relevant input and a starting point for forming a model. Then those wind power companies which had the required data available in both mentioned databases were selected and the data unified.

Only those companies which use solely wind energy (and their supplied to the electrical grid) to produce electric energy are included in the sample. That is the only activity of the analysed companies, and therefore, the companies that produce electrical energy from various energy resources are excluded from the sample. In that manner, one of the fundamental assumptions of the DEA method that the companies are mutually comparable and that they are operating in similar conditions is achieved (cf [31]).

The basic approach for the theoretic determination of the production process is the classic production technology described by the Cobb-Douglas production function and which can be, within energy utilities as the electrical energy production function, defined with the following formula:

$$\mathrm{E} = \mathrm{f}\ (\mathrm{L},\ \mathrm{K},\ \mathrm{F}) \tag{4.1}$$

with *E* being the produced electrical energy, *L* labour, *K* capital, *F* fuel (fuel/energy resource is, according to the classic economic theory the natural resource – natural factor).

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[1] The economic data is taken from the database "Amadeus" (https://amadeus.bvdinfo.com), technical data from wind turbine and wind power companies databases "The Wind Power" (http://www.thewindpower.net), and the wind speed and air density data is based on the ECMWF ERA- Interim methodology and were provided by https://www.sander-partner.com [30] upon request.

Inputs and outputs of the model are determined and presented with the following variables:

Inputs:

1 ***Wind turbine power variable*** refers to the nominal installed power of each wind turbine in a wind power company (expressed in kilowatts - kW);
2 ***Wind turbine number variable*** refers to the number of wind turbines located in a vicinity to each other, of the same type and exposed to the same wind;
3 ***Fuel variable*** refers to the speed of the transmission of wind power in a wind turbine which transforms into useable electric energy (expressed in kW);
4 ***Tangible fixed assets variable*** refers to the value of wind power installation, namely the wind turbines (expressed in thousands of EUR);
5 ***Receivables and other short-term assets variable*** includes receivables on state subsidies and incentives or business entities for electricity supplied to the electrical grid, receivables from group and related companies, receivables for short-term advances, time deposits, short-term financial receivables and other short-term financial assets (expressed in thousands of EUR);
6 ***Cash and cash equivalents variable*** refer to the total cash liquid assets, i.e., the money in the bank and/or the treasury and other short-term highly liquid investments owned by a wind power company (expressed in thousands EUR).

Outputs:

1 ***Annual electricity production variable*** refers to the estimated annual electricity generation of a wind power company, assuming the maximum utilization of installed capacities in the period of 2300 h per year (expressed in gigawatt hours – GWh);
2. ***EBITDA variable*** (Earnings Before Interest, Taxes, Depreciation and Amortization) refers to earnings before interest, taxes, depreciation and amortization and is an indicator of financial success of the company because it displays the “pure” profit of the company (expressed in thousands of EUR).

Technical features of the wind power company refer to the technical variables of each individual wind power company and include power and the number of wind turbines and fuel. Wind turbine is the fundamental component of the companies. Naturally, greater installed power of wind turbines enables greater production of electricity. Besides the installed power, it is also necessary to know the number of wind turbines in a wind power company. Their product presents the total nominal power of the company. However, in order to assess the relative efficiency of the company, it is necessary to separately measure the installed power, and the number of wind turbines of a wind power company. The last technical input needed for functioning of the wind power company is the fuel it uses in electricity generation. Essentially, this is the wind, namely the wind speed, which is the exogenous factor, dependant on the atmosphere. While reviewing the literature, it was determined that the wind speed is not significant or good enough variable in calculating the relative efficiency, and that it is necessary to determine a more precise variable for observing the fuel input. The process of forming the input (variable) of fuel is presented below [32]:

E_k = kinetic energy (J)
m = mass (kg)
v = wind speed (m/s)[2]
P = power (W)
N = wind turbine number
$\frac{dm}{dt}$ = mass flow velocity (kg/s)
$\frac{dE}{dt}$ = energy transfer rate (J/s)
ρ = air density (kg/m^3)[3]
A = wind turbine rotor surface area (m^2)
x = distance (m)
t = time (s)
r = blade radius (m)
C_p = power coefficient

From the starting point of the wind energy which it has with the wind flow, the kinetic energy of the mass in movement is presented with the equation:

$$E_k = 1/2\ m\ v^2 \tag{4.2}$$

The power of wind is the speed of transport or the transformation of energy presented in the following equation:

$$P = \frac{dE}{dt} = \frac{1}{2} v^2 \frac{dm}{dt} \tag{4.3}$$

Since the velocity of mass flow is:

$$\frac{dm}{dt} = \rho\ A\ \frac{dx}{dt} \tag{4.4}$$

and the velocity of the change in distance:

$$\frac{dx}{dt} = v \tag{4.5}$$

then it is:

$$\frac{dm}{dt} = \rho\ A\ v \tag{4.6}$$

and the wind turbine rotor surface area is the radius of the rotor’s blade expressed with the circle surface area equation:

$$A = \pi r^2 \tag{4.7}$$

Therefore, including equations (3.3) and (3.6), the wind power for the “entire” wind power company with a certain number of wind turbines can be defined as:

$$P = 1/2\ \rho\ A\ v^3\ N \tag{4.8}$$

Lastly, the kinetic energy of wind in the air flow in a certain time period *t* can be determined by multiplying the wind power with time. It should be noted that the maximum kinetic energy of the wind cannot be used in the wind turbine in which it is transformed into mechanic energy. This was established by German physicist Albert Betz who concluded in 1919 that a wind turbine cannot transform more than 16/27 (59.3%) of kinetic energy of the wind into mechanic energy (the so-called Betz law of Betz border). Therefore, the theoretic maximum of the energy efficiency of any wind turbine is 0.59 and it is called the power coefficient expressed as:

$$C_p = 0.59 \tag{4.9}$$

In order to fully assess the fuel input, Betz coefficient (3.9) also needs to be included into equation (3.8) which implies the final variable of fuels in the following form:

$$P = 1/2\ \rho\ A\ v^3\ C_p\ N \tag{4.10}$$

It is possible to conclude that the fuel variable (P) is determined by air density (ρ), wind turbine rotor surface area (A), wind speed (v), power coefficient (C_p) and the number of wind turbines (N). It is certain that the wind speed is simply one of the components which would not present the complexity of this input. In that view, the quality of fuel variable formed in this manner is especially notable, as a significant contribution in the input creation of this research.

In previous research which evaluated the relative efficiency by the DEA method, the fuel variable was not presented in a such complex equation but was described only partially. Iglesias, Castellanos, Seijas

[2] The wind speed factor is the average wind speed measured at the wind power company area every day from 1/1/2014 until 31/12/2014 every 3 h; at 12 a.m., 3 a.m., 6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., 9 p.m. at the height of 50, 100 or 150 m above ground level (depending on the wind turbine height).

[3] Air density factor is the average air density measured at the wind power company area every day from 1/1/2014 until 31/12/2014 every 3 h; at 12 a.m., 3 a.m., 6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., 9p.m. at the height of 50 m above ground level.

[8], while assessing technical (productive) efficiency of the sample consisting of 57 wind power companies in Spanish province Galicia, define fuel variable with the equation:

$$P = 1/2\ \rho\ A\ v^3, \tag{4.11}$$

without taking into consideration the limited factor of efficiency of energy transformation, in view of Betz coefficient. The mentioned coefficient completes fuel variable by providing the needed limitation in the use of wind power. In another paper, while evaluating the relative efficiency of the 74 commercial on-shore wind turbines whose manufacturers are classified among top 10 worldwide, Ertek, Tunç, Kurtaraner, Kebude [9] analyse the fuel variable only with the nominal wind speed, stating that the main issue in choosing the variables of the models is availability of the data. Finally, none of the authors determined the number of wind turbines (N) as an individual variable but the literature only takes into consideration the overall installed power of the wind power company. In this research, power is analysed by its elements – the installed power of the wind turbine and the number of wind turbines which are the variables that provide a more detailed display of the technical features of each wind power company, namely a more accurate detection in view of possible (potential) measures of individual variable in order to improve the relative efficiency of the company.

The wind speed and air density are determined by the atmosphere meaning that the company has no impact on it and it cannot directly control them. Such variables are called the uncontrollable inputs. However, in the fuel variable, the wind speed and air density present only a small amount compared with the wind turbine rotor surface area. Since the wind turbine rotor is a controllable factor which can be adjusted according to the company's needs in the process of production planning, the fuel variable, with the conditions ceteris paribus, will be presented as a controllable input.

The labour factor (*L*) in the production function appears as one of the fundamental factors of the production. Even though in a company, and in production in general, the labour input has the dominant function very often, in a wind power company the labour input is not necessary once the company starts operating. This is due to the fact that the electricity generation from the wind power is very highly technologically automatized. The studies show that for each 20 MW of installed capacities of the wind power company, only one or two full-time employed workers are needed in order to operate and maintain the wind power company during 20–30 years of its expected duration. It is stated that, in the phases of operation and maintenance of the lifelong cycle of a company, a low level of new employment possibilities is present. A medium level of technological development and a high one is present in the installation and deconstruction stages [22,33]. Furthermore, the majority of "local" workers in the wind industry are temporarily employed during construction (or installation of wind turbines) while the expertise and specialization level in technical maintenance or repairing of defective components of the facility does not need to be on a high level, unlike in the installation/deconstruction stage, and in particular the technological development stage [34]. In addition, in this research, a slight correlation has been established between the labour input, i.e., the number of workers in the wind power company and other observed variables, which confirms the assumption that their correlation does not exist. Therefore, the labour input is omitted (*post festum*) from the model of assessing the relative efficiency of wind power companies, contrary to the findings of individual authors [8]. This is further justified by the fact that approximately half of the wind power companies involved in the sample do not have a single employee in the one-year period of research.

After the technical characteristics of wind power companies, the **economic characteristics** of the models' variables presented as tangible fixed assets; receivables and other short-term assets; cash and cash equivalents of the company follows.

In wind power companies, the tangible fixed assets in its most significant part is the value of a wind power company or wind turbines (in addition to other forms of tangible fixed assets such as real estate, equipment, land and others). Although tangible fixed assets are used in business operations for a long period of time, in this research, the contribution of property to the business efficiency is assessed only during the period of one year.

Short-term assets of wind power companies refer to receivables and other short-term assets. In the context of wind power companies, receivables mostly represent receivables on electricity delivered to the electrical grid from various state authorities, agencies, business entities or energy market operators, as is the example of Croatia. Through its subsidies and incentives, the state purchases electricity generated by wind power companies trying to encourage and further develop renewable energy resources in the wind power segment.

Although both cash and cash equivalents of wind power companies are a part of high-liquidity short-term assets of companies, they are separated for the purposes of this analysis.

It should be noted that the above-mentioned manuscripts (the results of previous research) in the relative efficiency assessment models do not analyse the economic characteristics of wind power companies expressed in monetary units, as it will be shown in this study. Therefore, in previous studies, the allocative efficiency of the subjects is not evaluated, but solely their technical (productive) efficiency. As technical characteristics of wind power companies, Iglesias, Castellanos, Seijas [8] use the total nominal power, i.e., the installed wind power capacities and (previously presented) fuel variable as model inputs, while the electricity delivered to the distribution or transmission grid represents output. On the other hand, Ertek, Tunç, Kurtaraner, Kebude [9] use in their model the three key variables necessary for wind turbine operation: rotor diameter, nominal wind speed and the nominal output (the electrical energy generated by the wind turbine). Finally, it is emphasized a research in which Pestana Barros and Sequeira Antunes [10], using stochastic production econometric frontier, analyse the technical efficiency of sample of Portuguese wind farms from 2004 to 2008, taking into account the endogenous managerial practices, ownership and regulatory control on the heterogeneous cost frontier.

As announced in the methodological part of the research conducted in this paper, apart from six variables related to the model **inputs** (3 technical and 3 economic), the research also includes two **outputs** – generated electricity (technical characteristics) and EBITDA (economic characteristic). Generated electricity, as the only production output in the technical-technological process, is generated by the action of wind power in a wind turbine. The kinetic energy of the wind is originally transformed into mechanical energy and then into electrical energy. Once electricity is produced, it has to be delivered to the electrical grid to be transferred to the consumers and have a useable value. The second output included in the model is EBITDA. This variable directly indicates the company's performance, namely the financial result of the company realized in the observed year (accounting period). In addition to profitability analyses, EBITDA can also be used to evaluate the company's relative efficiency, eliminating the effects of financing decisions, prescribed tax rates, and the application of different accounting policies.

After selecting the appropriate input and output variables in the model for assessing the relative efficiency of wind power companies, the statistics of the observed variables used using the DEA method are presented below (Table 1).

Due to the fact that a number of wind power companies realized a loss in the observed year, with one company having the highest loss of 17.977 monetary units (EUR), and as such are not suitable for assessing relative efficiency, it should be noted that all values in the EBITDA variable are increased for 18.000 monetary units (EUR). This eliminated the negative value of the variable and allowed to evaluate the relative efficiency of the company's positive values, which represent one of the important assumptions of the DEA method. Such interventions are in line with the DEA method assumptions, and this is further explained. Similar as the negative values are not possible, in the mathematical

Table 1
Statistics of inputs and outputs in the DEA model.

	Wind turbine power (kW)	Wind turbine number	Fuel (kW)	Tangible fixed assets (1000 €)	Receivables and other short-term assets (1000 €)	Cash and cash equivalents (1000 €)	*Annual electricity production (GWh)*	*EBITDA (1000 €)*
Max	3600	59	58,406.6	278,774.772	30,628.051	11,856.335	317	51,223.406
Min	225	1	37.44	35.794	0	3.703	0.5	23.021
Average	1532.31	12.22	3352.78	28,533.42	2531.88	1085.57	50.82	20,502.54
SD	743.88	13.61	7244.95	48,586.29	5048.70	2210.60	64.34	5410.38

Source: Authors' calculation evaluated by the Data Envelopment Analysis method using the software package DEA-Solver Professional Release 11.0

programming of the DEA method, the value of zero (0) is replaced by a very low positive value (10^{-8}) with the identical result of relative efficiency. In selecting suitable input and output variables, it is necessary to assume their positive correlation as shown in the following Table 2.

Table 2 shows that correlation between inputs and outputs is positive and significant. The highest correlation of variables occurs with the number of wind turbines and produced electricity. They strongly depend on each other, i.e., when the value of the number of wind turbine is increasing, the value of the produced electricity increases as well. On the other hand, although the correlation between the number of wind turbines and EBITDA is significant, in the model is the lowest.

The next step in the research is the choice of the appropriate DEA model with regard to returns to scale and orientation. It is not possible to predict the activity of the observed wind power companies with regard to the returns. Therefore, it is necessary to evaluate the relative efficiency with the use of constant and variable returns to scale, and according to the results make a choice. This is shown in the following Table 3.

Table 3 shows the results of the relative efficiency of 78 entities (DMUs) – wind power companies evaluated by the Data Envelopment Analysis method using the software package DEA-Solver Professional Release 11.0 and by applying constant and variable returns to scale. There is a significant difference and a significantly greater number of efficient ($\theta^* = 1$) subjects evaluated by variable returns to scale. Also, the average result of efficiency is higher with variable returns, but with constant returns. This suggests the operation of companies with variable returns. Another argument for the use of variable return to scale is that for a variable return (VRS) model, it is possible to make translation (shifting) of data without changing the efficiency frontier which makes the classification of the DMU entities to inefficient or efficient (by the mentioned data transfer) is invariable or translation invariant [35].

When evaluating relative efficiency, the orientation indicates whether the model is oriented towards inputs or outputs, and it is necessary to determine either input decrease or output increase. The input-oriented model aims to reduce the input to the efficiency frontier at constant output, while the output-oriented model maximizes output in existing input capacities. In this research, the efficiency of wind power companies is based on the input-oriented model; the model that determines the minimum level of input for the achievement of the default output. The basic reason for choosing input-oriented DEA model is to better interpret the results of the research considering the relative efficiency of power companies. The input-oriented model with variable returns to scale is suitable for translation invariance with regard to output, and at the same time, not with regard to the inputs [36]. This indicates that it is possible to transform the negative values of output variables into positive values. As already pointed out, some wind power companies realized the negative value of the EBITDA variable in the observed year, and by the process of translation invariance, all the values of the mentioned variable of the observed companies were increased by 18.000 monetary units (EUR) and thus turned into positive values. Due to the translation invariance, the efficiency frontier has not changed despite the changed values of the EBITDA variable.

5. Empirical results and discussion

5.1. Assessment of the relative efficiency of wind power companies

Evaluating relative efficiency of 78 wind power companies is implemented by input-oriented BCC model that indicates variable returns to scale. Their relative efficiency result, as well as the country to which they belong, is listed in the following Table 4.

As already shown in Table 3, and confirmed in Table 4, 58 wind power companies (DMUs) are assessed as fully efficient and weakly efficient (ranking from 1 to 35). Out of these 58 companies, 34 were rated fully efficient, while 24 were rated as weakly efficient. The DMU function is fully/completely (100%) efficient if and only if $\theta^* = 1$ and all the additional variables are equal to zero ($s^{-*} = s^{+*} = 0$) while the DMUs are considered weakly efficient if and only if $\theta^* = 1$ and additional variables, i.e., input slacks (surpluses) and/or output slacks (defects) are different from zero ($s^{-*} \neq 0$, $s^{+*} \neq 0$) [37].

With the assessment of relative efficiency of wind power companies, the DEA method can also evaluate their super-efficiency. The super-efficiency model ranks highly efficient entities by giving them the result of efficiency greater than 1 (ranking from 1 to 31). With a higher result of efficiency, the subject is evaluated as a more efficient.[2] In the research, the relative efficiency evaluation is performed by the BCC orientation input model, and therefore, super-efficiency is implemented by the same model. The remaining 20 wind power companies are assessed relatively inefficient ($\theta^* < 1$).

It should be pointed out that although this research does not examine the direct impact of the state (reforms) on the efficiency, that is indirectly contained in all economic variables (inputs and outputs) of the model. In these values (tangible fixed assets, receivables and other current assets, cash and cash equivalents, EBITDA) the consequences of the activities, policies and legal provisions of the state or authorities of state institutions are included.

5.2. Source and range of inefficiency of wind power companies

Evaluating the relative efficiency implemented by the DEA method does not only allow estimating the current level of relative efficiency, or comparisons of relatively inefficient subjects with the ones that have the highest level of efficiency. Moreover, it is also of significant importance in the area of wind power efficiency management, providing information on how to eliminate inefficiency and identify sources and amounts of inefficiencies. In that respect, it is necessary to establish projections or improvements and to "shift" some of the factors to the efficiency frontier for any weakly efficient and relatively inefficient wind power company to be able to become efficient. Given the existence of 34 fully efficient wind power companies, below is an overview of projections of the

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[2] Elcomex EOL is assessed as the most efficient wind power company with efficiency score $\theta^* = 13.1909$. The company is owned by the corporation Enel Green Power and it is situated in Romania. It is also called Zephir I. It is one of the biggest companies in the research sample with 52 wind turbines of total installed power of approximately 120 MW. Even though the company has an extremely great power and wind turbine number, in the observed year it did not have a single employee.

Table 2
Coefficients of input and output correlation.

	Wind turbine power	Wind turbine number	Fuel	Tangible fixed assets	Receivables and other short-term assets	Cash and cash equivalents	*Annual electricity production*	*EBITDA*
Wind turbine power	1	0.31785	0.57090	0.59348	0.56465	0.24565	0.63882	0.42646
Wind turbine number	0.31785	1	0.36450	0.47539	0.36044	0.52659	0.82461	0.42017
Fuel	0.57090	0.36450	1	0.73091	0.74333	0.15455	0.60462	0.76311
Tangible fixed assets	0.59348	0.47539	0.73091	1	0.79896	0.40034	0.70274	0.51119
Receivables and other short-term assets	0.56465	0.36044	0.74333	0.79896	1	0.24161	0.57891	0.55767
Cash and cash equivalents	0.24565	0.52659	0.15455	0.40034	0.24161	1	0.49267	0.48107
Annual electricity production	0.63882	0.82461	0.60462	0.70274	0.57891	0.49267	1	0.50376
EBITDA	0.42646	0.42017	0.76311	0.51119	0.55767	0.48107	0.50376	1

Source: Authors' calculation

Table 3
Relative efficiency with the use of constant and variable returns to scale.

Relative efficiency score	CRS	VRS
Number of efficient DMUs[a]	33	58
Number of inefficient DMUs	45	20
Average efficiency score	0.9009	0.9652
Max. Efficiency score	1	1
Min. Efficiency score	0.4983	0.5702

[a] Because of the constraints in the software package, the number of fully efficient and weakly efficient entities with the highest efficiency score ($\theta^* = 1$) is shown.
Source: Authors' calculations

remaining 44 poorly performing and relatively inefficient wind power companies. The aforementioned projections, which are presented in the following Table 5, are the fundamental aim of this research, and apart from the determination, a solution to the problem of inefficiency is proposed.

Table 5 shows all weakly efficient and inefficient wind power companies with corresponding relative efficiency result and required changes or projections (in percentages) of individual variables in order to achieve a relative fully efficiency ($\theta^* = 1$; $s^{-*} = s^{+*} = 0$). Given the application of DEA input oriented model, in order to achieve relative efficiency, it is necessary to reduce the input while maintaining the existing output. The following is an overview of efficiency management in the example of two weakly efficient and relatively inefficient wind power companies, meaning determining the source of their inefficiencies and making recommendations for their elimination.

In order for the wind power company Scout Moor Wind Farm, from the weakly efficient wind power company group, to achieve fully relative efficiency, it would have to reduce tangible fixed assets and cash and cash equivalents by 0.001% each, even though such infinitesimal value may be neglected and the classification of the company Scout Moor Wind Farm as a weakly efficient one can be reconsidered. Other company inputs do not need to be changed in order to improve relative efficiency. Wind power company Scout Moor Wind Farm is one of the largest onshore wind power companies in England. After 7 years of identifying wind turbine locations and obtaining required permits, the company started operating in 2008. It consists of 26 wind turbines with a total installed capacity of 65 MW which is sufficient for supply approximately 40,000 households with electricity [38].

On the other hand, as the third worst-rated wind power company from relatively inefficient wind power company group, with the result of efficiency $\theta^* = 0.7692$, in order to improve its relative efficiency, Crno Brdo should adjust and reduce the values of all analysed inputs. It is necessary to reduce receivables and other short-term assets by as much as 72.42%, cash and cash equivalents by 65.99%, and installed wind turbine power by 42.94%. Other inputs observed in the model need to be reduced by approximately 23% each. The above indicates that the wind power company Crno Brdo has a surplus of unused capacities in its operation compared to other relatively efficient wind power companies. In fact, Crno Brdo could also achieve an equal level of output while decreasing the capacity or observed inputs. Such overcapacity represents opportunity cost for the company and implies irrational management with company's resources. In microeconomic theory, the described state does not ensure the achievement of equilibrium of the company (the point in which isocost line is a tangent of an isoquant), but implies production beyond the point of equilibrium. The wind power company Crno Brdo, or its wind turbines, is located near the town Šibenik in Croatia. There are 7 wind turbines installed in total power of 10.5 MW and the value of the investment is about 16 million euros [39].

Finally, as can be seen, the fundamental quality of fully efficient wind power companies is optimal capacity engagement and rational resource management. The mentioned quality lies primarily in the competence of the management and its good or not so good decisions. Therefore, undercapacity or overcapacity, as well as irrational resource management will imply unused capacity, inefficient operation and imbalance in the company.

For the purpose of determining the amount of relative inefficiency of wind power companies in general, significant importance is attached to the identification of the average amounts, or the average improvements for each observed input of the model. With such average adjustments (the reduction of some factors) possible achievement of relative efficiency at the aggregate size level is suggested. The average improvements in percentages for weakly efficient and relatively inefficient wind power companies are listed in the following Table 6.

Table 6 shows the various amount of projections or the average improvements that affect the relative efficiency of wind power companies. Extremely values are especially emphasized; number of wind turbines variable (3.6%) and nearly three times greater variable of receivables and other short-term assets (10.2%).

As previously pointed out, the highest value of average improvements in these deviations refers to the variable of receivables and other short-term assets (10.2%), which can be explained by the fact that the wind power company as such has the least influence on the formation of the value of the aforementioned variable, because the receivables for the electricity delivered to the electricity grid depend primarily on the decisions, regulations and legal acts of the state-owned authorities purchasing electricity, on the basis of a contract for the purchase of electricity. It is, therefore, a poorly or non–controllable variable from the company's management point of view.

It is assumed that the small value (3.6%) of the average improvements and deviations in the variable of the wind turbine number is due to the quality assessment of the wind power company structure in terms of wind turbine number, their distribution on the available (limited) land, and other, which is a variable, contrary to the previous one, certainly controllable nature and, therefore, under the authority of the company's management. The above-mentioned is in accordance with the research in which the most important variables for explaining the

Table 4
Relative efficiency of 78 wind power companies (DMUs).

Rank	DMUs	Country	Score
1	**ELCOMEX EOL**	Romania	13.1909
2	**SILKOMHÖJDEN ENTERPRISE**	Sweden	5.9666
3	**EVIVA AGIGHIOL**	Romania	5.7121
4	**UNIWINDET PARQUE EOLICO TRES VILLAS**	Spain	5.4959
5	**EXPLOTACIONES EOLICAS DE ALDEHUELAS**	Spain	4.6852
6	**LONGANO EOLICA**	Italy	4.4578
7	**VETROKOM**	Bulgaria	3.2890
8	**KRÅGE VIND**	Sweden	3.0036
9	**BENGTSSONS VIND & KRAFT**	Sweden	2.6595
10	**VINDKRAFT I VARNÄS**	Sweden	2.4291
11	**MAMMARPS WIND**	Sweden	2.4163
12	**EXPLOTACIONES EOLICAS SIERRA LA VIRGEN**	Spain	2.1531
13	**BLÅSUT VIND**	Sweden	1.9368
14	**KNÄPPLAN VIND**	Sweden	1.7455
15	**DRAGALIDEN VIND**	Sweden	1.7249
16	**EBBORP VIND**	Sweden	1.5467
17	**TOPLEŢ ENERGY**	Romania	1.4889
18	**VOLTWERK WINDPARK WÖRBZIG**	Germany	1.4792
19	**RYDSGÅRD VIND**	Sweden	1.4344
20	**HÅBO VINDKRAFT**	Sweden	1.3880
21	**VJETROELEKTRANA TRTAR KRTOLIN**	Croatia	1.3448
22	**EXPLOTACIONES EOLICAS EL PUERTO**	Spain	1.3312
23	**SCE WIND PUSCHWITZ**	Germany	1.3232
24	**SÖRGÅRDSVIND**	Sweden	1.2182
25	**PESTERA WIND FARM**	Romania	1.1896
26	**FLOSAL VIND**	Sweden	1.1878
27	**GISSE VIND**	Sweden	1.1285
28	**SALEBY VIND**	Sweden	1.1274
29	**PARQUE EOLICO CORRAL NUEVO**	Spain	1.0973
30	**KILABACKEN VIND**	Sweden	1.0240
31	**BACKGÅRDEN VIND**	Sweden	1.0181
32	**BONDORLUNDA VIND**	Sweden	1
32	**CERNAVODA POWER**	Romania	1
32	**RHYL FLATS WIND FARM**	United Kingdom	1
35	*BURGSTEIN WIND*	Sweden	1
35	*CORKERMORE WINDFARM*	Ireland	1
35	*ELEKTROWNIA WIATROWA KAMIEŃSK*	Poland	1
35	*FRI-EL GROTTOLE*	Italy	1
35	*HÄRJEVAD VIND*	Sweden	1
35	*HUNTER'S HILL WIND FARM*	United Kingdom	1
35	*KALIAKRA WIND POWER*	Bulgaria	1
35	*KLEVBERGET VIND*	Sweden	1
35	*KÖVLINGE VIND*	Sweden	1
35	*KROKA VIND*	Sweden	1
35	*LARGAN HILL WINDFARM*	Ireland	1
35	*LITTLE CHEYNE COURT WIND FARM*	United Kingdom	1
35	*PARQUE EOLICO DE ABARA*	Spain	1
35	*PARQUE EOLICO ESCEPAR*	Spain	1
35	*PARQUE EOLICO VILLAMAYOR*	Spain	1
35	*RYDA VIND*	Sweden	1
35	*SCE WIND BEPPENER BRUCH*	Germany	1
35	*SCOUT MOOR WIND FARM*	United Kingdom	1
35	*SIRAL ENERGI*	Sweden	1
35	*SKONBERGA VIND*	Sweden	1
35	*THE HOLLIES WIND FARM*	United Kingdom	1
35	*TÖS VIND*	Sweden	1
35	*TUNGELUNDA VIND*	Sweden	1
35	*VÄSTERVIND I SKALLMEJA*	Sweden	1
59	KNABS RIDGE WIND FARM	United Kingdom	0.9937
60	PARQUE EOLICO TESOSANTO	Spain	0.9908
61	RÖBERGSFJÄLLET VIND	Sweden	0.9892
62	KYRKBERGET VINDKRAFT	Sweden	0.9848
63	PARQUE EOLICO PERALEJO	Spain	0.9693
64	BRAHEHUS VIND	Sweden	0.9404
65	EXPLOTACIONES EOLICAS SASO PLANO	Spain	0.9344
66	HEDBODBERGET VIND	Sweden	0.9197
67	BRATTÖN VIND	Sweden	0.913
68	WINDKRAFT DIETLAS	Germany	0.8843
69	ΑΝΕΜΟΣ ALKYONIS ENERGY	Greece	0.8595
70	BLIEKEVARE VIND	Sweden	0.8361
71	GRANBERGET VIND	Sweden	0.8026
72	EUROWIND ORDONA	Italy	0.7971
73	PARQUE EÓLICO DE MARVILA	Portugal	0.7924
74	KIL VIND	Sweden	0.7896
75	VINDKRAFT I YTTERBERG	Sweden	0.7891
76	VJETROELEKTRANA CRNO BRDO	Croatia	0.7692
77	PARQUE EOLICO SANTA CATALINA	Spain	0.761
78	GREIFENSTEIN WIND	Sweden	0.5702

Source: Authors' calculation evaluated by the Data Envelopment Analysis method using the software package DEA-Solver Professional Release 11.0

amount of wind capacity have to do with the physical and geographic characteristics of a wind farm [40].

Among other factors, the deviations in values arelower. To conclude, in order to achieve relative efficiency, wind power companies should, on average, decrease receivables and other short-term assets by 10.2%, followed by fuel inputs, namely rotor blades for the highest share in fuel variables by 9.1%. The share of tangible fixed assets should be reduced by 7.1%, cash and cash equivalents by 6.7% and wind turbine power by 5.7%, in order to achieve relative efficiency of the wind power company. As already pointed out, the number of wind turbines at least affects the achievement of relative efficiency and the number of wind turbines should be reduced by 3.6% on average. The economic implications of the proposed reduction in inputs would ensure "return" to the company's equilibrium point.

5.3. *Managerial and policy implications*

Based on the results of the research, it is completely clear that they imply numerous reflections, primarily in the field of managerial decision-making, but also in the formation of public policies.

If we refer to one of the greatest highlights of the paper *"The first research that analyses the comprehensive performance of wind power companies including their economic and technical characteristics"*, it is clear that this research (compared to others) went a step further and that in addition to technical characteristics, by DEA analysis also included variables of economic type, both on the input side and on the output side, where each of them opens the "manage space", i.e., allows the appropriate management manoeuvre. While some variables are of a controllable nature and influenced by managerial decisions, others escape the control of management and can be regulated only by higher instances, those at the level of the country and its institutions.

Information which indicate concrete corrective activities, i.e., refer to required adjustments and improvements of the relative inefficient wind power companies are particularly important for all stakeholders who are directly involved in the power sector, particularly in the area of wind power renewable sources. Implementing clearly specified improvements through exactly defined sources (hosts) and amounts of inefficiency would improve operation of the company, increase its efficiency and achieve operation "in the best possible way." The company's efficiency could, consequently, have an impact on the competitive ability of companies in the industry. Also, by increasing efficiency, more resources would be provided which the company could use to further improve its operation. It is assumed that such a focused and proactive corporate governance model would contribute to the growth and development of the wind power industry, which would ultimately ensure a higher level of electricity supply and, in that sense, further complement the services in the market of traditional and renewable electricity sources, affect the further stimulation of the

Table 5
Projections of 44 weakly efficient and relatively inefficient wind power companies (DMUs) (%).

DMUs	Score	Wind turbine power (kW)	Wind turbine number	Fuel (kW)	Tangible fixed assets (1000 €)	Receivables and other short-term assets (1000 €)	Cash (1000 €)
BURGSTEIN WIND	1	0.001	0.001	0.059	0.001	0.133	0.001
CORKERMORE WINDFARM	1	0.006	0.006	0.015	0.018	0.006	0.007
ELEKTR. WIATROWA KAMIEŃSK	1	0.002	0.002	0.006	0.002	0.002	0.002
FRI-EL GROTTOLE	1	0	0	0	0	0.001	0.002
HÄRJEVAD VIND	1	8.048	0.001	0.001	29.734	0.001	60.625
HUNTER'S HILL WIND FARM	1	0.002	0.002	0.002	0.004	0.005	0.004
KALIAKRA WIND POWER	1	0.001	0.001	0.001	0.003	0.001	0.002
KLEVBERGET VIND	1	12.729	0.001	53.542	0.001	0.001	0.001
KÖVLINGE VIND	1	0.001	0.001	61.923	67.405	67.039	0.001
KROKA VIND	1	8.329	0.001	46.107	0.001	14.48	0.001
LARGAN HILL WINDFARM	1	0.012	0.055	0.056	0.015	0.012	0.012
LITTLE CHEYNE COURT WIND FARM	1	0	0	0.001	0	0.001	0
PARQUE EOLICO DE ABARA	1	0.002	0.002	0.002	0.006	0.006	0.002
PARQUE EOLICO ESCEPAR	1	0.001	0.001	0.001	0.001	0.007	0.001
PARQUE EOLICO VILLAMAYOR	1	0.002	0.002	0.002	0.002	0.005	0.002
RYDA VIND	1	3.36	0.001	41.123	0.001	18.709	23.285
SCE WIND BEPPENER BRUCH	1	0.003	0.003	0.007	0.003	0.006	0.011
SCOUT MOOR WIND FARM	1	0	0	0	0.001	0	0.001
SIRAL ENERGI	1	0.001	0.001	27.693	0.001	27.538	0.001
SKONBERGA VIND	1	0.03	0.063	0.03	0.03	0.03	0.03
THE HOLLIES WIND FARM	1	0.019	0.019	0.019	0.033	0.06	0.019
TÖS VIND	1	3.934	0.001	0.001	2.393	0.001	42.576
TUNGELUNDA VIND	1	0.144	0.207	0.043	0.043	0.254	0.043
VÄSTERVIND I SKALLMEJA	1	0.073	0.001	0.001	0.001	0.091	0.151
KNABS RIDGE WIND FARM	0.9937	43.387	0.628	0.628	0.628	0.628	0.628
PARQUE EOLICO TESOSANTO	0.9908	0.916	3.312	33.775	29.062	0.916	0.916
RÖBERGSFJÄLLET VIND	0.9892	4.309	1.08	1.08	1.08	1.08	1.08
KYRKBERGET VINDKRAFT	0.9848	7.681	1.52	1.52	22.066	86.054	1.52
PARQUE EOLICO PERALEJO	0.9693	22.119	3.071	3.071	3.071	32.151	3.071
BRAHEHUS VIND	0.9404	8.223	5.957	45.65	5.957	5.957	5.957
EXPL. EOLICAS SASO PLANO	0.9344	6.561	8.814	6.561	30.418	37.582	6.561
HEDBODBERGET VIND	0.9197	8.028	8.028	8.028	8.028	8.028	8.028
BRATTÖN VIND	0.913	16.9	8.697	67.516	20.632	8.697	8.697
WINDKRAFT DIETLAS	0.8843	11.567	11.567	11.567	11.567	39.273	11.567
ΑΝΕΜΟΣ ALKYONIS ENERGY	0.8595	14.054	14.054	14.054	14.054	14.054	14.054
BLIEKEVARE VIND	0.8361	16.392	16.392	16.392	16.392	16.392	16.392
GRANBERGET VIND	0.8026	19.743	19.743	19.743	19.743	19.743	19.743
EUROWIND ORDONA	0.7971	26.688	20.288	20.288	20.288	83.843	89.496
PARQUE EÓLICO DE MARVILA	0.7924	39.388	20.757	36.4	20.757	20.757	31.511
KIL VIND	0.7896	27.715	21.038	23.227	21.038	21.038	21.038
VINDKRAFT I YTTERBERG	0.7891	21.087	21.087	68.683	38.094	21.087	21.087
VJETROELEKTRANA CRNO BRDO	0.7692	42.943	23.077	23.077	23.077	72.416	65.988
PARQUE EOLICO SANTA CATALINA	0.761	23.904	29.452	23.904	83.627	90.725	23.904
GREIFENSTEIN WIND	0.5702	42.978	42.978	54.938	66.681	88.018	42.978

Source: Authors' calculation

Table 6
Average improvements for relatively inefficient wind power companies (DMUs) (%).

Wind turbine power (kW)	Wind turbine number	Fuel (kW)	Tangible fixed assets (1000 €)	Receivables and other short-term assets (1000 €)	Cash and cash equivalents (1000 €)
5.6582	3.6149	9.1127	7.1284	10.2164	6.6801

Source: Authors' calculation

economic activity of the national economy, etc. In this sense, it is really crucial to get such information and address it in the right direction.

Given the input-oriented model, the results of this research suggest that the best value and the smallest deviation (cf. Table 6) was achieved on the number of wind turbines variable (3.6%), and the worst value and the largest deviation on the variable of receivables and other short-term assets (10.2%). While the first variable is basically of a controllable nature and under the authority of the company's management, the second one is under the authority of higher instances. Moreover, among all other model variables, precisely the variable of receivables and other short-term assets indicates the characteristics of the least controllable model variable from the company's point of view. Since it is not directly controlled by the company and its management, it cannot easily be changed and adapted to the company's business goals, so this question becomes a policy-maker problem. This is in conformity with the actual market situation which is confirmed by the fact that, in Croatia for example, receivables increased in the observed period as well as collection period of receivables (e.g. Ref. [41]). Therefore, the improvement of the variable of receivables and other short-term assets, with the aim of achieving relative efficiency, will depend significantly less on the "efforts" undertaken by the wind power company management and significantly more on the institutional, economic and political environment in which the company operates. In this respect, the problem and its solution must be addressed "further", by authorities of state institutions.

Investing in environmentally-friendly technologies, such as wind power technologies, as one of the European "green" policies in implementing the European Green Deal, contributes to the target of at least 32% share for renewable energy by 2030 and with net-zero greenhouse gas emissions by 2050. In achieving that targets EU member states have to contribute with significant effort. Effective energy policies play a key role in the deployment of renewable energy technologies [42]. It is generally considered that advanced European member states are known for its high environmental standards, while advancing European member states are mostly efficiency driven economies with smaller relevance being assigned to environmental issues. This is also confirmed by numerous research as these below. In examining various environmental aspects, such as environmental (technical) efficiency or environmental performance assessment, environmental and resource pressure, or the change in carbon dioxide emissions, the advanced EU countries in contrast to the new (advancing) EU member states have a better scores in environmental issues [43–47]. Although previous research indicate certain regularities of environmental performance assessment of macroeconomic entities, i.e. EU member states, in this paper we do not analyse the aforementioned relations between advanced and advancing European member states regarding to the fact that this study does not analyse the environmental component of relative efficiency. The results of this paper show that relatively efficient and relatively inefficient wind power companies are located in all selected countries of Europe, i.e. both advanced and advancing EU member states and also one non-EU country (cf. Table 4).

Finally, it is believed that the results of the research related to all variables of a controllable nature should be of significant usefulness to management in decision-making processes and evaluation of the results obtained, as well as to identify existing shortcomings in business systems and justify their subsequent corrections and reforms. In this sense, the management of inefficient wind power companies should take into account the obtained results when making decisions in order to increase company efficiency. Namely, Färe, Grosskopf, Logan [5] pointed out that investigation of the causes of efficiency or inefficiency is important, but the measurement of efficiency by itself provide some important insights, i.e., discovering the patterns of efficiency performance without hypothesizing about the causal factors. Furthermore, Triantis [48] concluded that DEA research process and modeling effort should have the primary goal of establishing policies or procedures that can be implemented in real world and should offer the decision-maker an opportunity to learn about system behaviour, ask pertinent questions, collect accurate information and define more effective policies.

6. Conclusion

The fundamental goal of this research was to design and test the applicability of the DEA model for defining the efficiency of wind energy generation, as a tool for formulating decision makers' recommendations in optimizing wind farm operations. In that sense, variables of the model are classified according to technical and economic characteristics of wind power companies. The average improvements in technical features indicates relatively uneven projections of observed variables in the increase of relative efficiency of wind power companies, while economic features show more equal projections with the exception of greater value of variable of receivables and other short-term assets, and the lower value of wind turbine number variable. However, by looking at the average improvements of technical and economic characteristics as a whole (the average improvements of all input variables in the model), it is possible to perceive relatively uniform amounts of projections with mild deviations of value. The above-mentioned is in accordance with expectations, since it is necessary to manage quality in all segments and aspects of business operations in order to achieve the balance of engaged production factors (optimal production level in technical and economic terms). This proves that it is necessary to quality manage the overall resources of the wind power companies (its economic and technical characteristics). All of the above confirms the assumption of the research – the basic hypothesis of the work.

These are the unique contributions of this paper with regards to earlier literature:

- So far there has not been any research that includes such a huge number of wind power units across Europe, i.e., even 78 wind power companies from 12 selected European countries.
- As we have stated in the paper, the Data Envelopment Analysis method was applied (input-oriented BCC model), such as can be found in only two studies (focused on only one country, each). These studies measure the relative efficiency of wind farms and wind turbines by using DEA method, while another study assess the performance of wind farms by using stochastic frontier models.
- Existing wind energy performance studies focused on the technical characteristics of the wind farms with no attention paid to economic characteristics of wind power companies. Therefore, this research fills a literature gap by focusing on the comprehensive wind power companies performance including their economic and technical characteristics.
- The paper provides an insight into the modified form of the Cobb-Douglas production function in the measurement and evaluation of wind power company efficiency. In this study inputs of capital and fuel are used to generate outputs (annual produced electricity and EBITDA), although the general form of the production function suggests labour and capital.
- Additionally, previous research does not take into account the limited factor of efficiency of energy transformation, in view of Betz coefficient. On the other side, in this research we determined complex fuel variable with Betz coefficient, as a significant contribution in the input variable creation.
- Finally, in this research, we decomposed the overall input of installed wind power into its two indicators, the installed power of the wind turbine and the number of wind turbines, contrary to existing suggestions of the literature.

Efficiency of the energy sector and related renewable electricity segments has been a theme of interest for the academia as well as decision makers for long time. The performance evaluation of wind power companies is of considerable importance for all stakeholders to know whether they have managed their assets efficiently. Therefore, the findings of this study are expected to contribute to the regulators or policymakers, management of wind power companies itself, investors and existing knowledge on the operating performance evaluation of the wind power industry.

Certain limitations of this paper are in limited research period of one calendar year due to data availability, i.e., technical and economic wind power companies data. A better analysis of the performance evaluation of European wind power companies would be provided by a dynamic component of efficiency, the so-called "DEA window analysis" which represents change in efficiency over time. Besides the expanded research period of several years and "DEA window analysis", our suggestion for further research will be to examine the "potential" determinants of the relative efficiency of wind power companies. This second stage DEA analysis identifies the internal (company specific) and external (macroeconomic) factors which influence the efficiency of wind power companies. Additionally, further research results could be derived by relevant variables that define innovations in the field of electricity generation from wind power companies. The technological innovation shifts the production possibility frontier, and therefore impacts on technological progress and productivity. Further results of the Malmquist total factor productivity index, as the most commonly used measure of productivity change, will additionally contribute to the quality of efficiency assessment of wind power companies, and represent a step forward in the field of renewable energy management.

Credit author statement

Dario Maradin: Conceptualization, Data curation, Writing - original draft, Ljerka Cerović: Supervision, Writing - review & editing, Visualization, Alemka Šegota: Resources, Methodology, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A. Banshwar, N.K. Sharma, Y.R. Sood, R. Shrivastava, Renewable energy sources as a new participant in ancillary service markets, Energy Strategy Rev. 18 (2017) 106–120.

[2] H. Lund, F. Hvelplund, P.A. Østergaard, B. Möller, B.V. Mathiesen, P. Karnøe, A. N. Andersen, P.E. Morthorst, K. Karlsson, M. Münster, J. Munksgaard, H. Wenzel, System and market integration of wind power in Denmark, Energy Strategy Rev. 1 (3) (2013) 143–156.

[3] C.W. Cobb, P.H. Douglas, A theory of production, Am. Econ. Rev. 8 (1) (1928) 139–165.

[4] P.H. Douglas, The Cobb-Douglas production function once again: its history, its testing, and some new empirical values, J. Polit. Econ. 84 (5) (1976) 903–915.

[5] R. Färe, S. Grosskopf, J. Logan, The relative efficiency of Illinois electric utilities, Resour. Energy 5 (4) (1983) 349–367.

[6] A. Mardani, D. Streimikiene, T. Balezentis, M.Z.M. Saman, K.M. Nor, S. M. Khoshnava, Data envelopment analysis in energy and environmental economics: an overview of the state-of-the-art and recent development trends, Energies 11 (8) (2018) 1–21.

[7] A. Mardani, E.K. Zavadskas, D. Streimikiene, A. Jusoh, M. Khoshnoudi, A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency, Renew. Sustain. Energy Rev. 70 (2017) 1298–1322.

[8] G. Iglesias, P. Castellanos, A. Seijas, Measurement of productive efficiency with frontier methods: a case study for wind farms, Energy Econ. 32 (2010) 1199–1208.

[9] G. Ertek, M.M. Tunç, E. Kurtaraner, D. Kebude, Insights into the Efficiencies of On-Shore Wind Turbines: A Data-Centric Analysis. Innovations in Intelligent Systems and Applications, INISTA 2012 Conference, Trabzon, Turkey, 2012.

[10] C. Pestana Barros, O. Sequeira Antunes, Performance assessment of Portuguese wind farms: ownership and managerial efficiency, Energy Pol. 39 (6) (2011) 3055–3063.

[11] A.G. Abo-Khalil, S. Alyami, K. Sayed, A. Alhejji, Dynamic modeling of wind turbines based on estimated wind speed under turbulent conditions, Energies 12 (10) (2019) 1–25.

[12] B. Zghal, I.B. Mabrouk, L. Walha, K. Abboudi, M. Haddar, Analyses of dynamic behavior of vertical Axis wind turbine in transient regime, Adv. Acoustics Vibrat. (2019) 1–9, https://doi.org/10.1155/2019/7015262, 2019.

[13] M.-A. Asareh, Dynamic behavior of operational wind turbines considering aerodynamic and seismic load interaction, Doctoral Dissert. 2375 (2015).

[14] A. Ahlström, Simulating dynamical behaviour of wind power structures, Licentiate Thesis. Technical Reports from Royal Institute of Technology Department of Mechanics, 2002. SE-100 44, Stockholm.

[15] Y. Totsuka, H. Imamura, A. Yde, Dynamic behavior of parked wind turbine at extreme wind speed, in: Proceedings of First International Symposium on Flutter and its Application, 2016. First International Symposium on Flutter and its Application, Tokyo.

[16] F. González-Longatt, P. Wall, V. Terzija, Wake effect in wind farm performance: steady-state and dynamic behavior, Renew. Energy 39 (1) (2012) 329–338.

[17] S. Bisoi, S. Haldar, Impact of climate change on dynamic behavior of offshore wind turbine, Mar. Georesour. Geotechnol. 35 (7) (2017) 905–920.

[18] P. de Jong, C.A.S. Tanajura, A.S. Sánchez, R. Dargaville, A. Kiperstok, E.A. Torres, Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability, Sci. Total Environ. 634 (2018) 1540–1553, https://doi.org/10.1016/j.scitotenv.2018.03.256.

[19] P. de Jong, R. Dargaville, J. Silver, S. Utembe, A. Kiperstok, E.A. Torres, Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid, Appl. Energy 195 (2017) 538–555, https://doi.org/10.1016/j.apenergy.2017.03.058.

[20] P. de Jong, A. Kiperstok, A.S. Sánchez, R. Dargaville, E.A. Torres, Integrating large scale wind power into the electricity grid in the Northeast of Brazil, Energy 100 (2016) 401–415, https://doi.org/10.1016/j.energy.2015.12.026.

[21] P. de Jong, A. Kiperstok, E.A. Torres, Economic and environmental analysis of electricity generation technologies in Brazil, Renew. Sustain. Energy Rev. 52 (2015) 725–739, https://doi.org/10.1016/j.rser.2015.06.064.

[22] D. Maradin, Lj Cerović, T. Mjeda, Economic effects of renewable energy technologies, Naše Gospodarstvo/Our Econ. 63 (2) (2017) 49–59, https://doi.org/10.1515/ngoe-2017-0012.

[23] D. Maradin, Advantages and disadvantages of renewable energy sources utilization, Int. J. Energy Econ. Pol. 11 (3) (2021) 176–183.

[24] A. Charnes, W.W. Cooper, E. Rhodes, Measuring the efficiency of decision making units, Eur. J. Oper. Res. 2 (1978) 429–444.

[25] R.D. Banker, A. Charnes, W.W. Cooper, The use of categorical variables in data envelopment analysis, Manag. Sci. 30 (1984) 1078–1092.

[26] W.W. Cooper, L.M. Seiford, K. Tone, Introduction to Data Envelopment Analysis and its Uses, Springer, New York, 2006.

[27] Share of electricity production from wind, https://ourworldindata.org/grapher/share-electricity-wind?tab=table&time=2014..latest dataset.

[28] [dataset] Amadeus Database, https://amadeus.bvdinfo.com.

[29] [dataset] The wind power database, http://www.thewindpower.net.

[30] [dataset], Dataset for long-term wind and wave hindcast and daily forecast. https://www.sander-partner.com.

[31] D. Maradin, Lj Cerović, Possibilities of applying the DEA method in the assessment of efficiency of companies in the electric power industry: review of wind energy companies, Int. J. Energy Econ. Pol. 4 (3) (2014) 320–326.

[32] The royal academy of engineering, wind turbine power calculations, RWE npower renewables, mechanical and electrical engineering power industry. https://www.raeng.org.uk/publications/other/23-wind-turbine. (Accessed 12 January 2015).

[33] E. Llera-Sastresa, A. Aranda-Usón, I.Z. Bribián, S. Scarpellini, Local impact of renewables on employment: assessment methodology and case study, Renew. Sustain. Energy Rev. 14 (2) (2010) 679–690.

[34] M. Simas, S. Pacca, Socio-economic benefits of wind power in Brazil, J. Sustain. Develop. Energy, Water Environ. Syst. 1 (2013) 27–40.

[35] A.I. Ali, L.M. Seiford, Translation invariance in data envelopment analysis, Oper. Res. Lett. 9 (6) (1990) 403–405.

[36] W.W. Cooper, L.M. Seiford, K. Tone, Data Envelopment Analysis - A Comprehensive Text with Models, Applications, References and DEA-Solver Software, Springer, New York, 1999.

[37] W.W. Cooper, L.M. Seiford, J. Zhu, Data envelopment analysis: history, models and interpretations, in: Handbook on Data Envelopment Analysis vol. 71, Kluwer Academic Publishers, Boston, 2004, pp. 1–39. International Series in Operations Research & Management Science.

[38] http://www.peelenergy.co.uk/low-carbon-energy/wind-power. (Accessed 18 February 2015) accessed.

[39] L. Jerkić, Završila Gradnja Vjetroelektrane Crno Brdo/*The Construction of the Wind Power Company Crno Brdo Was Completed*, 2011. http://www.vjetroelektrane.com/hrvatska-i-regija/360-zavrsila-gradnja-vjetroelektrane-crno-brdo. (Accessed 9 March 2015).

[40] A. Staid, S.D. Guikema, Statistical analysis of installed wind capacity in the United States, Energy Pol. 60 (2013) 378–385.

[41] A. Bajo, Z. Ovanin, M. Primorac, H. Šimović, Croatian Wind Power Market, vol. 6, Institute of Public Finance, Fiscus, No., Zagreb, Croatia, 2018, https://doi.org/10.3326/efiscus.2018.6.

[42] A. Shivakumar, A. Dobbins, U. Fahl, A. Singh, Drivers of renewable energy deployment in the EU: an analysis of past trends and projections, Energy Strategy Rev. 26 (2019) 100402.

[43] Y.S. Duman, A. Kasman, Environmental technical efficiency in EU member and candidate countries: a parametric hyperbolic distance function approach, Energy 147 (2018) 297–307.

[44] M.T. García-Álvarez, B. Moreno, Environmental performance assessment in the EU: a challenge for the sustainability, J. Clean. Prod. 205 (2018) 266–280.

[45] N. Vlahinić Lenz, A. Šegota, D. Maradin, Total-factor energy efficiency in EU: do environmental impacts matter? Int. J. Energy Econ. Pol. 8 (3) (2018) 92–96.

[46] M.T. García-Álvarez, B. Moreno, I. Soares, Analyzing the environmental and resource pressures from European energy activity: a comparative study of EU member states, Energy 115 (2) (2016) 1375–1384.

[47] P. Fernández González, M. Landajo, M.J. Presno, The driving forces behind changes in CO2 emission levels in EU-27. Differences between member states, Environ. Sci. Pol. 38 (2014) 11–16.

[48] K.P. Triantis, Engineering aplications of data envelopment analysis, Int. Ser. Operat. Res. Manag. Sci. 164 (2011) 363–403.