

RELIABILITY OF RENEWABLE POWER GENERATION USING THE EXAMPLE OF OFFSHORE WIND FARMS

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Abstract

Research background: The issue of reliability and the cost of failure or maintenance costs of renewable energy sources, including wind farms, is becoming increasingly important, especially as the volume of electricity supply from such installations increases.

Purpose: The purpose of the paper is to evaluate the development of wind energy in European countries between 2010 and 2020. Evaluating the reliability of wind farm components and ensuring that wind farm infrastructure is available at a high level is crucial to the stability of the electricity supply system. Therefore, the paper presents, as a case study, a reliability estimation of one of the wind farms operating in the North Sea. The analysis is carried out on the basis of empirical data obtained from experts involved in the maintenance of this wind farm. The estimated reliability function is an important reliability indicator for users of this system. On the basis of the evaluated reliability function, for example, the system availability can be improved, and the maintenance costs of the system can be optimised.

Research methodology: Mathematical modelling was used to analyse system reliability. Further, in the developed reliability models, it was assumed that the system components have the multistate Weibull reliability functions with various parameters in their different reliability state subsets.

Novelty: Original study with literature review. In the context of the requirements for the transformation of the Polish energy sector, the presented approach can be used in the practical implementation of RES projects, taking into account the reliability of offshore wind farm installations.

Keywords: Reliability, failure costs, maintenance costs, renewable power, RES, offshore wind farm efficiency

JEL: A12, B16, B49, C02, C13, C25, Q40, Q42

1. Maintenance and failure costs and operational service strategies to preserve the reliability of production processes

The paper addresses the problem of equipment reliability associated with renewable wind energy generation. From an economic point of view, the reliability of production processes is important for achieving the expected financial result. An increase in reliability can determine to a significant degree the value of the entire project to its owners (Bęben, Chmielewski, 2012) which is a fundamental criterion when deciding whether to implement a project. Estimating the cost of power failures is difficult and imprecise because the economic value of reliability in electricity supply varies from user to user. It can also affect various aspects of the company and its customers, who will suffer a variety of consequences, including: economic (measurable monetary losses, costs and lost benefits), social (relating to disrupted leisure and professional activities) and organisational (organisational, procedural and other changes as a response to an emergency) (Zarzecki, 2008). Appropriate maintenance can prolong the life of an asset and prevent costly breakdowns that may result in lost production, failed shipping schedules and a decline in customer satisfaction (Nezami, Yildirim, 2013).

The term maintenance expense refers to any cost incurred by an individual or business to keep their assets in good working condition. These costs may be classified due to different criteria for many types e. g. spent for the general maintenance of items or they may be used for repairs (Trojan, Marçal, 2017).

Failure costs are those associated with correcting nonconforming material, including scrap, rework, repair, warranty actions, and others related to the correction of nonconformances. Many organizations further subdivide this category into internal and external failure costs (Kiran, 2017). The costs of fixed asset failure include direct costs of failure (e.g. the necessity to replace

or repair the fixed asset, destruction of materials processed during the failure, downtime costs – employee wages, extraordinary costs resulting from the necessity to remove the effects of the failure, e.g. an accident at work and possible compensation) and indirect costs (costs of lawsuits, contractual costs due to delayed or non-execution of the order, lost revenues/profits due to the unavailability of the machine/asset, loss of reputation among contractors, customers' resignation from cooperation).

Determining the optimal maintenance strategy for fixed assets (fixed assets, machinery and equipment) requires an analysis of 2 functions: total failure costs and maintenance (repair) costs, as shown in Figure 1.

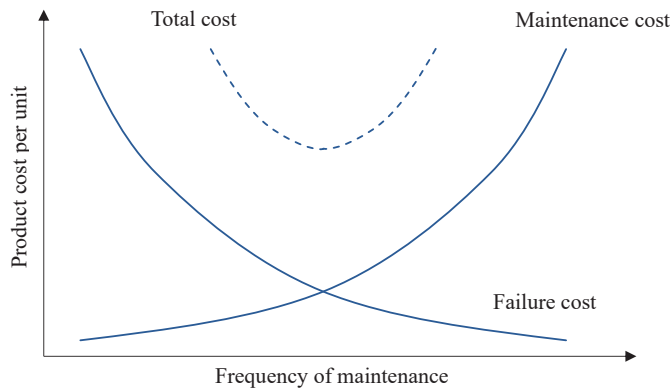


Figure 1. The total cost of the maintenance strategy

Source: Muhlemann *et al.* (2001).

Each company can adopt different maintenance strategies:

1. Preventive maintenance strategy – the more frequent the maintenance, the lower the failure costs, but the higher the maintenance costs.
2. Ad hoc maintenance strategy (breakdown repair) – the less frequent the overhaul, the higher the breakdown costs.

Other possible strategies are also mentioned in the literature (e.g. Bevilacqua, Braglia, 2000). Using failure cost information for testing and reliability assessment is a usual and long-standing practice (Weyuker, 1996).

The paper presents, as a case study, a reliability estimation of one of the wind farms operating in the North Sea. The analysis is carried out on the basis of empirical data obtained from experts involved in the maintenance of this wind farm. The estimated reliability function is an important reliability indicator for users of this system. On the basis of the evaluated reliability

function, the system availability can be improved and maintenance costs of the system can be optimised. This section of the paper presents the importance of reliability and the impact of the selected maintenance strategy on the company's costs.

2. Wind energy production and its efficiency in European countries

Global warming and environmental pollution are some of the main problems that the world is focusing on. Increased CO₂ emissions have contributed to negative environmental changes. The production of electricity and heat from coal and oil has negative impacts not only in environmental aspects. It also influences the economy and social sphere of different countries. Continuous increase in energy demand means, that the most commonly used energy sources are no longer sufficient. Today, it is necessary to invest in renewable energy sources, that do not cause devastating climate change.

The main sources of renewable energy are:

- solar energy,
- wind energy,
- water energy,
- biomass,
- geothermal energy (Mudryk, Werle, 2018).

This paper only deals with wind energy. Wind energy is one of the important sources of green energy in the world but also in Europe and its development and securing the continuity of supply of this energy is important for the economy of individual countries. A distinction is made between onshore and offshore windfarms. Offshore wind farms have higher investment and operating costs, but are more efficient because winds blowing over the sea are more stable and stronger than those blowing over land. Wind farms are a fast-growing sector of the energy industry. But will maintaining the current rate of onshore and offshore energy development be enough to meet the EU's 2030 climate targets? (Pioch, Chmielewski, 2018).

The construction of a wind farm is defined as a project, while its subsequent long-term operation is associated with activities referred to as processes. An important parameter describing a process is its reliability. Because wind farms operate in difficult conditions it is important to analyse their reliability. Often a problem in wind farm reliability analysis is the lack of detailed data on the intensity of pure failures of wind farm components. As is known, wind farms are regularly maintained and their elements are repaired. In (Scheu *et al.*, 2017), the authors pointed out this problem. Planning for the operation and maintenance of wind

farms based only on average failure rates can cause significant errors and, as the authors point out, the use of reliability functions for this task is necessary. The authors (Martin *et al.*, 2016) use a probabilistic failure event model based on the component lifecycle related to a bathtub curve. A wide review and classification of risk and reliability analysis methods applied in the offshore wind industry is contained in (Leimeister, Kolios, 2018). In the reliability studies of wind turbines and wind farms generally, a large variety of failure data and different ways of presenting them, can be noticed (Scheu *et al.*, 2017; Arabian-Hoseynabadi *et al.*, 2010; Jia *et al.*, 2016; Pinar Pérez *et al.*, 2013; Uzunoglu *et al.*, 2017). The variety of data results from their various origins, from different approaches to a failure analysis, and often from the lack of diversity of details during collecting failure data. To systematise this information, papers presenting a review of these data and various approaches to the reliability analysis of wind turbines, are particularly valuable (Pfaffel *et al.*, 2017; Artigao *et al.*, 2018).

For many years, many developed countries have placed great emphasis on renewable energy sources. Wind energy from wind farms is a great source of energy, which does not generate pollution and contributes significantly to the reduction of CO₂ in the atmosphere.

Table 1. Power production and wind farm efficiency in different European countries

Country	Electricity production (GWh)			Capacity (installed power) (GW)		
	2010	2015	2020	2010	2015	2020
UK	10.3	40.3	75.4	5.4	14.3	24.5
Germany	37.8	79.2	123.1	27.2	44.6	62.2
Spain	44.3	49.3	56.4	20.7	22.9	26.8
Denmark	7.8	14.1	16.3	3.8	5.1	5.3
Italy	9.1	14.8	18.8	5.8	9.1	10.9
Netherlands	4	7.6	15.3	2.2	3.4	6.6
Portugal	9.2	11.6	12.3	3.9	4.9	5.2
France	9.9	21.2	39.8	6.1	10.3	17.5
Poland	1.7	10.9	15.8	1.2	4.9	6.3
Croatia	0.1	0.8	1.7	0.1	0.4	0.8
Czech Republic	0.3	0.6	0.7	0.2	0.3	0.3
Romania	0.3	7.1	6.9	0.5	3.1	3
Hungary	0.5	0.7	0.7	0.3	0.3	0.3
Ireland	2.8	6.6	11.5	1.4	2.4	4.3
Greece	2.7	4.6	9.3	1.3	2.1	4.1
Sweden	3.5	16.3	27.5	2	5.8	10

Source: authors' own work based on data given in Wind Energy Barometer, a study carried out by EurObserv'ER, February 2012, February 2017, March 2022.

The capacity of wind turbines is the basic information about the efficiency of a wind farm, i.e. its ability to generate energy under optimal weather conditions. The higher the power, the more energy can be generated. As can be seen in Table 1, the increase in installed capacity does not always correspond to the increase in produced capacity, because the key factor in this case is the strength and stability of the wind. Nevertheless, from the data in Table 1, it can be concluded that the development of wind energy is clearly visible. Between 2010 and 2020 all of the mentioned countries except Hungary have increased the capacity of their wind farms and increased electricity production from wind farms. Of course, the amount of possible wind energy is not the same everywhere and varies quite considerably. Areas with high wind energy potential are distributed unevenly. Good conditions for the exploitation of wind energy usually exist in coastal areas and on vast plains. Among European countries, the most favourable conditions for the exploitation of wind energy potential are in the UK, France and Denmark. From Table 1 it can be seen that the most wind farms have been built in Germany, the UK and France. In 2020 the UK increased its wind energy production by 632% compared to 2010, Germany and France increased their wind energy production by 226% and 302% respectively in the same period.

Table 2. Share of wind energy produced in total energy produced in different European countries

Country	Percentage wind energy/ total energy produced		Change 2020/2016 (%)
	2016	2020	
Denmark	36.8	48	130
Ireland	27.0	38	141
Portugal	24.7	25	101
Spain	19.0	22	116
Germany	16.0	27	169
Romania	12.5	12	96
UK	12.4	27	218
Sweden	11.4	20	175
Lithuania	10.6	13	123
Netherlands	8.4	12	143
Greece	7.4	15	203
Poland	7.1	9	127
Italy	5.5	7	127
France	4.4	9	205
Hungary	1.6	2	125
Czech Republic	0.8	1	125

Source: authors' own work based on data given in Wind energy in Europe 2020 Statistics and the outlook for 2021–2025, WindEurope – February 2021 and Wind in power 2016 European statistics, WindEurope – February 2017.

All European countries are trying to increase their energy production from wind power. In Denmark, as much as 48% of the country's power generation comes from wind. The largest increases in wind energy production in 2020 compared to 2016 in the total energy balance are observed in the following countries: UK increase of 118%, France increase of 105%, Greece increase of 103%, Sweden increase of 75%, Germany increase of 69%, Netherland increase of 43%, Ireland increase of almost 41% and Denmark increase of over 30%. Only one European country analysed experienced a decline in the share of wind power in the total amount of energy produced during the period under review – Romania. For most European countries there can be seen a significant increase in the share of electricity production from wind. In the energy balance of some countries, this type of energy already accounts for about 1/3 of the total energy produced (Denmark, Ireland, Germany, the UK). Taking into account, the emerging trend in the coming years in other countries the share will be about 1/3 of production (Portugal, Spain). The functioning of the economy in these countries depends on the reliability of wind power systems.

Based on the data presented in the section, it can be concluded that the share of electricity production from RES is systematically growing in the analysed period.

3. Reliability of offshore wind farms

The study of the reliability of wind farms is important, because it allows for planning and cost-effective optimizing of the operation and maintenance of the various wind farm subsystems in such a way, as to ensure the efficiency of energy production at the required level.

All over the world, wind energy is one of the most popular sources of renewable energy and a constantly developing branch of energy. Thus, studying the reliability and availability of wind farms is an important aspect for their operation. In general, reliability is the probability that, at a given time and under given conditions, the system meets the requirements that it should perform according to its assigned tasks (Beben, Chmielewski, 2012). The paper defines reliability as the probability that the system is in the reliability state subset $\{\omega, \omega + 1, \dots, z\}$, $\omega = 0, 1, \dots, z$, at the moment t , while it was in the best reliability state z at the moment $t = 0$ (at the beginning). Availability is the probability that a system or component is in a state where it can perform a required function under given conditions at a given time – in the case of wind farms, produce electricity. The availability of wind farms is derived from their reliability.

Due to their operation in extremely difficult conditions, it is particularly important to analyse their reliability. In addition, their reliability is often worse than would be expected

due to severe environmental conditions affecting the reliability and lifetime of a wind farm. Moreover, the problem is often the lack of detailed data on pure failure intensities, as closely related to the operation of wind farms are regular, continuous inspections and repairs of wind farm infrastructure and its components.

This paper analyses the reliability of one of the offshore wind farms located in the North Sea using data from the operators of this wind farm. This type of industrial facility is created in a project formula over a period of 3–5 years, and then for about 20 years it functions thanks to the sum of all activities performed to generate electricity – the process of electricity generation. However, a prerequisite for its operation is to ensure the functionality of individual components, which significantly affects the cost of operating a wind farm. The reliability of individual elements is a determinant of the cost of operation and, consequently, the profitability of the entire process. Various measures of reliability are used in the literature. In the case under review, the average life in the state of reliability when the wind turbine does not require maintenance and repair was used as a measure of reliability.

3.1. Description of the wind farm – a case study

The paper considers the Gemini Wind Park located in the North Sea. The considered wind park consists of 150 wind turbines and two high voltage stations, as shown in Figure 2. Each turbine has a maximum output power of 4 MW, so in total the whole wind farm can produce 600 MW of renewable energy. Electric power is transmitted ashore by cable which is laid down on the bottom of the sea. Each wind turbine self-starts when the average wind speed reaches 3 to 5 m/s (meters per second). The output increases proportionately with the wind speed up to 12 to 13 m/s, at which point the power is regulated at a rated power of 4 MW. When the wind speed

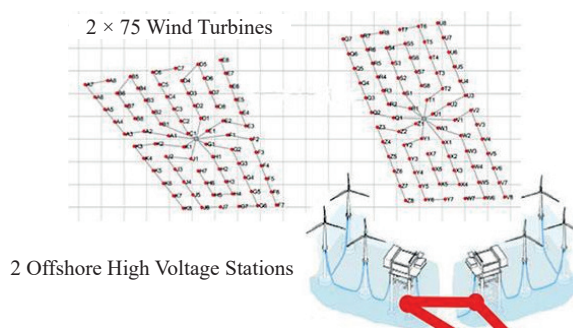


Figure 2. General scheme of an offshore wind farm

Source: reprinted with permission from Gemini Wind Park (2020, 2021).

exceeds the maximum operational limit of 25 m/s, the turbine shuts down by pitching its blades (turning them parallel to the air flow). When the wind speed drops back below the maximum limit, the turbine's systems automatically reset and begin to generate electricity again.

Two main technical subsystems S1 and S2 of the wind farm were distinguished, which are connected in parallel in terms of reliability. The subsystem S1 and S2 are identical and have the same reliability. Each subsystem consists of 75 wind turbines (WT) linked parallel with one high voltage station (VS). The system of 75 wind turbines and the high voltage station are connected in series in a reliability sense. The reliability structure of these two subsystems is presented in Figure 3.

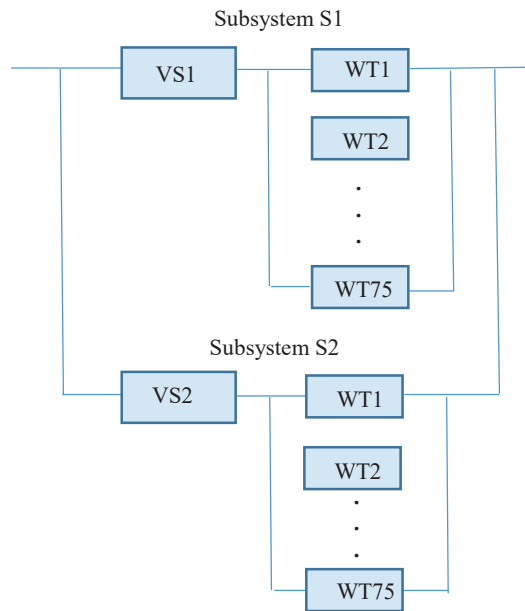


Figure 3. Reliability structure of an offshore wind farm

Source: authors' own work based on expert opinion.

In the case of elements connected in parallel, the failure of any element does not affect the reliability of the entire system – the elements replace each other. However, in the case of the serial connection of individual system elements, the reliability of the entire system depends on the individual elements. In the case of a large number of serial elements, maintaining the high reliability of the entire system requires the very high reliability of individual elements. The failure of one Serial Element Results In The Unavailability Of The Entire System.

3.2. Reliability evaluation of the studied offshore wind farm

Using the information obtained from the experts and operators of the considered wind farm, as in the Gemini Wind Park. 2020 (2020), it was assumed that the failure rates differ depending on the year of operation of the wind farm. Thus, three periods of operation time with different values of wind turbine failure rates were defined. More exactly, in the first year of operation, the so-called “early” failures occur, next a longer period of “fatigue” or “random” failures follows, and the last period of “wear-out” failures when the failure rate increases due to component fatigue – as assumed in the bathtub curve. For high voltage stations two periods with different values of their failure rates are characterized. The analysed wind farm, as also stated for wind turbines considered in (Arabian-Hoseynabadi *et al.*, 2010), is designed to be operated for 20 years. Taking into account the wind farm operators opinion and information given in (Arabian-Hoseynabadi *et al.*, 2010) the mean time to failure of the components of the S1 and S2 subsystems was established. The values of the mean time to failure are given in Table 3.

Table 3. Mean time to failure for wind turbine and high voltage station

Operation time	Mean time to failure μ for wind turbines (in years)
First year of operation – Period I	0.296
From 2 till 10 years of operation – Period II	0.384
After 10 years of operation – Period III	0.296
Operation time	Mean time to failure μ for high voltage stations (in years)
First 10 years of operation – Period I	3.5
After 10 years of operation – Period II	2

Source: authors' own work based on expert opinion.

Proposing a multi-state approach to a reliability analysis (Kołowrocki, Soszyńska-Budny, 2011; Soszyńska-Budny, 2021) of the wind farm infrastructure, three reliability states were distinguished for wind turbines, high voltage stations and for the entire wind park.

The reliability states for wind turbines are defined as follows:

state 2 – wind turbine is new and fully reliable, does not require any maintenance or repair,

state 1 – wind turbine is operational but due to ageing requires inspection, during which its renewal or maintenance is performed,

state 0 – wind turbine is damaged and cannot work.

In practice, it is well known that in the initial and in the final periods of operation the systems are more unreliable. In the reliability analysis, the Weibull distribution is a statistical model which takes into account the beginning and the end of the operation of the considered system. Considering this, it was assumed that the coordinates of wind turbine reliability functions are Weibull, $R(t, \omega) = \exp[-\alpha(\omega)t^{\beta(\omega)}]$, $t \geq 0$, $\omega = 1, 2$, where ω is the reliability state, $\alpha(\omega)$ is scale parameters in the reliability state subset $\{1, 2\}$, $\beta(\omega)$ is shape parameters in the reliability state subset $\{1, 2\}$, with the parameters given in Table 4.

The time for the first system inspection and maintenance was adopted as a mean lifetime in the reliability state “2”, i.e. 0.296 year. Since inspections and repairs are regularly carried out in wind farms, and their damage is often associated with external factors, it is difficult to obtain accurate and pure data on their lifetimes. In the proposed multistate approach, the system’s lifetime is equivalent to its lifetime in the reliability state subset $\{1, 2\}$, and it equals to 0.384 year.

Table 4. The parameters of the Weibull distribution for the wind turbine and high voltage station

Parameters for the wind turbine	In reliability state subset $\{1, 2\}$	In reliability state subset $\{2\}$
Parameter α	$\alpha_{WT}(1) = 5.326$	$\alpha_{WT}(2) = 8.964$
Parameter β	$\beta_{WT}(1) = 2$	$\beta_{WT}(2) = 2$
Parameters for the high voltage station	In reliability state subset $\{1, 2\}$	In reliability state subset $\{2\}$
Parameter α	$\alpha_{VS}(1) = 0.064$	$\alpha_{VS}(2) = 0.196$
Parameter β	$\beta_{VS}(1) = 2$	$\beta_{VS}(2) = 2$

Source: authors’ own work based on expert opinion.

The reliability function of a wind turbine, is given by a vector $R_{WT}(\bullet)$, (Kołowrocki, Soszyńska-Budny, 2011; Soszyńska-Budny, 2021) with the Weibull coordinates with parameters given in Table 4:

$$R_{WT}(t, 1) = \exp[-5.326t^2], \quad t \geq 0 \quad (1)$$

$$R_{WT}(t, 2) = \exp[-8.964t^2], \quad t \geq 0 \quad (2)$$

For high voltage stations, the reliability states are similarly defined as in the case of wind turbines: state “2” in which the station is fully operational, state “1” in which the station is operational but requires some inspections due to ageing, and state “0” when the station does not work and needs repair.

Similarly, as in the case of the wind turbine it was assumed that the coordinates of high voltage stations reliability functions are the Weibull distribution with the parameters given in Table 4. Consequently, the reliability function of a high voltage station, is given by the vector $R_{VS}(\bullet)$, where its coordinates are:

$$R_{VS}(t, 1) = \exp[-0.064t^2], \quad t \geq 0 \quad (3)$$

$$R_{VS}(t, 2) = \exp[-0.196t^2], \quad t \geq 0 \quad (4)$$

For all of the offshore wind farms, with the reliability structure is shown in Figure 3, the following three reliability states were distinguished: state “2” of total reliability, state “1” of partial reliability in which wind farm operation is less effective and its maintenance or renovation is required, and state “0” of wind farm failure.

Hence, the reliability function of the considered offshore wind farm is given by the formula (Kołowrocki, Soszyńska-Budny, 2011; Soszyńska-Budny, 2021):

$$\mathbf{R}(t, \cdot) = [1, \mathbf{R}(t, 1), \mathbf{R}(t, 2)], \quad t \geq 0 \quad (5)$$

where:

$$\mathbf{R}(t, 1) = 1 - [1 - R_{VS}(t, 1) \cdot [1 - [1 - R_{WT}(t, 1)]^{75}]^2 \quad (6)$$

$$\mathbf{R}(t, 2) = 1 - [1 - R_{VS}(t, 2) \cdot [1 - [1 - R_{WT}(t, 2)]^{75}]^2 \quad (7)$$

Next, substituting the reliability functions of the wind turbine (1–2) and high voltage station (3–4) into (6–7), the reliability function coordinates of the offshore wind farm take the form:

$$\mathbf{R}(t, 1) = 1 - [1 - \exp[-0.064t^2] \cdot [1 - [1 - \exp[-5.326t^2]]^{75}]]^2 \quad (8)$$

$$\mathbf{R}(t, 2) = 1 - [1 - \exp[-0.196t^2] \cdot [1 - [1 - \exp[-8.964t^2]]^{75}]]^2, \quad \text{for } t \geq 0 \quad (9)$$

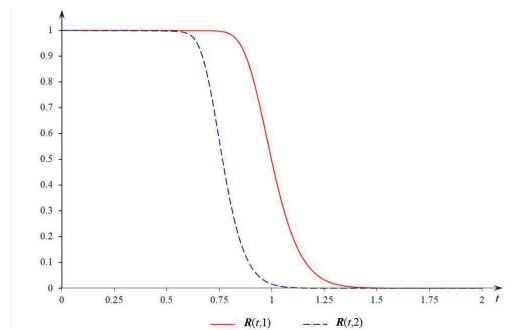


Figure 4. Graphs of the reliability function coordinates of the wind farm infrastructure

Source: authors' own work on the basis of formulae Uzunoglu *et al.* (2015); Pfaffe *et al.* (2017).

The reliability function is an indicator that does not give much practical information for users, engineers operating wind farms. However, having the reliability function, the indicators can be determined, which are very useful in testing the reliability and availability of wind farms, such as the expected values and standard deviations of system lifetimes, and the system risk function.

The expected values of system lifetimes in the reliability state subsets $\{\omega, \omega + 1, \dots, n_s\}$, $\omega = 1, 2, \dots, n_s$, are defined by the formula (Kołowrocki, Soszyńska-Budny, 2011; Soszyńska-Budny, 2021).

$$\mu(\omega) = \int_0^{\infty} \mathbf{R}(t, \omega) dt, \quad \omega = 1, 2, \dots, n_s \quad (10)$$

and the expected values of the system lifetimes in individual reliability states $\omega = 1, 2, \dots, n_s$, can be determined as follows

$$\bar{\mu}(\omega) = \mu(\omega) - \mu(\omega + 1), \quad \omega = 1, 2, \dots, n_s - 1, \quad \bar{\mu}(n_s) = \mu(n_s) \quad (11)$$

The standard deviation of system lifetime in the reliability state subset $\{\omega, \omega + 1, \dots, n_s\}$, $\omega = 1, 2, \dots, n_s$, is defined by the formula (Kołowrocki, Soszyńska-Budny, 2011; Soszyńska-Budny, 2021)

$$\sigma(\omega) = \sqrt{2 \int_0^{\infty} t \cdot \mathbf{R}(t, \omega) dt - [\mu(\omega)]^2}, \quad \omega = 1, 2, K, \dots, n_s \quad (12)$$

where $\mathbf{R}(t, \omega)$ is the reliability function and $\mu(\omega)$ are the expected values given by (10).

In the reliability analysis a critical state of a system can be distinguished. This critical state is one of the reliability states to exceed which is either dangerous for the environment or does not assure the necessary level of its operation process effectiveness. Then an important system reliability indicator is the time to the moment of exceeding the system reliability critical state which is called the system risk function. The system risk function is strictly related to the system reliability function and given by

$$\mathbf{r}(t) = 1 - \mathbf{R}(t, r) = P(T(r) \leq t), \quad t \geq 0 \quad (13)$$

where $r \in \{1, 2, \dots, K, \dots, n_s\}$ is the fixed critical reliability state and $\mathbf{R}(t, r)$ is the coordinate of the system reliability function.

Assuming that the inverse function $r^{-1}(t)$ of the system risk function (13) exists, the moment can be determined, denoted by τ , when the system risk exceeds a permitted threshold δ , from the following formula:

$$\tau = r^{-1}(\delta) \quad (14)$$

where the risk threshold δ is given by experts and system operators.

By assuming that the critical state of the wind farm infrastructure is state $r = 2$, from the formula (13) and using (9), the wind farm risk function can be determined. Next, based on this function, it can be determined from (7) the moment τ at which the risk function of the wind farm exceeds a certain permitted risk threshold δ . The values of exceeding moments counted in years for different risk thresholds are given in Table 5.

Table 5. Moment τ of exceeding a risk threshold δ by the risk function of wind farm infrastructure

Risk threshold	Moment τ of exceeding (in years)
0.01	0.592
0.02	0.615
0.05	0.644
0.10	0.669
0.20	0.700
0.30	0.723
0.40	0.744
0.50	0.765

Source: authors' own calculations on the basis of formulae Wind in power 2016 (2017).

Taking into account the reliability structure of the wind farm infrastructure, described in Section 3.1, a system of 75 wind turbines in subsystem S1 and S2 is considered as a parallel system. They can operate independently of each other. However, to ensure a certain minimum output power of a wind farm, a system of 75 wind turbines can be considered as an “ m out of n ” system. For example, assuming that 25 turbines out of 75 should operate in each subsystem, the wind farm infrastructure at least can produce 200 MW. In turn, to ensure a minimum energy supply of 400 MW, it should be assumed that at least 50 out of 75 turbines should operate in each subsystem.

Table 6 compares the mean values and standard deviations of wind farm lifetimes in the reliability state subsets $\{1, 2\}$ and $\{2\}$, assuming that a system of 75 turbines is a parallel system, in the second case for a “25 out of 75” system, and in the third case for a “50 out of 75” system. Their values are given in years.

Table 6. Mean values and standard deviations of wind farm lifetimes in reliability state subsets

System of 75 wind turbines	In reliability state subset $\{1, 2\}$ (in years)		In reliability state subset $\{2\}$ (in years)	
	$\mu(1)$	$\sigma(1)$	$\mu(2)$	$\sigma(2)$
p\Parallel	1.010	0.112	0.773	0.008
“25 out of 75”	0.477	0.020	0.368	0.009
“50 out of 75”	0.296	0.022	0.228	0.016

Source: authors' own calculations.

Comparing the mean values of lifetimes in the reliability state subsets for different configurations of the wind farm, it should be noticed that mean lifetime for “25 out of 75” reliability structure is about 53% shorter than for parallel reliability structure, and up to 71% shorter with assumed “50 out of 75” reliability structure of the wind farm infrastructure. If only one subset $\{2\}$ is used, the average lifetime in subsets of reliability states for different wind farm configurations is reduced compared to the previous variant by about 23% – but the variation in the mean (standard deviation) is significantly smaller.

These differences are significant, and determining at what minimum number of working wind turbines, working properly and providing adequate efficiency, is crucial for the reliability analysis of a wind farm, significantly affecting the excellence of the implementation of the process (Nierzwicki, Wiśniewska, 1995) – in our case, the process of electricity production.

The reliability of individual elements of the entire energy system has a significant impact on the amount of electricity produced.

Conclusions

The whole world is focused on finding and producing green energy to protect the environment. European countries are also moving in this direction. The war in Ukraine in particular shows the importance of RES as a component affecting energy prices in the entire EU energy system. For most European countries, a significant increase in the share of electricity generated from wind has been observed in recent years. Studying the reliability and maintenance

of wind farms is a very important aspect in this renewable energy research. The reliability of a wind farm affects the basic financial parameters generated by the entire project over its lifetime. High reliability, on the one hand, generates costs associated with its maintenance but, on the other hand, reduces costs associated with failure. Due to the difficult environmental and operational conditions that change over time, in the further analysis of the reliability and availability of the wind farm infrastructure, changing weather conditions and various operating states should be taken into account. The components of wind farm infrastructures in various environmental and operational states often have different reliability parameters, and thus affect the reliability of the entire wind farm infrastructure. The reliability of the entire system of which the offshore wind farm consists is also very much influenced by the proper configuration of the individual components of the wind farm under analysis. Its proper configuration can increase the reliability of the entire system as measured by the average lifetime by up to 23%, which has a positive impact on the financial parameters of the project.

References

- Arabian-Hoseynabadi, H., Oraee, H., Tavner, P.J. (2010). Failure modes and effects analysis (FMEA) for wind turbines. *International Journal Electrical Power Energy Systems*, 32(7), 817–824. DOI: 10.1016/j.ijepes.2010.01.019.
- Artigao, E., Martín-Martínez, S., Honrubia-Escribano, A., Gómez-Lázaro, E. (2018). Wind turbine reliability: A comprehensive review towards effective condition monitoring development. *Applied Energy*, 228, 1569–1583. DOI: 10.1016/j.apenergy.2018.07.037.
- Bęben, R., Chmielewski, M. (2012). Elektrownie wiatrowe jako przedmiot wyceny na rynku odnawialnych źródeł energii w Polsce. *Prace i Materiały Wydziału Zarządzania Uniwersytetu Gdańskiego*, 10(4), cz. 1, 5–21.
- Bevilacqua, M., Braglia, M. (2000). The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering & System Safety*, 70(1), 71–83. DOI: 10.1016/S0951-8320(00)00047-8.
- Gemini Wind Park (2020). *Maintaining the valuable assets*. Retrieved from <https://www.geminiwindpark.nl/gemini-in-full-swing.html#a4> (15.04.2021).
- Jia, X., Jin, C., Buzza, M., Wang, W., Lee, J. (2016). Wind turbine performance degradation assessment based on a novel similarity metric for machine performance curves. *Renewable Energy*, 99, 1191–1201. DOI: 10.1016/j.renene.2016.08.018.

- Kiran, D.R. (2017). *Total Quality Management. Key Concepts and Case Studies*. Elsevier. DOI: 10.1016/C2016-0-00426-6.
- Kołowrocki, K., Soszyńska-Budny, J. (2011). *Reliability and Safety of Complex Technical Systems and Processes: Modelling – Identification – Prediction – Optimization*. Springer. DOI: 10.1007/978-0-85729-694-8.
- Leimeister, M., Kolios, A. (2018). A review of reliability-based methods for risk analysis and their application in the offshore wind industry. *Renewable & Sustainable Energy Reviews*, 91, 1065–1076. DOI: 10.1016/j.rser.2018.04.004.
- Martin, R., Lazakis, I., Barbouchi, S., Johanning, L. (2016). Sensitivity analysis of offshore wind farm operation and maintenance cost and availability. *Renewable Energy*, 85, 1226–36. DOI 10.1016/j.renene.2015.07.078.
- Mudryk, K., Werle, S. (eds.) (2018). *Renewable Energy Sources Engineering Technology Innovation*. Springer. DOI: 10.1007/978-3-319-72371-6.
- Muhlemann, A.P., Oakland J.S., Lockyer K.G. (2001). *Zarządzanie: produkcja i usługi*. Wydawnictwo Naukowe PWN.
- Nezami, F.G., Yildirim M.B. (2013). A sustainability approach for selecting maintenance strategy. *International Journal of Sustainable Engineering*, 6(4). DOI: 10.1080/19397038.2013.765928.
- Nierzwicki, W., Wiśniewska, M. (1995). House of Quality. *Problemy Jakości*, 27(2), 6-9.
- Pfaffel, S., Faulstich, S., Rohrig, K. (2017). Performance and reliability of wind turbines: A review *Energies*, 10(1904), 1–27. DOI: 10.3390/en1011904.
- Pinar Pérez, J.M., García Márquez, F.P., Tobias, A., Papaalias, M. (2013). Wind turbine reliability analysis. *Renewable & Sustainable Energy Reviews*, 23, 463–472. DOI: 10.1016/j.rser.2013.03.018.
- Pioch, J., Chmielewski, M. (2018). Factors of change in the use of renewable energy sources in Poland as compared to EU member states. *Przestrzeń Ekonomia Społeczeństwo*, 14, 193–204. DOI 10.23830/14/II/2018/193204.
- Rausand, M., Barros, A., Hoyland, A. (2020). *System Reliability Theory: Models, Statistical Methods, and Applications*. John Wiley & Sons.
- Scheu, M.N., Kolios, A., Fischer, T., Brennan, F. (2017). Influence of statistical uncertainty of component reliability estimations on offshore wind farm availability. *Reliability Engineering & System Safety*, 168, 28–39. DOI: 10.1016/j.res.2017.05.021.
- Soszyńska-Budny, J. (2021). *Safety analysis of Critical Infrastructure: Impact of operation processes and climate change. Book series Springer, Lecture Notes in Intelligent Transportation and Infrastructure*. Springer. DOI: 10.1007/978-3-030-65339-2.

- Trojan, F., Marça, R.F.M. (2017). Proposal of Maintenance-types Classification to Clarify Maintenance Concepts in Production and Operations Management. *Journal of Business and Economics*, 8(7), 560-572. DOI: 10.15341/jbe(2155-7950)/07.08.2017/005.
- Uzunoglu, B., Amoiralis, F., Kaidis, C. (2015). Wind turbine reliability estimation for different assemblies and failure severity categories. *IET Renewable Power Generation*, 20, 892–899. DOI: 10.1049/iet-rpg.2015.0020.
- Weyuker, E.J. (1996). Using failure cost information for testing and reliability assessment. *Transactions on Software Engineering and Methodology*, 5(2), 87-98. DOI: 10.1145/227607.227608.
- Wind Energy Barometer (2012). A study carried out by EurObserv'ER – February 2012.
- Wind Energy Barometer (2017). A study carried out by EurObserv'ER – February 2017.
- Wind Energy Barometer (2022). A study carried out by EurObserv'ER – March 2022.
- Wind energy in Europe 2020 Statistics and the outlook for 2021–2025 (2021), WindEurope – February.
- Wind in power 2016 European statistics (2017). WindEurope – February.
- Zarzecki, D. (2008). Koszty awarii energetycznych. *Studia i Prace Wydziału Nauk Ekonomicznych i Zarządzania* 7, 89–104.

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- Soszyńska-Budny, J., Chmielewski, M., Pioch, J. (2023). Reliability of Renewable Power Generation using the Example of Offshore Wind Farms. *Folia Oeconomica Stetinensia*, 23(1), 228–245. DOI: 10.2478/fofi-2023-0012.