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Technological development of wind energy and compliance with the requirements for sustainable development

Postęp technologiczny energetyki wiatrowej a spełnienie wymagań zrównoważonego rozwoju

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Abstract
This article raises the issue of sustainable development in the context of technological advances in wind power. The authors focus mainly on identifying the risks which are inherent in the development of wind power and on the search for the answer to whether technological progress is conducive to reducing these risks. The evaluation of the impact of this progress is assessed in terms of: electric generator solutions, operational reliability, cost-effectiveness, site selection and optimal matching of generators to the environmental conditions. The community category is an additional non-technological category which is a deciding factor in democratic countries during investment decisions. The authors analysed a number of factors in this category, and concluded that only a responsible policy of providing information, fair treatment of the local community and a clearly defined distribution of profits contribute to long-term positive shaping of social attitudes.

Key words: sustainable development, wind energy, negative impact of wind turbines, wind power plant, localization of wind turbines, social factors of development

Streszczenie
Prezentowany artykuł porusza problematykę zrównoważonego rozwoju w kontekście postępu technologicznego elektrowni wiatrowych. Główna uwaga autorów skupiona jest na określeniu zagrożeń jakie niesie za sobą rozwój energetyki wiatrowej oraz na poszukiwaniu odpowiedzi, czy postęp technologiczny sprzyja ograniczeniu tych zagrożeń. Ocena wpływu tego postępu badana jest w kategoriach: rozwiązań generatorów elektrycznych, niezawodności pracy, opłacalności ekonomicznej, wyboru lokalizacji i optymalnego dopasowania elektrowni do warunków terenowych. Dodatkową nietechnologiczną kategorią, która w krajach demokratycznych decyduje o przeprowadzeniu inwestycji, jest kategoria społeczna. Autorzy analizują szereg czynników tej kategorii, a w konkluzji zwracają uwagę, że tylko odpowiedzialna polityka informacyjna, rzetelne traktowanie społeczności lokalnej i wyraźnie określony podział zysków przyczyniają się do długofalowego pozytywnego kształtowania postaw społecznych.

Słowa kluczowe: rozwój zrównoważony, energia wiatru, negatywne oddziaływanie turbin wiatrowych, lokalizacja turbin wiatrowych, elektrownie wiatrowe, społeczne czynniki rozwoju

Introduction

Sustainable development is a priority in today's economy (Piontek, 2000; Szkarowski, 2005). Intuitively, it is understood that wind power favours this development, but has it always been perceived as such and to what extent is the development of wind technology environmentally friendly?

Harnessing energy and using it for one's own purposes is one of the expressions of development of human civilisation. The ability to produce additional energy and managing it to achieve a desired effect was the driving force behind the accelerated development of societies. By utilising the power of animals and constructing machines, driven by energy derived from external sources, man could multiply the effects of his work.

From time immemorial, windmills have played an important role. They have been used for various purposes, but mainly for powering pumps in irrigation systems, actuating equipment to grind grain or to overcome great distances with sailing ships.

All these applications have played an important role in the development of societies. Already, during the Sumerian and Egyptian civilisations, windmills watered farmland. In more recent times they were used to drain areas in depressions as in the Netherlands or Żuławy Wiślane in Poland. The mill structures were quite well known in Europe in the late Middle Ages and were described as post mills, whilst their subsequent solutions were paltrock mills and the Dutch smock mills.

We have long since become accustomed to these systems of harnessing the wind. They appear to be natural, and their use does not raise any concerns. However, it was not always the case. Fear of the unknown rotating devices was quite real. Its echoes have survived into modern times as delusions with the fictional Don Quixote fighting windmills. Undoubtedly, in ancient times, the rotating blades of a windmill, generating noise and driving huge millstones or pumps would have aroused fears and concerns.

Could these systems pose a threat to sustainable development in those far distant times?

The question, posed this way, may seem surprising and could be classed as meaningless. And yet, in an indirect way, man's harnessing of wind power and its utilisation gave significant impetus to man's further development. Its elements were the management of new areas for cereal cultivation and the accompanying irreversible action of destruction of existing vegetation.

However, we are not surprised with contemporary reflections on the harmful effects of wind turbines. Yet they draw energy from a natural, renewable energy source which is the wind's kinetic energy. Their functioning is much more natural than that of large power stations using fossil fuels. Modern society is accustomed to consuming large amounts of energy. Since the first industrial revolution, the source of this energy was mainly fossil fuels (Mokrzycki, 2009). Today, in contrast to the negative effects of this wasteful economy, the search is on for new, less environmentally damaging methods of obtaining energy. Wind power is certainly one such source.

Despite the belief that this source brings incomparably less harmful effects than traditional fossil fuels, discussions, research and justification of the level of harmful effects must take place. This is especially important when the density of wind turbines increases significantly. Solutions should then be sought that will better serve the sustainable development of entire societies (Pawłowski, 2009).

This article attempts to formulate the main allegations articulated against wind turbines. A discussion was undertaken to determine to what extent these allegations are true and whether there are ways to reduce the adverse operational effects of wind turbines.

The discussion includes the technological development of wind power. There is also a brief discussion on whether the latest construction designs are conducive to reducing the negative impacts of wind turbines on the ecosystem. This discussion is supplemented by reflections on economic viability since fulfilling the investment conditions of profitability is essential for the further development of wind power.

However, public perception is the final approval. Regardless of any objective arguments, the so-called public opinion decides on whether to block any investments. Thus in the forthcoming discussion views have been formulated which describe what the expected public perception can be and what should be done to avoid unnecessary disputes.

Barriers to the development of wind power

The wind turbine discussion is multi-faceted. For the general public the most important appears to be that of the harmful impact on the environment.

The most well-known threat is noise generation and the inaudible infrasound. They arise as a result of the moving mechanical systems and aerodynamic effects. The low-frequency vibrations occur in the shadow of the tower which generates very low frequency sounds inaudible to the human ear. They are not indifferent to our skeletal system and internal organs since the resonant frequencies are very close to those of our organs. Their level but can be dangerous but only at a very close distance to the wind farms.

Infrasound effectively purges small rodents from its locality. This desired effect in our gardens, surprisingly, also has a negative effect. It contributes to a population increase in pest larvae which can attack plants and cause additional damage to crops.

The audible noise at the height of the nacelle can exceed 110 dB, but at a distance of 1-2 km falls to a level acceptable even by the strictest European standards (30-35 dB). The noise gradient may be greater due to obstacles or high air humidity. This problem is governed by regulations, including the Polish regulations (*Ministerstwo*.., 2012) which specify the isophonic contour lines.

Electromagnetic interference is another harmful effect. It can cause interference which disrupts electronic equipment such as TV, radio, mobile phones, radar and short wave radios (Figure 1). However, they are not a health risk.

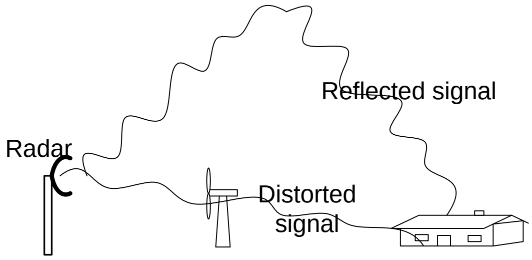

Figure 1. Interference due to electromagnetic interference in the received signal.

This interference is significant only within a 200 meter radius from the source. It should be mentioned that switching to digital transmission and reception, virtually eliminates this type of interference.

Another hazard is the flickering between shadow and light reflections. They can be a serious problem, particularly, when the shadow of the rotating blade falls on the narrow windows of premises occupied by people. Such a phenomenon may increase the likelihood of epilepsy and the risk of increased nervous tension. Since the length of the shadow depends on latitude, season and time of day, it is still possible to specify a minimum impact distance for this shadow. If such a hazard should occur, then for the Central European latitudes the requirement is that the distance between the wind turbine and the residential buildings be at least 6-8 rotor diameters.

The rotating blades also pose a real danger to birds. The linear velocities of the blades at their tips can approach 300 km/h. No bird is able to escape such a danger, and therefore it is forbidden to locate wind turbines along avian air corridors, on their breeding sites and near bird sanctuaries. If these conditions are met, strikes occur very sporadically. It is estimated that in the USA there are far more avian collisions with buildings than with operational wind turbines.

Power engineers reported comments are of quite a different nature. Wind turbines cause quite a big problem for Transmission System Operators (TSO). They are obliged to buy *green* energy generated by wind power. Unfortunately, it is impossible to predict well in advance, the amount of generated energy, and most of all when it will happen. Because of the many factors affecting wind generation, its direction and intensity, it is largely accepted that the wind is stochastic. For the TSOs it is very difficult to manage such a source of energy. During a wind turbine outage or when it is not working at full capacity, the operators must ensure a supply from another source. This requires additional infrastructure funding, having reserve sources of power on standby, and above all a different operational control and management of the power grid.

Grid operators: local investment conditions and grid codes

Wind turbines in the vast majority of cases, work with the electricity network. The electricity generated by these wind turbines is therefore transferred to the network. For this purpose power connections are needed. Where such connections can be located depends on the network operator. The point of connection is identified by the network operator based on the existing network structure, energy transmission properties, reception facilities as well as the distance from the wind turbines, and the supply voltage.

Increasing the density of the installed renewable energy sources has forced the need to adopt grid codes, so that it is possible to increase the number and the contribution from wind turbines in the power grid. In addition, since these regulations place new requirements on wind turbines, they still generally serve positively in their development and in increasing the reliability of the overall power grid.

Grid codes are technical interconnection requirements for the power grid. Up to the 1980s there had been no requirement for wind turbines or wind farms during faults or voltage disturbances, because the impact of wind farms on the power grid was negligible. The protection of wind turbines was limited to ensuring their safe operation. In the event of a disturbance resulting in a significant deviation of voltage or frequency, wind turbines were disconnected. However, increasing wind power penetration to the power grid has led to the revision of TSO requirements and an elaboration of the new grid codes. These codes demand that wind farms should contribute to the power grid in a similar way as conventional power stations do. Compliance with these requirements allows an increase in wind farm penetration without compromising power system stability and reliability. In different countries, grid codes correspond to the power network characteristics in these countries and the penetration level for these networks by the wind turbines.Therefore, grid codes vary considerably among themselves, although the following requirements are common in most of TSO rules. Generally, they expect a similar reaction to disturbances from wind turbines as from conventional generation systems. Under normal operational conditions grid codes specify the following characteristics (Altin et al., 2010; *Manual…,* 2012; *Network…,* 2007; Tsili, Papathanassiou, 2009; Elkraft, 2013; Eltra, 2004).

- Frequency and voltage ranges for continuous operation,
- Active power control and
- Reactive power or voltage control.

Additionally, in case of grid short circuits resulting in voltage dips, grid codes usually create:

- Fault Ride Through (FRT) and sometimes
- Reactive current or reactive power injection.

Figure 2 shows the differences between the standards for some European Transmission System Operators (REA, 2008; Elkraft, 2013; Eltra, 2004).

A comparison of certain national requirements for the continuous operation of wind turbines at frequencies, which differ from the rated conditions, shows significant variation. This is due to different levels of technological development for the grid, and capabilities to work as flexible generation systems. A high level of reserve energy sources leads operators to more liberal requirements, thereby making the obligation to work in a wide range of frequencies. On the basis of the sample data, Polish TSO requirements are relatively quite restrictive, because they require continuous operation in the narrowest frequency range from 49.5 to 50.5 Hz (*Manual of operation…*, 2012; Jarzyna, Lipnicki 2013).

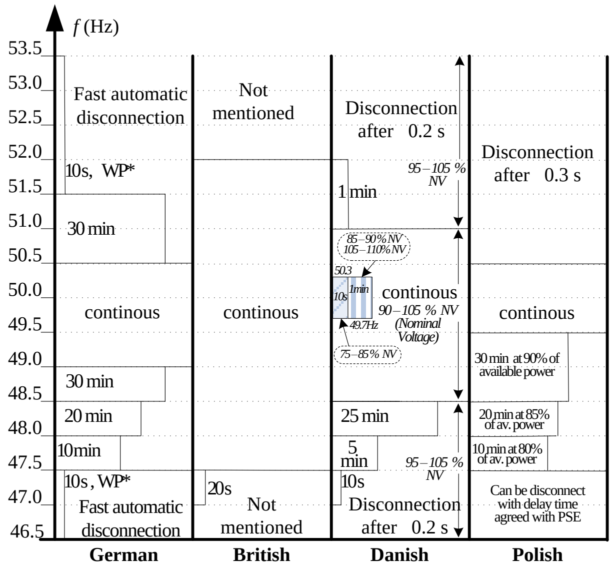

Figure 2. Operational requirements for a wind turbine at variable grid frequencies. The time in the rectangles depicts the minimum time the frequency relays are activated. Source: Authors' own work.

Technological development of wind energy

The investment boom in wind turbines followed the first oil crisis in the second half of the 1970s. At the time, within a short period of time, large areas of California became covered with wind turbines with capacities of up to 30 kW. Unfortunately, these investments were not thought through, were not preceded by environmental impact studies and in technological terms were very simple constructions. Consequently negative opinions were spread about them, which to this day investors installing present day solutions have to contend with.

The development of wind power in Europe was a lot more stable. Its progress since the 1980s is significant. For over twenty years the total capacity of installed power in wind turbines has increased almost quadratically. This increase has been accompanied by technological developments. Comparing the old solutions from the early 1990s to the current ones, the difference is enormous. Due to technological developments there has been a greater than 150-fold increase in power of the nominal manufactured systems (Figure 3).

Modern wind turbines have significantly better parameter values than those of the 1980s. They operate variably within a wide range of rotational speed. They achieve a higher efficiency, generate less noise and are more reliable.

The wind turbines obtain these properties through the use of vector controlled power electronic converter solutions. The operational variables and parameters are regulated and controlled internally by complex microprocessor systems.

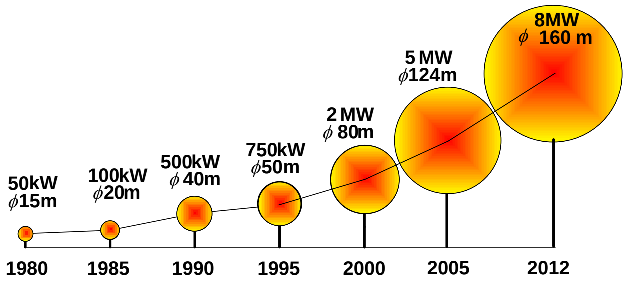

Figure 3. Development of wind turbines, their maximum power and rotor diameter. Source: Authors' own work.

Wind turbines operating at variable rotational speeds are usually coupled to the grid through AC/DC-DC/AC converters. Figures 4a, 4b and 4c show the basic wind turbine topologies (Altin et al., 2010; Tsili, Papathanassiou, 2009).

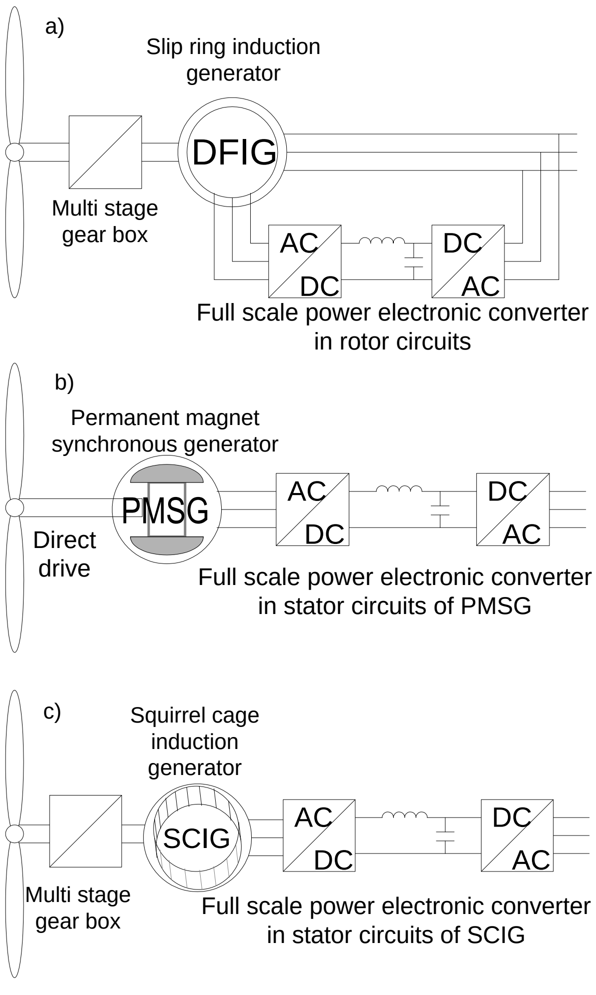

Figure 4. Modern variable speed generator configurations: a) Double Fed Induction generator, b) Direct drive with Permanent Magnet Synchronous generator and back to back converter full scale converter, c) Squirrel cage Induction Generator with back to back full scale converter. Source: Authors' own work.

The most common solution is the double fed induction generator (Figure 4a). Its construction is based on the slip ring induction machine, whose stator is directly connected to the grid, whilst the rotor is connected back to back to the full scale converter which allows bidirectional energy flow through the rotor circuits. As a result, the system can generate energy even below the synchronous speed, whilst for speeds above the synchronous speed, maximum power can be almost twice the power rating of the slip ring induction machine.

The solution in Figure 4b has the greatest efficiency and the lowest noise. Furthermore, it is the most resistant to voltage dips. Due to its own electromagnetic field in the rotor, these generators with electronic power converters are able to quickly restore voltages. For these reasons, in recent years, these solutions are becoming increasingly popular.

As can be seen in Figure 3 the unit capacity of wind turbines is constantly increasing. However, their growth is limited due to the weight of the turbine and the nacelle located at the top of the tower. For example, the total weight of the 4.5 MW Enercon E112 wind turbine with a PMSG generator is 440 tonnes, while the Enercon E-126 model is nearly 580 tonnes.

Such a large weight limits further growth in wind power capacity, especially above 10 MW. This limit can be overcome by using PMSG systems with a High Temperature Superconducting rotor and a non-magnetic pole body. Such solutions are expected to appear in 2016.

Technological progress by implementing sustainability

The described new constructions, especially the ability to work over a wide range of variable angular speeds significantly reduces infrasound generation. However, they cannot be completely eliminated in horizontal-axis turbines. The reason is the periodic movement of the blade near the tower. The resultant air pressure changes in the vicinity of the tower's tubular structure produces low-frequency noise. Wind turbines with towers comprising of lattice structures or with a vertical axis of rotation practically do not have this disadvantage.

The source of audible noise is the air flow around the blades and gearbox. In a gearless construction (Figure 4b) with a slow speed generator, the noise is reduced due to lack of a gearbox.

The noise generated by the airflow around the blades can be reduced for winds below the rated wind speed. Then specially selected construction material and the profile of the blades allow for laminar airflow. This results in an increase in torque and quieter operation.

When the turbine operates above the rated wind speed, up to the cut-off speed, the turbulence level increases which also increases the noise. It is only limited by changing the angle of attack of the blades, which reduces the torque without letting the wind become turbulent.

In conclusion, the lowest noise level from large wind turbines is from those that are gearless, variable speed, and with an adjustable blade pitch. The infrasound level can be limited by significantly fast torque regulators of vector controlled electronic power converters applied in all constructions listed in Figure 4.

The wind turbine manufacturer is required to disclose the level of interference and noise generated in the data sheets which can be used in simulations to assess the risk level. Such a risk assessment can be made on the basis of standards e.g. in Polish legislation there are noise regulations (*Ministerstwo…,* 2012). They can be used to construct isophonic contours, lines connecting points with the same noise level from the source. Doing this type of calculation should answer the question whether noise pollution is real.

The one factor that forced the described technological changes in wind turbines were the TSO rules. Further detailed discussion of them is not within the scope of this article. However, an interesting question is what the changes in grid codes have brought society? The answer is an increase in the reliability of the entire power system. Wind turbines have begun to be treated just like any other source of energy. It therefore requires a wide range of control and an active participation in rebuilding the voltage during short-circuits and switching between power lines.

Wind turbines also make a significant contribution to the creation of modern power systems known as smart grids. Contemporary wind turbine designs meet the requirements of such a system and can help to improve voltage quality and to reduce the risk of loss of voltage over large areas known as blackouts. As such incidents in Canada, USA and India have shown, activating the power grid after such failures can take up to a week.

The solutions to date demonstrate that in general the development of wind energy using modern solutions is a positive phenomenon. However, to realise it, financial resources are required and an expected return on this type investment. This is considered later in the article.

Evaluation of the Cost Effectiveness of Investments

From market profitability analysis the following can be differentiated:

- ✓ Investment profitability analysis of the project:
  - Simple (static) methods.
  - Dynamic (discount) methods.
- ✓ Financial profitability of the project:
  - Financial results analysis,
  - Cash flow analysis.

An economic analysis of the rentability of the investment enables one to estimate the basic static indicators like the Return on Investment Time (RoIT), return on capital, break-even point and dynamic indicators: discountable costs, Net Present Value (NPV), Internal Rate of Return (IRR), efficiency of investment and the time needed to receive the return on the investment. A more accurate outcome will be received when using dynamic methods including the whole investment period (Jarzyna et al., 2012).

Cash flow analysis is one of the most used methods for all financial analysis, especially when controlling the economic activity of the company. It is irreplaceable when synchronising investment incomes, activating production and developing the company's assets. The investor should be equipped with abundant financial means to cover costs of production, financial indebtedness, handling debt costs or taxes. Cash flow comparisons are usually made monthly or annually. The project is rated positively when there is favourable cash flow balance in all the periods considered (*Network…*, 2005).

These costs must be funded at the investment financing stage (in the form of equity, grants and loans) and at the wind farm operational stage (in the form of revenues from electricity sales and certificates of origin).

Profitability results should take into account different financial sources, cash flow indicators and wind capacity and wind turbine data. During current computations certain input data was assumed, which was related to a base value defined as the total investment value.

- Investors own funds 48.8 %,
- Bank credit 39.4 %,
- Government grants 11.9 %,
- Annual development costs 1.5 %,
- Period of credit reimbursement 5 years,
- Grace period of the credit 2 years,
- Discount rate 8 %,
- Rate of depreciation 5 %,
- Working life 20 years,
- Rated wind speed 12 m/s.

Based on a wind audit, an average annual wind velocity of 7 m/s was assumed. The capacity factor was determined as 27.6 %, which describes the total annual generated energy divided by the energy generated when the wind turbine is working continuously at the rated power (nameplate capacity) over one year.

For the forecasting Financial and Economic Balance, a two-year grace period was assumed before repayment of the bank loan in installments was required. Three variants of electrical energy price rises were considered. The Return on Investment Time of 6.8 years is required for a stable 1% annual price rise (Series 1). For comparison, a 4% increase in energy prices (Series 2) results in a 6 year RoIT payback period. However, variable energy price increases starting at 8% and dropping over 10 years to 1% (Series 3) result in a payback period of 5.4 years. Figure 5 shows a histogram for these three variants of the Financial Balance.

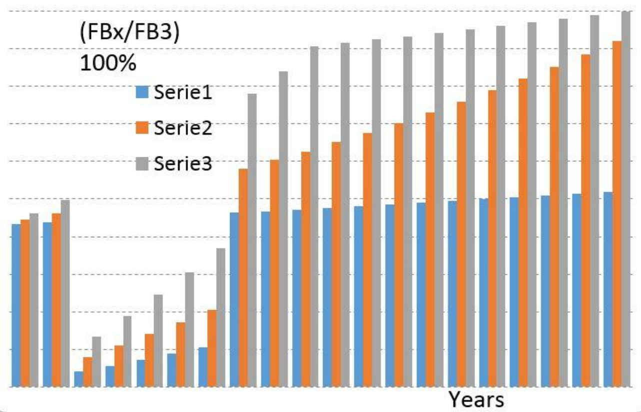

Figure 5. The Financial Balance (FB) computed for 3 variants of price rises and determined in relative values, where the highest annual FBx is the Base Value of Series x=1÷3. Source: Authors' own work.

Nevertheless, the Financial and Economic Balances depend mainly on the annual average wind speed. Figure 6 shows the effect of the average annual wind speed on the predicted RoIT for the project, where the rated wind speed is equal to 12 m/s.

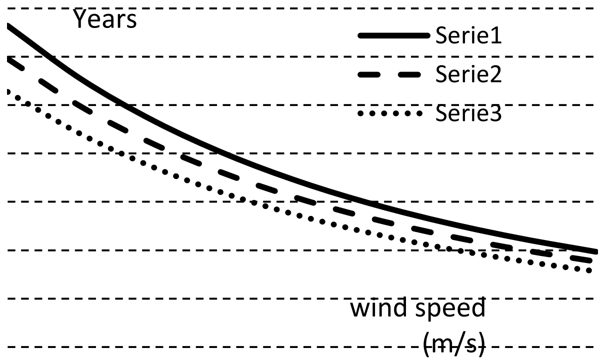

Figure 6. The dependence of the Return on Investment Time on the average annual wind speed for three price increase variants (as previously described). Source: Author's own work.

Assuming an Annual Wind Speed (AWS) of 7 m/s as the base value, a reduction of 20% to 5.6 m/s results in a near doubling of the RoIT. However, a 20% increase to 8.4 m/s, shortens the RoIT by up to 60%. For this reason, the key issue during the investment is the choice of location for the wind turbine. How to select a site and where to begin is described in the next section of this article which is related to a wind energy audit. Using innovative solutions analysis of wind strength definitely accelerates this stage and reduces the risk of making an erroneous decision.

The optimal choice of location is also an environmentally friendly target

The construction of a wind farm is limited by many factors. The basis is a business plan which forecasts revenue from the planned investment. Factors that are crucial to the profitability of the investment are the wind energy resources. They can be initially evaluated using meteorological parameters. These include:

- the average wind speed,
- the probability distribution of wind speed as a function of the frequency of its occurrence,
- the wind velocity gradient as a function of height.
- the level of turbulence and a wind rose.

The average annual wind speed has a major impact on the predicted generated power. From satellite observations, preliminary data on wind conditions can be obtained from the *Global Wind Speed Atlas*. A free version is available from webpage (*sanderpartner.com*, 2013). This data allows for a preliminary assessment of wind conditions for the selected area. The location is approximate and the data does not take into account long-term variations (Figure 7). To obtain more accurate data requires placing an order with a commercial company.

Detailed wind conditions are described on the basis of measurements carried out over at least a two-year period by specialist companies.

The wind speed which is included in these calculations is measured at the height of the installed nacelle. In this

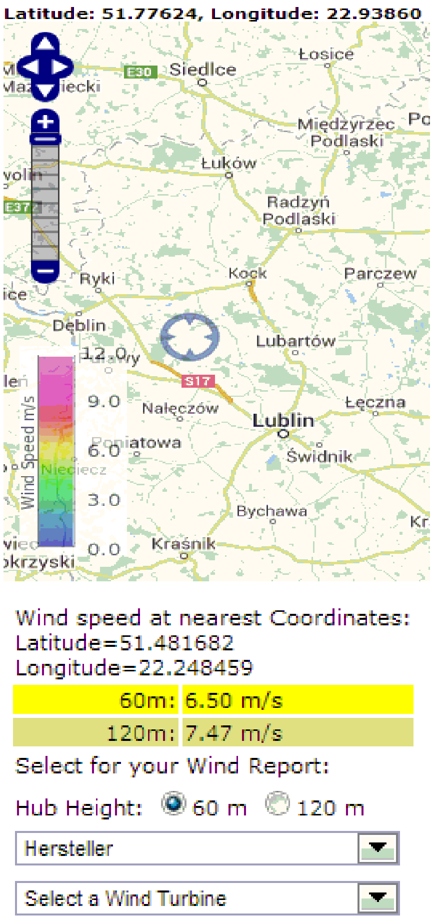

Figure 7. An example of a map copied from Sander + Partner with a selected measuring location with specific coordinates, and the average annual wind speed at a height of 60 and 120 m. Source: *sanderpartner.com* (2013).

way, wind speed changes can be averaged in the height function. The empirical formula for this speed is:

$$V_w(h) = V_{hub}\left(\frac{h}{h_{hub}}\right)^{\alpha} \qquad (1)$$

where:

h_{hub} – height of the installed nacelle,
h – the height at which the wind speed is measured,
V_{hub} – wind speed at height h_{hub},
$V_w(h)$ – wind speed at height h,
α – exponent, the value of which depends on the terrain classified by its roughness.

A terrain has the smallest impact when it is an open, calm sea (Terrain Roughness Class 0). Under such conditions, already at a height of about 30 m the surface friction is negligible, and the wind speed approaches the true wind speed, whose main components are the geostrophic and pressure-gradient winds (Lipnicki, 2012).

In areas with a higher Terrain Roughness Class, wind speed and direction is not determined until altitudes of 500 ÷ 1500 m. The estimated effect of roughness on wind speed in the height function is presented in the Normal Wind Profile Model – NWPM (2) (Kacejko, Wydra, 2011).

$$P_t = k \cdot S \cdot V_w^{\ 3} \cdot c_p(\lambda, V_w) \qquad (2)$$

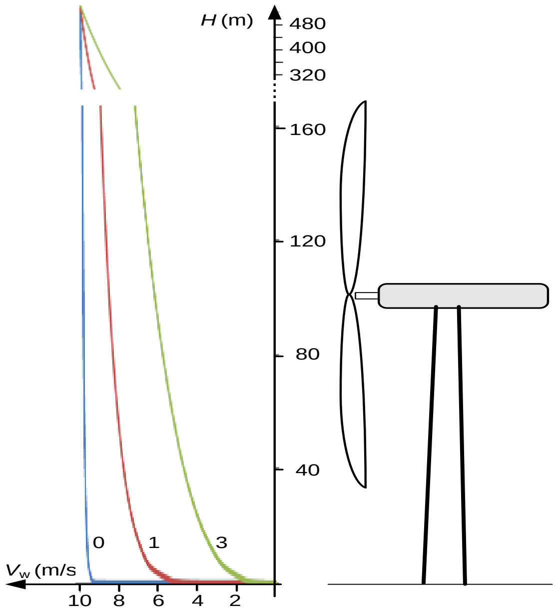

Figure 8. Wind speed characteristics using the NWPM model with the coefficient α = {0.01, 0.1, 0.3} at an actual wind speed of 10 m/s in a fixed zone. On the left hand side, three wind speed characteristics using the NWPM model with coefficient α = {0.01, 0.1, 0.3} corresponding to a Terrain Roughness Class of 0, 1 and 3. It is assumed that the set geostrophic wind speed occurs at a height of 500m and is 10 m/s. On the right hand side, for these three curves the wind turbine generates significantly different powers of 4.5 MW, 2.8 MW and 1.2 MW respectively (Jarzyna, 2011).

The average annual energy is determined using the relationship between the power generated by the air stream, which flows through the surface area described by the tips of the turbine blades. The resulting value is admittedly the most important, but not the only indicator in the assessment of wind energy. To determine the expected usable power of the turbine the wind speed range (cut-in ÷ cut-off) for which the wind turbine operates should be taken into account.

Most commonly turbine blades begin to rotate at a cut-in speed greater than 3.5 m/s. This lower speed limit is justified by the fact that the generated power is related to the wind speed cubed. Assuming that the wind turbine achieves its rated power at a wind speed of 13 m/s then the power output at a wind speed of 3.5 m/s is less than 2% of the rated power. This power in most solutions only slightly exceeds the resistance to motion, so it isn't worth to operate the wind turbine below this value.

In contrast, wind speeds over 25 m/s are usually the upper limit at which the turbine blades are brought to rest (cut-off). Above this speed, wind turbine

operation can be dangerous due to excessive mechanical stresses and possible blade vibrations caused by the turbulent air flow.
However, knowing the probability of occurrence of the different wind speeds the expected power yield can be determined. The calculation method is determined by the Wind Turbine International Standards (ENTSO-E, 2013). The algorithm described uses a two-parametric Weibull distribution. Examples of such distributions for two average annual wind speeds (V_r = 5 m/s and 8 m/s) which describe the distribution of wind speeds over a year is illustrated in Figure 9.

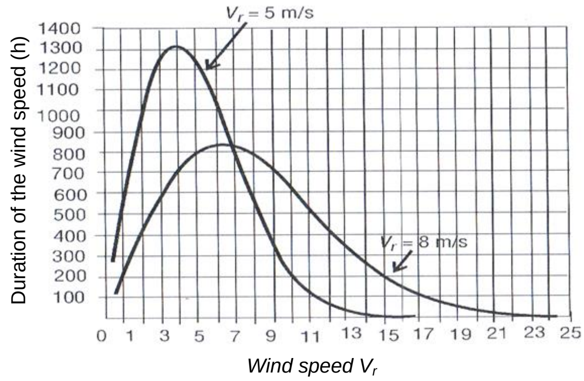

Figure 9. Wind speed probability function, used to describe the distribution of wind speeds over an extended period of time. Source: Authors' own work.

In addition, these distributions can be used to determine the distribution of power and can be useful when selecting the rated wind speed of the wind turbine.

Wind conditions and the choice of a wind turbine

The most important wind turbine parameters are:

- power,
- blade span,
- rated wind speed,
- cut-in wind speed,
- cut-off wind speed,
- the height of the siting of the nacelle,
- turbulence level.

Turbine capacity is directly related to the square of the span of the blades and the cube of the wind speed (2). Therefore, it indirectly depends on the height of the tower on which the nacelle is mounted (1). Examples of the power curve for a turbine as a function of wind speed is shown in Figure 10.
Therefore, it may happen that a turbine with a smaller blade span will have a higher power rating. However, this power will occur at higher wind speeds. Therefore, if an investor from the outset specifies the rated power, a multi-variant analysis should be performed, which consists of a cycle of calculations as proposed in Figure 11.

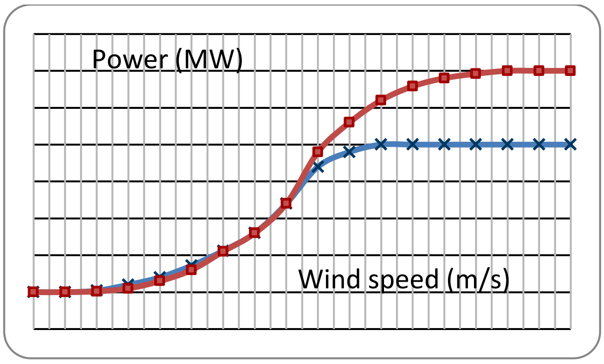

Figure 10. The power curve for two wind turbines with an identical blade span but different wind speed ratings. Source: Authors' own work.

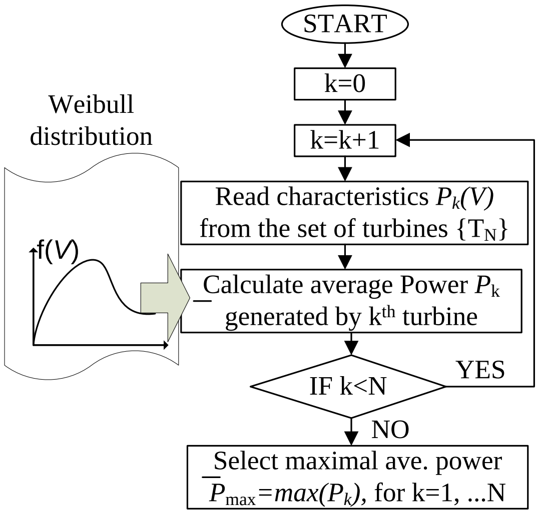

Figure 11. Algorithm for optimal wind turbine selection. Source: Authors' own work.

Knowing the wind speed distribution $f(V)$ and the wind turbine's power curve $P_k(V)$, the average power $\bar{P}_k$ can be determined for a wind turbine which it is able to generate from the wind in a given period of time. This power can be calculated from formula (3).

$$\overline{\boldsymbol{P}} = \int_0^\infty \boldsymbol{P}(\boldsymbol{V})\,\boldsymbol{f}(\boldsymbol{V})\,\boldsymbol{dV} \qquad (3)$$

It should be noted that the average on-shore power $\overline{\boldsymbol{P}}_k$ only fluctuates within (20 ÷ 25)% of the rated power.
$P_k(V)$ largely depends on parameters such as the cut-in wind speed $V_{cut\text{-}in}$ and the wind speed at which the rated power output V_n is achieved.
The amount of electricity generated annually E_a can be calculated from the relationship:

$$E_a = \overline{P}P_nT \qquad (4)$$

where:
E_a – electricity generated in kWh,
P_n – rated power output of the wind turbine,
T – number of hours in a year (8760 h).
The calculated amount of energy is the basis for estimating the expected annual energy profits.

Factors shaping public opinion

Sustainable development perspective must include not only environmental and economic, but also social issues.

Social opinions and attitudes have also a very large impact on the expansion of wind energy. Insufficient information and disseminating incorrect facts is a major concern when planning a wind farm. Of course, there are reasons for fear and anxiety on the part of residents. As mentioned previously, wind turbines bring disruption to the surrounding ecosystem, which may lead to adverse effects on health and quality of life.

During the decision-making process to build a wind farm, three social groups are formally involved:

- local population,
- local authorities and,
- investors.

This division does not include groups of people interested in promoting their own particular interests. These latter groups mainly exist as unidentified groups, using various social engineering tools, to achieve their own success. Experts appointed by them, or rather pseudo-experts assess the problem unilaterally without a proper objective assessment of the situation. The discussions, sometimes aggressive and demagogic, prevent factual analysis and objective assessment of the planned energy investment.

Local authorities often cannot cope with such a situation. Burdened with a political desire for reelection, they do not want to risk losing votes of the dominant group of voters and sometimes approve blatantly false solutions. It should be emphasised that such a stance from the authorities may affect both those in favour and those against the construction. A common feature of such conduct is the marginalisation of the experts' objective opinion, whose arguments are lost in the adversaries' vociferous slogans and social engineering methods.

The use of methods which shape social attitudes aimed at achieving a particular, biased objective, leads to a so-called groupthink. In the extreme, it is characterised by a complete loss of the sense of reality and an overestimation of one's own strength and ability to act. Such behaviour has been documented by J. Irving (1972) as symptoms of groupthink. As a result of the imposed self-censorship, members of the group subjected to this phenomenon, voluntarily impoverish their intellectual abilities, and become a tool in the hands of groups, whose arguments may be erroneous, but who are completely in pursuit of their own goals. This happens when wind turbines are built too close to residential buildings, or when e.g. due to infrasound or electromagnetic interference, wind turbines planned in compliance with all standards cannot gain the acceptance of the local community.

The greatest number of concerns relate to the effect of wind turbines on human health. Studies conducted in the UK (GWEC, 2006) have shown that factors such as noise, infrasound and shadow flicker do not have any harmful effects on human health if, during construction, wind turbine building regulations have been complied with. Paradoxically, greater adverse health conditions can be caused by man as a result of anxiety caused by fear of the negative impact of wind power on the human body.

It should be remembered that most of the negative consequences can be avoided by a reasonable distribution of wind turbines. Thus, the wind turbine should be so incorporated into the existing landscape so as not to change the perceptions and feelings of people who exist there every day.

Arranging the wind turbine site and land-use area, we must remember, that wind turbines occupy only 1% of the area leased by investors. The remaining 99% can be reasonably managed or exploited in a rational manner. These areas are currently used mainly for agriculture, but landscape architects can have room to maneuver here, or even make it a tourist attraction.

Sometimes, little public knowledge on energy efficiency and the expected benefits derived from producing this energy happens to be a big problem. The fact that the purchase and operation of wind turbines as well as other renewable energy sources results in the development of the local market and provides new places of work to a much greater extent than conventional power is not publicised. Furthermore, the consequences of environmental pollution in this case are virtually eliminated.

A hint on how to solve this type of problem is the Dutch experience (IEA, 2013). It consists in the introduction of the institutionalised form of discussion to encourage the exchange of ideas and to help reach compromised solutions. A special group of external independent experts (outside experts) raise public awareness through information campaigns. In the Netherlands this resulted in an increase in project transparency and an increase in confidence towards investors.

A long-term educational policy can also be carried out in schools. Such an example exists in some U.S. states (*Wind for…,* 2013), where education regarding renewable energy sources allows for a wider public discussion on the potential benefits which have an impact on the local market for goods and services.

An important aspect when constructing wind farms are the potential financial benefits charged to the local community. Many projects are blocked by protests linked to the unfair distribution of profits such as long-term lease agreements for farmers. A good solution to this issue could be an opportunity for the residents to invest themselves. For example, in Denmark the residents' share of the distributed income reaches almost 20% (REA, 2008). Such a

solution provides a choice for each potential beneficiary of whether he wants to achieve financial benefits associated with the development of wind energy in his place of residence.
Citing Section 4.1 of Recommendations for Developers (IEA, 2013):
To balance financial interests and thus create an increased potential for new and positive relationships between the wind energy project and the local residents/community, developers should consider the following:

- Boost the local economy by:
  - contracting with local companies for basic construction activities such as pouring foundations, building roads, establishing grid interconnection, and transporting equipment;
  - purchasing local products (e.g., gifts for VIPs, snacks for guided tours); and
  - hiring local residents for operations and maintenance labour, tour guides, etc.
- Allow residents/communities to participate as shareholders (potentially by offering them shares at a special price if otherwise not practicable).
- Create a positive link with the wind power production; for example, by setting up a company for the wind power project that is based in the municipality so that the taxes generated by the project flow to the host municipality.
- Consider allowing the residents/communities to purchase the locally generated electricity on preferential terms.
- Offer an *indirect* land rent or the ability of owners of neighbouring parcels to participate as shareholders.

There are also new opportunities. Renewable energy plants may be perceived as tourist attraction, as is the case of Morbach in Hunsrück in Germany. Old US army base is now a place, where different renewable energy technologies (including wind power) are presented, with thousands of visitors every year. There are even special tourist guides for those, who are interested in renewables, like German *Baedeker Deutschland – Erneuerbare Energien Entdecken (Germany – Explore Renewable Energy)*.
Various examples show that there is no standard answer to all concerns. In each case, an optimal solution should be sought in the local social context. Social acceptance and proper representation of specific projects in the media can be defined as a public consensus in the planning, construction and operation of wind farms.

Conclusions

Electricity generation using wind turbines does not produce greenhouse gases, and yet its development raises a number of concerns especially when they significantly aesthetically change the environment or when their work is a burden for the local community. The negative effects of operating wind turbines are felt to a greater extent. While the sound of old windmills could reassure and soothe us, it is the compounded operational noises of large wind turbines which cause exasperation. Sometimes we are more afraid of what our senses do not perceive, for example, infrasound and electromagnetic waves. The validity of some of these fears may be justified. That is why a reliable knowledge and an honest dissemination of information to the local communities is required.
The need for reliable expert information is extremely important, as the development of technologies for the production, design and commissioning of wind turbines is very dynamic. The development described in this article uncovers further the unknown properties of wind turbines. The authors suggest that the new wind turbine solutions are better suited for the needs of society. These solutions also contribute to reducing the negative impacts on the ecosystem.
Unfortunately, due to the aggressive policies of certain groups, facts are distorted and whole communities are misled. Such actions cause a lot of harm and introduce distrust.
For this reason, a comprehensive assessment of the impact on the environment is required, and thus a check on whether the conditions for sustainable development are satisfied. Only such a policy can bring long-term positive effects and significantly reduce installation errors and minimise adverse impacts on people and the environment, which is so important from the perspective of sustainable development.

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