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Review Article

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Effects of atmospheric discharges on wind farms performance: a review study

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Abstract. One of the factors that influence the energy projects' performance is the atmospheric conditions. Atmospheric discharges are a recurrent and natural phenomenon, that for the energy sector, represent a risk for the system functioning due to the possibility of damage to the equipment or indirect impacts, such as fires and transmission system shutdown, interrupting the energy supply, and causing socioenvironmental and economic impacts. This article analyzed the effects of atmospheric discharges on tall structures of energy projects performance, namely on wind farms. For that purpose, a systematic literature review was developed, and as complementary data some examples of Brazilian Environmental Impact Assessments of new wind farms projects were verified, to demonstrate the need to consider this parameter on the energy projects assessment. Thus, this review showed that better-quality information about atmospheric discharges, as main causes of the breakdowns and factors which influence the intensity and their geographical location, is important to prepare preventive maintenance plans in the short and long term. Moreover, the environmental studies of new energy projects do not consider this phenomenon as an external factor and their effects, such as the possible conflicts between the responsible enterprise and the affected population.

Keywords: Atmospheric Discharges / System risks / Economic losses / Wind farms

1 Introduction

According to the World Meteorological Organisation (WMO), lightning phenomena is defined as a flash of light, which is a manifestation of a sudden electrical discharge [1], that may be used for monitoring severe convection and precipitation, to improve estimates of severe storm and to provide early warnings for severe weather. In terms of global climate, lightning produces nitrogen oxides (NO_x) which influences ozone formation [2]. This phenomenon is one of the oldest recorded on Earth, and may be observed during: volcanic eruptions, highly intense forest fires, surface nuclear detonations, strong snowstorms, and large hurricanes and thunderstorms [3]. All over the world, at any time, it is estimated that there are more than 1.700 active electrical storms, which may generate over 100 flashes per second or 7–8 million strikes per day. Moreover, lightning may release 55 kWh of average energy [4].

In this setting, Brazil is the country with the highest incidence of lightning in the world, with more than 70 million discharges per year [5,6]. In 2020, the WMO validates a new world record for the greatest extent for a single lightning flash, which covered a horizontal distance of 709.8 km across parts of southern Brazil, on 31 October of 2018, being equivalent to the distance between London and the border of Switzerland near Basel. The previous record was for 321 km, on 20 June of 2007, across the U.S.A. in Oklahoma State. In addition, the new world record for the highest duration for a single lightning flash is 16.73 seconds from a continuous flash over northern Argentina on 4th March of 2019 [7].

In these circumstances, namely severe weather and atmospheric discharges, tall structures such as telecommunication towers, buildings, transmission systems towers, and wind turbines, are directly exposed to these environmental extreme conditions. This scenario is considered a real challenge to the energy sector due to the damages caused to the equipment and the related financial losses in the case of energy projects [8]. The atmospheric discharges are one of the major causes of disruptions in the energy supply of the transmission and distribution systems. It is important to highlight that a transmission line is mainly composed of tall towers, conductors, and cables. And it is randomly affected by

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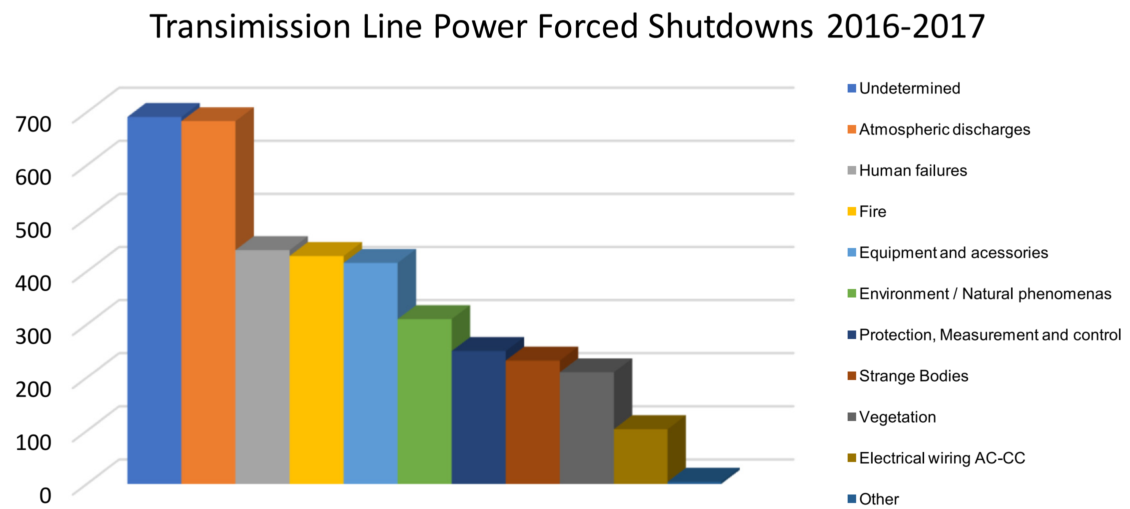

Fig. 1. Distribution of power forced shutdowns of Brazilian Transmission Energy System between 2016 and 2017. Adapted from: Relatório de Análise: desligamentos forçados do Sistema de Transmissão/ANEEL 2018.

lightning in its path. In this context, in North America, 26% of the breakdown of energy service in transmission lines up to 230 kV and 65% in lines up to 345 kV are provoked by lightning [9]. Furthermore, the United States spends up to U$ 20 billion every year to cover the damages to energy projects due to severe weather [8] In Brazil, the disruptions may reach almost 70% [10], which causes annual economic losses of up to U$ 1.1 million to the energy sector [11–13]. According to the National Agency of Energy Sector in Brazil (ANEEL), between 2014 and 2015, 15% (486 events) represented forced shutdowns in the transmission system [14]. During 2015 and 2016, the number of events of power-forced shutdowns rose to 614, whereas in 2016–2017 the registered cases were 683, which represents 18% of the total of incidents [15]. Figure 1 represents the distribution of power forced shutdowns between 2016 and 2017. As it can be seen, atmospheric discharges are the second cause of transmission forced shutdowns.

Concerning wind farms, in Denmark between 1990 and 1999, the owners of older and smaller wind turbines reported that, annually, 4% of the equipment are damaged by lightning, which means damages in 900 wind turbines, in an area where the lightning occurrence is considered low. In Germany, 70% of all faults were caused by indirect lightning strokes, while in Sweden, between 1992 and 1998, the annual average of damages to wind farms was 5.8% [16]. In 2009, a lightning event during an intensive thunderstorm destroyed part of a wind farm between Brieske and Schwarzheide, in Germany. Pieces of blades flew approximately 150 meters, landing nearby a highway and cutting several trees through the forest [17]. In another incident, the damages caused by a lightning strike in the North Sea near Helgoland (Germany) wind farm were so significant that its operation was no longer possible due to the cost-effectiveness [18].

In this context, this article aims to analyse the main aspects related to the lighting strokes in power tall structures, namely wind farms, through a systematic literature review, to demonstrate the importance of these occurrences and the subject to the energy sector, once this topic is frequently not incorporated in environmental analysis before new projects and their effects as financial losses, damages to the structures, disrupt of power supply and the impacts to the end consumers, (risk of death or injuries, property fire, and loss consumer goods) are underestimated in the energy sector planning.

2 Literature review

2.1 The lightning phenomena and tall structures

Atmospheric discharges are defined as a short time and a transitory spark of electricity in the atmosphere between clouds, the air, or the ground with a high electrical current, which may reach large distances [3, 6, 13]. Even if the exact process of how the clouds create the electrical charges is still not completely understood, the required conditions to generate lightning are fully known [3]. Besides that, the most accepted definition for the lightning formation process is the result of a dielectric breakdown created when the electric field intensity in a cloud raises to a point that may exceed the intensity that the air may sustain [19].

Thereby, lightning events are influenced by factors such as geographical location, meteorological and climatological conditions, and parameters [20]. In this framework, the atmospheric general circulation defines, on a global scale, the distribution of thunderstorms and in consequence the lightning events. This factor evidences the lightning geographic dependency [21], which also influences their frequency, seasonality, and main characteristics [22,23].

For instance, due to the solar heating and the water vapour available in the air, most of the lightning events occur during the summer in Europe, while only 3% of the annual lightning happens during the winter [22,24–26], Even though, the most energetic atmospheric discharges and whose inflicting severe harm are verified during the occurrence of winter thunderstorms, as these systems provide favourable conditions for upward lightning flashes [22, 23]. In this context, Japan presents a singular and ruthless environment, which creates favourable conditions for the development of the "winter lightning" phenomena [8,22,27]. Moreover, other areas present similar behaviour than in Japan regarding winter lightning, for instance, in Europe, areas along the Adriatic coast from Croatia to Greece are classified as "severe winter lightning activity" [26].

Even so, the physical processes are not fully consolidated, this phenomenon is widely analysed due to its interaction with wind turbines [26,28] and the severe damages to this equipment in winter thunderstorms, namely in Japan and Europe [21]. In this respect, winter lightning is responsible for more than 99% of the flashes which reached wind turbines along the west Japanese coast [24] therefore it was created a national regulation to control the adoption of higher standards of lightning protection [18,26]. A study between 2002 and 2006, shows that 36% of the damages to the blades occur in summer while 64% in the winter season. Moreover, the total interruption supplying time due to blade damage in winter is three times that during summer [28]. Additionally, other studies showed that, in short periods, some wind turbines were struck repeatedly, and in almost 5% of the incidents the lightning charge exceeded 300 °C [22,26].

Nevertheless, some characteristics of the winter lightning make it an unusual phenomenon: the upward flashes started with an upward leader from a structure on the ground, the bolts of lightning tend to be longer, but also are often mixed electrical polarity [22, 26], and it may vary from year to year not being constant [26]. In this context, tall structures may increase local stroke density [22, 26]. This can be seen, in Spain, where a monitoring wind farm revealed that the number of lightning increased three times with a similar total flash density [26]. Along with, during 4 years, 18 wind farms in the north of Spain were also monitored, and it was observed an increase of lightning activity close to wind turbines in years of winter lightning activity [26].

This is important, once certain tall structures act as a discharge collector [13], and under certain conditions, these structures may initiate upward lightning flashes [21]. Considering this type of structure, the lightning is classified as upward and downward and subdivided into positive and negative according to the polarity of the charge transferred by the cloud to the ground [20]. In this context, compared to wind turbines, the transmission lines present a quite different response when they are hit by lightning. In this case, it will provoke an isolation failure due to an unexpected or high overvoltage, which means a short circuit. This overvoltage can be classified as direct (when the line is hit directly) and induced (when the discharge hits near a line) [29]. Moreover, the main shutdown mechanisms by lightning are the flashover, the back flashover, and the midspan flashover [9, 30]. In a flashover case, the lightning strikes directly a phase conductor due to the absence of a protection cable or to a shielding failure [9, 30, 31]. In a black flashover, the discharge hits the tower structure or the cable guards [9, 30, 31], and in the midspan, flashover occurs a break in the air gap between the shielded cable and one of the phases when the lightning hits the midspan of the shielded cable [9, 30, 31].

2.2 Lightning effects and wind farms

In this sense, some aspects may explain the vulnerability of wind farms to lightning. The physical properties of location (such as the topography and the relief height above sea level) also influence the discharges and the working of the projects [26]. As an example, blade surfaces covered with sea salt or rainwater become more conductive, facilitating surface discharges to form, increasing the likelihood of a lightning strike. At the same time, the sea salt over the blade may reduce the discharges passing into the blade cavity and consequently decrease serious damages [28].

It is important to remember that a wind farm is composed of isolated "towers" with sensitive electronics components [32] and a particular shape and height [8, 26, 33]. In this context, it is considered that the risk of an object being struck by lightning grows with the square of its height. For instance, the probability of lightning striking a modern wind turbine with 110 m height is more than 6 times higher than the regular ones of 45 m [16]. Other studies observed that the stroke density increase in an area of 1 km of radius surrounded a turbine with 600 m, but also wind farms located in a terrain 400m above the ground level induce an average increase of 150% in lightning density compared to flat areas 2 km to 5 km away [22]. Additionally, for tall structures in exposed locations, their effective height is significantly higher than the real one, which implies that the wind farms will experience upward lightning strikes [20].

Furthermore, the most exposed part of the wind turbine is the blades [21, 33], which represent approximately 40% of the total turbine height [18]. Blades are also the most vulnerable component of the wind turbine, followed by the generator, controller, and the nacelle [33]. Besides that, blades suffer most of the total lightning strikes (almost 75%), presenting the longest downtime (around ten days after a stroke) and having high repair costs [33].

Notably, two other characteristics make the wind turbines a unique case and also may increase the risk of damage: the rotation of the blades [18] and the use of composite materials for their manufacture [18].

Concerning rotation, some studies point out that this aspect may affect the number of strikes of large wind turbines, but also may create an electric field that is necessary for triggering their own lightning [34]. In this context, two types of upward lightning are expected: events induced by nearby lightning flashes or self-initiated events [18, 35].

Based on a United States database, the injuries caused by lightning are concentrated at the tip of the blade [33], Indeed, the speed of the blade tips may reach 100 ms^{-1} for 50 m long blades. However, the modern blades may have more than 70 m [18]. Given that, wind turbines present a higher attractive radius for lightning when compared with a stationary structure with similar height [18].

Given what has been said, the materials used to manufacture the blades may have a different response. For instance, studies show that carbon-reinforced plastics are more electrically conductive, compared with glass [21] and wood epoxy blades are more lightning resistant [32], when compared to glass epoxy blades. It is important to highlight that the wind blades are commonly formed by two shells of composite materials (fibreglass, epoxy resin, polyurethane) in built-up layers [34] which enclose a spar [21], made with rigid polyurethane foam encased in fibreglass [34], with a protective waterproof gel coating on the outside [18, 21, 34].

Considering this, the major problem with the use of composite materials is the possibility of moisture inside the blades. As the polyurethane may have varying degrees of absorption and permeability, the moisture may penetrate in different locations in the interior of the blade via previous structural cracking or as a result of surface damage caused by previous lightning and may cause imbalances. Moreover, residual moisture inside the blade together with high temperatures of the discharges may provoke a steam pressure expansion and in consequence, it may occur: a "de-lamination; burst bonding; residue compromise; trailing edge cracking; detached blade pieces; de-bonding; longitudinal cracks; spar separation; fires due to the presence of hydraulic fluids/lubricants; or partial or complete blade destruction" [34].

According to the USA National Fire Protection Association handbook: "While physical blade damage is the most expensive and disruptive damage caused by lightning, by far the most common is damage to the control system" [32]. The effects and possible damages to the components of a wind farm are quite different, for instance, the electrical components will harm as same as other typical electrical systems [28].

In this setting, direct impacts to the nacelle, meteorological instruments, warning lights, and the spinner is not common. Besides these impacts being recent in the wind energy industry, there is little information about damages to tall precast towers [21].

Furthermore, if lightning hit an unprotected blade, the temperature may rise to more than 30.000 °C, which may cause an explosive expansion of the air within the blade and, in consequence, delamination, damages to the surface, melted the glue, cracking on the leading and trailing edges [32], spar rupture, separation, and surface tearing [28].

Most of the damage is restricted to the blades, which may be: marks on the topcoat, edge erosion, and cracks [36]. In some European regions, up to 8% of wind turbines suffer injuries due to lightning [38]. As some studies pointed out, almost 90% of lightning attachments are located beyond 1m from the blade tip where the thickness of the surface skin is up to 10 mm [34].

Based on past incidents due to winter lightning, a proposed classification of lightning damage, divide them into four categories: (i) catastrophic, which requires immediate turbine shut down due to a blade rupturing, burnout, and wire melting; (ii) serious damage, which requires immediate repair due to a surface cracking and surface; (iii) normal damage, that requires a repair as soon as possible due to a surface stripping and a receptor loss; and (iv) minor damage not requiring immediate repair due to receptor vaporization, surface scorching, surface blotching and surface delamination [21, 28].

Considering all these aspects, the final destination of the equipment, namely the blades, may be influenced at the end of life of wind farms. The process of remanufacturing depends on a relationship between the cost, the quality, the equipment performance, the working/maintenance, the technology, and the market [38]. Regarding the quality, damages on blades also occur for some reasons: wear, debris, precipitation, operational errors, manufacturing defects, and lightning. Blades with poor quality with not attractive prices to cover the decommissioning make reprocessing difficult [38] or even turn the refurbishment unavailable. In these cases, the only possible final destination for the blades is the landfill. Conversely, sending this equipment to landfills, in many European Union countries, is not a long-term option due to their legislation against composite waste. Thus, some companies are trying to reuse these materials in bridges, buildings, or urban furniture [38].

2.3 Protection measures

Facing these potential damages, protection measures may be different according to the location and individual sites [32]. Instruments such as weather-measurement systems and lightning sensors are used to measure and determine the possible location of a strike [5]. An installation of an independent lightning tower may be an effective solution, namely for areas with wind direction considered constant during lightning seasons. This structure may attract most of the lightning in the area, and in consequence, it will reduce the number of strikes but also the level of damage to blades [32].

In terms of equipment, a lightning protection system (LPS) is required to protect the integrity of all the components and electronic systems, reducing possible faults and injuries [36] and reducing the risk of production losses and higher repair costs, namely the offshore one [16].

Therefore, an LPS efficiency may be influenced by the region characteristics, the thunderstorm climatology, and the geographical distribution [21]. For instance, offshore locations are more sensitive to lightning strikes [16, 32]. Additionally, some parameters must consider: the number of flashes, type (upward and downward), their polarity, the energy [18], and also the effects generated by wind farms such as upward lightning flashes and a back-flow surge phenomenon [21].

In this sense, the LPS costs less than 1% of the total budget, lightning causes respond for 80% of wind turbine insurance claims [37], and up to 20% of the total cost destined to replace the damaged blades [34]. In insurance and service contracts, atmospheric discharges are considered a force majeure event, and the responsibility for repairs/replacements and related costs, in general, are not covered by the warranty, being the project owner the responsible for these costs [39]. In Germany, a southwestern wind farm remained 85% in the downtime and had losses due to lightning-related damages, which may be over $250.000 during its first full year of commercial working.

Another wind farm, Helgoland Island, was decommissioned due to financial losses above $540.000, in three years of working, and after being denied the insurance against further lightning losses [32]. The force majeure clause could be prejudiced for the project owners but it is also a barrier to improvements in LPS technology [39].

It is important to emphasize that even wind rotor blades equipped with protection mechanisms such as air-termination systems which are designed to resist about 98% of lightning strikes [34], the injury by lightning may still occur [21, 33]. This is one of the reasons that reason, for a lightning risk assessment the aim should be to establish a rational complementary strategy to prevent lightning damage [40]. Besides all the previous aspects considered for an LPS, the personnel risk should also be considered. It is also a very relevant issue for companies when there are casualties caused by lightning, due to potential litigation costs [41]. In case of evacuation, the size of the wind farms influences the evacuation time. In general, the evacuation time for wind farms is long, up to 20 min, a long warning range [41].

Therefore, based on a detailed risk management assessment, some measures may be adopted: (a) the installation of the receptor(s) and a down conductor, (b) the quality management of a blade, (c) the upgrade to blades with full-span pitch control, (d) the structural reinforcement of a blade and (e) the installation of an independent lightning tower. The solutions (a), (b), and (c) are strictly recommended for wind turbines located in areas of winter lightning activity [32].

Despite all the available technology in LPS or new improved materials and best techniques used to build the wind farms components, the best tool to protect the equipment and the surrounded area is accurate data about the discharges. In this sense, even with all technological advances in research of atmospheric discharges, the main issue is related to evaluating the lightning density in areas not covered by radars and other instruments. In these cases, in general, the iso-keraunic level (IKL) is used as an index of lightning severity [40], which means the number of days with lightning in a year for a certain area [13]. However, besides it is a good indicator for the atmospheric activity and is easy to be obtained, it may not be the best parameter to identify the lightning density on the ground, because sometimes is not coincident with the number of lightning strokes on the ground [40] and it may be influenced by the terrain characteristics [13]. Moreover, the iso-keraunic level may have errors once the discharges between clouds are counted which is irrelevant information regarding the equipment protection [13].

The particular behavior of the wind farms in a lightning environment should also be a part of the LPS strategy. For instance, the back-flow surge is responsible for breakdowns and burnouts in low-voltage circuits and surge arresters, but also is related to incidents in wind farms that were struck by the actual lightning and others in surrounding that had not been struck by any lightning [8, 27]. This phenomenon is created when a lightning current covers the blade to the base of the tower where it splits between the grounding systems and provokes the back-surge phenomenon. The arresters send the surge back to the power system instead of the grounding system [20, 34, 37]. Additionally, similar to the back-flow surge, the surge invasion phenomenon occurs when lightning strikes a distribution line of a wind farm and the surge flows to a customer's structure (as a telecommunication tower) and back to the distribution line [8].

Lastly, the "swept stroke" is a regular phenomenon in the avionics industry, however is not completely understood regarding wind farms. In a high static electric environment, corona and partial streamer discharges are developed and may sink ionized air in the air around the receptors or in other exposed areas and due to the intense thunderstorm winds may blow away to attach to a limited extent [25].

On the other hand, with the goals of the Directive 2009/28/EC of European Parliament and of the Council of suppling 20% of energy consumption from renewable energy [37] and the new goal of 32% of final energy consumption for 2030 the Renewable Energy Directive (EU) 2018/2001 [42], there is a significant increase of new farms projects and financial investments of billions of dollars.

Within this frame of reference, the most attractive and feasible areas for these new projects are like to be those in complex terrains, such as mountain tops or occupy particularly elevated plate(s), which are frequently associated with lightning activity and may have values of relative electrical soil resistivity [20]. Likewise, there is a growth of new offshore projects to achieve areas with stronger and more stable wind speeds, besides the higher complexity, costs, limited insurance solutions for these projects [43], and some uncertainties regarding lightning [18].

Therefore, for cost-efficient and safer projects, it is required their adaptation to the local atmospheric conditions and the actions of the meteorological systems of different scales [23]. This information is important for working and maintenance plans and to reduce possible systems faults [23].

2.4 Environmental studies

Environmental studies for new energy projects are composed of multidisciplinary academic research focused on the project's interaction with the biosphere. Additionally, it can identify external factors which may affect the project operation, for instance, how lightning interacts with energy projects. Moreover, based on environmental studies it can share knowledge for other researches, future forecasts, and the impacts of any measure. And develop awareness regarding the issues associated with the environment among stakeholders and project owners. Thus, as complementary data, it was selected seven Brazilian environmental assessments for new wind farm projects licensed by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA).

As the main result, it was verified a lack of information about the atmospheric discharges. In this context, the Brazilian assessments for the projects of "Complexo Eólico

- Eólicas Sul (Parque eólico Água Santa, Serra da Esperança e Rota das Araucárias)" of 2012 [44], "Central Geradora Eólica Fronteira Sul – Módulo I, II e III" of 2013 [45] and "Complexo Eólico do Contestado" of 2016 [46] only related lightning to the protection system of certain equipment. While the "Parque Eólico Minuano" assessment associates the atmospheric discharges to growth in insecurity by the local population, due to the possibility of the wind turbines attracting lightning [47]. On the other hand, in three environmental studies analyzed, there is no available information about the impacts, local characteristics, and protection equipment related to lightning [48–50].

Based on this, even with the academic research, the interaction in practice between wind turbines and lightning still presents some uncertainties. Moreover, if this interaction *in situ* were better studied it may produce more accurate information which may be used to improve the structures and protection systems.

3 Conclusion

To summarize, the main object of this article was to demonstrate the importance of the relationship between the lightning phenomena and tall energy projects (namely wind farms), based on a literature review. Moreover, it shows the main characteristics of atmospheric discharges, followed by their influence on wind farms, considering possible damages and protection mechanisms.

In this sense, atmospheric discharges are one of the oldest natural phenomena registered and are one of the main causes of the breakdown of the energy supply. Recent studies have been analyzing the effects and risks of lighting struck in tall energy projects, such as wind farms, which are exposed to environmental conditions, namely severe weather. The lack of accurate information about lightning aspects and the fact that this topic is sometimes underestimated by the energy sector. Given what has been said, the damages to these structures may lead to a power breakdown, financial losses, and issues to the population such as water supply and telecommunication disruption.

In the case of wind farms, due to their unique shape and their significant height, the damages of lightning to their components may be severe and imply stoppages, maintenance, high costs for repairing, and human injuries in worst-case scenarios. Sometimes, the injuries to the blade may affect their final destination in the wind farm's end of service, remaining as the last option: the landfill.

Furthermore, better-quality information is also important to prepare preventive maintenance plans in the short and long term. In addition, with the growing number of wind farms, to replace the fossil fuel energy projects, it will be required accurate data, as there is a possibility of the selected areas for these new projects be located in places that report a significant lightning activity. To sum up, better lightning information may avoid possible environmental impacts and power interruptions, improve the modes for operation during thunderstorms, reduce costs with maintenance and exchange the equipment, but also ensure a good quality of the equipment at the end of service, making it possible the adoption of other solutions instead to send the blades to the landfill.

For future articles, the main goal will be to expand the evaluation of how the lightning factor is described in environmental impacts assessments for new projects of tall energy projects, which include wind farms and transmission lines.

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