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Factors that influence the performance of wind farms

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ABSTRACT

This article aims to identify the conditioning factors that influence the operation and maintenance performance of wind farms. The research method included theoretical research and case studies in seven companies that own wind farms. Theoretical research covered the following themes: performance management process; performance measurement in power plants, highlighting the factors that affect performance in this type of industry, and; the characteristics of the Brazilian wind energy market. The case studies were conducted through interviews with managers, whose positions are at the strategic, tactical and operational levels, with the objective of identify the performance management processes existing in wind farms. As a result, it was verified that the performance of wind farms is mainly influenced by 5 factors: (1) Reliability of prospecting studies, (2) Construction quality and assembly, (3) Organizational learning, and (5) Coordination of the value chain.

1. Introduction

Brazil is one of the countries in the world that most invests in wind energy, while also being considered one of the most attractive for investments in renewable energy [1]. The competitiveness factors associated with this source of energy in Brazil are mainly: the wind potential, since the country has one of the best wind resources in the world, exceeding three times the local electricity needs; and in the auctions' model for contracting energy. Currently Brazil is ranked in 9th place of the TOP 10 in installed capacity, in the GWEC world ranking [2,3].

The use of new technologies, such as larger machines to enable gain in power and modern control and monitoring systems are initiatives that have resulted in an improved performance of wind farms. The average capacity factor of Brazilian wind farms in 2016 was 40.7%. In comparison, the average capacity factor of wind farms worldwide in 2015 was 23.8% [3]. This shows that Brazilian wind farms has remarkable energy productivity.

However, there are still considerable differences when comparing expected energy generation in wind farms and actual generation. These differences are caused by several factors, which are mostly related to failures that cause unavailability in the wind turbines and in the electric system of the wind farms, as well as in the transmission lines.

The unavailability of the wind farms subsystems may be due to internal aspects related to maintenance; or external, such as power outages; this entails considerable losses to investors. To solve problems related to failures, careful maintenance planning is necessary, and only possible through the effective monitoring of wind farm performance.

Performance is conditioned by organizational factors such as business strategy and objectives, processes, technologies involved, people, management culture, etc.; and external factors, such as policies and laws that regulate the activity, economy, and dynamics of the productive chain, among others. Knowing what these factors are and how they influence the results of the wind farms can enable the improvement of the performance management process, through actions focused on the critical aspects, with a view to increase the efficiency in the generation of energy.

In this context, the question for the research came up: "what are the factors that influence the performance of wind farms?". To answer this question, the purpose of this article is to identify the conditioning factors that influence the operation and maintenance of wind farms. The article is structured in 5 topics: (1) introduction; (2) literature review on the performance measurement; (3) research method; (4) analyzes and results; and (5) final considerations.

Abbreviations: ABEEólica, Brazilian association of wind energy; FCE, Free Contracting Environment; GWEC, Global Wind Energy Council; O&M, Operation and Maintenance; RCE, Regulated Contracting Environment.

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2. Literature review

2.1. Performance management

Performance management is the process by which the company manages its performance in line with its corporate strategies and functional objectives. The purpose of this process is to provide a feedback loop in a proactive control system where corporate and functional strategies are deployed across all business processes, activities, tasks, and personnel, and feedback is obtained through a Performance Management System, to enable appropriate management decisions [4].

To optimize the process of performance management, the strategic and environmental factors related to the business, as well as the organizational structure, processes, functions and relationships should be considered since the effectiveness of the process depends on how the information is used.

2.2. Performance drivers and killers

The term performance drivers was used in the Balanced Scorecard [5], referring to the factors that act as drivers for performance improvement. The variables that negatively influence the performance of the processes, on the other hand, are called performance killers [6,7].

Performance killers, whether or not they are strong enough to stop a process, are performance-reducing factors. These are factors such as: those related to the availability of critical equipment, health, safety and environment; bottlenecks in capacity, administration and inventory; incompetence; lack of adequate tools and facilities; procedures, information and communication flow systems and others [8].

Others that can also be considered as performance killers are: unavailability of material resources, spare parts, disabled personnel, insufficient IT support, lack of project support, poor time management, etc. According to maintenance management strategies, excessive maintenance tasks or non-optimized corrective maintenance are also considered performance killers; while prevention or forecasting activities can be considered performance drivers, according to their application and results achieved [9].

Performance drivers and killers should be investigated, primarily aiming to improve decision making in the performance management process. To define what they are, one must question and look for factors that improve or worsen overall performance. In this research they are called performance conditioning factors.

2.3. Performance measurement in power plants

Research with varied approaches to performance measurement in power plants lists some factors that affect performance in the power generation industry, as shown in Table 1, below.

Factors cited in the literature were grouped considering the scope (Fig. 1):

2.3.1. Project

Project management pipeline; consideration of local and social aspects in the choice of site; plant size; technology used; errors in wind studies, choice of machine type and layout definition; differences between the power curves reported by the manufacturer and those verified; and turbine configuration.

2.3.2. Management

Contractual definitions; organizational structure; operating environment; organization of work activities; diffusion of performance measurement culture; management knowledge and learning; use of tools to stimulate proactivity; time management; strategic focus; efficiency of the decision-making process; management inefficiency; changes in management; training of operators; inefficiency of operators; relationship with suppliers; use of appropriate performance indicators; quality of records; and modernization of structure.

2.3.3. Maintenance

Maintenance planning; use of the appropriate maintenance strategy; predictive maintenance; preventive maintenance; maintenance control; and maintenance management focused on the generation of value.

2.3.4. Information technology

Lack of specific measurement tools that consider managerial and environmental aspects; use of appropriate method to measure performance; use of appropriate tools to measure performance; and IT support.

2.3.5. Finance

Resource allocation; use of resources; control of costs and participation in the Clean Development Market.

2.3.6. External aspects

Sector policies; sector legislation; bottlenecks in the value chain; lack of integration and alignment in the value chain; environmental factors; and safety and health related factors.

2.3.7. Others

Economy of scale and type of capital (private vs. public);

In conclusion, factors affecting the performance of power generation plants may be internal or external, linked to the operational phase or to the previous stages of plant planning and implementation, contractual definitions and the characteristics of the investors. However, the result of the performance of the plants is mainly related to the operational phase, mainly regarding the capacities of the people involved in the process, the organization of activities, the use of resources, the planning and execution of maintenance, the use of tools to support the measurement performance, and the characteristics of the value chain that support the operation of the plant.

3. Research method

This research can be characterized as being of an applied nature [44], with a descriptive purpose [45] and a qualitative-quantitative approach [46,47]. The procedure chosen for the research consisted of case studies; and the research method covered the steps described below.

3.1. Theoretical research

Due to the main research question, "what are the factors that influence the performance of wind farms?", the theoretical research aimed to answer three other questions: (1) How the performance management process occurs; (2) How the performance measurement in power generation plants occurs and what factors affect performance in this type of industry; and, (3) How the Brazilian wind energy market functions.

The research was done through three distinct lines, as shown in Fig. 2. After the research problem was assessed and the study goal was defined, searches were done in the Thesis Virtual Library using the terms "performance measurement systems", "wind energy" and "wind power", and "wind farm operation & maintenance". The reading of the articles found allowed for the definition of the classic

Table 1
Factors that affect performance in power plants.

Research	Power plant type	Approach	Factors
[10]	Wind	Stochastic and econometric analysis	• Management inefficiency • Strategic focus • Control of costs • Sector policies • Contractual definitions
[11]	Wind	Data envelopment analysis	• Management inefficiency
[12]	Wind	Data envelopment analysis	• Consideration of local and social aspects in the choice of site
[13]	Wind	Data envelopment analysis	• Learning • Economy of scale
[14]	Wind	Data envelopment analysis Life cycle analysis	• Consideration of local and social aspects in the choice of site • Organization of work activities
[15]	Wind	Data envelopment analysis Stochastic frontier analysis	• Management inefficiency • Inefficiency of operators • Technology used • Sector policies • Sector legislation • Efficiency of the decision-making process • Errors in wind studies, choice of machine type and layout definition
[16]	Wind	Life cycle Analysis	• Participation in the Clean Development Market
[17]	Wind	MATLAB	• Differences between the power curves reported by the manufacturer and the verified
[18]	Wind	Performance measurement system	• Lack of integration and alignment in the value chain • Relationship with suppliers
[19]	Wind	Performance measurement system	• Sector legislation • Consideration of local and social aspects in the choice of site • Relationship with suppliers • Project management pipeline • Inefficiency of operators • Diffusion of performance measurement culture
[20]	Wind	Performance measurement system (Dashboard)	• Sector policies • Bottlenecks in the value chain • Lack of specific measurement tools that consider managerial and environmental aspects
[21]	Wind	Comparison between different methods	• Use of appropriate tools to measure performance
[22]	Wind	Monte Carlo simulation	• Predictive maintenance
[23]	Wind	Genetic algorithms	• Turbine configuration
[24]	Wind	Reliability thresholds	• Use of the appropriate maintenance strategy • Efficiency in the decision-making process
[25]	Wind	Stochastic programming model	• Use of the appropriate maintenance strategy • Resource allocation
[26]	Coal	Data envelopment analysis	• Management inefficiency • Operating environment
[27]	Geothermal	Performance measurement system	• Preventive maintenance • Use of appropriate performance indicators • Quality of records • Diffusion of performance measurement culture
[28]	Geothermal	Performance measurement system	• Use of appropriate performance indicators • Resource allocation • time management
[29]	Hydroelectric	Data envelopment analysis	• Management inefficiency • Use of resources
[30]	Hydroelectric	Analytic hierarchy process	• Use of the appropriate maintenance strategy • Management inefficiency
[31]	Gas Coal Oil	Data envelopment analysis	• Sector policies
[32]	Gas Coal Oil Thermal Hydroelectric Wind	Data envelopment analysis	• Plant size • Type of capital (private vs. public)
[33]	Hydroelectric Gas Geothermal	Data envelopment analysis	• Use of resources
[34]	Nuclear	Framework	• Management knowledge and learning • IT support
[35]	Nuclear	Performance measurement system	• Maintenance management focused on the generation of value • Resource allocation • Environmental factors • Safety and health related factors • Management knowledge and learning • Organizational structure
[36]	Nuclear	Performance measurement system	• Preventive maintenance • Maintenance management focused on the generation of value

(*continued on next page*)

Table 1 (*continued*)

Research	Power plant type	Approach	Factors
[37]	Solar	Data envelopment analysis Stochastic frontier analysis	• Resource allocation • Environmental factors
[38]	Thermal	Adaptive network based fuzzy inference systems	• Maintenance control • Plant size
[39]	Thermal	Data envelopment analysis	• Modernization of structure • Technology used • Changes in management
[40]	Thermal	Data envelopment analysis	• Diffusion of performance measurement culture • Use of appropriate tools to measure performance
[41]	Thermal	Data envelopment analysis	• Maintenance planning • Changes in operations management
[42]	Thermal	Data envelopment analysis Stochastic frontier analysis Adaptive network based fuzzy inference systems	• Predictive maintenance • Efficiency in the decision-making process • Use of tools to stimulate proactivity
[43]	Thermal	Data envelopment analysis Game theory	• Training of operators • Sector policies

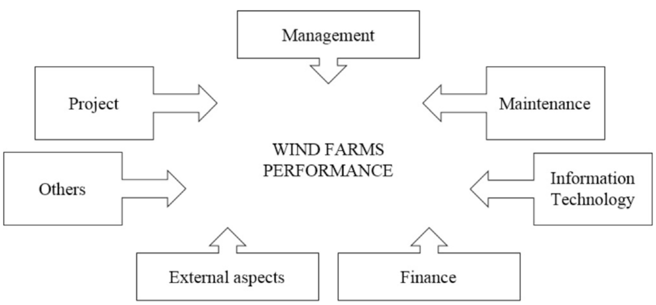

Fig. 1. Performance conditioning factors identified in the literature review.

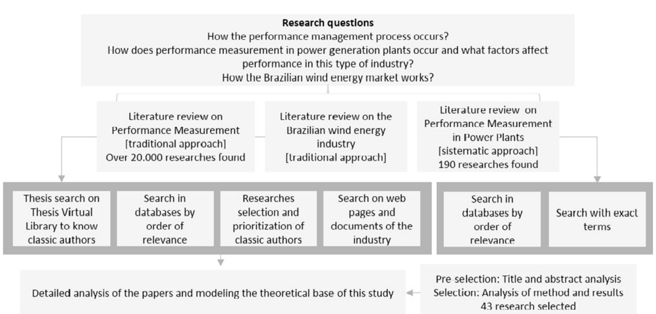

Fig. 2. Theoretical research procedure.

authors and the key words suitable for the following search, done in the "Portal de Periódicos Capes".

To survey the research material the term "performance measurement system" was used. Here, the works were selected by relevance (number of citations) and by authors, giving preference to the authors on the topic, which were identified with the previous reading of the theses.

As for the subject of performance measurement in power plants, the research approach was systematic [48,49], following a pre-established protocol. Combinations of the terms "performance measurement", "performance evaluation", and "power plant" were made. The pre-selection of articles was done by reading the titles and abstracts. After a complete reading of the pre-selected articles, those which specified the methodology used for performance evaluation, identified the performance conditioning factors and the results achieved, were maintained as the source for the construction of the theoretical bases of the research.

In addition, to understand the characteristics of the Brazilian wind energy market, which are determinant for the management of the performance of the wind farms, searches were made in reports and news stories from specific wind industry or renewable energy entities.

3.2. Case studies

The field research was carried out in wind farms in the state of Rio Grande do Norte, Brazil, which has the largest wind power capacity installed. The choice of the technical procedure in the case studies format was due to the understanding that wind farms are subject to different conditions of commercialization of energy and have different maintenance contracts with the suppliers of the wind turbines. Among other aspects they have strategic priorities, distinct forms of work organization and management culture, which are factors that directly influence the performance management process, as identified in the literature review.

The field research included technical visits and interviews to recognize the characteristics of the management of the ventures and analysis of the process of performance management in the wind farms. The interviews were carried out with 13 managers at the strategic, tactical and operational levels of the organization.

It is observed in Fig. 3 that, for each case, there is a collection/analysis flow. The initial research protocol (P1A - Protocol 1, Case A) was applied in an interview with the first informant (I1A - Interview 1, Case A). The information collected during the interviews was analyzed, together with data from reports, documents, etc. (A1A - Analysis 1, Case A). When necessary, the protocol was adjusted and the procedure of interviewing, analyzing and adjusting the protocol was followed until sufficient information was obtained. A final analysis of the case was carried out and followed the same step by step until sufficient information was available for the development of propositions. An inter-case comparison analysis was performed, using the confrontation with the theory to direct the development of propositions.

3.2.1. Selection of cases

A sample with cases that presented distinct characteristics was formed (Table 2), following the logic of cases of the polar type [50], in which cases with sharply contrasting characteristics highlight the differences being studied.

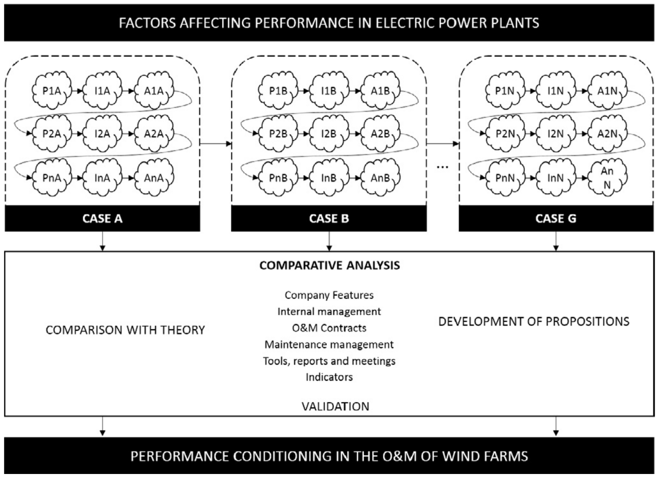

Fig. 3. Case study procedure.

4. Analysis and results

4.1. Brazilian wind energy market

The Brazilian electricity market is divided into two main commercialization environments: The Regulated Contracting Environment (RCE), with generation and distribution agents; and the Free Contracting Environment (FCE), composed of generators, distributors, traders, importers and exporters, as well as free and special consumers [51].

The ACR is managed by the Federal Government. In RCE, energy is contracted through public auctions, in order to supply the estimated demand of energy distributors. The auctions are open to public competition, contemplating existing electric power generation units and projects to be executed. The objective is, through the competition of the contracting value (R$/MWh) among the sources that participate, a contract for the lowest possible value will be finalized [51].

In the FCE, the contracting of energy occurs without coordination or direct interference of the Government. Bilateral contracts are signed between generation agents and consumers, and the operation may be brokered through traders. In this environment, generators, free consumers, self-producers, traders, importers and exporters of energy establish contracts of purchase and sale of energy with freely negotiated prices and quantities, according to specific marketing rules and procedures [52].

4.2. Management of operation and maintenance in wind farms

The places where the wind farms are located have characteristic profiles of wind variation. This profile is studied in detail before the implementation of the wind farm, through wind studies, which is useful for the definition of relevant aspects, such as the turbine model most suitable for the site and the best layout (of turbines) to be employed aiming for the maximum use of the wind.

The data obtained previously with the wind studies and the historical generation data of the wind farm indicates the periods of lower and higher quality of the wind at the site. This quality refers to the speed, direction and constancy of the wind, which are factors directly related to the use of wind energy to generate electricity. The logic applied in planning O&M activities is to schedule preventive maintenance for periods of lower wind quality, allowing subsystems to be available to operate as long as possible in the best wind periods, with a view to maximizing generation.

Maintenance of the turbines and the electrical system follow annual schedules where the activities that will be carried out each day are predefined. The companies responsible for the maintenance (of the turbines and the electrical system) elaborate their own schedule, observing the international standards, and submit it for analysis and validation by the wind farm management. The manager, on the other hand, requests the necessary adjustments in order to concentrate more on the maintenance in periods of low volume of wind at the site.

Due to warranty issues, the turbine maintenance schedule has less flexibility for change. On the other hand, the risks associated with the postponement of maintenance activities are greater for the electrical system. However, since the availability of the turbines depends directly on the availability of the electrical system, the planning of the two schedules is done together. The strategy of each company defines the priorities in managing the trade-off compliance maintenance versus maximizing power generation.

4.3. Performance conditioning factors of wind farms operation and maintenance

The theoretical research, the conduction of case studies and the intra-case and inter-case analyses allowed the evaluation of the factors that directly and indirectly influence the performance of wind farms (Fig. 4).

The factors are detailed below.

Table 2
Main characteristics of selected cases.

Case	Investors		No. of Wind farms	Volume in Operation	Entry into operation	
	Sector	Capital			Newest Wind farm	Older Wind farm
A	Renewable energy	Private	2	151.650 kW	2011	2010
B	Renewable energy	Private	8	207.000 kW	2016	2014
C	Real-estate and renewable energy	Private	2	28.800 kW	2012	2011
D	Energy and Telecommunications	Private e Public	7	75.708 kW	2015	2015
E	Engineering, Mining, Energy and Transport	Private	11	170.000 kW	2014	2014
F	Energy, Oil and Gas, Wind turbines	Private e Public	4	104.000 kW	2011	2011
G	Metalworking, Automotive and Renewable energy	Private	7	203.600 kW	2016	2012
Total: 7 companies			41	940.758 kW	2016	2010

The survey covered 7 companies owning 41 wind farms, out of 127 operating in Rio Grande do Norte, whose total operating volume represents 31.1% of the total volume in operation in the state.

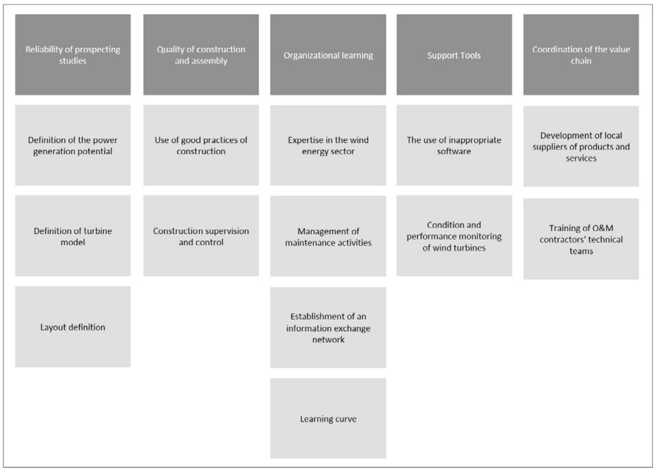

Fig. 4. Performance conditioning factors on wind farms.

4.3.1. *Reliability of prospecting studies*

4.3.1.1. Definition of the power generation potential. Projects of wind farms that are incorrectly sized, that is, that have errors from wind studies performed with low level of accuracy, induce the overestimation of the generation potential of the site. In these cases, when in operation, wind farms are likely to perform well below their expected lifetime performance.

4.3.1.2. Definition of turbine model and layout. Considering that the Contracted Energy of the wind farm, defined in the energy trading contracts, is based on the project data, the generation goal may become unattainable. In addition to the incorrect calculation of the site generation potential, other errors related to the reliability of the prospecting may occur, such as errors in the layout definition (turbine layout) and in the choice of the appropriate turbine model.

4.3.2. *Quality of construction and assembly*

4.3.2.1. Use of good practices of construction. Problems arising from the construction phase, due to the poor quality of installed equipment and the failure to adopt good building practices, cause failures during operation due to premature wear of structures and devices.

4.3.2.2. Construction supervision and control. It was observed in the case study that when the wind farms were acquired by the current owner company, after the construction began, there was a considerably greater report of technical failures directly related to the construction and assembly. This shows that the supervision and control of the construction activities by the company is therefore fundamental to solve future problems.

4.3.3. *Organizational learning*

4.3.3.1. Expertise in the wind energy sector. When a company that owns wind farms does not have wind power generation activity in its core business, management's monitoring of operational activities can be focused purely on financial results, to the detriment of process results. And in this type of activity, where the financial figures are considerably high, detecting losses may be impossible without a critical eye directly on the processes.

On the other hand, when the board understands the technical characteristics of the activity, the charge for process improvement becomes more effective, stimulating tactical level managers to seek the most varied means to achieve gains in generation. Without this, managers can act as observers of results, rather than outcome-influencers; that is, by adopting a reactive rather than a proactive stance. In that way wind farms end up performing less than would be possible if there were a closer and critical look at the processes.

Another relevant factor concerns the experience in negotiating O&M contracts. All the responsibilities and details related to the actions aimed at improving the performance of the turbines are covered by contractual clauses. Therefore, the experience of the generating company when defining the clauses of the O&M contracts with turbine suppliers can be decisive.

As the turbine suppliers arrived in Brazil with the experience of the foreign market and found new investors in the industry, with no previous experience with these definitions, the contracts of the oldest wind farms were signed with clauses that exempt important stock suppliers that would be decisive for the improvement of turbine performance. These issues may become the cause of heated discussions over the years of operation due to issues related to the payment of fines.

In addition, when a turbine supply contract is concluded, the generating company is dependent on the supplier, since it can only use the same company to carry out the O&M of the machines and to buy spare parts (due to issues related to the internal structure of the turbines, which varies from one manufacturer to another, there are still no companies in Brazil that service turbines from other manufacturers). Therefore, it is interesting that the definitions of the O&M contracts are already discussed at the time of purchase of the turbines, avoiding that the supplier makes too many demands or offers fewer counterparts later. Companies that closed O&M contracts only after the turbine warranty period lost trading power and were not able to resort to competing companies.

4.3.3.2. Management of maintenance activities. In the operational scope, the main factor that has a direct impact on the wind farms performance is maintenance management, which encompasses the planning and fulfillment of the different maintenance activities in the period. It is fundamental to carry out this planning based on the historical data of generation, as was seen in the case studies.

Another relevant factor is the effective control over the periodic activities of contractors, aiming at the quality of preventive maintenance. Effective supervision of contractor activities, through an experienced technical supervisor, is relevant to the outcome of maintenance, while considering the quality of services and meeting deadlines.

It is also important to highlight the criticality of the subsystems and the development of contingency plans. According to the analysis of the cases, the internal factor that has the greatest potential impact on the generation of a wind farm is electrical failures, in which the maintenance of substation and transmission line is extremely important. This indicates the need for a contingency plan; the result of a risk analysis and an economic feasibility analysis to define actions to mitigate causes of failure and rapid recovery.

In risk analysis, the subsystems and critical equipment are identified. In order to carry out this analysis it is necessary to list the possibilities of failures in the case of new wind farms and the history of failures in the case of older wind farms. This analysis should consider the frequency of occurrence and the impact on generation. For faults that occur more frequently and whose occurrence leads to a greater loss of generation the necessary actions must be listed to mitigate the risks, such as maintenance of stock of spare equipment, installation of equipment in redundancy, agreement of medium or long-term contracts with companies responsible for the recovery of failures in a predetermined maximum time, and the contracting of insurance, among others. Actions vary depending on the subsystem or equipment and the cost of implementing each action, compared to the cost of possible losses related to failure occurrences should be considered.

The analysis of the cases pointed out that maintaining a stock of spare parts and managing it based on the contingency service plan is essential to minimize downtime. Usually the wind farms replenish the stock of spare parts by means of a minimum purchase lot and the definition of this lot must consider the cost of the equipment and its importance/criticality for the operation.

4.3.3.3. Establishment of an information exchange network. Contact between wind farm managers is valid for exchanging information about suppliers, for sharing useful ideas to solve technical problems, for loaning specific equipment that a wind farm does not have in stock and for handling other issues adjacent to the wind farm, all of which can bring financial savings for the company.

Interaction with older wind farm managers is especially relevant for the exchange of supplier information. When a supplier has provided a service or sold a substandard product, this information circulates among wind farm managers, preventing one from facing the same problem that the other has already faced.

In Brazil there are still no formal initiatives for interaction between managers of wind farms, aside from the events organized by ABEEólica (Brazilian association of wind energy), which are more focused on the discussion of internal alternatives to solve specific problems. However, it has been noted in the case study that there are some informal activities of exchange of information and materials between managers who are friends, and that this type of initiative has a very positive impact on the performance of the wind farms, especially with regard to quick recovery of flaws due to exchange of equipment.

4.3.3.4. Learning curve. As observed in the case analysis, newer wind farms, which are starting operation, have a higher rate of failure. After years of operation, the failure rate decreases as well as the times and costs of repair due to the development of expertise by the owners, the evolution of the experience of the managers and supervisors, the adaptation of the maintenance activities and the adjustments of the equipment to the local standards.

However, observing the evolution of wind farms in other countries and taking into account the learning curve [53], it can be inferred that this fall in the occurrence of failures occurs only up to a certain point; this is where the depreciation of the equipment begins to be responsible for a new increase of flaws, this time gradual, reaching a standard of stability until the end of the useful life of the parks. In Brazil, the oldest wind farms have been in operation for 8 years, i.e., a quarter of the contract life, which is 20 years. These first wind farms are already in the stability phase and will eventually enter the period of increase of failures and consequent decrease in performance. This occurs around the eighth year of operation and will point to the need to implement improvements in the processes, equipment and overall performance management.

4.3.4. Support tools

Information Technology support is one of the important factors for performance management in wind farms since the tools can be decisive: both for the improvement and to cause the processes more flexible.

4.3.4.1. The use of inappropriate software. The use of some management tools in wind farms may not result in real performance gains if they are modeled for other types of industry and are not flexible, because they end up having their potential wasted for lack of adaptability to the performance measurement useful for the management of wind farms.

Using inappropriate software can lead to the practice of sins in performance measurement [54], how to measure only part of what matters, which is what occurs in the application of non-specific software; and not prioritizing the measurement, that is, deploying a software without first seeking to understand what information will actually be useful for improving performance, failing to maintain a real commitment to the use of measures.

4.3.4.2. Condition and performance monitoring of wind turbines. On the other hand, the use of software to monitor performance and turbine conditions is also decisive, since it allows the overall result of maintenance management to be optimized through predictive actions and scheduling of maintenance in periods of lesser potential impact on generation. It can also accomplish specific actions that directly impact the efficiency of the machines, contributing to the increase of the global performance of the wind farms.

4.3.5. Coordination of the value chain

4.3.5.1. Development of local suppliers of products and services. The Brazilian chain of products and services for wind farms is still in the structuring phase. Therefore, the difficulty of finding suppliers is a reality. In Rio Grande do Norte, a state that stands out in installed power in operation, there are still few companies that provide certain equipment and services, which means that the repair time for flaws and/or the cost of contracting increases considerably, in certain cases.

Added to this is the fact that the total cost of a failure is not only composed of the cost of spare parts but includes the cost of services and the lost generation cost. Therefore, it is common to compare the cost of contracting a given service in times of contingency, which is higher, with the cost of the lost generation.

This difficulty is greater in the first few years of operation of the wind farms until a network of suppliers is in place, which takes time and demands efforts from both wind farm managers and suppliers. Even so, there are currently no tools in Brazil that facilitate the search of suppliers and the formatting of networks to enable the rapid hiring of products and services for flaw repair.

4.3.5.2. Training of O&M contractors' technical teams. It is important to highlight the qualification of the contractors' technical teams. Technicians without the necessary qualification are less agile in maintenance activities. Some O&M companies have a considerable turnover of technicians and make them available to the wind farm teams where, at times, only one member has the necessary know-how to perform the maintenance. This occurs mainly in the electrical maintenance companies, according to the analysis of the cases and this was one of the aspects most cited by the interviewees.

Some generating companies are currently studying to incorporate electrical maintenance instead of renewing contracts with outsources; they understand that their own technical team, which has very low turnover, already has or can easily acquire the necessary qualifications to develop electrical maintenance processes.

5. Final considerations

This research identified the conditioning factors that affect the performance of wind farms after a review of the literature and conduction of case studies in 7 companies.

Theoretical research indicated that the factors that affect the performance of wind farms may be related to the wind farm design phase, business and process management, maintenance activities, the use of information technology, finance, external aspects, and other factors. After conducting the case study, the following were identified as main determinants of performance in the operation and maintenance of wind farms: Reliability of Prospecting Studies, Construction and Assembly Quality, Organizational Learning, Support Tools and Value Chain Coordination.

The Reliability of Prospecting Studies refers to the wind studies that are performed to define the capacity and layout of the wind farm, aspects that, if poorly dimensioned, may affect future performance. The Construction and Assembly Quality is related to the adoption of good practices during the development of the project and is linked to the depreciation of the equipment and consequently to the failures that occur during the operation.

Organizational Learning is the main conditioning and refers to the company's expertise in the wind sector, the profile of the people involved in the O&M of the wind farms, the coordination of operational and maintenance activities and the exchange of information between companies. Those are the aspects that have the greatest potential to affect performance.

The Support Tools are the software used for better benchmarking of results, supporting strategic decisions regarding maintenance. The Value Chain Coordination refers to the existing structure for the supply of parts and services in the industry, which is directly linked to the time to recover from failures.

Wind farms, compared to other types of ventures, have the peculiarity of having the operation and maintenance activities outsourced, almost in totality. Due to this, the management of the operational activities focuses particularly on the management of O&M contracts, turbines and the electrical system. This is besides other activities underlying the operation that have a direct or indirect influence on performance.

Field research has enabled detailed knowledge of the O&M management context of the wind farms. The characteristics of the investors were analyzed; the internal management models; the O&M contract types entered into; maintenance management, including planning and control of activities; the existing support tools, reports and meetings; and indicators used.

Regarding the characteristics of the investors, the field research indicated that companies that have the wind energy generation activity in their core business have management models focused on monitoring the results of the processes, while in some companies in other areas that started to invest in wind energy generation, commonly management is focused only on the financial results of the wind farms.

The O&M contracts are similar, with some differences. Partial O&M turbine contracts generally include preventive maintenance and corrective maintenance service. Full contracts include spare parts and may also include warranty for recovery from failures linked to external factors such as environmental factors. In the contracts, a minimum value of turbine operation time is set. The O&M contracts of the electric system are partial, excluding spare parts, causing the parks to keep spare parts. These contracts do not include availability issues.

Maintenance management includes the levels of control that wind farm management has over planning and carrying out maintenance activities, contractual clauses requiring performance improvement actions, relationships with contractors with a view to implementation of the identified necessary improvements and other aspects.

The use of performance indicators in wind farms is geared, in most cases, to the monitoring of Generated Energy. However, in some cases it was identified the use of indicators aimed at monitoring the performance of the Operation and Maintenance processes; as well as some indicators related to turbine efficiency. Financial indicators, in most cases, are used by companies' financial directories, not directly by tactical level managers.

The Brazilian wind industry is relatively new, when compared to its development in European countries, for example. It is understood that the process of maturation of the wind power generation activity in Brazil has begun to occur nowadays, and includes the gain of experience on the part of the entrepreneurs, the training of the technicians who work in the sector, the specialization and evolution of the processes of the companies that are part of the value chain, the evolution of public policies, and the use of new technologies, among other factors.

With this, the underlying aspects related to the Reliability of Prospecting Studies, Quality of Construction and Assembly, Tools of Supporting Organizational Learning have had a significant evolution. However, there is still a need for tools that allow greater integration along the value chain, which facilitate the rapid recovery of failures, being one of the factors that has the greatest potential impact on the performance of wind farms.

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References

[1] Cenários, A Crise Passa Longe Dos Ventos, Editora Brasil Energia, 2015, pp. 36–61.
[2] Abeeolica – Brasil destaca-se no ranking de investimento em energia renovável. Available in http://www.portalabeeolica.org.br/index.php/noticias/4134-brasil-destaca-se-no-ranking-de-investimento-em-energia-renov%C3%A1vel.html. Access in 01/12/2015.
[3] GWEC, Global Wind Report: Annual Market Update, 2016.
[4] U.S. Bititci, A.S. Carrie, L. Mcdevitt, Integrated performance measurement systems: a development guide, Int. J. Oper. Prod. Manag. 17 (1997) 522–534.
[5] R.S. Kaplan, D.P. Norton, Strategic learning & the balanced scorecard, Strat. Leader. 24 (1996) 18–24.
[6] A.H.C. Tsang, A strategic approach to managing maintenance performance, J. Qual. Mainten. Eng. 4 (1998) 87–94.
[7] A. Parida, U. Kumar, Maintenance Productivity and Performance Measurement, 2009.
[8] T. Markeset, U. Kumar, The use of life cycle cost and profit assessment to improve operation and supply chain management performance of complex oil production facilities, in: Proceedings of 1st International Conference on Operation and Supply Chain Management, Bali-Indonesia, Dec 15–17, 2005 paper 33.
[9] A. Parida, U. Kumar, Maintenance performance measurement (MPM): issues and challenges, J. Qual. Mainten. Eng. 12 (2006) 239–251.
[10] C.P. Barros, O.S. Antunes, Performance assessment of Portuguese wind farms: ownership and managerial efficiency, Energy Pol. 39 (2011) 3055–3063.
[11] E.S. Araújo, Avaliação de Desempenho de Parques eólicos portugueses, in: Dissertação (Mestrado em Engenharia) - Escola Superior de Tecnologia e Gestão Instituto Politécnico de Bragança, 2013, 2013, p. 133.
[12] A. Azadeh, S.F. Ghaderi, M.R. Nasrollahi, Location optimization of wind plants in Iran by an integrated hierarchical data envelopment analysis, Renew. Energy 36 (2011) 1621–1631.
[13] N. Ederer, Evaluating capital and operating cost efficiency of offshore wind farms: a DEA approach, Renew. Sustain. Energy Rev. 42 (2015) 1034–1046.
[14] D. Iribarren, et al., Environmental benchmarking of wind farms according to their operational performance, Energy 61 (2013) 589–597.
[15] G. Iglesias, P. Castellanos, A. Seijas, Measurement of productive efficiency with frontier methods: a case study for wind farms, Energy Econ. 32 (2010) 1199–1208.
[16] J. Yang, B. Chen, Integrated evaluation of embodied energy, greenhouse gas emission and economic performance of a typical wind farm in China, Renew. Sustain. Energy Rev. 27 (2013) 559–568.
[17] N.R.A. Santiago, Metodologias para avaliação do desempenho e previsão de avarias em turbinas eólicas utilizando a curva de potência do fabricante, in: Thesis (Master in Renewable Energy – Eletric Conversion and Sustainable Use) - Universidade Nova de Lisboa, Faculdade de Ciência e Tecnologia, 2012, p. 148, 2012.
[18] H.C.F. Varella, Medição de desempenho na cadeia de suprimentos da energia eólica: proposta de um conjunto de indicadores de desempenho, in: Thesis (Master in Production Engineering) - Universidade Federal Do Rio Grande Do Norte, 2013, p. 143. Natal, 2013.
[19] R. Schneider, R. Vieira, Insights from action research: implementing the balanced scorecard at a wind-farm company, Int. J. Prod. Perform. Manag. 59 (2010) 493–507.
[20] L.T.S. Silva, Sistema de medição de desempenho de sustentabilidade para empreendimentos eólicos no RN, in: Thesis (Master in Production Engineering), Universidade Federal do Rio Grande do Norte, Natal, 2015, p. 244, 2015.

[21] N.F.L. Cardoso, Metodologias de avaliação de desempenho de parques eólicos, in: Thesis (Master in Mechanical Engineering), Faculdade de Engenharia da Universidade do Porto, 2011, p. 108, 2011.
[22] X. Lei, P.A. Sandborn, Maintenance scheduling based on remaining useful life predictions for wind farms managed using power purchase agreements, Renew. Energy 116 (2018) 188–198.
[23] J.S. González, M.B. Payán, J.R. Santos, A.G.G. Rodríguez, Maximizing the overall production of wind farms by setting the individual operating point of wind turbines, Renew. Energy 80 (2015) 219–229.
[24] A. Erguido, A.C. Marquez, E. castellano, J.F.G. Fernandez, A dynamic opportunistic maintenance model to maximize energy-based availability while reducing the life cycle cost of wind farms, Renew. Energy 114 (2017) 843–856.
[25] X. Li, D. Ouelhadj, X. Song, D. Jones, G. Wall, K.E. Howell, P. Igwe, S. Martin, D. Song, E. Pertin, A decision support system for strategic maintenance planning in offshore wind farms, Renew. Energy 99 (2016) 784–799.
[26] H. Yang, M. Pollitt, Incorporating both undesirable outputs and uncontrollable variables into DEA: the performance of Chinese coal-fired power plants, Eur. J. Oper. Res. 197 (2009) 1095–1105.
[27] A. Elísson, Performance indicators for maintenance in geothermal power plants, in: Thesis (Magister Scientiarum Degree in Industrial Engineering), Faculty of Industrial Engineering, Mechanical Engineering and Computer Science University of Iceland, 2013, p. 88, 2013.
[28] J. Varney, S.J. Zarrouk, N. Bean, B. Bendall, Performance measures in geothermal power developments, Renew. Energy 101 (2017) 835–844.
[29] D.K. Jha, R. Shrestha, Measuring efficiency of hydropower plants in Nepal using data envelopment analysis, IEEE Trans. Power Syst. 21 (2006) 1502–1512.
[30] E.C. Özcan, S. Ünlüsoy, T. Eren, A combined goal programming–AHP approach supported with TOPSIS for maintenance strategy selection in hydroelectric power plants, Renew. Sustain. Energy Rev. 78 (2017) 1410–1423.
[31] T. Sueyoshi, M. Goto, DEA approach for unified efficiency measurement: assessment of Japanese fossil fuel power generation, Energy Econ. 33 (2011) 292–303.
[32] K. Sarica, I. Or, Efficiency assessment of Turkish power plants using data envelopment analysis, Energy 32 (2007) 1484–1499.
[33] B. Arabi, S. Munisamy, A. Emrouznejad, M. Toloo, M.S. Ghazizadeh, Eco-efficiency considering the issue of heterogeneity among power plants, Energy 111 (2016) 722–735.
[34] J.F.P. Grosbois, The impact of knowledge management practices on nuclear power plant organization performance, in: Thesis (Doctoral Program of Philosophy) - Management Faculty of Graduate and Postdoctoral, Carleton University Ottawa, Ontario, 2011, p. 508, 2011.
[35] A. Parida, U. Kumar, D. Galar, C. Stenström, Performance measurement and management for maintenance: a literature review, J. Qual. Mainten. Eng. 21 (1) (2015) 2–33.
[36] P. Vaisnys, et al., Monitoring the Effectiveness of Maintenance Programs through the Use of Performance Indicators, DG JRC – Institute for Energy, 2006.
[37] Z. Wang, Y. Li, K. Wang, Z. Huang, Environment-adjusted operational performance evaluation of solar photovoltaic power plants: a three stage efficiency analysis, Renew. Sustain. Energy Rev. 76 (2017) 1153–1162.
[38] A. Azadeh, M. Saberi, M. Anvari, A. Azaron, M. Mohammadi, Na adaptive network based fuzzy inference system-genetic algorithm clustering ensemble algorithm for performance assessment and improvement, Expert Syst. Appl. 38 (2011) 2224–2234.
[39] A. Fallahi, R. Ebrahimi, S.F. Ghaderi, Measuring efficiency and productivity change in power electric generation management companies by using data envelopment analysis: a case study, Energy 36 (2011) 6398–6405.
[40] R.F. Saen, Performance measurement of power plants in the existence of weight restrictions via slacks-based model, Benchmarking Int. J. 17 (2010) 677–691.
[41] S. Munisamy, B. Arabi, Eco-efficiency change in power plants: using a slacks-based measure for the meta-frontier Malmquist-Luenberger productivity index, J. Clean. Prod. 105 (2015) 218–232.
[42] M.S. Mehrabad, M. Anvari, A.M. Saberi, Targeting performance measures based on performance prediction, Int. J. Prod. Perform. Manag. 6 (2011) 46–68.
[43] M.J. Rezaee, A. Moini, A. Makui, Operational and non-operational performance evaluation of thermal power plants in Iran: a game theory approach, Energy 38 (2012) 96–103.
[44] P. Demo, Pesquisa: princípio científico e educativo, 2000. São Paulo: Cortez.
[45] R.K. YIN, Estudo de caso – planejamento e métodos, 2. ed., Bookman, Porto Alegre, 2001.
[46] J.W. Creswell, Research Design: Qualitative and Quantitative Approaches, Sage, London, 2003.
[47] P. Sampaio, et al., Photovoltaic technologies: Mapping from patent analysis, Renew. Sustain. Energy Rev. 93 (2018) 215–224.
[48] M. Pai, M. Mcculloch, J. Gorman, N. Pai, W. Enanoria, G. Kenndy, Systematic reviews and meta-analyses: an illustrated step-by-step guide, Natl. Med. J. India 17 (2004) 86–95.
[49] D. Cook, C. Mulrow, R. Haynes, Systematic Reviews: synthesis of best evidence for clinical decisions, Ann. Intern. Med. 126 (1997) 376–380.
[50] C. Voss, et al., Case research in operations management, Int. J. Oper. Prod. Manag. 22 (b. 2) (2002) 195–219.
[51] CCEE - Câmara de Comercialização de Energia Elétrica. Setor Elétrico Brasileiro. Available in: http://www.ccee.org.br/portal/faces/pages_publico/onde-atuamos/setor_eletrico. Access in 10/08/2017.
[52] MME - Ministério de Minas e Energia, Diretrizes básicas para implementação do novo modelo do Setor Elétrico, 2008.
[53] I. Staffell, R. Green, How does wind farm performance decline with age? Renew. Energy 66 (2014) 775–786.
[54] M. Hammer, The 7 deadly sins of performance measurement. Special report: measuring to manage, MIT Sloan Manag. Rev. 83 (2007) 80.