WIND FARMS RELIABILITY MODELLING FOR LIFE CYCLE COST ANALYSIS

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The present article explores the importance of developing a new methodology for the optimal sizing of a power generation system. To this aim, the proposed methodology is based on the analysis of the life cycle cost, which is composed by a set of differentiating costs. These differentiating costs will depend mainly on the variables of the equipment that make up the system, such as the cost of power generation, reliability of the equipment and the complete system, including the possibility of incorporating backup equipment. This analysis will allow to obtain an optimal number of such equipment. The size of the power generation system, in addition to assuming a minimum cost, have to fulfil the annual required power generated by the system itself. The proposed methodology consists of five stages: (i) Study of technical factors, (ii) Modelling and reliability analysis of the system, (iii) Application of the LCCA technique, (iv) Analysis of total costs and evaluation of scenarios to find the optimum n system size, complying with the requested generated power, (v) Sensitivity analysis and obtaining final results.

Keywords: wind farms, reliability, life cycle cost analysis, sizing of power generation systems, maintainability, economic assessment.

1. Introduction and motivation

The development of renewable energies is undoubtedly one of the great challenges facing countries and industrial processes, in order to make sustainable their activities in the medium - long term, taking care of the environment, through development and deployment of low-carbon energy technologies. Under this perspective, wind energy has stood out for its constant development and has become a very good alternative for electricity generation. (International Energy Agency, 2014).

Wind energy is an important source of renewable energy and reliability analysis is a critical issue for operating wind energy systems. Wind energy conversion is the fastest-growing source of new electric generation in the world and it is expected to remain that way for the next few decades. The wind energy potential in Chile in recent years has been assessed, placing it in the middle phases of research. Several studies have focused on the potential in a large scale approach (Watts and Jara, 2011), highlighting future studies (Watts, 2016) – the consequence of which is an increasing number of new projects, thus contributing to Chile's energy matrix.

Due to the extraordinary geographical conditions of Chile, and with its 4,300 kilometers of coastline enclosed by the Andes range, the wind energy potential of the country presents a great development opportunity.

However, Chile's energy matrix, as well as in other developing countries, still depends heavily on non-renewable sources such as oil and gas. Most of the energy demand is mainly satisfied by importing these sources from abroad, leading to a high external dependence, which is subject to the uncertainty of variability and economic cycles (Bustos et al., 2016). From this perspective, the incorporation of reliability analysis into renewable energy processes can make a significant contribution to its generalization, promoting the economic growth and development (Amri, 2017; González-Prida & Raman, 2014), reducing the environmental damage and, thus, contributing to the development by providing social services (Martinot et al., 2002).

A proper Operation and Maintenance management is the key to reducing downtime while increasing the availability of a wind farm. In the field of wind energy, some authors have

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defined a systematic mathematical approach to examine the impact of Operations and Maintenance (O&M) (Krokoszinski, 2003) in order to support investment decisions based on a clearly operational and process-orientated logic. Due to the lack of proper terms, it is possible to use production technology terms and newly defined terms such as Wind Farm Process and Total Overall Equipment Effectiveness (Total OEE) (Andersson and Bellgran, 2015), as well as to redefine the concepts for theoretical production time, available production time and valuable production time in terms of unit full load hours. With these concepts, Krokoszinski proposes a model that carries out a comprehensive description of the differences between the produced and delivered electrical energy, taking into account the external and technical losses, enabling the systematic description and quantifying the inherent losses in a wind farm (Krokoszinski, 2003). Considering the above, it is also possible to assume that current maintenance planning for wind turbines is still not optimized and, consequently, it could be much more efficient. This is probably due to the extra costs involved and the payback period of such investment, which has not been proven yet (Nilsson and Bertling, 2007). It is possible to conclude that up to now, the sizing of power generation systems (such as wind farms) has been based primarily on operational characteristics of technical equipment (e.g., power generation capacity, electrical performance), geographical and meteorological characteristics; in the case of renewable energies (wind speed and direction, temperature, altitude, soil conditions, etc.) and, of course, economic factors (e.g., acquisition cost of wind turbines, substations, wiring, geographic cost, economic performance of the generated power) (Cetinay et al., 2017), which can be treated as a basic reference framework, but it is worth highlighting that it does not include the reliability analysis under the life cycle cost approach.

From this perspective, one of the great challenges is the optimal siting and sizing of wind farms, taking into account variables such as wind characteristics and electrical grid constraints and including technical variables such as wind speed and specific characteristics for local energy demands (Cetinay et al., 2017). In view of the foregoing, it is established that the development of new models incorporating these variables will contribute to generate added value in wind farms planning. Therefore, the objective of this proposal is to contribute to the optimal sizing of wind farms considering the systemic reliability and the life cycle cost analysis (LCCA) achieving the expected power generation demands.

2. On the windfarm maintenance

As one of the fastest growing sources of the new generation of electricity in the world, over the last two decades, wind turbines have developed more power, going from 20 kW to 2 MW, and now there are even larger wind turbines in the design process. Proper management of the operation and maintenance of wind farm is the key to increasing availability and therefore development. This refers for example, to reducing unscheduled maintenance in months of high wind speed, locating such services especially in the months of low wind speed when necessary, reducing replacement costs. In practice, operational strategies involve owners and operators, gaining more experience and realizing the benefits of appropriately responding to operations and maintenance activities. The following list represents the trends identified in the operation and maintenance strategies:

(i) To start maintenance and repairs during periods of low winds (in order to reduce the impact on energy production).
(ii) To evaluate other strategies to optimize project performance, (for example, compensation between the payment of overtime and the loss of potential energy during periods of inactivity).
(iii) To conduct studies and / or initiate mitigation actions for storm damage.
(iv) To prioritize the responsibilities of maintenance personnel.
(v) To define the functions and responsibilities of the staff.
(vi) To invest in CBM techniques for critical items.

In general, failures occur due to the accumulation of irreversible changes that occur in the microstructure of a component subjected to a certain load or environmental conditions. In the worst cases, this accumulated damage may not be measurable or even detected until the failure occurs. The physics of the failure states that if the evolution of the damage can be understood, it will then be possible to develop precise predictive models that can be developed relative to the expected duration of the components. Andrawus et al. (2007) discuss the concept, relevance and applicability of techniques such as the DTMM (Delay-Time Maintenance Model) or the MFS (Modelling System Failure) for the wind energy industry. DTMM is a well-known system for its simplistic mathematical modelling. MSF is a technique that investigates the operations and failure patterns in the equipment, taking into account the distribution of the fault, the repair times, the possibility of spare parts and the availability of resources for compliance with the requirements of maintenance. On the other hand, compared to a CBM (Computer Based Maintenance) approach based on measurable parameters, the DTMM model examines the failure patterns in the equipment, taking into account the consequences of failures, inspection costs as well as the intervals to determine an optimal inspection interval. The determination of the optimal inspection interval is made in terms of the amount that a failure can affect the entire system.

In general, operators are usually not motivated to adopt the monitoring technology without reasonable economic justification (Zaher et al., 2009). Due to the large amount of information, the fact of trying to take into account the entire data for decision making becomes an impossible task. Therefore, a tool that detects this data and takes advantage of the most important ones could be beneficial. The use of real data may not be valid if they are of low quality (Sainz et al., 2009). With this consideration, the most required figure in the characterization of the wind turbine is the relative power curve, wind speed and energy production. At this sense, this proposal involves to take the available reliability data obtained and to use it to optimize the yield of the entire wind farm system.

3. Analysis proposal

To date, the dimensioning of a power generation system (such as a wind farm) has been based mainly on the operational characteristics of the equipment to be acquired (capacity for power generation, electrical efficiency ...), geographical characteristics and weather for renewable energy (for example, wind speed and direction, temperature, altitude, soil conditions ...) as well as, of course, economic factors (costs of acquisition of wind turbines, substations, wiring cost, cost of geographical location, economic performance of the power generated among others).

Although the foregoing conditions are essential and must be taken into account, consideration should also be given to technical and economic characteristics that affect the entire life cycle of the assets as well as variables related to the maintenance of the system. In this sense, this proposal presents a methodology to analyze the life cycle cost in different scenarios of demand and economic valuation of energy, in order to obtain optimum results in terms of the number of equipment (wind turbines in this case) that must conform the system (or wind farm).

3.1 *Theoretical Background*

There are several interrelated variables involved in wind farm planning, as depicted in Fig. 1. The diagram summarizes the relationship between these methodologies and tools in wind farms and the main variables to be obtained in order to support the decision-making process. The state of development of each of them is analyzed and reviewed below.

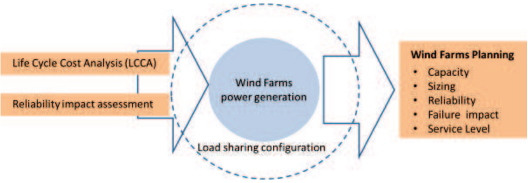

Fig. 1: Proposed diagram of the system variables

Issues related to Life Cycle Cost Analysis research have been developed further in recent years, both in the academic and industrial sectors. It is important to mention that other methodologies have emerged in the area of LCCA, such as: Life Cycle Costs Analysis and Environmental Impact, Total Costs Analysis of Production Assets, among others (Durairaj and Ong, 2002). Although these methodologies have their particular characteristics, regarding the estimation process of the costs for failure events impact, they commonly propose reliability analysis based on constant failures rates. The early implementation of cost analysis techniques allows the early evaluation of potential design problems and supports the user to quantify the potential impact on costs along the life cycle of the industrial assets (Durairaj and Ong, 2002).

LCCA is defined as an economic calculation technique which helps the optimal decision-making linked to the design process (Kirk and Dellisola, 1996). Moreover, it supports the selection, development and substitution of assets in a production system. Ideally, it evaluates the costs associated to the economic period of expected useful life in a quantitative way, expressed in yearly equivalent monetary units. Another definition (Yu et al., 2013) states that LCCA is a systematic process that uses techno-economic evaluation guidelines applied in the selection and replacement process of production systems, which allows the user to simultaneously consider both economic and reliable aspects, in order to quantify the real impact of the different costs throughout the asset life cycle in the whole system and, thus, to be able to select the asset that will bring the highest benefits to the productive system.

The huge number of variables that directly and indirectly affect the real costs (e.g., inflation, rise/decrease of the input costs, reduction/increase of the purchasing power, budget limitations, and competition boost) must be managed for estimating the real costs of an asset over its useful life. Those characteristics of the model generate a scenario of high uncertainty (Durairaj and Ong, 2002) and, at the same time, restlessness and interest in the total cost of the assets. Often, the total cost of the production system is not visible, particularly those costs associated with operation, maintenance, installation tests and staff training, among others.

The life cycle cost is usually determined by identifying a suitable function for each life phase of the asset over its entire life cycle. The next step is to calculate the cost of these functions and apply the appropriate costs during the whole extension of the life cycle. Once this process is finished, the life cycle cost should include all those costs related to design, fabrication and production (Ahmed, 1995). The characteristics of costs in the different phases of an asset's life cycle (Levy and Sarnat, 1990) are summarized as follows:

- Research, design and development costs (e.g., initial planning, market analysis, product research, design, engineering requirements).
- Production, acquisition and construction costs: industrial engineering, analysis of operations, production (i.e., manufacturing, assembly, tests), construction of facilities, process development, production operations, quality control and initial requirements of logistics support.
- Operation and support costs: operation inputs of the production system, planned maintenance, corrective maintenance (depending on the Reliability Factor) and logistical support costs during the system's life cycle.
- Removal and elimination costs: elimination of non-repairable elements along the life cycle, retirement of the system and recycling materials.

From the financial point of view, those costs generated along the asset life cycle are classified into two types as follows:

- CAPEX: Capital costs (design, development, acquisition, installation, staff training, manuals, documentation, tools and facilities for maintenance, replacement parts for assurance and withdrawal).
- OPEX: Operational costs (manpower, operations, planned maintenance, storage, recruiting and corrective maintenance - penalizations for failure events/low Reliability).

In general terms, it is assumed that reliability theory, together with asset's life cycle analysis, provides optimum support for the analysis and improvement of industrial plants (Daylan et al., 2016). The reliability and availability analysis, involving a set of technical and cost parameters, is crucial in evaluating the performance of an industrial process, specifically, a capital-intensive production process (Gang et al., 2015).

It is possible to classify wind energy production systems as complex systems in accordance with the flexibility they must have, in terms of the "productive" process configuration undertaken by them. Consequently, the reality of industrial processes shows that greater flexibility leads to improved productivity, process efficiency and, thus, overall results of companies. Within this context, dynamic systems are of great importance for modelling production processes. Dynamic systems are those that change over time, which means, their dependency relationships may vary according to the environment or their ability to function properly under different scenarios may be modified (Kristjanpoller et al., 2016b).

The reliability analysis is the cornerstone of an Asset Liability Management (ALM) study, since it is directly related to the failure behavior of each system component, establishing a dynamic dependency relationship between them, which will be crucial in assessing the criticality analysis and projecting costs during the investment and operational phase (CAPEX and OPEX) (Parra et al., 2012).

Considering the complex structure of wind farms, system reliability modelling is no easy task due to the dynamic relationships between the different elements and their logic configuration. In this regard, the Reliability and Failure Expect Impact methodology (FEI) (Kristjanpoller et al., 2016a; Kristjanpoller et al., 2017) can be very useful in an LCC analysis, contributing to an adequate reliability analysis for system components while considering their associated costs; the FEI methodology can be applied to any functional logic configuration, which is a quantitative and integral tool for the availability analysis.

The FEI methodology proposes a novel algorithm for estimating two impact indices known as the Expected Operational Criticality Impact (E-OCI) and the Expected Downtime Factor Propagation (E-DFP). Both are based on the reliability, maintenance capacity and expected impact of system elements according to different scenarios and configurations. These impact indices are based on a probabilistic approach and define the foreseen system conditions in terms of the evaluation of its possible scenarios (implicit behavior) and its functional logic configuration. Thus, these indices allow the user to fully compare the system elements, prioritize them and partially evaluate their effectiveness.

The FEI methodology is structured into four stages as summarized in Fig. 2.

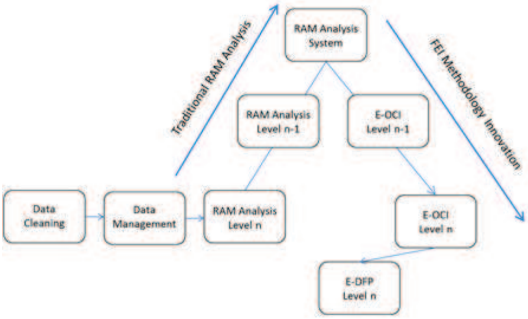

Fig. 2: FEI methodology (Kristjanpoller et al., 2016a, 2017)

One of the main drawbacks for designing wind power systems is that they have a service level variability. (Maleki et al., 2016). For this reason, alternatives such as hybrid wind/photovoltaic power generation systems have been developed in order to ensure a reliable energy supply by using at least one of the renewable energy sources (Baghaee et al., 2016). This kind of application is exactly what performs a redundancy or buffer analysis (Macchi et al., 2012). The effect of this type of hybrid systems could even be larger or be replaced by performing a logic configuration and plant reliability analysis in order to identify the failures impacts and to improve their detection level.

Based on the ISO 14040 and 14044 standards, Life Cycle Assessment evaluations have been developed in order to identify every procedure and phase of a wind farm project, but do not include reliability modelling; nor does it take into account the reliability impact assessment of different system configurations (Guezuraga et al., 2012). Under this perspective, there is a lack of systemic reliability modelling and logic configurations of the process itself, which may have a direct impact on the project costs and improvement opportunities.

The wind farms can be modelled by a load sharing configuration, for example. The load sharing configuration is characterized by a system that allows obtaining a required capacity based on the sum of all available elements that can even operate at a lower load than required (Kristjanpoller et al., 2014). The case of overcapacity will be characterized by showing a higher installed capacity than required; hence there will be a series of combinations which will enable the system to satisfy the same requirement. The equipment will be able to operate at different load levels. As a consequence of the above, the impact of the equipment on the system's performance will be variable and it will depend on the required load, equipment reliability and maintenance as well as other characteristics. It is therefore possible to initially establish the relationships between wind farms and the aforementioned settings.

Although the above variables are relevant for sizing and should be taken into account, it is also important to consider technical and economic variables that affect the entire life cycle of the assets, as well as variables related to maintainability and sustainability of the system concerned, where there is a lack of full development methodologies. This had encouraged the realization of this project.

4. Methodological proposal

In general terms, power generation systems stand out for their flexibility, high amount of devices and dynamism. The main feature of power sharing is that allows obtaining a required capacity based on the addition of individual capacity of the available equipment, which can even operate and generate a smaller amount of energy than the energy required individually. This overcapacity is characterized by having higher installed capacity for electricity generation than the one actually required. Thus, there will be a variety of equipment combinations that allow the system to satisfy the same energy requirement and, moreover, the equipment will be able to operate at different power generation levels.

On the contrary, there is a possibility of not oversizing the energy generation system, but it is possible to adjust its size in terms of the optimum amount of equipment to be installed. The latter depends on the requested power by each system component, its reliability, availability, maintainability and all other technical and economic characteristics of the system elements. From the above, it is observed that the evaluation must consider costs throughout the whole system life cycle, which can be a complex process.

Wind farms are particularly complex and large-scale investment facilities, what often makes them too difficult to develop, since they could have negative financial indicators. This implies that - from the design to the operational phase – the variables for each facility must be carefully researched, evaluated and projected in order to reverse the financial results. To this respect, the reliability analysis is a relatively new but scantly addressed issue in recent studies and research works.

In view of the above explanation, it is possible to design a methodological proposal and consider that it could have a great impact on the renewable energy sector, specifically on the wind farm design, since it integrates reliability modelling with life cycle cost analysis. This would improve the decision-making process involved both in the design and the implementation of the project. The proposed methodology is composed of five stages:

(i) Study of technical factors,
(ii) Modelling reliability and availability analysis of the system[a],
(iii) Application of the LCCA technique,
(iv) Analysis of total costs and evaluation of scenarios to find the optimum *n* system size, complying with the requested generated power,
(v) Sensitivity analysis and obtaining final results,

To apply the methodology, the proposed model is developed.

Table I. Variables and nomenclature

E	System(number of elements)
n	Total number of elements|E|
i	Element index ∈ {1,...,n}
s	Generated Power Economic Value ($/W)
r	Interest Rate (%)
t	Useful life (years)
T_T	Total time by year (hours)
T_F	Operation Time (hours)
A_{sist}	System Availability(%)
R	Reliability (%)
C_i^{EQ}	Capital Cost for element i ($)
C_i^{REP}	Repair and penalization cost for element i ($/h)
$C_{specific}$	Ineffiency costs ($/h)
$P_E^{required}$	Annual power required (W)
P_i^{EXP}	Expected annual power generated by element i (W)
P_E^{REAL}	System power generated (W/year)
P_i^{REAL}	Element power generated (W/year)
$MTTR_i$	Mean Time To Repair for element i (h)

According Woodward (1997), and Blanchard & Fabrycky (1998), the asset life cycle cost is composed by the sum of different components:

$$C_{TLC} = C_{AC} + C_{OP} + C_{PM} + C_{CM} + C_{MM} + C_{DIS} \quad (1)$$

Where:
C_{TLC} : Total Life Cycle Cost
C_{AC} : Capital Expenditures
C_{OP} : Operation and inefficiency costs
C_{PM} : Preventive maintenance costs
C_{CM} : Corrective maintenance costs
C_{MM} : Overhaul costs
C_{DIS} : Residual costs

Due to the objective the proposal, is possible to focus the evaluation only in the main differential costs for the decision making process, related to the number of elements for the windfarm. So, the total differential costs expression is:

$$C_{TD} = C_{AC} + C_{IN} + C_{CM} \quad (2)$$

Where:
C_{TD}: Total differential costs

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[a] As was discussed in Theoretical Background this is key stage and requires the implementation of and specific methodology, like FEI.

C_{AC}: Capital Expenditures
C_{IN}: Inefficiency costs
C_{CM}: Corrective maintenance costs

$$C_{AC} = Net\ Present\ Value\ (r,t) \sum_{i=1}^{n} C_i^{EQ} \quad (3)$$

The inefficiency cost is the result of the system unavailability and the specific inefficiency cost per hour, generally evaluated yearly:

$$C_{IN} = (1 - Asist) \times T_T \times C_{specific} \quad (4)$$

The specific inefficiency cost is estimated considering the difference between expected and real power generated.

$$C_{specific} = \frac{\Delta P}{T_F} \times s = \frac{P_E^{required} - P_E^{REAL}}{T_F} \times s \quad (5)$$

Substituting the expression (5) in (4), and considering the totality of equipment *n*, we obtain the following expression:

$$C_{IN} = (1 - A_{sist}) \times T_T \times \frac{\sum_{i=1}^{n}(P_i^{EXP} - P_i^{REAL})}{T_F} \times s \quad (6)$$

For the corrective maintenance costs, Woodward (1997) develops the specific modelling that can be extended for the *n* elements of the wind farm:

$$C_{CM} = \sum_{i=1}^{n}(1 - R_i(t)) \times MTTR_i \times C_i^{REP} \quad (7)$$

Grouping the previous equations (3), (6) and (7) in the general expression (2), we obtain the following formula:

$$C_{TD} = \left[\sum_{i=1}^{n} C_i^{EQ} \times \frac{r \times (1+r)^t}{(1+r)^t - 1}\right] + \left[(1 - A_{sist}) \times T_T \times \frac{\sum_{i=1}^{n}(P_i^{EXP} - P_i^{REAL})}{T_F} \times s\right] + \left[\sum_{i=1}^{n}(1 - R_i(t)) \times MTTR_i \times C_i^{REP}\right] \quad (8)$$

Knowing the variables included in expression (8) and defining the restriction associated to establishing a minimum threshold required for real annual power of the system:

$$P_E^{REAL} = \sum_{i=1}^{n} P_i^{REAL} \geq P_E^{required} \quad (9)$$

In this way it is possible to determine the optimum for the value n, representing the number of elements that should constitute that system that satisfies the previous boundary conditions at a minimum global cost, using simulation tools.

Conclusions

This article has discussed the need for a methodology to evaluate the optimal number of equipment of a complex energy generation system, proposing a sequence of stages and tools to obtain quantitative results analyzed by a mix of a technical and economical perspective. The above has a high relevance, since it allows the sizing of the systems, incorporating as key variables the minimum power required by the system or the economic valuation of the power generated. This cost model becomes an easy-to-implement method that can be decisive when analyzing over- or under-sizing (greater or lesser investment than required) versus expected results (higher or lower power generated compared to the required or expected profit).

The presented procedure can be applied to diverse industrial realities, especially to the activities of power generation with wind farms. The methodology pretends to be direct and transparent; however, its use with systems consisting of many elements requires the support of specialized computer tools. It is essential to compare the results obtained with the application of the methodology in relation to current practices, based on individual indicators without a systemic vision, which prevent an optimization of the sizing of the parks, and which are mainly based on average and unadjusted indicators.

The next step of this research is associated to a practical case development.

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