A model for assessing operation and maintenance cost adapted to wind farms in cold climate environment: based on Onshore and offshore case studies

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Abstract

The cumulative costs for O&M may represent as much as 65%-90% of a turbine's investment cost. The higher cost ratios are valid for offshore farms and for onshore farms located in cold, icy or remote areas. The ongoing studies conducted by wind energy in cold climates (IEA- Task 19) concluded that the increased O&M costs and extended downtime under icing conditions have to be taken into account. Therefore, in this study we developed a model for assessing the O&M cost of wind farms operated in cold climate. The model was verified using two methods: season-categorised method for downtime based on data reported by VTT and temperature-categorized method for production losses based on data collected from Aapua wind farm. Using the developed model gives a better understanding of the O&M cost of wind power systems taking into account relevant contextual factors. As well as, it helps the stakeholders to improve their decisions at different phases of the system's life cycle.

Keywords

Operation and Maintenance Cost; Cold Climate; Wind Farm; Life Cycle Cost; icing effect; Offshore; OEE; cost of energy, levelised production cost.

Introduction

According to a report published in year 2006 by Sandia National Laboratories, the cumulative costs for O&M may represent as much as 65%-90% of a turbine's investment cost. The higher cost ratios are valid for offshore wind farms and for onshore wind farms located in cold, icy or remote areas. The ongoing studies conducted by wind energy in cold climates (IEA- Task 19) have summarized the operational experiences in cold climate. They concluded that the increased O&M costs and extended downtime under icing conditions have to be taken into account. Consequently, wind farms in cold climates and at remote locations may act as test beds for offshore O&M practices. Another study, Design and Operation of Power Systems with Large amounts of Wind Power (IEA- Task 25) concludes that wind power variability and availability will impact operational security, reliability and efficiency. Cost reduction efforts in general focus on improving components, subsystems, grid, and power system reliability along with reducing the maintenance cost.

The efforts to minimize the O&M costs may start with identifying and gaining a better understanding of the current costs and the factors that drive the life cycle cost. Some of these factors will be common to wind farms, in general, but other factors will be site- and season specific, for example onshore or offshore if operated in cold climate.

Decisions made during the design and acquisition phases such as technology selection, how well it is designed, manufacturing quality of the components used, and the level of redundancy can dramatically influence the inherent reliability, which affects the number of failures. Using systems engineering principles in operation management can structure and improve the decision making process. Therefore the objectives of this paper are:

- To review the current cost estimation models and assess their characteristics
- To develop a contextual model for quantifying the operation and maintenance costs of wind farms over time.
- To develop a parametric model to estimate the cost and energy losses due to cold climate effects.

The organization of this paper is as follows: section two reviews the existing literature on cost estimation model of operation and maintenance aspects. The findings are classified and presented into a number of relevant categories. Section three presents the proposed model that was developed based on the features extracted from reviewed models. Section four presents a partial model verification with cold climate environment. Finally, the discussion, conclusions,
suggestion and recommendations for the future research work are presented.

2. Literature review

The authors have undertaken a review of available literature and practices related to models for assessing the operation and maintenance cost of wind farms. The objective of this review is to identify the available models, analyse and assess their characteristics in order to define the required features and attributes of new competitive models.

2.1 Operation and Maintenance costs.

In the first phase of wind energy development, the main emphasis has been on the technical and performance aspects of wind turbines and their associates. Nowadays, the development accelerated to include the cost-effectiveness concept as a must-have-feature in order to recognise the wind turbine as a viable contender for producing energy. By determining of the manufacturing, installation, operation and maintenance, and financing costs, the cost-effectiveness of a system can be addressed, in other words, taking into account the life-cycle processes and their cost categories which is the first principle of systems engineering approach. [1] Have discussed the economic aspects of wind energy and divided them into two factors: generating cost and market value of wind energy produced, as illustrated in Figure 1.

![Figure 1. Components of wind system economics. [1]](image)

The operation and maintenance is considered as a sizeable share of total generating costs of a wind turbine. The main purpose of any wind farm is to reduce the O&M costs. For this purpose, [2] recommended that one must begin with an understanding of the cost elements associated with the wind farm operation in order to be able to reducing the O&M costs. However, these cost elements are influenced by many factors such as turbine size and season- and site conditions.

In this paper, we are going to deeply focus on operation and maintenance cost since it is sensitive (i.e. highly affected by the farm site), and because we found many confusing issues which need more investigation. Therefore, we will discuss the following questions which are necessary for operational decision makers and designers:

**Why there are different presented numbers and percentages for operation & maintenance cost?**

[3] Shows that operation and maintenance costs are approximately 2-3 % of total investment costs for first two years of operation and slightly less than 5% of total investment costs for the next six years. [1] Shows that annual operation and maintenance costs generally range from 1.5% to 3% of the original turbine cost. [4] Stats that over the lifetime of the turbine, O&M costs might easily have an average share of approximately 20%-25% of the total levelized cost per kWh produced. The average share is related to age of a turbine; when the turbine is new the share is 10%-15% while it increases to at least to 20%-35% by the end of its life. [2] states that O&M costs can account for 10%-20% of the total “cost of energy” for wind project, and shows that Vachon has estimated that cumulative O&M costs can represent 75%-90% of a turbines investment cost.

**Shall we take into consideration the size of turbine, age differentiation and site conditions?** In order to understand the variation of O&M costs based on site, [5] states early models suggested that O&M costs of offshore farms account for some 25%-30% of the kWh price compared with 10-15% onshore. The technical university of delft in the Netherlands and ECN wind energy have independently attempted to model offshore wind farm costs, using the 500 MW DOWEC farm as a reference case. The cost models take into account preventive and corrective maintenance. They make clear that costs can be expected to vary widely according to many factors such as the size and reliability of the turbines, the means of access and maintenance chosen, distance from shore, water depth, and the wind farm size and climate characteristics.

**What are the considered cost categories within operation and maintenance costs?** [3] States based on German turbines DEWI (1997-2001) that cost categories of operation and maintenance with estimated percentages are: land rent (18%), insurance (13%), regular maintenance, repair and spare parts (43%, together with miscellaneous), administration costs (21%) and power from the grid (5%). [1] Shows another cost categorizing according to a study of California wind farm costs EPRI (1987) as follow:
labour (44%), parts (35%), operations (12%), equipment (5%), and facilities (4%). The cost also can separated into more sub-categories such as operations, scheduled maintenance and unscheduled maintenance as described in [2], where they also mentioned that the portion of O&M costs associated with unscheduled maintenance is between 30%-60% of the total, and generally increase as the project matures and equipment failure rate increase.

How to calculate the operation and maintenance costs?
Actually, the answer for this question will help in dealing with the vagueness- and difficulty of understanding and presenting the operation and maintenance cost. The differentiation is based on adding more specifications and information such as turbine- size and age, and site condition. This will give the presented numbers a contextual frame that will be helpful for comparative study in order to shift the experience from one domain to another. For instance, from onshore domain to cold climate domain, the same for cold climate to offshore domain and so on. Therefore, the cost estimation method shall take into consideration the contextual frame of the applied domain.

Another significant point that should be considered when using the cost estimation model is who is the user and for which purpose it is used? Obviously, one can find different groups who are interested in estimating the cost of operation and maintenance for various objectives, as follow:

1. The first group aims to get an estimate of the operation and maintenance cost to be factored into the project costs.
2. The second group wants it to be factored into the power production costs.
3. The third group tries to get an estimate (forecast) of the operation and maintenance (for short-term; 1, 2 or 5 years) cost in order to optimize their operational decisions.
4. The fourth group tries to get an estimate (forecast) of the operation and maintenance (for long-term: 20 years) costs in order to optimize its design decisions. In other words, to decide if it is reasonable to invest in the design stage and take into account the maintenance aspect by comparing the benefits (reduce failures, production losses, improve performance) of design for operation & maintenance and their cost.

Now, let us review the current practices and models for calculating the cost of energy and in particularly the operation and maintenance costs.

2.2 General cost calculation models
The cost of energy produced by a wind turbine is related to the incurred costs and quantity of energy generated by the turbine. Generally, the cost of energy can be calculated by dividing the total cost by the annual utilized energy [6], as illustrated in the following equation.

$$\text{Levelised production cost} = \frac{\text{Total cost}}{\text{Annual Utilized Energy}}$$

The challenge is to reduce the cost of energy; this can be done by optimising costs factors such as the operating and maintenance costs or by increasing the turbine’s energy production through improving the turbine’s availability.

More complex or simplified versions of this equation are discussed by researchers where the differentiation is based on what are the most important variables, cost categories and cost estimation methods related to their application field.

In wind power context, we found two models which can be considered as the most used cost estimation models: the first one is Modified NEA Model which is redeveloped by Riso laboratories and the second one is SANDIA laboratories Used Model.

2.2.1 Modified NEA Model
Originally, the model was developed in nuclear energy agency (NEA) for nuclear and coal fired power stations context, however, Riso laboratories [7] modified it to be useful in wind power context. The main idea is to calculate the cost of one production unit (kWh) averaged over the wind power station’s entire expected lifetime.

$$\text{Levelised production cost} = \frac{\sum_{i=1}^{n} AUE_i}{TC}$$

$$\sum_{i=1}^{n} \left(OM_i + SC_i + RC_i\right) \left(1 + r\right)^{-1} = \frac{SV}{\left(1 + r\right)^n}$$

$$AUE = F_{\text{performance}} \ast K_{\text{capacity factor}} \ast K_{\text{wind turbulence}} \ast K_{\text{power curve}} \ast K_{\text{availability}}$$

The levelised production cost (LPC) is given as the ratio of the total discounted cost (TC) and the total discounted utilized energy output (AUE). The following cost components are considered in TC: the investment cost, operation and maintenance cost, social cost, repair cost, and salvage value.
In reality, there are various types of losses affecting the annual potential energy output. Because of that, the equation for calculating the total utilized energy (AUE) is taking into consideration the potential energy output \( E_{\text{potential}} \) with a number of correction factors. The main correction factors which have been used are performance losses \( K_{\text{performance}} \), site losses \( K_{\text{site}} \), technical unavailability losses \( K_{\text{availability}} \), electric transmission losses \( K_{\text{transmissionloss}} \) and utilization losses \( K_{\text{utilization}} \).

2.2.2 SANDIA Used Model

This model and its calculation method [2] have been adopted by the department of energy in the low speed wind turbine program. It provides an approximated estimation of cost of energy (COE) taking in consideration equipment reliability which impacts the total cost of energy through scheduled and unscheduled turbine downtimes.

\[
\text{COE} = \frac{\text{ICC} \times \text{FCR} + \text{LRC}}{\text{AEP}_{\text{NET}}} + \text{OM}
\]

\[
\text{AEP}_{\text{NET}} = \text{AEP}_{\text{GROSS}} \times \text{Availability} \times (1 - \text{losses})
\]

Initial capital cost (ICC), levelized replacement cost (LRC) are the main categories of production cost. LRC is associated with overhauls and replacements of major components over the life of the wind turbine. The major components are those components whose expected life is less than the wind turbine’s design life and their replacement frequency vary over the equipment life where its assumed cost is spread over the turbine lifetime.

The model distinguishes and separates the operation & maintenance cost (OM) from production cost. Here, OM cost is assumed to include scheduled and unscheduled repair maintenance costs, and expenditures for replacement parts, consumables, manpower and equipments. The separation idea is used to indicate the differences between LRC cost and OM cost, and we try to summaries the model philosophy as follows:

- To show the difference in nature and characteristics of the two categories: LRC is related to replacement orders which are characterised by high downtimes and low frequency rate to failure. While OM cost is related to repair orders which are characterised by high rate of failure and relatively low downtimes.
- To show the contribution of each cost category and to highlight the possibility for further improvement: for example, turbine reliability directly affects the LRC which is the responsibility of design department while the OM cost is directly affected by turbine availability, maintainability, accessibility and supportability which are the responsibility of operation and maintenance staff.

A large percentage of LRC is due to inappropriate design assumptions, inadequate knowledge about the true operation environment and manufacturing quality control issues [2]. The real practices show discrepancy between the designers’ assumptions and real operating conditions. For instance designers assume to have equal design life of wind turbine and its major components. In reality, [2] clearly argue based on practical findings that there are numerous examples where the design life for major components is not realized in practice.

Observations on the two models:

The main difference between the two pervious models is how they define the losses or correction factors such as availability and performance needed to calculate real utilized energy. Therefore, we need to search for how to define the availability and losses for wind farms.

The second difference is about combine or separate operation and maintenance cost; it is clear that Modified NEA Model combine the O&M cost as part of production cost and divide it by the utilized energy quantity in order to have levelized production cost. However, SANDIA Used Model consists of two categories for operation and maintenance cost: LRC and annual O&M cost.

Differentiation of cost categories within the current cost estimation models especially in this rapid wind power industrial development is necessary to understand which are the critical cost categories and who is responsible for those cost categories. Because of the main purpose of using a cost estimation model is to improve the practices in design phase as well as operation and maintenance phase, more than quantifying the cost of energy as one block where definitely differentiation will not impact the final amount of cost of energy.

There is a need to have estimation of planned replacement maintenance cost (LRC) as estimated by designers as well as unplanned repair maintenance cost that is predicted by maintenance staff and operation expert based on their knowledge and experience of the true operation environment.

2.3 On-going research works

ECN [8, 9] is developing the operation and maintenance cost estimator (OMCE) with which owners and operators of offshore wind farms are able to better estimate and control the future operation and maintenance cost for next coming 1, 2, or 5 years.
The main objectives of OMCE model are to analyse operation and maintenance data which are collected from SCADA systems, load measurements data, and condition monitoring data, and to analyse load measurements for operation and maintenance optimization. The model performs probabilistic analyses in order to define the boundaries of uncertainty of failure occurring. Then basic trend analysis tools are used to determine how often unexpected failures may occur.

2.4 Practical needs for cost estimation models and their decision support features
In the following we discuss what we think is needed for improving the accuracy and effectiveness of a good cost estimation model.

1) Consider the practical maintenance categories. The service and repair companies use four maintenance categories based on the type of maintenance work and the complexity of the maintained component. In this context, complexity means different thing like difficult to investigate the failure and diagnose the problem, is the part available in stock or needs long time to get it, difficult to replace it due to its size, and difficult to repair on-site. Clearly defined the practical maintenance categories within offshore wind maintenance. Showed that, nowadays, some service companies start to provide package-maintenance and service work form standard to premium services.

2) The model parameters are related to the information system used by the company. Are the needed data clearly identified? Can they be available at the company? And are they accessible by the model user?

3) The model should consider technical performance measures such as the availability losses and performance losses due to cold climate conditions and convert them to economics measures. One of the well-known technical measures is the overall equipment effectiveness (OEE). It is a way to monitor and improve the efficiency of wind farm operations. It takes most common and important sources of power generating losses, places them into three primary categories and distils them into metrics that provide an excellent gauge for measuring where and how the wind farm stakeholders can improve. Usually, in manufacturing companies’ domain, OEE measures availability, performance efficiency and quality losses.

\[ \text{OEE} = \text{Availability} \times \text{Performance efficiency} \times \text{Quality Rate} \]

[12] Have adopted the OEE terms into wind farm process by considering wind farms performing a transformation of produced electrical energy to delivered (sold) electrical energy. This transformation process consists of an installation and their arrangement to form a wind farm, and of a process comprising operation and maintenance. Both are subject for optimization to maximize the annual energy output by minimizing the different kinds of losses.

2.5 Krokoszinski OEE Model for wind farms: with contributions
The idea of Krokoszinski model [12] is to describe and quantify the transformation of produced electrical energy at the terminals of the individual windmills to the total electrical energy at the grid connection point by quantifying and representing the external losses and technical losses of wind farms including grid in terms of the layout factor (LF), planning factor (PF) and overall equipment effectiveness (OEE) definitions. Krokoszinski model defined the responsibility and influence areas of engineering and operations planning phase and the operation and maintenance phase. In other words, he shows the root causes of the losses and in which phase of the life cycle processes the improvement shall be performed. Krokoszinski defined the approximated OEE as follows:

\[ \text{OEE} = \text{Availability} \times \text{Performance} \]

Krokoszinski has developed calculation scheme to quantify wind farm production losses in terms of planned and unplanned downtimes and speed losses and related the associated reduction of revenues to the theoretical maximum of annual wind park revenues. However, he did not include quality rate losses term, since it is considered as a non-relevant term for wind farm, as long as the unplanned power quality deficiencies really occur at grid connection point and, additionally, lead to the need to de-rate the wind farm power level.

2.5.1 Definitions of wind energy production and losses
According to [12] there are four terminologies of electrical energy: reference, theoretical, available and valuable. Note: all the electrical energy expressions are per year (8766 hours).

Reference electrical energy: represents the maximum energy that could theoretically be delivered into the grid at the grid connection point if it was not for the losses or outages.

Theoretical electrical energy: when you consider the wake losses due to the windmills arrangement within wind farm which is represented as a factor called layout factor (LF), the reference electrical energy is called theoretical electrical energy.

\[ E_{\text{theoretical}} = E_{\text{reference}} \times LF \]
Available electrical energy: it is the amount of energy that is available per year to be fed into the grid after subtracting the scheduled (planned) downtime losses from the theoretical electrical energy of the wind farm, which is represented as a factor called Planning factor (PF).

\[ E_{\text{available}} = E_{\text{theoretical}} \times PF \]

Where PF is:

\[ PF = \frac{T_{\text{available}}}{T_{\text{theoretical}}} = 1 - \frac{\sum_{t_1=t_s}^{t_2} \text{(planned downtime)}}{8766 \text{(hours per year)}} \]

Where \( n \) is the numbers of planned maintenance visits within one year which is known for the manufacturing company and service staff. Then by estimating the time losses due to each maintenance visit, the yearly energy losses due planned maintenance will be known.

Valuable electrical energy: it is the amount of energy that is delivered per year to be fed into the grid after subtracting technical losses (unplanned downtime losses and performance losses) from the available electrical energy of the wind farm.

\[ E_{\text{valuable}} = E_{\text{available}} \times OEE \]

Where OEE = Availability * Performance efficiency

2.5.2 Availability due to unplanned downtimes

Take into consideration that availability here is related to the unplanned downtime because already we have taking the planned downtime in the PF expression. Also, in order to have effective and company-user friendly model, it is easier for the user to collect data about the unavailable time due to unplanned downtimes than collect and analyse the whole available time data.

Actually, this type of availability (due to unplanned downtime) is affected by five main factors as explained in [13]: reliability (failure/ per), maintainability, serviceability, site-accessibility and maintenance strategy. The first three factors define together the theoretical availability; while the actual availability takes into consideration also site-accessibility and maintenance strategy. One addition factor that we can add here is the identifiability. It means the ability to determine the cause and effect relationships and identify the problem cause(s) quickly and easily in a good time. Based on this factor, maintenance manager can decide which type of maintenance issues are needed (staff, equipment, vessels, and spare parts) in order to make the service visit more cost-effective.

Offshore and difficult-accessible site highlight the effect of identifiability factor on overall availability. Nowadays, the service staff depend on using tries to identify the cause based on alarms form SCADA system and condition monitoring techniques to reduce the identification time and get more accurate understanding of the causes of the failures. Prognostic techniques also are suggested for predicting the useful life of different critical components. This improves the effectiveness of planning maintenance.

The availability losses per one unplanned downtime can be measured by the following equations.

\[ Availability_{\text{(Unplanned)}} = 1 - \frac{\sum_{t_1=t_s}^{t_2} \text{(Unplanned downtime)}}{8766 - \sum_{t_1=t_s}^{t_2} \text{(planned downtime)}} \]

\[ t_{\text{(Unplanned downtime)}} = t_{id} + t_{mp} + t_s + t_a + t_m \]

where:

- \( t_{id} \): Identification time
- \( t_{mp} \): Time for maintenance planning
- \( t_s \): Time for service
- \( t_a \): Time for accessibility
- \( t_m \): Time for maintenance (repair or replace)

In case that there is no historical data about the unplanned downtime, the calculation can be based on information about failure frequencies and reliability data provided by the manufacturers for specific components like gearbox, bearings, generator, transformers, etc.

2.5.3 Performance efficiency losses

Performance efficiency takes into account speed losses, which include any factor that causes the process to operate at less than the maximum possible speed, when running. Examples include snow and ice layers on the blades, blade shape deviation and bearings faults which lead to rotation braking as described by [12]. Figure (2) shows clearly that field performance curves for summer and winter data are different, they do not follow a perfect curve as the calculated one.

Briefly, the main effect of icing as [14] explained (based on case study conducted at Nygårdsfjell wind park) that the effect of icing is altered airfoil shape which is resulting in reduction in lift coefficient and increase in drag coefficient, thus, the reduction in production rate is expected and measured through the case study observations.

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The performance factor usually is described by power rate differences due to cold climate effects, where the energy production rate is helpful for that:

\[ P = \frac{\text{Generated Energy}}{\text{Available Energy}} \]

The available energy can be calculated based on wind speed data while generated energy is the final generated or delivered power of specific turbine and definitely should be less than the available energy due to icing effect as a reducing factor of lift coefficient.

### 3. The proposed cost estimation model

The general equation for calculating total cost of energy based on OEE method is as following:

\[
\text{Total cost} = \sum_{t=1}^{n} \left[ \frac{(OM_P + OM_{UNP} + SC_t + RC_t) - (E_{est} + P_{losses} \times \text{price})}{(1+r)^t} \right] + \frac{SV}{(1+r)^n} \\
AUE_t = ANE_t \times LF \times \frac{A_P \times A_{UNP} \times P}{\text{price}} \\
LPC = \frac{\text{Total cost}}{AUE_{NET}} \\
TCEL = \sum_{t=1}^{n} ((t_P \times E_{est}) + (t_{UNP} \times E_{est})) \times \text{price} + P_{losses} \times \text{price}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC</td>
<td>Levelised production cost</td>
</tr>
<tr>
<td>AUE_t</td>
<td>Utilized energy in year t</td>
</tr>
<tr>
<td>Total cost</td>
<td>Discounted present value of total cost of energy</td>
</tr>
<tr>
<td>I</td>
<td>Investment cost</td>
</tr>
<tr>
<td>OM_P</td>
<td>Planned O&amp;M cost</td>
</tr>
<tr>
<td>OM_{UNP}</td>
<td>Unplanned O&amp;M cost</td>
</tr>
<tr>
<td>SC_t</td>
<td>Social cost during year t</td>
</tr>
<tr>
<td>RC_t</td>
<td>Retrofit cost during year t</td>
</tr>
<tr>
<td>SV</td>
<td>Salvage value after n years</td>
</tr>
<tr>
<td>r</td>
<td>Discount rate</td>
</tr>
<tr>
<td>n</td>
<td>Economic lifetime</td>
</tr>
<tr>
<td>ANE_t</td>
<td>Net energy within year t</td>
</tr>
<tr>
<td>LF</td>
<td>Layout factor</td>
</tr>
<tr>
<td>A_P</td>
<td>Planned availability factor</td>
</tr>
</tbody>
</table>

The total cost consists of investment cost, total planned operation and maintenance costs, total unplanned operation and maintenance costs, social cost and retrofit cost, all of them during year \( t \). In addition to salvage value cost. The total utilized energy (kWh) consists of layout factor, planned availability factor, unplanned availability factor and performance factor.

The following equations are graphically explained in Figure 3, where there are two main goals; first one is to quantify the total cost of planned and unplanned maintenance costs besides showing the responsible stakeholder for each of them. Second one is to quantify the energy losses due to planned and unplanned downtimes and performance losses.

For calculating the cost of energy or levelised production cost, the user is going to do a summation of all the cost categories divided by the utilized energy that is estimated based on OEE method. While for energy losses, the user is going to multiply the total energy losses which are estimated based on unavailability losses due to both (planned and unplanned stoppages), and performance losses by the price of one kWh. This will enable the user to quantify: how much is lost and why? Furthermore, it helps to measure the cost effectiveness of the suggested improvement efforts.

### The benefits and originality of the proposed model

The developed model brings the following benefits:

- Demonstrates how the cost of energy can be calculated from cost and performance information
- Bring clarity to the cost estimation method
- Provides a framework for collecting information on devices at different stages of development.
4. Partial model verification with cold climate

The main feature of cold climate production is that total cost will increase together with the production losses. Actually, the effects of cold climate on the cost of energy are directly related to unplanned operation and maintenance cost and to energy losses due to unplanned downtimes and due to performance or speed losses. In order to understand the cold climate effect, the simplest way especially with limited information and data to assume that winter season is the main effect of cold climate. Thus, let us clarify how practically one could use the cost estimation model.

4.1 Using season-categorized method for downtimes: in the following we statistically analysed the downtime data (reported by VTT) for Finnish wind farms, [15]. The main objective of study was to test the hypothesis which argues that:

“There is no difference between winter mean downtimes and other seasons mean downtimes”.

The study has considered three different turbine sizes: 300 kW, 1000 kW, and 3000 kW. As a result of hypothesis test, the hypothesis was rejected for the three samples. This means that the winter downtimes are larger than other seasons’ downtimes. The result of the study is shown clearly in Table 1.
The main benefit of using this practical method is to establish a basement for estimating the availability correction factors which all cost estimation model try to define and talk about. Thus, if you say that the mean difference between winter downtimes season and other mean downtimes is 20.675 hour more for wind turbine with 300 kW, for example if normal downtimes is 100 hours, then winter downtimes factor is \( \frac{100}{100 + 20.675} = 0.833 \).

It means that if the company estimate that planned production hours in the winter will be for specific year 1000 hours, the actual production hours will be \( 1000 \times 0.833 = 833 \) hours due to the effect of cold climate.

4.2 Using temperature-categorized method for production losses

[16] Has conducted a study in Aapua wind farm (7 turbines of 2 MW) to investigate the energy losses during winter seasons in comparison to summer season from October 1st 2005 to March 31st 2009. The result of the study shows that “the average energy production losses, based on actual production, was 27.9% in the winter time \((t<+2 \, ^{0}C)\) and 6.6% in the summer time \((t>+2 \, ^{0}C)\)”.

5. Discussion and Conclusions

Table 1. Result of difference of means method

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hypothesis test result</th>
<th>Confidence interval</th>
<th>Mean difference (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 kW</td>
<td>Reject</td>
<td>Lower 13.179</td>
<td>Upper 28.172</td>
</tr>
<tr>
<td>1000 kW</td>
<td>Reject</td>
<td>Lower 9.9053</td>
<td>Upper 13.846</td>
</tr>
<tr>
<td>3000 kW</td>
<td>Reject</td>
<td>Lower 13.846</td>
<td>Upper 24.772</td>
</tr>
</tbody>
</table>

The current documentation system used by wind farms and the data and information of operation and maintenance practices are not completely helpful to verify the model and quantify the cost and energy losses in cold climate context. The operation and maintenance operations in the wind power sector involve many different stakeholders with various interests and responsibility. Therefore, using this model one can get a breakdown of all the losses with information about their possible route cause(s). Furthermore, it provides a clear estimate of relevant cost categories related to the responsible stakeholder. This can be considered as a type of visual management and opportunity for continuous improvement. The differentiation which has been used in the model to estimate the cold climate effective will be more accurate if we use temperature based estimate method.

Using the developed model gives a better understanding of the operational and maintenance cost of wind power systems taking into account relevant contextual factors. As well as, it helps the stakeholders to improve their decisions at different phases of the system’s life cycle.

Conducting more research and case studies to quantify the planned operation & maintenance factor, unplanned operation & maintenance factor and performance factor for wind farm in cold climate sites will give more realistic factor in order to use them for more accurate cost estimation.

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