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TRABAJO FIN DE GRADO

ECONOMIC ANALYSIS OF A PROPOSED NEW DIRECT-DRIVE PERMANENT MAGNET SYNCHRONOUS GENERATOR WIND TURBINE

Senior Thesis in Electrical and Computer Engineering

University of Illinois at Urbana-Champaign, May 2020

Urbana, Illinois

Autor: Daniel Mulas Hernando

Director: George Gross

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TRABAJO FIN DE GRADO

ECONOMIC ANALYSIS OF A PROPOSED NEW DIRECT-DRIVE PERMANENT MAGNET SYNCHRONOUS GENERATOR WIND TURBINE

Senior Thesis in Electrical and Computer Engineering

University of Illinois at Urbana-Champaign, May 2020

Urbana, Illinois

Autor: Daniel Mulas Hernando

Director: George Gros

To my family, who has always supported me.

ABSTRACT

Prevailing wind energy conversion systems (*WECS*) rely extensively on geared doubly-fed induction generators (*DFIG*s) in light of their reduced power electronics requirement. The existing permanent magnet synchronous generator (*PMSG*) based system demands a full-system-rated power converter to control energy flow. Such power electronics requirements have restricted the adoption of a *PMSG*-based system, despite its higher power density, increased efficiency, improved reliability, better grid-fault-ride-through capability, and reduced maintenance compared to a *DFIG*-based aggregation. The main challenge of the project is making an accurate economic assessment of the proposed designs of the *PMSG* and the power electronics (*PE*) associated with the design according to the input variables of each of the specific proposed technologies. The objective of this thesis is to work on the preparation of models for generation economic evaluation, the development for component-wise cost data, estimation of maintenance cost for the proposed drivetrain, taking into account distance to shore and power transmission, the analysis of parameter sensitivity and the comparative analysis of all the prototypes for the drivetrain and extension to an offshore wind project. We shall determine the levelized cost of energy (*LCOE*) for various values of the variables of the component-wise cost data. This work addresses the wind probabilistic characterization of a location from experimental wind data, the application of that wind characterization for the calculation of the expected annual energy generation of a single wind turbine (*WT*) with the mechanical characteristics of the proposed technology, and the cost analysis of the conventional and new proposed designs. The evaluation of metrics of interest such as *LCOE* and the fixed costs of the system for different proposed designs are useful for the evaluation of the characteristics of the most profitable designs and the designs with better generation performance. We compute valuable information for the choice of actual parameters of the *PMSG* and the *PE*. In addition, we evaluate the computed numerical results and provide concluding remarks of the economic evaluation of the proposed technology.

ACKNOWLEDGMENTS

I would like to thank my advisor, Prof. George Gross, for the dedication and support during the last two semesters and for making sure that I am always on the right track for the development of my thesis. Without his generous help and his strict methodology, I would have never been able to complete the thesis properly. I am also thankful to all the professors and staff that worked for the project “*MW*-Scale Power-Electronic-Integrated Generator with Controlled *DC* Output”, especially to Phuc (the leader of the project), the reliability team (Olaolu, Sara and Prof. Alejandro Domínguez-García), and Prerak (my partner for the economic assessment during the first semester).

I would like to express my gratitude to my roommates Mayoral, Michel and César, and all the other Spanish exchange students for all the happy and not so happy moments that we´ve been through during this wonderful year abroad. I am sure that we have built a family.

Last but not least, I would like to thank Fran, Álex, Julia, Mamá and Papá for the unconditional love, for believing in me more than I would do, and for investing in my education. I am forever grateful for the familiar and lovely environment where I grew up.

ANÁLISIS ECONÓMICO DE UNA NUEVA TURBINA DE VIENTO CON UN GENERADOR SÍNCRONO DE IMÁN PERMANENTE DE TRANSMISIÓN DIRECTA

Autor: Mulas Hernando, Daniel.
Director: Gross, George.
Entidad Colaboradora: University of Illinois at Urbana-Champaign

RESUMEN DEL PROYECTO

Los sistemas de conversión de energía eólica (*WECS*) predominantes dependen en gran medida de generadores de inducción de doble alimentación con engranajes (*DFIG*) a la luz de su requisito de electrónica de potencia reducida. El sistema basado en un generador síncrono de imán permanente (*PMSG*) exige un convertidor de potencia con transferencia completa para controlar el flujo de energía. Dichos requisitos de electrónica de potencia han restringido la adopción de un sistema basado en un *PMSG*, a pesar de su mayor densidad de potencia, mayor eficiencia, mayor confiabilidad y menor mantenimiento en comparación con una agregación basada en un *DFIG*. El principal desafío del proyecto es hacer una evaluación económica precisa de los diseños propuestos del *PMSG* y la electrónica de potencia (*PE*) asociados con el diseño de acuerdo con las variables de entrada de cada una de las tecnologías propuestas específicas. El objetivo de esta tesis es trabajar en la preparación de modelos para la evaluación económica de la generación, el desarrollo de datos de costes por componentes, la estimación del coste de mantenimiento para la transmisión propuesta, teniendo en cuenta la distancia a la costa y la transmisión de energía, el análisis de sensibilidad y el análisis comparativo de todos los prototipos para la transmisión y la extensión a un proyecto eólico marino. Determinaremos el coste nivelado de energía (*LCOE*) para varios valores de las variables de los datos de costes por componentes. Este trabajo aborda la caracterización probabilística del viento de una ubicación a partir de datos experimentales del viento, la aplicación de esa caracterización del viento para el cálculo de la generación anual de energía esperada de una sola turbina eólica (*WT*) con las características mecánicas de la tecnología propuesta y el análisis de los costes de los diseños convencionales y nuevos propuestos. La evaluación de métricas de interés como *LCOE* y los costes fijos del sistema para diferentes diseños propuestos son útiles para la evaluación de las características de los diseños más rentables y los diseños con mejor rendimiento de generación. Calculamos información de valor para la elección de los parámetros reales del *PMSG* y el *PE*. Además, evaluamos los resultados numéricos calculados y proporcionamos observaciones finales de la evaluación económica de la tecnología propuesta.

Palabras clave: Análisis económico, generador síncrono de imán permanente, *LCOE*.

1. Introducción

El objetivo del proyecto es proporcionar un cuidadoso estudio económico de la tecnología propuesta en el proyecto: “*MW*-Scale Power-Electronic-Integrated Generator with Controlled *DC* Output*”* y una detallada y justa comparación con el *PMSG* de transmisión directa de la Universidad Técnica de Dinamarca (DTU) [1]. Esencialmente, el proyecto es capaz de proporcionar un estudio tecno-económico a fondo de los costes de los componentes con especial énfasis en el *PMSG* propuesto y sistema de conversión *PE* asociado, que son los dos aspectos principales que dan lugar al objetivo de crear el sistema de conversión de energía de viento (WECS) más eficiente, fiable y compacto. Ese análisis tecno-económico requiere la comprensión en profundidad de las características de nuestros diseños *PMSG* y *PE* y la evaluación de sus costes asociados. La evaluación económica incluye la cuantificación de los elementos de coste de las características sobresalientes de cada diseño de configuración de *PMSG* y *PE* propuesto y su evaluación de fiabilidad para determinar sus impactos en los costes fijos asociados y los costes de operación y mantenimiento (*O&M*) de la producción eólica. Esta tarea implica la evaluación del desempeño del diseño propuesto en términos de la generación anual de energía (*AEG*) esperada para cuantificar la producción de energía de cada diseño propuesto y así, realizar un análisis de coste de energía nivelado (*LCOE*) en los diseños *PMSG* y *PE* propuestos.

2. Análisis económico de los diseños propuestos de *PMSG* y *PE*

El desafío en el desempeño de una evaluación económica de un proyecto eólico radica en una aproximación aceptable de los costes y la confiabilidad del *PMSG* propuesto y el subsistema de *PE* asociado. La información clave requerida para la evaluación económica son los costes fijos del *PMSG*, los costes fijos del subsistema *PE* asociado, los costes fijos del sistema emparejado compuesto por el *PMSG* y el *PE*, los costes fijos de todos los componentes de la turbina eólica, los costes de *O&M* por año de una turbina eólica, y la *AEG* esperada.

Dadas las variables anteriores, y teniendo en cuenta un parámetro estático que anualiza los costes fijos para producir un *cash-flow* anual uniforme establecido durante la vida útil del proyecto eólico, es decir, el factor de recuperación de capital (*c.r.f.*); es posible estimar una variable de mérito: el *LCOE*. Suponemos una vida útil de 20 años para este proyecto, que es el tiempo promedio por el cual el *WT* es reparable desde su instalación.

3. Resultados numéricos

Se muestran gráficas de resultados numéricos calculados de variables de mérito para cada diseño propuesto y mostramos los resultados de costes de operación y mantenimiento para los diseños convencionales y propuestos. Las gráficas de los resultados numéricos se calculan utilizando los datos recibidos de múltiples diseños *PMSG* y diseños *PE*.

El rendimiento de generación y el *LCOE* están representados en función del coste del *PMSG*, el coste de la *PE*, la densidad de costes del sistema propuesto, parámetros como la reactancia síncrona y la velocidad mecánica del rotor en *MPPT*.

4. Análisis de los resultados numéricos

Se proporciona información importante sobre los valores que funcionan de la manera más eficiente para la tecnología propuesta más rentable teniendo en cuenta los resultados numéricos proporcionados. Se representa el rango de los valores de los parámetros de todos los diseños propuestos. Finalmente, se muestra las características del diseño más económico.

5. Conclusiones

Se reúnen los métodos utilizados para estas tareas para construir un método sistemático para realizar la evaluación económica de un proyecto eólico, en general, y el de una turbina eólica, en particular. Los resultados de la evaluación nos permiten obtener información relevante sobre los diversos aspectos del diseño de la tecnología propuesta. Específicamente, se observa que, para obtener resultados económicamente más eficientes, el diseño *PMSG* y *PE* con los costes fijos más bajos no necesariamente tiene que conducir a los valores *LCOE* más bajos. Existen compensaciones entre los costes fijos de la tecnología propuesta y los costes de rendimiento de generación, cuyos impactos deben considerarse explícitamente para determinar el diseño económicamente más eficiente. Estas compensaciones son observables a partir de los cálculos del enfoque que se propuesieron para la evaluación económica. Por lo tanto, nuestro enfoque de evaluación económica propuesto es una contribución al análisis económico y la evaluación de proyectos eólicos marinos, así como a los diseños de *PMSG* y *PE* propuestos. En particular, las técnicas computacionalmente eficientes hacen posible la evaluación de una amplia variedad de casos de sensibilidad para los diferentes valores de parámetros de diseño. De hecho, esta capacidad permite la preparación de respuestas a una amplia gama de casos hipotéticos. Estas capacidades son de gran utilidad en la selección de la solución robusta de los parámetros de diseño de los diseños *PMSG* y *PE* más apropiados para cualquier conjunto de requisitos específicos.

Se resumen los resultados del análisis comparativo de los diseños actuales de *PMSG* y *PE* y el sistema *DTU* [1]. Debido a la falta de datos sobre los costes fijos y variables de muchos elementos del diseño y el uso de los datos disponibles en los diseños existentes como un marcador de posición por la falta de datos, los resultados hasta la fecha no capturan adecuadamente los impactos económicos de las mejoras en el diseño propuesto. Como tal, es mejor ver los resultados de nuestro análisis económico todavía como tentativos.

6. Referencias

[1] L. Sethuraman, M. Maness and K. Dykes, “Optimized Generator Designs for the *DTU* 10-*MW* Offshore Wind Turbine using GeneratorSE,” 35*th Wind Energy Symposium*, Jan. 2017.

ECONOMIC ANALYSIS OF A PROPOSED NEW DIRECT-DRIVE PERMANENT MAGNET SYNCHRONOUS GENERATOR WIND TURBINE

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SUMMARY OF THE PROJECT

Prevailing wind energy conversion systems (*WECS*) rely extensively on geared doubly-fed induction generators (*DFIG*s) in light of their reduced power electronics requirement. The existing permanent magnet synchronous generator (*PMSG*) based system demands a full-system-rated power converter to control energy flow. Such power electronics requirements have restricted the adoption of a *PMSG*-based system, despite its higher power density, increased efficiency, improved reliability, better grid-fault-ride-through capability, and reduced maintenance compared to a *DFIG*-based aggregation. The main challenge of the project is making an accurate economic assessment of the proposed designs of the *PMSG* and the power electronics (*PE*) associated with the design according to the input variables of each of the specific proposed technologies. The objective of this thesis is to work on the preparation of models for generation economic evaluation, the development for component-wise cost data, estimation of maintenance cost for the proposed drivetrain, taking into account distance to shore and power transmission, the analysis of parameter sensitivity and the comparative analysis of all the prototypes for the drivetrain and extension to an offshore wind project. We shall determine the levelized cost of energy (*LCOE*) for various values of the variables of the component-wise cost data. This work addresses the wind probabilistic characterization of a location from experimental wind data, the application of that wind characterization for the calculation of the expected annual energy generation of a single wind turbine (*WT*) with the mechanical characteristics of the proposed technology, and the cost analysis of the conventional and new proposed designs. The evaluation of metrics of interest such as *LCOE* and the fixed costs of the system for different proposed designs are useful for the evaluation of the characteristics of the most profitable designs and the designs with better generation performance. We compute valuable information for the choice of actual parameters of the *PMSG* and the *PE*. In addition, we evaluate the computed numerical results and provide concluding remarks of the economic evaluation of the proposed technology.

Keywords: Permanent magnet synchronous generator, economic, levelized cost of energy.

1. Introduction

The objective of this project is to provide a careful economic assessment of the proposed technology of the project "*MW*-Scale Power-Electronic-Integrated Generator with Controlled *DC* Output" and a detailed and fair comparison to the Technical University of Denmark (*DTU*) direct-drive permanent magnet synchronous generator (*PMSG*) [1]. In essence, the aim of the project is to be able to provide an in-depth techno-economic assessment of the cost components, with special emphasis on the proposed *PMSG* and power electronics (*PE*), which are the two key aspects to meet the objective to create the most efficient, reliable, and compact wind energy conversion system (*WECS*). That techno-economic analysis requires the understanding in depth of the characteristics of our *PMSG* and *PE* designs and the evaluation of their associated costs. The economic evaluation includes the quantification of the cost elements of the salient characteristics of each proposed *PMSG* and *PE* configuration designs and their reliability assessment so as to determine their impacts on the associated fixed costs and the operations and maintenance (*O&M*) costs of wind production. This task entails the performance evaluation of the proposed design in terms of the expected annual energy generation (*AEG*) to quantify the energy production of each proposed design so as to perform a levelized cost of energy (*LCOE*) analysis on the proposed *PMSG* and *PE* designs.

2. Economic analysis of proposed *PMSG* and *PE* designs

The challenge in the performance of an economic assessment of a wind project lies in an acceptable approximation of the costs and the reliability of the proposed *PMSG* and associated *PE* subsystem. The key information required for economic evaluation are the fixed costs of the *PMSG*, the fixed costs of the associated *PE* subsystem, the fixed costs of the paired system composed by the *PMSG* and *PE*, the fixed costs of all the components of a *WT*, the *O&M* costs per year of a *WT*, and the expected *AEG*.

Given the variables above, and taking into consideration an static parameter that annualizes the fixed costs to produce a yearly uniform cash-flow set over the lifespan of the wind project, i.e. the capital recovery factor (*c.r.f.)*; it is possible to estimate a well-known variable of merit interest: the *LCOE*. We assume a 20-year lifespan for this project, which is the average time for which the *WT* is repairable since it was installed.

3. Numerical results

We show plots of computed numerical results of variables of merit interest for every proposed design and show the *O&M* costs results for the conventional and proposed designs. The plots of the numerical results are computed by using the given data of multiple *PMSG* designs and *PE* designs.

Generating performance and *LCOE* are represented as a function of the cost of the *PMSG,* the costs of the *PE,* cost density of the proposed system, parameters like the synchronous reactance and the rotor mechanical speed at MPPT.

4. Analysis of the numerical results

We provide important insights of the values that work better for the most profitable proposed technology taking into consideration the provided numerical results. We represent the range of the values of the parameters of all the proposed designs. Finally, we provide the characteristics of the most economic design.

5. Concluding remarks

We assembled the methods used for these tasks to construct a systematic approach to perform the economic assessment of a wind project, in general, and that of as wind turbine, in particular. The results of the assessment allow us to obtain valuable insights into the various aspects of the design of the proposed technology. Specifically, we observed that for the most economically efficient results, the *PMSG* and *PE* design with the lowest fixed costs need not necessarily lead to the lowest *LCOE* values. There are trade-offs between the fixed costs of the proposed technology and the generation performance costs, whose impacts must be explicitly considered to determine the most economically efficient design. These trade-offs are observable from the computations of the approach we proposed for the economic assessment. Thus, our proposed economic assessment approach is a contribution to the economic analysis and evaluation of offshore wind projects as well as proposed *PMSG* and *PE* designs. In particular, the computationally efficient techniques make possible the assessment of a wide variety of sensitivity cases for the different design parameter values. Indeed, this capability allows the preparation of responses to a broad range of *what if* cases. These capabilities are of great usefulness in the selection of the robust solution of the design parameters of the most appropriate *PMSG* and *PE* designs for any set of specified requirements.

We summarize the results of the comparative analysis of the current proposed *PMSG* and *PE* designs and the *DTU* system [1]. Due to the lack of data on the fixed and variable costs of many elements of the design and the use of available data on existing designs as a place holder for the lacking data, the results to date fail to appropriately capture the economic impacts of the improvements in the proposed design. As such, it is best to view our economic analysis results as still tentative.

6. References

[1] L. Sethuraman, M. Maness and K. Dykes, "Optimized Generator Designs for the *DTU* 10-*MW* Offshore Wind Turbine using GeneratorSE," 35*th Wind Energy Symposium*, Jan. 2017.

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1 INTRODUCTION

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1.1 Motivation for a new *PMSG* and *PE*

Doubly-fed induction generators (*DFIG*s) is the predominant wind energy conversion system (*WECS*) in the market due to the reduced *PE* requirements. The *PMSG* system requires a fully-rated power converter, while *DFIG* is typically designed to handle one-third of the system rated power. That *PE* requirement has caused *PMSG* to be dismissed as an option, despite its higher power density, increased efficiency, improved reliability, and reduced maintenance compared to a *DFIG* system.

Recently, the U.S. Department of Energy (*DOE*) announced the selection of the New York State Energy Research and Development Authority (*NYSERDA*) to administer an *$* 18.5 million offshore wind research and development (*R&D*) consortium. The consortium brings together industry, academia, government, and other stakeholders to advance offshore wind plant technologies, develop innovative methods for wind resource and site characterization, and develop advanced technology solutions for the installation, operation, maintenance, and supply chain.

The proposed technology innovations directly contribute to further the *DOE*´s goals to develop improvements of offshore wind technologies with the focus on the *WECS* design for enhanced efficiency, cost-effectiveness, and reliability of the mechanical-to-electrical energy conversion and the associated *PE* innovations.

1.2 The Scope and Nature of the Economic Analysis

The cost-sensitivity information will provide us with an in-depth understanding of the cost causation impacts of the various design parameter choices and provide insights into their nature to inform decisions in the improvements in the designs for the best possible economic performance.

The economic analysis of this report did not consider policy incentives, the cost of building new transmission lines and the impacts of underlying economic conditions. We are not evaluating the capital recovery factor (*c.r.f.*), as we remain with *DTU* paper´s *c.r.f.*, which has a 10.8% value [1], in order to make a comparison of our results with those in the *DTU* literature. Two key aspects in the calculation of the cost elements are that the power level of the *WT* is 10 *MW* and that the operation of this large-size turbine is situated in an offshore setting. Since our project is focused on the economic assessment of a new proposed direct-drive *PMSG*, we assume that the balance of system (*BOS*) costs are constant for every proposed design. We have to mention that changing the design of the *PMSG* and *PE* may affect the costs of the other components but, we did not look for a method to estimate the costs of any of the rest of the components of the *WT* in terms of the characteristics of the new proposed *PMSG* and *PE* because we are focused on the *PMSG* and *PE* that constitutes the innovation in the new design. Then, we leave the costs for the non-*PMSG*/non-*PE* components the same so as to compare to the fixed costs from the literature. We assume that the material and preparation cost per kg of each of the elements of the *PMSG* is constant and that the structural mass of the *PMSG* remains unchanged too. Regarding the *O&M* costs calculation, we are following the same calculation methodology as the *DTU* paper [1] so as to make a considerable comparison between costs. We assume that labor costs and equipment costs remain unchanged due to the lack of information about input variables and the fact that the computational tool can only calculate those costs for a wind farm with multiple *WT*s and not a single *WT*. We assume that the availability of the *WT* is equal to 1 (100 %) until we have new information about its value.

We evaluate the impact of the fixed costs of the *PMSG* and *PE* on energy generation performance and cost density of the component, as well as the impact of reliability parameters like failure rate of a component and availability of the system on the *O&M* costs and the expected *AEG*. For the calculation of *O&M* costs, we will evaluate different maintenance strategies for the maximum possible operation time of the *WT* in an extension to an offshore wind project.

1.3 Overview of the Report

The report consists of five chapters and four Appendices. We provide a detailed description of the various parameters required and the evaluation of the various components for the *LCOE* determination. In addition, we perform the analysis of cost elements and the generation output performance of each of the proposed candidate *PMSG* and *PE* designs. We discuss from the economic point of view the selection of the *WT* design parameters, such as the mechanical rotor speed at the maximum power point tracking (*MPPT*) and the synchronous reactance value of the proposed *PMSG* design. We provide a detailed comparative analysis of the proposed *PMSG*/*PE* design results with those of the *DTU* report [1]. As our analysis is performed before the many additional design variations are considered in the tasks yet to be completed, the results are still tentative, but they do provide a basis for the assessment of the future designs in the completion of the work on the "*MW*-Scale Power-Electronic-Integrated Generator with Controlled *DC* Output".

Appendix A and Appendix B collects all the acronyms and notation needed for the understanding of the report. Appendix C entails the information for the proper wind probabilistic characterization from a given empirical data. Appendix D provides a detailed explanation of each of the possible maintenance strategies to determine the operations and maintenance (*O&M*) costs and the criteria for the election of the maintenance strategy for the report. In addition, Appendix D includes detailed information of maintenance categories, the fault type classes associated with each maintenance category and the repair costs associated with each fault type class.

2 ECONOMIC ANALYSIS OF PROPOSED *PMSG* AND *PE* DESIGNS

The challenge in the performance of an economic assessment of a wind project lies in an acceptable approximation of the costs and the reliability of the proposed *PMSG* and associated *PE* subsystem. The key information required for economic evaluation are the fixed costs of the *PMSG*, the fixed costs of the associated *PE* subsystem, the fixed costs of the paired system composed by the *PMSG* and *PE*, the fixed costs of all the components of a *WT*, the *O&M* costs per year of a *WT*, and the expected *AEG*.

Given the variables above, and taking into consideration an static parameter that annualizes the fixed costs to produce a yearly uniform cash-flow set over the lifespan of the wind project, i.e. the *c.r.f.*; it is possible to estimate a well-known variable of merit interest: the *LCOE*. We assume a 20-year lifespan for this project, which is the average time for which the *WT* is repairable since it was installed.

The *LCOE* is a measure of the constant annual cost of electricity generation in current dollars for the generation over its specified lifetime. It is used to compare different methods of electricity generation on a consistent basis. The *LCOE* is the average costs in current dollars of a unit of electricity generated that covers the total investment costs and the variable *O&M* costs of the generated energy over the specified financial life of the generation source. We devote this chapter to describe the methodology used for the preparation of the information required for the economic evaluation and the calculation of the expected *AEG* with the data provided from the *PMSG* design, the *PE* design and the reliability assessment. We apply the same methodology for each proposed design in order to make the corresponding economic and generation performance determination and to allow the meaningful comparison among all the candidate *PMSG*/*PE* designs proposed. We make use of the methodology in the development of the numerical results in the next chapter.

2.1 Wind Probabilistic Characterization

For the probabilistic characterization of wind distributions, wind speeds play a crucial role in estimating variables like the expected *AEG*.

There are two possible ways to determine the wind characteristics at a certain location. We could have constructed the wind probabilistic characterization using a Weibull/Rayleigh wind, which is a good closed form approximation of wind parametric distribution, but we characterize the wind speeds with empirical data from a broad set of measurements. Then, we use that empirical data to construct a wind speed histogram that represent a non-parametric wind distribution. We have enough knowledge to execute the Weibull/Rayleigh wind characterization technique, but we decided to use experimental data from Buoy 44,028 [2] instead. The experimental data extracted is represented in Figure 1.

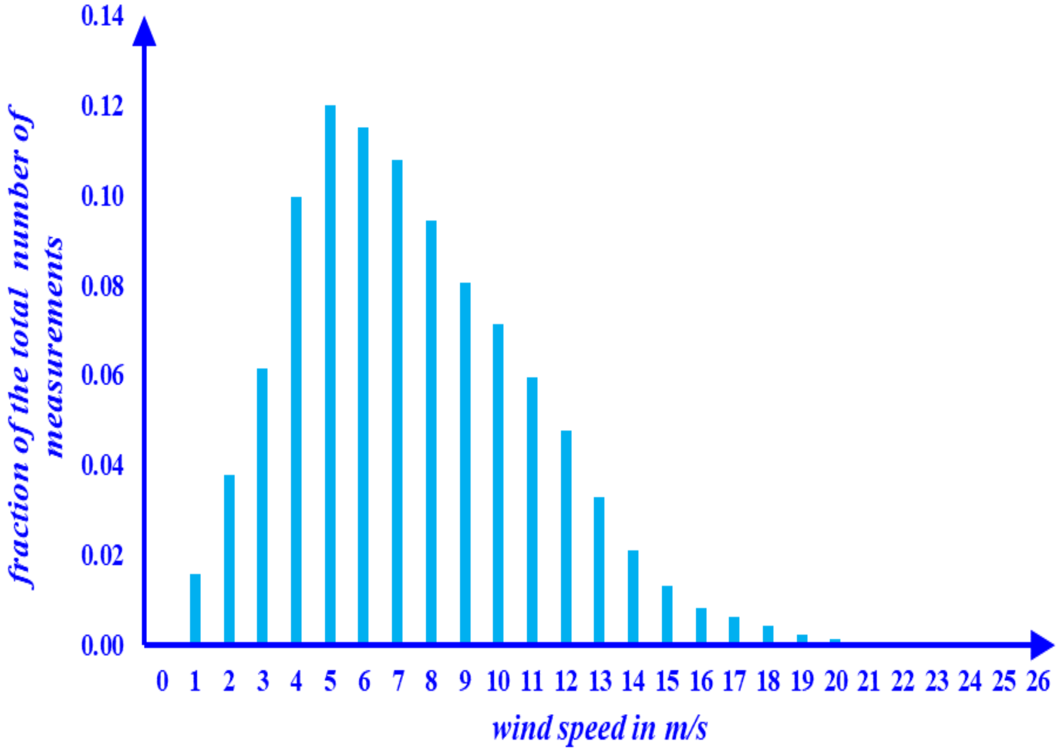

Figure 1: *Buoy* 44,028´*s histogram of fractions of the total number of measurements that fall in the winds speed buckets*

In the Appendix C, there is a wider explanation of wind data analysis. The histogram is constructed by placing each hourly measured value in the appropriate “bucket” of wind speed values. This histogram uses 22 “buckets” of integer wind speed values to determine the fraction of the total number of measurements according to the wind speed bucket.

Table 1: Required values to define $f_v(v)$

v_i	β_i
0	0.00E+00
1	1.57E-02
2	3.78E-02
3	6.14E-02
4	9.95E-02
5	1.20E-01
6	1.15E-01
7	1.08E-01
8	9.43E-02
9	8.05E-02
10	7.14E-02
11	5.95E-02
12	4.76E-02
13	3.27E-02
14	2.08E-02
15	1.30E-02
16	8.11E-03
17	6.22E-03
18	4.05E-03
19	2.16E-03
20	1.08E-03
21	0.00E+00
22	0.00E+00
23	0.00E+00
24	0.00E+00
25	0.00E+00

We approximate that between any two buckets that we have, there is a linear continuous function. Then, we approximate the probability density function as a continuous function. After that, we must discretize the function, so the area of the probability density function (*p.d.f.*) is equal to 1, as every *p.d.f.* By following the procedure below, we make use of an increasingly finer resolution grid. This assumption enables us to go from 22 "buckets" of integer values (Figure 1) to a continuously-valued *p.d.f.* as it is shown in Figure 2.

$$f_v(v) = \begin{cases} f_{1,v}(v), & 0 \le v < 1 \\ f_{2,v}(v), & 1 \le v < 2 \\ & \vdots \\ & \vdots \\ f_{24,v}(v), & 23 \le v < 24 \\ f_{25,v}(v), & 24 \le v \le 25 \end{cases} \tag{1}$$

To define $f_v(v)$, we determine the linear functions $f_{i,v}{}'(v)$ between integer values as it is shown in equation 13.

$$f_{i,v}{}'(v) = (v - v_{i-1})(\beta_i - \beta_{i-1}) + \beta_{i-1} \tag{2}$$

$$f_v{}'(v) = \begin{cases} f_{1,v}{}'(v), & 0 \le v < 1 \\ f_{2,v}{}'(v), & 1 \le v < 2 \\ & \vdots \\ f'_{i,v}(v), & i-1 \le v < i \\ & \vdots \\ f_{24,v}{}'(v), & 23 \le v < 24 \\ f_{25,v}{}'(v), & 24 \le v \le 25 \end{cases} \tag{3}$$

We add the factor u to the function, so the area of the probability density function (*p.d.f.*) is equal to 1.

$$u = \int_0^{25} f_v{}'(v)\, dv \tag{4}$$

$$f_v(v) = \frac{f_v{}'(v)}{u} \tag{5}$$

Now, we have the *p.d.f* properly defined. We illustrate $f_v(v)$ in Figure 2:

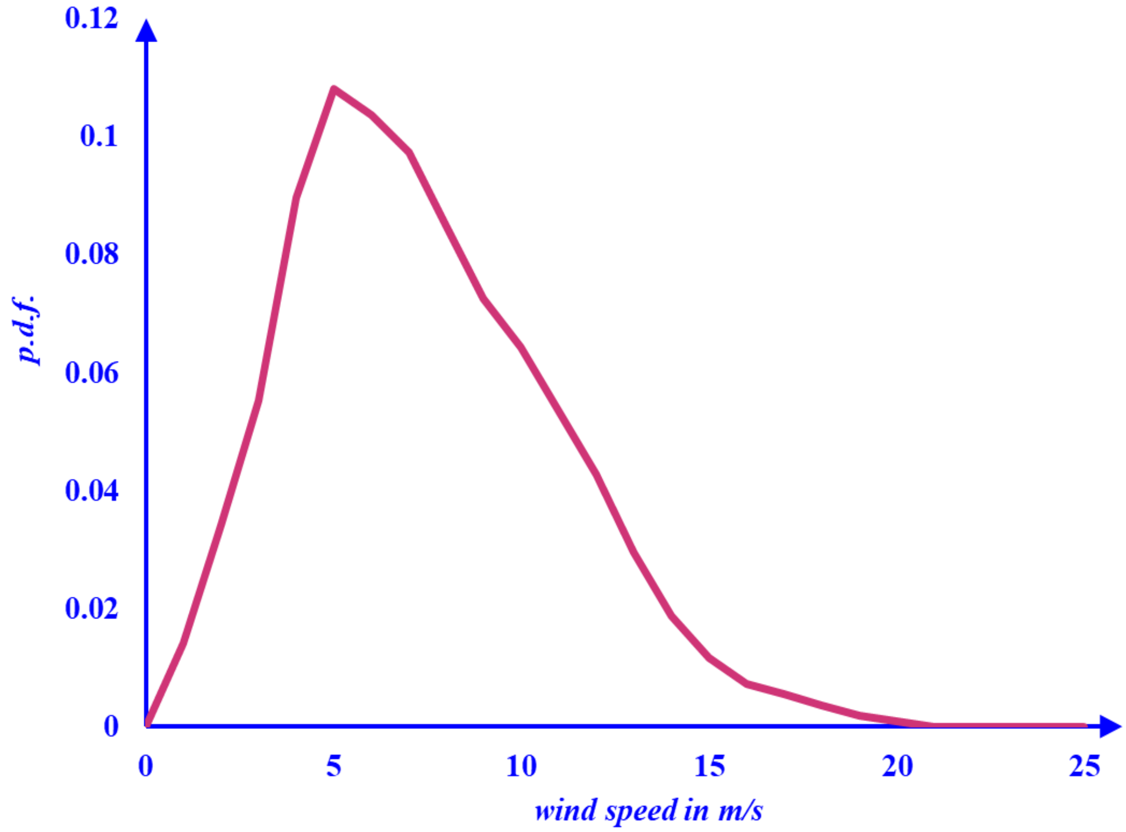

Figure 2: *Piece-wise continuous probability density as a function of wind speed*

We use the same *p.d.f.* $f_v(v)$ to calculate the expected *AEG* of each design in order to make a fair comparison between the generation performances of each of the proposed designs.

2.2 Expected Annual Energy Generation

AEG represents the expected energy produced by a single *WT* in a year. *AEG* is a crucial term for the *LCOE* calculation. The aim of this subchapter is to show a path for *AEG* calculation, considering the wind speed limitations of the generator (cut-in wind speed and furling wind speed), the mechanical characteristics and

DC output voltage limitations of our *PMSG* and *PE*, and the probabilistic wind characterization.

Wind speed is denoted by v. Cut-in wind speed is denoted by v_C and represents the minimum wind speed needed to start producing electricity. The *PMSG* system works with a *MPPT* system [3], which means that there is a limited speed range for the rotor mechanical speed, and consequently, a minimum rotor mechanical speed w_{MPPT}. Fixing the rotor mechanical speed leads to a sub-optimal electrical power extraction because the turbine no longer operates at the optimal tip speed ratio [4]. The wind speed according to the rotor at the optimal tip speed ratio λ_{opt} is denoted by v_{MPPT}. The rated wind speed is the minimum wind speed needed to activate the pitch control and generate the rated power of the *WT* P_R, the rated wind speed is denoted by v_R. The rotor mechanical speed at v_R is the rated rotor mechanical speed and it is denoted by w_R. The furling wind speed is the maximum wind speed for power generation, and it is denoted by v_F.

The characteristics for the wind speed limitations for our *PMSG* are shown in Table 1. The *p.u.* values are given dividing the values of the parameters in *m/s* or *r.p.m.* by the parameter base values which are the rated values (v_R for wind speeds and w_R for rotor mechanical speeds). The characteristics of the *PMSG* in *p.u.* are also given in Table 2. The methodology used for the calculation of electrical power in terms of wind speed is segregating into 5 intervals as it is represented in Table 3. Electrical power will be denoted by p_{elec} from now on.

In the interval *a*, the turbine does not rotate because the speed is inadequate to produce a torque that can overcome the turbine friction torque. In the intervals *b* and *c*, the power converter controls the amount of output mechanical power from the *WT*; at each wind speed the output mechanical power depends on the rotor mechanical

Table 2: Characteristics of a design of the *PMSG* and *PE* in terms of wind speeds, rotor mechanical speeds, rated power and radius of the three-blade turbine in m/s *r.p.m.* and *p.u.*

parameter	*value*
v_C	3 *m/s*
v_{MPPT}	6.6 *m/s*
v_R	12 *m/s*
v_F	25 *m/s*
w_R	9.6 *r.p.m.*
w_{MPPT}	5.28 *r.m.p.*
P_R	10,000 *kW*
r	76.8 *m*
$v_C^{p.u}$	0.25 *p.u.*
$v_{MPPT}^{p.u}$	0.55 *p.u.*
$v_R^{p.u}$	1 *p.u.*
$v_F^{p.u}$	2.08 *p.u.*
$w_R^{p.u}$	1 *p.u.*
$w_{MPPT}^{p.u}$	0.55 *p.u.*

Table 3: Wind intervals for *WT* operations

possible wind speed interval	*interval name*
$0 \le v < v_C$	a
$v_C \le v < v_{MPPT}$	b
$v_{MPPT} \le v < v_R$	c
$v_R \le v \le v_F$	d
$v > v_F$	e

speed w and the power coefficient κ, which is the ratio between the output mechanical power of the turbine and the available power from the wind speeds as it is represented in equation 6:

$$\kappa = \frac{p_{mec}}{\frac{1}{2}\rho\, a\, v^3}\ , \tag{6}$$

where p_{mec} is the mechanical power produced by the generator, ρ is the air density in *kg/m*^{3}, a is the turbine swept area of the three-blade system in *m*^{2}, and v is the wind speed in *m/s*. The tip speed ratio λ is the ratio between the speed at the tip of the blade and the wind speed:

$$\lambda = \frac{2\,\pi\, w\, r}{60\, v}\ , \tag{7}$$

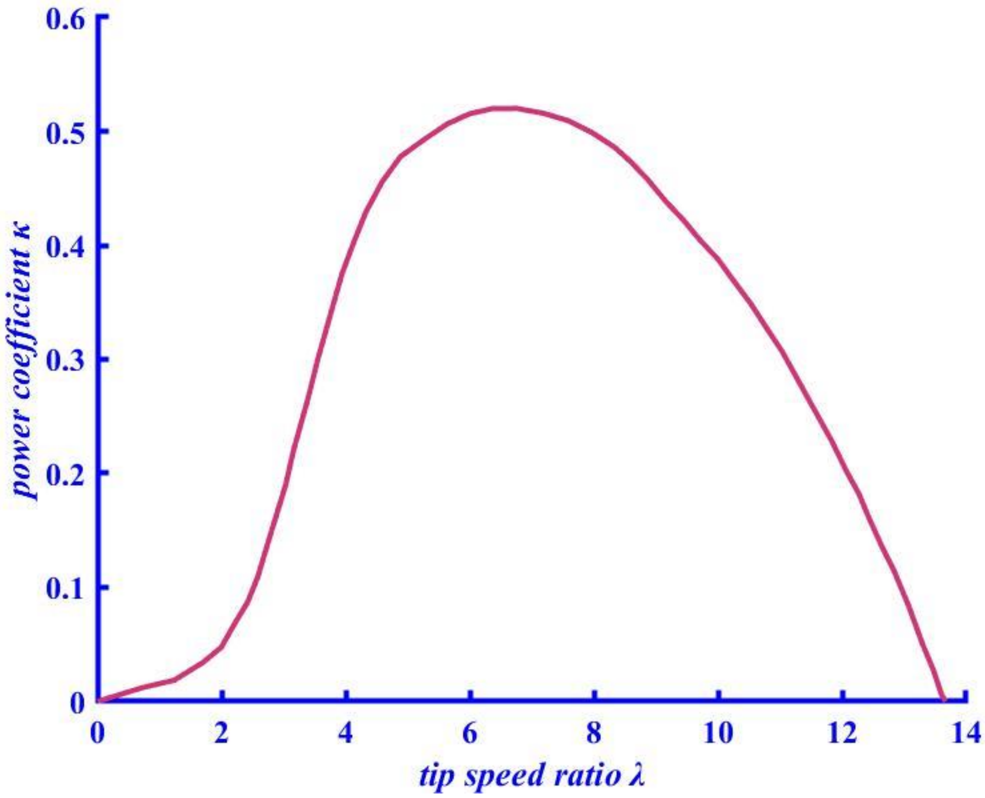

Figure 3: *A plot of* κ *vs.* λ *for a three-blade turbine*

where w is the rotor mechanical speed in *r.p.m.*, r is the radius of the three-blade turbine in *m*, and v is the wind speed in *m/s*. It is illustrated in Figure 3 an example of a κ *vs*. λ plot.

The difference between the interval b and the interval c is that in the interval b, the generator must rotate at a minimum speed to prevent and over voltage on the rectifier, and it results in a sub-optimal tip speed ratio λ [4]. However, in the interval c the rotor operates at an optimal tip speed ratio for every w. In the interval *d*, pitch control is activated, the rotor works at the rotor mechanical speed of w_R and the mechanical power extracted is the rated power. In the interval e, the turbine is shut down due to safety reasons.

With all the considerations mentioned above, we can plot the mechanical power output p_{mec} of the entire system, but our aim is to plot the electrical power output p_{elec}. Then, p_{elec} is given by:

$$p_{elec} = \eta_{PMSG}\, \eta_{PE}\, p_{mec} \tag{8}$$

The efficiency of a *PMSG* is approximately in the interval [92, 97] % and the efficiency of the *PE* is in the interval [87, 99] %. So, the impact of the efficiency is predominant compared to that of a design with a gearbox in the turbine, whose losses must lower considerably the overall efficiency of the turbine. The efficiency associated with a specific *PMSG* design varies with wind speed, as it is shown in Figure 4. The efficiency associated with a specific *PE* design varies with wind speed, as it is shown in Figure 5. The efficiencies in the interval *d* are the efficiencies obtained at wind speed v_R as it is the wind speed that corresponds with the rotor working at rated rotor mechanical speed w_R, i.e., in the interval *d*, the rotor speed is the constant speed w_R.

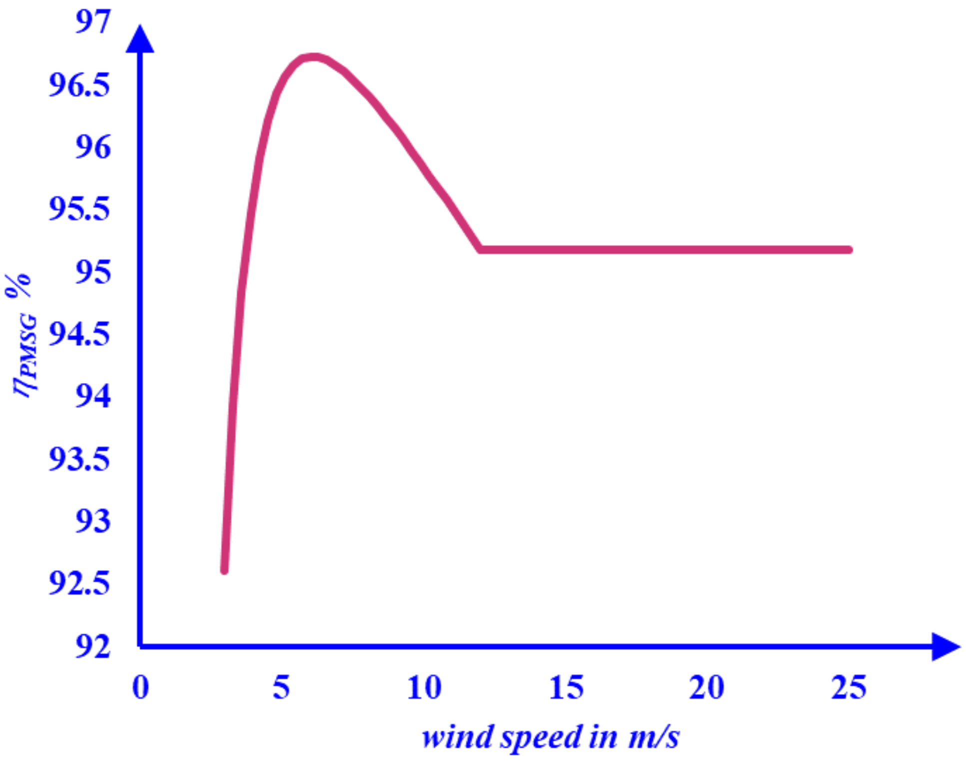

Figure 4: *Efficiency of an example of a PMSG design as a function of wind speed*

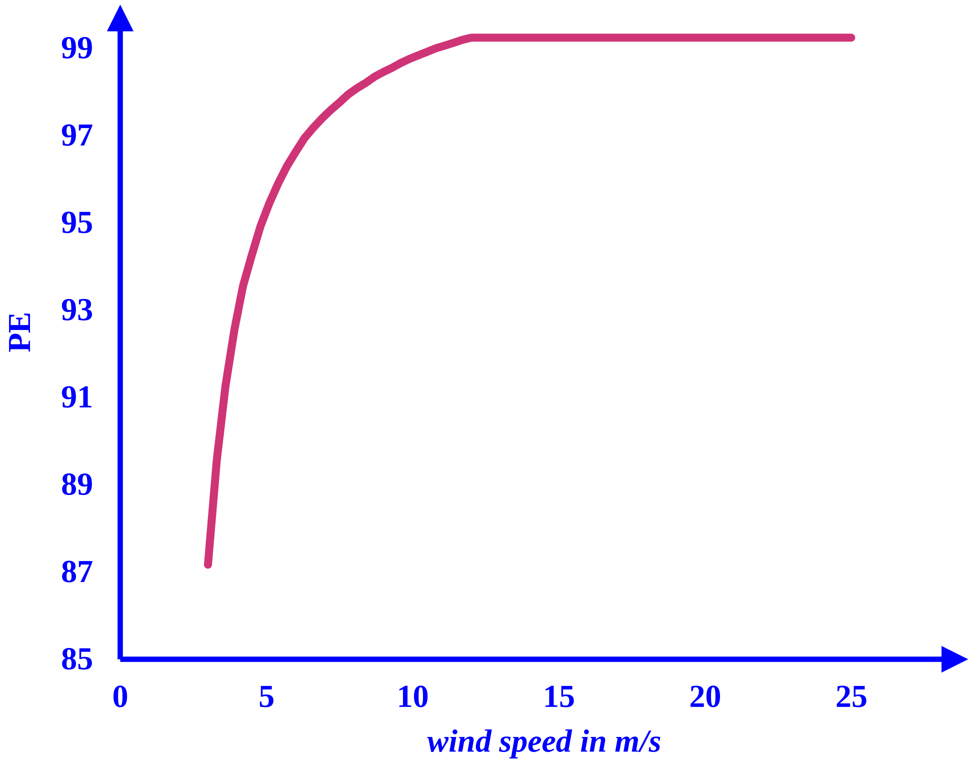

Figure 5: *Efficiency of an example of a PE design as a function of wind speed*

Taking into consideration the efficiencies of the system and the operation of the *WT* in each of the intervals previously mentioned, we calculate the output electric power as follows:

a

$$p_{elec}\big|_{0 \le v^{p.u} < v_C^{p.u}} = 0 \tag{9}$$

b

$$p_{elec}\big|_{v_C^{p.u} \le v^{p.u} < v_{MPPT}^{p.u}} = P_R\ \eta_{PMSG}\ \eta_{PE}\ \frac{\kappa}{\kappa_{max}}\ (v^{p.u})^3 \tag{10}$$

c

$$p_{elec}\ \big|_{v_{MPPT}^{p.u} \le v^{p.u} < v_R^{p.u}} = P_R\ \eta_{PMSG}\ \eta_{PE}\ (v^{p.u})^3 \tag{11}$$

d $$p_{elec}\,|_{v_R^{p.u} \le v^{p.u} \le v_F^{p.u}} = P_R\;\eta_{PMSG}\;\eta_{PE} \tag{12}$$

e $$p_{elec}\,|_{v_F^{p.u} < v^{p.u}} = 0 \tag{13}$$

where κ is the operational power coefficient and κ_{max} is the maximum power coefficient, which is the power coefficient at the optimal tip speed ratio. In Figure 6, we illustrate an example the electrical power output of a proposed design:

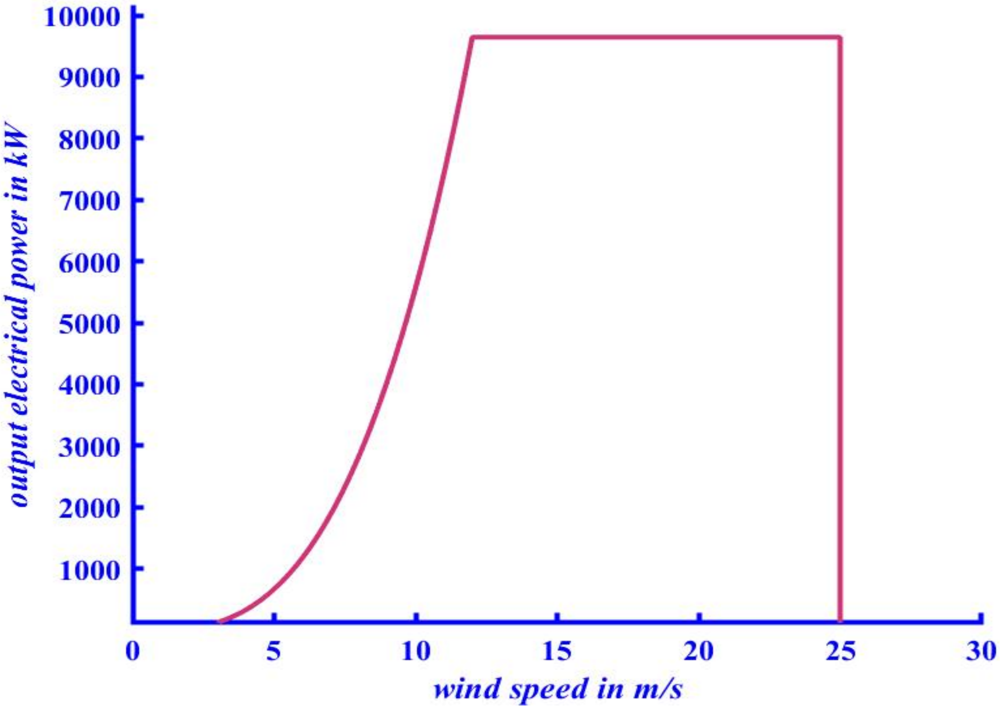

Figure 6: *Example of the plot of* p_{elec} *as a function of* v *for a specific design of the PMSG and PE*

With all the information above we can create the electric power function $p_{elec}(v)$. The availability α parameter is a main risk-influencing factor to mitigate risk for potential investors as it directly determines the obtainable income. It is multiplied by 8760, to represent the number of hours per year in that the *WT* is operational. The determination of the availability of our proposed technology is a variable that is in the milestones of the reliability assessment , so, as we mentioned in the subchapter 1.2 of the project, we assume it is 1 until we have new information about its value. Thus, the expected *AEG*, denoted by ε, is calculated as the contribution of wind speed probability density function to the output electric power function as it is shown in the equation 14:

$$\varepsilon = 8760\ \alpha \int_{0}^{\infty} f_v(v)\ p_{elec}(v)\ dv \tag{14}$$

as the *WT* doesn´t produce electrical power for wind speed values below the cut-in wind speed and above the furling wind speed, we simplify the equation by using equation 15 instead:

$$\varepsilon = 8760\ \alpha \int_{v_C}^{v_F} f_v(v)\ p_{elec}(v)\ dv \tag{15}$$

We restate equation 16 with the consideration of each of the wind generation intervals for electric power output:

$$\begin{aligned}\varepsilon = 8760\ \alpha\ P_R \Bigg[\int_{v_C}^{v_{MPPT}} & f_v(v)\ \eta_{PMSG}(v)\eta_{PE}(v)\frac{\kappa(v)}{\kappa_{max}}\left(\frac{v}{v_R}\right)^3 dv \\ & + \int_{v_{MPPT}}^{v_R} f_v(v)\ \eta_{PMSG}(v)\eta_{PE}(v)\left(\frac{v}{v_R}\right)^3\ dv \\ & + \int_{v_R}^{v_F} f_v(v)\ \eta_{PMSG}(v)\ \eta_{PE}(v)\ \ dv\Bigg].\end{aligned} \tag{16}$$

To end up this subchapter, before moving on to the estimation of the cost elements, Figure 7 represents the flowchart to calculate the expected *AEG*. We notice that $f_v(v)$ is a piece-wise continuous function with independent functions for each of the wind speed intervals as it is shown in equation 17:

$$f_v(v) = \begin{cases} f_{1,v}(v), & 0 \le v < 1 \\ f_{2,v}(v), & 1 \le v < 2 \\ & \vdots \\ f_{i,v}(v), & i-1 \le v < i \\ & \vdots \\ f_{24,v}(v), & 23 \le v < 24 \\ f_{25,v}(v), & 24 \le v \le 25 \end{cases} \tag{17}$$

To simplify the flowchart in Figure 7, we determine the equations w, x, y and z.

$$w = \int_{i-1}^{v_{MPPT}} f_{i,v}(v)\eta(v)\frac{\kappa(v)}{\kappa_{max}}\left(\frac{v}{v_R}\right)^3 dv + \int_{v_{MPPT}}^{i} f_{i,v}(v)\eta(v)\left(\frac{v}{v_R}\right)^3 dv \tag{18}$$

$$x = \int_{i-1}^{i} f_{i,v}(v)\eta(v)\frac{\kappa(v)}{\kappa_{max}}\left(\frac{v}{v_R}\right)^3 dv \tag{19}$$

$$y = \int_{i-1}^{i} f_{i,v}(v)\eta(v)\left(\frac{v}{v_R}\right)^3 dv \tag{20}$$

$$z = \int_{i-1}^{i} f_{i,v}(v)\eta(v)\, dv \tag{21}$$

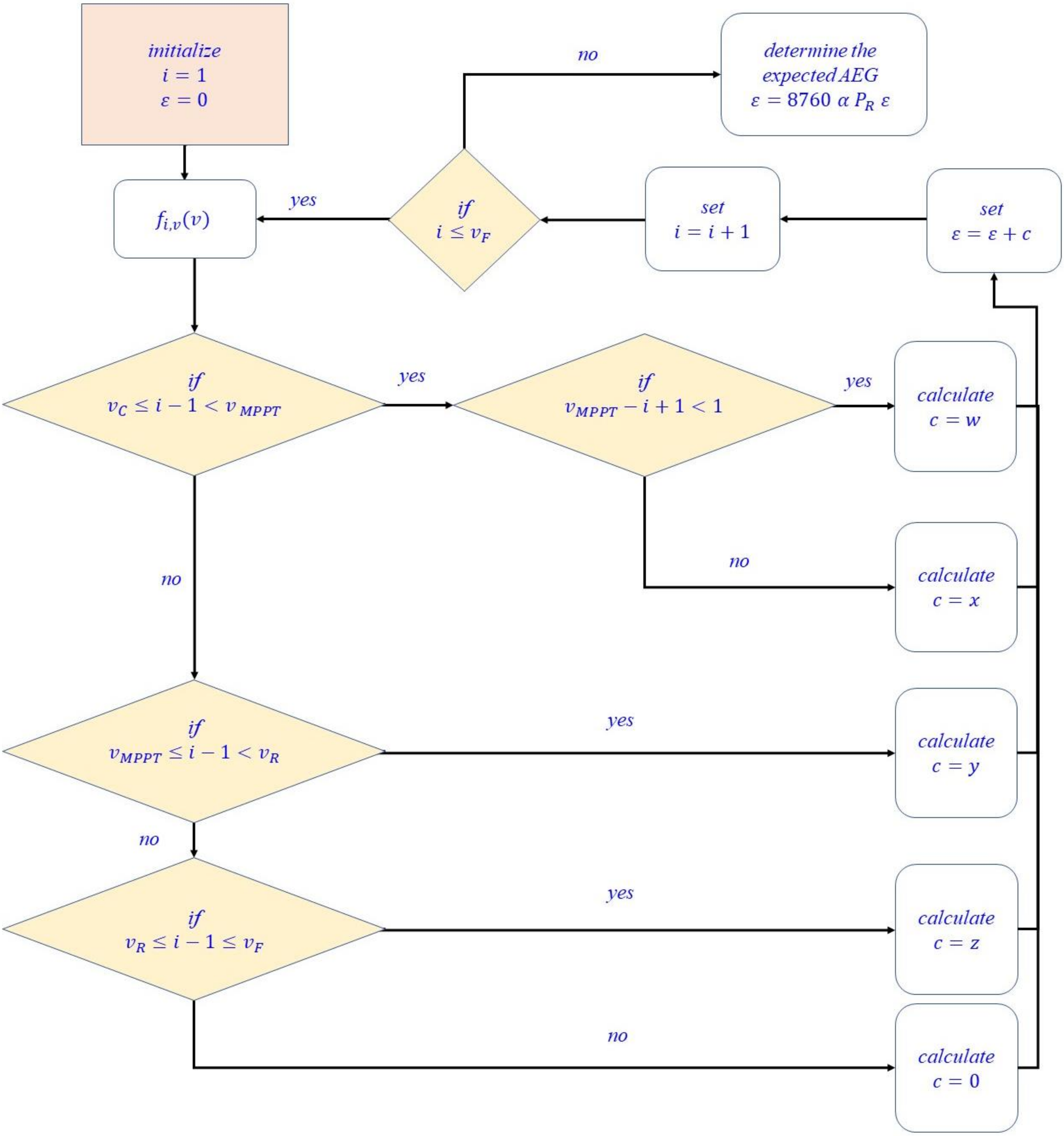

Figure 7: *Flowchart for the calculation of the expected AEG* ε

2.3 The Data for the Cost Elements

The principal cost elements of an offshore *WT* are the fixed costs and the *O&M* costs. The fixed costs are the investment costs required to make possible the commercial operation of a *WT*. Those costs that constitute the cost components of the *WT* and the balance of system (*BOS*) costs are the two types of fixed costs. The costs that include the turbine installation, the site preparation, installation of underground utilities, access and buildings for *O&M* costs are the *BOS* costs. The fixed costs of all non-*PMSG*/non-*PE* components are shown in Table 4.

Table 4: Fixed costs of all non-*PMSG*/non-*PE* components

turbine component	*cost* in *$/kW*
blades (3)	91.4
hub	45.7
pitch mechanism and bearings	40.3
main bearings	34.3
spinner, nose cone	2.9
mechanical brake, high speed coupling	2.8
main shaft	148.5
yaw drive and bearing	22.5
main frame	118.8
electrical connections	75.9
hydraulic cooling system	31.3
nacelle cover	6.3
control, safety system and condition monitoring	11.2
tower	190.6
misc.	10
total	832.5

This results in *$* 8,325,000 for the fixed costs of all non-*PMSG*/non-*PE* components The *BOS* costs are estimated to be 1,640 *$/kW*, that supposes a 16,400 *k$* investment for a 10-*MW WT*. The cost breakdown below and the *BOS* costs are values taken from the *DTU* paper [1]. The *PMSG* costs estimation are computed using Table 5:

Table 5: Costs of the *PMSG*

element	*mass in kg*	*material and preparation cost in $/kg*	*cost in $*
PM	m_{PM}	c_{PM}	$m_{PM}\ c_{PM}$
iron	m_{Fe}	c_{Fe}	$m_{Fe}\ c_{Fe}$
copper	m_{Cu}	c_{Cu}	$m_{Cu}\ c_{Cu}$
structural steel	m_s	c_s	$m_s\ c_s$

where m represents the mass of each of the elements of the *PMSG* and c represents the material and preparation costs per kg of each of the elements of the *PMSG*. We use the identical values for the costs per kg as those in the *DTU* paper [1], represented in Table 6. Furthermore, we use the same structural iron mass for each generator design in this evaluation as we mentioned in the 1.2 subchapter. The key elements that change from one design to another are the mass of the permanent magnet m_{PM}, the mass of the iron m_{Fe} and the mass of the copper m_{Cu}.

Table 6: Material and preparation costs per kg used in each of the *PMSG* designs

material and preparation cost in $/kg	*value in $/kg*
c_{PM}	95.000
c_{Fe}	0.556
c_{Cu}	4.786
c_s	0.501

We use the data presented in Table 5 and Table 6 to calculate the fixed costs $c_{f,PMSG}$ of a *PMSG* design using the relation:

$$c_{f,PMSG} = c_{PM}\, m_{PM} + c_{Fe}\, m_{Fe} + c_{Cu}\, m_{Cu} + \ c_s\, m_s \ \$ \tag{22}$$

The calculation of the costs of the *PE* requires a list of the number of active rectifiers n_a and the number of passive rectifiers n_p in the *PE* design. The *DTU* report uses a single active rectifier. The total cost of power electronics in the *DTU* generator is 213.7 *$/kW*. The *NREL* design for a 5-*MW WT* mentions the cost of power electronics to be 200 *$/kW*, the number from the *DTU* seems like a reasonable number. Moreover, since we are mostly concerned about the comparison of *LCOE* with the conventional design, we can assign a value of *B* as the cost in dollars per *kW* for an active rectifier in *DTU* design. We assume that the passive rectifier takes one-fifth of the active rectifier [5], we have 0.2 *B* as the cost of the passive rectifier. The *PE* costs estimation are computed following the Table 7:

Table 7: Costs of the active rectifier and the passive rectifier

element	*rating* in *kW*	*per unit cost in $/kW*	*cost in $*
active rectifier	x_a	B	$x_a\ B$
element	*rating* in *kVA*	*per unit cost in $/kVA*	*cost in $*
passive rectifier	x_p	$0.2\ B$	$x_p\ 0.2\ B$

where x represents the rating in kW or kVA of the rectifier and B is the cost of an active rectifier (baseline/conventional design) in *$/kW*. We use Table 7 to calculate the fixed costs of the *PE* design $c_{f,PE}$, by computing equation 23:

$$c_{f,PE} = n_a\ x_a\ B + n_p\ x_p\ 0.2\ B\ \ \$ \tag{23}$$

Since the scope of our study is focused on improving the deployment of the improvements of the *PE* and the *PMSG* designs of the *WT*, we use the *DTU WT* as the reference design with respect to which we compare the costs of the proposed design.

The *O&M* costs are the costs of repair and transportation per year with the purpose of obtaining the most efficient availability of the *WT*. There are trade-offs between the *O&M* costs of the *WT* and the availability of the wind farm because, the goal to ensure the highest availability requires higher *O&M* costs and may not produce the optimal strategy for profits. We use the software *ECN* Tool v4.4 [6] to compute the *O&M* costs.

There are three distinct categories of *O&M* costs:

- material costs: referred to the costs of repair or replacement of certain components of the offshore wind farm per year;
- labor costs: depend principally on the crew size and salaries per year;

- equipment costs: costs of transportation of the crew and the replacement equipment based on the fuel required for such activities each year.

There are three types of issues with the sustainability of the wind farm:

- corrective *WT*: repair or replacement of the components of the *WT*;
- corrective balance of plant (*BOP*): adjustment of certain mismatches in the transformer, the foundation, and the cables within the farm;
- preventive: periodic farm inspections to make appropriate adjustments to reduce likelihood of equipment outages.

There are multiple input variables involved with the calculation of these three types of costs mentioned above and we don´t have information on most of the input variables of the labor costs and equipment costs. We can calculate the material costs of our proposed design as the input parameters are the failure rates of the components and the repair costs, which are two input variables that we have information about. But we don´t know the input variables of the labor costs; the crew size, the work schedule and the no. of hours needed per repair. We also don´t have knowledge about the input variables of the equipment costs, as we don´t have information about the crew size, the preventive wind limits, the fuel costs and if a jack up barge is needed for the repair of some of the components. For the scope of work of our project (a single *WT*), we can´t compute the labor costs and the equipment costs under a specific maintenance strategy, so we assume that the only costs that change with the reliability information given by the reliability assessment are the material costs, as we mentioned in the 1.2 subchapter.

Given this situation, we displayed in Table 8 an ECN Tool cost breakdown of an offshore wind farm with 100 5-*MW WT*s [7]. The chosen maintenance strategy is step 1 + variation *b*. The different maintenance strategies and the reason why we chose this one is widely explained in Appendix D.

Table 8: Cost breakdown of a 100 5-*MW WT*s farm with maintenance strategy step 1 + variation *b*

type of costs	*issues with the sustainability*	*cost* in *k$/yr*
material costs	*corrective WT*	16,684
	corrective BOP	58
	preventive	1,574
labor costs	*corrective WT*	3,457
	corrective BOP	4
	preventive	1,911
costs of equipment	*corrective WT*	14,812
	corrective BOP	1,463
	preventive	1,565
total	*corrective WT*	34,953
	corrective BOP	1,525
	preventive	5,050
	total O&M costs	41,528

From Table 8 we have the total *O&M* costs of a 100 5-*MW WT*s farm and our aim is to evaluate the *O&M* costs of a single 5-*MW WT*, denoted by $c_{O\&M}^{5-MW}$; so, we divide the total *O&M* costs by 100, that results in *$*415,280 per year for a single turbine. We assume that the corrective *BOP* and preventive costs of the material costs remain unchanged as those costs are not design dependent. These assumptions leave us with the calculation of the corrective *WT*´s material costs, which take into account: the failure rate of each component λ_c; the probability of occurrence of each of the maintenance categories π_γ; the maintenance category (γ) and the fault type class (ξ). The details are explained in Appendix D. We use equation 24 to calculate the annual corrective material costs of a component of the *WT* mc_c:

$$mc_c = \lambda_c \sum_{i=1}^{f} \pi_\gamma(i) * c_\xi(i) \quad \$/yr \,, \tag{24}$$

where i takes values from 1 to k, k is the number of fault type classes that the component has, π_γ is the probability of occurrence of the maintenance category, and c_ξ corresponds to the cost of each of the fault type classes in *$/failure*. We use the word “preliminary” to note the components whose reliability information is given by the literature of the 5-*MW WT* [7]. We calculate the material costs of the preliminary components because we must replace their material costs with the material costs of the proposed technology. Just to clarify the way the corrective material costs of a component of the *WT* is calculated, we show an example of the necessary information from a component in Table 9 for the calculation represented in the equation above:

Table 9: Preliminary reliability information for corrective material costs of the gearbox [7]

component	λ_c	γ	π_γ	ξ
gearbox	0.5076	2	0.4500	ii
		5	0.4500	x
		6	0.1000	xiii

We denote mc_{GB}^{p} as the preliminary corrective material costs of the gearbox. 900; 90,000 and 180,000 are the costs associated with the fault type class ξ. The only components of interest are the gearbox, as our proposed design doesn´t have a gearbox; the generator, and the *PE*, as those are the components of our proposed design.

$$\begin{aligned} mc_{GB}^{p} &= 0.5076\ (0.45\ 900 + 0.45\ 90{,}000 + 0.1\ 180{,}000\ ) \\ &= 29{,}900.18\ \ \$/yr; \end{aligned}$$

These material costs are recalculated with our variables to replace the preliminary material costs. We show the material costs of the preliminary components in Table 10:

Table 10: Corrective material costs of the preliminary components of interest

component	mc^p *in $/yr*
gearbox	29,900.18
generator	22,041.96
PE	37,805.36

where mc^p represents the corrective material costs of a preliminary component. The information for the corrective material costs of the proposed *PMSG* and *PE* with a conventional design are shown in Tables 11 and 12. The material costs of the gearbox in our proposed design is 0 as we don´t use a gearbox in our design.

Table 11: Reliability information for corrective material costs of the proposed *PMSG* of the conventional design

component	λ_c	γ	π_γ	ξ
PMSG	0.076	2	0.9740	ii
		4	0.0260	vi
		6	0.0000	xii

Table 12: Reliability information for corrective material costs of the *PE* with the conventional design (1 active rectifier)

component	λ_c	γ	π_γ	ξ
PE	0.258	2	0.7424	ii
		4	0.2340	vi
		6	0.0236	xiv

The failure rates and the probabilities of occurrence from Table 10 and 11 are provided by the reliability working group and contrasted with a reliability of *WT*s paper [8]. We show the material costs of the proposed components in Table 13:

Table 13: Corrective material costs of the proposed components of interest for a conventional design (1 active rectifier)

component	*mc in $/yr*
PMSG	244.46
PE	11,085.78

Once we have the corrective material costs of the preliminary components and the proposed components, you only have to use equation 25:

$$c_{O\&M} = \frac{10}{5}\left(c_{O\&M}^{5-MW} + \sum_{i=1}^{k} mc_i - mc_i^p\right); \tag{25}$$

where k is the number of components whose reliability information change regarding the preliminary components, i takes values from 1 to k, $c_{O\&M}^{5-MW}$ are the *O&M* costs per year of a single 5-*MW WT* with the preliminary costs, mc are the corrective material costs per year of a proposed component and mc^p are the annual preliminary corrective material costs of a component. In our case, *k*=3 (gearbox=1, *PMSG*=2 and *PE*=3). We use the scaling factor $\frac{10}{5}$ as an assumption with the purpose of scaling the costs to a 10 *MW WT* project.

The reliability information for a proposed design with the *PMSG* and the *PE* composed by 1 active rectifier and 3 active rectifiers is still under analysis. The last update that we have is that the main difference between the conventional design and the next proposed design isn´t in the architecture but is in how the power processed affects the demagnetization curve of the permanent magnet. The analysis of how this affects the reliability of the *PMSG* is not trivial and we can´t have that finished before this report is published so we are assuming the same reliability information for the *PMSG* of the conventional design (Table 10). For the *PE* architecture, i.e. 1 active rectifier and 3 passive rectifiers, we use a failure rate of 0.056 failures per year for the proposed *PE* design and the rest of the reliability information remains the same as it is shown in Table 14.

Table 14: Reliability information for corrective material costs of the *PE* with the new proposed design (1 active rectifier and 3 passive rectifiers)

component	λ_c	γ	π_γ	ξ
PE	0.056	2	0.7424	ii
		4	0.2340	vi
		6	0.0236	xiv

With this information we are able to compute the *O&M* costs of the conventional design and the proposed design. The results are shown in the next chapter.

2.4 Summary

We present the methodology for wind probabilistic characterization and the adequate preparation for the wind probabilistic data in order to be compatible with the computation of the *AEG*. We calculate the electric power output for each of the wind speeds segregating into 5 intervals taking into consideration the efficiencies at each wind speed. With the combination of the electric power output and the probability for each of the possible wind speed values, we can calculate the expected *AEG* of each specific design. Then, we focus on the methodology used for the fixed costs of the proposed *PMSG* and *PE* designs. Besides, we explain the assumptions for *O&M* costs calculation. Finally, we come up with the *O&M* cost calculation for the conventional and proposed design. In the next chapter, we show the numerical results for each of the *PMSG* and *PE* designs and present the *O&M* costs for our conventional and our proposed design.

3 NUMERICAL RESULTS

In this chapter, we show plots of computed numerical results of variables of merit interest for every proposed design and show the *O&M* costs results for the conventional and proposed designs. The plots of the numerical results are computed by using the given data of multiple *PMSG* designs and *PE* designs.

The key information required for economic evaluation are the fixed costs of the *PMSG* $c_{f,PMSG}$ in *$*, the fixed costs of the *PE* $c_{f,PE}$ in *$*; the cost density of the paired system composed by the *PMSG* and *PE* $c_{d,sys}$ in *$/kW*, the fixed costs of all the components of a *WT* c_f, the annual *O&M* costs of a *WT* $c_{O\&M}$, and the *AEG*, denoted by ε. The parameter that annualizes the capital costs to produce a yearly uniform cash-flow set over the life of the wind project is the *c.r.f.*, denoted by Φ. The *LCOE* is calculated using the commonly used formula for wind results in equation 26 [9].

$$LCOE = \frac{\Phi\, c_f + \, c_{O\&M}}{\varepsilon} \quad \$/kWh \tag{26}$$

LCOE is a metric of merit interest for the economic evaluation of the project as it measures the net present cost of electricity generation in *$/kWh* for a generating wind farm over its lifetime. As our project is focused on a single *WT*, we calculate the inputs for the *LCOE* for a single wind turbine instead of a wind farm.

We use the ε as a metric of merit interest for the evaluation of the generation performance of the *WT*. The plots of the numerical results are shown in Figures 8-20:

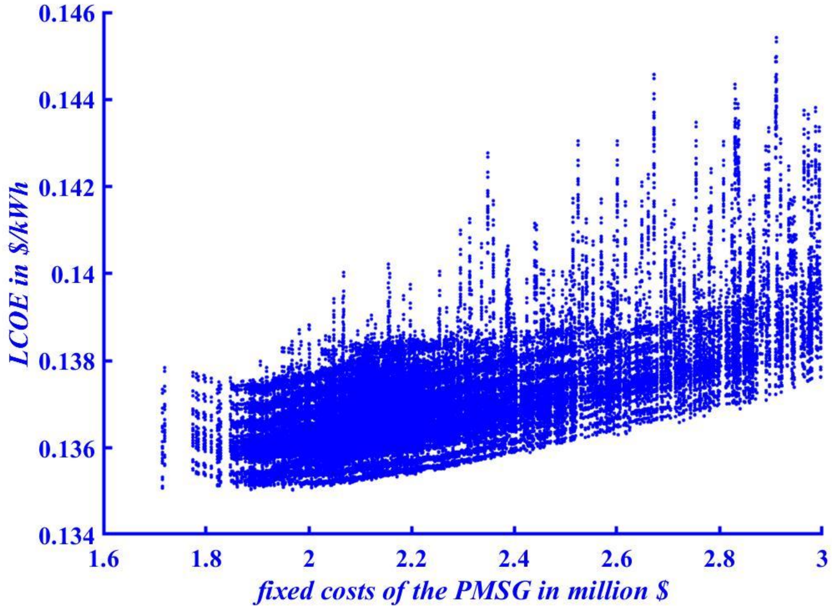

Figure 8: *Plots of the LCOE as a function of the PMSG fixed costs*

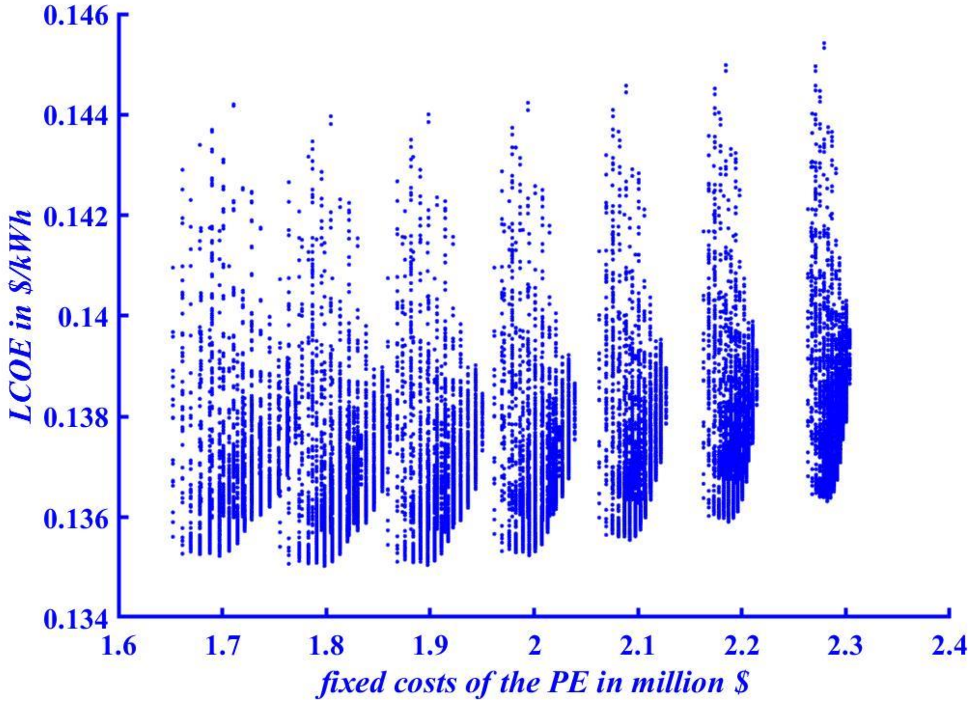

Figure 9: *Plots of the LCOE as a function of the PE fixed costs*

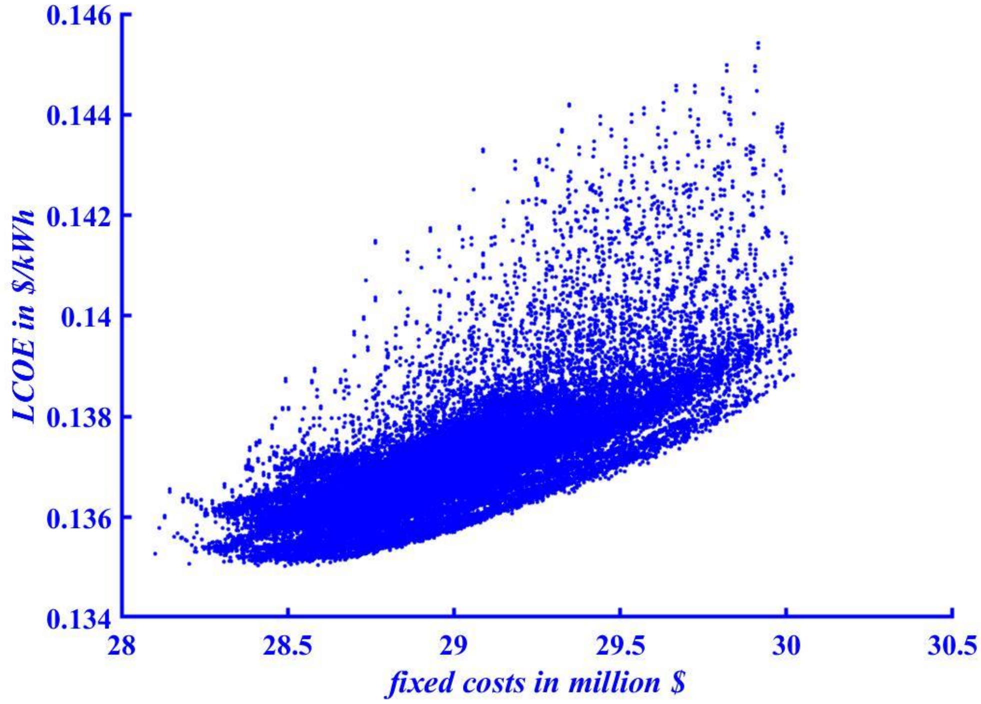

Figure 10: *Plots of LCOE as a function of the fixed costs*

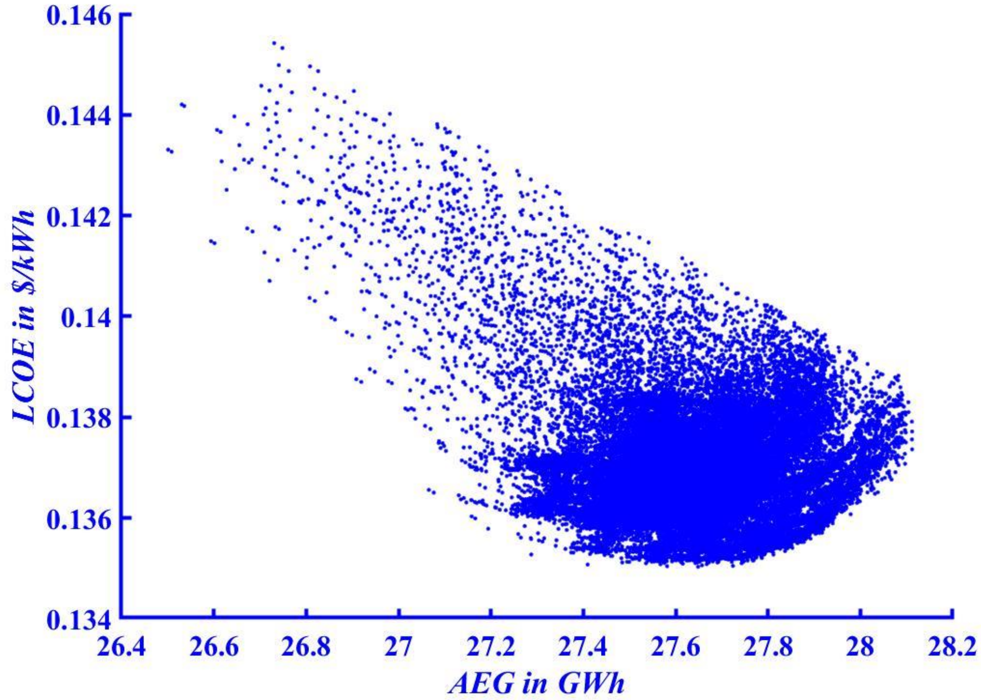

Figure 11: *Plots of LCOE as a function of AEG*

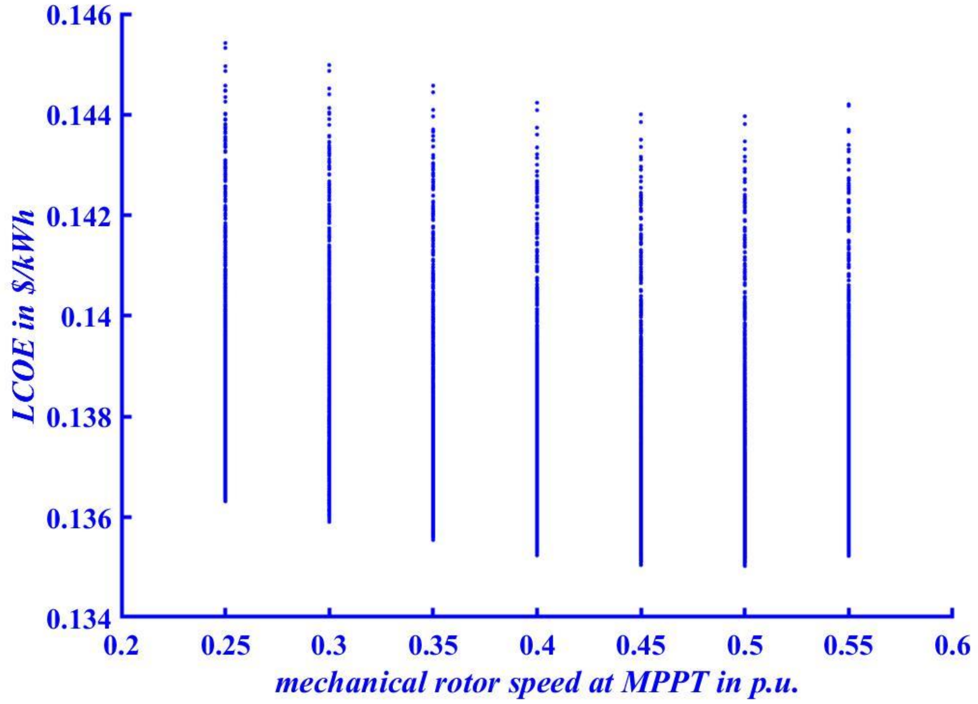

Figure 12: *Plots of the LCOE as a function of the mechanical rotor speed at MPPT*

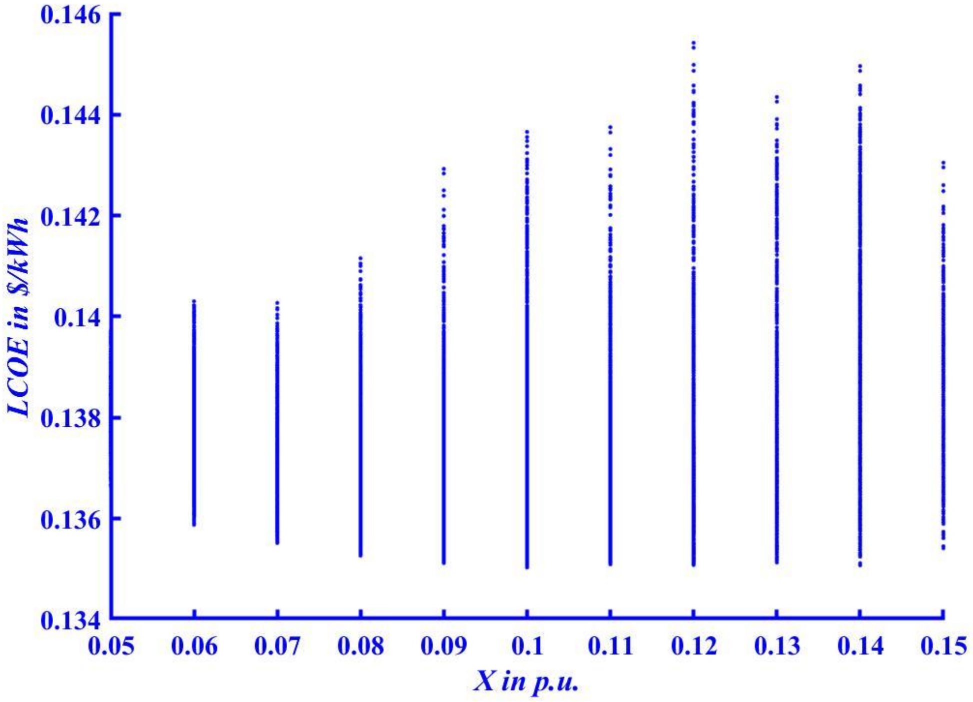

Figure 13: *Plots of the LCOE as a function of the per unit synchronous inductance*

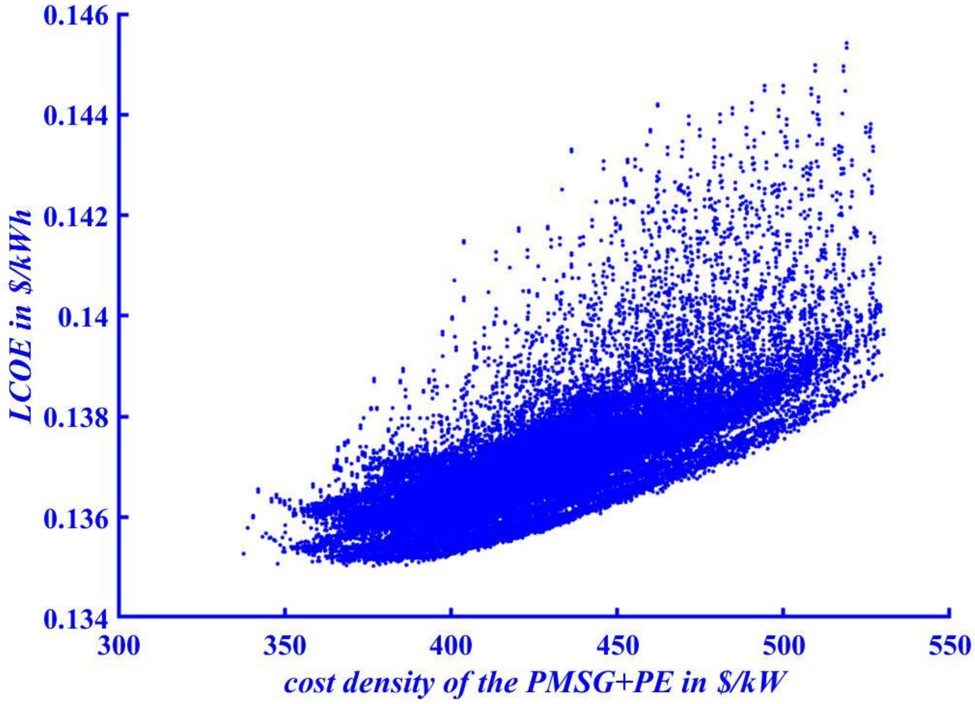

Figure 14: *Plots of the LCOE as a function of the cost density of the PMSG and PE*

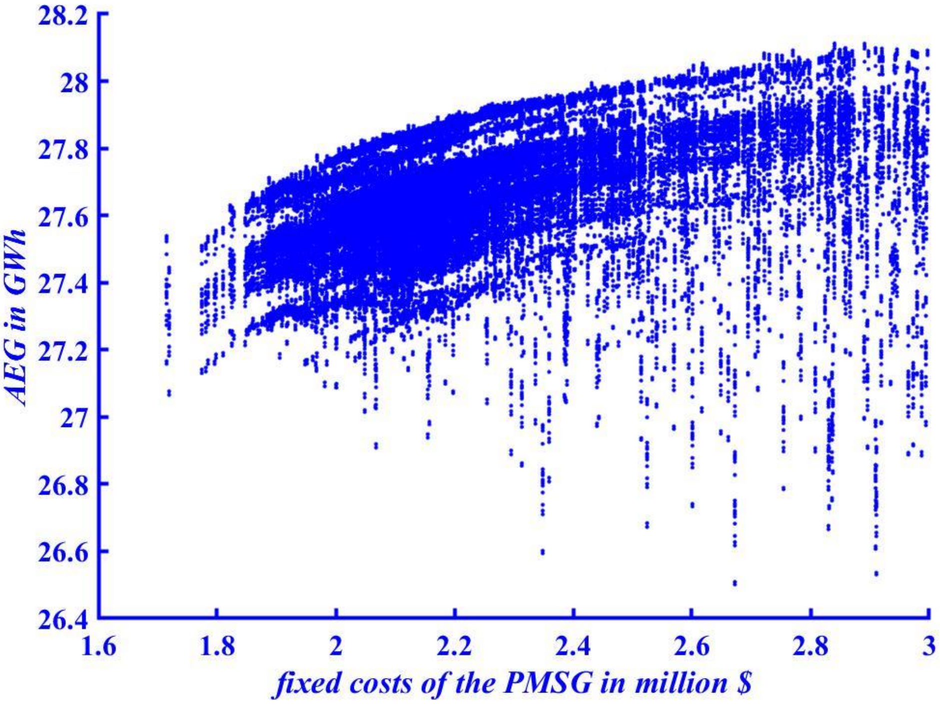

Figure 15: *Plots of the expected AEG as a function of the PMSG fixed costs*

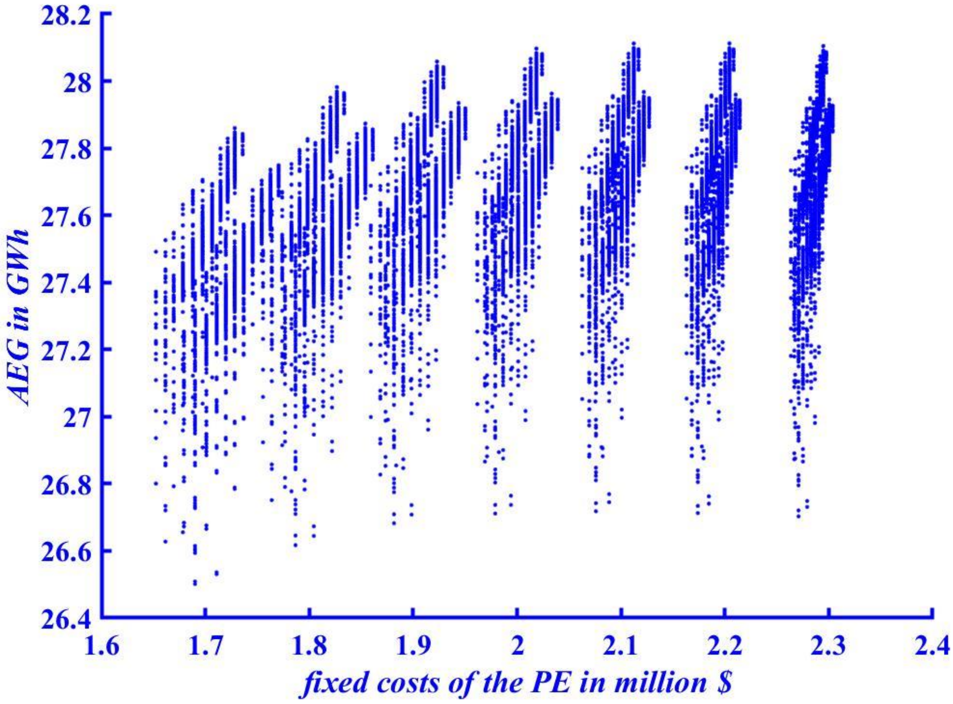

Figure 16: *Plots of the expected AEG as a function of the PE fixed costs*

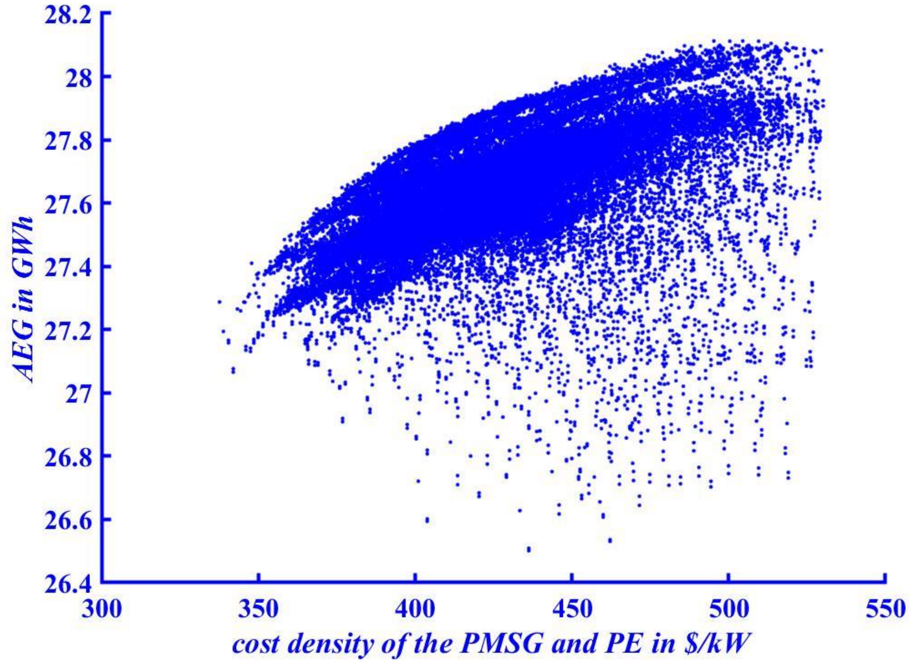

Figure 17: *Plots of the expected AEG as a function of the cost density of the PMSG and PE*

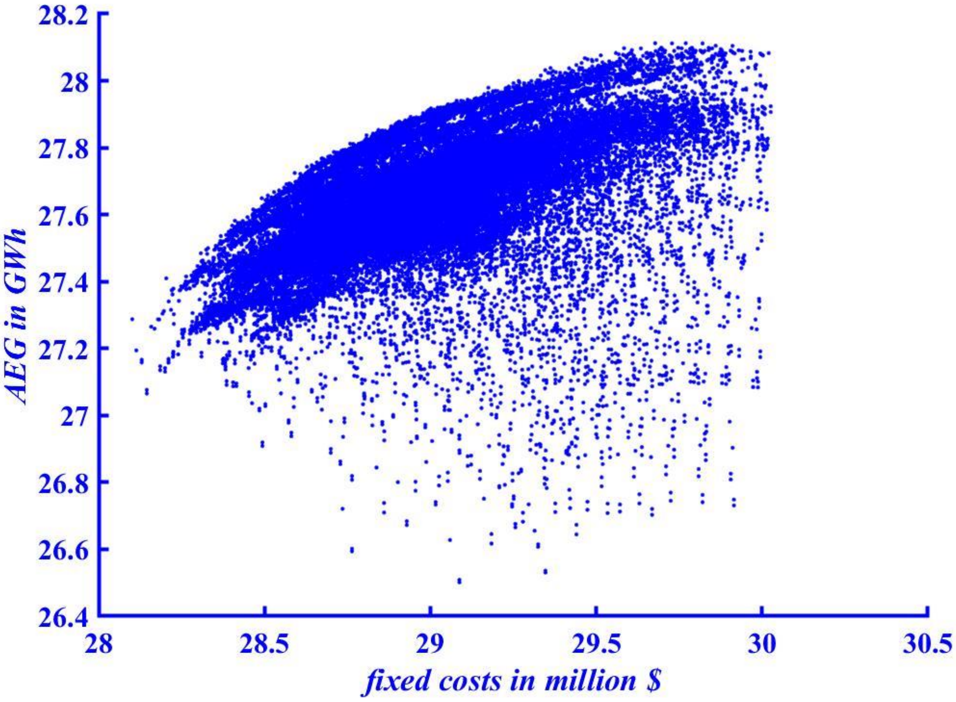

Figure 18: Plots of the expected AEG as a function of the fixed costs

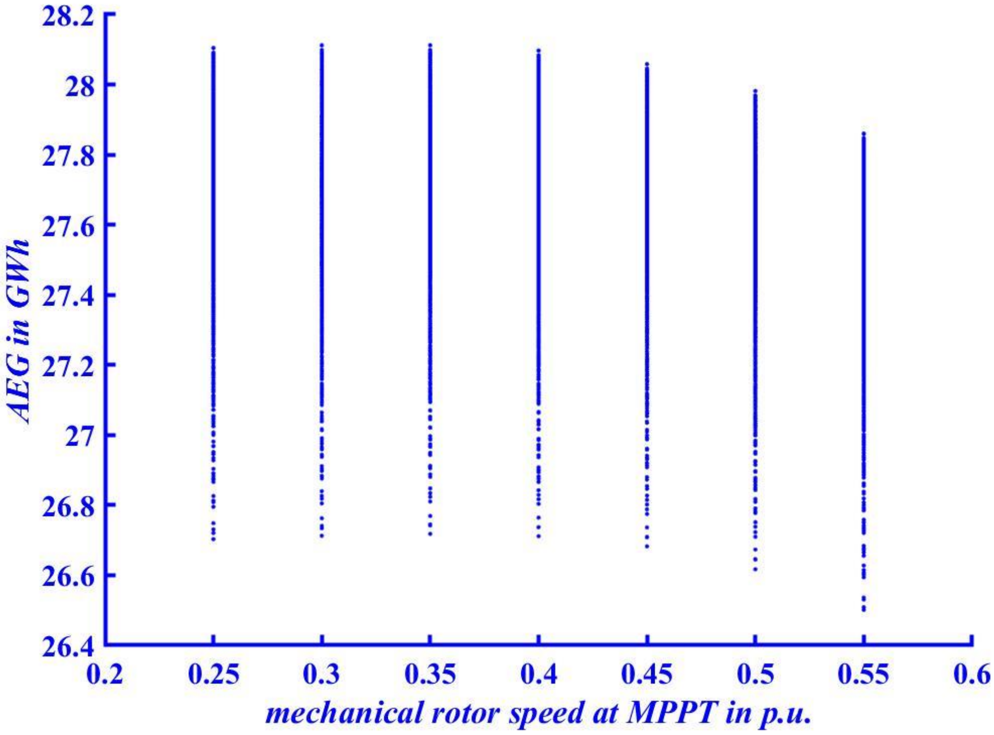

Figure 19: *Plots of the expected AEG as a function of the rotor mechanical speed at MPPT*

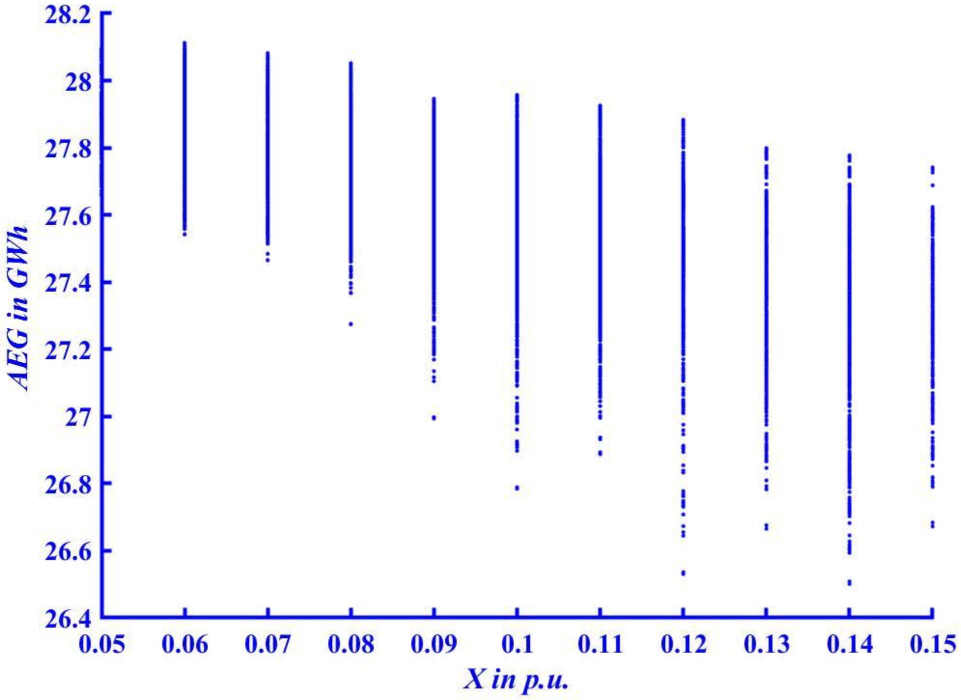

Figure 20: *Plots of the expected AEG as a function of the per unit synchronous inductance*

We show the *O&M* costs for each type of design in Table 15:

Table 15: *O&M* costs evaluation of the DTU conventional design, our conventional design, and our proposed design

type of design	*DTU conventional design*	*our conventional design*	*proposed design*
$c_{O\&M}$ *in $/yr*	626,000	673,725	656,366

4 ANALYSIS OF THE NUMERICAL RESULTS

We applied the computation of the numerical results for the proposed designs to study the designs with better generating performance and the most profitable designs. The study evaluate two metrics of merit interest, *LCOE* and expected *AEG*, as a function of other variables like the fixed costs of the *PMSG*, the fixed costs of the *PE* associated, the fixed costs of the *WT*, the cost density of the proposed technology (*PMSG* and *PE*), the mechanical rotor speed at *MPPT* and the per unit synchronous reactance value. The last two variables mentioned are chosen by the *PMSG* design group and the numerical results associated with those two variables can provide important insights of the values that work better for the best generating performance and the most profitable generator.

First, we show a table with the maximum and minimum values of each variable in Table 16.

Table 16: Maximum and minimum values for variables of interest

variable	*maximum*	*minimum*
LCOE	0.1454 *\$/kWh*	0.1350 *\$/kWh*
ε	28.11 *GWh/yr*	26.50 *GWh/yr*
c_f	30.02 *million \$*	28.10 *million \$*
$c_{f,PMSG}$	2.99 *million \$*	1.71 *million \$*
$c_{f,PE}$	2.30 *million \$*	1.65 *million \$*
$c_{d,sys}$	530.12 *\$/kW*	337.65 *\$/kW*

The annual *O&M* costs $c_{O\&M}$ aren´t shown in the table above because these costs don´t change depending on the specific proposed design. The $c_{O\&M}$ for each of the proposed designs is 656,366 *\$/yr*. From the given results in Table 16, we observe that the impact of the proper choice of a specific proposed design over the *LCOE* can impact on a 7.15 % reduction, which is a considerable reduction.

In Figure 8, we observe that the most economic results in terms of *LCOE* in the lower bound of the points cloud match with the most economic results in terms of the fixed costs of the *PMSG*. The width of the points cloud denotes that there are multiple *PMSG* designs with approximately the same fixed costs but with different generating performance. The points in the lower bound in Figure 8 corresponds to the designs with the highest efficiencies. If we take a look at Figure 15, we observe that the fixed costs of the *PMSG* tend to have a proportionally direct relation with the generating performance of the turbine, this fact haven´t impacted as much as expected to the *LCOE* (Figure 8), so we can say that sacrificing generating performance of the *PMSG* for lower costs as long as we take the most efficient generator designs is the best option for us. In Figure 10, we appreciate that the *LCOE* is almost linear in the lower bound of the point cloud, and we observe that the plot has some outliers in the upper part of the plots. In Figure 8, we see that the most economic *PMSG*s have a cost of 1.71 *million $*, but there are designs that achieve a similar *LCOE* at a cost of 1.88 *million $*. With Figures 13 and 20, we see the impact of the synchronous reactance of the generator in *p.u.* to the *LCOE* and the *AEG*. In Figure 13, we observe that the reactance values that can get to a lower *LCOE* are in the interval [0.1, 0.14], but we don´t perceive a direct relation between the value of the reactance and the *LCOE*. In Figure 20, we observe that there is a direct relation between the synchronous reactance and the generating performance: the lower the synchronous reactance, the better generating performance. So, I suggest using a per unit reactance of 0.1 as it is the lowest value of the interval mentioned above in order to look for the designs with the best generating performance.

Regarding the best design for *PE*, we observed in Figure 9 and Figure 16 that the fixed costs of the *PE* are divided in 7 clusters. If we take a look at the number of possible values for mechanical rotor speed at *MPPT*, we observe that there are also 7 possible values. In addition, we observe that the upper and lower bounds of *LCOE* values of the clusters in Figure 9 match with the upper and lower bounds of the *LCOE* of a specific rotor mechanical speed in Figure 19. In Table 17 we show the *LCOE* intervals for each of the clusters and for each of the specific mechanical rotor speeds at *MPPT* to determine which cluster corresponds to which mechanical rotor speed.

Table 17: *LCOE* intervals for 7 clusters and 7 mechanical rotor speed at *MPPT* in *p.u.*

no. of cluster in Figure 9	*LCOE interval of the cluster in $/kWh*	*mechanical rotor speed at MPPT in p.u.*	*LCOE interval of the mechanical rotor speed at MPPT in $/kWh*
1	0.1352-0.1442	0.25	0.1363-0.1454
2	0.1350-0,1440	0.30	0.1359-0.1450
3	0-1351-0.1440	0.35	0.1356-0.1446
4	0.1352-0.1442	0.4	0.1352-0.1442
5	0.1356-0.1446	0.45	0.1351-0.1440
6	0.1359-0.1450	0.5	0.1350-0.1440
7	0.1363-0.1454	0.55	0.1352-0.1442

We can clearly see that cluster 1 corresponds to 0.55 *p.u.*, cluster 2 corresponds to 0.5 *p.u.*, cluster 3 corresponds to 0.45 *p.u.* and so and so on. If we look at the table above, the cluster that tends to achieve the lowest *LCOE* is the second one, which corresponds to a mechanical rotor speed at *MPPT* of 0.5 *p.u.*

The characteristics and the results obtained for the proposed design with the lowest *LCOE* are shown in Table 18:

Table 18: Characteristics and results for the most economic design

variable	*value*
$LCOE$	0.1350 *$/kWh*
ε	27.65 *GWh/yr*
c_f	28.49 *million $*
$c_{f,PMSG}$	1.97 *million $*
$c_{f,PE}$	1.80 *million $*
$c_{d,sys}$	376.7 *$/kW*
$c_{O\&M}$	656,366 *$/yr*
$X_{p.u.}$	0.1 *p.u.*
$w_{MPPT}^{p.u}$	0.5 *p.u.*

5 CONCLUDING REMARKS

In this chapter, we summarize the work presented in the thesis and discuss some possible directions for future work.

5.1 Summary of the Report and its Contribution

In this report, we provided appropriate methodologies for the wind probabilistic characterization, the calculation of the expected *AEG* of a 10-*MW WT*, the evaluation of the costs of the proposed technology components and the evaluation of the annual *O&M* costs for a single wind turbine. We also assembled the methods used for these tasks to construct a systematic approach to perform the economic assessment of a wind project, in general, and that of as wind turbine, in particular. The results of the assessment allow us to obtain valuable insights into the various aspects of the design of the proposed technology. Specifically, we observed that for the most economically efficient results, the *PMSG* and *PE* design with the lowest fixed costs need not necessarily lead to the lowest *LCOE* values. There are trade-offs between the fixed costs of the proposed technology and the generation performance costs, whose impacts must be explicitly considered to determine the most economically efficient design. These trade-offs are observable from the computations of the approach we proposed for the economic assessment. Thus, our proposed economic assessment approach is a contribution to the economic analysis and evaluation of offshore wind projects as well as proposed *PMSG* and *PE* designs. In particular, the computationally efficient techniques make possible the assessment of a wide variety of sensitivity cases for the different design parameter values. Indeed, this capability allows the preparation of responses to a broad range of *what if* cases. These capabilities are of great usefulness in the selection of the robust solution of the design parameters of the most appropriate *PMSG* and *PE* designs for any set of specified requirements.

We summarize in Table 19 the results of the comparative analysis of the current proposed *PMSG* and *PE* designs and the *DTU* system [1]. Due to the lack of data on the fixed and variable costs of many elements of the design and the use of available data on existing designs as a place holder for the lacking data, the results to date fail to appropriately capture the economic impacts of the improvements in the proposed design. As such, it is best to view our economic analysis results as still tentative. Indeed, the *PMSG* and *PE* designs are fluid and much more realistic *O&M* costs will be available once the reliability assessment progresses further. However, the systematic approach proposed for the economic assessment provides a solid basis to assess the ongoing improvements in the *PMSG* and *PE* designs and the realistic representation of reliability performance of the designs on the *O&M* costs. Moreover, the capability to perform sensitivity studies is a major aid to identify the specific *PMSG* and *PE* design combination to attain the lower *LCOE* values to meet the goal for their reduction.

The expected *AEG* seem to be a factor that makes the difference in this comparison, if we would have obtained the same ε as in the *DTU* design, our *LCOE* would be 0.1123 *$/kWh*, a result that would be closer to the expectations of our project.

Table 19: Numerical results in comparison to the DTU report [1]

parameters of interest for economic assessment	*our proposed design*	*DTU design*
LCOE	0.1350 *$/kWh*	0.1277 *$/kWh*
ε	27.65 *GWh/yr*	33.24 *GWh/yr*
c_f	28.49 *million $*	28.95 *million $*
$c_{f,PMSG}$	1.97 *million $*	1.12 *million $*
$c_{f,PE}$	1.80 *million $*	2.14 *million $*
$c_{d,sys}$	376.7 *$/kW*	325.6 *$/kW*
$c_{O\&M}$	656,366 *$/yr*	626,000 *$/yr*

5.2 Directions for Future Work

There are several areas that require attention to bring about improvements in the various elements of the proposed approach. One area is the acquisition of wind data collected with a considerably higher resolution grid than integer-valued wind speed data used in the calculations in this report. Such data will allow the construction of more realistic wind characterization of wind regimes on a seasonal or monthly basis. In this way, the expected *AEG* evaluation can capture the seasonal or monthly changes in the wind regime to allow its higher fidelity approximation. Another area of interest is a more detailed assessment of the availability of the *WT* availability α, as more insights into the reliability assessment analysis become available. An issue of interest is whether a multi-state availability model may provide a more realistic representation of the *WT* than the current two-state representation. Similar issues arise for the *PE* design, for which only very limited data are available. For example, considerably more data are needed for the failure rates of the switches and diodes used in the *PE* design particularly given their deployment for a 10-*MW PMSG* turbine. We have noticed that the input parameters for the proposed *PE* remain unchanged as they are calculated for a specific architecture were the power transmitted by each of the rectifiers is 0.25 *p.u.* (because in the proposed design there are 1 active and 3 passive rectifiers, 4 in total). But what really happens is that the power transmitted by the active rectifier is in the range between [0.22, 0.29] *p.u.*, and the power transmitted by the passive rectifiers is the complementary power to reach 1 *p.u.* We think it is a meaningful consideration as the failure rates of the switches and diodes of the *PE* can vary considerably taking in to account the power level of the project. Indeed, there is a lack of data on the sensitivity of the failure rates of the proposed *PE* as a function of the power transmitted by the active rectifiers. Another issue concerns the inadequacy the data available on active and passive rectifiers in specific architectures and their performance. The additional data and possibly more realistic models of the performance of the rectifiers will improve the representaion of the *O&M* impacts on the annual *O&M* costs. These data and modeling improvements are all key to realistically represent the new *PMSG* and *PE* designs on the annual *O&M* costs. Indeed, these impacts will provide a more realistic determination of the corresponding *LCOE* values. In addition, I consider the possibility of using a new correction factor for the *O&M* costs calculation as the values obtained for the conventional design are considerably overpriced compared to the conventional *DTU* design.

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APPENDIX A: LIST OF ACRONYMS

WECS	wind energy conversion system
DFIG	doubly-fed induction generator
PMSG	permanent magnet synchronous generator
PE	power electronics
LCOE	levelized cost of energy
WT	wind turbine
MW	megawatts
DC	direct current
DTU	Technical University of Denmark
O&M	operation and maintenance
AEG	annual energy generation
DOE	Department of Energy
NYSERDA	New York State Energy Research and Development Authority
R&D	Research and Development
c.r.f.	capital recovery factor
p.d.f.	probability density function
MPPT	maximum power point tracking
BOS	balance of system
NREL	National Renewable Energy Laboratory
ECN	Energy research Centre of the Netherlands
BOP	balance of plant
γ	maintenance category
ξ	fault type class
SODAR	sonic detection and ranging
LIDAR	light detection and ranging
r.v	random variable
kW	kilowatts
GWh	gigawatts hour
MT	metric ton

APPENDIX B: NOTATION

$f_v(v)$	wind speed *p.d.f.*
v	wind speed in *m/s*
v_C	cut-in wind speed in *m/s*
w_{MPPT}	rotor mechanical speed at *MPPT* in *rpm*
λ_{opt}	optimal tip speed ratio
v_{MPPT}	wind speed at *MPPT* in *m/s*
P_R	rated power in *kW*
v_R	rated wind speed in *m/s*
w_R	rated rotor mechanical speed in *rpm*
v_F	furling wind speed in *m/s*
r	radius of the three-blade turbine in *m*
$v^{p.u}$	wind speed in *p.u.*
$v_C^{p.u}$	cut-in wind speed in *p.u.*
$v_{MPPT}^{p.u}$	wind speed at *MPPT* in *p.u.*
$v_R^{p.u}$	rated wind speed in *p.u.*
$v_F^{p.u}$	furling wind speed in *p.u.*
$w_R^{p.u}$	rated rotor mechanical speed in *p.u.*
$w_{MPPT}^{p.u}$	rotor mechanical speed at *MPPT* in *p.u.*
κ	operational power coefficient
p_{mec}	mechanical power generated at a certain wind speed in *kWh*
ρ	air density in kg/m^3
a	turbine swept area of the three-blade turbine in m^2
λ	tip speed ratio
w	rotor mechanical speed in *rpm*
η_{PMSG}	efficiency of the *PMSG* at a certain wind speed
η_{PE}	efficiency of the *PE* at a certain wind speed
κ_{max}	power coefficient at optimal tip speed ratio
p_{elec}	electric power output
$p_{elec}(v)$	electrical power output as a function of wind speed

$\eta_{PMSG}(v)$	efficiency of the *PMSG* as a function of wind speed
$\eta_{PE}(v)$	efficiency of the *PE* as a function of wind speed
$\kappa(v)$	operational power coefficient as a function of wind speed
m_{PM}	mass of permanent magnet in *kg*
m_{Fe}	mass of iron in *kg*
m_{Cu}	mass of copper in *kg*
m_s	mass of structural iron in *kg*
c_{PM}	material and preparation cost of the permanent magnet in *$/kg*
c_{Fe}	material and preparation cost of the iron in *$/kg*
c_{Cu}	material and preparation cost of the copper in *$/kg*
c_s	material and preparation cost of the structural iron in *$/kg*
$c_{f,PMSG}$	fixed costs of the *PMSG* in *$*
x_a	active rectifier rating in the *PE* design in *kW*
x_p	passive rectifier rating in the *PE* design in k*VA*
n_a	number of active rectifiers in the *PE* design
n_p	number of passive rectifiers in the *PE* design
B	conventional/baseline design cost of *PE* in *$/kW*
$c_{f,PE}$	fixed costs of the *PE* in *$*
$c_{O\&M}^{5-MW}$	*O&M* costs per year for a single 5-*MW WT* in *$/yr*
mc_c	corrective material costs of a *WT* component (c) in *$/yr*
γ	maintenance category index
ξ	fault type class index
λ_c	failure rate of a component (c) in *failures/yr*
π_γ	probability of occurrence of a γ
c_ξ	cost of the ξ in *$/failure*
f	number of ξs of the component whose material costs are being evaluated
mc_c^p	corrective material costs of a *WT* preliminary component (c) in *$/yr*
$c_{O\&M}$	*O&M* costs of a *WT* in *$/yr*
k	number of components whose reliability information change regarding the preliminary components
c_f	Fixed costs of the whole *WT* in *$*
ε	*AEG* of a *WT* in *kWh/yr*

$c_{d,sys}$	cost density of the proposed system (*PMSG* and *PE*) in *$/kW*
Φ	*c.r.f.* of a *WT* project
$LCOE$	*LCOE* of a *WT* design in *$/kWh*
$X_{p.u.}$	synchronous reactance of the *PMSG* in *p.u.*
$\underline{V}$	wind speed as a random variable

APPENDIX C: WIND DATA ANALYSIS

This appendix is made using as a reference Prof. Gross´ notes for wind data analysis [10]. The collection of sufficient wind data to allow the generation estimation is an essential task in any wind project assessment at a specified site. Various measurement devices like cup, sonic detection and ranging (SODAR), and light detection and ranging (LIDAR) anemometers provide the ability to measure wind speed, its direction and other relevant metrics of interest.

Wind is a highly uncertain phenomenon with high variability and wide changes over a brief period of time; as a result, wind speed exhibits much volatility and randomness. While wind speed is a continuous variable, wind speed data are collected on a sampled basis: values are measured on a periodic basis, such as hourly, every 10 minutes or every minute. Wind data for wind analysis requires the collection around-the-clock of wind speed measurements at the altitude of interest at a frequency commensurate with the nature and scope of the analysis.

The measurement scheme requires the specification of the smallest indecomposable unit of time:

- for planning evaluation and assessment, the collection of data on an hourly or half–hourly basis is, typically, adequate
- for the analysis of dynamic phenomena such as stability, the collection has to be at a much finer resolution than hourly to capture the short time constants of such phenomena

The wind data collected may be used to approximate the probability distribution of wind at a specified site. We make use of such approximations under the implicit assumption that natural phenomena, such as wind, continue to behave in the future in a way similar to their past behavior. Suppose we wish to probabilistically characterize the wind speed at a given site and at its specified altitude: for that purpose, we collect hourly measurements over a long period of time and construct a histogram of the measured values. We discretize the wind speed axis, e.g., we use the integer values of wind speed, say from 0 to 25 m/s and we create 26 “buckets” of speed values. We place each hourly measured value in the appropriate “bucket”, and we construct a histogram of the historical data such as shown below in Figure C1.

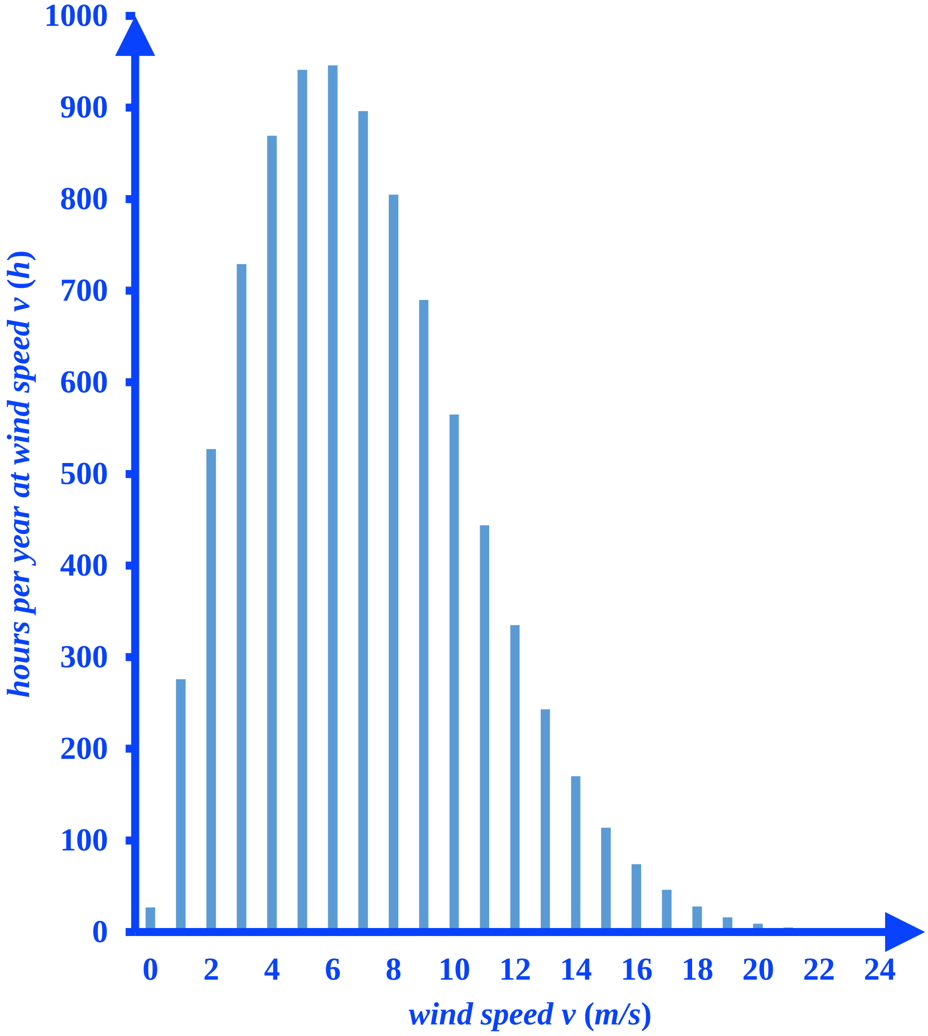

Figure C1: *Example of a histogram of the historical wind data*

We interpret the height of each bar at wind speed value v in the histogram as the number of hours with wind speed value v. We normalize the vertical axis values by dividing the number of hours of each bar by the total number of hours to obtain the fraction of the total hours at a particular wind speed v (Figure C2).

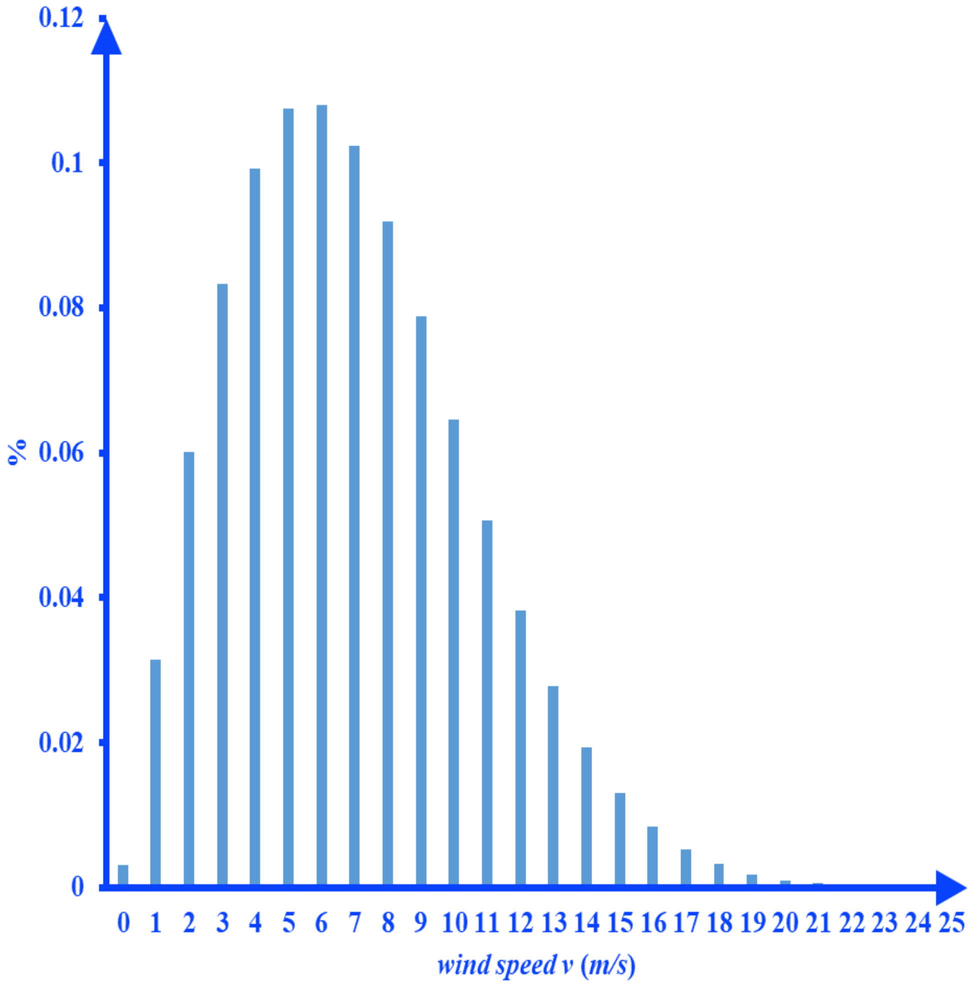

Figure C2: *Previous figure but with the hours per year at v speed normalized*

Clearly, each bar has a value < 1 and the sum of all the bars must be exactly 1. In effect, we obtain a probability mass function of the wind speed. To understand the probability interpretation, we view wind speed as a random variable (*r.v.*) $\underline{V}$ whose realizations are given by the histogram. The normalized histogram provides the probability associated with each of the possible discrete-valued realizations. The bar of the mass density function at the wind speed v provides

$$P\{\underline{V} = v\} = probability\ of\ wind\ speed\ at\ v\ m/s\ . \qquad (27)$$

We discretized the values of $\underline{V}$ by creating the 26 discrete buckets 0, 1, 2, … , 25 but in reality, wind speed does not take discrete values since it is a continuously-valued variable.

Alternatively, we may consider to make use of an increasingly finer resolution grid so as to capture the fact that $\underline{V}$ is a continuous *r.v.*

We associate with the continuous *r.v.* $\underline{V}$ a *p.d.f.* $f_{\underline{V}}(v)$ with the following properties:

$$f_{\underline{V}}(v) \geq 0 \qquad \forall\, v \geq 0 \quad , \tag{28}$$

$$\int_{0}^{\infty} f_{\underline{V}}(v)\, dv \; = 1 \quad . \tag{29}$$

For an infinitesimally small $\delta > 0$:

$$P\{v < \underline{V} \leq v + \delta\} \approx f_{\underline{V}}(v)\, \delta \; , \tag{30}$$

$$P\{v_1 < \underline{V} \leq v_2\} = \int_{v_1}^{v_2} f_{\underline{V}}(v)\, dv \quad . \tag{31}$$

The *p.d.f.* $f_{\underline{V}}(\cdot)$ provides a complete analytic characterization of the continuous *r.v.* $\underline{V}$. We may readily compute any function of $\underline{V}$ by calculating the average wind speed $\overline{v}$ (equation 22) and the wind speed cubed (equation 23):

$$\overline{v} = \int_{0}^{\infty} v\, f_{\underline{V}}(v)\, dv \, , \tag{32}$$

$$E\{\underline{V}^3\} = \int_{0}^{\infty} v^3\, f_{\underline{V}}(v)\, dv \, ; \tag{33}$$

and the number of annual hours $v_1 < \underline{V} \leq v_2$: we compute equation 34.

$$8760 \int_{v_1}^{v_2} f_{\underline{V}}(v)\, dv \quad . \tag{34}$$

APPENDIX D: MAINTENANCE STRATEGIES, MAINTENANCE CATEGORIES AND FAULT TYPE CLASSES

All the information from this appendix is gathered from the *NREL* report "Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy" [7]. In terms of the maintenance strategy that we chose for our *O&M* costs estimation, all the possible maintenance strategies and their results are shown in Table D1 and Table D2. Note that the costs showed in these tables are estimated for a 100 5-*MW WT*s farm.

Table D1: Summary of *O&M* strategies studied with highest improvement opportunity

O&M strategy	α (%)	*results note*
baseline O&M scenario	84.5	*this is the baseline O&M scenario*
step 1: Improved crew transfer	93.3	*significant effect compared to baseline: total O&M decreased by $ 24.8 M*
step 1 + variation a: mother vessel	95.2	*analysis does not account for increased cost of mother vessel; indication: $ 15 - $ 20 M/year when rented from spot market*
step 1 + variation b: project-owned jack-up vessel	93.8	*accounts for changes in operating expenses, but not capital cost of project owned jack-up vessel.*
step 1 + variation c: helicopter access	93.9	*increased operational costs. Does not account for additional turbine investment costs for landing platform*
step 1 + variation d: advanced CBM	93.7	*results shown are for 50 % detection rate with 0 % false alarms. Does not account for investment and operational costs for condition-based monitoring (CBM) systems*

Table D2: Summary of costs of potential preferred *O&M* strategies

maintenance strategy		*baseline*	*step 1*	*step 1 + variation a*	*step 1 + variation b*	*step 1 + variation c*	*step 1 + variation d*
type of costs	*issues with the sustainability*	*cost in k$/yr*	*cost in k$/yr*	*cost in k$/yr*	*cost in k$/yr*	*cost in k$/yr*	*cost in k$/yr*
material costs	*corrective WT*	16,684	16,684	16,684	16,684	16,684	16,684
	corrective BOP	58	58	58	58	58	58
	preventive	1,574	1,574	1,574	1,574	1,574	1,574
labor costs	*corrective WT*	4,366	4,366	3,457	4,366	3,857	4,366
	corrective BOP	5	5	4	5	5	5
	preventive	2,103	2,103	1,911	2,103	2,103	2,103
costs of equipment	*corrective WT*	18,426	17,339	14,812	5,170	20,264	17,339
	corrective BOP	1,464	1,463	1,463	1,463	1,464	1,463
	preventive	1,487	1,585	1,565	1,585	1,653	1,585
total	*corrective WT*	39,476	38,389	34,953	26,220	40,805	38,389
	corrective BOP	1,527	1,527	1,525	1,527	1,527	1,527
	preventive	5,164	5,262	5,050	5,262	5,330	5,262
	total O&M costs	46,168	45,178	41,528	33,009	47,663	45,178

Individually, a number of the *O&M* strategies we evaluated offer potential to improve both the wind plant availability and the *O&M* costs for the baseline scenario. We sought to identify which combination of these *O&M* strategies would lead to the greatest reduction in cost compared to the baseline. The two *O&M* strategies with the highest potential to improve availability and reduce revenue losses are: investment in an improved crew transfer system (e.g., application of a workboat with less restrictive weather limitations), and using a mother vessel to provide accommodation at the wind plant instead of daily transfer from the harbor. Both strategies focus on a reduction of the waiting time caused by bad weather conditions, which is the primary driver for the low wind plant availability in the baseline scenario. Individually, each of these strategies has the potential to reduce the total *O&M* effort from the baseline by more than $\$$ 20 million. The *O&M* effort is the money that you are not earning because some of the *WT*s of the wind farm are not operational. Other *O&M* strategies (helicopter access and advanced *CBM*) also yielded improvements, albeit much smaller than for the improved crew access system and mother vessel accommodation. On the other hand, ordering spare parts directly from the factory, rather than storing them onsite, causes longer downtimes and could decrease availability compared to the baseline. These findings suggest that an improved crew access system in combination with a mother vessel accommodation would be the preferred *O&M* strategy. However, because each strategy addresses the waiting time caused by bad weather conditions, we cannot assume that the total improvement compared to the baseline equals the sum of the individual strategies. We evaluated the cost savings associated with an improved crew access system (compared to the baseline) as well as the cost savings associated with four other scenarios (various combinations of an improved crew access system, plus one additional *O&M* improvement strategy). To identify a preferred *O&M* strategy, we first had to establish the capabilities of an improved crew transfer system and calculate the wind plant availability for different weather windows (combinations of significant wave height and wind speed). For the preferred *O&M* scenario, we assume that the workboats used can operate up to a significant wave height (Hs, max) of 1.5 m and maximum wind speed ($Vmax$) of 12 m/s. These limits are typically valid for workboats used for maintenance of offshore wind plants in Europe [7] and are therefore considered realistic for use in the U.S. market, if the vessels were built in or relocated to the U.S. We also assume that the travel speed of the improved workboat is equal to the baseline workboat (one-way travel time is 2.6 h). However, because of the workboat's improved capabilities, it is also expected that the day rate for the improved workboat will be higher compared to the baseline. As a best estimate, we assume an increase in cost of 25 %, which results in a day rate of *$* 2,500.

The additional four strategies we evaluated were composed of this specific improved crew transfer system scenario, which employs these specific work boat specifications (step 1), plus one of the *O&M* strategies below:

- variation a: mother vessel. Travel time of the workboats is reduced from 2.6 to 0.5 h because they are launched from the mother vessel. An offshore premium of *$* 175/h is considered for the technicians who, in this scenario, must live and work offshore for a prolonged period of time.

- variation *b*: jack-up barge owned by project. The mobilization and travel costs for the jack-up vessel are set to zero, because it is no longer rented from the spot market.. Only an estimation for the *O&M* costs, related to the jack-up being applied for *O&M* purposes, is made because a more detailed modeling of a project-owned jack-up vessel is needed. No logistics time is considered for the jack-up barge.

- variation *c*: helicopter access. Crew transfer for small repairs and inspections is done by helicopter. Helicopter access is not limited by wave height. Additional capital expenses (e.g., helicopter access at each turbine) are not considered.

- variation *d*: advanced condition-based monitoring. Employing advanced *CBM*, we assume 50% of medium and large corrective repairs on the drivetrain system can be avoided with preventive maintenance. For these repairs, the turbine is only shut down during the actual replacement.

We use a two-step approach to evaluate the preferred *O&M* strategy. The first step involves only the inclusion of improved workboats as the initial preferred *O&M* strategy. The second step adds the other strategies are ed as variations to the initial preferred *O&M* strategy to evaluate their potential for additional cost reduction.

Using only the improved access system (workboats capable of operating up to 1.5 m significant wave height) results in savings of approximately *$* 24.8 million annually compared to the baseline, which is a result of the reduced waiting times due to poor weather conditions. It must noted that these significant savings are realized because the baseline work boat was chosen to reflect the currently available work boats in the United States, which are optimized for the offshore oil and gas industry, not the offshore wind industry. If the offshore wind industry were to grow significantly in the United States, it would be reasonable to assume that even first of-a-kind wind plants would use work boats similar to those in Europe (with a 1.5-m significant-wave height). However, because they are not currently available in the United States, this type of workboat was not considered for the baseline.

The results for variation *a* (improved crew access system plus use of a mother vessel) indicate that additional savings of around *$*9 million can be expected when the maintenance is organized from a mother vessel, because this strategy further reduces travel times. When a mother vessel is rented from the spot market, estimates of annual costs fall between *$* 15 million and *$* 20 million [7], which indicates that for the selected wind plant location the use of a mother vessel will be prohibitively expensive. For wind plants located further offshore, the use of a mother vessel will likely be part of the preferred *O&M* strategy. It was beyond the scope of this analysis to identify the cross over point at which the distance from shore is great enough that the costs of a mother vessel are offset by the savings from reduced travel time between the wind plant and harbor. To accurately evaluate at which distance from shore this turning point lies, time series data with wave height and wind speed for a number of locations with different distances from shore would be needed because these parameters can vary significantly from one location to the next.

The results of variation *b* (improved crew access system plus a project-owned jack-up vessel) indicate potential cost savings of approximately *$* 13.3 million compared to Step 1 (jack-up vessel is rented from the spot market). These findings assume that no variable costs other than *O&M* costs are incurred for the jack-up vessel and that the jack-up vessel is always available (logistics time is equal to 0 *h*). If the project-owned jack-up vessel is also suitable for the wind plant installation and decommissioning phases, larger cost savings are possible. However, this method also requires a more detailed assessment of the investment costs for such a vessel. Operational costs must be considered when the vessel is also applied for the installation and decommissioning phases, as well as when the vessel is in standby or idling. To better assess whether the use of a project-owned jack-up vessel is a cost-effective solution, we conducted a separate, more detailed assessment presented in Section 5.3.

The results for variation *c* (improved crew access system plus helicopter access) show that having helicopter access for small repairs and inspections will slightly improve wind plant availability but will also lead to higher costs. The reduced revenue losses do not offset the higher costs of repair with the helicopter; the total *O&M* costs will increase by approximately *$* 1.1 million. The main reason for this is that accessing the turbine via helicopter is not feasible for repairs that require the delivery of spare parts. It is worth noting that operating helicopters will also require the addition of landing platforms for the technicians on the turbines; these are additional costs that we did not account for in our analysis. For wind plants located further offshore, the use of a helicopter may have a positive effect on the total *O&M* effort. As with the analysis of the mother vessel, to accurately evaluate at which distance from shore this cross over point occurs, it is necessary to have time series data with wave height and wind speed for a number of locations with different distances from shore. These data are needed because the wind and wave conditions affect decisions about which vessel (or helicopter) to employ for a given repair and affect the timing of those repairs.

The analysis for variation *d* (improved crew access system plus the installation of advanced condition based monitoring systems at the drive train and generator systems), shows that if more than 50 % of the medium and large replacements on both systems can be detected, at least *$* 1 million annually could be saved compared to the Step 1 scenario (improved crew access system only). This cost savings estimate does not account for the costs associated with additional inspections caused by false alarms or the investment costs for the actual monitoring systems. It is worth noting that we do not know whether a target of 50 % failure prediction can be achieved by these systems; 50 % was used as a best estimate given our current understanding of *CBM* systems.

After all these assumptions, step 1 + variation *a* and step 1 + variation *b* were our preferred *O&M* strategies and finally, we chose step 1 + variation *a* because we decided to not include the project-owned jack up vessel to the fixed costs of the project. These decision leaves with the second most economic option in terms of *O&M* costs, but the best option in terms of availability. Even though, the availability parameter is not used for our economic analysis because calculating the availability of a single *WT* is in the proposed milestones of the project and we will include that parameter whenever we have it.

Fault type class (ξ) and maintenance categories (γ) are concepts that have been appearing throughout the *O&M* cost calculation and it is important to know their meaning. Each component has different fault type classes , and a material cost associated with the fault type class (c_ξ), that leading to a more common case, it would be equivalent to evaluating each maintenance category of a car and the cost associated in terms of time specifications and type of repair.

Six different γs for the *WT*s are identified for the baseline and advanced strategies. All six maintenance categories are widely discussed in [7] and are shown in Table D3.

Certain fault type classes correspond to certain maintenance categories (Table D4), and each fault type class, according to the characteristics assigned, correspond to a material cost (Table D5).

Table D3: Types of maintenance categories for *WT*s

maintenance category	
γ	*description*
1	*remote resets, no access, only downtime*
2	*inspection and small repair inside, only personnel and tools, repair time* 2 *to* 6 *h* (*e.g., replacement of generator fuses*)
3	*inspection and small repair outside, only personnel and tools, repair time* 6 *to* 10 *h (e.g., cleaning of blades*)
4	*replacement of small parts* (≤ 2000 *kg*), *internal crane, hoisting outside, repair time typically* 8 *to* 24 *h* (*e.g., replacement of pitch motor*)
5	*preventive replacement of small parts* (≤ 2000 *kg*), *internal crane, hosting outside, repair time typically* 8 *to* 24 *h* (*e.g., replacement of pitch batteries*)
6	*replacement of large parts* (≥ 2000 *kg*), *external crane on jack-up vessel needed,* (*e.g., replacement blade, pitch bearing, etc.*), *repair time typically* 24 *to* 40 *h*

Table D4: Maintenance categories and fault type classes for *WT* failures

maintenance category		*fault type class*	
description	γ	*description*	ξ
Remote reset (*only downtime, no visit*)	1	*no crew, repair time is* 2 *h*; *no costs*	i
inspection and small inside repair	2	*small crew, repair time is* 4 *h; costs of consumables*	ii
Inspection and small outside repair	3	*small crew, repair time is* 8 *h, costs of consumables*	iii
Replacement small parts (< 2 *MT*) *internal crane*	4	*small crew, repair time is* 8 *h, low costs*	iv
		small crew, repair time is 16 *h, low costs*	v
		large crew, repair time is 16 *h, medium costs*	vi
		large crew, repair time is 24 *h, medium costs*	vii
		large crew, repair time is 24 *h, high costs*	viii
Preventive replacement small parts (*< 2 MT*) *internal crane*	5	*small crew, repair time is* 8 *h, low costs*	ix
		large crew, repair time is 16 *h, medium costs*	x
Replacement large parts (*< 100 MT*) *large external crane*	6	*large crew, repair time is* 24 *h, medium/high costs*	xi
		large crew, repair time is 24 *h, high costs*	xii
		large crew, repair time is 40 *h, medium/high costs*	xiii
		large crew, repair time is 40 *h, very high costs*	xiv

Table D5: fault type classes material costs

fault type class classification		c_ξ
description	ξ	*$*
no crew, repair time is 2 *h, no costs*	i	0
small crew, repair time is 4 *h, costs of consumables*	ii	900
small crew, repair time is 8 *h, costs of consumables*	iii	900
small crew, repair time is 8 *h, low costs*	iv	9,000
small crew, repair time is 16 *h, low costs*	v	9,000
large crew, repair time is 16 *h, medium costs*	vi	90,000
large crew, repair time is 24 *h, medium costs*	vii	90,000
large crew, repair time is 24 h, high costs	viii	450,000
small crew, repair time is 8 *h, low costs*	ix	9,000
large crew, repair time is 16 *h, medium costs*	x	90,000
large crew, repair time is 24 *h, medium/high costs*	xi	180,000
large crew, repair time is 24 *h, high costs*	xii	270,000
large crew, repair time is 40 *h, medium/high costs*	xiii	180,000
large crew, repair time is 40 *h, very high costs*	xiv	900,000

APPENDIX E: SUSTAINABLE DEVELOPMENT GOALS (*SDG*)

The investment on an offshore wind project of these nature supposes social, economic, and environmental benefits for the territory and local communities. Offshore wind is willing to become an important pillar of the future American green energy system. Wind power is a clean and renewable source of energy in a global context of growing social concerns about climate change and energy supply. It is traditionally linked to very strong and stable levels of public support. The most recent empirical evidence on public opinion towards wind energy, both in the *EU* and in the *US* institutions, supported that favorable perception of this wind energy source among citizens. However, experience in implementing wind projects shows that social acceptance is crucial for the successful development of specific wind energy projects. A large-scale wind farm project will contribute to policy objectives on climate change, green growth, and social development. The development of a project of this nature supposes a positive economic impact to the population on the nearest coast and generates hundreds of jobs for the construction of the wind farm and hundreds of jobs for the operation and maintenance of the wind farm during its lifetime.

As we mentioned in the Motivation for a new *PMSG* and *PE* subchapter, the U.S. Department of Energy (*DOE*) announced the selection of the New York State Energy Research and Development Authority (*NYSERDA*) to administer an *$* 18.5 million offshore wind research and development (*R&D*) consortium. The consortium brings together industry, academia, government, and other stakeholders to advance offshore wind plant technologies, develop innovative methods for wind resource and site characterization, and develop advanced technology solutions for the installation, operation, maintenance, and supply chain.

The proposed technology innovations directly contribute to further the *DOE*´s goals to develop improvements of offshore wind technologies with the focus on the *WECS* design for enhanced efficiency, cost-effectiveness, and reliability of the mechanical-to-electrical energy conversion and the associated *PE* innovations.