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Article

Wind Turbine Power Curve Upgrades

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Abstract: Full-scale wind turbine technology has been widely developing in the recent years and condition monitoring techniques assist at the scope of making 100% technical availability a realistic perspective. In this context, several retrofitting techniques are being used for further improving the efficiency of wind kinetic energy conversion. This kind of interventions is costly and, furthermore, the estimation of the energy enhancement is commonly provided under the hypothesis of ideal conditions, as for example absence of wakes between nearby turbines. A precise quantification of the energy gained by retrofitting is therefore precious in real conditions, that can be very different from ideal ones. In this work, three kinds of retrofitting are studied through the operational data of test case wind farms: improved start-up through pitch angle adjustment near the cut-in, aerodynamic blade retrofitting by means of vortex generators and passive flow control devices, extension of the power curve by raising cut-out and high wind speed cut-in. SCADA data are employed and reliable methods are formulated for estimating the energy improvement from each of the above retrofitting. Further, an insight is provided about wind turbine functioning under very stressing regimes, as for example high wind speeds.

Keywords: wind energy; wind turbines; SCADA; retrofitting; performance evaluation.

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1. Introduction

Wind turbine technology and condition monitoring techniques [1] have been continuously evolving and the operational unavailability of a wind turbine is estimated nowadays to be of the order of 3% of its lifetime [2]. The target of 100% of technical availability is therefore becoming realistic and this motivates the research about further optimization of the efficiency of wind kinetic energy conversion. The retrofitting of wind turbines, in order to improve the power production, is therefore becoming a common practice. This kind of interventions has material and labor costs and producible energy is lost during installation. For this reason, it is crucial to inquire if the performance upgrade justifies the cost of the retrofitting. One key point is that the estimate of the guaranteed energy improvement is commonly provided by the wind turbine manufacturer under the hypothesis of ideal operation conditions of the wind turbines. Instead, the real operation conditions of wind turbines are commonly very different from ideal ones, because of wake interactions [3–7] and-or terrain effects [8–11].

Wind turbines are subjected to non-stationary conditions because of the stochastic nature of the resource and therefore it makes little sense to compare the energy production of a wind turbine before and after an upgrade. Therefore, commonly, the power curve is studied [12]: it is the relationship between wind speed and power output and the International Electrotechnical Commission (IEC) [13] has established widely accepted standards for analyzing it. Basically, the power output of the wind turbine is averaged on wind speed intervals (commonly of 0.5 m/s); the dependency on environmental factors is addressed by normalizing the wind speed to standard air density conditions. Further, data describing the wind turbine operating under the wake of a nearby one are filtered away.

The study of the IEC power curve might not be precise enough to distinguish performance improvements of the order of the percent of the Annual Energy Production (AEP), as in the case of

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retrofitting; further, for some reason as in one of the test cases of the present work, it might happen that the approach can't be employed at all. One might therefore possibly invoke other kinds of precision modeling of wind turbines power curve. It actually is a very fertile field in the scientific literature [14–17]: as regards these models, the main drawback for their application to the study of wind turbine upgrades is that they are too complex and not enough flexible to be applied to the range of different criticality that the study of wind turbine upgrades poses.

The above shortcomings are both circumvented in the present study: this work actually is a collaboration between academia and industry. The industry is Renvico srl [1], owning and managing 335 MW of full-scale wind turbines in Italy and France. Some wind turbines owned by Renvico have been retrofitted in several ways: this has been a pilot test and the decision of extending the retrofitting to the other wind turbines in the corresponding wind farms has been based on the assessment, coming from this study, of the real profit on the pilot test cases. The SCADA data from the retrofitted and non-retrofitted wind turbines from the wind farms of interest have therefore been shared with the University of Perugia. This academia-industry collaboration, as shall be shown in the next Sections, has produced methods for the study of power curve upgrades, standing at the frontier of the scientific debate and being as well integrable in the everyday industrial management of the wind turbines. This kind of studies on this subject, basing on operational data, has been very recently developing in the scientific literature: in [18], a kernel plus method is adopted for computing wind turbine performance upgrades. The test cases are pitch angle control optimization and aerodynamic retrofitting (vortex generators installation on the blades [19]). As regards vortex generators, the numerical study of their effect has attracted a certain attention in the scientific literature: in [20], three different blades equipped with vortex generators have been designed and several stall and pitch regulated wind turbine models have been simulated by means of Blade Element Momentum (BEM) theory; in [21], the physics of vortex generators on wind turbine DU97-W-300 airfoil is studied through three-dimensional numerical models; in [22], the S809 airfoil is analyzed. In [23] the effects of two types of flow control devices, vortex generators and Gurney flaps, on the power output performance of a 5 MW wind turbine is studied by means of BEM theory. As regards vortex generators and the ex-post study of power production increase through operational data, in [24], an academia-industry joint study is presented and production of two onshore test case wind farms is considered. On one hand, SCADA data with 10 minutes of sampling time are employed; on the other hand, high-frequency power data are employed: the estimates of production improvement are shown to be similar.

Summarizing, in this work, three test-cases are presented and discussed:

1. Optimization of the pitch angle control system near the cut-in, for an improved start-up;
2. Blade retrofitting through the installation of vortex generators and passive flow control devices;
3. Extension of the power curve for very high wind speed, by raising the cut-out and high wind speed cut-in.

The test cases 1 and 2 have been studied using the same kind of method: the estimate of the energy improvement is basically computed by comparing the actual production in a post-upgrade period against the simulation of how much the wind turbine would have produced under the same wind conditions if the retrofitting hadn't been installed. For doing this, a model of the pre-upgrade behavior is needed: this is achieved by modeling the pre-upgrade power output of the retrofitted wind turbines by means of an Artificial Neural Network (ANN). The main difference between the case 1 and the case 2 is the selection of the inputs to the model. In particular, the test case 2 is challenging because, after the upgrade, the nacelle wind speed measurements are not reliable and therefore can't be used as inputs to the model. Further, the site is very complex [10,25] and it is difficult, although necessary, to use the nearby wind turbines as references for the environmental conditions. Despite the different complexity,

[1] www.renvicoenergy.com

the criticality of test cases 1 and 2 is the same: modeling as precisely as possible the pre-upgrade power output of the upgraded wind turbines.

As regards the test case 3 and in general the comprehension of the power curve for very high wind, the criticality is not in the precision of the power curve modeling, also because at rated power the errors have a lower relative importance. In this case, the issue is understanding the wind conditions and the logic of the control system before and after the upgrade. This subject has deserved a certain attention in the scientific literature: for example, in [26], the impact of the hysteresis phenomenon on the energy production is studied. The hysteresis is a control system logic for preventing the wind turbine to be subjected to severe dynamic loads: the wind turbine cuts out at a wind speed of the order of 25 m/s and cuts in again when the wind speed lowers several m/s, as for example at 20 m/s. In [27], control strategies for allowing wind turbines to operate above the cut out are studied, basing on the study of the fatigue loads. In [28], an extension of the power curve for very high wind, similar to the one analyzed in this work, is discussed.

On the grounds of the above discussion anticipating some main issues analyzed in this work, it is evident that SCADA-based approaches for the study of wind turbine power curve upgrades must conjugate precision with adaptability to different types of criticality and to different availability and quality of the data. The test cases presented in this work represent an interesting scenario of possible problems and solutions and are therefore useful for the scientific community and the industry as well. Summarizing, the structure of the manuscript is as follows: in Section 2, the test case of pitch angle optimization near the cut in is described. Section 3 is devoted to the test case of aerodynamic wind turbine blade retrofitting through vortex generators and passive flow control devices. Section 4 is devoted to the test case about the extension of wind turbine power curve above the cut out. Test case wind farms, data sets, methods and results are described in each of the Sections 2, 3 and 4 for each test case. Finally, in Section 5, conclusions are drawn and further directions of the present work are indicated.

2. Test case 1: improved start-up through pitch angle optimization

2.1. The wind farm and the data sets

Five wind turbines having 2.5 MW of rated power each are installed in a gentle terrain in France. The rotor diameter is 90 meters and the hub height is 80 meters. Three wind turbines (T1, T2, T3) have been retrofitted with a control system upgrade improving the pitch position for low wind speed, near the cut-in. Two wind turbines (T4, T5) haven't been retrofitted.

The SCADA data sets at disposal are collected with 10 minutes of sampling time. The following data sets are employed:

- D0 is employed for training the model: it goes from 01/05/2016 to 01/05/2017;
- D1 is employed for testing the model: it goes from 01/05/2017 to 01/09/2017;
- D2 is employed for computing the performance upgrade: it goes from 27/09/2017 (date of installation of the improved start-up) to 18/01/2018.

2.2. The method

The model has been focused on the $[3, 7]$ m/s interval of wind speed because the retrofitting acts near the cut-in: therefore each data set has been filtered accordingly. Notice that measurements corresponding to wind turbines operating under the wake of a nearby turbine are not filtered away, because the objective of this study is computing the performance improvement in real operation conditions.

The model is a feedforward ANN, with this structure:

- The output $y(\mathrm{x})$ is the power produced by each wind turbine.

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- The inputs are nacelle wind speed and wind direction (in the form of sin and cos of the nacelle wind direction θ). Therefore, $x_1 = v$, $x_2 = \sin\theta$, $x_3 = \cos\theta$.

The wind speed has been renormalized according to the meteorological conditions, for taking into account effects due to the variation of the density of the air. The air density averaged on 10 minutes basis is:

$$\rho_{10min} = \frac{B_{10min}}{R_0 T_{10min}} \quad (1)$$

where B is the measured air pressure, T is the measured absolute air temperature, $R_0 = 287.05 \left[\frac{J}{kg \cdot K}\right]$. For a wind turbine with active power control, the normalization is applied to the wind speed, as follows [13]:

$$V_n = V_{10min} \left(\frac{\rho_{10min}}{\rho_0}\right)^{\frac{1}{3}}. \quad (2)$$

The proposed method goes as follows: the model, trained with the D0 data set, is employed to simulate the power output using the D1 and D2 data sets and the residuals between simulations ($\hat{y}$) and measurements (y) are analyzed before and after the installation of the improved start-up. In other words, one has to observe how the residuals change when the improved start-up has been installed. Besides, the number of neurons of the model has been established my minimizing the mean absolute error in predicting the power output in the D1 data set. For $i = 1, 2$, one computes

$$\Delta_i = 100 * \frac{\sum_{\mathrm{x} \in \mathrm{Data_i}} (y(\mathrm{x}) - \hat{y}(\mathrm{x}))}{\sum_{\mathrm{x} \in \mathrm{Data_i}} y(\mathrm{x})}. \quad (3)$$

Since Δ_i is constructed with the relative discrepancies of power data each having the same sampling time (10 minutes), the quantity $\Delta = \Delta_2 - \Delta_1$ provides a percentage estimate of the energy improvement. Further, a Student's t-test can be performed to detect the difference in the residuals $R(\boldsymbol{x}_1)$ and $R(\boldsymbol{x}_2)$. The t statistic is computed as

$$t = \frac{\bar{R}_2 - \bar{R}_1}{\sigma_R \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}. \quad (4)$$

In Equation 4, N_1 and N_2 are the number of measurements respectively in D1 and D2, $\bar{R}_2$ and $\bar{R}_1$ are the average residuals between measurement and model respectively in D1 and D2 and σ_R is given by

$$\sigma_R = \sqrt{\frac{(N_1 - 1)S_1^2 + (N_2 - 1)S_2^2}{N_1 + N_2 - 2}}, \quad (5)$$

where S_1 and S_2 are the standard deviations of the residuals in data sets D1 and D2.

In this case, it is also possible to study straightforwardly the wind turbine power curve for obtaining a mostly qualitative picture of the performance improvement. This has been done and a refinement with respect to the IEC guidelines has been adopted: the considerable data population in the $[3, 7]$ m/s wind speed interval[2] allows to average the power output in wind speed intervals of 0.25 m/s without compromising the statistical significance of the analysis.

2.3. The results

In Figures 1, 2, 3 and 4, some power curves are reported. The data sets are respectively all the available data before the upgrade (D0 and D1 jointly) and after the upgrade (D2). T1, T2, T3 in Figures 1 to 3 are the three retrofitted wind turbines, T4 hasn't been retrofitted.

[2] else, besides, the adoption of the improved start-up wouldn't justify the installation cost.

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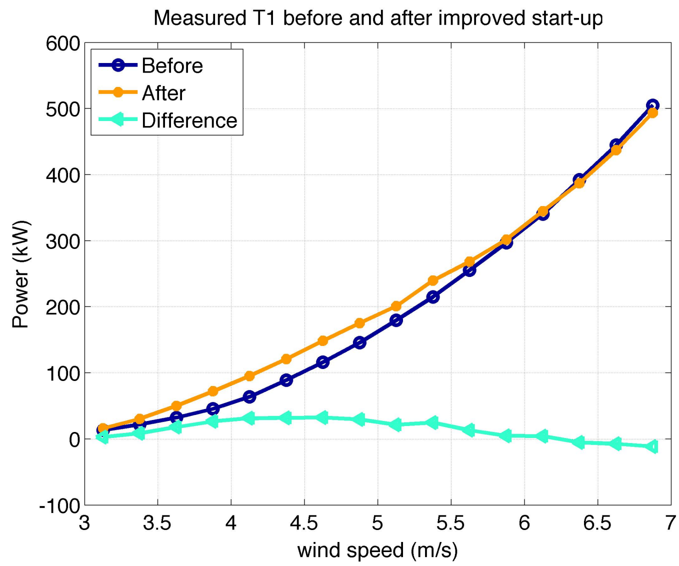

Figure 1. Power curve of wind turbine T1 before and after the retrofitting.

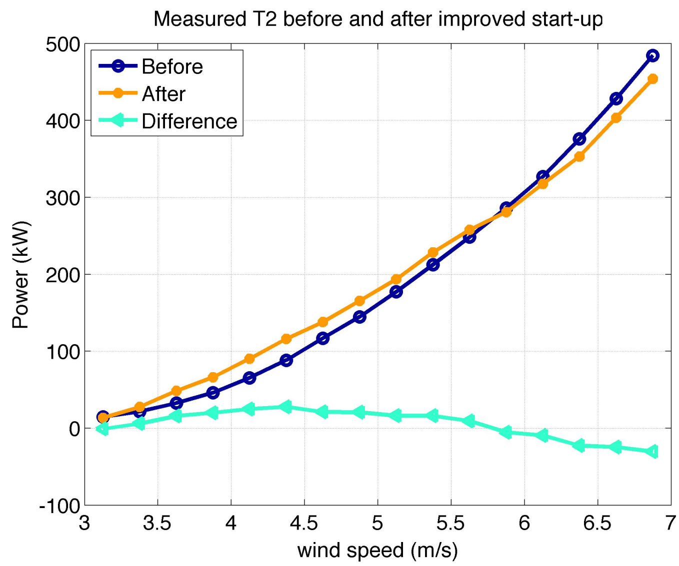

Figure 2. Power curve of wind turbine T2 before and after the retrofitting.

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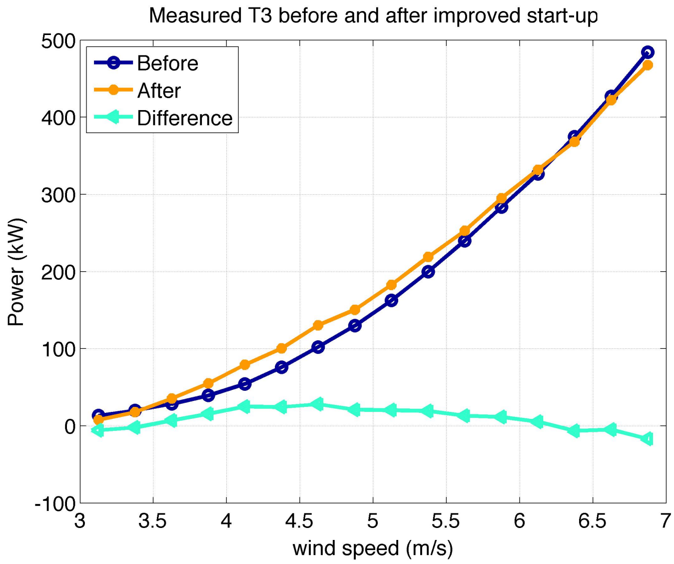

Figure 3. Power curve of wind turbine T3 before and after the retrofitting.

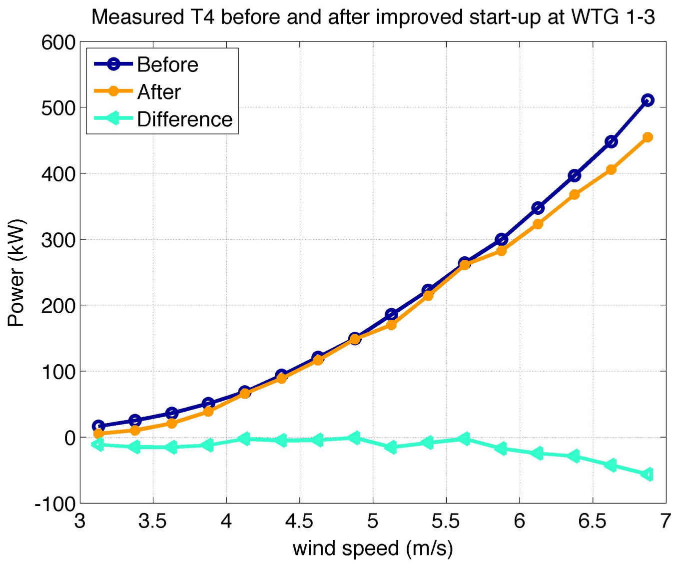

Figure 4. Power curve of wind turbine T4 before and after the retrofitting of the WTG1-WTG2-WTG3 wind turbines.

From Figures 1 to 3, it arises clearly that the performances of T1-T2-T3 have improved with respect to before the retrofitting and this is especially visible if comparing against the power curve of turbine T4 (Figure 4) measured in the same periods. As a quantitative support to this picture, the value of the t statistics comes at hand: it is of the order of 10^{-11} for each of the retrofitted wind turbines, thus supporting that D1 and D2 shouldn't be considered data sets coming from the same ensemble.

In Table 1, the results are reported for the estimate of the energy improvement for T1, T2, T3 during the period D2. Notice that this estimate is a percentage referred to the amount of energy produced during D2 in the $[3, 7]$ m/s interval.

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Table 1. Results for the estimation of energy production improvement in the [3,7] m/s interval.

Wind Turbine	Δ
T1	+4.35%
T2	+5.95%
T3	+3.76%

In Table 2, the values of Δ from Table 1 are converted in percentages of improvement with respect to the total energy produced during D2. This quantity is indicated with Δ_E.

Table 2. Estimate of the energy improvement with respect to the overall production during D2

Wind Turbine	Δ_E
T1	+0.51%
T2	+0.77%
T3	+0.49%

As a further comment, notice that the above estimate (Table 2) might be not representative of the long-term wind intensity statistics: namely, because it refers to autumn and winter, when there is scarcity of wind near the cut-in with respect to summer. For this reason, finally, the results of Table 1 have been projected to a twelve months data set for obtaining a simulation of the long-term improvement, basing on the estimate 1. The results are collected in Table 3.

Table 3. Long-term estimate of the energy improvement with respect to the overall production, basing on the results from Table 1.

Wind Turbine	Δ_E
T1	+0.88%
T2	+1.39%
T3	+0.74%

From Table 3, it arises that the long-term estimate of energy improvement shows significant differences from turbine to turbine: for example, the improvement for T2 is estimated to be twice as for T3. This would not be observable from the power curves in Figures 2 and 3, because they are similar. Further, by weighting the power curves against a unique Weibull distribution for the site (as common in the estimate of Annual Energy Production), the difference from turbine to turbine wouldn't be highlighted. Therefore, the lesson is that being driven by data in the training of the model and in its application is fundamental to observe the energy improvement with a fine grain.

3. Test case 2: aerodynamic retrofitting through vortex generators and passive flow control devices installation

3.1. The wind farm and the data sets

17 wind turbines having 2.3 MW of rated power each are installed in a very complex site [10,25]. The rotor diameter is 93 meters and the hub height is 80 meters. T7 is the wind turbine that has undergone aerodynamic blades retrofitting.

Three SCADA data sets, having 10 minutes of sampling time, are employed:

- D0 is employed for training the model: it goes from 01/01/2016 to 01/01/2017;

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- D1 is employed for testing the model: it goes from 01/01/2017 to 01/07/2017;
- D2 is used for quantifying the performance improvement: it goes from 01/09/2017 to 01/04/2018.

The data sets D0 and D1 refer to periods during which the standard blade configuration was adopted, the data set D2 describes T7 wind turbine adopting the retrofitted blades.

3.2. The methods

The production increase is estimated similarly in principle to the case of Section 2: by observing how the difference between simulated and measured power output of turbine T7 behaves before and after the installation of the aerodynamic upgrade. In order to do this, a model must be formulated. The output y of the model is the power production of T7. In this case, the formulation of the model is more complicated with respect to Section 2: it is hypothesized that the nacelle transfer function of turbine T7 hasn't been updated by the manufacturer after the installation of the flow control devices. Therefore, the nacelle wind speed of T7 can't be used as input for the model because the measurements during the D2 data set are not reliable. An argument for supporting this hypothesis is the following: in Figure 5, the power coefficient $C_p = \frac{P}{\frac{1}{2}\rho A v^3}$ as estimated from the SCADA data during the D2 data set is reported as a function of the wind speed. P is the measured power output, ρ is the air density on site, A is the blade swept area and v is the undisturbed wind speed as reconstructed from the nacelle wind speed through the nacelle transfer function. In Figure 5, the power coefficient measurements for T7 and for a sample wind turbine (T2) from the rest of the wind farm are reported and it clearly arises that the measurements for T7 are implausible because they are often of the order of twice the Betz limit. Therefore, it must be argued that the wind speed measurements at T7 are implausible. Sideways, this implies that the straightforward power curve analysis according to IEC guidelines [13] can't be performed for turbine T7.

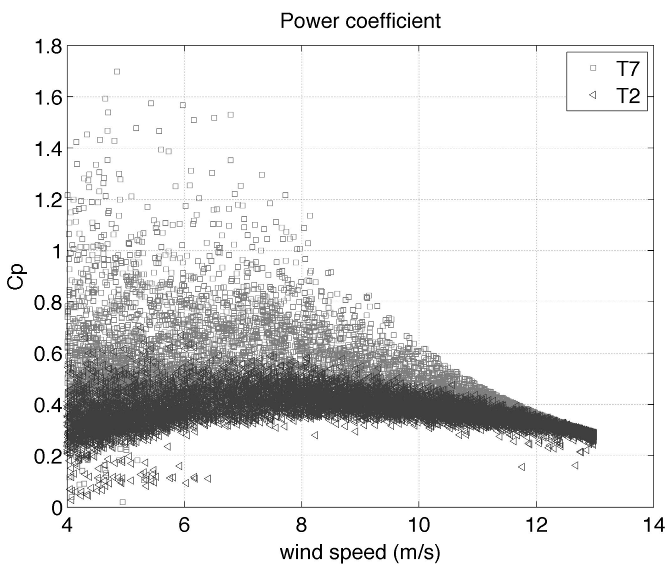

Figure 5. he power coefficient C_p, as computed from the SCADA data, vs. nacelle wind speed: T7 and a sample wind turbine (T2), D2 data set.

On the grounds of the above discussion, it is then necessary to adopt the wind turbines nearby T7 as references for constructing the model. Due to the severe complexity of the terrain, it has been considered more solid to use as reference the power output of the nearby turbines rather than the nacelle wind speed.

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The inputs x to the model are therefore the power outputs of a certain number of turbines nearby T7. The selected model is a feedforward ANN model. The number of neurons in the hidden layer and the number of inputs have been selected by minimizing the mean absolute error between simulation and measurements in the testing period D1. The inputs are selected to be the power outputs of wind turbines T1, T2, T3, T4, T5, T6, T8, T9.

The data sets are filtered on the condition of power output production from the T1-T9 wind turbines. Further, data are filtered on power production of T7 below the rated, because at rated power the upgrade has no effect. Similarly to what is done in Section 2, the measurements corresponding to wind turbines operating under the wake of a nearby turbine are not filtered away.

3.3. The results

In this case, due to the fact that the nacelle transfer function hasn't been updated and therefore the nacelle wind speed measurements in the data set D2 are implausible, the power curve plot for wind turbine T7 can't be performed.

In order to have an insight into the performance improvement produced by the retrofitting, it is possible to plot $R(x_1)$ and $R(x_2)$ on a sample model run: this allows to appreciate how the residuals between measurements and simulations vary after the retrofitting.

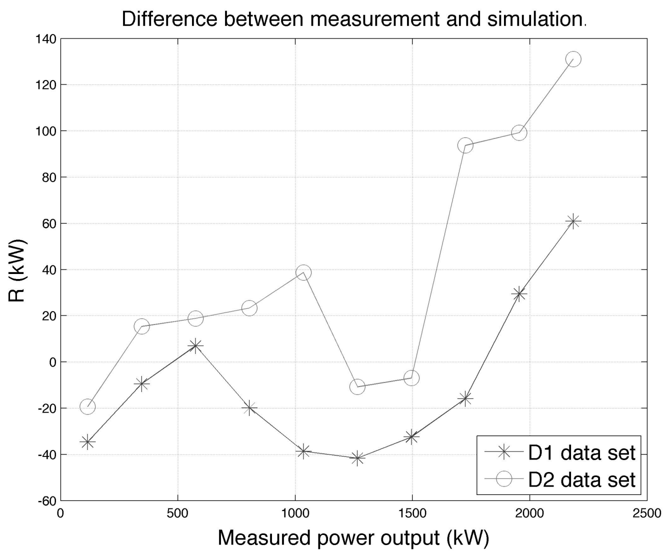

Figure 6. The average difference between T7 power measurements and simulation (Equation 1), for data sets D1 and D2 on a sample model run.

In Figure 6, the sets $R(x_1)$ and $R(x_2)$ are plotted after being averaged within intervals having amplitude of the 10% of the rated power. Observing Figure 6, it arises that the performances are similar before and after the upgrade approaching the cut-in, while the improvement is more and more clear approaching rated power. In this case, due to the complexity of the site, the results vary from model run to model run in a way that can't be neglected: for this reason, the procedure has been repeated several times, until the standard deviation of the results reaches a reasonable plateau. The average energy improvement is computed as $\Delta = 3.9\%$. In other words, the estimate is that T7 has produced, during data set D2 and below rated power, the 3.9% more than it would have done without retrofitting. Further, the probability that there hasn't been an improvement is computed, using the t statistic, as being of the order of 10^{-14}.

Moreover, similarly to what has been done in Section 2.3, it is possible to estimate how much Δ amounts with respect to the total energy produced by T7 during the D2 data set: the result is

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$\Delta_E = 1.9\%$. Similarly to Section 3.2, this result has also been converted into a long-term estimate and the results is that the increase in AEP is of the same order of Δ_E. Finally, it is important to notice that the reported results are of the order of a third lower than the estimate provided by the wind turbine constructor under the hypothesis of ideal operating conditions.

4. Test case 3: the extension of the wind turbine power curve above the cut out

4.1. The wind farm and the data sets

The wind farm is the same of Section 3. Refer to that Section for some basic information about the wind turbines.

The SCADA data set, here on named D1, employed for the following analysis has 10 minutes of sampling time and goes from 01/01/2017 to 01/01/2018. This data set corresponds to a period during which all the wind turbines of the farm have been equipped with the high wind speed control system upgrade.

In the following Table 4, the nomenclature for the high wind speed analysis is reported.

Table 4. Nomenclature of the high wind speed control system management

Nomenclature	Wind Speed Regime
v_{in}^{bef}	high wind speed cut-in wind speed before the control system upgrade
v_{out}^{bef}	cut-out wind speed before the control system upgrade
v_{max}^{bef}	shut-down wind speed before the control system upgrade
v_{in}^{aft}	high wind cut-in wind speed after the control system upgrade
v_{out}^{aft}	cut-out wind speed after the control system upgrade
v_{max}^{aft}	shut-down wind speed after the control system upgrade

Basically, v_{out} is the average wind speed at which the control system stops the wind turbine; v_{in} is the high wind speed cut-in, i.e. the average wind speed below which the wind turbine restarts after a cut-out; v_{max} is the gust wind speed, i.e. the maximum wind speed at which the control system stops the wind turbine. The SCADA data set at disposal includes minimum, maximum, average and standard deviation on the 10 minutes. Therefore, v_{in} and v_{out} are monitored by looking at the average SCADA wind speed, v_{max} is monitored by looking at the maximum SCADA wind speed.

4.2. The methods

The estimation of the improvement in energy production is done through the analysis of SCADA data of wind speed and production. The high wind speed upgrade extends the power curve above the pre-upgrade cut out wind speed: therefore, in this wind speed interval, whatever production measured post-upgrade is a gained production because pre-upgrade the wind turbine would be stopped. The downside is that, for wind speed between the post-upgrade cut-in and the pre-upgrade cut-out, the power production is derated: according to the pre-upgrade logic, except for the case of wind turbine in hysteresis, the production would be rated power, while, according to the post-upgrade logic, the production is less than rated. Therefore the energy balance is tricky: if a wind turbine experiences high wind mainly in the unfavorable interval corresponding to de-rating, the upgrade might have a negative effect.

This can be understood by comparing qualitatively the power curves before and after the upgrade: in Figure 7, a sample power curve before the installation of the upgrade is reported. In Figure 8, a sample power curve after the installation of the upgrade is reported. In Figures 7 and 8, vertical lines are reported in correspondence of v_{in}^{bef} and v_{out}^{bef} (dashed lines) and v_{in}^{aft} and v_{out}^{aft} (solid lines).

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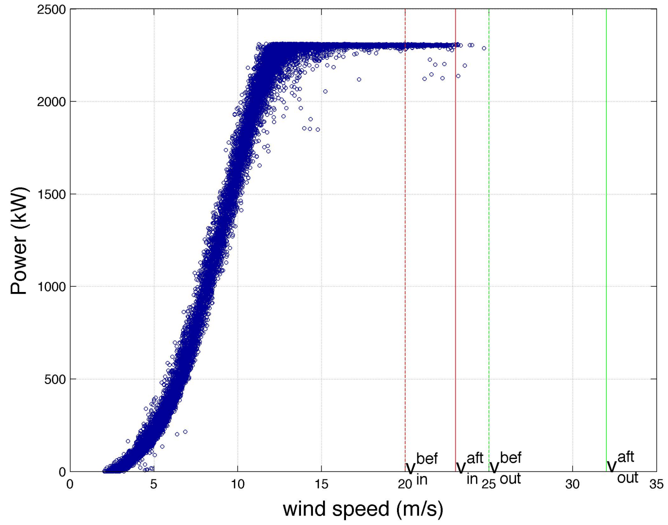

Figure 7. A sample power curve before upgrade.

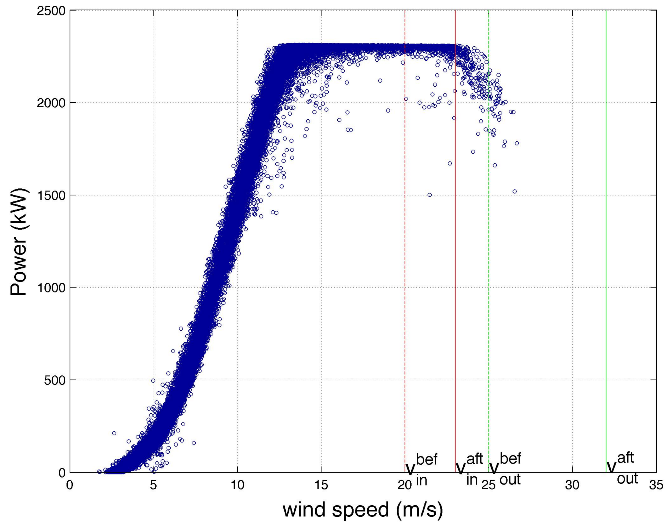

Figure 8. A sample power curve after upgrade.

For computing the energy balance, the following conditions are therefore verified:

- if $v_{in}^{bef} \leq v \leq v_{out}^{bef}$ and $v_{max}^{bef} \leq v_{max} \leq v_{max}^{aft}$: the wind turbine has gained its measured production;
- if $v > v_{out}^{bef}$ and $v_{max} < v_{max}^{aft}$: the wind turbine has gained its measured production;
- if $v_{in}^{bef} \leq v \leq v_{out}^{bef}$ and $v_{max} < v_{max}^{bef}$ and the wind turbine would be in hysteresis according to the pre-upgrade logic: the wind turbine has gained the measured production;
- if $v_{in}^{bef} \leq v \leq v_{out}^{bef}$ and $v_{max} < v_{max}^{bef}$ and the wind turbine would not be in hysteresis according to the pre-upgrade logic: the wind turbine has lost the difference between the rated and the measured production.

As briefly discussed in Section 1, the criticality in this case doesn't lie in the modeling of the power curve, but rather in the comprehension of the logic of the control system. It is therefore useful to

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compare the computation of the energy improvement against a simulation of the energy improvement in the same data set. In this case, the power curve for wind speed higher than v_{out}^{bef} is taken from the indications of the wind turbine manufacturer and is here on indicated as P. The following conditions are therefore verified:

- if $v_{in}^{bef} \leq v \leq v_{in}^{aft}$ and $v_{max}^{bef} \leq v_{max} \leq v_{max}^{aft}$: the wind turbine should gain rated power;
- if $v_{in}^{aft} \leq v \leq v_{out}^{bef}$ and $v_{max}^{bef} \leq v_{max} \leq v_{max}^{aft}$: the wind turbine should gain the power indicated by the P model;
- if $v > v_{out}^{bef}$ and $v_{max} < v_{max}^{aft}$: the wind turbine should gain the power indicated by the P model;
- if $v_{in}^{aft} \leq v \leq v_{out}^{bef}$ and $v_{max} < v_{max}^{bef}$ and the wind turbine would not be in hysteresis according to the pre-upgrade logic: the wind turbine has lost the difference between the rated and the power indicated by the P model;
- if $v_{in}^{bef} \leq v \leq v_{in}^{aft}$ and $v_{max} < v_{max}^{bef}$ and the wind turbine would be in hysteresis according to the pre-upgrade logic: the wind turbine should gain rated power;
- if $v_{in}^{aft} \leq v \leq v_{out}^{bef}$ and $v_{max} < v_{max}^{bef}$ and the wind turbine would be in hysteresis according to the pre-upgrade logic: the wind turbine should gain the power indicated by the P model.

4.3. The results

In Table 5, the results are reported. The measured energy production improvement (second column) and the simulated energy production improvement (third column), basing on the measured wind conditions, are reported. It is important to notice that the simulated energy improvement is of the order of twice the measured one: 1.06% of the total production of the wind farm against 0.44%.

Table 5. Estimation of the measured and simulated energy production improvement: D1 data set

Wind Turbine	Measured extra production (% of the total actual)	Simulated extra production (% of the total actual)
T1	0.55	0.78
T2	0.63	0.76
T3	-0.07	1.73
T4	0.51	1.76
T5	0.91	2.48
T6	2.04	3.50
T7	0.65	1.49
T8	-0.01	0.18
T9	-0.04	0.49
T10	0.06	0.62
T11	0.31	0.32
T12	0.36	0.56
T13	0.50	0.57
T14	0.02	0.03
T15	0.00	0.14
T16	-0.02	0.67
T17	0.03	0.22

The mismatch between simulated and measured energy improvement (Table 5) has stimulated a further analysis about its causes. It has been observed that the measured power output is very similar to the simulated one according to the indications from the manufacturer, when the wind turbine operates in the high wind region. The point is that the wind turbine is not always operating in the high wind region when it is expected to. An analysis of the wind turbine states during the shutdowns in the high wind speed region has revealed that there are issues related to vibrations and to the control system (spikes in the generator revolutions per minute). Therefore, the lesson is that if a wind farm owner intends to assess the theoretical profitability of the high wind speed power curve upgrade basing solely on the wind conditions measured at wind turbine nacelle, it must be taken into account that, doing this, an upper limit is obtained and the actual improvement can be considerably lower, in a way that is unpredictable without modeling the vibration and the control of the wind turbine.

5. Conclusions

It is non-trivial to realistically estimate the energy production improvement from wind turbines retrofitting. The reason is basically that wind turbines operate under non-stationary conditions, because of the stochastic nature of the wind. Once a retrofitting has been adopted, it is possible to measure the energy production and, in order to quantify the profitability, one has also to estimate how much the wind turbine would have produced in the same conditions, but without the upgrade. It is therefore needed to model the pre-upgrade power output of the retrofitted wind turbine with precision.

These issues are common in the everyday practice of wind turbine management at the industrial level but their possible solution involves methods standing at the frontier of the scientific research. Actually, some interesting papers on the subject in the scientific literature are quite recent [18,24]. For these reasons, this work has been organized as a collaboration between academia and industry and the results of this work have been used by the involved company to assess the profitability of some wind turbine retrofitting and to evaluate the possibility of extending it to other wind turbines in the corresponding wind farms. One key point of the present work is that a common unpleasant limitation is circumvented: typically, the estimation of energy improvement is provided by the wind turbine manufacturer to the management under the hypothesis of ideal operation conditions (flat terrain, absence of wake interactions and so on). Real operation conditions are very different from ideal ones and it is therefore important to compute the energy improvement basing on real statistics, as is done in this work.

An upgrade of the power curve of a wind turbine can be classified basically according to two categories:

- below rated power, given a wind speed, the wind turbine produces more than before the upgrade because of the optimization of the control system or because of aerodynamic optimization;
- the range of operational wind speed is extended, typically in the very high wind region, and therefore the upgrade makes the wind turbine operate when it wouldn't do according to the pre-upgrade behavior.

In the former case, the challenge in computing the effect of the upgrade is the precision modeling of the power output below rated power. In the latter case, the challenge rather lies in the comprehension of the logic of the control system regulating the shutdown or the power production. In this work, three test cases have been studied: two belong to the former category and one to the latter:

1. Pitch angle optimization near the cut-in;
2. Aerodynamic optimization through the installation of vortex generators and passive flow control devices;
3. Extension of the power curve in the high wind region through the raising of the cut-out and high wind speed cut-in.

The first two cases have been studied by modeling the power of the retrofitted wind turbines by means of an ANN model. The difference between the case 1 and the case 2 is basically in the availability and the quality of the data sets and, consequently, in the complexity of the proposed model: as regards the case 2, the nacelle wind speed measurements post-upgrade at the retrofitted wind turbine are not reliable and therefore can't be used as input to the model. Further, the terrain is very complex and it is non-trivial to employ the nearby wind turbines as references and construct a model having the necessary precision. As regards case 3, the energy improvement is computed by comparing the pre-upgrade to the post-upgrade control system logic according to the measurements of power output and of wind speed at the nacelle of the wind turbines.

Summarizing, the main findings for each test case are the following:

1. In this case, it possible to observe a production improvement near the cut-in also using the average power curve method according to the IEC guidelines. The added value of the proposed method is in the fact that, being driven by the wind statistics at each wind turbine, it is possible to distinguish more finely the behavior of each wind turbine. The order of magnitude of the energy improvement is 1% (1.4% in the most profitable wind turbine, 0.7% in the less profitable).
2. In this case, it is not possible to employ straightforward approaches like the IEC power curve and therefore the proposed method is even more valuable because it circumvents the limitations of the data set. The estimate is that the retrofitting has an impact of the order of 2.0% of the AEP. This estimate is of the order of one third lower than the one provided by the wind turbine manufacturer.
3. The extension of the power curve in the high wind region has been estimated weighting an order of 0.5% of the AEP of the wind farm since it has been installed. It has been observed that this amount is of the order of half the expected, according to the measured wind conditions. The mismatch between measurement and simulation is explained by the fact that there are frequent shutdowns, due to vibration and control issues, when the wind turbine is expected to work at high wind speed.

Summarizing, in this work an ensemble of wind turbine power curve upgrades has been considered and this has allowed to highlight the criticality of each test case. This can be useful for the industry, because it demonstrates the profitability of including frontier research in the wind farm management, and for the academia, because the objective and the testing ground of this kind of works are peculiar with respect to the literature in wind turbine power curve modeling.

Further possible directions of the present work include the extension of the test cases, the comparison of several approaches (it would be interesting, for example, to compare with the kernel plus method of [18]). Moreover, some kinds of retrofitting, as for example the test cases 2 and 3 of the present work, call for an improved effort in the condition monitoring of the wind turbines: it would be extremely valuable to model [29–31] and to study experimentally how the retrofitting affects the mechanical behavior of the wind turbines, especially for very stressing external conditions as in the case of high wind speed.

References

1. Yang, W.; Tavner, P.J.; Crabtree, C.J.; Feng, Y.; Qiu, Y. Wind turbine condition monitoring: technical and commercial challenges. *Wind Energy* **2014**, *17*, 673–693.
2. Tchakoua, P.; Wamkeue, R.; Ouhrouche, M.; Slaoui-Hasnaoui, F.; Tameghe, T.A.; Ekemb, G. Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges. *Energies* **2014**, *7*, 2595–2630.
3. Barthelmie, R.J.; Hansen, K.; Frandsen, S.T.; Rathmann, O.; Schepers, J.; Schlez, W.; Phillips, J.; Rados, K.; Zervos, A.; Politis, E.; others. Modelling and measuring flow and wind turbine wakes in large wind farms offshore. *Wind Energy* **2009**, *12*, 431–444.
4. Barthelmie, R.J.; Pryor, S.C.; Frandsen, S.T.; Hansen, K.S.; Schepers, J.; Rados, K.; Schlez, W.; Neubert, A.; Jensen, L.; Neckelmann, S. Quantifying the impact of wind turbine wakes on power output at offshore wind farms. *Journal of Atmospheric and Oceanic Technology* **2010**, *27*, 1302–1317.
5. Hansen, K.S.; Barthelmie, R.J.; Jensen, L.E.; Sommer, A. The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm. *Wind Energy* **2012**, *15*, 183–196.
6. Grassi, S.; Junghans, S.; Raubal, M. Assessment of the wake effect on the energy production of onshore wind farms using GIS. *Applied Energy* **2014**.
7. Moriarty, P.; Rodrigo, J.S.; Gancarski, P.; Chuchfield, M.; Naughton, J.W.; Hansen, K.S.; Machefaux, E.; Maguire, E.; Castellani, F.; Terzi, L.; others. Iea-task 31 wakebench: Towards a protocol for wind farm flow model evaluation. part 2: Wind farm wake models. Journal of Physics: Conference Series. IOP Publishing, 2014, Vol. 524, p. 012185.

Peer-reviewed version available at *Energies* **2018**, *11*, 1300; doi:10.3390/en11051300

8. Politis, E.S.; Prospathopoulos, J.; Cabezon, D.; Hansen, K.S.; Chaviaropoulos, P.; Barthelmie, R.J. Modeling wake effects in large wind farms in complex terrain: the problem, the methods and the issues. *Wind Energy* **2012**, *15*, 161–182.
9. Rodrigo, J.S.; Gancarski, P.; Arroyo, R.C.; Moriarty, P.; Chuchfield, M.; Naughton, J.W.; Hansen, K.S.; Machefaux, E.; Koblitz, T.; Maguire, E.; others. Iea-task 31 wakebench: Towards a protocol for wind farm flow model evaluation. part 1: Flow-over-terrain models. Journal of Physics: Conference Series. IOP Publishing, 2014, Vol. 524, p. 012105.
10. Castellani, F.; Astolfi, D.; Mana, M.; Piccioni, E.; Becchetti, M.; Terzi, L. Investigation of terrain and wake effects on the performance of wind farms in complex terrain using numerical and experimental data. *Wind Energy* **2017**, *20*, 1277–1289.
11. Hyvärinen, A.; Segalini, A. Effects from complex terrain on wind-turbine performance. *Journal of Energy Resources Technology* **2017**, *139*, 051205.
12. Carrillo, C.; Montaño, A.O.; Cidrás, J.; Díaz-Dorado, E. Review of power curve modelling for wind turbines. *Renewable and Sustainable Energy Reviews* **2013**, *21*, 572–581.
13. IEC. Power performance measurements of electricity producing wind turbines. Technical Report 61400–12, International Electrotechnical Commission, Geneva, Switzerland, 2005.
14. Lydia, M.; Kumar, S.S.; Selvakumar, A.I.; Kumar, G.E.P. A comprehensive review on wind turbine power curve modeling techniques. *Renewable and Sustainable Energy Reviews* **2014**, *30*, 452–460.
15. Pelletier, F.; Masson, C.; Tahan, A. Wind turbine power curve modelling using artificial neural network. *Renewable Energy* **2016**, *89*, 207–214.
16. Taslimi-Renani, E.; Modiri-Delshad, M.; Elias, M.F.M.; Rahim, N.A. Development of an enhanced parametric model for wind turbine power curve. *Applied energy* **2016**, *177*, 544–552.
17. Ouyang, T.; Kusiak, A.; He, Y. Modeling wind-turbine power curve: A data partitioning and mining approach. *Renewable Energy* **2017**, *102*, 1–8.
18. Lee, G.; Ding, Y.; Xie, L.; Genton, M.G. A kernel plus method for quantifying wind turbine performance upgrades. *Wind Energy* **2015**, *18*, 1207–1219.
19. Øye, S. The effect of vortex generators on the performance of the ELKRAFT 1000 kw turbine. 9th IEA Symposium on Aerodynamics of Wind Turbines, Stockholm, ISSN, 1995, pp. 0590–8809.
20. Mueller-Vahl, H.; Pechlivanoglou, G.; Nayeri, C.; Paschereit, C. Vortex generators for wind turbine blades: A combined wind tunnel and wind turbine parametric study. ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. American Society of Mechanical Engineers, 2012, pp. 899–914.
21. Gao, L.; Zhang, H.; Liu, Y.; Han, S. Effects of vortex generators on a blunt trailing-edge airfoil for wind turbines. *Renewable Energy* **2015**, *76*, 303–311.
22. Wang, H.; Zhang, B.; Qiu, Q.; Xu, X. Flow control on the NREL S809 wind turbine airfoil using vortex generators. *Energy* **2017**, *118*, 1210–1221.
23. Fernandez-Gamiz, U.; Zulueta, E.; Boyano, A.; Ansoategui, I.; Uriarte, I. Five megawatt wind turbine power output improvements by passive flow control devices. *Energies* **2017**, *10*, 742.
24. Hwangbo, H.; Ding, Y.; Eisele, O.; Weinzierl, G.; Lang, U.; Pechlivanoglou, G. Quantifying the effect of vortex generator installation on wind power production: An academia-industry case study. *Renewable Energy* **2017**, *113*, 1589–1597.
25. Castellani, F.; Astolfi, D.; Burlando, M.; Terzi, L. Numerical modelling for wind farm operational assessment in complex terrain. *Journal of Wind Engineering and Industrial Aerodynamics* **2015**, *147*, 320–329.
26. Horváth, L.; Panza, T.; Karadža, N. The influence of high wind hysteresis effect on wind turbine power production at Bura-dominated site. Proc. Eur. Wind Energy Conf. Exhibition, 2007.
27. Markou, H.; Larsen, T.J. Control strategies for operation of pitch regulated turbines above cut-out wind speeds. *Proceedings of EWEC 2009 (Marseilles, France, 16-19 March* **2009**.
28. Jelavić, M.; Petrović, V.; Barišić, M.; Ivanović, I. Wind turbine control beyond the cut-out wind speed. Annual Conference and Exhibition of European Wind Energy Association (EWEA2013), 2013.
29. Bossanyi, E.; King, J. Improving wind farm output predictability by means of a soft cut-out strategy. European Wind Energy Conference and Exhibition EWEA, 2012, Vol. 2012.
30. Petrović, V.; Bottasso, C.L. Wind turbine envelope protection control over the full wind speed range. *Renewable Energy* **2017**, *111*, 836–848.

Peer-reviewed version available at *Energies* **2018**, *11*, 1300; doi:10.3390/en11051300

31. Petrović, V.; Bottasso, C.L. Wind turbine optimal control during storms. Journal of Physics: Conference Series. IOP Publishing, 2014, Vol. 524, p. 012052.