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Performance analysis of an operating windfarm of 21 MW in Greece for a period of three years

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Abstract

Wind power is currently the fastest growing exploited source of energy globally. Hence there is an urgent need to understand how wind turbines perform from different perspectives. Even though condition monitoring systems have a huge impact in optimizing wind farm performance via fault anticipation, they do omit several aspects concerning performance. Seemingly, there is a scarcity of studies that attempt to deliver a quick and practical method for wind farm performance analysis, which is the aim of this study.

This paper presents a methodology for evaluating the performance of operating wind farms via the use of the Supervisory Control and Data Acquisition System (SCADA) and modeled data. The potential annual energy is calculated per individual turbine, factoring in underperforming/loss events to present their power output in accordance with a representative derived operational power curve. Losses/underperformance events are calculated and categorized into several groups, aimed at identifying and quantifying their causes.

The methodology requires both anemometry data from the SCADA system, an onsite meteorological mast, a lidar in combination with the mast as well as modeled data. The discrepancy of the data representing the valid points of the power curve is also taken into consideration when assessing performance, i.e. wind speed vs power output of events that are not loss/underperformance. Production loss and relative standard deviation of power/energy output are the main results obtained in this paper. Finally, a number of optimization measures are suggested in order to boost performance, which can enhance a wind farm's financial results.

To assess the reliability of the proposed methodology, a case study was conducted and evaluated. The case study concerns a windfarm with nominal capacity of 21MW in Kitheronas, Viotia county, Greece which has been operational since November 2014. The case study shows that the methodology is capable of determining potential energy and associated losses/underperformance events. Several questions were raised during the assessment and are discussed in this work, recommendations for optimization measures are presented at the end of the paper. It also contains a discussion on the limitations and uncertainties associated with the presented methodology and case study.

Keywords: performance analysis, windfarm, underproduction, energy losses

1. Introduction

Concerns relating to climate change are a priority for global collaboration. Efforts are being made to keep the planet within +2°C above the pre-industrial period. [1]. According to the Environmental Protection Agency in the United States, the energy and heating sector was responsible for the biggest share of global greenhouse gas emissions in 2010 with 25% of total emissions [2]. Therefore, a pioneering transition toward a cleaner energy system is required. Among the various clean energy sources, wind power has emerged as the fastest growing exploited energy source in the world [3]. Hence there is an urgent need to minimize the levelized costs of energy and enhance asset management mechanisms. Accordingly, it is of great importance to come up with optimization techniques to maintain prices in a range that delivers fast growth, especially in light of the trend in using tenders and market-based support systems in most European Union (EU) member states [4]. Since power is the fundamental product of wind turbines, it makes sense for researchers to start their investigations with power performance. A standard way to test power performance is presented in international standard IEC 61400-12-2. The

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methodology aims to correct the NTF, using another meteorological anemometer located within a distance of 2-4 D (where D is the turbine rotor diameter). The contractual power curve is derived by applying necessary corrections and filtrations, such as air density correction and filtration of operational alarm code flagged events. This is very important when attempting to derive a representative operational power curve. A comparison with the manufacturer's power curve is made. This results in power performance testing in accordance with IEC standards [5]. Kim et al. [6] succeeded in conducting a power performance test of a wind turbine located at a distance of about 11 D to the met mast in compliance with the procedure provided in IEC 61400-12-2. The team concluded that the new method is valid and can reduce costs significantly compared to the one proposed in IEC 61400-12-2, since one met mast can be used for a larger number of turbines than even those located at longer distances. In both cases, the presence of an external source for measuring the undisturbed wind flow in front of the rotor is a requirement, although located at different distances from the targeted turbine for power testing, 2-4 D in IEC 61400-12-2 and > 4D [6]. This entails high costs for wind farm operators and in many cases there is insufficient space to install high measurement masts. Oh and Kim [7] denoted the impracticality and economic infeasibility in the case of power performance testing an entire wind farm according to IEC 61400-12-2. Accordingly, they proposed a simpler method for power performance analysis. Power performance verification was executed by comparing the AEP from contractual and measured power curves for a wind farm of five turbines. The authors linked the Ruggedness Index (RIX) of each wind turbine to check performance deviation from the contractual power curve. RIX expresses the average of elevation differences between adjacent cells of a digital elevation grid; in other words, it represents the average slope of a center area in reference to adjacent areas of the same size. Another approach based on the contractual power curve is found in the work of Nymfa Noppe, (2014). The methodology entails calculating the operational power curve based on IEC 61400-12-2 and then comparing it to the contractual power curve. Using the SCADA data for assessing performance of wind turbines through loss calculation is a badly under-investigated topic. Only a handful of researchers have published studies covering this issue. As part of the extensive project "Assessment and optimization of the energy production of operational wind farms" [8] the authors attempted to assess the performance of operating wind turbines by calculating the relative production loss (RLoss) using SCADA data. The same approach is present in the paper of Singh (2013). This methodology starts by deriving the operational power curve after applying the necessary corrections and a number of filtration criteria. Then the expected power is calculated, denoted as PEP (total theoretical production summed over all events when the Wind Turbine Generator (WTGs) have been identified as not running at full performance) in [8] and as theoretical power in [9]. Then, the difference between expected power and actual produced power is the respective loss/gain for each wind turbine. While Lindvall et al. [8] called it loss ratio, Singh (2013) introduced the energy ratio parameter, which is simply actual produced power divided by expected power. This allows a relative comparison of wind turbines in the same farm against each other to determine the most underperforming ones. This energy ratio indicator is highly beneficial when assessing the deterioration of wind turbine performance. The studies of Lindvall et al. [8] and Singh [9] emphasize the use of a service book in addition to the proposed methodologies. This will give finer detail about the events where turbines are underperforming and consequently facilitate the identification of underperformance reasons, hence informing performance optimization measures.

2. Scope of the study

While most of the research within this field is mainly about condition monitoring and costly power test performance in compliance with IEC standards, few reports have addressed performance analysis via use of SCADA data. This paper attempts to deliver a practical, quick and convenient way of assessing the performance of an operating wind farm via use of anemometry data from the SCADA system, an onsite meteorological mast, a lidar in combination with the mast as well as modeled data. The method works either as independent assessment tool or as a complementary tool for a condition monitoring system. This study investigates the following questions:

1. How much is the potential energy production?
2. How big is the production loss?
3. What are the main reasons behind the differentiation of energy production?
4. What optimization measures can be taken in order to improve energy productivity?

3. Methodology

It is very important for wind farm operators and project managers to understand why windfarms underperform. This enables operators to either optimize the wind farm or further investigate a specific aspect where a turbine/windfarm is underperforming. Accordingly, this will result in a number of optimization measures that in turn seek to boost the profitability of the wind farm.

Assessment of a wind farm is carried out by calculating the potential energy production, using four different inputs, and a comparison with the real energy production will be done. Due to technical problems at the windfarm (damage to a high voltage line – heavy winter environmental conditions and limitations at a certain wind turbine, low wind data availability of the onsite mast) the study will look at the second operational year of the windfarm.

The four scenarios for the estimation of energy production (including only wake losses and availability losses) are the following:

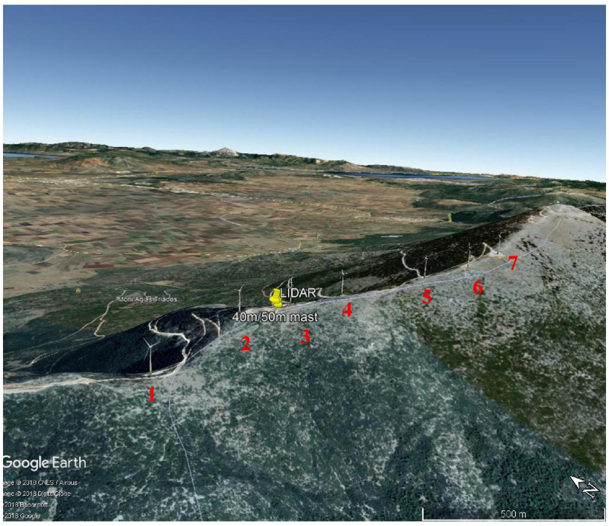

Figure 1: The site of the windfarm in Google Earth

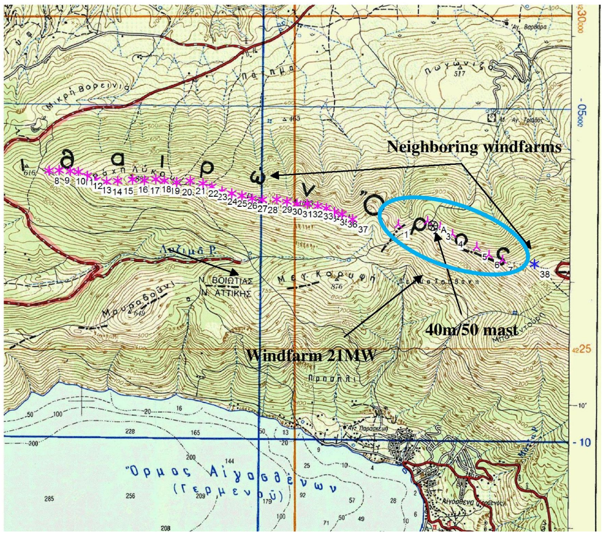

Figure 2: Site of the windfarm and of neighboring windfarms in 1/50,000 scale map

1. Use of wind turbines' wind data
2. Use of wind data of 40 m onsite mast sited between 2nd and 3rd windturbine
3. Use of available wind measurements (40 m and 10 m masts) in the pre-construction phase
4. Use of combined wind data of 40 m onsite mast with the measurements of lidar at the level of 78 m above ground level.

Moreover, the power curves are analyzed and compared with the expected power curves based on the windturbines' data (SCADA data). This methodology is suitable when the power curve measurement procedure based on IEC 61400-12-1 has not been performed.

The proposed methodology will be conducted and evaluated with regard to a case study concerning a 21 MW windfarm in Viotia county, Greece.

All wind potential and energy production calculations are performed using DTU WAsP, EMD WindPro and CRES Windrose software.

Figure 3: Photo of the windfarm, near to windturbine no 7

4. Project information

4.1. Overview of turbine type: Enercon E82-E4, hub height: 78 m, tower type: steel, wind class: IA rated power 3.0 MW, quantity: 7, mean wind speed at hub height: 10m/s

The windfarm is located at Kitheronas mountain, Viotia, Greece in a complex terrain area at an altitude of 1000 to 1200 m above sea level. The project is connected to National Electric System via Substation 20/150kV – Kitheronas and an overhead high voltage line of approx. 13.5 km.

5. Results

5.1. Time period—control of long-term wind climate

The dates for the three-year operation of the windfarm is 01.12.2014—30.11.2017. After thorough analysis of the available SCADA data and wind data, this paper uses the second year of operation: 01.12.2015—30.11.2016. The other two years encountered technical problems mainly with the high voltage line (reduced availability) and power limitations at one windturbine. Additionally there is low data availability at the onsite mast due to winter-time environmental conditions.

[11] at 100m agl (N.38.180, E.23.240) which is at a distance of one kilometer from the 40 m mast. The statistical method MCP Matrix was applied using EMD WindPro (monthly values of wind speed) of the 40 m mast and the grid point. The correlation was excellent, with a correlation factor of 0.94. The data availability of the time series of the second year of operation is 98.4%, which is very high. This period is taken as representative of the long-term period of 1993-2017 (25 years) (wind speed factor equals one), so it is helpful for evaluating the energy productivity of the windfarm.

Table 1: Technical data of windturbine E-82 E4 [10]

Technical specifications E-82 E4	
Rated power, kW	3,000
Rotor diameter, m	82
Hub height, m	69/78/84
Wind zone (DIBt)	-
Wind class (IEC)	ICE/EN IA and IEC/EN IIA
WEC concept	Gearless, variable speed, single blade adjustment
Rotor	
Type	Upwind rotor with active pitch control
Rotational direction	Clockwise
No. of blades	3
Swept area, m^2	5,281
Blade material	GRP (epoxy resin); Built-in lightning protection
Rotational speed, m	Variable, 6 .. 18
Pitch control	ENERCON single blade pitch system; one independent pitch system per rotor blade with allocated emergency supply
Drive train with generator	
Main bearing	Double row tapered/cylindrical roller bearings
Generator	ENERCON direct-drive annular generator
Grid feed	ENERCON inverter
Brake systems	3 indepentent pitch control systems with emergency power supply Rotor brake Rotor lock
Yaw system	Active via yaw gear, load-dependent damping
Cut-out wind speed, m/s	28 .. 34 [with ENERCON storm control]
Remote monitoring	ENERCON SCADA

5.2. Time period—control of long-term wind climate

The annual energy production at the SCADA level (sum of energy production of seven windturbines after wake losses, real technical availability and no other losses) for the second operational year is 60.548 MWh. The technical availability of this year was 98% without any serious problems or operational interruptions.

5.3. Energy production estimation based on one year windturbines' wind data

The annual energy production estimation based on one year wind data from the windturbines (after wake losses and loss of technical availability -2%) using combined EMD WindPro and DTU WAsP is 62.973 MWh.

5.4. Energy production estimation based on one year wind data from 40 m mast

The annual energy production estimation based on one year's wind data from the 40 m onsite mast (after wake losses and loss of technical availability -2%) using combined EMD WindPro and DTU WAsP is 75.685 MWh.

5.5. Energy production estimation based on wind data at pre-construction phase

The financing of the windfarm was based on an energy yield assessment based on measurements from 1 year (7 months of measurements from 40 m onsite mast and correlating data from a 10m mast). The total period was 11/1/2008-10/1/2009. The correlation factor was very good (R=0.97) and the data availability of measurements was 85%. The annual energy production estimation(after wake losses and loss of technical availability -2%) is 72.149 MWh. WindSim software was used.

5.6. Energy production estimation based on one year's wind data from 40 m mast and operation of lidar at 78 m agl

Lidar measurements (with lidar Windcube) started on Thursday November 2, 2017 and ended on Tuesday March 27, 2018. CRES supervised the whole measurement campaign. Wind data from an existing 50m high meteorological mast (same position and measurement levels as the 40 m mast), approximately 45m away (operated by an accredited laboratory), are used for the purpose of correlation-validation of the LIDAR dataset.

There was excellent correlation with measurements of the mast and the wind data of neighboring wind turbines (R=0.995 with mast measurements). The wind shear factor (a) between 40 m and 78 m (hub height of windturbines) is –0.035.

SCADA data for the two neighboring wind turbines (nos. 2 and 3) were made available by the Company to the author, in order to perform some preliminary correlations. The height of 78m (hub height) of lidar measurements was used

Figure 4: Photo from the lidar position, near to windturbine 3 and 50 m mast

Figure 5: Photo of the lidar used, from CRES

for the following results. Data concurrency was checked and verified through maximization of the correlation coefficient. It is underlined here that nacelle anemometers are influenced by the rotating blades and often “corrected” by wind turbine manufacturers with transfer functions established at sites not similar to this one. Additionally, when considering free-flow conditions, lidar position should be taken into account.

Therefore, comparisons are indicative and should be used only to establish general trends, such as:

1. Lidar wind speed is systematically higher (on average 8%-9%) than that of nacelle anemometers
2. Lidar wind direction and nacelle direction sensor are in good agreement.

Having this new information about real wind shear from 40 m to 78 m, a new energy production calculation was done using EMD WindPro and DTU WAsP software packages in combination, taking the same losses as mentioned above. The result was 69.959 MWh/year.

5.7. Comparison of energy production estimations vs real energy production

The comparison of four scenarios versus real energy production for the second year is illustrated in the following table:

5.8. Power curve analysis

The power curve of Enercon E82 E4-3.0MW as given by the manufacturer for air density of 1.225 kg/m³ (sea level) was corrected using EMD WindPro software for every wind turbine of the wind farm (altitude of 1000 .. 1200 m asl) based on the temperature of the second year, as shown in Fig. 6 (5% error).

Based on SCADA data, the real power curves are extracted for the second operational year. There is remarkable deviation from the expected corrected power curves, as illustrated in Fig. 6. Fig. 7 presents the power curves for wind turbine no. 7 indicatively, as the same results appear for the whole wind farm.

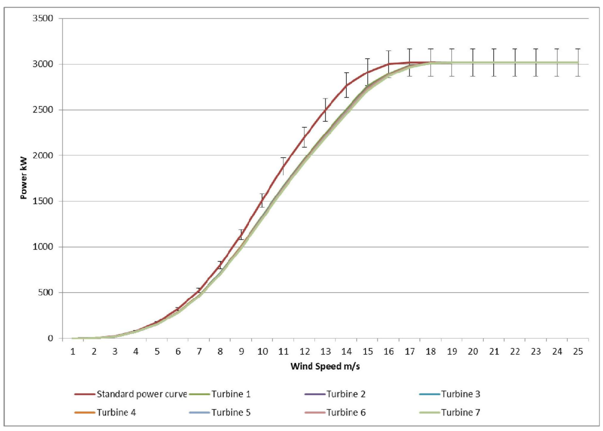

Figure 6: Standard power curve and the power curves for the seven wind turbines for the second year of operation.

Table 2: Results of comparison of estimations versus real energy production for the second year of operation

2^{nd} year of operation		Difference	Dif, %
EMD WindPro (WAsP) based on WTs data	62,973,100 kWh	2,424,666	-3.9
EMD WindPro (WAsP) based on 40 m mast meas.	75,684,500 kWh	15,136,066	-20.0
Pre-construction energy estimation	72,149,000 kWh	11,600,566	-16.1
EMD WindPro (WAsP) based on 40 m mast meas./lidar 78.3 m	69,959,000 kWh	9,410,566	-13.5
Reality	**60,548,434 kWh**		

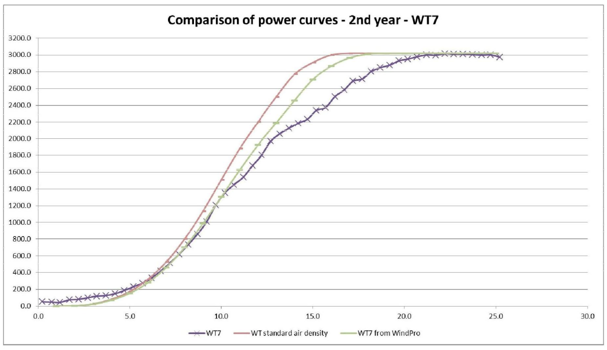

Figure 7: Comparison of power curve of 7th wind turbine (real vs corrected from WindPro)

6. Conclusions-discussion

6.1. Main reasons for underperformance

The above analysis clearly shows an underperformance of the wind farm in terms of energy productivity, which based on the new lidar data is approximately 13.5%. The reduced power curves of the wind turbines are the main reason.

Possible reasons for the discrepancy between real and predicted wind farm energy production are:

1. The quality of wind resource assessment at pre-construction phase
   Often an inadequate site assessment is the source of lower than expected energy production, not the unsatisfactory power performance of the wind turbines. In this case measurements were supplied by 40 m and 10 m onsite masts, but the availability of measurements was insufficient and the height at which the measurements were made was not at the limit of 2/3 of hub height, as per MEASNET guidelines [12]. The longterm correction was done by using the only long-term data available at that time (NCEP/NCAR), but now there are better alternatives with high spatial and time data resolution such as EMD ConWx mesoscale data.
2. Differences between real and expected power curves

Some manufacturers promise clients unrealistically optimistic power curves which have not been measured according to international accepted guidelines. High reliability and quality of measured power curves are guaranteed by qualified institutions only (accreditation according to EN 45001, MEASNET-members). Most manufacturers offer products based on power curves measured on prototype turbines. Thus a further source of uncertainty can originate from differences between the individual wind turbine and the prototype, e.g. due to non-optimal wind turbine settings (pitch control, yaw misalignment, NTF calibration, component failure especially rotor blades and electrical control system etc.).

The power performance of wind turbines can also be effected by aging of the turbines (regular wear and tear) and environmental impact (rotor blade degradation, dirt, salt on rotor blades). Such effects can be identified by monitoring wind turbine power performance over the whole lifetime of the wind farm in order to initiate appropriate action, e.g. replacing components and cleaning rotor blades.

6.2. Proposed optimization measures

The quality of pre-construction energy yield assessment must be high and guide the investor to a result with minimum uncertainty. Critical factors are: the representative measurement campaign, the reliable estimation of power losses and the robust long-term correction of the results.

Also, the nacelle anemometers must be calibrated in a wind tunnel by a qualified institution according to the MEASNET guidelines [12].

It should be noted that turbine manufacturers set the power curve of a specific turbine in a flat terrain. It is important to understand how wind speed values are provided: the anemometer measures the wind speed behind the rotor and then a Nacelle Transfer Function (NTF) is applied which aims to estimate the undisrupted wind speed in front of the rotor based on the measured wind speed behind the rotor. So there are uncertainties in power curve measurements of 6-12% (including site calibration) [13] and this uncertainty will be 10-20% in complex terrain in terms of energy production [5].

We strongly recommend verifying the wind farm power curve against measurements in order to optimize wind turbine operation and to validate the power curve guaranteed by the manufacturer. We propose applying the power curve measurements and site calibration based on IEC 61400-12-1 edition 2 2017. If this procedure is not applied, one solution for reliably investigating wind farm performance is the use of spinner anemometer system like ROMOWIND method [14].

ROMO Wind's iSpin technology measures the wind at the spinner in front of the wind turbine rotor, where the wind conditions are more stable and predictable. In front of the wind turbine the wind measurement is only affected by the shape of the spinner and slower wind speed (due to the rotor – induction effect) compared to the free wind speed measured by a wind met mast at two to four rotor diameter distance. Both of which can be easily factored in. This system is capable of producing measurement figures for yaw misalignment, inflow angle, turbulence intensity and power curves for all wind turbines.

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