Assessing annual energy production using a combination of lidar and mast measurement campaigns

Rachid Mkhaitari, Yamina Mir, Mimoun Zazoui
Laboratory of Materials, Energy and Control Systems, Faculty of Science and Technology of Mohammadia (FSTM), Hassan II University of Casablanca, Casablanca, Morocco

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ABSTRACT

The current study evaluates the wind potential at early stage of wind project using met mast and lidar. The wind data obtained from a met mast located away from the turbines can be hindered by obstacles, leading to limited coverage and height, it negatively impacting the project's performances. To address the above limitations, the study suggests implementing a secondary measurement approach utilizing Lidars in various locations to cover the full study area. This work assesses the two measurements campaign and compares the wind potential evaluated with data measured by met mast and lidars. The simulations of two wind data base are quantified referring to the main key performance indicators for a project of total capacity of 140 MW. The results show significant improvement in gross and net production for all exceedance scenarios, with 2% increase on the P90, and an improvement in the annual capacity factor by 1.09%. The use of Lidar data referenced to a met mast leads to accurate and bankable data, with the advances of cost and logistics, Lidars helps in layout configuration and performance evaluation.

Corresponding Author:

Rachid Mkhaitari
Laboratory of Materials, Energy and Control Systems
Faculty of Science and Technology of Mohammadia (FSTM), Hassan II University of Casablanca
Casablanca, Morocco
Email: rachidmkhaitari@mail.com

1. INTRODUCTION

The evaluation of a mega wind project is the preliminary phase where the potential site is identified and selected for further milestones. The first simulation of the wind data and the assessment of the related parameters are the primary basis for converting a site from a study area to a development zone. In giga wind projects, the met mast is the meteorological station for wind data, it serves as a reference for the analysis of the energy production and associated key performance indicators. However, the study area may have some constraints in terms of land and accessibility that need to be considered for the erection of the met mast. As per international standards, the coverage are of a met mast is usually limited to a radius up 10km for flat parcels. Installing multiple measuring masts in the same project zone can be costly particularly during the initial prospecting phase and may not meet the necessary protocols for a bankable measurement campaign. To overcome this issue with the optimized charges, the recommended approach in this study is to implement light detection and ranging (Lidar) technology sensors, to effectively overcome local limitations and guarantee complete coverage of the project location [1]. Previous use of Lidar has demonstrated its capability to measure wind data at varying altitudes, up to 200 m, as well as its ease of transportation and setup, making it a convenient option for wind measurement without the need for complicated procedures [2]. In the subsequent examination, a concrete case of wind project farm will be presented where Lidar wind data is analyzed and evaluated in relation to the performance of a 140 MW wind project. The results of the analysis will be used to compare the annual production and key performances of the site with previous simulation results obtained from the local mast data. This comparison will provide valuable insights into the effectiveness of Lidar technology in assessing wind conditions and the potential impact on the performance of the wind project. Overall, the goal of this analysis is to determine the usefulness of Lidars data with met mast in evaluating wind projects, and to gain a better understanding of how this mix technology can be practically used to optimize the project [3].

2. METHOD

Lidar is calibrated with existing mast and exposed for measurement on several points allowing the most area coverage, the measured data is completed and compared with data already measured by the met mast. The lidar's data are generally more representative is shown Figure 1, to ensure accurate database, the Lidar needs to measure for a minimum of 6 months per position. For the purpose to acquire a full understanding of the wind conditions, it is important to collect data over a long period of time to capture seasonal and annual variations in wind patterns. The initial configuration of the sensors should be oriented towards the north direction to ensure optimal data collection. The Lidar is configured to meet the following conditions:

- Each bin (one speed step) must include a minimum of 30 minutes of data
- The database must include a minimum of 180 hours of data

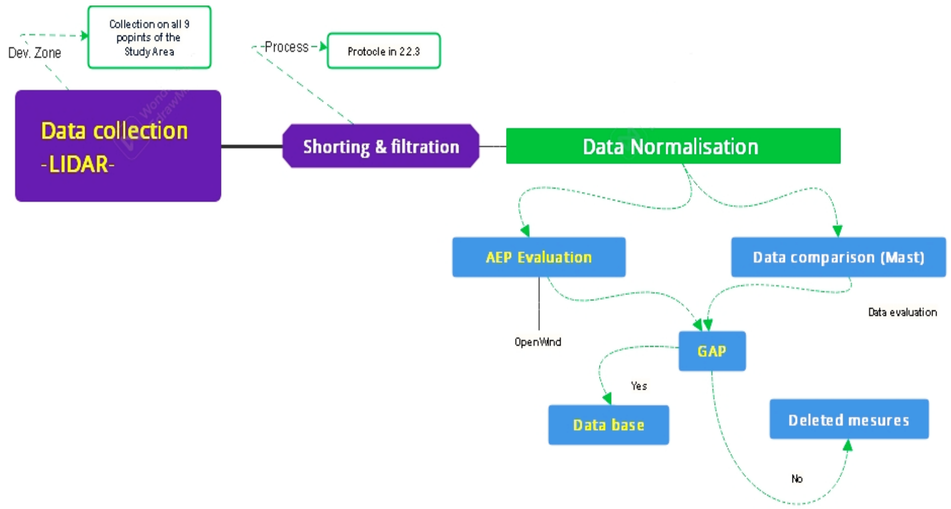

Figure 1. Process for Lidar's data collection

When Lidar captures incomplete data, it is replaced by a linear interpolation of adjacent bins. This is a widely accepted method for dealing with missing data and it helps to ensure that the data is as accurate as possible. The data should be normalized and reported according to absolute air density, as per the guidelines specified in page 8 of IEC 61400. This standard provides detailed procedures for measuring wind data for electricity production utility. The normalization process is a common practice ensures that the data are valid and consistent, and can be used for calculations and predictions of wind conditions in the study area. This is important for assessing the wind potential, designing and optimizing the wind project, more than complying with international standards [4]. After data collection, the filtering and sorting of data remains necessary in order to keep the true values and remove erroneous ones: i) Eliminate negative power values and zero values. Eliminate speeds between 3 m/s and 25 m/s; ii) By linear function refines non-existing bins on adjacent bins and eliminate disturbance directions; and iii) Loop 30 min of data for each bin. Complete 180 hours in the database

The simulation of the AEP and ACF values are computed using OpenWind. It requires a comprehensive and precise set of 10min data in CSV file, including wind speed, wind direction, air density and temperature for a minimum period of one year [5]. OpenWind is tailored based on local wind conditions, grid losses, availability, and technical limitations in order to provide accurate results. This work refers to the best practices for wind potential assessment as outlined in the IEC 41600 standards. It refers to a reel onsite collected wind data of 2 years (Sep. 2017 to Sep. 2019) that was measured by a local met mast of 82 m. Additionally, the study refers also to data that was collected and measured by Lidars placed closely to turbine positions. This supplementary Lidar data is utilized to complement the data from the met mast and to cover the entire study zone, providing a more comprehensive assessment of the wind potential in the area [6].

The Lidar is Windcube technology, ultraportable and waterproof, allowing vertical and horizontal wind sensing tools that measure under challenging climatic conditions. The Lidars are placed in predefined positions with the understanding that the length of measurement can only cover a radius of 2 km per position. The technology is considered to be a reliable and accurate tool for measuring wind conditions, and is able to provide valuable insights into the wind patterns. The use of Lidar will enable the measurement of wind at different heights, which will be crucial for assessing the wind potential and for the design and optimization of the wind project [7]. Lidar at each point of measurement is verified and calibrated before the measurement campaign. The calibration and certification process are needed to guarantee that is working correctly and measuring wind within the expected accuracy range. The process includes several tests carried out to make sure of optimal working condition. This process can be subcontracted to a third party, that have the necessary knowledge to verify the Lidar sensor and ensure that it complies with the established standards and regulations allowing to optimize the project design [8].

QGIS is extensively used in this work for composing various maps and for exploring spatial data interactively, with the purpose of configuring turbine positions and assessing terrain roughness and constraints. The final outputs of QGIS are considered as the foundation for further and advanced analysis of the layout configuration. It is adaptable and can be tailored to meet specific and unique needs, thanks to its extensible architecture and open access libraries that can be used to create additional layers and schemes.

2.1. Yield assessment based on met mast data

2.1.1. Met mast of 82 m

Local met mast is equipped with various sensors such as anemometer and wind vane, as well as a datalogger for communication with servers. The installation of the met mast is carried out in accordance with international guidelines for measuring wind parameters. The protocol is outlined in IEC 41600 and MEASNET guidelines (pages 50 to 56), with additional specifications for site assessment. These guidelines provide a detailed procedure for determining the generation performance characteristics of the adopted wind technology. The measured data collected by the met mast is analyzed and used to generate detailed reports that can be used to make informed decisions about the wind project. In this study, the available data were collected since Sep. 2017. Without a comprehensive and accurate wind database, the simulation would not be reliable and the results could not be used to make informed decisions about the wind project. Additionally, the met mast is an essential tool for measuring wind conditions and provides data that is critical for assessing the wind potential of the area, designing and optimizing the wind project, and complying with international standards [9].

2.1.2. Development zone

The study refers to international vortex and satellite wind data and to identify the most advantageous study area in terms of wind speed and load factor [10]. The chosen study area not only presents a high wind potential but also benefits from its proximity to the HV grid line of 400 kV, which facilitates easy access to the electrical substation. The proposed project has a rated capacity of 140 MW based on GE 5MW turbines, the selection process for the wind turbine model involved evaluating multiple factors, including the local wind characteristics and the performance of the turbine in terms of capacity and efficiency. The RD of 158 m is designed to maximize energy production by effectively harnessing the wind conditions in the area. The larger rotor diameter allows for increased energy generation compared to smaller turbines, making it a better fit for the specific wind conditions in the location Figure 2.

In Figure 3, the red line illustrates boundary of the reserved parcel and the position of the met mast. However, as per the met mat is 10km far from the turbines, the actual configuration does not fully comply with best practices as per the international standards. These standards suggest that measurements taken at such a distance could not accurately reflect the wind regime at all turbine's positions [11]. Despite this limitation, after data assessment and analysis, a 2 years period was selected for the short-term wind regime analysis for the development zone. Over this period, the average measured wind speed was 7.5 m/s at 82 m on the ground level (AGL), and the prevailing wind directions were from the South and South West. This information is crucial for designing the project and for assessing the wind potential of the area Figure 3.

2.1.3. AEP simulation (met mast 82 m)

The study uses long-term tools of extrapolation, namely MCP linear regression, wind index, and MCP Matrix, to generate updated wind data base for 20 years. However, the MCP methods are only considered if all the assessed data passes a given value of 0.7, while the wind index approach refers to the same values but in another monthly averaged R-values. For any chosen base of dataset, the practical extrapolation tools are applied based on the data and the averages of monthly values. After evaluating different combinations of reference data and extrapolation methods, the study identifies the Matrix MCP method using MERRA-2 data [12] at access point 5.0°E 50.5°N as the method with the least uncertainty and therefore selects it as the optimal combination for the study. In the long-term extrapolation tools based on MCP Matrix method, the results of are presented in Table 1, it includes Weibull main parameters for each sector at 100 m, and variation of the long-term wind potential such as the distribution of wind, average wind speed, frequency, and energy roses. The study shows that the average wind speed forecasted for the long-term is bit less than what is collected for the short period, with a value of 6.62 m/s versus 6.63 m/s. The main dominant wind direction come from SSW and WSW consistent with the observed short-term data [13], [14].

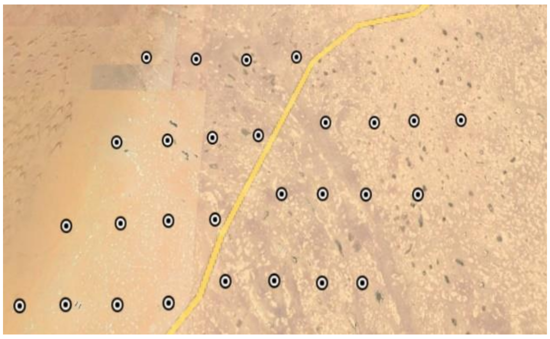

Figure 2. Study area including turbines positions

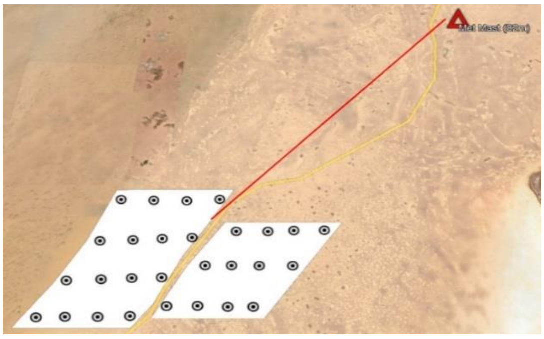

Figure 3. Existing met mast (10 km far from de zone)

Table 1. Long-term extrapolation

Wind measurement device	[-]	Mast
Height AGL	[m]	100
Arithmetic mean wind speed	[m/s]	6.62
Weibull mean wind speed	[m/s]	6.63
Weibull A	[m/s]	7.48
Weibull k	[-]	2.355
Prevailing wind directions	[-]	SSW-WSW
Wind directions with most energy content	[-]	SSW-WSW

OpenWind is the platform that is primarily used on international level for wind assessment. It uses satellite data or 10min data measured onsite to evaluate different scenarios of net and gross production, and the levels of exceedance starting from P50, P90 to P99 [15]. It is widely known and used refereeing to the proven accuracy. In this study, OpenWind is used to test the levels of variation on the annual energy production for the same turbine configuration and same technical characteristics. The main production results expected for a 20year period are summarized in Table 2. These results are important for assessing the power generation as well as the economic viability of the project [16]. The yield assessment as presented shows the following: i) In P50 the average for the capacity factor achieves approximately 59%; ii) On P95 the load factor is around 51%; iii) The yearly average production is 489 GWh (optimization of 72 GWh in the P50) Table 2.

The distance separated the mast from the project zone have an impact on the representativeness of the measurements for the study area. Roughness is a main parameter in the assessment that can impact the wind shear value. Any modification of the roughness parameters will have influence on the wind shear, that is able to propagate vertically over the project parcel. The performance impact of these changes on the measurement campaign varies with the distance to roughness profile, moreover it dependent on the atmosphere and the specific characteristics of the site. In this case, considering the distance that separate the met mast from the project zone, it can be inferred that the measurements may not be entirely representative of the wind conditions in the full study area. This is important to take into account when assessing the wind potential of the area, designing and optimizing the wind project and complying with international standards [17].

2.2. AEP based on lidar data

2.2.1. LIDAR measurement campaign

The Lidar measures the wind through the swept area at high altitude and takes turbulence into consideration, which reduces the uncertainty of measurements. The equipment is designed to collect 10min data over heights ranging from 0 to 200 m. It is important to highlight that used equipment must be synchronized to GMT time in order to have the same reference as the turbine and SCADA systems. This is important because it allows for accurate and reliable data collection, and ensures that the data can be compared and analyzed consistency. Lidar placement in accordance with IEC 61400V1 standards, must be aligned with the positions and heights of the wind turbines. It ensures that the sensor can capture wind conditions at the same heights as the turbine, allowing for accurate and reliable measurement campaign. The angle of emission of the light detection and ranging (Lidar) rays is 60°. Lidar sensors are used to measure wind conditions and other environmental factors in wind energy projects. According to industry standards, the optimal position for the Lidar sensor is between 220 and 250 m above the ground. This height provides optimal coverage of the project site, ensuring that the measurements taken by the Lidar are representative of the wind conditions over the entire area. Additionally, positioning the Lidar at this height minimizes the impact of any obstacles such as trees, buildings, or other structures, which may impact the accuracy and validity of the collected wind data. The combination of the 60° angle of emission and the ideal placement between 220 and 250 m ensures that the Lidar readings are accurate and closer to the wind conditions at the project development zone [18].

Table 2. Yield assessment met mast

Probability of exceedance	Annual energy production (GWh)	Annual capacity factor (%)
P50	561.98	59.19
P76	534.12	56.26
P84	519.83	54.76
P90	506.96	53.4
P95	489.62	51.57
P98	469.05	49.41
P99	454.7	47.9

2.2.2. LIDAR configuration

In Figures 4 and 5, nine positions defined for Lidars to cover up to 95% of the area. The positions are carefully selected to make sensors able to capture wind conditions from all directions at different heights which is crucial for assessing the wind potential, designing and optimizing the wind project and complying with the standards. The proposed positions are configured in a manner that is designed to cover the full zone, with a particular focus on capturing the wind measurements, this is to ensure that the Lidar is able to capture wind conditions that are representative of the conditions that the wind turbines will be exposed to [19].

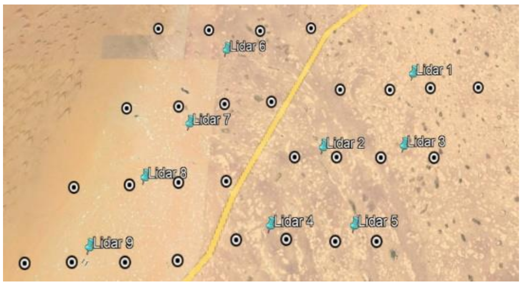

Figure 4. Turbine layout and Lidar positions

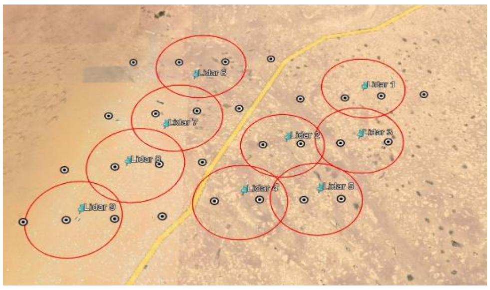

Figure 5. Area covered by Lidar

2.2.3. Wind data assessment

The measure correlate predict (MCP) algorithms are used to extrapolate the collected wind of the measurement campaign to a long-term period. This algorithm method allows first to configurate the links between the onsite measured wind data (measurement campaign outputs) and the long-term period reference data sets. This process is applied to the entire reference data, in order to elaborate a long-term time database of wind direction and wind speed along the site. This process is important for assessing the wind potential of the area, designing and optimizing the wind project, and complying with international standards.

In Figures 6 and 7, the values have been gathered and recorded as part of a measurement campaign assessment. The purpose is to collect data for further analysis and comparison. The data will be used to assess the performance of the measurement system and to evaluate the accuracy of the wind speed and direction readings. By comparing the collected data, it will be possible to identify any trends, patterns, or anomalies in the wind conditions, which can then be used to improve the accuracy of future wind measurements. The figures show visual representations of the wind speed and wind direction, which helps to make the data easier to understand and interpret. By plotting the data in this way, it is possible to see the overall trend in wind conditions over time, as well as any fluctuations or changes that may have occurred.

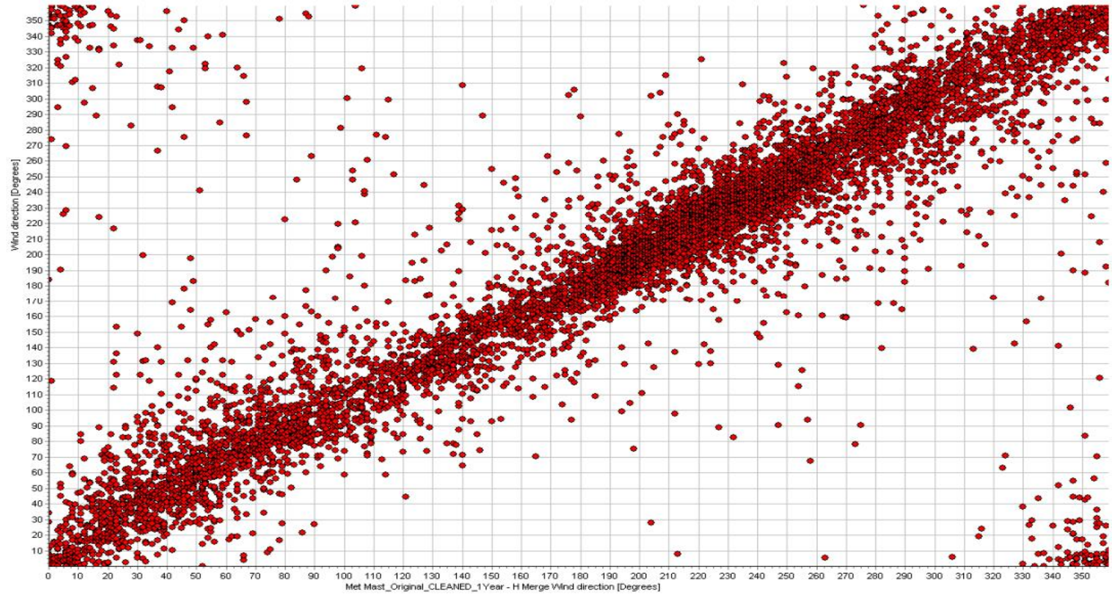

Figure 6. Wind Direction data comparison

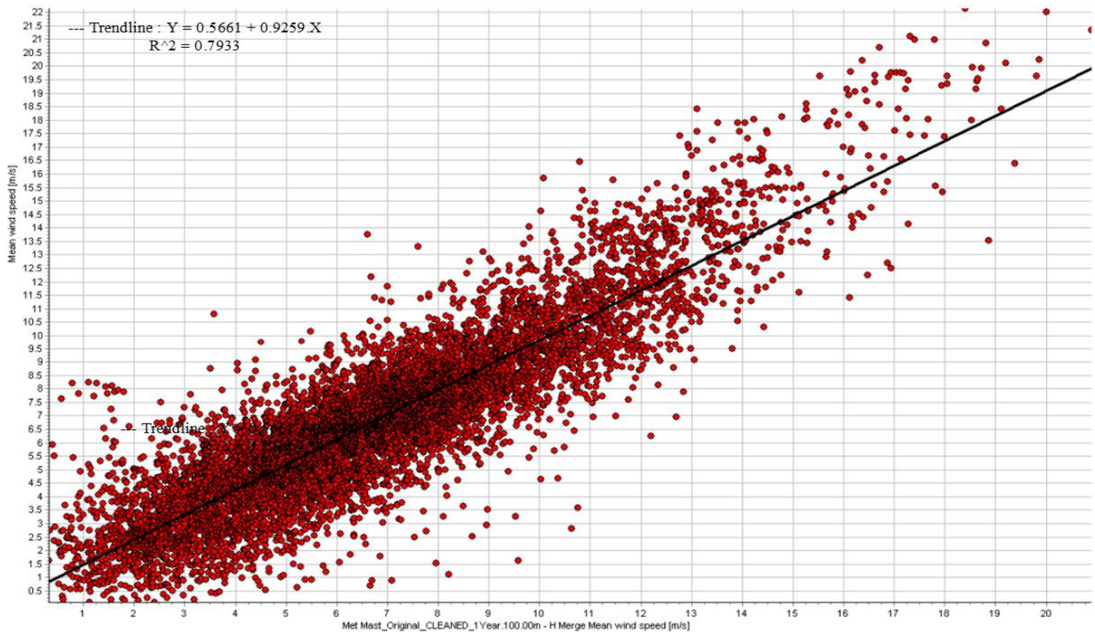

Figure 7. Wind Speed data comparison

The calculation of uncertainty figures is a complex process that takes into account multiple parameters, such as the quality and reliability of reference data, the method of extrapolation used to predict future values, and other factors that contribute to the accuracy of the calculation. This process involves analyzing the impact of each parameter on the calculation outcome, and determining which combination of parameters results in the lowest uncertainty. The use of the combination with the lowest uncertainty is crucial for ensuring the validity and reliability of the results. The uncertainty figure, therefore, serves as an important tool for evaluating the accuracy of a calculation and for making informed decisions based on the results. In Table 3, the shared data present the long-term wind regime parameters simulated for the case study, it shows the main wind directions, the linked frequency, and the registered average value of wind speeds. The following Figure 8 and Figure 9 illustrate the data on Table 3 by showing the Weibull distribution and the rose of main parameters (mean speed, energy, frequency). The main wind direction allows the precise focus for turbines configuration and final XY positions.

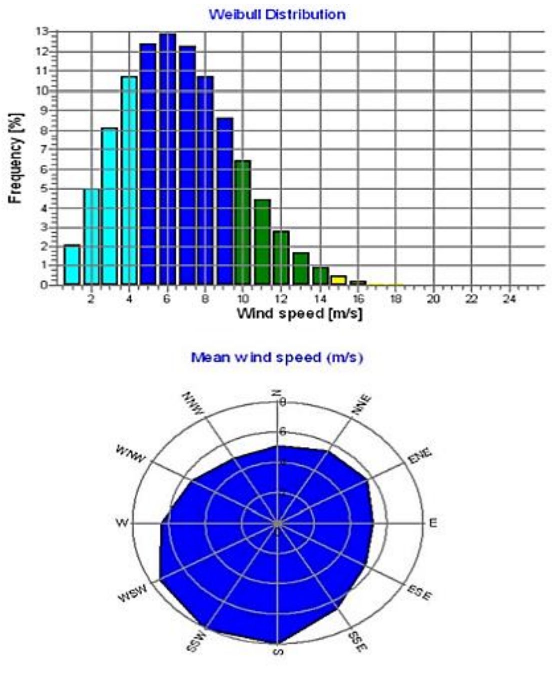

Figure 8. Weibull distribution and mean wind speed

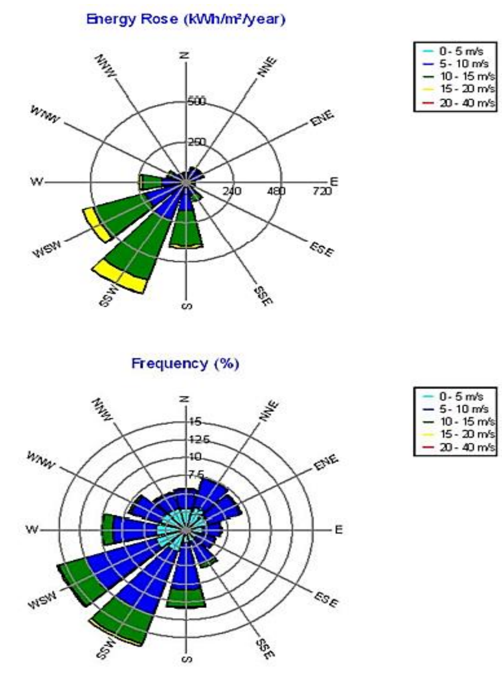

Figure 9. Energy rose and frequency distribution

Table 3. Long term wind regime

Sector	A-parameter (m/s)	K-parameter	Frequency (%)	Wind speed (m/s)
N	5.73	2.630	5.6	5.09
NNE	6.17	2.743	7.5	5.49
ENE	6.38	2.794	6.9	5.68
E	5.91	2.753	4.2	5.26
ESE	6.27	2.902	3.7	5.59
SSE	7.37	2.744	5.6	6.56
S	8.92	3.040	10.9	7.97
SSW	9.10	2.680	17.1	8.09
WSW	8.44	2.508	15.9	7.49
W	7.24	2.242	9.9	6.42
WNW	6.23	2.412	7.1	5.52
NNW	5.53	2.211	5.4	4.90

3. RESULTS AND DISCUSSION

3.1. AEP simulation

After collecting and analyzing the collected wind data, the final step is to calculate the energy productions with various probabilities (P75, P90, P95 percentiles) over different periods of time such as 1 year, 10 years, 15 years, and 20 years. This is done using the data collected from the Lidar sensor, met mast, and other sources. These calculations are important for assessing the wind potential of the area, designing and optimizing the wind project, and complying with international standards. The 20 years annual energy productions (AEPs) are calculated by summing up the energy production for each year over a period of 20 years. These calculations provide valuable insights into the expected energy production of the wind project over a long period of time, which is crucial for assessing the economic viability of the project and making informed decisions about its development in Table 4 and Table 5 [20], [21].

Table 4. Yield assessment with using Lidar (P90 main used for application)

Probability of exceedance	Annual energy production (GWh)	Annual capacity factor (%)
P50	573.35	60.39
P75	545.02	57.41
P84	530.44	55.87
P90	517.30	54.49
P95	499.61	52.63
P98	478.62	50.42
P99	463.98	48.87

Table 5. P50 energy production scenarios

Parameters	Values	Parameters	Values
Ideal energy (GWh)	693.42	Capacity factor (%)	60.39
Theoretical gross energy (GWh)	691.79	Topographic efficiency (%)	99.76
Gross energy (GWh)	691.79	Array efficiency (%)	97.96
Net energy (GWh)	573.35		

3.2. Results of the AEP and ACF

After analyzing the Lidar's wind data, the yield assessment was launched based on this data (blue line in Figure 10). This assessment showed an added production of 10 GWh on P90 and 13 GWh on P50. Additionally, the annual capacity factor was evaluated for the two assessments as shown in Figure 11. The ACF is a measure of the actual energy production compared to the maximum energy production that could be generated. It is increased by 1.09% for P90 scenario and 1.2% for P50. Means that by using Lidar data, the energy production is expected to be higher than the energy production predicted by the met mast data [22].

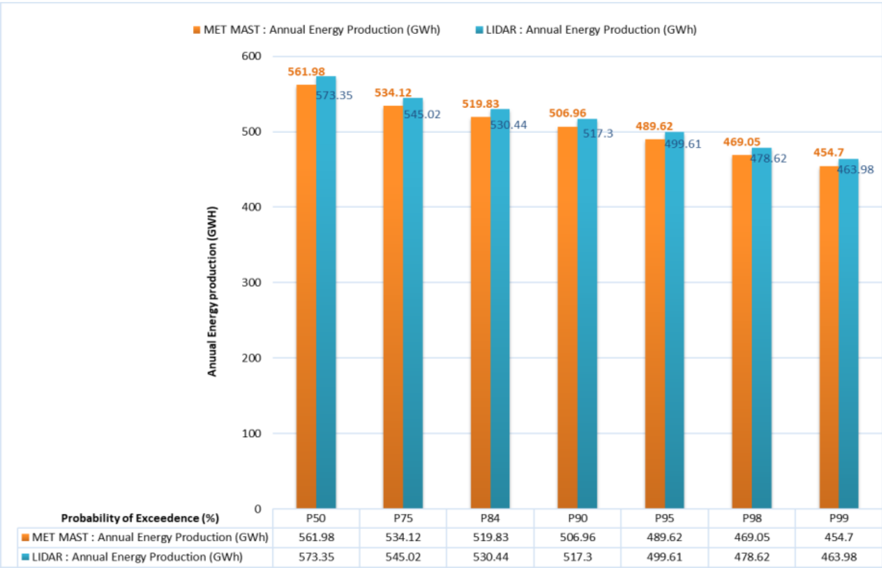

Figure 10. Comparison of the annual energy production Mast vs Lidar (GWh)

Figure 11. Comparison of the ACF improvements Mast vs Lidar (%)

On the exceeding scenario P90, the added volume of 13 GWh represents 2.56% of the net simulated AEP based on the mast data. This means that by using Lidar data, the energy production is expected to be

2.56% higher than the production predicted by the mast data. The net energy exceeded with given probabilities is crucial for the project development and risk assessment, as well as for all optimizations. This is because the net energy provides valuable insights into the expected energy production of the project over a long period of time, which is crucial for assessing the economic viability and making informed decisions about the development [23]. The Lidar simulation is done under the consideration that the net AEP is the most probable production that follows a normal distribution characterized by a mean value wind parameter equal to a standard deviation. By simulating the net production using Lidar data, it allows the possibility to improve the performances needed for wind projects, specifically the net volume and the ACF indicator. The ACF is a measure of the actual energy production compared to the maximum energy production that could be generated [24]. By simulating the net energy and the ACF, it provides valuable insights into the expected energy production and the overall performance of the wind project. This information can be used to optimize the project and make it more efficient, which can ultimately lead to cost savings and increased revenue [25].

3.3. Discussions

The mechanical loads analysis (MLA) is a recommended method for specifying the suitability of the turbine to the project. The MLA analyzes the turbine's conformity and ability to withstand wind loads that it will be exposed to in the specific location, it also helps to determine if the cutout and recut in wind speeds, which are the minimum and maximum wind at which the turbine can safely operate, require adjustment to mitigate specific loads. If the loads analysis concludes that correlation is needed to reduce loads, the MLA report will state the reduced cutout wind speeds and the applicable wind direction sector(s). This is important as to improve the turbine's performance by adjusting the cutout and recut in wind speeds to match the specific wind conditions of the location. MLA is also used in designing the turbine and foundation, it helps to make sure that the turbine structure and its parts are suitable for the site, and that it can withstand the loads that it will be exposed to, such as wind, vibration, and others [26].

The use of Lidar technology to improve the accuracy of wind data in project assessments, Lidar data are combined with met mast data to provide a comprehensive understanding of wind conditions of the area. In order to accurately predict the turbine's power output over its lifetime, it is important to consider the annual average air density, as it affects the turbine's performance [27]. Additionally, the basis for power production warranty must be chosen for the turbulence degree for the majority of data points from the power curve test, to provide a realistic estimate of the turbine's performance. By optimizing the turbine's settings to match the specific wind conditions, it can lead to cost savings and increased revenue.

For accurate onsite energy assessment, the turbulence intensity must be considered. It can vary from low, medium to high and can be determined by comparing the measured 10min averaged data in each wind speed bin to the expected conditions of the new wind farm during the O&M. This will help to ensure that the selected turbulence intensity level represents the actual site conditions and can be used to optimize the performance. It is important to consider and to selected carefully the turbulence intensity as it affects the power generation parameters and the turbine’s loads. OpenWind is used as basis for the analysis, it requires a detailed terrain model that describes elevation and other relevant constraints that affect the wind temporary regime and are not modeled as roughness. The project plot model referenced in the actual work case represents the conditions and it is assumed that will remain unchanged during the wind farm operations. It is essential to ensure that the wind flow model is accurate and can be used to optimize the project performances [28], [29]. Roughness is a part of wind model equation that take control over the wind shear for different heights. It is closely linked to land parcel and zone roughness. Changes works in roughness and length type leads to variations in wind shear values. The impact of these changes will appear directly referring to the distance to onsite roughness profile, however, it is also closely linked to local meteorological conditions [30].

The solution is to use Lidars for the measurement of wind data at different heights, as it is easy for logistics and does not require complicated procedures for the configuration [31]. It is used to compose maps and explore spatial data for the configuration of wind turbine positions and terrain roughness analysis. OpenWind is the wind resource assessment tool that are used to model the wind regime at a particular site. They take into account atmospheric conditions and parameters, like wind speed and wind direction and air density to provide an accurate representation of the wind resource [32]. The models are configured to take into account specific conditions such as local topography and land use, to improve their accuracy. By using the models, developers can optimize the production and annual capacity factor (ACF) of a wind project [33].

4. CONCLUSION

The measurement campaign is the main sources of uncertainty that must be considered in wind assessment. To evaluate the uncertainty, it is crucial to ensure that the location of wind measuring station is in accordance with known standards and reference conditions. If the measurement station is located far from the project plot, the data may not accurately reflect the onsite true potential. Lidar can be particularly useful for complementing wind site assessment campaigns and improving performances. Yield assessment was conducted by comparing data from a local met mast located 10 km from the project zone versus data from Lidars located close to the wind turbines. The wind data collected by the Lidars during the measurement campaign shows a significant improvement in the capacity factor simulation, which is a measure of the wind potential of the site. This improved accuracy in the simulation leads to an overall increase in the annual volume of energy production. Additionally, Lidar systems are able to provide higher resolution and more accurate data compared to traditional mast stations, which can enhance the precision of wind resource assessment and energy yield prediction for wind farm projects. Lidar systems have become a valuable tool for wind measurement and yield assessment in wind energy projects. By supplementing traditional mast stations with Lidar data, it is possible to improve the accuracy of wind potential simulation and increase the annual volume of energy production. Uncertainty can arise from a variety of sources, such as inaccuracies in measurements and data processing. Some of these uncertainty components can be directly evaluated in terms of annual energy production, while others are first evaluated in terms of annual capacity factor, and then after transformed into uncertainties in terms of power generation through the application of a sensitivity factor in the measurement campaign. Major source of uncertainty is the long-term extrapolation uncertainty, which is related to the quality of the reconstruction of wind regime. This uncertainty results from calculation that takes into consideration varied parameters such as the type of data collection, the correlation and the long-term extrapolation. Lidars have been found to be particularly useful in addressing these uncertainty components and improving the accuracy of wind assessment.

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BIOGRAPHIES OF AUTHORS

Rachid Mkhaitari was born in 1990, Ph.D. researcher at the FSTM and O&M expert for wind energy. He graduated in 2015 as an engineer in Electromechanics specialized in renewable energy at the ENSMR. Actually, working on wind energy performances and the Main research direction is for the compliance of wind assets with the grid codes of grid operators in the Laboratory of Materials, Energy and Control Systems. He can be contacted at email: rachidmkhaitari@gmail.com.

Yamina Mir is State Doctor, received the Ph.D. degree in Physics, now works at FSTM with experience as an animator in quality and energy management, a researcher in photovoltaics and energy efficiency, and a former technical manager of an industrial construction center. She also has experience as a quality auditor and technical expert in BVQI and SEMAC/IMANOR. With her full broad expertise, Well-equipped to conduct research, develop and implement quality management and energy efficiency plans, and manage technical projects. She can be contacted at: yaminamir47@gmail.com.

Mimoun Zazoui is State Doctor, received the Ph.D. degree in Sciences of Physics. Now, works at FSTM, head of Condensed Matter Physics and Renewable Energy Laboratory, head of thin films Materials and Photovoltaic Conversion. Vice-Chair of Development of Renewable Energy Moroccan Society. He manages the role of main leader for many Research Projects and Financed Programs. Expert and Scientific Evaluator of Research Works and Projects. He can be contacted at email: zazouimimoun@yahoo.fr.