WHITE PAPER

How well are South African wind farms performing?

Analysis of Round 1 wind farms.

Lloyd's Register

The South African wind industry is relatively young, particularly when compared to the 'home' of modern wind energy in Europe and North America.

Great progress has been made under the Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) and South Africa is now home to over 25 wind farms with more due to begin generating electricity in the coming months and years.

Those first wind farms that achieved preferred bidder status within REIPPPP Round 1 and began achieving commercial operation in late 2013 were pioneers, taking a big share of the risk as first entrants to this market.

When working for the wind energy consultancy Wind Prospect, I clearly remember the rush as we produced the Forecast Energy Sales Reports for many of the projects bid within Round 1. These assessments formed the cornerstone of the business case for each project, with vast sums of money invested based on our calculations. Of course I was curious at the time: how good are the energy yield predictions we made?

Now we have the ability to answer that question as we have a sufficient period of wind farm generation data to assess how well those projects are performing. This piece of work places the performance of South African wind farms in the wider context, allowing comparison for project owners and investors to understand how they are operating relative to each other and also international wind farms.

I'm proud to be able to share this work with you and believe it represents a hugely valuable set of results to provide confidence in future investments in wind farms. This work also informs improvements to be made when modelling projects going forward and evaluating their risk.

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Executive summary

Wind resource assessments are the cornerstone of any financial model of a wind farm. They represent a key input into the calculation of revenue and therefore the valuation of a potential investment. In South Africa the first wind farm investments under the REIPPPP took place in 2012 and we now have the opportunity, as sufficient operational data is available, to evaluate the accuracy of the wind resource assessments.

Historic validation of wind resource assessments has focussed on projects in Europe and North America therefore this study is the first of its kind.

This work seeks to address the following questions critical to understanding the valuation of wind farms in South Africa:

- How accurate were the wind resource assessments in Round 1?
- What were the causes of those discrepancies?
- For investment decisions made today how accurate are wind resource assessments in 2018?
- Finally, how do investment decisions based on wind resource assessments in South Africa compare to other countries?

This work has taken data provided by six of the Round 1 windfarms, comprising a total of 562 MW of generating capacity and ~850 turbine years of data. This information was analysed in detail in the form of an operational yield assessment, using the same process as those used for investment decisions.

Having analysed the operational data from the Round 1 wind farms, and gained a detailed understanding of the performance of each wind farm, a thorough investigation of the differences with the 2012 pre-construction yield assessment has been presented.

In addition, the original assessments (from 2012) were updated to account for the latest energy yield modelling approaches and to understand the accuracy of investment decisions made today.

This study has shown that the wind resource assessments used for Round 1 on average over-predicted the energy yield by 4.9%; this figure agrees with other international validation studies. Detailed analysis has shown that the largest cause of discrepancies, in order of magnitude, were the wind flow / wake model, the wind turbine performance, loss assumptions and the long-term wind speed.

Using the latest techniques, the wind resource assessments provided much more accurate estimates with a remaining bias of just 1.4% across the sites studied.

The availability of the wind farms in South Africa was compared with other studies of wind farms in Europe and North America and the performance of the sites within this study was very favourable compared to the European and American sites. The average wind farm availability was 97.6% across the sites examined.

This work has validated the improvements to modelling of energy yield – leading to more robust valuation of wind farms and increased confidence for investors.

From the analysis undertaken we conclude the following:

- South African wind farm yield predictions are just as accurate as those from other established wind markets in Europe and North America. It is noted that this is a study into a subset of 6 operational wind farms in South Africa, and should not necessarily be concluded as industrywide.
- Care should be taken with old pre-construction predictions – there is potential for significant bias in these results.
- However, no significant bias is observed with 2018 wind resource assessments if they use the latest approaches and methodologies.
- Investors should critically review pre-construction energy yield assessments to support informed investment decisions, guidance on what this entails is provided within this report.
- For the valuation of operating wind farms, operational yield assessments, with datasets greater than one year should be considered preferential to pre-construction assessments due to the reduced inherent uncertainty.
- Finally, the wind farms within South Africa are performing in line with international benchmarks for availability.

This whitepaper details a high-level overview of the work performed, full technical details can be found within a scientific journal paper to be published within the Journal of Energy for Southern Africa, with further details available on request.

Contents

1. Overview

The valuation of a wind farm requires a detailed understanding of the site's wind resource. Wind from the atmosphere turns the blades of the turbine, spinning the generator and producing energy. This energy is sold to the grid to generate revenue for the wind farm owners. The risk associated with this valuation depends on how well the wind resource is predicted within the financial model.

Wind resource assessment is an engineering discipline that has been developed over recent decades combining a mixture of scientific formulae, engineering assumptions and experience of historic wind farm performance. The models that have been designed to represent wind farm yield have been developed and validated based on wind farm data that has been available – predominantly from European and North American wind farms.
Historically pre-construction energy yield assessments have over-predicted energy yield of wind farms, this is a bias that the industry has been aware of for over a decade, without an immediately established reason. This over-prediction has led to inflated valuations of project revenues and profit margins on wind farms being hit. Several validation studies, although none including any wind farms in Africa, have been undertaken to evaluate the accuracy of the industry as a whole – the change in accuracy of wind resource assessments over time is shown in Figure 1 below.

This work seeks to address this historic over-prediction and answer the following questions critical to understanding the estimation of project energy yields:

- How well did Round 1 predictions in 2012 perform?
- Where do the discrepancies arise?
- Using the latest techniques, how well would a pre-construction assessment performed in 2018 represent wind farm yield?
- Finally, with the data provided within this study how well are the South African Round 1 wind farms performing against international benchmarks?

This whitepaper details a high-level overview of the work performed, full technical details can be found within a scientific journal paper to be published within the Journal of Energy for Southern Africa, with further details available on request.

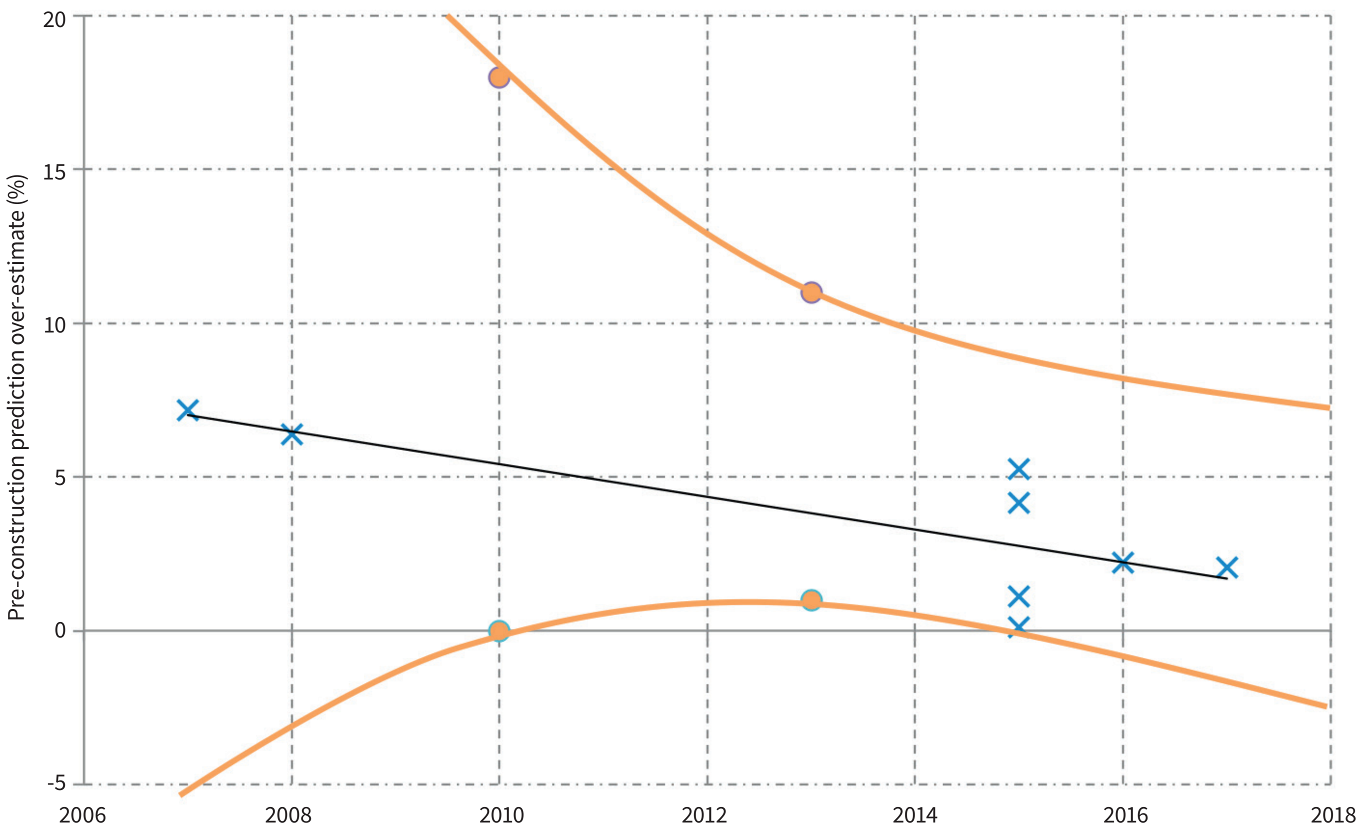


Figure 1: Plot showing over-prediction of wind resource assessments from validation studies over time. The crosses represent the results of individual studies, Orange lines represent indicative confidence range based on these studies [1] [2] [3] [4] [5] [6] [7] [8].

2. Inputs

The following input data was provided for each project, a list of the wind farms is provided in Table 1 and a map in Figure 2.

- Pre-construction energy yield assessment
- SCADA data including
  – Power production
  – Windspeed
  – Pitch angles
  – Rotor RPM
  – Generator RPM
- Substation metered data
- Monthly operator reports
- If available , power curve test reports

Quantity of data analysed within the study

562mw

~850 turbine years

>12 million data points

Wind Farm	Number of Turbines	Turbine rating (MW)	Time Period of SCADA Data Available
Cookhouse	66	2.1	December 2014 - September 2018
Dassiesklip	*9*	*3.0*	*n/a*
Dorper	40	2.5	July 2016 – May 2018
Hopefield	37	1.8	February 2014 - September 2018
Jeffrey's Bay	60	2.5	December 2013 – November 2017
Kouga	32	2.5	December 2015 – August 2018
Noblesfontein	*41*	*1.8*	*n/a*
Van Stadens	9	3.0	August 2014 – October 2016

Table 1: Round 1 wind farms (wind farms in italics not included)

Figure 2: Location of Round 1 wind farms

3. Process

First, a detailed assessment of the operational data from each wind turbine is required to allow for fair comparison with the pre-construction yield assessment, an outline of these processes is given in Figure 4 (over page), and these include:

1. SCADA data processing: converting all of the raw data, which is different for nearly every wind farm, into a consistent format.
2. Data tagging and cleaning: 10-minute data is categorised, this allows later calculation of the impact of losses and turbine performance, the categories used are:
   I. Invalid data: erroneous or missing readings;
   II. Unavailability: when the turbine is not operating, for example due to maintenance;
   III. De-rating: when the turbine is curtailed at higher wind speeds to reduce overall power production, often used when an export limit is imposed on the project;
   IV. Sub-optimal power performance: when the turbine is operating outside normal operation;
   V. Normal operation: when the turbine is operating as expected.

   An example of a tagged and cleaned power curve is given in Figure 3 on the following page.

3. Production normalisation: using the cleaned power curves the energy that the wind farm would be produced if operating 100% of the time, with no turbine performance problems, is calculated.
4. Long-term assessment: this step accounts for the difference in the wind conditions observed during the measurement period and the long-term conditions and accounts for the variability of wind speeds year to year.

5. Future loss assumptions: based on the previously tagged data and experience, account is made for future losses including turbine and grid availability, and turbine performance/degradation.
6. Project yield: the long-term project energy yield (P50) results from the steps above, this can be directly compared to the pre-construction assessment. These values are subject to the uncertainty of each of the steps of the analysis.

Having analysed the operational data from six operational Round 1 wind farms, and gained a detailed understanding of the performance of each wind farm, a thorough investigation of differences with the 2012 pre-construction yield assessment can be made.

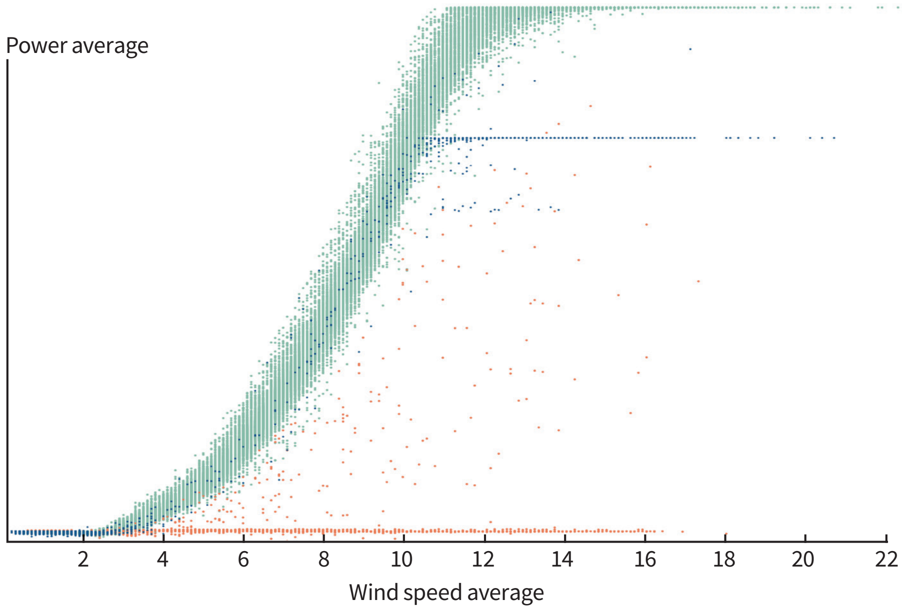


Figure 3: Example of cleaned and tagged power curve for a generic wind turbine

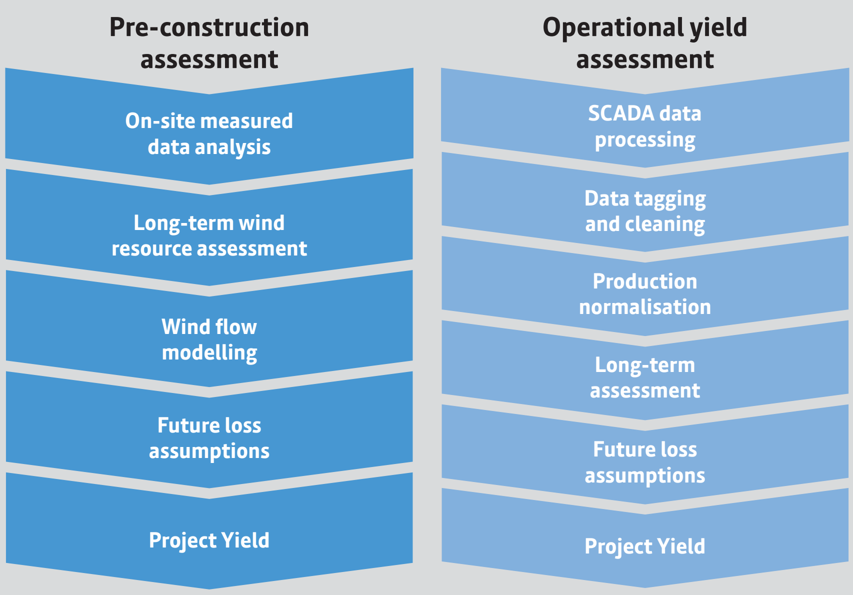


Figure 4: Steps within Pre-construction and operational yield assessments

The following metrics have been assessed for each site:

- Accuracy of the pre-construction wind resource assessment performed in 2012 with errors within the model identified, broken down into the following categories:
  - Loss assumptions;
  - Turbine performance;
  - Long-term wind speed;
  - Wind flow/wake modelling errors;
  - Other errors.
- Accuracy of a pre-construction wind resource assessment performed using 2018 techniques.
- Site performance:
  - Wind farm availability;
  - Electrical Losses;
  - Wind turbine performance against pre-construction power curve.

As a final step, the impacts of changes to the pre-construction yield assessment approach has been evaluated for each site to gain an understanding of whether 2018 methodologies are more accurate, and the causes of the remaining discrepancies.

This is an important step, as has been seen, the accuracy of wind resource assessments has improved significantly over recent years so there is value in understanding both how historic and new models perform. This will also allow for identification of future areas of research and development required to further increase the confidence in project valuations.

4. Results

4.1. How well did Round 1 predictions in 2012 perform?

The energy yield assessments for Round 1, in general, over-predicted the site energy yields. For each site a normalised value relative to the pre-construction assessment P10 (10-year), P50 and P90 (10-year) values is presented in Figure 5.

On average (mean) the 2012 assessments over-predicted the P50 by 4.9%. All projects do outperform their pre-construction P90 estimates – Figure 5 presents the normalised P90 (as not all projects have the same P50:P90 ratio). This result and the over-prediction of energy yields in 2012 is in-line with expected figures from other international validation studies, displayed in Figure 1.

4.2. Where do the discrepancies arise?

Through detailed analysis it has been possible to isolate the causes of the discrepancies. The magnitude of each (mean absolute error) is shown in Figure 6.

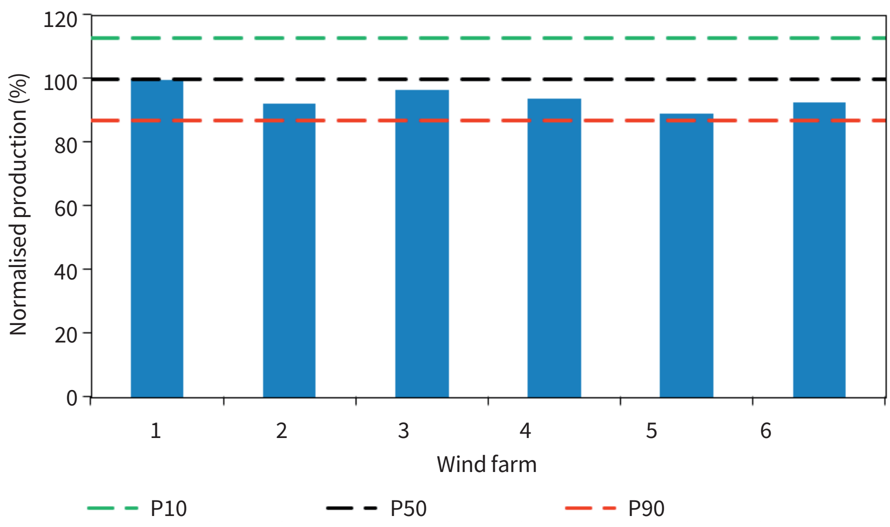


Figure 5: Normalised production for each wind farm (blue bar) relative to the pre-construction P10 (green line), P50 (black line) and P90 (red line)

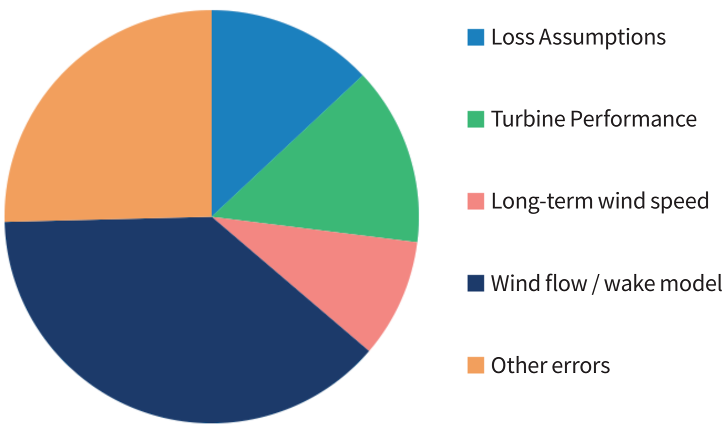


Figure 6: Breakdown of mean absolute error within the analysis

Commentary on each category is provided below.

4.2.1. Loss assumptions

The pre-construction loss assumptions from 2012 resulted in an under-prediction of the actual yield on average by 1.2%. When the impact of this conservatism is removed then the overall model bias is increased for 2012 assessments. It should be noted that this bias is not consistent across all sites and the magnitude varies significantly (from 0.0% to 5.3% with a mean absolute error of 1.8%). A comparison of the assumptions used in 2012 with those measured and those used within assessments in 2018 is given in Table 2 on the following page. It is noted that the largest improvement is seen in the grid availability which is significantly higher than was predicted within the pre-construction assessments.

4.2.2. Wind turbine performance

Wind turbine performance is assessed by comparing the power curve measured on-site during operation with the power curve provided by the wind turbine manufacturer for use in the pre-construction assessment (normally the warranted curve). This has been done using IEC power performance tests, which are considered the best practice approach to assessing turbine performance. This has demonstrated a consistent over-prediction of pre-construction energy yield, i.e. the measured power curve is lower than the warranted curve.

This result is somewhat expected as the 2012 assessments did not consider major reduction in turbine performance (it is noted that two of the pre-construction assessments did include a nominal 0.5% loss). Power curve uncertainty was instead dealt with in the uncertainty assessment, and so is included in the P90 (etc) figures. The differences range from 0.7% to 3.9%, however this has potential to increase if additional

Loss category	Mean 2012 value	Measured value	2018 value
Wind turbine availability	96.1%	97.6%	97.0%
Balance of Plant availability	99.8%	99.8%	99.8%
Grid availability	98.7%	99.2%	99.8%
Electrical loss	97.4%	97.9%	n/a

Table 2: Comparison of loss assumptions with measured values.

analysis into site specific turbine performance loss was undertaken. The average of the pre-construction estimates is 99.8% which compares to an average 98.5% from the measured data. It should be noted that whilst for most sites the wind turbine performance is within normal bounds, one wind farm reported very high levels of wind turbine under-performance (>3%) which it was not possible to investigate in additional detail within this study.

4.2.3. Long-term wind speed

Following an analysis of wind speeds over the longer term, it has been seen that across the fleet of wind farms the wind speeds during the operational period to date is 99.2% of the predicted long-term average (varying from 97.8% to 100.2% across the projects). Assuming the historical trends are representative of the future then on average the wind speeds in the future are anticipated to be slightly higher than the operational period to date.

For a normal wind resource assessment, a long-term analysis compares the site measured data with a long term dataset measured at a location offsite. This validity of this process depends on the accuracy and quality of the offsite measurement location. In South Africa, these offsite locations were not considered to add value to the process, and it was considered in all of the pre-construction predictions from 2012 that a long-term adjustment using off-site data would not increase the confidence within the long-term resource assessment.

In this work, LR has used the latest methodologies and incorporated re-analysis datasets to check on the long term trends in the region.

The results demonstrate that this has led to significant bias within the assessments. The range of long-term bias introduced is between a 3.9% over-prediction to a 3.8% under-prediction of wind speed. The mean absolute error is 1.2% across the sites.

4.2.4. Wind flow/ wake modelling errors

In the pre-construction assessments, the wind speeds are modelled using WAsP with some supplemental Computational Fluid Dynamics (CFD) analysis if required, to determine the wind speed variation across the site and the different wind turbine locations.

This is identified as the biggest cause of discrepancy with the pre-construction predictions with a mean

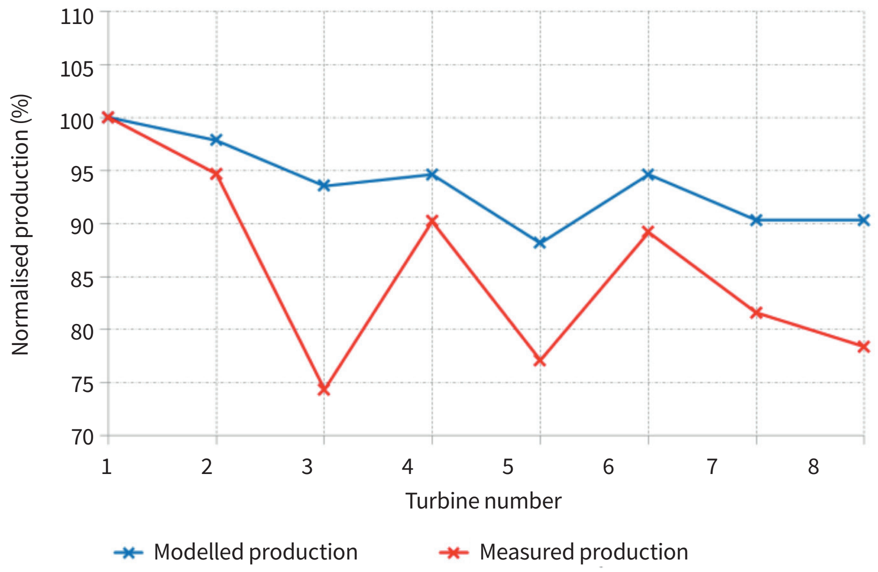


Figure 7: Pattern of production for a subset of one-site (anonymised)

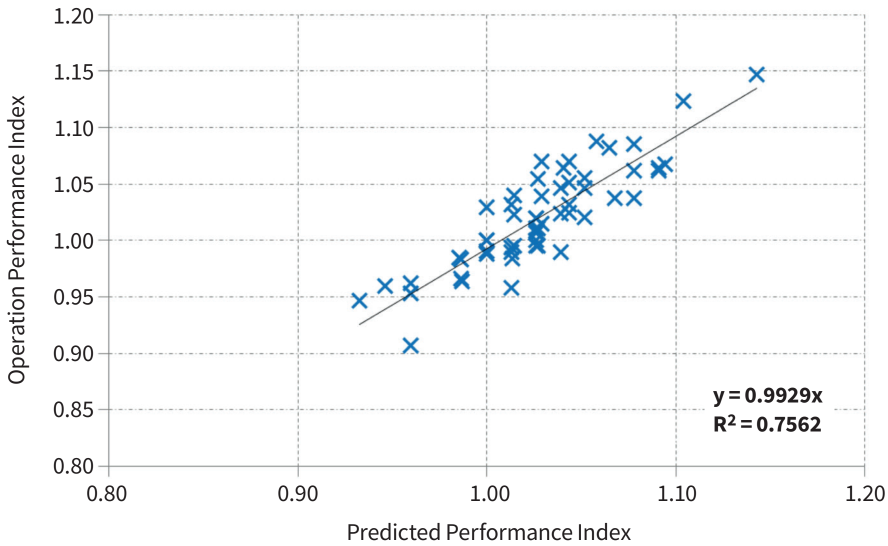


Figure 8: Pattern of production per-turbine normalised against wind turbine closest to the mast

absolute error of 5.2% of the energy yield. It is also found to be the most consistent across the different sites (ranging from 3.5% to 7.3%). This has been investigated on a site by site basis and therefore to protect the anonymity of the sites limited details can be presented here.

Two examples of the investigations are given in Figure 7 and Figure 8 on the previous page. Note that these results are a subset of the wind farms (there are no wind farms with only eight turbines) and as such the results could be from any project.

Figure 7 shows the variation of yield through the wind farm, the yield all turbines have been normalised (i.e. divided by the yield of a reference turbine) against the wind turbine considered to be closest to freestream (the reference turbine). This clearly shows that the pattern is similar and therefore the wake model is working to some extent; however the magnitude of the variation is underestimated within the flow model resulting in an overall over-estimation of project yields.

Figure 8 shows the variation of performance where each turbine is associated with the most representative mast (undertaken within the pre-construction assessment). Within each cluster the yield is normalised against a turbine at, or very near, the mast location. For sites where the model predicts the magnitude of change well the slope will be equal to one. Within the example site, Figure 8, the plot demonstrates that the wind flow model is performing well; with the slope between operational performance and predicted performance having a gradient of 0.99. This is a measure of how well the wind flow represents extrapolation of yield across different conditions. For some sites this figure showed an inherent bias within the model.

It is also clear that the coastal sites experience significantly higher wind flow modelling errors than those inland.

This is attributed to three main factors:

- Wind flow model, from site specific investigations it can be seen that the wind climate varies significantly across the sites which occur near the coast due to the step change in external conditions as the land meets the sea.
- Wake modelling, these sites wake model results are significantly poorer than those inland due to the change in turbulence and the complexities of the wake interaction.
- Wind turbine performance, coastal flow conditions are poorly understood across the industry, therefore it is anticipated that there may be increased levels of turbine performance loss than would be typically calculated. The few power performance test results provided support this conclusion of high impact and variability.

The authors note that vertical extrapolation errors have not been examined in detail within this work as across the sites the measurement masts are very close to the turbine hub heights (typically 10 m or less). This is not the case for sites with projects in later REIPPPP rounds, as wind turbine hub heights have increased. This may have a significant impact on future yield prediction accuracy.

4.2.5. Other errors

Having attributed the errors above to specific causes there is a remainder on many sites. This figure is likely due to one of the reasons above but it simply has not been possible to categorise or isolate the cause. It should also be noted that all the analysis above is subject to limitations and uncertainty and therefore this remainder also represents the confidence in the analysis.

4.3. Using the latest techniques how well would a pre-construction assessment performed in 2018 represent wind farm yield?

As part of the study the pre-construction yield assessments were updated to represent the latest methodology and assumptions applied in 2018. Since 2012 notable changes in the wind flow modelling process include:

- Improvements in the understanding of long-term wind reference sources in South Africa [1], [2], [3], [4].
- Updates to wind flow models used.
- Higher resolution wind shear matrices applied to vertical extrapolation of mast data.
- Wake model improvements include better account for the low turbulence often seen in South Africa.
- Better informed loss assumptions for availability and turbine performance losses.

These result in significantly improved the accuracy of the predictions resulting in an average (mean) over-prediction of 1.4%, compared with the 4.9% based on the 2012 assessment process.

The flow of errors from the 2012 pre-construction assessment through to a 2018 pre-construction assessment relative to the operational performance observed by the Round 1 projects is given in Figure 9 on the following page. This shows the average contribution of each source error discribed above on the projects, they also highlight that for the 2012 predictions there was a case of 'two wrongs making a right'. As an example the average over-conservatism of the losses largely was cancelled out by the over-optimism related to turbine performance. Both of these biases have been corrected within the estimates made in 2018 resulting in a small residual over-prediction (1.4%) for the sites within our sample.

Again, this is in line with what is expected within up to date pre-construction predictions, as shown in Figure 1. Looking at the spread of pre-construction predictions it is shown in Figure 10 that the 2018 assessments are much closer to what is being observed operationally, the spread of these assessments is also lower which suggests that the improvements made within the process have resulted in both more accurate but also more consistent project valuations.

4.4. Finally, with the data provided within this study how well are the South African Round 1 wind farms performing against international benchmarks?

South African wind farms are performing in line with international benchmarks on turbine availability. The average (mean) availability across the projects studied is 97.6% which compares with other studies values of 96.3% [5] [6]. Due to the anonymity of these studies it has not been possible to consider the turbine model, size, age or type of contractual arrangements in place which all have a significant impact on site availability. Nevertheless this figure for South Africa still compares favourably.

South African projects are also performing relative to their pre-construction assessments at the same level as their international peers based on assessments at the time. The corresponding industry improvements to methodology have also been seen reflected within this study.

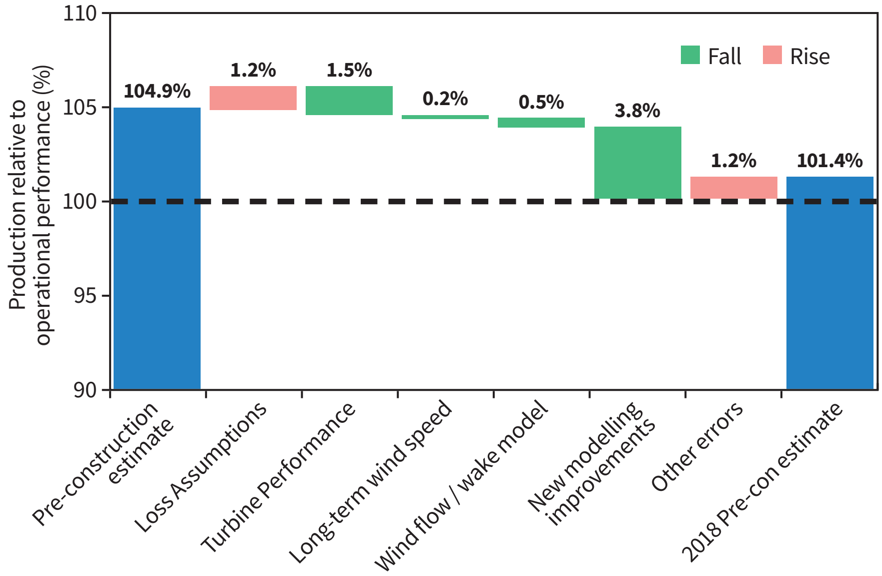


Figure 9: Waterfall plot showing the mean contribution of errors, from pre-construction assessment in 2012 to one performed in 2018 (details of how each are calculated have been given above in section 4.2). The black line (100%) represents long-term operational performance

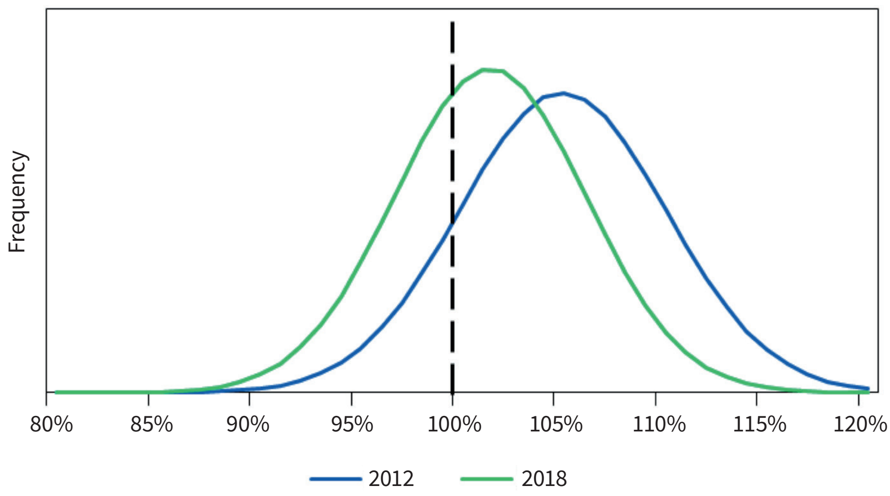
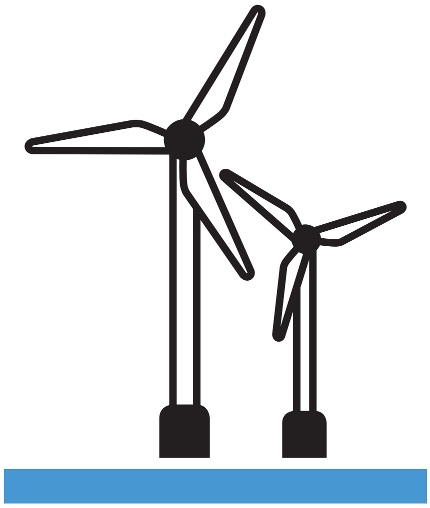


Figure 10: Performance of pre-construction assessments against operational performance



Wind farm availability

97.6%

South Africa average

96.3%

Global LT average

Across the wind farms studied, the operational period to date has been 1.1% below the expected long-term wind speed, therefore yields from Round 1 projects are expected to rise above the observed production to date, assuming the historic long term trends are representative of future wind speed variability.

It should be noted that this figure varies with individual wind farms experiencing wind speeds from 2.2% below to 0.2% above the long-term average.

5. Conclusions

This work has shown that South African wind farm energy yield prediction accuracy is in-line with international experience (from Europe and North America) both at the time of the investment in 2012 and now in 2018. For international investors South African wind farm yield predictions are just as accurate as those from established wind markets in Europe and North America. It is noted that this is a study into a subset of 6 operational wind farms in South Africa, and should not necessarily be concluded as industrywide.

Care should be taken with old pre-construction predictions – there is potential for significant bias in these results. However, no significant bias is observed with 2018 wind resource assessments if they use the latest approaches and methodologies. This work has validated the improvements to modelling of energy yield – leading to more robust valuation of wind farms and increased confidence for investors.

Investors evaluating pre-construction yield assessments should critically review them; a high-quality pre-construction yield assessment includes the following:

- International standard levels of turbine, Balance of Plant and grid availability assumptions should be applied.
- An account for turbine performance losses – this should consider the site conditions.
- For coastal sites additional measurements should be taken to ensure the wind conditions are adequately represented where current industry models are not capturing the flow effects.
- Wake modelling should include account for the site specific turbulence.

South African wind farm yield predictions are just as accurate as those from established wind markets in Europe and North America.

- A long-term adjustment of the wind regime, including appropriate uncertainties, should be investigated thoroughly to avoid significant bias within the predicted long-term wind speed.
- Vertical extrapolation approach should be justified including investigation into time-varying shear variations for sites where the hub height is significantly higher than measurement height.

For the valuation of operating wind farms, operational yield assessments, with datasets greater than one year should be considered preferential to pre-construction assessments due to the reduced inherent uncertainty. The wind farms within South Africa are performing in line with international benchmarks for availability.

The authors note that whilst the 2018 updated assessments within this limited sample demonstrated an over-prediction 1.4% this figure should not be considered to represent the bias within all pre-construction yield assessments. Additional analysis of more projects as they come online will refine this figure and determine whether any statistically significant bias is observed.

6. Next-steps

As mentioned above, one area that has not been validated, as it has negligible impact on Round 1 wind farms, is the vertical extrapolation in wind conditions, this will be much more significant for later Round projects as hub heights have increased significantly since Round 1. This should be examined within future studies.

The impact of coastal wind flow effects needs to be examined in more detail; this area is currently under investigation throughout the industry however the impact on wind flow, wake and turbine performance modelling should be investigated.

A clear extension to this work is to add newer wind farms into the study, those from Round 2 onwards will increase confidence in the conclusions and examination of a wider variety of site conditions. Additional data from these projects in the future will also allow for investigation into the impacts of degradation of turbine performance.

This work has focussed on the P50 energy yield, additional studies with more data points would be able to also examine and validate the confidence associated with the pre-construction predictions.

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8. Acknowledgements

The authors would like to thank the wind farm owners who provided their data to the study:

- Kouga Wind Farm;
- Dorper Wind Farm RF (Pty) Ltd;
- Globeleq South Africa Management Services (Pty) Ltd;
- Africoast Energy (Pty) Ltd;
- Umoya Energy (Pty) Ltd;
- Cookhouse Wind (Pty) Ltd.

Staffan Lindahl founder of Lindahl Ltd and producer of the SIFT operational SCADA analysis software (https://www.lindahl.ltd/sift), for the invaluable software and also great customer service.

All MERRA-2, ERA-Interim and ground station datasets were downloaded using WindPRO software v3.1.617 developed by EMD International A/S: http://www.emd.dk or http://www.WindPRO.com.

The ERA5 data has been Generated using Copernicus Climate Change Service Information 2018.

Lastly, the authors would like to acknowledge the Global Modelling and Assimilation Office (GMAO) and the GES DISC (Goddard Earth Sciences Data and Information Services Center), as well as the European Center for Medium-Range Weather Forecasts for the dissemination of MERRA and ERA-Interim.

9. About LR

Lloyd's Register (LR) is a global engineering, technical and business services organisation wholly owned by the Lloyd's Register Foundation, a UK charity dedicated to research and education in science and engineering. Founded in 1760 as a marine classification society, LR now operates across many industry sectors with some 9,000 employees based in 78 countries.

We have a long-standing reputation for integrity, impartiality and technical excellence. Our compliance, risk and technical consultancy services give clients confidence that their assets and businesses are sage, sustainable and dependable. Through our global technology centres and research network, we are at the forefront of understanding the application of new science and technology to future-proof our clients' businesses.

Who we are

We are a leading global provider of engineering and technology-centric professional services that improve the safety and performance of complex, critical infrastructure for our clients and for society.

Social business

Our profits fund the Lloyd's Register Foundation, a charity dedicated to research and education in science and engineering.

1760

History

Founded in 1760 as a marine classification society.

What sets us apart

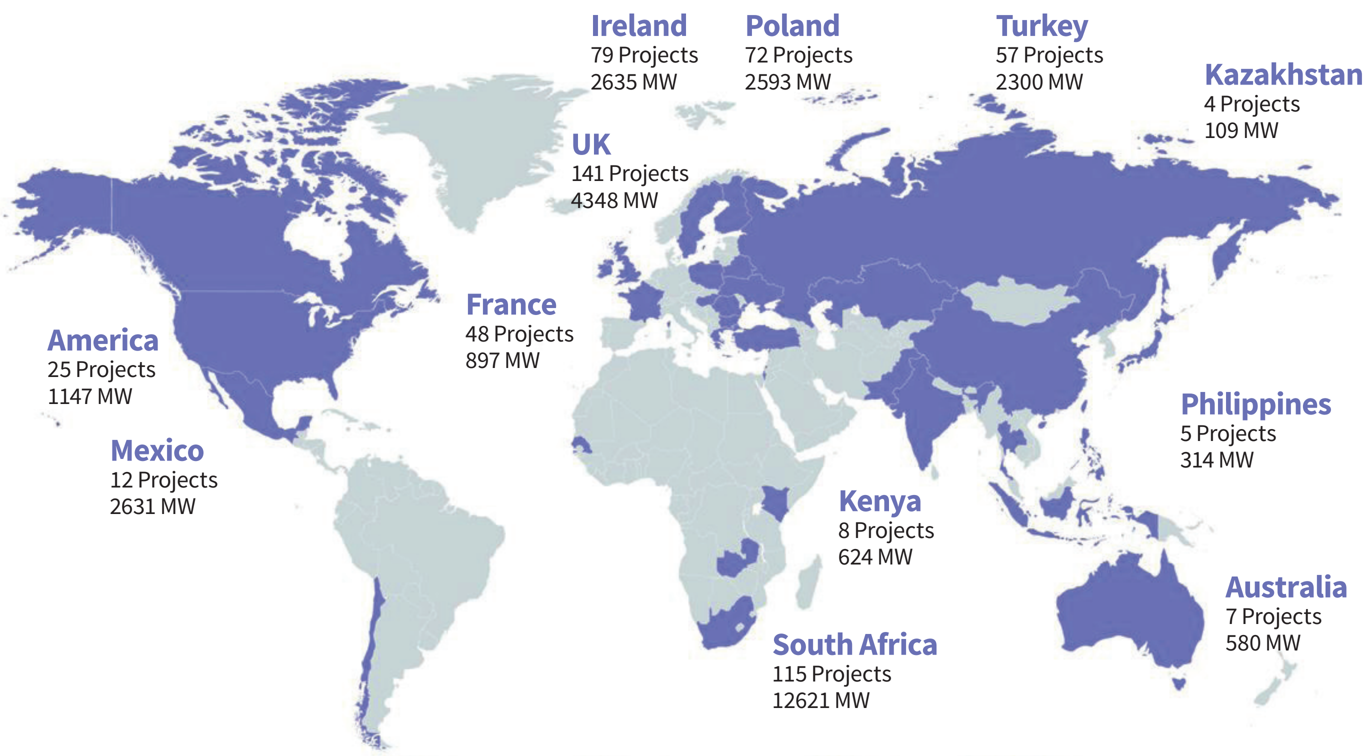
- Social business
- Technical expertise
- Independence
- Breadth of service
- Global reach

LR's Energy Resource Services team has over 40 years of experience in wind resource assessment both for onshore and offshore wind farms. Our global track record is shown in Figure 11 on the following page.

In South Africa our ERS team have worked on 65% of all selected preferred bidders within the REIPPPP.

In addition to our commercial work we also work hard to perform research and development and bring new innovations to market and share with the industry. In South Africa, in addition to this piece of work, we have improved the understanding of project energy yield through the following research highlights:

- Inter-annual variability: reducing the industry standard uncertainty assumptions applied in South Africa.
- Facility Power Curves: improving the methodology defined within the PPA (Power Purchase Agreements) to avoid double-counting of wind turbine downtime events leading to excessively low Facility Power Curve calculations.



40+ years **25+** countries **36+** GW **600+** projects

Figure 11: LR's Energy Resource Services track record

Additional services

In addition to wind and energy resource services, LR provides services to the wind industry in the following areas:

- Site assessment;
- Risk management;
- Grid connections;
- Certification and classification;
- Performance optimisation;
- Owner's engineer;
- Technology qualification.

For further information on any of these services, please get in touch using the contact details provided below.

Lloyd's Register

Get in touch

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