Summary
Wind farms represent a complex system in which relatively simple technology interacts with poorly characterised and complex wind conditions according to relationships which are inadequately understood or represented. Optimising wind farms entails achieving sufficient understanding of both wind conditions and asset response to them to predict energy production, fatigue loads and remaining life of components; to diagnose unsatisfactory performance; and to indicate effective design and control strategies and productive inspection, repair and maintenance schedules and interventions that improve asset reliability and yields. This is a key topic as the wind energy capacity coming out of warranty globally on an annual basis begins to exceed the new capacity being installed under warranty. This out of warranty capacity is now eligible for optimisation and life extension. Key cultural and organisational considerations necessary for achieving these benefits are outlined.

1. Introduction
The successful delivery of wind power projects requires:

- A complete, accurate and detailed understanding of the wind conditions prevailing at wind farm sites under consideration, and
- A thorough understanding of the response of wind power assets to these conditions.

If these are known,

- The observed wind resource can be reconciled with revenues generated during the post-construction phase of operations, and
- Observed expenditure and production post-construction can be reconciled with predictions made on the basis of pre-construction wind resource and site suitability assessments.

Fulfilling these requirements means wind farms can be optimized during both design and operation to maximize output and minimise operational expenditure. Understanding asset performance lowers risk and improves confidence in financial projections.

2. Unified data requirements
A single unified approach to the assessment of wind power assets’ total lifecycle compatibility is required. This considers the compatibility of the wind turbine with the environmental (wind) conditions that will prevail during its entire design life. Consideration of its design; its context within an array and surrounding topography; and its upkeep, operation, inspection, repair and maintenance is required in order to achieve meaningful and lasting asset optimisation. Currently this approach is impeded by discrepancies between the different project data requirements whose fulfilment are deemed necessary during pre- and post-construction phases of project delivery. These discrepancies are an artefact of different limitations in measurement opportunity. These are now being overcome using, for example, lidar, and procedures for project development and operation should be revised to reflect this. It is now possible to observe and characterise adverse wind conditions pre-construction whose occurrence would not previously have been detected until their consequences were manifested post-construction.

Figure 2: lidar measurements of wind turbine wakes

Historically the data acquisition agenda on which the asset’s total lifecycle compatibility has been based has typically been set entirely by pre-construction priorities. These priorities have arisen from the need to secure finance and support investment decisions. The data requirements this...
entails have been artificially limited hitherto by restricted opportunities to make measurements using, for example, met mast mounted cup anemometry. Limitations in the capabilities of the available instrumentation have imposed restrictions on the availability of data that have been reflected in the incomplete requirements of pre-construction wind project assessment criteria. Problems arise when these incomplete requirements are assumed to be complete. Some significant issues have come to light only after construction is finished and the wind farm is operational, when they have been manifested as poorer than expected wind turbine availability or power performance.

New tools and techniques, such as lidar, are available that allow the adoption of a more unified approach to data acquisition and analysis suitable for full lifecycle project optimization. A key task when understanding the performance of a wind farm is the reconciliation of the observed resource available for generation with the power production that is achieved. This is shown in Figure 1.

Of the available resource, we see some is not extracted due to adverse inflow conditions related to shear, veer, flow inclination, turbulence, wakes and so on. Further loss is due to turbine downtime and low availability, arising from component failure, for example. Sub-optimal performance can occur in periods during which the turbine is available for generation as a result of, for example, incorrect control set-points, and pitch and yaw errors. Some small amount of energy is deposited in components. This is significant if a bearing or lubricant temperature signature can be detected in the SCADA data as a result to indicate incipient failure and allow timely intervention to avert high costs.

This document reviews the new frontiers in the ever-changing technical context in which wind projects are delivered, as new measurement opportunities, and the analyses that exploit the data acquired as a result, bring our assessments closer to an accurate representation of the reality of the challenges facing successful operation of wind power assets.

Figure 3: known unknowns and unknown unknowns

Successful delivery of wind power projects requires that you can

- Describe the data requirements that arise during different phases in wind project delivery and how these relate to real project objectives and measurement opportunities
- Differentiate between risks associated with real world wind conditions, and risks that are artefacts of our limited but improving ability to assess those conditions
- Make progress towards a unified and well supported view of our assets’ compatibility with real world wind conditions over the full project lifecycle

3. Get the dumb stuff right first (and give the clever stuff a chance)

Five key observations may be made in relation to project optimisation to clear the larger hurdles and give analysts and engineers a better chance at securing further significant improvements in asset performance and longevity [1]. The requirements that arise as a result are listed below.

1. Processes and procedures need to be in place which ensure actions recommended by analysts are implemented by technicians (don’t let reports gather dust in an in-tray)
2. Everyone who has a valid contribution to make should be enabled to make that contribution (encourage feedback at all levels)
3. Barriers to effective co-operation must be identified and dismantled (have a blame-free, outcome-driven, exciting, collaborative culture)
4. Compared to failure, data is cheap (don’t let turbines die because their status or the wind conditions they have to tolerate are not known as fully as possible)
5. Ours is a young industry that still has much to learn (always be open to innovation)
The benefits of effective performance monitoring and condition monitoring techniques are often obscured by the gross effects of simple and easily avoidable problems. A lack of common standards and formats for data inhibit the development and adoption of effective and consistent analysis techniques. It is important to ensure the availability of adequate resource, in terms of skilled, trained personnel. There are no examples or case studies where adequate investment has been made in data acquisition. Short-sighted measures such as failure to maintain site met masts or even their decommissioning and removal frustrate efforts to acquire and understand vital information about the wind conditions impacting wind power assets. Complex wind conditions can occur for a variety of reasons. Wind turbines wakes measured using lidar are shown in Figure 2.

In the light of these concerns the 5 Items listed above can be re-stated as Two Golden Rules of wind farm optimisation:

1. No-one knows everything, but everyone knows something
2. Good turbine performance is in everyone’s interest.

Artificial barriers to effective wind turbine and wind farm optimisation arise due to the assignment of responsibility on the basis of commercial arrangements rather than technical requirements. At all times, the two rules above should be remembered.

![Figure 5: neglected intermediate load scenarios](image)

**4. Measurement and reality**

Our incomplete understanding can be seen in the observation of high impact phenomena which were previously neglected. New measurement opportunities made available by lidar give us:

- Access to information that would not otherwise be available using met masts and
- Early access to information that was already available using met masts

We must modify our procedures to take advantage of these opportunities to reduce project uncertainty and improve IRR or NPV.

We can now design measurement campaigns based on:

- Desired project outcomes rather than limited sensor capabilities (“what do I want to measure” rather than “what can I measure”)
- Unified data requirements: acquire project critical data pre-construction rather than wait to observe potentially adverse consequences of prevailing wind conditions post-construction.

As a consequence, more complete characterisation of wind conditions is possible, allowing complete uncertainty assessments and the transformation of what were previously “unknown unknowns” into “known unknowns” amenable to analysis, as shown in Figures 3 and 4. Initially our “known unknowns” are represented by medians and means of, for example, Annual Energy Production (AEP). “Known unknowns” arise and are accommodated in uncertainty analyses as a result of, for example, measurement and modelling uncertainties. However, wind conditions that impact our project outcomes but which are not assessed, such as, for example, low level jets, represent another source of uncertainty that has been neglected, the so-called “unknown unknowns”. As these become more fully characterised using new methods and instruments these phenomena are incorporated into our procedures. The assessment which was previously considered complete turns out to have been incomplete as a result of the discovery of “unknown unknowns” that were previously neglected.

Many of these phenomena represent intermediate mechanical fatigue load cases which are not currently accommodated in wind turbine design and testing guidelines. Loads are normally represented as either common but relatively benign fatigue loads or rare and damaging extreme loads. It is seen that a neglected intermediate class of events exists, comprising load cases that are both more severe than fatigue loads and more frequent than extreme loads. This is shown in Figure 5.

**5. Epistemology and the eolicist**

Eolics is the interdisciplinary field of study related to wind phenomena that is emerging in response to the application of innovative measurement and modelling techniques in response to wind industry demands – the instruments and methods whose impact on established procedures is discussed in preceding sections [2]. Eolics entails the adoption – for the first time – of a scientifically robust approach to wind assessment, in which model predictions can be selected as accurate or rejected as inaccurate very precisely with reference to measurements.
which match the predictions of the models in terms of sophistication and detail. That is, measurements made available using instruments such as lidars are providing us with data that – for the first time – "looks like" CFD model output and allows unambiguous identification of which specific model predictions are correct, therefore providing us with an opportunity to improve our scientific understanding of wind conditions as embodied in the equations which the CFD models solve.

The importance of acknowledging the incompleteness of our assessments hitherto is emphasised by the unexpected adverse consequences of previously neglected phenomena, such as Low Level Jets, which impact project performance. The science and engineering that will deliver successful wind projects in the future is intrinsically collaborative. It will satisfy the epistemological needs expressed above and fulfill the requirements and satisfies the rules listed in Section 3.

A good example of eolics in action is shown in Figures 6 to 9. Unexplained lost yield is being incurred as a result of a very high incidence of high turbulence trips. The influence of nearby forestry is assessed using CFD as shown in Figure 6. A lidar RHI scan is used to acquire a matching dataset of direct measurements, shown in Figure 7. This allows validation of the appropriate CFD model using comparisons between directly observed lidar radial velocity measurements and radial velocities relative to the lidar location predicted by the model. These comparisons are shown in Figure 8. The model can then be used to predict the consequences of proposed forestry scenarios, as shown in Figure 9, and the most advantageous scenario can be chosen.

6. Conclusions

Data requirements for pre-construction wind assessments have typically reflected limitations in measurement opportunity; while post-construction a deeper understanding of the wind conditions and the response of wind power assets is necessary for their optimisation. New technology is overcoming these limitations and it is now possible to observe adverse conditions pre-construction rather than wait for their manifestation in sub-optimal performance post-construction. Wind asset optimisation is therefore supported by the adoption of a single unified set of data requirements throughout the project lifecycle, based on the representation or reality rather than the limitations of our instruments.

6. References