Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Laser Ablation for Wind Turbine Blade Contaminant Classification, Quantification and Removal
Lead Grantee (Organisation)	Dublin City University
Lead Grantee (Name)	John Costello
Final Report Prepared By	John Costello
Report Submission Date	August 31st 2024

	Name	**Organisation**
Project Partner(s)	Paddy Hayden	University College Dublin
Collaborators	Jamie Goggins and William Finnegan	University of Galway
Collaborators	David Burke and Cathal Lally	Generation and Trading, ESB, 27 Fitzwilliam Street Lower, Dublin 2

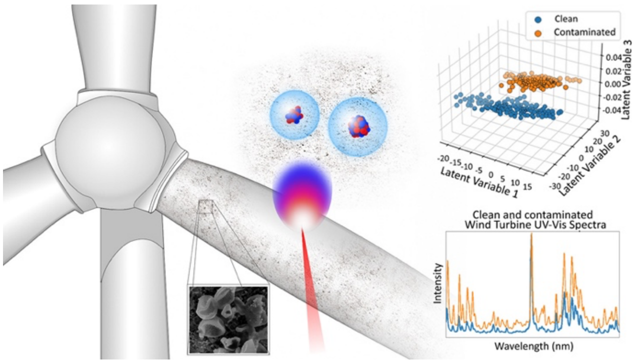
Project Summary (max 500 words)

Please provide an overview of your project, the context, objectives, key results and outcomes.

Context and Overarching Objective

It has been well established by both computational fluid dynamic (CFD) modelling and wind tunnel tests that the fouling of wind turbine (WT) blades has a negative effect on their aerodynamic performance and hence on the wind to electrical energy conversion efficiency (CE). Since reductions of up to 40% have been reported and it is necessary to keep blades clean to ensure optimal efficiency. Currently the only solution is wet cleaning, which is labour intensive, hazardous and dirty. This project investigated the use of laser ablation (the removal of thin layer of material from a surface by pulsed laser irradiation) as a means of removing surface contaminants. As a side, and very important effect, the material ablated forms a light emitting plasma plume which contains spectral signatures, atomic emission lines (and sometimes molecular bands) that are fingerprints of the elements (sometimes molecular materials) constituting the material ablated allowing them to be classified and (under ideal conditions) quantified. This technique is known as

LIBS (laser induced breakdown spectroscopy). The basic project concept is illustrated in the schematic below.



Concept - a laser remotely cleans the blade while imaging/spectroscopy, supported by machine learning, detects the end point for the laser to raster to the next area to be irradiated.

The spectral (or image) signatures can be used to identify when all contaminants have been removed and the blade surface is clean, key for process control should the idea be deployed widely after the RDD phase. In addition, the laser beam can potentially be *raster scanned* over the blade to clean the whole surface in remote or 'standoff' mode. In summary, *the overarching objective of the project* was to explore the application of laser ablation to both classify and quantify blade fouling and to provide an alternative safe, clean and efficient solution to it for wind energy providers.

Key Results and Outcomes

1. It proved possible to both deliver laser pulses to targets located at distances of up to 30 m and detect LIBS signals at that distance. (Workpackage 1)

2. Using LIBS combined with machine learning (ML) it was possible to both detect and classify contaminants. In addition, LIBS with ML made it possible to demonstrate end-point-detection for cleaning on coupons from decommissioned WT blades (Workpackage2 and 4)

3. We found a broad region of laser fluence over which pulsed Nd:YAG lasers (wavelength = 1064 nm) could be used to safely removing surface contaminant layers without damaging the WT blade surface. In fact, 3D optical profiling showed that in some LA parameter regions, the surface could be restored to its original, smooth and unfouled condition (Workpackage 3)

4. We discovered that remote imaging combined with ML acted as an excellent alternative to LIBS for the detection of contaminants on WT blades, important as it removes the need for the use of a laser for this part of the cleaning process (end-point-detection). Removing the LIBS laser greatly simplifies the system. In addition, it was found that, with the application of bespoke algorithms, WT blade damage could be detected. The optical system is extremely simple and cost effective, consisting of an astronomical telescope equipped with a machine vision camera. It could prove a useful complement to traditional drone based camera inspection (Workpackages 1 and 5)

5. Many sensitive laboratory techniques like optical and electron microscopy, 3D profilometry, EDX, XPS and TOF-SIMS were applied to WT blade material type and contaminant analysis. ML+LIBS was then compared with them for both investigations (fouling and material type) with a view to benchmarking the laser technique against these gold standard, in-the-lab techniques

Keywords (min 3 and max 10)	Laser Ablation, LIBS, Spectroscopy, Imaging, Machine Learning, Turbine Blades

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

In the following Section, please provide a clear overview of your project, including details of the key findings, outcomes and recommendations. The section headings below are provided as a guide, please update or add to these as best suits your project.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

It has been well established in the literature that surface contamination can adversely affect the aerodynamic performance of aerofoils and hence the efficiency with which turbines can convert wind to electrical power. Hence it is critical to ensure that turbine blades are kept as free as possible of contaminants. This project investigated the use of laser ablation (the removal of thin layer of material from a surface by pulsed laser irradiation) as a means of removing surface contaminants. As a side, and very important effect, the material ablated forms a light emitting plasma plume which contains spectral signatures, atomic emission lines (and sometimes molecular bands) that are fingerprints of the elements (sometimes molecular materials) constituting the material ablated allowing them to be classified and (under ideal conditions) quantified. This technique is known as *LIBS (laser induced breakdown spectroscopy)*. In addition, the signatures can be used to identify when all contaminants have been removed and the blade surface is clean (figure 1), key for process control should the idea be deployed widely after this RDD phase.

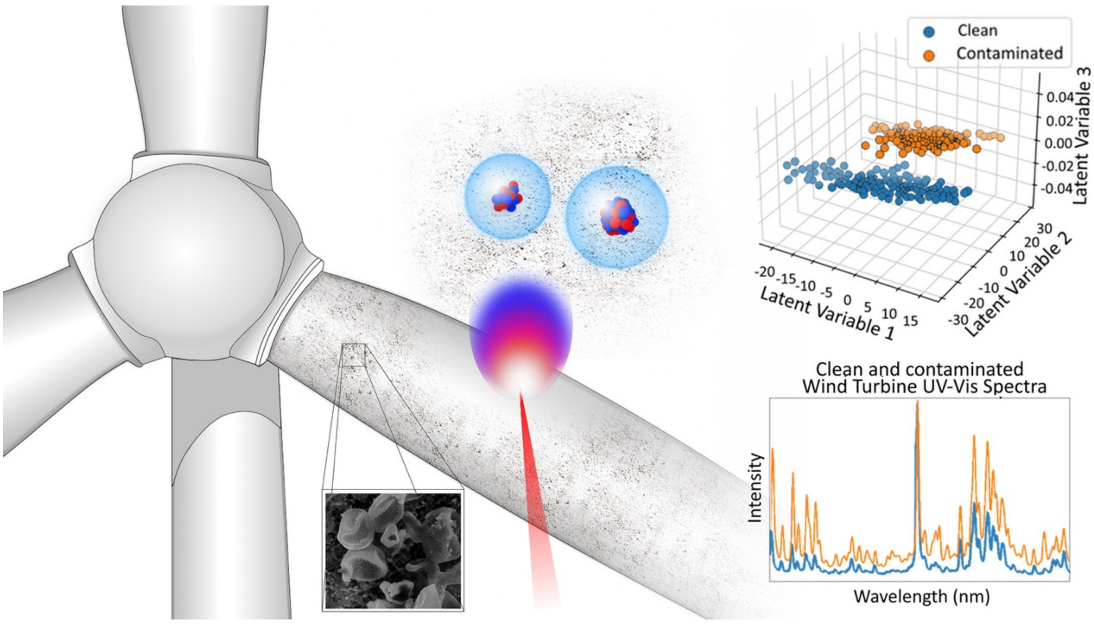


Figure 1. Concept - a laser remotely cleans the blade while imaging/spectroscopy, supported by machine learning, detects the end point for the laser to raster to the next area to be irradiated.

Relatedly one must also determine the point at which the laser has adequately removed contaminants from the current *Area of Irradiation (AoI)* before moving to the adjacent AoI, i.e., interim end-point-detection. For both steps (presence / absence of fouling) we investigated LIBS as a means of discriminating between clean and fouled wind turbine blade samples. In particular, we performed LIBS in both the Vacuum Ultraviolet (VUV) and Ultraviolet Visible (UV-Vis) spectral ranges. Analysis of the spectra showed only slight variations in the constituent materials between clean and contaminated blade samples. In order to address this challenge, the efficacy of a number of machine learning and statistical methods for clean versus contaminated blade classification was investigated. Four methods (Partial Least Squares Discriminant Analysis (PLS-DA), Support Vector Machines (SVM), Competitive Learning (CL), and Convolutional Neural Networks (CNN)) were evaluated. The spectral regions where machine learning algorithms were applied was determined via a volumetric ellipsoid overlap test based on Principal Component Analysis (PCA). It was found that SVMs provided the most accurate methodology for binary classification of clean vs contaminated blades whilst also yielding the shortest run time.

During the project we also established that WT blade video imaging combined with YOLO (you only look once) processing could be used to isolate contamination locations in real time. Other ML algorithms could be used to bring minor blade defects, not obvious to the naked eye, into sharp relief. We also applied highly sensitive laboratory based chemical/physical analytical techniques to the analysis of blades and determined the ranges of laser fluence leading to surface cleaning without WT blade damage.

2.2 Introduction to Project

Wind energy provides a clean, sustainable alternative to fossil fuels, allowing for the generation of electricity, without the direct emission of greenhouse gases [1,2,3]. Due to the ideal climatology of the island, Ireland is well located to take advantage of the potential that wind energy provides [4,5]. In this respect, maximization of the output energy and extension of the lifespan of wind turbines is critically important from a socio-economic perspective. Previously reported investigations [6,7,8,9] have highlighted the detrimental effect of contamination on the performance of wind turbines. One inherent complication is the fact that the nature of contaminants present on the blades of a wind turbine depends on the turbine's location. Typical contaminants include organic matter such as insects [10,11], birds, and plant matter, as well as inorganic matter such as soil, sand, ice and dust. In addition, salt contamination [12] plays a key role for turbines installed in maritime environments. The urgent need for a cost-effective, efficient, green and non-hazardous cleaning process, provides the impetus for pursuing alternative solutions to manual cleaning. In this project we have investigated laser ablation (LA) as a method for cleaning wind turbine (WT) blades. Laser cleaning has been used for applications like paint removal from metals [13] and is even proposed for window cleaning [14], however the key challenge is removing contaminants without damaging the delicate WT surface. The project structure is shown schematically below.

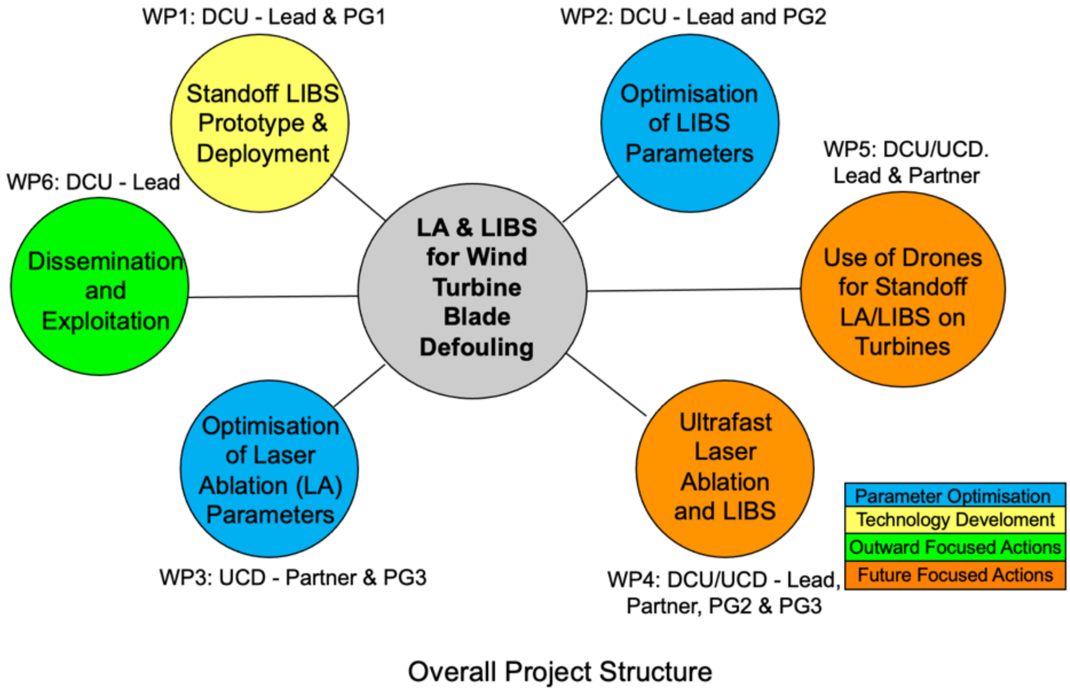


Figure 2. Project broken down by workpackages. PG – Postgraduate (PhD) student, 3 funded by the award.

Although all laser ablation tests were carried out under controlled laboratory conditions, we combined LIBS with machine learning techniques applied to contaminated wind turbine blades with a view to the possibility of integrating these methods into a standoff laser ablation setup in the future (for outside use of high lower, Class IV lasers, both regulatory and health/safety challenges need to be addressed). That stated, standoff LIBS for material analysis is a well-established application, as shown in e.g., historical architecture [15] and in large scale infrastructure testing such as rust detection on pylons [16]. Laser ablation has been applied extensively, including, but not limited to, investigations regarding archaeological artefacts and paintings [15,16,17,18], biological materials like tissues [19,20] and other materials (see e.g. review [21]). In a natural extension of this work it is envisaged that the laser ablation process will be used to selectively remove the unknown contaminants that will, in turn, be identified by means of LIBS. The latter is a versatile technique that has found various applications [22], (e.g. in geology [23, 24], archaeology [25], pharmaceutical analysis [26,27], environmental analysis [28, 29] and materials science [30,31]). Importantly, a closed-loop LIBS configuration [32] has been previously implemented to both monitor and control the process of cleaning the surface of a material. As it offers the significant advantage of online monitoring, this arrangement can be used to track the effectiveness of laser cleaning, via dynamical analysis of the associated plasma plume. The basic project concept is illustrated in the image below.

Working in the UV-Visible part of the spectrum allows for in the field LIBS measurements and the laser itself can be used for in situ cleaning of the wind turbine blades. The latter requires a thorough understanding of the wind turbine blade composition so that the laser parameters for optimal cleaning are established prior to the deployment of the LIBS system, another key aim of the project.

It should be noted that although a number of LIBS studies on materials mimicking wind turbine blades have been made, especially focused on salt contamination [35,36], to the best of our knowledge LIBS has not yet been applied to explore fouling on decommissioned wind turbine blade surfaces. Additionally, to the best of our knowledge, the combination of LIBS with machine learning (ML) has not yet been applied to naturally contaminated turbine blades. There are several key outcomes from the project which are summarised in Section 2.4 below.

2.3 Project Objectives

No:	Objective Description:
1.	Design, construction, characterisation and field testing of a prototype standoff LA and LIBS system for blade defouling
2.	Determine the optimum laser / focussing parameters to from suitable plasmas for LIBS on turbine blades
3.	Determination of optimal laser and optical focusing parameters for laser ablation of contaminants with zero damage to blade surfaces
4.	Evaluation of femtosecond (fs) laser filaments for the classification and quantification of contaminants in standoff (remote) operation
5.	Feasibility for Drone use in Standoff LA and LIBS
6.	Rollout of Dissemination and Exploitation Plan

Summary of Key Findings/Outcomes

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

- *Innovation 1: Long distance LA laser pulse delivery and LIBS detection*

  It proved possible to both deliver laser pulses to targets located at distances of up to 30 m and detect LIBS signals at that distance (Workpackage 1). We already know that we can extend optical detection limits to hundreds of metres (cf. Innovation 3) and with appropriate laser technology, laser pulse delivery can be extended to similar distances (cf. reference 15 below).

- *Innovation 2: Machine learning applied to LIBS for material and contaminant detection.*

  Using LIBS combined with machine learning (ML) it was possible to both detect and classify contaminants. In addition, LIBS with ML made it possible to demonstrate end-point-detection (when the WT blade surface is reached) for cleaning on coupons from decommissioned WT blades (Workpackage 2 and 4). Further it was possible to use it to distinguish between different blade materials with very similar elemental compositions.

- *Innovation 3: LA can clean blades safely and may even restore WT blade surfaces*

  We found a broad region of laser fluence over which pulsed Nd:YAG lasers (wavelength = 1064 nm) could be used to safely removing surface contaminant layers without damaging the WT blade surface. In fact, 3D optical profiling showed that, in some LA parameter regions, the surface could be restored to its original, smooth and unfouled condition (Workpackage 3).

- *Innovation 4: Remote imaging with machine learning as a standoff LIBS alternative*

  We discovered that remote imaging combined with ML acted as an excellent alternative to LIBS for the detection of contaminants on WT blades, important since it could significantly simplify future in-the-field systems by removing the need for a (second) laser for this part of the cleaning process (i.e., end-point-detection). In addition, it was found that, following the application of bespoke algorithms (e.g., YOLO, Peiyuan Jiang et al. / Procedia Computer Science 199 (2022) pp 1066–1073), potential WT blade damage could also be detected. The optical system is extremely simple and cost effective, consisting of an astronomical telescope equipped with a machine vision camera and could prove a useful complement to traditional drone based camera inspection (Workpackages 1 and 5).

- *Innovation 5: Application of gold standard laboratory analytical techniques*

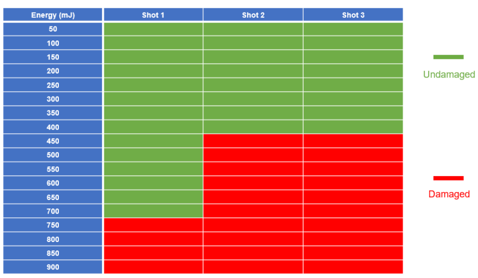
  Many sensitive (gold standard) laboratory techniques like optical and electron microscopy, 3D profilometry, EDX, XPS and TOF-SIMS were applied to WT blade material type and contaminant analysis. ML+LIBS was then compared with them for both investigations (fouling and material type) with a view to benchmarking the laser technique against these gold standard, in-the-lab techniques (Workpackage 2).

Further details (with images and tables as appropriate) on the above technical innovations can be found in the annual reports submitted to the SEAI and summarised in a presentation that can be downloaded from here.

2.4 Project Impact

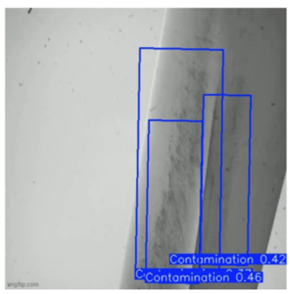
Clearly position the impact of your project with reference to the needs of the Irish Energy Sector, national and international policy objectives, and SEAI's remit.

The decarbonisation of the energy sector is a key priority for all stakeholders mentioned. Wind energy is a key part of the renewables mix and will require not just the development of new on- and off-shore wind farms but also a focus on optimising the performance of all wind turbines (WTs) and extending the lifetimes of existing WTs. Current *cleaning methods and drone inspections*, respectively, execute these tasks. *Our TRL1/2 early stage research project show that laser ablation and ground based (telescope) imaging are potential alternate, and complementary, laser/optical techniques for these key tasks.* In the images below we show a range of fluence which cleans and protect WT blades, in-the-field testing of WT blade imaging and a video frame with YOLO real time contamination/potential damage detection.



Nd:YAG laser pulse energy for damage-free WT blade cleaning

WT imaging at an ESB windfarm



Video frame with real-time YOLO algorithm output

Discuss the key impacts of your project: societal, economic, technological or otherwise. Clearly identify and highlight the value of your project in the wider context.

At this point the key impacts of the project are technological. Three PhD students have been trained in the application of lasers and optics to wind turbine technology. Laser-WT specific papers have begun to appear from the project and the remote imaging has commercial potential. One of the PhD students, Seamus Cummins, received the Grant Thornton High Achieving Merit Award at the 2024 Student Entrepreneur Awards for his concept business plan and presentation. Placed 2nd amongst the final 10 contestants (>100 teams), it shows the economic/commercial potential of this aspect of the project.

2.5 Recommendations

Please highlight any implications/opportunities/recommendations for Ireland (e.g., for policy makers, for the research community, for industry) based on the work carried out in the project.

Laser and optical technologies have already been deployed on wind turbines (WTs) or at wind farms. Two are well established, namely drones for WT inspection [37] and LIDAR or light detection and ranging (effectively laser based radar) for wind pattern analysis [38, 39]. Our TRL1/2 level project shows that the application of lasers and optics could be extended to include in-the-field contaminant presence/absence and possible damage zones (via ground based telescopic imaging with machine learning – already shown), contaminant presence/absence and chemical composition detection (via LIBS with machine learning – shown in laboratory tests), and laser ablation cleaning (shown in laboratory tests). *The main issue here will be deployment of Class IV lasers in the open and the need for appropriate regulation and controls and perhaps even legislative recommendations*. Most safety protocols deal with enclosed systems or systems deployed in research laboratories or medical facilities. Certainly, an expert group to make recommendations would facilitate an expanded role for lasers in wind energy R&D. The experience of advanced military operators of Class IV lasers would be important.

2.6 Conclusions and Next Steps

In summary

- Lasers, optics and spectroscopy combined with AI/ML open up many new opportunities for wind energy R&D*
- Opportunities cover both basic research and potentially commercialisation
- To scale and deploy Class IV laser-based techniques at WFs involves some technical and regulatory hurdles that need to be scaled (but most likely can be)
- The project has made some good progress and discovered some very useful new avenues not originally envisaged in the RDD proposal (e.g., ML with LIBS, Imaging with ML and Analytical Chemical/Physical Techniques, all applied to WT blades)

*The use of ROVs (e.g., https://cris.ie), to combine some/all of the above, should be considered

In terms of potential for new business or IP generation:

- The most obvious immediate opportunity is in imaging with ML (Cummins) – Potential Spinout
- Any clean, green, safe alternative to current practice has potential but needs relevant partners (e.g., Drones, ML/AI, Bespoke Laser Designers, Regulators, etc.)

Next steps:

- PhD thesis writeups
- Further manuscripts submitted for publication
- Spinout idea based on ground based inspection technology being developed
- A large scale (e.g., EU EIC Pathfinder) project to move to higher TRLs should be considered

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