



## IEA Wind Task 32 and Task 37: Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering

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*Published in:*  
Journal of Physics: Conference Series

*Link to article, DOI:*  
[10.1088/1742-6596/1618/4/042029](https://doi.org/10.1088/1742-6596/1618/4/042029)

*Publication date:*  
2020

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Simley, E., Bortolotti, P., Scholbrock, A., Schlipf, D., & Dykes, K. (2020). IEA Wind Task 32 and Task 37: Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering. *Journal of Physics: Conference Series*, 1618(4), [042029]. <https://doi.org/10.1088/1742-6596/1618/4/042029>

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To cite this article: Eric Simley *et al* 2020 *J. Phys.: Conf. Ser.* **1618** 042029

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# IEA Wind Task 32 and Task 37: Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering

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Keywords: Lidar-Assisted Control, Systems Engineering, Optimization, IEA Wind

**Abstract.** Lidar-assisted control is a promising technology for reducing the levelized cost of energy from wind turbines, but quantifying its impact at the overall system level requires sophisticated systems engineering analysis and optimization frameworks. The joint workshop on Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering was held by the International Energy Agency Wind Task 32 (Lidar) and Task 37 (Systems Engineering) in October 2019 to address this challenge. This paper summarizes the outcome of the workshop and presents a road map for further research. The most promising applications of lidar-assisted control identified at the workshop and discussed here include 1) increasing annual energy production, 2) decreasing capital expenditure costs by reducing design loads, 3) extending turbine lifetime by reducing operating loads, and 4) enabling wind turbine class upgrades. For each application, we review the state of the art and highlight remaining research needs. Finally, we discuss strategies for addressing these research needs by conducting high-fidelity systems engineering optimizations.

## 1. Introduction

Lidar-assisted control (LAC) holds potential for increasing the power output from and reducing the structural loads on wind turbines [1]. These benefits have been demonstrated through simulations [2, 3] as well as field experiments [4]. It is difficult to determine the potential impact of LAC on the levelized cost of energy (LCOE) from wind turbines, however, because of several areas of uncertainty, including 1) how the load reduction might impact component design; 2) the reliability of the LAC system during the turbine lifetime; and 3) the total cost of the lidar during the turbine lifetime, including operation-and-maintenance (O&M) costs. Addressing these areas of uncertainty is necessary to enable widespread adoption of LAC technology. To address these barriers, the joint workshop on Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering was held by the International Energy Agency (IEA) Wind Task 32 (Lidar) and Task 37 (Systems Engineering) in October 2019, combining the LAC experience of Task 32 with the knowledge of wind turbine optimization from Task 37 [5]. The workshop builds on ideas developed in previous Task 32 workshops on Optimizing Lidar Design for Wind Turbine



Control Applications [6] and Certification of Lidar-Assisted Control Applications [7]. The aim of the workshop was to identify objectives, models, and optimization strategies that could be used to assess the LCOE reduction enabled by LAC, resulting in a road map for further research.

During the workshop, several applications of LAC for reducing LCOE were discussed in the context of systems engineering. In this paper, we review the state of the art, challenges, and proposed research priorities for the most promising LAC applications identified, namely:

- Section 2: Increasing annual energy production (AEP)
- Section 3: Decreasing capital expenditure (CapEx) costs by reducing design loads
- Section 4: Extending turbine lifetime by reducing operating loads
- Section 5: Enabling wind turbine class upgrades.

In Section 6, we briefly review additional application areas for LAC that were proposed at the workshop but were considered secondary objectives. Next, in Section 7, we propose elements of a systems engineering perspective for optimizing wind turbines with LAC based on the outcome of the workshop. We conclude the paper by providing a brief summary and outlook in Section 8.

## 2. Increasing Annual Energy Production

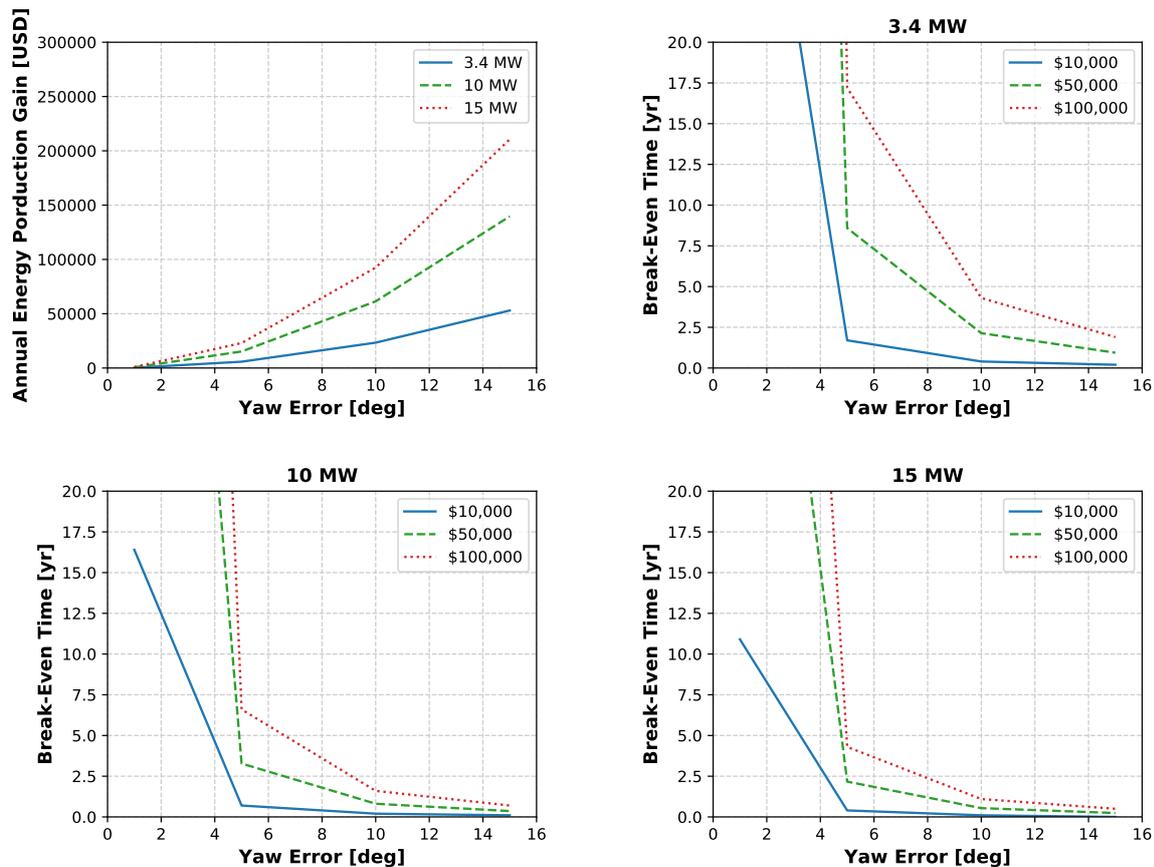
A general area of interest for wind turbine and wind plant controls (regardless of sensor input) is increasing AEP, which is often the most immediate way to reduce LCOE and increase profits for wind turbine owners. Lidars have potential to augment the effectiveness of various AEP strategies through improved characterization of the real-time inflow to a wind turbine or wind plant.

### 2.1. State of the Art

One application of LAC that shows particular promise is to use the lidar as an additional wind direction sensor to reduce yaw misalignment, thereby increasing the power produced and ultimately increasing AEP. Conventional horizontal-axis upwind turbines rely on a wind vane sensor to measure the wind direction as an input to an actively controlled yaw system. This sensor is typically located on the aft portion of the nacelle roof behind the rotor plane. With this setup, biases can be introduced in the signal from the disturbed flow as a result of the vane's location in the near rotor wake as well as from disturbances from aerodynamic influences by the nacelle geometry. This can be corrected by using a transfer function in the controller [8], but performance will depend on how well the transfer function is modeled. Additionally, if the vane is damaged, slips on its mount, is installed/calibrated improperly, etc., a bias in the measurement could be introduced, resulting in an operational yaw error. Lidars can correct for this by taking remote measurements spatially far from the rotor and nacelle. The lidar measurements can either be used to calibrate an existing vane and/or transfer function for an active yaw controller [9] or be fed directly into the controller in place of the vane sensor [10]. Both methods have shown that the yaw error can be reduced, resulting in gains in power production [9, 10, 1].

A simple cost analysis is performed here to investigate how a lidar can be used to increase AEP by improving yaw alignment. The analysis, which is run by adopting the set of IEA Wind Task 37 reference wind turbines [11, 12], tries to quantify the financial gain generated by the increased AEP and the time to break even given the cost of the lidar. The analysis assumes yaw bias values of  $1^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$  and lidar lifetime costs of USD 10,000, 50,000, and 100,000.

The assumptions taken in this analysis consist of an electricity sale price of  $\$0.12/\text{kW-h}$ , a constant yaw bias for the turbine that can be fully corrected thanks to the lidar, and an air density of  $1.225 \text{ kg/m}^3$ . The study also assumes that the power loss from a yaw bias is equal to the square of the cosine of the yaw bias and that wind is Rayleigh distributed given the International Electrotechnical Commission (IEC) wind site class. AEP is computed by



**Figure 1.** Gain in USD from the increased AEP (top left) and breakeven time in years for varying lidar costs for the 3.4-MW (top right), 10-MW (bottom left), and 15-MW (bottom right) reference wind turbines.

integrating the product of the reference turbine power curve, the wind speed distribution, and the hours in a year. With this, and with the assumed price of electricity, a dollars-per-year gain can be realized. From the gain, a breakeven time frame can be determined for the specific cost of the lidar. Results generated by following this approach are shown in the plots in Fig. 1.

The plots show that as the yaw bias increases, the AEP gain increases dramatically because of the power loss being proportional to the squared cosine of the yaw bias. The lines also show that as the turbine increases in rated power, the AEP gain generated by the lidar also increases, and as a result the breakeven time frame for the cost of the lidar decreases. The results show that for a 3.4-MW wind turbine, the lidar system becomes competitive only for yaw errors greater than 5 degrees and a lidar price significantly less than USD 100,000. These numbers change for larger nameplate powers, and the bigger the turbine, the more expensive the lidar system can be. The plots also show, however, that for yaw errors less than 5 degrees, a lidar system is likely not financially justifiable if it is used only to reduce the yaw error to improve AEP. Note that this analysis is very idealistic, and a more refined research investigation is recommended. This is discussed in Section 2.2.

## 2.2. Research Priorities

Section 2.1 presented the state of the art of research focused on adopting lidar to reduce yaw error and improve AEP; however, research so far has focused on relatively old kilowatt-scale wind turbine models, which historically have exhibited large yaw errors. AEP improvements obtained using a lidar system for modern wind turbines with potentially well-calibrated wind vanes should be investigated further. The simple example presented in Section 2.1 is affected by possibly optimistic assumptions, which should be assessed in detail. Among others, the presence of a static yaw error is likely an incorrect assumption because wind turbines operate with a range of yaw errors. The analysis also does not consider the dynamics of the yaw controller, which would vary the distribution of yaw errors depending on how the controller is implemented. Additionally, a lidar has the potential to reduce a yaw bias, but the dynamics of the turbine and lidar system will never eliminate it completely. There is also a need to evaluate such LAC strategies against other novel techniques using existing available turbine sensor information to seek yaw error correction, such as consensus-based control [13].

Overall, it is recommended to first quantify the yaw errors experienced by modern wind turbines. Notably, industry participants at the workshop highlighted that modern configurations could experience average yaw errors less than 1 degree. If errors approach values as high as 5 degrees, higher fidelity studies are recommended. These should account for the full aeroservoelastic behavior of the wind turbine, and they should accurately model the inflow conditions, lidar measurement process, and controller.

## 3. Reducing Wind Turbine CapEx

A second application of LAC is to reduce the loading on the wind turbine system, which could result in lighter, less expensive designs.

### 3.1. State of the Art

Research in the area of LAC for load reduction has mostly focused on fatigue loads, although some investigations of extreme load reduction have been performed. Most LAC research for load reduction has focused on feed-forward collective pitch control, which has a high technology-readiness level compared to other LAC strategies, such as individual pitch control. Collective pitch LAC is successful in reducing thrust-driven fatigue loads aligned with the wind direction, such as tower fore-aft moments, whereas loads driven by gravity (e.g., blade edgewise moments) or torque (e.g., drivetrain loads) cannot be significantly alleviated. For example, through aeroelastic simulations, Bossanyi *et al.* [2] reported lifetime fatigue load reductions of 10%–14% for tower base fore-aft bending moments and 3.5%–4.5% for blade root out-of-plane bending moments. Using a different aeroelastic simulation environment, Schlipf [3] found that lifetime tower base fore-aft and blade root out-of-plane fatigue loads can be reduced by 18.3% and 10.7%, respectively, with a 5.9% reduction in low-speed shaft torque fatigue loads as well.

Elorza *et al.* [14] investigated the potential for extreme load reduction using LAC by reducing the turbine's generator speed set point or by setting bounds on the pitch angle in response to detected gusts. Considering the design load cases (DLCs) from the second edition of the IEC 61400-1 standard [15], the authors identified the potential for extreme load reduction for different components by determining the gap between loads from DLCs for which control is active and loads from DLCs where control does not have an impact, such as parked cases. Elorza *et al.* [14] found that LAC can reduce extreme blade root edgewise loads by 10%, tower base bending moments by 5%, and hub bearing moments by 13%. Blade root flapwise loads were found to be driven by a noncontrolled DLC, which LAC does not impact. The authors focused on responding to uniform gusts (e.g., the extreme operating gust), but additional load reduction potential exists for control strategies that address other extreme wind events, such as extreme shear or wind direction changes.

One challenge of designing wind turbines that rely on LAC for extreme load reduction is simulating realistic lidar measurements for extreme wind fields. Most extreme wind fields defined by the IEC 61400-1 standard [16] do not contain turbulence, resulting in simulated lidar measurements with unrealistically high accuracy. To enable more realistic and robust evaluations of LAC for extreme load reduction, Schlipf and Raach [17] developed a method for generating constrained turbulent wind fields matching a prescribed rotor-average gust shape. In response to a more realistic turbulent extreme operating gust, the authors demonstrated a tower base extreme load reduction of 38.5%. Hagemann *et al.* [18] extended this constrained wind field method by considering realistic turbulent wind fields containing extreme horizontal and vertical wind shear as well.

### 3.2. Research Priorities

Workshop participants discussed the need to demonstrate CapEx reductions of at least 1%–3% for LAC to be of interest to wind turbine manufacturers. Despite the significant progress in load reduction with LAC, determining the impact on CapEx costs remains challenging. First, translating load reduction to cost reduction is not trivial and requires a sophisticated bottom-up design systems engineering approach. Additionally, depending on the turbine parameters and wind class, the design of individual components might be driven either by fatigue or by extreme loads; thus, both fatigue and extreme load reduction capabilities should be demonstrated for wide adoption of LAC. Several research priorities for demonstrating and quantifying CapEx reductions are briefly discussed here.

**3.2.1. Ultimate Load Reduction** Although the bulk of LAC research has focused on fatigue loads, extreme load reduction is increasingly becoming a priority for enabling CapEx reduction. For example, on many modern turbines with large, flexible rotors, blade designs are driven by extreme tip deflection constraints rather than fatigue loads. Whereas LAC strategies have been developed for responding to extreme gusts, many component designs are driven by DLCs containing extreme direction changes or extreme wind shear, which have not been addressed in as much detail by the LAC community. Ultimate load reduction for DLCs during normal power production (DLCs 1.x [16]) should be the focus of LAC as long as these DLCs are design driving; however, it is common for extreme wind conditions during parked operation (DLCs 6.x) to drive the design of many turbine components. If this is the case, the use of lidar preview measurements to properly orient the turbine in response to extreme direction changes could enable load reduction and should be explored further. Finally, to allow a fair evaluation of load mitigation strategies for extreme wind events, additional research is needed to develop realistic lidar measurement simulations for extreme wind direction changes (DLC 1.4 in IEC 61400-1 Ed. 3 [16]) and extreme wind shear (DLC 1.5). In addition to adding turbulence to these extreme wind fields, uncertainty in the speed of advection of the wind field toward the turbine and the direction of propagation (in the case of DLC 1.4) should be included.

**3.2.2. Control Strategies for Limited Availability** Relying on LAC for extreme load reduction requires lidar measurements to be available during extreme events. Although lidar availability is typically high, there are times when atmospheric conditions (e.g., heavy fog or low aerosol density) prohibit reliable lidar measurements; therefore, backup control strategies, such as derating, should be developed with the goal of preventing excess loading during periods of LAC unavailability. The AEP penalty incurred by derating must then be included in the calculation of LCOE. For example, if lidar availability is assumed to be 95%, with derated operation occurring the remaining 5% of the time, AEP should be calculated as  $0.95 \cdot \text{AEP}_{\text{LAC}} + 0.05 \cdot \text{AEP}_{\text{derate}}$ , where  $\text{AEP}_{\text{LAC}}$  is the resulting AEP with LAC active, and  $\text{AEP}_{\text{derate}}$  is the lower AEP value when the turbine is derated. Because of the potentially strong dependence of LCOE on lidar

availability, workshop participants suggested the use of lidar availability “classes” indicating the expected level of availability resulting from site-specific atmospheric conditions. Further, any correlation between lidar unavailability and the extreme wind conditions that LAC is intended to address should be considered.

*3.2.3. Varying the Turbine Design Lifetime* Given the promising fatigue load reduction capabilities of LAC, workshop participants raised the possibility of designing turbines for longer lifetimes (e.g., 30 years), for which fatigue loads are more likely to surpass ultimate loads as design drivers because of the additional load cycles. Turbine lifetime could even be treated as a free variable in the LCOE optimization process. But because of industry familiarity with designing turbines for 20-year lifetimes, the economic benefits and certification challenges that accompany longer turbine lifetimes require further investigation.

#### 4. Wind Turbine Lifetime Extension

In a scenario where wind turbines are already installed, the fatigue load reduction typically obtained by LAC can be used to extend the operating lifetime of the turbine, increasing the amount of energy produced.

##### 4.1. State of the Art

A simplified estimation of the lifetime extension (LTE) potential from LAC for each component can be determined by comparing the damage equivalent loads (DELs) with LAC and baseline control [19]. For example, LAC might be able to increase the tower lifetime by  $1.5\times$ ; however, if there is no margin on torque-related loads such as shaft loads, for which LAC is less effective, a slight derating could be necessary to fully exploit the fatigue load reduction over all components. A first study highlighting a sequential approach for the optimization of the lidar scan trajectory, lidar data processing parameters, and the feedback parameters is presented in [20].

A simplified estimation of the LTE potential for each component based on the load reduction from LAC compared to conventional control (FB) can be calculated by:

$$\text{LTE} = \left( \frac{\text{DEL}_{\text{LAC}}}{\text{DEL}_{\text{FB}}} \right)^{-m}, \quad (1)$$

where  $m$  is the Wöhler exponent [19]. For steel components (e.g., tower) with  $m = 4$ , a load reduction of 10% would yield a LTE of approximately  $1.5\times$ . If this LTE can be obtained for all components, every year of the remaining lifetime can be replaced by 1.5 years with LAC. The benefit of this strategy would be that for times when the lidar is not available (e.g., because of low backscatter) and this situation can be detected, the turbine could operate with the conventional controller. This would only reduce the LTE without further impact. An important consideration is that LAC is more likely to reduce the thrust-related loads, such as tower fore-aft bending moment or blade out-of-plane bending moment. If the turbine does not have a margin on torque-related loads such as shaft loads, a slight derating could be necessary to fully exploit the fatigue load reduction over all components. Because minor derating usually has only a small effect on thrust-related loads, derating and LAC complement each other to balance out loads.

The benefit to using this approach for a systems engineering case study is that no complex cost model is needed. The turbine’s structure is fixed, and the loads are kept within the margins; thus, the additional energy gained can be evaluated with an average energy price against the additional investments. Based on our knowledge, however, the LTE strategy discussed here has not yet been applied.

#### 4.2. Research Priorities

One main research priority for LTE applications is to better understand the economic benefits of the extended lifetime. For example, the reduction of the energy yield during the early period of a wind turbine's lifetime might be economically less attractive, even if more energy can be harvested after the original lifetime. Properly discounting the additional energy production after the wind turbine's originally planned lifetime would help with understanding the net present value of LTE via LAC. Because LTE will incur additional costs and would require a modification of the existing control system, the strategy might be attractive only for a subset of existing turbines.

### 5. Reducing LCOE by Wind Class Upgrade

The use of LAC to enable wind turbines to operate at sites with more demanding wind characteristics than those for which they were originally intended was identified as another avenue for LCOE reduction by eliminating the need for a more expensive turbine design.

#### 5.1. State of the Art

Although an existing turbine design might not benefit significantly from LAC, load reduction from LAC could allow the turbine to remain within its design load envelope in wind classes with higher turbulence intensity or mean wind speed. For example, the tower of a Class IIIB wind turbine [16] could be ultimate load dimensioned and unable to benefit from fatigue load reduction from LAC. If the tower instead becomes fatigue load dimensioned in a more turbulent wind environment, however, LAC could be used to reduce the fatigue loads to an acceptable level, potentially enabling the turbine to operate at Class IIIA sites with higher turbulence intensity.

Depending on the specific design drivers, LAC might be able to allow a turbine to safely operate at sites with higher wind speeds as well. If a turbine spends more of its lifetime operating in above-rated wind conditions, more opportunity would exist for fatigue load reduction from lidar-assisted pitch control; however, the extreme wind events the turbine would be subjected to would likely be more severe, increasing ultimate loads as well.

#### 5.2. Research Priorities

Because of the lack of research in the area of wind class upgrades, different wind turbine designs should be investigated to estimate the potential for LCOE reduction. For the wind turbines considered, the full suite of DLCs could be evaluated with and without LAC for a wind turbine class with higher turbulence (e.g., Class IIIB  $\rightarrow$  Class IIIA) or higher mean wind speed (e.g., Class IIIB  $\rightarrow$  Class IIB). Assuming LAC is being used solely for fatigue load reduction, if the ultimate loads in the new wind class remain within the design envelope using baseline control, but fatigue loads exceed the design envelope for certain components, the potential exists for LAC to enable a wind class upgrade. As long as LAC reduces the fatigue loads to within the original design envelope in the new wind class, the turbine could safely operate in the more demanding environment. Even if LAC cannot enable safe operation in a new IEC wind class, it could potentially be used to facilitate deployment in more locations based on site-suitability studies.

A summary of the LAC applications discussed in this paper is provided in Table 1 along with a qualitative ranking of their potential impact to the target LCOE reduction category, the criticality of lidar availability to realizing the potential improvements, and the maturity of the technological development (in terms of technology readiness level (TRL)). We highlight lidar availability requirements because imperfect availability is often viewed as a barrier to the use of LAC.

**Table 1.** Summary of LAC applications for LCOE reduction, including our characterization of the potential impact on the LCOE reduction category; the required level of lidar availability; and the general TRL.

LCOE Category	LAC Application	Potential Impact	Required Availability	TRL	Comments
AEP	Yaw error bias correction	Medium	Low	High	AEP impact depends on level of wind vane calibration
CapEx	Fatigue load reduction	Medium	Medium	High	Requires fatigue-driven design
CapEx	Extreme load reduction	High	High	Low	Sensitive to lidar availability; unclear how to simulate extreme wind fields for design
CapEx	Wind class upgrade	Medium	Medium	Medium	Scenarios in which fatigue load reduction can enable a wind class upgrade should be identified
Lifetime energy production	Lifetime extension from load reduction	Medium	Medium	Medium	Uncertainty on economic impact of lifetime extension

## 6. Other Potential Lidar-Assisted Control Applications

Although the four most promising LAC applications identified during the workshop were highlighted in Section 2 through Section 5, additional LAC use cases were proposed that could merit further investigation in a systems engineering context. These additional applications are briefly described here.

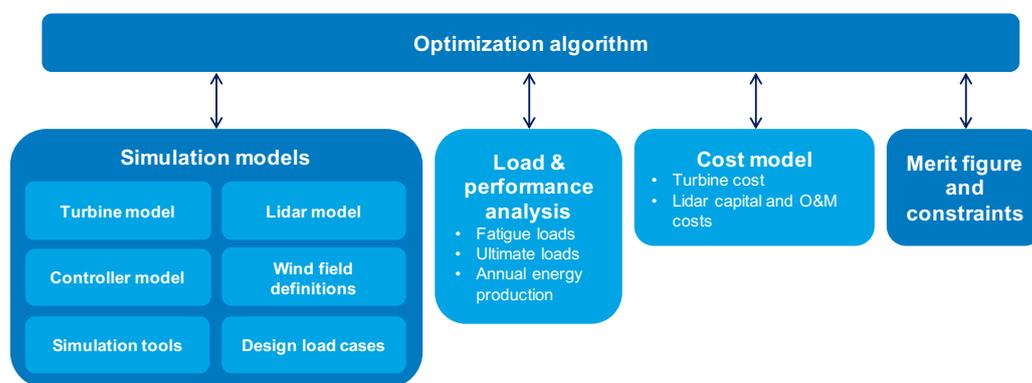
- Wind plant control: Lidar measurements could be used as part of a wind plant control strategy for increasing energy production or reducing structural loads by influencing wake behavior. For example, measurements of the wind inflow or the degree of wake impingement could assist with load balancing, wherein upstream turbines are derated to reduce loads experienced by downstream waked turbines, thereby helping to balance the loading at each turbine while maintaining acceptable energy production.
- Risk reduction: Even if imperfect lidar availability (or other factors) prohibits the use of LAC for reducing extreme design loads, extreme event detection via lidar measurements can act as a form of additional insurance. Although lidars might not be able to detect every problematic gust, using LAC to protect the turbine from the majority of extreme events could reduce the risk enough to permit operation in more challenging environments.
- Increasing the rotor size or tower height: The discussion of LAC for CapEx reduction at the workshop focused on reducing the cost of an existing turbine configuration via load reduction; however, the optimization problem could be reframed to enable greater power capture through a larger rotor or taller tower while maintaining the original design loads.
- Dynamic power rating: Lidars can be used to characterize the turbulence level of the wind inflow. This information could be used to allow the turbine to safely produce more than its

rated power when operating in wind conditions deemed benign from a loads perspective.

- Avian and bat detection: Lidar systems are capable of detecting the presence of hard targets along the beams. This information could potentially be used to reveal the presence of birds and bats as part of a smart curtailment strategy for reducing bird and bat fatalities.

## 7. Opportunities for a Formal Systems Perspective

To address all the points mentioned in the preceding sections, workshop attendees highlighted the need to adopt optimization frameworks that can evaluate the impact of LAC on the whole wind turbine system (see Fig. 2). This will challenge the state of the art in modeling for LAC systems; however, the fidelity level required for analysis of LAC impacts on turbine performance and loads will challenge the state of the art in systems engineering of wind turbines as well.



**Figure 2.** Wind turbine optimization structure.

### 7.1. Improving Systems Engineering Methods

Systems engineering approaches to integrating LAC into the turbine design process should have the potential to explore the full solution space while capturing the design trends for each relevant component of the wind turbine system. In terms of wind turbine analysis, the workshop attendees highlighted that a full aeroservoelastic model fed with turbulent wind conditions represents the appropriate fidelity level. Notably, the adoption of such models typically implies the need for fairly sophisticated optimization algorithms [21]. The load and performance metrics that are generated by dynamic simulations are indeed often discontinuous, especially as a result of the dynamic behavior of wind turbine controllers. These could, for example, trigger a shutdown, or induce a nonlinear response to resonance effects, generating discontinuities in outputs of interest such as power production and maximum tip deflection. Aeroservoelastic simulations are also computationally demanding, with run times on the order of minutes, if not hours. Finally, the LCOE response surface is often very flat, making it difficult to identify trends in response to parameter variations [22]. Overall, wind turbine design approaches that model the full aeroservoelastic behavior of the wind turbine are often built with nested structures [23], which are found to return better convergence trends and ultimately more accurate results than brute-force monolithic approaches.

Workshop attendees also highlighted that the analysis should not be restricted to a single case; rather, it should assess the impact of LAC for different turbine markets, specific power configurations, and wind classes. Indeed, such parameters greatly affect the design drivers of a machine and could greatly impact the effects that LAC generates. To follow such an approach, load rankings and design drivers of existing reference wind turbines should be highlighted and validated against existing industrial machines.

### 7.2. Design-Oriented Turbine Cost Modeling

Attention should be paid to the LCOE cost analysis. This requires not only a reliable lidar cost model (see Section 7.3) but also an accurate cost breakdown of LCOE in terms of turbine capital costs, balance-of-station costs, and O&M costs. One source of data on existing costs for wind systems is updated annually at the National Renewable Energy Laboratory [24]. Most data associated with wind turbine design, however, are based on high-level aggregated data for existing commercial designs, which makes it difficult to assess the impacts of design changes on LCOE. A design-based cost model might be needed for major components, such as the blade (see [25] for an example of such a design-based model).

### 7.3. Lidar Cost Modeling

Common to all applications of LAC discussed in this paper is the need for a detailed lidar system cost model to be included in the analysis of LCOE. The model should include the impact of the number of beams, measurement range, availability, required maintenance, and lifetime. Although initially fixing the lidar parameters prior to optimizing the wind turbine design might be desirable to reduce complexity, the cost model should reflect the specific choice of parameters on the cost of the lidar. Further, the cost model should incorporate the estimated cost savings associated with the mass production of lidars for control applications, even if these efficiencies have not yet been realized. Finally, the maintenance costs of the lidar throughout the lifetime of the turbine should be included in the cost model, especially because these could be higher than the initial CapEx cost of the lidar. Because of the lack of historical information about the cost of nacelle lidars for control applications and the proprietary nature of future cost estimates, the workshop participants proposed that a third party, such as a consultant, work with different lidar manufacturers to develop a generic lidar cost model.

## 8. Conclusions

Based on results from the recent IEA Wind Task 32/Task 37 workshop on Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering, we presented four main applications of LAC for reducing the LCOE of wind turbines, and we presented several additional use cases worth exploring further. We then proposed elements of a research plan for identifying the benefits of LAC using a systems engineering approach. More information about the ideas presented and discussed at the workshop can be found in the meeting minutes, available on the workshop website [5]. Moving forward, a substantial joint LAC/systems engineering research effort is needed to evaluate and quantify the benefits of LAC discussed here.

## 9. Acknowledgments

The authors would like to thank all attendees of the IEA Wind Task 32/Task 37 workshop on Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering held in Amherst, MA, October 17–18, 2019. Their precious contributions are summarized in this work.

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

## References

- [1] Scholbrock A, Fleming P, Schlipf D, Wright A, Johnson K and Wang N 2016 Lidar-enhanced wind turbine control: Past, present, and future *American Control Conference (ACC)* (Boston, MA, USA) pp 1399–1406
- [2] Bossanyi E, Kumar A and Hugues-Salas O 2014 *Journal of Physics: Conference Series* **555** 012011
- [3] Schlipf D 2016 *Control Concepts for Wind Turbines* Ph.D. thesis University of Stuttgart Stuttgart, Germany
- [4] Kumar A, Bossanyi E, Scholbrock A, Fleming P, Boquet M and Krishnamurthy R 2015 Field testing of lidar assisted feedforward control algorithms for improved speed control and fatigue load reduction on a 600 kW wind turbine *European Wind Energy Association Annual Event* (Paris, France)
- [5] IEA Wind 2020 IEA Wind Task 32 + Task 37 Workshop 15: Optimizing wind turbines with lidar-assisted control using systems engineering URL <https://community.ieawind.org/task32/events/event-information/workshop-15>
- [6] Simley E, Fürst H, Haizmann F and Schlipf D 2018 *Remote Sensing* **10** 863
- [7] Schlipf D, Hille N, Raach S, Scholbrock A and Simley E 2018 *Journal of Physics: Conference Series* **1102** 012010
- [8] Mittelmeier N and Kühn M 2018 *Wind Energy Science* **3** 395–408
- [9] Fleming P, Scholbrock A, Jehu A, Davoust S, Osler E, Wright A and Clifton A 2014 *Journal of Physics: Conference Series* **524** 012002
- [10] Scholbrock A, Fleming P, Wright A, Slinger C, Medley J and Harris M 2013 Field test results from lidar measured yaw control for improved yaw alignment with the NREL Controls Advanced Research Turbine *33rd Wind Energy Symposium and AIAA SciTech Conference* (Kissimmee FL, USA)
- [11] Bortolotti P, Canet Tarres H, Dykes K, Merz K, Sethuraman L, Verelst D and Zahle F 2019 IEA Wind Task 37 on systems engineering in wind energy - WP2.1 reference wind turbines Tech. Rep. NREL/TP-5000-73492 NREL
- [12] Gaertner E and *et al* 2020 Definition of the International Energy Agency Wind 15-megawatt offshore reference wind turbine - International Energy Agency Wind Task 37 on systems engineering in wind energy - WP2.1 reference wind turbines Tech. Rep. NREL/TP-5000-75698 NREL
- [13] Annoni J, Bay C, Johnson K, Dall'Anese E, Quon E, Kemper T and Fleming P 2019 *Wind Energy Science* **4** 355–368
- [14] Elorza I, Iribas M and Edurne M 2013 On the feasibility and limits of extreme load reduction for wind turbines via advanced sensing: a LIDAR case study *American Control Conference (ACC)* (Washington, DC, USA) pp 1436–1441
- [15] IEC 61400-1, Second edition 1999 Wind turbines - Part 1: Design requirements, International Electrotechnical Commission
- [16] IEC 61400-1, Third edition 2005 Wind turbines - Part 1: Design requirements, International Electrotechnical Commission
- [17] Schlipf D and Raach S 2016 *Journal of Physics: Conference Series* **753** 052011
- [18] Hagemann T, Haizmann F, Schlipf D and Cheng P 2017 Realistic simulations of extreme load cases with lidar-based feedforward control *German Wind Energy Conference (DEWEK)* (Bremen, Germany)
- [19] Engels W P, Marina A J, Kanev S K and van der Hoek D C 2017 Condition based control Tech. Rep. ECN-E-17-047 ECN Wind Energy
- [20] Schlipf D, Fürst H, Raach S and Haizmann F 2018 Systems engineering for lidar-assisted control: A sequential approach *WindEurope 2018 Conference at the Global Wind Summit* (Hamburg, Germany)
- [21] Bortolotti P, Bottasso C L, Croce A and Sartori L 2019 *Wind Energy* **22** 65–79
- [22] Bortolotti P, Bottasso C L and Croce A 2016 *Wind Energy Science* **1** 71–88
- [23] Bottasso C L, Bortolotti P, Croce A and Gualdoni F 2016 *Multibody System Dynamics* **38** 317–344
- [24] Stehly T and Beiter P 2019 2018 cost of wind energy review Tech. Rep. NREL/TP-5000-74598 NREL
- [25] Bortolotti P, Berry D, Murray R, Gaertner E, Jenne D, Damiani R, Barter G and Dykes K 2019 A detailed wind turbine blade cost model Tech. Rep. TP-5000-73585 NREL