1 December 2019

Minutes
of the IEA Wind Task 32+Task 37 Workshop #15 on
Optimizing Wind Turbines with Lidar-Assisted Control using Systems Engineering

Date: 17th and 18th October 2019

Venue: University of Massachusetts Amherst, Amherst, MA, USA

Following the NAWEA/WindTech 2019 Conference

Workshop leaders: *Task 32:* Eric Simley (NREL), *Task 37:* Pietro Bortolotti (NREL)

Organization team: Katherine Dykes (DTU Wind Energy), Holger Fürst (SWE), David Schlipf (WETI), Andy Scholbrock (NREL)

Introduction to the Topic

The goal of IEA Wind Task 32 is to identify and mitigate barriers to the use of wind lidar for wind energy applications including site assessment, power performance testing, loads and control, and measurements in complex flow. Within the topic of loads and control, Task 32 has been active in mitigating barriers to the use of lidar-assisted wind turbine control. The purpose of IEA Wind Task 37 is to coordinate international research activities to analyze wind power plants as holistic systems. Through the development of analysis tools and reference models, Task 37 advances systems engineering methods for reducing the levelized cost of energy of wind energy projects.

Lidar-assisted control (LAC) is effective at reducing structural loads on wind turbines, which has been demonstrated through simulation as well as field testing. However, it is difficult to determine the reduction in cost-of-energy that can be achieved through the use of LAC, especially because of the additional costs associated with integrating lidar hardware into the turbine design. Furthermore, LAC is often analyzed using existing turbine designs. Systems engineering presents an opportunity to directly include the use of LAC during the turbine design process to optimize the levelized cost-of-energy. The aim of this workshop is to combine the experience in lidar-assisted controller design and modeling from Task 32 with the knowledge of systems engineering analysis using reference wind turbine models from Task 37 to show how wind turbines can be optimized with LAC.

Objectives

The primary objective of the workshop is to identify a process for determining the reduction in cost-of-energy made possible by LAC. This objective can be divided into the following steps:

1. To identify models and simulation capabilities that need to be established to include LAC in the wind turbine optimization process
2. To identify reference wind turbine models and controllers that can be used to quantify the benefits of LAC

3. To propose a process for optimizing a reference wind turbine and baseline controller using LAC
4. To discuss opportunities to further collaborate on the proposed wind turbine optimization research

Concept

The workshop is split into six main sessions:

1. Educational Session: Understanding LAC and systems engineering
2. Presentations on the benefits of LAC
3. Discussion of models needed to include LAC in the wind turbine optimization process
4. Presentations on wind turbine optimization using systems engineering
5. Discussion of methods for optimizing wind turbines with LAC
6. Development of a research plan for optimizing wind turbines with LAC

Expected Outcome

The outcome of the workshop will be

- An exchange of experience in wind turbine optimization with systems engineering and LAC
- Initiation of a working group to write a white paper containing a roadmap for including LAC in the optimization of the cost-of-energy of wind turbines
- Identification of opportunities to pursue further research on wind turbine optimization with LAC

Day 1

Introduction

9:30	**Introduction** ● Purpose of the workshop and agenda - **Eric Simley and Pietro Bortolotti, NREL** ● Presentation round – all (please send us your slide, see practical arrangements)

Purpose of the workshop and agenda - Eric Simley and Pietro Bortolotti, NREL

- Eric introduces IEA Wind Task 32 as well as the workshop motivation and agenda
- The objective of IEA Wind Task 32 is to identify and mitigate barriers to the deployment of wind lidar for wind energy applications by enabling the exchange of experience between different stakeholders. The focus areas within Task 32 are:
  - Site assessment
  - Power performance
  - Loads & control
  - Complex flow
  - Out-of-the-box
- Previous Task 32 workshops related to lidar-assisted control (LAC) include:
  - Workshop #2: Optimizing lidar design for wind turbine control applications
  - Workshop #10: Certification of lidar-assisted control applications
- Pietro introduces IEA Wind Task 37, presenting the recently concluded Phase I and the newly approved Phase II. The four work packages are
  - WP 1: work aims at defining common guidelines for integrated research, design and development of wind energy systems
  - WP 2: work aims at defining reference wind energy systems, both at turbine and plant level
  - WP 3: work aims at defining benchmarking multi-disciplinary design, analysis, and optimization exercises at various system levels, e.g. wind turbine aerodynamics, wind farm layout, etc.
  - WP 4: the work package aims at organizing a series of workshops with two different themes. The first one is about common studies on an advanced design challenge, the second one is about system level evaluations of state-of-the-art technologies. This workshop is the first one of the second series of workshops, connecting the LAC community with the SE community.
- One of the main barriers to the use of LAC identified by Task 32 is a lack of clarity in the cost-benefit analysis. For example, how can the cost reduction resulting from load reduction from LAC be quantified, and will the cost savings outweigh the additional cost of the lidar?
- Task 32 workshop #8 provided ideas for how to include LAC when analyzing turbine loads, where issues such as quantifying lidar availability and the applicability of LAC with imperfect lidar availability to extreme load reduction were discussed
- The above points motivated the focus of workshop #15: Collaborating with Task 37 to determine how to assess the cost-benefit relationship of LAC using systems engineering methods

Presentation round – all (please send us your slide, see practical arrangements)

The participants introduced themselves and presented their slides, explaining their experience in systems engineering and/or lidar-assisted control and their expectations for the workshop.

Educational Session: Lidar-assisted control and systems engineering

11:00	**Educational Session: Lidar-assisted control and systems engineering** ● Overview of lidar-assisted control - **Andy Scholbrock, NREL** ● Overview of wind turbine systems engineering - **Pietro Bortolotti, NREL and Katherine Dykes, DTU Wind Energy**

Overview of lidar-assisted control for wind turbines - Andy Scholbrock, NREL

- Lidars can be used for feed-forward controls to reduce turbine loads, particularly for tower load reduction
- Lidars can be used for yaw control to reduce wind turbine yaw misalignment
- Lidars can be used for wind plant level control, possibly for closed loop wake redirection
- *Comment*: Feedforward control could also be useful in below-rated operation (region 2) if the turbine is derated. Feedforward control could also help in the region 2.5 transition, when pitch and torque control are active.
- *Question*: How does wind veer impact lidar yaw measurements?
  - *Answer:* Not sure, the results presented were averaged over many wind veer conditions
- *Question*: How many seconds of preview do you have for LAC and how much preview do you need, especially given slow pitch rate?
  - *Answer*: For the LAC experiments on the CART turbine at NREL, the lidar provided 4 seconds of preview. Preview is mostly needed to make up for the delay from filtering the lidar measurements. Only 2 seconds of preview were needed to overcome the filter delay.
- *Question*: How does the load improvement from LAC scale with turbine size?
  - *Discussion*:
  - Load reduction will depend on the rotor stiffness, which changes with turbine size
  - Rotor inertia scales with size too, so the feedback controller will have a harder time reacting based on changes in rotor speed for larger turbines. This presents an opportunity for LAC.
  - For larger rotors, controlling low frequencies is more important, and lidar is more accurate at measuring low frequencies of the wind
  - If the cost of the lidar stays the same but the turbine grows in size, the relative cost of the lidar decreases, which is an advantage for LAC
  - For larger turbines, lifetime extension from LAC could be more valuable
- *Question*: How many lidars are needed for wind farm control?
  - *Answer*: It isn't clear how many (for example, if one is needed for each turbine)
- *Comment*: The gains from lidar-assisted yaw control depend on the amount of vane error, which depends on the calibration of the vane and the calibration degradation over time. Vane errors as high as 15° have been observed for a group of turbines.

Overview of wind turbine systems engineering Part 1: Systems engineering for wind turbines: Overview of existing approaches and ongoing R&D - Pietro Bortolotti, NREL

- Systems engineering for wind turbines is more challenging than it may seem at first sight
- The biggest challenges are a computationally expensive set of aeroservoelastic simulations, the need for an autotuning controller, discontinuities in the load outputs, and a flat levelized cost of energy solution space
- In terms of workflow architecture, everyone has been using his/her own method, ranging from low-fidelity monolithic approaches to nested multi-fidelity algorithms
- WISDEM represents a great platform to investigate the benefits of lidar assisted control

- *Question*: Can a data-driven approach be used to train low-fidelity models from high-fidelity simulations?
    - *Answer*: This is hard to do, especially given how many design load cases need to be considered. It is better to get in the right direction with low and mid-fidelity models. Multifidelity and adjunct modeling approaches can be used too.
- *Comment*: DTU has an auto-tuning PI controller that can be used in wind turbine optimization
    - *Discussion*:
    - Auto-tuning controllers are not representative of industry methods
    - The controller used for optimization should have easily accessible parameters that can be included in the optimization
    - There is a debate about whether controller parameters should be optimized as part of a sub-optimization or as part of a monolithic optimization

Overview of wind turbine systems engineering Part 2: Overview of Task 37: Wind turbine systems engineering - Katherine Dykes, DTU Wind Energy

- This presentation provides a brief look at historical developments in using systems engineering for wind turbine design and where we are today
- It also briefly covers an overview of the IEA Wind Task 37 wind energy systems engineering activities

Understanding the benefits of lidar-assisted control

13:15	**Understanding the benefits of lidar-assisted control, Chaired by Andy Scholbrock, NREL** Invited presentations from the stakeholders with time for questions ● DTU SpinnerLidar for Upwind Inflow and Turbulence Measurements - **Torben Mikkelsen, DTU Wind Energy** ● Developing the Usage of Wind Turbine Integrated Lidars - **Matthieu Boquet, Leosphere** ● Benchmark Test of Lidar-Assisted Control using a 300 kW Wind Turbine - **Hirokazu Kawabata, AIST** ● Mitsubishi Electric’s Nacelle-Mounted LiDAR for Lidar-Assisted Control of Wind Turbines: Recent Progress and Benefits - **Shumpei Kameyama, Mitsubishi Electric Corporation** ● Tools for Systems Engineering for Lidar Assisted Control - **Steffen Raach, sowento**

DTU SpinnerLidar for Upwind Inflow and Turbulence Measurements - Torben Mikkelsen, DTU Wind Energy

- 2D rotor scan, 400 points per second, line-of-sight measurements
- Inflow shear, veer and wake detection
- Turbulence: measures all six co-variances, 10-minute averaged, un-truncated, averaged over rotor plane upwind
- Provide data for feed-forward control—e.g. via POD methods
- Enables 3D mean wind field reconstruction

Developing the Usage of Wind Turbine Integrated Lidars - Matthieu Boquet, Leosphere

- There is a pressing **need to disseminate the achievable benefits of permanently integrated turbine-mounted Lidars** at a wider scale within the wind industry, in particular to demonstrate the gains for wind turbine OEMs’ customers
- Indeed the **value of integrated Lidars goes beyond wind turbine CAPEX reduction**, because they also enable the increase of AEP, as well as provide continuous acquisition of quality wind data collection for multi-usages like monitoring and improving turbine and farm performance and costs

- The cost of integrated Lidars is decreasing thanks to a better integration into wind turbines, technology and production process improvements, and the effect of volume sales
- Today, given the wide range of achievable benefits, and although it is recognized that **Lidar acceptance takes time, the technology is passing the steps and there does not seem to be any unbreakable barrier to achieve a positive RoI for wind turbine OEMs, wind farm developers and operators**

Benchmark Test of Lidar-Assisted Control using a 300 kW Wind Turbine - Hirokazu Kawabata, AIST

- AIST has started LAC benchmark tests using LIDAR, which can control scanning patterns
- Availability was the parameter that most influenced the benefits of LAC
- The impact of complex terrain on the benefits of LAC needs to be clarified

Mitsubishi Electric's Nacelle-Mounted LiDAR for Lidar-Assisted Control of Wind Turbines: Recent Progress and Benefits - Shumpei Kameyama, Mitsubishi Electric Corporation

- The current status of Mitsubishi Electric's nacelle lidar was introduced
- The basic performance was verified by DNV-GL. The effect of LAC using the Mitsubishi lidar has been studied using simulations under collaborative work with Sowento.
- One idea for the cost-benefit performance calculation regarding the LAC was shown: lifetime extension from 20 years to 25 years enabled by LAC
- *Question*: Are new lidar technologies, such as lidar for self-driving cars, applicable to LAC?
  - *Discussion*:
  - Lidar for self driving cars is designed to detect range, not velocity, so it not directly applicable to LAC
  - The Spidar lidar uses direct detection technology, instead of the more common Doppler-based method. Measurements can be provided at a rate of 7 Hz.
- *Question*: Can edgewise blade loads be reduced with LAC?
  - *Discussion*:
  - Not all loads can be reduced using LAC
  - It is difficult to determine how to convert fatigue load reduction to cost reduction

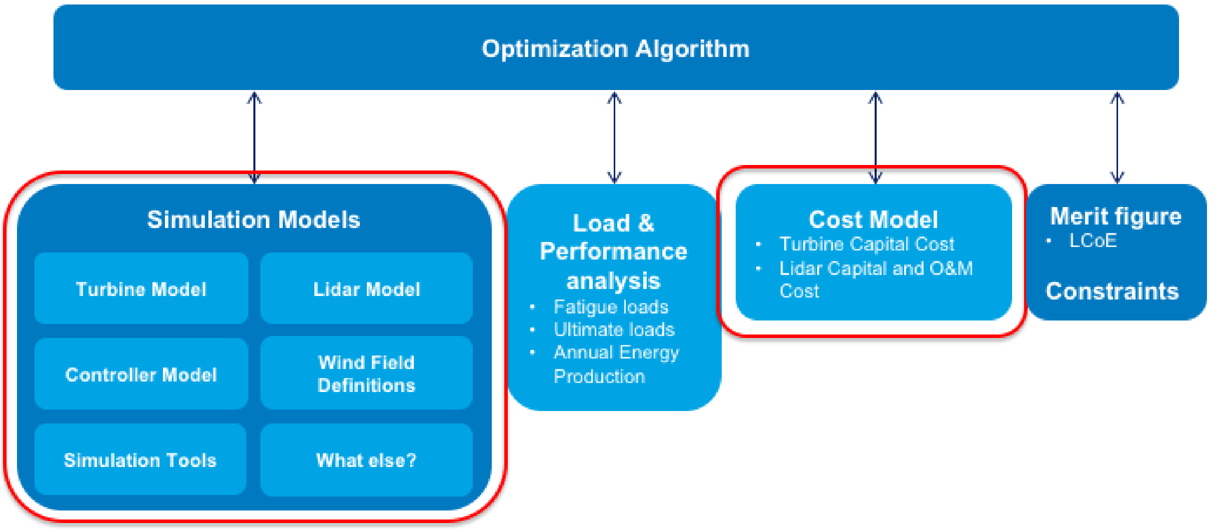
Tools for Systems Engineering for Lidar Assisted Control - Steffen Raach, sowento

- Implementation of Lidar-Assisted Control (LAC) for Systems Engineering follows a modular approach: Lidar Data Processing, Feedforward Controller, Feedback Controller; which enables the development towards a Smart Lidar and an advanced leverage of the provided preview information in the controller
- Two lidar simulators have been presented, one implemented in FAST (in cooperation with the University of Stuttgart and the University of Flensburg) and one cross-tool lidar simulator calculated in the frequency domain (available at sowento)
- sowento is providing basis versions of the modules to the IEA community

Identifying models needed to include lidar-assisted control in wind turbine design

15:15 - 16:45	**Identifying models needed to include lidar-assisted control in wind turbine design, Chaired by David Schlipf, WETI** ● Group discussion in small groups ● Presentation of results to plenary ● Discussion and documentation of results

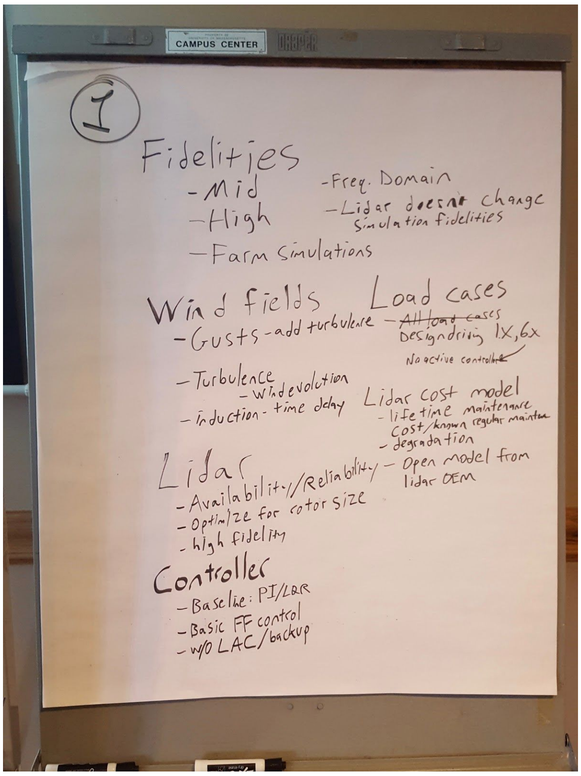
The following diagram, which illustrates the framework for optimizing wind turbines with LAC, was presented. This group discussion session focused on simulation and cost models that could be used to optimize wind turbines with LAC.



The participants split into four groups and were asked to brainstorm answers to the following questions:

1. What models and fidelities are needed?
    - Turbine
    - Controller
    - Lidar and data processing
    - Cost …
2. How should we simulate?
    - Wind fields
    - Load cases…
3. How should we validate our models?
    - Field testing
    - Wind tunnel…

Results from each group are below.

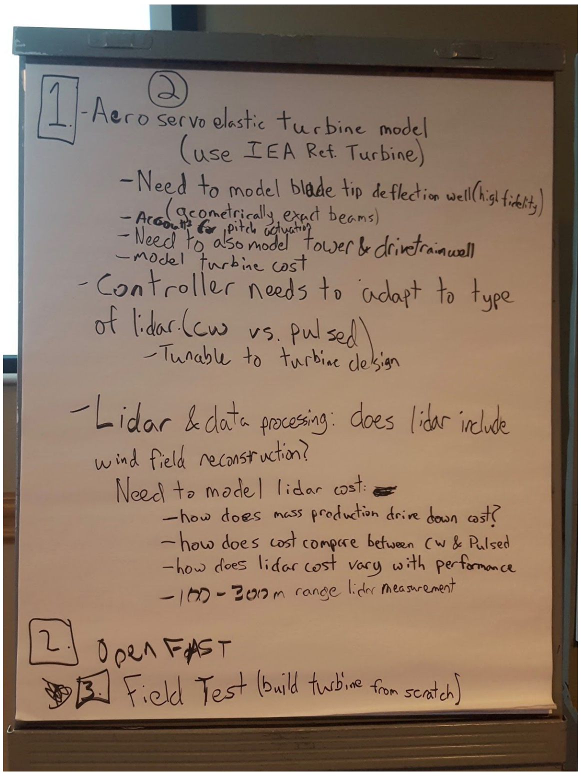


Group One

The group discussed the various fidelity levels, concluding that the analysis should be conducted at various levels to capture all effects. Lidar measurements can even be modeled in the frequency domain. The wind fields should model unsteady effects such as turbulence and gusts, and the load cases 1.X and 6.X should be part of the analysis. Turbulence can be added to coherent gusts to make the corresponding lidar measurements more realistic.

In terms of Lidar, the group found that a cost model should be developed including costs for maintenance and degradation effects. A generic cost model should be developed and made publicly available with input from Lidar OEMs. The simulation model for the Lidar should include availability and reliability and should be high fidelity.

Finally, the controller should have a baseline version equipped with a PI or an LQR formulation, but should also include a feed-forward logic and should be able to switch on/off the Lidar. Simulations should be performed without Lidar control to represent periods of unavailability.



Group Two

The group started the discussion focusing on the turbine model, which the group thought should be modeled with a full aeroservoelastic solver. This indeed allows capturing of the blade tip deflections, which are crucial blade design drivers, as well as fatigue loads, which are design drivers of the tower structure. The newly developed IEA reference wind turbines could be used.

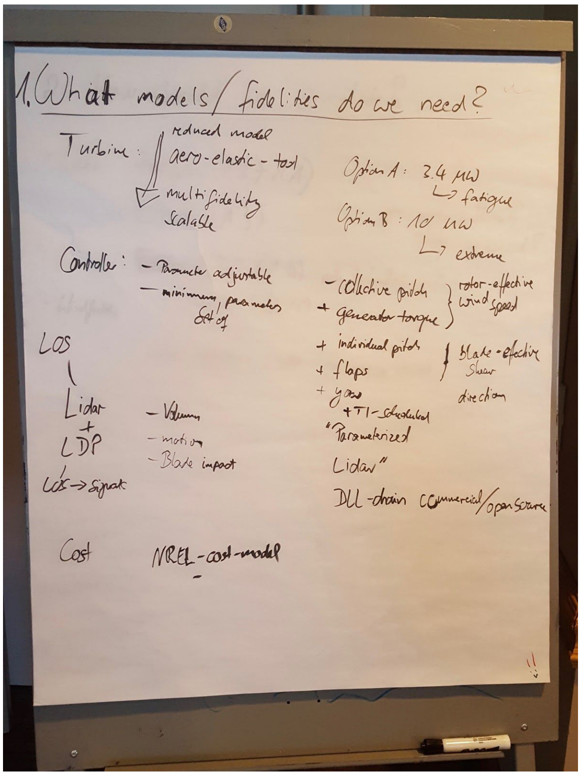
The group also highlighted the need for accurate drivetrain models and not only a blade-centric modeling of the problem. Accurate turbine cost models should also be used. For example, the cost impact of blade pitch actuation reduction should be considered.

The main drawback of this choice is the high computational costs that aeroservoelastic models incur, and the need for geometrically exact beam formulations worsens things.

Controller requirements identified by the group include the abilities to adapt to the specific

Lidar technology used and to be tunable to the turbine design.

In terms of the Lidar system, a cost model should be used and it should capture the main cost trends, such as how does cost vary with performance, how costs will decrease in the next years thanks to mass production, and finally which Lidar technology should be used. Additionally, Lidars with measurement ranges from 100-300 m should be considered. To conclude the discussion, the group also highlighted the importance of field testing to help validate the numerical analyses.



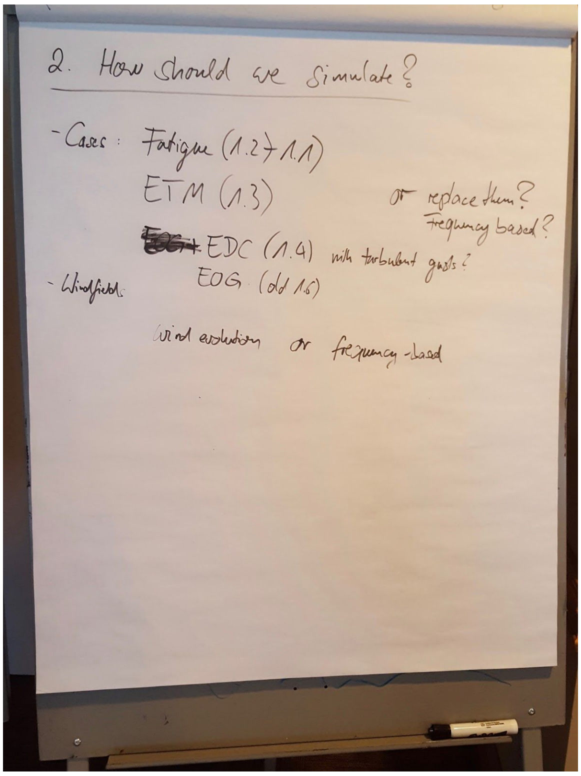
Group Three

The group started the discussion at the turbine level, highlighting the need for a multi-fidelity scalable simulation framework that ranges from reduced models to full aero-servo-elastic simulations. Mid-fidelity simulations can be used to understand the opportunities. Reduced order models can be used to determine how the turbine design changes before moving to high fidelity models.

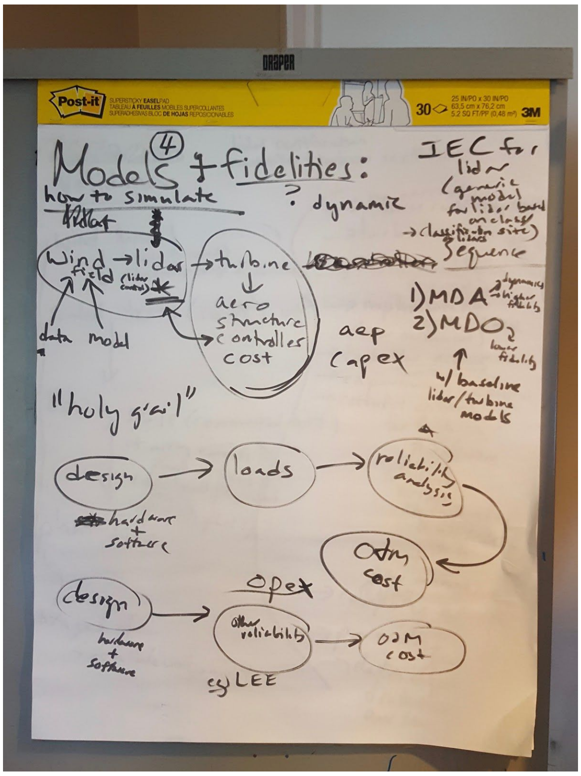
The controller should also be scalable, with multiple features supported, such as collective and individual pitch control, flaps, yaw control, and Lidar. However, only a small set of tunable parameters should exist. The group proposed the following priority for Lidar controller types to use for turbine design. First, feedforward collective pitch control, because it is easy to implement and only required rotor effective wind speeds, followed by feedforward generator torque control. More advanced Lidar-based controllers, such as IPC, flap control, yaw, and TI-scheduled control, which require more detailed wind measurements, can then be explored.

In addition to volume averaging, the group suggested that details such as nacelle motions and blade blockage should be considered in the Lidar model. Variables such as the Lidar beam opening angler should be parameterized. Additionally, proprietary Lidar data processing using DLLs, for example, should be possible.

A detailed cost model should be made available for the turbine and Lidar. The NREL cost model is a possible starting point.



In terms of simulations, a first option is to redesign the IEA Wind 3.4MW land-based reference wind turbine, which is fatigue driven, while a second option is to simulate the IEA Wind 10MW offshore reference wind turbine, which is extreme driven. The minimum set of design load cases should include DLC 1.2 for fatigue, DLC 1.1 and 1.3 for ultimates, DLC 1.4 (maybe adjusted with turbulence to allow more realistic lidar measurements) to simulate the extreme direction change, and the extreme operating gusts of DLC 2.3. However, the possibility of replacing the time domain simulations with frequency-domain calculations was proposed. Finally, the wind fields should be simulated in the time domain with wind evolution added, but frequency domain simulations may also be a possibility.

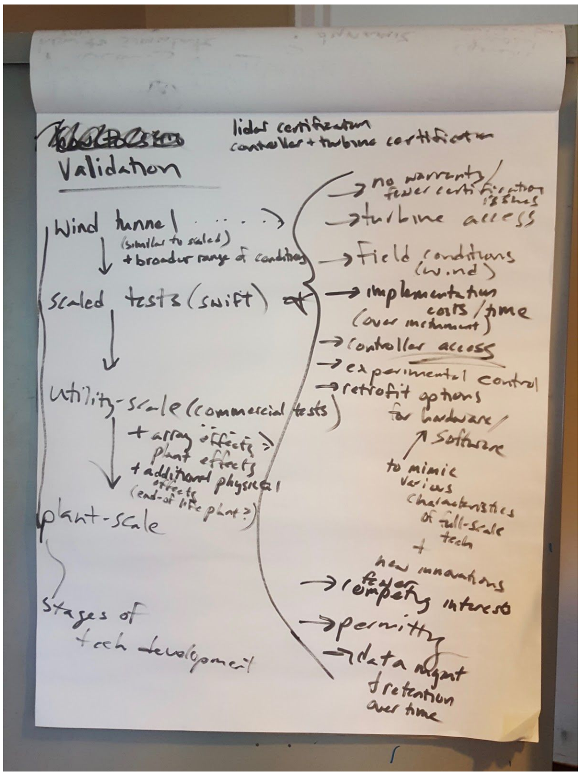


Group Four

The last group focused on the multi-disciplinary analysis (MDA) and optimization (MDO) processes (with MDA for understanding the opportunities first, then MDO with low order models as a next step), identifying the most important modules as design, loads, reliability analysis, and operation and maintenance costs. Linking these modules can be considered the "holy grail" chain, where the links between loads and reliability and reliability and operation and maintenance costs are still challenging.

In terms of the Lidar model, the group raised the point that Lidar availability depends on the site characteristics and proposed the idea of different availability "classes," similar to IEC turbine classes.

The group also stressed the importance of a validation process, which could start from wind tunnel experiments to test a broad range of conditions, then move to small scale field testing, using facilities such as Swift from Sandia National Laboratories in Texas, then end with utility- and plant-scale testing. The full process may be lengthy and an equilibrium should be found between costs and time, but this is the recommended track for product development and ultimately commercialization. This process should shed light on a long list of open points



that Lidar control would raise, such as a change (and maybe a reduction) of the certification burden, the levels of access needed between the Lidar, turbine, and controller, retrofit options, and data analysis and retention over time. The validation process would also help shed more light over the exact wind conditions that turbines face.

Day 2

The day started with a recap of Day 1 conducted by Pietro and Eric going through talks and group discussions. The summary of the group discussions that was presented is shown below.

Identifying Models Needed to Include LAC in Wind Turbine Design: Summary of Day 1

Turbine	Controller	Lidar	Cost Model
•Mid/high fidelity: Aeroservoelastic (e.g. FAST) •Low fidelity: Frequency domain? •IEA 3.4 MW reference turbine •Fatigue load driven	•Simple baseline controller: adjustable parameters, small number of parameters •Fine-tune later •Priorities for LAC: •FF collective blade pitch •FF generator torque •IPC, flap, yaw	•Distinguish between CW and pulsed •Low order: generic coherence •High order: volume averaging, motions, blade blockage •Availability % •Lidar availability class •Lidar data processing: •Wind field reconstruction complexity	•NREL cost model •Sandia cost model •Additional benefits •Grid support, acoustics… •Lidar cost model •Simple cost model: Capital+O&M •Function of scan parameters, reliability

Load Cases	Wind Fields	Validation	
•Fatigue loads •Frequency domain •Time domain •DLCs 1.x normal power production •DLCs 6.x parked •Priority •1.2 NTM •1.3 ETM •1.4, 1.5 •w/ and w/o LAC	•Turbulent: add wind evolution •Coherent gust: add turbulence, wind evolution	•Subscale field testing	

A short Q&A session initiated with the most relevant point being raised by Josh Paquette from SNL: Lidars could be used at the plant level to aid DLCs 6.x parked cases. During these conditions, the park could yaw appropriately in anticipation of a gust several km out. After the discussion, the four talks started.

Wind turbine optimization using systems engineering

9:00	**Wind turbine optimization using systems engineering, Chaired by Pietro Bortolotti, NREL** Invited presentations from the stakeholders with time for questions ● Towards a System Perspective on LAC: Some Preliminary Findings on the Turbine-Level Cost/Benefit Analysis - **Carlo Bottasso, TUM** ● LAC at GE as an Experiential Overview - **Bernie Landa, GE Renewables** ● Rotor and Turbine System Trends and Tradeoffs – An OEM Perspective - **Kristian Dixon, Envision Energy** ● Systems Engineering for Lidar-Assisted Control: A Sequential Approach - **David Schlipf, WETI**

Towards a System Perspective on LAC: Some Preliminary Findings on the Turbine-Level Cost/Benefit Analysis - Carlo Bottasso, TUM

- Three turbines of different size and wind class are re-optimized from the structural point of view, considering an interval of possible load reductions provided by LAC
- Results indicate modest—if any—effects for the medium-size turbine, and slightly larger—but still quite modest—benefits for the larger one, only for the most optimistic of the load reductions considered
- The benefits are mostly in the tower re-design thanks to reduced fatigue loading, with only minor effects on the rotor
- *Question*: What cost of energy reduction is needed for industry to be interested?
    - *Answer from wind turbine OEM*: More than 1% cost reduction, and the uncertainty should be considered. Otherwise, the cost reduction is washed out by the uncertainty in component costs.
- *Comment*: As with other rotor innovations, such as aeroelastic tailored blades, the system benefits of LAC should be considered (in addition to load reduction), such as enabling taller towers or larger rotors

LAC at GE as an Experiential Overview - Bernie Landa, GE Renewables

- Systems engineering for lidar assisted control at GE has involved both maturing the sensor technology for nacelle based measurements and performing comprehensive simulation and field testing of fatigue load reductions and power performance improvements
- Value streams evaluated have been feed forward control, improved yaw tracking, and market expansion with marginal benefit to turbine LCOE with non-lidar based options having an advantage for managing mechanical loads and power performance objectives
- Adoption of lidar sensing technology requires a continued focus by sensor OEMs for price deflation, improved models & methods for capturing real wind coherency, and use cases that offer low risk for deployment to a turbine fleet
- *Comment*: In the evaluation of opportunities, typical losses due to vane misalignment of 0.25% were stated. However, losses as high as 5% have been observed.
    - *Response*: If calibrated properly, the losses will be low. In terms of being able to improve dynamic tracking of the wind direction, there is a tradeoff between dynamic error and actuator duty cycle that needs to be considered.

Rotor and Turbine System Trends and Tradeoffs – An OEM Perspective - Kristian Dixon, Envision Energy

- Blade design driving loads (and other non-commodity components) are highly sensitive to location in design space and the specific location in design space is a function of particular product constraints i.e. target market specifications, turbine load constraints etc.
- From a blade design standpoint, designs have moved from high C_p - low TSR fatigue driven designs, to mid C_p - high TSR tip deflection driven designs. Lidar systems do not reach an availability of 100% and therefore so far cannot be used to target the more sensitive blade design drivers. This would have a real impact on blade design.
- What types of loads are targeted for LIDAR assisted control may vary widely between OEMs and the academic community should use a range of OEM representative models for research so that results are applicable for industry.
- The transfer function between load and cost reduction is non-linear for most components and much less than 1:1 and must be included in LCOE feasibility studies. The problem of multiplying small numbers makes it such that near term LIDAR based cost reduction potential using fatigue only load reduction seems limited. Large cost reductions will only result from comprehensive load reductions on all channels (extreme and fatigue).
- *Question*: What are relevant trends with larger rotors?
  - *Answer*: Higher TSR, slender blades. For the western market, higher Cp rotors. If blades contain more carbon to increase stiffness, fatigue load reduction could be more promising to reduce cost.
- *Comment from Kristian*: Researchers should focus on IEC design load cases 1.x, or even just 1.2 and 1.3. The solutions to address other DLCs are often OEM-specific.
- *Question*: What CapEx reduction is needed for LAC to be of interest to OEMs?
  - *Answer*: 2-3% CapEx reduction is needed to be above the noise. Otherwise, the gains are buried in variations in negotiations with suppliers over component costs.

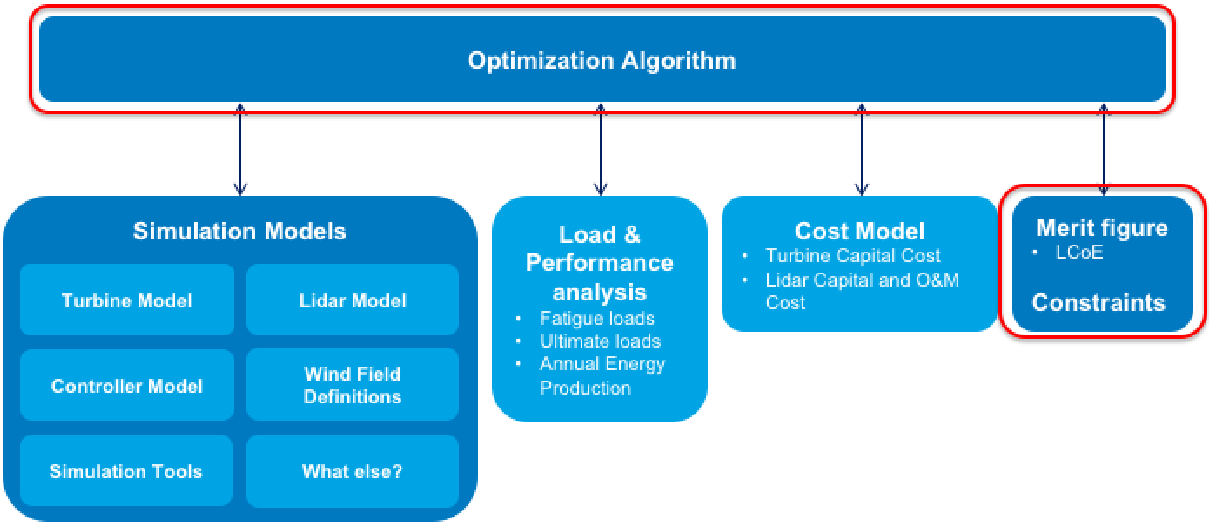
Systems Engineering for Lidar-Assisted Control: A Sequential Approach - David Schlipf, WETI

- A sequential approach is helpful to efficiently optimize a lidar-assisted control application:
  - Lidar hardware optimization with correlation model
  - Lidar data processing optimization with reduced simulation model
  - Controller optimization with full simulation model
- First results show that combining LAC and de-rating is very promising for life-time-extension
- A concept how to auto-tune a baseline controller for the IEA Wind Task 37 3.4 MW RWT is presented: Separation into static and dynamic parameters is useful.
- *Question*: How can the smallest detectable eddy size be determined from the lidar measurement coherence curve?
  - *Answer*: It is the inverse of the frequency where coherence = 0.5, after accounting for a factor of 2π for radial frequency
- *Comment*: Aware of a UK wind farm owner that is interested in lifetime extension, so it is good to include as an optimization objective

Identifying methods for optimizing wind turbines with lidar-assisted control

10:45	**Identifying methods for optimizing wind turbines with lidar-assisted control, Chaired by Eric Simley, NREL** ● Group discussion in small groups ● Presentation of results to plenary ● Discussion and documentation of results

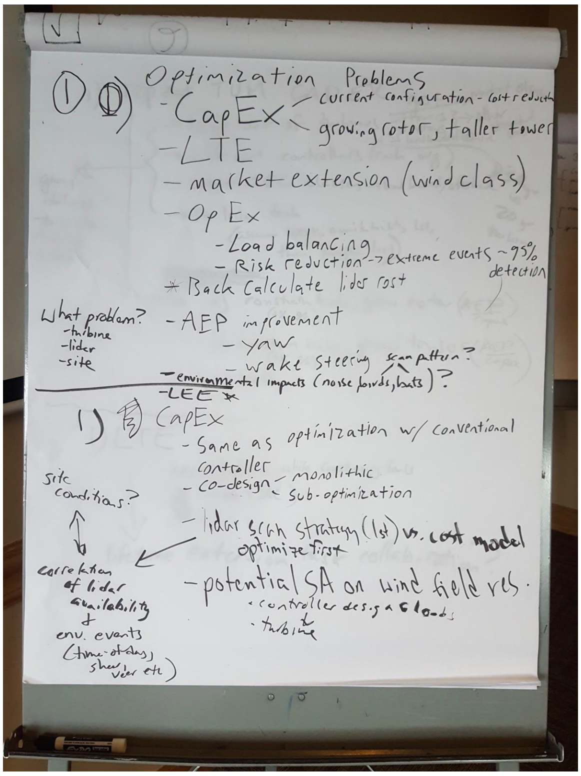
Referring again to the diagram illustrating the framework for optimizing wind turbines with LAC, this session focused on optimization algorithms, merit figures, and constraints that could be used when optimizing wind turbines with LAC.



The participants once again split into four groups and were asked to brainstorm answers to the following questions:

1. How could we set up the optimization problem?
   - What control and lidar parameters could be adjusted?
   - What LAC constraints could be considered?
   - What are useful merit figures?
2. What optimization algorithms could be used?
   - What is the right workflow?
   - How do we combine different simulation fidelity/fidelities?

Results from each group are below.



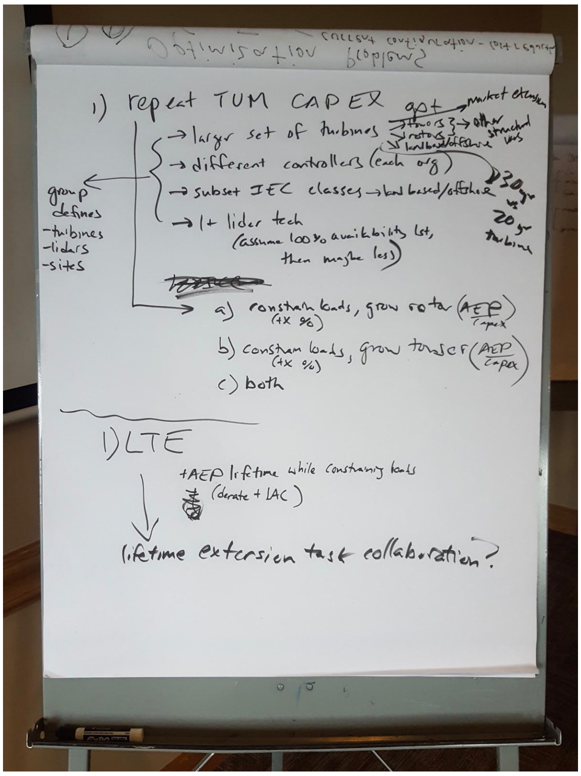
Group One

The group started the discussion highlighting that a CAPEX reduction is possibly not the most promising target in an optimization of a wind turbine with LAC. If a reduction of CAPEX is pursued, the same optimization approach as for a conventional controller could be taken, adding however co-design capabilities with a monolithic or sub-optimization approach.

More promising targets than a CAPEX reduction were found in extending the wind turbine class, load balancing by combining with wind farm control, lifetime extension, and finally risk reduction by capturing extreme events even if availability is not 100%.

An open question of the group was whether Lidars can help with mitigating noise or even help detect birds and bats.

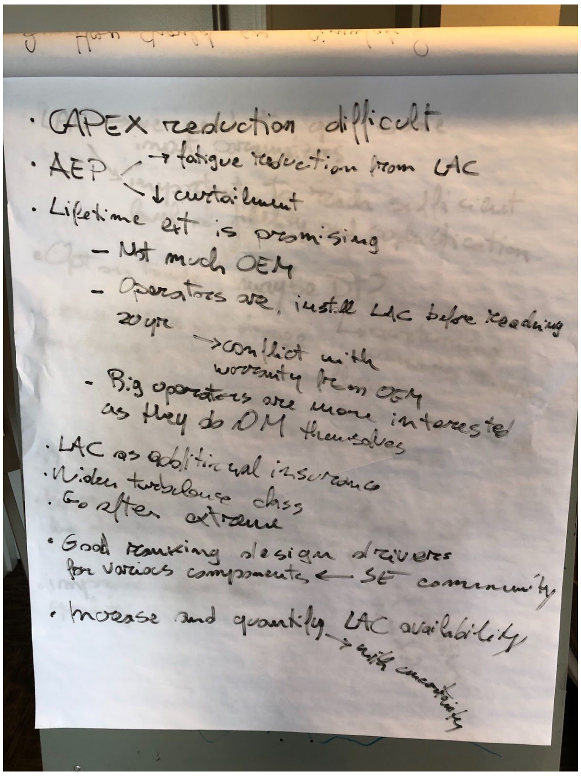
No matter the optimization approach, the group agreed that Lidar cost models are crucial and that the lidar scan pattern can be optimized first before the turbine optimization, but the



resulting Lidar cost should be considered. Furthermore, site selection may also be an important factor in the optimization, if for example there is a correlation between lidar availability and site conditions like shear, veer, and stability.

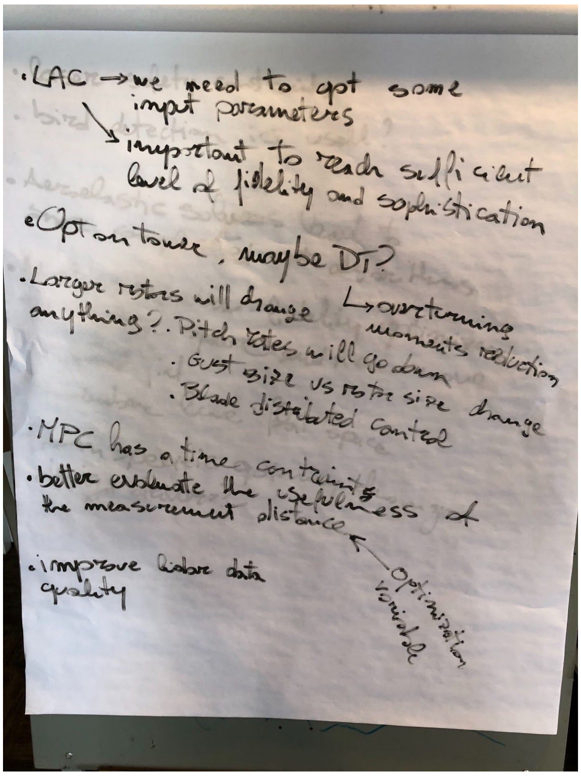
The group then outlined a scenario for examining the potential for CAPEX reduction by extending the optimization study Carlo Bottasso presented. For example, different combinations of turbines, lidars, and site characteristics (e.g., IEC classes) could be considered. In a round robin type exercise, researchers could use their own controller and look at increasing AEP/CAPEX by constraining loads while growing the rotor size or tower height as an alternative to reducing the CAPEX. The idea of optimizing turbines with Lidar control for lifetimes greater than 20 years (30 years) was also raised.

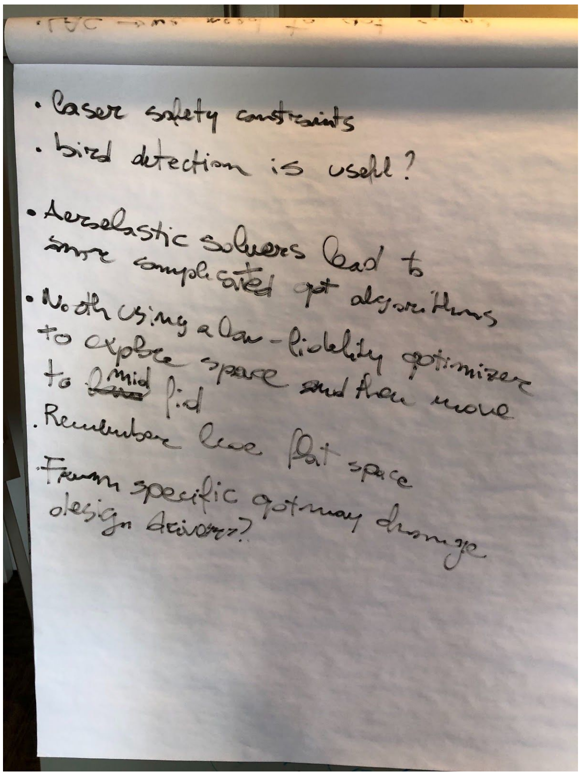
Finally the group highlighted the need for understanding the economics better, especially for the lifetime extension opportunity, with the suggestion to cooperate with the newly started IEA Task on lifetime extension.



Group Two

The group started the discussion highlighting that the conclusion from the morning session is that the margins for a CAPEX reduction and/or an AEP improvement may be limited. However, more sophisticated controllers could be examined to see if there are additional opportunities. The group also commented that the LAC community should pursue extreme load reduction capabilities to create more value from CAPEX reduction. The group saw instead more promise in the lifetime extension that a LAC system could open up. This aspect might not be very relevant for the OEMs, but may spark the interest of operators, who would need to install LAC systems in advance of the 20 years limit to collect data and reduce the fatigue margins. Big operators may be more interested than small ones as they do maintenance to the turbines themselves, and are therefore not constrained by the OEM warranty terms, while smaller operators typically leave this to the OEMs. LAC can also be seen as an additional insurance by detecting extreme conditions or could widen the turbulence class.





The group highlighted the need for a complete ranking of the design drivers of each component. This task should be conducted by the SE community and it would greatly help the LAC community (and others as well). The LAC community should instead focus on a clear quantification of LAC systems and how this impacts the cost of the system. This lead the discussion to the need of a cost model for the LAC system, where the list of input parameters should be clearly defined and the level of fidelity should accurately capture the various trends.

In terms of optimization, the group again recalled the morning presentations and how the advantages have concentrated on the tower. An open question was whether drivetrain components could also benefit from LAC, which has the potential to reduce rotor overturning moments. The bearings could for example benefit from that.

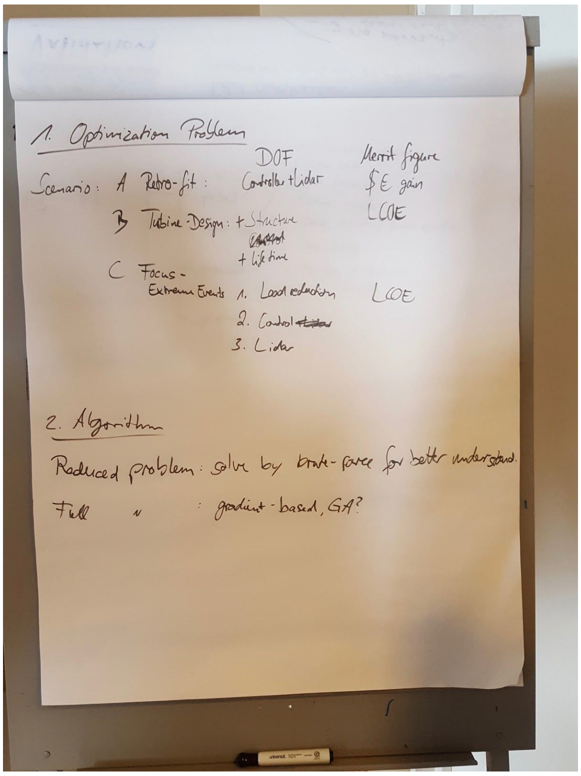
What is the effect of rotor size on the design of wind turbines equipped with LAC? Three main factors were identified: 1) pitch rates are decreasing (so preview from Lidar could be more impactful), 2) gust size vs. rotor size proportions may change, and 3) blade distributed control may become more appealing.

When optimizing the LAC itself, the measurement distance should be a design variable in an optimization study, allowing its impact on LAC cost and load reduction capabilities to be determined. LAC data quality should also be topic of improvements, together with laser safety constraints. The need to increase and quantify Lidar availability (along with uncertainty quantification) was also brought up.

What are other potential benefits of a LAC system mounted on a wind turbine? Could it be used for bird detection?

In terms of optimization algorithms, the group highlighted that aeroelastic solvers should be included in the analysis, although this usually leads to more complicated optimization algorithms. At this stage, there could still be value in adopting lower-fidelity approaches to assess the solution space and later move to mid-fidelity tools that include full aeroelastic simulations. The group concluded the brainstorming session with a reminder about the issue of the flat solution space for LCOE minimization and the fact the different wind turbines designed for different markets have very different sets of design drivers and could see smaller or larger benefits from a LAC integration.

Comment: Regarding interest in lower specific power turbines, the BAR project (Big Adaptive Rotor) is using a rotor with 150 W/m2. This model will be made available and could be considered in LAC optimization studies.



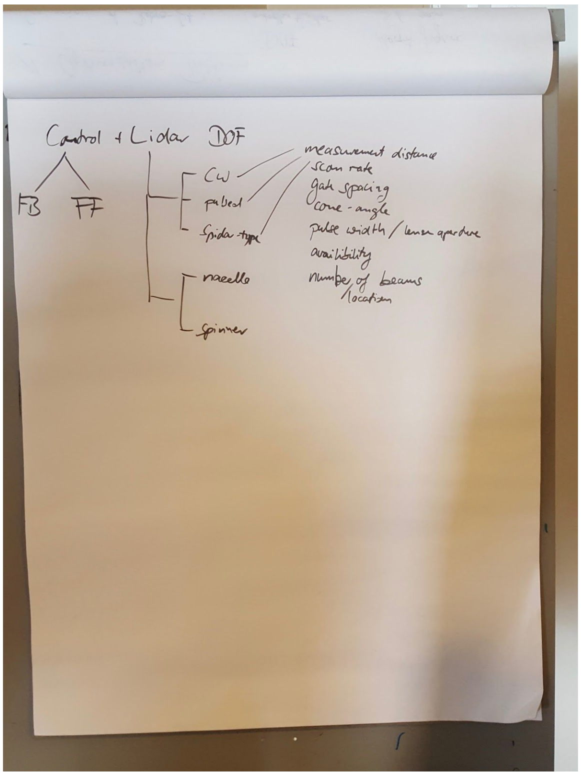
Group Three

The group discussed three optimization scenarios. They suggested interpreting the optimization problem as a retrofit problem with the merit figure being the additional revenue. For the turbine design scenario, the group highlighted how the turbine lifetime could be a free parameter when maximizing the levelized cost of energy and that LAC could be used for either lifetime extension or lifetime reduction. While the former is more popular, the latter might actually represent a more financially appealing option. The third scenario presented was a focus on extreme load reduction, where first the desired extreme load reduction is identified and then the controller and Lidar characteristics needed to achieve the reduction are determined.

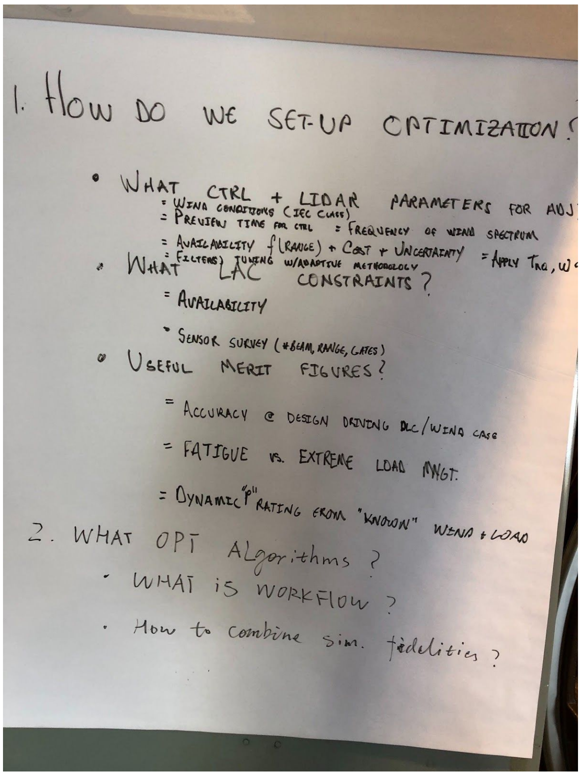
In terms of optimization algorithm, the group suggested reducing the complexity of the problem to conduct a wide exploration of the solution space using a brute force approach for example. Then higher resolution optimization can rely on gradient-based or genetic algorithm methods.

In terms of LAC parameters to optimize, the group concluded that there are discrete optimization variables, for example choosing between continuous wave vs. pulse systems vs. Spyder-type Lidars and determining if the Lidar is nacelle-mounted or spinner-integrated. But there are also “continuous” optimization variables, like the preview distance, measurement volume, number of range gates and beams, and availability.

Question: Does treating lifetime as a free variable make sense to industry?



Discussion: This goes against market conventions and how the standards are defined. Furthermore, it is unclear if derating up front to achieve a longer lifetime is an attractive option. Customers tend to prefer generating more energy early in the lifetime when the net present value impact is higher.



Group Four

The group started the brainstorming with a question: what wind conditions shall we target (e.g., IEC class, mean wind speed, shear, TI, extreme gust conditions)? The group highlighted that the further the preview time is stretched, the more time the controller has to control the rotor, but the lower the coherent bandwidth of the wind hitting the rotor becomes. The AEP may also decrease if the rotor is controlled for load reduction to early.

Another line of discussion faced the issue of limited Lidar availability. Availability is a function of range and cost and should be accompanied by uncertainty. The researchers and designers should focus on what could happen when the Lidar is not available. How should a LAC-designed turbine be controlled if LAC is not available? Availability is also not just 0 or 1, and the quality of measurements changes a lot depending on the conditions. An idea could be to introduce tier levels about the quality of the information that can be extracted from the wind.

Another open question was: what could we do if we knew the wind better? One answer is that we could use better measurement filters that adapt to the measurement quality to minimize measurement error. A second answer is that we could implement dynamic measurement

	ranges. In this case, multi-beam, multi-range Lidar systems are needed. Next, the Lidar accuracy during design driving load cases/wind conditions was suggested as a possible merit figure. An additional application of LAC was then introduced. Lidar measurements could enable a dynamic power rating using information about the wind conditions. If there is sufficient known remaining lifetime margin at a given site, the power rating of the turbine could be increased to generate more energy. Finally, the group tried to define suggestions for further research. One area of needed improvements is about the match between Lidar availability and design driving wind conditions. Another area is about extreme load reduction. Overall, there is a need for a better assessment of the load ranking and the design drivers. These topics should be addressed by the SE community. *Comment*: Availability could be correlated with design driving conditions (e.g., day/night dependence of availability). *Comment*: Adaptive controller tuning could be a possibility by monitoring measurement quality and comparing to the measurement coherence the controller was designed for.

Workshop summary and follow up

13:15 15:00	**Workshop summary and follow up, Chaired by Eric Simley and Pietro Bortolotti, NREL** Full group discussion on the following topics ● Summarize steps that need to be completed to perform wind turbine optimization with lidar-assisted control ● Plan to write a white paper outlining the steps that should be completed to optimize wind turbines with lidar-assisted control ● Where should research focus? ● Funding schemes for further research ● Topics for new workshops

The workshop concluded, highlighting the most promising and most needed research paths. These are listed here:

1. Load reduction - fatigue load reduction thanks to LAC has been proven, but the same cannot be said for extreme loads. Research efforts should be dedicated to proving that extreme events can be captured and the corresponding extreme loads can be alleviated. The challenge of availability lower than 100% should be assessed, evaluating control solutions when the Lidar generates poor or null measurements and how all this impacts turbine design.

2. Holistic system impact of LAC - Detailed frameworks for wind turbine design should be made available to evaluate in depth the pros and cons of a novel technology such as Lidar assisted control. Opportunities for lifetime extension should be part of the analysis.
3. Wind reconstruction: efforts should be dedicated to improving wind field reconstruction capabilities aiming at a better representation of small and large eddies.

Specifically, the following items were discussed with some of the key points listed.

- Plan to write a white paper outlining the steps that should be completed to optimize wind turbines with lidar-assisted control
    - There is interest in submitting a conference paper acting as a whitepaper describing the outcome of the workshop
    - There is interest in creating a 1-2 page whitepaper about a lidar cost model, with lidar manufacturer input
- Where should research focus?
    - Further developing capabilities for reducing extreme loads
        - Detecting extreme shear
    - Exploring system level benefits beyond the tower and rotor alone
        - The SE community can highlight design drivers and help identify load reduction targets
    - Wind field reconstruction
        - How might wind field reconstruction methods depend on atmospheric conditions?
    - Developing lidar cost models to incorporate into optimization framework
        - Should capture the cost impact of the number of beams, etc.
        - Not enough historical data available to estimate cost models
        - NREL cost model strategy could be a starting point
        - A third party, such as a consultant, would likely be best positioned to work with lidar OEMs to create an open lidar cost model
    - Developing a financial model for lifetime extension applications
        - A new IEA Wind task on this topic has started
    - Developing auto-tuning reference controllers that can easily be applied to turbine optimization
    - Exploring non-conventional control strategies, such as model predictive control (as the baseline controller and combined with LAC)
        - Will LAC always add benefits to a more advanced baseline controller, or could the gains be redundant?
    - Establishing generic lidar models and feedforward controllers for researchers to use
    - Validating wind field reconstruction methods for shear, veer, and other wind characteristics to build confidence in more sophisticated LAC strategies
        - Improving wind field estimators
    - Applying LAC to distributed control along the blade
    - Expanding LAC to wind farm control applications
    - Determining if there is more benefit from LAC for offshore applications
    - Investigating ways of combining lidar measurements with data from other sensors
    - Improving systems engineering tools
        - Increasing the fidelity of WISDEM to include LAC
- Funding schemes for further research
    - Creating a whitepaper will be a good start for applying for funding
    - International collaboration will be more challenging funding-wise, but is an important aspect of this research
- Topics for new workshops

- From the Task 37 side, work package 4 presents the opportunity for a workshop on loads and control, possibly with EERA JP Wind
- A workshop with the new IEA Wind lifetime extension task could be fruitful. Similarly, a collaboration with the new IEA Wind digitalization task could be of interest.
- A workshop focusing on the application of WISDEM to turbine optimization (potentially with LAC) is of interest
- Could there be a workshop looking at the possibility of designing turbines for 30-40 year lifetimes, where LAC might be able to play an important role?

Participant List

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