INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

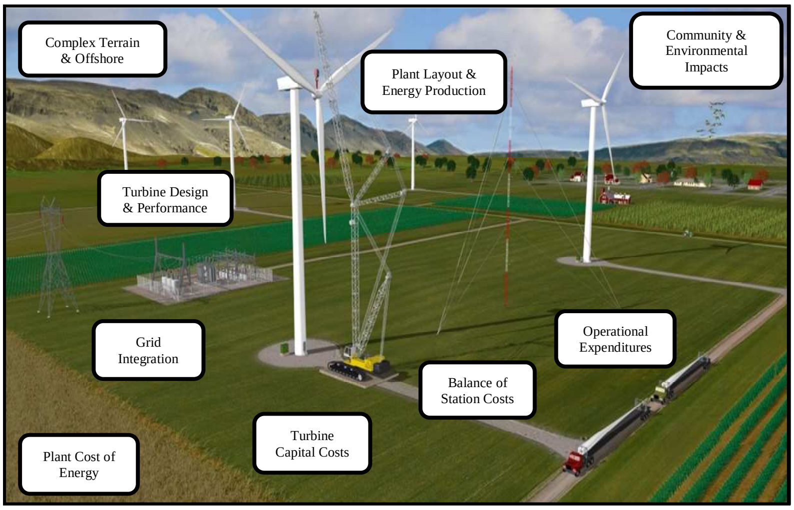
IEA R&D Wind Task 11 - Topical Expert Meeting #80

Wind Energy Systems Engineering: Integrated RD&D

National Renewable Energy Laboratory (NREL), National Wind Technology Center

Broomfield, CO, USA

January 12th and 13th 2015



National Renewable Energy Laboratory (NREL), ´

National Wind Technology Center

Scientific Co-ordination: Félix Avia Aranda

CENER (Centro Nacional de Energías Renovables)

Ciudad de la Innovacion 7, 31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail: favia@cener.com

Disclaimer:

Please note that these proceedings may only be redistributed to persons in countries participating in the IEA RD&D Task 11.

The reason is that the participating countries are paying for this work and are expecting that the results of their efforts stay within this group of countries.

The documentation can be distributed to the following countries: Denmark, Republic of China, Finland, Germany, Ireland, Italy, Japan, Republic of Korea, Mexico, the Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom and the United States.

After one year the proceedings can be distributed to all countries, that is March 2016

Copies of this document can be obtained from:

CENER
Félix Avia Aranda
Ciudad de la Innovación 7
31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail: favia@cener.com

For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Austria, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Carballeira Wind Farm - Spain

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on "Social Acceptance of Wind Energy Projects", "Wind Integration Studies" and. "Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment".

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

CENER
Félix Avia Aranda
Ciudad de la Innovación 7
31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail:favia@cener.comE-mail:favia@cener.com

COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Risø National Laboratory
Republic of China	Chinese Wind Energy Association (CWEA)
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Umwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	KEMCO (Korea Energy Management Corporation)
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten – Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

CONTENTS

PRESENTATIONS

1. INTRODUCTORY NOTE

Background

Over the last few decades, wind energy has evolved into a large international industry involving major players in the manufacturing, construction, and utility sectors. Coinciding with industry growth, significant innovation in the technology has resulted in larger turbines and wind plants with lower associated costs of energy. However, the increasing importance of wind energy's role within the electricity sector imposes more requirements on the technology in terms of performance, reliability, and cost. To address these changing expectations, the industry has made efforts that focus on achieving a variety of goals including reducing installed capital costs for the turbine and plant, decreasing the downstream costs for operation and maintenance (O&M), increasing energy production, and minimizing negative external impacts such as noise emission or habitat disruption. In many cases, these goals involve trade-offs. For example, up-front investment in a robust component design may avoid large downstream costs for component repair and replacement. In another case, the design of a machine with a higher tip speed can reduce required torque and loads through the drivetrain, but at the same time these higher tip speeds can lead to more aero-acoustic noise that adversely impacts surrounding communities. Such trade-offs as these exist throughout the entire system.

To fully assess how a change in a design parameter affects the myriad of objectives in system performance and cost, a holistic and integrated approach is needed. Integrated system research, design and development (RD&D) can provide opportunities for improvements in overall system performance and reductions in overall cost of energy. At the same time, there are significant challenges to developing such integrated approaches, both within and across organizations. There is a need to explore both the opportunities and the challenges for applying systems engineering to integrated wind energy RD&D across the entire wind energy system. This need surfaces both in the tools and methods used in wind plant RD&D.

Integrated System Tools and Methods

Advanced tools and methods deal with the design tools (models and information) used in wind energy RD&D processes and how an increasingly integrated approach to their use may provide benefits and impose challenges. This is broken down into three sub-areas:

Increasing ***breadth*** *of scope in wind energy RD&D methods and tools*

Wind energy is a complex "systems of systems." Wind power plants are similar systems in which components are collected into subsystems (i.e., stages of a gearbox), subsystems into even larger subsystems (i.e., the drivetrain), and into a larger complete machine (the turbine), which have interactions at higher system levels (from the plant to the electric grid). Methods within the field of systems engineering, such as multidisciplinary design analysis and optimization (MDAO), have been applied for many years to the engineering and design of aerospace and automotive technologies and are increasingly being applied to wind energy technology. Modifying or innovating around one part of the system can have far-reaching impacts in other areas of the system. There is a need to understand how integrated system modeling is currently used in the wind industry and where more integrated approaches are needed. There is also a need to review where opportunities exist to leverage experience from other industries (i.e. automotive, aerospace).

*Increasing **depth** of scope in wind energy RD&D*

Various levels of fidelity are possible to represent every part of the system. These levels are characterized by different amounts of modeling uncertainty, accuracy and information availability. Various efforts are underway to make use of and even couple high-fidelity models of different parts of the system including complex flow, wind turbine aerodynamics, structural dynamics and design and even detailed manufacturing cost models for specific components. There is a need to understand where different fidelities of models are being used in wind energy RD&D and where opportunities exist to better couple between high-fidelity models, make better use of surrogate modeling. In addition, there is a need to understand current practices in wind energy for transferring detailed information and uncertainties about various subsystems across models and design processes.

*Leveraging improvements in **computing and data science** in wind energy RD&D*

Computational resources continue to improve and petascale computing is being leveraged for flow modeling and other applications. At the same time, significant development is underway in a collection of methodological areas in "data science" including statistics, uncertainty modeling, etc. which are highly relevant to wind energy systems. The need is to understand where these methods are currently being used in wind energy RD&D and what opportunities exist for better integrating them into system design processes as well as system operation. A complementary need exists to understand the current use and opportunities for high performance computing in wind energy system modeling.

Frameworks for Integrated System Modeling and Design

In addition to exploring the state-of-the-art in breadth, depth and computing capabilities for integrated wind system analysis, the workshop will discuss the need for common frameworks for integrated system modeling and design. Common frameworks in modeling can enable accurate comparisons between different analytical modeling tools as well as enable more seamless collaboration among a variety of stakeholders. In the former case, the ability to define standardized input/output and interfaces among software packages can allow for more accurate comparison of analysis results among the very broad set of software tools used by the industry for system analysis. In the latter case, barriers to information exchange across and even within organizations can be addressed by the use of standardized frameworks where interfaces between historical silos are well-delineated or even support coupling of analysis tools across traditional boundaries.

Closely coupled to the need for frameworks from an integrated modeling perspective is the need for reference cases at both a wind turbine and plant level to again enable comparison across analyses as well as to support collaboration in the wind energy RD&D process. Several reference turbines have been developed in the past, and these past efforts have served as common start points for huge numbers of research analyses and even design efforts. Increasingly, however, the wind turbine analysis is not done in a vacuum and there is a need to define reference plants as well for analysis of the whole system. This workshop will tackle the topic of reference wind turbine and plants in terms of the needs and potential plans for collaborative development of a standard set that can be used by researchers and practitioners from industry as well as laboratories and academia. Past efforts will be surveyed and the need to standardize descriptions and support development of reference turbines and plants will be discussed.

References:

- *Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems.* NREL Report No. TP-5000-52616.
- NREL Wind Energy Systems Engineering Website & Newsletter
- Framework for Unified Systems Engineering & Design of Wind Plants (FUSED-Wind)

Objectives

The US DOE (NREL National Wind Technology Center) and Danish Energy Agency (DTU Wind Energy) jointly proposed an IEA Wind Task 11 Topical Expert Meeting on "Wind Energy Systems Engineering: Integrated RD&D" in order to promote the investigation of this important topic. The primary goals of the meeting are to: 1) identify opportunities for integrated system engineering applied to wind energy RD&D, 2) discuss potential challenges to implementing more integrated approaches, and 3) suggest a path forward for IEA Wind activity related to integrated system RD&D for wind energy. Suggested topics for discussion are based on the above areas advanced modeling tools as well as organizational processes.

- Advanced modeling and design tools and methods:
  - Advanced methods in multi-disciplinary design analysis and optimization (MDAO)
  - Dealing with uncertainty throughout the system – methods and models
  - Increased use of multi-fidelity modeling and surrogate modeling approaches
  - High performance computing applications in wind energy
  - "Big data" and data science: managing information resources in design
  - "Big data" and data science: managing information resources in operation

- Frameworks for Integrated System Modeling and Design
  - Frameworks for integrated wind energy system modeling
  - Reference wind turbines and wind plants

2. INTENDED AUDIENCE

Participants will typically represent the following types of entities:

- Universities and research organizations
- Manufacturers of wind turbines
- Power companies and wind turbine developers
- Certification institutes and consultants
- Government representatives

The national members invited potential participants from research institutions, universities, manufacturers of wind turbines, power companies, developers, certification institutes, consultants, government representative and any other organizations willing to present proposals, studies, achievements, lessons learned, etc., and to participate in the discussions.
Each participant is expected to give a short presentation of their experiences in the field. The presentations can be on any topic that is in line with this Introductory Note. Each presentation is allocated 15-30 minutes, including questions and a discussion. However, the length of time available is somewhat dependent on the number of presentations to be given.

One of the goals of the meeting will be to gather existing knowledge on the subject and come up with suggestions and recommendations on how to proceed with future developments.

3. AGENDA

<u>Monday the 12th January</u>

>09:00 **Registration and Breakfast**. Collection of presentations

>09:20 **Introduction by Hosts**
Ms. Katherine Dykes, NREL National Wind Technology Center, USA & Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

>09:40 **Recognition of Participants**

>09:45 **Introduction by Task 11 Operating Agent.**
Felix Avia, Operating Agent Task 11 IEAWind R&D

●10:00 – 10:15 Coffee Break

<u>10:15 – 11:15: 1st Session Individual Presentations: Advanced design tools and methods including MDAO</u>

>10:15 **High-Fidelity Aerodynamic Shape Optimization Methodology for Wind Turbine Blades**
Mr. Tristan Dhert, University of Michigan, USA

>10:35 **Aero-structural design of rotors**
Dr. Carlo Bottasso, Wind Energy Institute, Technisch Universität München, Germany

>10:55 **Use of uncertainty quantification techniques in wind turbine design**
Mr. Graeme McCann, DNV GL, United Kingdom

●11:15 – 11:30 Coffee Break

<u>2nd Session Individual Presentations: Advanced design tools and methods including MDAO from a wind turbine OEM perspective (11:30 am – 12:15 pm)</u>

>11:30 **Integrated System Design and Optimization at Alstom**
Mr. Jon Campbell, Alstom, USA

>11:50 **Multi-objective Global Optimization for Wind Turbine Rotor Design**
Mr. Kristian Dixon, Siemens Wind Power, USA

●12:15 – 13:00 Lunch

13:00 – 15:10: 3rd Session Individual Presentations: Frameworks for Integrated Wind Energy System Modeling and Design

>13:00 **OneWind Frame**
Dr. Urs Wihlfahrt, Fraunhofer IWES, Germany

>13:20 **FAST: A Developer-Community Framework for Multi-Physics Engineering Models**
Dr. Jason Jonkman, NREL National Wind Technology Center, USA

>13:40 **Towards the Integration of Multi-scale Atmospheric Models & Wind Energy Systems**
Dr. Javier Sanz Rodrigo, CENER, Spain

●14:00 – 14:10 Coffee Break

>14:10 **The Framework for Unified Systems Engineering and Design of Wind Plants (FUSED-Wind)**
Ms. Katherine Dykes, NREL National Wind Technology Center, USA and Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

>14:30 **WISDEM and TOPFARM: Two FUSED-Wind based toolsets**
Ms. Katherine Dykes, NREL National Wind Technology Center, USA and Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

>14:50 **Optimization of offshore wind turbines – Emulation of wind farm design for system level objective function evaluation**
Dr. Michiel Zaaijer, Delft University of Technology, The Netherlands

●15:10 – 15:30 Coffee Break

15:30 – 16:45: 1st Breakout Sessions: Advanced Modeling and Frameworks

- **Group 1: Advanced modeling and design tools and methods including MDAO**
Led by Dr. Shreyas Ananthan, DOE EERE, USA & Dr. Frederik Zahle, DTU Wind Energy, Denmark
- **Group 2: Frameworks for Integrated Wind Energy System Modeling and Design**
Led by Ms. Katherine Dykes, NREL National Wind Technology Center, USA & Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

16:45 – 17:30: Presentations from group breakout sessions by group leaders and group discussion on future collaboration on advanced modeling tools and frameworks
Led by Ms. Katherine Dykes, NREL National Wind Technology Center, USA & Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

●17:30 End of the Tuesday meeting

●18:00 Informal dinner in downtown Boulder

Tuesday the 13th of January

9:00 – 10:20: 3rd Session Individual Presentations: Reference Turbines

>09:00 **Development of a Set of New Reference Wind Turbine Models – Reflecting on the NREL 5 MW Reference Turbine**
Dr. Amy Roberston, NREL National Wind Technology Center, USA

>09:20 **Design of Reference Wind Turbine Blades of Varied Configuration and Scale**
Dr. Todd Griffith, Sandia National Laboratories, USA

>09:40 **Design and Deployment of the DTU 10 MW Reference Turbine**
Dr. Frederik Zahle, DTU Wind Energy, Denmark

●10:00 – 10:20 Coffee Break

>10:20 **12MW Floating Offshore Wind Turbine**
Dr. Hyunkyoung Shin, University of Ulsan, Republic of Korea & Dr. Minwon Park, Changwon National University, Republic of Korea

>10:40 **Integrated Wind Energy System Modeling: A control engineering perspective**
Mr. David Schlipf, University of Stuttgart, Germany

●11:00 – 11:20 Coffee Break

11:20 – 12:20: 4th Session Individual Presentations: Reference Plants

>11:20 **Characteristics of Reference Wind Plants Required to Meet Different Research Objectives**
Dr. Patrick Moriarty, NREL National Wind Technology Center

>11:40 **Overview of the NOWITECH Reference Wind Turbine and Wind Farm**
Dr. Karl Merz, SINTEF Energy Research

>12:00 **Role of Reference Wind Plants in Benchmarking Optimization Tools**
Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

>12:20 **Offshore Cost of Energy**
Mr Bruce Valpy, BVG Associates

12:40 – 13:15 Lunch

13:15 – 14:30: 2nd Breakout Sessions: Reference Turbines and Plants

- **Group 1: Reference Turbines**

Led by Karl Merz, Sintef Energy Research, Norway & Dr. Frederik Zahle, DTU Wind Energy, Denmark

- **Group 2: Reference Plants**

Led by Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

14:30 – 14:45: Presentations from group breakout sessions by group leaders

14:45 – 15:30 Group discussion on future collaboration on reference turbines and plants

Led by Karl Merz, Sintef Energy Research, Norway & Dr. Frederik Zahle, DTU Wind Energy, Denmark

15:30 – 16:15 Group discussion on future collaboration across topics of advanced models, frameworks and reference turbines and plants

Led by Ms. Katherine Dykes, NREL National Wind Technology Center, USA; Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark; Karl Merz, Sintef Energy Research, Norway & Dr. Frederik Zahle, DTU Wind Energy, Denmark

- ***16:15 End of Meeting & Optional Tour of NREL National Wind Technology Center***

3. LIST OF PARTICIPANTS

The meeting was attended by 21 participants from 8 countries. Table 1 lists the participants and their affiliations.

	Family Name	Last Name	Job Center	Country
Mr	Frederik	Zahle	DTU Wind Energy	Denmark
Dr	Pierre-Elouan	Réthoré	DTU Wind Energy	Denmark
Mr	Flemming	Rasmussen	DTU Wind Energy	Denmark
Mr	Kenneth	Thomsen	DTU Wind Energy	Denmark
Mr	Urs	Wihlfahrt	Fraunhofer IWES	Germany
Mr	David	Schlipf	Stuttgart Wind Energy - University of Stuttgart	Germany
Dr	Carlo L.	Bottasso	Technische Universität München (TUM)	Germany
Dr	Minwon	Park	Dept. of EE, College of Mechatronics, Changwon National University	Korea (Republic of)
Dr	Hyunkyoung	SHIN	University of Ulsan	Korea (Republic of)
Mr	Karl	Merz	SINTEF Energy Research	Norway
Dr	Javier	Sanz	CENER, National Renewable Energy Center of Spain	Spain
Dr	Michiel	Zaaijer	Delft University of Technology	The Netherlands
Mr	Graeme	McCann	McCann	United Kingdom
Mr	Jon	Campbell	Alstom Power	USA
	Sandy	Butterfield	Boulder Wind Consulting	USA
Dr	Andrew	Ning	Brigham Young University	USA
Dr	Amy	Roberston	National Renewable Energy Laboratory (NREL)	USA
Dr	Mike	Robinson	National Renewable Energy Laboratory (NREL)	USA
Dr	Jason	Jonkman	National Renewable Energy Laboratory (NREL)	USA
Ms	Katherine	Dykes	National Renewable Energy Laboratory (NREL)	USA
Dr	Daniel	Griffith	Sandia National Laboratories	USA
Dr	Shreyas	Ananthan	U.S. Department of Energy	USA
Mr	Tristan	Dhert	University of Michigan	USA

iea wind

The International Energy Agency Implementing Agreement for
Co-operation in the Research, Development, and Deployment of Wind Energy Systems
www.ieawind.org

The International Energy Agency Implementing Agreement for
Co-operation in the Research, Development, and Deployment of Wind Energy Systems
www.ieawind.org

4. SUMMARY

The two days of presentations and discussions created enthusiasm amongst the group on the various topics related to wind plant integrated RD&D. At the end of the workshop, most participants felt that continued discussions and potentially an IEA Wind task on the topic would be a good path forward. On top of this, the group generally felt that future efforts should be even more broad in their inclusion of stakeholders across the wind energy industry from component suppliers to owner/operators. One short term suggestion was for the core group involved with the planning of the TEM to do an outreach campaign to additional stakeholders to 1) survey the alignment of their activities and interests with the various workshop topics and to 2) recruit them to participate in follow-on meetings and the IEA Wind task development effort.

There was less agreement within the group about the areas that should be top priority for focus in ongoing efforts. These different areas including advanced methods in multi-disciplinary design, analysis and optimization, integrated RD&D frameworks, and reference turbines and plants. Generally, all the topics were seen to be important but limited resources may mean focusing early efforts on certain themes over others. However, a long term plan inclusive of all activities was recommended as an appropriate way to organize an IEA Wind task proposal.

Moving to the specific topic areas, there was consensus that each topic was important and some of the priorities within each topic were identified. However, the specifics of how each topic area should be addressed in a future collaborative effort (through IEA Wind or otherwise) resulted in interesting debate and a variety of perspectives. For reference turbines, there was the most consensus about what actions were needed and the group even developed a relatively specific plan about the steps needed in the development of a collection of reference wind turbines. Given that there have been several prior meetings related to this topic and the need had been identified for some time across multiple parties, the level of interest and concrete planning was expected. For reference plants on the other hand, there was less agreement about the types of reference plants needed and the path to obtain them. This was an area that highlighted the need for additional discussion and stakeholder engagement.

For advanced methods in multi-disciplinary design, analysis and optimization, the discussion focused mainly on the need for benchmarking efforts in MDAO at different levels of the system. There was a lot of enthusiasm about the topic, but a lot of different perspectives on what the main foci should be. Generally, there was thought that starting simpler (perhaps with the rotor, or even just the aerodynamics of the rotor) might be a good place to start because there are several groups engaged with MDAO work in that space and the problem is more contained than at higher system levels. The group felt that continued discussion on the topic would be needed as part of an IEA Task proposal development. Finally, the group identified the utility that systems engineering / integrated RD&D frameworks could bring to the wind energy community primarily to transfer knowledge across traditional silos. The group felt that the framework should not be tied to a particular software platform, but that a more "pseudocode" type of approach could be very useful for providing a framework guideline which could be implemented by stakeholders in any number of different software platforms. Good examples of existing frameworks were the FAST, FUSED-Wind and OneWind platforms presented in the workshop. More discussion and the development of an IEA Wind Task proposal on the topic was encouraged.

All groups found some common ground and were very encouraging of the idea of forming an IEA Wind Task on integrated RD&D around the four themes discussed at the workshop. More detailed summaries of each area are provided below:

Group 1: Advanced methods in multi-disciplinary design, analysis and optimization

The discussion in this group session quickly centered around the need for defining benchmark optimization problems. Publications on the subject of optimization were felt to seldom describe the problem formulation i.e. simulation codes, design variables, constraints and objectives to a level of detail to make them reproducible. This makes it difficult to compare results from different papers, since their approaches often differ considerably. It was agreed that a common set of benchmark problems could become a very valuable learning experience for the community. The discussion then turned towards how the benchmark problems should be defined, and how many. There was agreement that the initial focus should be on rotor design, and then with increasing complexity include more components on the turbine. There was less discussion of the plant optimization class of problems, however, these were agreed to also be important. As to problem types, opinions here differed, since one argument was that it was important to include all the necessary disciplines, i.e. aerodynamics, structures, stability and control. Others argued that few research groups had the capability of solving such a complex problem, and in order for everyone to be able to participate, problems with very little complexity were also necessary. A list of problem suggestions was created:

Rotor optimization problems:

- Planform, fixed absolute thickness distribution,
- Planform, elliptical structural cross-section (has an analytical solution),
- Planform and internal structure.

Turbine optimization problems:

- Fixed rotor geometry, optimize controller,
- Planform and controller,
- Planform and drivetrain,
- Planform, drivetrain, control, substructure.

Plant optimization:

- Layout
- Layout, plant control

This list was agreed to simply be a first brainstorm since a lot more discussion of the details of the problems had to be done before anything could be decided. There was, however, general agreement that the first set of benchmark optimization problems should be kept fairly simple to build up experience with this type of exercise. There was generally a lot of enthusiasm around this, both from academia and the industry represented.

Group 2: Frameworks for integrated RD&D of wind plants

The group discussion on frameworks for integrated system modeling and design of wind plants was generally encouraging of a future collaborative effort. The group felt that more discussion was definitely needed to bring in a wider set of perspectives from stakeholders to determine the best path forward. However, the group had a general consensus around several themes. These key recommendations included:

- Care should be taken to balance between a framework that is too abstract and one that is too concrete. At the extreme, a framework could be ontology but this may not be helpful enough; however, one that is tied too much too specific software will use utility since most folks will want to have their own frameworks.
- The framework should enable a world of "wind apps." However, the framework goes beyond an OS for the world of application development, since it also has to do with how models interface to each other.
- Care should be taken in defining the scope – one can always go super broad, but then this limits the potential utility and also may make the problem of defining the framework intractable. Thus, the focus should be on the next level from where we are today – whether that is aero-structural or other; when you are starting from 0 any improvement is an infinite improvement.
- The effort should include not just the framework itself but the support structure for framework including best practices, trainers, guidance on optimization/fidelity (and this may tie into the other areas such as benchmarking).
- The primary user types should be an important consideration. Users could include component/turbine/developer/owner & operator/etc. The first user is likely R&D but could potentially be everyone. The goal is to enable the transfer of knowledge across the system and between stakeholders. Ultimately, we want to make it easier for various groups to do systems engineering applied to wind energy RD&D.

Group 3: Reference Turbines

In the session on reference wind turbines, there was general consensus that a set of three designs would be within a reasonable scope of development, and would meet the most critical needs of both academia and industry. The selection of turbines is based on key market segments as identified by the industry participants, Siemens and Alstom Wind.

One reference turbine would be designed for primarily onshore locations with moderate, Class III winds. The rating is 3 MW, with the rotor diameter comparatively large (low Pr/A) in order to provide an acceptably high capacity factor. The drivetrain is geared.

A second reference turbine would have a rating of 5 MW or 6 MW, and fill two roles: in land-based wind farms, it would be intended for situations where constraints on the positioning of turbines require higher ratings to achieve the desired plant output. This turbine size is also representative of the current state-of-the-art for offshore plants. From the research perspective, the turbine of this size would provide a direct comparison with the previous-generation NREL 5 MW reference turbine. The drivetrain should be direct-drive.

The final reference turbine would be based on the DTU 10 MW rotor design, and intended for installation in large offshore wind plants. The existing DTU 10 MW reference turbine has a low-ratio geared drivetrain; a direct-drive version should also be made available.

From a practical standpoint, the design activity would be coordinated by a supervisory group, under an IEA Task. Both academia and industry should be involved in the design process. The OCx series of studies, investigating various offshore foundation types, provides precedence for this sort of collaboration.

There was some discussion about how optimal the design should be. It was agreed that the reference designs do not need to be formally optimized to some criteria; they should be representative of the state-of-the-art, and contain a complete description at least to the extent that aeroelastic and fluid dynamic models can be constructed. The various components should be designed on a consistent basis.

Group 4: Reference Plants

The group started with a discussion on what reference wind plants could be used for and three main topics emerged:

- Inputs and outputs (I&Os) to run and compare wind plant design tools
- As an input to a wind plant simulation tool
- I&Os for a verification and validation process of wind plant simulation tools.

Then, the group had a discussion on the level of details necessary to bring enough of interest and use cases on the reference wind plant. There is a balance to find between the complexity of the description and the use cases we foresee being used in a close future. The type of detail needed for different wind plant elements differ substantially depending on the use case (i.e. balance of station cost analysis versus a wind-plant controller design)

The group listed examples of existing use-cases where we could use a reference wind plant:

- EERA-DTOC has three different scenarios for testing and validating the use of a wind plant cluster planning tool. The scenarios range from close future to far future, looking at different possible associated wind turbine, foundation, electrical grid cable technologies.
- In the wind plant layout optimization research community, there is a need to have realistic reference wind plants to define the same inputs to the optimization and compare as baseline.
- Similarly, a reference wind plant could be used to demonstrate wind plant control capabilities.

There is a challenge in defining the inputs to strictly that some models have a different interpretation of the inputs, which can lead in "forking" of the wind plant definition. This happened in OC3, where people couldn't agree on the interpretation of some inputs, (e.g. the turbulence intensity). Another example is in the EWEA technical workshop on wind resource modelling, the users have a wide interpretation of roughness inputs, which can lead to a large uncertainty propagated to the outputs.

The type of necessary information about wind plants was discussed:

- Wind turbine description
- Wind turbine layout
- Local wind resources
- Wind plant component and financial costs

The task for defining reference wind plants could be used as a research bounty, where we define the necessary pieces of information to run certain types of simulation or design tools, and then the industry can come with their own cases to challenge the research community to make better tools. There is in particular a need to define standard input and output files to make that work easier for the community. This work could be part of the future IEA-Task on system engineering.

There has been a lot of work within IEA-Task 31 to define wind farm flow model benchmarks, and the associated wind plants definition are publically available. For instance, in the case of Horns Rev and Lilligrund, the full representation of the wind turbines were recreated as reference wind turbine models.

A large focus should be put on Verification and Validation and Uncertainty Quantification. This requires information about the associated input and output uncertainties of the reference wind plants.

In order to excite the interest of the industry to help us to define the reference wind plants, we should organize one-on-one site visits to discuss the topic with them. This could be done during the first phase of the IEA-Task to inform and gather feedbacks from the industry about their interest and needs.The reference plants should be available on a common platform, with possibility to discuss, reference articles. It should be a community website.

Presentation and Discussion Minutes

Monday January 12th

Day 1 Presentations

9:20 ***Introduction* by Katherine Dykes, NREL; Dr. Pierre-Elouan Réthoré, DTU Wind Energy Denmark**

Session 1 Presentations

10:05 - 10:25 **High-Fidelity Aerodynamic Shape Optimization Methodology for Wind Turbine Blades**
Mr. Tristan Dhert, University of Michigan, USA

Q&A
Q – Did you look at the thrust?
A – Yes
Q – Did you constrain it?
A – No. I think after this meeting I will include constraints.
Q – What is the initial CP before optimization?
A – It was the same blade for every region. We only had one year to perform the optimization
Q – Do you have industry partners?
A – Not yet.

10:25: - 10:45 **Aero-structural design of rotors**
Dr. Carlo Bottasso, Wind Energy Institute, Technisch Universität München, Germany

Q&A
Q -How long does it takes to set up?
A - One to two days at the most. We have the ability to run on multiple cores.
Q - That is for a single machine?
A - Yes
Q - Have you compared optimizations for aero and structure without doing a sub optimization?
A - We have compared optimizations for aero and structure, but you cannot afford to do sub optimization.

10:50 – 11:10 **Optimization of offshore wind turbines – Emulation of wind farm design for system level objective function evaluation**
Dr. Michiel Zaaijer, Delft University of Technology, the Netherlands

Q&A
First or second order reliability you can introduce
Q – How do you quantify?

A – You want to look at things like the fidelity of the model. Approaches provide a framework. Probabilistic approach proves a degree of frameworks allow you to inject that back into the process
Q – Do you have a plan to assess models?
A – I'm not sure any one organization has that ability.

Session 2 Presentations

***11:30 – 11:42*(11:50) Integrated System Design and Optimization**
Mr. Jon Campbell, Alstom, USA

Q&A
Q – On mass optimization customization, how far up design process can that reach?
A – Your selection of predetermined set of options varies with tower heights and size of rotor
Q – Do you take wake into consideration?
A – Yes, It's part of the tools package
Q – Regarding the turbine optimization level, how does the process work with your suppliers and where does the design authority reside? How does it work with the various users?
A – It depends on the component.
But for smaller components we take commercially available components.

***11:50(3)–* 12:07 (10) (12:10) Rotor design; Perspectives on Industrial Applications MDO at Siemens Wind Power**
Mr. Kristian Dixon, Siemens Wind Power, USA

Q&A
Q – More parameters add more time to do optimization. Does that include pitching loads? Do you use the results of the optimizations in real conversations?
A – We take a boot strapping approach using simple models to start with and in the end you have more details about design and you can run a full elastic simulation and go from there. In the past I was burned by going too high and failing too early.
Q – Have you compared new approach with more classic COE approach?
A - I have not done an extended study due to lack time. I am a big fan of the multi-objective approach. Making sure whatever candidates we come up with are valid.

Session 3 Presentations

1:05 – 1:25(17) **OneWind Frame**
Dr. Urs Wihlfahrt, Fraunhofer IWES, Germany

Q&A
Q – Is this a code that would be publicly shared?
A – Yes. We want to use this for commercial applications

***1:25 - 1:45(38)*FAST: A Developer-Community Framework for Multi-Physics Engineering Models**

Dr. Jason Jonkman, NREL National Wind Technology Center, USA

Q&A
Q – Considering this community framework, is there an MOU in place?
A – An MOU has not been set up for this model yet. The source code we developed. We push open source agreements. We want to make that available to the community. We do not share intellectual property. Need to determine what those collaborations will look like. We are basing thisa lot on the WRF model.
Q – Will FAST still be FAST?
A – Yes, we want to maintain some basis of probabilistic design parts of FAST
Q – On the level of interfacing,will there be an area of cooperation where you can exchange models?
A – Backbone will be different. Definitely there is room for sharing modules. If we do this together we can achieve a lot more than if NREL does this alone.

1:45 – 2:05 (58) **Towards the Integration of Multi-scale Atmospheric Models & Wind Energy Systems**
Dr. Javier Sanz Rodrigo

2:20 – 2:40(34)**The Framework for Unified Systems Engineering and Design of Wind Plants (FUSED-Wind)**
Ms. Katherine Dykes, NREL National Wind Technology Center, USA and Dr. Pierre-Elouan Réthoré, DTU Wind Energy, Denmark

2:40 – 3:00(53) **WISDEM and TOPFARM: Two FUSED-Wind based toolsets**
Ms. Katherine Dykes, NREL National Wind Technology Center, USA and Dr. Pierre-Elouan Réthoré, DTU Wind Energy, Denmark

Q&A
Q – Considering the complexity of system, does the project have a plan for capturing lessons learned so that we don't end up with only 5 people that know how to operate this system?
A – We do want to provide that type of training for WISDEM. We have not talked about that yet
Q – How confident are you about the fatigue app
Q –We have a model that quantifies that. In many cases you take a wind turbine you and you could say that it's the same as a car. When you try to sell it after five years, it has lost its value.
We have a project with Vestas with a technical reference turbine and we are hoping that it will engage this type of framework.

3:05 – 3:25 (18)**Optimization of offshore wind turbines**
Dr. Michiel Zaaijer

Q&A
Q – You have a tool that is state of the art. Would you expect to get the same costs for an old wind farm as you get for a current wind farm?

A – Although details change, much remains the same over time. Although we have progressed, much of the literature has come from that earlier time. So optimization does not change over time.
Q – OEMs are not interested in gaining this level of optimization - can you expand on that?
A – I'm not saying they are not interested. They are. Inside the company, you don't find the company can deal with it. So they go to you for help. I can see that as an outsider. I see less inside the companies.

Day 1 Group Discussions
3:45 - 5: 1st Breakout Sessions: Advanced Modeling and Frameworks

Group 1: Advanced modeling and design tools and methods including MDAO
Led by Dr. Shreyas Ananthan, DOE EERE, USA & Dr. Frederik Zahle, DTU Wind Energy, Denmark

Questions to consider for discussion:

Where is optimization and uncertainty sensitivity analysis used currently in wind energy system design both within and across disciplines? What are the trends in expanding the scope? What are the limitations to doing so?

Which models do we consider advanced in an SE context? What levels of fidelity?

What usage scenarios are there for advanced models in an SE presently? In 5 years? In 10 years?

How can we increase the direct use of advanced models in MDAO? What role will adjoint optimization and other techniques?

Is there a need for creating optimization benchmarks for advanced models? Both single discipline and multi-discipline?

In which areas can advanced models bring significant breakthrough for design of next generation WE systems?

How will advanced modeling and analysis techniques be used to support future design standards and methodologies?

Discussion

Are we talking through the elements of an IEA collaborative opportunity?
Should the main focus of this be on the system design?
We're discussing both.

Are there models today that we should like to use that are not being used for optimization?
How do we get them to think in terms of optimization? Based on a specific concept.
We should try to scope the work and what sort of models we should be concerned with?
It's not just the models, but the methodologies that we use that are important.

Do we need to look at design standards? Are current design standards appropriate?
There are different levels of uncertainty. How do we account for the fact that they all have different abilities, different errors? Is there a need to quantify the error from a systems view point?

If we have benchmarking tests, do we want to separate them into subsystems and formulate some way to start the benchmarking exercises?
We have to agree on a set of starting conditions and define a first suite for doing this comparison.
This could be a good learning exercise. It could lead to different conclusions.
There is a lot of energy and practice around certain aspects of the problem – the turbine vs. the plant. We could formulate a sequence of benchmarks that looks at a component, a turbine, and a plant. The physics of each one is different but they all need to be in the wind plant benchmark that we would attempt. We could find some constraints to do that and capture how people deal with uncertainty. We need a definition of uncertainty and definition of constraints.

COE models are equally as important as the physics models. There is a very large set of problems we could engage with. We need to cut it down.
What we need is a network where we can discuss design. The objective is to develop the basis for what to do in the future.Whatever common denominator we can create would be helpful.
There is a danger in having only one tool.
It sounds like if we should have a single reference design and something that looks like a problem set. Then we should seek to obtain a set of results that are acceptable. Start with simple problems that give you well defined optimum and everyone should get the same result.
It sounds like the discussion is more around the frameworks and what the best practices are. We still need to learn how to plug in existing models and make them work.

There are a number of options for best practice outcomes and the linkages between models are a huge one. Uncertainty definitions are another option for best practices. The idea of extracting from high fidelity models that allow you to do design work within a framework are good options for those kinds of comparisons and best practices.
What pitfalls are there in making designs? We see a lot of optimization in airfoils. We need to be able to apply these optimizations across the system. The objective now is three angles of attack. We need to take same perspective for all optimizations that we want to pursue.
We get the opportunity to evaluate each other's design. That is strength of having common benchmarks.
Maybe the models are not as important as the problem.
We need to create a matrix where we have different design levels and the various elements.

The problem of optimizing an airfoil is separate. I see that as a separate problem. Here we are talking about bringing it all together. For me we have to start with the rotor and go from there to the wind turbine, and then the wind plant. We need to formulate the problem in a way that is model independent. It is part of the whole system.

Very few people take into account the shape of the airfoil in a free form sense.
I think bringing all the pieces together will be very beneficial.
The optimization of the airfoil should be brought into the larger design problem.
Who would be able to participate in such a benchmarking exercise?
Everyone was concerned about the individual components. Now people realize we can do more.

If we define problems that are relevant and independent of a model, then people will prefer to participate.We will be able to quantify everyone's progress.
How do we know we are doing an apple to apple comparison so we can go back and make an improvement?

Today we can use different methods to get different results and then compare them.
If we end up with different results, then what? We have to have a learning process. How are we going to go back and improve the models, the interfaces?

What is the sufficient level of data? What is the required level of reporting? How did they get to this result? We need to keep it model agnostic. But we need to learn what is necessary for benchmarking. Maybe we need to ask OC4 and OC5.

In OC3 – OC5, with every tiny result you have to share your result, your approach,and you're modeling assumptions. Then if there is a difference you have to step back.
We benchmark a certain case, then we look at whether the Navier-Stokes equations were complex or not.
We need to split it up so that people have to go through some preliminary exercises.

Matrix of elements:
Components

Aero	Structure	Controls	Noise	Cost	… Rotor

This type of matrix will not work.
Perhaps we need to list of problems we want to address?
Rather than list every problem, maybe we should think of what is the simplest multidisciplinary problem.
Are there simple problems that we can start benchmarking?
We are drawn to reference turbines – such as the 5 MW referenceturbines. Those are places where we might start. We take a reference and then we keep the loads fixed and enlarge the aerodynamics for power capture. Identify a number of reference solutions. Formulate classes of problems from rotor to plant.

Rotor
Turbine
Plant

Can we have enough of a plant model available that the rotor and turbine can have that feedback? We need module capability in all aspects of the plants even if that is not a key area of interest.

We need to establish a single point on which to focus. We should focus on design. Design brings it all together. Are we talking about turbine design or wind plant design? The answer will be different. How does plant control impact the wind turbine design? The design is the common thread. Bottasso thinks there is a conflict.

Rotor optimization problems

- Planform optimization. Thickness of design.
- Planform + Elliptical cross section
- Planform + internal structure

Turbine

- Fix the rotor, Optimize controller
- Rotor + control
- Rotor + drivetrain
- Rotor + drivetrain + control + substructure

Plant

- Topology
- Plant control + topology

What other components should be included. Tower? Coupling components?
We should do a mix of physics models and cost models. Cost models are very sensitive to physics model outputs.

What sort of constraints are we including? IEC standards?
Do we want to compare quite flexible amounts of models or do we want tight control on the type of problem to be solved?
We should keep the problem simple to start with and keep the same load, but increase energy capture. This will create learning opportunities.

Whoever has an interest in helping formulate the problems should participate.
Why don't we try to promote sessions at conferences and have workshops about the design problems?

Summary

The discussion focussed on the importance of benchmark problems. The focus was on the problem formulation. Start with a simple problem then increase complexity. People can use their own framework to solve the problem. What level of fidelity is needed to solve this problem?Focus was mostly on the rotor. The take away is that this form could be really good at looking at design as a task rather than the model. How can we learn from each other as to what is important and what is not important?

Group 2: Frameworks for Integrated Wind Energy System Modeling and Design

Led by Ms. Katherine Dykes, NREL National Wind Technology Center, USA & Dr. Pierre-Elouan Réthoré, DTU Wind Energy, Denmark

Questions to consider for discussion:

What do we mean by framework? How can we define it?

How can we avoid/resolve silo effects? Intra-organizational challenges?

What application areas would frameworks really be useful for? Component design? Turbine design? Plant design?

Secondary Questions

How can we make it easier for everybody to do system engineering?

What frameworks already exist and how can they be categorized?

What collaborations already exist around the development of such frameworks?

What could be gained by a broader-based effort to develop framework(s) for wind plant integrated RD&D?

Who would potentially use the frameworks and in what ways?

Ideally, how many different types of frameworks would exist and how would they differ? Interact?

When thinking about a framework design, what things are important to include and what should be excluded to ensure enough flexibility?

How could collaboration/advancement be promoted by an IEA Wind task focusing on SE?

How do you ensure people use the frameworks properly? What training is needed?

What benchmarking is needed?

Discussion

What do we mean by framework?

It is an organization of a workflow of models that manage exchange of information.
It is the top thing of organization.
Does that include model validation?
An important aspect is that I know my models but I don't know my neighbor's. Validation, or confirming the uncertainty about other models is important to avoid silo effects.
What does it do? What is its functionality? Not optimization – that's what you are trying to verify.
Describes OpenMDAO and how it is working.
OpenMDAO is workflow not optimization. Aren't we looking for something more wind specific?
We have been struggling for many years to validate sub-models (separate issue). There has been so much trust in sub-levels that we can combine it.We are looking to combine sub-models, wake models, or larger models.
Framework could be more of ontology
Procedure for doing measurements. Framework is software (concrete). Framework is ontology.FAST as part of WISDEM. FAST has loads analysis and loads analysis integrated with design.
There are some advantages to well-defined frameworks like OpenMDAO. OpenMDAO is thought through vs. tailoring down to well-integrated models running on desktops. It depends on what scope you are trying to solve. Each module could be a framework. At the wind plant level, a collage will have to be well managed, orchestrated in sequence, and run on large systems.

It should be an system Engineering Framework.
What is system engineering? A framework is a special layer of software on which you can build applications.
Overlaps are good, so the framework doesn't have to be specific and it is good for competition. Maybe AWS has an application that runs on both. This is good as long as applications that apply are not lost when moving from one framework to another. We need to make developments multi-purpose so that they don't just fit in specific context.
Interfaces are likely okay way of optimizer work. May be faster than another. Framework gives support function. Framework is hard to switch from once it is established.
Framework – concept showing chart and all things hooked together materializes through software application. Anyone can implement however they want.
Workflow as pseudo code – OpenMDAO output is pseudo code – stylize this for standard of wind energy.
This shouldn't vary too much.

What about VAWT technology?
Aeroelastic code works with one like a framework connects models higher level with other codes
We are here as subdomain experts but want to integrate across.Unified code of interfaces
I miss workflow with all the levels of modeling – i.e. extreme conditions usually block application area?
Grid representative

Want to get one step further out. We rely on AE model. Want to see if we can combine model and learn
Grid can be modularized with all modules that are collected.
If you can change one component, you should change interface. I.e. normal gearbox to hydraulic gearbox. Standard interface would be flexible – Want to check this framework.
Block has to communicate how it can be connected to others.
Also has master block that checks these things.I.e. new model for rotor. How do you check grid compliance?
Should be able to.
Frame – with new stuff framework can't do everything – undefined variable.
App designers enough to design without too much rigidity – not just IOS.
Whole set of wind apps that will work together. (more than IOS). Those are the interfaces. If I set off to design my app, this is how it will work.

Who are the Users?
Should make it easier to do SE
Who would use these tools? R&D group, product line/platform manager.
All big organizations are matrix. One group would need to own it – would oversee all the modules.
Wind plant guy→potential user.
Owner and operator have a requirement to have a delivered product theyare trying to optimize. They are looking at a wind plant tool with fixed hardware trying to optimize cost.
This is the "Holy Grail." Not necessarily different, different levels. Plant level tool – integrated package - is it a turbine or am I running it on my system?
Today choose between 5 turbines.
We are not choosing between rotor diameter, and control strategy in a plant, etc.
We are providing a service in reliability/controls.
Optimize turbine as part of plant, plant to energy as next step – controls matter. Every time we have framework, can always think in terms of next step. AE code has been focus for many years. Need to take to the next step.
Grid perspective includes (new owner and operator here) running into curtailment issues. How can I do that in most cost effective manner? Interconnect ability and grid performance become important (raise it one level higher)
For the future? Go right down supply chain. Need flexible blade guy. Make if flexible enough so it can evolve.
So much is available for analysis. Challenge – users want to fix part and play with other parts. Optimization strategies are needed for different uses. What modules to select for guidance – fidelity.
Who would be first user?
This is a win-win for developer and supplier. What part or who needs this most?
We need to raise education/knowledge of the community in general – a transfer of knowledge across everyone.
Developer has a job to do. Is it worth learning the framework? If it's too complex, does it create confusion? Can I just buy it?
We need to connect different experts.Just connecting two experts would be a big gain.

We in R&D need to get the bugs out before we turn it loose. The research community needs to go to the next level and provide a standard definition of the scope of problems – what major components to include.Connecting two experts is infinite improvement if there is no interconnection at present.
Industry is trying to grapple with this now. It can't sit in the R&D community too long.
Systematic V&V / UQ. Industry will get involved and pick and choose what they want. It is always unique at industry level. Bottom line – it's always good to have physics-based development (physics/framework). Value engineered, systemized, well validated, documented. We don't need to solve for industry. We just need to provide capability industry can select from.   AE and component vs. plant design, which has the largest impact on COE? Plant design is the other perspective.But we don't have answers until we have tools. Tools would provide some enabling of this.

Framework within the IEA Context?

Everyone is doing their thing and probably won't use it if we make it tied to particular software. Don't have to decide what framework
Programming skills versus GUI. End users to make it easier.
FAST was early development – wasn't about usability – about aerodynamics. Not in stage now to become ease of use.
Extra parameter without GUI challenge.
Short-term research, long-term industry deployment.
Even if its research objectives – the user requirements should come from industry driven by research but with heavy industry input. Bottom up and top down at some time.
IEA proposal is a good idea. IEA task integration of executive committee – have cross task collaboration
Feasible work plan and concept design
It certainly would be helpful to look at this. Not sure the task is long term. Systematic process of what framework should do.

Summary

The group generally agreed that further discussion on frameworks should be pursued. There was a lot of discussion about what a framework meant – whether it should be tied to concrete software or if it should be as abstract as ontology. The theme of a platform for "wind apps" was met with a good amount of enthusiasm. But it was also felt that the framework should not just be the goal but also other elements of best practices, training, etc. were important. A general recommendation was that more discussion with a broader stakeholder group would be needed to really make decisions about the best path forward.

TUESDAY, JAN. 13th

Day 1 Presentations
Session 1 Presentations

9:00 Development of a Set of New Reference Wind Turbine Models – Reflecting on the NREL 5 MW Reference Turbine
Dr. Amy Roberston, NREL National Wind Technology Center, USA

Q&A
Q - Why do we need a 10 MW reference turbine as part of the family if DTU has one?
A - We would want to leverage what exists

9:20 Design of Reference Wind Turbine Blades of Varied Configuration and Scale
Dr. Todd Griffith, Sandia National Laboratories, USA

Q&A
Q - What is the upper limit of blade length with respect to logistics and transport?
A - If you look at WindPACT this would exceed the limits; how large can you go with a HAWT rotor, we can pin that down; focused on design requirements
Q - Are FEM for model publically available? What tools did you use to get to final geometry? What precursors to FEM?
A - Geometry for first three blades – up scaled chord and twist distribution of the NREL 5 MW/DOWEC – for final design used HarpOPT and other tools to design new chord and twist; from there NuMAD was used to design the blade – outputs fast and ANSYS for FEM – primarily buckling calculations
Q - Have you looked at sectional blades?
A - That was not part of this project, but part of outputs that summarized challenges and opportunities – and that is one of key challenges; if you are going on land have to segment these blades, maybe not offshore

9:40 Design and Deployment of the DTU 10 MW Reference Turbine
Dr. Frederik Zahle, DTU Wind Energy, Denmark

Q&A
Comment: with many of these rotors, there is not a lot of attention to root section; and many of these have roots that add a lot of weight to the blades
A - Yes, that is true; we were discussing whether turbine should take into account detail of bolts and roots and we left it – it got into manufacturability – but we had to stop at some point
Q - What is root diameter?
A - Quite big; INNwind looking to reduce it to 4.6 m
Comment: The problem was it was thin – so with bolt resizing increase thickness a lot then weight becomes big and becomes metric for comparison
Q - Was there consideration of pitch bearing? 5.4 m pitch bearing would be hugely expensive

A - No – we didn't use cost models to evaluate
Q – What are the macro performance characteristics of this design compared to Vestas 8 MW, etc. – is it really representative of those architectures; is it representative of what modern designs are capable of?
A – No, I wouldn't say so – challenge with making the aerodynamic design, people who make airfoil design available commercially, we would not put state-of-the-art airfoils in these reference designs; so they are not state-of-the-art; they are from 1980s; good soil conditions, but not for far-aft locations of transition points so l/d characteristics are not great; but in terms of structural design – better to get feedback from industry
Q - Did you have external review from industry?
A - Vestas was involved with review – didn't have any major modifications

10:15 12MW Floating Offshore Wind Turbine

Dr. Hyunkyoung Shin, University of Ulsan, Republic of Korea & Dr. Minwon Park, Changwon National University, Republic of Korea

Q&A
Q - How close are you to having SC generator?
A - Technology already achieved almost to 3 MW turbines, prototypes also done by several other countries
Q - The 36 MW generator paid by navy?
A - Yes the navy
Q - Turbine design, candidate for reference turbine? Open?
A - We will build open source platform including software and even hardware after 3 years of research; right now it's a trial design; we will have a website in 3 years or so
Q - Any industrial companies?
A - No – just Korean government supports
Q - Does floating system compensate for the thrust?
A - In open sea, we have this current – this is also a thrust force on the floater, so we have some idea and need autonomous control of hydrofoil to counteract this forces
Q - What is the energy consumption?
A - Generate wave energy from it, and can use motor action in storm weather
Q - Through open innovation and open platform can increase the knowledge
A - Can also move turbines based on wind direction; slightly – to move away from the wake for example
A - If we are worried about the drift, we can add redundancies, one line from bottom of ocean – don't need expensive mooring
Q - Back-up safety against drift is one line with a weight – just safety if passive mode of wave damping doesn't work
A - Several kind of safety – one is active, one is mooring line, control length of hydrofoil (one is short and one is long) (to make different thrust forces)
Q - Generator – as generators get large rpm is lower, advantage to rpm for SC?
A - If rpm lower then may not need gearbox

10:35 Integrated Wind Energy System Modeling: A control engineering perspective

Mr. David Schlipf, University of Stuttgart, Germany

10:55 Offshore cost of energy: Making sense of the European story so far and reflections on system engineering opportunities
Mr. Bruce Valpy, BVG Associates Ltd, UK Q&A

Q&A
Q - Multi-variable wind farm – what is that based on?
A - On offshore; really going from state-of-the-art processes today actually being used in wind farm design today – quite dominated by energy considerations; to moving to taking into account uncertainty in a much better way, but also water-depth, O&M strategies, and a whole lifetime approach – rather than the energy dominated approach which we see now – which leads to an effort to limit wake effects for area you are working with
Q -Has the results been incorporated into crown estate view?
A - Some of this work came from work done for crown estate and extensive interviews with key OEMs and other industry partners – later work comes from looking at results from prior work and seeing were biggest benefits could be for future cost of energy (can almost put percentages on them)
Q - From integrated design perspective, a lot of offshore design work is quite compartmentalized; any movement to get entities responsible for system integration of design of the whole process;
A - Dong is leading this effort in Europe; they are taking that system approach a fair distance; other developers that have won contracts who are much more naïve still driven by defining specific contract packages, getting lowest prices for each package and defining the interfaces themselves – practical but wasteful for COE
Comment - what range of WACC – kept a constant cost of capital; 10% real pre-tax cost of capital; it's hard because with utility lead efforts you don't find out – it's an internal decision; if its financed you can look at cost of debt and equity
Q - Power station characteristics? Controllability? Does that have value?
A - In work with crown estate, it was hard to put value to that – more of a national market consideration; controllability changed horns rev controllability but not in UK or other wind farms per se

11:20 Characteristics of Reference Wind Plants Required to Meet Different Research Objectives
Dr. Patrick Moriarty, NREL National Wind Technology Center

11:40Overview of the NOWITECH Reference Wind Turbine and Wind Farm
Dr. Karl Merz, SINTEF Energy Research

Q&A
Q - I've seen presentations on Norcowe wind farm; how does this align?
A - We are interested in aligning with this – they are interested more in atmosphere than environmental conditions; so they chose FINO, whereas we are interested in controls, etc. so we chose a different site
Q - Can you tell us about the plans for modeling different wind farm flows?

A - Used simple 2-D model from DTU to account for wake; so no coupling between the atmosphere and the wind plant; energy production is decently model
Q - Do you want to include atmospheric models?
A - Yes – that is definitely the goal

12:00 Role of Reference Wind Plants in Benchmarking Optimization Tools
Dr. Pierre-Elouan Réthoré, DTU Wind Energy, Denmark

Day 2 Group Discussions

1:15 – 2:30: 2nd Breakout Sessions: Reference Turbines and Plants

Group 1: Reference Turbines

Led by Karl Merz, Sintef Energy Research, Norway & Dr. Frederik Zahle, DTU Wind Energy, Denmark

Questions and Discussion

What are the research needs that are to be addressed by reference wind turbines?
Do we agree on a general outline of a small, realizable family of reference wind turbines or are there conflicting views?

How do we incorporate what has been done so far/is planned in the near term?

Is a reference wind turbine at an optimum/on a Pareto front, or it is generated using good, standard design practices?

We take two turbine designs that are out there now and present them in a consistent format. List the things that are missing.

Develop three approaches to updating NREL 5-MW turbine or base three reference machines on turbines that are currently on the market. Two of them should be direct-drive units, one for offshore and one for onshore.

What changes would come about if we change to a direct drive?

A 3-MW would be beneficial. It would be useful if we could leverage that.

5 and 10 MW turbines are the two platforms to start with. Blade cost model, airfoil database models should be included.
We need to avoid OEMs with unique solutions, unique technologies.

What about parameters like nacelle mass? Where are the uncertainties in the NREL model?

The group decided on the need for three reference turbines – 3 MW, 5 MW, and 10 MW

The research community has limited resources for generating and maintaining a detailed set of reference wind turbine designs. What should the focus of a collaborative effort be?

Can we agree that x, y, and z research groups are going to sit down together?
Having the collaborative within an international framework gives us more leverage.
Do we create a separate IEA task to develop the reference wind turbines?

If we create an IEA task, it has to be financed from by the contributing countries and organizations.

If we start a collaboration task on reference wind turbines, how rigid should it be?

I don't think the research should be on the development of the reference wind turbine. The reference wind turbine should be the starting point. At the moment we are converting a 2-bladed version of a reference turbine. If we took the 10 MW and modified it slightly, would that work?
The reference turbine should be something that can go in the R&D direction that we want to go.

An IEA task is a starting point and hopes to get some funding from the respective countries/regions.
Should we have two separate tasks; a reference turbine task and an SE task? Are they the same or separate?
Jason thinks this should be one task. You need good reference models for SE. Optimization could be the first task. The same people would work on both. It does not make sense to have two.
It could be an OC3 like task. OC3 started by figuring out how to do it and then came up with reference turbines. Developing the NREL 5-MW reference turbine took a month of work. This effort will take more.
The DTU turbine took months. Repeating this effort for another turbine will be significantly faster.
But who will do it. How will it happen?
It will be difficult to do a community design. It will take longer.

As starting design, we keep it simple, than other people can branch it out. The primary components would have to be done in one place.

NREL FOA 415 to design hurricane resilient turbine for DOE with different groups was done with a stepwise project. Using the same process, we could get to a reasonable system.

Each component could be optimal but not necessarily the system.

We need as much input from everyone as possible.

Different IEA tasks can provide input in all areas for a reference wind turbine. Can we reach out to those groups to help develop a reference turbine?

Is the development of a small family of reference wind turbines organized and controlled by a central supervisory body? Or is the role of the collaboration to generate an open platform where new versions of the initial designs are continually updated by the community? Or both?

We need to agree on size.
We should try to limit it. The more we have the more confusion there will be.
This platform could provide reference systems that could be used across all projects.
Having three different designs that all organizations can work on would good create reference turbines they can all agree on.
To have some effort to develop a reference turbine on smaller turbines could be beneficial.

If industry could take part, that would be good. In the long run, we would use research resources in the best way. We would optimize the impact of the research.
Let's not forget the operators. OEMs that could use these turbines would also want to have input.
Having an industry connection to this work is really important. Information pulled from industry would improve the confidence in our models.
The NREL 5-mw can also provide a lot of historic information.
At a minimum, we need two machines, one that is land-based and one offshore.

Offshore vs land-based. Is the same reference turbine applicable?

You want a capacity factor machine and a position-constrained machine. The interior of a wind farm that is low wind speed could be relevant.

It is important that we take a look at the current market trends for state of the art and then settle on one of them. It would be a quick way to get started. For European we could look at the 401 30 or Ge 1.6. Look at those market segments and turbines and pick one to start with.

What level of detail is needed for the reference turbine?

Like the approach taken with the DTU 10 MW. You have the structural detail and controller.
The DTU turbine has things that are missing from the NREL 5 MW.
To what level do we need to go to for use in other applications?
More fidelity for CFD?
It is important to be reasonably accurate. We need to account for events such as buckling, etc. It does not need to be super sophisticated. The control plays an important role in design.
It we do good job covering a range machines; people in controls could see the different applications.

Is DTU model sufficient in level of detail?

Is the aerodynamic design sufficient? Would it require new airfoils? The performance of the airfoils on the DTU is not good. Are we going to pay someone to design a good set of airfoils?

The design needs to be consistent and complete.
You have in-house airfoils but they are commercialized. Do optimization of those airfoils and capture the trade-offs.
Don't change the DTU turbine, change others.
That must be something the companies compete on.

We will take the DTU 10 and will update it for a 3 MW and 5 MW.

We could develop a new substructure with a floating design. The turbine will not change as much as the control system and the tower/support structure. This would be beneficial for the 5 MW.

Thoughts on how the repository of design data might be organized? Reference foundations? Reference manufacturing processes? Reference assembly and installation (especially offshore)?Reference operation and maintenance schedules?Reference environmental conditions?
Reference cost models? Reference objective functions? Reference workflow or methods?

O&M planning schedule? Or should we focus on structure and aerodynamics?
We need to focus on as much of the core as possible.

Repository – who will be the keepers? How do you fund that?
A limited number of people upload according the predetermined format. We need to be sure we have someone with the knowledge needed to do that. Someone needs to take ownership

Foundations will come after

Environmental conditions? Having reference conditions are useful. Don't know if it's related. Not here.
We need to organize by class for design point.
It would be useful to look at a Midwest climate with jet and an offshore. We design for class and then look at what happens.
The reference turbine is not going to be an optimum design so we don't need to worry about cost models yet. It's not something that drives the design. It can be done later.
Not looking at 10 mw land based.

Is it desired to challenge the IEC design basis?

OEMs would like to challenge the IEC design base. Should we be challenging the IEC load cases?
It's easier to define by class.

Would it be useful to develop a small turbine reference turbine – 10-kW? Some day small wind designers will use the same design methods used by the large turbine designers, and at that time, a reference turbine may be needed.

Summary

General consensus from the group on what is needed:
Three reference turbines/market based
Class III wind, 3 MW onshore, capacity factor constrained, geared
Class ??, 5 MW, direct-drive, position-constrained
DTU 10 MW, existing + direct-drive, intended for offshore.

The process for generating the initial RT point designs is

- Create an IEA Task: Systems engineering and RT's/RWF's in one task.
- Apply for funding regionally
- Participate in a design activity coordinated by a supervisory group

The design process will more or less follow that established for the DTU RT. Also OC3 precedence, agree on the workflow first, then make the reference design. The design process may be sequential and should involve different organizations and if possible industry. Link to other existing IEA tasks (Aerodynamics, reliability) for possible contributions to the design.

Small (10kW-50kW) turbines??? This market segment should be represented in future meetings.

Group 2: Reference Plants

Led by Katherine Dykes, NREL and Pierre-Elouan Réthoré, DTU Wind Energy

Questions of concern for discussion:

Discussion

Based on wind turbine references, some cannot get started to have a conversation without some reference with which to begin that conversation. It is a research necessity. Also we need a baseline for making it better. How much detail? Would you also provide the lay out? It would be best to define wind direction and boundary.WE need a baseline on which to compare.

The more you specify the more you are able to bring in users. Even could specify which tools are being used. Then each can select what part is to be improved in their research.

Should define where we see Systems Engineering being used

When we talk reference plant, where do we see role of SE? This can affect usefulness of plant.
Reference plant complexity of specification - anyone can use detail or throw away what is not needed.
I.e. varying vs. average water depths.
OC3 – analysts same inputs – just turbine aero, then onshore, then offshore. Couldn't get agreement – there were so many assumptions on inputs.
Inputs relatively simple – constant depth but close to realistic – tuning analysis is most useful piece – tremendous value in this – same input, same output, the vary the configurations.

This is an analyst's view. For optimization, we need to broaden the focus.
There is much more uncertainty in interpretation of inputs than in the interpretation of the output from the tools. I.e. tip losses. U.S. and Europe could not ignore totally colored results.
Many things like this, one could fear we won't get to SE if we focus totally on baseline (takes a year to agree on baseline).That's what happened in OC3 research driven by people and need a reference plant for that purpose. Look for more for this – IEA is a good place.

There should be a goal around building a consensus on best practices for a design process.Grow sourcing in design process.

Another point to be made – for the reference plant, V&V and VQ processes are missing. What is being modeled is important. Don't just want models – can have lots of models but a reference plant is different from a model. Many want it to be an existing plant where you have data for V&V.
Are you limited to IP in that case?
Maybe not for older plants. We need more information on what we have. OEMs are opening up more about sharing this information to do V&V and VQ (should be open).
Model vs. real plant. Probably would go with real plant.

IEA→goal to have industry come with datasets and have different experts solve it. Not just on tuning, but what are parallel realizations afterward.
In the OC3, a plot of scatter that is as god as it will get; we get an uncertainty band.
Certification hat – one of more complex is design evaluation and loads evaluation. How does certification body know tools are good? Depends on uses of the group. Old technology site may be useful for some stuff, but may not be useful for others. For some work, old and robust doesn't matter.
SE is a step forward in design and optimization than in improving analysis.

To pursue V&V and VQ: Verification leads to proven software with (simple problem set) defined uncertainties. Validation is for software optimization process – not dependent on validated plant model.
We don't even have plants to do full analysis.
There is a struggle with code-to-code comparison – garbage in, garbage out – we need to understand uncertainties to ground truth. Give insight but from indstury perspective. We can't rely on models if risk of uncertainty is too high.
Ongoing work on validation side?
Task 31 is doing that. Horns rev→wake effects data, reference wind farm in itself, bunch of benchmarks. Huge spread physics not so different inputs and validation data. Interpretation is different.
Validation is all about power prediction, solving time-averaged power. The devil is in the details. It is all about loss.
Task 31→conclusion can go into more detail.
If you go to developers for specific, they say yes, or else they say no dice. Good hypothesis and request will get data.
DTU published good stuff on Horns Rev.
Expensive tests
Some work on Stuttgart Fino /Alpha Ventus should be classic.

Wind plant, design of wind plant, costs of the wind plant → these uses require different levels of analysis and specificity. What can we provide to help?
Take SE with plant design a step forward. Still have details on all these – aero, etc, but maybe plant level can be done even if those things are
Tremendous value to a standard plant even if it's not real, to prompt investment into the next step.Really high uncertainty.
It goes back to having a plant to start with right now ad hoc – all things for plant to do COE if you are comparing one technology to another.
Should it be theoretical plant or based on realistic plant?
Horns Rev: NREL 5-MW benchmarking level (no validation date) never measurable→can never a tip loss. Horns Rev with V80 and put NREL 5-MW in and redesign. More turbines in deeper water, defining project inputs project in a particular environment.

Why don't we just define project, if it's already there, we have data, in time data from operator more and more realistic
Project doesn't need work, just data. We would be re-designing farm that is already there.

Reference problem and reference plant i.e. redesign with different technology as a problem – a west of use cases and exercise around.
If you have all the detail, abstract a way to what you need, i.e. comparing foundation technology with depth. Site remains the same.
Going with offshore technology, we need realistic offshore conditions. First is data repository and appropriate access. Second stage is benchmarking, design, etc.
We always want real data. Topfarm used Middlegrund. We need common input files.
Total parameters for every body and most people use subset of parameters.
Alpha Ventusis small and good for control, etc., but maybe not be representative. Need to be trained in what data represents
Data needs to depend on problem. Where does SE play a role? Where is it useful and for whom? Developer?OEM for turbine?Foundation?

As sites become more complex, more and more OEMs are doing site analysis and assessment and saying we need integrated model:

1) Fiduciary responsibility
2) Insight into tech innovations needed.

We are looking at integrated system more and more. Some OEMs are looking at shifting to vertical integration.

To get all detailed data
May not get all the detailed data we need. Instead, what would be right for V&V processes, i.e. turbine responds like this → if I put all turbines in a farm can I get away with one turbine.
A possible task is assessing what VQ approach would be so that you can do what you needed to do.
If you get data in standard format: format, data, and problems.
Make it interactive.
There were limitations on data that wasn't provided. Task 31 – standard input is needed.
Aren't we talking about the basis of design?
Are some plants out there with costs available?
Some data are difficult to model, some are difficult to get.
Useful to have some basis in reality – real cost or what it would cost to build today. Comparing to some point of cost rather than just being out there. SE→having cost structure there in place
There if you have good reason for why it is easier to get, i.e. sometimes mass is more relevant than cost.
The point made earlier – 5-MW was to compare baseline of comparison. Reference plant similar – opt comparison – same physics comparison, etc. Low-hanging fruit will be integrated plant control. There is so much to be done.
Plant may be similarly limited like the 5 MW.
Doesn't have to be right
5 MW is a design. Is it a design or just a plant?
Don't have to be optimum, realistic
So reference turbine needed. Danish authority asked DTU to create realistic layout for turbine another type of interest from authorities to make reference plants.

Example potential use turbine off the shelf and use it in plant layout design – turbine fixed, specific design foundation, control, cable.
For use cases to compare approaches break down barriers → controls turbine plant.There are a variety of users and use cases that look from plant layout to sophisticated control strategies that affected how we would develop a reference plant

Summary

The group considered how do we design a plant? And also, how do we get to a standard design? The general consensus is that we need this effort on reference plants.

We need to develop a site where we want to develop a wind plant with conditions or it could be an existing wind plant. We need reference wind farms, but we also need reference designs. This needs to be done with an optimization technique. We need to have a baseline that we can use for comparisons.

The plant just needs to be the same as the representative turbine. It does not need to be so complicated.
The group considered if we can pull design data from an existing wind plant. We have a reference site and a reference plant that includes reference wind turbine. Based on that starting point we have a design process. It will be made publicly available to see how that design can be improved on. We want to have an impact on future development. We want to drive the development. Develop the tools and new substructures that make it feasible.

This needs to be done on the IEA level where you could integrate different objective together and define different work packages that can accommodate as many people as possible. Benchmarking is the way to plan things. It's the way to compete. Develop a baseline project that will allow people to compete.

Some specific goals the group discussed were:

- Benchmarking of the design of wind plants/define reference plant – use a classical approach and then a MDO approach – show differences.
- Define users and use cases. Information needed – where does data come from?
- Involve a large community to iterate on the gaps and challenges and to define tasks (i.e. really will need a lot of input from key stakeholders including developers and owner/operators)

2:45 – 3:30 Group discussion on future collaborations

Round-Robin Final Thoughts on Collaboration from Each Participant

It's a pretty simple process from the IEA exec committee perspective. It requires two or more members to define a common interest. We already had that coming into this meeting. And then it's really important to have a good work plan with realistic goals that you can achieve in 3 to 4 years. One of your country's leaders needs to be the operating agent. It requires a vote from the Executive Committee. The next meeting is in May. This could be presented at that time.

The key element should be the reference turbine and the plant that is full of reference turbines and conditions need to be nailed down. If we do that, the research activities that launch out of that is the real place where the work gets done. So we can have a real set of references, clearly specify the use cases, and launch work packages. There is interest in wakes, controls, and offshore. We need to construct packages that impact those areas.

You need broader stakeholder input. You need to demonstrate near-term value. That will shape the way you move forward. We also need to think about standards, gaps we have in standards, how they are structured.

We may want joint actins similar to CENERand conduct workshops every two years.

The discussion of plants and reference turbines has been very useful. We need good reference wind turbine models. Existing models have been very successful. Benchmarking is complicated – how to define the process that is of value to everyone. Avoid having the results posted separately. We need to come together as a community. We should do more workshops, conduct summer schools to teach students, reach out to the community, and have sessions on design, and workshop in the coming months.

We need more engagement with OEMs and project developers.

Models and framework. It would begood to have a set of standardized turbines and a reference framework for functionality.

I am encouraged by this discussion on benchmarking. We need to set up a benchmarking exercise. It's a good way to get people to collaborate in non-threatening environment. Having an IEA task around optimization benchmarking would be a good exercise. This is a good way to get industry involved.

From the OEM point of view, we understand the need for SE tools. It would be beneficial to have a user interface that is quick and easy to learn. The ability to use existing in-house tools with existing toolsets would be great.

Sometimes we lose the broad view when we focus on specific problems. Having a wind plant reference model will be useful to the control community. It's really important to have workshops and meetings rather than conference calls to have people work on together on the topic.

We are already doing some benchmarking exercises within IEA foraeroelastic tools and CFD. Extending that to some kind of SE benchmarking would be good.

This effort should focus on SE, not system analysis. They are linked. Create a network to create tools and methods to be implemented by end users. OEMs and others can use to reduce the COE.

Regarding reference models, it would be very valuable to have a mechanism for a feedback loop. Information needs to be captured and fed back for the benefit of the greater community.

The reference turbine for the 10 MW class should use a super conductor generator. With that you can reduce nacelle weight and the tower and base can be changed. We can design with a different concept and reduce cost.

Floating and super conducting can be good items for reference turbine

The challenge is to move it from this group to industry. There are many uses for reference projects. We would like to see a reference site with reference turbine.

The focus of the IEA task not should be on developing a reference turbine. We need to use what's out there and think of end use cases.

We need to be doing multidisciplinary analysis and have more meetings with higher frequency. Work on frameworks in the sense of defining the blade environment analysis tool, optimization, iteration, etc. Use the IEA environment for definition and then make them accessible.

IEA task framework is the best way to develop reference turbine models.

Optimization and benchmark problems are the most important things to get completed soon. From OEM, torque problems don't have fidelity. This would be good for students. Toy problems will really help. They establish a benchmark for evaluation. The same approach is valuable to help with reducing COE. Benchmarking is most important.

We need SE tools. We need analysis pack with complete workflow, including the turbine and grid control. If we have an organization, it will help me choose research projects that contribute to the greater community.

This gathering of experts is inspiring. I hope the IEA task can be a way to demonstrate that SE can change things. I hope that it draws industry in and that they will come to us with their problems.

Benchmarking is most exciting. It is good to demystify benchmarking. We need to shed more light on it. We should pose some grant challenges, such as we would like to take this platform and decrease COE by this much, then work together to solve this problem using these frameworks.

Do something on the short term. Do a proposal for an IEA task. Do a framework for a reference wind plant. Create structure to work on turbine and framework that builds out to benchmarking once we gain input from relevant stakeholders.

We should keep the collaboration moving forward and the IEA framework is the best approach.
Anyone that wants to be involved, whether it's doing a workshop or proposal, we are happy to have you participate.

Form a group to discuss the proposal development and subsequent collaboration.

During the IEA task discussion, we touched briefly on the need for an internal champion and upper management support for the adoption of SE tools at the turbine and plant level (at an OEM). It would be extremely helpful to quantify the benefits of optimized systems, which would assist upper management to accept and champion their use.

PRESENTATIONS

Topical Expert Meeting #80 on:

Wind Energy Systems Engineering: Integrated RD&D

Introductory Remarks:

Ms. Katherine Dykes, NREL National Wind Technology Center, USA &

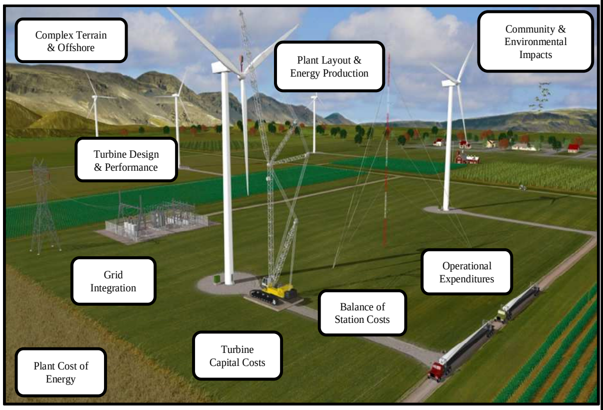
Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

January 12^{th}-13^{th}, 2015

NREL National Wind Technology Center Boulder, CO, USA

Wind Energy Systems Engineering: Integrated RD&D

- Why integrated RD&D? Wind energy plants are systems which are complex and highly coupled
  - Complex and uncertainty design conditions
  - Large supply chains and many stakeholder
  - Very large technical systems in scale / huge civil engineering projects
  - Operating over long period of time
- Overall meeting goal: exploring and assessing how current and future RD&D practices do/will handle wind plant system complexity and uncertainty



Wind Energy Systems Engineering: Integrated RD&D

- Exploring and assessing Integrated R&D from different vantage points:
  - Increased breadth in RD&D: working across many stakeholder groups, increased use of multi-disciplinary design, analysis and optimization (MDAO) and uncertainty techniques in RD&D processes
  - Increased depth in RD&D: working with various model fidelity representations of the technology
  - Leveraging capabilities in computing and data science: both of the above increasingly involve HPC and advanced data analysis techniques

Wind Energy Systems Engineering: Integrated RD&D

- Exploring and assessing Tools for Integrated R&D via integrated software frameworks and reference turbines / plants:
  - Frameworks allow standardized approaches to integration of software models for turbines and plants
  - Reference turbines and plants give industry practitioners and researchers common platforms for exploring new technology developments, design practices, and more

Wind Energy Systems Engineering: Integrated RD&D

- Agenda:
  - Day 1: Advanced Modeling and Frameworks
  - Day 2: Reference Turbines and Plants
- General Meeting Organization:
  - Several presentations to provide insight into active research on integrated RD&D topics
  - Breakout sessions to encourage in-depth discussion on meeting topics and to develop recommendations for short and long term needs in integrated RD&D
  - Large group discussion sessions to bring together overall content to recommend next steps and potential development of proposal for IEA Wind task on integrated RD&D

iea wind

Wind Energy Systems Engineering: Integrated RD&D

- Introductions…

iea wind

iea wind

Topical Expert Meeting #80 on:

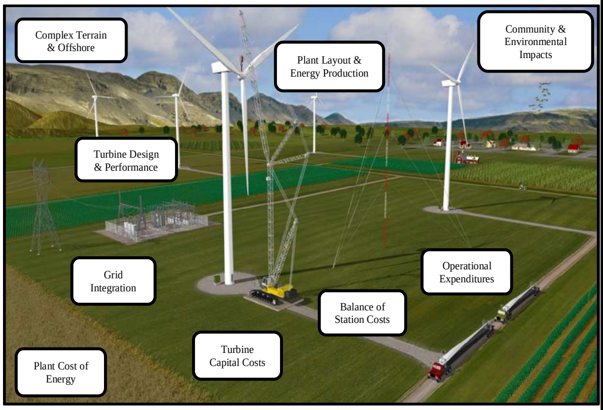
Wind Energy Systems Engineering: Integrated RD&D

Introductory Remarks:
Ms. Katherine Dykes, NREL National Wind Technology Center, USA &
Dr. Pierre-Elouan Rethore, DTU Wind Energy, Denmark

January 12th-13th, 2015
NREL National Wind Technology Center Boulder, CO, USA

Wind Energy Systems Engineering: Integrated RD&D

- Why integrated RD&D? Wind energy plants are systems which are complex and highly coupled
  - Complex and uncertainty design conditions
  - Large supply chains and many stakeholder
  - Very large technical systems in scale / huge civil engineering projects
  - Operating over long period of time
- Overall meeting goal: exploring and assessing how current and future RD&D practices do/will handle wind plant system complexity and uncertainty



1/12/2015 iea wind 2

1

Wind Energy Systems Engineering: Integrated RD&D

- Exploring and assessing Integrated R&D from different vantage points:
  - Increased breadth in RD&D: working across many stakeholder groups, increased use of multi-disciplinary design, analysis and optimization (MDAO) and uncertainty techniques in RD&D processes
  - Increased depth in RD&D: working with various model fidelity representations of the technology
  - Leveraging capabilities in computing and data science: both of the above increasingly involve HPC and advanced data analysis techniques

iea wind

1/12/2015 3

Wind Energy Systems Engineering: Integrated RD&D

- Exploring and assessing Tools for Integrated R&D via integrated software frameworks and reference turbines / plants:
  - Frameworks allow standardized approaches to integration of software models for turbines and plants
  - Reference turbines and plants give industry practitioners and researchers common platforms for exploring new technology developments, design practices, and more

iea wind

1/12/2015 4

Wind Energy Systems Engineering: Integrated RD&D

- Agenda:
  - Day 1: Advanced Modeling and Frameworks
  - Day 2: Reference Turbines and Plants
- General Meeting Organization:
  - Several presentations to provide insight into active research on integrated RD&D topics
  - Breakout sessions to encourage in-depth discussion on meeting topics and to develop recommendations for short and long term needs in integrated RD&D
  - Large group discussion sessions to bring together overall content to recommend next steps and potential development of proposal for IEA Wind task on integrated RD&D

1/12/2015 iea wind 5

Wind Energy Systems Engineering: Integrated RD&D

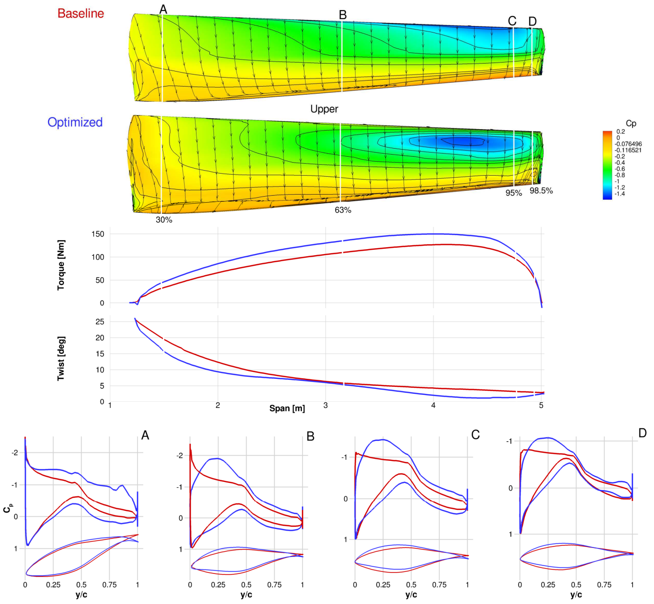
- Introductions…

1/12/2015 iea wind 6

3

High-fidelity aerodynamic shape optimization for wind turbines

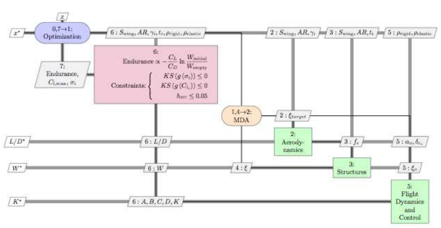
Tristan Dhert
Joaquim R. R. A. Martins
http://mdolab.engin.umich.edu



Email address:
tr.dhert@gmail.com
jrram@umich.edu

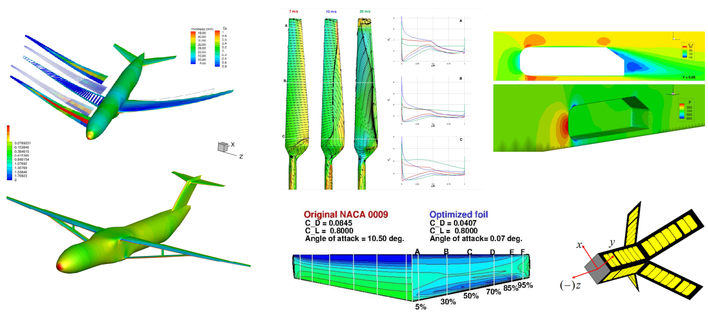
MDOlab research is divided into two main thrusts

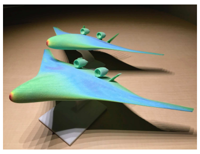
Fundamental MDO algorithms

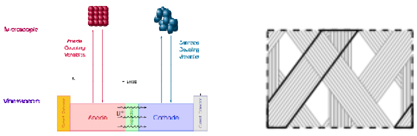


$$\frac{\partial R}{\partial u}\frac{du}{dr} = \mathcal{I} = \left[\frac{\partial R}{\partial u}\right]^T \left[\frac{du}{dr}\right]^T$$

Applications of MDO







MDO for Aircraft Configurations with High-fidelity (MACH)

Python user script
Setup up the problem: objective function, constraints, design variables, optimizer and solver options

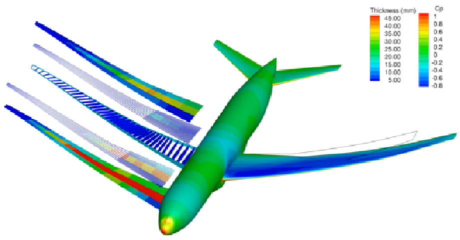
Optimizer interface
pyOpt
Common interface to various optimization software

- SNOPT
- Other optimizers

Aerostructural solver
AeroStruct
Coupled solution methods and coupled derivative evaluation

- Structural solver — *TACS* — Governing and adjoint equations
- Flow solver — *SUmb* — Governing and adjoint equations

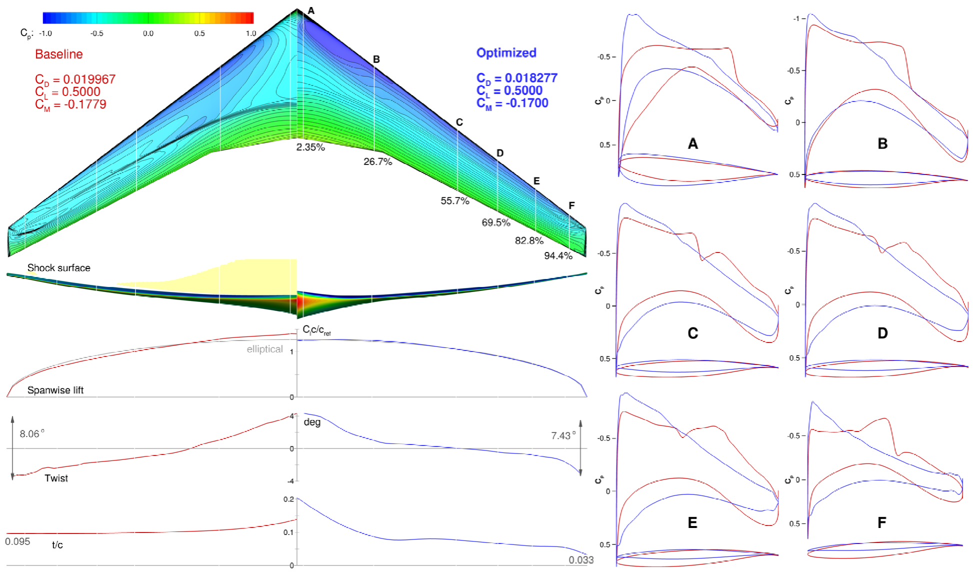
Geometry modeler
DVGeometry/GeoMACH
Defines and manipulates geometry, evaluates derivatives



- Underlying solvers are parallel and compiled
- Coupling done through memory only
- Emphasis on clean Python user interface
- Solver independent

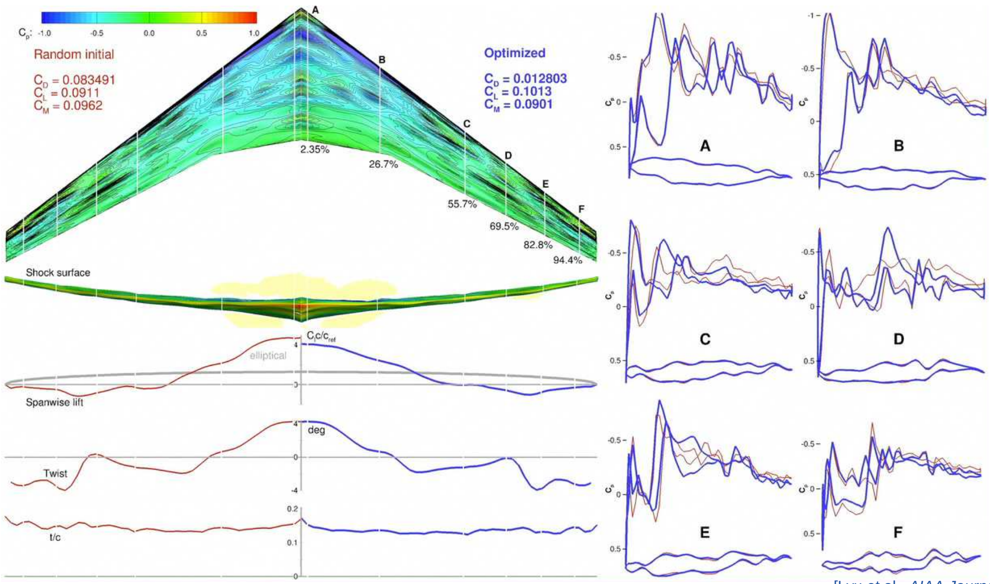
[Kenway et al., *AIAA J.*, 2014]
[Kennedy and Martins, *Finite Elem. Des.*, 2014]

Optimization can refine good designs…



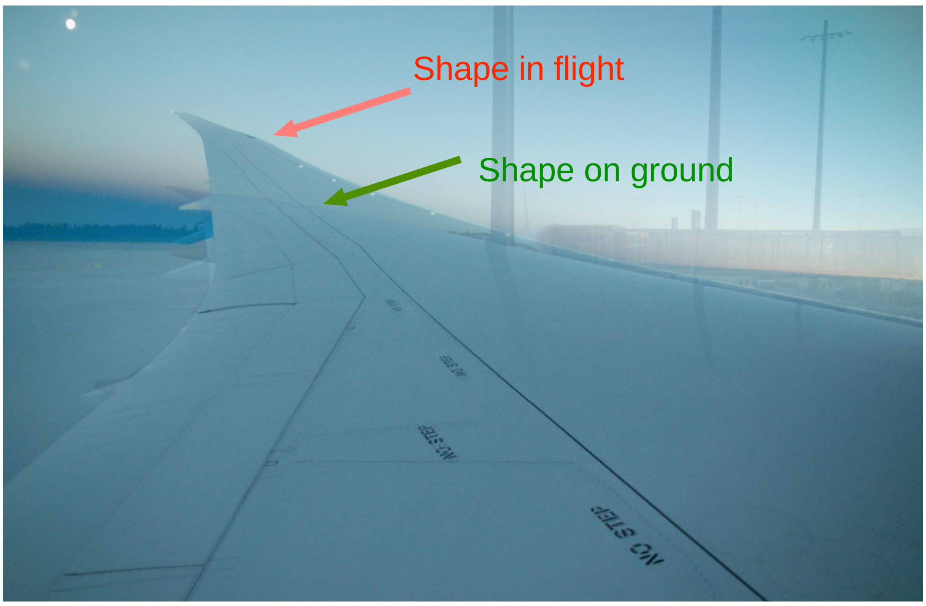
[Lyu et al., *AIAA Journal*, 2014]

…but can we start from really bad designs?

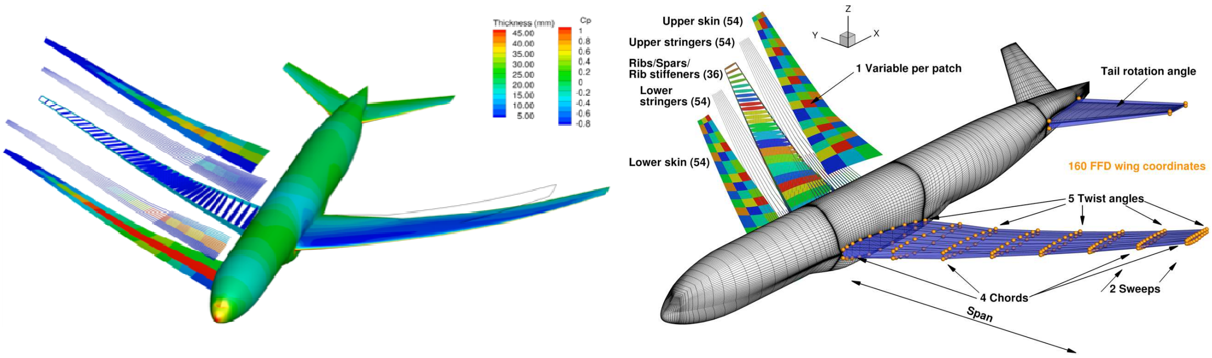


[Lyu et al., *AIAA Journal*, 2014]

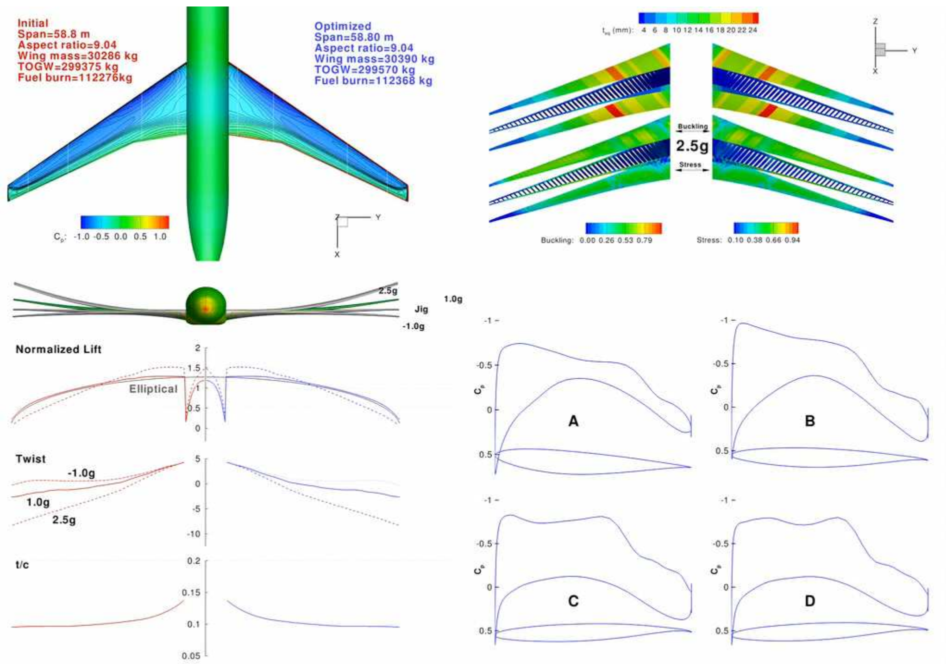
Wing design demands more than just aerodynamics



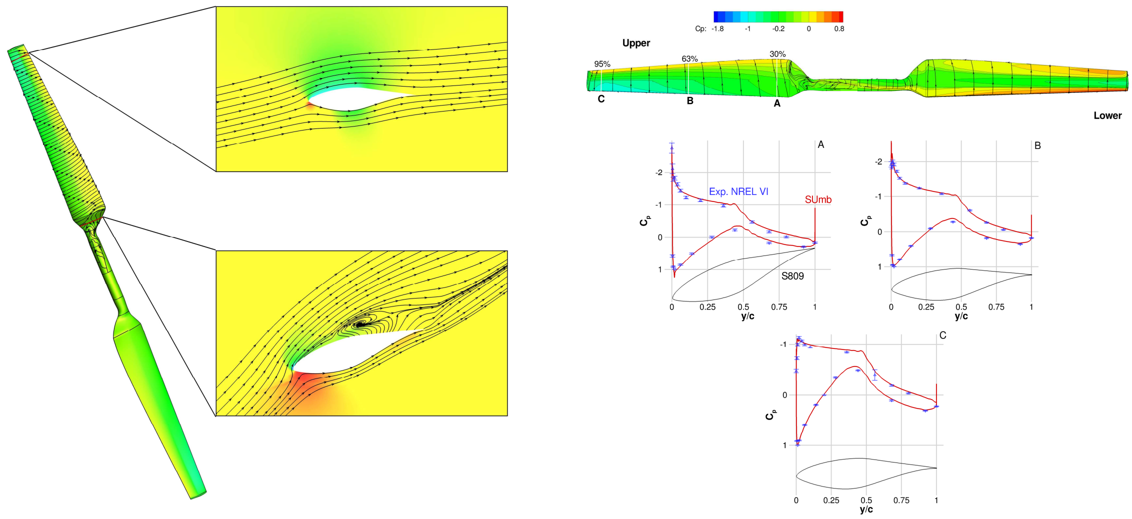
Want to optimize both aerodynamic shape and structural sizing, with high-fidelity



[Kenway et al., *AIAA J.*, 2014]
[Kennedy and Martins, *Finite Elem. Des.*, 2014]

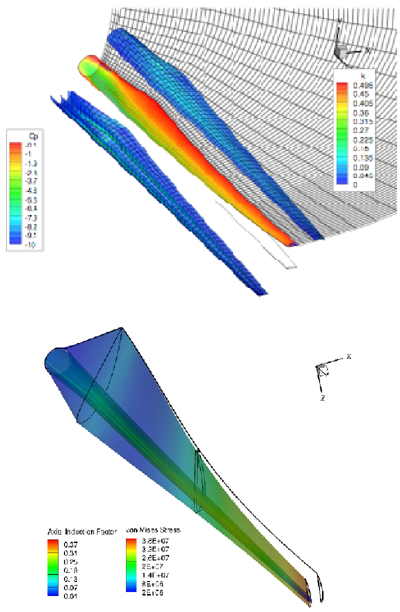


This aerostructural optimization framework can be adapted for the design of wind turbine blades



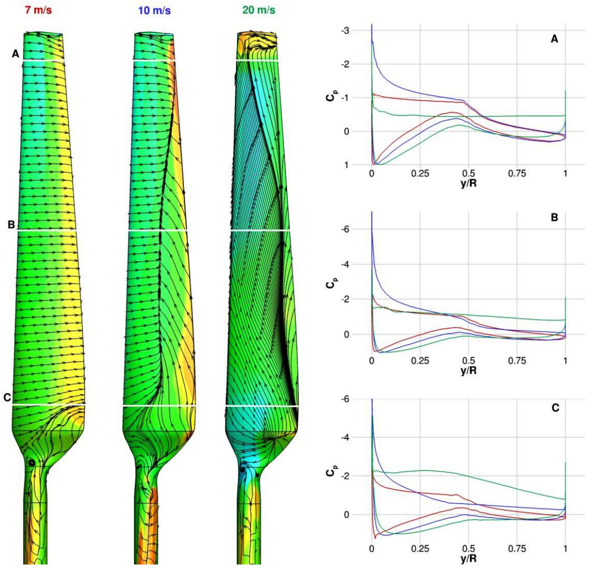
Our previous effort were limited to low-fidelity aerodynamic models

- Aerostructural analysis using 3D panel method and FEM
- Aerostructural optimization with BEM theory and beam finite elements
- Aerodynamic shape optimization by use of BEM theory

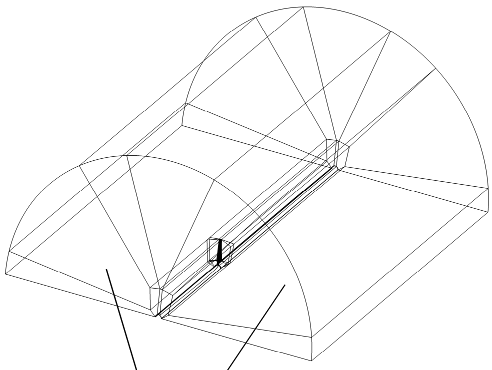


We can now perform steady-state RANS analysis in the rotating frame

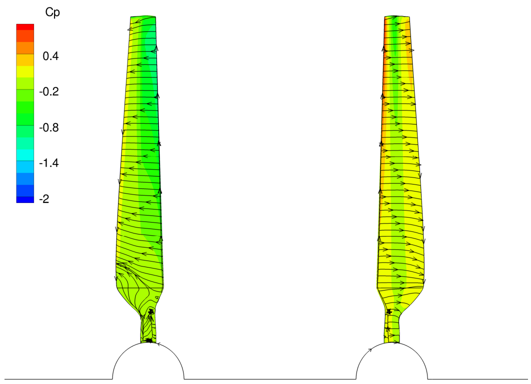
- Structured compressible RANS-based solver 'SUmb'
- Roe scheme without limiter
- Spalart–Allmaras turbulence model
- Wind speeds: 5, 7, 10, 13, 15, 20, and 25 m/s



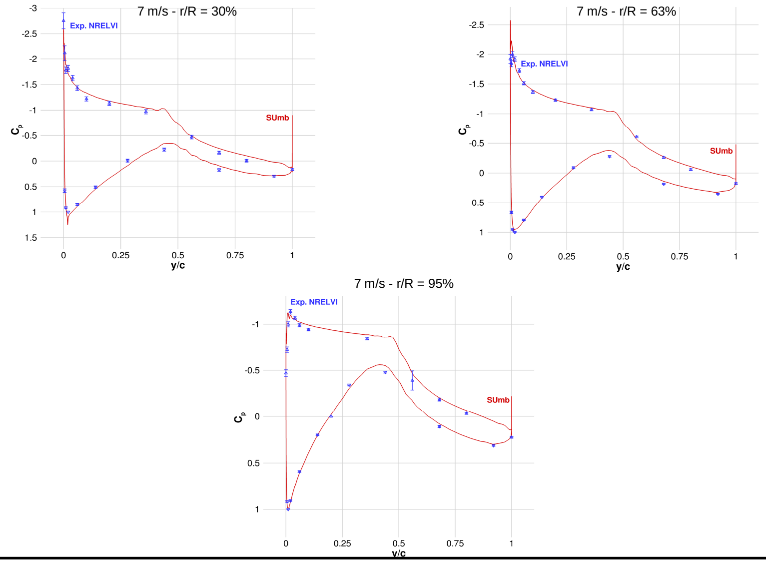
Reducttion of computational costs by use of periodic boundary conditions



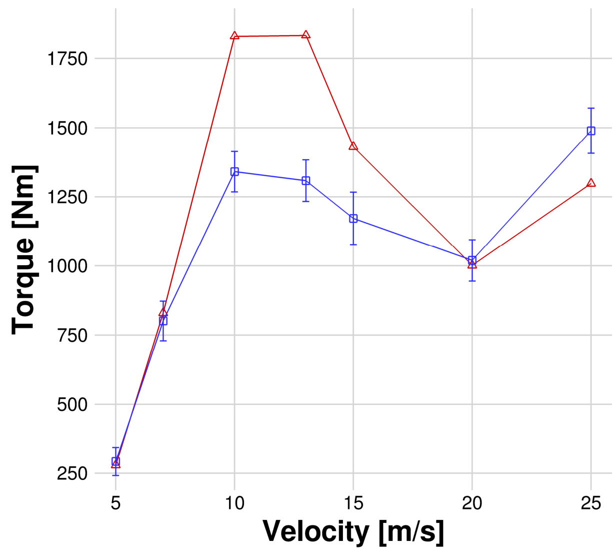
periodic boundary conditions



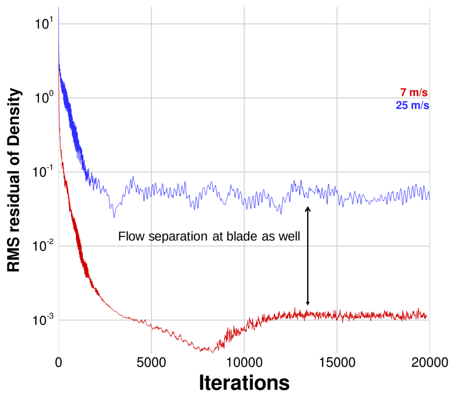
Attached flows are well predicted for the NREL VI sequence S experiment

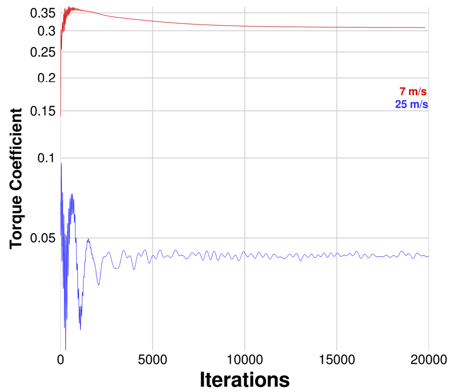


While attached flows are well predicted, the separated flow conditions are not



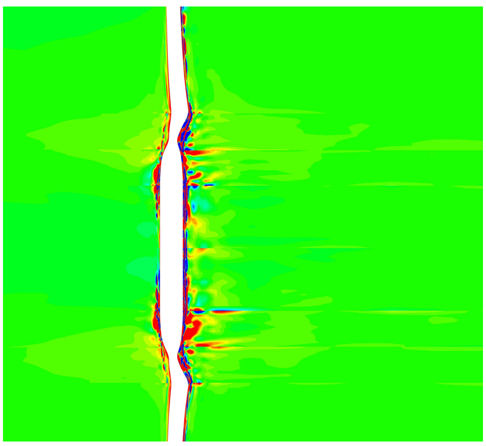
… but stagnation in residuals due to unsteadiness at cylindrical -and transition part

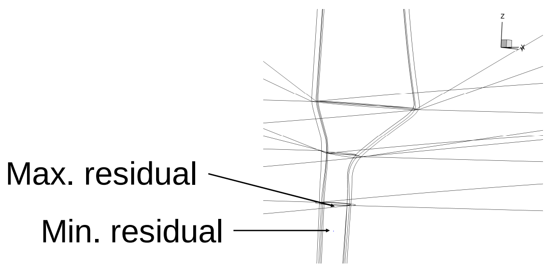




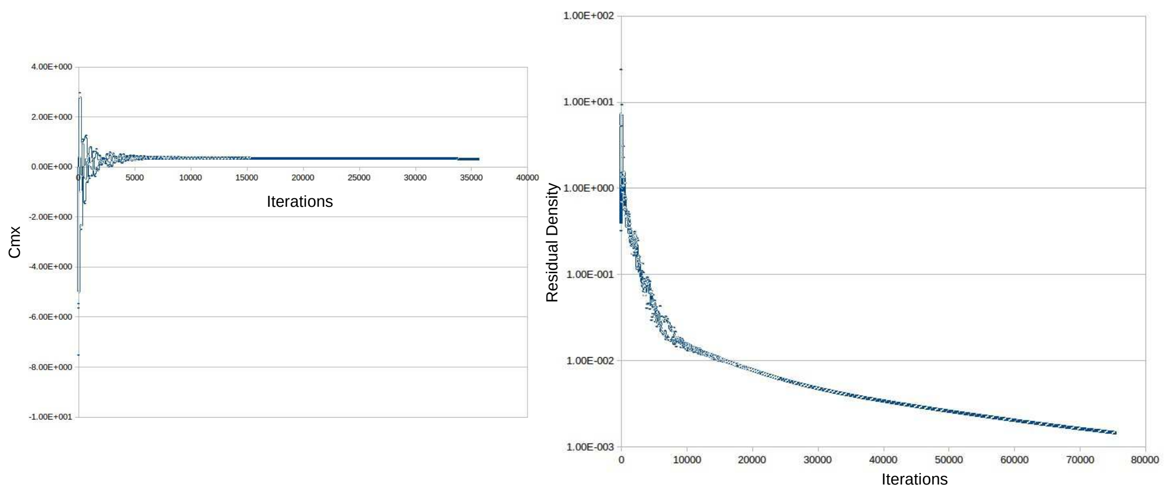
Steady-state adjoint stagnates! ⟶ No optimization possible

Possible unsteadiness at cylinder and transition

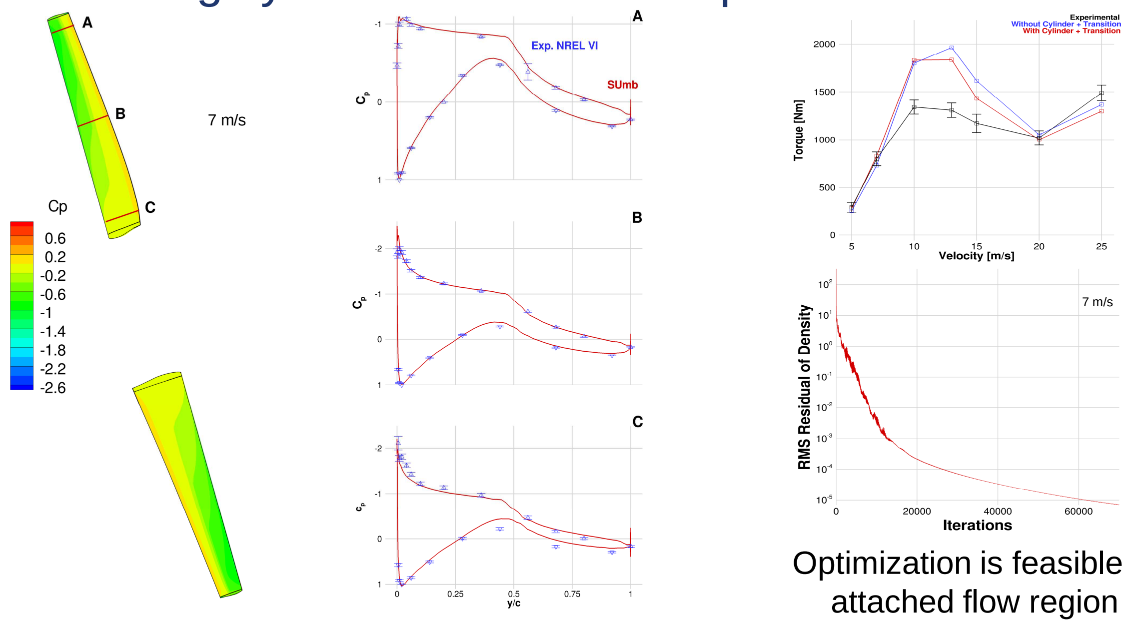




Turkel's preconditioner does result in residual convergence, but it takes longer…

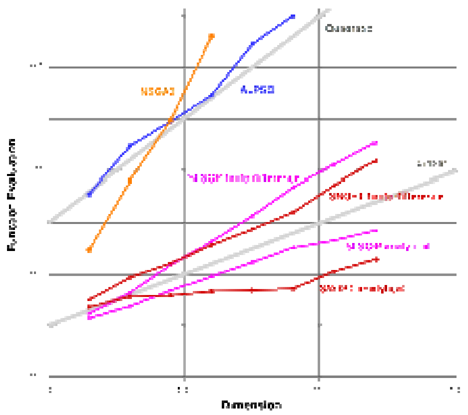


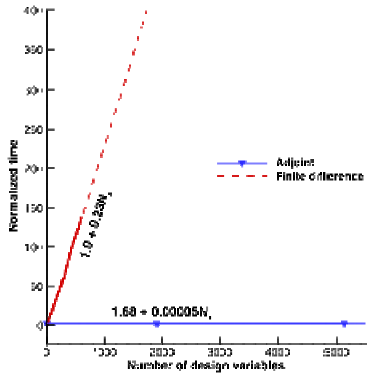
Removing cylinder and transition part works!

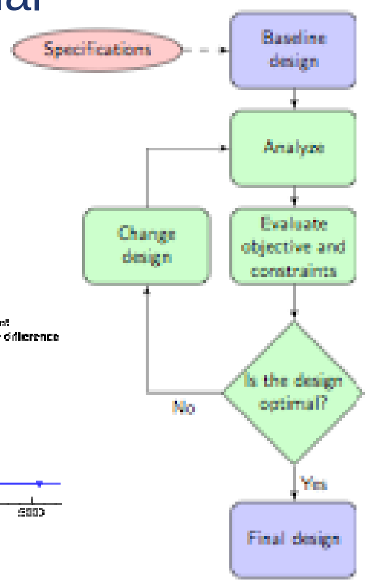


Optimization is feasible in attached flow region

Gradient-based optimization is essential for large set of design variables

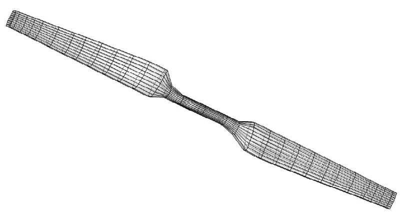


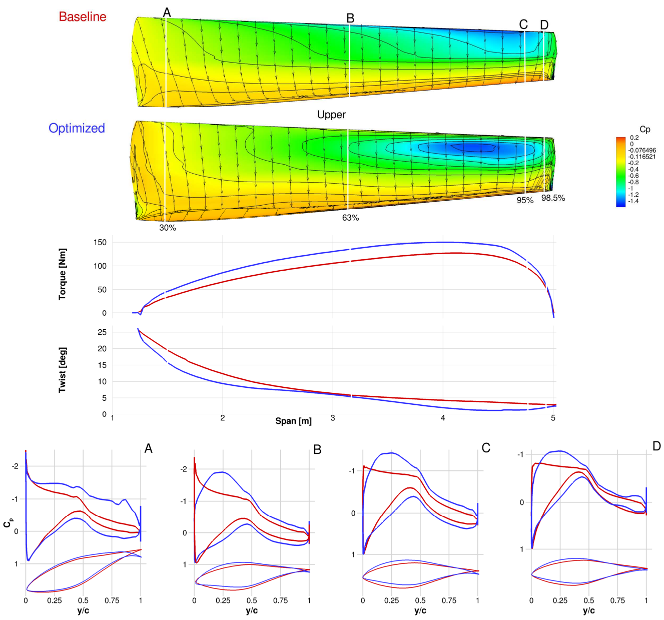




22.4% increase in torque by subtle changes in shape and twist

- Maximizing torque
- 496 design variables: shape and twist
- thickness -and linear constraints

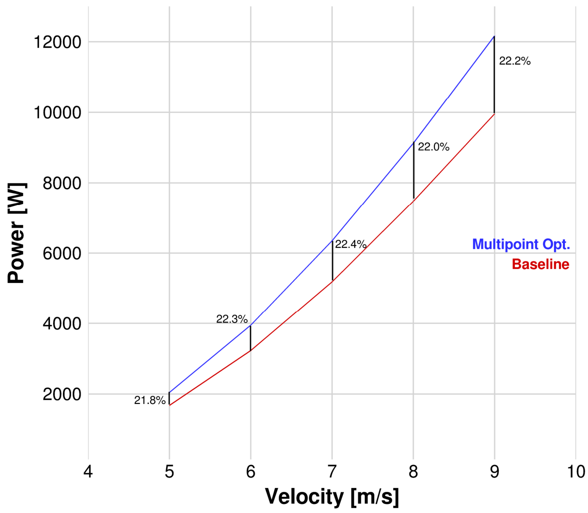




26.5% improvement in Annual Energy Production

- Optimize the design for various wind speeds (cut-in to rated wind speeds)
- AEP based on Rayleigh distribution
- Dutch part of the North Sea

AEP Initial :19.9 MWh
AEP Optimal: 25.3 MWh



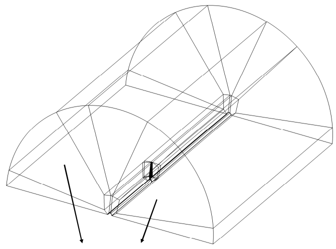
Summary

ient-based aerodynamic shape optimization methodology is developed for wind turbine

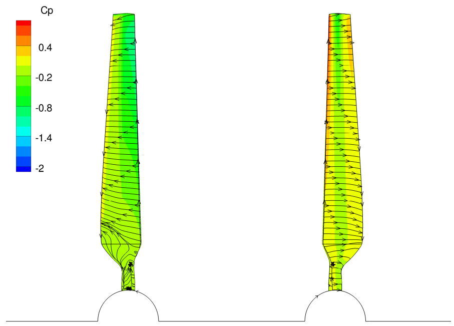
- Gradient computation and Optimization
- Unsteadiness results currently in non-solvable optimization
- Fast and Robust Aerodynamic Shape optimization

Future Work

- Unsteady Adjoint solver for optimization of quasi-steady solutions
- Mesh perturbation method for Periodic Boundary Conditions
- Adding more design variables (Pitch, Rotating Speed, and planform) and constraints (separation, bending moments) for more realistic designs
- Aerostructural optimization

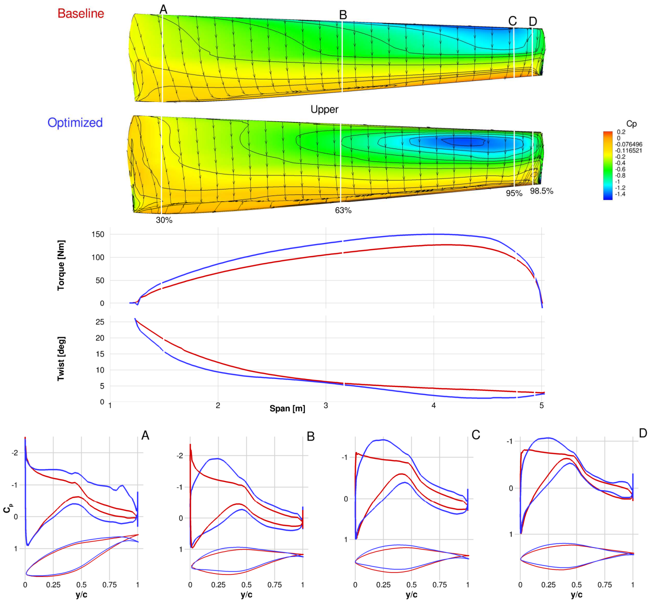


periodic boundary conditions



High-fidelity aerodynamic shape optimization for wind turbines

Tristan Dhert
Joaquim R. R. A. Martins
http://mdolab.engin.umich.edu

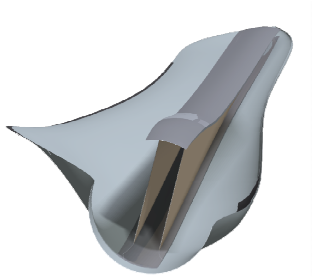


Email address:
tr.dhert@gmail.com
jrram@umich.edu

Technische Universität München
Wind Energy Institute

Aero-Structural Design of Rotors

Carlo L. Bottasso
Technische Universität München & Politecnico di Milano



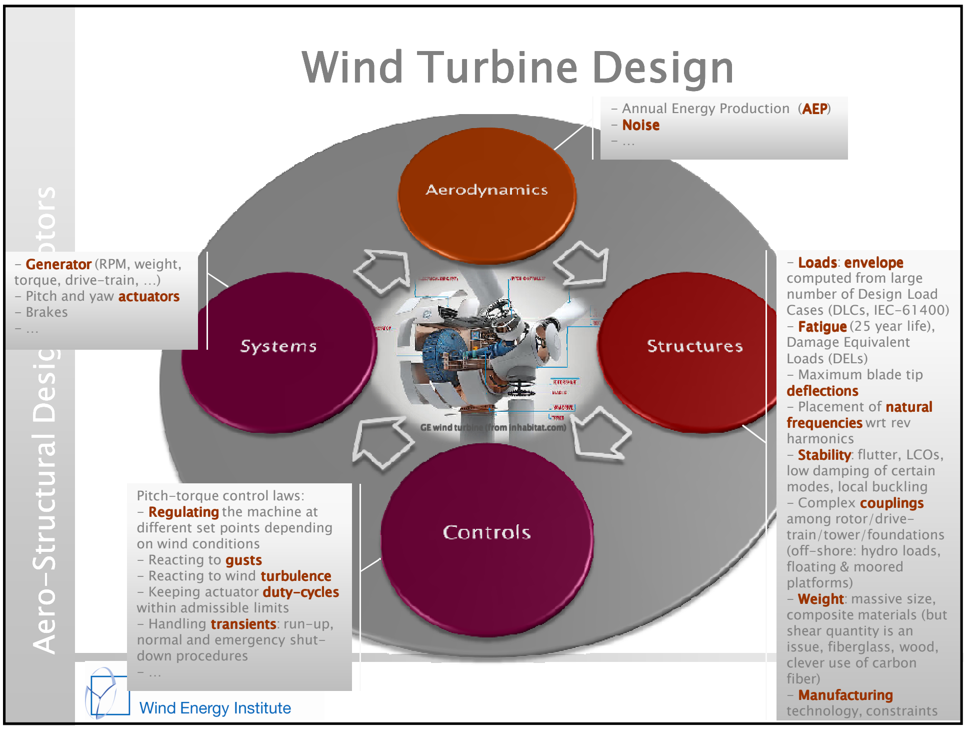
IEA Wind TEM 80
NREL, NWTC, 12-13 January 2015

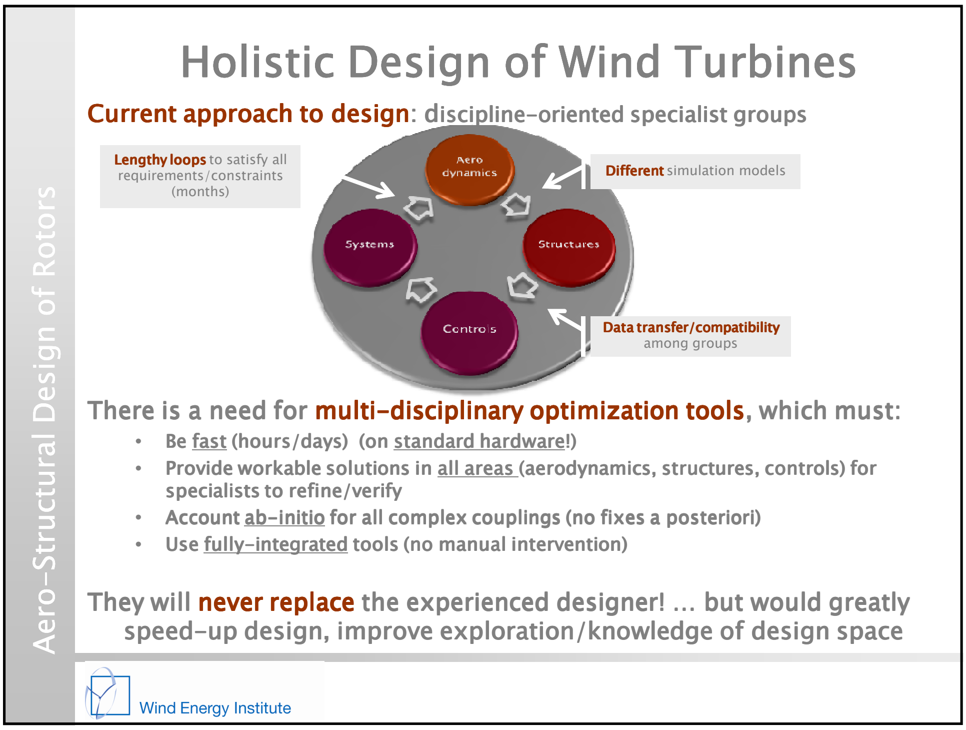
Aero-Structural Design of Rotors

Presentation Outline

- Introduction and motivation: the need for an integrated aero-structural design approach
- Cp-Max and Cp-Lambda: a high fidelity design and simulation environment
- Applications and results
- Conclusions and outlook

Wind Energy Institute


Wind Turbine Design
Aero-Structural Design of Rotors
– Annual Energy Production (AEP)
– Noise
– …
Aerodynamics
Systems
Structures
Controls
– Generator (RPM, weight, torque, drive-train, …)
– Pitch and yaw actuators
– Brakes
– …
– Loads: envelope computed from large number of Design Load Cases (DLCs, IEC-61400)
– Fatigue (25 year life), Damage Equivalent Loads (DELs)
– Maximum blade tip deflections
– Placement of natural frequencies wrt rev harmonics
– Stability: flutter, LCOs, low damping of certain modes, local buckling
– Complex couplings among rotor/drive-train/tower/foundations (off-shore: hydro loads, floating & moored platforms)
– Weight: massive size, composite materials (but shear quantity is an issue, fiberglass, wood, clever use of carbon fiber)
– Manufacturing technology, constraints
Pitch-torque control laws:
– Regulating the machine at different set points depending on wind conditions
– Reacting to gusts
– Reacting to wind turbulence
– Keeping actuator duty-cycles within admissible limits
– Handling transients: run-up, normal and emergency shut-down procedures
– …
GE wind turbine (from inhabitat.com)
Wind Energy Institute


Holistic Design of Wind Turbines
Aero-Structural Design of Rotors
Current approach to design: discipline-oriented specialist groups
Lengthy loops to satisfy all requirements/constraints (months)
Different simulation models
Aero dynamics
Systems
Structures
Controls
Data transfer/compatibility among groups
There is a need for multi-disciplinary optimization tools, which must:
• Be fast (hours/days) (on standard hardware!)
• Provide workable solutions in all areas (aerodynamics, structures, controls) for specialists to refine/verify
• Account ab-initio for all complex couplings (no fixes a posteriori)
• Use fully-integrated tools (no manual intervention)
They will never replace the experienced designer! … but would greatly speed-up design, improve exploration/knowledge of design space
Wind Energy Institute

Aero-Structural Design of Rotors

Motivation: the Need for Combined Aero-Structural Design

Cost model (Fingersh at al., 2006):

$$CoE = \frac{FixedChangeRate * InitialCapitalCost(p)}{AEP(p)} + AnnualOperatingExpenses(p)$$

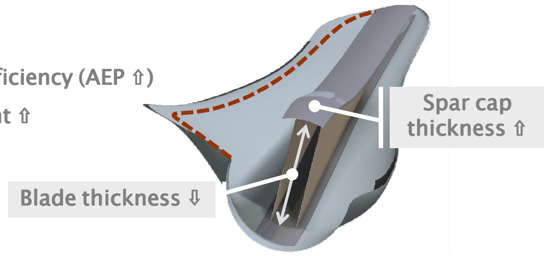
where p = design parameters

Strong couplings between aerodynamic shape (AEP) and structural sizing (blade cost)

Example:

Reduce solidity to increase efficiency (AEP ⇧)

Consequence: effect on weight ⇧



Wind Energy Institute

Aero-Structural Design of Rotors

Motivation: the Need for Combined Aero-Structural Design

Cost model (Fingersh at al., 2006):

$$CoE = \frac{FixedChangeRate * InitialCapitalCost(p)}{AEP(p)} + AnnualOperatingExpenses(p)$$

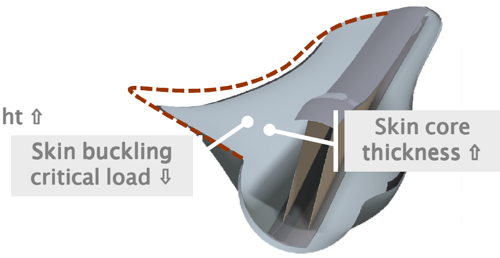
where p = design parameters

Strong couplings between aerodynamic shape (AEP) and structural sizing (blade cost)

Example:

Increase solidity

Consequence: effect on weight ⇧



Wind Energy Institute

Aero-Structural Design of Rotors

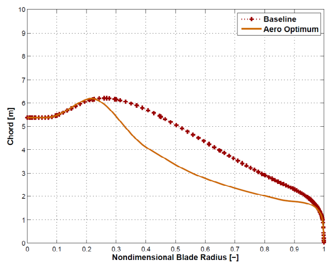
Motivation: the Need for Combined Aero-Structural Design

Example: INNWIND 10 MW HAWT (class 1A, D=178.3, H=119m)

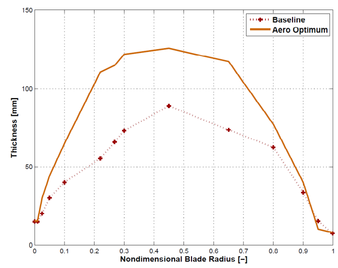
Baseline design by INNWIND consortium

1. Perform purely aerodynamic optimization for max(AEP)
2. Follow with structural optimization for minimum weight

Chord ▼



Spar cap ▼



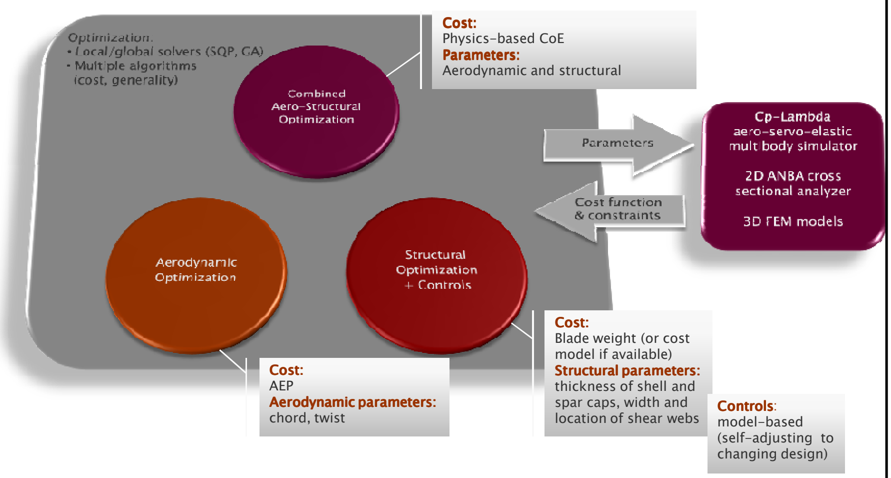
Dramatic **reduction in solidity** to improve AEP leads to **large increase in weight**

⇨ **CoE increases** (+2.6%)

Wind Energy Institute

Aero-Structural Design of Rotors

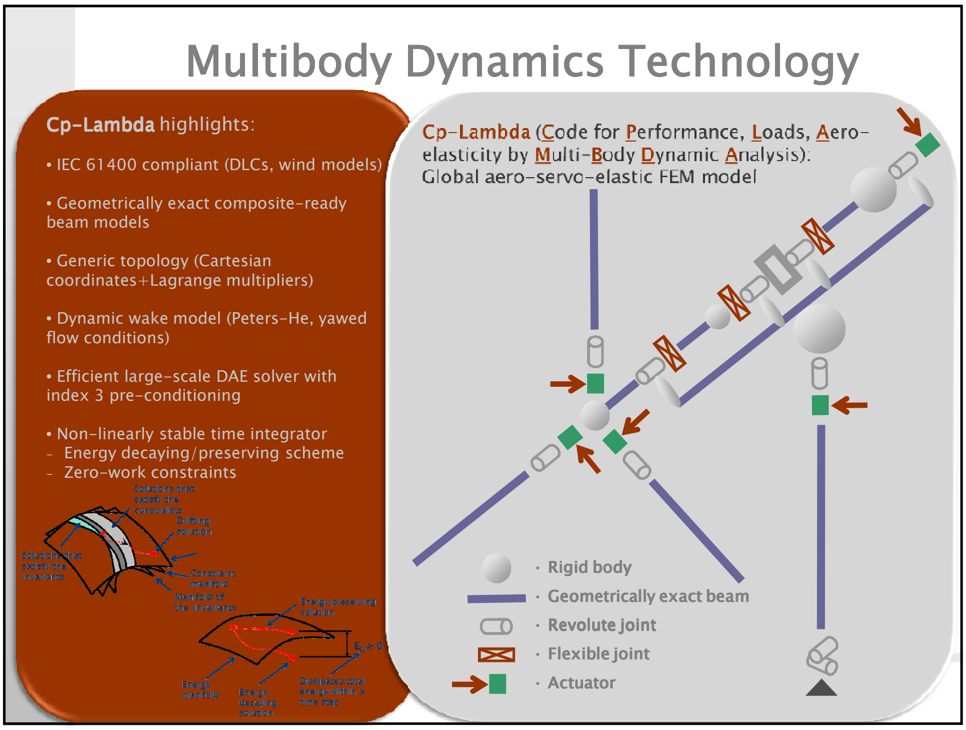
Cp-Max Rotor Design Environment

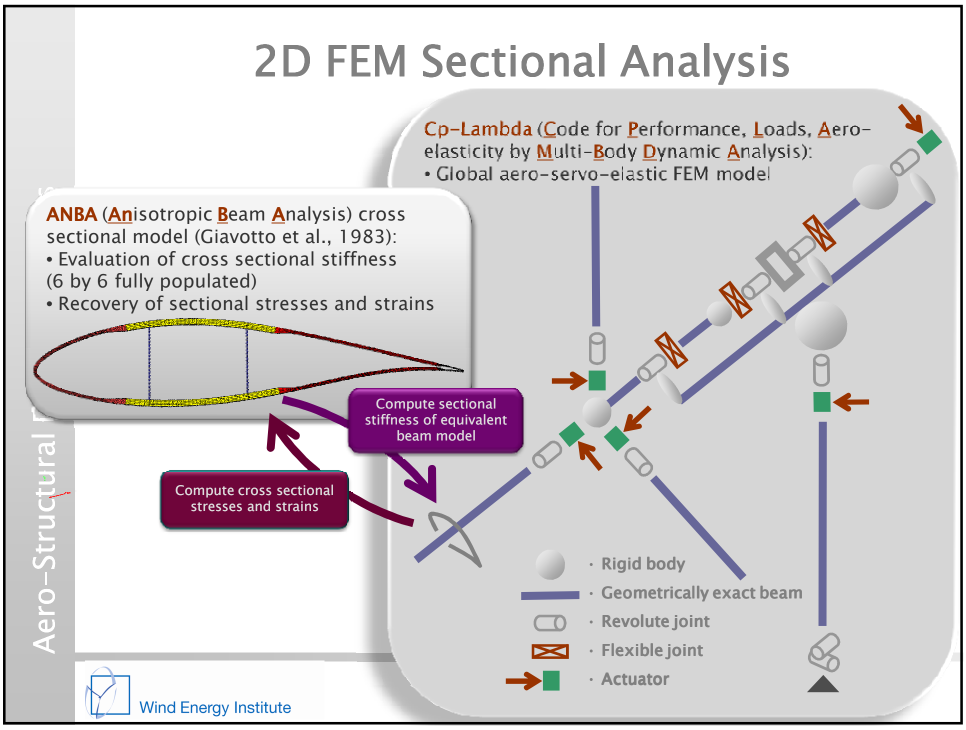


First release: 2007, improved and expanded since then

Applications: academic research and industrial blade design

Wind Energy Institute


Multibody Dynamics Technology
Cp-Lambda highlights:
• IEC 61400 compliant (DLCs, wind models)
• Geometrically exact composite-ready beam models
• Generic topology (Cartesian coordinates+Lagrange multipliers)
• Dynamic wake model (Peters-He, yawed flow conditions)
• Efficient large-scale DAE solver with index 3 pre-conditioning
• Non-linearly stable time integrator
- Energy decaying/preserving scheme
- Zero-work constraints
Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis):
Global aero-servo-elastic FEM model
Rigid body
Geometrically exact beam
Revolute joint
Flexible joint
Actuator


2D FEM Sectional Analysis
Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis):
• Global aero-servo-elastic FEM model
ANBA (Anisotropic Beam Analysis) cross sectional model (Giavotto et al., 1983):
• Evaluation of cross sectional stiffness (6 by 6 fully populated)
• Recovery of sectional stresses and strains
Compute sectional stiffness of equivalent beam model
Compute cross sectional stresses and strains
Rigid body
Geometrically exact beam
Revolute joint
Flexible joint
Actuator
Aero-Structural
Wind Energy Institute

Aero-Structural Design of Rotors

Recent New Feature: Free-Form Design

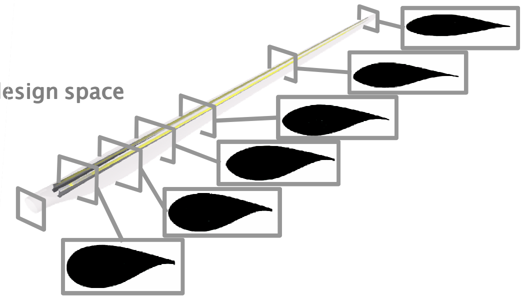
Standard blade design process: select collection of existing suitable airfoils

Exploration is limited to pre-assumed airfoils

Airfoil shape: strong influence on aero performance but also on structural sizing

Issues with current approach:

- **Incomplete exploration** of design space
- **Suboptimal solutions**



Free-form optimization (Bottasso et al. 2014, 2015):

1) Genuine 3D optimization:

- Airfoils are designed **together** with the rest of the blade
- More complete exploration of the design space

2) Relieve the designer from a priori choices

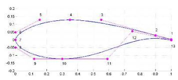
Wind Energy Institute

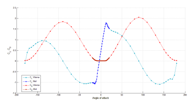
Aero-Structural Design of Rotors

Free-Form 3D Aero-Structural Optimization

Design **airfoils together with blade**:

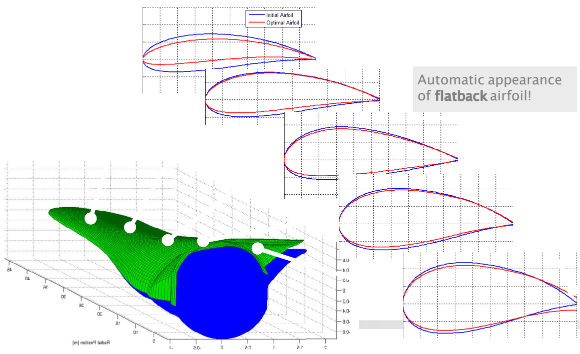
- Bezier airfoil parameterization
- Airfoil aerodynamics by Xfoil + Viterna extrapolation



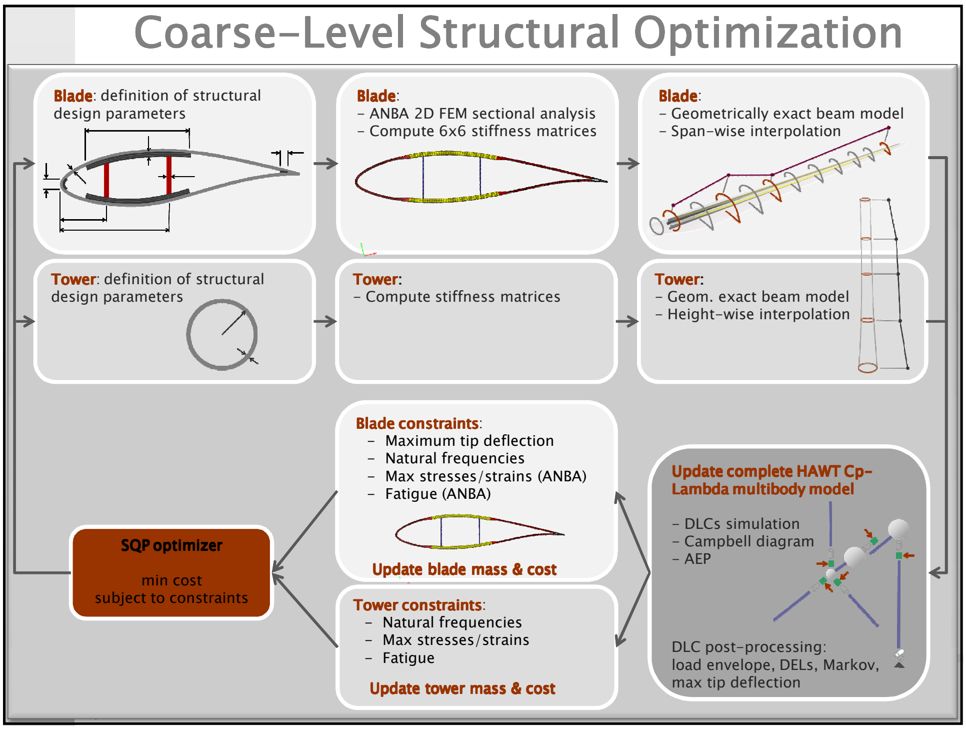


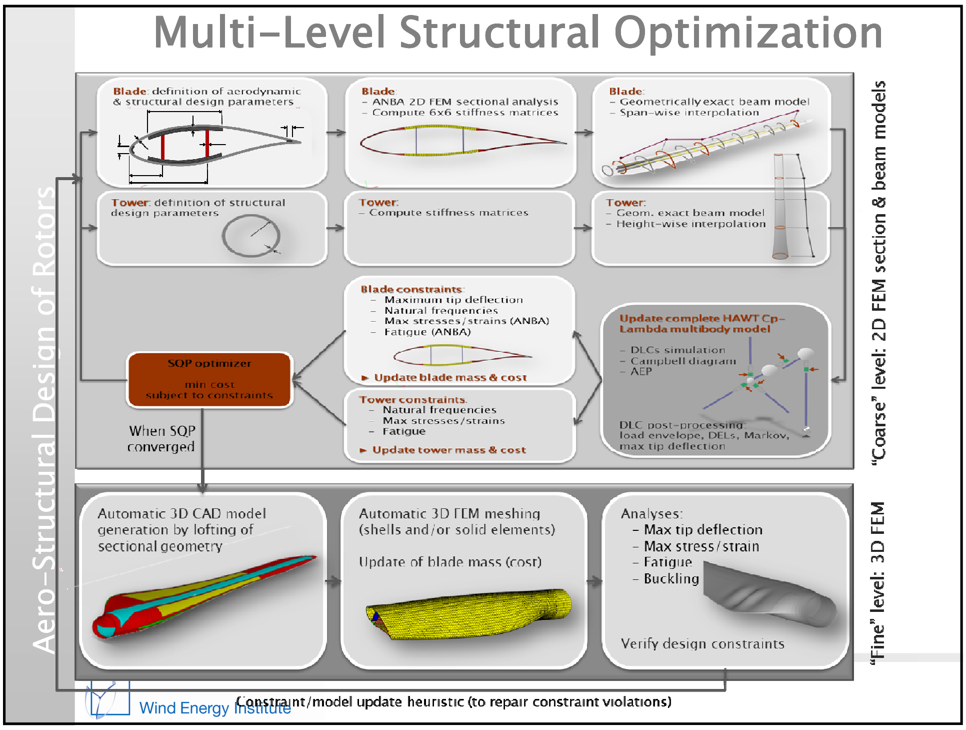
Additional constraints:

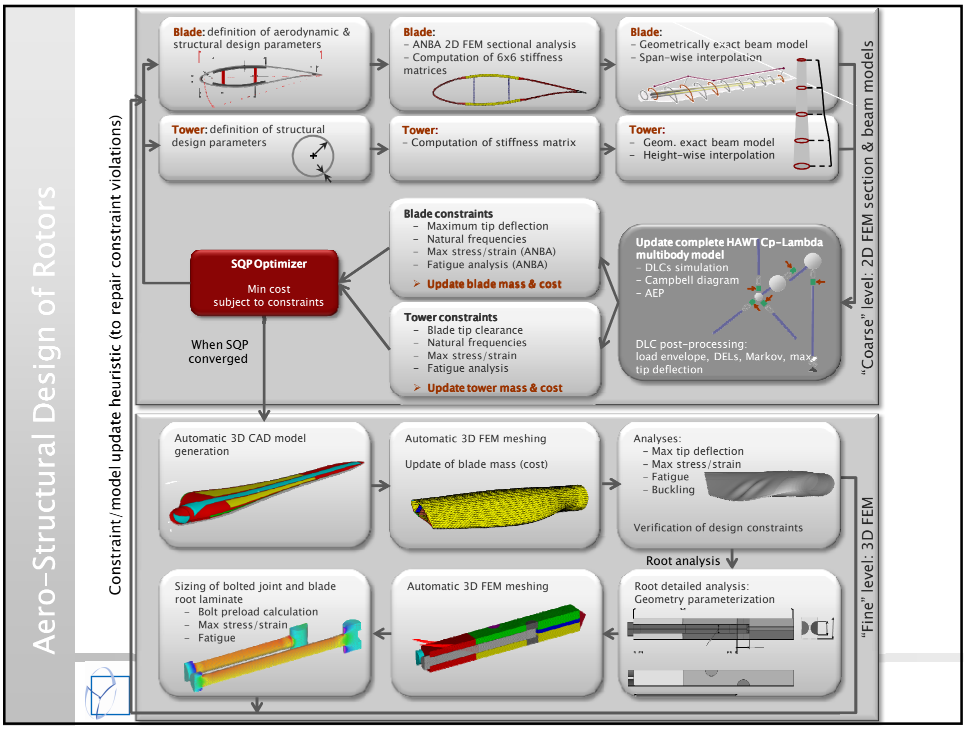
- C_L max (margin to stall), geometry



Wind Energy Institute

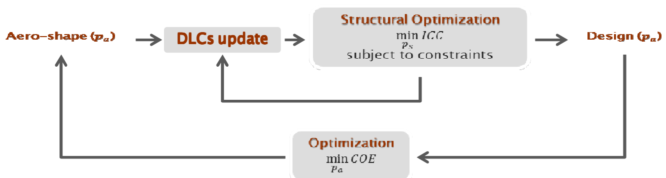

Coarse–Level Structural Optimization
Blade: definition of structural design parameters
Blade:
– ANBA 2D FEM sectional analysis
– Compute 6x6 stiffness matrices
Blade:
– Geometrically exact beam model
– Span–wise interpolation
Tower: definition of structural design parameters
Tower:
– Compute stiffness matrices
Tower:
– Geom. exact beam model
– Height–wise interpolation
Blade constraints:
– Maximum tip deflection
– Natural frequencies
– Max stresses/strains (ANBA)
– Fatigue (ANBA)
Update blade mass & cost
SQP optimizer
min cost
subject to constraints
Tower constraints:
– Natural frequencies
– Max stresses/strains
– Fatigue
Update tower mass & cost
Update complete HAWT Cp–Lambda multibody model
– DLCs simulation
– Campbell diagram
– AEP
DLC post–processing:
load envelope, DELs, Markov,
max tip deflection


Multi–Level Structural Optimization
Aero–Structural Design of Rotors
Blade: definition of aerodynamic & structural design parameters
Blade:
– ANBA 2D FEM sectional analysis
– Compute 6x6 stiffness matrices
Blade:
– Geometrically exact beam model
– Span–wise interpolation
Tower: definition of structural design parameters
Tower:
– Compute stiffness matrices
Tower:
– Geom. exact beam model
– Height–wise interpolation
Blade constraints:
– Maximum tip deflection
– Natural frequencies
– Max stresses/strains (ANBA)
– Fatigue (ANBA)
Update blade mass & cost
SQP optimizer
min cost
subject to constraints
When SQP converged
Tower constraints:
– Natural frequencies
– Max stresses/strains
– Fatigue
Update tower mass & cost
Update complete HAWT Cp–Lambda multibody model
– DLCs simulation
– Campbell diagram
– AEP
DLC post–processing:
load envelope, DELs, Markov,
max tip deflection
"Coarse" level: 2D FEM section & beam models
Automatic 3D CAD model generation by lofting of sectional geometry
Automatic 3D FEM meshing (shells and/or solid elements)
Update of blade mass (cost)
Analyses:
– Max tip deflection
– Max stress/strain
– Fatigue
– Buckling
Verify design constraints
"Fine" level: 3D FEM
Constraint/model update heuristic (to repair constraint violations)
Wind Energy Institute



Aero-Structural Optimization

External Aerodynamic Internal Structure (EAIS) (Bottasso et al 2014b):



External optimizer handles only chord design parameters

Twist design parameters have modest effect on COE ⇨ handled by aero optimization for max(C_P)

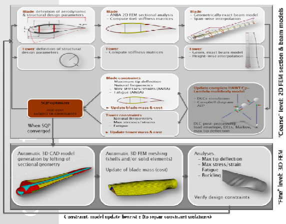
Temporary load freezing (Bottasso et al 2012 and 2014a) to handle:

- Large cost of recomputing DLCs
- Possible non-smoothness of the solution space

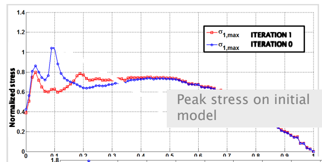
Aero-Structural Design of Rotors

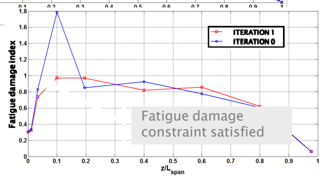
Wind Energy Institute

The Importance of Multi-Level Blade Design

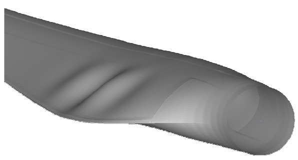


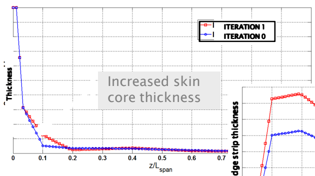
Stress/strain/fatigue:
- Fatigue constraint not satisfied at first iteration on 3D FEM model
- Modify constraint based on 3D FEM analysis
- Converged at 2nd iteration

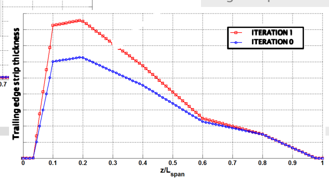




Buckling:
- Buckling constraint not satisfied at first iteration
- Update skin core thickness
- Update trailing edge reinforcement strip
- Converged at 2nd iteration







Aero-Structural Design of Rotors

Wind Energy Institute

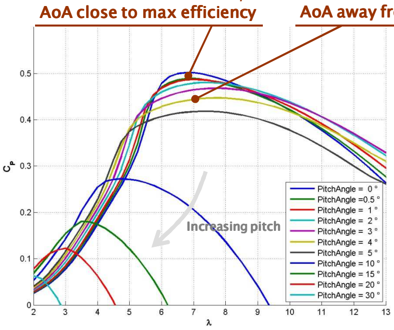
Applications: the Case of LIRs

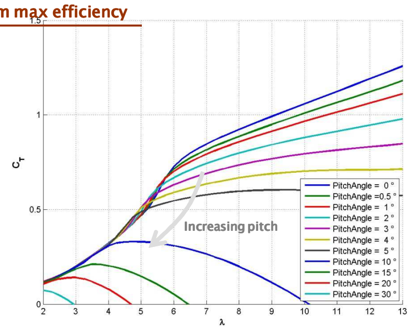
Low Induction Rotors: trade aerodynamic efficiency (lower induction) for reduced loading (increased swept area – power capture)

Simple solution: use different pitch setting

Max C_P
Axial induction close to 1/3
AoA close to max efficiency

Lower C_P
Lower axial induction
AoA away from max efficiency





However, **not an optimal solution**: would need ad-hoc airfoils

Aero-Structural Design of Rotors

Wind Energy Institute

Aero-Structural Design of Rotors

Application to Low Induction Rotors

Objective function: max(AEP) (as in Chaviaropoulos et al. 2014), or min(CoE)
Design variables: radius, chord, twist, airfoils (about 100 dofs)
Constraints: thrust (not to exceed baseline), 1st flap frequency, C_L max (margin to stall), DLCs

◄ INNWIND 10MW

	max(AEP)	min(CoE)	min(CoE) free-form
C_P	0.434 (LIR)	0.473	0.483
Radius	+15.60%	+3.97%	+3.34%
Limiting constr.	Frequency	Stress	Stress
AEP	+ 7.83%	+2.68%	+2.95%
Blade mass	+16.17%	-25.10%	-27.60%
COE	-1.14%	-2.40%	-2.91%

▼ 2MW

	min(AEP)	min(CoE)	min(CoE) free-form
C_P	0.466 (LIR)	0.480	0.480
Radius	+ 6.54%	+2.64%	+2.48%
Limiting constr.	Frequency	Stress	Stress
AEP	+ 4.93%	+2.62%	+2.56%
Blade mass	+6.60%	-12.40%	-15.13%
COE	+0.22%	-1.89%	-2.20%

LIR appears only for max(AEP), not min(CoE)

Wind Energy Institute

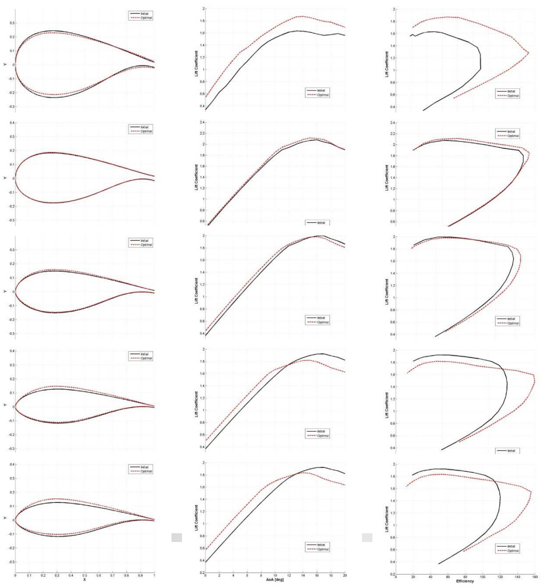
Aero-Structural Design of Rotors

Application to Low Induction Rotors

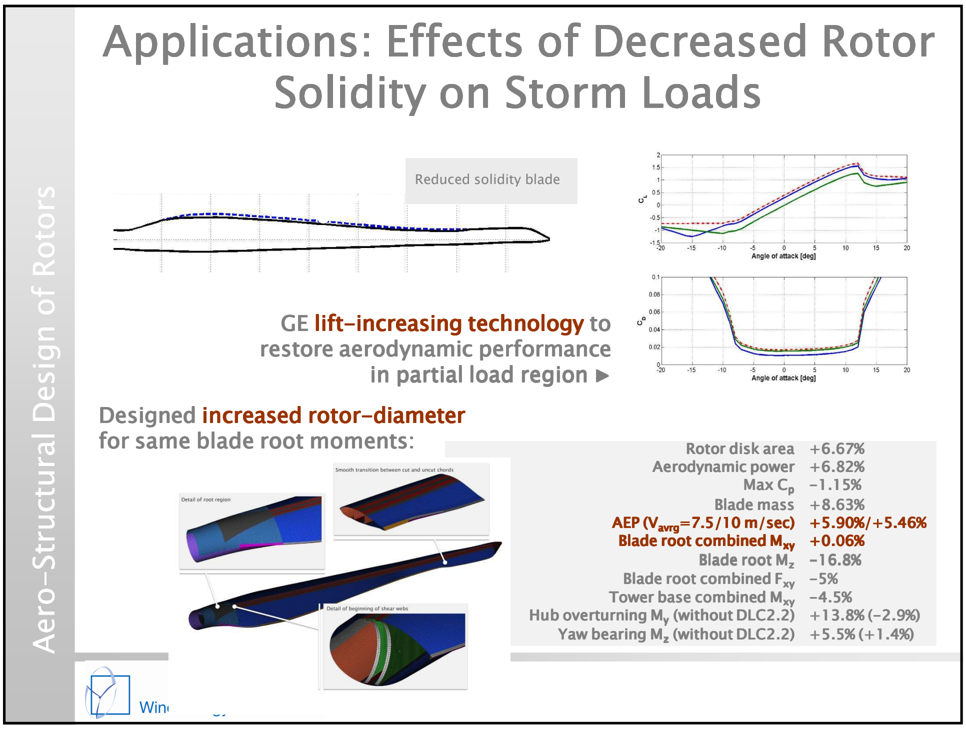
INNWIND 10 MW

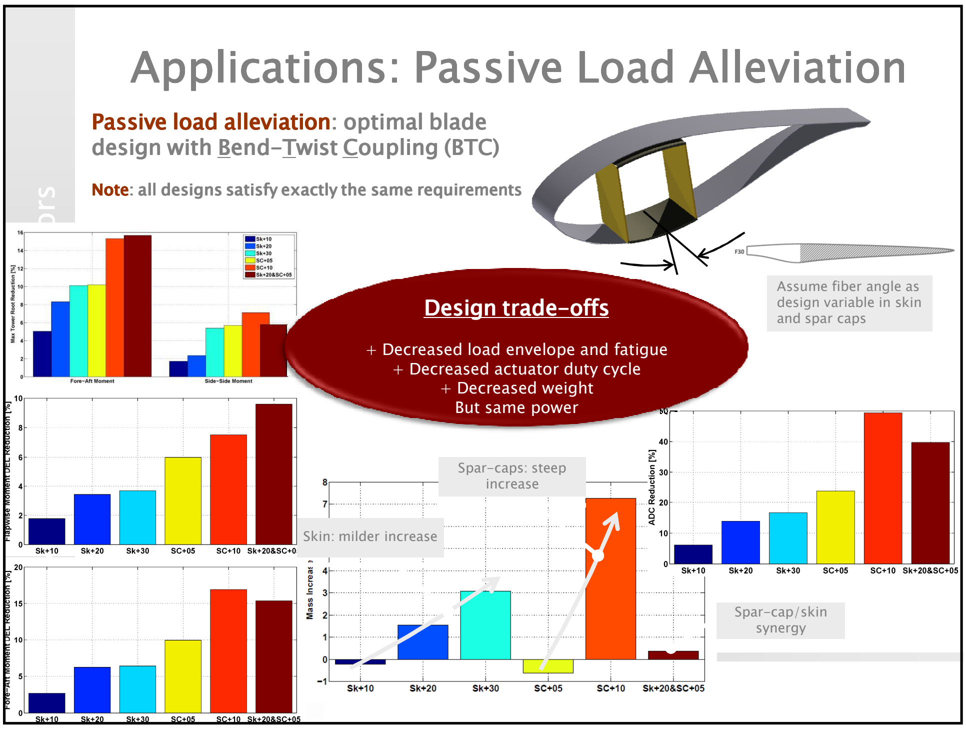
Slight adjustment of airfoils:
- Small increase in camber
- Improved efficiency

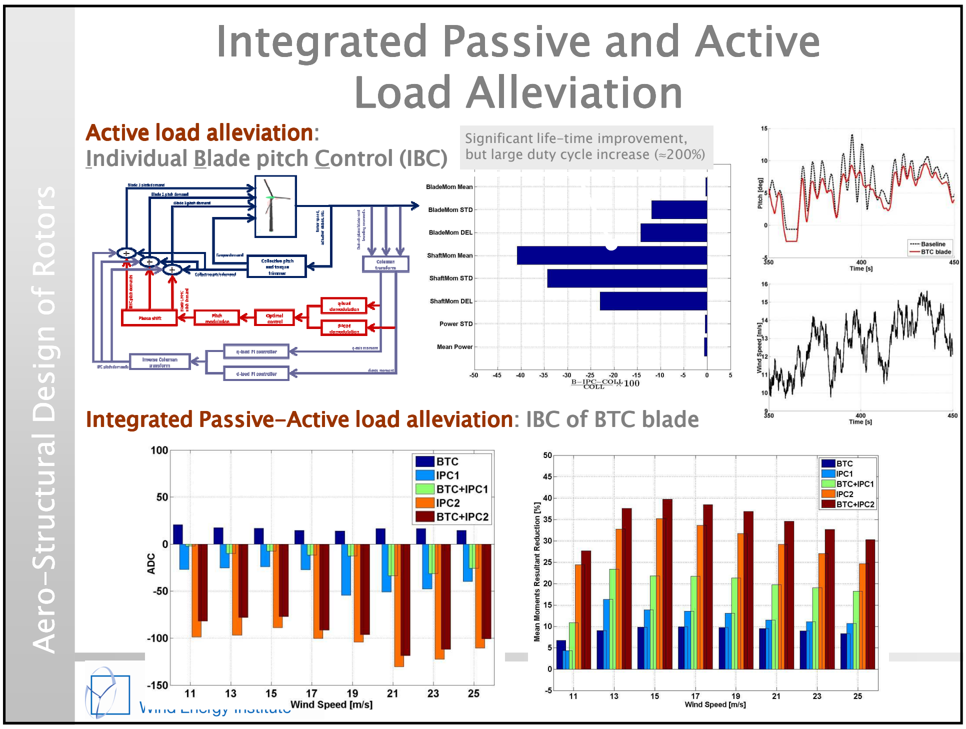
Diameter growth limited by spar stress allowable



Wind Energy Institute


Applications: Effects of Decreased Rotor Solidity on Storm Loads
Aero-Structural Design of Rotors
Reduced solidity blade
GE lift-increasing technology to restore aerodynamic performance in partial load region ▶
Designed increased rotor-diameter for same blade root moments:
Rotor disk area +6.67%
Aerodynamic power +6.82%
Max Cp −1.15%
Blade mass +8.63%
AEP (Vavrg=7.5/10 m/sec) +5.90%/+5.46%
Blade root combined Mxy +0.06%
Blade root Mz −16.8%
Blade root combined Fxy −5%
Tower base combined Mxy −4.5%
Hub overturning My (without DLC2.2) +13.8% (−2.9%)
Yaw bearing Mz (without DLC2.2) +5.5% (+1.4%)
Angle of attack [deg]


Applications: Passive Load Alleviation
Passive load alleviation: optimal blade design with Bend-Twist Coupling (BTC)
Note: all designs satisfy exactly the same requirements
Design trade-offs
+ Decreased load envelope and fatigue
+ Decreased actuator duty cycle
+ Decreased weight
But same power
Assume fiber angle as design variable in skin and spar caps
Spar-caps: steep increase
Skin: milder increase
Spar-cap/skin synergy
Fore-Aft Moment
Side-Side Moment
ADC Reduction [%]
Sk+10
Sk+20
Sk+30
SC+05
SC+10
Sk+20&SC+05


Aero–Structural Design of Rotors
Integrated Passive and Active Load Alleviation
Active load alleviation:
Individual Blade pitch Control (IBC)
Significant life–time improvement, but large duty cycle increase (≈200%)
BladeMom Mean
BladeMom STD
BladeMom DEL
ShaftMom Mean
ShaftMom STD
ShaftMom DEL
Power STD
Mean Power
Time [s]
Baseline
BTC blade
Integrated Passive–Active load alleviation: IBC of BTC blade
BTC
IPC1
BTC+IPC1
IPC2
BTC+IPC2
ADC
Wind Speed [m/s]
Mean Moments Resultant Reduction [%]
Wind Energy Institute


Aero–Structural Design of Rotors
Some Blades Designed with Cp–Max
16 m ▶
◀ 24 m
45 m ▶
Wind Energy Institute

Aero-Structural Design of Rotors

Conclusions

- **Strong couplings** between aero and structural design variables
- **Multi-level approach** to marry high fidelity and computational effort
- **Free-form design** further enlarges the solution space

Open issues/outlook:
- CoE: solutions are **sensitive to cost model**, need detailed reliable models that truly account for all significant effects (currently implementing sophisticated Sandia CoE model)
- Free-from: need **higher fidelity tools** (CFD) for airfoil design (multi-level Xfoil-CFD?)
- Freeing of **additional parameters**: prebend, precone, sweep, BTC, …

Wind Energy Institute

Aero-Structural Design of Rotors

Detailed Information


C.L. Bottasso, P. Bortolotti, A. Croce, F. Gualdoni, `Integrated Aero-Structural Optimization of Wind Turbine Rotors', Multibody System Dynamics, to appear, 2015


C.L. Bottasso, A. Croce, L. Sartori, F. Grasso, `Free-form Design of Rotor Blades', Journal of Physics: Conference Series 524, 012041, 2014


C.L. Bottasso, F. Campagnolo, A. Croce, S. Dilli, F. Gualdoni, M.B. Nielsen, `Structural Optimization of Wind Turbine Rotor Blades by Multi-Level Sectional/Multibody/3DFEM Analysis', Multibody System Dynamics, 32:87-116, 2014


C.L. Bottasso, F. Campagnolo, C. Tibaldi, `Optimization-Based Study of Bend-Twist Coupled Rotor Blades for Passive and Integrated Passive/Active Load Alleviation', Wind Energy, 16:1149-1166, 2013


C.L. Bottasso, A. Croce, F. Campagnolo, `Multi-Disciplinary Constrained Optimization of Wind Turbines', Multibody System Dynamics, 27:21-53, 2012


O.A. Bauchau, A. Epple, C.L. Bottasso, `Scaling of Constraints and Augmented Lagrangian Formulations in Multibody Dynamics Simulations', ASME Journal of Computational and Nonlinear Dynamics, 4:021007, 2009

We also offer:
- Consulting services (blade design, loads, aeroservoelasticity, controls, …)
- Training on Cp-Max and Cp-Lambda

Wind Energy Institute

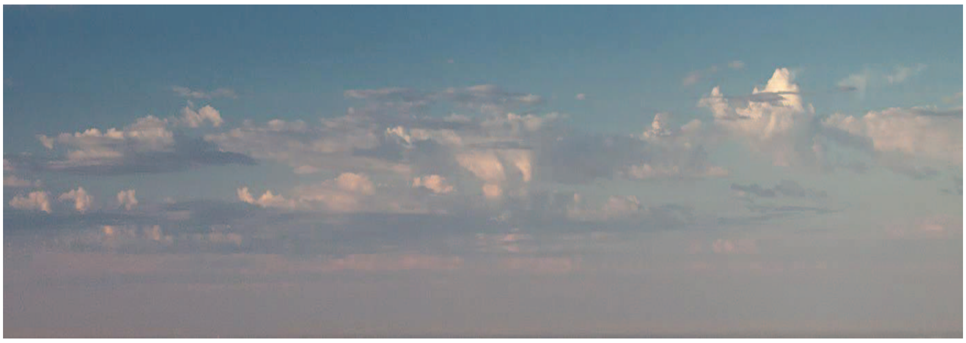
DNV·GL

DNV GL – RENEWABLES ADVISORY

UNCERTAINTY QUANTIFICATION TECHNIQUES IN WIND TURBINE DESIGN

GRAEME MCCANN – DEPUTY HEAD OF TURBINE ENGINEERING

SAFER, SMARTER, GREENER



"The world is noisy and messy.
You need to deal with the uncertainty"

- Daphne Koller

Content Uncertainty Quantification in Wind Turbine Design

the **sources** of uncertainty

the **quantification** of uncertainty

the **future** of uncertainty

... in wind turbine design

3 DNV GL © 2014 DNV·GL

The Sources of Uncertainty

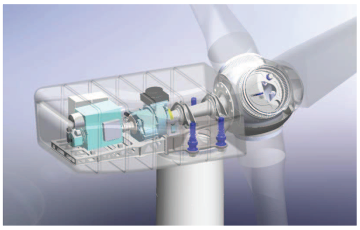
Two fundamental types of uncertainty in a design process:

- **Aleatoric uncertainty** - physical (objective) variation
- **Epistemic uncertainty** - subjective knowledge

In principle:

Aleatoric is fixed (unless you alter the physical system)
Eg. turbulence, material yield/fatigue strength

Epistemic is reducible (if better knowledge or more information is available)
Eg. site conditions parameters (AMWS, Iref), aerodynamic models



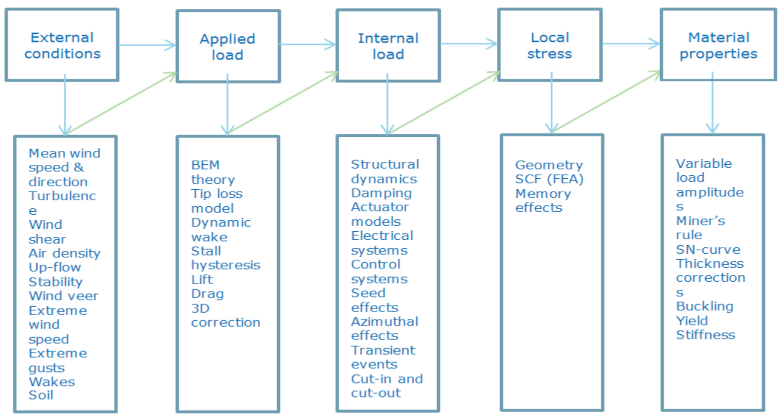
4 DNV GL © 2014 DNV·GL

The Sources of Uncertainty

Uncertainty can reside in both the inputs to a design model, and the model itself -

The Sources of Uncertainty

Uncertainty can reside in both the inputs to a design model, and the model itself -



The **Quantification** of Uncertainty

Question: How sensitive is our design to uncertainty? Does it matter?

- **STEP A:** Define numerical model (eg. aero-elastic model, FEA, etc)
- **STEP B:** Define uncertainties in i) inputs and ii) sub-models
- **STEP C:** Propagate uncertainties through the model

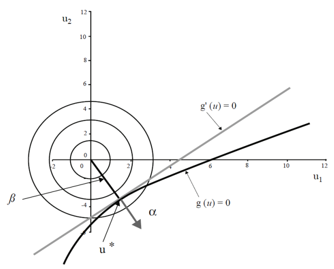
7 DNV GL © 2014 DNV·GL

The **Quantification** of Uncertainty

Step C: Propagation Techniques

A statisticians play-ground!

Numerous methods available[1]:



- Linear perturbation
- Monte Carlo simulation
- First/Second Order Reliability Methods
- Advanced spectral methods (chaos expansions)
- Gaussian emulators
- etc, etc…

[1] e.g., Sudret. B., "Uncertainty propagation and sensitivity analysis in mechanical models – contributions to structural reliability and stochastic spectral methods", doctoral thesis, Université Blaise Pascal, 2008.

8 DNV GL © 2014 DNV·GL

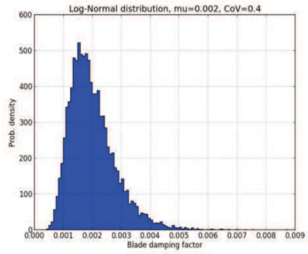
The Quantification of Uncertainty

Some examples…

1) UQ using linear perturbation: $M(x) = M(x_0) + \sum_{i=1}^{M} \frac{\partial M}{\partial x_i}\Big|_{x=x_0} (x_i - x_{0,i})$

Full fatigue and extreme IEC load envelopes run for generic 7MW turbine with following model inputs perturbed:

Parameter	Variation	Probability Distribution
Tower Young's Modulus	+/- 5%	Normal (μ=1.0, σ=0.05)
Tower density	+/- 5%	Normal (μ=1.0, σ=0.06)
Tower damping factor	0.001, [0.005], 0.01	Lognormal (μ=0.005, σ=0.4)
Blade Young's Modulus	+/- 5%	Normal (μ=1.0, σ=0.05)
Blade mass	+/- 5%	Normal (μ=1.0, σ=0.06)
Mass imbalance	+/- 1%	Normal (μ=1.0, σ=0.05)
Blade damping factor	0.001, [0.005], 0.01	Lognormal (μ=0.002, σ=0.4)
Blade Xp stiffness	+/- 5%	Normal (μ=1.0, σ=0.05)
Blade Yp stiffness	+/- 5%	Normal (μ=1.0, σ=0.05)
Nacelle mass	+/- 10%	Normal (μ=1.0, σ=0.05)

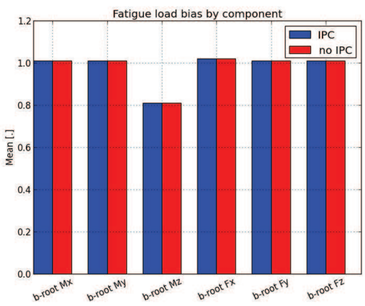


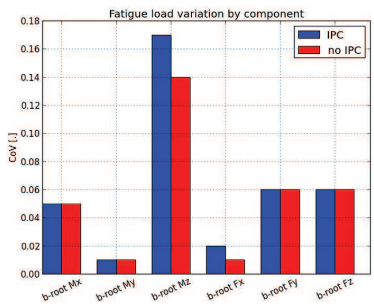
The Quantification of Uncertainty

Some examples…

1) UQ using linear perturbation: $M(x) = M(x_0) + \sum_{i=1}^{M} \frac{\partial M}{\partial x_i}\Big|_{x=x_0} (x_i - x_{0,i})$

Stochastic response of key outputs quantified (expected and COV):





Load response COV generally < 6%, blade root Mz > 15%

The Quantification of Uncertainty

Some examples…

2) UQ using polynomial chaos expansion (PCE):

PCE construction used to approximate the output of an expensive simulation model using a meta-model composed of polynomial families.

$$Y = \mathcal{M}(X) = \sum_{\alpha \in \mathbb{N}^M} y_\alpha \Psi_\alpha(X)$$

Distribution	Polynomial	$W(\xi)$	Interval
Gaussian	Hermite $H_n(x)$	$\exp(-\xi^2)$	$(-\infty,\infty)$
gamma	Laguerre $L_n(x)$	$\exp(-\xi)$	$[0,\infty]$
beta	Jacobi $G_n(p,q,x)$	$(1-\xi)^{p-q}\xi^{q-1}$	$[a,b]$
uniform	Legendre $P_n(x)$	1	$[a,b]$

Note that $[a, b]$ denotes a specific interval.

The Quantification of Uncertainty

Some examples…

2) UQ using polynomial chaos expansion (PCE):

e.g., analysis of IEC **DLC4.2** (gust + grid loss) with stochastic inputs:

						Truncated?	
Parameter	Units	Dist type	E<>	COV	U range	lower	upper
gust amplitude	m/s	Log-N	9.12	0.1		80% E	120% E
gust period	s	Log-N	10.5	0.1		80% E	120% E
wind direction	deg	Uniform	n/a	n/a	[-8:+8]		
air density	kg/m³	Log-N	1.225	0.1			
damping factor	[.]	Log-N	0.005	0.4		20% E	120% E
nacelle mass	kg	Log-N	350000	0.1		90% E	110% E
shut-down time	s	Uniform	n/a	n/a	[15:30]		
initial azimuth	deg	Uniform	n/a	n/a	[0:90]		
shear exponent	[.]	Normal	0.1	0.25			

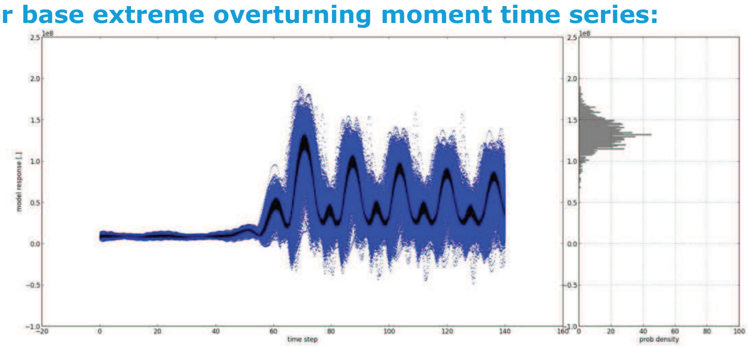
The Quantification of Uncertainty

Some examples…

2) UQ using polynomial chaos expansion (PCE):

e.g., analysis of IEC **DLC4.2** (gust + grid loss) with stochastic inputs:

Tower base extreme overturning moment time series:



13 DNV GL © 2014 DNV·GL

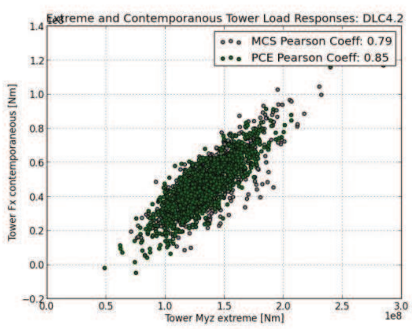
The Quantification of Uncertainty

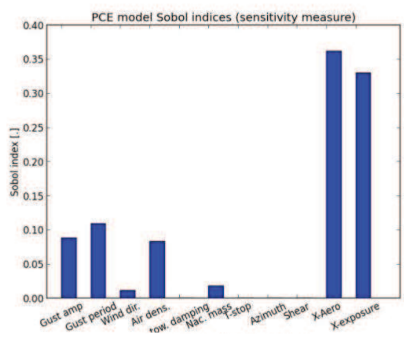
Some examples…

2) UQ using polynomial chaos expansion (PCE):

e.g., analysis of IEC **DLC4.2** (gust + grid loss) with stochastic inputs:

Tower base extreme overturning moment analysis:





14 DNV GL © 2014 DNV·GL

The Quantification of Uncertainty

Some examples…

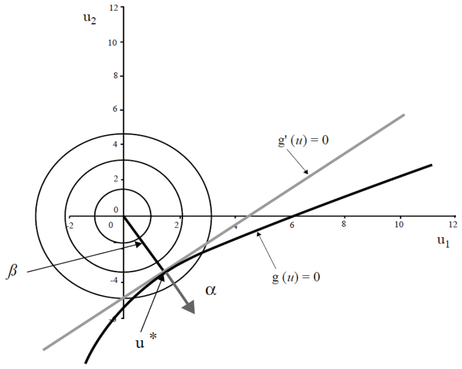
3) UQ using Structural Reliability methods (e.g., FORM/SORM):

First/Second Order Reliability Methods used to assess the tail behaviour of limit state G-functions.

G(X,Y) G < 0: failure

X: Load-related parameter
Y: strength-related parameter

Probability of failure = P[G<0]



The Quantification of Uncertainty

Some examples…

3) UQ using Structural Reliability methods (e.g., FORM/SORM):

e.g., fatigue analysis of large offshore WTG cast iron mainframe:

Stochastic variables:

Variable	Distribution	Mean	COV	S.D.
m_{rotor}	Lognormal	1	0.10	0.1
X_{dyn}	Lognormal	1	0.05	0.05
X_{exp}	Lognormal	1	0.05	0.05
X_{aero}	Gumbel	1	0.10	0.10
$X_{lowcycle}$	Normal	1	0.03	0.03
X_{RFCC}	Normal	1	0.05	0.05

Variable	Distribution	Mean	COV	S.D.
$X_{Miner's}$	Lognormal	1	0.30	0.30
$X_{fatstrength}$	Lognormal	1	0.167	0.167
$X_{infcoeff}$	Normal	1	0.02	0.02

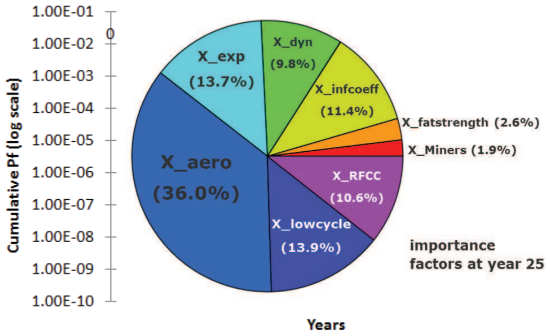
The Quantification of Uncertainty

Some examples…

3) UQ using Structural Reliability methods (e.g., FORM/SORM):

e.g., fatigue analysis of large offshore WTG cast iron mainframe:

Results:

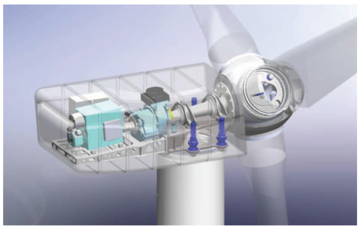


17 DNV GL © 2014 DNV·GL

The Future of Uncertainty

How do we (typically) deal with uncertainty in WTG design today?

i) Improve accuracy of design models (e.g., Bladed, FAST) to reduce bias
ii) Characteristic levels for key design parameters to mitigate under-conservatism
iii) Safety factors for both load and resistance side of design equation
iv) Verify design assumptions with field measurements



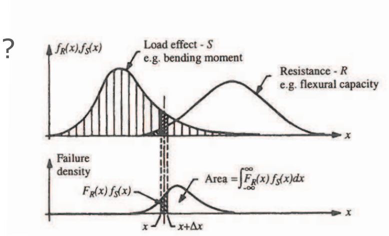
18 DNV GL © 2014 DNV·GL

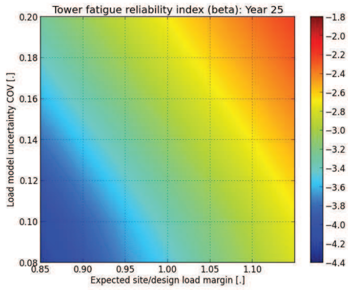
The Future of Uncertainty

A more probabilistic approach to design…?

Pros:
- a more rational basis for design and siting
- a facility to reward 'better' methods, models & monitoring
- a natural vehicle for life-cycle assessment (SIM, life extension etc)

Cons:
- difficulty of implementation
- challenge to standardize
- What about the uncertainties we don't know about?





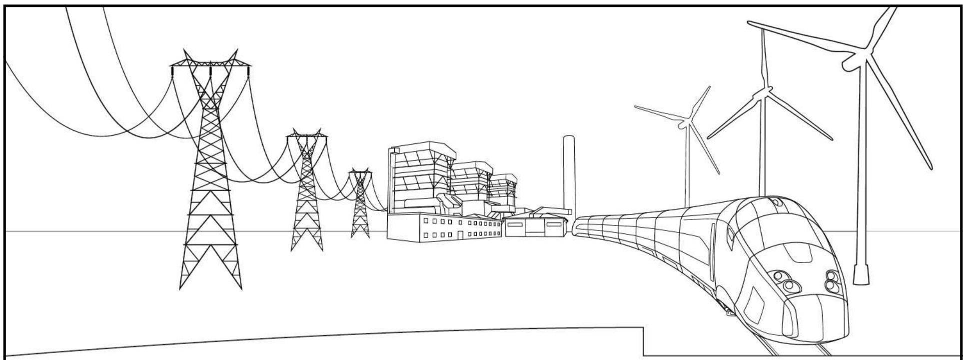
19 DNV GL © 2014 DNV·GL

DNV·GL

GARRAD HASSAN TURBINE ENGINEERING

Thanks for your attention

SAFER, SMARTER, GREENER



Integrated System Design and Optimization

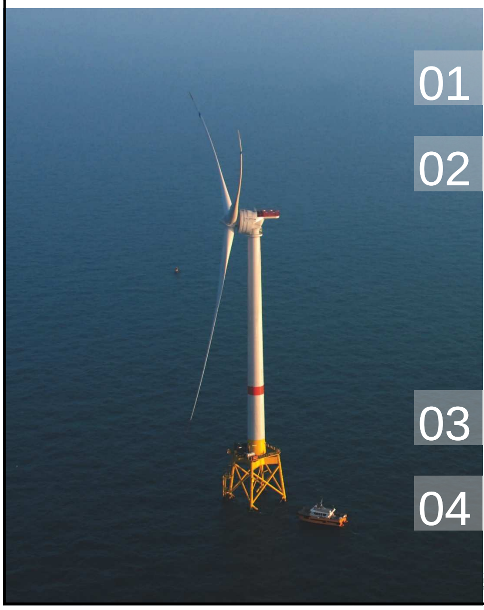
Jon Campbell

Boulder, CO

01/12/2015

ALSTOM
Shaping the future

Agenda



ALSTOM

Introduction

- The need for integrated system-level design and optimization is understood and accepted.
- Driven by market competitiveness – must minimize costs and maximize performance.
- Wind farms fall into the category of "mass customization".
- Use of integrated system design has multiple benefits:
  1. Identification of system design drivers → reduction of time at early stages of the project; R&D cost savings.
  2. Reduction of cost of energy and project risk → more room to optimize and identify critical risks due to multiple results.
  3. Increases competitive advantage → enables OEM's to deliver optimized solutions to customers.

ALSTOM

Alstom Current Methods

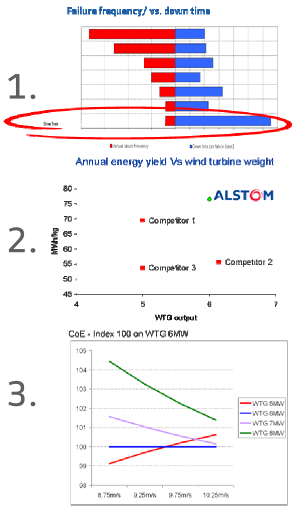
Component Level	Turbine Level	Wind Farm Level
• SAMCEF	• SAMCEF	• Openwind
• ANSYS	• modeFrontier	• Excel
• Ncode	• BLADED	
• modeFrontier	• Matlab	
• Hyperworks	• FAST	
• Matlab	• Excel	
• Excel		
• Several others		

Applications for various system levels and phase in the design process

ALSTOM

Conceptual Design: Haliade™ 150-6MW

Major design choices targeting to reduce wind offshore CoE



Drive Train → DIRECT DRIVE

Rotor diameter → 150M

Power rating → 6MW

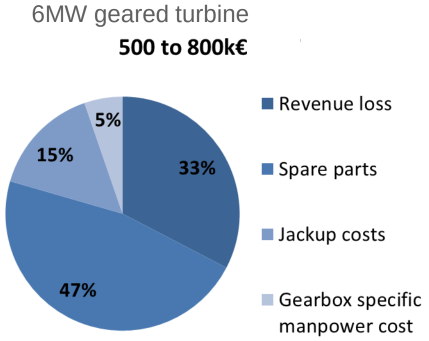
Direct Drive decision driven by reliability and cost reduction

ALSTOM

Drivetrain

Cost-benefit analysis during conceptual design phase

Net Present Value of costs: 500-800k€ estimated lifetime extra costs for a 6MW geared turbine



NPV of Gearbox specific costs (Alstom estimate)

- Considering one gearbox change over 20 years
- 2 campaigns of 50% of gearbox replacement around WF midlife
- Assuming perfect planning of gearbox repairs (predictive condition monitoring avoiding unscheduled downtime)
- Extra preventive maintenance for lubrication and oil changes

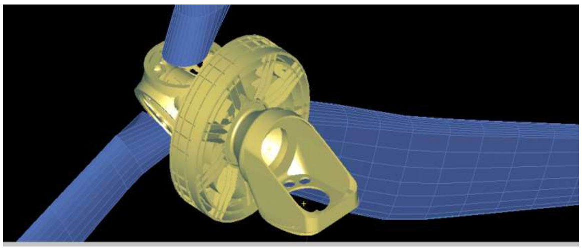
Conceptual design studies supported by "Pro Forma" analysis

ALSTOM

Drivetrain – Component/Turbine Design Level

Alstom uses SWT - Samcef Wind Turbines
- Global analyses of complete machines or local analyses of single components available in the same environment
- Also use Samcef Field for PRE and POST-Processing.

Modules that are called from SWT or Samcef Field:
- Samcef Dynam: Solver for modal analysis, superelement creation.
- Samcef Mecano: Solver for time-domain analysis.
- Samcef Nonlinear Motion Analysis: to simulate flexible dynamics with high accuracy.



Integrated aero/hydrodynamic loads and FEA.

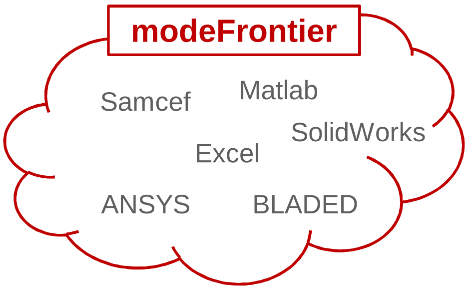
ALSTOM

Tower & Substructure - Integrated System Design

- Integrated structural dynamics:
  - Accurate structural dynamics
  - Accurate load response
  - Accurate numerical integration
  - Accurate extreme and fatigue structural design
- What we have in-house:
  - Know-how on complex sub-systems (SSI, WSI, Structural Analysis, and SAMCEF knowledge)
  - SAMCEF Multibody code → combines the aero-servo-hydro-elastic + FEM capabilities into 1 code.
  - modeFRONTIER → Software manager & optimization platform. Able to couple input-output codes in a single workflow.

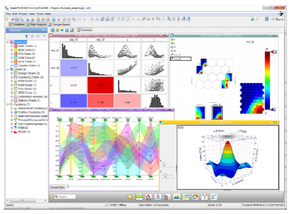
ALSTOM

Optimization with modeFrontier



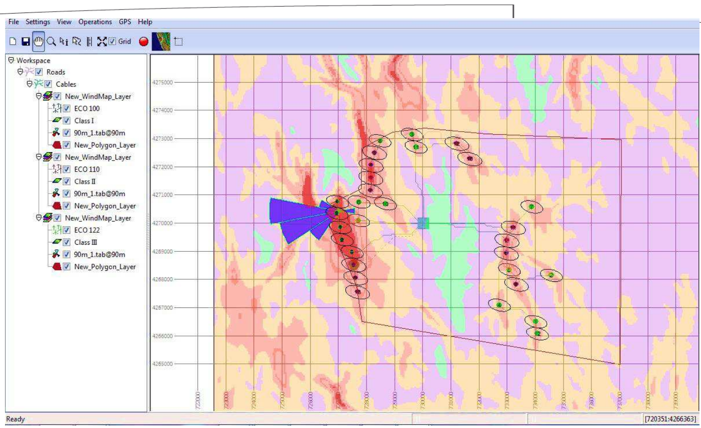
Key Features:
- Allows for integration of various simulation tools
- Design of Experiments
- ~30 types of optimization algorithms
- User interface – GUI driven
- Analysis "wizard"

To optimize 1 tower:
- 17K – 20K cases
- ~ 15.5 hours of runtime
- Runs on a dual core mobile workstation



ALSTOM

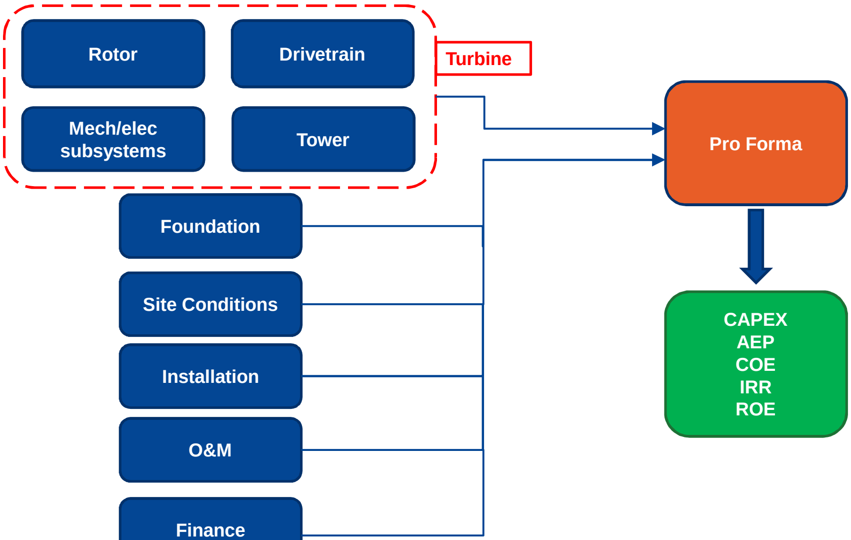
Farm-Level Analysis and Optimization



- Alstom uses Openwind for farm layout optimization – turbine location and spacing; model different turbine configurations in a single farm.
- COE: maximize production, minimize installation and BOP costs.
- Used in conjunction with our Pro Forma analysis tool.

ALSTOM

Economic Value Analysis – “Pro Forma”



ALSTOM

Future – Platform Evolution

Investigating expanded Integrated Systems Design capabilities

- Revised Pro Forma with integrated transfer functions
  - Expanded conceptual design tool
  - Improved fidelity in COE optimization
- LMS Boss Quattro for LMS SAMCEF optimization
  - Parametric studies
  - Monte Carlo method
  - Optimization and updating
  - Design of experiments methods
- Integrating economic value analysis and additional subsystems into modeFrontier®.

ALSTOM

Management of ISD Tools

Considerations for ISD platform selection, design and use

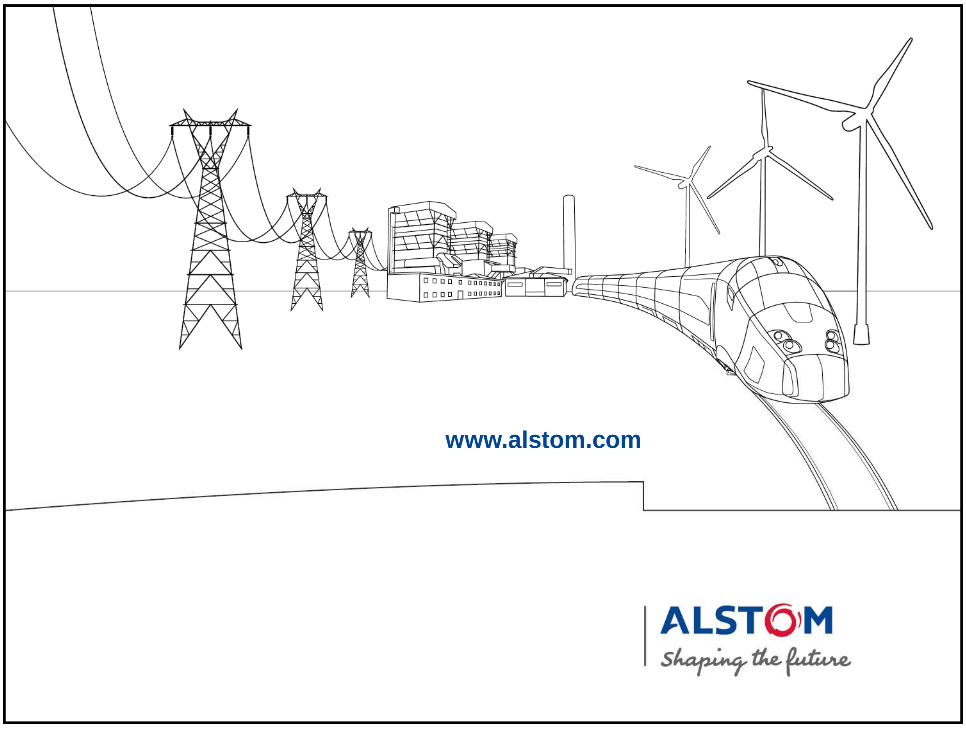
- Organizational goals – i.e. conceptual design, marketing strategy, specification, detailed design etc.
- Complexity
- Features/capabilities
- Cost of implementing
- Cost of maintaining
- Size of team/resources
- Skill level of team members (ease of use, user interface, programming)
- Computing system requirements
- Communication between user groups
- Internal/external marketing, demonstrate value.

ALSTOM

Conclusion

- Integrated system-level design is needed to compete in the marketplace and deliver optimized wind farm solutions.
- Alstom methodology currently uses a variety of tools at the component, turbine and wind farm levels.
- Tools and methods continue to evolve into a more integrated platform.
- Select the platform appropriate for organizational goals.
- “Sell it” internally and externally, demonstrate the value of new system design capabilities – serves as a differentiator and increases an OEM’s competitive advantage.

ALSTOM


www.alstom.com
ALSTOM
Shaping the future

SIEMENS

- Recap: the rotor design problem
- Recap: SWP rotor optimization process
- Application of MDO: Analysis of a design space by comparison of different technology (Pareto) fronts for changing system constraints
- Example: NREL 5MW rotor design problem
- Challenges of industrial MDO application
- Questions

International Energy Agency – Topical Expert Meeting #80

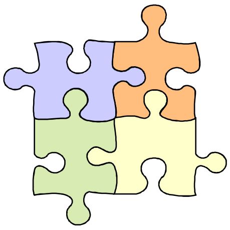
2 of 18

SIEMENS

How to minimize total COE? Accurate cost modelling

- Many disciplines, complex, coupled system, many aspects are unpredictable

- **engineering**
- **admin**
- **BOM**
- **manufacturing**



- **transport & construction**
- **service**
- **balance of station**
- **financing**

- Cost model that combines various sub-disciplines may not be desirable –
  many 'costs' cannot be estimated up-front (i.e. organizational cost, market 'fit' etc.) or insufficient data to construct meaningful model

- **Simplify** – solve the problem using a multi-objective approach –
  give decision-makers the data necessary to make trade-off choices directly including 'non-quantifiable' costs

SIEMENS

Multi-objective rotor design problem w/ non-linear constraints:

- Performance
  - AEP
  - Capacity factor (some markets)
  - Robustness / soiling insensitivity
- Acoustics
  - Site and region specific
- Loads & Controls
  - Normal operation, emergency stop, fault conditions,
  - Blade loads: fatigue and extreme
  - Component loads: fatigue and extreme
- Blade Structure
  - Blade mass / cost
  - Fatigue strain / extreme loads, tip deflection constraint
  - Panel buckling, edge buckling
  - Manufacturing constraints
- Drive Train
  - Generator torque limit
  - Power & frequency converter limits

Simplify to ~3 objective problem, with the rest being constraints- for example, find Pareto front in terms of:

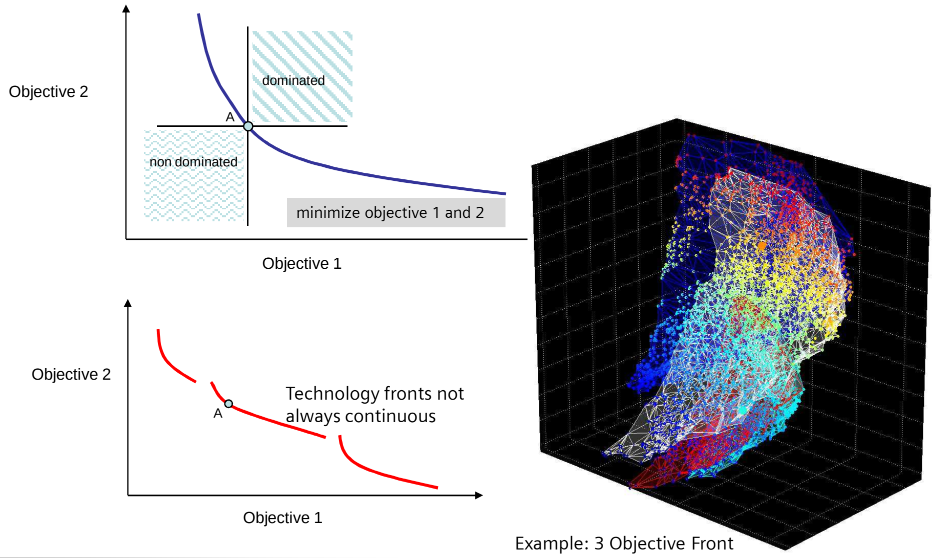
1. **AEP**
2. **Loads Metric**
3. **Blade Mass**

Many ways to setup the problem (nesting etc)

More objectives possible, but for every additional objective, computational cost **x10**

SIEMENS

A Pareto front gives the possible trade-offs between objectives



International Energy Agency – Topical Expert Meeting #80

 5 of 18

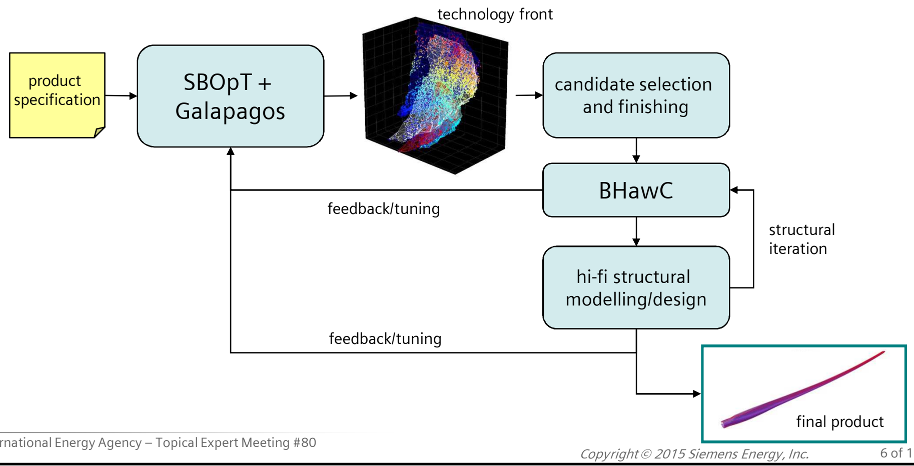
SIEMENS

Siemens Blade Optimization Tool (SBOpT) + Galapagos GA Optimizer

- Evaluates 500,000+ blades in an evening within Galapagos and HPC cluster, produces N-dimensional Pareto front between various design objectives

BHawC

- FE code for aero-elastic simulation of entire turbine system



International Energy Agency – Topical Expert Meeting #80

 6 of 18

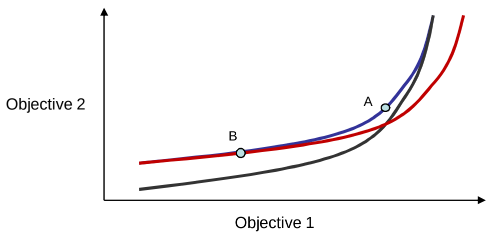
SIEMENS

- Parameter studies about a fixed planform can only go so far…
- Instead, it's desirable to assess the multi-objective impact of various system constraints / parameters in a way that takes advantage of full design freedom that is available
- Compare Pareto fronts generated for slightly different problems (i.e. constraints, technology assumptions etc.)

- **Noise**
- **Soiling sensitivity**
- **Allowable tip deflection**
- **Blade structural technology / material choice**
- **Component load constraints**
- **Airfoil selection**
- **Rated power / rated torque**
- **Wind resource**
- **Design for manufacture**
- **Transportation**
- **Cost**

and many others…

SIEMENS

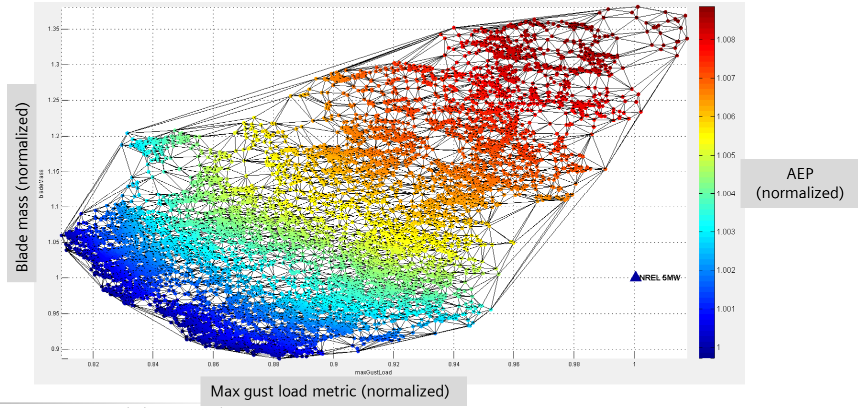


Advantages of front comparison over conventional parameter/sensitivity studies:

- DOFs are fully exploited (optimized) to take advantage or compensate for system parameter/constraint changes such that solution set is pareto optimal and represents the **fully-coupled impact** of desired change
- Sensitive to design space location – *design sensitivity in context*
- Optimizer can discover non-intuitive solutions that may be unique to problem description - Useful for challenging conventional wisdom (i.e. *are high modulus materials really necessary?)*

SIEMENS

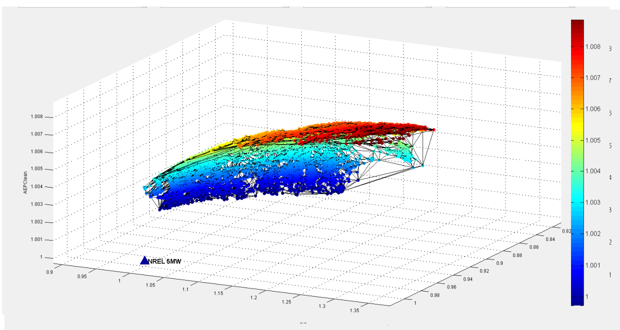
- NREL 5MW rotor as described in *NREL/TP-500-38060*
  http://www.nrel.gov/docs/fy09osti/38060.pdf J. Jonkman et. al.
- Spanwise distributions of relative thickness, twist and chord treated as free DOFs
- All other turbine parameters left as-is.
- 1A wind resource
- NREL 5MW evaluated using SWP *Integral Blade™* structural technology



International Energy Agency – Topical Expert Meeting #80

9 of 18

SIEMENS



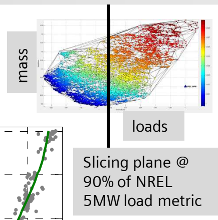
Stay tuned for full movie at NREL SE Workshop later this week!

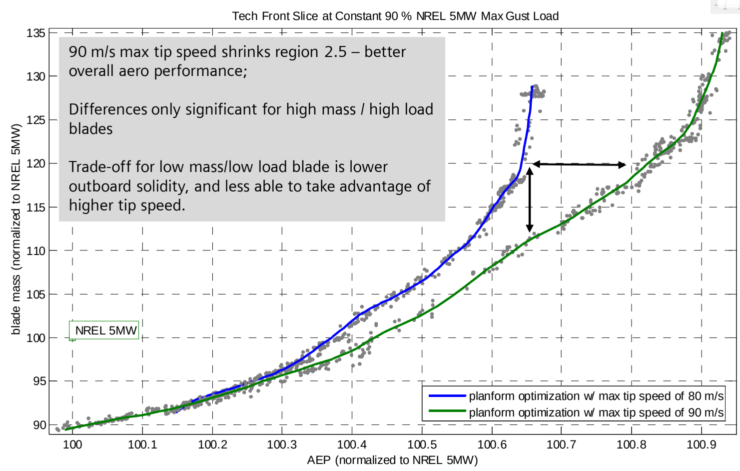
International Energy Agency – Topical Expert Meeting #80

10 of 18

SIEMENS

- 80m/s vs. 90 m/s maximum tip speed planform design Pareto (technology) fronts



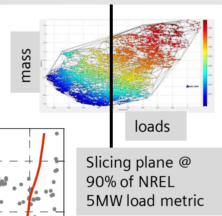


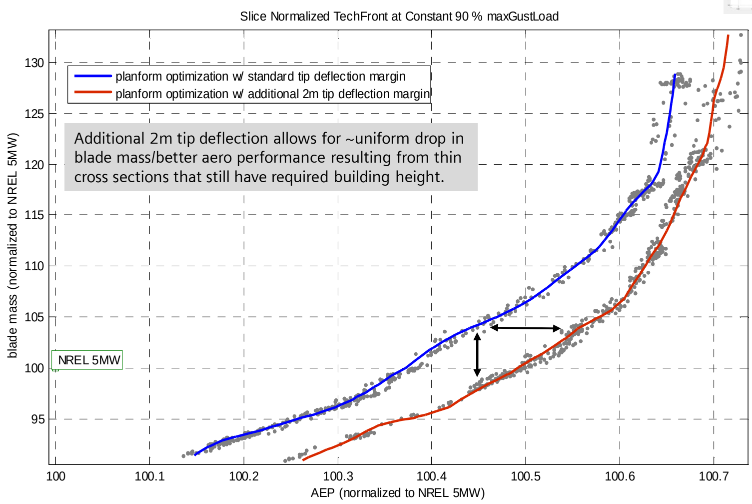
International Energy Agency – Topical Expert Meeting #80

11 of 18

SIEMENS

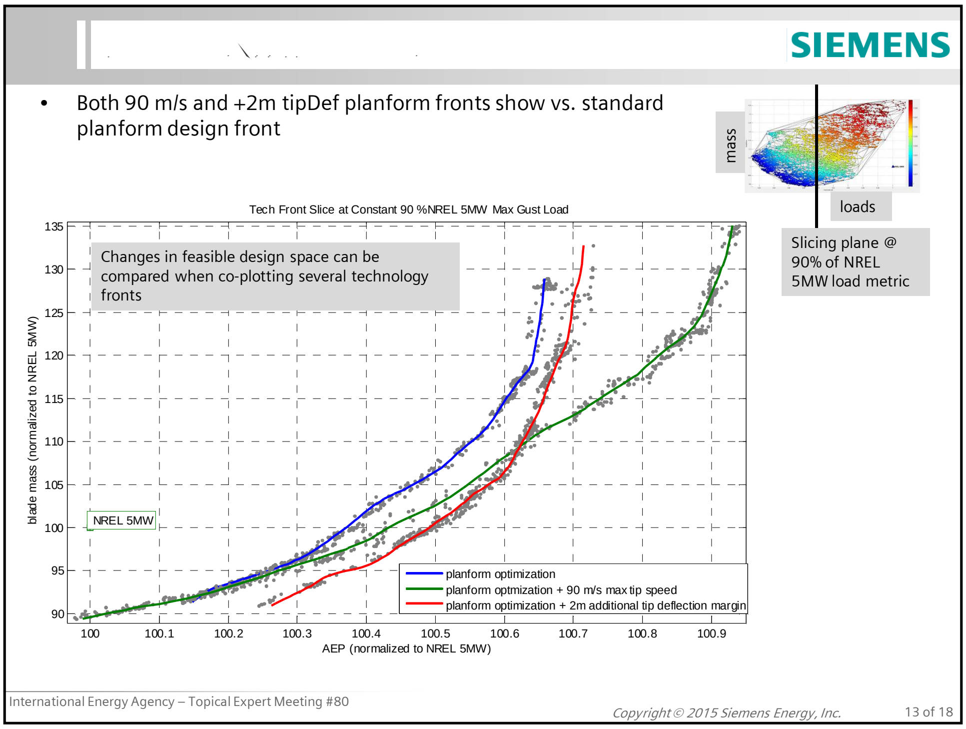
- Standard vs. 2m additional tip deflection margin planform design technology fronts.

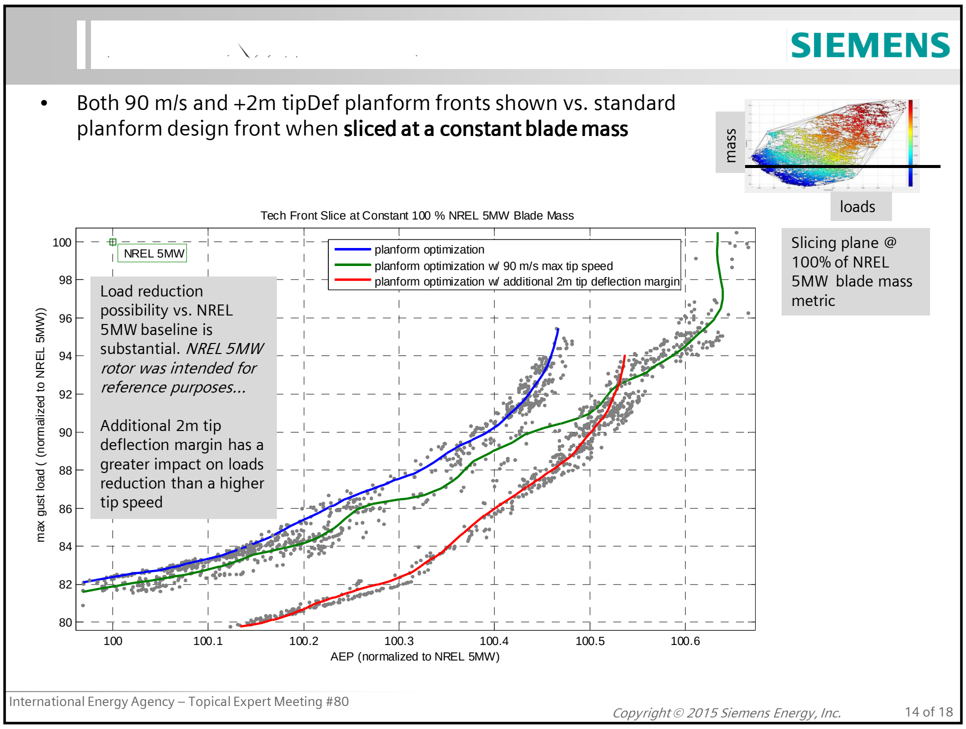




International Energy Agency – Topical Expert Meeting #80

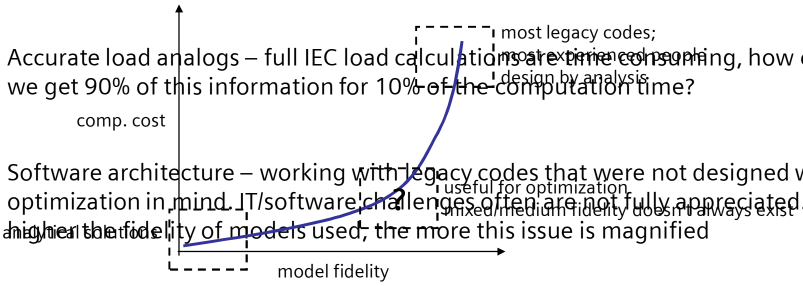
12 of 18


SIEMENS
Both 90 m/s and +2m tipDef planform fronts show vs. standard planform design front
mass
loads
Slicing plane @ 90% of NREL 5MW load metric
Tech Front Slice at Constant 90 %NREL 5MW Max Gust Load
Changes in feasible design space can be compared when co-plotting several technology fronts
NREL 5MW
blade mass (normalized to NREL 5MW)
AEP (normalized to NREL 5MW)
planform optimization
planform optmization + 90 m/s max tip speed
planform optimization + 2m additional tip deflection margin
International Energy Agency – Topical Expert Meeting #80
Copyright © 2015 Siemens Energy, Inc.
13 of 18


SIEMENS
Both 90 m/s and +2m tipDef planform fronts shown vs. standard planform design front when sliced at a constant blade mass
mass
loads
Slicing plane @ 100% of NREL 5MW blade mass metric
Tech Front Slice at Constant 100 % NREL 5MW Blade Mass
NREL 5MW
Load reduction possibility vs. NREL 5MW baseline is substantial. NREL 5MW rotor was intended for reference purposes...
Additional 2m tip deflection margin has a greater impact on loads reduction than a higher tip speed
max gust load ((normalized to NREL 5MW))
AEP (normalized to NREL 5MW)
planform optimization
planform optimization w/ 90 m/s max tip speed
planform optimization w/ additional 2m tip deflection margin
International Energy Agency – Topical Expert Meeting #80
Copyright © 2015 Siemens Energy, Inc.
14 of 18

SIEMENS

- Speed vs. fidelity trade-off. - OR - cycle time vs. confidence level
- Maximizing engineering iterations, <1 day cycle time
- Accurate load analogs – full IEC load calculations are time consuming, how can we get 90% of this information for 10% of the computation time?
- Software architecture – working with legacy codes that were not designed with optimization in mind. IT/software challenges often are not fully appreciated. The higher the fidelity of models used, the more this issue is magnified



SIEMENS

- 'Silo thinking' - disciplines operating in isolation or with limited contact
- Manual / design by analysis works, especially when you have an acceptable starting point, so why change?
- Unease / lack of knowledge of optimization methods in general, especially those not exposed to it during their education
- Over selling optimization – its not a push-button solution, just a more powerful technique.
- Successful and reliable optimization can difficult and time consuming…
  OEMs sell turbines not models.
- Unusual results are common– expect the unexpected
- Trust is hard to gain – easy to lose. Communication and expectations must be managed carefully

SIEMENS

- SWT-6.0-154
- SWT-4.0-130
- SWT-3.0-108
- SWT-2.3-108





SIEMENS

OneWind

Concepts and Products

Urs Wihlfahrt

urs.wihlfahrt@iwes.fraunhofer.de

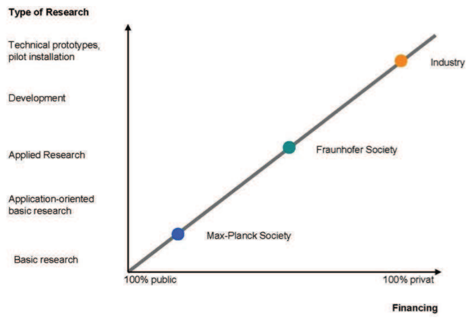
Agenda

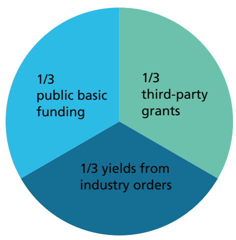
Agenda

Fraunhofer IWES

Fraunhofer-Gesellschaft: Industry focus as success factor

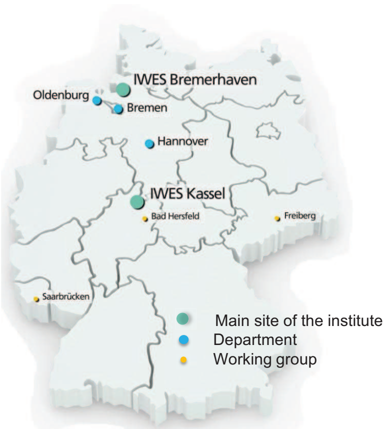
- Largest organization for applied research in Europe
- More than 80 research institutions, including 67 Fraunhofer institutes in Germany
- More than 24,000 employees, mainly with natural or engineering science education
- € 2.0 billion annual research budget totaling





Fraunhofer IWES

Fraunhofer Institute for Wind Energy and Energy System Technology (IWES North-West)



- **Managing Director:**:
  Prof. Dr.-Ing. Andreas Reuter
- **Research Spectrum:**
  Wind energy from wind physics up to energy network feeding
- **Budget 2014:**
  around €14 million
- **Staff:**
  150 employees
- **Previous investments in the establishment of the institute:**
  €50 million
- Strategic Association with ForWind and the German Aerospace Center (DLR)

Research Alliance
Wind Energy

Fraunhofer
IWES

Accelerated time-to-market by realistic testing

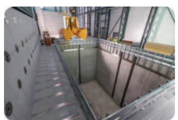
Rotor Blade Test Hall up to 90 meter

- Testing of design prior to series production
- Simulation of 20 year life-spans in a few months
- max. static bending moment 115,000 kNm; max. dynamic bending moment: +/- 30,000 kNm

DyNaLab with 10 MW Drive Performance / Peak 15 MW

- Norminal torque: > 8,6 MNm
- Rotor load application unit for dynamic bending moments, thurst and radial forces
- Artificial network: 44 MVA installed inverter power

Support Structure Test Center



- Testing support structure fatigue behaviour
- Solving production problems through design changes
- Scale of 1:10 - 1:3,5

Fraunhofer
IWES

Agenda

Fraunhofer IWES

OneWind Concept
- Background
- Consistent modeling
- Base technologies

OneWind Modelica Library

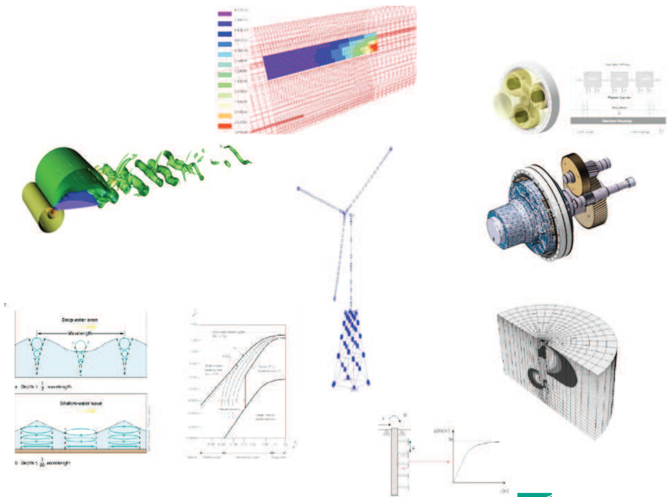
OneWind Software Products

Extensions

Conclusion

Fraunhofer IWES

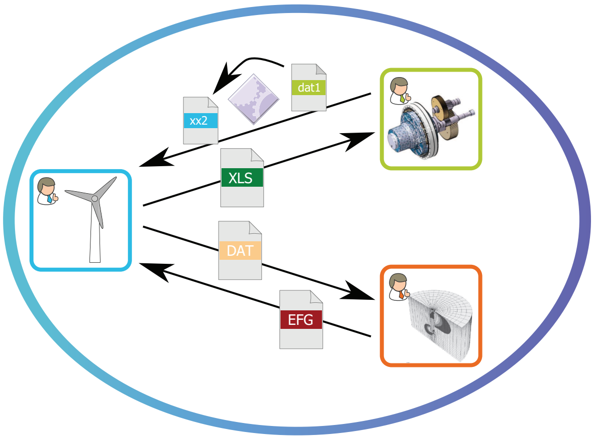
Multiple domains



Fraunhofer IWES

Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

Cooperation in the design process

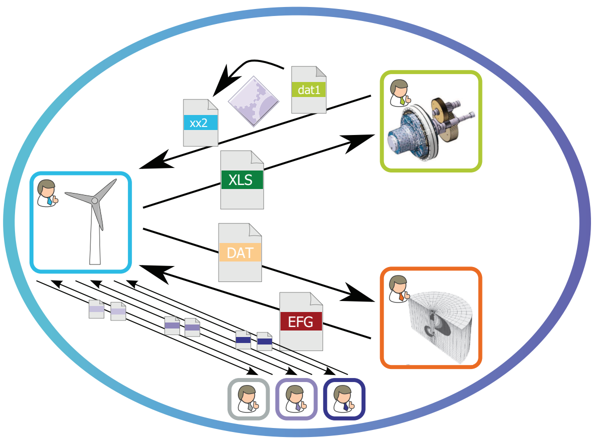


January 12th, 2015 6 © Fraunhofer

Fraunhofer IWES

Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

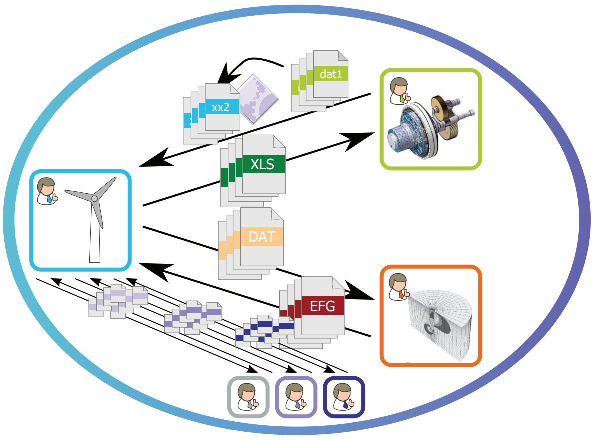
Cooperation in the design process



January 12th, 2015 6 © Fraunhofer

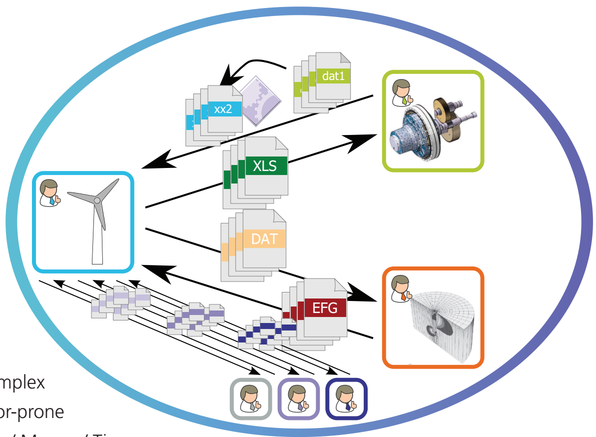
Fraunhofer IWES

Cooperation in the design process



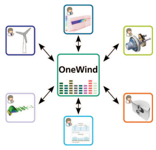
Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

Cooperation in the design process



- Complex
- Error-prone
- Risk / Money / Time

Consistent modeling



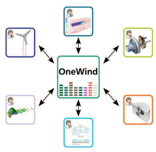
All components of a wind turbine

- in **one** numerical model
- with **different** levels of detail
- and automatic **transformation** of models

Fraunhofer IWES

Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

Consistent modeling



All components of a wind turbine

- in **one** numerical model
- with **different** levels of detail
- and automatic **transformation** of models

Project OneWind

duration: 2009 – 2014
budget: 5.7 Mio. €
personnel: ≤ 10 employees

Supported by:

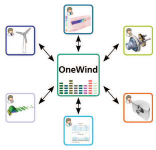
Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

January 12th, 2015 7 © Fraunhofer

Fraunhofer IWES

Consistent modeling



All components of a wind turbine

- in **one** numerical model
- with **different** levels of detail
- and automatic **transformation** of models

No more:

- Tool-Vendor dependency
- Time consuming data exchange
- Errors due to different versions of models
- Detailed knowledge of different tools necessary

Project OneWind

duration: 2009 – 2014
budget: 5.7 Mio. €
personnel: $\leq$ 10 employees

Supported by:

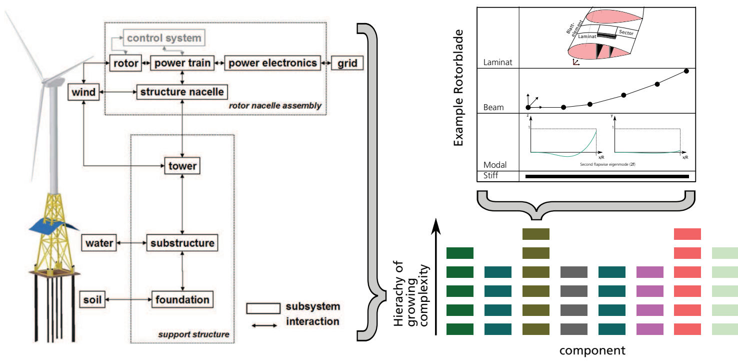
Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Fraunhofer IWES

Concept

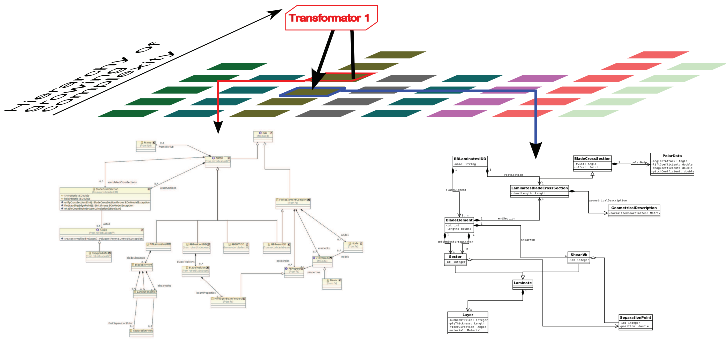
- **Purely parametric** component models (Engineer Design Data)



Fraunhofer IWES

Concept

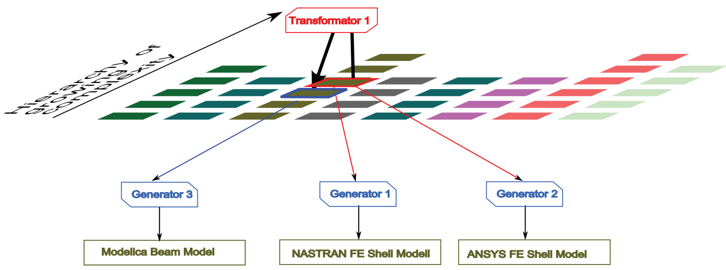
- **Purely parametric** component models (Engineer Design Data)
- **Transformation** between different levels of detail



Fraunhofer IWES ○○○ | OneWind Concept ○○○●○ | OneWind Modelica Library ○○○○ | OneWind Software Products ○○○○ | Extensions ○○ | Conclusion

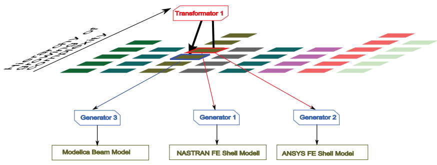
Concept

- **Purely parametric** component models (Engineer Design Data)
- **Transformation** between different levels of detail
- **Generation** of models for calculation



Concept

- **Purely parametric** component models (Engineer Design Data)
- **Transformation** between different levels of detail
- **Generation** of models for calculation



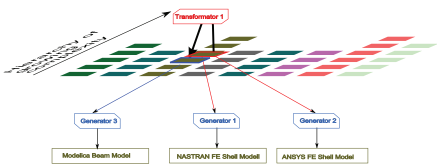
Advantages:

- Consistency of the models with different levels of detail
- Decoupling of model and tool knowledge

Fraunhofer IWES

Concept

- **Purely parametric** component models (Engineer Design Data)
- **Transformation** between different levels of detail
- **Generation** of models for calculation



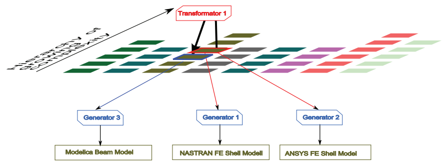
Advantages:

- Consistency of the models with different levels of detail
- Decoupling of model and tool knowledge

Fraunhofer IWES

Concept

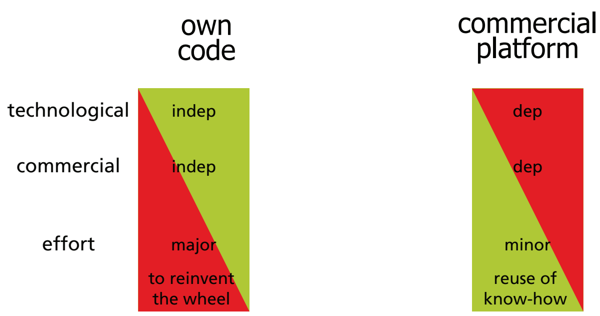
- **Purely parametric** component models (Engineer Design Data)
- **Transformation** between different levels of detail
- **Generation** of models for calculation



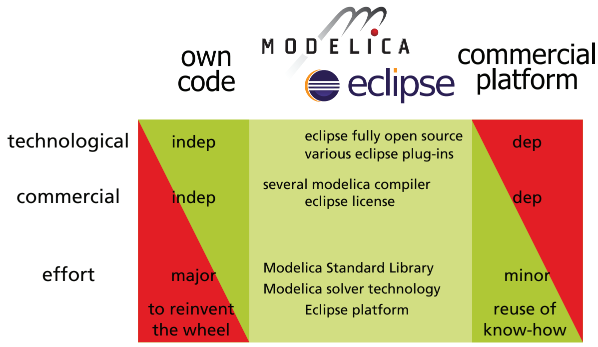
Advantages:

- Consistency of the models with different levels of detail
- Decoupling of model and tool knowledge

OneWind base technologies: Modelica and Eclipse



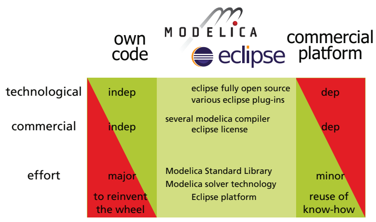
OneWind base technologies: Modelica and Eclipse



Fraunhofer IWES

Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

OneWind base technologies: Modelica and Eclipse



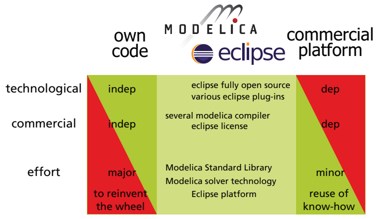
MODELICA

- Open source language for physical modeling (ODE)
- Separation of physics and numerics and → intuitiv to engineers
- Extensive Modelica Standard Library (MSL)
- Vendor independent, component based, extensible

eclipse

Fraunhofer IWES

OneWind base technologies: Modelica and Eclipse



Modelica

- Open source language for physical modeling (ODE)
- Separation of physics and numerics and → intuitiv to engineers
- Extensive Modelica Standard Library (MSL)
- Vendor independent, component based, extensible

eclipse

- Open source community
- Reuse of techniques from software development: plug-in framework, support for collaboration (subversion, tickets)
- Domain specific models → EMF
- Example: Eclipse Automotive Industry Working Group

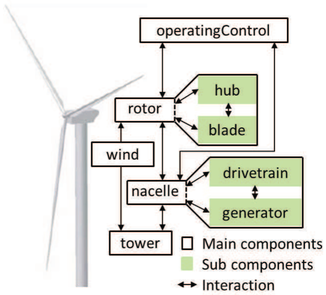
Fraunhofer IWES

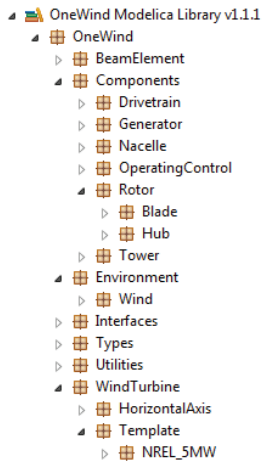
Agenda

Fraunhofer IWES

OneWind Modelica Library

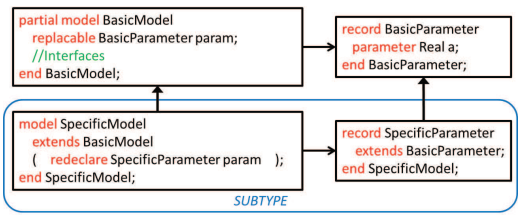
- Modelica based
- Component based (exchangeable, extendible)
- Source code / no blackbox
- Modal reduction of blades and towers
- Including NREL offshore 5MW baseline wind turbine
- Verification OC3





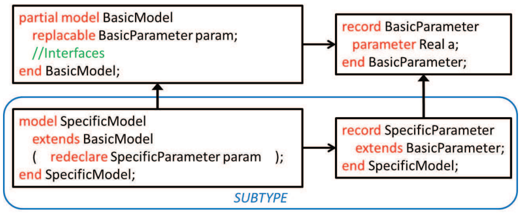
Fraunhofer IWES

Inheritance concept of library



Fraunhofer IWES

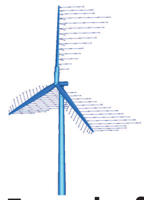
Inheritance concept of library



Example Code

```
model WindTurbine
 extends OneWind.OnshoreWindTurbine
  (
   //=== rotor ===
   redeclare OneWind.RotorModal rotor
   //=== tower ===
   ,redeclare OneWind.TowerModal tower
   //=== nacelle ===
   ,redeclare OneWind.NacelleRigid nacelle
   //=== operating control ===
   ,redeclare OneWind.Control operatingControl
   //=== wind ===
   ,redeclare OneWind.WindTurbulent wind
  );
end WindTurbine;
```

Graphical output

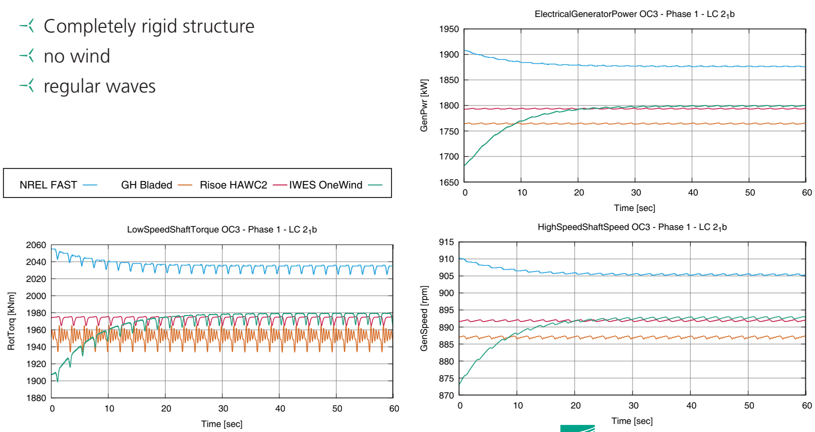


Fraunhofer IWES

Verification

OC3 Phase 1 LoadCase 2.1b

- Completely rigid structure
- no wind
- regular waves

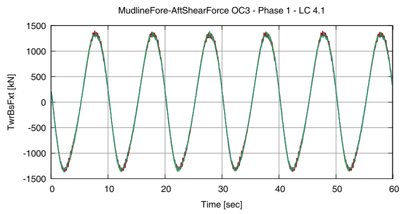


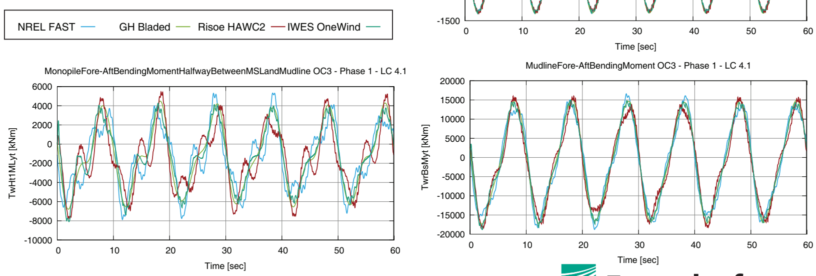
Fraunhofer IWES

Verification

OC3 Phase 1 loadcase 4.1

- Flexible offshore structure
- constant wind
- no waves





Fraunhofer IWES

Agenda

Fraunhofer IWES

OneWind Concept

OneWind Modelica Library

OneWind Software Products
- Framework
- Product overview
- Look and feel

Extensions

Conclusion

Fraunhofer IWES

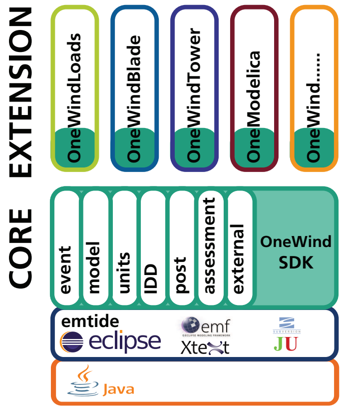
OneWind-framework structure

Concept

- Modeling windturbines and workflow
- Engineering Design Data
- Core / extension

Software engineering

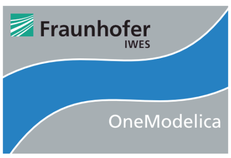
- Eclipse Rich Client Platform (RCP)
- Continuous integration build
- Documentation within products
- Tests within the products



Fraunhofer IWES

OneWind-Products

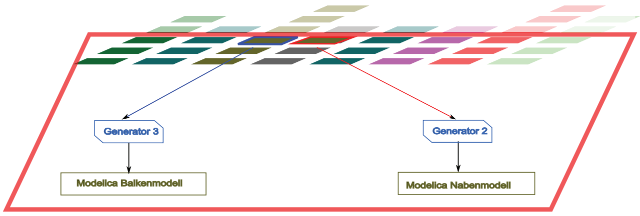
- OneWindLoads — Load calculation
- OneWindBlade — Structure design of rotorblades
- OneModelica — Integrated development environment for Modelica
- OneWindSDK — Software Development Kit for OneWind products



Fraunhofer IWES

OneWind-Products

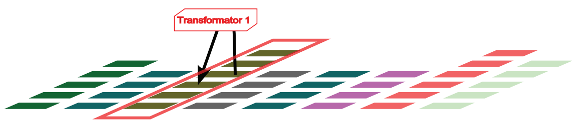
- OneWindLoads — Load calculation
- OneWindBlade — Structure design of rotorblades
- OneModelica — Integrated development environment for Modelica
- OneWindSDK — Software Development Kit for OneWind products



Fraunhofer IWES | OneWind Concept | OneWind Modelica Library | OneWind Software Products | Extensions | Conclusion

OneWind-Products

- OneWindLoads — Load calculation
- OneWindBlade — Structure design of rotorblades
- OneModelica — Integrated development environment for Modelica
- OneWindSDK — Software Development Kit for OneWind products



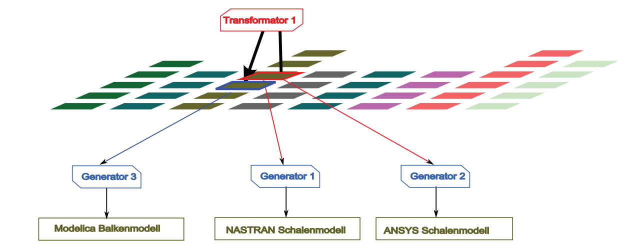
OneWind-Products

- OneWindLoads   Load calculation
- OneWindBlade   Structure design of rotorblades
- OneModelica   Integrated development environment for Modelica
- OneWindSDK   Software Development Kit for OneWind products

Fraunhofer IWES

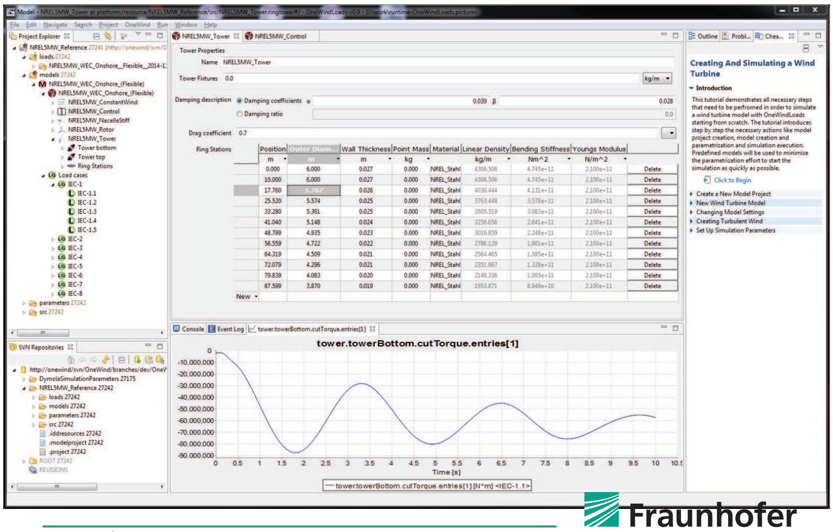
OneWind-Products

- OneWindLoads   Load calculation
- OneWindBlade   Structure design of rotorblades
- OneModelica   Integrated development environment for Modelica
- OneWindSDK   Software Development Kit for OneWind products



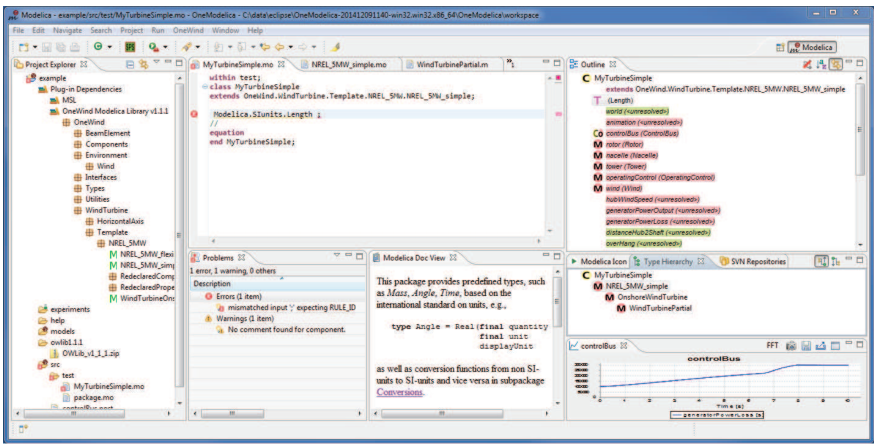
Fraunhofer IWES

Look and Feel of OneWindLoads



Fraunhofer IWES

Look and Feel of OneModelica



Fraunhofer IWES

Agenda

Fraunhofer IWES

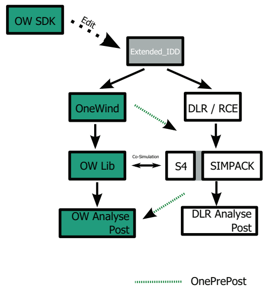
Extension of the framework

“Fast approach” – Modelica based
- Enhancements of single component
- Usage within library for loads calculation
- OneModelica

“Complete approach” – OneWind-Framework based
- Engineer Design Data – model for new component
- Transformations, generators and assessments
- Core / Extension based ⇒ OneWind Product
- OneWindSDK

Fraunhofer IWES

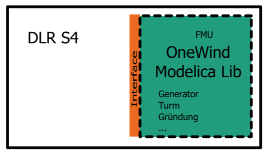
Ongoing work



Project Wind Muse

- Cooperation IWES – DLR
- Combine tools from IWES and DLR

- combined parametric model `Extended_EDD`
- Enhanced load case management
- OnePrePost (alternative simulator)
- Modelica model exchange via Functional Mock-up Interface (FMI)



Fraunhofer IWES

Agenda

Fraunhofer IWES

Conclusion

OneWind is

- Consistent modeling with different levels of details
- "OneWind Modelica Library" tool for loads calculation
- Extensible software framework for wind-energy applications

Fraunhofer IWES

Fraunhofer IWES OneWind Concept OneWind Modelica Library OneWind Software Products Extensions Conclusion

THANK YOU FOR YOUR ATTENTION

Any questions?

urs.wihlfahrt@iwes.fraunhofer.de

Fraunhofer IWES

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

FAST: A Developer-Community Environment for Multi-Physics Engineering Models

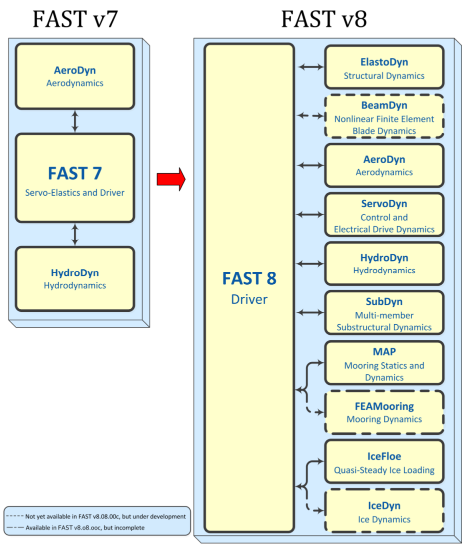
IEA Wind Task 11 TEM #80 on, "Wind Energy Systems Engineering: Integrated RD&D"

January 12-13, 2015

Jason Jonkman, Ph.D.
Senior Engineer, NREL

The FAST Multi-Physics Engineering Tool

- **FAST** is DOE/NREL's premier open-source wind turbine multi-physics engineering tool
- **FAST** is undergoing a major restructuring, with a new modularization framework (v8)
- Not only is the new framework supporting expanded functionality, but it is facilitating the establishment of a code-development community for multi-physics engineering models



IEA Wind Task 11 TEM #80 | 2 | National Renewable Energy Laboratory

3 Frameworks Pursued Under A2e (All Promote Collaborative Research)

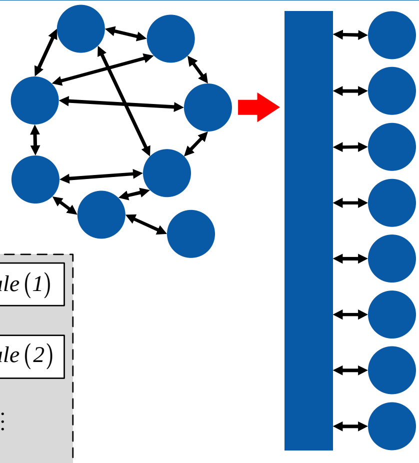
	High-Fidelity Modeling (HFM)	Multi-Physics Engineering Modeling (MPEM)	System Design & Analysis (SDA)
Objective	Massively parallel calculations of "ground truth"	Coupled physics modeling practical to engineering design	Coupled system interactions involving design, performance & cost
Analysis Type	Time domain	Time domain & linearization	Not necessarily time domain
Hardware	Modern HPC	Both HPC & desktops	Both HPC & desktops
Physics/ Coupling	Focus on fluids across scales (atmosphere ⇔ plant ⇔ turbine), with a structural model	Coupled aero-hydro-servo-elastics involving: • Models with nonlinear & differential-algebraic equations • Range of time/space scales • Range of model fidelity	Integrates design, performance, & cost models & provides advanced analysis methods (MDAO, UQ, etc.)
Favors	High fidelity over flexibility & ease of use	Efficiency with accuracy for iterative & probabilistic analysis over fidelity	Flexibility in coupling different model types over time/space coupling

Physics Modeling Needs for Practical Engineering Design

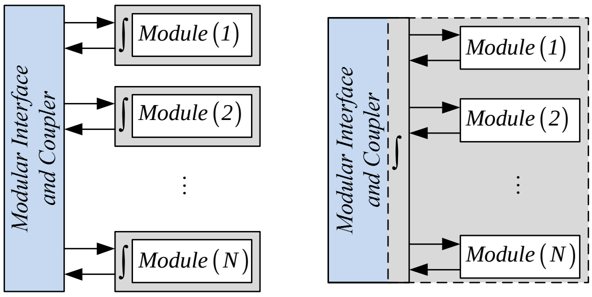
- Capture aero-hydro-servo-elastic couplings within turbines & between turbines within wind plants with enhanced accuracy based on improved understanding of the relevant physics
- Range of fidelity to target specific problems of OEMs (design) & owner-operators (siting)
- Verification & validation to understand where models are suitable & where they are not
- Maintain computational efficiency to support a highly iterative & probabilistic design processes, & system-wide optimization
- Nonlinear time-domain for standards-based load analysis
- Linearization for controls design, stability analysis, & gradients for optimization within systems engineering
- Support for new technology (including new sensors & actuators, innovative structural components, & novel architectures)
- Support unique needs of nascent offshore industry (including metocean conditions, hydrodynamic loading, substructures, & larger components)

What is the FAST Modularization Framework?

- A means by which various mathematical models are implemented in distinct modules & interconnected to solve for the global, coupled, dynamic response of a system



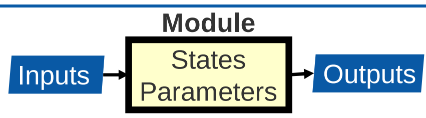
Interconnected Physics Domains, Coupled Through a Driver



Loose- (Left) & Tight- (Right) Coupling Schemes

IEA Wind Task 11 TEM #80 5 National Renewable Energy Laboratory

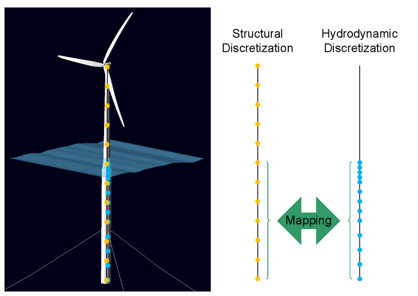
Design Features of the Framework



- Module-independent inputs, outputs, states, & parameters
- States in continuous-time, discrete-time, & in constraint form
- Loose & tight coupling*
- Independent time & spatial discretizations
- Time marching, operating-point determination*, & linearization*
- Data encapsulation & dynamic allocation
- Save/retrieve capability*

For Each Time Step (From t_n):
1) Extrapolate Inputs to t_{n+1}
2) Advance States to t_{n+1}
3) Solve for Outputs & Inputs @ t_{n+1}
4) Correct (Go Back to 2) or Save

PC-Based Loose-Coupling Algorithm



Mapping Independent Discretizations

*Not yet available

IEA Wind Task 11 TEM #80 6 National Renewable Energy Laboratory

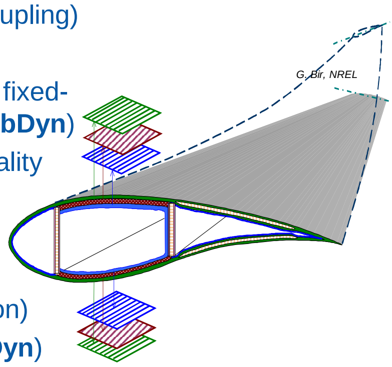
Recent & Current Work

Recent Work:

- Developed framework & converted **FAST**
- Developed **SOWFA** (**FAST-OpenFOAM** coupling)
- Added DWM
- Added capability for multi-member offshore fixed-bottom support structures (**HydroDyn** & **SubDyn**)
- Greatly expanded floating offshore functionality (**HydroDyn** & **MAP**)

Current Work:

- Complete framework (esp. OP & linearization)
- Aero-elastics overhaul (**AeroDyn** & **BeamDyn**) & validation against Siemens ATB
- Further floating functionality expansion (**FIT** & **FEAM**) & validation (OC5 & CFD)



Blade Twist Induced By Anisotropic Layup

Vision for a FAST Development Community

DOE Program Management
- Establish/maintain board & maint. team
- Manage program

Strategic Board (Labs, Universities, Industry)
- Identify strategic directions
- Engage research community

Maintenance Team (Labs & Key Developers)
- General code & website maintenance
- Support users
- Train developers
- Advise development projects
- Review/correct/approve code
- Integrate modules
- Distribute code
- Independent test & V&V

Developers (Labs, Universities, & Industry)
- Engage boards
- Develop code within the context of the FAST modularization framework
- Test & V&V
- Documentation
- Demonstration

Users (Anyone)
- Apply software to engineering problems
- Report software issues to maintenance team
- Request new features

Development Process in a Code-Development Community

Step	Responsibility
1) Identify new development	Strategic Board, Maintenance Team, & Developers
2) Establish collaboration	Maintenance Team & Developers
3) Develop plan	Developers
4) Code within framework	Developers
5) Local test & V&V	Developers
6) Documentation	Developers
7) Demonstrate improvement	Developers
8) Submit to repository	Developers
9) Review/correct/approve	Maintenance Team
10) Global test & V&V	Maintenance Team
11) Distribute software	Maintenance Team

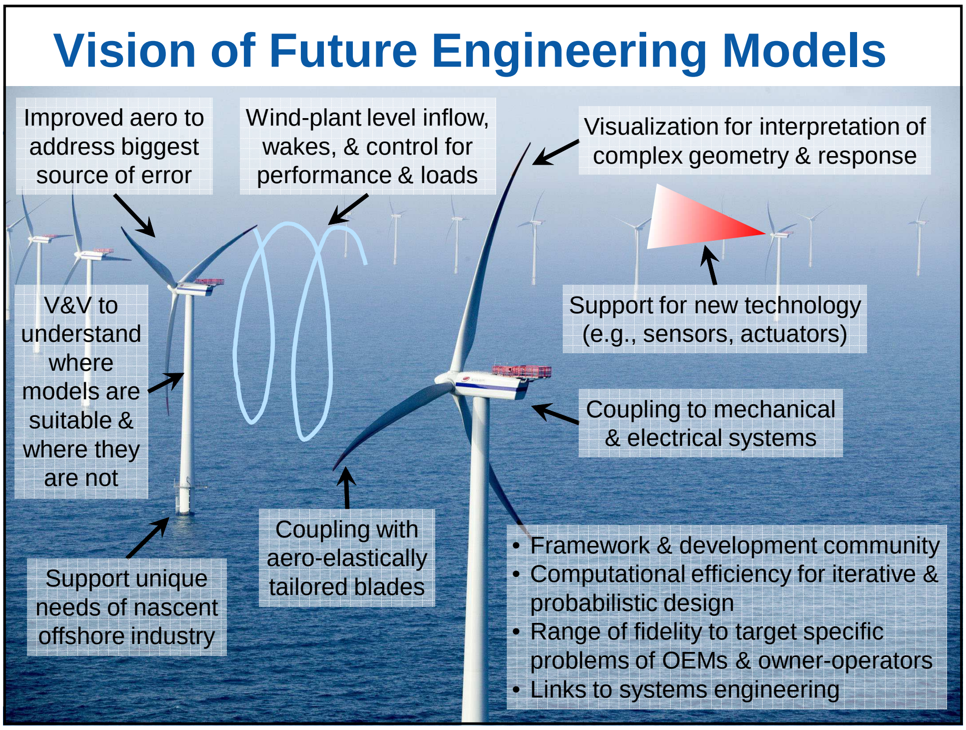
Where Development Community Stands & Tasks Remaining

Progress Towards Establishing a FAST Development Community:

- Developed the modularization framework to be used as code backbone
- Established regression tests for code checking
- Documented theoretical basis, coding requirements, & recommended practices
- Developed a source-code-control repository
- Collaborated with several external contributors through FOA 415 projects & others:
  - Many others across the research community have customized **FAST** without collaboration
- Supported large user base through forums & workshops

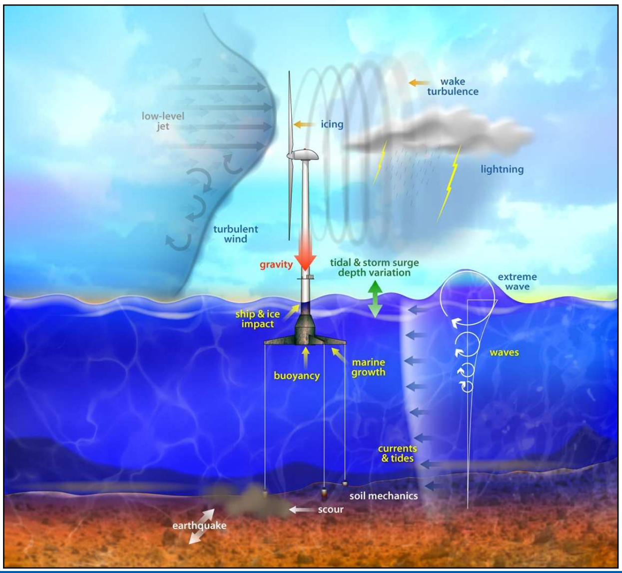
Tasks Remaining to Establish a Development Community:

- Complete the **FAST** modularization framework & incorporation of important features from **FAST** v7
- Establish a DOE program-wide shared vision for a developer community paradigm
- Establish strategic board & maintenance team
- Advertise new development community paradigm
- Establish development community training workshops
- Initiate development community collaborations


Vision of Future Engineering Models
Improved aero to address biggest source of error
Wind-plant level inflow, wakes, & control for performance & loads
Visualization for interpretation of complex geometry & response
V&V to understand where models are suitable & where they are not
Support for new technology (e.g., sensors, actuators)
Coupling to mechanical & electrical systems
Coupling with aero-elastically tailored blades
Support unique needs of nascent offshore industry
• Framework & development community
• Computational efficiency for iterative & probabilistic design
• Range of fidelity to target specific problems of OEMs & owner-operators
• Links to systems engineering

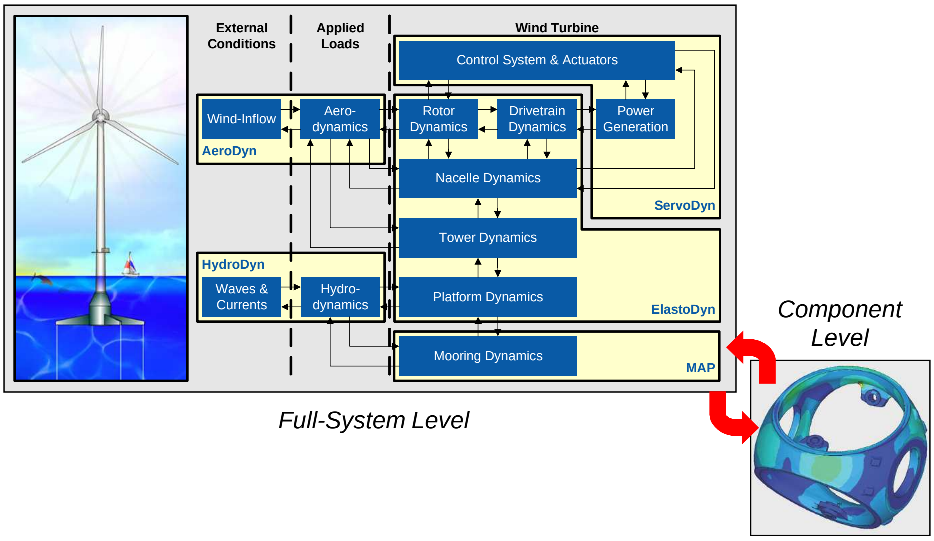

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
More information @: https://nwtc.nrel.gov
Carpe Ventum!
Jason Jonkman, Ph.D.
+1 (303) 384 – 7026
jason.jonkman@nrel.gov
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Introduction & Background
Modeling Requirements



- Coupled aero-hydro-servo-elastic interaction
- Wind-inflow:
  - –Discrete events
  - –Turbulence
- Waves:
  - –Regular
  - –Irregular
- Aerodynamics:
  - –Induction
  - –Rotational augmentation
  - –Skewed wake
  - –Dynamic stall
- Hydrodynamics:
  - –Diffraction
  - –Radiation
  - –Hydrostatics
- Structural dynamics:
  - –Gravity / inertia
  - –Elasticity
  - –Foundations / moorings
- Control system:
  - –Yaw, torque, pitch

Modeling Requirements & Challenges
NREL's FAST Aero-Hydro-Servo-Elastic Tool



NREL's FAST CAE Tool

Aerodynamics (AeroDyn, SOWFA)

	Physics	Models Available	Developments/Needs
Wind Inflow	• Atmospheric turbulence • Discrete events • Wake & array effects	• Direct measurements • Spectral methods (**TurbSim**) • CFD (**OpenFOAM**)	• Site-specific models • Consideration of atmospheric stability • Advancement of wake & array models
Airfoil Aero-dynamics	• Rotational augmentation • Unsteady aero. • Deep stall • Tip & hub loss	• Steady 2D (**XFoil**) • Empirical corrections: – Selig/Du/Eggers – Beddoes-Leishman – Viterna	• Improved empirically & CFD-derived corrections • CFD
Induction	• Axial • Tangential • Skewed flow	• Blade-element/ momentum (BEM) • Generalized dynamic wake (GDW) • CFD (**OpenFOAM**)	• Improved empirically & CFD-derived corrections • Vortex methods

IEA Wind Task 11 TEM #80 15 National Renewable Energy Laboratory

NREL's FAST CAE Tool

Hydrodynamics (HydroDyn)

	Physics	Models Available	Developments/Needs
Waves & Current	• Regular • Irregular • Extreme • Spreading	• 1^{st}- & 2^{nd}-order • Directional spreading • Steady currents	• User-defined waves • Wave stretching • Higher-order theories • CFD
Viscous Loads	• Flow separation	• Strip theory (Morison)	• Automated coefficients • CFD
Potential-Flow Loads	• Radiation: – Added mass – Damping – Memory effects • Diffraction	• Strip theory • 1^{st}- & 2^{nd}-order panel methods (e.g., **WAMIT**)	• MacCumy-Fuchs & Rainey load models • Nonlinear fluid-impulse theory • CFD
Buoyancy Loads	• Static pressure • Dynamic pressure	• Strip theory • Panel methods	• CFD
Ice Loads	• Static & dynamic	• Quasi-steady	• Dynamic sea ice models

IEA Wind Task 11 TEM #80 16 National Renewable Energy Laboratory

NREL's FAST CAE Tool

Controller & Electrical Drive (ServoDyn)

	Physics	Models Available	Developments/Needs
Control & Protection System Logic	• Torque • Blade-pitch • Nacelle-yaw • Brakes • Continuous or discrete	• Simple • User subroutine • **Bladed**-style DLL • **MATLAB/Simulink & LabVIEW** (in **FAST** v7 only)	• Better support for mechanical faults • More built-in options • Wind-plant control
Sensors & Actuators	• Sensors • Servo motors • Hydraulics	• Motion & load feedback • 2nd-order yaw actuator	• Better physics • Blade-pitch DOFs & actuators • Mass-damper DOFs • SMART blades
Electrical Drive	• Generators • Power electronics • Grid connection	• Simple induction • Thevenin-equivalent • **SimPowerSystems** toolbox (**FAST** v7)	• Model more details • Model turbine-grid interaction • More built-in options

IEA Wind Task 11 TEM #80 — 17 — National Renewable Energy Laboratory

NREL's FAST CAE Tool

Structural Dynamics (ElastoDyn, SubDyn, MAP)

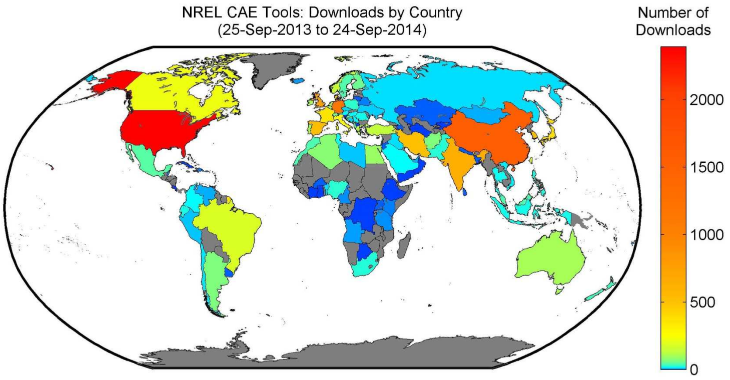
	Physics	Models Available	Developments/Needs
Beams (e.g., Blades, Towers, & Sub-Structures)	• Gravity & inertia: – Centrifugal – Gyroscopic – Coriolis • Bending • Torsion • Shear • Stretching • Geometric NL	• Sectional analysis: – Analytical – Empirical – Planar 2D FEM (e.g., **VABS**) • Modal/nonlinear beam with bending • Linear FEM with C-B (**SubDyn**)	• Modal with bending, torsion, shear, & stretching • Multi-body simulation (MBS) • Nonlinear beam (1D) FEM • Plate (2D) or solid (3D) FEM
Other (e.g., Nacelle, Drivetrain, Platform)	• Gravity & inertia • Rigid or flexible	• Rigid (MBS) • Quasi-static moorings (**MAP**)	• Other flexibilities • Drivetrain dynamics • Foundation dynamics • Mooring dynamics
Inter-connection	• Rigid • Joints	• Removal of unneeded DOFs	• Algebraic constraints • Improved friction

IEA Wind Task 11 TEM #80 — 18 — National Renewable Energy Laboratory

NREL's FAST CAE Tool

Users of NREL-Developed Tools

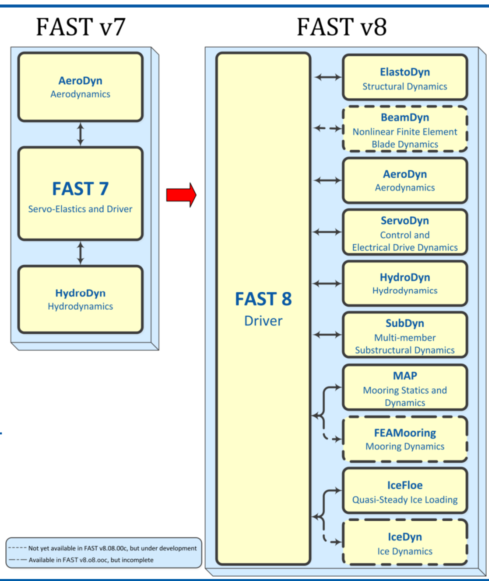
- Developed as free, publicly available, open-source products
- Used worldwide by industry, researchers, & academia
- In last 12 months, there have been 12,995 unique downloads by 4,374 users from 1,917 organizations in 114 countries



FAST Modularization Framework

Recent Developments

- Recently **FAST** & its various modules (including **AeroDyn** & **HydroDyn**) have been converted to a new modularization framework
- Splitting of **FAST** into:
  - **FAST** driver (glue) code
  - **ElastoDyn** module for structural dynamics
  - **ServoDyn** module for controller & electrical drive
- Introduction of:
  - **SubDyn** module for multi-member substructure structural dynamics
  - **MAP** module for multi-segmented mooring quasi-statics
  - **IceFloe** for quasi-steady sea ice



Functions of the FAST Driver ("Glue Code")

FAST
Driver ("Glue Code")

Loose coupling:
- Drives time-domain solution forward
- Calls individual modules
- Derives module inputs from outputs:
  - Including mesh-to-mesh mapping
  - Including interpolation/extrapolation in time

Tight coupling*:
- All of the above, plus
- Integrates coupled system equations using a common solver
- Determines operating points
- Performs model linearization

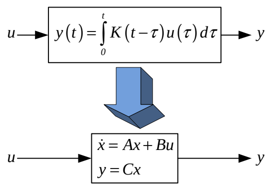
↔ **AeroDyn** Aerodynamics
↔ **HydroDyn** Hydrodynamics
↔ **ServoDyn** Control & Electrical Drive
↔ **ElastoDyn** Structural Dynamics
↔ **SubDyn** Multi-Member Substruct. Dyn.
↔ **MAP** Mooring Statics & Dynamics
↔ **IceFloe** Quasi-Steady Ice Loading

Tight coupling is not yet available

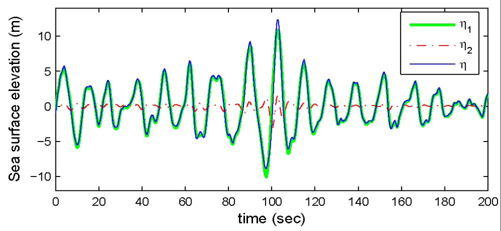
IEA Wind Task 11 TEM #80 | Wind Turbine Modeling Workshop | 21 | National Renewable Energy Laboratory

Recent & Current/Planned Work
Recent Developments

- Developed framework & converted **FAST**
- Aerodynamics:
  - Added tower drag loading
  - Developed **SOWFA** (**FAST-OpenFOAM** coupling)
- Hydrodynamics:
  - Added linear SS-based radiation formulation alternative to convolution
  - Added multi-member strip theory
  - Added wave directional spreading
  - Added 2nd-order hydrodynamics
- Control & electrical drive:
  - Made **Bladed**-style DLL one of the defaults
- Structural dynamics:
  - Introduced **SubDyn** & **MAP**



Reformulation of Radiation Convolution to Linear SS Form



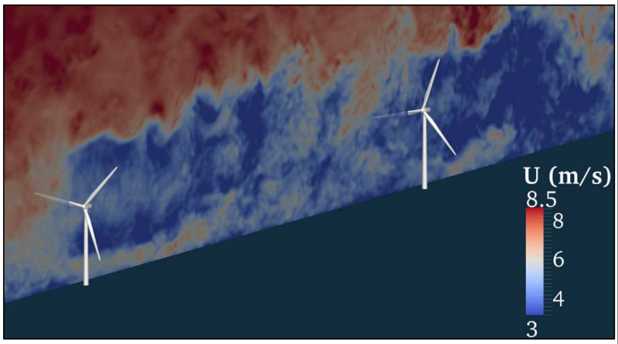
Sea-Surface Elevation (η) from the Summing of 1st- (η_1) & 2nd- (η_2) Order Waves

IEA Wind Task 11 TEM #80 | 22 | National Renewable Energy Laboratory

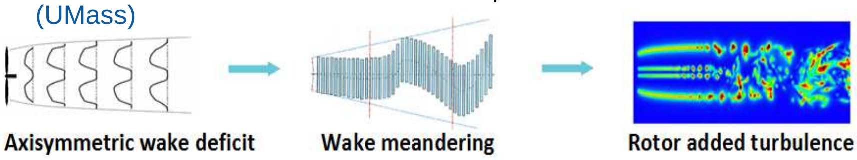
Recent & Current/Planned Work

Current & Planned Work

- Further framework development
- Aerodynamics:
  - **InflowWind** module
  - **AeroDyn** overhaul
  - **FAST-OpenFOAM-WRF** coupling
  - Dynamic wake meandering (DWM) (UMass)



*Example **SOWFA** Simulation*

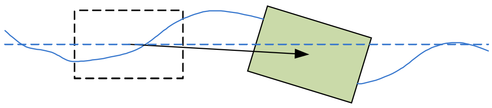


Dynamic Wake Meandering Model

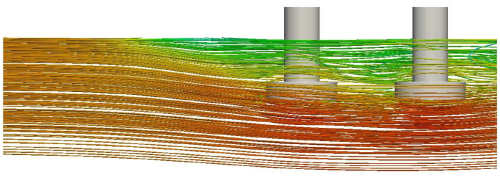
Recent & Current/Planned Work

Current & Planned Work (cont)

- Hydrodynamics:
  - User-defined wave input
  - Nonlinear fluid-impulse theory for large displacements (MIT)
  - Ice loading (DNV & UMich)
  - Verification against CFD (UMass)
- Control & electrical drive:
  - **MATLAB/Simulink** interface
  - Mass-damper DOFs (UMass)
  - Wind farm super controller in **SOWFA**



Sea-Surface Interaction With a Platform Experiencing Large Displacement

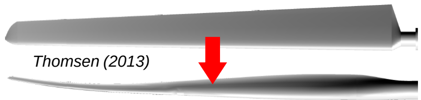


CFD Solution for Steady Current Past the OC4-DeepCwind Semi-Submersible

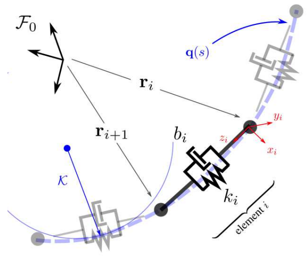
Recent & Current/Planned Work

Current & Planned Work (cont)

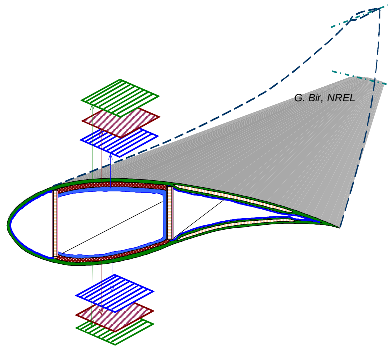
- Structural dynamics:
  - **BeamDyn** nonlinear (geometrically exact) beam spectral FE
  - **MAP** lumped-mass mooring dynamics
  - **FEAMooring** dynamics (TAMU)
  - **OrcaFlex** mooring dynamics



Advancement in Blade Design



*Lumped Mass Representation for Mooring Dynamics in **MAP***



Blade Twist Induced By Anisotropic Layup

Model Verification & Validation

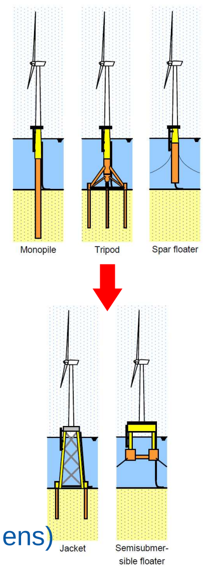
Verification

Overview

- IEA Wind Task 23 (OC3) & Task 30 (OC4) projects used to benchmark offshore WT CAE tools
- Over 130 participants from 40 organizations in 16 countries verified over 20 CAE tools
- Led by NREL & Fraunhofer-IWES

Phases

- OC3 ran from 2005 to 2009:
  - Phase I: Monopile + Rigid Foundation
  - Phase II: Monopile + Flexible Foundation
  - Phase III: Tripod
  - Phase IV: Floating Spar Buoy
- OC4 running from 2010 to 2013:
  - Phase I: Jacket (local structural dynamics)
  - Phase II: Floating semisubmersible (complex hydro)
- Ongoing: Verification of **FAST** against **BHawC** (Siemens)



Model Verification & Validation

Validation

- Data from multiple FOWT tests being used to validate **FAST**:
  - DeepCwind – 1/50th-scale wind-wave tank testing at MARIN of 5-MW atop 3 floaters: spar buoy, TLP, & semi
  - SWAY – 1/6th-scale of 5-MW downwind turbine atop a TLS in Norway
  - Hywind – Siemens 2.3-MW atop Statoil spar buoy in Norway
  - WindFloat – Vestas V80 2-MW atop a PPI semisubmersible in Portugal

DeepCwind Test

SWAY Prototype

Hywind Prototype

WindFloat Prototype

- Ongoing:
  - IEA Wind Task 30 (OC5) focused on validation
  - Validation of **FAST** with **BeamDyn** against Siemens 2.3-MW with ATB

IEA Wind Task 11 TEM #80 | 27 | National Renewable Energy Laboratory

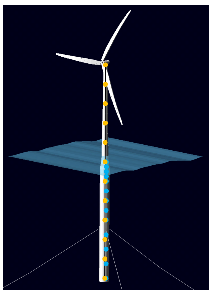
FAST Modularization Framework

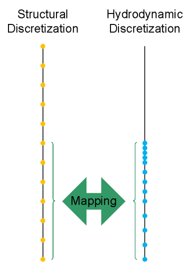
Status – Framework Features Developed to Date

- Core mathematical basis
- Module source code template (Fortran)
- Registry for automatic generation of general code
- Programmer's Handbook
- Glue code supporting PC-based loose coupling with time-step subcycling of modules
- Mappings between module-unique spatial discretizations for point- & line-element meshes
- Tests of simple examples
- Conversion of **FAST**

For Each Time Step (From t_n):
1) Extrapolate Inputs to t_{n+1}
2) Advance States to t_{n+1}
3) Solve for Outputs & Inputs @ t_{n+1}
4) Correct (Go Back to 2) or Save

PC-Based Loose-Coupling Algorithm





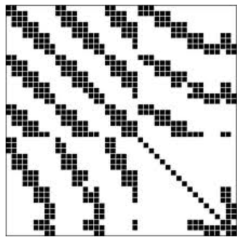
Mapping Independent Structural & Hydrodynamic Discretizations

IEA Wind Task 11 TEM #80 | 28 | National Renewable Energy Laboratory

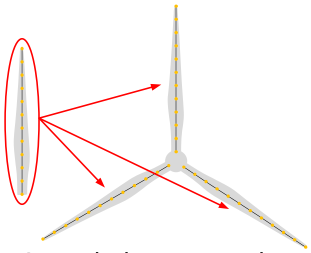
FAST Modularization Framework

Status – Framework Features Still to be Developed

- Loose coupling with module-independent time steps
- Mesh-to-mesh mappings for surface- & volume-element meshes
- Tight coupling
- Operating-point determination
- Linearization
- General algorithmic improvement for code efficiency (sparse storage, etc.)
- Advanced modularization features (parallel processing, etc.)
- International code-development community



Sparse Matrix



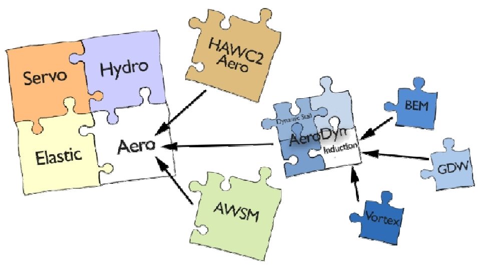
From One Blade to an Entire Rotor

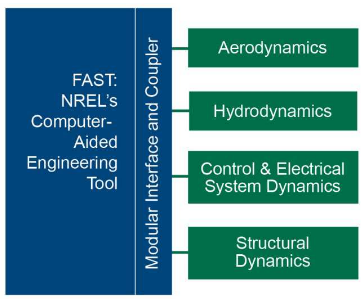
IEA Wind Task 11 TEM #80 | 29 | National Renewable Energy Laboratory

FAST Modularization Framework

Benefits of the Framework

- Address key modeling needs
- Improve ability to read, implement, & maintain source code
- Increase module sharing & shared code development across wind community
- Improve numerical performance & robustness
- Greatly enhance flexibility & expandability to enable further developments of functionality without need to recode established modules

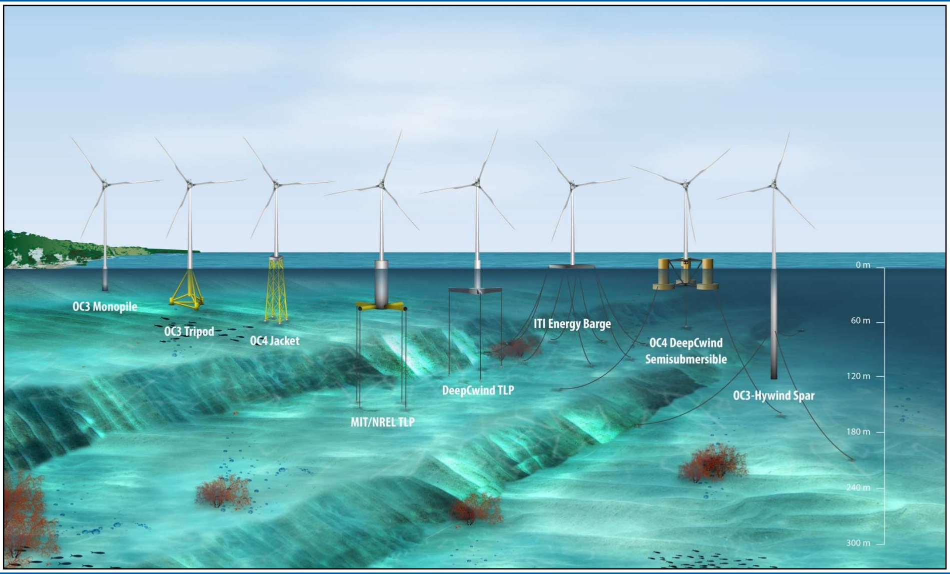




IEA Wind Task 11 TEM #80 | 30 | National Renewable Energy Laboratory

Introduction & Background

Offshore Wind Turbine Concepts



Introduction & Background

Floating Wind Industry Status

Developer	• Statoil, Norway	• PPI & EDP, Portugal	• METI, Japan	• MOE, Japan
Platform	• "Hywind" spar buoy with catenary moorings	• "WindFloat" semi-submersible with catenary moorings	• Mitsui semi-submersible with catenary moorings	• Spar buoy with catenary moorings
Wind Turbine	• Siemens 2.3 MW	• Vestas V80, 2 MW	• Hitachi 2-MW downwind	• Hitachi 2-MW downwind
Status	• $70M demonstration project in North Sea • First PoC installed in Summer 2009 • More optimized demonstrator under development	• $25M demonstration project in Portugal • First PoC installed Fall 2011 • EU FP7-funded "Demofloat" testing & validation project • US project underway	• Installed in Summer 2013 near Fukushima • Part of the $189M "Fukushima Forward" project in 2011-2015, which will also have two 7-MW turbines	• 2-MW full-scale system installed in Fall 2013 in Kabashima, Japan • Followed 100-kW half-scale system • Testing & validation underway

Wind Turbine Design Challenges

Economic Challenges → Technical Challenges

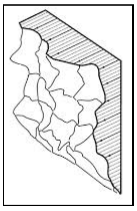
- It *is* technically feasible to develop FOWTs
- Developing *cost-effective* FOWTs, however, requires considerable thought & analysis
- The economic challenges impart *technical* challenges

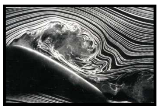
IEA Wind Task 11 TEM #80 33 National Renewable Energy Laboratory

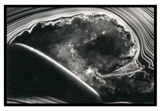
Wind Turbine Design Challenges

Wind Conditions & Aerodynamic Loads

- Large spatial-temporal variations in wind inflow:
  - Shear & veer
  - Turbulence & gusts
  - Atmospheric stability
  - Large coherent structures
  - Wake & array effects
  - Influence of complex terrain
- Aerodynamic interaction with the wind turbine:
  - Induction
  - Skewed wake
  - Tip & hub losses
  - Rotational augmentation
  - Unsteady aerodynamics, including dynamic stall





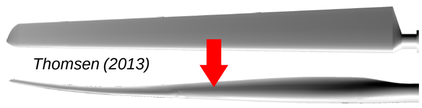


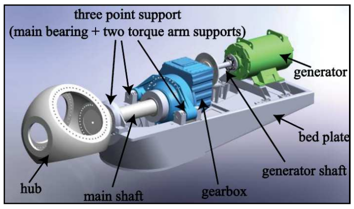
IEA Wind Task 11 TEM #80 34 National Renewable Energy Laboratory

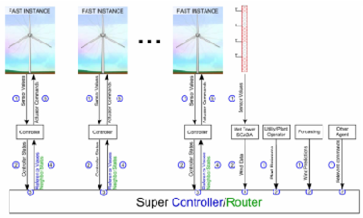
Wind Turbine Design Challenges

Structural & Control Behavior

- Variety of turbine architectures
- Structural response:
  - Large flexible composite blades
  - Aerodynamic interaction
  - Interaction with mechanical (e.g., gearbox/bearings) & electrical (e.g., generator/grid) systems
- Passive & active controls:
  - Sensors & actuators
  - Individual turbine operational control:
    - Conventional pitch, torque, yaw
    - Active aero (e.g., trailing-edge devices)
    - Passive load-alleviation (e.g., blades with bend-twist coupling)
  - Safety & protection systems
  - Wind-plant control





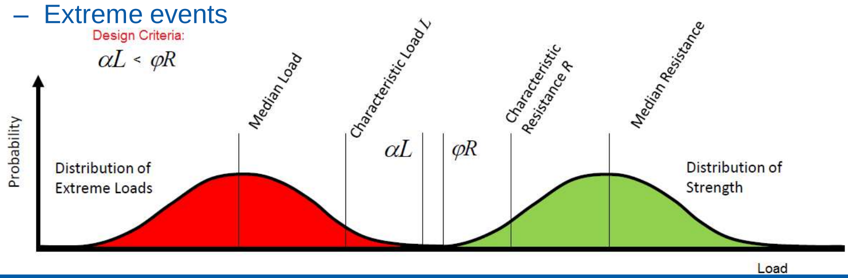


Wind Turbine Design Challenges

Evaluation of Response Across Many Conditions

- Evaluation of response:
  - Ultimate loads for 50-yr extreme
  - Fatigue loads for 20-yr life
  - Aero-servo-elastic stability
- Across a range of conditions:
  - Operational
  - Start-up/shut-down events
  - Fault
  - Extreme events

Design Situation	DLC	Wind Condition	Other Conditions	Type of Analysis
Power production	1.x			
Power production plus occurrence of fault	2.x			
Start up	3.x			
Normal shut down	4.x			
Emergency shut down	5.x			
Parked	6.x			
Parked with fault	7.x			
Transport, assembly, and maintenance	8.x			

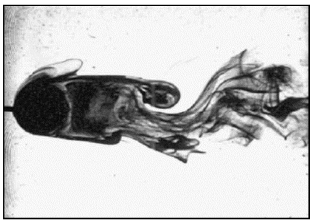


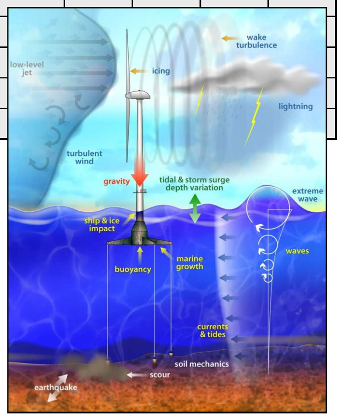
Floating Wind Design Challenges

Sea States & Hydrodynamic Loads

- Large variation in sea states:
  - Irregular waves
  - Steep/breaking waves
  - Tides/surges
  - Currents
  - 9D+ probabilistic design space of wind/wave/current
  - Tropical cyclones
- Hydrodynamic interaction with floater:
  - Diffraction
  - Radiation
  - Hydrostatics
  - Viscous effects
  - Slap loads
  - Ice

Design Situation	DLC	Wind Condition	Wave Condition	Directionality	Other Conditions	Type of Analysis
Power production	1.x					
Power production plus occurrence of fault	2.x					
Start up	3.x					
Normal shut down	4.x					
Emergency shut down	5.x					
Parked	6.x					
Parked with fault	7.x					
Transport, assembly, and maintenance	8.x					





Floating Wind Design Challenges

Structural & Control Behavior

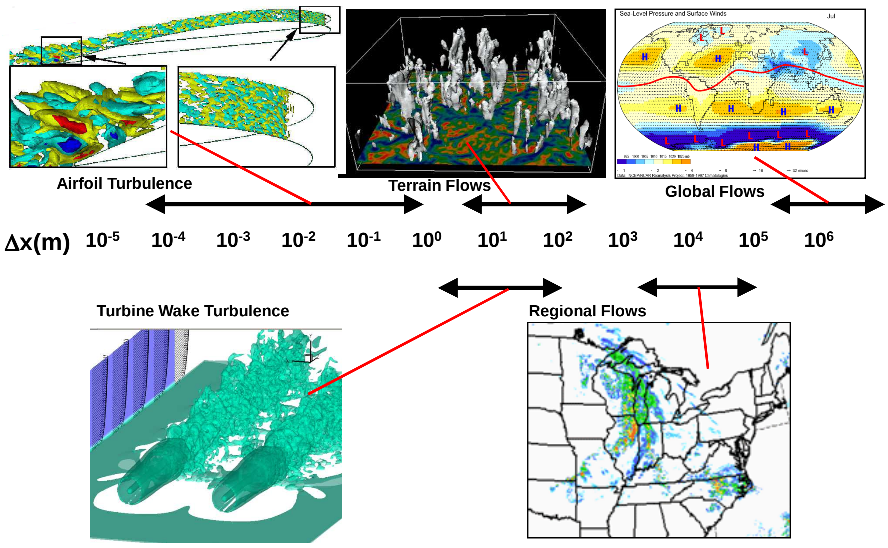
- Variety of architectures
- Low-frequency modes:
  - Influence on aero. damping & controller stability
- Large platform motions:
  - Coupling with turbine
  - Complicated aero.
  - Interaction with waves
- Wind/wave stationarity
- Stationkeeping system
- Dynamic stability as opposed to traditional static stability
- Construction & O&M

+ relative advantage
0 neutral
– relative dis-advantage

	TLP	Spar	Barge
			
Pitch Stability	Mooring	Ballast	Buoyancy
Natural Periods	+	0	–
Coupled Motion	+	0	–
Wave Sensitivity	0	+	–
Turbine Weight	0	–	+
Moorings	+	–	–
Anchors	–	+	+
Construction & Installation	–	–	+
O&M	+	0	–

Modeling Requirements & Challenges

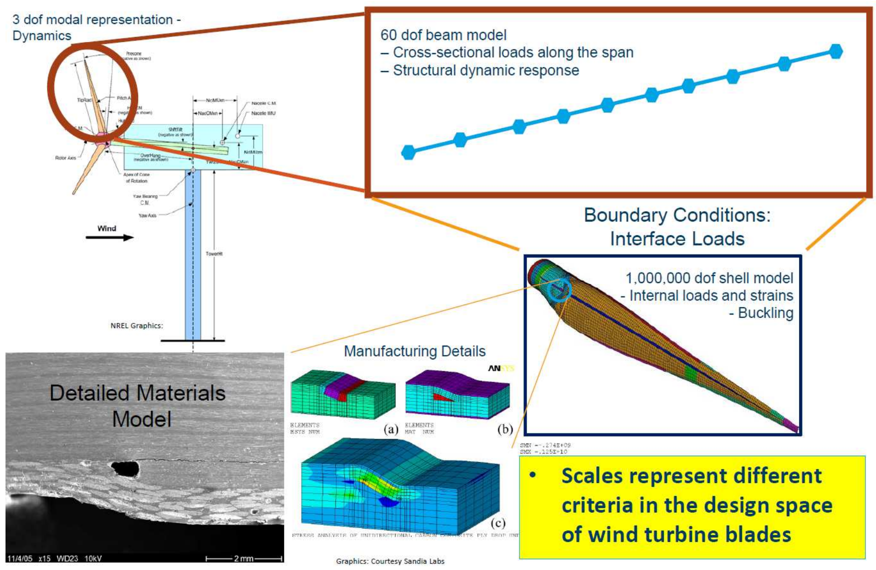
Aero. Scales Range Over 10 Orders of Magnitude



IEA Wind Task 11 TEM #80 39 National Renewable Energy Laboratory

Modeling Requirements & Challenges

Range of Possible Structural Modeling Fidelity

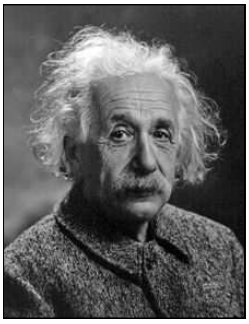


- Scales represent different criteria in the design space of wind turbine blades

IEA Wind Task 11 TEM #80 40 National Renewable Energy Laboratory

Modeling Requirements & Challenges

Famous Modeling Quotes



Einstein Principle

"A model should be as simple as possible, but no simpler."

George E.P. Box

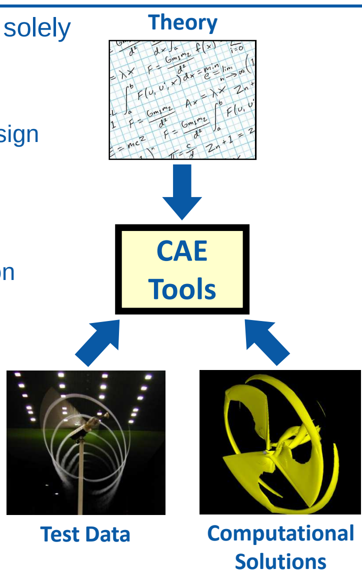
"Essentially, all models are wrong, but some are useful."

IEA Wind Task 11 TEM #80 41 National Renewable Energy Laboratory

Modeling Requirements & Challenges

Balance Between Performance & Accuracy

- To address WT design challenges, one can't solely rely on massively discretized HPC solutions
- CAE tools are required for:
  - Conceptual, initial, iterative, & probabilistic design
  - Loads & stability analysis
  - Controls development
  - System-level optimization
  - Development of any new technology innovation
- WT CAE tools are:
  - Nonlinear time-domain multi-physics (aero-hydro-servo-elastic)
  - Capture system-level physics interactions
  - Derived from theory/fundamental laws of physics, with appropriate simplifications & assumptions, & supplemented with computational solutions & test data
  - Not fully predictive, so V&V is fundamental



IEA Wind Task 11 TEM #80 42 National Renewable Energy Laboratory

FAST Modularization Framework

Why was a New Framework Needed?

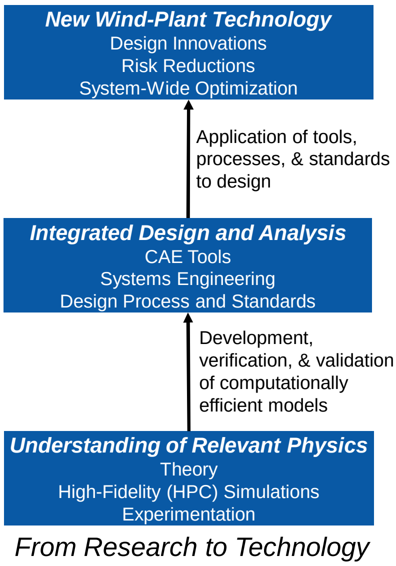
Problem	Solution
• Limited range of modeling fidelity	• Framework allowing modules to be exchanged • Development of new modules of higher fidelity
• Solution driven by structural solver	• Separate module interface & coupler
• Inability to isolate a given model • Inability to be driven by other codes	• Modules that can be called by separate driver programs or interfaced together to form a coupled solution
• Dependent spatial discretizations & time steps across modules	• Library of spatial elements & mesh-to-mesh mapping • Data transfer with interpolation/extrapolation in time
• Inability to linearize all system equations	• Tight coupling with options for operating-point determination & linearization
• Focus on single turbine	• Dynamic allocation of modules for wind-plant simulation
• "Spaghetti code" due to unclear data transfer & global data	• Modularization with data encapsulation
• Limited number of developers due to code size & complexity	• Modularization of code into separate components • Programmer's handbook explaining code development requirements & best practices
• Potentially poor numerical accuracy & stability	• Multiple coupling schemes & integration/solver options

IEA Wind Task 11 TEM #80 43 National Renewable Energy Laboratory

Other NREL Activities in FOWT

Overview

- Development, verification, & validation of software, including **FAST**
- Development of design requirements for FOWT:
  - Simulation length & wind/wave misalignment requirements
  - IEC FOWT TS
  - Hurricanes
  - BOEM regulations
  - Ice
- Support for US offshore development:
  - Modeling
  - Testing
  - Economic analysis
  - Siting
  - Controls development



IEA Wind Task 11 TEM #80 44 National Renewable Energy Laboratory

Conclusions & Outlook

Summary

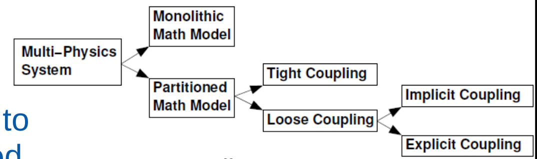
- CAE tools are required to address WT design challenges, so that WTs are:
  - Innovative
  - Optimized
  - Reliable
  - Cost-effective
- Improved models are needed to address/develop:
  - Upscaling to larger sizes
  - Novel architectures
  - Novel control devices
  - Coupling to offshore platforms
  - Design at the wind-plant level
  - System-wide optimization

SWT-6.0-154 with Airbus A380

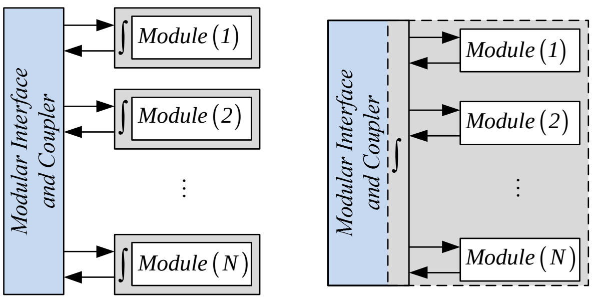
Horns Rev Wind Farm

What is the FAST Modularization Framework?

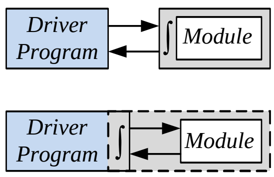
- A means by which various mathematical models are implemented in distinct modules & interconnected to solve for the global, coupled, dynamic response of a system



Coupling Taxonomy



Loose- (Left) & Tight- (Right) Coupling Schemes



Uncoupled Solution of a Module Intended for Loose (Top) & Tight (Bottom) Coupling

CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Towards the integration of multi-scale atmospheric models and wind energy systems

Javier Sanz Rodrigo

IEA Task 11 TEM#80, NREL, 12-13 January 2015

Gobierno de Navarra

Contents

1. Context of Wind Resource Assessment (WRA) research
2. The New European Wind Atlas (NEWA, 2015-2019)
3. IEA Task 31 “Wakebench” Phase 2: VV&UQ of wind farm flow models (2015-2018)
4. WRA within the WESE framework
5. Conclusions

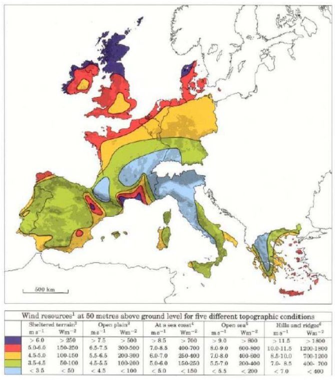
CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Gobierno de Navarra

WRA Context: The Tradition

Traditional wind resource assessment focus on three elements:

1. Wind farm design by maximizing the Annual Energy Production (AEP) Methodologies based on the EU Wind Atlas methodology developed by Risø (1989)
   - ❑ Wind climatology based on mast measurements + long-term corrections
   - ❑ Microscale steady-state flow model
   - ❑ Idealized power curve
2. Verifying site suitability (IEC site assessment)
   - ❑ based on short-term mast measurements
3. Quantifying AEP uncertainties
   - ❑ based on engineering methods



European Wind Atlas. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Gobierno de Navarra

WRA: Moving Forward

FROM	TO
1. AEP not the only design driver especially in complex terrain and offshore	1. Use cost of energy (COE) instead by assessing CAPEX+OPEX (minimize cost/MWh or maximize IRR)
2. Electrical and availability losses based on "experience"	2. Site-dependent simulated losses based on scenarios of grid infrastructure (curtailment) and environmental conditions (icing, logistics, etc)
3. Microscale mean flow model not sufficient in large wind farm clusters	3. Meso-micro modeling to combine relevant scales contributing to AEP
4. Idealized power curve $P(U_{hub})$ not suitable in steep terrain and under stable conditions	4. Realistic power-curve $P(U_{hub}, TI, \text{etc})$ by turbine modeling
5. Short measurement periods not representative for extremes	5. Use downscaled long-term reanalysis products
6. AEP uncertainty is not a Gaussian process	6. Model of uncertainty propagation of inputs and models

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Gobierno de Navarra

WRA: Project Finance

- Power purchase agreements (PPA) for project finance based on a fixed price along the 20-year lifetime of a wind farm are too challenging nowadays
  - ❑ Electricity rates difficult to predict (market volatility)
  - ❑ Risk of project underperformance (future wind variability, curtailment, etc)

- Instead, more flexible instruments are introduced to mitigate the risks associated to market and wind variability
  - ❑ Hedge contracts to negotiate production differences
  - ❑ Need some knowledge of wind predictability at different scales (inter-annual, inter-monthly, day-ahead, etc) since it is based on these differences that the contract is negotiated
  - ❑ Time varying IRR

- **From**: long-term AEP distribution → **To**: scenarios (time series) of future wind power production (virtual wind farms)

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES · Gobierno de Navarra

New EU Wind Atlas (NEWA)

- 2015 – 2019
- ERA-Net Plus: 13 M€
  - 1/3 EU funds
  - 2/3 National funds
- 8 countries
- Coordinator: Jakob Mann (DTU-Wind)
- To start soon…

- Main objective:

The assessment and mapping of wind resources towards the reduction of uncertainties to less than 3% for flat homogenous terrains, and to less than 10% for any terrain, concerning wind energy production and wind conditions that affect the design of wind turbines.

www.euwindatlas.eu

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Ciemat — Gobierno de Navarra

NEWA: Project Structure and Deliverables

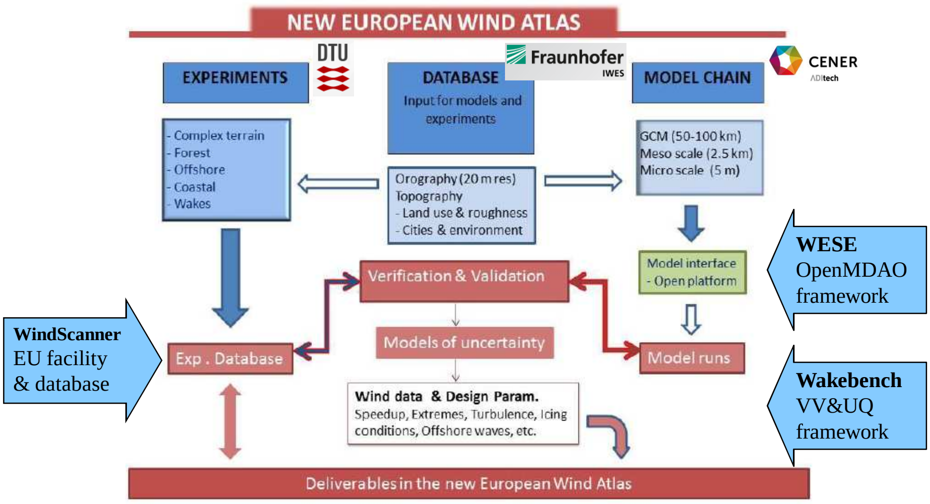


Diagram from Hans E. Jørgensen (DTU-Wind)

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Ciemat — Gobierno de Navarra

NEWA: Experiments

Patchy forested hill near Kassel

- Fraunhofer-IWES test site with 200-m tower
- Windscanner.eu experiment in July 2014

Perdigao double-hill, steep terrain

- Participation of US through a NSF project

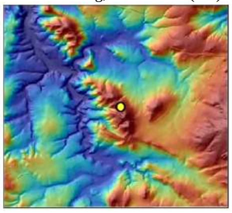
Alaiz complex terrain mesoscale

- Ebro valley large-scale channeling
- Hill-mountain interaction
- Wakes, forest

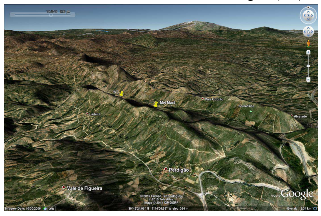
Northern EU coastal-offshore

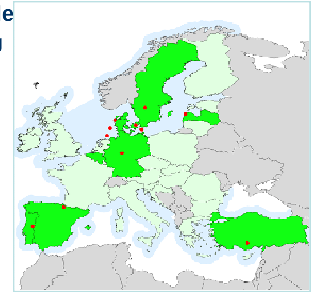
- Network of tall met masts
- Satellite data
- Long-range scanning lidars measuring from the coast
- Lidars on ferries
- Focus on mesoscale models

Rödeser Berg, near Kassel (GE)

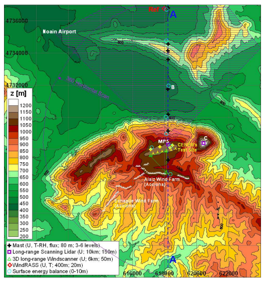


Perdigao (PT)





Alaiz (SP)



CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Gobierno de Navarra

---

iea wind

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

IEA Wind Task 31 Wakebench

Phase 2 (2015-2018)

Validation Verification and Uncertainty Quantification (VV&UQ) of wind farm flow models

Javier Sanz Rodrigo, Iván Moya Mallafré (CENER),
Patrick Moriarty (NREL), Pierre-Elouan Réthoré (DTU)

Gobierno de Navarra

Context and Issues

Models…

- Wide range of models with different fidelity levels (from linearized to full LES)
- Wind industry progressively adopting design tools with higher levels of multidisciplinary integration
- Lack of wind flow modeling standards lead to high user dependencies

Experimental data…

- High-fidelity experimental data scarce, typically limited to academic test cases
- Large amount of proprietary operational data, not available in general

Model evaluation…

- Model intercomparison benchmarks are very often biased (lack of information about experimental data, unfair comparison among models of different scope, etc)
- Lack of industry standards to assess model suitability to intended use
- Lack of open-access repositories for model evaluation (most of the data comes from journal articles or through bilateral data licensing agreements)

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES | GOBIERNO DE ESPAÑA MINISTERIO DE INDUSTRIA, ENERGÍA Y TURISMO MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD | Ciemat | Gobierno de Navarra

Needs

Models…

- Have to be certified for the intended use
- Users are also a very influencial part on the modeling so they alse need to be certified

→ Flow modeling standards (or best practice guidelines) are necessary

Experimental data…

- Sustained provision of experimental data is required for the continuous improvement of models and standards

→ Remove barriers to guarantee access to operational (industry) data

Model evaluation…

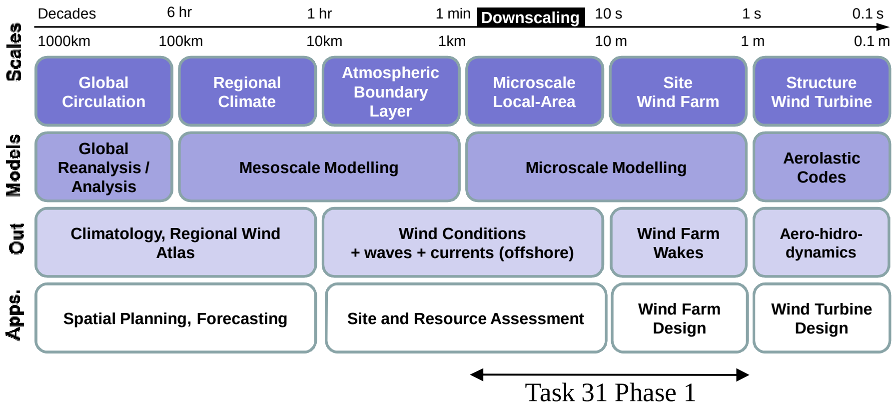
- Adopt model evaluation procedures that can be mutually adopted by the wind energy community

→ Generate *strong-sense* benchmarks: engineering standards that define a comprehensive framework for model testing, the requirements for model intercomparison and a set of acceptance criteria considering the intended use of the models

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES | GOBIERNO DE ESPAÑA MINISTERIO DE INDUSTRIA, ENERGÍA Y TURISMO MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD | Ciemat | Gobierno de Navarra

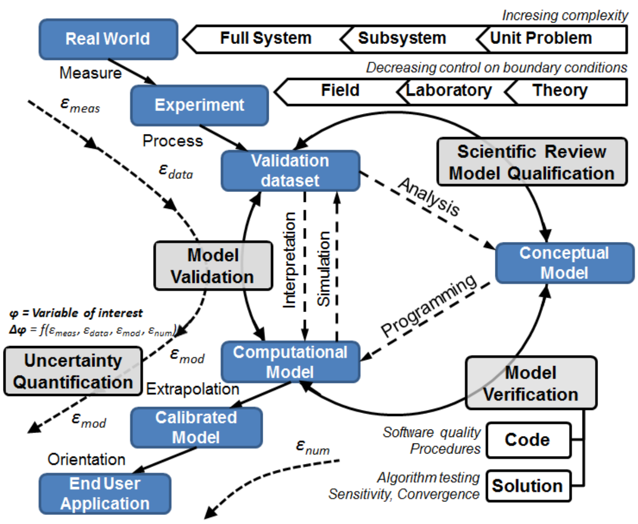
Extended Modeling Scope

- Extend validation to mesoscale and near-wake modeling in order to cover all the relevant atmospheric scales of a wind farm
- Focus on wind resource and site assessment applications



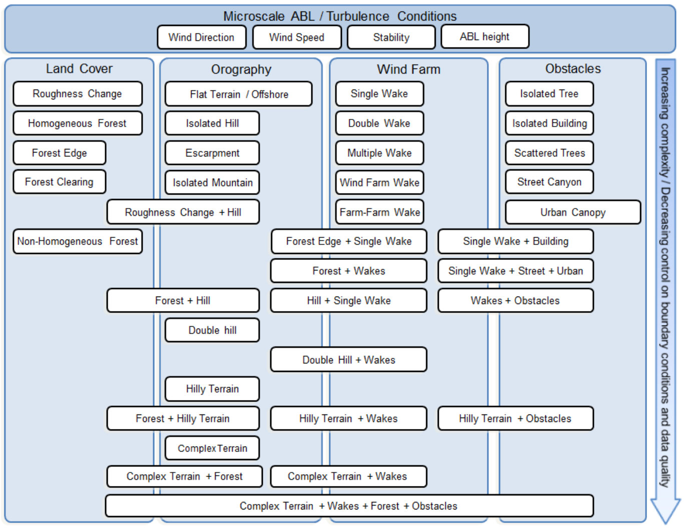
CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES Gobierno de Navarra

Extended Evaluation Framework



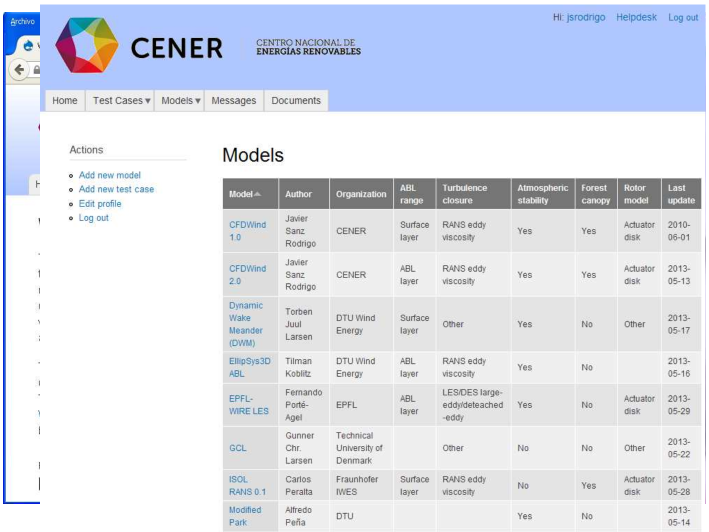
CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES Gobierno de Navarra

Building-Block (microscale) Model Evaluation Framework



CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Windbench.net: Online management of validation benchmarks

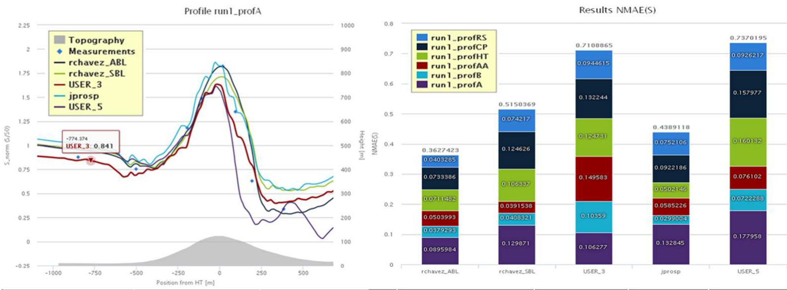


Model	Author	Organization	ABL range	Turbulence closure	Atmospheric stability	Forest canopy	Rotor model	Last update
CFDWind 1.0	Javier Sanz Rodrigo	CENER	Surface layer	RANS eddy viscosity	Yes	Yes	Actuator disk	2010-06-01
CFDWind 2.0	Javier Sanz Rodrigo	CENER	ABL layer	RANS eddy viscosity	Yes	Yes	Actuator disk	2013-05-13
Dynamic Wake Meander (DWM)	Torben Juul Larsen	DTU Wind Energy	Surface layer	Other	Yes	No	Other	2013-05-17
EllipSys3D ABL	Tilman Koblitz	DTU Wind Energy	ABL layer	RANS eddy viscosity	Yes	No		2013-05-16
EPFL-WIRE LES	Fernando Porté-Agel	EPFL	ABL layer	LES/DES large-eddy/deteached -eddy	Yes	No	Actuator disk	2013-05-29
GCL	Gunner Chr. Larsen	Technical University of Denmark		Other	No	No	Other	2013-05-22
ISOL RANS 0.1	Carlos Peralta	Fraunhofer IWES	Surface layer	RANS eddy viscosity	No	Yes	Actuator disk	2013-05-28
Modified Park	Alfredo Peña	DTU			Yes	No		2013-05-14

- ✓ **Repository** of models, test cases and benchmarks
- ✓ **IPR protection** ensured by allowing data owners to control the users accessibility
- ✓ **Peer-reviewed** by Scientific Committee members

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Windbench.net: Online benchmarking

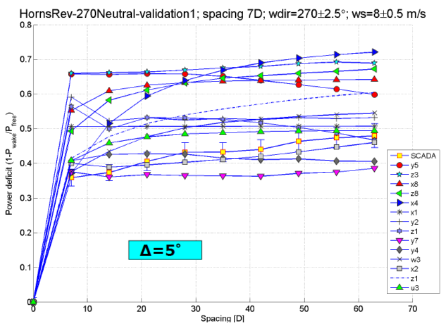


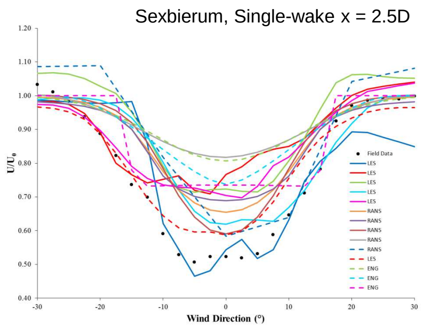
Profile\User		rchavez_ABL	rchavez_SBL	USER_3	jprosp	USER_5
run1_profRS	NMAE (S) NMAE (TKE)	0.04 0.12	0.07 0.16	0.09 0.06	0.08 0.17	0.09 0.25
run1_profCP	NMAE (S) NMAE (TKE)	0.07 0.35	0.12 0.38	0.13 0.41	0.09 0.16	0.16 0.28
run1_profHT	NMAE (S) NMAE (TKE)	0.07 0.39	0.11 0.37	0.12 0.69	0.05 0.37	0.16 0.35
run1_profAA	NMAE (S) NMAE (TKE)	0.05 0.28	0.04 0.32	0.15 0.34	0.06 0.4	0.08 0.29
run1_profB	NMAE (S) NMAE (TKE)	0.04 -	0.04 -	0.1 -	0.03 -	0.07 -
run1_profA	NMAE (S) NMAE (TKE)	0.09 0.23	0.13 0.29	0.11 0.36	0.13 0.27	0.18 0.46

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Gobierno de España — Ministerio de Industria, Energía y Turismo — Ministerio de Economía y Competitividad — Ciemat — Gobierno de Navarra

Reducing the spread

- Decrease user dependencies
- In-depth analysis of model performance
- Some benchmarks will be explored in finer detail to better quantify the uncertainty of a range of models for different phenomena





CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Gobierno de España — Ministerio de Industria, Energía y Turismo — Ministerio de Economía y Competitividad — Ciemat — Gobierno de Navarra

WRA within the WESE framework

Characteristics

- **Holistic**: multi-scale full-system analysis
- **Multidisciplinary**: meteorology + wind engineering + financing + social
- **Integrated**: address different end-user needs (not only developer)
- **Life-cycle oriented**: WRA as planning + operation to minimize LCOE

Framework

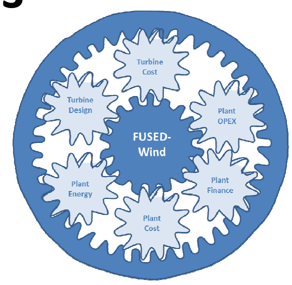
- **OpenMDAO**: to interconnect models using the same I/O interfaces
- **Windbench**: to benchmark models and carry out a systematic verification and validation process
- **Uncertainty Quantification**: on inputs and models (deterministic vs probabilistic approach)
- **Analysis**: evaluate different KPIs, reports
- **Optimization**: using different cost models depending on the stakeholder(s) objective(s)
- **Organization**: management of model developers and end-users (who develops what, user requirements, data needs, etc)
- **Collaboration**: open-source, web-based, joint-developments, etc

Conclusions

- New era of wind resource assessment technology coming up → It is timely to define end-user requirements considering integrated approaches like WESE
- Need to focus on "reducing the spread" of our flow models in order to be able to standardize WRA methodologies
  - ❑ The VV&UQ process should become an integral part of the WRA methodologies both at the model developer and end-user sides
- New experimental databases will substantially improve our understanding of the complex flow physics of wind farms but…
- We also need industry to engage with the provision of high-quality data in order to populate the validation range
- Flow models moving towards more integration of meso to micro scales
  - ❑ Better physical insight
  - ❑ More opportunities to consider life-cycle integrated models


www.cener.com
CENER
CENER
CENTRO NACIONAL DE
ENERGÍAS RENOVABLES

The Framework for Unified Systems Engineering and Design of Wind Plants (FUSED Wind)



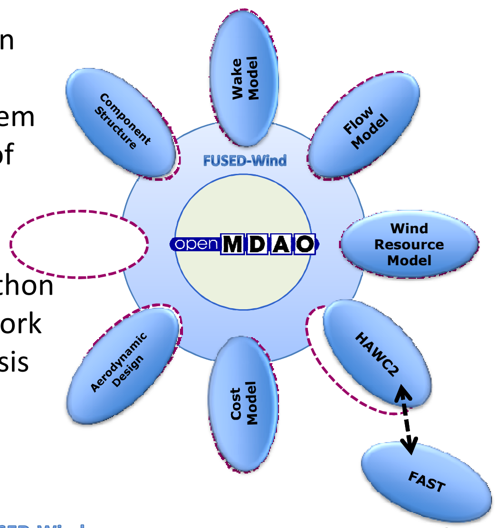
IEA TEM #80 on Wind Energy Integrated RD&D
January 12th, 2015

Pierre-Elouan Rethore & Frederik Zahle, DTU Wind Energy
Katherine Dykes & Peter Graf, NREL National Wind Technology Center
Andrew Ning, Brigham Young University

FUSED-Wind

FUSED Wind

- Collaborative effort between **DTU** and **NREL** to create a **F**ramework for **U**nified **S**ystem **E**ngineering and **D**esigned of **W**ind energy plants.
- Based on OpenMDAO, a python based **Open** source framework for **M**ulti-**D**isciplinary **A**nalysis and **O**ptimization.



1/16/2015 FUSED-Wind 2

FUSED-Wind

- The FUSED-Wind mission is to establish an open-source collaborative platform for research in wind energy MDAO:
  - Define standard interfaces for wind turbine and plant models
  - Define standard assemblies for common wind energy workflows that are "model agnostic"
  - Establish a library of wind energy model wrappers and utilities to support common analyses
  - Provide standard generic tools to use in wind energy (e.g. standard inputs / outputs files, IEC load calculation, multi-fidelity, UQ)

1/16/2015 FUSED-Wind 3

User scenarios:

"As a wind turbine engineer I would like to …"

- Perform multi-disciplinary optimization/analysis of a wind turbine with my own sub-models
- obtain easily a "second opinion" on my design by swapping the aero-elastic model
- run an optimization with turbine component and aeroelastic models of varying levels of fidelity
- expand the optimization to include 3rd party energy production and cost models

1/16/2015 FUSED-Wind 4

User scenarios:

"As an innovative component technology designer I'd like to…"

- Perform multi-disciplinary optimization/analysis of a wind turbine with my own sub-models for my component technology
- obtain easily a "second opinion" on my design by comparison to conventional technology
- run an optimization with turbine component and aeroelastic models of varying levels of fidelity
- expand the optimization to include 3rd party energy production and cost models

1/16/2015 FUSED-Wind 5

User scenarios:

"As a wind farm planner I would like to …"

- Perform multi-disciplinary optimization/analysis of a wind farm with my own sub-models
- obtain easily a "second opinion" on my design by swapping the wind farm flow model
- run an optimization with wind farm flow models of varying levels of fidelity
- expand the optimization to include 3rd party turbine and cost models

1/16/2015 FUSED-Wind 6

User scenarios:

"As a researcher I would like to …"

- have a common multi-disciplinary optimization-analysis framework to apply my model in a larger context and to other models
- have standard assemblies to benchmark optimizers on the same problem
- have a platform for promoting and getting feedback on my models
- to make my model as "easy to use" as possible by my collaborators and end-users

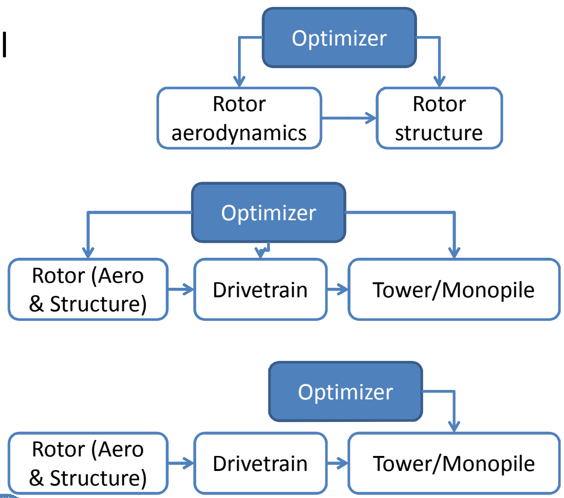
1/16/2015 FUSED-Wind 7

Example Applications

1) Rotor Aero-structural optimization

2) Full turbine redesign

3) Design of substructure for specific offshore sites



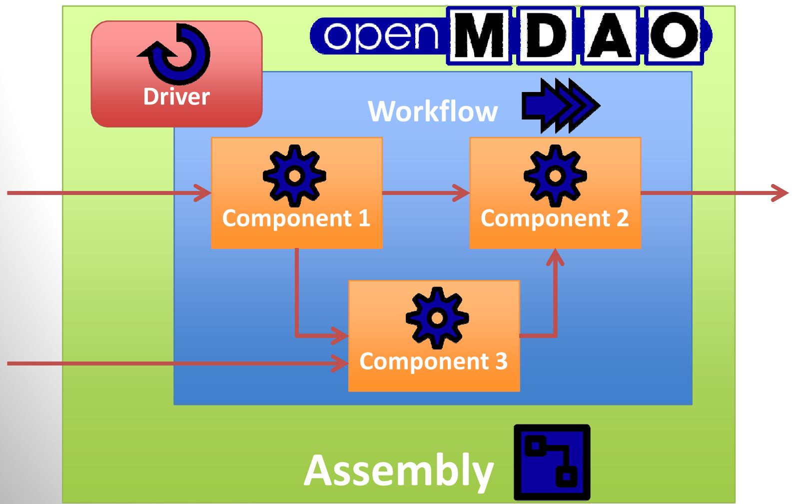
1/16/2015 FUSED-Wind 8

FUSED-Wind Interface Definitions

- Environmental conditions
- Wind turbine
  - Blade geometry and airfoil data
  - Detailed structural description
  - Aerodynamic outputs
  - Solver interfaces
- Wind plant
  - Layout
  - Wake models
  - AEP, Capacity factor
- Wind plant cost
  - Balance of Station
  - Operational Expenditures
  - Financing

1/16/2015 FUSED-Wind 9

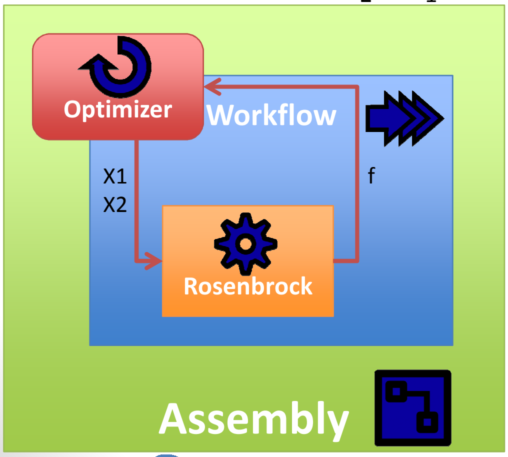
What is OpenMDAO?



1/16/2015 FUSED-Wind http://www.openmdao.org 10

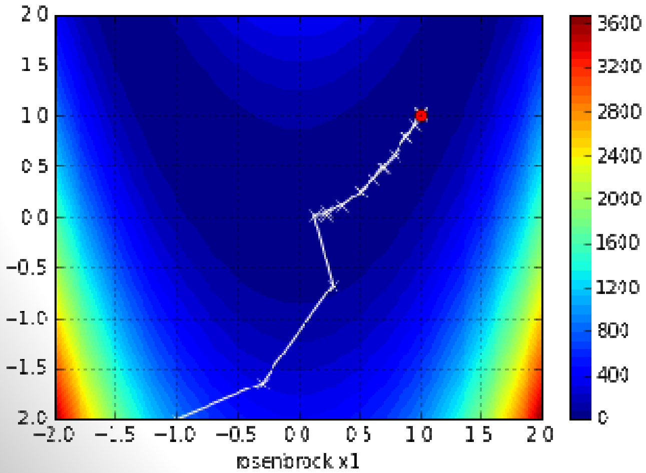
OpenMDAO Example: The Rosenbrock Optimization

The Rosenbrock function: $f = 100(x_2 - x_1^2)^2 + (1 - x_1)^2$



1/16/2015 FUSED-Wind 11

OpenMDAO Example: The Rosenbrock optimization



1/16/2015 FUSED-Wind 12

Different Types of Drivers in OpenMDAO

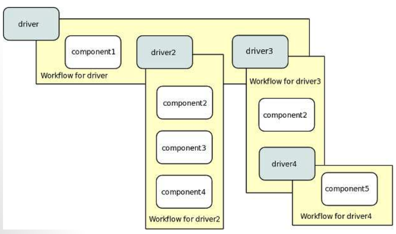
- **~50 Optimizers**
  - Native optimizers built into OpenMDAO and other available from plug-ins (DAKOTA, pyOpt)
  - Support for analytic gradients
- **Uncertainty Analysis**
  - Native drivers for Design of Experiments, Sensitivity Analysis, Uncertainty Quantification and many others available from plug-ins (DAKOTA, pyOpt)
- **Support for Parallelism**
  - Current version of OpenMDAO (v. 0.10.3) supports parallelism across workflow
  - Future versions of OpenMDAO will support parallelism across and within components using MPI.

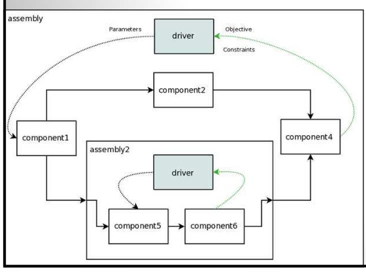
1/16/2015 FUSED-Wind 13

Reconfiguration of OpenMDAO Assemblies

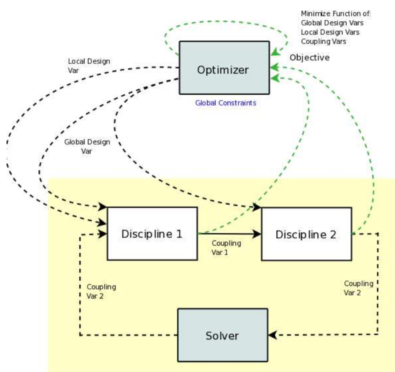
Increases Potential Analysis Complexity

Several nested drivers within one assembly

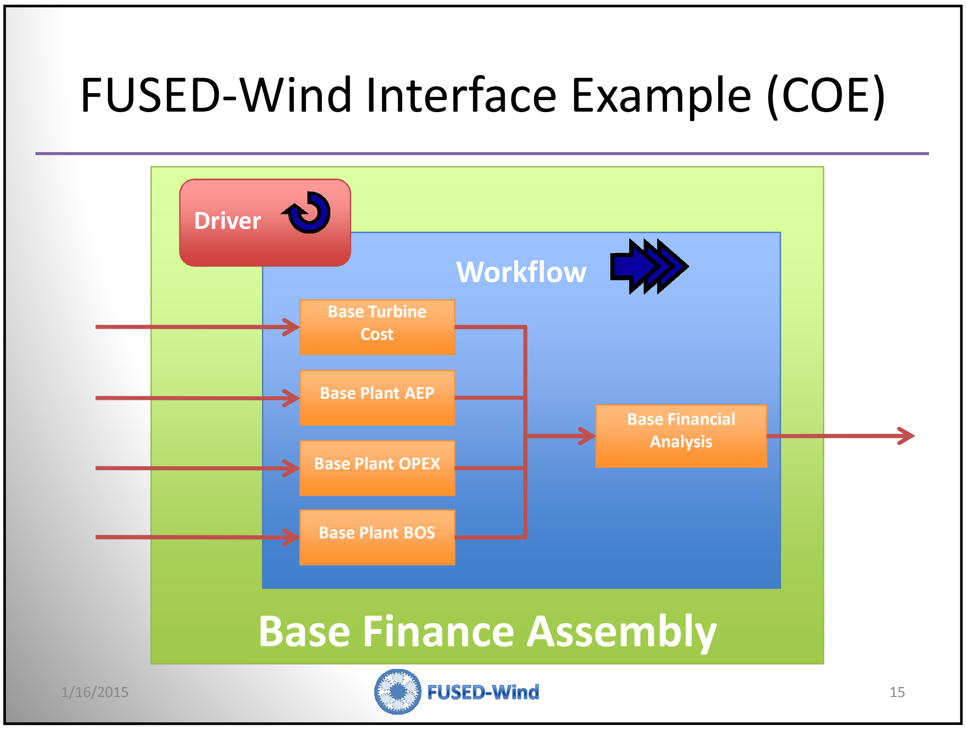


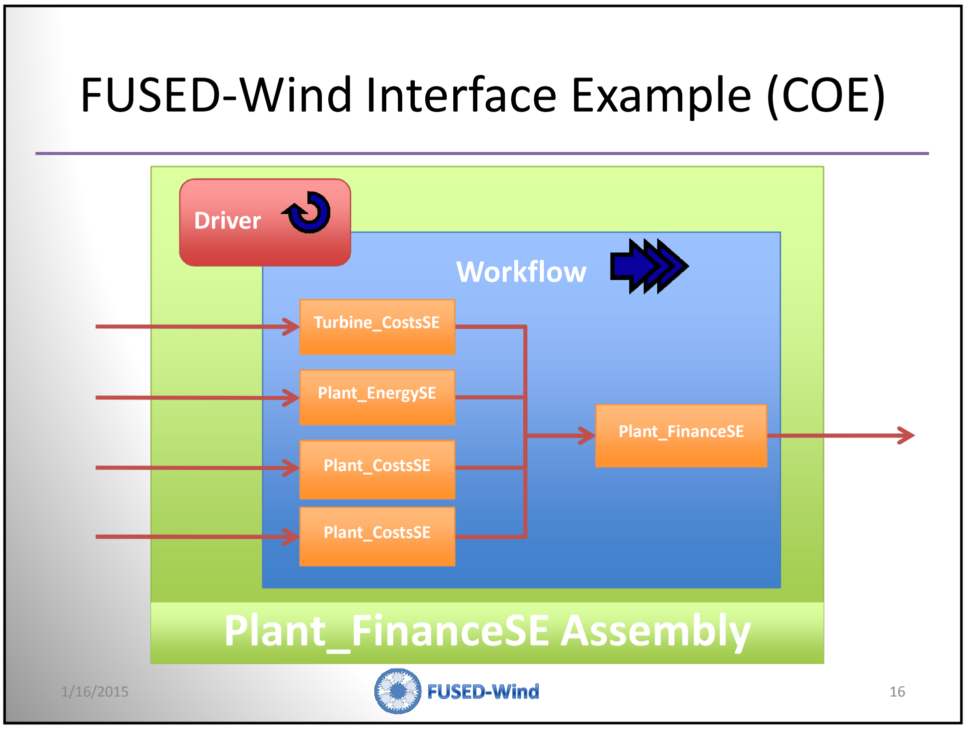


OpenMDAO handles the local and global analysis dependencies



FUSED-Wind 14


FUSED-Wind Interface Example (COE)
Driver
Workflow
Base Turbine Cost
Base Plant AEP
Base Plant OPEX
Base Plant BOS
Base Financial Analysis
Base Finance Assembly
1/16/2015
FUSED-Wind
15


FUSED-Wind Interface Example (COE)
Driver
Workflow
Turbine_CostsSE
Plant_EnergySE
Plant_CostsSE
Plant_CostsSE
Plant_FinanceSE
Plant_FinanceSE Assembly
1/16/2015
FUSED-Wind
16

Models currently wrapped to FUSED-Wind

- DTU:
  - AirfoilOpt2:
    - Xfoil
    - EllipSys2D
  - HawtOpt2:
    - HAWC2
    - HAWCstab2
    - BECAS
    - CSProps
    - EllipSys3D
  - TOPFARM
  - Wake models:
    - GC Larsen
    - NO Jensen
    - FUGA
    - EllipSys3D (wind farms)
  - WAsP-CFD
  - WRF
- NREL:
  - WISDEM
    - Turbine_CostsSE
    - Plant_CostsSE
    - Plant_EnergySE
      - Includes AWS Truepower openWind wrapper
    - Plant_FinanceSE
    - AeroelasticSE
      - Includes FAST7 wrapper (will include FAST8)
    - RotorSE
    - DriveSE
    - Tower/MonopileSE
    - JacketSE
    - FLORISSE
    - WindSE

1/16/2015 FUSED-Wind 17

ROADMAP

- v0.1: Jan 2015
  - Website
  - Public release
  - Standard interfaces for plant cost, energy production and turbine design
  - Gather stakeholder feedback
- v0.2: June 2015?
  - Adapt framework to accommodate models from new collaborators
  - Swappability of key models:
    - Benchmarking of NREL and DTU turbine aero-structural design codes
    - HAWC2/FAST
    - WAsP/OpenWind
  - Standard input/output files for
    - wind turbine
    - wind farm

1/16/2015 FUSED-Wind 18

Farther Ahead

- Incorporation of high-fidelity CFD / FEM turbine models
- Multi-fidelity modeling with combined analysis with several models
- FUSED-Wind as a platform of collaboration in EU projects (IRP-Wind, NEWA, OEUVRE) and potentially others
- Automatic benchmarking with windbench.net
- ….more ideas?

1/16/2015 FUSED-Wind 19

TOPFARM, HawtOpt, AirfoilOpt: Three FUSED-Wind based toolsets

Pierre-Elouan Réthoré, Frederik Zahle
Et al
DTU Wind Energy

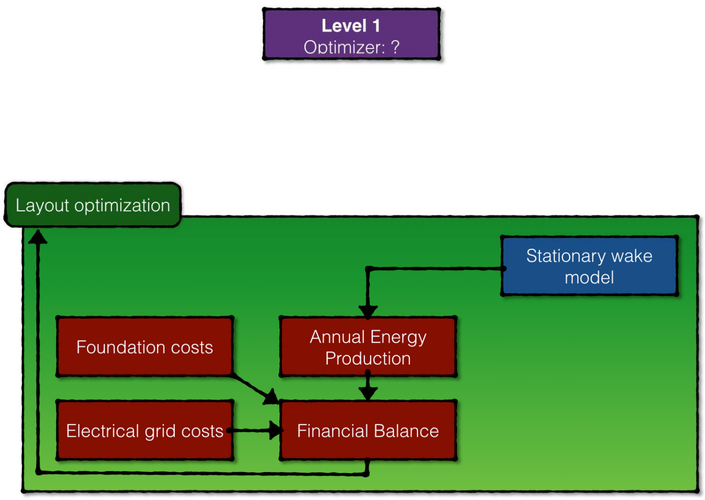
Outline

- TOPFARM
  - Vision
  - System
  - Current status
  - FUSED-Wind interfaces utilized
  - Roadmap
- HawtOpt
- AirfoilOpt

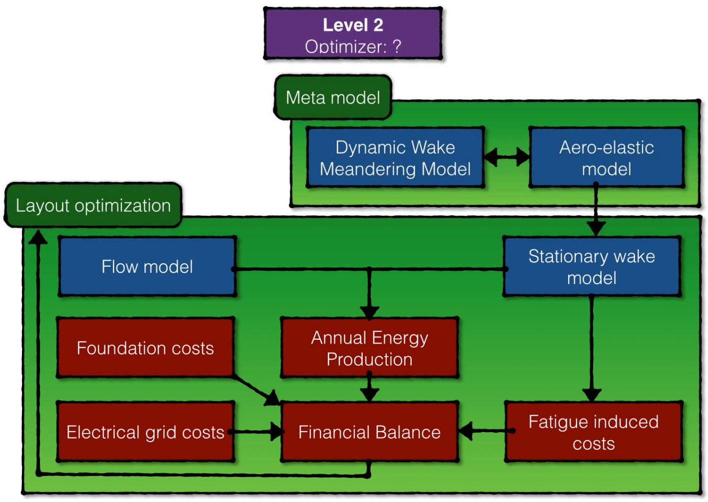
TOPFARM - Vision

- A collaborative open source framework to optimize onshore and offshore wind farms
- Offering the ability to optimize wind farms taking into account all relevant aspects, including wake induced fatigue
- A model “agnostic” reference workflow to benchmark sub-components
- An industry friendly framework that can easily be implemented in-house, while accommodating existing workflows and models

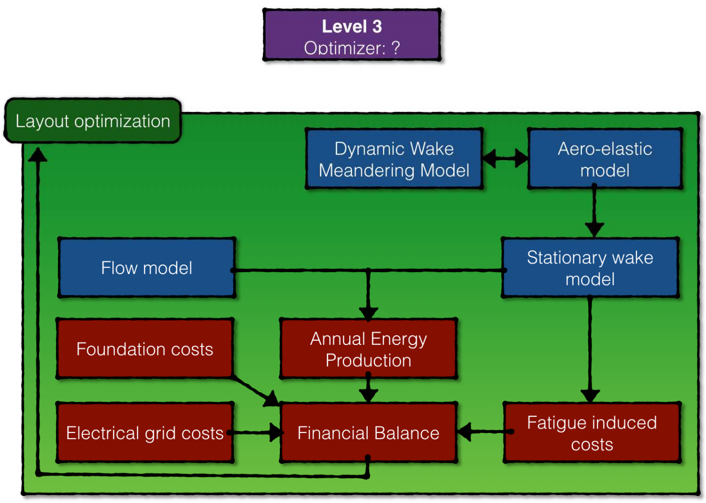
TOPFARM – System



TOPFARM - System



TOPFARM - System



TOPFARM – Current Status

- v0.1 will soon be released in open source on github
- It allows to do a wind park optimization using a FUSED-Wind compatible wind farm flow model (GCL is included)
- A simple electrical grid cost model
- A simple offshore foundation cost model

FUSED-Wind Interfaces Utilized

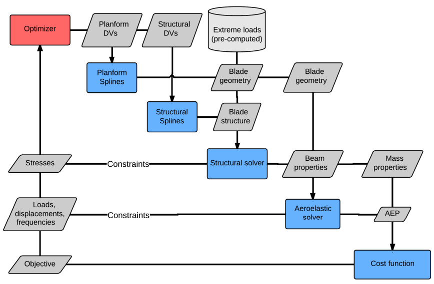
- Wind Farm Layout
- Wind Rose
- Wind Farm Cost Models
- Wind Farm Flow Model
- Wind Farm AEP calculation
- Wind Turbine Description

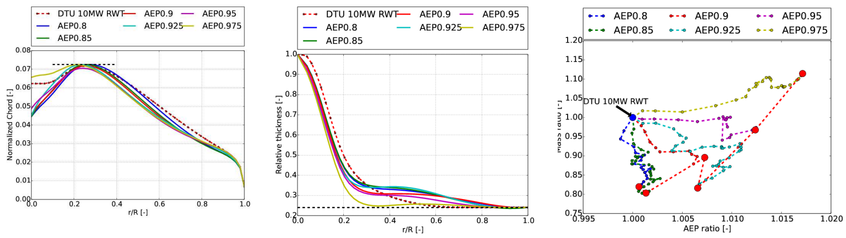
TOPFARM - Roadmap

- **v0.1** January 2015:
  - Level 1
  - wake: GCL
- **v0.2** June 2015:
  - Level 2
  - Fatigue cost model
  - wake: GCL, NOJ, Ainslie, FUGA
  - Definition of DTU Wind new cost model
  - Parallelization of the optimization on cluster
- **v0.3** January 2016:
  - Level 3
  - Connection to WAsP-CFD
  - wake: EllipSys3D

HawtOpt2: Tool for Aero-Servo-Elastic Design of Wind Turbines

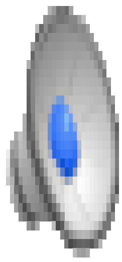
- Simultaneous optimization of blade planform and detailed internal structure.
- Simulation codes: BECAS (structure), HAWCStab2 (loads, displacements, frequencies).
- Allows for systematic exploration of different objectives and constraints.
- Frequency placement, controller tuning
- Passive load alleviation using bend-twist coupling
- Frequency based fatigue model





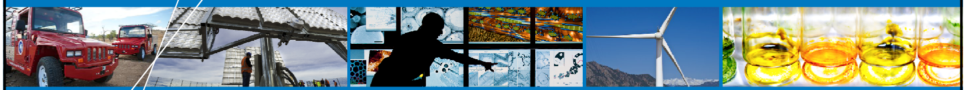
AirfoilOpt2: Tool for aerodynamic, acoustic and structural design of Airfoils

- Aerodynamics predicted by either XFOIL of EllipSys2D (2D CFD)
- Cross-sectional structure: BECAS
- Trailing edge noise: TNO-like based on boundary layer input from either XFOIL or EllipSys2D
- Example: multi-point optimization of a 30% airfoil
  - Maximize L/D at three AOAs mixed tripped/free transition
  - Constraints on spar-cap box size
  - Constraints on transition close to stall



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Introducing WISDEM:
An Integrated System Modeling for Wind Turbines and Plants



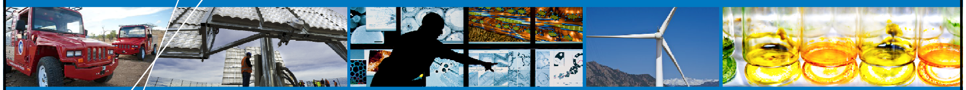
January 12th, 2015

Katherine Dykes, Peter Graf, George Scott, Andrew Ning, Ryan King, Yi Guo, Taylor Parsons, Rick Damiani, Fort Felker and Paul Veers

Outline

- NREL NWTC Wind Energy Systems Engineering Program and Software
  - Integrated Wind Turbine and Plant Modeling
  - Software Platform
  - Summary and Future Work

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Integrated Wind Turbine and Plant Modeling

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Wind Energy System Cost of Energy

- **Often use simplified Cost of Energy representation as global system objective:**

$$COE = \frac{F * (CAPEX) + OPEX}{AEP}$$

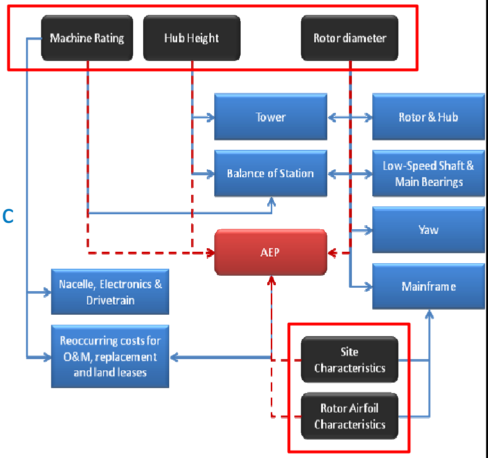
  - Where COE is cost of energy, CAPEX is the sum of BOS is Balance of Station cost, TCC is Turbine Capital Cost (for full project), F is the financing rate to annualize investment costs, OPEX are the annual operating expenses and AEP is the net annual energy production

NATIONAL RENEWABLE ENERGY LABORATORY 4

Determining Wind Cost of Energy

- **Current "NREL Cost and Scaling Model" uses parameterized functional relationships calibrated to historical trends**
  - o Originated with detailed design studies in early 2000s (WindPACT)
  - o Abstraction to simple parametric relationships
  - o Useful for two primary types of analyses on system costs:
    - – Changing input factor prices over time
    - – Scaling of conventional technology within a limited range
  - o Publically available model

Current structure of cost model



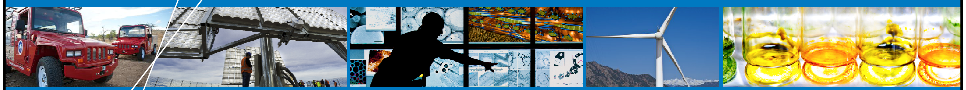
NATIONAL RENEWABLE ENERGY LABORATORY 5

NREL Wind Energy System Engineering

The National Wind Technology Center (NWTC) wind energy systems engineering initiative has developed an analysis platform and research capability to capture important *system interactions* to achieve a better understanding of how to improve *system-level performance* and achieve *system-level cost reductions*.

NATIONAL RENEWABLE ENERGY LABORATORY 6

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Software Platform

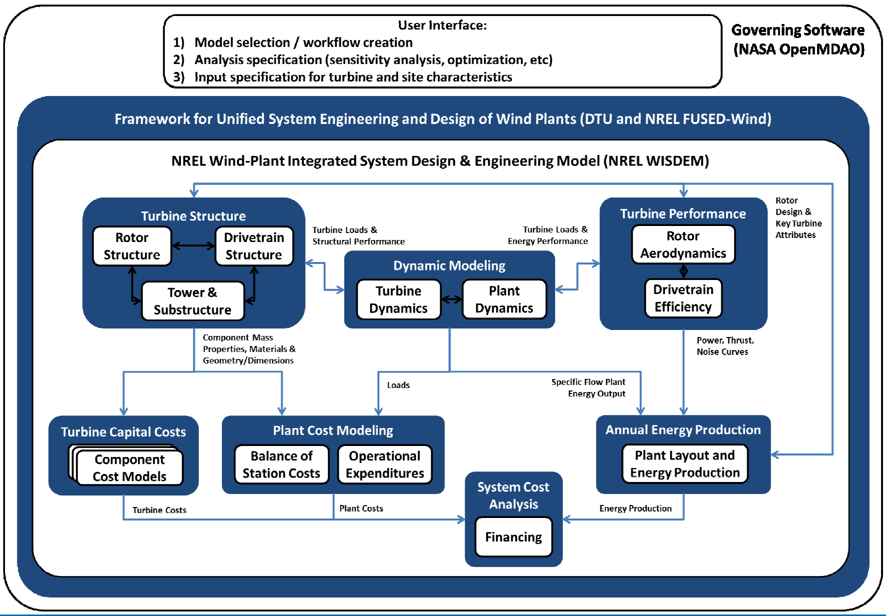
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL Wind Energy System Engineering

- **NREL has a Systems Engineering effort to develop, maintain, and apply a software platform to:**
  - Integrate wind plant engineering performance and cost software modeling to enable full system analysis.
  - Apply of a variety of advanced analysis methods in multidisciplinary design analysis and optimization (MDAO) and related fields.
  - Develop a common platform and toolset to promote collaborative research and analysis among national laboratories, industry, and academia.

NATIONAL RENEWABLE ENERGY LABORATORY 8

Systems Engineering Software Framework



NATIONAL RENEWABLE ENERGY LABORATORY 9

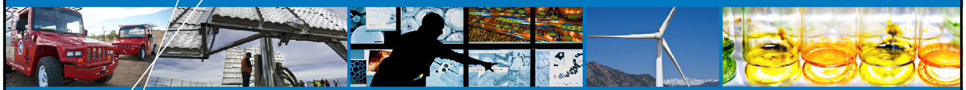
Systems Engineering Software Framework

- Integration of models into FUSED-Wind based WISDEM (http://nwtc.nrel.gov/WISDEM) includes several areas:
  1. Turbine component structure and cost models
  2. Plant energy production and cost models
- For each area, multiple levels of fidelity possible

Rotor Aero	Rotor Structure	Nacelle Structure	Tower & Support Structure	Turbine Costs	Plant BOS Costs	Plant OPEX	Plant Energy Production	Plant Finance
NREL CSM				NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM
RotorSE	RotorSE	NacelleSE (with DriveSE option)	TowerSE / JacketSE	Turbine_ CostsSE	NREL Onshore / Offshore BOS	NREL OPEX / ECN Offshore O&M Model	AWS Truepower openWind	NREL System Advisor Model

NATIONAL RENEWABLE ENERGY LABORATORY 10

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Summary and Future Work

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Summary

1. WISDEM is a capability for modeling integrated wind plant systems for performance and cost – with ability to select model fidelity for different parts of system.

2. Initial work shows improved ability to capture system interactions moving to new SE model set and perform a large number of different types of analysis

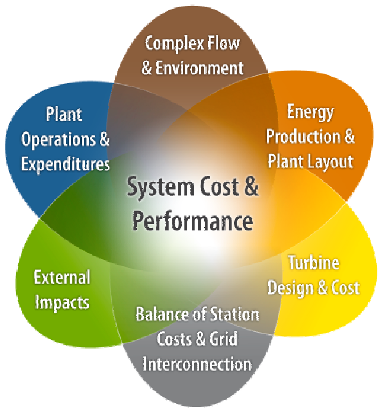
3. Tool provides ability to investigate system changes and innovations for overall cost of energy

4. Research design (model selection, variable and constraint specifications, etc.) becomes critical with a flexible system-level model.

NATIONAL RENEWABLE ENERGY LABORATORY 12

Discussion / Q&A

http://www.nrel.gov/wind/systems_engineering



http://nwtc.nrel.gov/WISDEM

NATIONAL RENEWABLE ENERGY LABORATORY 13

Optimisation of offshore wind turbines

Emulation of wind farm design for system level objective function evaluation

Michiel Zaaijer - 12 January 2015

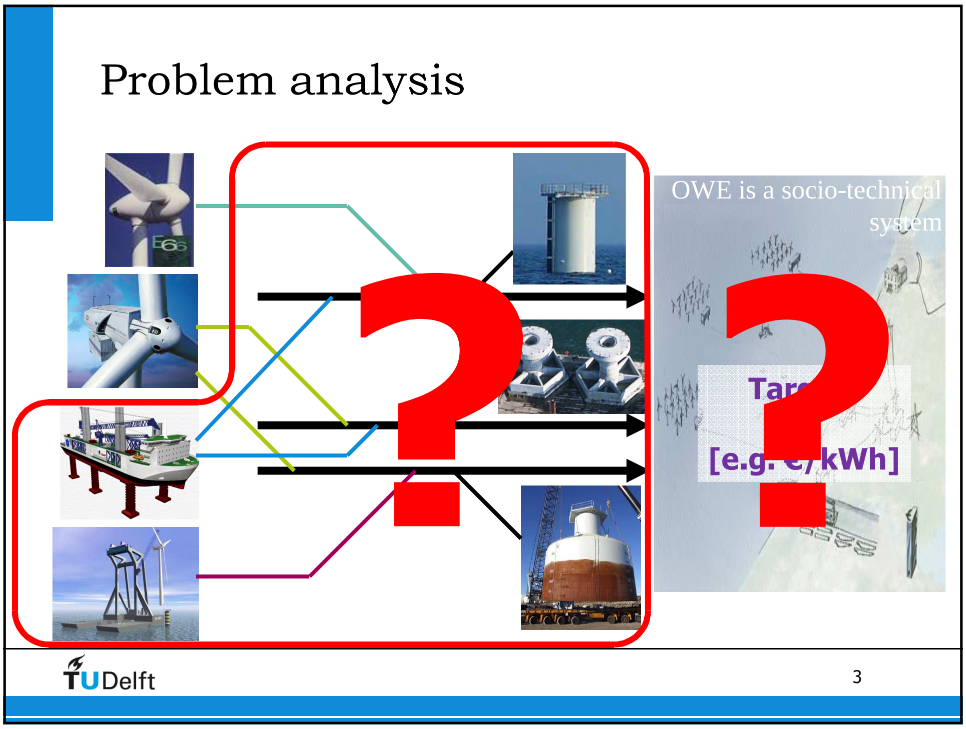
DUWIND
DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE

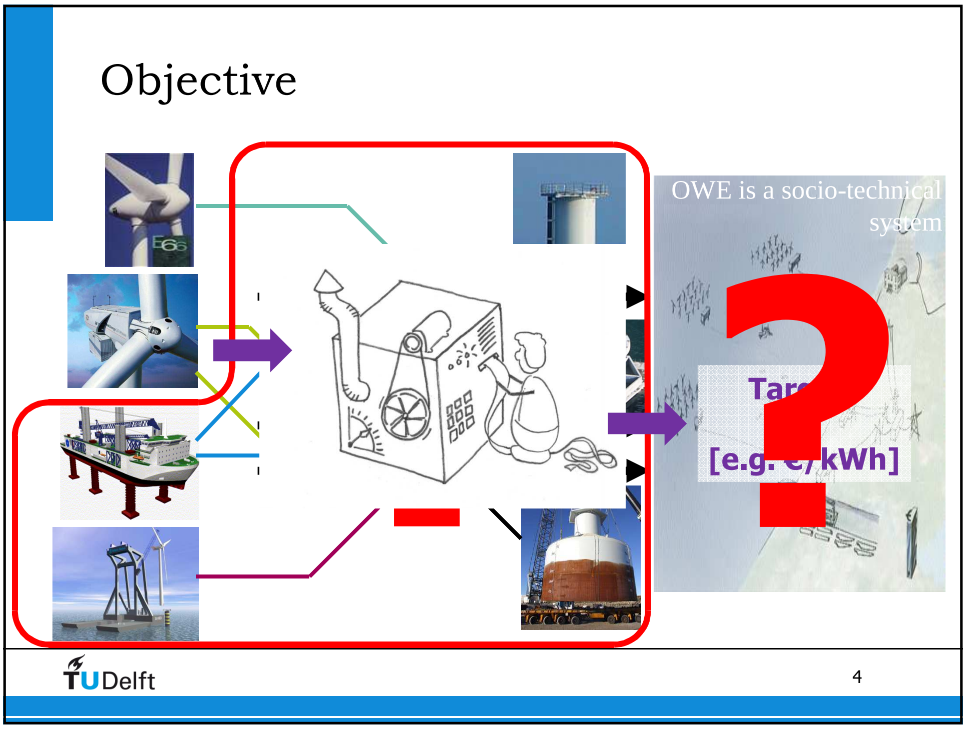
TUDelft Delft University of Technology
Challenge the future

Overview

- Problem analysis and objective
- Structure of wind farm design tool
- Appraisal of the tool
- Validation of the optimisation method
- Conclusions

TUDelft 2


Problem analysis
OWE is a socio-technical system
Tar
[e.g. €/kWh]
TUDelft
3


Objective
OWE is a socio-technical system
Tar
[e.g. €/kWh]
TUDelft
4

Formal definition of the optimisation

Problem of the user

$$\min_{\mathbf{x}_i} k(\mathbf{x}_i)$$
$$s.t. \quad \mathbf{g}_i(\mathbf{x}_i) \leq 0$$
$$\mathbf{h}_i(\mathbf{x}_i) = 0$$

Problem of the tool

$$k(\mathbf{x}_i) = \min_{\mathbf{x}_e} f(\mathbf{x}_i, \mathbf{x}_e)$$
$$s.t. \quad \mathbf{g}_j(\mathbf{x}_i, \mathbf{x}_e) \leq 0 \quad j = i, e$$
$$\mathbf{h}_j(\mathbf{x}_i, \mathbf{x}_e) = 0 \quad j = i, e$$

In words

The user optimises RNA design variables, subject to his/her own constraints, using the tool to evaluate the objective function.

The tool optimises the farm design variables, given the design vector of the user.

TUDelft 5

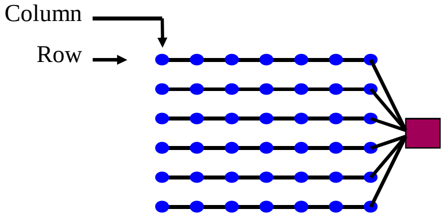
Overview

- [x] Problem analysis and objective
- [ ] Structure of wind farm design tool
- [ ] Appraisal of the tool
- [ ] Validation of the optimisation method
- [ ] Conclusions

TUDelft 6

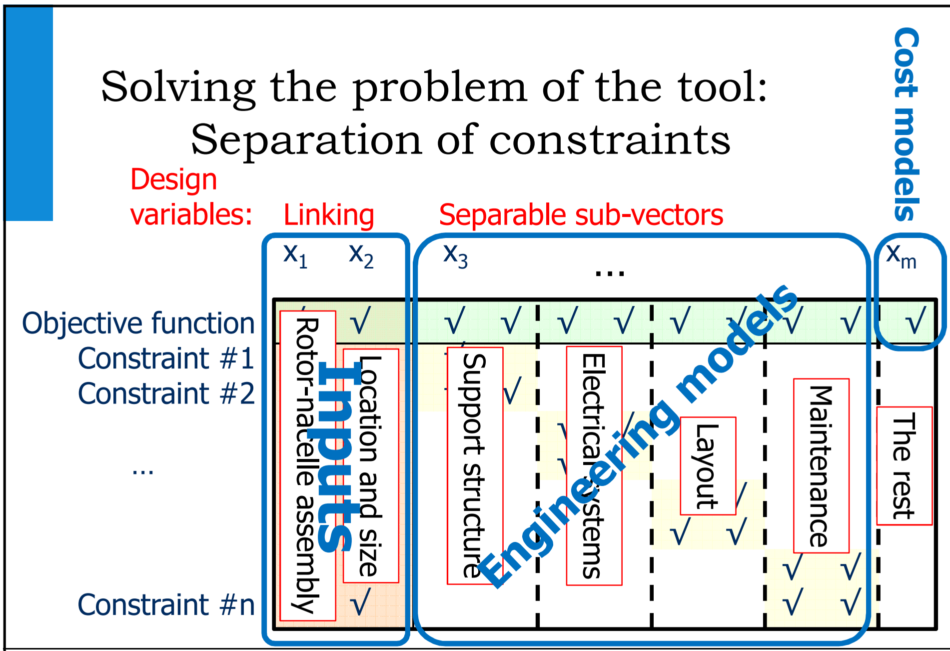
Scope: Dimensioning for fixed configuration

- Monopile – transition piece – conical tower
- Rectangular array – different spacing in rows & columns
- AC infield and transmission system
- Transformer & reactive power compensation onshore & offshore
- Straightforward maintenance strategy
- …



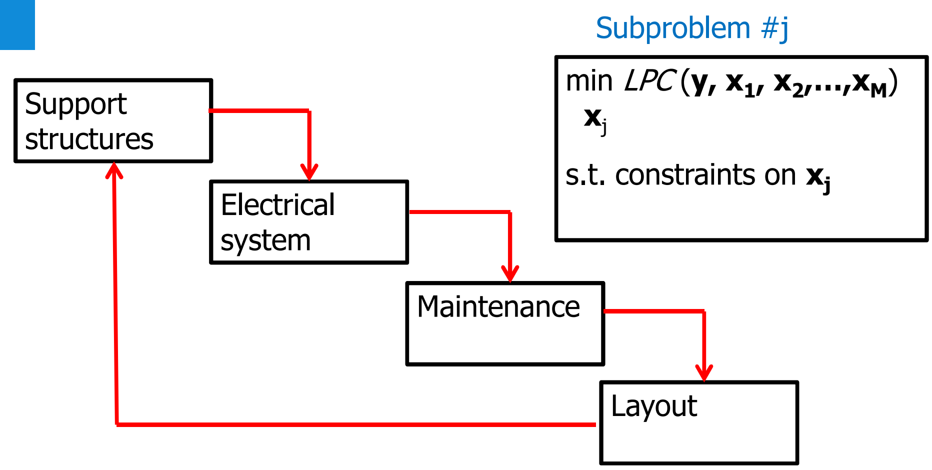
TUDelft 7

Solving the problem of the tool: Separation of constraints



TUDelft 8

Sequence of optimisation



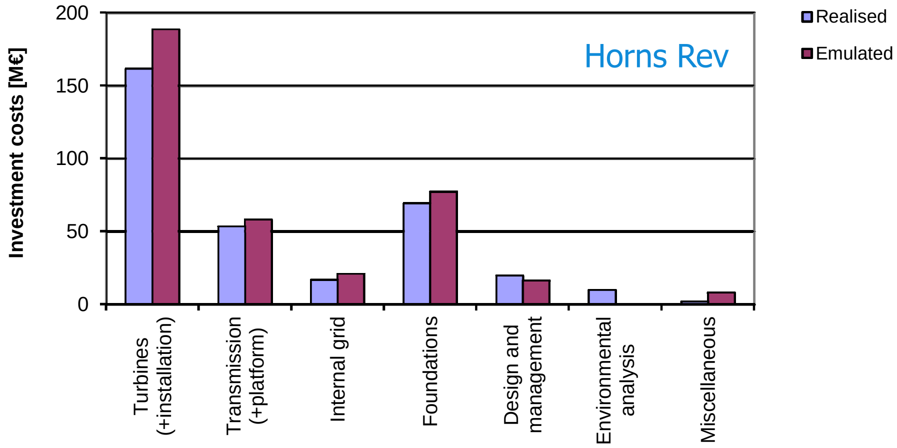
TUDelft 9

Overview

- Problem analysis and objective ☑
- Structure of wind farm design tool ☑
- Appraisal of the tool ☐
- Validation of the optimisation method ☐
- Conclusions ☐

TUDelft 10

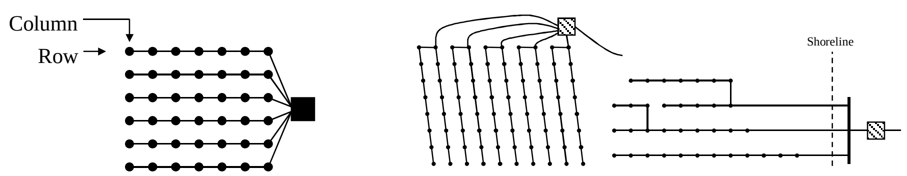
Verification of the tool



TU Delft 11

Example of detailed analysis and difference

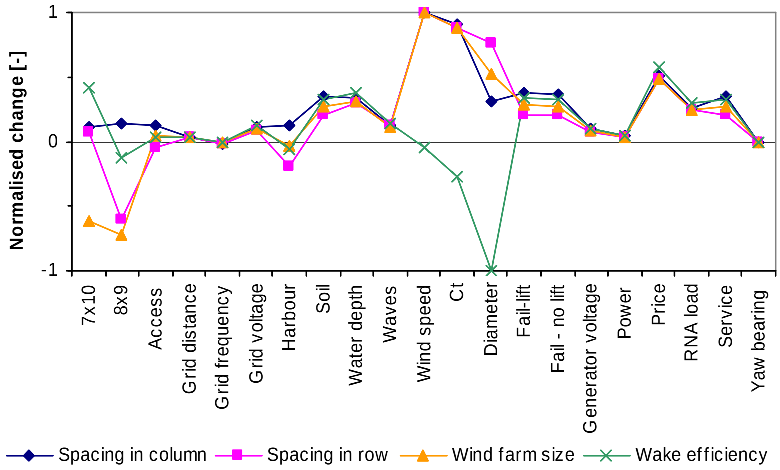
	Horns Rev		BOW		OWEZ	
	Real.	Emul.	Real.	Emul.	Real.	Emul.
Spacing in column [m]	560	761	750	758	1000	750
Spacing in row [m]	560	670	500	850	645	844
Array efficiency [%]	90.2 - 94.2	92.9		94.4	91.7-93.4	93.6



Implemented (BOW similar, 4 rows) Horns Rev OWEZ

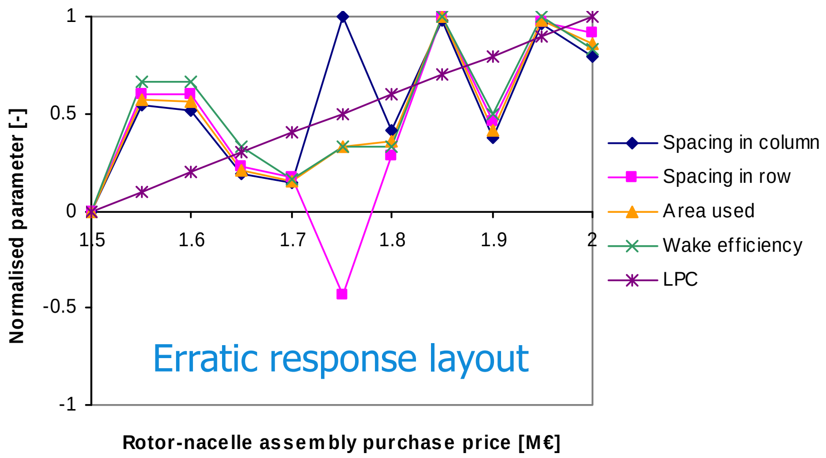
TU Delft 12

Example of sensitivity analysis



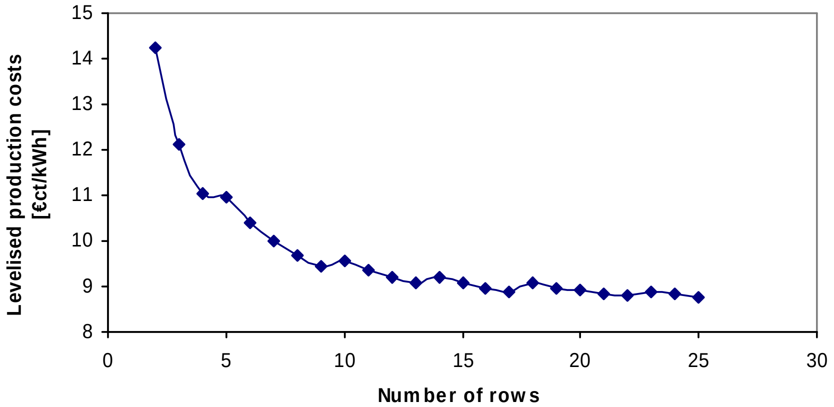
TUDelft 13

Example of not so nice response



TUDelft 14

Example of not so nice response



Discretisation of # of crews

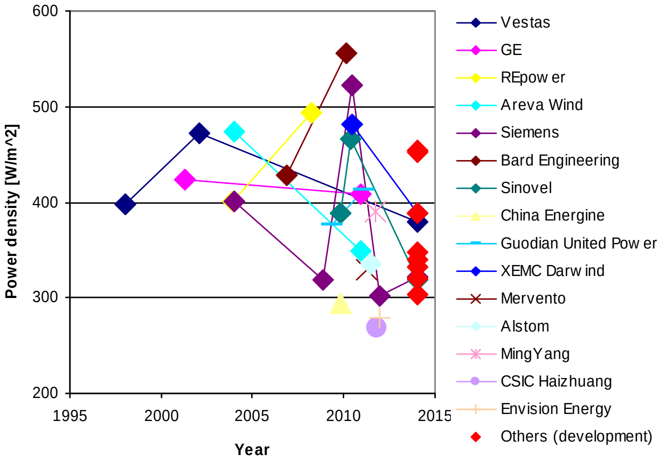
TU Delft 15

Overview

- Problem analysis and objective ☑
- Structure of wind farm design tool ☑
- Appraisal of the tool ☑
- Validation of the optimisation method ☐
- Conclusions ☐

TU Delft 16

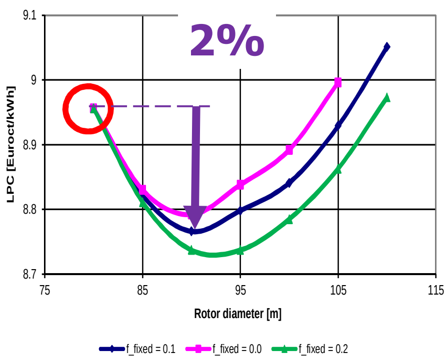
Background for the test



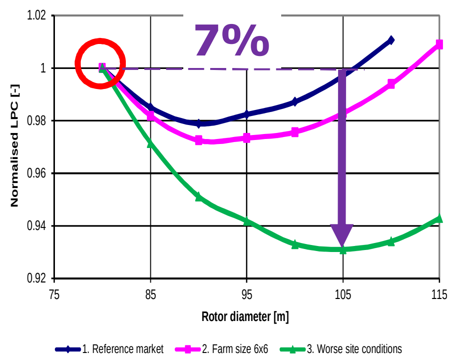
TU Delft 17

Example of diameter optimisation

LPC(D_{rotor}) @reference

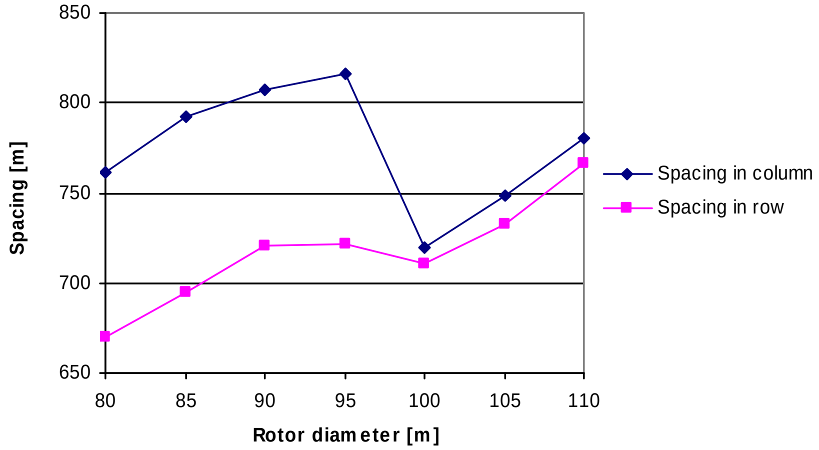


LPC(D_{rotor}) @other markets



TU Delft 18

Cause of the 'ripple' in the response



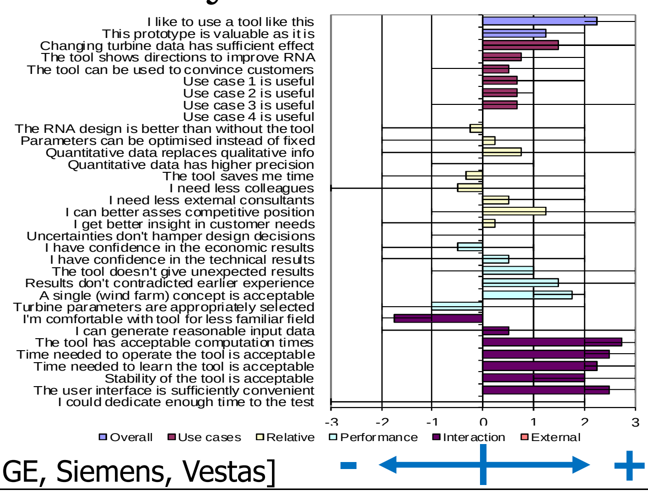
TU Delft

19

Utility perceived by users

Satisfaction with utility

Satisfaction With performance



[Darwind, DNV-GL, GE, Siemens, Vestas]

TU Delft

20

Overview

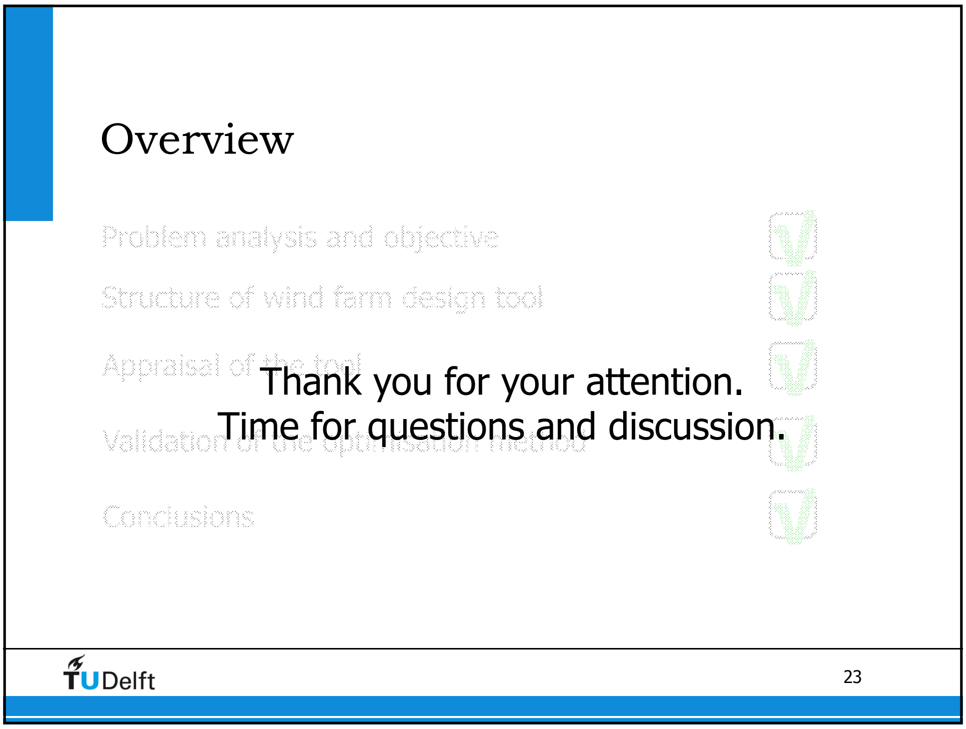
- Problem analysis and objective ☑
- Structure of wind farm design tool ☑
- Appraisal of the tool ☑
- Validation of the optimisation method ☑
- Conclusions ☐

TU Delft 21

Conclusions and reflections

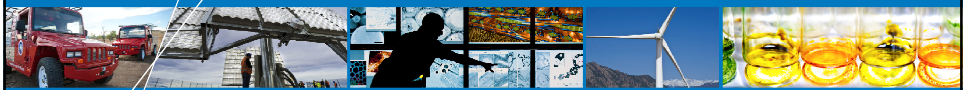
- Emulating WF design (with fixed configuration) is feasible
- Absolute accuracy is OK; Trends are in line with expectation
- Response (LPC) significant enough for optimisation of RNA
- Erratic response due to discretisation is a threat
- (Potential) users confirm (potential) utility
- Current mind-set and organisation of companies not ready
- Spin off for tool: WF developers; Prioritising innovation & research
- … but such engineering/cost modelling tools have different requirements

TU Delft 22


Overview
Problem analysis and objective
Structure of wind farm design tool
Appraisal of the tool
Validation of the optimisation method
Conclusions
Thank you for your attention.
Time for questions and discussion.
TU Delft
23

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Development of a Set of New Reference Wind Turbine Models – Reflecting on the NREL 5 MW Reference Turbine



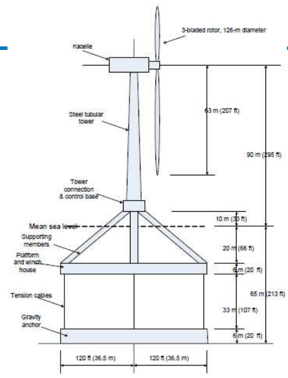
Amy Robertson

TEM #80 – Wind Systems Engineering Integrated RD&D

January 13, 2015

NREL 5MW Turbine - History

2004	First developed to support U.S. DOE conceptual design studies (e.g., CMA)
2005-2009	Adopted & further refined for use in the IEA Wind Task 23 Subtask 2 OC3 project
2006-2011	Adopted & further refined as the reference WT under EU UpWind research program
2007-	Worldwide adoption as a reference WT



CMA TLP

iea wind

Task 23 Offshore Wind Technology and Deployment

UpWind

NREL 5MW Turbine - Data Sources

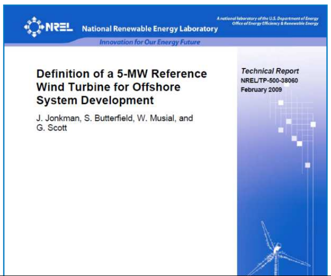
- **Composite of model properties, taken from the best publicly available & most representative specifications at the time (2004)**
  - Real data from the Multibrid M5000 & REpower 5M prototypes
  - Conceptual models used in the WindPACT, RECOFF, & DOWEC projects
  - Heavily influenced by REpower 5M & DOWEC

REpower 5M Wind Turbine

DOWEC Demonstrator Turbine

NREL 5MW Turbine - Specifications

- **Specifications include:**
  - Blade structure & aerodynamics
  - Hub
  - Nacelle
  - Drivetrain
  - Tower
  - Control system:
    - Generator torque
    - Blade pitch
  - Several offshore support structures:
    - Fixed
    - Floating
- **FAST aero-hydro-servo-elastic models**



Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple Stage Gearbox
Rotor Diameter	126 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

Summary of Properties

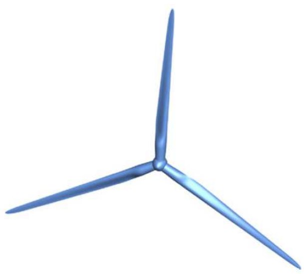
NREL 5 MW Reference Turbine - Success

- **Applications:**
  - OC3/OC4 project – code-to-code verification work
  - UpWind project – adapted turbine to benchmark innovation
  - Research on:
    - Assessment of modeling approach improvements on system behavior
    - Assessment of design improvements to blades or other components of turbine
  - Testing of scaled offshore wind system designs
    - University of Maine, Innwind, DeepCwind, University of Ulsan, MARIN

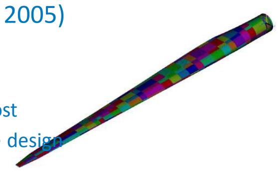
NATIONAL RENEWABLE ENERGY LABORATORY 5

NREL 5MW Turbine - Limitations

- Lack of information on:
  - Rotor external geometry not well defined for CFD:
    - Several groups have taken liberties to develop these
  - No detailed cross-sectional layup & composite-material properties:
    - Reverse-engineered by SNL
  - No detailed drivetrain specification
  - No control logic for start-up, shut-down, & yaw functions
  - Safety/protection functions not well integrated
  - No costs
  - No wind-plant specification
- Cannot be easily scaled to other power ratings
- System not optimized for today's market (optimized in 2005)
  - High-speed, geared drivetrain
  - Low power rating
  - Power curve is conservative and will skew predicted AEP and cost
  - Much heavier than modern turbines – affects support structure design



Rotor Geometry for CFD by Bazilevs et al



ANSYS FE Model by Resor

NATIONAL RENEWABLE ENERGY LABORATORY 6

Need For Other Sized Reference Turbines

- **Provide a baseline for:**
  - Design studies
  - Advanced technology assessments
  - Design methodology research
  - General wind turbine research
  - Cost modeling
- **Offshore wind**
  - Substructure designers limited by lack of turbine models
  - Validation work – many times turbine information not available
- **Systems engineering application**

NATIONAL RENEWABLE ENERGY LABORATORY 7

Approach for Creating New Reference Turbines

- **Develop 2-3 point designs that align with industry standard power ratings, and span probable design space (select from: 3, 4, 6, 7, 8, and 10 MW)**
  - How do we choose the industry standard?
  - How do we obtain the details we need to create the models?
  - Leverage existing models

NATIONAL RENEWABLE ENERGY LABORATORY 8

Family of Wind Turbines?

- **What level of consistency should there be between the reference model architectures and features?**
  - One approach is to take industry standard for each power rating (direct drive)
  - Remain generic, and allow flexibility for changing components
  - Or, do you stay consistent and just "scale-up" NREL 5 MW – keeping consistent features and performance

Scaling Methodology

- **Develop methodology to then interpolate and extrapolate between point designs**
- **Parameters to be varied include:**
  - Rated power
  - Diameter
  - Airfoils
  - Control strategy
  - Torque-speed-pitch operating schedule
  - Generator and drivetrain configuration
  - Wind climate (mean wind speed)
  - Site (land, offshore)
  - Support structure type (bottom-fixed/floating)

Additional Components

- **Include controller and tower definition**
  - Would need multiple to meet land-based and offshore needs
- **Would also be nice to have generic substructure model for offshore applications**
  - The OC4 DeepCwind semisubmersible has been used extensively in research due to its open publication
- **Reference wind farms**

NATIONAL RENEWABLE ENERGY LABORATORY 11

Community involvement

- **Create a website for the baseline models**
- **Community could then upload:**
  - Modifications of the designs
    - Different turbine components
    - Different controllers
    - Different towers
  - Models of the turbines in different design tools
- **Could also allow for substructure models to be uploaded**
- **Regulated or un-regulated?**
  - If regulated, could create numbering system for the modifications so that people can know exactly what model is used in research

NATIONAL RENEWABLE ENERGY LABORATORY 12

Altering of Baseline Definition

- **Develop method to also alter model to individual turbine specifications**
  - Rotor size
  - Generator rating and type
  - Mass
  - Natural frequencies

NATIONAL RENEWABLE ENERGY LABORATORY 14

Interpolation to other power ratings

- **Create a scaling method to get to a specific power rating from these references (10% or less interpolation/extrapolation)**

NATIONAL RENEWABLE ENERGY LABORATORY 15

Issues In Creating New Reference Systems

- **Is a generic (reference) model a sufficient substitute for the actual properties when examining coupled response behavior of a system?**
  - What's the % difference in loads/response behavior between a generic model and a specific model.
    - Perhaps perform a verification against an example dataset that we have.
  - Would this be sufficient for assessing extreme loads in the support structure, for instance?
  - Would it be sufficient for validation work?

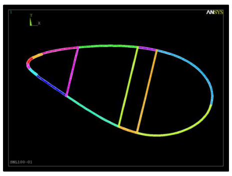
NATIONAL RENEWABLE ENERGY LABORATORY 16

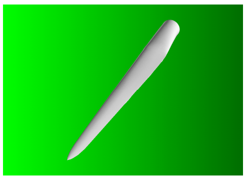
JUNE 2015

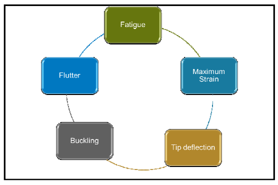
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
25	26	27	28	29	30	31
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31	1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31	1	2	3	4	5	6

Exceptional service in the national interest

Sandia National Laboratories







Large Wind Turbine Blade Reference Designs: Blade Design & Manufacturing Cost Models

D. Todd Griffith (dgriffi@sandia.gov)
Sandia National Laboratories

IEA Topical Experts Meeting #80 (1/13/2015)

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. SAND2014-1418P

Timeline for 100-meter blade studies

- 2009: Project start, scaling studies, parameters for the baseline 100-meter blade
- 2011: Completed and published the SNL100-00 All-glass Baseline Blade
- 2011-2012: Carbon design studies: SNL100-01 Blade
- 2012-2013: Advanced core studies: SNL100-02 Blade
- 2013-2014: Flatback airfoils/slenderness studies: SNL100-03 Blade

Blade design studies required a turbine model for aero-elastic loads analysis: we up-scaled the NREL 5MW turbine model and also released that model as a 13.2 MW reference with the blade files

2

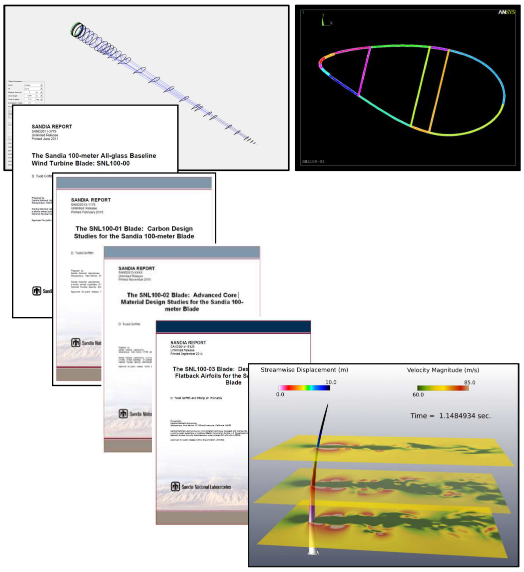
Large Offshore Rotor Development (100-meter Blade Project)

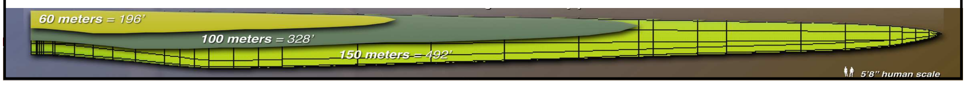
Sandia National Laboratories

- **Summary**
  - Advanced large blade design studies aimed to **reduce technology risk**; enable cost-effective large rotors
  - **Public domain blade project**
- **Objectives/Focus Areas**
  - Identify trends and challenges
  - **Detailed 100-meter reference designs**
  - **Targeted follow-on studies**: **advanced concepts, materials**, flutter, manufacturing cost trends, **thick airfoils**, CFD
- **Products**
  - Design reports
  - 100-m blade and 13.2 MW turbine reference models

http://largeoffshorerotor.sandia.gov

- **Partners:**
  - **None funded, In-kind**
  - **70+ users**





Detailed Design: Loads and Safety Factors

Sandia National Laboratories

Acceptance of the design to blade design standards is a key element of the work; Class IB siting

Wind Condition	Description	IEC DLC Number	Design Situation (Normal or Abnormal)
ETM (Vin < Vhub < Vout)	Extreme Turbulence Model	1.3	Power Production (N)
ECD (Vhub = Vr +/- 2 m/s)	Extreme Coherent Gust with Direction Change	1.4	Power Production (N)
EWS (Vin < Vhub < Vout)	Extreme Wind Shear	1.5	Power Production (N)
EOG (Vhub = Vr +/- 2 m/s)	Extreme Operating Gust	3.2	Start up (N)
EDC (Vhub = Vr +/- 2 m/s)	Extreme Wind Direction Change	3.3	Start up (N)
EWM (50-year occurrence)	Extreme Wind Speed Model	6.2	Parked (A)
EWM (1-year occurrence)	Extreme Wind Speed Model	6.3	Parked (N)

Safety factors for materials and loads included for buckling, strength, deflection, and fatigue analyses

Baseline Materials Data: Sources

- **Montana State Test Data for glass materials**
- Core, resin, coating from other sources (Upwind program, suppliers)

Table 19. Material Property Data Selected from DOE/MSU Database

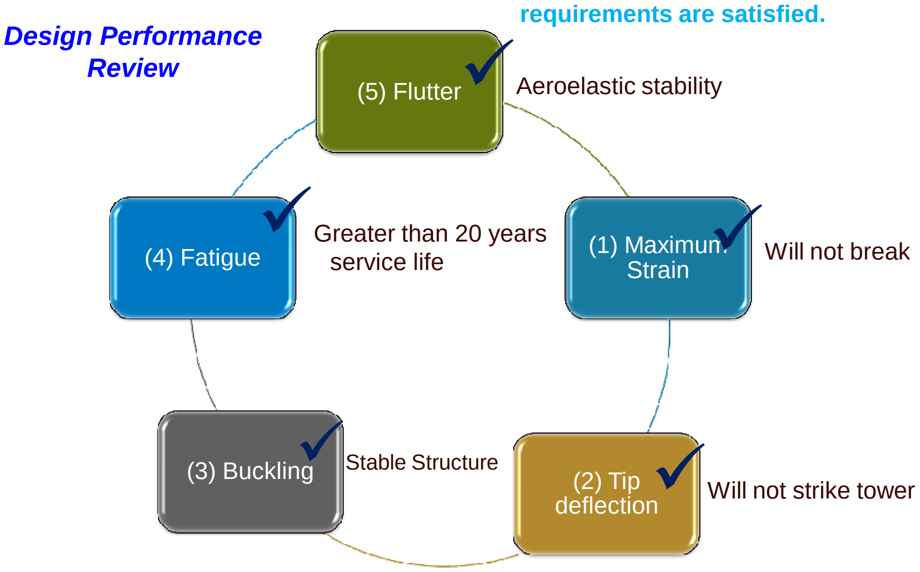
Laminate Definition			Longitudinal Direction								Shear
			Elastic Constants				Tension		Compression		
VARTM Fabric/resin	lay-up	V_F %	E_L GPa	E_T GPa	υ_{LT}	G_{LT} GPa	UTS_L MPa	ε_{max} %	UCS_L MPa	ε_{min} %	τ_{TU} MPa
E-LT-5500/EP-3	$[0]_2$	54	41.8	14.0	0.28	2.63	972	2.44	-702	-1.53	30
Saertex/EP-3	$[\pm 45]_4$	44	13.6	13.3	0.51	11.8	144	2.16	-213	-1.80	----
SNL Triax	$[\pm 45]_2[0]_2$	---	27.7	13.65	0.39	7.2	----	----	----	----	----

E_L and E_T - Longitudinal & transverse moduli, υ_{LT} - Poisson's ratio, G_{LT} & τ_{TU} - Shear modulus and ultimate shear stress. UTS_L - Ultimate longitudinal tensile strength, ε_{MAX} - Ultimate tensile strain, UCS_L - Ultimate longitudinal compressive strength. ε_{MIN} - Ultimate compressive strain.

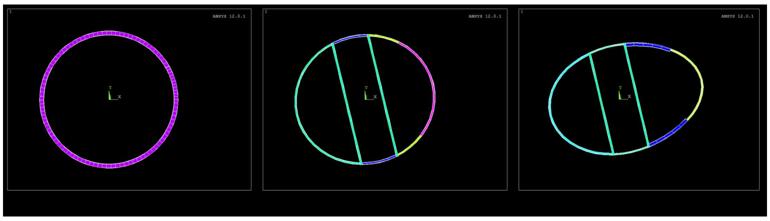
5

Blade Design Cycle

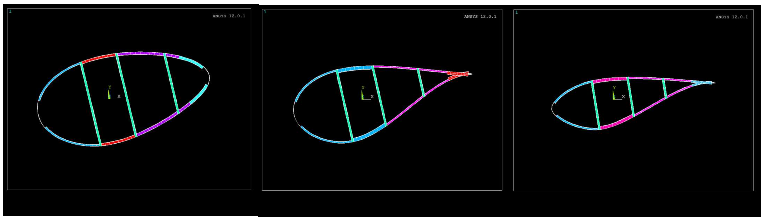
Repeat design loop until all design requirements are satisfied.



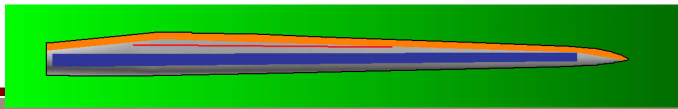
SN100-00: Layup



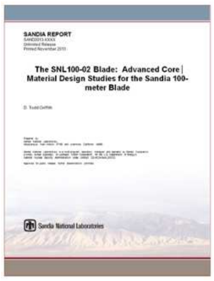
(a) 0.0 meters (root circle) (b) 2.4 meters (shear webs begin) (c) 8.9 meters(transition)



(d) 14.6 meters (third web begins) (e) 19.5 meters (max chord) (f) 35.8 meters

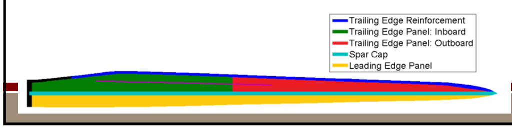


Design Scorecards for all Designs Ex. SNL100-02



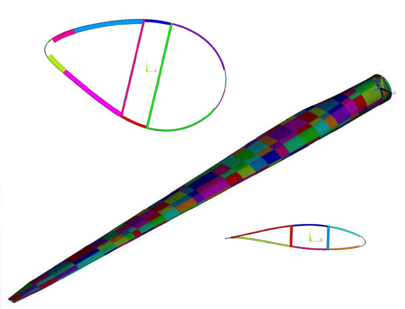
Parameter	Value
Blade Designation	SNL100-02
Wind Speed Class	IB
Blade Length (m)	100
Blade Weight (kg)	59, 047
Span-wise CG location (m)	31.95
# shear webs	3
Maximum chord (m)	7.628 (19.5% span)
Lowest fixed root natural frequency (Hz)	0.55
Control	Variable speed, collective pitch
Notes	7% (weight) parasitic resin, carbon spar, advanced core

Material	Description	Mass (kg)	Percent Blade Mass
E-LT-5500	Uni-directional Fiberglass	8,964	15.2%
Saertex	Double Bias Fiberglass	8,706	14.7%
Carbon Prepreg	Conceptual Laminate	10,103	17.1%
EP-3	Infused Resin	22,836	38.7%
Balsa	Balsa Core	2,625	4.4%
PET Foam	Foam Core	4,883	8.3%
Gelcoat	Coating	925	1.6%



Max operating speed: 7.44 RPM
Cut in/out wind speed: 3.0/25.0 m/s

61.5 m blade layup



- **Intended uses for blade model**
  - A starting point for blade design optimization or parameter studies
  - Blade structural design tool verifications and validations
- **IEC Turbine Class I-B (same as NREL 5 MW)**
- **120 m rotor size (same as NREL 5 MW)**
- **Not intended uses for blade model**
  - Not a model for effective CFD simulation; Ray Chow's 5 MW blade model is more appropriate
  - Not an optimal blade design; an optimized blade was created and documented in SAND2014-3136, Effects of Increasing Tip Velocity on Wind Turbine Rotor Design
- **Blade geometry**
  - Replicated the chord, twist, and thickness schedule of the NREL 5 MW reference
  - Used the same airfoils as the NREL 5 MW reference

POC: Brian Resor

Sandia National Laboratories

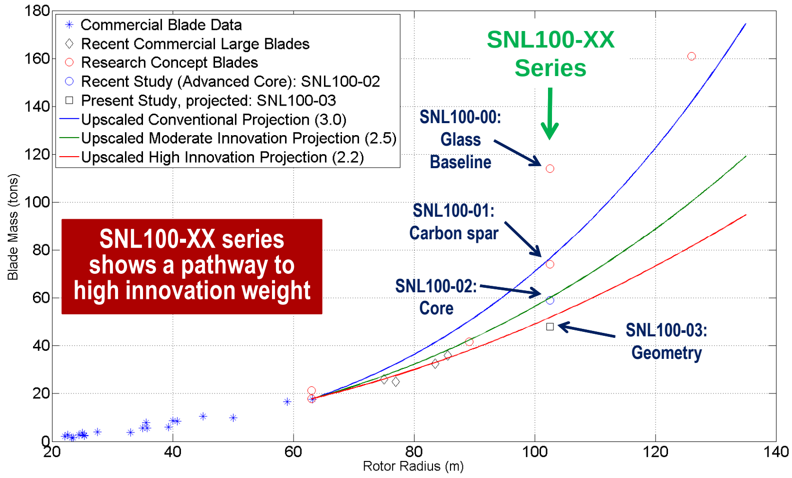
SNL100-00 Follow-on Studies

Sandia National Laboratories

These are the follow-on study areas addressed by Sandia; many additional issues addressed by users of the 100-meter blade reference models.

1. Sandia Flutter Study
2. Altair/Sandia CFD Study
3. Sandia Blade Manufacturing Cost Model
4. 100m Carbon Design Studies: SNL100-01
5. 100m Core Material Studies: SNL100-02
6. 100m Aero-structural Studies: SNL100-03

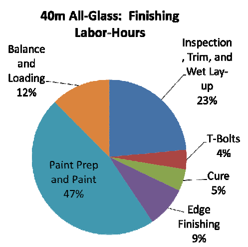
Industry survey of blade mass: Commercial blades (20-60 meters), recent large prototype blades (73-83 meters), and research concept blades (61.5, 86, 100, 123 meters)

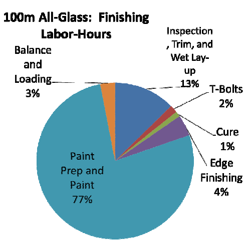


3. Sandia Blade Manufacturing Cost Model (version 1.0)

- Components of the Model:
  - Materials, Labor, Capital Equipment
  - Detailed Labor Breakdown by major operation
  - Reports: SAND2013-2733 & SAND2013-2734

Important Study of Labor Operations Trends with Scale





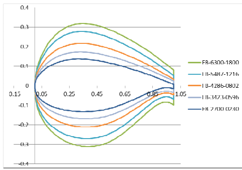
One example: An analysis of labor costs shows the growth in labor hours for area-driven manufacturing tasks such as paint prep and paint as blades grow longer.

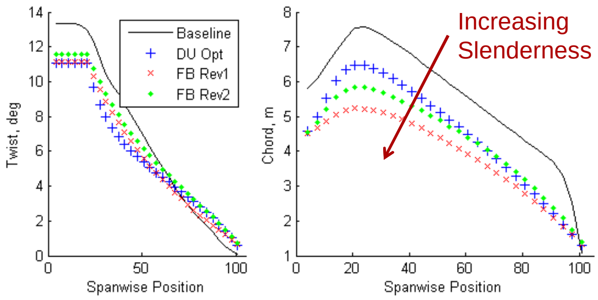
12

6. Flatback airfoils/Slenderness Study (SNL100-03)

Sandia National Laboratories

Opportunity to reverse many trends, including:
- Weight growth
- Buckling
- Flutter, Deflection, Fatigue
- Surface Area Driven Labor Operations



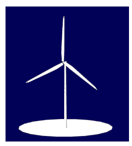


Increased blade slenderness has advantages and disadvantages – these design studies aid in better understanding the trade-offs

Resources, Model Files, Next Steps

Sandia National Laboratories

Model files on Project Website (both blade and turbine)
- http://largeoffshorerotor.sandia.gov



What's Available:

1. **Detailed Blade Models (Layups + Geometry)**
   - **SNL100-00, SNL100-01, SNL100-02, SNL100-03**
   - **61.5 meter (5 MW)**
2. **SNL13.2-00-Land Turbine Model (in FAST)**
3. **Sandia Blade Manufacturing Cost Model – version 1.0**
4. **Design Reports**

Next Steps? Sandia is looking to contribute both existing and to future Blade & Turbine Reference Models and Cost Models

D. Todd Griffith dgriffi@sandia.gov

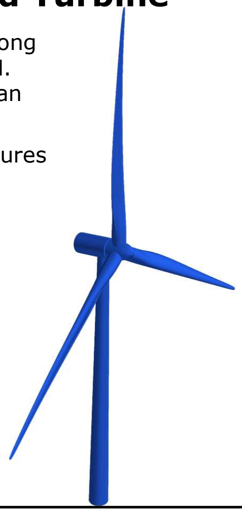
This work was funded by the US DOE Wind and Water Power Technology Office.

DTU

The DTU 10-MW Reference Wind Turbine

Christian Bak, Frederik Zahle, Robert Bitsche, Taeseong Kim, Anders Yde, Lars Christian Henriksen, Morten H. Hansen, José Blasques, Mac Gaunaa, Anand Natarajan

Section for Aeroelastic Design and Section for Structures
Technical University of Denmark
DTU Wind Energy – Risø Campus

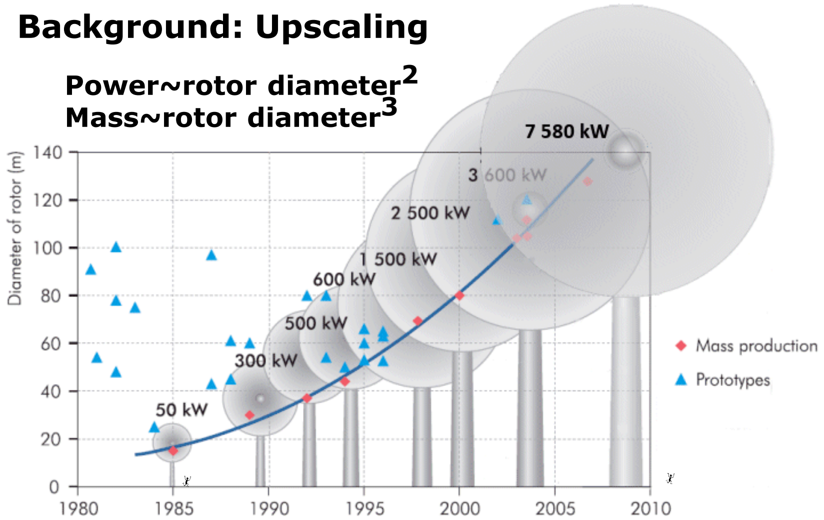


DTU Wind Energy
Department of Wind Energy

DTU

The DTU 10 MW Reference Wind Turbine Background: Upscaling

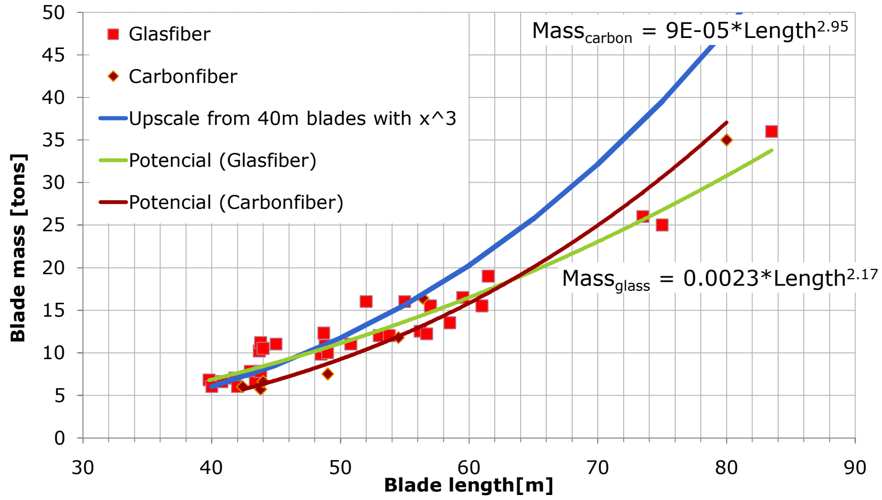
Power~rotor diameter^2
Mass~rotor diameter^3



Source: International Energy Agency (IEA)

2 DTU Wind Energy, Technical University of Denmark

The DTU 10 MW Reference Wind Turbine
Background: Upscaling blades



3 DTU Wind Energy, Technical University of Denmark

The DTU 10 MW Reference Wind Turbine
Objectives

- **The purpose with the design is:**
  - To achieve a design made with traditional design methods in a sequential MDO process
  - Good aerodynamic performance and fairly low weight.
  - To provide a design with high enough detail for use for comprehensive comparison of both aero-elastic as well as high fidelity aerodynamic and structural tools,
  - To provide a publicly available representative design basis for next generation of new optimized rotors.

- **The purpose is not:**
  - To design a rotor pushed to the limit with lowest weight possible,
  - To push the safety factors as much as possible,
  - Provide a design of a complete wind turbine – focus is on the rotor,
  - To provide a design ready to be manufactured; the manufacturing process is not considered.

4 DTU Wind Energy, Technical University of Denmark

The DTU 10 MW Reference Wind Turbine The Design Process

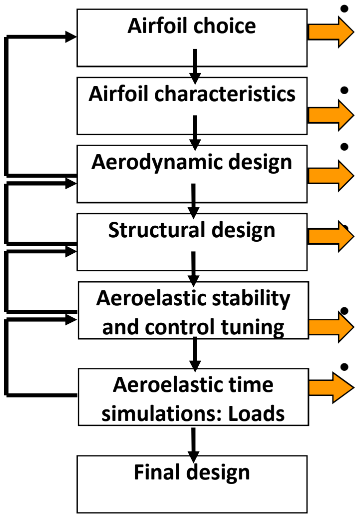
- DTU Wind Energy is responsible for developing a number of wind turbine analysis codes that are all used by industry in their design of wind turbines and use them in the design of the DTU 10MW RWT:
  - **HAWC2** (multibody time domain aeroelastic code)
  - **HAWCstab2** (Aero-servo-elastic modal analysis tool)
  - **BECAS** (Cross-sectional structural analysis tool)
  - **HAWTOPT** (Wind turbine optimization code)
  - **EllipSys2D / 3D** (RANS / DES / LES Navier-Stokes solvers)
- Other solvers used: Xfoil, ABAQUS
- In our normal research context we do not normally use these tools in a synthesized manner in a design process.
- The exercise for us was to apply our tools and specialist knowledge in a comprehensive design process of a 10 MW wind turbine rotor, something we have not done to this level of detail before.
- Identify areas in the design process suited for more integrated MDO architectures.

The DTU 10 MW Reference Wind Turbine Design Summary

Description	Value
Rating	10MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Medium speed, Multiple stage gearbox
Rotor, Hub diameter	178.3m, 5.6m
Hub height	119m
Cut-in, Rated, Cut-out wind speed	4m/s, 11.4m/s, 25m/s
Cut-in, Rated rotor speed	6RPM, 9.6RPM
Rated tip speed	90m/s
Overhang, Shaft tilt, Pre-cone	7.07m, 5°, 2.5°
Pre-bend	3m
Rotor mass	229tons (each blade ~41tons)
Nacelle mass	446tons
Tower mass	605tons

DTU

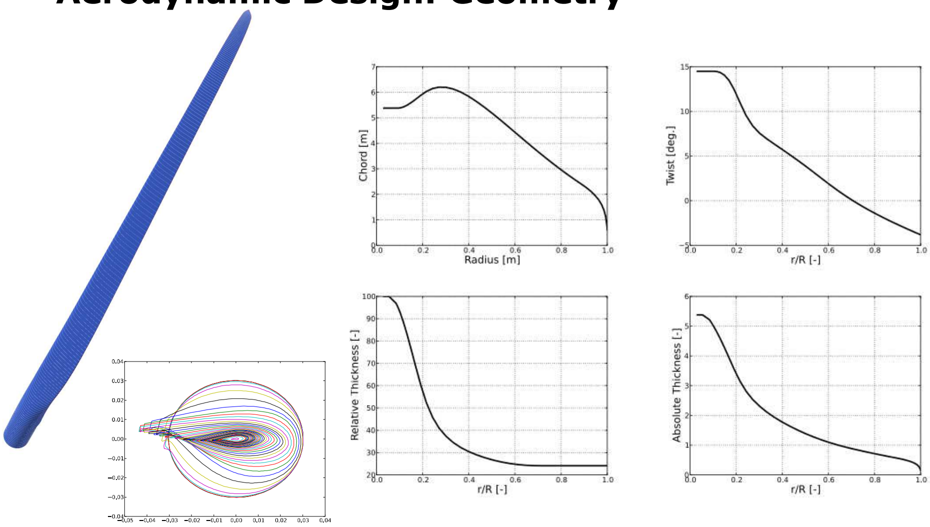
The DTU 10 MW Reference Wind Turbine
The method



- FFA-W3-xxx airfoils. 24.1% to 36.0% relative thickness, 48% and 60% airfoil scaled from FFA-W3-360 and cylinder.
- 2D CFD computations at *Re* $9x10^6$ to $13x10^6$ 3D corrected
- HAWTOPT numerical optimizations. Max tip speed = 90m/s, λ=7.5, min relative airfoil thickness = 24.1%
- ABAQUS (6.11) FEM computations. Uniaxial, biaxial and triaxial laminates were used together with Balsa as sandwich core material
- HAWCSTAB2 (aero-servo-elastic stability tool) computations including controller tuning.
- HAWC2 (aeroelastic code) computations. Class IA according to IEC-61400-1 standard for offshore application

DTU

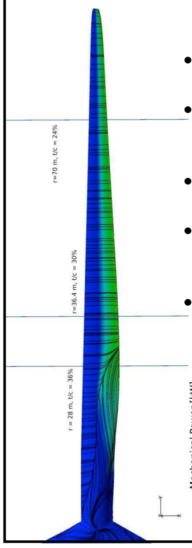
The DTU 10 MW Reference Wind Turbine
Aerodynamic Design: Geometry

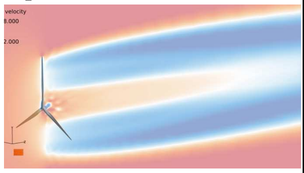


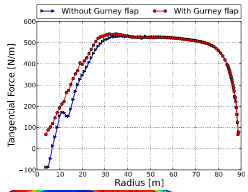
DTU

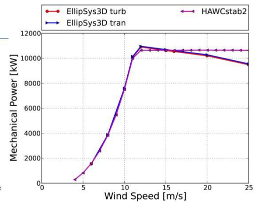
The DTU 10 MW Reference Wind Turbine
Aerodynamic Design: 3D CFD analysis

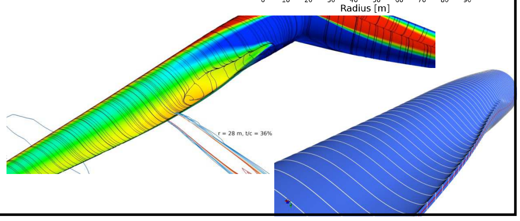
- Automated workflow from 2D blade definition/airfoil family -> 3D shape -> 3D volume mesh,
- 3D CFD validation of performance predicted using BEM,
- Blade performance in the root area was not satisfactory due to use of thick airfoils (t/c > 0.36 for r/R < 0.30).
- Gurney flap were used to remedy this, increase in CP of 1.2% at design TSR.
- Resulted in adjustment of airfoil data and new design iteration adopting the modified root layout.
- (Automated derivation of 3D airfoil data).







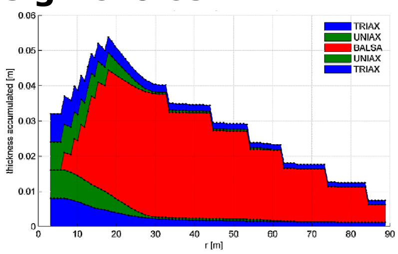


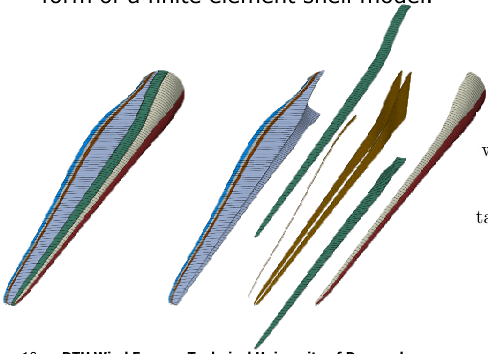


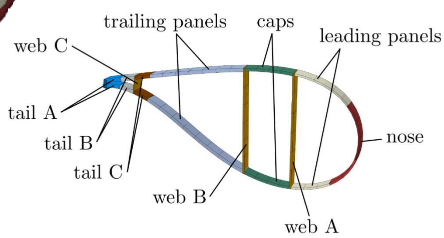
DTU

The DTU 10 MW Reference Wind Turbine
Structural Design: Basic design choice

- A ”box-girder” design approach is used.
- For layup definition the blade is partitioned into 100 regions radially and 10 regions circumferentially.
- A complete description of the blade’s geometry and layup is generated in the form of a finite element shell model.



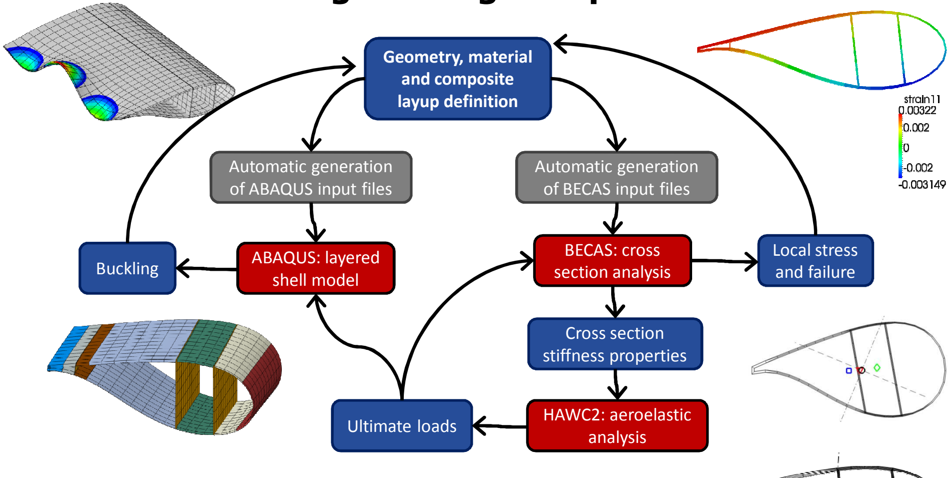




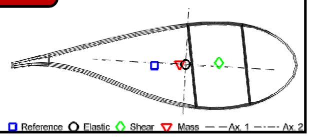
10 DTU Wind Energy, Technical University of Denmark

DTU

The DTU 10 MW Reference Wind Turbine Structural Design: Design loop



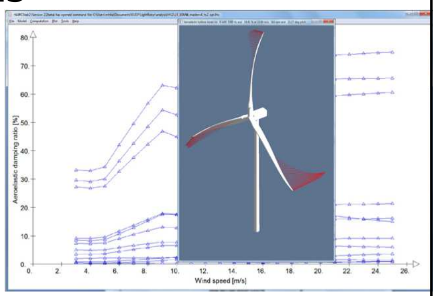
		Load case	γ_F [–]	F_x [MN]	F_y [MN]	F_z [MN]	F_{res} [MN]	M_x [MNm]
F_x	max	dlc5.1	1.35	0.9531	-0.2915	1.0163	0.9967	25.2834
	min	dlc1.3	1.35	-0.8724	0.3672	2.2653	0.9465	-8.9863
F_y	max	dlc1.3	1.35	0.4949	1.6055	2.4138	1.6801	-52.9810
	min	dlc6.1	1.35	0.0504	1.1862	0.2782	1.1872	44.0922

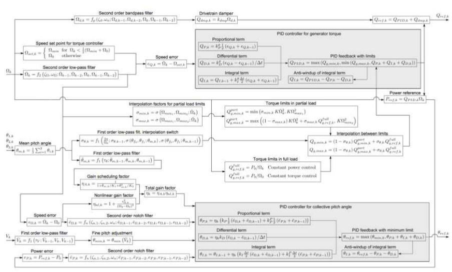


DTU

The DTU 10 MW Reference Wind Turbine Aero-servo-elastic analysis

- HawcStab2 used to analyze the modal properties of the wind turbine:
  - frequencies, damping ratios, and mode shapes.
- The DTU Wind Energy controller was revised and tuned specifically for the DTU 10 MW RWT.
- To avoid tower mode excitation from 3P frequency, minimum RPM = 6.
- Report and source code on controller available.

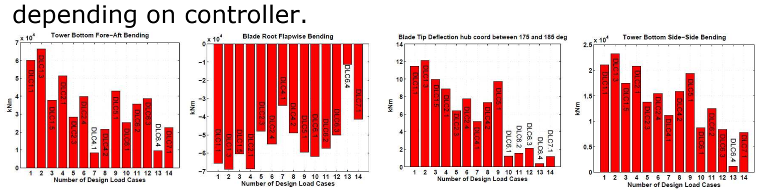




12 DTU Wind Energy, Technical University of Denmark

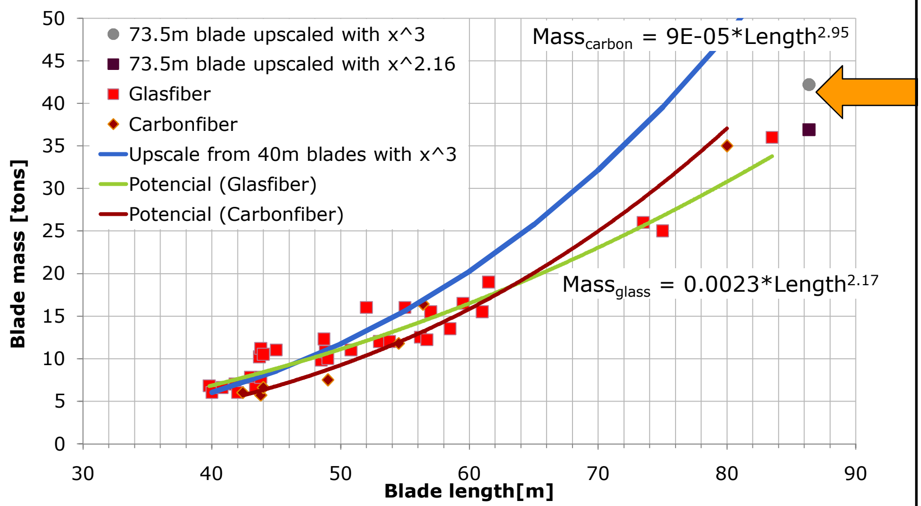
The DTU 10 MW Reference Wind Turbine Load calculations: HAWC2

- DTU 10MW RWT: IA according to IEC-61400-1 (3rd edition)
- The suggested load cases by IEC standard must be verified in order for withstanding all loading situations during its life time.
- Most of design load cases are considered except DLC8, which is for transport, assemble, maintenance, and repair cases, and DLC 1.4, DLC 2.2, DLC 3.1, DLC 3.2, and DLC 3.3 which are very depending on controller.



13 DTU Wind Energy, Technical University of Denmark

The DTU 10 MW Reference Wind Turbine How the blade compares to existing ones



14 DTU Wind Energy, Technical University of Denmark

The DTU 10 MW Reference Wind Turbine Summary of design challenges

- Transition from laminar to turbulent flow in the boundary layer of the airfoils:
  - The result is uncertainty of the aerodynamic performance and thereby on loads and especially the power
- To reduce the blade weight, the blade design needs to be ”stress/strain” driven rather than ”tip deflection” driven.
  - The result is a pre-bend design,
- The control of the rotor must take several instability issues into account, e.g. coinciding frequencies from the tower eigen frequency and 3P at low wind speeds,
  - The consequence was determination of the minimum rotational speed
- Blade vibrations in stand still
  - Vibrations at 90 degrees inflow direction can probably be avoided by pitching each blade differently
  - Vibrations at 30 degrees inflow direction can be reduced by ensuring ”smooth” airfoil characteristics

15 **DTU Wind Energy, Technical University of Denmark**

The DTU 10 MW Reference Wind Turbine Availability

- It is available as a comprehensive release consisting of
  - Fully described 3D rotor geometry,
  - Basic tower and drive train,
  - 3D corrected airfoil data (based on engineering models),
  - 3D CFD surface/volume meshes,
  - Comprehensive description of structural design,
  - Controller,
  - Load basis calculations using HAWC2,
  - Report documenting the design.

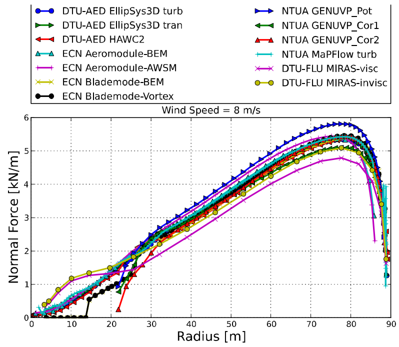
- Go to: **dtu-10mw-rwt.vindenergi.dtu.dk**
- Today 322 persons are registered users
- The turbine is used in many projects
  - The EU projects InnWind, MareWint, IRPWIND
  - Several Danish National projects

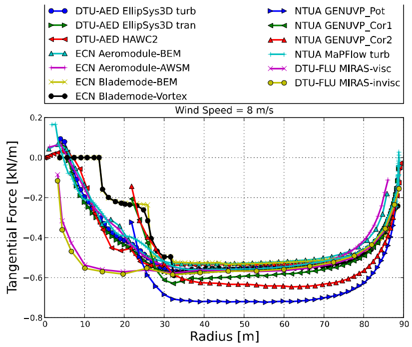
16 **DTU Wind Energy, Technical University of Denmark**

DTU

INNWIND Benchmark

- Example of comparison of codes at 8 m/s





17 **DTU Wind Energy, Technical University of Denmark** 19 January 2015

DTU

Lessons Learnt

- Small adjustments are needed:
  - Control
  - Minor errors in the report
  - Other users found design limitations, how can we get those back into future revisions of the design?
- Future
  - Branches to the design is planned to be part of the homepage such as new rotors, towers, jackets etc
  - New designs made based on the HawtOpt2 code

- Should all the data be moved to a central reference wind turbine database?

18 **DTU Wind Energy, Technical University of Denmark** 19.01.2015

DTU

The DTU 10 MW Reference Wind Turbine Acknowledgements

- Thanks to:
  - EUDP for partly financing the EUDP 2010 I Light Rotor
  - The EU project InnWind for reviewing the wind turbine
  - A lot of people that has been a part of the discussions.

DTU

Thank you for the attention!

iea wind

NREL
NWTC, Broo
mfield,
CO, USA

12MW Floating Offshore Wind Turbine

TEM #80, IEA Wind Task 11

Jan. 12~13, 2015

Prof. SHIN, Hyunkyoung*, Prof. PARK, Minwon** & Dr. LEE, Hakgu***

*University of Ulsan, **Changwon National University, *** Korea Institute of Materials Science, Korea

Ulsan & Changwon , Korea

Wikipedia 2014

Light through Darkness

KOREA (South)

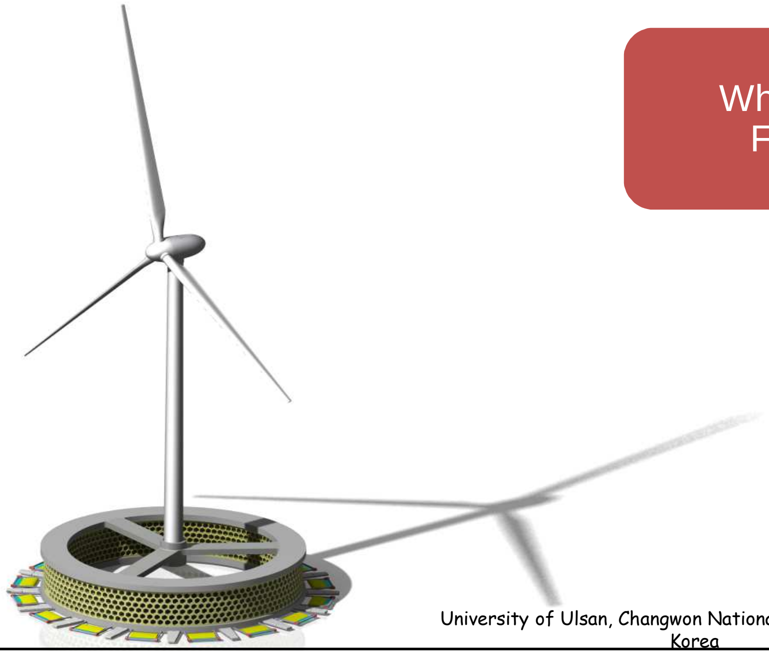
Area: 99,720 km²
Population: 49 million
GDP: US$ 1.16 trillion
World's 15th largest economy (IMF/2012)
Political, Economical and Regulatory stability
Investment grade AA(World Bank/2013)

Ship Market : 40% (World rank 1)
Hyundai Heavy Industries. Co. Ltd
Automobile Market : 9% (World rank 5)
Hyundai-KIA Motor
Mobile phone Market : 30% (World rank 1)
SAMSUNG (GALAXY)
Semi-conductor : 14.7% (World rank 3)
SAMSUNG
Display (TV etc.) : 48.7% (World rank 1)
SAMSUNG, LG …..

Kim Yuna
at the Vancouver 2010 Winter Olympics

CONTENTS

1. Critical Needs in Korea



Why 12MW FOWT?

University of Ulsan, Changwon National University & KIMS Korea

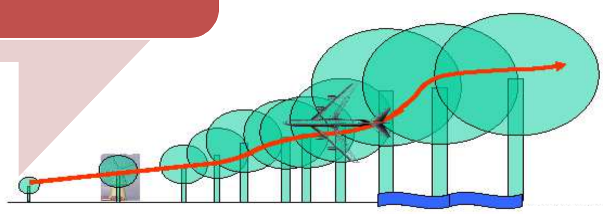
1. Critical Needs in Korea

Why 12MW FOWT?

- Wind Industry : System & Supply Chain
  (HHI, SHI, DSME, STX)
- Energy Poverty : Light through Darkness

Quantum Jump :

LCOE Reduction based on Innovative Technology & Open Innovation

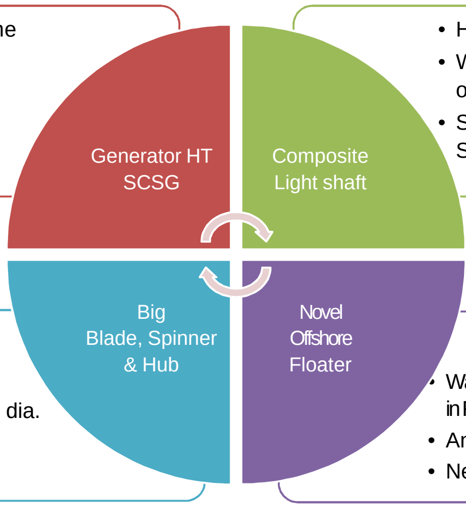


6

2. 12 MW FOWT : GreenTech Challenges

- Light weight/Small Volume
- HT SCSG
- Direct driven

- Hybrid Structure
- Weight reduction & Heavy T orque Transfer
- Shear & Bending Support Structure



- Transportation Problem
- Casting Problem over 6m dia.
- BlockAssembly(Shipbuilding)

- Wave/Solar Energy Offshore Floater in Finite/Deep Sea
- Anti-motion System
- New Stationkeeping with GPS

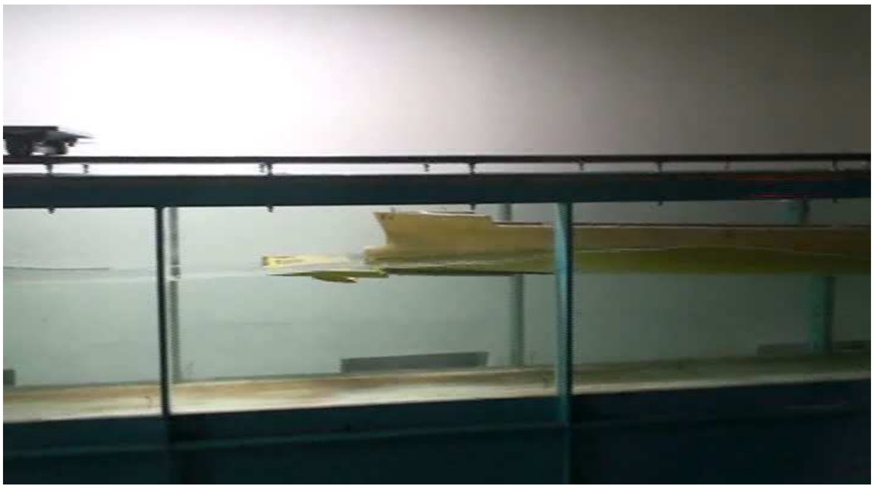
7

3. Floater @12 MW Solution

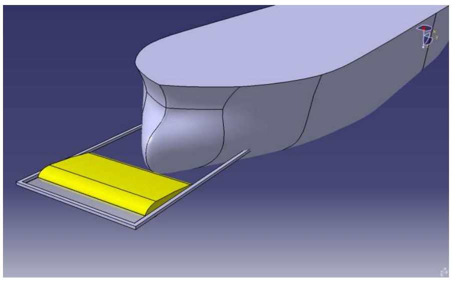
3-1. Wave energy propulsion
3-2. Novel stationkeeping system with GPS
3-3. Passive/Active modes
3-4. Anti-motion system

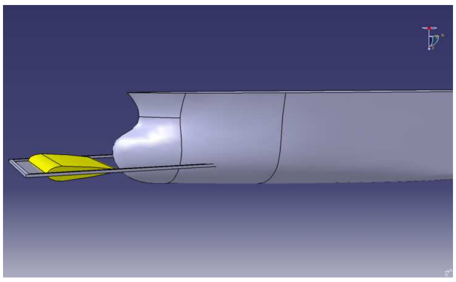
8

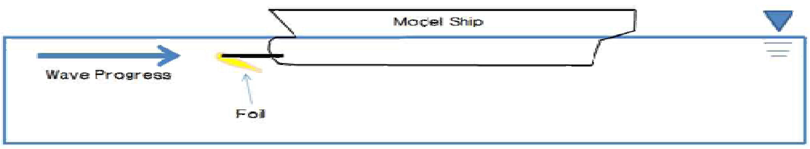
3-1. Wave Energy Propulsion



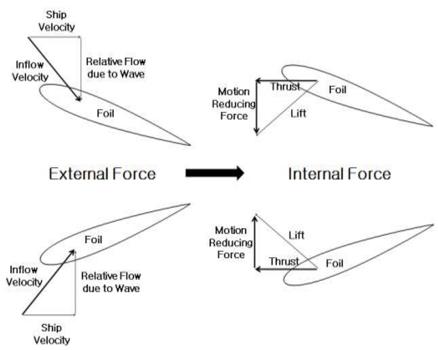
3-1. Wave Energy Propulsion

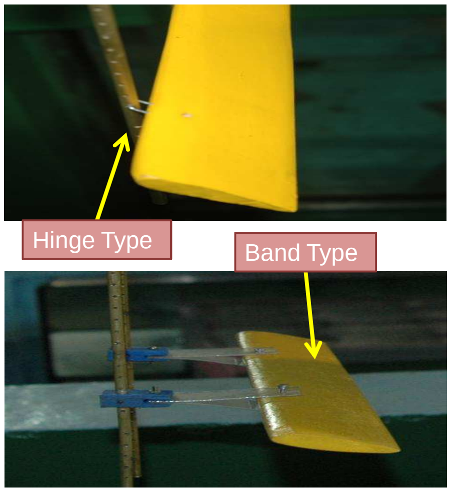




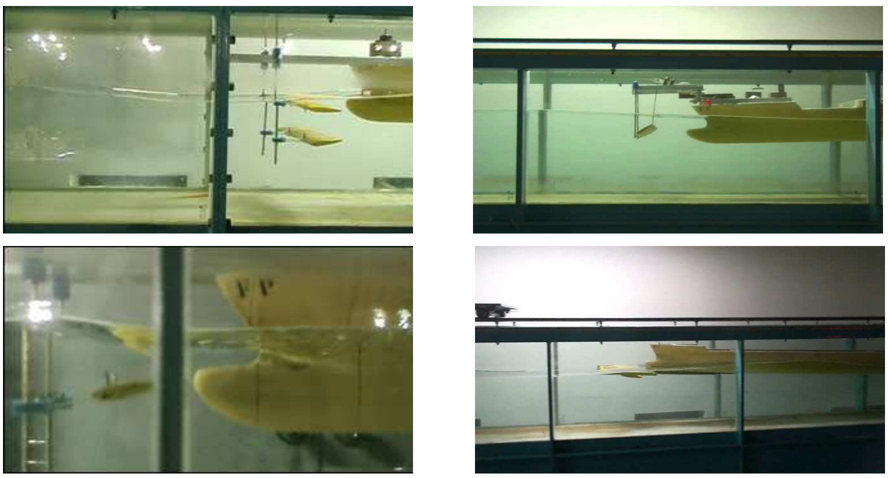


3-1. Wave Energy Propulsion

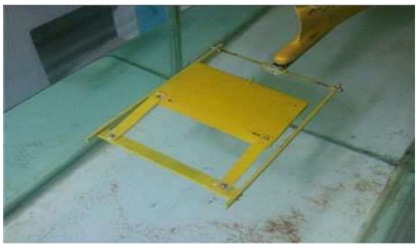


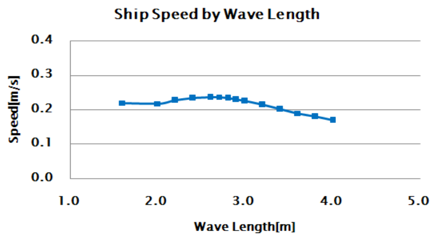


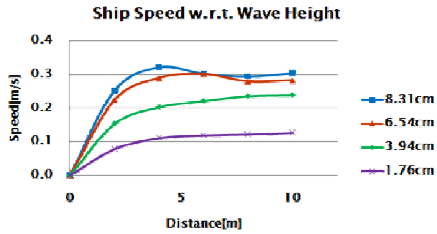
3-1. Wave Energy Propulsion



3-1. Wave Energy Propulsion

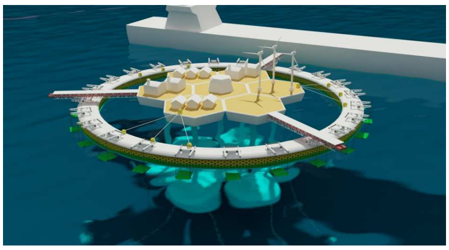


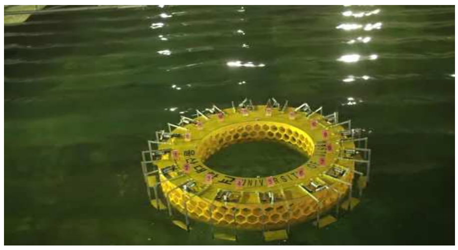


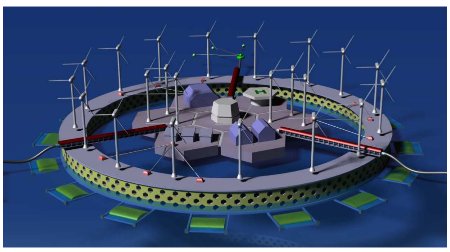


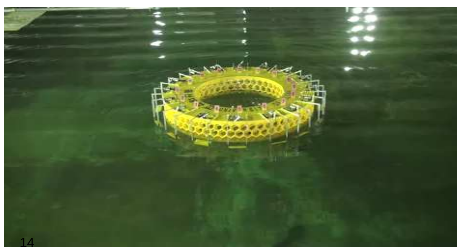
3-2. Novel Stationkeeping System with GPS

FOIL-BAND Solution for Offshore Structure Stationkeeping

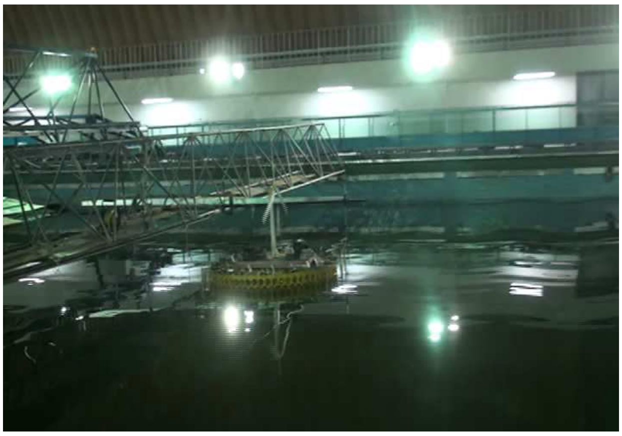






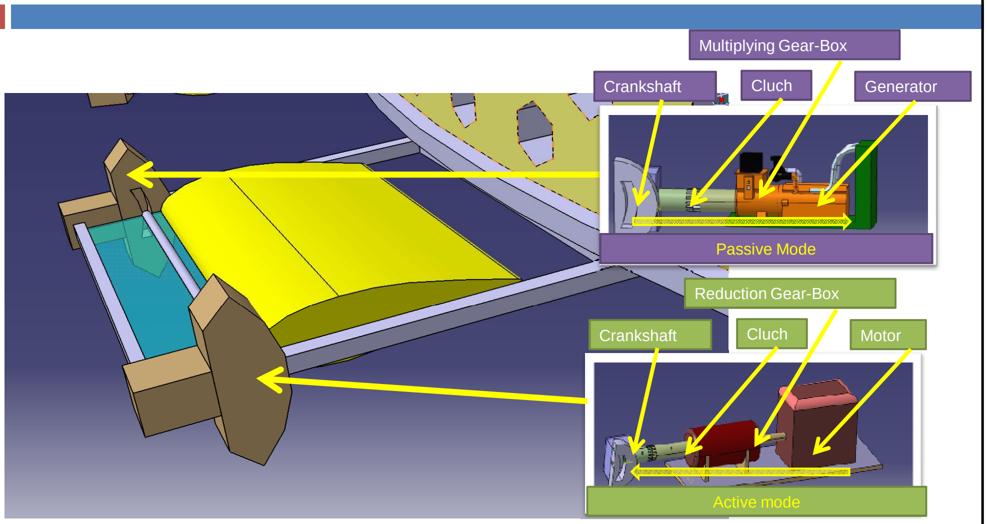


3-2. Novel Stationkeeping System with GPS for Shallow/Deep sea



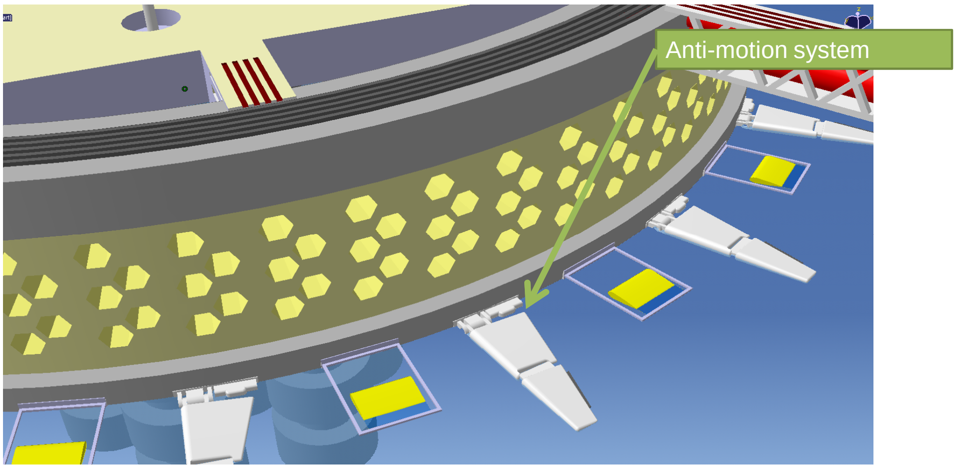
15

3-3. Passive/Active mode



16

3-4. Anti-motion system



17

4. RNA @12 MW Solution

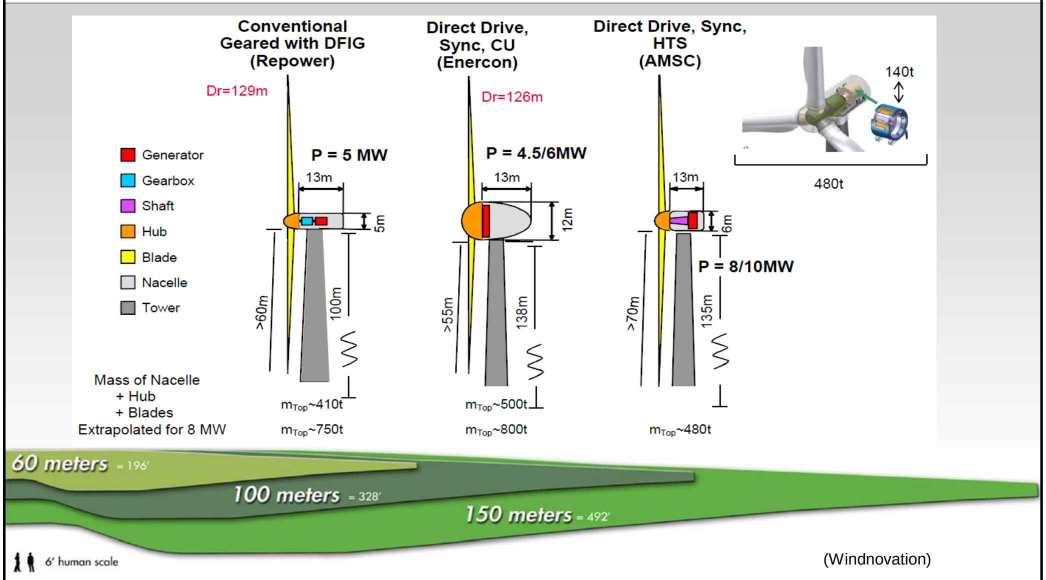
4-1. Composite Light Shaft

4-2. Blade

4-3. Spinner and Hub

18

4. RNA @12MW Solution



(Windnovation)

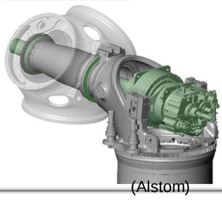
19

4-1. Composite Light Shaft

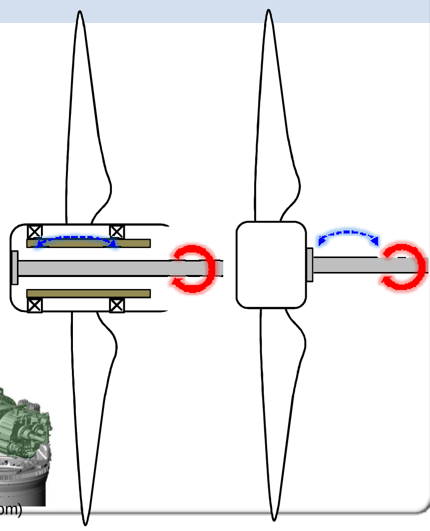
- New proposed type
- Conventional type

- Light weight composite shaft
  - composite shaft for heavy torque
  - hybrid support structure against bending

item	unit	target
12MW shaft weight	ton	50
Composite shaft torque	MNm	12
Composite shaft fatigue life	year	20
Hybrid support structure capacity	MW	12



(Alstom)



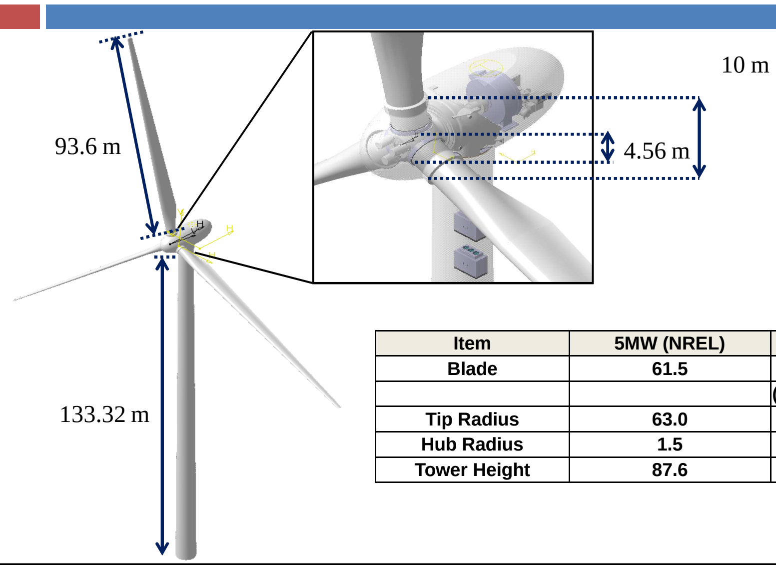
4-2. Blade

4-2-1. Extrapolation for 12 MW FOWT
4-2-2. Numerical Analysis
4-2-3. Wake from 12MW Wind Turbine Blade

21

4-2-1. Extrapolation for 12 MW FOWT

Items	Target
Rated power (MW)	12.5
Rated rotating speed (RPM)	10
Rated torque (MNm)	11.46



Item	5MW (NREL)	12MW
Blade	61.5	93.6
		(Extrapolation for 12MW)
Tip Radius	63.0	95.88
Hub Radius	1.5	2.28
Tower Height	87.6	133.32

4-2-1. Extrapolation for 12 MW FOWT

Items	Target
Rated power (MW)	12.5
Rated rotating speed (RPM)	10
Rated torque (MNm)	11.46

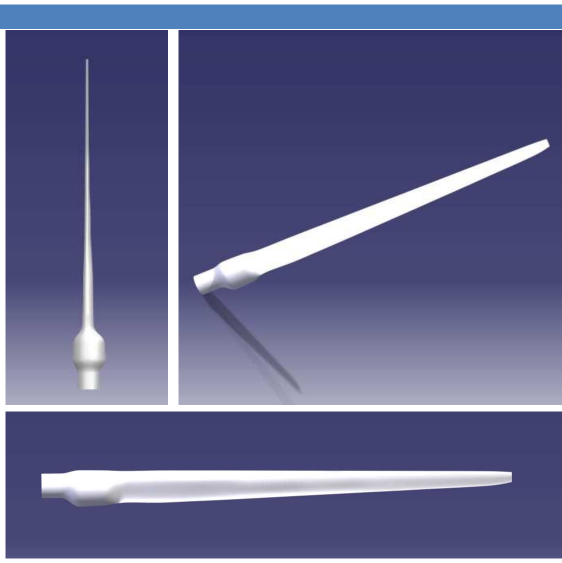
5MW (NREL)

RNodes (m)	AeroTwst (º)	DRNodes (m)	Chord (m)	Airfoil (-)
2.8667	13.308	2.7333	3.542	Cylinder1.dat
5.6	13.308	2.7333	3.854	Cylinder1.dat
8.3333	13.308	2.7333	4.167	Cylinder2.dat
11.75	13.308	4.1	4.557	DU40_A17.dat
15.85	11.48	4.1	4.652	DU35_A17.dat
19.95	10.162	4.1	4.458	DU35_A17.dat
24.05	9.011	4.1	4.249	DU30_A17.dat
28.15	7.795	4.1	4.007	DU25_A17.dat
32.25	6.544	4.1	3.748	DU25_A17.dat
36.35	5.361	4.1	3.502	DU21_A17.dat
40.45	4.188	4.1	3.256	DU21_A17.dat
44.55	3.125	4.1	3.01	NACA64_A17.dat
48.65	2.319	4.1	2.764	NACA64_A17.dat
52.75	1.526	4.1	2.518	NACA64_A17.dat
56.1667	0.863	2.7333	2.313	NACA64_A17.dat
58.9	0.37	2.7333	2.086	NACA64_A17.dat
61.6333	0.106	2.7333	1.419	NACA64_A17.dat

12MW

RNodes (m)	AeroTwst (º)	DRNodes (m)	Chord (m)	Airfoil (-)
4.363	13.308	4.160	5.391	Cylinder1.dat
8.523	13.308	4.160	5.866	Cylinder1.dat
12.683	13.308	4.160	6.342	Cylinder2.dat
17.883	13.308	6.240	6.936	DU40_A17.dat
24.123	11.480	6.240	7.080	DU35_A17.dat
30.363	10.162	6.240	6.785	DU35_A17.dat
36.603	9.011	6.240	6.467	DU30_A17.dat
42.843	7.795	6.240	6.098	DU25_A17.dat
49.083	6.544	6.240	5.704	DU25_A17.dat
55.323	5.361	6.240	5.330	DU21_A17.dat
61.563	4.188	6.240	4.955	DU21_A17.dat
67.803	3.125	6.240	4.581	NACA64_A17.dat
74.043	2.319	6.240	4.207	NACA64_A17.dat
80.283	1.526	6.240	3.832	NACA64_A17.dat
85.483	0.863	4.160	3.520	NACA64_A17.dat
89.643	0.370	4.160	3.175	NACA64_A17.dat
93.803	0.106	4.160	2.160	NACA64_A17.dat

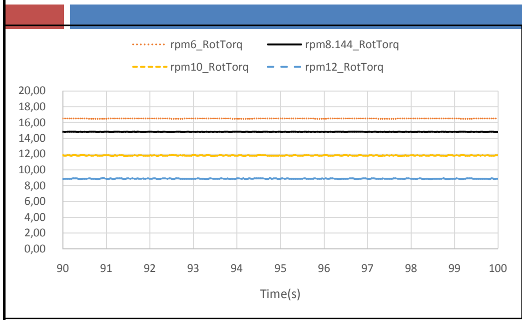
4-2-1. Extrapolation for 12 MW FOWT
- Blade Shape (CATIA)

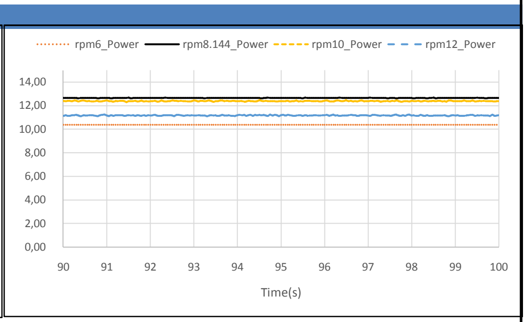


4-2-2 Numerical Analysis
- Rotor Torque & Power of 12MW

11.4 m/s (Steady wind)

Items	Target
Rated power (MW)	12.5
Rated rotating speed (RPM)	10
Rated torque (MNm)	11.46



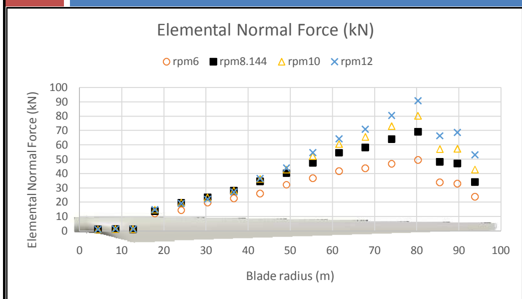


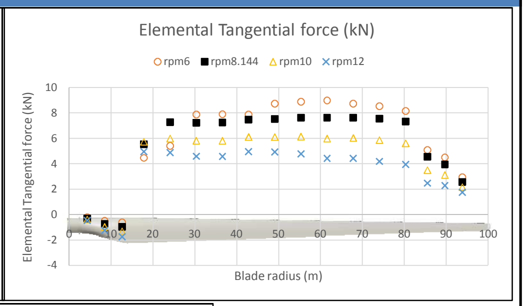
RPM	FAST_Torque (MNm)	FAST_Power (MW)
6	16.4977	10.3658
8.144	**14.8286**	**12.6464**
10	**11.8232**	**12.3812**
12	8.8879	11.1688

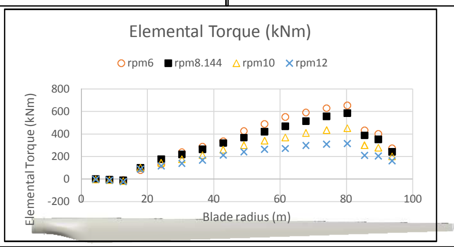
Numerical results from WINDS are about the same as those from FAST (AeroDyn).

4-2-2. Numerical Analysis
- Elemental loads/moments on a blade

11.4 m/s (Steady wind)



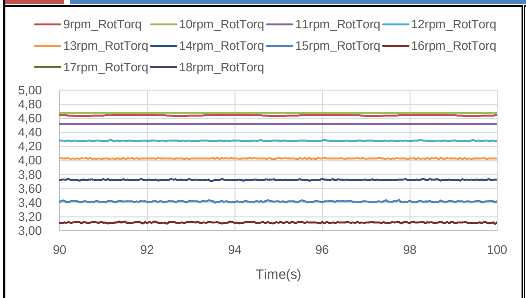


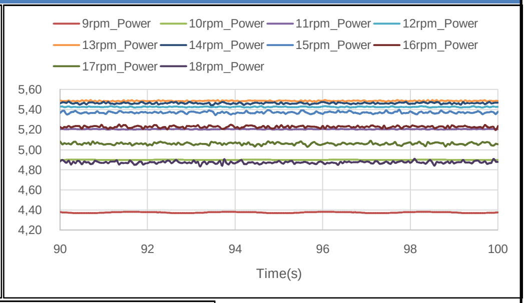


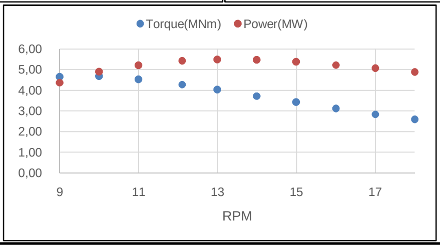
4-2-2 Numerical Analysis

- 5MW (NREL) Rotor Torque & Power with respect to high RPMs without blade pitch control

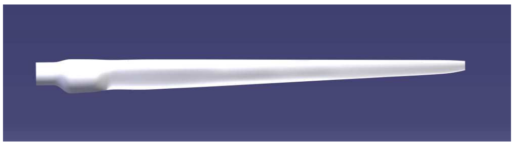
11.4 m/s (Steady wind)



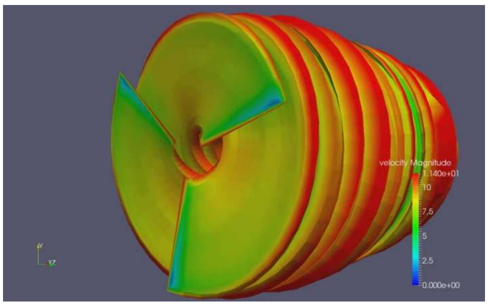


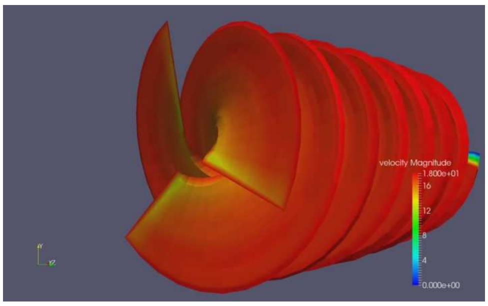


4-2-3. Wake from 12MW Wind Turbine Blade



(CATIA)





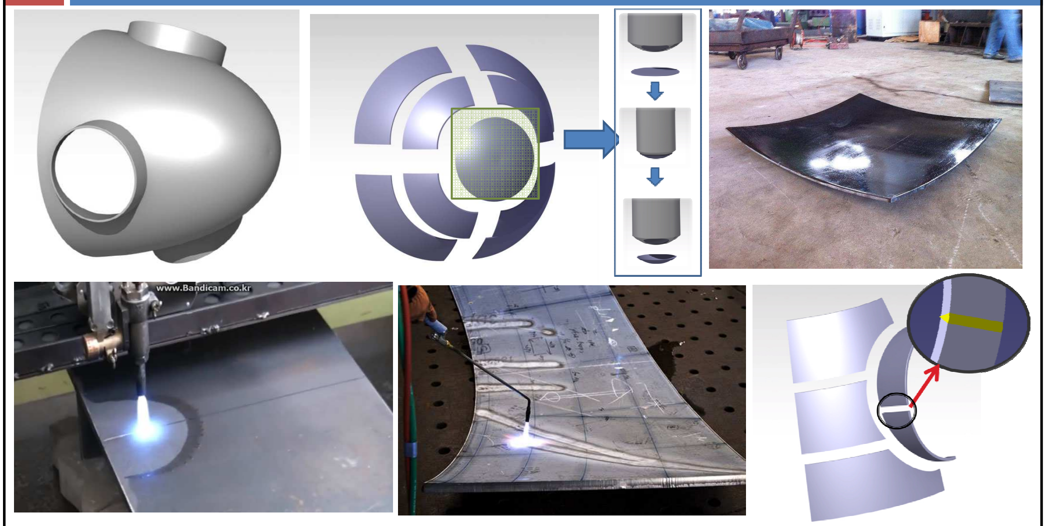
11.4m/s, TSR 7.0, Pitch Angle(deg) 0°

18.0m/s TSR 4.43 , Pitch Angle(deg) 14.9°

(WINDS)

4-3. Spinner and Hub of 12MW FOWT

- Block Assembly (Shipbuilding)



5. HT SCSG @12 MW Solution

5-1. Reason why we should use superconducting generators (Aeolos)
5-2. Road to 12 MW Aeolos
5-3. Project of 12 MW Aeolos
5-4. Characteristic Evaluation Device for HTS Field Coil

30

5-1. Reason why we should use superconducting generators

➢Gear box issue

Economic efficiency

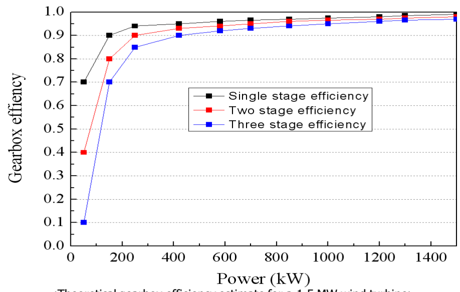
Gear Driven? Direct driven?

Three stage gearbox	Two stage gearbox	One stage gearbox	Direct driven

Light weight (Low installation cost) — Heavy weight (High installation cost)

High maintenance cost, Low efficiency — Low maintenance cost, High efficiency

Ref. Wind power monthly, wind turbine gearboxes and the effort to improve their reliability



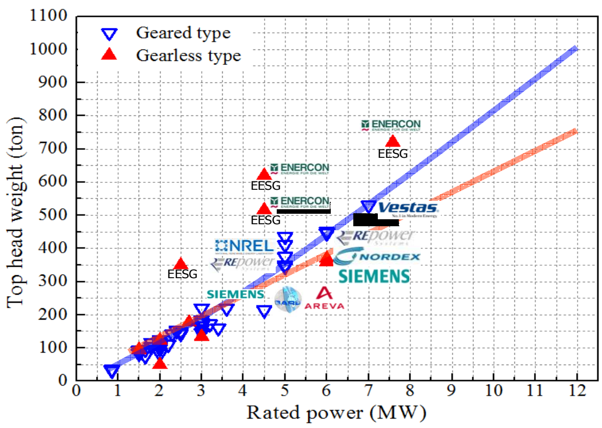
<Theoretical gearbox efficiency estimate for a 1.5 MW wind turbine>

Ref. A Preliminary Evaluation of a Multiple-Generator Drivetrain Configuration for wind Turbines

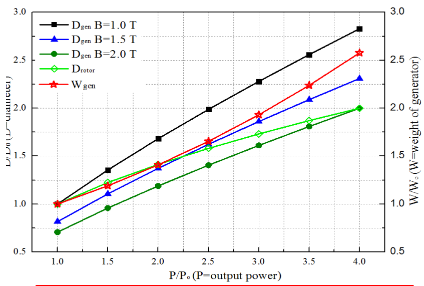
5-1. Reason why we should use superconducting generators

p.32/22

➢Weight trend of top head (incl. blade, hub and nacelle)



➢Output power of synchronous generator



$$P = B \times k_w N \times i \times D_{gen}^2 L_{gen} \times \omega$$

$$P = K \times D_{gen}^2 L_{gen} \times rpm$$

$$\therefore K = B \times k_w N \times i \times \frac{2\pi}{60}$$

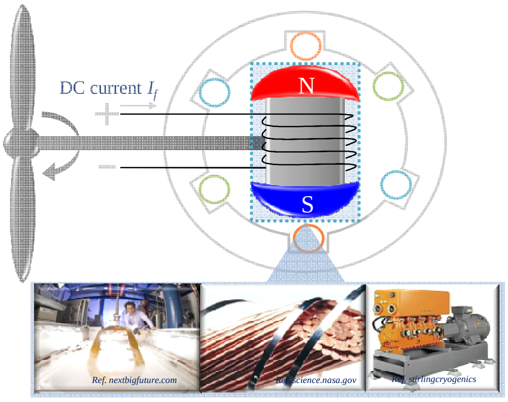
Magnetic field

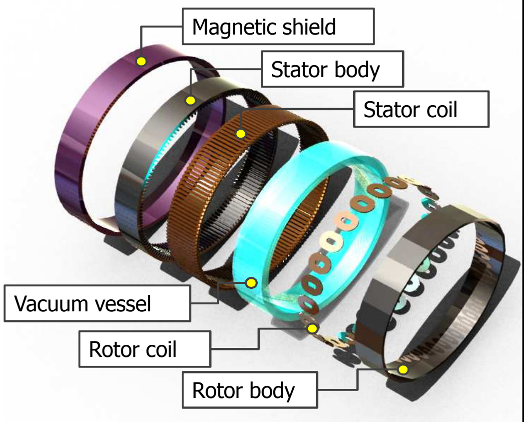
✓12 MW Tower head weight (gearless type): ~750 (ton) (advanced GFRP/CFRP)
✓12 MW Tower head weight (geared type): ~1000 (ton)
Mechanical stress and cost of foundation and tower are increased to support blade, hub and nacelle.
➔Superconducting generator can reduce the top head weight due to high magnetic field.

5-1. Reason why we should use superconducting generators

p.33/22

➢Configuration of the superconducting generator





- **Rotor coils:**
Copper coil or Permanent magnet
→ Superconducting coil (with DC current excitation)
- **Temperature:**
Room temperature → Cryogenic temperature

- **Rotor part:** Superconducting coils, Rotor body, and Vacuum vessel
(Superconducting coils are cooled in the vacuum vessel at cryogenic temperature.)
- **Stator part:** Copper coils, Stator teeth, and Magnetic shield

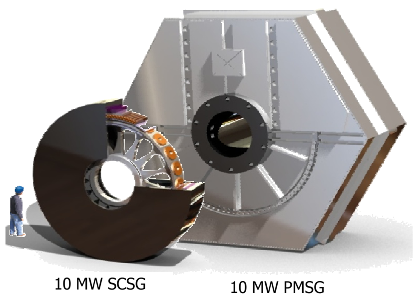
5-1. Reason why we should use superconducting generators

p.34/22

➢Advantages of the superconducting generator

❖ Volume and weight of the generator

- Generator volume ↑ = Turbine weight ↑
- Superconducting generator can reduce volume and weight



❖ Magnetic field of the generator

- Magnetic field ↑ = Generator volume ↓ = Generator weight ↓

❖ Construction cost of the wind turbine

- Generator volume ↑ = Turbine weight ↑
- Tower & foundation cost ↑ = Construction cost ↑
- Superconducting generator can reduce the construction cost

Aeolos(風神) : superconducting generators

Aerodynamic Energy from Ocean and Limitless power Of Superconductivity

5-2. Road to 12 MW Aeolos

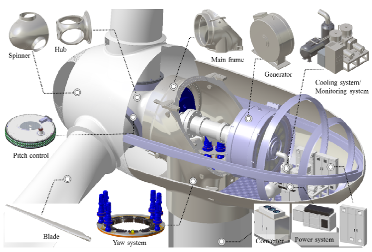
p.36/22

VISION; 12 MW Aeolos technology roadmap over the next 10 years

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

	1st Phase	2nd Phase	3rd Phase
	Design in detail for 3 years & 10kW model size	Down scale prototype manufacturing	Commercial Beta-type fabrication
Total 3 MW		3 MW class proto-type manufacturing	3 MW class field test
Total 12 MW	12 MW design in detail	12 MN·m torque test unit	12 MW real system fabrication

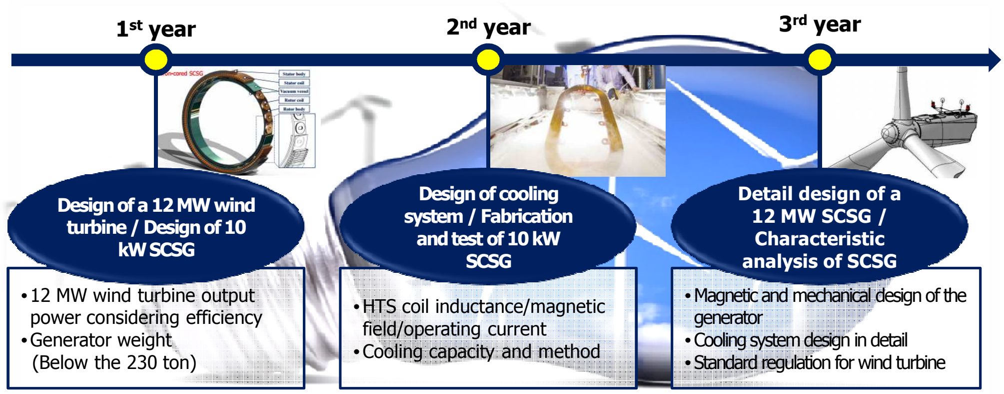
➢Plan of the technology application



Blade	3 MW conventional	12 MW newly developed
Tower	3 MW conventional	7~8 MW conventional
Hub	3 MW conventional	12 MW newly developed
Generator	3 MW newly developed	12 MW newly developed
Converter	3 × 1 MW conventional	3 × 4 MW conventional
Foundation	3 MW conventional	7~8 MW conventional

5-3. Project of 12 MW Aeolos

➢ Development of 12 MW Superconducting Synchronous Generator



Year	Appraisal
1st yr. Design of a 12 MW wind turbine	Confirm 12 MW wind turbine output power with the HTS generator
2nd yr. An HTS pole manufacturing for the HTS generator	HTS one pole coil test in liquid nitrogen based on design results of the 12 MW HTS generator (<10% error of simulation result)
3rd yr. Detail design of a 12 MW wind turbine with cooling system	Validity and review of the 12 MW wind turbine detail design using 3D CATIA program from related experts

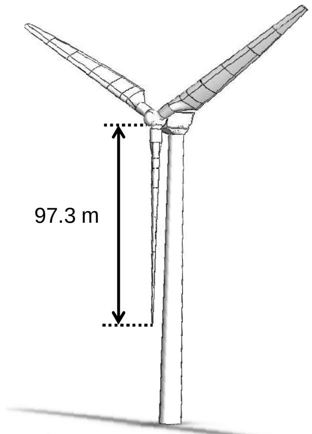
울산대학교 창원대학교 CHANGWON NATIONAL UNIVERSITY KIMS

5-3. Project of 12 MW Aeolos

p.38/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	Design of 10 kW class SCSG
Design of HTS field coil by type of HTS wires	Design of cooling system for 10 kW class SCSG



Items	Value
Rated output power P_N (MW)	12
Shaft power P_T (MW)	12.96
Rated ideal wind velocity V_{RI} (m/s)	11.4
Tip speed ratio λ (V_R)	8.9
Rotor diameter 2R (m)	194.6
Tip speed V_{TIP} (m/s)	85.6
Rotation speed ω_R (rad/s)	1.047 (=10rpm)
Maximum power coefficient C_{Pmax}	0.48
Mass density of the air ρ (kg/m^3)	1.225

$$R_{blade} = \sqrt{\frac{2P_T}{\rho C_p \pi V^3}} = \sqrt{\frac{2(1+\varepsilon)P_N}{\rho C_p \pi V^3}}$$

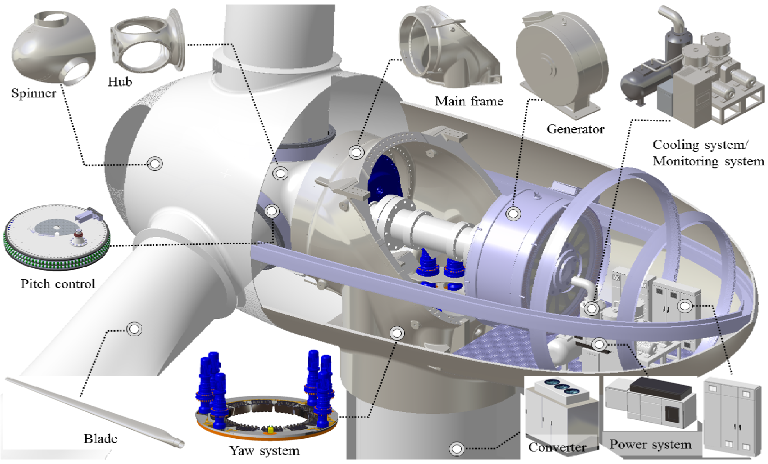
- ρ: Air density, 1.225 kgm^{-3}
- C_p: Max. power coefficient of rotor
- V: Rated ideal wind velocity
- P_T: Mechanical power of the rotor shaft
- P_N: Rated power of wind turbine
- $P_T = (1+\varepsilon)P_N$ includes a loss factor of the drive train (ε~8%)

5-3. Project of 12 MW Aeolos

- 3rd year; Detail design of 12 MW class SCSG including the cooling system

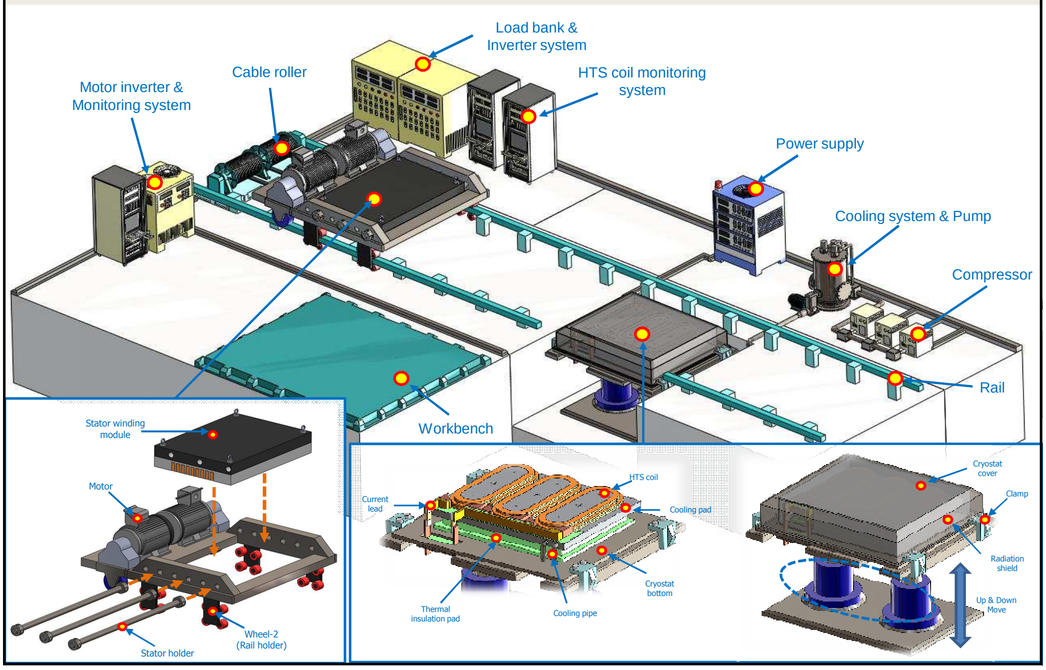
Characteristics analysis of 10 kW class SCSG
Redesign of HTS field coil and SCSG based on analysis results of 10 kW class SCSG
Whole design of 12 MW class SCSG for wind turbine (CATIA)

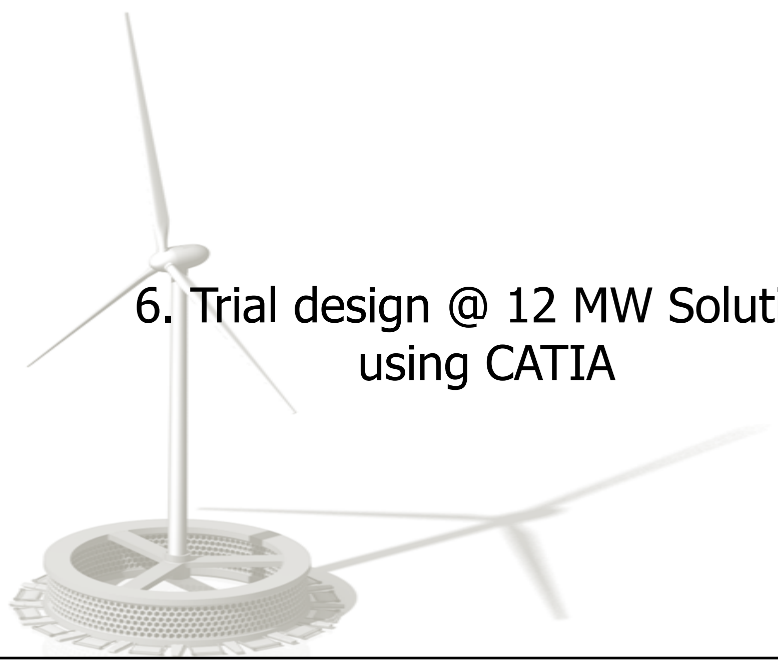
✓ 12 MW class wind power generation system (CATIA)



Consideration items
Superconducting generator
Composite Light shaft
Floater
Cooling system
Main frame
Yaw / Pitch system
Hub / Blade / Tower
Converter / Power system
Nacelle cover
Tighten screw / Wiring
Structural qualification
Law and regulations

5-4. Characteristic Evaluation Device for HTS Field Coil

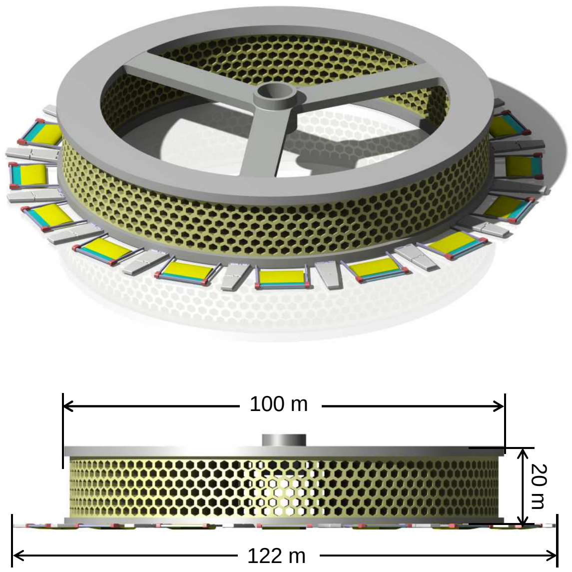


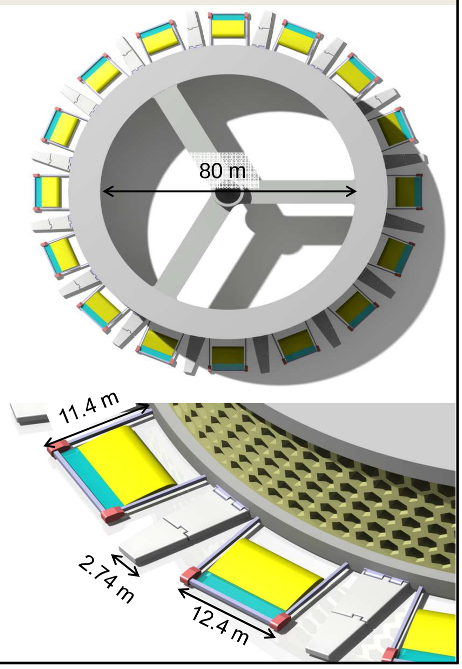


6. Trial design @ 12 MW Solution using CATIA

Drawing of 12 MW Floater

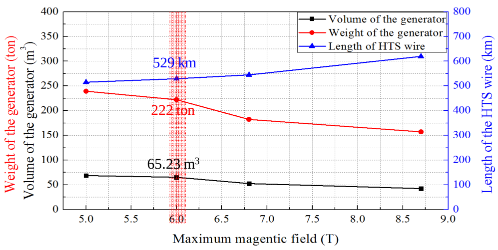
➢ Floater



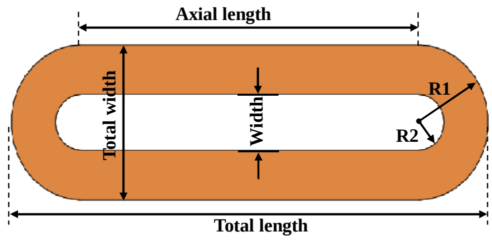


Drawing of 12 MW Aeolos

➢ Designed 12 MW SCSG



➢ Specifications of designed rotor coil



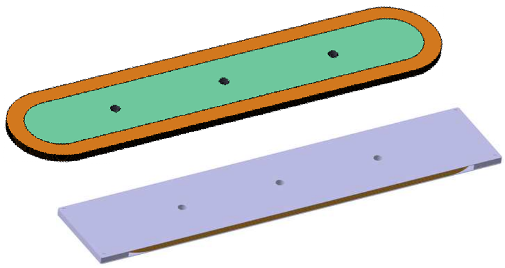
Items	Value
Rated power (MW)	**12.5**
Rated L-L voltage (kV)	6.6
Rated armature current (A)	918.5
Rated rotating speed (RPM)	**10**
Rated torque (MN·m)	**11.46**
The length of air gap (mm)	20
Thickness of vacuum vessel (mm)	50
Safety margin of operating current (%)	30
Width of the SC wire (mm)	**4**
Thickness of the SC wire (mm)	**0.1**
Maximum magnetic field (T)	**6**

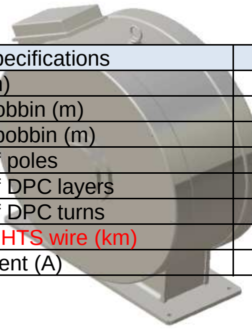
Specifications	Value
Axial length (m)	1.7
With of the DPC (mm)	0.5
The number of DPC layers	**6**
The number of DPC turns	**800**
Total length of HTS wire (km)	**529**
Operating current (A)	123
The number of stator slots	144
The number of stator coil turns	**20**
Volume of SCSG (m^3)	**65.23**
Active weight of SCSG (ton)	**222**

Drawing of 12 MW Aeolos

➢ 12 MW superconducting wind power generator

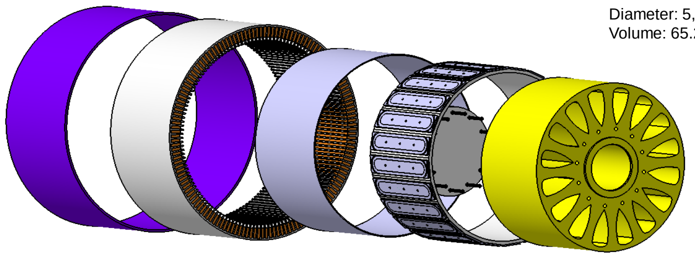
✓ Rotor coil of 12 MW class SCSG



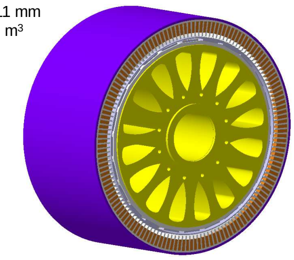


Specifications	Value
Axial length (m)	1.7
Width of the bobbin (m)	0.27
Radius of the bobbin (m)	0.135
The number of poles	24
The number of DPC layers	6
The number of DPC turns	800
Total length of HTS wire (km)	529
Operating current (A)	123

✓ Overall structure of 12 MW class SCSG



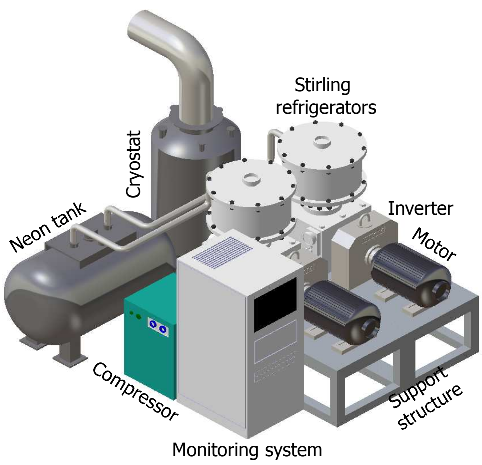
Diameter: 5,911 mm
Volume: 65.23 m³



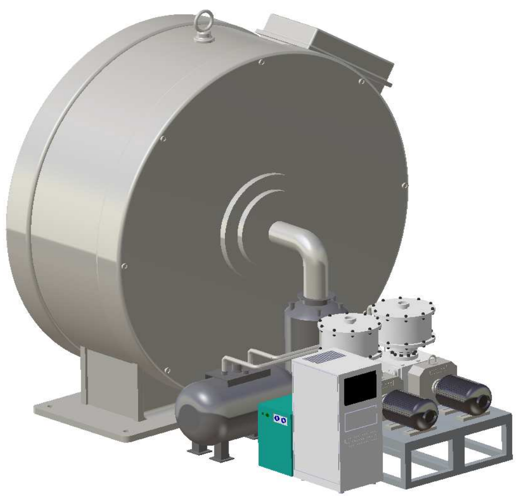
Drawing of 12 MW Aeolos

➢ Cooling system

✓ Cryogenic cooling system



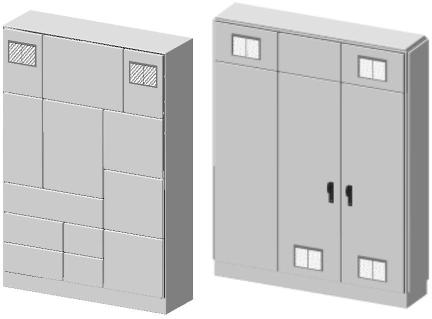
✓ Cooling system / SCSG



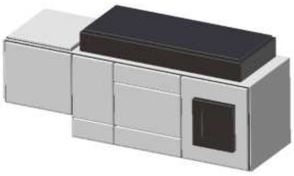
Drawing of 12 MW Drive Train

➢ Electric power equipment

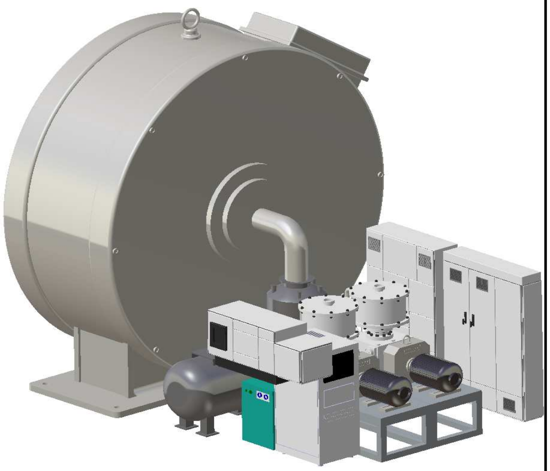
✓ Power distribution controller



✓ Power supply and controller

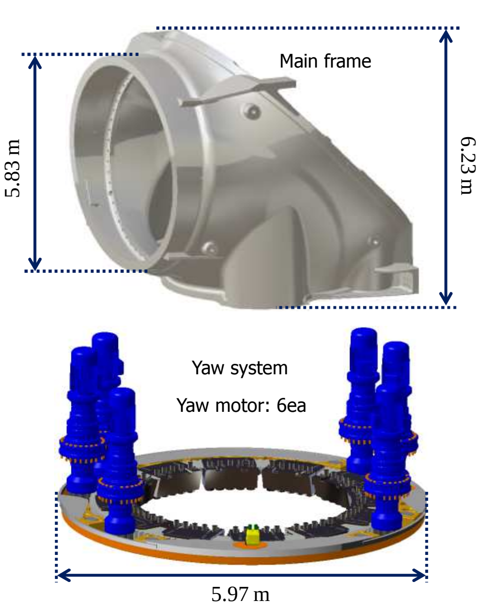


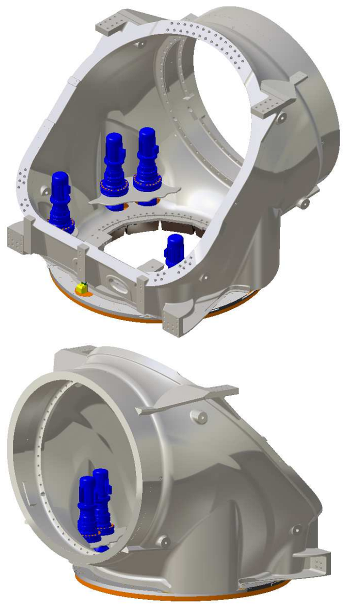
✓ Power equipment / Cooling system / SCSG



Drawing of 12 MW Nacelle

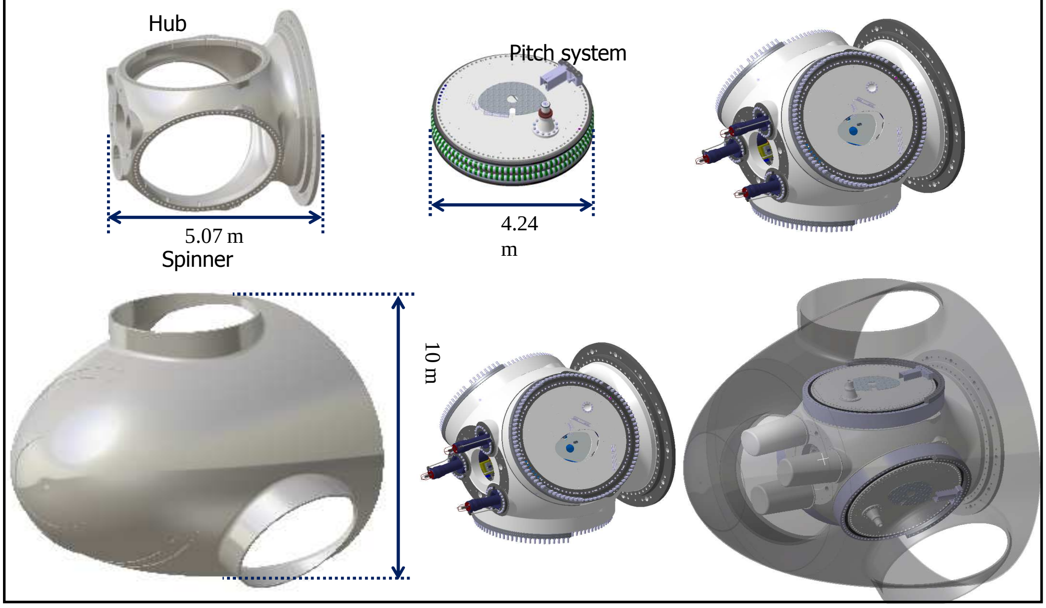
➢ Main frame / Yaw system





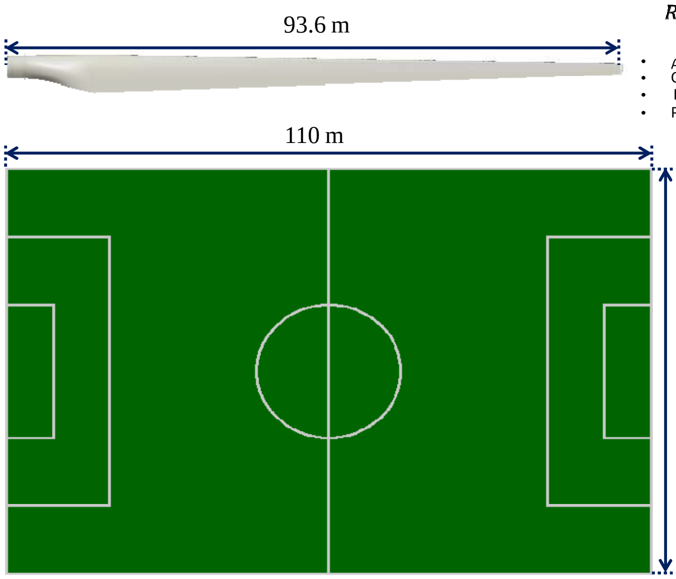
Drawing of 12 MW Nacelle

- Hub / Pitch system / Spinner



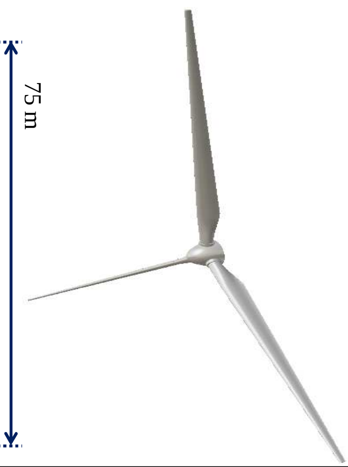
Drawing of 12 MW Blade

- Blade



$$R_{blade} = \sqrt{\frac{2P}{\rho C_p \pi V^3}} = \sqrt{\frac{2P}{\rho C_p \pi V^3}}$$

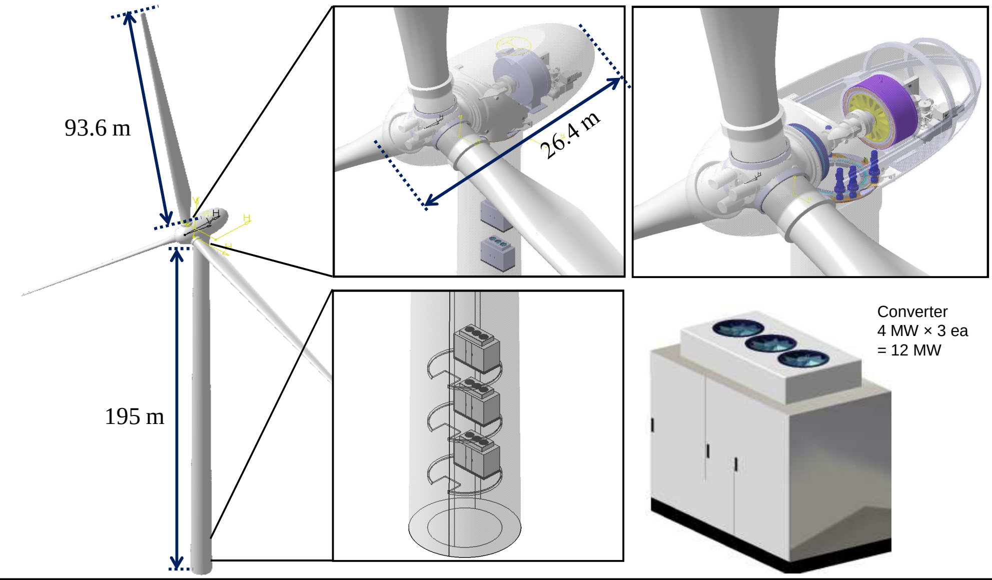
- ρ : Air density, 1.225 kgm^{-3}
- C_p : Max. power coefficient of rotor
- V : Rated ideal wind velocity
- P_N : Rated power of wind turbine



Drawing of 12 MW Nacelle/Tower

- Nacelle cover / Tower / Converter

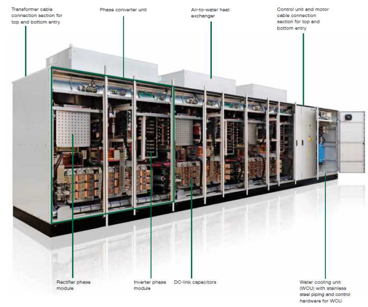
➢Whole shape of the 12 MW wind power generation system



Drawing of 12 MW Converter

- Specifications of the converter system (model ACS 5066-W2A-D5)

- Power range 5 to 32 MW (6.0 to 6.9 kV)
- Water cooling
- Superior arc protection function for very fast arc detection and elimination
- Low harmonic solution (36-pulse configuration)
- Available with an integrated input transformer or external input isolation transformer
- Available for induction, synchronous motors



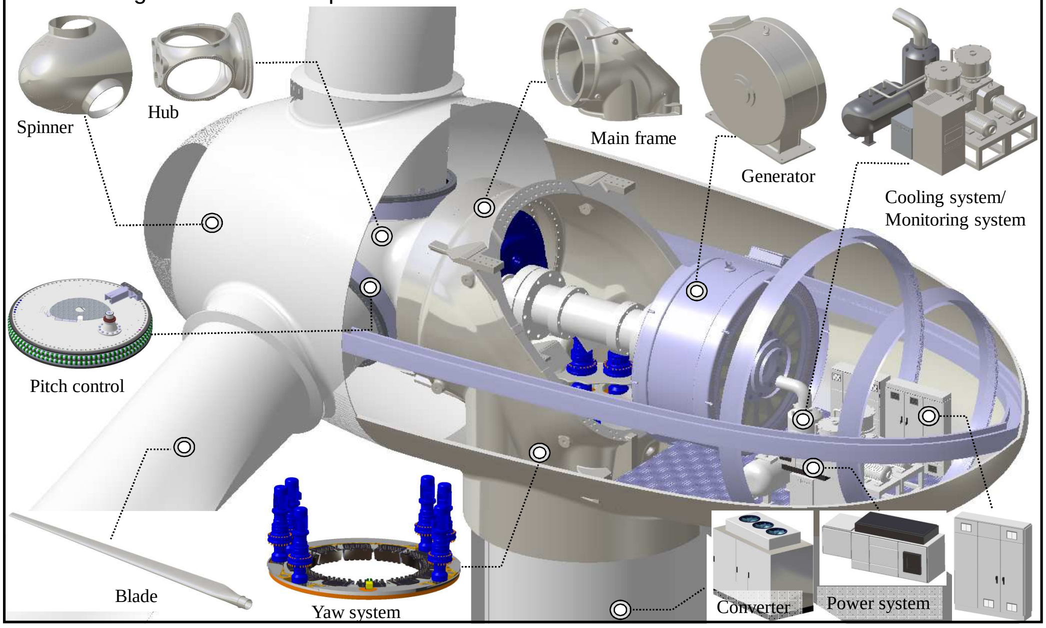
Ref) www.abb.com

Motor data			Converter	Converter data			
Voltage	Shaft power *		Type code	Power	Current	Length**	Weight ***
kV	kW	hp		kVA	A	mm	kg
6,600 V							
6.6	7510	10060	ACS 5066-W1A-D5	7700	670	7130	8000
6.6	9360	12540	ACS 5066-W1B-D5	9600	840	7130	8000
6.6	11120	14900	ACS 5066-W1C-D5	11400	1000	7130	8000
6.6	13940	18680	ACS 5066-W2A-D5	14300	1250	9130	10000
6.6	16670	22340	ACS 5066-W2B-D5	17100	1500	9130	10000
6.6	19500	26130	ACS 5066-W3A-D5	[illegible]	[illegible]	[illegible]	[illegible]
6.6	22330	29920	ACS 5066-W3B-D5	[illegible]	[illegible]	[illegible]	[illegible]
6.6	25640	34360	ACS 5066-W4A-D5	[illegible]	[illegible]	[illegible]	[illegible]
6.6	27890	37370	ACS 5066-W4B-D5	28600	2500	15815	20000
6.6	33440	44810	ACS 5066-W4C-D5	34300	3000	15815	20000

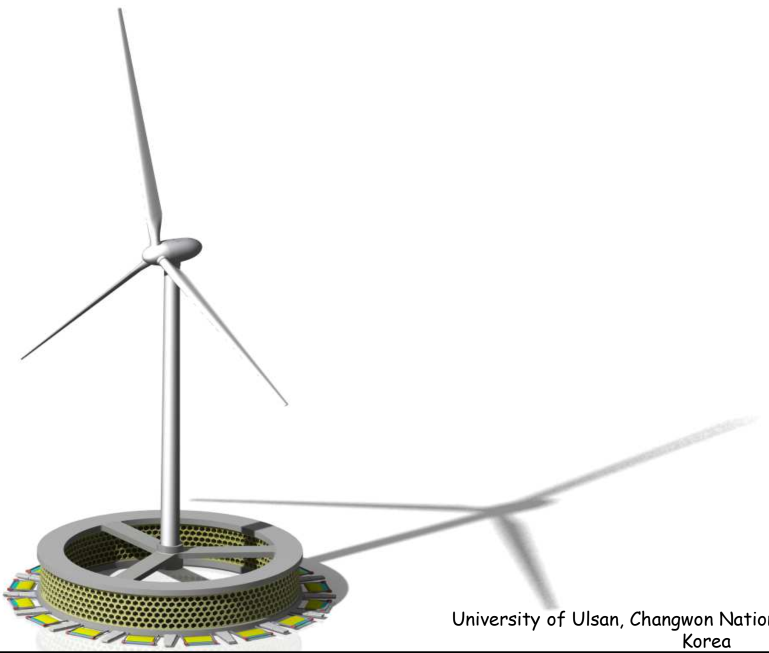
General dimensions ACS 5000 water cooled
Cabinet height: 2360 mm excl. cooling fans
2710 mm incl. auxiliary cooling fans
Cabinet depth: 1600 mm

Drawing of 12 MW Nacelle

- Drawing of the whole shape



12MW Novel FOWT



University of Ulsan, Changwon National University & KIMS
Korea

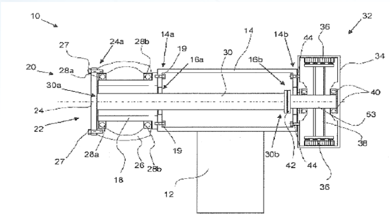
Acknowledgement

This work is supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) : Program No. 20142020103560

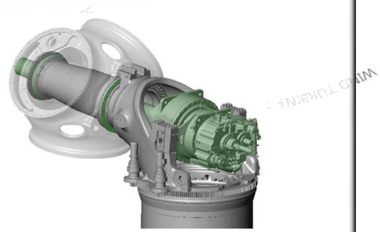
THANK YOU VERY MUCH FOR YOUR ATTENTIONS.

1차년도: 설계요구도 정립 및 하중 분리구조 개념설계

- 개발 내용
  - **하중 분리구조 개념설계**
    - 목적 : 전단 및 굽힘 지지구조와 토크 전달구조 개념 설계
    - 현황 및 문제점
      - 기존의 하중 분리구조 회피설계 도출
      - 경량화 설계가 요구됨
    - 접근방법
      - 지지구조 개념설계 / 토크 전달구조 개념설계



굽힘 및 토크 하중을 분리시킨 flexible shaft 구조 (EP2397690 A1)



굽힘 및 토크 하중을 분리시킨 경량 Nacelle 구조 (Alstom)

KIMS Korea Institute of Materials Science

WIND TURBINE TECHNOLOGY RESEARCH CENTER

1-3. 12MW 부유식 해상풍력발전시스템 LCOE 절감

❑ LCOE의 가격 비교

구분	6[MW]FOWT	12[MW] FOWT	LCOE계산식
Project scale	500[MW]	500[MW]	$\frac{총지출비용}{총발전량}$ =
FOWT 년간 생산량	60[대/년]	60[대/년]	
CAPEX	60[억원/MW]	40[억원/MW]	$\frac{\sum_{t=1}^{n}\frac{I_t+M_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}}$
이용률	35%	35%	
OPEX	49.7[원/kWh]	49.7[원/kWh]	
운전설계수명	25년	25년	
전력판매액	250[원/kWh]	250[원/kWh]	=130원+2X60원
LCOE	**245.7[원/kWh]**	**180.4[원/kWh]**	SMP REC

❑ WTG의 국제 시장 가격 동향

풍력발전기 3MW	가격	6MW= 3MW×2sest	풍력발전기 6MW	
VESTAS V112-3.0MW	40억원	80억원	150억원	SIEMENS SWT-154-6.0MW
SINOVEL SL-3000	30억원	60억원		

❑ 3[MW] VESTAS 가격 동향 (치열한 가격 경쟁)

- 2008년 V90-3.0 : 50억원/대
- 2012년 V112-3.0 : 40억원/대

❑ 결론

- 기술선진국
  - 시장 확대에 따른 지속적 가격 경쟁력 확보
  - 지속적인 성능향상
- 중국
  - 물량에 따른 가격 공세
  - CDB를 통한 2%대의 100% 금융지원
- 국내 시장
  - 향후 500[MW] 이하의 시장과 최소 200여대/년

❑ 전략

- 점진적 개발 전략에서 과감한 Quantum Jump
- 기술 시장 선도

58

1-3. 12MW 부유식 해상풍력발전시스템 LCOE 절감

□ Siemens 6MW OEM/License 생산 시 제조단가 분석

구분	중량 (Ton)	Price (백만원)	비고
Floater	2,000	6,400	Source:DOE PJT
Nacelle + Rotor	360	16,000	
Tower (90m)	300		Source:중량추정
합계	**2,660**	**22,400**	

□ 결론 **8.4백만원/톤**
- WTG의 국내 License 생산 공급 할 경우 국내 조선산업 보다 높은 사업규모와 사업성
- 대량연속생산이 가능하며, 대량생산을 통한 가격경쟁력

□ 분야 산업별 Structure 제조 가격
- Offshore structure : 10M KRW/Ton
- Ship structure : 4.5M KRW/Ton
- Wind Tower structure : 2.0M KRW/Ton
- **Floater의 제조 가격의 목표 : <3.0M KRW/Ton**

59

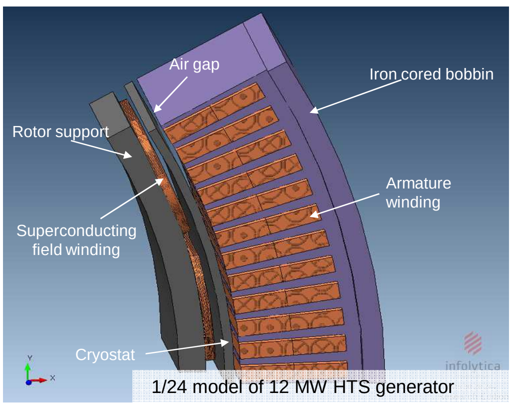
5-3. Project of 12 MW Aeolos

p.60/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	Design of 10 kW class SCSG
Design of HTS field coil by type of HTS wires	Design of cooling system for 10 kW class SCSG

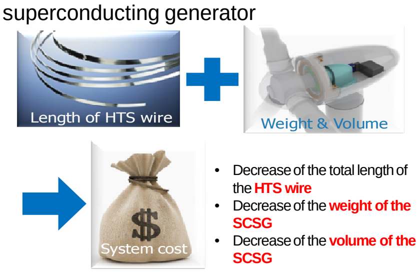
✓ Development of 3D FEM analysis model



1/24 model of 12 MW HTS generator

✓ Development of optimal design method
- Optimal design example
  - Taguchi method
  - Response surface method
  - Multi-disciplinary optimization
  - Genetic algorithm

✓ Targets for the optimal design of 12 MW superconducting generator



- Decrease of the total length of the **HTS wire**
- Decrease of the **weight of the SCSG**
- Decrease of the **volume of the SCSG**

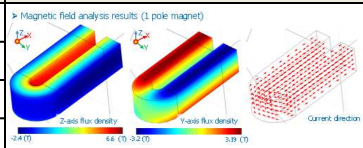
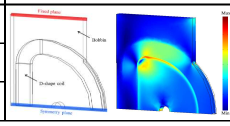
5-3. Project of 12 MW Aeolos

p.61/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	Design of 10 kW class SCSG
Design of HTS field coil by type of HTS wires	Design of cooling system for 10 kW class SCSG

✓ Design of HTS field coil

Process	Consideration	Properties	Configuration
Electromagnetic analysis	Component of the HTS field coil	Width / Thickness of HTS wire	
		Axial length	
		Turns of the coil	
		Number of layer	
	Development of the 3D FEM analysis model	HTS field coil	(see Specifications table below)
		Bobbin	
Structure analysis	Electromagnetic force		
	Coil size (mm) / Support area (mm²)		
	Maximum magnetic field (T) / Torque (N·m)		
Evaluation item	• Test of magnetic field, inductance, operating current of the HTS field coil by using the 3D FEM program • Loads and stress analysis of the HTS field coil by magnetic field and torque • Comparative analysis of magnetic field of HTS field coil by electromagnetic and structure analysis		

Specifications	Value
Axial length (m)	0.5
The number of poles	**24**
The number of DPC layers	**5**
The number of DPC turns	**1,287**
Total length of HTS wire (km)	579

Physical Properties	Metric
Density	2.70 g/cc
Mechanical Properties	**Metric**
Hardness, Brinell	82
Hardness, Knoop	106
Hardness, Rockwell A	35.5
Hardness, Rockwell B	50
Hardness, Vickers	92
Tensile Strength, Ultimate	255 MPa
Tensile Strength, Yield	241 MPa
Elongation at Break	9.0 % @Thickness 1.59 mm
Modulus of Elasticity	68.9 GPa
Poissons Ratio	0.33
Shear Modulus	25.8 GPa
Shear Strength	152 MPa

5-3. Project of 12 MW Aeolos

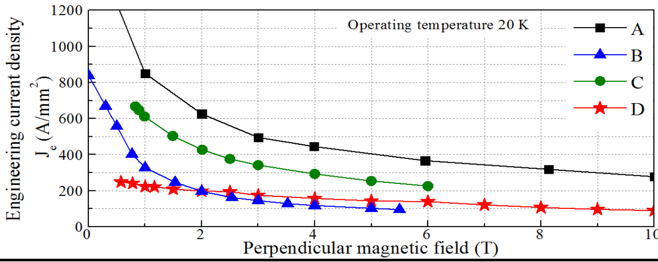
p.62/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

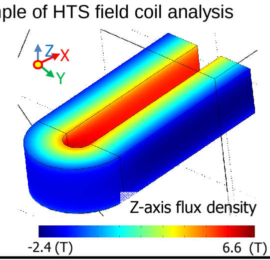
Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	Design of 10 kW class SCSG
Design of HTS field coil by type of HTS wires	Design of cooling system for 10 kW class SCSG

✓ Specification of the HTS wires

Symbol	A [1]	B [2]	C [3]	D [4]
Type	(GdY)BCO	YBCO	(Gd)BCO	Bi-2223
Thickness (mm)	0.1	0.2	0.3	0.36
Width (mm)	4	4.8	5	4.5
Min. RT bend diameter (mm)	11	30	-	60
Max. RT rated tensile stress (MPa)	550	150	-	250
Critical current (self field, 77 K)	100 A	100 A	230 A	200 A



✓Example of HTS field coil analysis



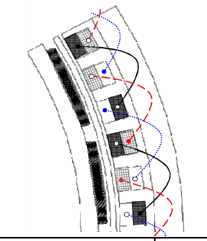
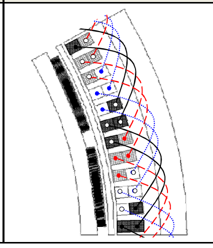
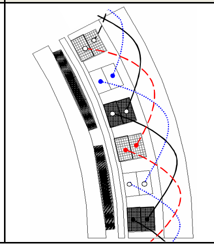
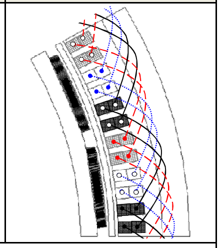
5-3. Project of 12 MW Aeolos

p.63/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine
Development of 3D FEM model for 12 MW SCSG
Development of optimal method for 12 MW SCSG
Design of HTS field coil by type of HTS wires
Design of stator coil by armature winding method
Design of stator coil by material of stator teeth
Design of 10 kW class SCSG
Design of cooling system for 10 kW class SCSG

✓ Design of stator coil according to armature winding method

Parts	Short pitch - Concentrated winding	Short pitch - Distributed winding	Full pitch - Concentrated winding	Full pitch - Distributed winding
Configuration				

Types and characteristics of winding method		
Types and characteristics of winding method	Arrangement method	• Distribution winding: Decrease the EMF, Harmonic wave, leakage reactance
		• Concentration winding: Decrease the loss and cost, Increase the torque ripple
	Coil pitch	• Short-pitch: Decrease the EMF, Harmonic wave, quantity of copper
		• Full-pitch: Decrease the noise, reduction efficiency by copper loss
Evaluation items	• Comparative analysis of torque ripple, harmonic wave, and THD • Comparative analysis of output power and efficiency	

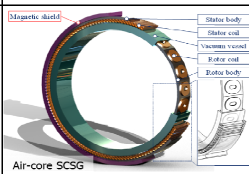
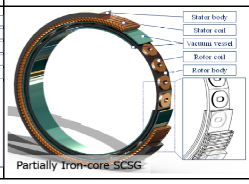
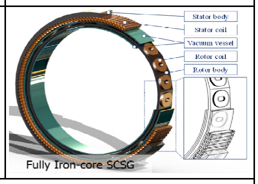
5-3. Project of 12 MW Aeolos

p.64/22

➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine
Development of 3D FEM model for 12 MW SCSG
Development of optimal method for 12 MW SCSG
Design of HTS field coil by type of HTS wires
Design of stator coil by armature winding method
Design of stator coil by material of stator teeth
Design of 10 kW class SCSG
Design of cooling system for 10 kW class SCSG

✓ Design of stator coil according to material of rotor and stator body

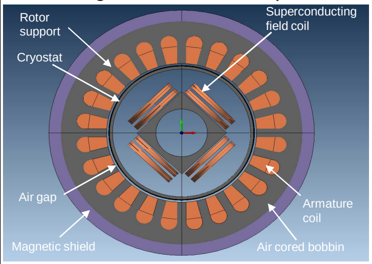
Parts		Air-core material	Partially Iron-core material	Fully Iron-core material
Rotor	Rotor coil	HTS wire	HTS wire	HTS wire
	Vacuum vessel	Stainless steel	Stainless steel	Stainless steel
	Rotor body	Stainless steel or FRP	Stainless steel or FRP	Laminated silicon steel
Stator	Stator coil	Copper wire	Copper wire	Copper wire
	Stator body	Stainless steel or FRP	Laminated silicon steel	Laminated silicon steel
	Magnetic shield	Laminated silicon steel	-	-
Configuration				
Evaluation items		• Analysis of efficiency through the output power of the generator • Comparative analysis of generator weight • Design of magnetic shield to protect surrounding equipment from the high magnetic field		

5-3. Project of 12 MW Aeolos

➢ 1st year; Optimal design of 12 MW class wind power generation system

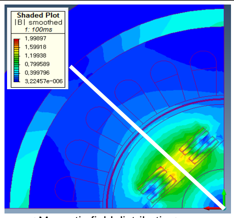
Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	**Design of 10 kW class SCSG**
Design of HTS field coil by type of HTS wires	Design of cooling system for 10 kW class SCSG

✓ Design of 10 kW SCSG (Basic design, Detail design of HTS field coil)

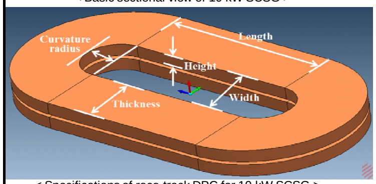


< Basic sectional view of 10 kW SCSG >

Item	Value
Rated power	10 kW
Rated L-L voltage	380 V
Rated armature current	15 A
Rated rotating speed	600 RPM
Rated torque	160 Nm
Number of pole	4
Rated frequency	20 Hz
Number of phase	3
Number of DPC/pole	2

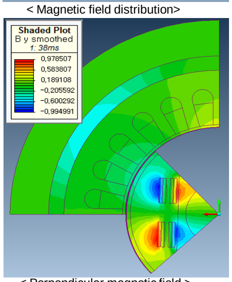


< Magnetic field distribution>



< Specifications of race-track DPC for 10 kW SCSG >

Symbol	Value (mm)
Width	20
Length	220
Height	4
Thickness of insulation	2
Curvature radius	10



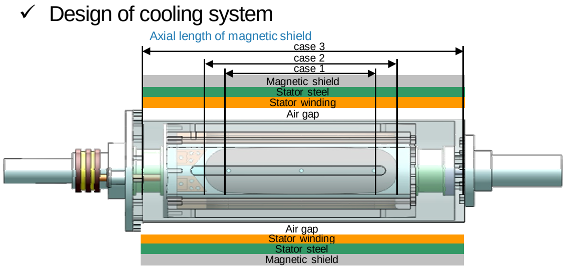
< Perpendicular magnetic field >

5-3. Project of 12 MW Aeolos

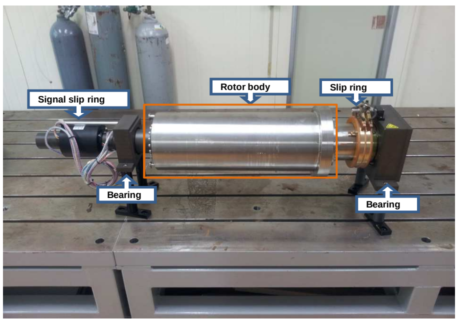
➢ 1st year; Optimal design of 12 MW class wind power generation system

Design of 12 MW class wind turbine	Design of stator coil by armature winding method
Development of 3D FEM model for 12 MW SCSG	Design of stator coil by material of stator teeth
Development of optimal method for 12 MW SCSG	Design of 10 kW class SCSG
Design of HTS field coil by type of HTS wires	**Design of cooling system for 10 kW class SCSG**

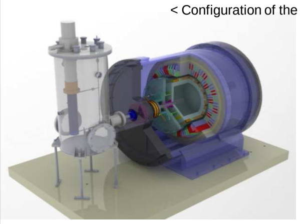
✓ Design of cooling system



< Configuration of the HTS rotor system>



< Structure of the HTS rotating system >



✓ Material of each part

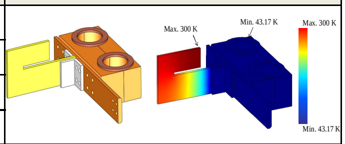
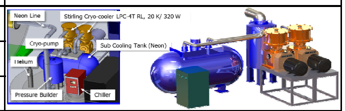
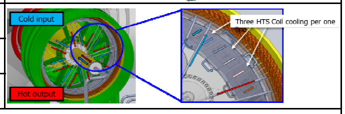
Symbol	Value	Symbol	Value
Stator coil	Copper	Bobbin of HTS field coil	Aluminum
Bobbin of stator coil	FRP	Magnetic shield	M-27 24 Ga

5-3. Project of 12 MW Aeolos

➢ 2nd year; Design of cooling system / Fabrication and test of 10 kW SCSG

Design of cooling system and structure according to shape of the generator
Design of 12 MW class SCSG considering cooling system
Fabrication and test of 10 kW class SCSG

✓ Design of cooling system / Design of 12 MW SCSG considering cooling system

Process		Consideration	Configuration
Cooling system	Thermal analysis (Heat load)	Current lead (Conduction)	
		System structure (Conduction)	
		Radiant heat (Radiation)	
		Joule heat (Harmonic component)	
	Cooling method	Refrigerator / Refrigerant	
		Refrigerant operation method	
		Heat exchanging system	
	Structure	Cryostat (in generator)	
		Structure disk / Rotor body	
		HTS field coil bobbin	
Evaluation items	• **Cooling method** (choose the heat load, refrigerator, refrigerant) • **Detail design of cooling system** (heat exchange system, refrigerant operation method) • Design plan of power consumption, operating and maintenance cost)		

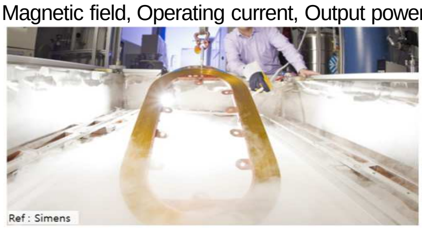
5-3. Project of 12 MW Aeolos

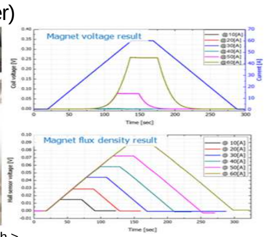
➢ 2nd year; Design of cooling system / Fabrication and test of 10 kW SCSG

Design of cooling system and structure according to shape of the generator
Design of 12 MW class SCSG considering cooling system
Fabrication and test of 10 kW class SCSG

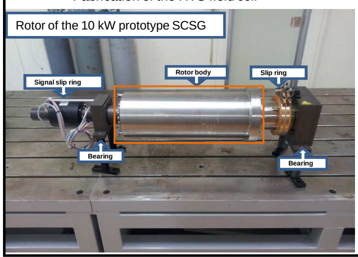
✓ Fabrication and test (Inductance, Magnetic field, Operating current, Output power)

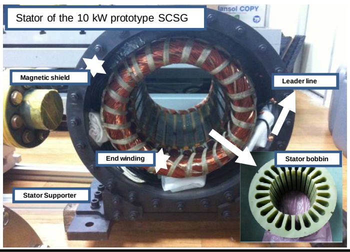
< Fabrication of the HTS field coil >

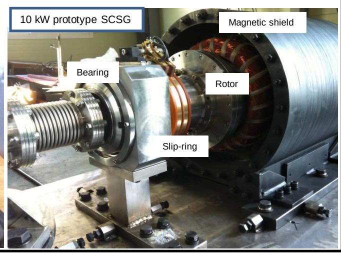




< Test of the HTS field coil in LN2 bath >





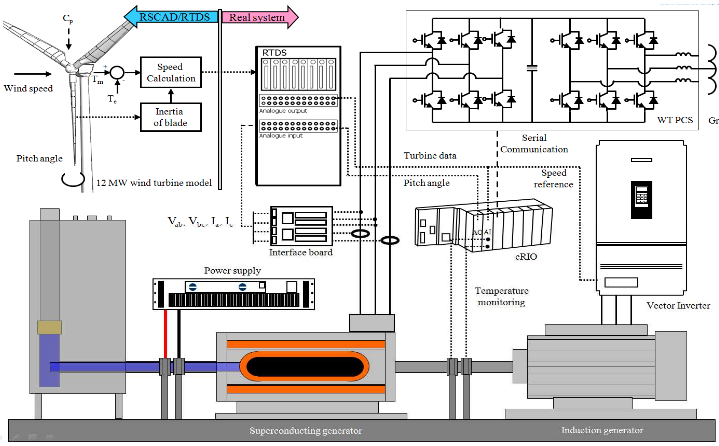


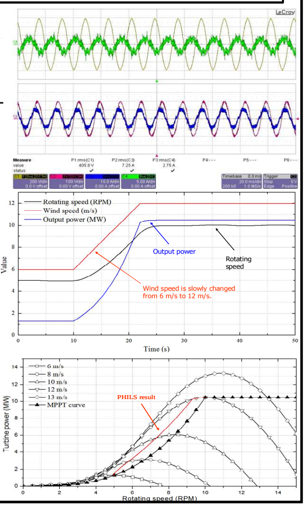
5-3. Project of 12 MW Aeolos

- 3rd year; Detail design of 12 MW class SCSG including the cooling system

Characteristics analysis of 10 kW class SCSG
Redesign of HTS field coil and SCSG based on analysis results of 10 kW class SCSG
Whole design of 12 MW class SCSG for wind turbine (CATIA)

✓ Characteristics analysis of 10 kW class SCSG (using PHILS)





< Test configuration of the superconducting wind generator>

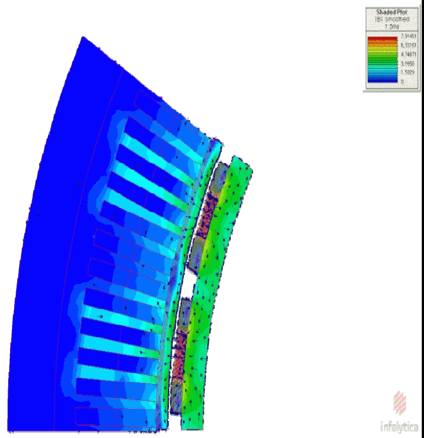
5-3. Project of 12 MW Aeolos

- 3rd year; Detail design of 12 MW class SCSG including the cooling system

Characteristics analysis of 10 kW class SCSG
Redesign of HTS field coil and SCSG based on analysis results of 10 kW class SCSG
Whole design of 12 MW class SCSG for wind turbine (CATIA)

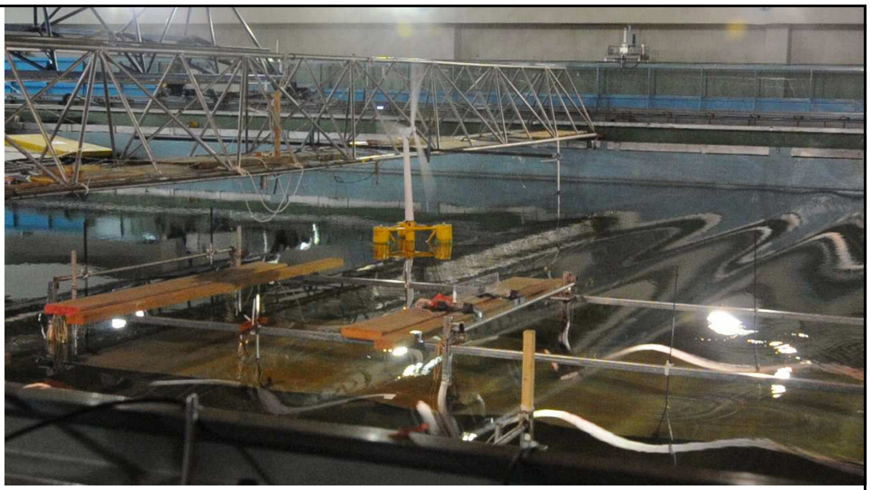
✓ Specifications of designed 12 MW class SCSG

Parts	Properties	SCW
Drive-train	Rated power (MW)	12.5
	Operating temperature (K)	20
Rotor	The number of rotor poles	24
	Effective length (mm)	1,700
	Rotation speed (rpm)	10
	Turns of SC coil	850
	The number of DPC layers	4
	Field current of SC coil (A)	133
Stator	The number of slot	144
	Turns of copper coil	18
	Diameter (m)	5.2
	Rated output frequency (Hz)	2
Magnetic field	Perpendicular magnetic field (T)	5.1
	Maximum magnetic filed (T)	7.8
Volume of the generator (m^3)		36.23
Weight of the generator (ton)		180



iea wind

NREL NWTC,
Broomfield,
CO, USA



12MW Floating Offshore Wind Turbine

TEM #80, IEA Wind Task 11

Jan. 12~13, 2015

Prof. SHIN, Hyunkyoung *, Prof. PARK, Minwon** & Dr. LEE, Hakgu***

* University of Ulsan, **Changwon National University, *** Korea Institute of Materials Science, Korea


Light through Darkness (NASA, Feb. 2014)

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Integrated Wind Energy System Modeling: A control engineering perspective

David Schlipf, Frank Sandner, Steffen Raach, Friedemann Beyer, Denis Matha and Andreas Rettenmeier

Topical Expert Meeting on
Wind Energy Systems Engineering Integrated RD&D
13th of January 2015, Boulder, USA

SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Motivation

Wind turbine dynamics depend strongly on the controller.

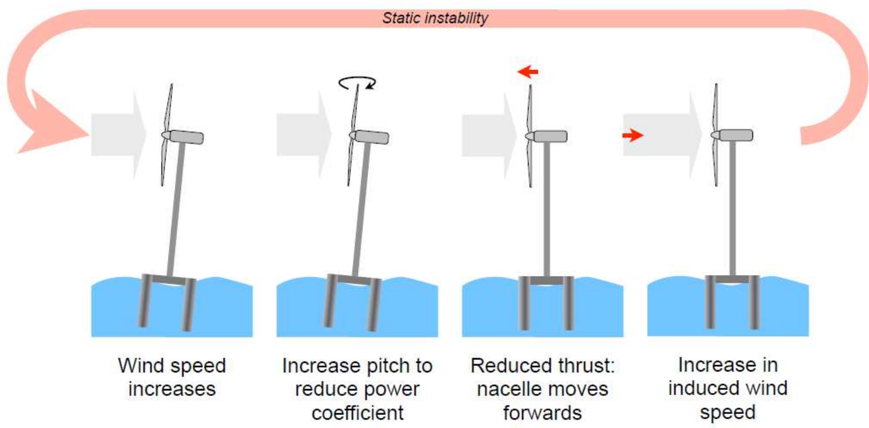
Particularly true for floating wind turbines!

2

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Motivation



[van der Veen, Couchman, Bowyer. *Control of floating wind turbines*, ACC2012]

3

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Motivation

Wind turbine dynamics depend strongly on the controller.

Particularly true for floating wind turbines!

Including control in system optimization is essential!
But how can this be done?

4

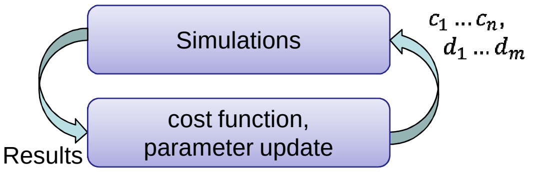
Content

5

Possibilities of Integrated System Optimization

1. “Model-free” approach

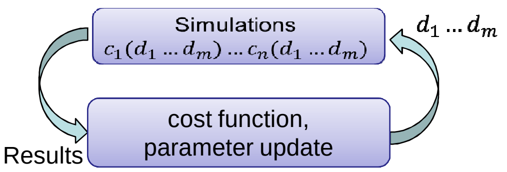
Add controller parameter ($c_1 \dots c_n$) to other design parameters ($d_1 \dots d_m$).



- Increase of complexity
- controller can be instable
- update difficult
- ➢ Not the best idea

2. “Model-based” approach

Parametrize controller ($c_1 \dots c_n$) as function of design parameters ($d_1 \dots d_m$).

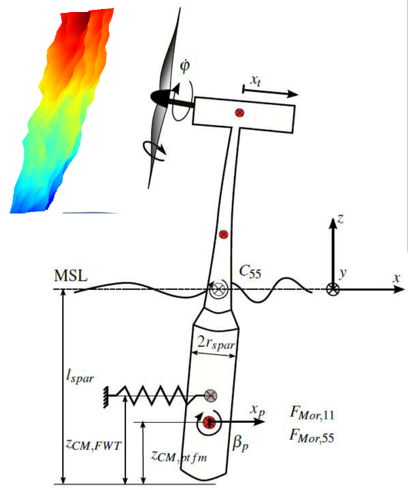


- only stable controller
- less complexity
- control tuning parameter
- ➢ model needed

6

www.uni-stuttgart.de/windenergie

Example for Model-based Approach: Platform Optimization



Find best spar buoy regarding

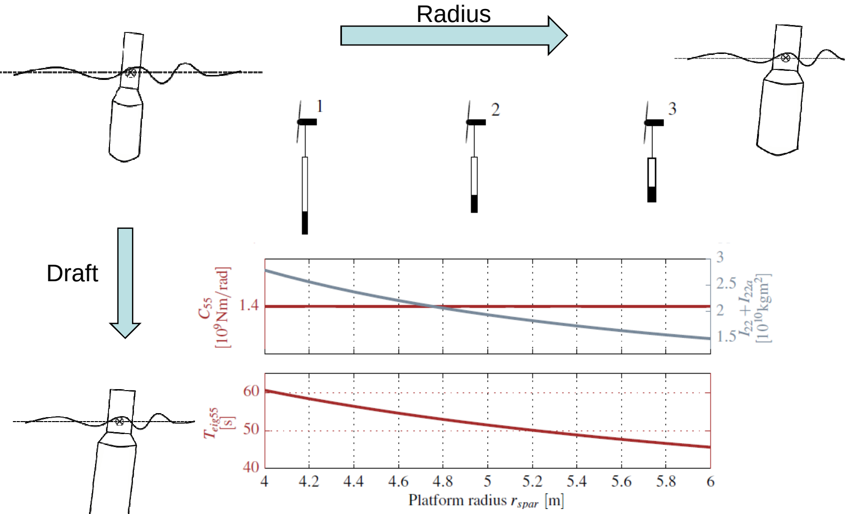
$$J = \sigma^2(k_\varphi \dot{\varphi}) + \sigma^2(k_{x_t} \dot{x}_t)$$

- minimizing rotor and tower motion for simulation above rated wind
- only pitch controller active
- NREL 5MW reference wind turbine
- “brute force” optimization

[Sandner, Schlipf, Matha, Cheng. *Integrated Optimization of Floating Wind Turbine Systems*, OMAE 2014]

www.uni-stuttgart.de/windenergie

Spar Platform Design Space



- 3 platforms selected with same hydrostatic restoring
- ➢ Integer optimization $d \in$ (Design 1, Design 2, Design 3)

University of Stuttgart Germany

www.uni-stuttgart.de/windenergie

Parameterizing the PI-Controller

- Collective pitch controller is parametrized with
  - Proportional gain k_P
  - Integrator time constant T_i
- "Model-free": simulating each platform with different k_P and T_i solving

$$\min_{d,k_P,T_i} J$$

- "Model-based": simulating each platform with critically stable pairs of k_P and T_i solving

$$\min_{d,T_i} J \text{ with } k_p(T_i)$$

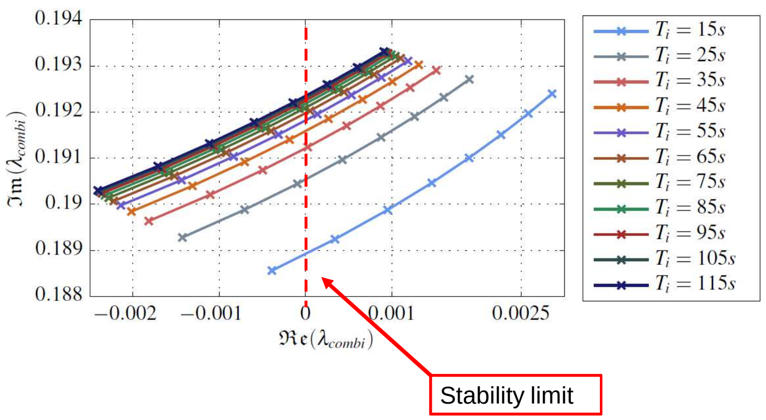
  - close to critical stable assumed to be a good choice
  - can be found by linearization of wind turbine and root locus analysis
  - smaller design space and only stable simulations

9

University of Stuttgart Germany

www.uni-stuttgart.de/windenergie

Root Locus Analysis



- Stable combinations of k_p and T_i for each design d
- ➢ Vary T_i and adjust $k_p(T_i)$

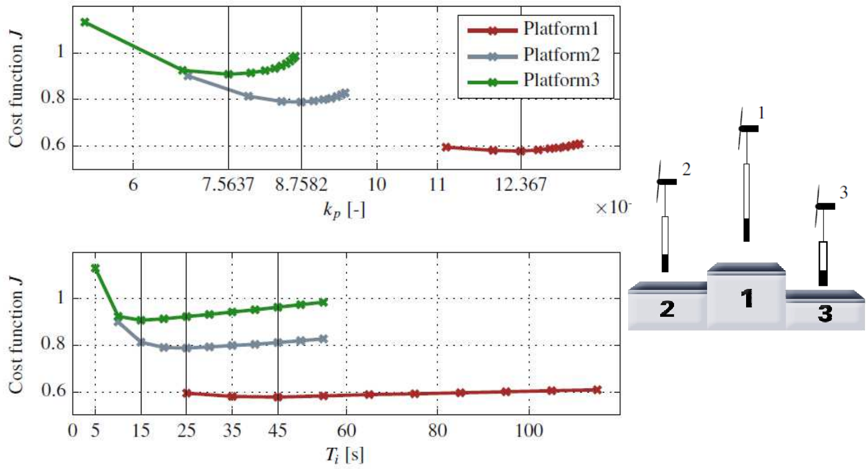
10

University of Stuttgart Germany

www.uni-stuttgart.de/windenergie

Brute Force Optimization with Nonlinear Model

Cost function: Rotor speed $\dot{\varphi}$ and tower bending x_t: $J = \sigma^2(k_\varphi \dot{\varphi}) + \sigma^2(k_{x_t} x_t)$

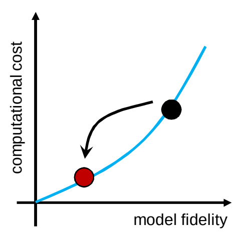


11

University of Stuttgart Germany

www.uni-stuttgart.de/windenergie

Need for Nonlinear Reduced Models



- Tuning of conventional linear controller within system optimization is possible.
- But is it really the best way?
- Optimal controller based on nonlinear controller maybe more useful.

[Sandner, Raach, Schlipf, Cheng. *Prospects of Linear Model Predictive Control on a 10MW Floating Wind Turbine*. OMAE2015?]

12

University of Stuttgart
Germany

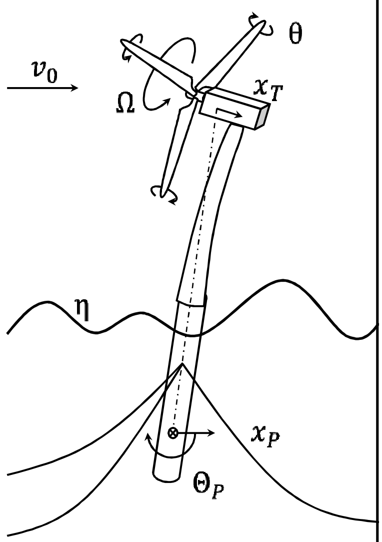
www.uni-stuttgart.de/windenergie

Modeling – Simplified Low Order Wind turbine (SLOW)

Only 5 Degrees Of Freedom
- tower and rotor motion (2 DOFs)
- platform surge and pitch (2 DOFs)
- linear 2nd order pitch actuator (1 DOF)

Only 2 Disturbances
- rotor effective wind v_0
- wave height η

Reduced Simulation Model
- based on [Sandner et al. 2012]
- reproduces overall dynamics
- focus is set on computational speed



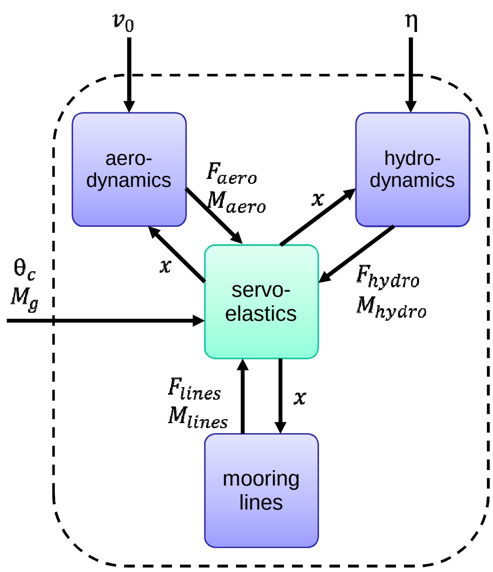
[Schlipf, Sandner, Raach, Matha, Cheng, Nonlinear Model Predictive Control of Floating Wind Turbines, ISOPE2013]

13

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Modeling – Internal Model (SLOW)



Servo-Elastics
- Newton-Euler formalism
- symbolic programming

Aero-Dynamics
- v_0 averaged over rotor disc
- power + thrust coefficients

Hydro-Dynamics
- Morison's equation
- deep water approximation

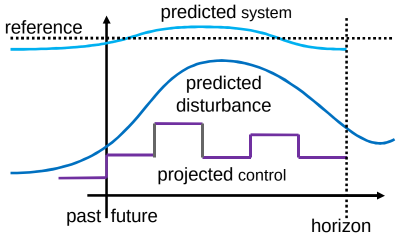
Mooring Lines
- quasi static fairlead forces
- polynomial fit

14

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Controller Design – Nonlinear Model Predictive Control



Basic Idea

- Solves optimal control problem: Optimizes control inputs over a horizon
- Closed loop by Iteration:
  - application of short sequence
  - update of initial conditions

NMPC can …

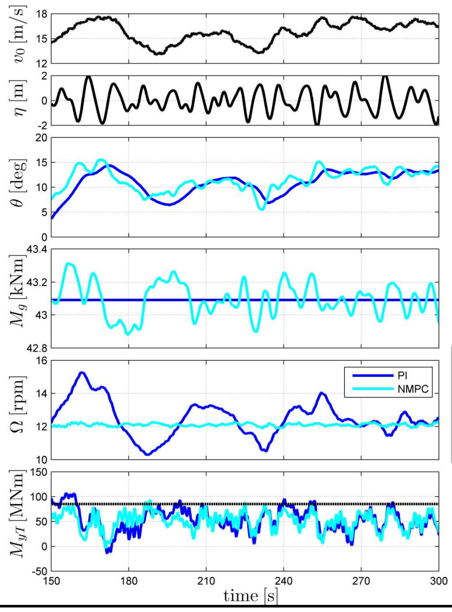
- … handle multivariable control naturally.
- … consider actuator and systems constrains.
- … use nonlinear models, trade off between performance and computational effort.
- … use predicted disturbances.

15

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Results – NMPC on NREL 5MW



IEC Design Load Case 1.1

- Internal model SLOW
- Simulation model FAST
- 3D wind field with $16\ m/s$ and $15.4\ \%$ turbulence intensity
- irregular waves $H_s = 3.37\ m$
- normal operation

Comparison NMPC to PI

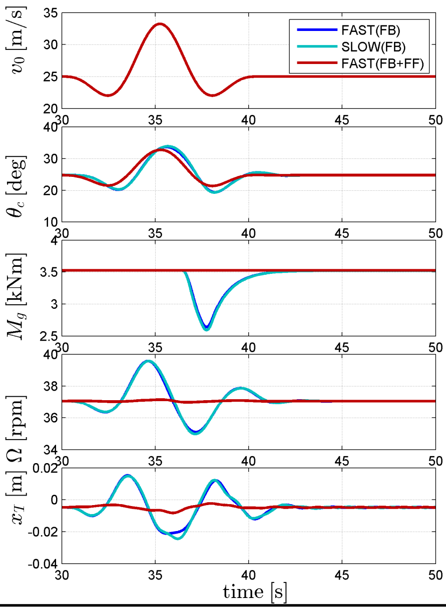
- less power and speed variation
- small benefit for loads (soft gains)

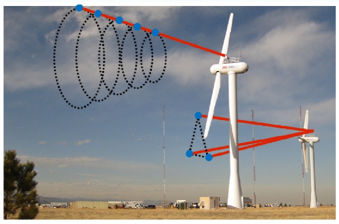
16

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Results – Feedforward on CART3





Simulations for lidar-assisted control

- EOG at 25 m/s
- Perfect wind preview
- SLOW with only 3 states very similar to FAST with 36 states
- Planned to be used with DTU lidar within INNWIND.EU
- Reduced model is invertible!
- Less rotor speed variation and tower oscillation

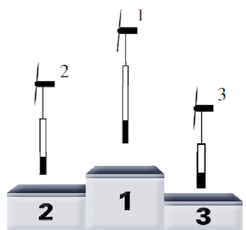
17

University of Stuttgart
Germany

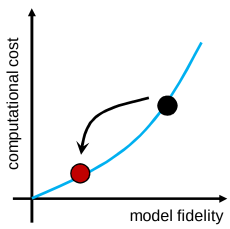
www.uni-stuttgart.de/windenergie

Conclusions

- wind turbine dynamics depend strongly on the controller - especially floating ones (but not only)
- control should be included in platform design and system optimization
- totally free control parameter difficult
- ➢ Model based parameterization ("self tuning") to use only stable und useful controllers
- ➢ Some control tuning parameters still useful



- There is a need for reduced nonlinear models
- ➢ Can be used, in industrial application to accelerate design process between partners
- ➢ Can be used in optimal controllers (model itself is parameterization for controller)



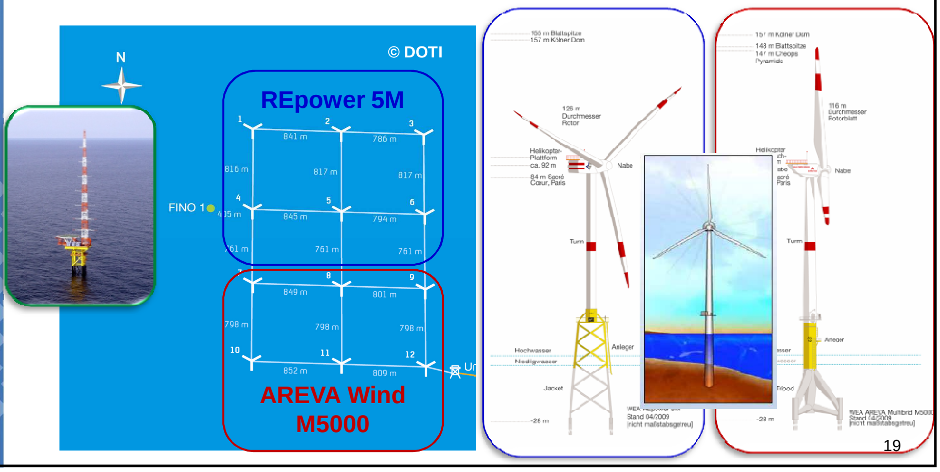
18

University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Proposal for a Reference Wind Farm

Basic Idea: Using 12 NREL 5MW reference wind turbines at alpha ventus



19

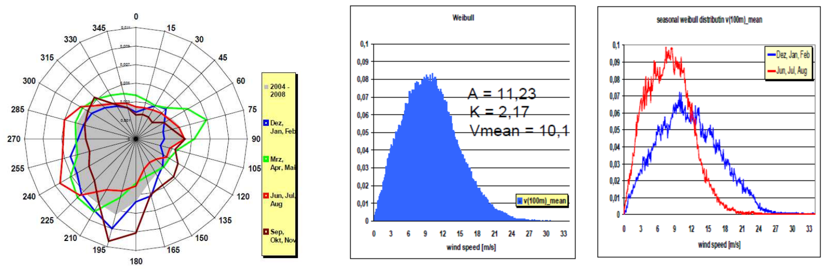
University of Stuttgart
Germany

www.uni-stuttgart.de/windenergie

Proposal for a Reference Wind Farm

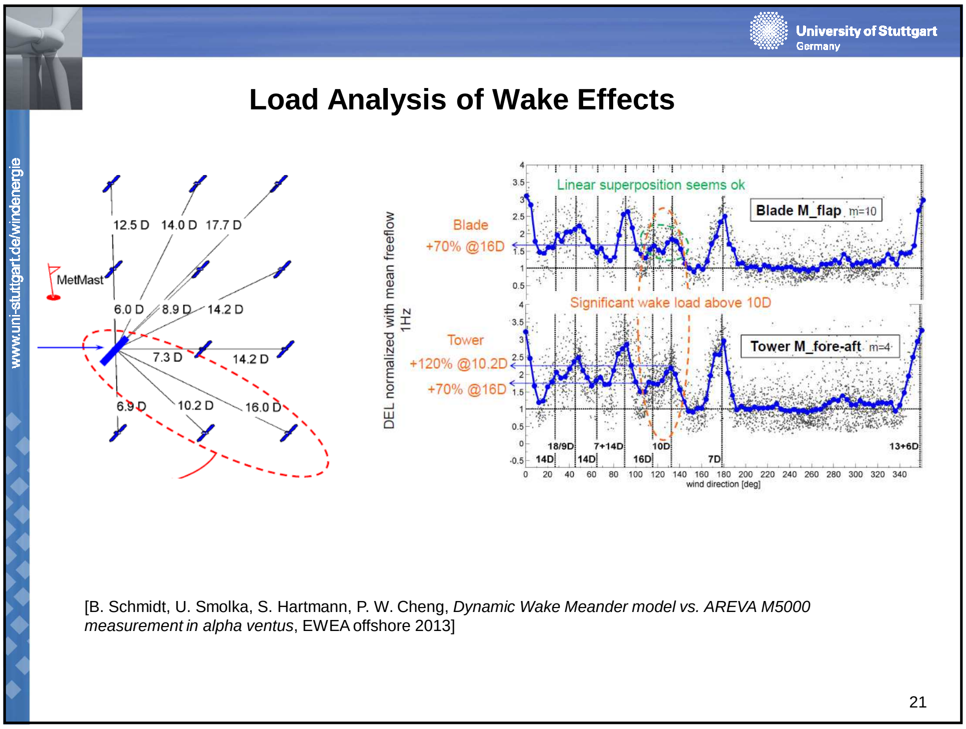
Advantages of using NREL 5MW reference wind turbines at alpha ventus

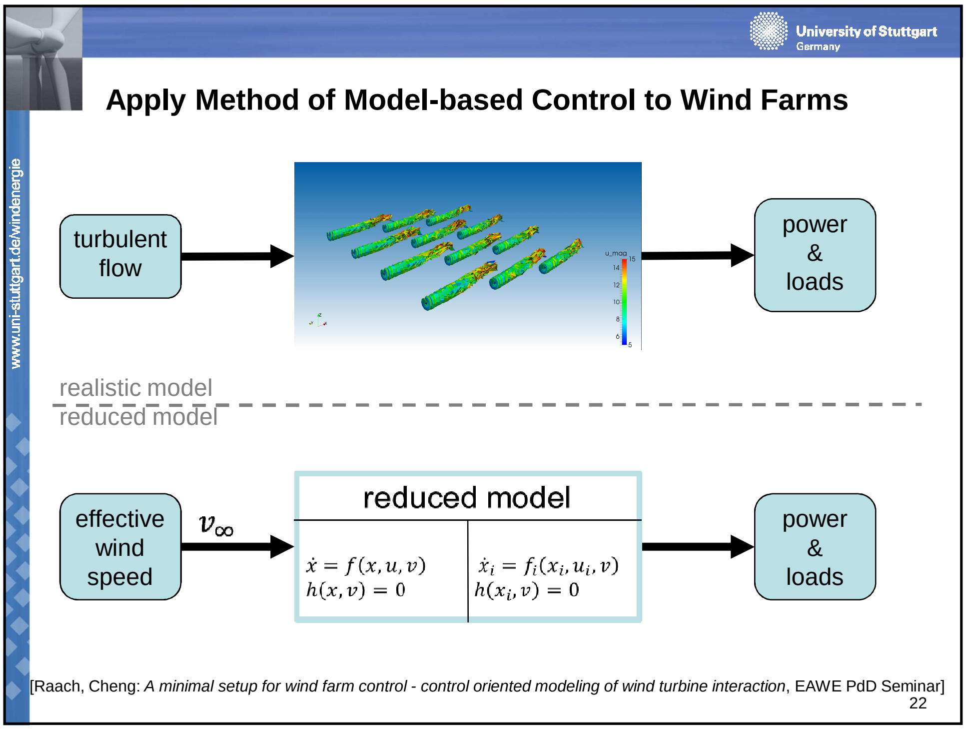
- Public available oceanic and meteorological data
- Public available turbines positions
- Good size for controller research
- Publications on wake models and wind farm effects



[Beeken, Neumann, Westerhellweg: *Five years of operation of the first* offshore wind research platform in the German Bight – FINO 1, DEWEK 2008]

20


University of Stuttgart
Germany
www.uni-stuttgart.de/windenergie
Load Analysis of Wake Effects
MetMast
12.5 D
14.0 D
17.7 D
6.0 D
8.9 D
14.2 D
7.3 D
14.2 D
6.9 D
10.2 D
16.0 D
DEL normalized with mean freeflow
1Hz
Linear superposition seems ok
Blade
+70% @16D
Blade M_flap m=10
Significant wake load above 10D
Tower
+120% @10.2D
+70% @16D
Tower M_fore-aft m=4
18/9D
14D
7+14D
14D
16D
10D
7D
13+6D
wind direction [deg]
[B. Schmidt, U. Smolka, S. Hartmann, P. W. Cheng, *Dynamic Wake Meander model vs. AREVA M5000 measurement in alpha ventus*, EWEA offshore 2013]
21


University of Stuttgart
Germany
www.uni-stuttgart.de/windenergie
Apply Method of Model-based Control to Wind Farms
turbulent flow
power & loads
realistic model
reduced model
effective wind speed
v_∞
reduced model
$\dot{x} = f(x, u, v)$
$h(x, v) = 0$
$\dot{x}_i = f_i(x_i, u_i, v)$
$h(x_i, v) = 0$
power & loads
[Raach, Cheng: *A minimal setup for wind farm control - control oriented modeling of wind turbine interaction*, EAWE PdD Seminar]
22

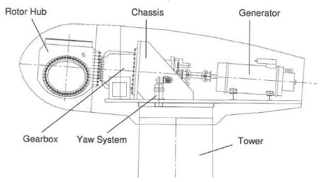
WINDFORS Wind Energy Research Cluster

Current status: research turbine

- We are in intensive contact with FWT (successor of Fuhrländer AG)
- Wind turbine FL-600 no longer built and installed in Germany
- Willing to share controller data, turbine model for simulations, drawings etc. for research purposes (no IP regulations) → full access
- Technical service still available
- Either installation of used wind turbines (approx. 10 years old) or manufacturing of new turbines when more than 4-5 turbines are needed.

Technical specifications

- Rated Power: 600kW
- Hub height: 75m
- Rotor diameter: 50m
- Variable speed
- Three individual el. pitch motors



[Fig. Fuhrländer, WindForS]

23

WINDFORS Wind Energy Research Cluster

Vision: Research turbines on different sites and in different terrain

- Different sites (flat terrain, forested terrain, complex terrain, etc.)
- Same turbine type at each site
- Comparison of turbine behaviour, turbine control, meteorology, etc.

TEXAS TECH UNIVERSITY
IOWA STATE UNIVERSITY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories
University of Colorado Boulder

DTU Wind Energy Department of Wind Energy
ECN
CENER ADItech
WINDFORS
DLR
ForWind

24

BVGassociates

Offshore cost of energy: Making sense of the European story so far and reflections on system engineering opportunities

IEA TEM#80
Boulder, US
13 January 2015
Bruce Valpy

BVGassociates

Agenda

Contents

- Cost of Energy calculation
- EU CAPEX trend to date
  - Reported
  - Modelled
  - Differences
  - Causes
- EU LCOE trend to date
- Future
  - Beyond the Crown Estate study
  - System engineering opportunities

Selected clients

BVG Associates

- Market and supply chain
  - Analysis and forecasting
  - Strategic advice
  - Business and supply chain development
- Economics
  - Socioeconomics and local benefits
  - Technology and project economic modelling
  - Policy and local content assessment
- Technology
  - Engineering services
  - Due diligence
  - Strategy and R&D support

BVGassociates

2/11

BVGassociates

Cost of energy

Basics

LCOE

$$\text{LCOE} = \frac{\sum_{i=-m}^{n} \left((C_i + O_i + D_i) \;/\; (1+W)^i\right)}{\sum_{i=-m}^{n} \left(E_i \;/\; (1+W)^i\right)}$$

Where:

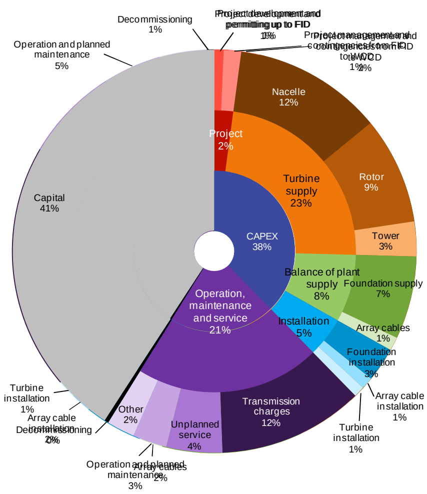
LCOE Levelised cost of energy in £/MWh
= revenue needed (from whatever source) to obtain rate of return W on investment over life of the wind farm
(tax, inflation etc. not modelled)

C_i Capital expenditure in £ in year i
O_i Operational expenditure in £ in year i
D_i Decommissioning expenditure in £ in year i
E_i Energy production in MWh in year i

W Weighted average cost of capital in % (real)
= (cost of debt x % dept) + (return on equity x equity portion)

n Operating lifetime of wind farm (baseline 20 years)
m Years before start of operation when expenditure first incurred
i i year of lifetime (-m, ..., 1, 2, …n)

LCOE breakdown – for specific US site; FID in 2020

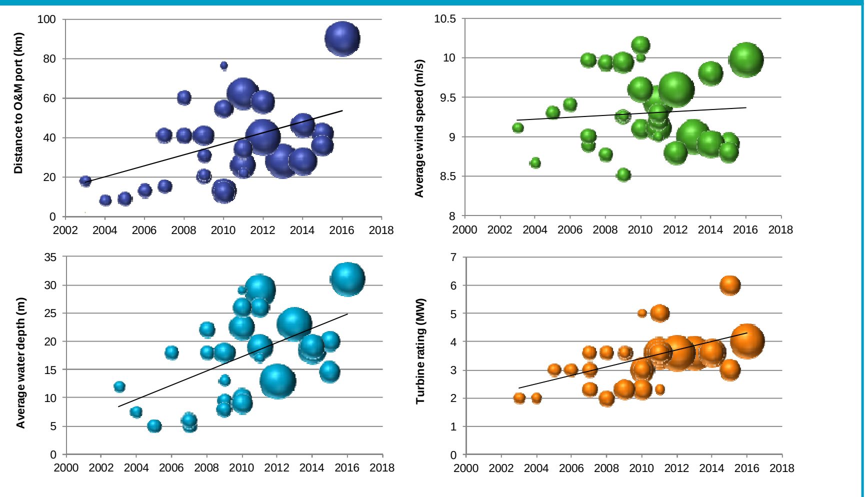


BVGassociates © BVG Associates 2015 3/11

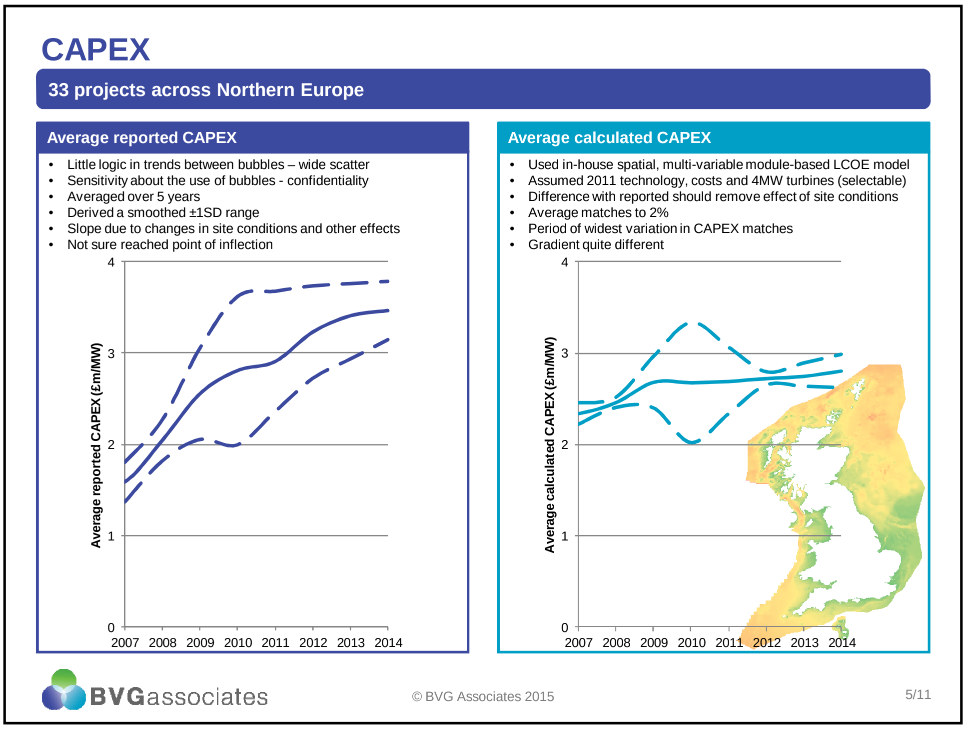
EU Sites

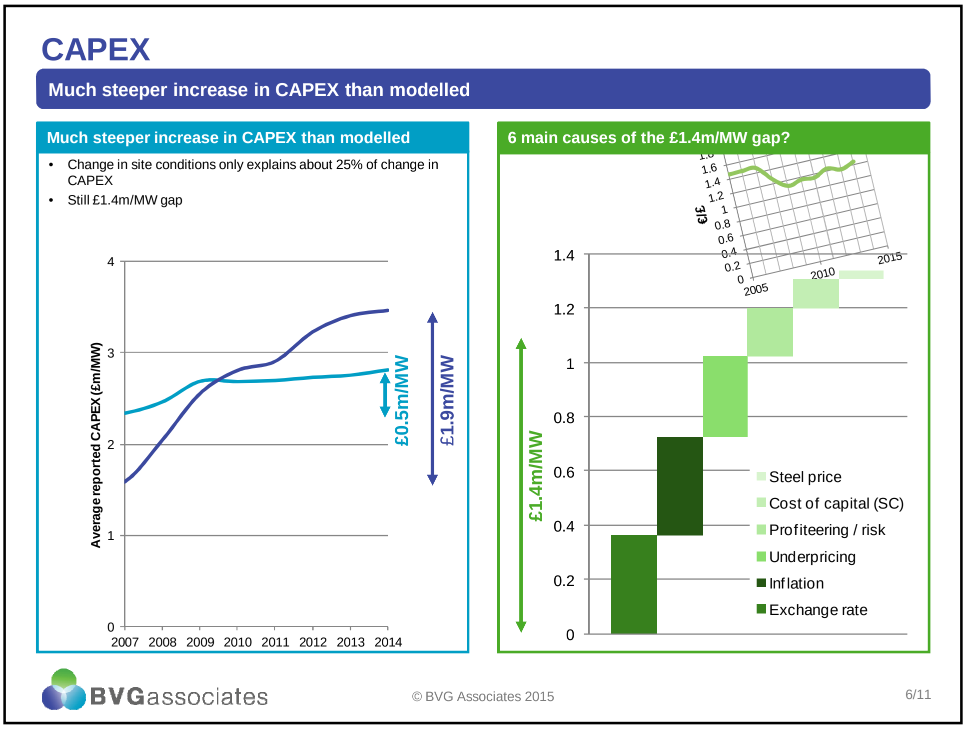
33 projects across Northern Europe

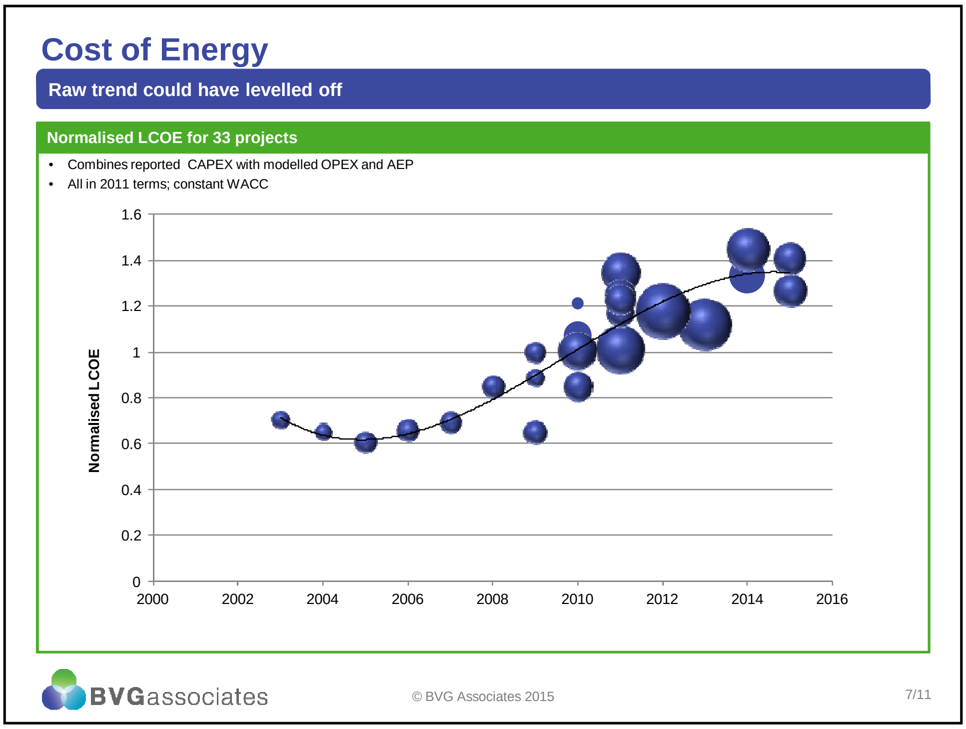
Significant variation, but upward trends in difficulty and turbine size

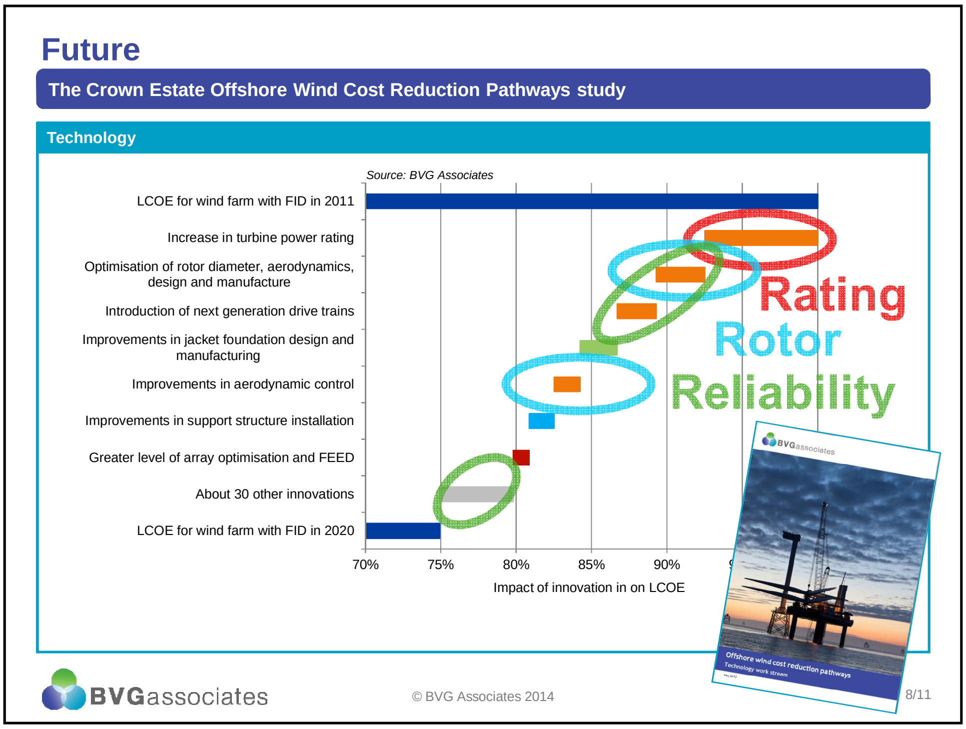


BVGassociates © BVG Associates 2015 4/11


CAPEX
33 projects across Northern Europe
Average reported CAPEX
• Little logic in trends between bubbles – wide scatter
• Sensitivity about the use of bubbles - confidentiality
• Averaged over 5 years
• Derived a smoothed ±1SD range
• Slope due to changes in site conditions and other effects
• Not sure reached point of inflection
Average reported CAPEX (£m/MW)
2007 2008 2009 2010 2011 2012 2013 2014
Average calculated CAPEX
• Used in-house spatial, multi-variable module-based LCOE model
• Assumed 2011 technology, costs and 4MW turbines (selectable)
• Difference with reported should remove effect of site conditions
• Average matches to 2%
• Period of widest variation in CAPEX matches
• Gradient quite different
Average calculated CAPEX (£m/MW)
2007 2008 2009 2010 2011 2012 2013 2014
BVGassociates
© BVG Associates 2015
5/11


CAPEX
Much steeper increase in CAPEX than modelled
Much steeper increase in CAPEX than modelled
• Change in site conditions only explains about 25% of change in CAPEX
• Still £1.4m/MW gap
Average reported CAPEX (£m/MW)
2007 2008 2009 2010 2011 2012 2013 2014
£0.5m/MW
£1.9m/MW
6 main causes of the £1.4m/MW gap?
£1.4m/MW
€/£
2005
2010
2015
Steel price
Cost of capital (SC)
Profiteering / risk
Underpricing
Inflation
Exchange rate
BVGassociates
© BVG Associates 2015
6/11


Cost of Energy
Raw trend could have levelled off
Normalised LCOE for 33 projects
• Combines reported CAPEX with modelled OPEX and AEP
• All in 2011 terms; constant WACC
Normalised LCOE
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2000
2002
2004
2006
2008
2010
2012
2014
2016
BVGassociates
© BVG Associates 2015
7/11

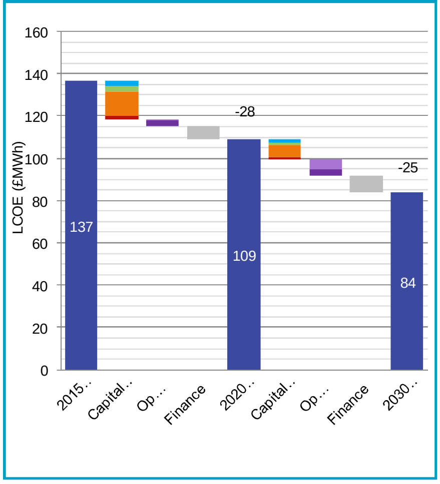

Future
The Crown Estate Offshore Wind Cost Reduction Pathways study
Technology
Source: BVG Associates
LCOE for wind farm with FID in 2011
Increase in turbine power rating
Optimisation of rotor diameter, aerodynamics, design and manufacture
Introduction of next generation drive trains
Improvements in jacket foundation design and manufacturing
Improvements in aerodynamic control
Improvements in support structure installation
Greater level of array optimisation and FEED
About 30 other innovations
LCOE for wind farm with FID in 2020
70%
75%
80%
85%
90%
Impact of innovation in on LCOE
Rating
Rotor
Reliability
Offshore wind cost reduction pathways
BVGassociates
© BVG Associates 2014
8/11

BVGassociates

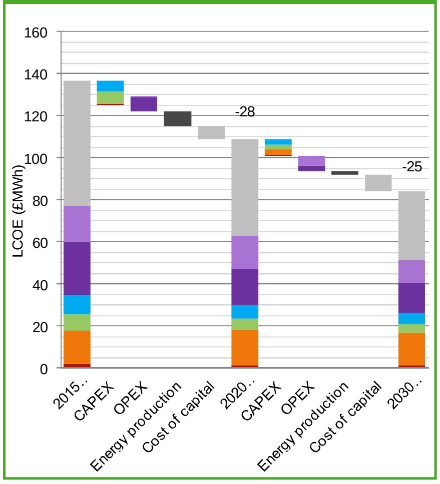
Future

Reductions dominated by turbine and technology, moving to finance and supply chain (P80 case)

Due to innovations in...



Impact on...



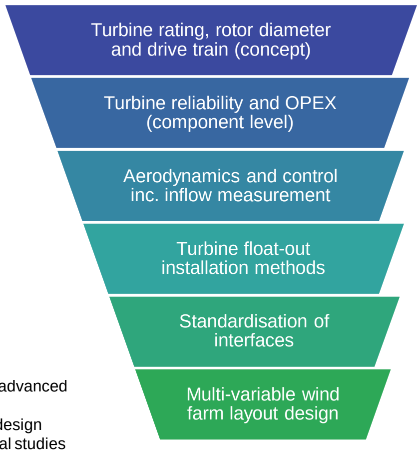
Project | Turbine | Balance of plant | Installation | Wind Farm | Transmission | Energy production | Cost of capital

BVGassociates © BVG Associates 2015 9/11

Future

System engineering approach

Systems engineering opportunities with largest remaining LCOE impact



Plus:
- Operations management with advanced weather forecasting
- Holistic tower and foundation design
- FEED geophysical geotechnical studies
- …

BVGassociates © BVG Associates 2015 10/11

BVGassociates

Thank you

BVG Associates Ltd.
The Blackthorn Centre
Purton Road
Cricklade, Swindon
SN6 6HY England, UK
tel +44 1793 752 308

The Boathouse
Silversands
Aberdour, Fife
KY3 0TZ Scotland, UK
tel +44 1383 870 014

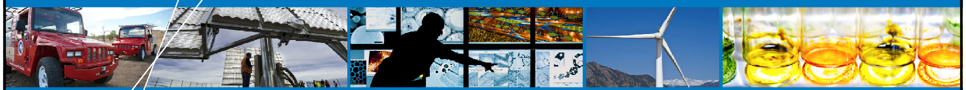
BVG Associates LLC
4444 Second Avenue
Detroit, MI
48201 USA
tel +1 206 459 8506

info@bvgassociates.co.uk
@bvgassociates
www.bvgassociates.co.uk

BVGassociates

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Characteristics of Reference Wind Plants to Meet Different Research Objectives



Patrick Moriarty

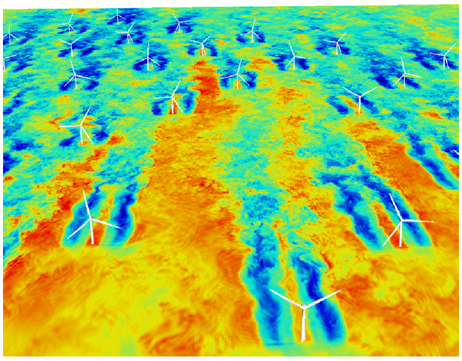
The Need

- **As with reference turbines, reference wind plants are needed to benchmark technology developments**
- **Snapshot of the current state of the art – generic and representative**
- **Challenge – every wind plant is unique to its environment and developer**
  - Multiple reference plants may be required
  - Research with reference plants may help standardize plant design (e.g. IEC 61400-15)

NATIONAL RENEWABLE ENERGY LABORATORY 2

Research Depends on End User

- **Turbine Manufacturer**
  - o Energy capture
  - o Structural reliability
  - o Control systems
- **Plant Developer**
  - o AEP layout optimization
  - o P99/P50 - Uncertainties
  - o Atmospheric variations and wakes
  - o Terrain and vegetation
- **Utility/Owner Operator**
  - o Ramps, grid reliability and curtailment
  - o Wildlife impacts
  - o Noise
  - o Plant control e.g. wake steering



Wind speed contours through the Lillgrund wind plant

NATIONAL RENEWABLE ENERGY LABORATORY 3

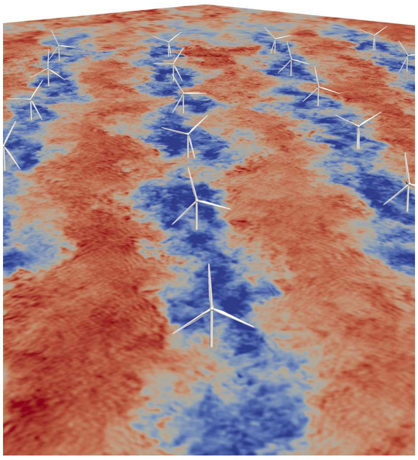
Future plant research areas

- **Site specific design of plant turbines**
  - o Plant modified IEC load cases
- **Advanced controls**
  - o Tighter spacing with wake steering
  - o Atmospheric dependent
  - o Next generation noise and wildlife mitigation
- **Layout optimization for reduced uncertainty**
  - o Energy production
  - o Fatigue loads
  - o Forecastability – higher penetrations
  - o Grid sensitivity

NATIONAL RENEWABLE ENERGY LABORATORY 4

Variables at Subsystem Level

- **Turbines**
  - Height
  - Diameter
  - Tilt
  - Thrust and Power vs. WS
  - Rotor speed
- **Plant**
  - Number of turbines
  - Spacing
  - Control
- **Environment**
  - Terrain
  - Surface condition (e.g. vegetation)
  - Wind rose
  - Atmospheric stratification & turbulence



NATIONAL RENEWABLE ENERGY LABORATORY 5

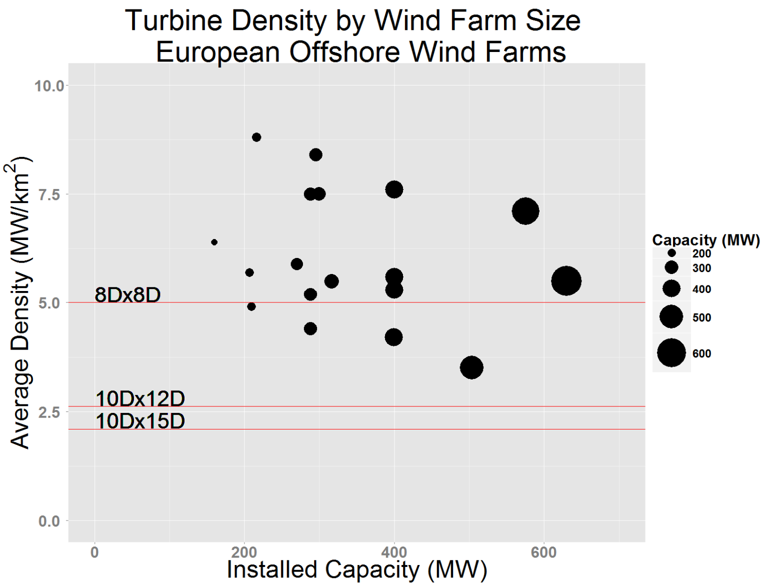
Energy Capture Sensitivity

Parameter	*Δ e from average*	*Range of parameter values*
Wind speed	+1.73 to 2.39% for 1 ms^{-1} increase	U = 5-15 ms^{-1}
Turbine spacing	+1.06 to 1.49 % for 1 D spacing increase	4-20 D, U=5-15 ms^{-1}
Turbulence intensity	+0.98 to 1.40% for 1% increase	5-13% TI, U=7-8 ms^{-1}
Atmospheric stability	-8.13 to +9.71% over range of stabilities	U = 5-15 ms^{-1}

Barthelmie et al., 2013

NATIONAL RENEWABLE ENERGY LABORATORY 6

Spacing



NATIONAL RENEWABLE ENERGY LABORATORY 7

Reference Wind Plant Ideas

- **Offshore**
  - 100 - 6 MW turbines
  - 100 m hub height
  - North Sea wind environment
  - 10D spacing - square layout
- **Onshore**
  - 100 - 3 MW turbines
  - 90 m hub height
  - Mildly complex terrain (e.g. rolling hills) with 1m vegetation height
  - Midwestern US wind environment
  - 3D x 10D spacing – east-west strings

NATIONAL RENEWABLE ENERGY LABORATORY 8

The NOWITECH 10 MW
Reference Turbine
Version 0

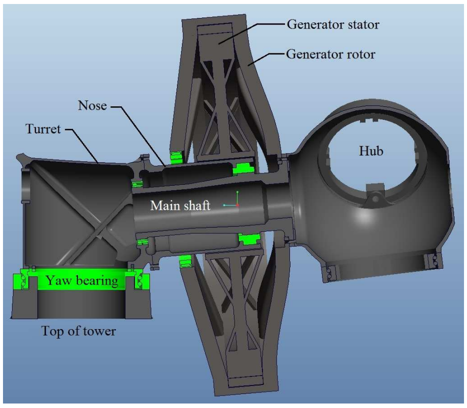
and

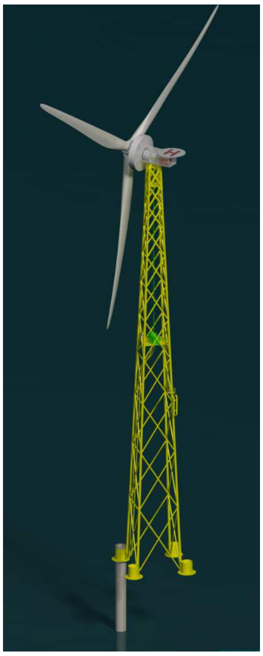
The Dogger Bank Reference Wind Farm

Karl Merz
SINTEF Energy Research
January 13, 2015

Nowitech Reference Turbine

Mechanical load path





Graphics by E. Agnalt.

Wholly or partly designed:
- Blades
- Hub
- Main shaft
- Generator (electric)
- Nacelle frame
- Tower top transition piece
- Tower
- Piles
- Pitch and torque controls

Not designed:
- Pitch drives
- Generator structure
- Yaw drive
- Pile sleeves

- Secondary structures
(may influence sea loads)

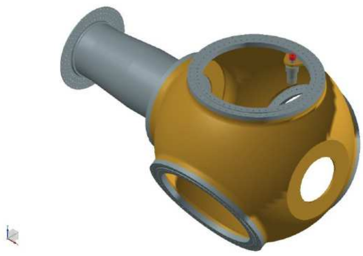
Hub

Designed by Khan[1] with static stress analyses using a maximum Von Mises stress of 167 MPa.

Material is ductile cast iron.

Load cases included only windspeeds of 10 and 30 m/s, not the most critical rated windspeed of 13 m/s. Stochastic extrapolation of extreme loads was not employed.

Hub mass as designed is 63.4 tonnes; it is recommended to assume 80 tonnes for dynamic analysis of support structure components.



[1] Khan, M.A. Design of Rotor Hub for NOWITECH 10 MW Reference Wind Turbine. MS Thesis, Department of Engineering Design and Materials, Norwegian University of Science and Technology, Trondheim, Norway, 2012

Main shaft

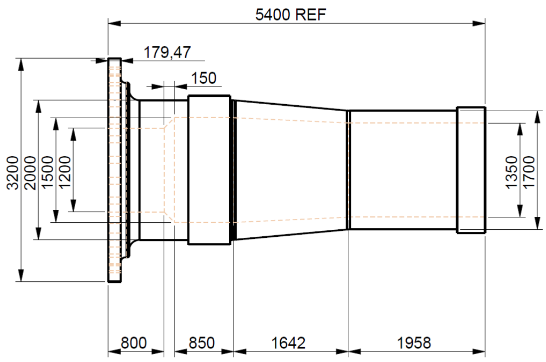
Designed by Khan[1] with static stress analyses using a maximum Von Mises stress of 167 MPa.

Material is ductile cast iron.

The limitations on the analysis mentioned for the hub apply here as well.

The mass of the shaft as presently designed is 56.7 tonnes.

Preliminary fatigue analysis is underway. (Bredesen)

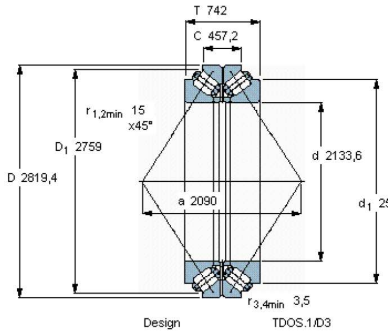


Graphics by E. Agnalt

[1] Khan, M.A. Design of Rotor Hub for NOWITECH 10 MW Reference Wind Turbine. MS Thesis, Department of Engineering Design and Materials, Norwegian University of Science and Technology, Trondheim, Norway, 2012

Main bearings: selected from catalog

Selected preliminarily on the basis of lifetime cycling under conservative (biased high) loads.[1]



Fixed, front bearing: SKF BT2B 332497/HA4
Double-row tapered roller bearing.

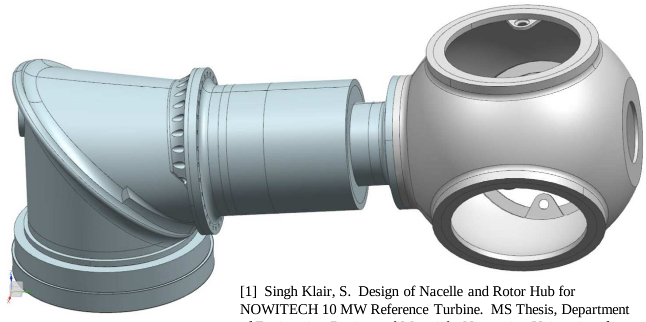
Floating, back bearing: SKF 248/1800 CAK30FA/W20
Spherical roller bearing.

[1] Smith, E.B.; *Design of a Nacelle for a 10 MW Wind Turbine*; MS Thesis, NTNU, 2012

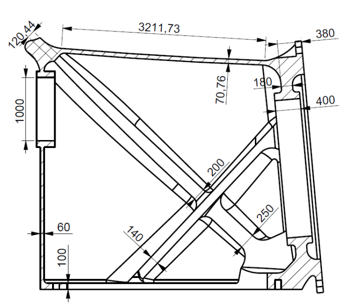
Turret and Nose (Nacelle Bed Frame)

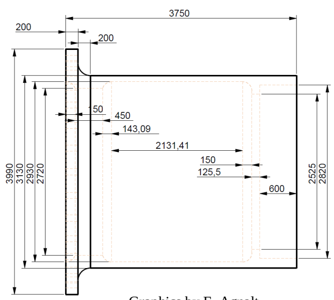
Designed by Singh Klair[1] with a static strength check against a chosen max stress of 200 MPa.

Extreme loads from L. Frøyd's FAST analyses of IEC DLC's.



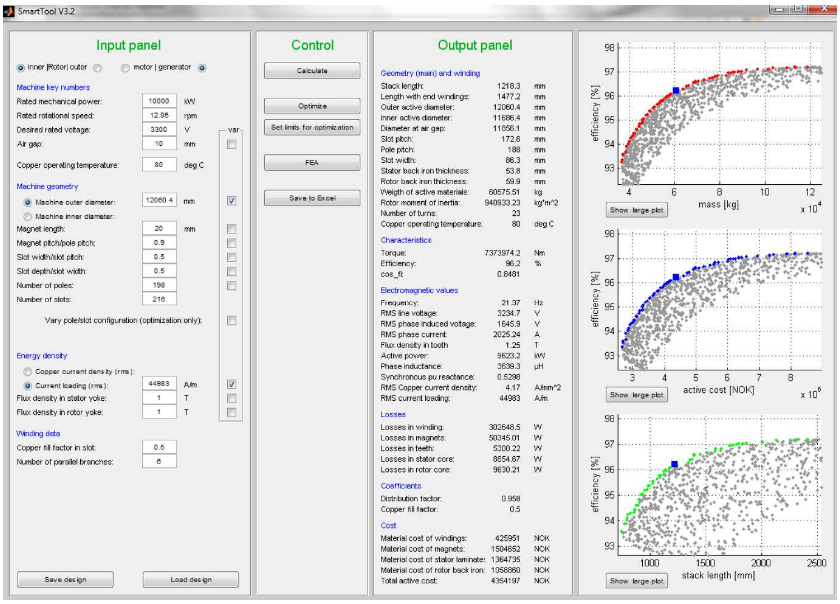
[1] Singh Klair, S. Design of Nacelle and Rotor Hub for NOWITECH 10 MW Reference Turbine. MS Thesis, Department of Engineering Design and Materials, Norwegian University of Science and Technology, Trondheim, Norway, 2013.





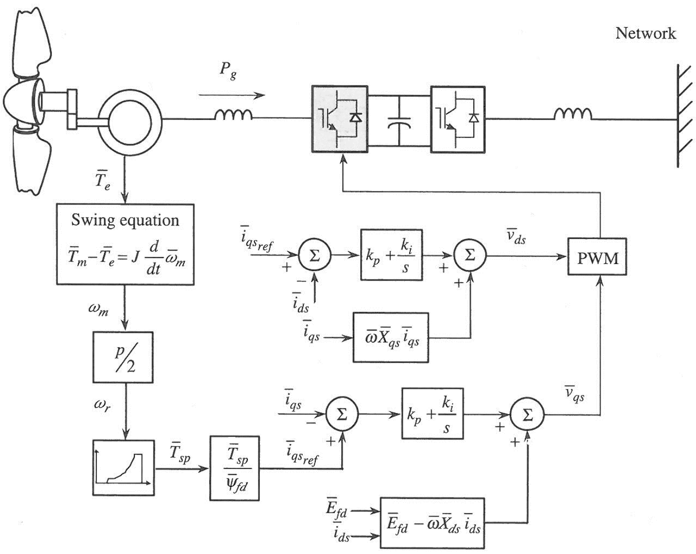
Graphics by E. Agnalt

Generator
A generator has been sized using the SmartMotor design tool "SmartTool". Mass is estimated at between 120 and 200 tonnes.



Liseth, H.E.; Nilssen, R.; "10 MW Reference Wind Turbine"; NTNU, 2011

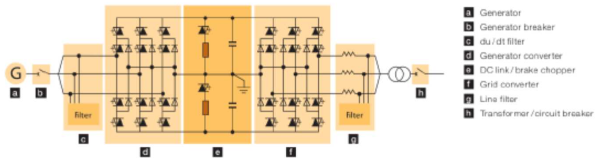
Generator/converter electric controls
A detailed definition of the system parameters is not yet given.



Anaya-Lara, O., et al.; *Wind Energy Generation – Modelling and Control*; Wiley, 2009

Converter

We have specifications.



Dahlhaug, O.G., et al.; *Specification of the NOWITECH 10 MW Reference Wind Turbine*; NOWITECH report, January 2012

	Symbol		Unit
Converter configuration		AC-grid: BTB DC-grid: AC/DC-converter	
AC/DC (DC/AC) Converter topology		3l-NPC	
DC/DC converter		Step-up, with electrical isolation between low and high voltage side	
Nominal AC-voltage	$V_{n,conv}$	4 (line-line, rms)	kV
Nominal AC-current	$I_{,conv}$	1.8 (rms)	kA
Nominal DC-voltage	$V_{dc.n}$	6.5	kV
IGBT switching frequency	$f_{sw,n}$	1.5	kHz
Modulation type		PWM with 3rd harmonic injection	
Protection		Two DC-choppers	
Cooling system		Water cooled	

Transformer

Placement in the nacelle or on the access platform?

	Symbol		Unit
Transformer rating	$S_{n,trans}$	10.0	MVA
Nominal voltage (turbine/grid side)	$V_{n,trans,1/2}$	4 /35 (rms)	kV/kV
Nominal current (turbine/grid side)	$I_{n,trans,1/2}$	1.44/0.165	kA/kA
Transformation ratio	n_{trans}	1:8.75	
Electrical frequency	f_n	50	Hz
Cooling system		Oil/liquid	
Estimated weight	m_{trans}	30,000	kg

Overview of the Dogger Bank Reference Wind Farm

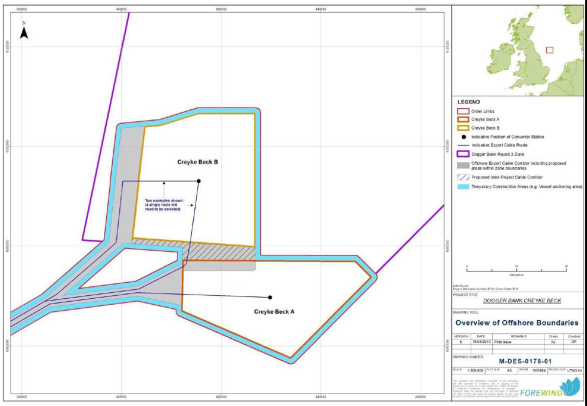
Dogger Bank – Creyke Beck A

Base case for further trade studies

1.2 GW, 120 10 MW turbines:

DTU rotor,
NOWITECH nacelle/systems
DTU tower

Foundations are not yet specified

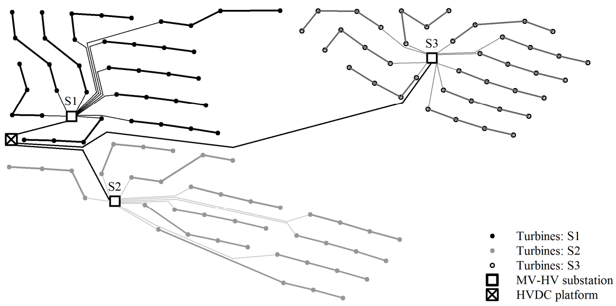


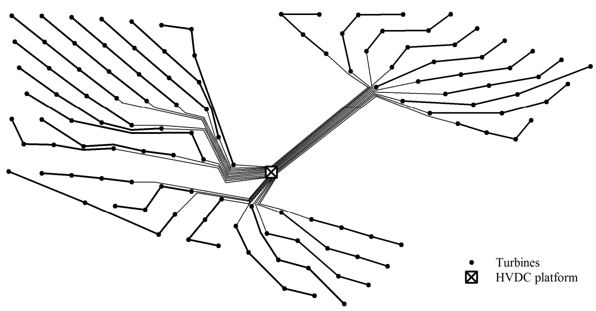
Forewind Consortium; *Dogger Bank Creyke Beck Environmental Statement: Chapter 5, Project Description.* 2013.

Presently released (memos are published):
- Layout (most important parameter: spacing between turbines)
- Expected AEP(V_∞,θ) for each turbine
- Design and analysis of the collection/transmission grids
  - MVAC-HVAC-HVDC, MVAC-HVDC, MVAC-HVAC

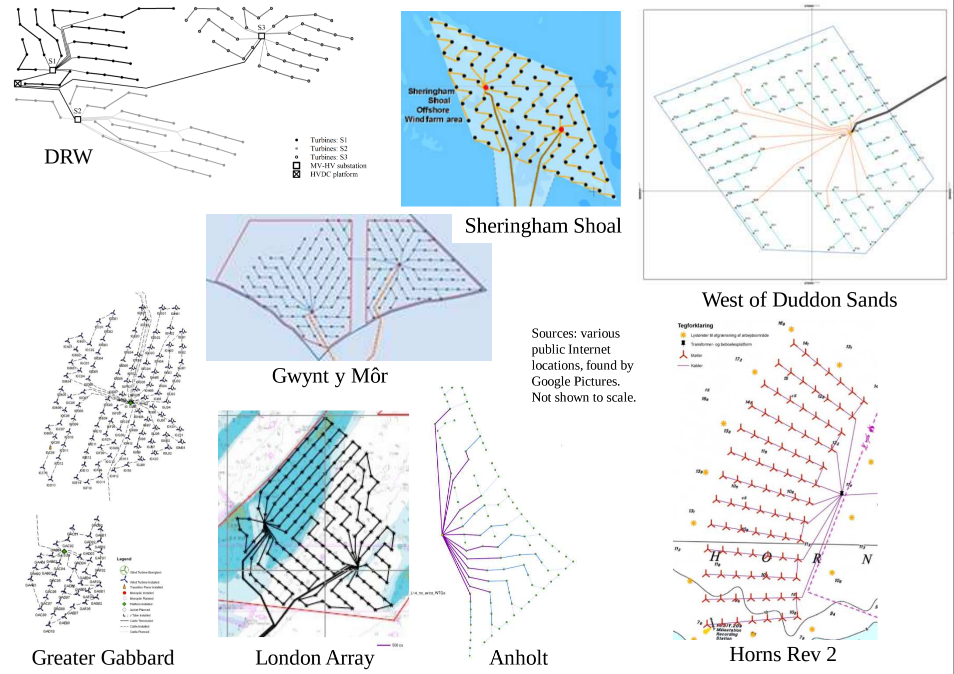
Later releases:
- Supervisory control system, additional benchmark results

Layouts

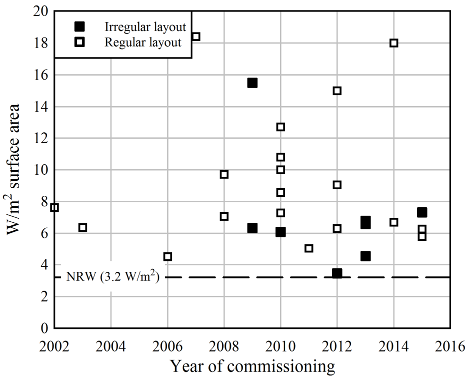


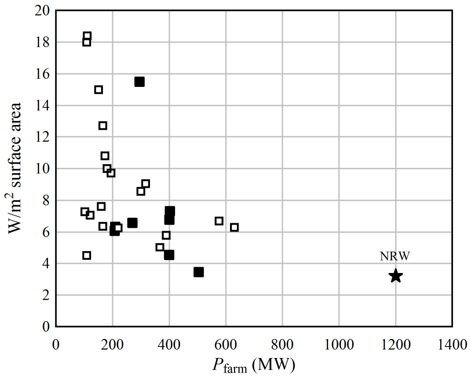


A comparison of layouts



Turbine spacing



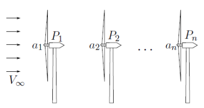


Hypothesis: Global (atmospheric boundary-layer) wake effects drive up the characteristic *s*/*D* spacing between turbines in very large wind farms.

Hypothesis: Diminishing per-turbine costs of marine operations make higher turbine densities economical in "small" wind farms.

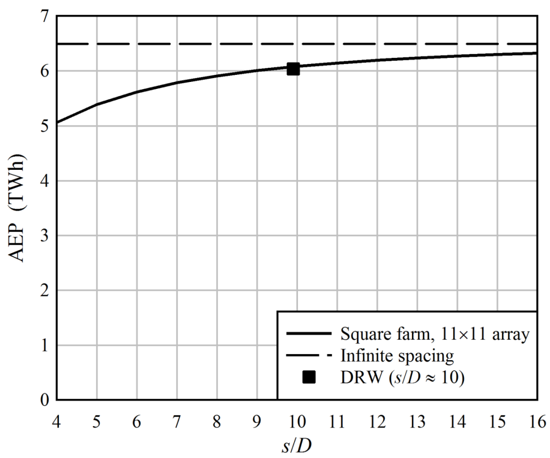
It is relatively easy to rescale the existing pattern (depart from the "actual" Creyke Beck case).

Contrast the NRW with:



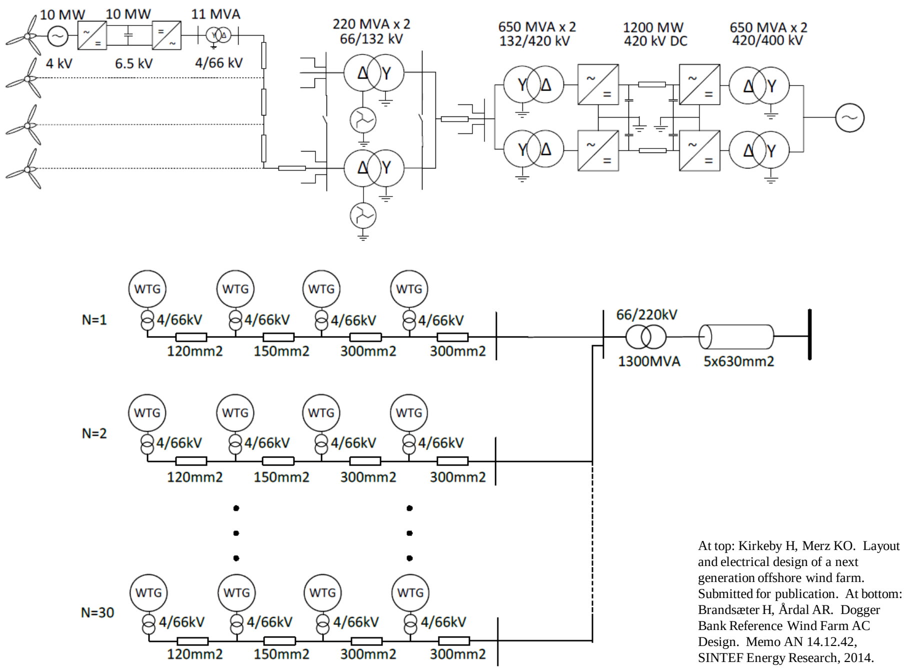
At left: van Dam FC, *et al.*; A maximum power point tracking approach for wind farm control; presented at The Science of Making Torque from Wind, Oldenburg, Germany, October 9-11, 2012.

AEP versus spacing



Hypothesis: For wind farms with relatively uniform spacing, AEP depends primarily upon the spacing and not the shape of the outer boundary.

Electrical designs



At top: Kirkeby H, Merz KO. Layout and electrical design of a next generation offshore wind farm. Submitted for publication. At bottom: Brandsæter H, Årdal AR. Dogger Bank Reference Wind Farm AC Design. Memo AN 14.12.42, SINTEF Energy Research, 2014.

Cost analysis

Infrastructure		Specification	Price (M€) 33 kV		66 kV		66 kV no substation	
WTG	Switchgear	120×		7.87		10.88		10.88
Cables	33 kV		(396 km)	130.37				
	66 kV				(328 km)	91.55	(490 km)	154.22
	132 kV		(129 km)	128.70	(129 km)	128.70		
	Deployment			19.20		17.90		16.65
Substation	Platform	3× 33/132 kV		92.40				
		3× 66/132 kV				92.40		
	Installation	18 days, 2 vessels		12.00		12.00		
Converter station	Switchgear	3× 132kV		2.76		2.76		
		24× 66kV						2.18
Energy losses	Levelized COE	(Efficiencies indicated)	(98.42%)	138.00	(98.68%)	115.29	(99.34%)	57.65
Total cost				**531.03**		**471.48**		**241.58**

Kirkeby and Merz, *op. cit.*

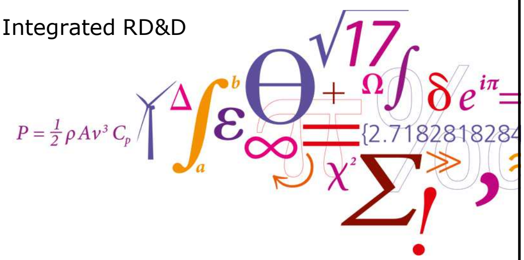
DTU

Role of Reference Wind Plants in Benchmarking Optimization Tools

Pierre-Elouan Réthoré

Topical Expert Meetin #80 on
Wind Energy Systems Engineering Integrated RD&D

January 13 2015
NREL NWTC



DTU Wind Energy
Department of Wind Energy

DTU

State of the art of wind plant layout optimization

- Herbert et al. Energies 2015
- 25 papers / year
- A lot of work from experts in single components or optimizer algorithm
- Large amount of time getting up to speed with previous work **-> Limits complexity, waste time**
- A lot of work based on slightly different workflow of models **-> difficult to compare results**
- A lot of work based on Mosetti94 reference wind plant **-> not too realistic & less relevant**

How to improve from there?

- Realistic reference wind plants:
  - Increasing complexity (1D - real complex terrain)
  - All inputs / constraints clearly detailed
  - Uncertainty described clearly
- Standard workflows of models:
  - Benchmarking sub-models and optimization algorithms over the same problems

DTU Wind Energy, Technical University of Denmark

Publishing

- Reference wind plants and reference worflows should be published with a version number (e.g. DOI).
- Open source/access is a big plus!

DTU Wind Energy, Technical University of Denmark