INTERNATIONAL ENERGY AGENCY

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

*Topical Expert Meeting #89 on*

# Next Grand Vision for Wind Energy

**Next technology and infrastructure challenges to realize wind's full potential**

*IEA Wind Task 11- Topical expert meeting on a Grand Vision for Wind Energy*

*October 22-23, 2017*

*NREL, Golden, Colorado, USA*


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Turbine Technology : Joshua Paquette, SNL & Mike Robinson, NREL
Atmospheric Science & Forecasting : Melinda Marquis, NOAA & Pat Moriarty, NREL
Plant Control & Operations : Lucy Pao, CU Boulder & Paul Fleming, NREL
Grid Integration : Katherine Dykes, NREL
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# 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, 26 contracting parties from 22 countries, the European Commission, and Wind Europe, participate in IEA Wind. Austria, Belgium, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of China, 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). Recent developed RPs were on "Wind Farm Data Collection and Reliability Assessment for O&M Optimization (Task 33)" (RP#17) and "Floating Lidar Systems (Task 32 in coordination with the Offshore Wind Accelerator initiative)" (RP#18).

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

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| COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11 | |
|---|---|
| **COUNTRY** | **INSTITUTION** |
| Denmark | Danish Technical University (DTU) - Riso National Laboratory |
| Finland | Technical Research Centre of Finland - VTT Energy |
| Germany | Federal Ministry for Economic Affairs and Energy (BMWi) |
| Ireland | Sustainable Energy Ireland – SEI |
| Italy | Ricerca sul sistema energetico, (RSE S.p.A.) |
| Japan | New Energy and Industrial Technology Development Organization (NEDO) |
| Mexico | Centro Mexicano de Innovación en Energia Eólica (CEMIE-Eólico)- Instituto Nacional de Electriciadad y Energías Límpias (INEEL) |
| Netherlands | Rijksdient voor Ondernemend Nederland (RVO) |
| Norway | The Norwegian Water Resources and Energy Directorate - NVE |
| Republic of China | Chinese Wind Energy Association (CWEA) |
| Spain | Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas 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 |

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## PRESENTATIONS

**1. IEA Wind Task 11 Base Technology Information Exchange**
*Lionel Perret, Task 11 OA, Planair SA, Switzerland*

**2. The European Academy publication of Long-Term Research Challenges (25)**
*Joachim Peinke, University of Oldenburg, Germany*

**3. The Need for Truly Open Data Sets**
*Carlo Bottasso, TU Munich, Germany*

**4. LCOE projections and opportunities with concerted effort**
*Ryan Wiser, LBNL, USA*

**5. Increasing Wind Energy Value to the System & Addressing Non-technical Deployment Challenges**
*Paul Veers and Katherine Dykes, NREL, USA*

**6. Perspectives on Long-Term Research**
*Daniel Laird, NREL, USA*

# 1. INTRODUCTORY NOTE

## Background

The wind industry has realized substantial growth reaching nearly 0.5 TW of installed capacity in 2016 and producing about 4% of global electricity demand in 2015.1 Equipment, installation and operation costs have decreased while energy production per turbine has increased. Integration challenges in the broader electric system have been successfully addressed in many markets as the level of wind energy contribution to particular systems has grown to 10-15% and beyond. Offshore wind technology is leveraging industrialization and standardization pathways which are accelerating cost-effective deployment similar to that realized by the land-based wind industry in the past decade. Figure 1 illustrates levelized cost of energy over the past decades and associated learning rates. Future deployment pathways associated with historical learning rates are illustrated relative to a baseline identified by leading wind industry experts.2 What does the future of the wind industry hold?

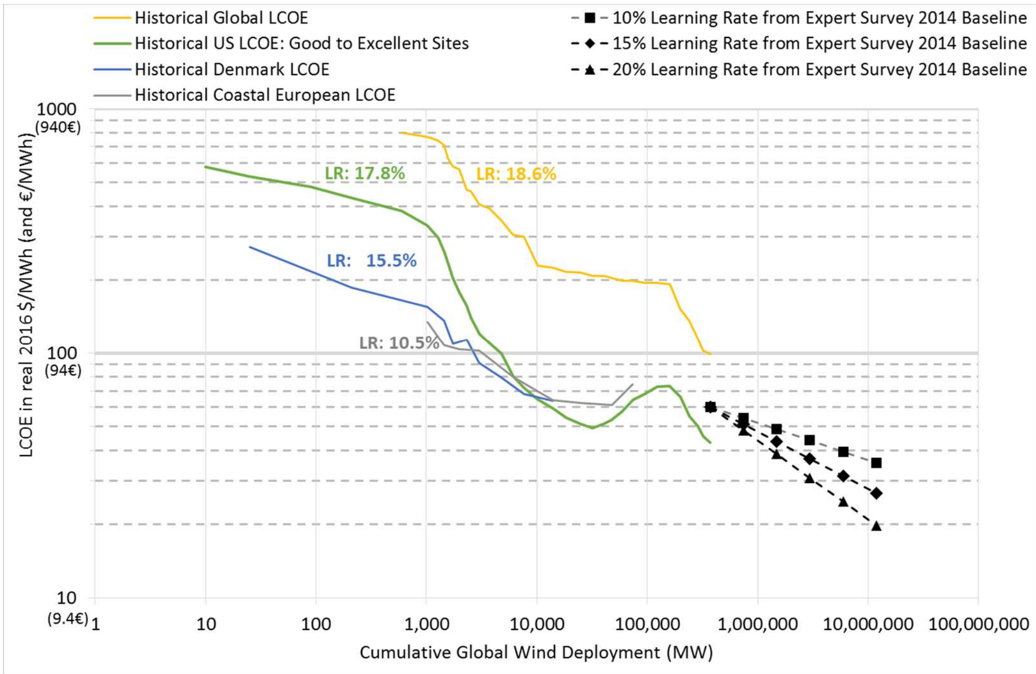


**Figure 1. Historical learning rates and illustration of future deployment levels assuming continued learning. Source: Expert survey on future cost of wind energy (Wiser et al., 2016) updated to 2016 USD; future deployment based on historical learning rates added by authors.**

A variety of scenarios for future wind deployment illustrate a range of possibilities including from annual installations sustained near current-levels to rapid growth in annual installation. Achieving the highest levels of future wind deployment will require "strong international political commitment towards meeting climate goals and national energy policy driven by the need for enhanced energy security, price stability, job creation and the need to conserve our precious fresh water resources" (GWEC 2016). Over the next decades, wind-generated electricity could grow to provide over a third of global electricity demand; wind technology could become a primary electricity generation technology.

To realize the full potential for wind technology, a paradigm shift in the innovation context for wind energy is required. In addition to political commitment, wind technology and infrastructure innovation will be required. This workshop will bring together experts to identify and characterize the technology and infrastructure innovations that will enable aggressive wind industry growth such

[1] http://www.gwec.net/

[2] Wiser et al., (2016). https://emp.lbl.gov/publications/forecasting-wind-energy-costs-and

that wind is a key source for global electricity generation in the decades to come.

## Objectives

In a workshop setting, experts will be encouraged to provide input and insights associated with scenarios that yield aggressive wind industry growth globally. The focus will be on wind turbine and wind plant technology and associated wind industry and electric system infrastructure advances. Questions for discussion include:

- What conditions affect wind growing incrementally until it is a dominant source for global electricity generation? Relatedly, where does a paradigm shift take place in terms of technology pathways today and wind turbine and wind plant technology as a dominant electricity generation technology in the global grid system in 2030/2050?
- What are R&D challenges that arise in an aggressive (paradigm shifting) growth scenario relative to incremental growth?
- What innovative infrastructure developments would support aggressive wind deployment (e.g., transmission infrastructure, storage technologies)? What is the current state-of-the-art in these technologies and what are the major challenges with these systems in realizing a wind energy dominant electricity grid of the future?
- How does wind turbine and wind plant technology need to evolve to meet different infrastructure developments and different market contexts (e.g., established vs. emerging)?

## Intended participation

Participants include strategic, system-level thought leaders with wind research, technology, cost, and/or market expertise. Representation from both established and emerging wind market participants will provide a breadth of expertise. All participants will be expected to contribute to break-out sessions targeted at eliciting perspectives related to future wind deployment challenges from both technology and infrastructure perspectives.

## Expected Outcomes

One outcome of the meeting will be a global agenda to move toward wind technology as a primary electricity generation option that is articulated in a published article (see for example, http://science.sciencemag.org/content/356/6334/141). This involves structured ideas and concepts regarding activities that the wind industry R&D community can undertake to influence wind technology becoming a primary electricity generation source to meet global electricity demand. This information will be utilized by the IEA Wind Executive Committee to develop a five-year strategic plan and by other participating organizations to inform R&D activities.

## 2. AGENDA

### Sunday, Oct. 22nd (Marriott Denver West meeting rooms)

> *The Sunday session is devoted to brainstorming and discussion of what the energy landscape, and wind energy contributions, will look like in 2050, as well as what the most challenging aspects of getting from here to there will be.*

4:30 PM Check in and Badging

5:00 PM Social hour / Future Scenario Game

During the Social hour, workshop participants will be asked to participate in a casual brainstorming exercise around wind industry development objectives of 1) LCOE, 2) grid integration and 3) deployment. For each topic, participants will be asked to think about different opportunities and barriers to the improvement in each objective and to rate the difficulty associated with each. Discussion is encouraged among the participants.

6:00 PM Hosted Dinner

7:00 PM Grand Vision Scenario Premises

Welcome and Workshop Introduction (Paul Veers, NREL)

In preparation for the next day's activities, workshop participants will engage in a guided discussion over the key premises behind a Grand Vision of the future for wind energy as a primary source of energy for the world. Topics covered will include the level of wind energy as a percentage of total generation, the portion of which is offshore, the level of solar and other renewable deployment that exists, the type of computing, data management, sensing and other enabling technologies that are available to the industry.

8:30 PM Adjourn for the day

### Monday, October 23rd (NREL, RSF, Beaver Creek Room)

*The Monday meetings are organized around three main breakout sessions where attendees will be asked to create a list of most critical issues in achieving the needed* 1) LCOE *and* 2) Value *to achieve the landscape discussed in the Sunday meeting. Then, the last breakout,* 3) Research, *we will gather the fundamental issues needed to achieve the 2050 vision. Breakout sessions will be divided into small groups according the categories below.*

**Schedul**e

7:45 AM Bus departs from Marriott (Parking is also available at NREL entrance gate if you drive.) In good weather, it is a short (~1km) walk

8:00 AM Arrival, check-in and continental breakfast 8:30 AM Introductions of new attendees

8:45 AM Introductory Addresses

- Welcome; Paul Veers (3 min)
- Peter Green, NREL Director-Science & Technology (5)
- Lionel Perret and Ignacio Marti, *Introduction to IEA Wind TCP and Task 11* (15)
- Joachim Peinke, University of Oldenburg and Carlo Bottasso, TU Munich: *The European Academy publication of Long-Term Research Challenges* (25)

- Katherine Dykes, *Summary of Sunday Night activity and Instructions for Breakouts* (12)

9:45 AM Guiding talk

- Ryan Wiser, LBNL, LCOE projections and opportunities with

concerted effort

10:05 AM Guidance for Breakouts and Locations – Katherine Dykes

10:10 AM Breakouts on Wind Plant LCOE (divided into the six breakout groups listed above)

In this first session, we address the classic metric of LCOE which is still one of, if not the, most critical metric for evaluating a wind plant. In each breakout, workshop participants will evaluate technology needs for further reduction to LCOE and its main elements: energy production, capital costs, operational expenditures and financing.

11:30 AM Wind Plant LCOE Breakout Reporting 12:00 PM Lunch and continued discussion

1:00 PM Guiding talk

- Paul Veers, NREL, New paradigms for wind value beyond LCOE

1:20 PM Breakouts on Wind Plant Value and Deployment (divided into the five breakout groups)

In this second session, we look more broadly at what will allow or impede massive amounts of wind energy deployment. In each breakout, workshop participants will address needs for increasing deployment that are not LCOE-centric and may include grid integration issues, deployment barriers, resource availability, infrastructure and more.

2:40 PM Wind Plant Value and Deployment Breakout Reporting

3:10 PM Break

3:30 PM Guiding talk

- Daniel Laird, NREL, Perspectives on Long-Term Research at a Fundamental Level 3:50 PM groups

The last break-out session will be used to identify critical research needs for enabling technologies that reduce LCOE and/or enable further deployment of wind energy to achieve the scale of the Grand Vision.

5:10 PM Research Needs Breakout Reporting

5:45 PM Wrap-up & Next Steps

- Paul Veers, NREL, Goal: A high-level publication that illustrates wind’s potential and maps out the opportunities that can be realized through fundamental research

6:00 PM No-Host Social Hour (Marriott Denver West)

**Small Groups for breakout sessions**

1) manufacturing and industrialization, installation and logistics (Berry & Laird),
2) land-based turbine technology, design, scaling, energy access and capture (Paquette & Robinson),
3) offshore turbine and foundation technology, marine construction and access (Manwell & Robertson),
4) wind plant technology control, storage and design (Pao & Fleming),
5) atmospheric science, forecasting, and condition-based optimization (Moriarty & Marquis).

Originally, there was a sixth group, but registration was not large enough to keep it separate, so the impact on of these issues should be considered by all of the five above groups.

6) Operations and asset management, reliability and life extension.

*A seventh small group will also be conducted on:*

*7) Grid integration and operations; energy transfer, stability , storage and markets*

*This meeting will be held on November 10, 2017 in Mexico at the conclusion of the IEA Task 25 (Grid) meeting to capture critical input on this very important issue.*

## 3. LIST OF PARTICIPANTS

The meeting was attended by 42 participants from 11 countries. Following, the lists of participants and their affiliations.

| Name | Country | Company/Organization |
|---|---|---|
| Aaron Barr | US | MAKE Consulting |
| Amy Robertson | US | NREL |
| Andrew Clifton | DE | WindForS - Wind Energy Research Cluster |
| Andrew Oliver | US | RES Americas |
| Anna Maria Sempreviva | DK | DTU |
| Brian Smith | US | NREL |
| Carlo Bottasso | DE/IT | TUM |
| Charles Meneveau | US | JHU |
| Daniel Averbuch | FR | IFPEN |
| Ebba Dellwik | DK | DTU |
| Eric Lantz | US | NREL |
| Erik Hale | US | EDF |
| Ignacio Marti | DK | DTU |
| James Manwell | US | College of Engineering, UmassAmherst |
| Jan Tessmer | DE | DLR |
| Jim Ahlgrimm | US | DOE |
| John McCann | IRL | SEAI |
| Joaquim Peinke | DE | U. Oldenburg |
| Jonathan Naughton | US | University of Wyoming |
| Joshua Paquette | US | SNL |
| Katherine Dykes | US | NREL |
| Libing Zou | CN | Mingyang |
| Lionel Perret | CH | Planair |
| Lucy Pao | US | University of Colorado |
| Martin Kühn | DE | ForWind - Center for Wind Energy Research |
| Melinda Marquis | US | NOAA |
| Michael Muskulus | NO | NTNU |
| Mike Derby | US | DOE |
| Mike Robinson | US | NREL |
| Ndaona Chokani | CH | EPFL |
| Ola Carlson | SE | Chalmers University of Technology |
| Patrick Moriarty | US | NREL |
| Paul Fleming | US | NREL |
| Paul Veers | US | NREL |
| Ryan Wiser | US | LBNL |
| Sandy Butterfield | US | Boulder Wind |
| Stephan BARTH | DE | ForWind - Center for Wind Energy Research |
| Steven Saylors | US | Vestas |
| Tino Oldani | US | Ingersol |
| Xabier Munduate | ES | CENER |
| Daniel Laird | US | NREL |

| | | |
|---|---|---|
| Derek Berry | US | NREL |
| Scott Carron | US | NREL |
| Doug Rhoda | US | DMS |
| James Earle | US | DMS |
| Eric Smith | US | Keystone Towers |
| Gavin Smart | UK | ORE Catapult |
| Jason Fields | US | NREL |
| Johney Green | US | NREL |
| David Edward Weir | NO | NVE |
| Peter Green | US | NREL |

*Figure 1: Participants in the IEA WInd TEM #89*

Prior to the actual TEM, a pre-meeting was held with the Utility Variable Integration Group (UVIG) fall meeting. Attendees for that meeting included:

| **Name** | **Country** | **Organization** |
|---|---|---|
| Paul Veers | US | NREL |
| Katherine Dykes | US | NREL |
| Mark Ahlstrom | US | Nextera Energy |
| Charlie Smith | US | UVIG |
| Nicole Segal | US | NERC |
| Bruce Rew | US | SPP |
| Michael McMullin | US | MISO |
| Brett Wangen | US | Peak Reliability |
| John Simonelli | US | ISONE |
| Nick Miller | US | GE |
| Aidan Tuohy | US | EPRI |
| Jim Baak | US | Stem |
| Charlton Clark | US | DOE |
| Aaron Bloom | US | NREL |
| Paul Denholm | US | NREL |
| Mark O’Malley | US | NREL |

Following the TEM #89 in Colorado, a separate meeting was also held in conjunction with IEA Wind Task 25 to focus specifically again on electric grid related issues associated with the Grand Vision.

Participants in the TEM #89 Task 25 follow-on meeting included:

| **Name** | **Country** | **Organization** |
|---|---|---|
| Paul Veers | USA | NREL |
| Katherine Dykes | USA | NREL |
| Brian Smith | USA | NREL |
| Charlie Smith | USA | UVIG |
| Hannele Holttinen | Finland | VTT |
| Nicolaos Antonio Cutululis | Denmark | DTU Wind Energy |
| David Campos-Gaona | UK | U. of Strathclyde |
| Jose Manuel Franco Nava | Mexico | INEEL |
| Jaime Agredano Diaz | Mexico | INEEL |
| Esmeralda Pita Jimenez | Mexico | INEEL |
| Debbie Lew | USA | GE |
| Jody Dillon | Ireland | U. College of Dublin |

*Figure 2: IEA Wind Task 25 Breakout Session at INEEL, Cuernacava, MX*

# 4. SUMMARY

The Grand Vision for Wind Energy workshop sought to bring together a group of experts to consider the question of how to enable a future where wind supplies greater than 50% of our global electricity consumption? The attendees were asked to create a vision for wind where:

- Cost of energy for wind is less than that of natural gas fuel and solar (cheapest global electricity resource), and/or
- Wind plants are like traditional thermal plants that provide significant value in terms of reliability and flexibility

The overall workshop was organized into four working sessions. The first working session was meant to solidify the context (grid architecture, markets, environmental, social, etc) for the vision of wind energy supplying over fifty-percent of global electricity demand. In the next two sessions, participants explored technology innovation opportunities for wind energy within this Grand Wind Vision context. The second session looked at driving the levelized cost of energy (LCOE) for wind to levels so that it would be the least expensive energy generation technology and thus spur huge amounts of wind energy deployment. The third session considered looking beyond LCOE to increasing the overall system value that wind energy provides to the grid in terms of reliability – providing significant capacity value and dependable ancillary services. Finally, the fourth session considered what R&D challenges limited the ability to realize the LCOE and system value improvements for wind energy that had been identified in the prior two sessions. The outcome for the workshop would then be:

- Identification and ranking of high-priority wind energy technology opportunities for significantly reducing LCOE and improving grid system value
- Identification and ranking of Grand R&D challenges associated with those technology opportunities along with recommended actions to address those challenges

Following the TEM, volunteers from the workshop will work together to develop a high-impact journal article that described the vision and challenges including some supporting techno-economic analysis.

## Session 1: Grand Vision Scenario Development

### Inputs to TEM from UVIG

Prior to the TEM, a meeting was held in conjunction with the Utility Variable Integration Group (UVIG) to help better understand what the future grid system would look like if wind were to provide over fifty percent of the electricity supply. Attendees for the grid context discussion included representatives from UVIG, NextEra, GE, ISO-NE, MISO, SWPP, NERC, DOE, EPRI, NREL, and STEM.

The group began by discussing the context of challenges related social acceptance. It was generally agreed that social science issues related to wind energy deployment are absolutely critical to exploring a scenario where wind energy provides more than half of global electricity supply. The group agreed that the topic could easily make up its own entire workshop and should be a key consideration in any Grand Vision for the future of wind energy.

Next, the group turned to the consideration of more technical issues related to wind energy deployment. Some of the key discussion points included:

- A future where over fifty-percent of energy is provided by renewables (similar to a DNV GL forecast that was presented to the group) is not aggressive enough. The scenario needs to involve at least eighty-percent of electricity coming from renewables with fifty-percent or more likely coming from wind energy.
- Currently, natural gas is so cheap right now that reaching eighty-percent of electricity from renewables seems impossible. In order to get to eighty-percent, significant innovation will be needed – for cost-competitive wind energy.
- However, at the same time, it's not only science that will enable that competitiveness – institutional change plays a key role as well. For example, the generation side is "relatively easy" while we need to get significant transmission built which is "extremely hard". Another example area is storage. The technology exists and has existed but institutional changes could help incentivize deployment of storage to the levels needed to enable a high-renewables-penetration future.
- In any scenario, the group emphasized the need to maintain reliability and compliance. For the bulk system, increasing transmission and storage were viewed as key enabling technologies. The discussion of transmission was extensive and considered scenarios where you had to simply use existing assets more efficiently (using dynamic line ratings and improvement contractual availability for example) versus situations where central governments mandated expansion using policy and legal mechanisms.
- At the same time, shifting wind and solar to look more like "grid forming converters" was seen as necessary for scenarios where renewables provide the bulk of the electricity supply. Wind in this future will have to expect curtailment and de-rating to be the norm – a paradigm shift in how wind power plants operate. At the extreme, future wind technology would be "designed for curtailment," that is, designed to operate almost all the time at some level of capacity (or with integrated storage) and act more like a traditional dispatchable plant that could ramp up or down power on-demand. This is of particular importance to overcome seasonality issues associated with both wind and solar energy.
- However, there was also consideration of the future grid in terms of the role of the bulk versus distributed systems. In the future, if there is enough generation and storage on distribution networks, the overall role of the bulk electricity generation and transmission system may be less crucial. This perspective included a large amount of deployment of electric transportation, distributed solar, demand response and related technologies. With enough deployment of these distributed technologies, it may be possible to have a much more elastic electricity load profile in the future – something that reaches almost a flat line or a step-function by season.
- For all contexts, the group generally agreed that such a high-level scenario of renewables would require significant changes in market design. The system is huge and complex. This future will require harmonization and coordination across many different agencies and jurisdictions. A key part of this coordination and evolution of markets would be real-time pricing – to ensure that all assets on the grid (distributed

and bulk) respond as needed at all time-scales to ensure efficient and reliable grid operation.

- A key aspect of using wind and solar to support the grid centered around inertia and maintaining grid frequency when there are few large thermal assets to physically provide inertial response. One response would be to have a variable frequency or DC system – which could be possible if end-use applications (i.e. synchronous motors) were eliminated. What if we were to design the grid with a blank sheet of paper to be an all-renewable supplied system? What would be the design and operational characteristics of all the technology elements of the system from generation, transmission to distribution?

Additional discussion over this future scenario context included input from the IEA Wind Task 25 in a follow-on meeting held at INEEL in Mexico on Nov. 10th, 2017. Key discussion points from the group included:

- The emphasis on market design is critical. If we drive down the cost of energy for renewables (like solar and wind) towards zero then prices for energy will in turn be driven down towards zero and energy markets will not be viable. In the extreme, scarcity pricing where prices are zero almost all the time and high for very-small portions of the year collapses to a capacity market. The bottom-line is that capacity and service markets need to be compensated to ensure reliable operation of the grid at all time-scales.
- Closely tied to system design is system design. We are moving towards an era of a converter-dominated system where you can't rely on physical inertial from physical assets as we have done in the past. There is a huge amount of interaction between converters in the system and the grid will be come weaker and weaker (well below 80% penetration of renewables). Even now there are issues and until we address them, curtailment for wind will be a norm.
- Another closely related them is inadequacy of transmission. Transmission is perhaps the most problematic issue / limiting factor to the future vision – the path of building out transmission for the future vision is unclear. Research funding on transmission is not prioritized – the criticality of transmission to the high renewables future isn't well communicated to decision-makers.
- For electrification of other sectors, storage and demand response, the need is clear. The goal is to have very flexible loads, or sinks, for variable electricity generation. There are many ways to do this but for storage, many think that power to X (where X is gas, ammonia, liquids, other industrial fuels) is likely because of the storage density of these assets. A lot of seasonal variability can be handled this way (though not completely because some large demand sources are still quite inelastic – like large scale manufacturing systems, i.e. aluminum). The main challenge to the development of these technologies is cost-effective electrolyzer systems.
- All agreed again that social acceptance is indeed a critical and large issue that needs to be addressed both for power plants but for transmission in particular. Some research organizations and even utility organizations are now engaging actively with social scientists to address social acceptance of these technologies.

Through the discussion, the group laid out a series of characteristics for the high-renewables future of the electricity (and overall energy) system. The future scenario resulting from the discussions with UVIG (as well as the TEM #89 meetings in Colorado and with the IEA Wind Task 25 in Mexico) includes:

- Generation mix:
  - 80% renewables – instantaneous generation of >100%
  - Retirement of older traditional assets and reuse of transmission in those areas
  - No thermal assets in the system at all
- Electrification of energy system (heat, electricity, industrial, water)
  - These non-traditional assets can also provide significant storage capacity
  - These assets are also responsive (to some degree) to real-time price signals
- Storage / demand response
  - Seasonal storage is widely available (or Power to X is cost-effective)
  - Demand response enables a highly elastic load-profile
- Transmission
  - Maximized use of existing assets/corridors – dynamic line/transformer ratings, upgrades
  - New technologies – DC transmission, high temperature, superconducting, modular power flow control
  - Low-cost underground transmission is available
- System design
  - All converter based-system
    - Inertia-less system
    - Fast/transient stability challenges overcome
    - Wind and solar are "grid forming converters"
  - Distributed system design and operation as important as bulk system (a holistic system)
- Market design and coordination
  - Real-time pricing
  - Transformation of capacity, energy, service, other??? Markets
  - Zero-marginal cost energy world
  - Wind allowed to provide ancillary services
- Institutional and regulatory context
  - Breakthrough institutional settings – harmonization of regulation
  - Larger balancing areas
  - Optimal use of transmission (i.e. WECC Transmission contractual availability is increased)
- Wind plants
  - Black-start capability is possible
  - High capacity value
  - Always running partially curtailed to provide services (designed for curtailment)
  - Geographically disperse

- Social acceptance (need engagement with social scientists)
    - Socially acceptable from perspectives of society and the environment (transmission as well as generation)

For all of these areas, it was noted that multiple future scenarios are possible and it would be good to consider not just one vision of the future, but two or more scenarios that reflect different potential realizations of the future electric system. This input was used to develop scenarios to aid the brainstorming activities of the TEM #89.

## Scenarios for the Grand Vision of Wind Energy

The outcome of the UVIG session was used to construct two scenarios for consideration by the participants in the TEM #89. These were meant to provide two extremes of the future (with a target year of 2050) and the resulting objectives for wind power plant design would be different. In the first scenario, the gird would support large amounts of wind energy without significant burden being placed on wind technology itself. Large amounts of transmission, storage, changes in the distribution system, power electronics etc would allow for high levels of wind in the system without requiring significant capacity and services from wind plants. Thus, the focus for wind energy innovation would be, as it has been historically, on **decreasing LCOE**. In the second scenario, however, constraints on all other aspects of the system described above would force wind to be "designed for curtailment" and provide significant capacity value and services to the grid. In this case, wind power plants would have to be designed to provide **increased system value**. The two scenarios for LCOE and system value are shown in the below table:

*Table 1: Scenarios for WInd Energy Grand Vision Breakout Sessions*

<table>
<tr><th>Scenario 1: Objective of Lowest Possible Wind Plant LCOE</th><th>Scenario 2: Objective of Highest Possible Wind Plant Contributed System Value</th></tr>
<tr><td colspan="2">Generation:</td></tr>
<tr><td colspan="2">• Wind energy >50% global electricity supply</td></tr>
<tr><td colspan="2">• Renewables > 90%</td></tr>
<tr><td colspan="2">• Global energy is electric (transportation, heating)</td></tr>
<tr><td>Transmission and storage are ubiquitous (seasonal storage available)</td><td>Transmission is constrained and storage is limited (no seasonal storage availability)</td></tr>
<tr><td>Distribution:</td><td>Distribution:</td></tr>
<tr><td>• Large amounts of electric vehicles, demand response, solar – bulk and distributed systems are both significant</td><td>• Limited amount of distribution-side capacity (electric vehicles, demand response, solar) – mostly a bulk system</td></tr>
<tr><td>• Load is highly elastic</td><td>• Load is highly inelastic</td></tr>
<tr><td>Market/system design:</td><td>Market/system design:</td></tr>
<tr><td>• Advanced energy, capacity and service markets where wind participates (but energy is dominant revenue stream)</td><td>• Advanced energy, capacity and service markets where wind participates (capacity and service payments are substantial)</td></tr>
<tr><td>Socio-economics:</td><td>Socio-economics:</td></tr>
<tr><td>• Few constraints on siting</td><td>• More constraints on siting</td></tr>
</table>

| | |
|---|---|
| (environmental, social) with increased deployment | (environmental, social) with increased deployment |
| • Lowest cost electricity prioritized | • Local economic development prioritized |

In both future scenarios, the level of wind energy in the system is greater than 50% of overall electricity supply. However, in the former case, the need for capacity value and grid services from wind energy is not dissimilar from today with massive transmission, storage and build-out of the distribution system (with electrified transport, solar, storage and demand response) able to balance the variability of wind. Thus, wind plant designers and operators can focus simply on driving down the cost of each kilowatt-hour to the lowest possible value (lowest possible LCOE). In the second extreme case, the electric grid ultimately is not significantly different in terms of system structure from today and there is limited build-out of transmission, storage and the distribution system. The burden of providing capacity value and services to the grid is much higher then and wind plant designers and operators have to give up some LCOE in order to provide more value to the system. In a presentation, by Ryan Wiser, LBNL, this was illustrated quite well in the simple graphic shown below:

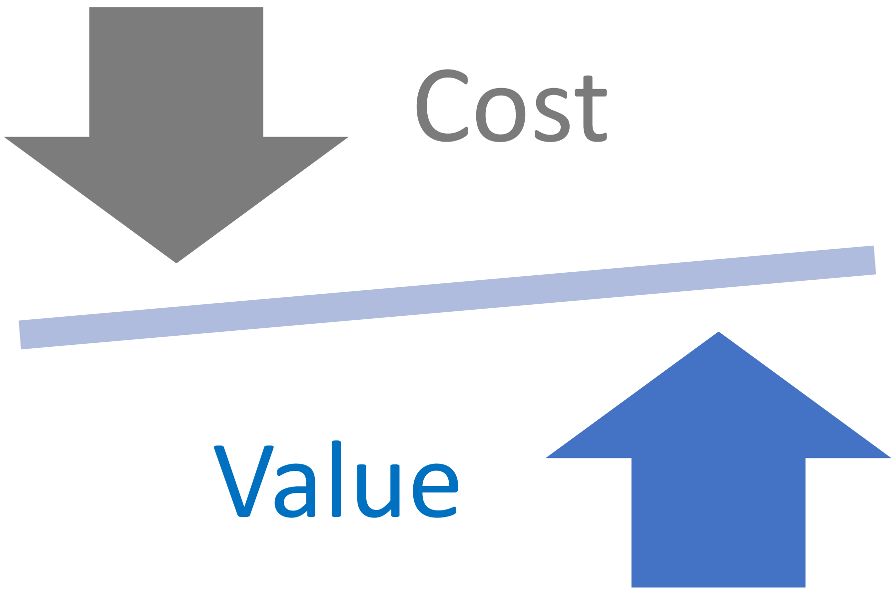


*Figure 3: Future wind power plants will have to consider trade-offs in design and operation between LCOE and system value. Depending on the architecture and make-up of the future grid, the relative importance of each will change. Thus, this TEM considered each objective separately. Follow-on efforts by working group efforts will work to create a vision that harmonizes across the two objectives since both will be critical to the future of wind energy deployment.*

The TEM attendees discussed the scenarios and considered recommendations for potential changes. Some key topics that came up were:

- The group acknowledged that the two "goalpost" scenarios were quite extreme and that the actual future would likely fall somewhere in between the two.
- While policy was not part of the scenario development (policy was not considered in the overall Vision discussion), it's importance in determining the future of the electric grid was acknowledged as critical. In particular, policy around carbon emissions (whether through taxes, quotas, etc) was seen as paramount to influencing future

technology trajectories.

- Relatedly, the cost of other technologies was an important area that many thought merited consideration. Implicitly, the LCOE scenario assumes driving down wind costs to be competitive with natural gas and solar but the final scenario for the paper should consider this explicitly.
- Just as with the UVIG meeting, system reliability was seen as critical to any future scenario and an important part of the discussion for both scenario 1 and 2 (but scenario 2 in particular).
- Not explicitly mentioned was the market design issues related to integration of balancing areas which was also recommended for inclusion in final scenario definition.
- Another consideration was that wind energy be used to generate other forms of energy than electricity (i.e. producing fuels, desalination, etc). This was seen as particularly important and a potentially parallel trajectory to electrification of transport.
- In formulating the future scenario, the overall amount of energy needed (as population grows, countries industrialize, etc) should be considered and supplying energy should be analyzed not in the sense of bulk production but also in a time-series context because the dynamic behavior over time is critical to understanding the viability of any future technology scenario.
- Finally, the group considered how climate change will likely play a significant role in when and how wind energy systems are deployed in the future. Some key questions are:
    - How can wind energy help mitigate not only the drivers of climate change (GHG's) but also the IMPACTS of climate change? Things such as water scarcity, system reliability , etc.
    - How will the changing climate impact wind energy systems? We expect extremes (wind, temp, precipitation) will become more extreme, how will this change design conditions and design approaches for wind turbines?

## Results for Breakout Sessions 1 (LCOE), 2 (System Value) and 3 (R&D Challenges)

A series of presentations were given to motivate the breakout sessions that followed the scenario development. A high-level summary of the preliminary conclusions (from the discussion following each breakout) is included in the below table.

*Table 2: High-level Preliminary Takeaways from Each Session*

| | LCOE Session | Value of Wind and Deployment Session | R&D Grand Challenges |
|---|---|---|---|
| **Manufacturing and Industrialization** | On-site manufacture of transport-constrained wind turbine components | Recyclability of wind turbine components (i.e. composites) | New high resolution model to accurately understand interaction of manufacturing process, design and performance (design for manufacturability) |
| | Targeted automation for wind blade production | | Additive manufacturing processes for composites and metals |
| | Additive manufacturing of major components and tooling (lower cost and improved functionality) | | |
| **Turbine Design** | Larger Rotors | High capacity factor machines | Assessing the inflow characteristics across very large rotor diameters; veer, shear, 3-D distribution turbulence; wake inflow coupling |
| | Design for reliability, integrated system-level design | Design/Control for Ancillary Services and Grid Stability | Physical understanding of the boundary layer physics (subviscous and mixing layer) - multi-scale |
| | Wind Plant Flow Control | Value Optimized Design/Operations Strategy | Impacts and potential for two-way coupling and effects on the BL inflow |
| | Design standards that acknowledge plant level physics | Technologies to mitigate acoustics | Assessing wake dynamics (generation, meandering, dissipation) and subsequent array interation effects. |
| | Turbine Upscaling | Technologies to mitigate wildlife impacts | Validation and verification of the simulation and design tools that would include: new instrumentation, open data access to the research community, common "big science" grand challenges |
| | Taller Towers | Technologies to mitigate visual impacts | |
| | Hybrid plant (PV/Wave) | Technologies to mitigate issues with ice and radar interference | |
| | Alternative technologies (i.e. airborne wind) | | |
| **Atmsopheric Science and Forecasting** | Advanced / validated models of the climate, plant and turbine | Better forecast of loads at different scales | Atmospheric science to build a bridge between the different sciences of wind energy |
| | Improved forecasting techniques | Improved predictions of grid stability in planning | Modeling of the entire chain of physics at extremely high resolution |
| | | Big data that feeds back to forecast, use of wind plant SCADA data for forecasting (across many plants) | |
| | | Improved forecasting for noise impacts and migration bird & bats | |
| | | Create social acceptance through energy production app, temperature, visualization tool | |
| **Plant Controls and Operation** | Wind farm control for power maximization and for structural loads reduction | Provision of ancillary services (not including storage) | Full end to end validated modeling capability for the atmosphere to grid |
| | Co-design of wind plant (layout, choices of turbines, etc.) and wind plant controls | Geographic diversity | Validated power system model with large amount of wind power, storage, solar, flex loads |
| | Understanding inflow and actively controlling wind flow through wind plant | Hybrid wind system services (with solar, storage, electric vehicles, etc.) | |
| | Strategically optimize for power and/or lifecycle based on PPA | Combining wind with storage at multiple time frames (seconds, hours, days, seasons) | |
| | Machine learning with big data for structural health monitoring | Larger than GW scale wind plants | |
| | Hybrid wind/solar/storage plants and control | Regional control of wind plants | |
| | Drones and robotic O&M innovation in field repair | Monetizing the value of negligible water use in wind power generation | |
| | HVDC and control of HVDC | Wind for X (desalination, carbon capture, ammonia, server farms, hydrogen, aluminum, chemicals) | |
| **Grid integration** | | Grid-forming wind power plants (black start capability, ancillary services) | Develop fundamentals, operational principals and design the paradigm for converter-dominated electricity systems |
| | | Co-optimized wind power plants for grid operation and performance\ | For the defined system, develop multi-scale modeling across the entire converter-dominated system with sufficiently accurate modeling of the converters |
| | | Design of wind plants for grid operation (high capacity factor, over-building, designed for de-rating, curtailment) | Understand market design that enables a reliable, stable, resilient and low-cost converter-dominated electricity system |
| | | Flexible AC Transmission Systems (FACTS) | Intelligent Wind Power Plant with Integrated Data and Modeling for Co-Optimization of the power plant for revenue, grid integration and reliability |
| | | Precise control, modeling of all assets in converter-dominated system | |
| **Offshore** | Floating support structures manufactured with standardized, modular components | Energy storage, fuel production (hydrogen, ammonia), desalination | Improved, multiscale validated design tools (including test facilities for validation) including accurate fatigue assessment |
| | Class-based designs with site suitability assessment (inc. considering hurricanes/tropical cyclones | Offshore electrical infrastructure innovations (superconducting, HVDC, super subsea grids) | Develop better techniques to characterize the metocean conditions, including soils |
| | Smarter, more predictive O&M practices (e.g condition monitoring, robots for inspection, access, quayside maintenance) | Improved market structures that maximize use of transmission / optimize infrastructure across multiple wind plants | Plant-level holistic design optimzation process for floating wind systems (including controls co-design) |
| | Co-optimization of turbine and support structure designs (particularly for floating turbines) | Offshore social/environmental issues and synergies - i.e. design for fisheries | Data mining strategies for condition monitoring, operations and control |
| | Novel turbine concepts including downwind, VAWT and airborne wind | Strategic opportunities for job creation and business development synergies with energy intensive industries | Large-scale optimization problems involving wind plant and electrical infrastructure |
| | Offshore electrical infrastructure innovations particular around tranmission | | |

Following the meeting, each breakout group leadership reported on the findings from its individual sessions with more detail. These findings are reported by breakout group in the following sub-sections.

### Manufacturing and Industrialization

The manufacturing group explored manufacturing specific pathways to achieve the goal of wind energy supplying 50% of the global electrical demand by 2050. The team brainstormed over three breakout sessions focusing on; 1) lowering wind plant LCOE, 2) providing value beyond LCOE, and 3) identifying research needs. From these discussions the group was able to consolidate and prioritize the enabling technologies and research needs into Tier 1 and Tier 2 technology opportunities, with Tier 1 being identified as the most promising.
The Tier 1 technologies identified by the group were; 1) on-site manufacturing, 2) automation, and 3) recyclability.

- On-site manufacture of transport-constrained wind turbine components, such as blades and towers, was the clear leader in enabling technologies as larger rotors and higher hub heights have a large impact on LCOE. The discussions surrounding on-site manufacturing revolved around on-site specific tools and tooling, unconstrained turbine design, simplified and continuous manufacturing processes, field assembly processes, mobility, additive manufacturing, and environmental requirements of materials and processes. The research needs identified were environmentally robust materials (e.g. paints and resins), workflow optimization for reduced facility footprint, welding technologies to improve fatigue curves (e.g. laser welding), downstream effects of component growth (e.g. hubs, bedplates and generators), and mobile tooling.

- Automation was a hot topic, and specifically targeted automation for wind blade production was identified by the group as a Tier 1 enabling technology. Discussions amongst the group revolved around tolerances, metrology, single machines with continuous processes, and quality control. The research needs identified were embedded blade laminate metrology, out of mold referencing and indexing technologies, in-situ non-destructive inspection, and the speed/cost/quality needed for automated additive manufacturing technologies such as automated fiber placement machines and 3d printing.

- Finally, recyclability was identified by the group as a Tier 1 enabling technology. Discussions amongst the group revolved around potential future industry recyclability mandates, and ways to reduce content ending up in landfills. The research needs identified were largely materials based with the group identifying biodegradable materials, end of life triggered phase change materials, recyclable thermosets and thermoplastics, advanced materials research, as well as alternative technologies such as energy capture from incineration.

The Tier 2 technologies identified by the group were; 1) segmentation of large turbine components, 2) rural manufacturing economic development, 3) embedded/embodied energy in manufacturing, 4) upstream NDE (non-destructive evaluation) technologies in blade manufacturing, 5) multi-use and flexible manufacturing facilities, and 6) advanced/novel low cost material and manufacturing processes.

- The research needs identified by the group for segmentation involved mechanical and adhesive joint technologies that maintained quality, reduced mass and part count, as well as increased fatigue and fretting resistance.

- The research needs identified for rural manufacturing economic development involved researching and pairing high energy manufacturing processes with low cost rural energy (i.e. hydro, solar or wind) and labor sources.

- The research needs identified for embedded/embodied energy in manufacturing involved researching the entire product lifecycle with focus on standardization and carbon capture.

- The research needs identified for upstream NDE (non-destructive evaluation) technologies in blade manufacturing involved upstream real-time feedback loops to detect such things as defects, non-conformances, resin voids, and fiber alignment issues to limit repair and improve quality in the manufacturing process.

- The research needs identified for multi-use and flexible manufacturing facilities involved identifying compatible technologies and product lines which could be manufactured in the same manufacturing facility to offset risk, reduce capital costs, and maintain profit margins in a variable economic landscape.

- The research needs identified for advanced/novel low cost material and manufacturing processes revolved around modifying existing or identifying new technologies and processes to meet wind specific volume and cost requirements.

There was general agreement among the group that a subsequent workshop focused on the Tier 1 opportunities is needed.

The group discussed many topics, and to be comprehensive, all of the ideas not previously listed as Tier 1 or Tier 2 opportunities, are included below. During the LCOE session the group discussed; thermally welded joints with thermoplastic resins; toughened material systems to target erosion; monetization of blade recycling; advanced materials to reduce factory CAPEX (e.g. less cycle time, energy); digital twins; floating foundations using COTS (commercial off-the-shelf) components; manufacturing processes with defined (not best) quality; reduction of factory scrap and recycling; standardization of wind turbine components across the industry; low cost carbon or alternative precursors for wind turbine blades; crane free tower installations; 10+ MW onshore turbines; floating manufacturing plants; AM generators; superconducting generators; supply chain issues (e.g. bearings); reducing market/manufacturing risks through policy/incentives/stabilization; scaling effects on non-conformance issues (i.e. defects); advanced composite manufacturing with 3d printing; advanced blade repair methods; advanced design optimization and manufacturing using AI (Artificial Intelligence) and HPC (High Performance Computing); advanced/novel materials (macro/micro composites). And during the added value session the group discussed; local workforce impact (domestic/local); standardization/characterization of grid services; characterization of ports/infrastructure needs for offshore wind (leveraging oil and gas); multi-use/flexible manufacturing (e.g. blades/boats, rails/towers).

### Turbine Design

The Land-Based Technology breakout group identified needed technology improvements in the areas of LCOE, Value, and Deployment to achieve high wind penetration levels. Larger rotors, improved wind plant flow control, and increased system reliability were determined to be the most significant contributors to lowering LCOE. The development of larger rotors will require further development of technologies to mitigate loads, including on-blade aerodynamic controls and turbine and plant-level flow sensing, as well as solving the logistics issues associated with transportation of large blades (joints, on-site manufacturing, etc.), and the widespread, reliable implementation of carbon fiber in blades. Improving wind plant flow control will enable future plants to capture more of the energy available in the wind, and this will depend on designing rotors with reduced wake effects and turbine designs that entrain more flow into the plant. System reliability can be improved through understanding the drivers and processes of damage growth, and incorporation of that knowledge into validated models.

To provide more value to the grid, higher capacity factor wind plants are needed, along with the ability to provide ancillary services and maintain system stability. Higher capacity factor wind plants reduce the amount of installed capacity needed to achieve a given penetration level and serve as a replacement for some of the baseload generators that will be coming offline. Future wind plants will also need to take on some if not much of the ancillary services and system stability features that are now provided by conventional generators. This will require modifications to turbine/plant controls and electrical infrastructure. Finally, mitigating acoustics and impacts to wildlife were seen as the most important areas of research for increasing deployment.

### Atmospheric Science and Forecasting

The breakout group on atmospheric science held multiple conversations about the grand challenges in this area and finally converged on the following:

The ability to run very large-scale simulations, e.g., blade-resolving, smooth transition from micro to large scale on the order of 1000 km, whose output is made available to the public. Such simulations would contain a yearly cycle of atmospheric modeling, and there would be ~ 30 such very large simulations performed. These simulations would be benchmarks for smaller-scale simulations, the output for all of which would be provided for use by the public. Simulations would be verified against observations. The simulations would model the one-way and two-way coupling of wind plants to the atmosphere, the foundation (ground or water), and the real-time dynamics of the turbines and impacts on wind power production. This will require novel supercomputing capabilities. The full system must be modeled, including aerodynamics, aeroacoustics, hydrodynamics, hydrology, and the grid. The simulations will be limited by the questions about the representatives of the simulations based on the turbine specifications, plant layout, etc. Impacts of climate change on the atmosphere must also be included. The simulations will provide estimates of uncertainty in the wind resource and wind forecasts.

To support this grand challenge of running the very-large scale simulations, a number of supporting elements were identified: Multi-fidelity, reduced-order, hierarchical models as identified in IEA task #37; advances in HPC; observations; and information science to provide cataloguing and taxonomy of big data. The concept of a "model backbone" to support model interoperability that would increase efficiency in model development was discussed. Multiple spatial and temporal scales of the atmosphere must be bridged smoothly. Research would be advanced if the private sector would share data with researchers. There is a recent agreement for such data sharing in Denmark, which may serve as a model for broader data sharing.

There was a larger discussion about creating an ecosystem for innovation which includes:

1. Creating a motivating and funded environment for advanced research and education in energy meteorology
2. Creating the systems required to efficiently exchange information about the entire wind plant including its operating atmosphere. Specifically this is information systems, taxonomy and standards for how is data is stored and structured. This is viewed as an enabling piece for research and further advanced topics such as data science and machine learning
3. Data sharing and data access are barriers today that will need to be removed in order to achieve the research outcomes for very high penetrations of wind

The need for uncertainty quantification and improved skill resource assessment and operational forecasting was identified. Uncertainty quantification and improved skill in resource assessment specifically related to impacts of deploying more and more wind plants, as well as those of the changing climate, were discussed. Forecasting improvements from the minute to the seasonal time frame are needed. Lastly, improved modeling of the evolution of the wind resource, in the horizontal and vertical dimensions, with and without the coupling of turbines, is needed. This will inform turbine design conditions. As turbine design conditions change, turbines will change, and their impact on and coupling to the atmosphere will change. We must be able to model all of this.

### Plant Controls and Operation

The wind plant control and operations group considered a variety of technologies which could be used to both reduce the Levelized Cost of Energy (LCOE) of wind energy as well as to increase the broader value of energy production from wind. The research which would best enable the realization of these technologies was also considered.

In general, the group observed that reducing LCOE is the key focus of more near-term technological improvements and research. Reducing LCOE makes wind more and more competitive with all forms of energy production and strongly enables increased deployment of wind energy. However, on a longer time frame leading to very high penetration in 2050, increasing the overall value that wind energy provides to the larger power grid will become more dominant. In a grid with very high wind and solar PV penetration, value capabilities such as providing ancillary services to stabilize the grid are likely to become more important than low cost.

A number of technologies were rated by the group as having a high importance for reducing LCOE. One major technological improvement to plant operations is expected to be wind farm controls. Wind farm controls involves coordination of the control systems of turbines within a farm to achieve better overall results in energy production and loads mitigation than only focusing on controlling turbines individually. A second set of improvements is expected to come from the implementation of system-engineering and co-design practices to wind farm design. In these techniques, the wind farm, including control system, is designed and optimized holistically to achieve better results than a sequential design process that focuses on only one aspect (layout, controls, etc.) at a time. A third technological innovation to reduce LCOE is using a deeper understanding of atmospheric inflow to tailor wind farm control operations to the specific existing conditions. A fourth technology would be allowing wind farms to adapt controller settings either towards maximizing power or maximizing lifetime depending on the site conditions, power purchase agreement, turbine manufacturer specifications, etc. Using big data for structural health monitoring (SHM), optimization of existing systems and predictive failure are also seen as additional high-value innovations. Finally, allowing control systems to apply real-time machine learning and adaptation was also considered a high-value LCOE technology. Additional value is expected to be derived from moving the collection grid to a DC grid with DC/DC converters proving voltage step-up and power flow control. This grid would deliver higher efficiency and thereby increase energy delivered to the grid. Other ideas such as the use of drones and robots in operations and maintenance, HVDC, storage, and hybrid wind/solar/storage were also discussed but were considered to have less impact on the LCOE of wind energy.

Technologies related to increasing the broader value of wind energy focus on making wind more attractive to grid operators, and are expected to overtake cost as key considerations in the medium to long term. A chief technology on this list, implementation of ancillary services from wind, is an exception as it is already a reality in many locations. However, ancillary services cover a range of technologies (providing inertia, primary and secondary response, providing black-start, operating on islands, providing voltage support and reactive power control, responding to inter-area oscillations), and all of these technologies can be advanced and utilized to a greater extent in the future. A second set of technologies seeks to make wind more reliable through large area assimilation. The idea is to aggregate data and controls of farms spanning large geographically diverse regions, allowing a larger “super” wind farm to use wider knowledge of resource data for more precise control, and deploy services at a larger level, using a more widely distributed resource to significantly increase the reliability of wind as a power plant. The group also proposed a greater role for hybrid plants, those which mix wind, with for example solar and storage. Such plants use the complementary capabilities of different technologies to maximize value. Storage itself is seen as another provider of value, and could be used for short-term storage (seconds to hours) for power control, on a scale of a day to smooth diurnal cycles, and up to seasonal storage. Other ideas (ultimately considered to have lower impact) were also discussed, including using wind for many processes (desalinization, carbon capture, server farms, etc.), using wind on ships, using wind to bring high-quality internet to rural areas, and secondary usage of support structures in offshore wind for fish farming and other purposes. One important broader value of wind energy – that wind energy requires negligible water usage – should be emphasized more in advocating for wind, as nearly all other sources of energy require higher usage of limited water resources.

In considering the research which would enable these technologies, the group sees a wide variety of research topics which can be arranged into two grand challenges. The first is the development of a truly end-to-end model of a wind farm, from the atmosphere through to the grid. Such a model, or more accurately a hierarchy of models with different trade-offs of fidelity and computational efficiency, will be critical to enabling many of the LCOE-focused innovations. The second grand challenge is a detailed power system model, again incorporating multiple time scales and with good-enough fidelity, to optimize wind plants and the grid for high levels of renewables.

Beyond these two research topics, the group recognized two additional specific research topics. One is a greater understanding of off-nominal operation of wind turbines. Many technologies, from wind farm control to grid support services, propose to operate wind turbines in new paradigms, and while much data has been collected on wind farms operating normally, extensive simulation and field-testing will be required to fully characterize off-nominal situations. Finally, mapping new controllers and services directly to turbine lifetime, will greatly enable improved evaluation of new technologies.

## Offshore Specific Technologies

Offshore wind energy could benefit from research in a number of topic areas. Some of these are similar to research requirements for land based wind energy; others are quite different. Some of the key ones are summarized by category below.

Meteorological/oceanographic (Metocean) conditions

Metocean conditions are particularly important vis-à-vis the design of offshore wind turbines and wind plants, but they are also important for installation, operation and maintenance. There is need for better understanding of the wind conditions at the height of the rotor, both existing and projected, which correspond to heights in the 100 -300 m ASL range. Topics of importance include wind shear, turbulence, gusts, spatial and temporal correlations, stability, jets and veer. These features are affected by the sea itself so simultaneous consideration of oceanographic conditions (sea temperature, sea state, etc.) is needed. For the sea surface, better understanding is required of waves, including non-linear waves and extreme waves. Particular attention needs to be given to metocean conditions during hurricanes and tropical cyclones. In the near term, coastal and near shore conditions needed to be studied, particularly breaking waves. Over the mid and longer term, conditions further from shore and in deeper water need to be better understood. In all cases, continuous development and improvement of instrumentation for measuring metocean conditions particularly of the wind at heights well above sea level is needed. These include floating and scanning LIDARs, radar and satellite based measurement devices. Work in this area will span the time periods of near to long term.

Wind Turbine/Plant Design

Offshore wind turbines are already commercial, but there is still considerable opportunity for reducing their cost, improving their reliability, and developing support structures that will allow them to be sited further from shore and in increasingly deeper water. Important areas for research are increasing the rated power associated with a single support structure and in developing larger, but still readily deployable, support structures, both fixed and floating. Fundamental questions still exist regarding ultimate scales of wind turbines rotors, as well as the interaction of inputs and effects across a wide range of scales. Behavior of materials, especially large scale composites subject to high cycle fatigue requires fundamental research. The design process of individual wind turbines as well as the entire wind plant requires a thorough reassessment. A comprehensive eliability based design approach, which considers the entire plant and not just individual turbines, needs to be developed. This will likely include applications of class based design standards throughout the turbines and the entire plant. As progressively larger wind plants are built, integrated system level “cradle to grave” design will be needed. This should consider all aspects of the plants, from environmental impact through manufacturing, deployment and operation to repowering and then recycling or disposing of those items that have been replaced. Examination of issues regarding soil structure interactions for both fixed foundations and mooring systems is needed - soil behavior in deep water may well be different from that in relatively shallow water. For all situations, continuous improvement of modeling codes is needed, particularly in developing methods to interface models of behavior at different scales. In order to validate the models, there is need for considerable research to better understand where scale models can be used as well as methods and instrumentation for acquiring and appropriately utilizing full scale data of many sorts. Full scale offshore measurement facilities, such as the German FINO platforms but of even more comprehensive scope and in a range of metocean conditions, will be extremely useful. Throughout this process, consideration needs to be given to other different rotor configurations than are commonly used, but which may have some distinct advantages offshore. Possibilities include downwind rotors, two-blade rotors, morphing rotors, multiple rotors, vertical axis rotors and airborne wind turbines.

Electrical aspects

Offshore wind turbines are becoming increasingly large and will likely soon be able to generate 15 MW or more from a single rotor. At these scales, consideration of distinct generator designs is worthwhile. Such generators may well incorporate superconducting components. They will also likely be operated in conjunction with power electronic converters, which could also benefit from further development at these scales. The overall control of the complete generator/convertor system may also benefit from the incorporation of short term energy storage, such as supercapacitors.

Energy System Integration

As more offshore wind plants are constructed, the integration of these plants into the overall energy system becomes progressively more challenging, from both a technical and market point of view. This will be especially true as wind plants begin to replace conventional power plants; the wind plants will need to play a role in supplying many of the ancillary services currently supplied by conventional plants. In this regard, the electrical grid itself may need to become more "intelligent" and will need to play a more active role in the distribution of power than it currently does. In the energy system of the future, energy storage, load management, wind forecasting as well as more flexible conventional generators will all play a role. Designers and researchers familiar with the details of wind turbine operation will necessarily participate in development of these technologies.

Maintenance

Maintenance of land based wind turbines is now relatively straightforward. Maintenance of offshore wind turbines is much more problematic, largely due to difficulties of access and the possibility that specialized heavy lift vessels would be needed for much of the work. Technologies such as conditioning monitoring, remote sensing, failure prediction and robotics will be needed. Innovations particular to offshore wind will likely be required. Turbine designers should, to the extent possible, endeavor to make the turbines as reliable as possible so as to minimize the need for work at sea. The possibility of bringing floating offshore wind turbines back to port for major work will need to be considered.

Operation

Operation of offshore wind turbines in groups or plants will be similar in many ways to land based turbines. Topics such as forecasting, wake effects and energy deficit recovery will be important but different to the degree that the metocean conditions are different offshore. An additional factor to consider offshore is the need to predict the sea state, in so far as it affects access to and maintenance of the turbines. In the case of multiple, large offshore plants, one more factor to consider is how the presence one plant will affect the wind resource at another.

Social and Environmental Factors

There are many environmental factors to consider in the design of offshore wind plants, including effect on the habitats of various species, such as of fish, birds and marine mammals. Sound transmission offshore is in many ways different than on land and will need to be better understood. Among other considerations, sound may be transmitted through the water as well as on land. Although people do not normally live in the offshore environment, there are many human activities offshore which need to be considered and addressed. One of the more significant of these is fisheries. Development of land based support and supply infrastructure, including manufacturing facilities, ports and harbors, will also have societal implications which will need to be addressed. In some cases, there may be ancillary benefits resulting from offshore wind energy developments which need to be identified.

Priorities

As offshore wind energy develops it makes sense to address the most immediate issues first, but also to also begin to research those topics that will become important as the development continues. Immediate priorities, then, should focus on topics of relevance to early deployments, particularly those relating to existing technologies (8-10 MW turbines) in relatively shallow waters (less than approximately 50 m) and relatively close to shore (less than 50 km). Much research particular to wind turbines themselves will be done by manufacturers, but in other areas, such as model development and validation, characterization of the marine environment, and basic environmental assessments, research can be undertaken by the national laboratories and academia.

For the mid and longer terms of the future, characterization of the metocean environment further offshore will be needed. Improvements in and standardization of the methodology are necessary to bring down costs while securing the data that is relevant. Research into larger turbines, their support structures and constituent materials will be needed. Innovative concepts should also be evaluated. This will include development of suitable new models, which should link together all the scales of interest. Methods to validate those models will also be needed. This will likely include expansion of existing test facilities, and construction of new ones, especially for support structures and for full or near full scale offshore testing. The models will also be used to underpin design standards, which will require continual updating. Floating offshore wind turbines, with their many degrees of freedom and special design considerations, will need considerable work. Extensive research and development will also be required on grid integration and energy storage.

Overarching topics that will require fundamental research throughout the next several decades include: metocean conditions, integrated design methods; high cycle fatigue of large components in offshore conditions; soil structure (foundation/anchors) interactions; social and environmental impacts; multi scale model development and validation; remote sensing and robotics; large scale data collection, processing and analysis; and grid integration/energy storage.

# 5. PRESENTATIONS

## Introductory Addresses

Lionel Perret, Task 11 OA, Planair SA, *IEA Wind Task 11 Base Technology Information Exchange*

The meeting started with an overview of Task 11 activites, new developments and the new information exchange portal.

Joachim Peinke, University of Oldenburg *The European Academy publication of Long-Term Research Challenges* (25)

This presentation highlighted the need of new focus for long term wind energy research. Recommended topic areas for research include:

- Multi-disciplinary approach, including environmental and sustainability aspects
- Large Scale : use of new layer of atmosphere, more focus in economics and environmental values
- Multi-scale aspects from millimeters to hundreds of kilometers, methods to bridge scales
- Bid data what to do this new knowledge, to extract the essential information, to identify fatigue for example
- Validation an precision : new to unify and validate, need a precision, not yet the case in aerodynamics

Carlo Bottasso, TU Munich *The Need for Truly Open Data Sets*

This presentation highlighted the value that open data sets can provide to research communities in advancing research and innovation. The presentation pulled in examples from the Rotorcraft community which has a stronger history than the wind industry for sharing detailed design information. A particular project involved a heavily instrumented vehicle and an extensive test campaign that yielded a large public dataset for research and several workshops. The analysis of the data had an enormous impact on education and research.

The wind industry needs a similar effort and this will involve collaboration with industry. To date, most data sets and projects involve hypothetical rotor and turbine designs and code-to-code comparison rather than validation using real machine design and operational data. This will only take the research community so far and may limit advancement of science and technology for the whole industry. One comment from the audience noted that publically funded efforts should make a concerted effort to yield public datasets as a requirement.

## LCOE Session

Ryan Wiser, LBNL, *LCOE projections and opportunities with concerted effort*

Wind energy has grown exponentially over the last decades but its contributions to the global energy system are still small. Factors influencing growth to date have been innovations in turbines with larger rotors and higher capacity factors for overall very low cost of energy (comparable to natural gas fuel costs). However, several risks to future wind energy growth exist including:

- Policy instability persists and the presence of policy support for wind energy is not

certain
- Falling costs of natural gas and solar energy so that wind energy needs to lower costs in order to stay competitive
- As wind energy deployment increases, the market saturates which reduces the overall potential revenue for wind plants (falling market prices and increased curtailment)

In the future, we will have to consider balancing cost and value (returning to our overarching objectives for the workshop of looking at decreasing LCOE and increasing system value).

## Value of Wind Session

Paul Veers and Katherine Dykes, NREL, *Increasing Wind Energy Value to the System & Addressing Non-technical Deployment Challenges*

The guiding talk to motivate the breakout session on increasing system value started again by highlighting what the future may look like with renewables providing fifty-percent or more of the global energy supply. In these scenarios, wind power plants operate very differently than they do today. The norm of operation is curtailment and they are expected to provide significant support to the grid in terms of capacity value as well as grid services. In this future world, a greater share of the overall revenue to power plants is earned through capacity and service markets versus energy markets (the traditional dominant source of revenue).

In addition, as deployment of wind energy grows, it will have to address various non-market challenges such as environmental, social and security issue. A review of an NREL study showed that most of the US is affected by at least one challenge to wind power development (whether environmental, radar, lack of transmission, etc). In addition, wind energy has the potential to gain support by providing value to the local community and enabling workforce development. The breakout session that followed this talk considered innovation opportunities to address both increased system value as well as mitigating challenges to deployment and providing support for economic and workforce development.

## R&D Session

Daniel Laird, NREL, *Perspectives on Long-Term Research*

A short talk was used to motivate the final session around identifying R&D challenges to advance the future of wind energy towards the Grand Vision. The talk specifically highlighted some of the key research areas that are of focus to the US DOE Wind Energy Technology Office research program. These included:
- System Management of Atmospheric Resources through Technology (SMART) Wind Power Plants where the physics across all geographic and temporal are well understood to enable advanced wind power plant design, control, and operation.
- Seamless and robust grid integration featuring wind plants that provide advanced grid services and energy storage
- Forecast and power system dispatch coupling atmospheric sciences, power system modeling, and system state estimation
- Advanced manufacturing capabilities enabling very large turbine deployment
- Offshore floating wind technology to enable vast deployment of offshore wind energy

## 6. Review of TEM #89 with the IEA Wind Executive Committee

Following the TEM #89 meetings, a review session was held in conjunction with the IEA Wind ExCo #80 meeting in Huatulco, Mexico. IEA Wind will be updating its strategic plan in the coming year and the Grand Vision effort will directly support that process. The summary of the meeting discussion follows.

Firstly, following a background presentation on the Grand Vision for wind energy, the group had a general discussion around the effort:

- In terms of defining a Grand Vision scenario, we need not only to consider the energy context but "mega-trends" that will impact the future. VTT has been investigating these in its future scenario analysis and shared some content related to the topic. A few key aspects are population dynamics, migration and climate change. We don't need to assess this ourselves but we can draw upon a literature in this space to try to inform the "mega-trends" context for the vision.
- The topic of distributed wind was brought up by several ExCo members. It is viewed that distributed wind will be a major contributor to wind energy in several countries (including US and European countries) and the TEM #89 effort has been lacking this. Distributed wind in the future could be as large as offshore wind in many markets. Not only this, the idea of a "decentralized" grid (versus considering distributed and centralized/bulk systems separately) was proposed as a framework for considering both distributed and bulk energy systems in a single vision.
    - In addition, it is likely that follow-up meetings or TEMs will build upon the utility-scale centric TEM #89 effort.
- Social acceptance was brought up again as a key topic and this is another area which merits its own set of activities and meetings. A host of topics related to social acceptance will be important in particular to the IEA Wind strategic planning effort.
- The policy context was also cited as lacking from the current effort. It was acknowledged that this is important but outside the scope. However, "mega-trends" in policy may be something to consider as part of the vision as well.
- Given that many applications of wind energy in the future may be in areas without significant electricity generation present, there actually may be opportunity to use these systems as sources of learning (the "blank sheet") for areas of the world where entrenched interests and legacy systems significantly influence future developments.

Once the group discussed the Grand Vision overview and context, there was an in-depth discussion on the R&D challenges:

- A key theme that kept resurfacing during the conversation was "how is this exciting?". Solar energy seems to capture the imagination – interesting and novel materials, the ability to integrate it with every day life, etc – while wind is still large horizontal machines clustered in a farm. The excitement was not really reaching many in the ExCo which means to a non-wind audience the excitement is likely to be completely missing.
- Some topics that were brought up which seemed to garner more excitement were big data/IoT/digitalization/AI and novel technology concepts like airborne wind. The data topic is a key part of the output from the TEM #89 thinking across all breakout groups. While airborne wind was mentioned, it was not selected as a top priority. This brought up the tension between having the vision be relevant to the current wind industry and also be attractive to a more general public/political audience. On the one hand, if we consider technologies to far outside of the scope of current industry

interests, then they will be highly skeptical of the efforts. On the other hand, we will not build the excitement in a non-wind audience if the proposed R&D challenges aren't "exciting".

- A few things that did seem to gain interest were the need to push towards improving fundamental physics across scales (spatial and temporal) and disciplinary boundaries and the interplay of that activity with big data/digitalization/AI –without tying it too much to improved models. Following the TEM #89 it was proposed that wind energy may be an application that is different from many data applications due to the complex nature and the need to do more integrated physics-based modeling with data approaches than other technologies applications. Wind energy could perhaps be a leading application to push the entire scientific community forward in advancing integrated physics-based modeling and AI methodologies.
- The summary that was provided noticeably missed materials based research and this was brought up as an area where potential significant advancements could be made in many areas of wind turbine / plant technology. In particular, focused research on wind applications for these materials could make significant leaps forward. This brought up the idea of how concentrated effort of "wind energy science" in a particular area may create step-changes in innovations (such as the development of dedicated airfoils for wind turbine applications in the latter part of the $20^{th}$ century).
- For the strategic plan, it was suggested we might use the concept of "core competencies for wind energy" as umbrella topics for other areas. For instance, noise as a subset of aerodynamics research. Considerable discussion is still needed to flesh out not only the Grand Vision perspective but also how this will tie directly to the strategic planning for IEA Wind.