LONG-TERM RESEARCH AND DEVELOPMENT NEEDS FOR WIND ENERGY

FOR THE TIME FRAME 2012 to 2030

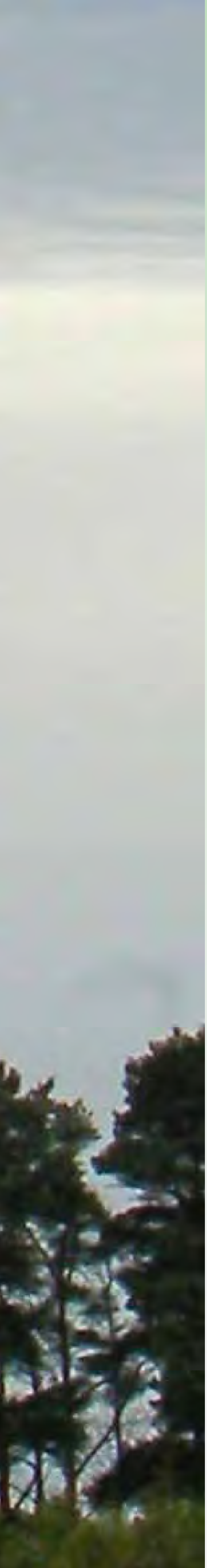
iea wind

Ad Hoc Group Report to the Executive Committee of the International Energy Agency

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

Approved by the IEA Wind Executive Committee

July 2013



Preface

This report on long-term research and development (R&D) needs for wind energy was produced by the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind), which forms part of a program of international energy technology collaboration under the auspices of the International Energy Agency (IEA). In 2012, 25 contracting parties from 20 member countries, the Chinese Wind Energy Association (CWEA), the European Commission (EC), and the European Wind Energy Association (EWEA) participated in IEA Wind.

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 research tasks regarding cooperative research, development, and demonstration (R, D&D) of wind systems. For the latest information and publications of IEA Wind, please visit www.ieawind.org.

Table 1. Participants in IEA Wind in 2012

Country / Organisation	Contracting Party To Agreement
Australia	Clean Energy Council
Austria	Republic of Austria
Canada	Natural Resources Canada
China	Chinese Wind Energy Association
Denmark	Ministry of Economy and Business Affairs, Danish Energy Authority
European Union	The European Commission
EWEA	European Wind Energy Association
Finland	The Finnish Funding Agency for Technology and Innovation (TEKES)
Germany	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Greece	Centre of Renewable Energy Resources (CRES)
Ireland	Sustainable Energy Authority of Ireland
Italy	RSE S.p.A. and ENEA
Japan	National Institute of Advanced Industrial Science (AIST)
Korea	Government of Korea
México	Instituto de Investigaciones Eléctricas (IIE)
Netherlands	The Netherlands Agency
Norway	Norwegian Water Resources and Energy Directorate (NVE) and Research Council of Norway
Portugal	National Laboratory of Energy and Geology (LNEG)
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)
Sweden	Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy
United Kingdom	Department of Energy and Climate Change (DECC) (2012); National Renewable Energy Centre (Narec) (2013)
United States	U.S. Department of Energy

Executive Summary

During the first 35 years of modern wind energy deployment, national R&D programs played an important role in making wind turbines more cost effective and reliable. These programs along with demonstration activities in cooperation with industry have helped make wind generation a significant contributor to meeting the world's energy demand.

Looking forward, much of the world has ambitious plans to expand wind energy development that will require specific R&D to accomplish. Achieving these ambitious goals will require public and private R&D funding carefully directed to the topics most likely to accelerate wind energy deployment.

Market-driven upscaling (increasing the size and output) of wind turbines, widespread deployment on land, and increasing use of offshore applications have introduced design challenges, integration issues, and social and environmental issues that researchers must solve for the pace of development to continue.

Investment should be targeted to the topics identified by the experts who contributed to this document. The overall aim of future research is to support development of cost-effective wind power plants[1] that can be connected to an optimised and efficient grid, providing grid support when needed or be used as non-grid-connected turbines. Significant cost reductions are possible with R&D to reduce loads.

IEA Wind conducts periodic assessments of experts to determine long-term R, D&D needs for wind energy. The resulting documents have helped the wind community in general, and IEA Wind in particular, to direct efforts on important research topics.

To encourage and support the technological development and global deployment of wind energy technology, this report presents the R&D priorities identified by the IEA Wind ExCo members and the operating agents (OA) of research tasks. More than 94 research priorities were proposed. Experts were asked when research results should be expected and the topics were divided according to a short-term (0-5 years), mid-term (5–10 years), or long-term (10–20 years) time frame. IEA Wind has just completed a Strategic Plan for the term 2014–2019[2] that addresses some of these research topics through its cooperative research tasks or by assembling experts to share information and plan joint activities.

The research issues with results expected in the short-term time frame were as follows:

- Resource characterization for offshore and land-based deployment
- International wind atlases
- Cost effective manufacturing methods
- State-of-the-art methods and testing facilities for large wind turbine components
- Advanced electric system design for high levels of wind penetrations
- Improved methods for electricity markets
- Grid codes and wind plant internal grid design
- Issues of spatial planning
- Tools to identify cost drivers of wind energy technology
- Recycling of wind turbines.

Research issues with results expected in the mid-term time frame include the following:

- Siting optimisation
- Build environment resource assessment
- Wind plant complex flow modelling and experimentation
- Wind and power production forecasts
- Systems engineering to optimise designs
- Integrated numerical design tools for wind turbines in deep waters offshore
- Distributed systems improved design
- Wind turbines in diverse operating conditions
- Novel rotor architectures
- Noise reduction technology
- Novel drivetrain designs and topologies
- Advanced power electronics
- Support structure design and optimisation
- Advanced wind turbine controls
- Offshore installation and logistics
- Small wind turbine manufacturing
- Operational data management
- Operations and Maintenance (O&M) and diagnostic methods
- Testing facilities and methods
- Transmission planning
- Offshore transmission planning
- Power system studies
- Distributed wind on the grid
- Human use effects and mitigation
- Environmental strategies and planning
- Workforce education

The issues identified to produce results in the long- term time frame are as follows:

- Atmospheric complex flow modelling and experimentation
- Marine environment design conditions
- Floating offshore wind plants
- Innovative turbines and components
- Active blade elements
- Advanced blade materials
- Advanced generator design
- Advanced offshore support structures
- Advanced wind turbine and wind power plant controls
- Advanced manufacturing methods
- High-reliability system development
- Grid operational tools
- Smart grid architectures
- Mitigate impacts on marine environments

The members of the IEA Wind Implementing Agreement will use this document to identify areas for co-operation to mutual advantage. In addition, it is hoped that other research organisations will find this document useful in setting their own research agendas to advance wind energy technology.

Under the umbrella of the IEA Wind, the next challenge is to design and carry out research and development projects to address the specific topics outlined in this document. Appendix A includes a description of active research tasks of IEA wind in 2012.

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[1] Also known as wind farms, wind power plants consist of many wind turbines and function as a conventional electrical generation plant connected to the transmission grid.
[2] The approved End-of-Term Report and Strategic Plan can be downloaded from: www.ieawind.org

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Foreword

This document builds upon and updates a 2001 publication of IEA Wind addressing research needs: *Long-Term Research and Development Needs for Wind Energy for the Time Frame 2000 to 2020* [1].

The latest in a series of recommendations by IEA Wind on the subject of R&D needs, this report draws upon a 2011 IEA Wind Topical Expert Meeting on the subject of long-term R&D needs [2]. After the Expert Meeting, an ad hoc group requested R&D priorities from the IEA Wind Executive Committee Members. All experts were asked to classify research that should produce results in the short-, mid-, and long-term time frame.

The ad hoc group reviewed recent strategy documents of the IEA Secretariat and IEA Wind. The group reviewed the proceedings of the Experts Meeting and the expressed priorities of the IEA Wind members to write the first draft of this document. The report was then reviewed by all members of IEA Wind and this final version incorporates their valuable comments. *The Long-Term Research and Development Needs for Wind Energy for the Time Frame 2012 to 2030* has been approved by the Executive Committee of the IEA Wind Implementing Agreement.

The next challenge is to design and carry out research and development projects to address the specific topics outlined in this document. The members of the IEA Wind Implementing Agreement will use this document to identify areas for co-operation to mutual advantage. In addition, it is hoped that other research organisations will find this document useful in setting their own research agendas to advance wind energy technology. To follow the progress of IEA Wind or to download an electronic version of this document, visit www.ieawind.org.

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1 Background

During the first 35 years of modern wind energy deployment, national R&D programs and cooperative R&D efforts, such as IEA Wind, have played an important role in making wind turbines more cost effective and reliable. These programs along with demonstration activities in cooperation with industry have helped make wind generation a significant contributor to meeting the world's energy demand. Now that wind energy is part of the electrical generation mix, it is more important than ever to carry out carefully targeted R&D to support the growing wind market and increase the contribution of this clean energy source.

When the IEA Wind agreement began its work in 1977, the need for R&D was widely recognised, and many countries initiated national R&D programs. As knowledge developed, research was directed towards specific questions relevant for wind technology, such as wind modelling, resource assessment, aerodynamics, and structural dynamics. IEA Wind produced Recommended Practices[3] from some of its cooperative research that contributed to standardisation and design codes for market development and international trade in wind technology.

The very success of these R&D activities is defining the need for continued research to ensure continued expansion of cost-competitive wind generation. Many countries have ambitious plans to expand wind energy development [3]. Achieving these ambitious goals will required improved understanding of resources, technology, operations, environmental impacts, and social issues.

To help advise governments on R&D strategy, IEA Wind has sponsored Topical Expert Meetings (TEM)[4] to develop research topics needed to advance wind energy. In 1995, a TEM drew the following conclusions:

"*… we have now reached a stage where the industry should be able to foot a larger share of the R&D bill. Also the fact that the industry has moved from the precompetitive phase into the competitive stage indicates that most of the product and component development should take place within the companies.*

However, there was consensus on the view that there is still a need for basic, generic research to be carried out outside the companies and

[3] The latest IEA Wind Recommended Practices can be downloaded from ieawind.org/Task_11/recomend_pract.html

[4] The latest summaries and proceedings from IEA Wind Topical Experts Meetings can be downloaded from ieawind.org/Task_11/topical_experts.html

wholly or partly funded by public money, and that this need will continue as long as there is wind energy development…" [7].

The conclusions at the 1995 meeting are still valid today. Industrial R&D efforts have developed larger and more effective wind systems utilising knowledge developed from national and international R&D programs. Yet the demands of the market and the size of the machines being developed today argue for collaboration to validate designs and codes [11, 12].

1.1 The Wind Energy Market

The market for wind energy is growing and is making a significant impact on global energy supply. At the beginning of 2013, wind generating capacity of 282.5 GW was installed worldwide (Figure 1). During the past 10 years, wind energy installed capacity has grown at about 22%/yr [15].

Offshore wind is playing a larger role in the market. In Europe alone, 2012 saw completion of 293 new offshore wind turbines, in nine wind power plants totalling 1.66 GW [16].

Small wind applications and hybrid technologies are operating in many countries with good market prospects. At the close of 2010, the installed capacity of small wind systems was estimated at 443 MW worldwide with more than 650,000 units in operation. By the end of 2011, more than 330 small wind manufacturers were offering commercial generation systems. An additional 300 firms were supplying parts, technology, consulting, and sales services [17].

1.2 Future Markets

In 2011, most of the high-growth markets were outside of Europe and North America. The Chinese market had stabilised somewhat and markets in India, Brazil, and México were growing rapidly. Emerging markets in Eastern Europe offered hope, as the European Union marches towards its 2020 renewable energy targets. Canada and Australia are potentially substantial markets which could add significantly to global growth figures; and South Africa has now entered the market in earnest [15].

Annual market growth rates of about 8% have been forecast, which would add about 255 GW in the 2012–2016 period. Overall, wind energy is expected to reach a total capacity just under 600 GW by the end of 2016 (Figure 2).

Between 2011 and 2020, EWEA expects the annual offshore market for wind turbines to grow steadily from 1 GW in 2011 to 6.9 GW in 2020 (Figure 3). In 2010, offshore wind power made up 9.5% of the annual wind energy market. By 2020, offshore is expected to make up 28% of the annual wind energy market [6].

Markets in areas considered as cold climates[5] are also increasing. Cold climate areas are characterised by good wind resources and low population, which together makes cold climates areas attractive for wind energy generation. It has been estimated that installed capacity in cold climates is approximately 60 GW [25] and represents about 25% all wind energy markets. Market in areas with high likelihood of icing is smaller, estimated at almost 10% of all markets.

Small wind turbine installations are expected to increase due to continuing political support. In recent years, global installed capacity of small wind turbines has increased 35% each year. This rate of growth is forecast to continue through 2015, reaching an annual installation of 288 MW of small wind turbines. Responding to this expansion, individual countries and the international small wind community are establishing more rigorous and structured standards and policies to regulate the market and support investments. Based on a conservative assumption, the market could subsequently see a steady compound growth rate of 20% from 2015 to 2020. The industry is forecast to add 750 MW annually in 2020 and achieve a cumulative installed capacity of 3,817 MW by 2020 [17].

1.3 Cost

Wind power has experienced important cost reductions as research has improved the technology and capacities have expanded. Experience curves based on historic records show learning rates up to 10%. Figure 4 shows one experience curve elaborated for wind power capital cost [19].

The cost of wind energy in cold climates can be higher than in more moderate climates. This can be due to reduced energy yield caused by icing of rotor blades and/or increased investment costs of turbines with anti- or de-icing systems and other adapted technology possibly needed in cold climate sites. Research to reduce the costs of these technologies will open more high-resource areas in cold climates to wind development.

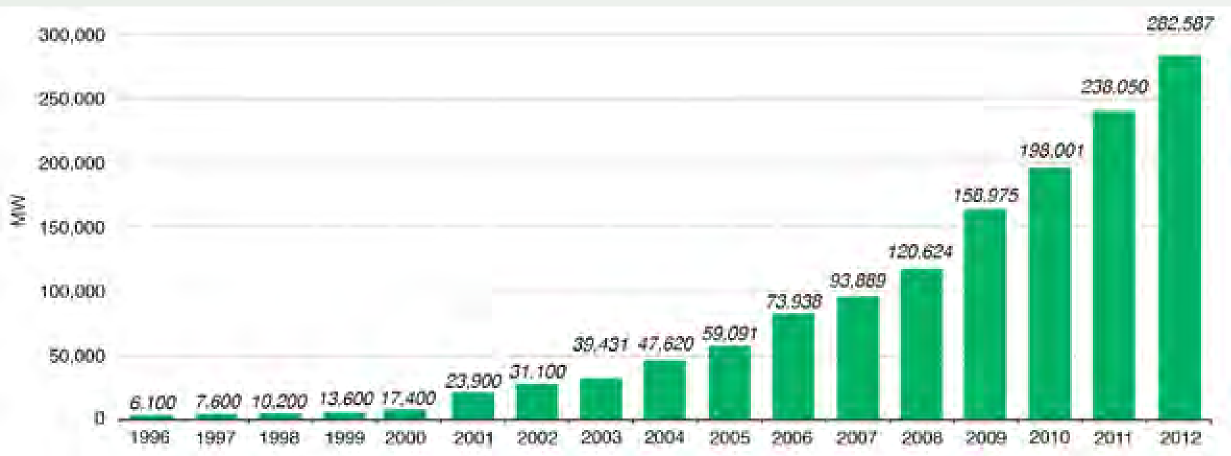

Figure 1. Global Cumulative Installed Wind Capacity 1996–2012 [15]

[5] Cold climates are areas where wind turbines are exposed to icing conditions or low temperatures outside the design limts of standard wind turbines (definition according to IEA Wind Task 19 – Wind Energy in Cold Climates).

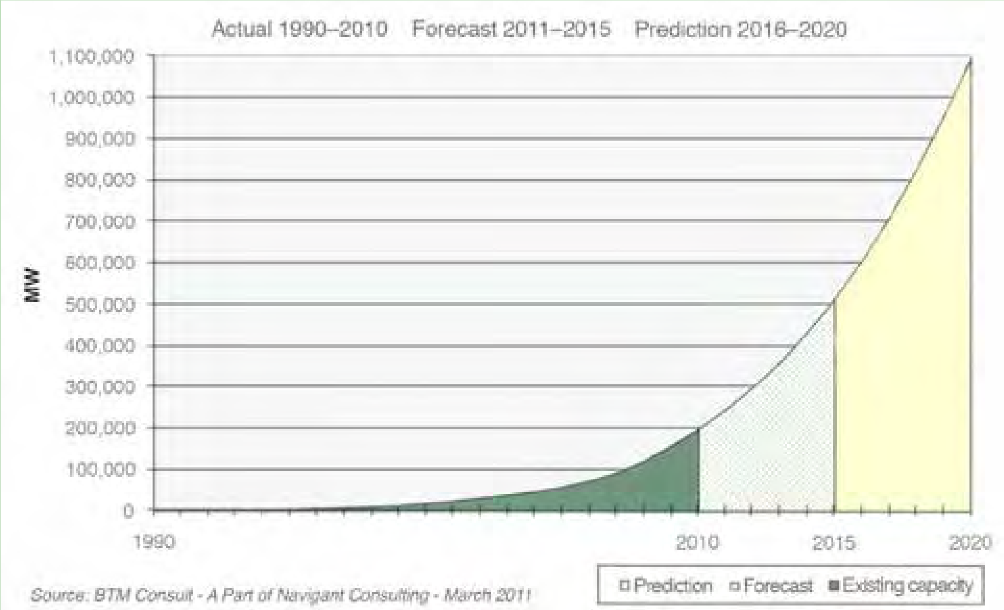

Figure 2. Prediction of Cumulative Global Wind Power Development (1990–2020) [18]

Though much progress has been made, R&D to reduce costs in the offshore wind sector remains a high priority. Along with improved performance, significant improvements will be required in cost for utility-scale offshore wind power plants in order to achieve parity with the levelised cost of energy (LCOE[6]) parity with conventional fossil fuels. The 2011 National Renewable Energy Laboratory (NREL) reference offshore wind project shows an LCOE of 225 USD/MWh (173 EUR/MWh). Additionally, Bloomberg New Energy Finance recently calculated that the LCOE for offshore wind projects financed in 2012 and Q1 2013 remains at 209.8 USD/MWh (161 EUR/MWh). BNEF forecasts LCOE of 166.8 USD/MWh (128 EUR/MWh) by 2020.

Technology R&D efforts should follow an integrated systems approach, encompassing the entire wind power plant, as no single component or subsystem improvement will achieve the necessary LCOE reductions. R&D contributions related to resource characterisation, next generation technology, grid integration, and social acceptance will all act to improve access to better wind resources, thereby reducing the LCOE.

The main reason for the recent increases in project costs has been the rapidly rising cost of commodities in general, and

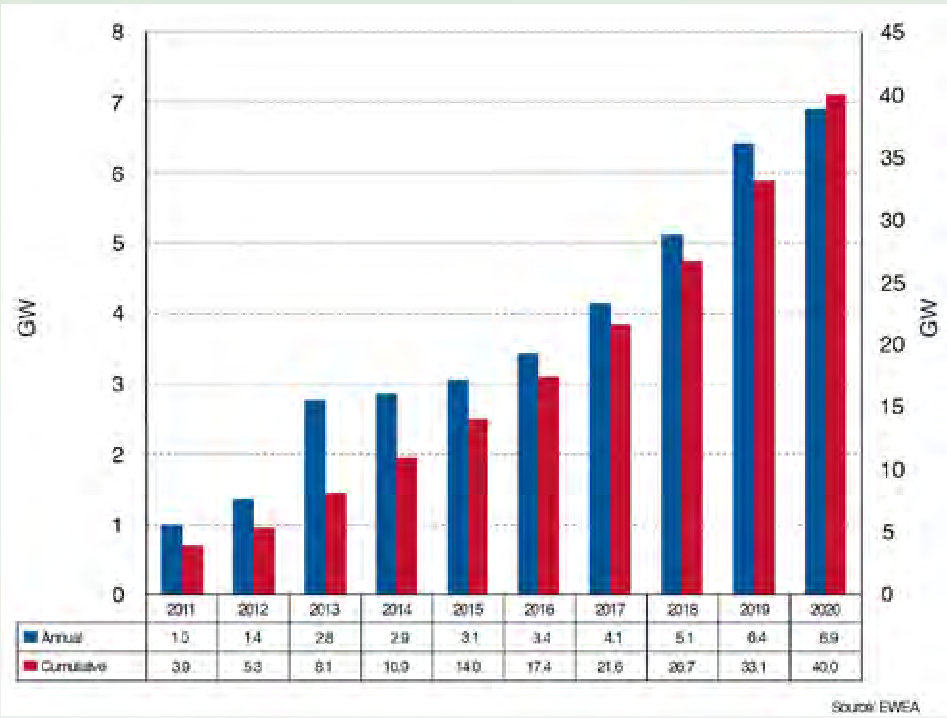

Figure 3. Predictions of Offshore Wind Annual and Cumulative Installations in Europe (2011–2020) [6]

[6] LCOE is defined as: LCOE = present value of total costs ($)/ lifetime energy production (megawatt–hours)

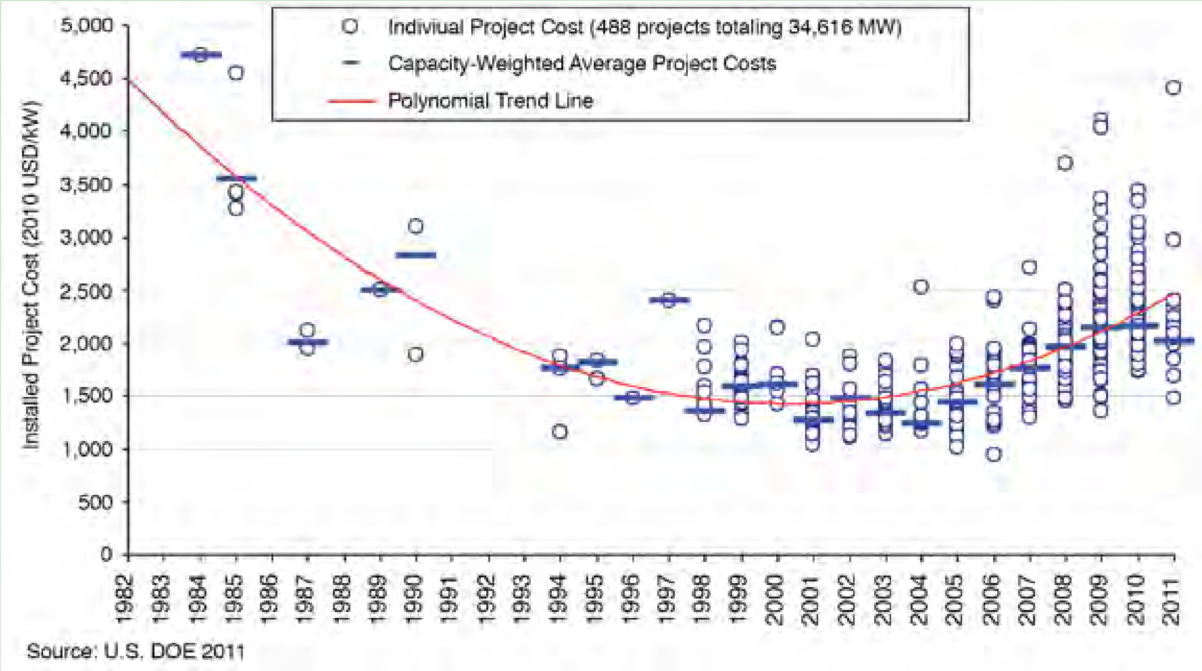

Figure 4. Evolution of Installed Wind Project Capital Costs (1982–2011) [19]

steel and copper prices in particular. Also the increase of wind turbine size and the new offshore developments is raising the average installed project cost. However, recent studies foresee a reduction in the capital cost for offshore wind [19]. This trend can already be seen in Figure 5 for year 2011 and has been reported as on-going for year 2012. According to some assessments, the cost of offshore wind power plants in 2012 varied from 3.4–4.0 million EUR/MW (4.3–5.0 million USD/MW) [21]. Reasons for the increase in offshore project costs include installing in deeper waters, using larger turbines, and competing with increasing demand from installations on land.

In the United States, the installed cost of a small wind turbine ranged from 3,000–6,000 USD/kW (2,307–4,604 EUR/kW) in 2011. In contrast, the installed cost of a small wind turbine in China averaged approximately 1,600 USD/kW (1,230 EUR/kW) in 2011. Cost remains the most influential factor in the dissemination of small wind turbines. Policies and economic incentives have more effect on grid-tied systems than on off-grid systems [15].

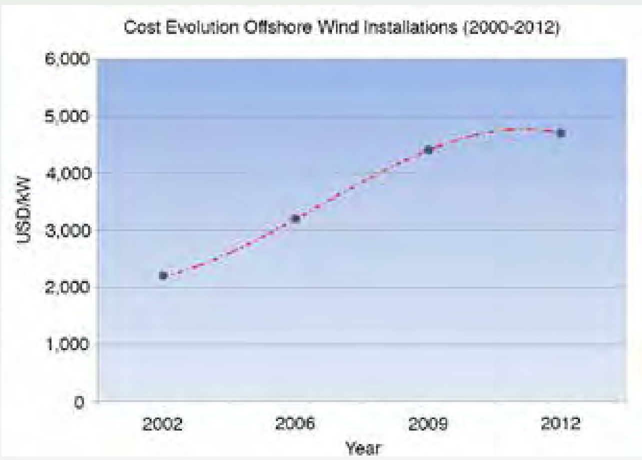

Figure 5. Total Cost of Offshore Wind Installations [21]

1.4 Reducing Costs through R&D

The markets for land-based and offshore wind are both growing and can benefit from targeted R&D to reduce costs. Installed capacity for land-based wind power consists of many subcategories of weather conditions and site topologies. When wind power is installed in mountains, for example, weather conditions can be demanding. Demanding weather conditions include cold climates (low temperatures and/or icing conditions), hot climates (deserts, tropic), high humidity and salt exposure, and climates with extremely high wind speeds, such as typhoons. These special conditions are worth noting, especially when analysing differences in cost of energy figures, because turbines installed in those areas typically require more expensive technology than turbines installed to areas with moderate climate or flat terrain.

Research conducted in IEA Wind Task 26 Cost of Wind Energy has examined the impacts of R&D on the cost of wind turbine components. Table 2 summarises opportunities envisioned to apply to land-based wind energy projects, based on engineering studies and expert elicitation. Much of the opportunity to drive down costs is perceived to be in the design and performance of wind turbines. O&M strategies and manufacturing efficiencies are also anticipated to help reduce the cost of wind energy [19]. Many fundamental elements of wind turbine innovations are directed at reducing loads. They include advanced control systems to assist in shedding loads, advanced condition monitoring to minimise major component failures and unplanned turbine downtime, and forward-looking resource evaluation (i.e., seeing the wind that

Table 2. Potential Sources of Future Wind Energy Cost Reductions [23]		
R&D/LEARNING AREA	**POTENTIAL CHANGES**	**EXPECTED IMPACT**
Drivetrain Technology	Advanced drivetrain designs, reduced loads via improved controls, and condition monitoring (Bywaters et al. 2005)	Enhanced drivetrain reliability and reduced drivetrain costs
Manufacturing Efficiency	Higher production volumes, increased automation (Cohen et al. 2008), and onsite production facilities	Enhanced economies of scale, reduced logistics costs, and increased component consistency (allowing tighter design standards and reduced weights)
O&M Strategy	Enhanced condition monitoring technology and design-specific improvements and improved operations strategies (Wiggelinkhuisen et al. 2008)	Real-time condition monitoring of turbine operating characteristics, increased availability, and more efficient O&M planning
Power Electronics / Power Conversion	Enhanced frequency and voltage control, fault ride-through capacity, and broader operative ranges (UpWind 2011)	Improved wind power plants power quality and grid service capacity, reduced power electronics costs, and improved turbine reliability
Resource Assessment	Turbine-mounted real-time assessment (e.g., LIDAR) linked to advanced controls systems, enhanced array impacts modelling, and turbine siting capacity (UpWind 2011)	Increased energy capture while reducing fatigue loads, allowing for slimmer design margins and reduced component masses; increased wind power plant performance
Rotor Concepts	Larger rotors with reduced turbine loads allowed by advanced controls (Malcolm and Hansen 2002) and application of light-weight advanced materials	Increased energy capture with higher reliability and less rotor mass; reduced costs in other turbine support structures
Tower Concepts	Taller towers facilitated by use of new design architectures and advanced materials (Cohen et al. 2008, LaNier 2005, Malcolm 2004)	Reduced costs to access stronger, less turbulent winds at higher above-ground levels
Anti- and de-icing Technologies	Adaptive heating and temperature control of large areas in flexible blades. Retrofitted blade heating systems. Efficient and wear resistant anti-icing coatings.	Reduced cost of energy due to reduced cost of anti- and de-icing systems and improved energy yield in cold climates.

is approaching the turbine) in order to better position turbines to maximise/optimise production and/or minimise loads.

In the next term of IEA Wind, Task 26 participants will also explore the cost drivers and experience for offshore wind power plants.

2 Objectives of Future R&D

To date, the global research community has reduced wind turbine LCOE by analysing wind energy systems and targeting R&D at specific opportunities to improve cost and performance. This research has resulted in larger wind turbines, enhanced energy capture, improved component performance, and reduced O&M costs. Several nations have already achieved high penetration of wind into their electrical grids, and many others would like to continue moving in this direction.

Significant opportunities remain to reduce wind power plant LCOE and increase the deployment of wind energy. Exploiting these opportunities will require multi-year research programs involving research institutions from many countries. With this in mind, it is prudent to expand the R&D focus to also study how the wind power plant system performs as a whole, and to optimise the performance and cost associated with operation.

The primary drivers of cost for wind power plants are as follows:

- Annual energy capture of the wind power plant
- Costs of the individual wind turbines
- Operational costs associated with utility-scale wind power plants (operational forecasts, O&M costs, and grid integration costs).

Wind R&D programs can serve the global wind industry well by prioritising their R&D investments in-line with these primary LCOE drivers and any non-technical market barriers that may be constraining deployment.

Market-driven up-scaling (increasing the size and output) of wind turbines, widespread deployment on land, and increasing use of offshore applications have introduced issues involving the resource, design, operation, integration, and social and environmental impacts that researchers must solve for the pace of development to continue.

Significant cost reductions are possible with R&D in these strategic areas. Four general research topics and their associated detailed research needs are identified in the following text and tables. This research agenda should be pursued by the international wind community to accelerate the implementation of wind energy worldwide.

1. Characterise the wind resource
2. Develop next generation technology
3. Improve grid integration
4. Address social, environmental, and educational issues

Table 3 lists general research topics addressed by the experts during development of this document. Tables 4–7 lay out the detailed research needs and approaches.

3 Research Needs for Wind Energy Development

The following tables address four strategic research topics and present detailed R&D needs. Research needs have been distilled from nearly 100 specific suggestions of the IEA Wind ExCo members, the TEM participants, and the ad hoc group that included current operating agents of IEA Wind research tasks. Each table addresses one of four general research areas: 1: Wind Characteristics, 2: Wind Power Technology, 3: Grid Integration, and 4: Social Acceptance, Environmental Impacts, and Educational Issues. Detailed R&D needs that apply specifically to utility markets, offshore markets, and small (small- and medium-sized wind turbines) markets are called out directly in this section in individual tables.

Addressing these research topics will provide incremental improvements as well as explore revolutionary concepts to further improve wind turbine technology. For planning purposes, the time frame for research results to be obtained is divided into three time frames: Short-term (0–5 years), Mid-term (5–10 years), and Long-term (10–20 years).

Table 3. General Research Topics to be addressed
Wind Characteristics
Resource assessment and siting
Design conditions
Short-term forecasting
Next Generation Wind Power Technology
System design
Advanced controls
Advanced rotors
Advanced drivetrains & power electronics
Support structure design
Manufacturing and installation
Reliability
Grid Integration
Transmission planning and development
Power system operation
Wind power plant internal grid
Mitigate Market Barriers
Social acceptance
Environmental impacts
Educational issues

3.1 Characterise the Wind Resource

R&D activities will address wind characterisation to improve the accuracy of resource assessment for optimal siting and operation of wind power plants and turbines, understand and reduce wake array losses, and produce more accurate forecasting of performance and output. Wind characterisation has an impact on both wind cost of energy and transmission and power system flexibility. For example, allowing for improved integration into the electrical grid. See Table 4 for details on the research needs.

3.1.1 Resource Assessment and Siting

International wind atlases displaying the latest resource assessment data will contribute to good site selection and accurate estimations of project economic feasibility. Consistent methods for characterising icing conditions will be applied to increase the accuracy of production calculations.

R&D is needed to establish the reliability and accuracy of remote sensing measurements techniques (sodar[7] and lidar[8]) as compared to conventional measurements such as cup or sonic anemometers mounted on towers. Improved remote sensing technology and will be used for wind energy resource assessment and wind turbine operation. Sensors mounted on meteorological masts (met masts) can introduce large flow distortions into the data. Sensors on masts also are too expensive for resource assessment offshore and at the heights of up-scaled turbines (over 200 m) on land. Remote sensing instruments can measure the flow up to the heights of the tallest anticipated wind turbines and are significantly less expensive to use than met-masts. Remote sensing techniques that have been validated and standardised will provide cost-effective, accurate resource assessment in open or complex siting environments. For example, lidar devices mounted on wind turbines could accurately measure wind speed and direction contributing to control strategies that reduce loads and make wind turbines more efficient.

Optimised siting strategies based on validated, standard methodologies and models will help lower the LCOE from wind power plants. The built environment resource is important to understand for the placement of small wind turbines. R&D to understand turbulent flows and reduced energy will improve turbine designs and help predicting performance.

Atmospheric complex flow models and experiments linking all temporal and spatial scales will improve understanding of the wind resource and siting options. Improvements to optimise wind power plant performance will lead to improvements in short-term and day ahead wind forecasts, better wind power plant layouts and siting to reduce wake and climatological effects, reduce maintenance costs associated with wakes, higher performance of the wind plant in totality and reduced uncertainty and risk for bankable industry investments.

[7] Sonic Detection And Ranging (sodar)
[8] Light Detection And Ranging (lidar)

Table 4. Wind Characteristics Research Needs

Detailed Research Topics	Market	Time Frame
Resource Assessment and Siting		
International Wind Atlases Develop publicly accessible database of land-based and offshore wind resources and conditions; improve the accuracy of wind resource estimates.	All	2017 Short-term
Icing Conditions Consistent method(s) for characterisation of icing conditions during resource assessment	Utility	2017 Short-term
Remote Sensing Techniques High spatial resolution sensing technology and techniques for use in high-fidelity experiments, both in the laboratory and in the field (e.g. LIDAR/SODAR/RADAR development).	Utility	2017 Short-term
Siting Optimisation Planning methodologies for siting and development of wind plants, including the development of better developer tools based on state-of-the-art models and the standardisation of micro-siting methodologies. Refine and set standards for wind resource modelling techniques.	Utility	2022 Mid-term
Built Environment Resource Assessment Improve siting tools and methodologies for building-integrated small wind turbines.	Small	2022 Mid-term
Atmospheric Complex Flow Modelling and Experimentation Develop integrated, fully coupled models linking all relevant temporal and spatial scales of the wind flow life-cycle: large-scale climatology, meso-scale meteorological processes, micro-scale terrain, and wind power plant flows. Validate these models through extensive testing and long-term data collection in offshore, coastal, inland, and complex terrain conditions.	Utility	2030 Long-term
Design Conditions		
Wind Power Plant Complex Flow Modelling and Experimentation Develop integrated, fully coupled models linking all relevant temporal and spatial scales of wind plant aerodynamics: inflow conditions, wake creation and ingestion, blade aerodynamics, blade tip compressibility, and other intra-plant flows. Extensive experimentation is required to validate these models, including laboratory-scale tests, wind tunnel tests, full-scale multi-MW wind turbine tests, and operational wind plant tests. Experiments must include multiple terrain types, both on- and off-shore.	Utility	2022 Mid-term
Marine Environment Design Conditions Measurement, modelling, characterisation and design case development for the complex interactions among wind, waves, turbulence and current. This includes handling of extreme conditions such as typhoons and icing.	Offshore	2030 Long-term
Short Term Forecasting		
Wind Forecasts Meteorological wind forecasts, with a feed-back loop from wind power plant on-line data to weather forecasting.	Utility	2022 Mid-term
Power Production Forecasts Accurate power forecasts for use in power system operation, with consideration of storm and icing forecasts.	Utility	2022 Mid-term

3.1.2 Design Conditions

Wind power plant complex flow modelling and experimentation contributes to understanding the complex multi-scale aerodynamics involved with modern wind power plants. This area of R&D is extremely important for future innovation to reduce LCOE. Improved methods for predicting 3-D aerodynamic behaviour and aeroelastic stability are essential for calculation of loads on turbines. Integrated numerical design tools are required to account for the complex operating environment of wind turbines installed offshore, especially in deep waters. Design tools must account for the wind and sea environment, hydrodynamic and aerodynamic loads, structural dynamics and elasticity, generator behaviour, and automated control systems. Design elements to be considered include upwind and downwind rotors, mechanical and hydraulic transmissions, gearboxes, generators, towers and support structures, floats, and anchoring systems. R&D to develop and validate these tools is a high priority for offshore wind development.

Marine environment design conditions must be measured, modelled, and characterised to develop design cases for offshore wind. Accurate characterisation of the offshore resources using the state-of-the-art methodologies and equipment is very costly, so development of new systems and procedures will advance development of the offshore wind market.

3.1.3 Short-Term Forecasting

Better wind resource characterisation also leads to improved wind forecasting. Reliable predictions of power output on different time scales increase the value of wind energy. R&D to improve existing forecasting and power production models, including better modelling of different weather conditions, will reduce wind power plant performance uncertainty.

3.2 Develop Next Generation Wind Power Technology

Technology R&D activities will explore system design and advanced controls at the turbine and wind power plant levels, for both land-based and offshore wind, to reduce maintenance costs and increase production. Activities will assess advanced components including rotors, drivetrains, power electronics, support structures, manufacturing and installation, and reliability and testing. Wind power technology research activities reduce the LCOE from wind through innovations in components and structures that result in reduced cost or improved energy capture. Technology research can also impact social acceptance. For example, innovations that reduce turbine noise, or floating offshore wind turbines that are out of the view from shorelines are technology developments that improve acceptance of wind deployment.

3.2.1 System Design

Systems engineering, an integrated design approach, will be used to optimise wind power plants both through improvements to turbine technology and through design and operation of multi-turbine wind power plants. With the increasing

Table 5. Wind Power Technology Research Needs

Detailed Research Topics	Market	Time Frame
System Design		
Systems Engineering Systems engineering provides an integrated approach to optimising the design of wind power plants from both a performance and cost optimisation perspective.	Utility	2022 Mid-term
Wind Turbine Scaling Improve understanding of design requirements for turbines in the 10-20 MW range, and develop offshore reference designs.	Offshore	2022 Mid-term
Wind Turbine Design Tools Improve full computational fluid dynamics (CFD)-structure interaction tools, aerodynamic engineering methods, hydrodynamic linking capabilities, and overall model accuracy and performance of land-based and offshore wind turbines and their components. Include integrated numerical design tools system dynamics models for offshore wind plants in deep water.	Utility	2022 Mid-term
Distributed Wind Systems Optimise system designs for community scale projects such as wind-diesel systems and the built-environment. Develop procedures and design tools for building integrated small wind turbines with improved performance and reliability.	Small	2022 Mid-term
Wind Turbines in Diverse Operating Conditions Improve system designs for diverse environments such as cold climates, tropical cyclones, and low wind conditions.	Utility	2022 Mid-term
Floating Offshore Wind Plants Examine diverse system architectures and novel designs that may result in cost effective deployment of floating offshore wind plants in deep waters; studies should Include industrialisation analysis and standardised load analyses.	Offshore	2030 Long-term
Innovative Turbines and Components Examine diverse system architectures and novel designs including exploration of radical design options.	All	2030 Long-term
Advanced Rotors		
Novel Rotor Architectures Explore large, flexible rotors and unique design concepts by comparing engineering codes and advanced aerodynamic models.	Utility	2022 Mid-term
Noise Reduction Technology Explore novel devices, blade design and control techniques that may allow for reduced blade noise and/or increased tip speed at existing noise levels.	Utility	2022 Mid-term
Active Blade Elements Develop load reducing technologies such as control surfaces and flexible blade technology that can facilitate active flow control systems and improve rotor control dynamics.	Utility	2030 Long-term
Advanced Blade Materials Investigate advanced materials such as carbon fibre and “smart” materials that will facilitate cost effective lighter, stiffer blades.	Utility	2030 Long-term

Table 5. Wind Power Technology Research Needs (Continued)		
Detailed Research Topics	**Market**	**Time Frame**
Advanced Drivetrains and Power Electronics		
Novel Drivetrain Designs and Topologies Direct-drive other advanced designs (concerning weight, size, encapsulation and reliability); magnetic materials, and alternatives to rare earth magnets.	Utility	2022 Mid-term
Advanced Power Electronics Develop cost-effective, high efficiency power electronics and high performance power electronics materials. Innovations must also allow for improved grid support services.	Utility	2022 Mid-term
Generator Design Design and develop medium-speed, superconducting, and other advanced generator designs.	Utility	2030 Long-term
Support Structure Design		
Design Optimisation and Analysis Explore stronger, lighter structural materials, and identify potential steel replacements for towers.	Utility	2022 Mid-term
Advanced Offshore Support Structures Develop next generation concepts including floating structures, alternative bottom fixed foundation types for use in water depths up to 50 m.	Offshore	2030 Long-term
Advanced Controls		
Wind Turbine Controls Continue develop of load reducing advanced controls that incorporate advanced algorithms, lidar/sodar/radar wind measurements, and blade/rotor based sensors and technologies. Integration of these controls with active control devices must also be considered.	Utility	2022 Mid-term
Wind Power Plant Control Methods Develop novel wind power plant control methods for reducing aerodynamic losses, accounting for wakes and wake dynamics, optimising performance, and improving reliability through reduced turbine loads. Optimise the balance between performance, loading and lifetime.	Utility	2030 Long-term
Manufacturing and Installation		
Offshore Installation and Logistics Develop cost-effective installation technologies and techniques; make available sufficient purpose-designed vessels; improve installation strategies to minimise work at sea; and make available sufficient and suitably equipped large harbour space.	Offshore	2022 Mid-term
Small Wind Turbine Manufacturing Improve largescale manufacturing process for small wind turbines in order to enhance economies of scale and cost reduction.	Small	2022 Mid-term
Advanced Manufacturing Methods Investigate manufacturing cost optimisation, automation of blade manufacturing, anti-fatigue manufacturing technology of key structural components, carbon fibre blade manufacturing and possibilities of blade elements/segmented blades, localised, large-scale manufacturing for economies of scale, and the use of recyclable components.	Utility	2030 Long-term
Reliability and Testing		
Testing of Small Wind Turbines Establish testing procedures for building integrated small wind turbines and facilitate the creation of testing facilities capable of serving the small wind turbine market.	Small	2017 Short-term
Operational Data Management Develop standardised and automated wind plant financial and technical data management processes and transparent and internationally accepted data collection best practices. Include reliability characteristics such as failure rates and repair times in the data bases.	Utility	2022 Mid-term
O&M and Diagnostic Methods Optimise O&M strategies. Improve diagnostic methods for generators, converters, bearings and mechanical components, and develop predictive maintenance tools and advanced condition monitoring techniques. Analysing life-time consumption, failure mode analysis, modelling of growth of damage on cracks. Improved repairing techniques especially offshore.	Utility	2022 Mid-term
Testing Facilities and Methods Design and construct new state-of-the-art component and system testing facilities. Develop advanced methods for testing large components in the lab by simulation of the most relevant physical environmental conditions and using hardware in the loop principles.	Utility	2022 Mid-term
High Reliability System Development Develop components with increased lifetimes and that function under failure conditions. It is also important to improve reliability for electrical components (e.g. less temperature cycling) and minimise O&M for remote locations (e.g. far offshore).	Utility	2030 Long-term

size of turbines, new stability problems can occur. Solving the aeroelastic problems is a prerequisite for reliable upscaling. Improved wind turbine design tools are needed, including full CFD-structure interaction tools, aerodynamic engineering methods, and hydrodynamic linking capabilities. Integrated numerical design tools are also needed for system dynamics models for offshore wind plants in deep water. Research must develop solutions which can guarantee a high level of operational security for offshore wind energy plants. This requires efforts to develop turbine technology specific to offshore applications including sub-structures, grid connection/integration, and O&M schemes.

Improved designs of small wind turbines could expand this growing market and improve the energy contribution of these machines. In developing countries where off-grid and mini-grid applications prevail, small wind turbines with improved designs will operate more efficiently and therefore replace more diesel generation.

3.2.2 Advanced Rotors

Novel rotor architectures will improve capacity factors through new designs that operate through a wider range of wind speeds. To overcome increases in blade cost, blades must be made lighter, stiffer, and smarter (i.e., load shedding and adaptive technologies). Other rotor research topics include improved design tools, advanced aerodynamic controls, active control surfaces for blades, and advanced blade materials.

3.2.3 Advanced Drive Trains and Power Electronics

R&D is needed on advanced drive trains, innovations in power electronics, and improved generator designs to reduce the LCOE, improve production, and enhance grid support characteristics.

3.2.4 Support Structure Design

In offshore wind power plants, platforms and service vessels are a significant source of cost. R&D is needed to lower the cost of these technologies.

3.2.5 Advanced Controls

Wind turbine controls R&D will allow wind-sensing technology such as lidar and sodar to provide improved data to feed-forward control systems. Next generation control algorithms will maximise capacity factor across entire wind power plants.

3.2.6 Manufacturing and Installation

New manufacturing methods could also contribute to the reduction of wind turbine costs. In particular, automation of blade manufacturing processes, as well as the manufacturing processes of key wind turbine structural components is an important research challenge.

3.2.7 Reliability and Testing

Reliability research will lead to more reliable, less costly wind turbines and wind power plants. Predictive maintenance tools are needed to reduce O&M costs; performing informed preventive maintenance can reduce the need for corrective maintenance. At present, wind power plant O&M costs are dominated by corrective maintenance—the replacement or repair of parts that are failing. Developing tools to improve preventive maintenance strategies requires analysis of past performance and standard approaches to reporting.

Enhanced test stands and uniform test protocols for wind turbines and components could improve design validation, certification, tools validation, and R&D projects. The upscaled wind turbines with rated power over 5 MW demand facilities with the capacity to test the new large components, like blades, gearboxes, and generators. Test facilities involve significant capital costs and require experienced technicians and regular maintenance. However, once established, additional test facilities could be used by manufacturers of wind turbines and components, wind power plant operators, grid operators, and researchers and developers to reduce costs and increase reliability.

Standard test procedures have been developed for components, sub-systems, full wind turbines, and wind power plants. However, the new larger components are challenging the validity of the test procedures to determine acceptable strain of machine elements and groups of components. Developing new testing procedures, mainly in the sector of components fatigue testing, was identified as a high priority to reduce cost and increase reliability.

3.3 Wind Integration

Adding wind power will bring about a variable and only partly predictable source of power generation to a power system that must balance generation and varying demand at all times. High penetration of wind power has impacts that have to be managed through proper wind power plant interconnection, integration of the generation, transmission planning, and system and market operations. As wind and other renewable energy sources continue to become a larger part of the world's energy mix, issues of cost effective integration into the electrical power system continue to gain in importance. Table 6 lists the detailed research needs assembled by the experts.

3.3.1 Transmission Planning and Development

The effect of high penetration levels, where wind becomes a dominating part of the power system, is not completely clear. Future integration studies should take into account the foreseen high penetration of photovoltaics and ocean power. In many regions these combinations may help smooth the variability of individual technologies.

Development of tools for modelling and controlling energy supply to the electric grid will be essential to large-scale deployment of wind energy, especially in areas where the share of wind energy is high. Transmission planning in larger areas (interconnection wide) and future meshed offshore grids connecting different market regions are important topics, including development of HVDC grids. Developing flexibility of all power system parts, from generation technologies to

Table 6. Wind Integration Research Needs

Detailed Research Topics	Market	Time Frame
Transmission Planning and Development		
Transmission Planning Develop interconnection-wide transmission infrastructure plans in concert with power plant deployment plans. Develop and implement plans for continental-scale transmission overlays to link regional power markets under high wind penetration scenarios. Also investigate the potential for high voltage direct current (HVDC) transmission.	Utility	2022 Mid-term
Offshore Transmission Planning Progress and implement plans for offshore grids, linking offshore wind resources and bordering power markets. Develop tools for offshore electric design, transnational offshore grid design, and offshore wind plant power management.	Offshore	2022 Mid-term
Power System Operation		
Electricity Markets Advance strategies for high-penetration levels of wind; improve operational methods and electricity market rules; accelerate development of larger-scale, faster and deeper trading of electricity through evolved power markets; and enable wind power plants bidding for ancillary services.	Utility	2017 Short-term
Grid Codes and Support Capabilities Harmonise grid code requirements, improve compliance testing, and conduct code testing (e.g. via voltage source convertor).	Utility	2017 Short-term
Power System Studies Conduct power system studies for scenarios involving high penetration of wind and other variable renewables, both in larger footprints and in smaller systems. Include studies addressing electric vehicle integration, demand side flexibility, enhanced flexibility from conventional generation units, and storage. Incentivise timely development of additional flexible reserves, innovative demand-side response and storage integration.	All	2022 Mid-term
Distributed Wind on the Grid Investigate micro generation in urban and inhabited areas, low cost and reliable SCADA's for small wind turbine smart grid integration, and the impacts of integrating small wind systems onto the grid.	Small	2022 Mid-term
Grid Operational Tools Develop new computing architecture for real-time information from increasing amounts of renewable generators and advance probabilistic planning tools and information and communication technology (ICT). Study system operation when reaching non-synchronous system, close to 100% from asynchronous generation.	Utility	2030 Long-term
Smart Grid Architecture Research smart grid architectures for renewable and distributed power generation, transmission and distribution. Also conduct modelling, implementation and experimental testing of virtual wind power plants.	Utility	2030 Long-term
Wind Power Plant Internal Grid		
Wind Power Plant Grid Control Improve voltage control and frequency control systems that can monitor and predict of voltage dips.	Utility	2017 Short-term
Design Tools for Offshore Wind Power Plant Electrical Design Develop tools for offshore grid and wind power plant electric design; optimise grid design within offshore wind power plants; and examine direct current grids for offshore plants.	Offshore	2017 Short-term

demand side options, and operational practices that incentivise the use of all flexibility is important when managing increased variability and uncertainty. Electricity storage technologies may also bring solutions for the future even if their cost effectiveness is still low compared to other forms of flexibility.

3.3.2 Power System Operation

Adding wind power will bring about a variable and only partly predictable source of power generation to a power system that must balance generation and varying demand at all times. High penetration of wind power has impacts that have to be managed through proper wind power plant interconnection, integration of the generation, transmission planning, and system and market operations.

Research is needed on power system operation and grid integration of high amounts of wind generation. R&D activities should publish information on power system operation with wind to enhance transmission planning and development; improve power system operation; and improve the internal grid within wind plants. As grid operations and wind integration processes and procedures become more defined, the costs associated with wind integration are expected to be reduced.

3.3.3 Wind Power Plant Internal Grid

R&D is needed to optimise the connections among wind turbines within a wind power plant both on land and offshore. Technology and techniques are needed to anticipate and control voltage and frequency.

3.4 Increase the Social Acceptance of Wind Energy

Research related to social, environmental, and educational issues guides the regulatory and permitting process, enabling authorities to make well-informed decisions regarding wind deployment. Repowering, offshore deployment, expansion of the grid, and larger turbines will provoke new debates that need to be understood. Sharing information on new approaches will be helpful [17]. Table 7 lists the research needs to make progress on social, environmental, and educational issues.

3.4.1 Social Acceptance

Research is needed on issues that affect wind siting, acceptance, and maximisation of social benefit. R&D should explore practices affecting social acceptance, the cost of wind energy, and the environmental impacts. Results should help manage the impacts of wind development and help direct research investments. As knowledge is shared with regard to these issues, the licensing and permitting process can become more streamlined and timely, reducing the pre-construction licensing costs imposed on wind developers. Also understanding social issues and the elements of wind energy costs will help guide investment funds in all research categories.

Issues that would benefit from further international and interdisciplinary discussion include:

- Assess projects in a comprehensive way by taking into account all aspects ranging from the concerns of the host communities to the distribution of costs and benefits as well as the legislative framework and decision making. Accelerate and simplify the building permission process.
- Further knowledge on the impacts of wind power plants on the quality of life, for example concerning noise and sound, long-term exposure, impacts on sleep physiology or the efficacy of setbacks. Better understanding is needed on the influence of mass media and social media on social acceptance. Discussion is also needed of models and methods to monitor and assess social acceptance.

3.4.2 Environmental Impacts

Interaction between wind turbines and wildlife must be incorporated in the deployment process. This requires better understanding of background data and the behaviour of different species. This holds for both onshore and offshore application. In particular environmental peculiarities in offshore can be very different in different regions. Data and information must be collected and shared for the most promising onshore and offshore areas for wind energy deployment.

Recycling wind turbine components will reduce adverse effects of decommissioning wind turbines after end of service life and enhance the environmental benefit of wind energy. About 80% of a wind turbine system (including cabling) can be recycled. Recycled materials can be used successfully in other products. Current blade technology, however, presents challenges. A study performed at Technical University of Denmark in 2007, predicted that beginning in 2040, 380,000 metric tonnes of fibre composites will have to be disposed of each year.

Table 7. Wind Social, Environmental, and Educational Research Needs

Detailed Research Topics	Market	Time Frame
Social, Educational, and Environmental Issues		
Social Acceptance		
Spatial Planning Methods and Tools Develop methods and tools for spatial planning to meet economic, social and environmental objectives, all with the objective of ensuring social acceptance.	All	2017 Short-term
Cost Drivers of Wind Energy Develop accepted methods to calculate the cost of wind energy and identify the cost driving components for research investments.	Utility	2017 Short-term
Human Use Effects and Mitigation Generate insight into human-use conflicts (e.g., radar, view shed, noise, property values) that will allow decision-makers and communities to site projects in such a way as to maximise socioeconomic benefit and minimise conflicts with other users.	All	2022 Mid-term
Environmental Impacts		
Recycling and End of Life Planning Conduct policy studies and develop strategies for wind turbine end of life and recycling procedures and best practices.	All	2017 Short-term
Environmental Strategies and Planning Institute a coordinated strategy to gather, analyse, and publicly disseminate environmental data, modelling tools, and related technologies. This will allow the industry to better understand and mitigate potential environmental impacts of land-based and offshore wind power development.	Utility	2022 Mid-term
Issue Mitigation for Marine Environments Assess impacts of offshore project installation and operation, validate models that can be used to predict the impact of future projects, and develop a suite of instrumentation and techniques that can be used by future projects to measure and mitigate, where necessary, environmental impacts.	Utility	2030 Long-term
Educational Issues		
Workforce Education Increase the supply of educated personnel, considering all levels of education, targeting specific actions to increase opportunities for education, and exploring the potential of long distance education solutions.	All	2022 Mid-term

Research into environmentally benign disposal of blade composite materials is needed to develop new methods for more efficient burning or pyrolysis. Also research in new blade materials made from natural fibres (flax) and other new materials should be carried out to avoid issues at the end of service life. The logistics of decommissioning can be improved through R&D to establish a system for collection and reuse of materials. An improved system could include national or regional incentives to promote recycling. These could be similar to the EU waste directive and systems in other industries (automotive, tires, and electronic equipment) where the manufacturers must reclaim worn-out products.

The environmental advantages of wind energy, such as reduced emissions of CO_2 and other greenhouse gases must be conveyed to the public. Public attitudes towards wind energy, as well as the influence from visual impact and interacting use of the landscape by different interest groups, have to be incorporated in the process of deployment.

Understanding of sound generation and transportation over large distances is essential to improving technology and siting strategies. Challenges offshore are related to the acoustically hard water surface. Initial estimations that wind turbines may emit more sound offshore without disturbing onshore dwellings must be studied. Better knowledge and methods for design and prediction of sound must be validated to actual experiences. Attention should to be given to the fact that offshore construction and operational activities are accompanied by sound emissions to the marine environment. R&D is needed to minimise any negative effects of such acoustical influences.

3.4.3 Educational Issues

As deployment of wind power plants accelerates, even more educated personnel will be needed for all aspects of wind energy. Graduate students benefit from active research projects, experts from related fields benefit from interdisciplinary Topical Experts meetings and conferences, new majors at academic and technical institutions attract talented young people into the wind energy field.

4 Conclusions

Significant cost reductions are possible with R&D in the strategic areas of wind characteristics, wind power technology, wind integration, and social, environmental and educational issues. R&D should characterise the wind resource to support reliable and cost-optimised technology. R&D should develop

Table 8. Research Tasks Continuing into the Next Term (2014–2019)

Task No.	Task Name and Operating Agent (OA)	Duration[9]
11	Base Technology Information Exchange OA: Vattenfall, Sweden (1987–2008) changed to CENER, Spain	2009–2012; 2013–2014
19	Wind Energy In Cold Climates OA: Technical Research Centre of Finland (VTT), Finland	2001–2011; 2012–2015
25	Power Systems With Large Amounts of Wind Power OA: VTT, Finland	2005–2011; 2012–2014
26	Cost of Wind Energy OA: National Renewable Energy Lab (NREL), United States	2008-2011; 2013-2016
27	Small Wind Turbine Labels for Consumers/ Small Wind Turbines in Turbulent Environments OA: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain	2008–2011; 2012–2015
28	Social Acceptance of Wind Energy Projects OA: ENCO Energie-Consulting AG, Switzerland	2007–2011; 2012–2014
29	MexNex(T): Analysis of Wind Tunnel Measurements and Improvement of Aerodynamic Models/ MexNext II OA: ECN, the Netherlands	2008–2011; 2012–2014
30	OC3/OC4: Offshore Code Comparison Collaborative (Continuation); OA: NREL, the United States and Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Germany	2010–2013
31	WAKEBENCH: Benchmarking of Wind Farm Flow Models OA: CENER, Spain, and NREL, United States	2011–2013
32	LIDAR: Wind Lidar Systems for Wind Energy Deployment OA: ForWind Centre for Wind Energy Research, Germany	2011–2014
33	Reliability Data: Standardising Data Collection for Wind Turbine Reliability and Operation and Maintenance Analyses OA: Fraunhofer IWES, Germany	2012–2014
34	Environmental Assessment and Monitoring for Wind Energy Systems OA: NREL, United States	2013–2016
35	Full-Size Ground Testing of Wind Turbines and Components OA: Rheinisch Westfälische Technische Hochschule (RWTH) Aachen University, Germany	2013–2016

[9] Extension of these tasks beyond the listed terms is very likely. The task participants will evaluate the benefits of continued co-operation to address the priority areas of the Strategic Plan.

wind turbine technology for future applications such as large, highly reliable machines for offshore applications in shallow or deep waters. R&D should develop technology that facilitates the integration of this variable energy source into energy systems. R&D should improve existing methods to forecast electricity production from wind energy systems and to control wind power plants for optimal production and distribution of electricity. And R&D should address challenges related to implementation uncertainties such as physical planning to optimise land use and minimise negative effects to people and nature. The overall aim of future research is to support development of cost-effective wind turbine systems that can be connected to an optimised and efficient grid or be used as nongrid-connected turbines.

The issues identified for long- term R&D are mainly basic research topics, adding intelligence to the complete wind sector. According to the experts, major R&D issues with results expected in the long-term time frame are:

- Aerodynamic experiments on model wind turbines in large wind tunnels and on a full-scale multi-MW wind turbines at test sites
- Terrain and rotor flow interaction and topology optimisation for siting wind power plants with respect to loads, power, and cost
- Standardisation of micro-sitting methodologies based on state-of-the-art models and measurement techniques
- New and cost-effective materials for wind energy systems; smart materials and structures
- Minimisation of environmental impact and securing social acceptance; offshore-specific environmental impact studies

The IEA Wind agreement has 13 active research tasks addressing some of the needs identified in this document (Table 8). The Appendix lists more details about those tasks and the approaches that will be used to advance technology evolution, technology deployment, and market facilitation.

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Appendix: Research Activities of IEA Wind

The IEA Wind agreement of the International Energy Agency has been active in wind energy research since 1977. During the next 5-year term (through 2019) the work will be guided by its Strategic Plan contained in the document End-of-Term Report 2009–2013 and Strategic Plan 2014–2019. For research planners, material relevant to this research needs document has been extracted from that IEA Wind Strategic Plan.

I Technology Evolution

As described in the IEA Wind Strategic Plan, the following IEA Wind research tasks will contribute to technology evolution topics identified for the next term.

Task 11 Base Technology Information Exchange

Task 11 promotes wind turbine technology and deployment through Topical Expert Meetings for information exchange on R&D topics selected by the ExCo. During the upcoming term approximately four Topical Expert Meetings will be held each year (20 for the term). These meetings will address topics coming out of research tasks as well as research topics identified in this strategic plan that are not yet addressed in research tasks.

Task 19 Wind Energy in Cold Climates

In the coming term, participants in this task will support a market study for wind energy in cold climates. This work will demonstrate the demand for improved technology. The participants will update the Recommended Practices and State-of-the-Art report to include the latest research results. They will work to compare icing forecast and mapping methods, include cold climate issues as part of certification and design processes, develop ice sensor classification, improve knowledge of safety related issues (ice throw, ice induced noise, etc.), and improve knowledge of ice loads on offshore foundations.

Task 27 Small Wind Turbines in Turbulent Sites

Task 27 participants will develop a Small Wind Turbine Association of Testers and conduct research to evaluate wind characteristics in areas of high turbulence (rooftops, complex terrain, etc.) and effects on small turbine performance. The work will support development of a Recommended Practice on micro-siting and predicting energy production of small turbines in highly turbulent sites (urban or suburban, rooftop, forested, etc.). The work will provide data and results along with guidance for a new design classification with specific guidance on I15 or similar variables for IEC 61400-2 and new information on external conditions i.e. the normal turbulence model and extreme direction change found in Section 6 of 61400-2. In addition, the participants will compare existing power performance test results (typically from accredited power performance test organisations) to power performance results taken in highly turbulent sites. These results will contribute to design and deployment of small wind turbines in appropriate environments for durability and good energy production.

Task 29 MexNext II Validating Aerodynamic Models

Task 29 participants have established an aerodynamic research consortium (including Suzlon Blade Technology, Vestas, Enercon, WindNovation, Garrad Hassan and Partners) that will evaluate detailed aerodynamic measurements (from wind tunnel experiments and field operations) to validate and improve aerodynamic models, including: free vortex wake models, computational fluid dynamics blade flow and near wake flow, yawed flow models, dynamic inflow models, instationary airfoil aerodynamics, general inflow modelling (non-uniformity between blades), and 3-dimentional models (including tip effects). “Lost data” from experiments or tests that have never been analysed will be explored in the next two years of the project for added insights to aerodynamic models. In addition, the “Mexico” scale test turbine will be used by the European Strategic Wind tunnels Improved Research Potential project to provide data to Task 29 and others. These results will benefit wind turbine designers by improving or increasing confidence in aerodynamic models.

Task 30 Offshore Code Comparison for Foundations

Task 30 participants have been comparing and verifying computer codes (more than 22) for coupled dynamic analysis of offshore wind turbine support structures (monopile, tripod, floating spar buoy, jacket, and semisubmersible). The group is preparing an extension proposal to build on its completed work over the next three years. It is expected to improve the design of offshore wind turbines, including support structures thanks to verified and improved codes for jacket and semisubmersible substructures.

Task 31 Benchmarking Wind Farm Flow Models

Task 31 participants will improve atmospheric boundary layer and wind turbine wake models for use in wind energy by benchmarking different wind and wake modelling techniques. The large number of participants will ensure comprehensive work to identify and quantify best practices for using these models under a range of conditions, both land-based and offshore, from flat to very complex terrain. The work will define quality-checked procedures for the simulation of wind and wakes. This information will be useful to wind turbine designers as well as for applications in siting of wind power plants.

Task 35 Full-Size, Ground-Testing of Wind Turbines and Components

Task 35, approved in 2013, will address the lack of uniform procedures for ground testing. The first two subtasks will document and develop recommendations for test procedures of wind turbine blades and drive trains. The output of this task should increase the comparability of ground test results, improve confidence in tests of wind turbine durability, and develop technical requirements that will be recognised internationally by standards and certification organisations.

II Technology Deployment and Market Facilitation

As described in the IEA Wind Strategic Plan, the following IEA Wind activities will advance technology deployment.

Task 11 Base Technology Information Exchange

Task 11 gathers experts to present the latest results on narrow topics and discuss solutions in a small group setting.

Invited experts from many countries and organisations share information and work to develop recommended practices for wind energy activities. As an important instrument of IEA Wind, the Task 11 Topical Expert Meetings begin conversations about new technical and scientific developments and information needs. Task 11 is also an important catalyst for starting new IEA Wind research tasks.

Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power

Task 25 has been active since 2006 addressing issues of power systems and wind energy. The overall goal is to provide information to facilitate the highest economically feasible wind energy penetration within electricity power systems worldwide. The participants support this goal by analysing and further developing the methodology to assess the impact of wind power on power systems. IEA Wind Recommended Practice 16: Wind Integration Studies (in review) includes guidelines on the recommended methodologies for estimating the system impacts and the costs of wind power integration. The task will also formulate best practice recommendations on system operation practices and planning methodologies for high wind penetration.

Task 26 Cost of Wind Energy

Task 26 has been working since 2009 to provide understanding of the past, present, and future costs of wind energy using transparent methodology. The participants have established an international forum for exchange of knowledge and information related to the cost of wind energy. It will identify the major drivers of wind energy costs (e.g., capital investment, installation, operation and maintenance, replacement, insurance, finance, and development costs) and quantify the differences of these cost elements among participating countries. Additionally, the task will develop an IEA Wind Recommended Practice that includes an internationally accepted, transparent method for calculating the cost of wind energy. The next term will begin assessing the costs of offshore wind.

Task 27 Consumer Labelling of Small Wind Turbines

Consumer Labelling of Small Wind Turbines (Task 27 completed and extended with new technology research work plan—see above). RP 12 Consumer Label for Small Wind Turbines (2011) has been included as an appendix to the International Electrotechnical Commission (IEC) TC 88 standard on wind system testing. In 2012, the IEC compliance group began work to implement the labelling of small wind turbines applying the IEA Wind RP 12.

Task 28 Social Acceptance of Wind Energy Projects

Even where the economics of wind energy are favourable, deployment can only occur when the public and the planning authorities accept the technology. This requires an appreciation of the benefits of wind energy that weigh against any local negative impacts. The evaluation of this balance is often complicated by subjectivity and by the circulation of misinformation. This task will improve decision-makers' ability to evaluate wind projects by continuing to provide high-quality information and analysis to member governments and commercial sector leaders by addressing wind's benefits, markets, and policy instruments.

Task 32 Lidar for Wind Energy Deployment

Task 32 provides a forum for experts to exchange experience and progress on the performance of lidar devices, associated measurement techniques, and the effect of operational and site conditions for wind energy applications. Subtask 1 addresses calibration and classification of lidar devices. Subtask 2 addresses procedures for site assessment. Subtask 3 addresses procedures for turbine assessment. Expected results include differentiation of technical aspects of lidar systems compared to conventional anemometry; performance evaluation of lidar systems for resource assessment and prediction of the annual energy production, namely, wind speed, turbulence, stability, and boundary-layer characteristics in flat as well as complex terrain, and offshore; evaluation of lidar-based power curve measurement methods during simple and complex inflow conditions through benchmark studies with new lidar-based measurement techniques and conventional procedures; definition of approaches to estimate the inflow conditions related to mechanical loads of wind turbines by means of lidar systems.

Task 33 Standardising Wind Turbine Reliability Data

Task 33 will provide an open forum on wind turbine failure and maintenance statistics. Participants will exchange experience from individual research projects; develop an IEA Wind Recommended Practice for collecting and reporting reliability data; and identify research, development, and standardisation needs for collecting and reporting reliability data. The expected results include state-of-the-art reports on the following topics: (1) initiatives concerning reliability, (2) flow of maintenance information, and (3) tools for O&M planning and overview of data needs.

Task 34 Environmental Assessment and Monitoring

Task 34 will share information from completed and on-going environmental assessment and monitoring efforts on land and offshore, both pre- and post-construction, to: (1) improve monitoring approaches; (2) make data easily accessible to all interested parties; (3) aggregate information on biological species affected; (4) aggregate information on effects of mitigation strategies; and (5) identify successful approaches to monitoring impacts, analysis techniques, and assessment methodologies. The expected results include a publicly accessible database with documents on monitoring, assessing, and mitigating environmental impacts of wind energy projects land-based and offshore; a State-of the-Science report on accepted methodologies for environmental assessments for land-based projects, offshore, and, potentially, distributed technologies; and a research compendium of publicly available data on impacts.

Notes

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