Ministry of New and Renewable Energy
Government of India

NIWE (ISO 9001 Certified)

WIND TURBINE TECHNOLOGY R&D for INDIA 2020-2030

A White Paper submitted by
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I. BACKGROUND:

India's Intended Nationally Determined Contribution (INDC) aims to base 40% of the total installed power generation capacity on non-fossil fuel resources by 2030 with international support on technology transfer and financing. This includes Government of India's target of achieving 175GW of RE by the year 2022 that marks 75 years of our independence. It also aims to reduce the emissions intensity of GDP by 33 to 35 percent from 2005 levels by 2030. In addition, Hon'ble Prime Minister of India, at the recently concluded United Nations Climate Action Summit in New York, committed to increasing India's RE target to 450 GW as a part of a stronger climate action plan. Non-conventional energy received FDI inflow of US$ 9.1 billion between April 2000 and December 2019. With government's ambitious green energy targets, the sector has become quite attractive for both foreign and domestic investors. By 2028, India can see investment worth US$ 500 billion in renewable energy.

It is estimated that viable wind power potential across globe is 72 TW, which is four times more than the current World's total energy demand. India itself having wind potential, of 695 GW @ 120 m above ground level (38.4 GW is the installed capacity as on 30.11.2020) and is set to increase with increase in hub heights with modern turbines going up to 150m, which has to be tapped at faster manner to increase the green energy contribution towards meeting the various national and international targets and to mitigate the climate changes issues.

The Indian land-based wind market has historically been a focal point for many domestic wind turbine manufacturers and suppliers with an annual manufacturing capacity of around 10 GW. This strong domestic supply capacity for the on shore wind market suggests that potential also exists to supply significant portions of the future expansion in both onshore & offshore wind market domestically to serve the country's demand.

II. OBJECTIVES OF FUTURE R&D IN WIND TURBINE TECHNOLOGY

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 in amalgamation with wind industry. 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.

Wind R&D programs can serve the global/ domestic 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 use of offshore applications have introduced a number of issues in the resource mapping, design, operation, integration, social and environmental impacts that researchers need to solve for faster adoption to continue. The following four general research topics and their associated detailed research needs are discussed below, which may be pursued by the domestic wind community to accelerate the implementation of wind energy domestically & worldwide.

i. Characterise the wind resource
ii. Develop next generation technology
iii. Improve grid integration
iv. Address social and environmental issues

III. AREAS OF FOCUS FOR WIND TURBINE TECHNOLOGY R&D

1. Wind Characteristics Research Needs

1.1. Resource Assessment and Siting

Wind Atlas: Develop publicly accessible database of land-based and offshore wind resources and conditions; improve the accuracy of wind resource estimates; Development of indigenous numerical down-scaling model; Correction of Global Wind Models; Validation and bias correction for wind potential maps; Prediction of Spatial wind variation

Icing Conditions: Consistent method(s) for characterisation of icing conditions during resource assessment

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 development); Standardization of remote sensing devices

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.

Built Environment Resource Assessment: Improve siting tools and methodologies for building-integrated small wind turbines.

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.

Resource Forecasting for medium term and long term and big data analytics: Develop integrated, fully coupled models linking all relevant temporal and spatial scales for forecasting medium term and long term wind profile. Validate these models through extensive testing, atmospheric information and big data analytics in offshore, coastal, inland, and complex terrain conditions.

1.2. 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.

Marine Environment Design Conditions (Offshore): 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.

Forecasting and Power Production Forecasts: Accurate power forecasts for use in power system operation, with consideration of storm and icing forecasts; Wind Hind-casting

2. Wind Power Technology Research Needs

2.1. 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.

Wind Turbine Scaling: Improve understanding of design requirements for turbines in the 10-20 MW range, and develop offshore reference designs.

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.

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.

Wind Turbines in Diverse Operating Conditions: Improve system designs for diverse environments such as cold climates, tropical cyclones, and low wind conditions.

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.

Innovative Turbines and Components: Examine diverse system architectures and novel designs including exploration of radical design options.

2.2. Advanced Rotors

Novel Rotor Architectures: Explore large, flexible rotors and unique design concepts by comparing engineering codes and advanced aerodynamic models.

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.

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.

Advanced Blade Materials: Investigate advanced materials such as carbon fibre and “smart” materials that will facilitate cost effective lighter, stiffer blades.

2.3. 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.

Advanced Power Electronics: Develop indigenous cost-effective, high efficiency power electronics and high performance power electronics materials. Innovations must also allow for improved grid support services.

Generator Design: Design and develop medium-speed, superconducting, and other advanced generator designs.

2.4. Support Structure Design

Design Optimisation and Analysis: Explore stronger, lighter structural materials, and identify potential steel replacements for towers.

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.

2.5. Advanced Controls

Wind Turbine Controls: Continue develop of indigenous load reducing advanced controls that incorporate advanced algorithms, lidar/sodar wind measurements, and blade/rotor based sensors and technologies. Integration of these controls with active control devices must also be considered.

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.

2.6. 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.

Small Wind Turbine Manufacturing: Improve largescale manufacturing process for small wind turbines in order to enhance economies of scale and cost reduction.

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.

2.7. Reliability and Testing

Testing of 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.

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.

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.

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.

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).

3. Wind Integration Research Needs

3.1. Transmission Planning and Development

Transmission Planning: Develop interconnection-wide transmission infrastructure plans in conjunction 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.

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.

3.2. 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.

Grid Codes and Support Capabilities: Harmonise grid code requirements, improve compliance testing, and conduct code testing (e.g. via voltage source convertor).

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.

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.

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.

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.

3.3. 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

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.

4. Wind Social and Environmental Research Needs

4.1. 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.

Cost Drivers of Wind Energy: Develop accepted methods to calculate the cost of wind energy and identify the cost driving components for research investments.

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.

4.2. 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.

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

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.

IV. CONCLUSION

Significant cost reductions are possible with R&D in the strategic areas of wind characteristics, wind power technology, wind integration, and social and environmental issues. The focused area of R&D shall support

- Characterising the wind resource to support reliable and cost-optimised technology.
- In developing wind turbine technology for future applications such as large, highly reliable machines for offshore applications in shallow or deep waters.
- In developing technology that facilitates the integration of this variable energy source into energy systems.
- To improve existing methods to forecast electricity production from wind energy systems and to control wind power plants for optimal production and distribution of electricity.
- 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. The issues identified for long-term R&D are mainly basic research topics, adding intelligence to the complete wind sector (additional research areas/ list are detailed in Appendix). Accordingly, 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 turbine 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

Overall, addressing these research topics will provide incremental improvements as well as explore revolutionary concepts to further improve wind turbine technology.

Appendix

A. Aero and Fluid Dynamics

- Development and use of CFD tools
- Flows in wind farms
- Layout of wind farms in complex terrain
- Noise from wind turbines and wind farms
- Fluid-structure interaction
- Safety analysis in aerodynamics
- Aerofoil/rotor design

B. Aerofoil and Rotor Design

- Aerodynamic blade design and Smart rotor control
- Low noise aerofoils and rotors
- Aerodynamic modelling in aero-elastic tools
- Modelling and characterisation of aerofoil flows
- Blade tip design
- Noise field measurements and analysis
- Leading edge erosion and vortex generators
- Conceptual design, Low-Wind, airborne, tip-rotor
- Wind farm flows

C. Composites Analysis and Mechanics

- Composites failure analysis
- Damage evolution
- Damage modelling
- Advanced materials models
- NDT of composites
- Structural health monitoring
- New composite materials
- Leading edge erosion
- Life extension of blade
- Repair of blades
- Improved test specimens
- Coatings, Adhesives and bond lines
- Nano-composite materials

D. Composites Manufacturing and Testing

- Cure cycle design
- Leading edge erosion
- Fatigue of composites
- New materials for wind turbine blades; e.g. hybrid composites, thermoplastic composites, bio based fibres and resins
- Structural elements in wind turbine blades; e.g. sandwich, ply drops, wrinkles
- Recycling of composites
- Sustainability of materials and processes

E. GRID Integration and Energy Systems

- ❖ Variability & uncertainty of weather dependent generation for grid and energy system planning
- ❖ Power systems with high shares of converter based renewable generation
- ❖ Grid connection and offshore transmission
- ❖ Modelling, design, operation and electrical control of wind and hybrid power plants
- ❖ Wind power forecasting
- ❖ Energy system integration and balancing

F. Measurement Systems and Methods

- ❖ Development of new measurement sensors and methods
- ❖ Data acquisition systems and software
- ❖ Wind speed uncertainty
- ❖ Experimental measurements: (Wind, wind turbines, noise, in-situ blade pressure and speed, wakes and blockage)

G. Meteorology and Remote Sensing

- ❖ Doppler LIDAR's for research in wind resources, wind turbine control, wind tunnels, and flow around wind turbines and other objects
- ❖ Extraction of wind resources, flow patterns, waves, precipitation, and sea temperature offshore and land surface characteristics from satellites
- ❖ Experimental validation of theories and models of flow in the atmosphere and around wind turbines

H. Resource Assessment and Meteorology

- ❖ Development of multi-scale modelling chain
- ❖ Spatial mapping for wind climate estimation and turbine design parameters
- ❖ Air-sea interaction and wind-wave coupled modelling
- ❖ Interactions of wind, wave, wind farm
- ❖ Uncertainty assessment
- ❖ Effects of climate change on wind energy resources
- ❖ Variability and extremes.

I. Response, Aero- elasticity, Control and Hydrodynamics

- ❖ Dynamic analysis of on- and offshore turbines
- ❖ Load analysis for new turbine concepts
- ❖ Controller design for performance and load reduction
- ❖ Real time model-data assimilation for aero-elastic response
- ❖ Wind turbine loads in cold climate and icing
- ❖ Modelling, test methods and control for floating wind turbines

J. Structural Design and Testing

- Structural design, innovative manufacturing and testing of wind turbine blades
- Test, analysis and simulation of support structures and metal components
- Scanning, inspection and structural health monitoring
- Creating and using digital twins of structures and their components
- Development of advanced software tools for design, fatigue and failure prediction.

K. Structural Integrity and Loads Assessment

- Probabilistic integrated design of offshore structures including floating wind turbines, drivetrains and rotors
- Reliability based wind farm operation for decision support for maintenance, life extension, power uprating, down-rating
- Artificial Intelligence models for self-diagnostics and autonomous/semi-autonomous decision making (machine-to-machine) to enable smart turbines and farms
- Wind farm upscaling for large scale offshore wind farms including planned maintenance, supply chain prediction and re-powering
- Wind turbine configuration design and optimization for Power-2-x configurations such as Hydrogen generation and storage

L. System Engineering and Optimization

- Wind farm design optimization
- Wind farm flows, operation and control
- Hybrid power plant design and operation (including power-to-x)
- Energy community design and operation
- Multidisciplinary optimization of systems and structures
- Innovation impacts to wind energy systems

M. Society, Market & Policy

- Planning & development of wind energy projects
- Sustainable technology & science
- Wind energy markets, economics & finance
- Energy policy design
- Sustainability transitions
- Technological innovation and industry formation
- Science communication

N. Testing and Calibration

- Wind turbine test methods – loads, power, noise and power quality
- Lidar calibration methods
- Developing measurements methods (eg., including Lidars)
- Wind / inflow measurements
- Assessment of operating windfarms