



Deliverable D5.13, Technology Roadmap

Agreement n.:

308974

Duration

November 2012 – October 2017

Co-ordinator:

DTU Wind



The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7-ENERGY-2012-1-2STAGE under grant agreement No. 308974 (INNWIND.EU).

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Document information

Document Name:	Technology Roadmap with path from innovative project results towards implementation in the market
Document Number:	Deliverable D5.13 version A
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Document Type	Report
Dissemination level	PU
Review:	DTU Wind
Date:	October 2017
WP:	5
Task:	5.13
Approval:	Approved by WP Leader

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CHAPTER 1 INTRODUCTION

1.1 Background and objectives

This document is part of the INNWIND.EU integrated project. The INNWIND.EU project aims at a reduction of cost of energy generated by future large scale offshore wind turbines in deep waters. The objectives of the projects are an innovative design of a high performance offshore wind turbine and hardware demonstrators of some of the critical components. The project focuses on the development of future wind turbines with a rated power of 10 to 20 MW that can be manufactured in series production.

This document describes the technology roadmaps identifying the path of innovative design of these chosen critical components from present status to large scale integration of the project results in the future wind energy market. The technology roadmaps are made to help identify challenges and opportunities as:

- Challenges and opportunities for market entry;
- New standards and design guidelines or amendments of existing standards and guidelines facilitating the entry of innovations into the market;
- Possible amendments of design concepts mitigating the development risks and speeding up the entry into the market.

The road maps show which activities are addressed within the INNWIND.EU project and what the expected results will entail, towards large scale application and cost reduction.

1.2 Scope: the chosen major innovations of the INNWIND.EU project

In INNWIND.EU WP 5, technology roadmaps are presented for ten major innovations indicated in the Description of Work. The chosen innovative subsystems for the technology roadmaps are:

1. WP1: Advanced control with forward looking lidar
2. WP1: 10MW reference wind turbine
3. WP1: 20 MW reference wind turbine
4. WP2: Active control for smart blades
5. WP2: Passive control and structural optimisation for lightweight rotors
6. WP3: Medium temperature superconducting generators
7. WP3: High temperature superconducting generators
8. WP3: Pseudo direct drive generators
9. WP4: Low-cost bottom-mounted support structures
10. WP4: Cost effective floating support structures

The superconducting generators are separated into medium and high temperature superconducting generators.

Table 1-1 summarises the chosen innovations, stating a short description and the responsible partner within the INNWIND.EU project for each. The content for the technology roadmaps has been delivered from the mentioned work packages.

Table 1-1: Summary of the 11 chosen subsystem developments

Work Package	Subsystem innovation ¹	Description	Responsible partner
WP1: “Conceptual Design”	Advanced control with forward looking lidar	Hardware Demonstration of Spinner Lidar: Upwind full 2D rotor plane inflow measurements for enhanced feed-forward based control.	DTU
	10MW reference wind turbine	Wind turbine at 10MW rated power and 178.3m rotor diameter; design as conservative as possible	DNV GL (UK)
	20MW reference wind turbine	Wind turbine at 20MW rated power and 252.1m rotor diameter; design as conservative as possible	DNV GL (UK)
WP2: “Lightweight rotor”	Active control for Smart blades	Scaled test on rotating test rig.	DTU
	Passive control and structural optimisation for lightweight rotors	Conceptual design: Manufactured and laboratory tested scaled blades and sections with tailored structural couplings	DTU
WP3: “Electro-mechanical conversion”	Superconducting generators	Medium temperature superconducting generator: Hardware demonstration: laboratory testing.	DTU
		High temperature superconducting generator: Hardware demonstration: laboratory test of superconducting direct drive generator pole pair. Capacity 3 to 6 MW	DTU
	Pseudo direct drive generators	Hardware demonstration: laboratory test of pseudo direct drive generator, 100 to 200 kW.	Magnomatics
WP4: “Offshore foundations and support structures”	Cost effective floating support structures	Competitive design solutions for 10MW turbines supported by small-scale demonstrators and waves tank tests	CENER
	Low- cost bottom-mounted support structures	Detailed design solutions for 10-20MW turbines, supported by innovations and scaled tests on component level	Rambøll

¹ The scales for testing these innovations can be found in the figures of the corresponding technology roadmaps (e.g. Figure 2-2 for the WP1: Advanced control with forward looking lidar)

1.3 Technology development phases

For each innovation, the development from innovation stage to large-scale implementation is addressed separated into four development phases:

- The development of innovative components,
- The integration of the innovation into the relevant subsystem,
- The integration of the innovation into the system: a wind turbine generator (WTG),
- The commercial application in large scale implementation in offshore wind farms.

The roadmaps will describe the development of the innovation from invention to large-scale implementation and will help identify the challenges to be overcome for each phase towards large-scale application. The last phase, large-scale application, is considered achieved when a certain market share is obtained for wind turbines with the specific innovation. A basic implementation rate for offshore wind farms is assumed; see Figure 1-1.

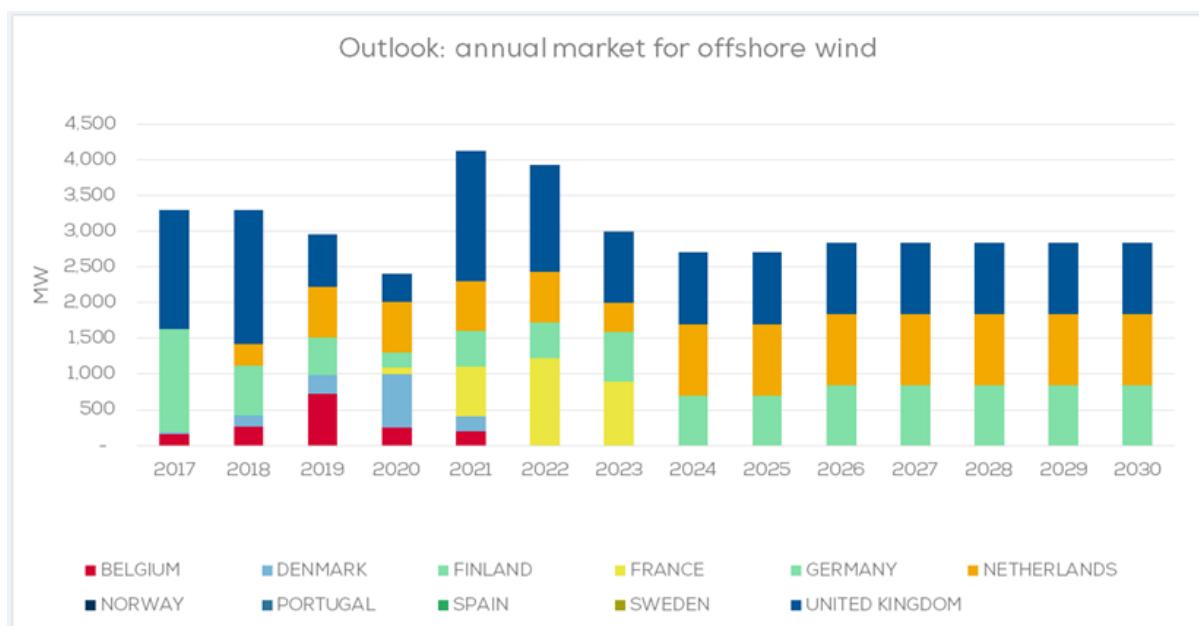


Figure 1-1: Annual installation offshore wind, Source EWEA, 2017 [1]

The four development phases represent developments on four different levels.

- The component level represents the development of the components of the innovation, e.g. actuators, cryostats and steel welding joints.
- The subsystem level represents the integration of the new components into the relevant subsystem, e.g. blades and generators.
- The system level represents the integration of the innovative subsystem into a wind turbine generator prototype.
- The commercial application, represents the integration of the innovation into large, commercial wind turbines on a large scale.

Because each development phase represents the development on a different level, different activities are relevant for each development phase. In general, the activities listed below can be identified in each phase with an associated TRL range. The latter is given as an indication of where most of the activities fall in, for the roadmaps presented in this report. Please keep in mind that there are bespoke activities per phase and per innovation, and that all TRLs can apply to each phase. These general activities per phase are:

1. Component development
 - a. Laboratory tests (TRL 3-4)
 - b. Field tests (TRL 5-6)
2. Subsystem development
 - a. Scaled laboratory tests (TRL 4)
 - b. Scaled field tests (TRL 5-6)
3. System development
 - a. System integration of innovative subsystem (TRL 5-6)
 - b. Proof of integrated concept (TRL 6-7)
 - c. Prototype testing, full scale testing (TRL 7-8)
4. Commercial application
 - a. 0-series (TRL 8-9)
 - b. 1-series (TRL 9)

For each innovation, it will be presented which type of activities in which phase are included in INNWIND.EU project. In addition to the above phasing of the developments the Technology Readiness Level (TRL) and the Manufacturing Readiness Level (MRL) will be specified in the roadmaps of the innovations. TRLs will be represented by green hexagons and MRLs, by purple ones. They will be both specifically linked to the milestone objectives.

A brief description of the TRL definitions is given in Table 1-2. The full TRL definitions from the European Commission are included in Appendix A [2]. The MRL definitions are given in Appendix B [3].

TRL level	Description [2]	Wind Turbine Development Phase
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	Commercial turbine (0 series)
8	System complete and qualified	Prototype according to certification requirements
7	System prototype demonstration in operational environment	Pre production prototype
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Functional prototype
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Key aspects environment
4	Technology validated in lab	Integration of components
3	Experimental proof of concept	Feasibility / concept design
2	Technology concept formulated	
1	Basic principles observed	

Table 1-2: Technology Readiness Level definitions (based on [2])

The time-to-market of an innovation will be driven by TRLs or MRLs depending on aspects such as: application, quantity to be produced, market sector, supply chain, how difficult it is to produce it in terms of size, equipment or technology required, if it is a state-of-the-art technology or it is a technology transfer, etc. Figure 1-2 depicts how these two levels relate for two different industries: the USA Department of Defence (DOD) and the automotive industry. These two industries have different objectives: while the DOD aims to accomplish highly innovative functions, with state of the art technology, of a limited quantity; the automotive industry focuses on accomplishing high technological functions aiming at mass production and therefore, at lowering manufacturing costs. Consequently, the DOD can be considered to be driven by the TRL and the automotive industry to be driven by the MRLs. More information can be found in [5, 7].

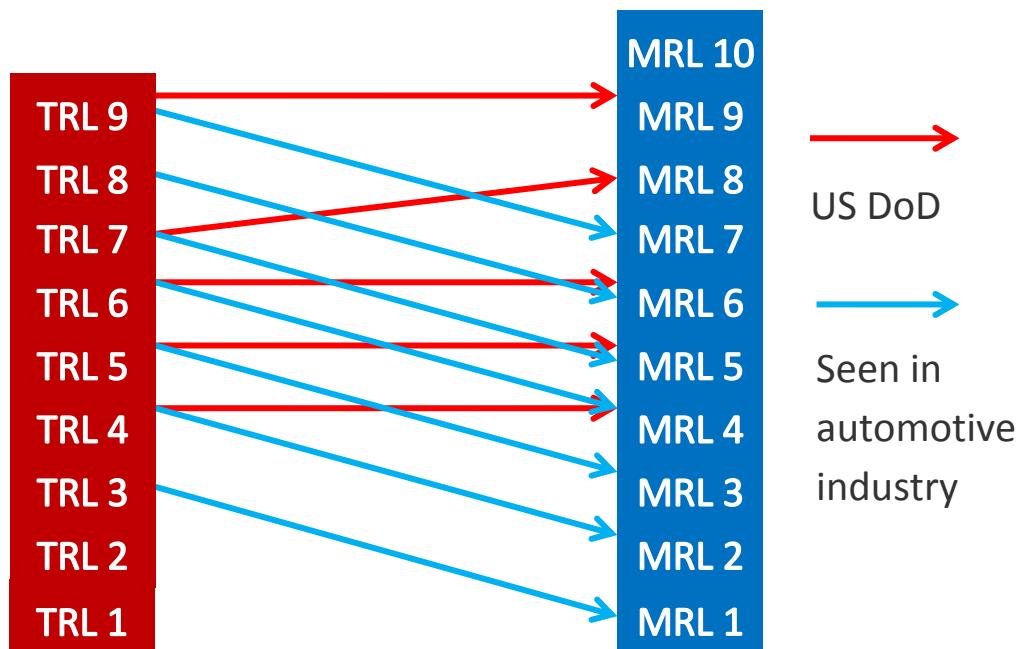


Figure 1-2: Relation between TRLs and MRLs for USA Department of Defense and the automotive industry

For the wind energy industry, the relation between TRLs and MRLs is expected to be somewhere in the middle of these two industries.

Depending on the innovations, different phases of innovation development are addressed in these work packages: the scope within INNWIND.EU for each technology will differ. Not all phases need to be included; in general, the challenges for the commercial application should be identified but it is not expected that series production itself will start within the timeframe of the INNWIND.EU project.

1.4 System impact and costs

For each innovation, the success of the innovation depends on a number of system aspects, categorised in system impacts and system costs. For each innovation, the system impacts and system costs particular for that work package will be discussed, based on these identified system aspects.

System impacts

The system can be impacted by the innovation on its:

1. Load mitigation and reduction
2. Reliability
3. Impact on power performance

System costs

The system costs can be affected by the innovation due to changes to:

1. Components
2. System integration
3. Manufacturing and fabrication
4. Transport and installation
5. Operation and maintenance
6. Decommissioning

1.5 The Technology Roadmaps

For the development of the technology roadmaps, all innovations are presented in the following format:

- General description of component or subsystem addressed in the work package of the innovation, stating
 - the objective: how will this innovation reduce the costs for WTGs
 - the component, subsystem and system level
 - the expected system impact of adapting said component or subsystem,
 - The expected system costs: where is cost reduction expected
- Description per innovation
 - Its history and status,
 - The challenges and opportunities in the development of this innovation,
 - The activities for this development within INNWIND.EU
 - The expected results within INNWIND.EU,
 - The Technology Roadmap with a timeline

The challenges are possible showstoppers and requirements that need to be addressed. Such challenges could arise from the integration into the (sub-) system: the innovation needs to meet certain requirements. On the other hand, the integration may set some requirements on the (sub-) system that needs to be identified as well. Identified opportunities are also mentioned. Certain amendments to current standards or guidelines may for instance facilitate market entry. Each

phase may represent its own advantages, challenges and requirements, as different system levels are addressed.

For the technology road maps, the expected time line is incorporated to illustrate when the challenges from the different development phases are expected to be addressed.

In the presentation of the technology roadmaps, all nine technology roadmaps are depicted in the same format. The format represents a timeline, with the years on the horizontal axis and development phases separated in 4 rows. Within these phases and following the timeline, current and further required actions are shown as blue arrows. If there is an INNWIND.EU contribution through the timeline, this would be shown in **bold** font, and the blue arrow will be highlighted with a dark-outline and be accompanied by the INNWIND.EU logo. Please note that activities in the roadmaps showing INNWIND.EU contributions can extend beyond the deadline of the INNWIND.EU project. This is because these activities are expected to be continued by other parties and/or by INNWIND.EU partners with different funding. The expected achievement of an objective is marked as an orange, outlined box with a time-marking triangle.

CHAPTER 2 INNOVATIONS FROM WORK PACKAGE 1

2.1 Introduction

Work Package 1: conceptual design

The overall objective of Work Package 1 is to develop and apply methodologies for assessing in a solid, quantifiable, manner innovative designs at the subsystems and turbine system level combined with advanced controls and sensors and accounting for the external conditions of multi-MW turbines in large offshore wind farms.

One of the Work Package 1 tasks is to define a Reference wind turbine to serve as the benchmark upon which all innovations made in the project will be tested. This wind turbine capacity is set to be 10 MW, as the low end of the capacity range investigated by INNWIND.EU. The high end of this range is 20 MW.

Another technology considered in Work Package 1 is advanced control making use of a forward looking lidar (Light Detection And Ranging) systems. This is a mature technology applied in other fields, including obtaining meteorological data for wind farm planning, onshore and offshore.

Development levels

The division in component-subcomponent-system for lidar innovation is as follows:

- 1) Component level: none
- 2) Subsystem level: lidar
- 3) System level: wind turbine prototype development
- 4) Commercial application

For the 10 and 20 MW reference turbine the required developments are different. For the 10 MW reference no significant developments are needed on component level or sub-system level:

- 1) Component level: none
- 2) Subsystem level: none
- 3) System level: wind turbine prototype development
- 4) Commercial application

For the 20 MW reference turbine various components need to be developed as the present supply chain of some major components is insufficient to produce the required scale:

- 1) Component level: none
- 2) Subsystem level: blades, pitch bearing, gearbox or direct drive generator
- 3) System level: wind turbine prototype development
- 4) Commercial application

System impact

The addition of lidar technology to the WTG does interact with the overall dynamic behaviour and cost optimisation of the other turbine parts and the mechanic loading on the major components. An optimum integrated design takes this load mitigation into account to reduce the component CAPEX. Reliability aspects have to be evaluated. Erroneous signals may lead to increased loads. Adequate standards and guidelines on this topic would be very helpful for the market introduction. Further reliability aspects need to be included in the economic assessment of the innovation. A small improvement of power performance may also be achieved.

System costs

The costs for the lidar will increase CAPEX. This could be balanced by reduced cost for structural and mechanical components at the lower load level with forward looking lidar and could be balanced by improved power performance with lidar applied.

The system costs and cost of energy for the 10 MW and the 20 MW reference turbines will be assessed in WP1.

2.2 Forward looking lidar

Present status

Lidar is used nowadays in different fields where remote sensing proves useful, such as atmospheric physics, geomatics, transport vehicles, spaceflight, etc.

Currently, stand-alone lidar systems are used and liked by the wind industry, mainly for wind resource assessment. They have been tested and used in onshore and offshore environments, in fixed and floating structures.

There are also nacelle mounted lidars available commercially but they haven't been yet included in certification guidelines for wind turbines. IEC61400-1 Edition 4 (due for publication in 2017) does not include any standards for LiDAR which means that LiDAR systems will be require certification by a risk based approach. For more details on certification and standards, please refer to deliverable D5.14.

Looking forward LiDARs mounted on the nacelle, blades or spinner could provide great advantages for the controller to load reduction, power performance optimisation and safety enhancement due to their capability of assessing the wind before it is seen by the rotor. The accuracy of the data in terms of wind speed and direction seems to be, or close to be, comparable to those of the anemometer and wind vane; however, methods to obtain reliable turbulence intensity data are still under development and testing.

The Spinner Lidar measures the wind turbine axial inflow in the approaching upwind wind field in a two-dimensional (2D) plane at select upwind distances in front of the rotor. Over the scanned rotor plane as many as 400 measurement points are registered per second. When processed in real time, these measurements reveal incoming wind gusts, wind shear, wind veer and turbulence mapped over a 2D scanned surface. Give a lead time of 5-10 seconds, this information when feed to the controller, provide advanced feed-forward information, that can be used to reduce loads on the turbine and also yaw, and pitch the turbine for enhanced production. Information about gusts and strong wind shear can be used to mitigate severe effects of non-homogeneous inflow.

The Spinner Lidar has been developed during 2010 - 2013 as part of a now finished HTF (Danish National Advanced technology Foundation) supported project: "Integration of Wind LIDAR's In Wind Turbines for Improved Productivity and Control".

During this projects demonstrating phase, a Spinner Lidar was test-operated in a test turbine type NM80 at Tjæreborg Enge in July 2012. The 2D Spinner Lidar was then prepared for installation in CART3 at NREL; Golden, Co, USA by 1 December 2013. The Cart3 turbine was run partly by its own wind measurement systems and by inflow signals derived from the 2D Spinner Lidar. The hardware demonstration of the Spinner Lidar took place in 2016 at NREL. This has not been used directly for control, but the control algorithms can use these measurements, when they are validated in the future.

Lidar use for offshore wind turbines is not limited to wind characterisation. They can also characterise the sea state and predict wave loading on the turbine.

Challenges and opportunities

The challenge for wind lidar based control is to convince the wind turbine manufactures about the benefits of lidar-assisted preview controller design so they will build in Lidars as OEM from the beginning in new products. Also we have identified an after-market retrofit opportunity for forward looking Lidar technology. Economic Lifetime extension may be achieved with the technology. This is best done by demonstration and examples.

More specific challenges identified for the commercial application of forward looking lidar systems are:

- Maintainability and reliability of lidar systems.
- Data accuracy, understanding the uncertainties to improve data reliability.
- Mitigating actions to compensate for periods of unreliable, or lack of, data.
- Cost reduction.

The opportunities are to demonstrate enhanced productivity and load reduction using forward looking lidars. Previous simulations (HTF project) have so far shown a potential for enhanced power production by as much as 5 % from enhanced lidar based Yaw control, 0.5 - 1 % enhances AEP by lidar based cyclic and collective pitching, and by as much as 30 % reduction of certain turbine wind loads (e.g. in tower root-bending moments) when the turbines speed control is based on upwind rotor plane previewed wind lidar measurements.

The following opportunities can mitigate risks and reduce time to market:

- Investigating further:
 - different means of lidar measurements in wind turbine control,
 - the reduction in extreme and fatigue loads of the wind turbine,
 - assessment of the CAPEX reduction that can be achieved through the use of advanced control strategies that make use of lidar measurement,
 - Improving reliability of forward looking lidar data and mitigating the system impacts. The improved reliability of LiDAR will reduce maintenance cost and frequency of maintenance/recalibration actions to a level similar to current sonic anemometers
- Cost reduction perhaps by lowering lidar specifications or by an improving supply chain. Once the manufacturers know which wind variables they need to be measured and how, specific LiDARs could be designed with optimized cost, simplifying the design and eliminating non-wanted features from general "general purpose" LiDARs

- Certification guidelines to help the industry understand the risks and benefits of the use of lidar in offshore wind turbines. For new wind turbines, this would open the path to lighter designs and hopefully lower costs.
- Providing the appropriate scenario to facilitate the implementation of lidar use on existing wind turbines, for instance to increase power performance by power curve comparison.
- Providing certification guidelines to facilitate the use of lidar on already designed wind turbines. The cost benefit could be increasing rotor diameter due to load reduction.

Development within INNWind.EU

Within the INNWind.EU project, one of the sensors investigated as part of the development of innovative measurements and sensors for control is the DTU-developed Spinner Lidar.

Part of this task focuses on identifying strategic elements to help commercialise forward looking lidar systems, tailored to the wind energy industry needs. The specific tasks within INNWind.EU are focus on:

- Understanding measurement capabilities of lidars for control purposes
- Simulating load mitigation using lidar measurements

The scope of these activities falls in the subsystem development phase, as depicted in Figure 2-1. Lidar technology is mature, and this facilitates a rapid development path, of forward looking lidars on offshore wind turbines, to commercial application.

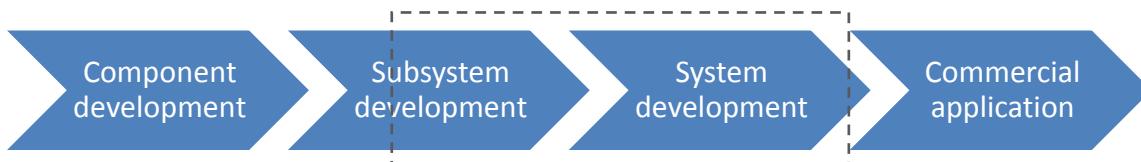


Figure 2-1: INNWind.EU scope for advanced control using a forward looking lidar

Expected results

Hardware Demonstration of Spinner Lidar: Upwind full 2D rotor plane inflow measurements for enhanced feed-forward based control.

Future developments

Outside the INNWind.EU scope are failure mitigation of unreliable lidar signals, maintainability and reliability aspects, prototyping and the implementation of facing looking lidars in wind turbines.

Technology roadmap

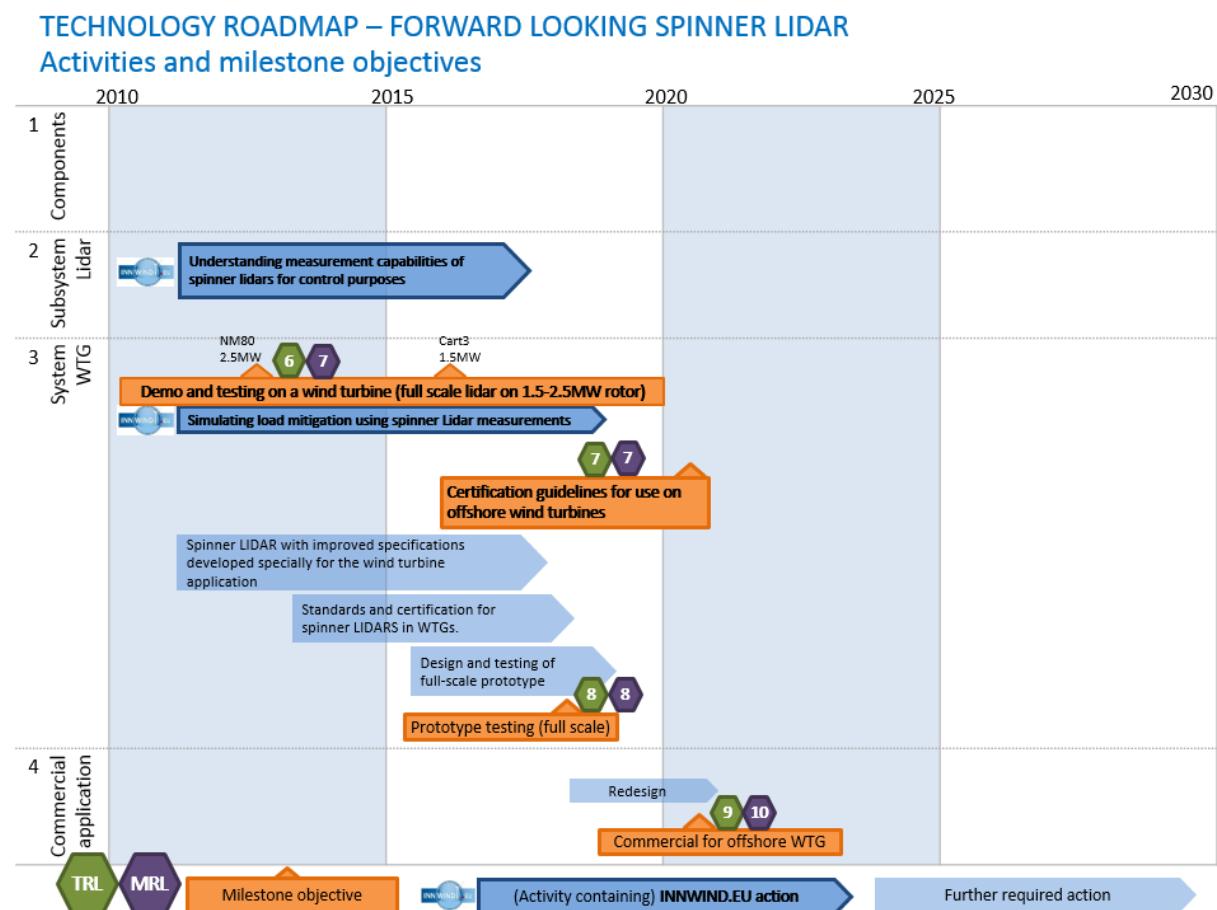


Figure 2-2: Technology roadmap of forward looking spinner lidar

2.3 A 10 MW wind turbine

Present status

The technology to produce 10 MW turbines is ready and available. Turbines at 10 MW rating are already in conceptual design phases, using existing technologies. For most structural and mechanical components the power rating has limited influence on the design requirements, the impact of the rotor diameter is far larger. The largest prototypes available now already have rotor diameters very close the diameter of the 10 MW reference turbine.

Challenges and opportunities

There are a few items to consider for the commercial application of a 10 MW wind turbine:

- The reference turbine is a scaled up conventional design. This may not lead to the optimum economic design. Design optimization at this scale is desired.
- The industrialization of large main components and the availability of large offshore bespoke installation and maintenance vessels for this scale of turbines is progressing in

parallel with turbine development. Although this results in a development risk, providing that turbine design work is being done in close communication with potential installation contractors, the risk can be minimised.

The following opportunities can mitigate risks and reduce time to market:

- Better insights in the cost breakdown.
- Availability of onshore test locations for prototype testing. Ideally these test locations should be near the coast with high annual wind speed. The noise emission constraints at the site should not be limiting the turbine tip speed during testing.

Development within INNWIND.EU

Within the INNWIND.EU project the 10 MW reference wind turbine (RWT) has been defined. The current report describes in details the aerodynamics, the structural layout, the control and the aeroelastic characteristics. 10MW innovative designs have also been proposed and aeroelastically defined.

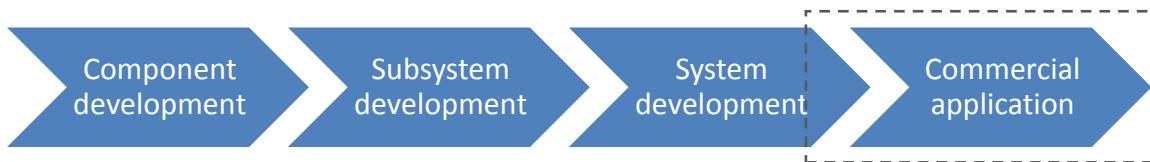


Figure 2-3: INNWIND.EU scope for a 10 MW reference turbine

Expected results

Document the complete 10MW offshore reference wind turbine (RWT) and a number of promising innovative 10MW designs (such as low induction and/or aeroelastically tailored blades, PDD generator, king-pin designs, innovative jackets). The support structure data will be derived in collaboration with Work Package 4. The final description will include the wind turbine characteristics and a detailed aeroelastic model of the RWT.

Future developments

Innovations in the component and system design can bring down the cost of energy. Wind turbine OEMs will have to design, develop and test prototypes before bringing any products on the market, as Vestas and Siemens are already doing.

Technology roadmap

TECHNOLOGY ROADMAP – 10MW (178m Rotor diameter) REFERENCE TURBINE Activities and milestone objectives

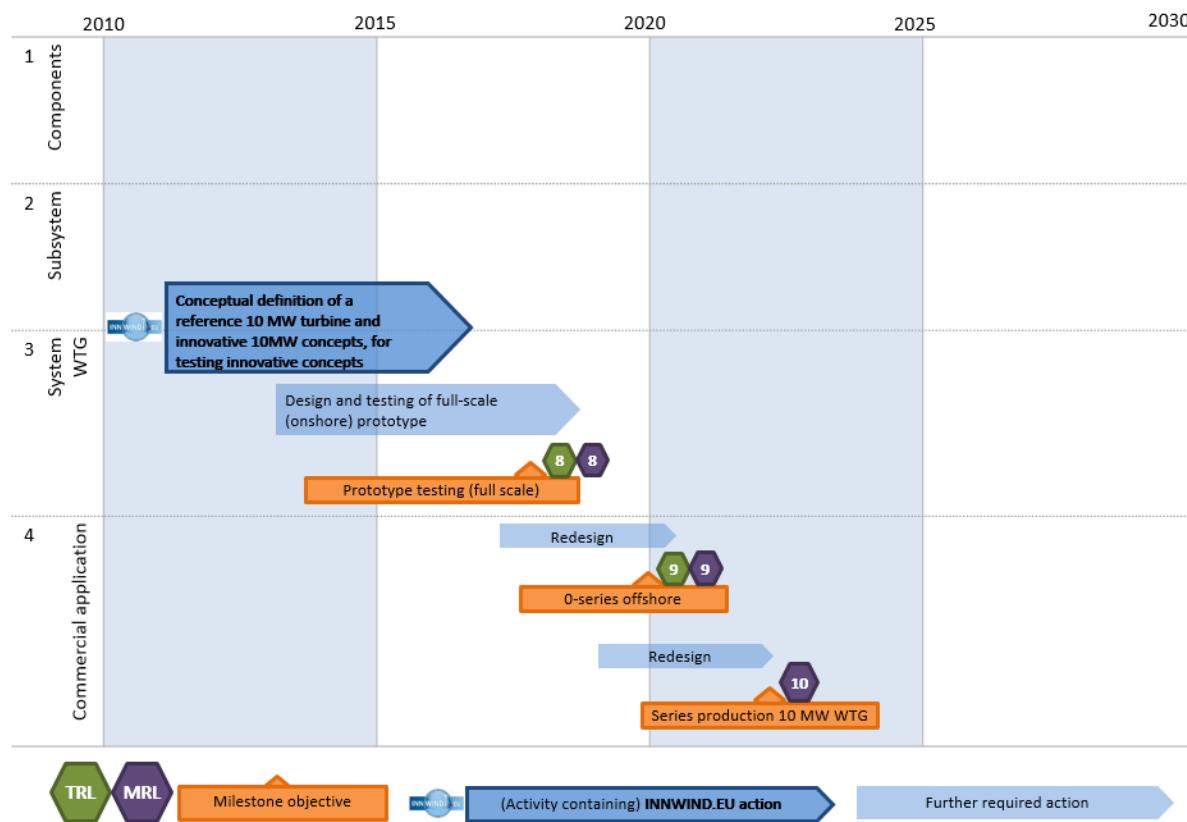


Figure 2-4: Technology roadmap of INNWIND.EU reference wind turbine

2.4 A 20 MW wind turbine

Present status

The development of a 20 MW RWT has been completed. This was derived after adapting an upscaled design to face the specific challenges of a 10MW+ jacket mounted turbine (3P support structure resonance in variable speed zone)

Most of the current components applied to wind turbines can be upscaled, however, that is unlikely to result in an economic design owing to the manufacturing constraints in the supply chain.

Challenges and opportunities

The present supply chain of a number of main components is not capable of producing the required size:

- Pitch bearing

- Direct drive generator or advanced gearbox technology allowing an economic design at required scale.
- Blades at required length and blade testing facilities
- Availability of economic installation and maintenance vessels

Following the square-cube law the costs of the main structural components of the turbine would give a too large raise of CAPEX, however the support structure scales more favourably and the cost model shows that the LCoE can potentially be lower than for 10MW. It is a trade-off of increasing turbine cost, slightly improving the AEP but reducing support structures and BoP costs along with O&M costs.

Significant load mitigation or radically new designs for these main components would improve the economics of a 20MW wind turbine.

The following opportunities can mitigate risks and reduce time to market:

- Load mitigation: this is being addressed in the tasks on advanced control and Lidar in Work Package 1 and in the blade designs in Work Package 2
- The generator design is addressed in Work Package 3.
- New designs of the support structure are addressed in Work Package 4 aiming at reduced costs of the component.
- Design and testing of large pitch bearings. Together with the design the manufacturing capability needs to be upscaled to allow production at sufficient size. Alternative to the application of single moment carrying bearing that are now applied a new blade root hub interface could be designed allowing a double bearing layout. This solution can be integrated in a new bearing type or sub-system.
- Blade test facilities of sufficient capacity
- Availability of economic installation and maintenance vessels

Development within INNWIND.EU

Within the INNWIND.EU project the 20 MW reference turbine will be the high end design to serve as the benchmark upon which all innovations made in the project will be tested.

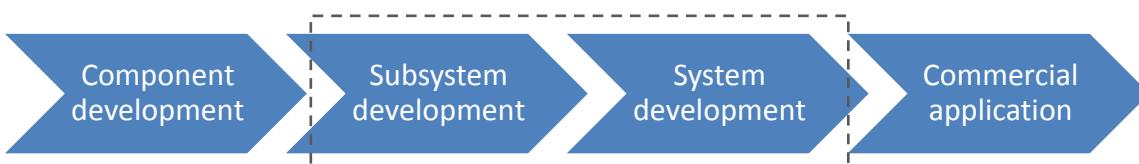


Figure 2-5: INNWIND.EU scope for a 20 MW reference turbine

Expected results

A cost breakdown and cost sensitivity results based on actual basic design of the main components will be delivered.

Future developments

It is unclear whether a 20MW turbine will be able to yield lower cost of energy than a 10 or 15 MW wind turbine and it is highly site dependant. Innovations in the component and system

design can bring down the cost of energy. Wind turbine OEMs will have to design, develop and test prototypes before bringing any products on the market.

Technology roadmap

TECHNOLOGY ROADMAP – 20MW (252m Rotor Diameter) REFERENCE TURBINE Activities and milestone objectives

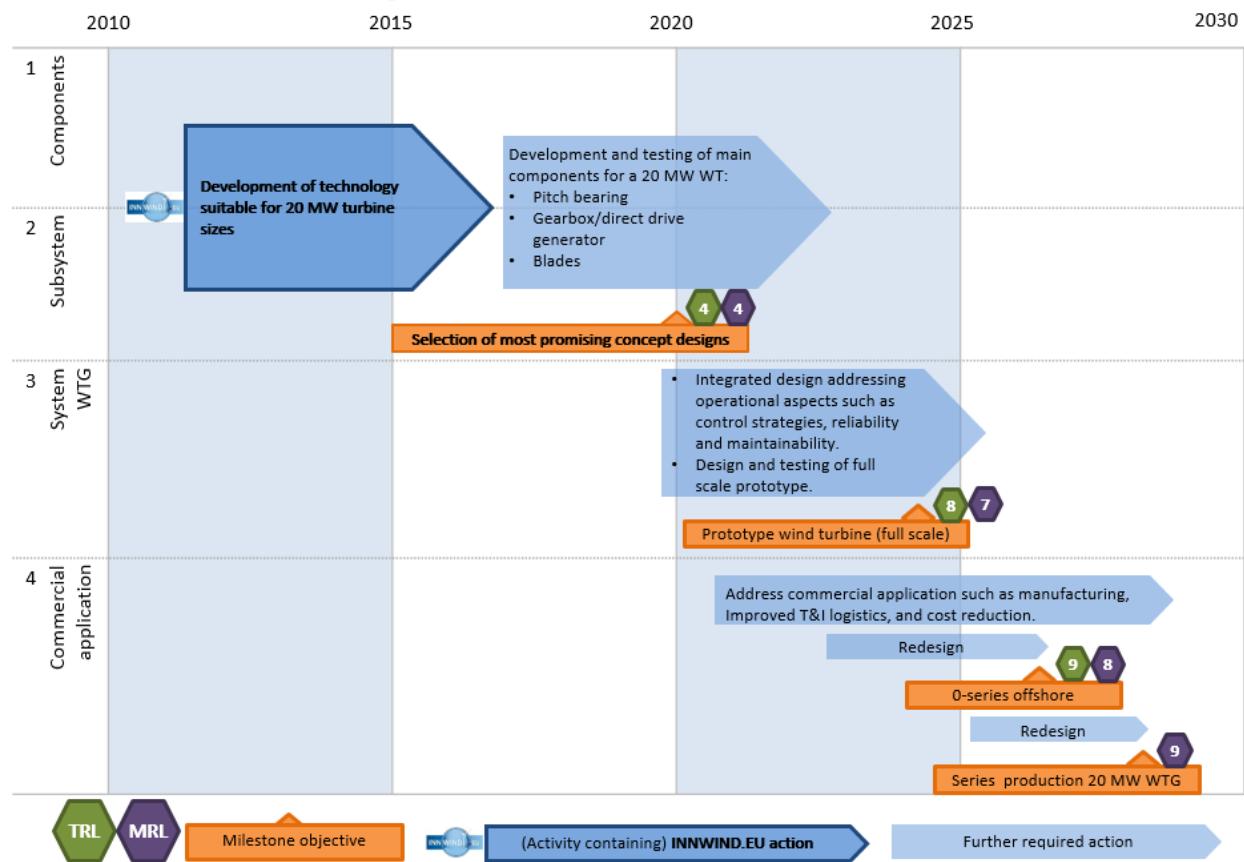


Figure 2-6: Technology roadmap of the 20 MW INNWIND.EU reference turbine

CHAPTER 3 INNOVATIONS FROM WORK PACKAGE 2

3.1 Introduction

Work Package 2: lightweight rotors description and objectives

Work package 2 focuses on lightweight rotors. In upscaling, wind turbines rotor diameters are increased to large sizes and the weight of the blades are increasingly becoming a problem. If the loads on the blades can be mitigated or reduced, lightweight rotors can be used. This load reduction or mitigation could be achieved using active or passive controls. Blade designs with active and/or passive actuators aim at load mitigation and increase of aero-elastic stability and utilisation of this potential for stretching the blades and thereby, significantly, enhance the power performance. The increase in power performance has shown to be the most cost effective way to benefit from load reductions. Active systems require sensors. The concept of some variants of smart blade technologies has already been proven in small scale laboratory tests or large scale tests in the field.

Development levels

The division in component-subsystem-system is as follows:

- 5) Component level: actuators, sensors, smart material
- 6) Subsystem level: blades, rotors
- 7) System level: wind turbine prototype development
- 8) Commercial application

The third level of prototype development entails the integration of the active and passive controlled, structurally optimised and stretched blades in an overall wind turbine design, optimised for lowest costs of energy.

For each new blade technology the development stages will be different depending on the actual technology under development. The complexity of the system, the required level of integration with the blade design or controller design and the immaturity of the components will all impact on the necessity and lead-times of the different development phases. On a component level, it should be noted that well-proven systems from other industries may still require extensive development and testing as the conditions, constraints and requirements in the wind turbine application are likely to be different.

System impact

The aim of smart rotors to reduce (fatigue) loading could result in a reduction of maintenance requirements and improved structural reliability of the wind turbine. However, adding components is likely to contribute to a higher failure rate of the overall turbine. The effect on direct O&M costs and revenue losses needs to be examined.

Load mitigation has in most cases an impact on the power performance of the rotor, which for the same blade length might reduce power output, however, as loads are reduced this also opens up for the application of longer blades without increasing loads, which results in higher power output. This was analysed within the project, and the conclusion supports this principle.

A robust and reliable system is key for successful introduction. In failed conditions, the mechanical loads on the turbine could increase. Failures need to be minimised and the failure modes and their impact on system loading need to be evaluated. Possible revenue losses caused by an increased failure rate can be mitigated by fault tolerant control strategies and component design.

In integrating components into the blade, one has to deal with a mass penalty to the blade, due to the mass of the actuators and sensors, the control unit, and local reinforcement of the blade for mounting smart blade components. Aeroelastic tailoring might also introduce added mass.

System costs

System cost reduction can arise due to reduced loading on structural components. This has to be balanced versus the extra cost of the components: the costs of the sensors, actuators, central control, and adaptation of the basic blade design.

3.2 Active control of smart blades

Present status

The desired innovation is a system to perform distributed spanwise local active control (using trailing edge flaps) of loads and power as an addition to usual blade pitch control. It is considered combined ultimately with optimised passive control and thus represents a set of extra “degrees of freedom” in the overall optimisation process on load reduction and power enhancement leading to possible cost reduction.

Development of the concept is in the initial phase within the wind turbine industry; and the first demonstration on a full scale turbine is planned for the near future outside the project.

A new smart blade concept design interacts with the overall dynamic behaviour and cost optimisation of the turbine and the mechanical loading on the major components. Therefore the technology roadmap includes prototype testing of a new turbine type.

Challenges and opportunities

The following challenges can be identified:

- Identification of appropriate combined active and passive control characteristics and their potential for load reduction and power- and stability enhancement. One challenge will be the selection of the most promising concepts as there are numerous options, and it might be, that there are many solutions with equal performance in the space from fully active to passive control
- Development and design of concepts and integration in the blade. Structural integration of sensors and actuators in a highly flexible system is challenging as strength, fatigue and stability characteristics need to be maintained at costs that are still competitive. Additionally, the potential solution must be integrated in the loop of the design to avoid increasing on wind turbine noise.
- Overall turbine sensing and control system. Complexity of the controller algorithms will increase due to MIMO controller algorithms. Fail-safe fall-back conditions need to be established and inaccuracy of the sensors must not result in increased control loads that reduce reliability.
- Lightning protection. Large turbine blades have a high probability of being hit by lightning during its lifetime. In present blade design the use of all conductive material is avoided

except in the lightning protection system. This puts challenges to the design of the sensors, actuators, communication lines and possible power supply.

- Reliability of the active control system. Adding components will increase the failure rate of the total system. The increase in failure rate needs to be small in order to have a minimum impact on the annual energy yield and direct O&M costs. Offshore maintenance on blades is very costly. A possible negative impact on annual energy yield can be mitigated by fault tolerant control strategies. The different failure modes of the system need to be analysed as these have an impact on the feasibility of different fault tolerant control strategies.

The following opportunities could mitigate risks and reduce the time to market:

- The further development, integration, benchmarking and validation of design tools.
- Return to fail-safe mode upon failure in active control system.
- Active control considered as an add-on to passive control.
- Full integration of blade and turbine control and design conditions in the turbine design loop.

Developed within INNWIND.EU

Within the project, the basic concepts and the evaluation of performance have been developed, as well as the control schemes for passive and active control, on component/subsystem level, as well as for the entire wind turbine prototype.

In Figure 3-1 the scope of activities for this topic within INNWIND.EU is depicted.

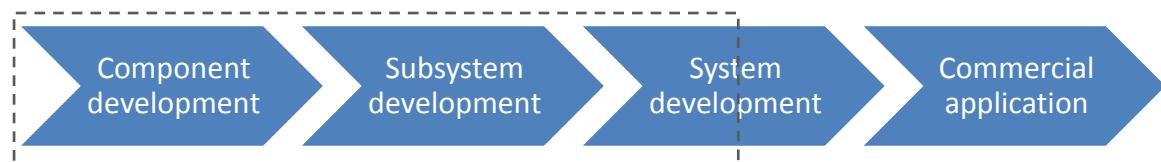


Figure 3-1: INNWIND.EU scope for active control of smart blades

Final result

The final results within the INNWIND.EU project are

- a set of validated tools, for design and optimisation with distributed blade control,
- a demonstration at both laboratory-, rotating test rig and smaller size wind turbine scale,
- a quantification of the potential of the use of trailing edge flaps for a full size wind turbine in operation.

Further developments

The commercial application phase is not addressed within the INNWIND.EU project; after the project the prototype will have to be demonstrated on large commercial wind turbines.

Technology roadmap

TECHNOLOGY ROADMAP – ACTIVE CONTROLS FOR SMART BLADES (Trailing edge flaps) Activities and milestone objectives

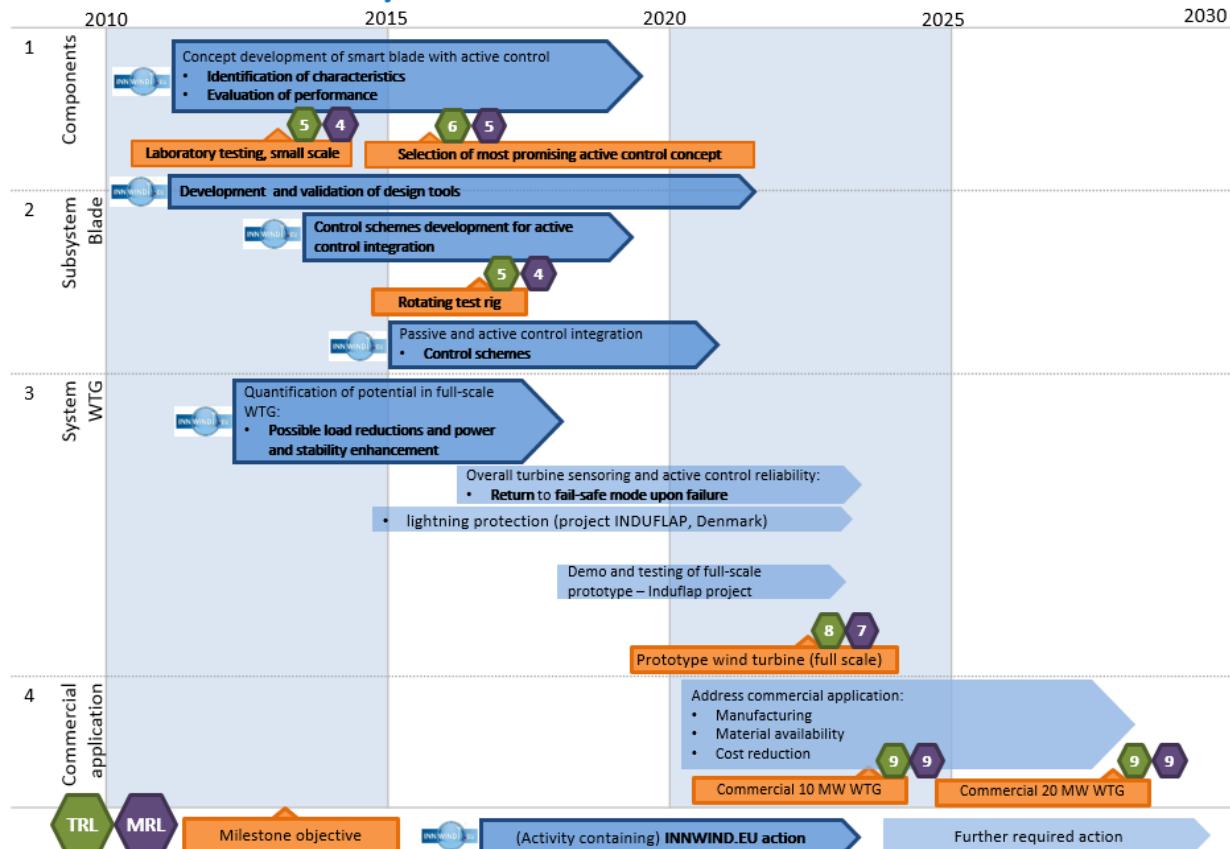


Figure 3-2: Technology roadmap of active control for smart blades

3.3 Passive control and aerodynamic / structural optimisation for lightweight rotors

Present status

The structural optimisation and gradual increase in aerofoil thickness in order to achieve more lightweight rotors has been going on continuously for decades. However, the limitation due to stiffness requirements has been a limiting factor. This is changing at the moment with the widespread use of prebend blades (forward bend blades to obtain enough tower clearance), and a less restricted structural optimisation and development of new concepts can begin. This causes higher flexibility, nonlinear effects and couplings between deformations, that at the same time offer the possibility for the introduction of the concept of passive control.

The desired innovation is a dedicated optimised aerodynamic and lightweight structural design with tailored structural- and aeroelastic couplings to accommodate passive control.

Challenges and opportunities

The following challenges can be identified:

- Identification of appropriate passive control characteristics.
- Identification of new aerodynamic rotor concepts and targets for dedicated airfoils
- Realisation of optimal structural couplings with existing methods and materials. Some control characteristics, like full pitch control, are probably impossible to obtain by purely passive couplings due to limitations in material characteristics. The use of structural couplings to morph airfoils will be limited by the required strength and allowed strain of a blade.
- Innovation might need extensive new validation.
- Integration of the passive control concept into overall turbine design and handling of possible modifications to turbine concept. This might lead to concepts that are outside the present design standards.

The following opportunities could mitigate risks and reduce the time to market:

- The further development, integration, benchmarking and validation of design tools.
- Considering structural optimisation of lightweight structures in itself a way to achieve part of the objectives.
- Integrating structural optimisation and passive control.

Developed within INNWIND.EU

Within INNWIND.EU, the basic passive control concepts will be developed. The effects on aerodynamic and structural performance due to the integration of such concepts will be evaluated. For example, the torsion coupling to the flapwise loading obtained by tailored placement of the sparcaps within the blade is a passive control concept to reduce loads (and possibly increase stability) that has been integrated in the blade design. Furthermore, tools will be developed and validated.

In Figure 3-3 the scope of activities for this topic within INNWIND.EU is depicted.

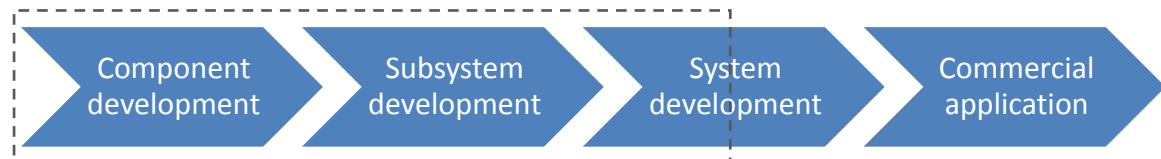


Figure 3-3: INNWIND.EU scope for passive control and structural optimisation of the lightweight rotor

Expected final result

The expected final results are a set of validated tools, a demonstration at laboratory- and smaller size wind turbine scale, and a quantification of the potential of the different concepts in full size wind turbine operation.

Further developments

Outside the INNWIND.EU scope are further developments concerning the implementation of (parts of) the concept into existing blade design by adjusting fibre lay-up schemes or introducing

geometric couplings (through pre-sweep and spar cap placement for instance) and structural design to obtain more favourable aeroelastic characteristics with respect to load reduction and stability enhancement. The next step is purely new blade designs, where all combined aerodynamic and aeroelastic characteristics are considered from the beginning of the design phase, and this is being implemented in the industry during the final year of the project. Next, prototypes should be demonstrated on large commercial wind turbines, which is also gradually happening.

Technology roadmap

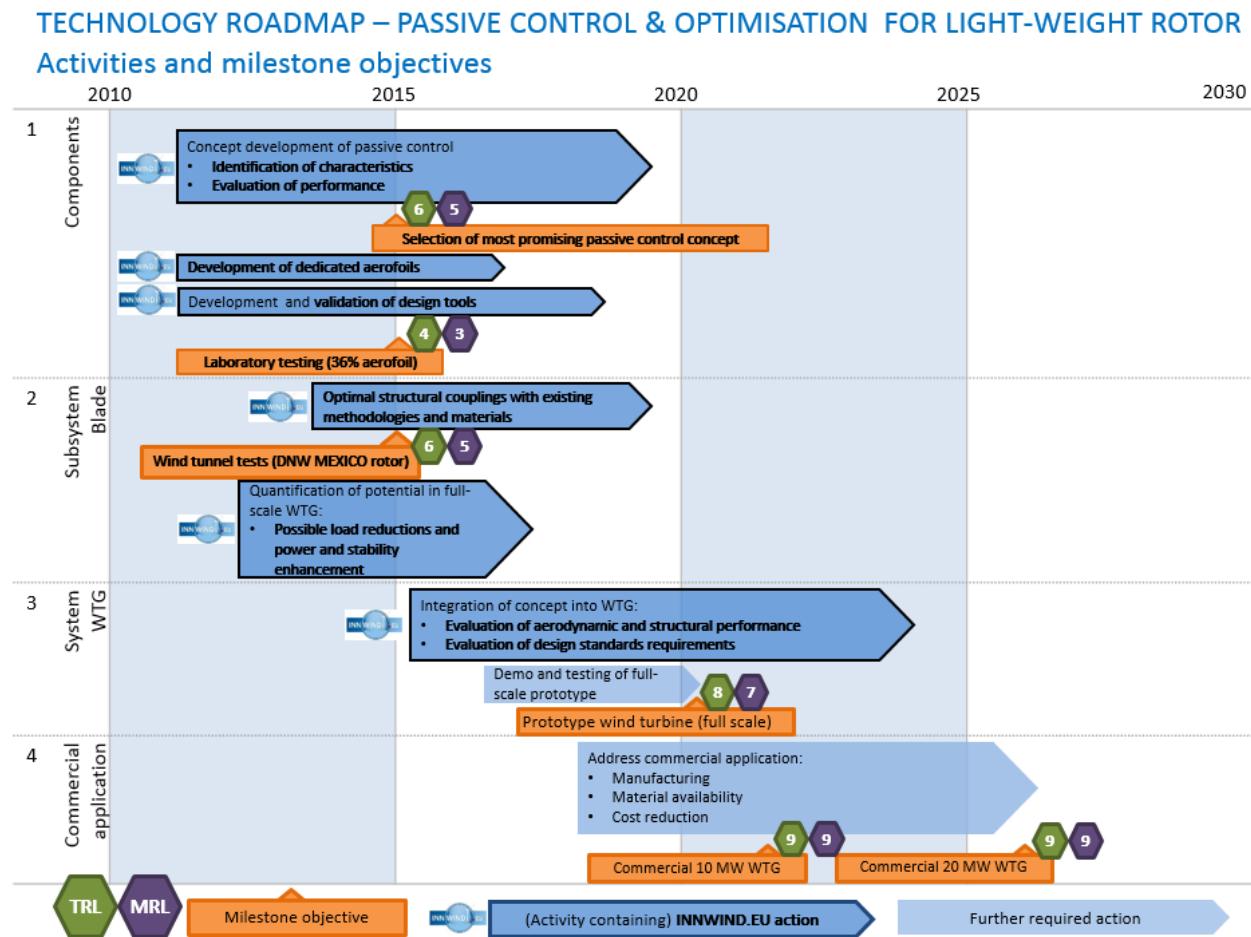


Figure 3-4: Technology roadmap of passive control & aerodynamic and structural optimization of a low-weight rotor

CHAPTER 4 INNOVATIONS FROM WORK PACKAGE 3

4.1 Introduction

Work Package 3: New generators, description and objectives

In Work Package 3 “Electro-mechanical conversion”, the innovative component under development concerns the generator. Both the generator and gearbox are components in the nacelle with high consequence of failure. The direct drive generator, negating the gearbox in the drive train, is deemed to increase the reliability of the drive train. A second gain could be reduced top mass due to a lighter weight drive train, easing installation and loads. Third, permanent magnet price development could drive to a direct drive type of generator. Finally, any small increase of AEP due to a better performing drive train has a very strong impact on the cost of wind electricity.

The generator innovations aim at a direct-drive generator without the regular gearbox. The first is a superconducting generator, a direct drive generator that could lower reduce drive train weight considerably. The second innovation concerns a pseudo-direct drive generator, as magnetic gears are incorporated within the generator.

Development levels

The division in phases is as follows:

- 1) Component development: e.g. structural parts, coils, wires, pole pairs, and pumps.
- 2) Subsystem level: the generator and its layout
- 3) System level: wind turbine prototype development
- 4) Commercial application

The third level of prototype development entails the integration of the new generator technology in an overall wind turbine design optimised for lowest costs of energy and Prototype testing (proof of design).

System impacts

A new generator technology does not necessarily interact with the overall dynamic behaviour and cost optimisation of the other turbine parts and the mechanic loading on the major components. Therefore it may be feasible to exchange the drive train of an existing wind turbine with an innovative system without major changes. The feasibility of this is dependent on the mechanical dimensions and interfaces of the new generator. Easy integration reduces risks, development time and cost. A reduced tower top mass in case of a lightweight drive train reduces overall loads, and the reliability of the system (e.g. by the cancellation of the gearbox) may be affected positively.

But a new generator concept may have other impacts on the design of the rest of the turbine: e.g. a large short-circuit torque may have a negative impact on the costs or complexity of other (drive train) components. The dynamic behaviour in normal production and in extreme external conditions or faulted conditions is of importance. New components may introduce new uncertainties and fault conditions. It needs to be assessed how the new generator concept influences reliability and overall power performance.

System costs

For new generator concepts, (in-) dependence on rare earth elements can have a (positive) negative effect on the costs.

It has to be assessed how increasing reliability, thereby lowering O&M costs, and increasing the price of the generator weigh against each other. This will also be discussed within the different options for a superconducting generator, as different options for superconductors could increase the price of the generator itself due to more expensive components, but due to improved reliability, efficiency and reduced weight a more expensive solution might still be favoured.

4.2 Superconducting generators

Present status

Superconducting direct drive wind turbine generators offer the possibility to be about half the size of the current permanent magnet direct drive generators at 10 MW, but with a very small to zero dependence of the Rare Earth elements which are needed in large quantities in the strong $R_2Fe_{14}B$ magnets (~ 0.6 - 1 ton PM/MW and R = Rare Earth element such as Nd, Pr and Dy).. The partial load efficiency of these types of generators is quite similar to the PM machines.

The current challenge of superconducting generators is the price and the unknown reliability of the new cooling devices needed to keep the superconductors cold. The price is tightly related to the type of superconducting wire that is chosen for the field coils, and also to the possible operation temperature dictated by the critical temperature T_c , below which the wires become superconducting. The 3 wire candidates are:

1. NbTi, low temperature superconductor, operated at $T = 4.2$ K, and with $T_c = 10$ K (-263 °C).
2. MgB₂ or medium temperature superconductor operated around 10-20 K and with $T_c = 39$ K (-234 °C)
3. Second generation (2G) RBa₂Cu₃O_{6+x} (RBCO), the high temperature superconductor tapes operated around $T = 20-50$ K and with $T_c = 93$ K (-180 °C)

Only the NbTi wire is industrially established and used in large quantities for magneto-resonance-image (MRI) scanners, Nuclear Magnetic Resonance (NMR) magnets for research as well as accelerators (CERN). The development stage of the technology is at demonstration of the entire generator at full size. All the components are well developed individually, but a central question is if they can cope with the turbine environment. A generator design has been proposed by GE Global Research and there are no technical issues preventing the construction of the entire generator system. One major concern is the reliability of slip rings transferring the full rated power from a rotating armature, because the superconducting field windings are fixed to the nacelle making a cooling system based on liquid helium heat pipes possible. A second concern is the reliability of the relatively complicated cooling system. The price estimate of the NbTi generator looks quite promising due to the low price of the wire.

Superconductivity in MgB₂ was discovered in 2001 and the development stage of the technology is at coil demonstration at scales suitable for a wind generator. The MgB₂ superconductor wire is now available in long length from a small number of manufacturers. It opens up for the possibility to operate at $T = 10-20$ K, where NbTi is no longer superconducting and without using liquid helium. MgB₂ is not as powerful a superconductor as NbTi and the challenge is to design an economical generator system by taking advantage of a higher operation temperature compared to NbTi.

RBCO wires have been developed for about 15 years by a relatively small number of companies. The coated conductor direct drive generator is based on the usage of the high temperature superconductor $\text{RBa}_2\text{Cu}_3\text{O}_{6+x}$, which becomes superconducting at $T = 93 \text{ K}$ for $\text{R} = \text{Yttrium (Y)}$. This gives the possibility to operate the superconductor at $T = 20-40 \text{ K}$ and considerable simplifications of the cryostat, torque tube and cooling system are envisioned. There have been several full scale demonstrations of large electrical superconducting machines based on the $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}$ (Bi-2223) high temperature superconducting wire (American Superconductors, Siemens corporate technology and Converteam (now GE)). These demonstrations have mainly been targeted at ship propulsion applications with rotation speeds of 120 rpm. Thus the wind turbine generators have to decrease the rotation speed by a factor of 10 and increase the torque with a corresponding factor of 10 from state of the art.

The main challenge is lowering the high price of the coated conductor wire. The Bi-2223 wire hold a matrix of silver around the superconductor putting a limit on how low the price can become. This resulted in the creation of the coated conductor technology, which is based on cheap metals. American Superconductor has proposed the SeaTitan turbine holding a 10 MW superconducting direct drive generator to be based on the coated conductor that they produce. The development stage of the coated conductor technology is at coil demonstration at scales suitable for a wind turbine generator until a turbine generator tailored tape is further developed and the ratio between price and performance is increased by a factor of 4. The major producers of coated conductors are currently running development programs to obtain such improvements by 2015. The technical integrity of the improved coil technology can already be demonstrated at lower temperature than expected operation temperature.

Challenges and opportunities

The choice of the superconductor wire affects the system costs. Whereas NbTi is ready to be used, MgB_2 and the coated conductor need further development to reduce the price. The turbine application will offer a significant market and economy of scale should be able to drive down the conductor price. Considerable upscaling of the production volume is needed if superconducting generators are to cover say 10 % of the EU offshore capacity by 2030 (100 GW covered by 10 MW turbines give 10000 turbine and 10 % is therefore 1000 Superconducting turbines). Thus in order for superconducting direct drive to become economical feasible, then one can either choose the well-established NbTi wire and build a more complicated cryostat and cooling system, or the development of wires operating at higher temperature and use a less complicated cryostat and cooling system, yielding also a better generator efficiency since LTS cooling is energy demanding.

In all the generator systems a new type of cooling system is introduced and it can have a large impact on the reliability of the system. A standard for specifying and testing the reliability of such machines when exposed to the environment of a 10-20 MW turbine would be very valuable in the further design, because a central question is if they must be mechanically decoupled from the cryostat and if they can operate in a rotating frame.

It should be noted that a strategic consideration in the above choice is related to the possible gasses used in the cooling systems. Helium (He) is needed to obtain $T = 4.2 \text{ K}$, whereas neon (Ne) offers cooling at $T \sim 25 \text{ K}$ and hydrogen (H_2) could be used for $T \sim 18 \text{ K}$, but the use of H_2 increases safety concerns. Helium is a limited resource, since He is light enough to leave the planet when released to the atmosphere. The estimated amount of helium in a 10 MW generator is estimated (by GE) to be 9100 L or 1.6 kg, which can be compared to a worldwide annual usage of 7000 tons of helium for cooling MRI systems (2010). Thus the 10 % EU offshore share sums up to about 2 tons, which will cost about 31 k€ in total using current He prices, and one can therefore neglect the He supply concern in the near future. Helium is often extracted from natural

gas and depletion of natural gas could entail future shortages, although the increased shale gas production might offer a new supply source.

On the subsystem level, the generator itself, the challenge lies in the design of a feasible subsystem combining the superconductor, the cryostat/torque tube and the cooling system. The construction of a large cryostat will be a major challenge, since they also must be transported to the turbine for installation. The issue of constructing a 5-6 meter large vacuum chamber of the cryostat is considered as a major challenge and the possibility to make segmentation of such a generator is considered as a key opportunity to reduce the time to market. It is believed that this segmentation of the cryostat is possible for the coated conductor as this has a 'high' operational temperature, which also allows for simpler cooling machines.

Challenges and opportunities per superconductor choice

As explained above, the choice for either NbTi, MgB₂ or RBCO superconducting tapes will impact the system in its entirety. Per superconducting generator the challenges and opportunities will be listed on component, subsystem and system level.

NbTi based generator:

Component level:

- The NbTi wire is produced on a large scale for MRI systems and accelerators (CERN). The unit length can be up to 10 km and the price is in the order of 1 Euro/m. The superconducting properties are very good, but it has to be operated at T = 4.2 K.
- Coil technology is well known and used by the MRI industry winding up to 50 km / machine.
- Cooling machines: All available from the MRI industry, but little knowledge if they can operate reliable in a turbine environment (ex. vibrations and extreme loads).
- Heat pipes: Is used in the MRI industry, but up-scaling to larger size must be done.
- Slip-rings: A technology transfer of slip rings from hydro power plants is envisioned, but the reliability when exposed to the turbine environment is unknown.

Sub-system level:

- Cryostat: The cryostat providing the thermal isolation of the superconducting coils must be prototyped and up-scaled from the current size of MRI machines. A central part of the cryostat design is the integration of the torque tube element transferring the torque from the turbine blades and to the cold superconducting coils. Secondly the reliability of the cryocooler cold heads installed into the cryostat must be investigated. The cryostat and rotor of the GE global Research proposal are ready to be proven by demonstration.
- Armature technology: Directly transferred from normal manufacturing of large electrical machines, since it is based on copper conductors and magnetic steel laminate teeth.

System level:

- There are no major technical challenges preventing the construction of the GE NbTi generator, but demonstrating the reliability of the entire generator when exposed to the wind turbine environment (vibrations and extreme loads) will be needed. GE Wind has with the acquisition of the Haliade 150 – 6 MW offshore turbine a turbine which could hold the NbTi superconducting generator proposed by GE Global Research by making some changes. The major change will be to place the armature rotating on the outside of the generator and slip rings for bringing the power to the nacelle will be needed.

Commercial application:

- The time to market of the NbTi generator can in principle be quite fast, since all major components are available. The estimated amount of NbTi wire in a 10 MW generator is 720 km (3.8 tons) and will sum up to 720000 km (3800 tons) of wire if the 10 % EU offshore capacity must be fulfilled by 2030. This must be compared to an annual production of 600 tons NbTi wire just for the MRI industry. Thus if the production of 67 superconducting 10 MW turbines per year is assumed to start from 2015 then the additional demand of NbTi wire will be approximately 255 tons / year and constitute an increase of 42 %. Such an increase has been fulfilled before with additional demand coming from large scale projects like the Large Hadron Collider (LHC) of CERN or the construction of the fusion experiment ITER.
- As mentioned in the introduction then the He consumption due to the new heat pipe technology will be quite limited and can almost be neglected.
- The number of cryocoolers needed will be in the order of 4000 and the number of cryostats will be 1000, which both is comparable to the demand of the MRI industry and should be possible to fulfil.

MgB₂ based generator:

Component level:

- MgB₂ wires: The price of the wire is about 4 Euro/m and the critical current in high magnetic field (2-3 Tesla) is high enough to be considered for direct drive wind turbine generators. The piece length is several km being long enough for winding large coil. A considerable up-scaling of the production is expected and a target price of 1 Euro/m has been suggested within a few years.
- Coil technology: Low field coils have been tested for future MRI systems, but the number of high field coil demonstrations is limited. Thus demonstration of high field coils suitable for a wind generator is needed.
- Cooling machines: T = 10 K cold heads are available from the MRI industry where they are used to cool the shield of the systems.
- Heat pipes: One could consider liquid hydrogen at T = 18 K, which is a very effective cooling media. The safety issues are however considerable as well as the risk of diffusion into the vacuum of the cryostat, but since hydrogen is already used routinely to cool large generators in power plants it could still be considered. Direct conduction cooling is the most obvious technique to distribute the cooling power, but the question is if it is sufficient. Thus a circulating cold gas or mixtures of cryogens is an alternative cooling method which should be considered.
- Slip rings: If the superconductor field coils rotate there might be a need to transfer the excitation current through slip rings, but the power needed for that is very small. Are available commercially. An alternative is a rotating transformer.
- Rotating gas coupling: If the compressors for the cooling machines are mounted in the nacelle then a rotating gas coupling is needed to bring high pressure helium lines to the cold heads. The Helium gas is at room temperature. Such couplings are available commercially.
- Rotating cryogen coupling: If cold heads are not used for the direct cooling of the superconducting coils then one will need a rotating coupling capable of transferring cold cryogen gas (He, H₂ or Ne) to the field windings. Some experiments have been done and a few commercial solutions are offered. The operation experience is however very limited.

Sub-system level:

- Cryostat: The construction of the cryostat is again key for subsystem level. The coils, torque tubes, vacuum and cooling system must be combined and should operate reliably in the wind turbine environment.
- A major challenge will be to design a conduction cooled system with a sufficient high efficiency and reliability.
- Armature technology: Directly transferred from normal manufacturing of large electrical machines if magnetic teeth can be used. If an air-cored armature is needed some development is needed.

System level:

- The construction of an entire MgB₂ generator will need a considerable development work on the integration of the coils into a suitable cryostat and cooling system tailored to a specific turbine.

Commercial application:

- An MgB₂ generator can be demonstrated in full-scale with the current wire production volume, but a considerable ramping up of the production will be needed in order to capture a 10 % market share of the EU offshore wind capacity by 2030. First estimates of INNWind.EU show a usage of around 650 km MgB₂ wire for a 10 MW generator, giving a total demand in the order of 650.000 km of wire for a 10 % EU offshore market share. The annual world-wide production of MgB₂ wire is estimated to be 1000-5000 km: considerable upscaling will be required to fulfil the additional demand. The demand from the MRI industry will most likely drive this upscaling of production however, as it is putting a large effort into reducing their dependency in liquid helium. The price of the MgB₂ wire is therefore expected to decrease as a result of the learning curve of the MRI technology.

Coated conductor based generator:

Component level:

- RBCO tape: The coated conductors are made by depositing very thin layers of ceramics on a metal strip, which is covered by metals for protection. The RBCO layer is only a few micro meter thick and constitutes a filling factor of only 0.5 % of the tape cross section. The tape is mainly produced with a width of 4-12 mm and a thickness in the order of 0.1-0.2 mm. It is produced in 1 km length, but homogenous single piece lengths are only in the order of 100-300 m and must be improved.
- The current price of the tape is about 24 Euro/m and is expected to remain high, but the critical current at T = 30 K and B = 2.5 Tesla of the tapes is predicted to increase by a factor of 4 by 2015, whereby the amount of tape needed in a generator is reduced by a similar factor. This improvement is targeted by increasing the thickness of the RBCO layer and optimizing the nano-engineering of the defects in the RBCO structure.
- Coil technology: Rotor coils for superconducting machines have been made using coated conductors from American Superconductor as well as SuperPower. The demonstration of the B = 2.5 Tesla target field at T = 30 K is however needed to prove that the tape is not degraded during the winding, subsequent cooling or magnetizing of the coil. The coil should be based on 12 mm wide tapes instead of the 4 mm because that will eventually be more cost competitive.
- Cooling machines: Cryocooler for T = 20-30 K have been demonstrated for the Bi-2223 machines and the experience can be used again.
- Heat pipes: Liquid neon heatpipes and thermosyphons have been demonstrated at T = 25 K and can be reused. Direct conduction cooling and a circulating cold gas is an alternative cooling method, which should be investigated.

- Slip rings: Same arguments as for MgB₂.
- Rotating gas coupling: Same arguments as for MgB₂.
- Rotating cryogen coupling: Same arguments as for MgB₂.

Sub-system level:

- Cryostat: The construction of the cryostat can in principle be simplified by removing a radiation shield between the room temperature wall and the cold coil support structure. This will allow a smaller air-gap distance and thereby a more powerful generator or a cheaper generator using less superconductor.
- Armature technology: Directly transferred from normal manufacturing of large electrical machines if magnetic teeth can be used. If an air-cored armature is needed some development is needed on that.

System level:

- As for the NbTi generator then there are no major technical issues preventing the demonstration of a full scale coated conductor generator, but the price of the coated conductors must be reduced by improved tape properties before the generator becomes feasible. One obstacle is however the limited single piece length (100-300 m) of the tape, which will cause an introduction of splicing of tapes in the coil winding if the coil is large.

Commercial application:

- The INNWIND.EU estimate of the amount of coated conductor presently needed to build a 10 MW generator is in the order of 350 km, which would result in 350000 km of tape needed to supply 10 % of the EU offshore capacity by 2030. The current annual production of coated conductor tape is 1000-2000 km. Thus one could in principle demonstrate a full-scale generator with the current production volume, but it would probably be advisable to await longer single piece lengths.
- The coated conductor generator is at a stage where the integrity of the coils, the cooling technology and the cryogenic integration can be demonstrated for reliability. The wind power application of coated conductors can provide a major push for the development of the tapes, because it will bring a market of the size of the MRI industry. This push will probably not be done by the MRI industry as expected for the MgB₂ wire, because the coated conductors are very hard to join in a superconducting joint, which is essential for the functionality of the MRI machines. The technical demand for the wind turbine generator is not as demanding, whereby the coated conductor is more suitable for the turbine generators<?>.

Developed within INNWIND.EU

Conceptual generator models have been developed to clarify the physical origin of the performance indicators of the INNWIND.EU project. The focus has been in the medium temperature superconductor MgB₂ and the high temperature superconductor RBCO. MgB₂ was investigated by a team at SINTEF, Technical University of Delft and Technical University of Denmark. The main finding on optimization of the major performance indicator being the Levelized cost of energy of MgB₂ superconducting generators is shown in figure 4-0a. The different topologies of the generators called T1-T12 have an increasing amount of magnetic steel laminates included in order to reduce the amount of superconductor used and thereby cost of the generators (T1 is an air cored machine meaning no iron laminates to close the magnetic flux lines more effectively, whereas T12 holds as many laminated as possible to confine the magnetic flux in the airgap of the machine). What is shows is the resulting levelized cost of energy taking the entire INNWIND.EU 10 MW reference turbine into account with 3 different scenarios of the

cost and performance of the MgB₂ wire. The baseline scenario assumes that the cost and critical current density $J_c(B)$ of the MgB₂ superconducting wire is as it was found by the INNWIND.EU project when demonstrating a scaled MgB₂ field coil. 3 future scenarios bases on the assumption that the cost of the MgB₂ wire is reduced by a factor of 4, or the critical current density $J_c(B)$ of the wire is increased by a factor of 4 and finally the combination of the two previous scenarios. The INNWIND.EU interpretation of the result is that for the current MgB₂ performance the lowest LCoE is obtained with a machine containing as much iron as possible in the form of the T12 topology. A central question is of course if the weight of such a generator is sufficient low to compete with the alternative drive trains used by the wind sector. Figure 4 -Ob is showing the resulting active masses of the generators and an estimate on how low this should be to compete with a permanent magnet direct drive generator. It is found that the T12 version of the MgB₂ machine will be too heavy compares to the alternatives and it is therefore interesting to investigate if the future scenarios will change that situation. By comparing the plot of the LCoE and the active mass it is seen that the cost difference between the different topologies are reduced when using the future scenarios and that topologies with lower active mass could be chosen.

The main conclusion on the 10 MW MgB₂ direct drive generator is that it is technically possible to build such a generator, but with current cost of the MgB₂ it is too expensive and the resulting generator too heavy. It is however indicated that this can be changed if the cost or the performance of the wire is improved. In order to obtain such goals one will have to examine the possible learning of ramping up the production of MgB₂ superconducting direct drive generators. Figure 4-Oc is showing a scenario of how that could take place within the next decade. The historic installed wind turbine power capacity for EU and the world is plotted along with the EU offshore capacity as well as some predictions of how the wind capacity is expected to develop in order to support a renewable energy transition of Europe. A scenario of demonstrating a new 10 MW offshore wind turbine drive trains technology is shown by assuming 1 turbine is installed around 2018 and tested for a few years. After that the next few turbines are installed and tested, but then an increase ramp up of installation is assumed in order to provide 10 GW of wind capacity by 2030 using this new technology. This target is chosen such that the new drive train technology will cover approximately 10% of the offshore EU capacity by 2030. From an industrial point of view it is probably not interesting to show that a 10 MW superconducting generator can be built, but more to show that the upscaling towards the 10 GW is possible. One major barrier for doing this will be if the wire is available in sufficient quantities. Thus a central question is how large the wire production volume is compared to such a demand and secondly how much learning in terms of cost reduction and increased superconducting properties will be possible if superconducting wire production volume is ramped up. The current production volumes of the different wires we discussed previously and compared to the 10 GW scenario outlined above.

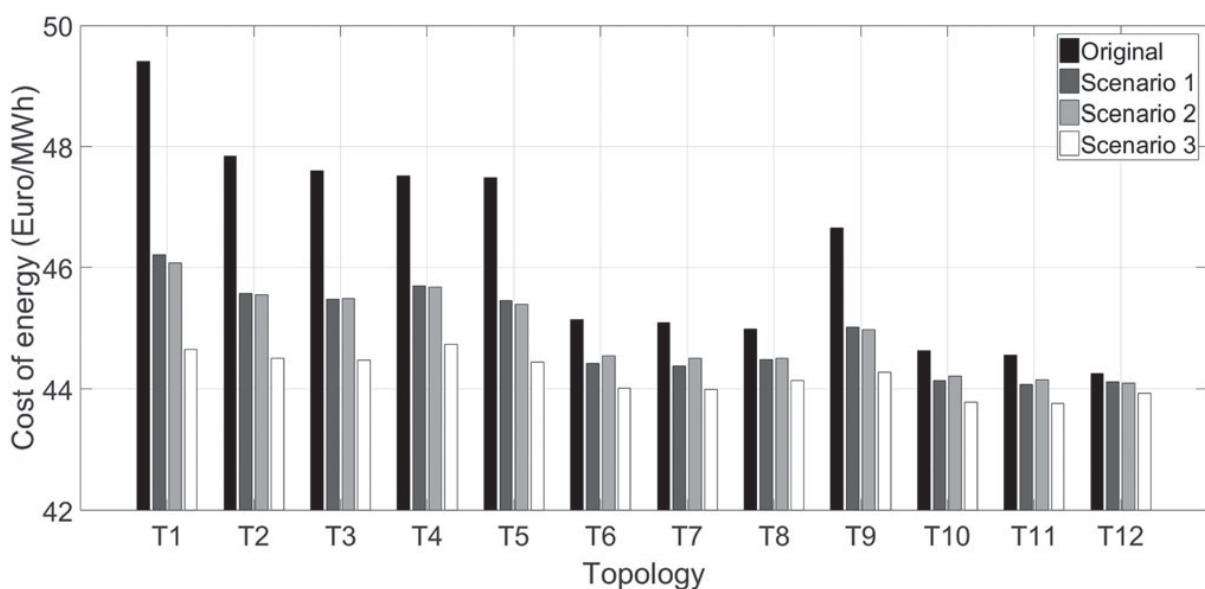


Figure 4-1: Comparison of Levelized Cost of Energy of the a series of superconducting generator topologies T1-T12 with the scenarios of the MgB₂ wire cost: 1) present, 2) 4 times cheaper wire, 3) wire with a 4 times higher critical current and 4) combination of 2) and 3). Reproduced from Liu et. al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, 5202007 (2017).

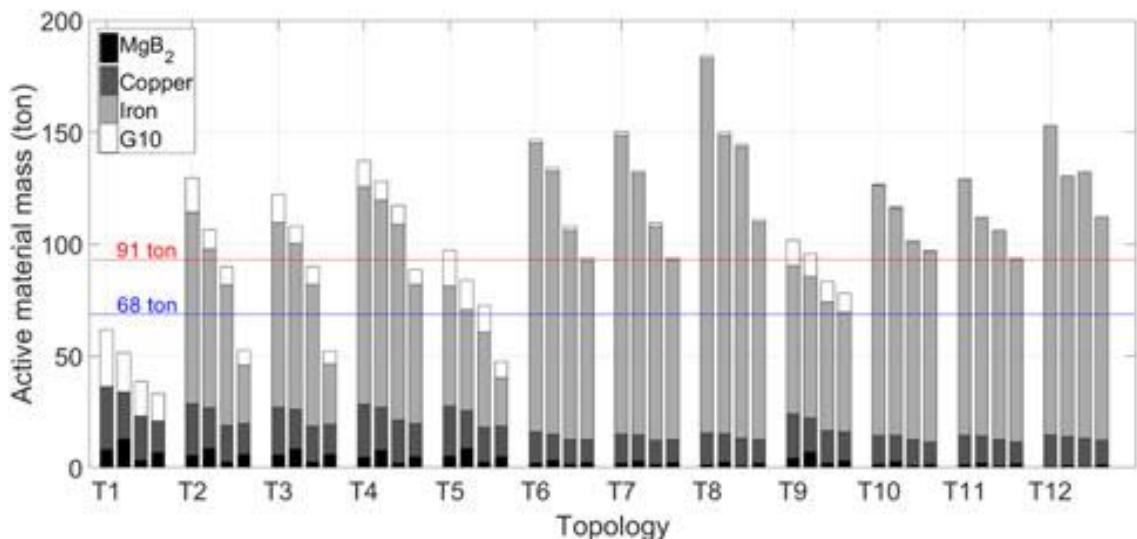


Figure 4-2 Comparison of masses of the active materials of the MgB₂ superconducting generators for a series of generator topologies. The horizontal lines indicate estimates of total active material mass targets. It is seen that the cheap topologies T10-T12 of figure 4-0a are too heavy even with the future improved wire properties. Thus the topologies T1-T5 and also T9 are promising candidates for superconducting direct drive generators, which can both meet the weight and cost criteria in the future with scenario 4). Reproduced from Liu et. al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, 5202007 (2017).

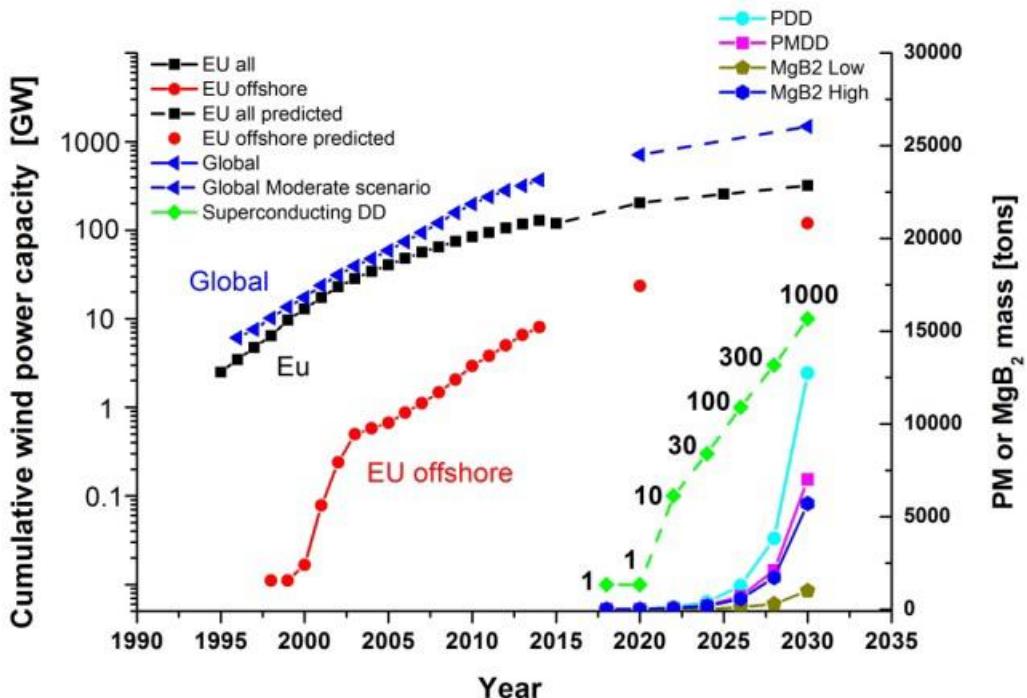


Figure 4-3 Scenario for introducing 10 GW of superconducting direct drive wind turbine generators into the European offshore fleet by 2030. The installed wind power capacity of Europe and the world is plotted along with the offshore capacity of Europe. A hypothetical scenario of installing the first two 10 MW superconducting turbine around 2018-2020 is shown with a following ramp-up of installations in order to reach a 1000 turbines by 2030. The right hand axis is illustrating the amount of active materials in the form of Nd-Fe-B Permanent Magnet (PM) or MgB₂ superconductor if the 10 GW are based on Superconducting Direct Drive (MgB₂), Permanent Magnet Direct Drive (PMDD) or the Pseudo Magnetic direct drive (PDD).

Reproduced from Abrahamsen et. al., EWEA proceedings (2014).

Learning obtained in the INNWind.EU project

For the medium temperature SC generator, a MgB₂ coil of 0.8 m length and opening of 0.3 m with a ~ 8 cm x 8 cm cross section have been designed, constructed and tested at T = 18 K in order to establish the performance indicators of a MgB₂ based generator of 10 MW. The race track coil consists of 10 double pancake coils and a total of 4.5 km of MgB₂ wire has been wounded up. The demonstration has shown that 7 out of 10 coils are performing as expected, whereas 3 of the coils are showing a partial normal resistive response. Thus it must be concluded that coil manufacturing still needs improvement and that a 70 % success rate for the coil manufacturing is not sufficient for series production. Based on the demonstration then the TRL of the MgB₂ coil for the 10 MW generator is estimated to be TRL 4: Demonstration in laboratory and installation in a generator will be needed to lift it to TRL 5.

For a high temperature SC generator, a superconducting pole coil has been demonstrated by Siemens Wind Power in order to investigate the technical feasibility of the coated conductors. The choice of the coated conductor is related to the highest possible operation temperature, because that is believed to allow a cryostat that can be segmented. Secondly the high operation temperature allows simpler cooling machines, which could be easily replaced and are not an integrated part of the cryostat. The manufacturing of a coated conductor race track coil showed that out of the 8 single pancake coils 5 passed the initial precooling test and 3 pancake coils were combined into the final race track coil. The coil was tested at T = 30 K up to an operation

current of $I = 450$ A, which is lower than the design target of 650 A, because signatures of resistive behaviour was observed. Measurements of AC losses were done and further testing of the race track coil at operation currents higher than $I = 450$ A was not attempted, because the resistive signature was permanent after the initial ramping of the current. It is concluded that the manufacturing of racetrack coils based on the coated conductors will need more work and that the Technical Readiness Level (TRL) of the technology is estimated to be TRL = 4 Demonstration in laboratory similar to the MgB₂ coil demonstration.



Figure 4-4: INNWIND.EU scope for following the research into the NbTi low temperature superconductor generator



Figure 4-5: INNWIND.EU scope for research into the MgB₂ medium temperature superconductor generator

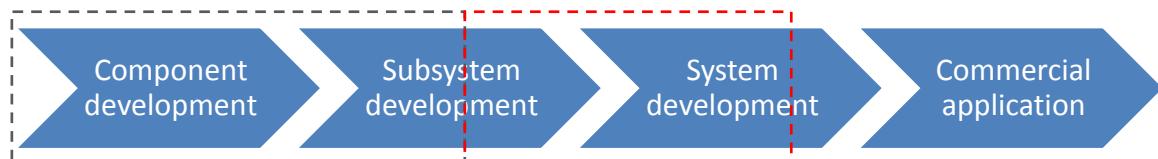


Figure 4-6: INNWIND.EU scope for research into the high temperature coated superconductor generator.
 Note: Black box is indicated work on coil demonstration not expanded to the system level, because the Levelized Cost of Energy was found to be higher than what is expected from the permanent magnet direct drive technology of Siemens Wind Power.

Expected final result

- A superconducting direct drive concept targeted at the INNWIND.EU reference turbine for rated power levels of 10 to 20 MW.
- The demonstration of an MgB₂ rotor coil.

Further developments

The Cost of Energy evaluation of the INNWIND.EU project indicates that superconducting generators most likely have to be based on topologies, where the amount of magnetic laminates are reduced and amount of superconducting wire is increased from the possible minimum in order to result in a competitive weight. The INNWIND.EU investigations are indicating that better performing superconducting wires with a 4 times smaller cost or 4 times better critical current might allow weigh competitive topologies in the future. For both the MgB₂ and the coated conductor high temperature wires it is expected that a rather large production upscaling will be needed to provide in the order of 10 GW offshore wind power by 2030. It is believed that such an upscaling of production volume will allow a substantial cost reduction as well as further development of wires with better performance.

During the INNWIND.EU project the improvement of the MgB₂ wires has been modest and it seems upscaling production volumes with known wire geometries has been the focus. In case of the high temperature superconducting coated conductors it has been reported that the critical current of coated conductors has increased by a factor of 4 for wires relevant of the wind turbine generator. Further improvement are expected as production volume is increased.

One major challenge remaining in the development of the superconducting wind turbine generator is to establish the reliability of the cooling system integrated into a full generator. The Ecoswing project is attempting that for a 4 MW generator and recently a 2 MW medium speed generator has been demonstrated by the ICMAB-GAMESA collaboration.

Technology roadmaps

In Figure 4-7 to Figure 4-8 the technology roadmaps are given for both medium and high temperature superconductor wire choices.

TECHNOLOGY ROADMAP – MgB₂ MEDIUM TEMPERATURE SUPER CONDUCTOR GENERATOR

Activities and milestone objectives

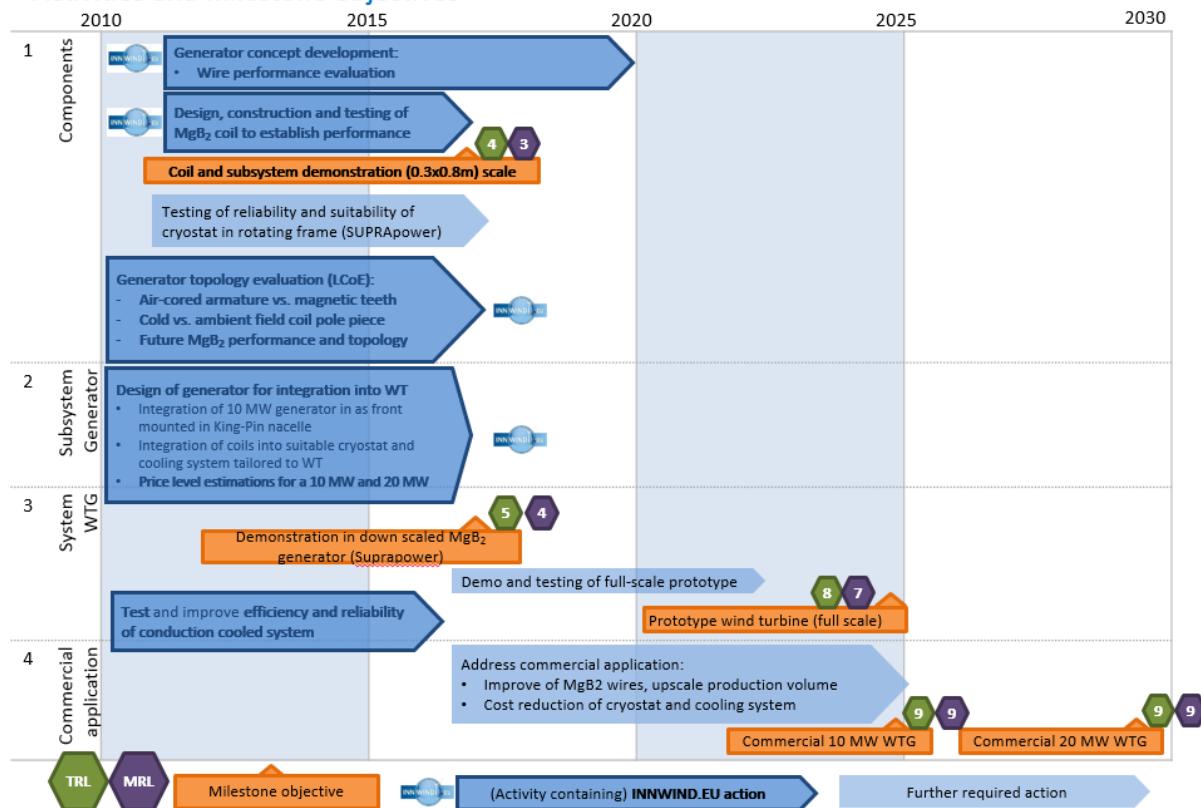


Figure 4-7 Technology roadmap of MgB₂ wire choice

TECHNOLOGY ROADMAP – YBCO HIGH TEMPERATURE SUPER CONDUCTOR GENERATOR Activities and milestone objectives

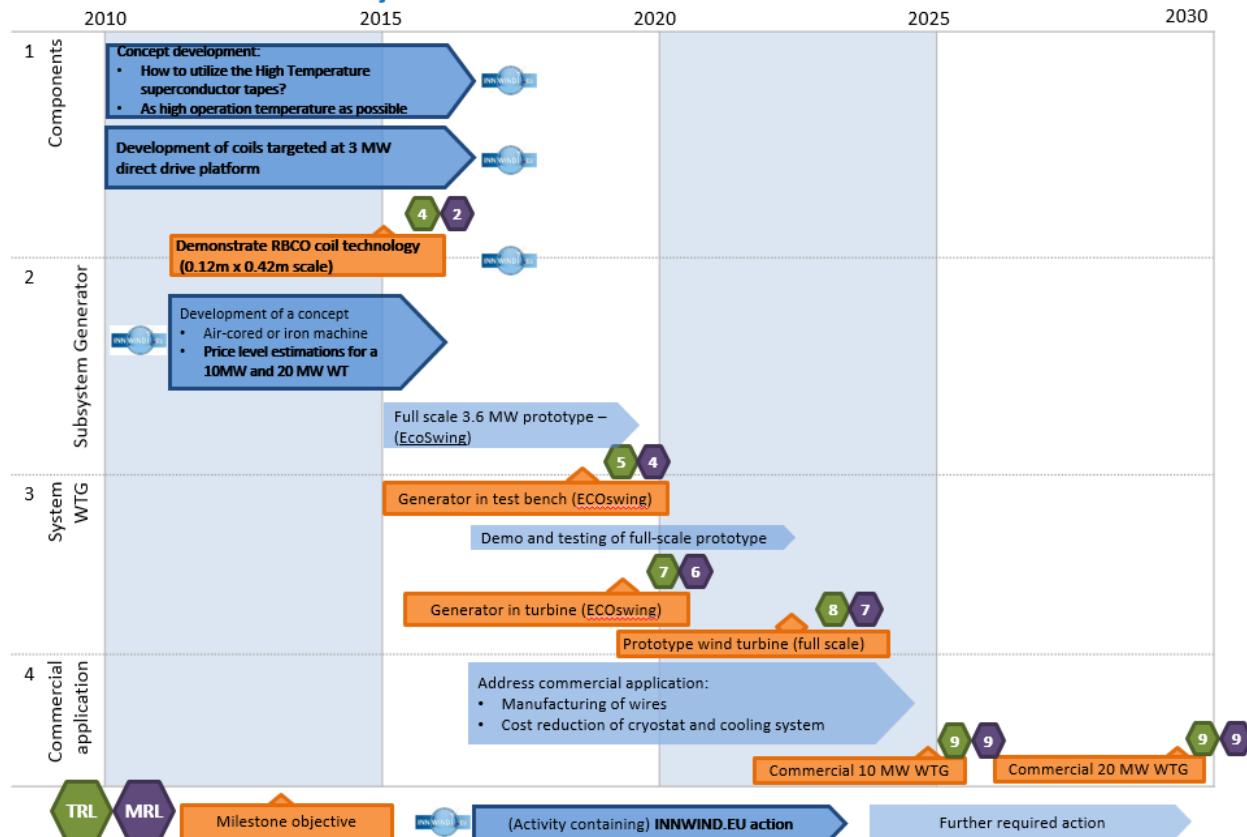


Figure 4-8 Technology roadmap of YBCO wire choice

4.3 Pseudo direct drive generators

Present status

The PDD technology has been developed from initial research into magnetic gears that was undertaken at Sheffield University. Magnomatics has developed the basic gear technology into a variety of electrical machines up to 1 m diameter. The market for several sectors has been investigated by Magnomatics and certain markets with high potential for commercialisation of larger machines have been identified, typically large, offshore wind installations, marine propulsion and several industrial applications.

The technology has been proven in smaller machines, but there are challenges in scaling the machines to greater than 10MW scale.

The advantages of the PDD for large offshore wind turbine applications are the relatively small size and low weight, high efficiency and low maintenance requirements.

Currently wind turbine drive systems can be broadly categorised as geared drive or direct drive. It is argued that for large offshore applications the adoption of a geared drive system will lead to a

failure rate that, when coupled with the service schedule and logistical difficulties, will give offshore wind turbine systems that are commercially unviable.

To achieve the very high torques at low speeds in direct drive systems, brushless permanent magnet generators are typically used due to their superior torque density and torque-speed characteristics.

However, due to limits on magnetic, electrical and thermal stresses, even when employing high energy rare-earth permanent magnets, the continuous torque output per-unit-volume/mass is limited. The resulting generator required for direct drive is then prohibitively large and the cubic scaling law will dictate that this type of system is not feasible for the large offshore wind turbines considered.

The PDD employs a magnetic gear stage, and the purpose of this is two fold. Firstly the size of the generator is minimised by virtue of the torque converter which is analogous to a mechanical gear in this respect and secondly the (mechanical) gearbox system with the very high “consequence of failure” is removed from the system.

A PDD is a full magnetic and mechanical integration of an electrical generator and magnetic gear. The resulting electrical machine is the Pseudo-Direct Drive (because it has the characteristics of a direct-drive machine, although it uses a magnetic gear to achieve its very high torque-densities).

Challenges and opportunities

The main challenge is one of scaling the technology to large scale machines. A new supply chain will have to be developed to meet the challenges inherent in scaling up of the technology.

The demonstrator will be designed and optimised to both provide experimental validation of the software developed and demonstrate the predicted performance from system modelling under actual test conditions.

Several of the components of the PDD – namely the stator and high speed rotor – are already manufactured in machines of similar size and complexity, therefore manufacturing of these components should be relatively risk free. There has been a progressive development in increase of size of the unique, product type specific components manufactured under various development programmes – specifically the pole piece rotor. The challenge of manufacturing this component to meet the demands of 10MW and 20MW machines had been considered during these development programmes and scaling to the size required for 10 and 20MW is included in the modelling phase of the programme under deliverable 3.21.

Developed within INNWIND.EU

Through the INNWIND.EU programme a number of representative technology demonstrators have been designed, manufactured and tested and the design software and optimization tools significantly advanced and verified through these scaled demonstrators.

- 1) The University of Sheffield developed analytical models for the rapid analysis, and hence optimisation, of large diameter magnetic gears and magnetically geared electrical machines. The analytical models were verified through numerical finite element models and shown to have a high degree of correlation.
- 2) These analytical tools were employed to optimise 10MW and 20MW designs with optimisation criteria such as maximum airgap shear stress and overall efficiency, whilst

minimising the mass of rare-earth PM materials, employed. The achievable efficiencies were >98.5%. The dimensions of these optimised machines were then employed in structural concept designs to predict the RNA mass. The predicted generator mass of 150tonnes (50 tonnes active) shows significant benefit over typical direct drive and those predicted for SC generators.

- 3) The analytical tools were used to predict the performance of the 5kNm scaled demonstrator manufactured by Magnomatics and showed good agreement both on the prediction of local field quantities, and the induced voltage, torque and efficiency.
- 4) An initial scaled demonstrator (150kW / 5kNm) was designed, manufactured and tested by Magnomatics. Results showed good agreement with the UoS model at speeds/frequencies representative of a large wind turbine.
- 5) A further scaled demonstrator (300kW / 16kNm) was introduced into the project at a later stage. However, the initial manufactured unit suffered from number of deficiencies that were addressed under the InnWind project.
- 6) The stator had initially been wound with copper strip windings. These suffered from excessive AC losses (due to proximity effects) which were causing an additional 7kW of copper loss. This incurred a penalty of around 1.5% on the efficiency. Under the Innwind project this stator was rewound with Litz wire, with additional slot-to-slot transposition and re-tested. This saw an increase in rated efficiency from 94% to 95.5%.
- 7) The pole-piece rotor employed in the initial design, manufactured from discrete pole-pieces, GF spacers and metallic tie-bars, had been labour intensive to manufacture (and would not scale well) and had metallic strengthening tie-bars which added a parasitic loss, reducing efficiency. Further, there were concerns over the modal excitation of the structure and issues of noise and vibration (the latter potentially contributing to premature failure of the structure). This arises from the requirement to make the structure stiff in order to handle the very high torque loads and the radial pull of the permanent magnet rotors. Under the Innwind project, a number of alternative pole-piece rotors were designed, and the most promising structure manufactured and tested with in the 300kW, 16kNm PDD. This employed a monocoque/monolithic structure wound with a bespoke lay-up of fibre composite material with damping layers (constrained layer damping material).
- 8) The lessons learned from these two demonstrators are being employed in the design of a 500kW, 225kNm wind turbine generator being designed under the DemoWind CHEG (Compact High Efficiency Generator) project. This is a 2.4m diameter machine that will provide an additional scaling point on the roadmap towards multi-megawatt machines.

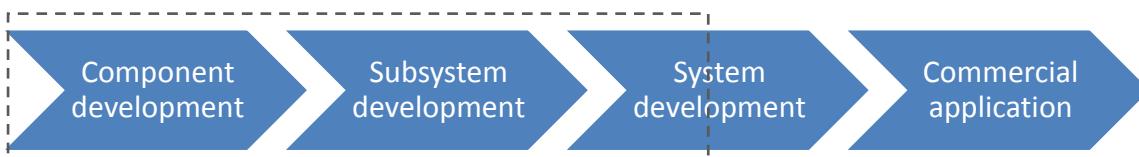


Figure 4-9: INNWIND.EU scope for research into the pseudo-direct drive generator

Expected final result

- 1) The design of full scale 10-20MW PDD machines optimised using validated analytical design tools.
- 2) Validation of design tools using a 5kNm scaled demonstrator.
- 3) 5kNm and 16kNm scaled demonstrators experimentally validated, providing scaling points along the roadmap towards larger machines and verifying the achievable efficiency of the PDD.
- 4) A de-risked pole-piece rotor structure (a key and unique component within the PDD) and a coherent, multi-physics design methodology for pole-pieces of various sizes.
- 5) The Innwind consortium will be briefed on the detailed design of a 500kW, 225kNm scaled demonstrator of a wind turbine generator, based on the lessons learned from the two previous scaled demonstrators, funded by the DemoWind CHEG project.

Further developments

The 500kW /225kNm DemoWind CHEG generator will be manufactured by Magnomatics and project partner ATB Laurence Scott in H2-2017. The machine performance will be validated at the UK's Offshore Renewable Energy Catapult (OREC) in Blyth at the end of 2017/early 2018. The generator from this project will then be tested further (e.g. endurance testing on a dynamometer) under a further DemoWind project (CHEF) by project partner Norvento, manufacturer of small-medium Wind Turbine based energy systems based in Spain, in 2018. A further programme, under which the 500kW generator will be integrated into a nacelle and operated up a pole in an experimental wind farm is anticipated.

Once the larger scale machine has been validated (at scale) a programme to establish a definite route to market within the large offshore wind market is envisaged, with similar opportunities in markets with similar performance requirements, such as marine propulsion and some large off-road automotive markets identified.

Full scale prototypes will be developed in partnership with OEM's to establish the PDD in utility scale wind turbine and other identified applications.

Technology roadmap

See Figure 4-10.

TECHNOLOGY ROADMAP – PSEUDO DIRECT DRIVE GENERATOR

Activities and milestone objectives

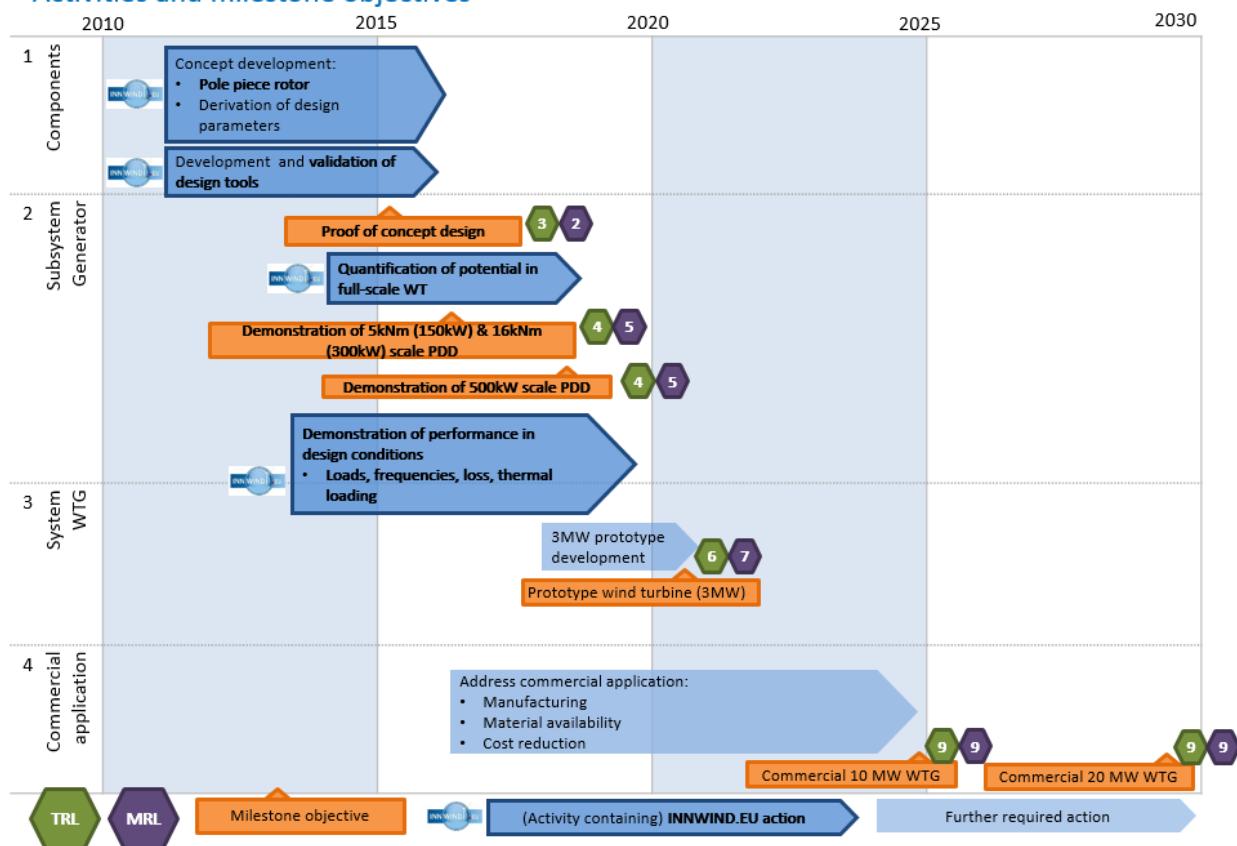


Figure 4-10: Technology roadmap Pseudo direct drive generator

CHAPTER 5 INNOVATIONS FROM WORK PACKAGE 4

5.1 Introduction

Work Package 4: Support structures, description and objectives

The innovations in Work Package 4 “Offshore foundations and support structures” are related to different support structure types; bottom-mounted and floating support structure types.

Currently complex bottom-mounted support structures are not available for mass-production at reasonable costs. Therefore support structures need to be developed that reduce costs and at the same time enable mass-production and better logistics (i.e. installation).

Floating support structures are not commercially available yet and therefore here the driving goal is to enable floating structures an entry as a commercially available alternative, also on a competitive level compared to bottom-mounted alternatives.

Development levels

The division in development phases is as follows:

- 1) Component level: e.g. materials, welds, ballasting, pumps, mooring system
- 2) Subsystem level: support structure development
- 3) System level: prototype development
- 4) Commercial application

It should be noted that the tower is considered a part of the support structure. It is feasible to develop a new support structure without the need of developing and prototype testing of a new turbine, however, active load mitigation concepts via the turbine can enable lighter and thus more cost-effective designs of the support structure. Thus, the turbine has an influence factor towards the support structure, which will also be considered in the project by integrated design methods and simulations of the system “offshore wind turbine”.

For the two support structure types, different activities in the development phases are to be expected due to the present status and type of structure.

System impact

As stated, a support structure is not expected to influence the overall design and cost optimisation of the turbine. But, this is only valid as long as its natural frequencies do not affect the overall system dynamics in a too negative way. The turbine has of course a significant influence on the support structure in terms of structural frequencies and loads. Therefore it will also be considered if and how novel turbine controls can be used to positively influence the support structure. This will obviously always be considered in a cost of energy perspective, i.e. the savings in support structure costs have to be compared in relations to losses in the turbines (power) performance and cost of load mitigation measures (for example, greater pitch travel with IPC making pitch bearing/drives more expensive, active features on blades).

System costs

An optimum support structure design needs to take BOP and O&M into consideration. Here the goal will be to develop support structures that are cost effective in CAPEX (i.e. their fabrication costs), but also having a positive effect on OPEX-related topics, such as O&M, and overall project logistics, such as transport, installation and decommissioning.

The material and fabrication costs to be addressed include the direct material costs, such as steel tonnage, the fabrication costs, such as welding and material handling costs.

Assessment of transport and installation (T&I) costs are vital for support structures. This includes assessing the weather sensitivity of the installation, determining the operational requirements for installation vessels, and assessing the installation flexibility w.r.t. local soil conditions and water depth. Vessel capacity and installation strategy are also of impact on the T&I costs will be assessed in the project.

For the Operation and Maintenance costs of the entire structure, the support structure and the wind turbine, accessibility is an issue. For the floating support structure, the dynamic behaviour will be of influence on the accessibility.

5.2 Low-cost bottom-mounted support structures

Present status

At present there is some insecurity in the industry regarding the type of offshore support structures. In the past, monopile structures were the governing foundation type, as most of the developed offshore sites were in shallow water and used wind turbines with an installed capacity of less than 4 MW. After that period, the first medium- and deep-water projects with turbines in the 5 to 6 MW range supported by complex structures like jackets were enabled with significant problems in terms of costs and logistics for the support structure. Due to that, the current trend in the market goes back to monopiles, as this technology is fully understood and the risks are considered much lower compared to complex support structures like jackets, in particular with respect to fabrication and the related supply-chain. The support structure supply-chain currently prepares itself for so-called XL monopiles, which are piles with diameters of up to 10m and overall tonnages of more than 1500t.

Looking at the goals of INNWIND.EU, this trend is setting the scene for the project. The currently discussed XL monopiles might still be cost-effective solutions for turbines in the 5-7MW class, but not for turbines in the scale of 10-20MW as studied in INNWIND.EU. Therefore jackets structures will be required again in some years as soon as these large >10MW turbines are becoming commercially available. Therefore the goal with respect to bottom-mounted structures within INNWIND.EU must be to develop innovation that enables jackets to become a cost-effective solution for turbines in scale of >10MW. Here in particular the current risks seen in the market need to be mitigated by developing modular structures suitable for series production. For the cost-effectiveness of such jackets, new types of materials and components will be analysed as new materials as well as other innovations are relevant to ensure low CAPEX.

Challenges and opportunities

The main challenge in this work package is the derivation of necessary innovations on the component level and the final combination of such developments within an overall structural application. In the overall project, the entire scope of design, fabrication, and Transport&

Installation (T&I) have to be considered for the evaluation of the cost-effectiveness of an innovation in the support structure.

A cost model will be developed to estimate the cost reduction expected to be achieved.

Also, synergies between other R&D projects will likely provide an opportunity by enabling cross-project knowledge transfer. The cooperation with industry partners in the work package will ensure a close link with the future application of the innovative support structures.

Developed within INNWIND.EU

For bottom-mounted structures, the focus will be on innovative structural designs on the component level (e.g. new materials, new structural parts and new types of fabrication and installation techniques) as well as on novel structural designs, such as suction bucket foundations.

Finally a close link to the wind turbine shall be enabled and thus turbine controls can actively be used to enable more cost-effective support structure designs. This is ensured by including the turbine within the integrated design process in WP4 and by enabling a close link to the other activities within INNWIND.EU in the area of controls and load mitigation concept development.

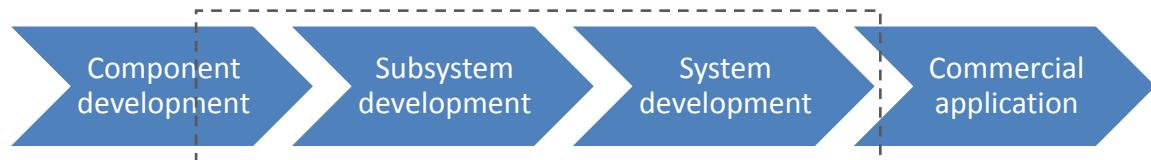


Figure 5-1: INNWIND.EU scope for bottom-mounted support structures

Expected final result

The expected final results are designs of bottom-mounted support structures for large wind turbines and/or water depth that enable significant cost reduction: approximately 20% compared to the cost level at the start of INNWIND.EU. This includes the ability to produce these structures in large numbers as well as in a modular manner to ensure an application within offshore wind projects down to 50m water depths.

Further developments

In order to transfer the results to “commercial applications”, the results need to be made available to fabricators and the supply-chain, i.e. the final applicators of such concepts.

Technology roadmap

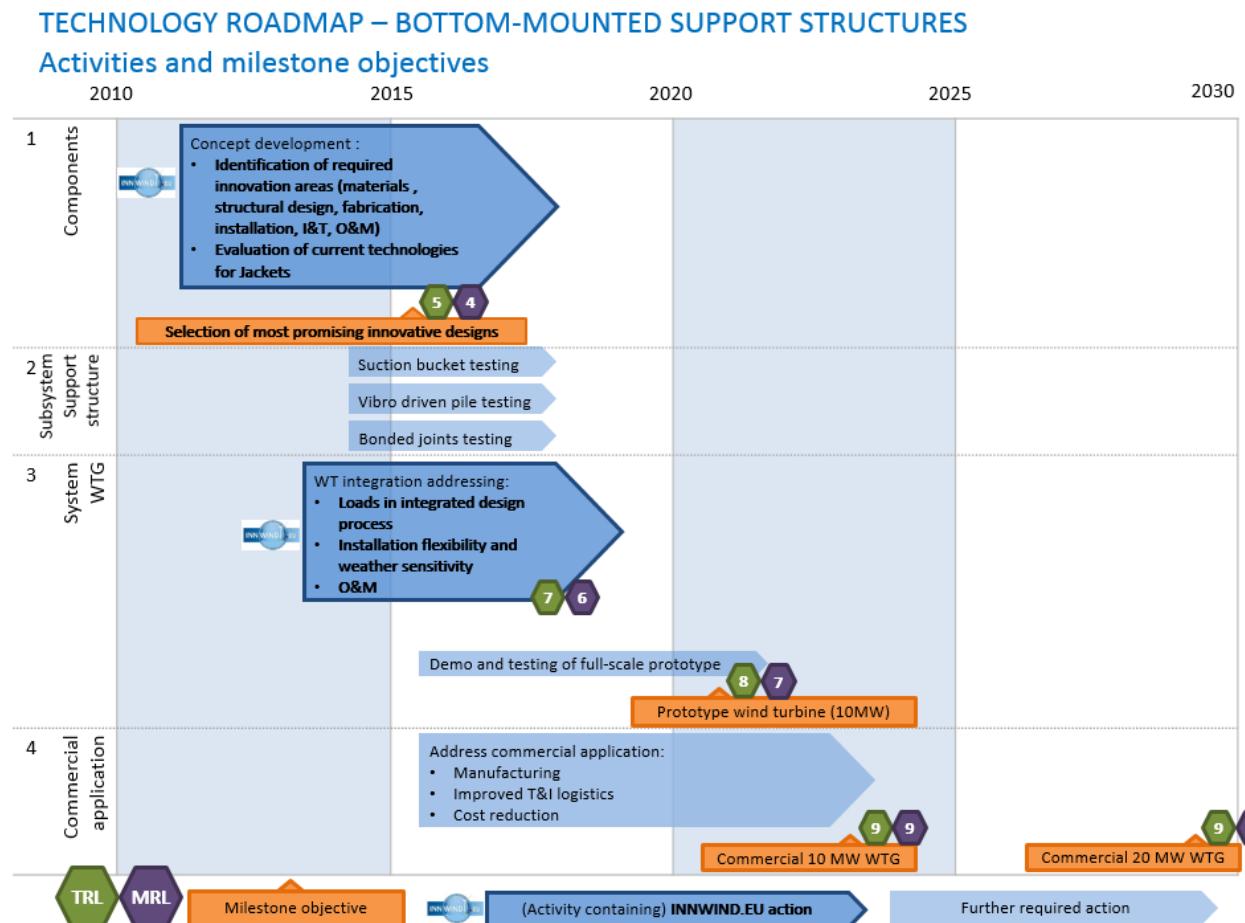


Figure 5-2: Technology roadmap bottom mounted support structures for wind turbines

5.3 Cost effective floating support structures

Present status

At present, there are some prototypes of scaled floating support structures that have been tested, but no commercial floater is available at present. Furthermore, the used design methods and standards have just been established and further validation, for example with the aid of scaled-tests, is still necessary.

This status defines the scope of the development in WP4 on floating support structures, which is the validation of methods for the design of floating structures and the derivation of concepts that fulfil commercial criteria, such as competitive costs compared to bottom-mounted alternatives taking into account fabrication and installation.

Challenges and opportunities

The detailed engineering of a floating structure including concepts for fabrication and installation is a challenge for cost-effective floating support structures. Furthermore there are still difficulties to achieve an integrated system approach for the design process compared to bottom-fixed solutions. The experience in this area is still limited.

Within INNWIND.EU, although the cooperation between a large number of partners can be challenging, the inclusion of major stakeholders within the project form an opportunity for the development of floating support structures. INNWIND.EU includes the wind turbine as a focus area and synergies between the advancement in controls and the identification of key factors like stability and low load levels for floating structures are expected. Also, INNWIND.EU provides the link to commercial application; this link is often found to be lacking in other R&D projects.

Developed within INNWIND.EU

For floating support structures, the focus will lie on the development of the right design environment (tools and processes) and the subsequent direct application within concept development. The objective is the development of concepts applicable for large turbines.

Finally, a close link to the wind turbine shall be enabled and thus turbine controls are to be used actively to enable more cost-effective support structure designs. This will be in close collaboration with other work packages within INNWIND.EU and other ongoing R&D projects.

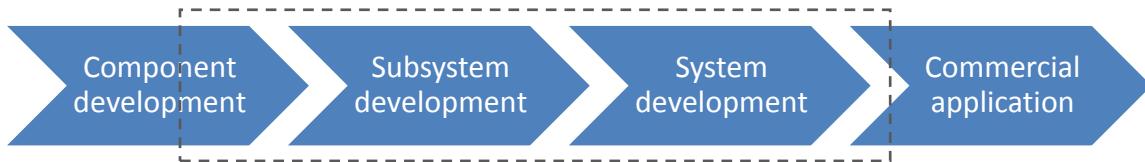


Figure 5-3: INNWIND.EU scope for floating support structures

Expected final result

The expected final results are validated design methods and procedures as well as structural designs of floaters that fulfil commercial criteria with respect to cost, but also fabrication and installation in large numbers.

Further developments

In order to transfer the results to “commercial applications”, the results need to be made available. This will be ensured through the involved industry-partners within the work package, but also close collaborations to other initiatives, such as the OC4 project.

Technology roadmap

See Figure 5-4.

TECHNOLOGY ROADMAP – FLOATING SUPPORT STRUCTURES

Activities and milestone objectives

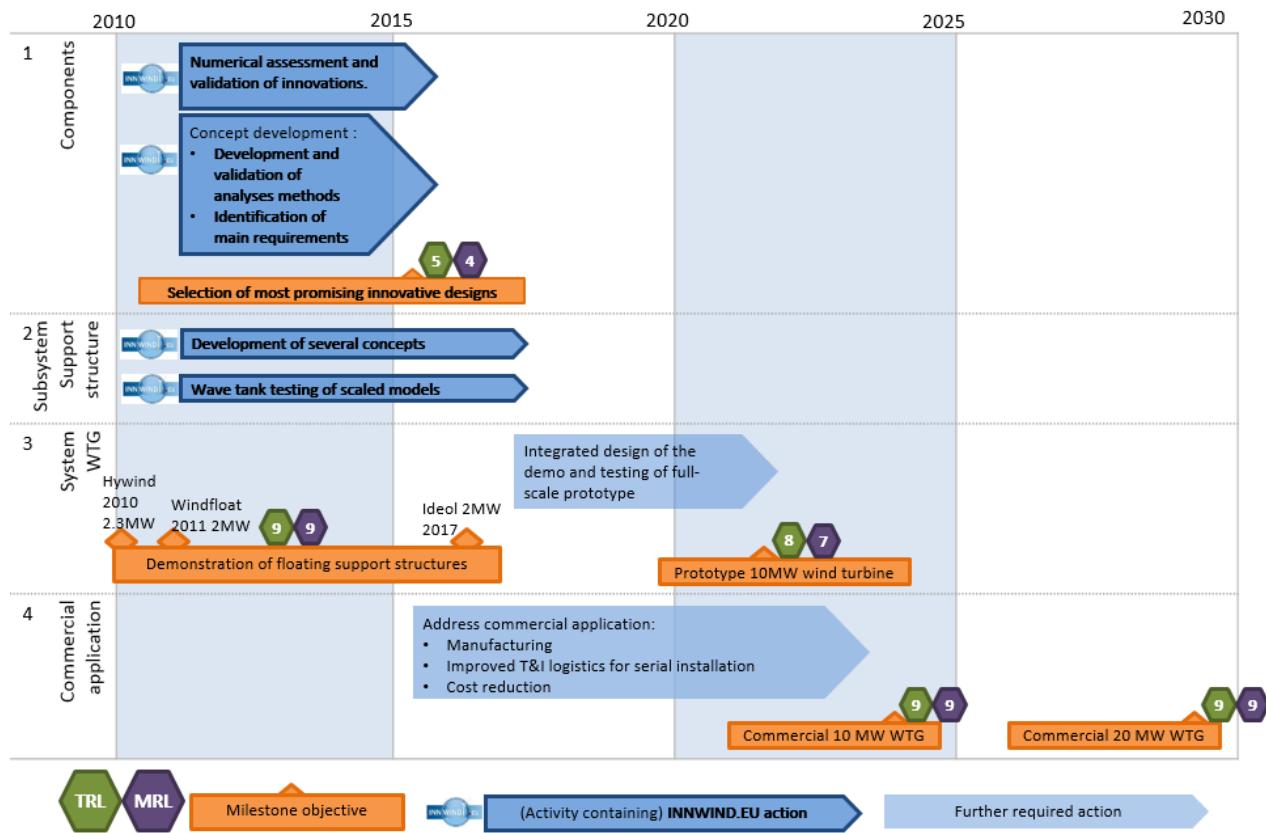


Figure 5-4: Technology Roadmap cost effective floating support structures

CHAPTER 6 CONCLUSIONS

Technology roadmaps for all major innovations in the project have been defined. These technology roadmaps have sufficient detail to facilitate discussions about reducing the time-to-market of these innovations and to reduce risks. Within work package 5 the technology roadmap has been used as a starting point for identification of requirements for standards and guidelines in the task 5.2.

A few key conclusions are outlined below:

- Active controls for Smart blades – trailing edge flaps. The project successfully demonstrated this technology and further validated simulations models. Given the conclusions with the 20MW scale wind turbine, as in that the conventional pitch bearing at the blade root is unfeasible, trailing edge flaps will likely have a very key roll in realisation of new rotor technology.
- Superconducting technology requires further development to achieve reliability (automated manufacture/winding process) and at current prices for SC wire and PM material, its not economic, however there are strong motivations for nacelle mass reductions at 20MW scale where there are no penalties in terms of support structure costs as the 1st mode frequency is already low enough, even with nacelle mass reduction (unlike at 7-10MW scale)
- Of all the technologies developed as part of the project, the PDD is has perhaps the clearest route to market with plans already in place for a 500kW wind turbine prototype next year and some side discussions with another participant about possible development of a larger scale PDD wind turbine.
- 20MW reference turbine – although manufacturing technology does not yet exist for a lot of aspects of this, many of the technologies developed within Innwind EU will help facilitate the route to market. One very key outcome of the project is the conclusion that at 20MW scale, the 1st mode frequency is naturally lower, leaving the way clear for much more optimum support structure design (bigger foot print, stiffer and lighter), also mass savings in the nacelle, for example as could be achieved with SC technology.

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APPENDIX A: TECHNOLOGY READINESS LEVELS (TRL)

TRL definitions from the European Community (EC) are below as described in [2]. A more extended description and supporting information are copied from [6].

EC definition of Technology Readiness Level (TRL) [2]	DOD definition of Technology Readiness Level (TRL) [6]	Description [6]	Supporting information [6]
TRL 1 – basic principles observed	Basic principles observed and reported	Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.	Published research that identifies the principles. References to who, where, when.
TRL 2 – technology concept formulated	Technology concept and/or application formulated	Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
TRL 3 – experimental proof of concept	Analytical and experimental critical function and/or characteristic proof of concept	Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
TRL 4 – technology validated in lab	Component/subsystem validation in laboratory environment	Standalone prototype implementation and test. Integration of technology elements (first step to see if components work together). Experiments with full-scale problems or data sets.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	System/subsystem/component validation in relevant environment	Thorough testing of prototype in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the “relevant environment” differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
TRL 6 – technology	System/subsystem model or	Prototyping implementations on full-scale realistic problems. Partially	Results from laboratory testing of a prototype system that is near the

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demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	prototype demonstration in a relevant environment	integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application	desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
TRL 7 – system prototype demonstration in operational environment	System prototype demonstration in an operational environment	System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
TRL 8 – system complete and qualified	Actual system completed and qualified through test and demonstration in operational environment	End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	Actual system proven through successful mission operations	Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.	OT&E reports.

APPENDIX B: MANUFACTURING READINESS LEVELS (MRL)

MRL definitions found for the EC and DOD are the same [3, 7]. Extended descriptions are copied from copied from [7].

Manufacturing Readiness Level (MRL) [3, 7]	Description [7]
MRL 1: Basic Manufacturing Implications Identified	The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies.
MRL 2: Manufacturing Concepts Identified	This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined needs. This typically includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.
MRL 3: Manufacturing Proof of Concept Developed	Beginning of the validation of the manufacturing concepts through analytical or laboratory experiments. Materials and/or processes have been characterized for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess some limited functionality.
MRL 4: Capability to produce the technology in a laboratory environment	Technologies should have matured to at least TRL 4. Required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
MRL 5: Capability to produce prototype components in a production relevant environment	Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.
MRL 6: Capability to produce a prototype system or subsystem in a production relevant environment	Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes completion of S&T development and acceptance into a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design of critical components has been completed and producibility assessments of key technologies are complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a production relevant environment. A

Manufacturing Readiness Level (MRL) [3, 7]	Description [7]
	<p>cost analysis has been performed to assess projected manufacturing cost versus target cost objectives and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment (ICA) has been completed. Long-lead and key supply chain elements have been identified.</p>
MRL 7: Capability to produce systems, subsystems, or components in a production representative environment	<p>Technologies should be on a path to achieve TRL 7. System detailed design activity is underway. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Production tooling and test equipment design and development have been initiated.</p>
MRL 8: Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	<p>Technologies should have matured to at least TRL 7. Detailed system design is essentially complete and sufficiently stable to enter low rate production. All materials are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. The engineering cost model is driven by detailed design and has been validated with actual data. The Industrial Capabilities Assessment for Milestone C has been completed and shows that the supply chain is established and stable.</p>
MRL 9: Low rate production demonstrated; Capability in place to begin Full Rate Production	<p>At this level, the system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials are available to meet planned rate production schedules. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets have been met, and learning curves have been analysed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement.</p>
MRL 10: Full Rate Production demonstrated and lean production practices in place	<p>System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. Engineering/design changes are few and generally limited to quality and cost improvements. All materials, tooling, inspection and test equipment, facilities and manpower are in place and have met full rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.</p>