Initial roadmap with path from innovative project results towards implementation in the market

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CHAPTER 1 INTRODUCTION

1.1 Innwind.EU

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

This document describes the initial technical 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:

- Prerequisites and possible show-stoppers 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. This initial roadmap will be further developed in the next stages of the project.

1.2 The chosen major innovations of the Innwind.EU project

In Innwind.EU WP 5, technology roadmaps will be described for six major innovations indicated in the Description of Work: two innovations arising for work packages 2-4 each. Later in the process it was decided to add the low temperature superconducting generator to the list next to the high temperature superconducting generator. The six chosen innovative subsystems for the technology roadmaps are:

1. WP2: Active control for smart blades
2. WP2: Passive control and structural optimisation for lightweight rotors
3. WP3: Superconducting generators
4. WP3: Pseudo direct drive generators
5. WP4: Low-cost bottom-mounted support structures
6. WP4: Cost effective floating support structures

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 6 chosen subsystem developments.

Work Package Subsystem	Subsystem innovation	Description	Responsible partner
WP2: "Lightweight rotor"	Active control for Smart blades	Hardware demonstration: Full scale test in the field at 2 MW wind turbine	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	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

1.3 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 as stated in Figure 1-1.

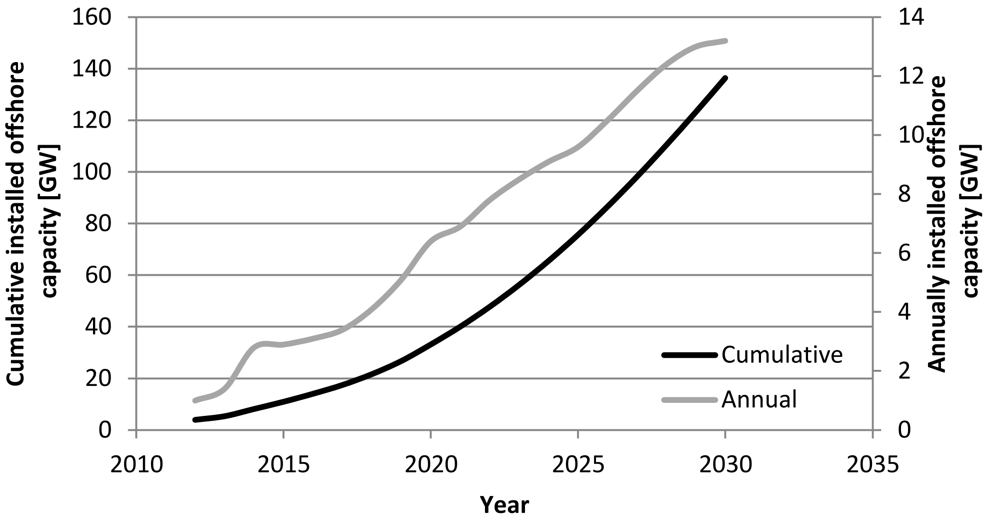

Figure 1-1: Annual and cumulative installed offshore wind, based on EWEA estimates.

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 fourth level, 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 following activities can be identified in each phase:

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

For each innovation, it will be presented which type of activities in which phase are included in Innwind.EU project.

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 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 work package, 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 roadmaps

For the development of the road maps, first the present status and its expected advantages are identified. The present status entails which phase the innovation was in before the start of the Innwind.EU project.

For each phase, challenges are identified: these 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 need 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 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 road maps, all seven technology roadmaps are depicted according to the same legend. Challenges are summarised for each phase, and the length of the bar represents the possible duration of the development phase. If the bar ends in a dashed outline and striped fill, this extra duration is possible delay. The activities and expected results within Innwind.EU are named below the graph, as well as remaining future work to be done towards large-scale application that is not addressed within the Innwind.EU project. In Figure 1-2 the legend of the roadmap is more graphically explained.

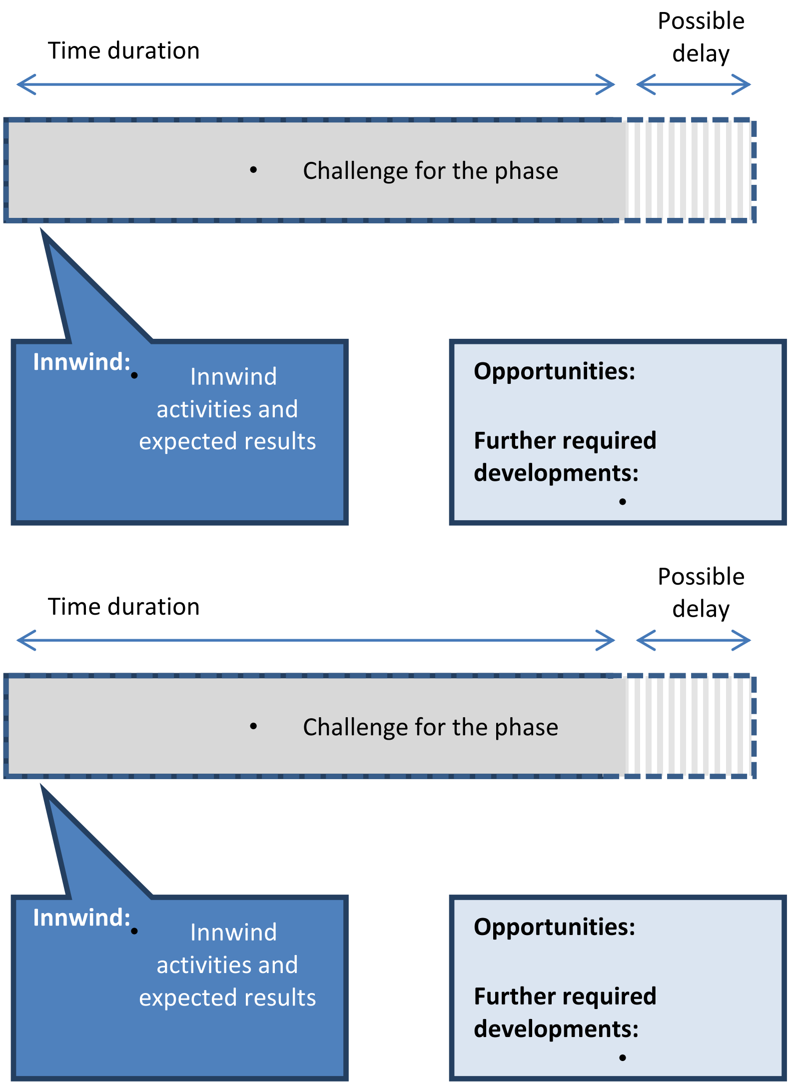

Figure 1-2: Legend for the roadmaps.

CHAPTER 2 INNOVATIONS FROM WORK PACKAGE 2

2.1 Introduction

Work Package 2: lightweight rotors

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 without, too significantly, compromising on power performance. 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 phases

The division in phases is as follows:

1) Component level: actuators, sensors, smart material
2) Subsystem level: blades, rotors
3) System level: wind turbine prototype development
4) Commercial application

The third level of prototype development entails the integration of the active and passive controlled, structurally optimised 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 needs to be analysed.

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.

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 could 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.

2.2 Active control of smart blades

Present status

The desired innovation is a system to perform distributed spanwise local active control 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; however, there is no application in the industry so far.

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.

Timeline

The anticipated timeline for the development of local active control is:

- The development of the component (sensors and actuators): 6 years
- The development of the relevant subsystem: their integration of components into the blade, a rotor with active control: 8 years
- The development of the system: a wind turbine generator (WTG) prototype: 10 years
- The commercial application in large scale implementation in offshore wind farms: 15 years

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

- Overall turbine sensoring 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. The 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 Innwind.EU project, the basic concepts and the evaluation of performance will be developed, as well as the control schemes for passive and active control together, on component/subsystem level, as well as for the entire wind turbine prototype.

In Figure 2-1 the scope of activities for this topic within Innwind.EU is depicted.

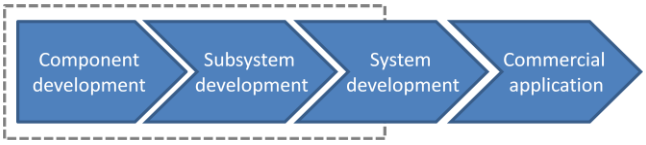

Figure 2-1: Innwind.EU scope for active control of smart blades.

Expected final result

The expected 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, and
- a quantification of the potential of the different concepts in full size wind turbine 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.

Preliminary roadmap

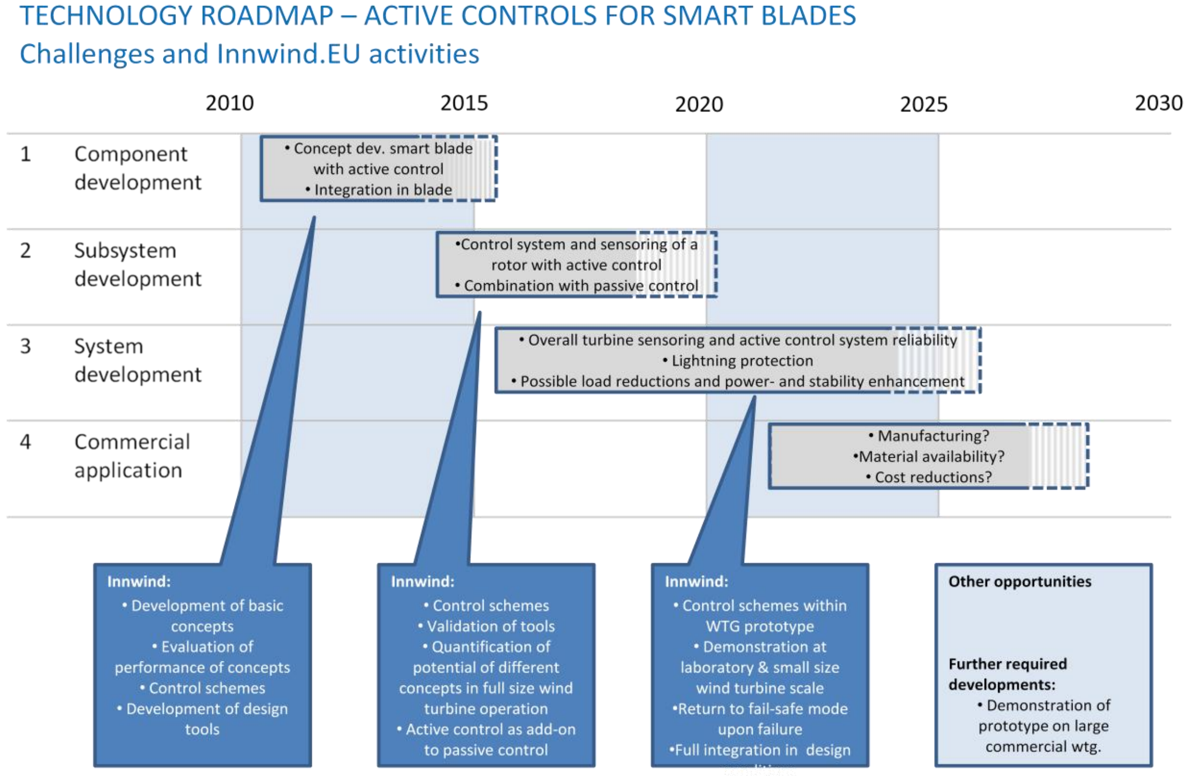

Figure 2-2: Technology roadmap of active control for smart blades

2.3 Passive control and aerodynamic / structural optimisation for lightweight rotors

Present status

The structural optimisation and gradual increase in airfoil 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.

Timeline

The anticipated timeline for the development of lightweight aerodynamic/structural design passive control is:

- The development of the component, blade: 4 years

- The development of the relevant subsystem, rotor with control: 5 years
- The development of the system: a wind turbine generator (WTG) prototype:7 years
- The commercial application in large scale implementation in offshore wind farms: 8 years

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 methodologies and materials. Some appropriate control characteristics, like full pitch control, is probably impossible to obtain by purely passive couplings due to limitations in material characteristics. Morphing airfoils from structural couplings between deformations will also be subject to limitations with the requirements to strength and strain.
- Innovation of appropriate concepts to fulfil requirements might lead to designs that are controversial and would 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 concepts and the evaluation of aerodynamic and structural performance will be developed. Like for a two-bladed teetering rotor, the teetering function is a passive control concept to reduce loads and increase stability, such principles will be integrated in the blade design. Furthermore tools will be developed and validated as well as the basic performance of the concepts.

In Figure 2-3 the scope of activities for this topic within Innwind.EU is depicted.

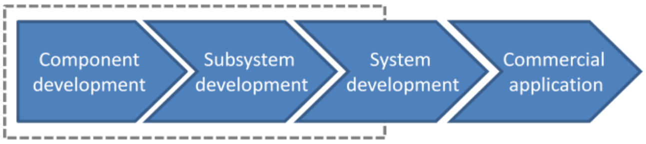

Figure 2-3: Innwind.EU scope for passive control and structural optimisation of the lightweight rotor.

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

Demonstration of prototype on large commercial wind turbines. Further developments will be the implementation of (parts of) the concept into existing blade design by adjusting fibre lay up schemes 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 form the beginning of the design phase.

Preliminary roadmap

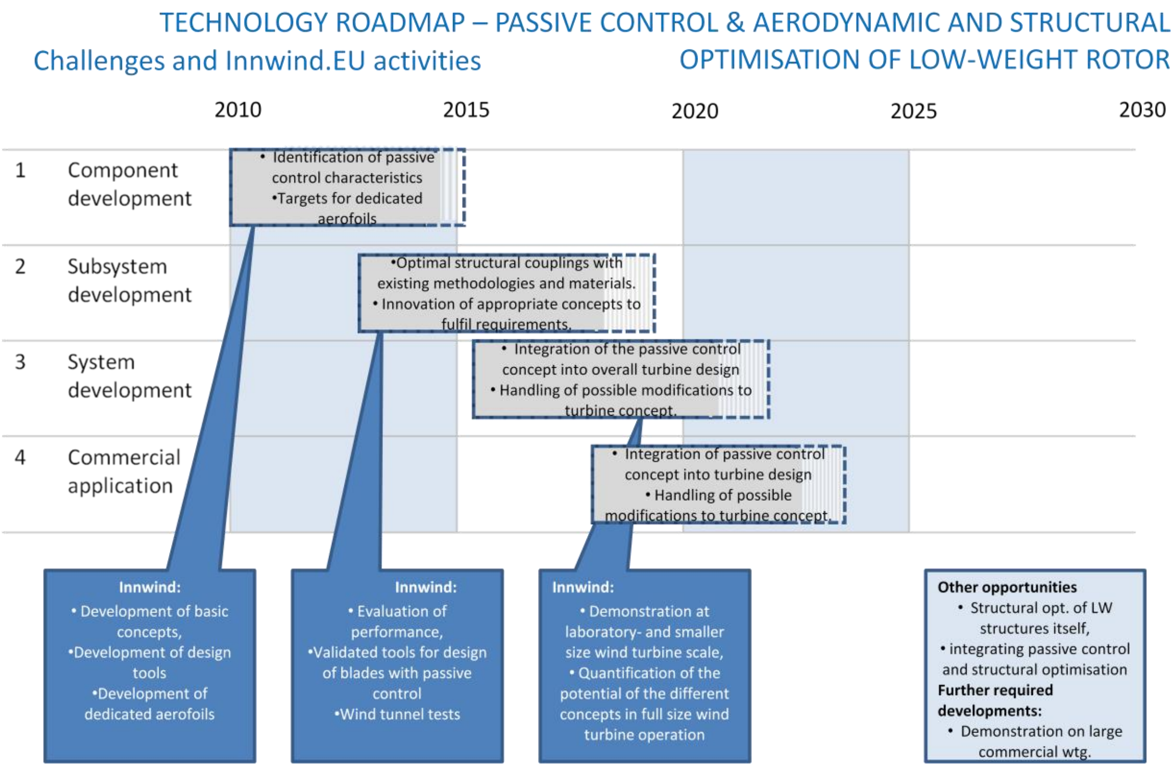

Figure 2-4: Technology roadmap of passive control & aerodynamic and structural optimization of a low-weight rotor

CHAPTER 3 INNOVATIONS FROM WORK PACKAGE 3

3.1 Introduction

Work Package 3: New generators

In Work Package 3 “Electro-mechanical conversion”, the innovative component under development concerns a generator. Both the generator and gearbox are components in the nacelle with high failure rates. 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 phases

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 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 and efficiency a more expensive solution might still be favoured.

3.2 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 (~ 0.6 - 1 ton/MW) in the strong $R_2Fe_{14}B$ magnets. 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 offered by the different types of superconducting wires. The 3 wire candidates are:

1. NbTi, low temperature superconductor, operated at T = 4.2 K,
2. MgB_2 or medium temperature superconductor operated around 10-20 K and finally
3. Second generation (2G) $YBa_2Cu_3O_{6+x}$ (YBCO), the high temperature superconductor tapes operated around T = 20-50 K.

Only the NbTi wire is industrially established and used in large quantities for magneto-resonance-image (MRI) scanners 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 in liquid helium heat pipes possible. The price estimate of the NbTi generator looks quite promising due to the low price of the wire.

Superconductivity in MgB_2 was discovered in 2001 and the development stage of the technology is at coil demonstration at scales suitable for a wind generator. The MgB_2 superconductor wire is now available in long length from a small number of manufactures. 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.

YBCO 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 $YBa_2Cu_3O_{6+x}$, which is becoming superconducting at T = 93 K. This gives the possibility to operate the superconductor at T = 20-40 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 $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (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 K, whereas neon (Ne) offers cooling at T ~25 K and hydrogen (H_2) could be used for T ~ 18 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, MgB_2 or YBCO 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 water 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 do not currently have a turbine where the proposed superconducting direct drive generator can be incorporated, since the GE 4.1-113 wind turbine have the direct drive generator positioned behind the tower and the GE NbTi generator is designed for being installed between the blades and the tower. Thus integration into a specific turbine will need more work.

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 could 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.

MgB_2 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 are limited. Thus demonstration of high field coils suitable for a wind generator is needed. Additional work must be done on the design of the quench protection of the coils.
- 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 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 trough slip rings, but the power needed for that is very small. Are available commercially.
- 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, H_2 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 subsystem where the coils, torque tubes, vacuum and cooling system must be combined and should operate reliable under exposure to 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 MgB_2 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 MgB_2 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 MgB_2 wire is therefore expected to decrease as a result of the learning curve of the MRI technology.

Coated conductor based generator:

Component level:

- YBCO 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 YBCO layer is only 1 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 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 YBCO layer and optimizing the nano-engineering of the defects in the YBCO 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.
- 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<?>.

Timeline

1) NbTi: Could be demonstrated in a turbine at full scale within some years.
2) MgB2: Large coils and subsystem demonstration in a few years. Wire performance improvements needed to make the solution feasible, but this could be provided by the MRI industry.
3) Coated conductor: Coil and subsystem demonstration in a few years. Tape performance must be improved to reduce the amount of tape needed. The wind application will be large for the coated conductor manufactures and can provide the market that makes up-scaling and driving down cost possible. The full scale application is therefore linked to a joint development of the tape technology.

Developed within Innwind.EU

Conceptual generator models will be developed to clarify the physical origin of the performance indicators of 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 will be designed, constructed and tested in order to establish the performance indicators of a MgB2 based generator of 10 MW.

For a high temperature SC generator, a superconducting pole-pair will be 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 a simpler cooling machines, which should be easily replaced and not an integrated part of the cryostat. Thus a concept of a segmented cryostat and torque tube replacing the outer rotor of the present Siemens Wind Power turbines will be developed.

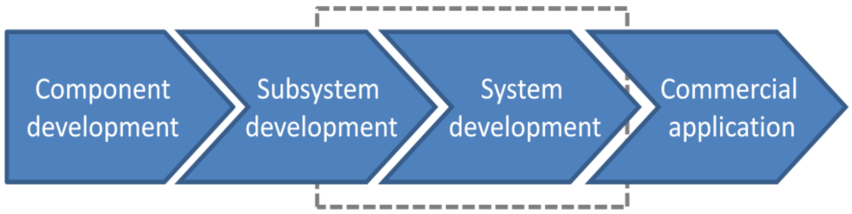

Figure 3-1: Innwind.EU scope for research into the NbTi low temperature superconductor generator.

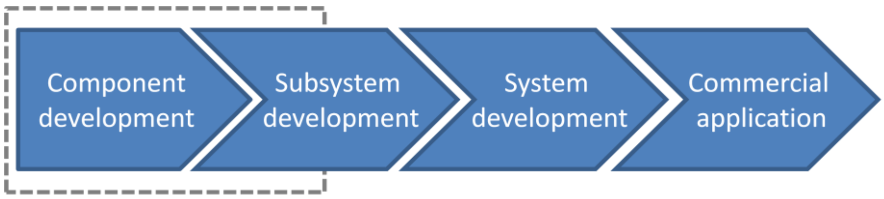

Figure 3-2: Innwind.EU scope for research into the MgB_2 medium temperature superconductor generator.

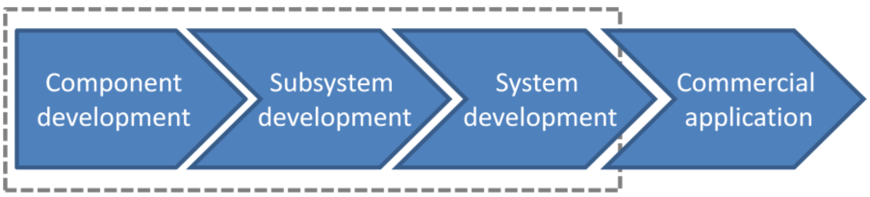

Figure 3-3: Innwind.EU scope for research into the high temperature coated superconductor generator.

Expected final result

- A superconducting direct drive concept targeted at the Innwind.EU reference turbine for rated power levels of 10 to 20 MW as well as a segmented concept suitable for the present Siemens Wind Power direct drive turbines.
- The demonstration of an MgB2 rotor coil.

Further developments

The Cost of Energy evaluation of the Innwind.EU project will indicate how to further develop the superconducting technology by advising what the optimal weight and also price of the generator should be from the offshore turbine point of view.

Preliminary roadmaps

In Figure 3-4 to Figure 3-6 the preliminary roadmaps are given for all three wire choices. Please note that the first, NbTi wire, is not further developed within Innwind.EU and is only added for completeness.

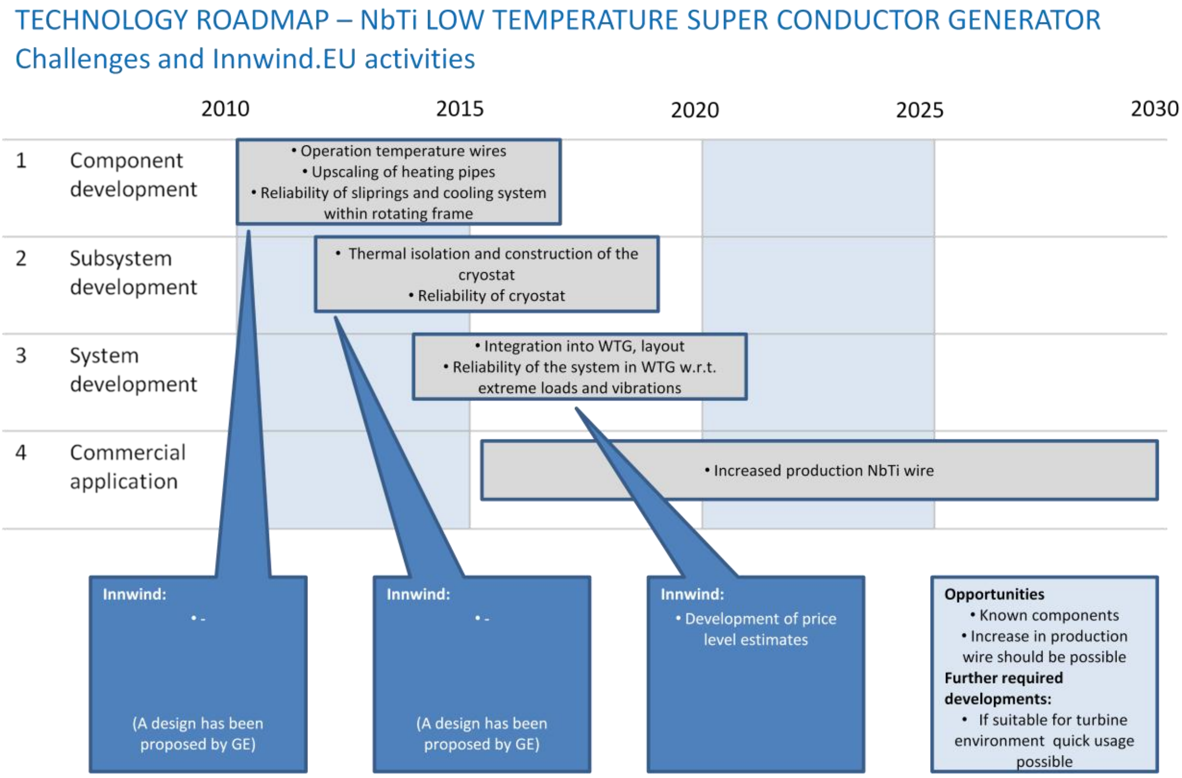

Figure 3-4: Technology roadmap of NbTi wire choice.

TECHNOLOGY ROADMAP – MgB_2 MEDIUM TEMPERATURE SUPER CONDUCTOR GENERATOR
Challenges and Innwind.EU activities

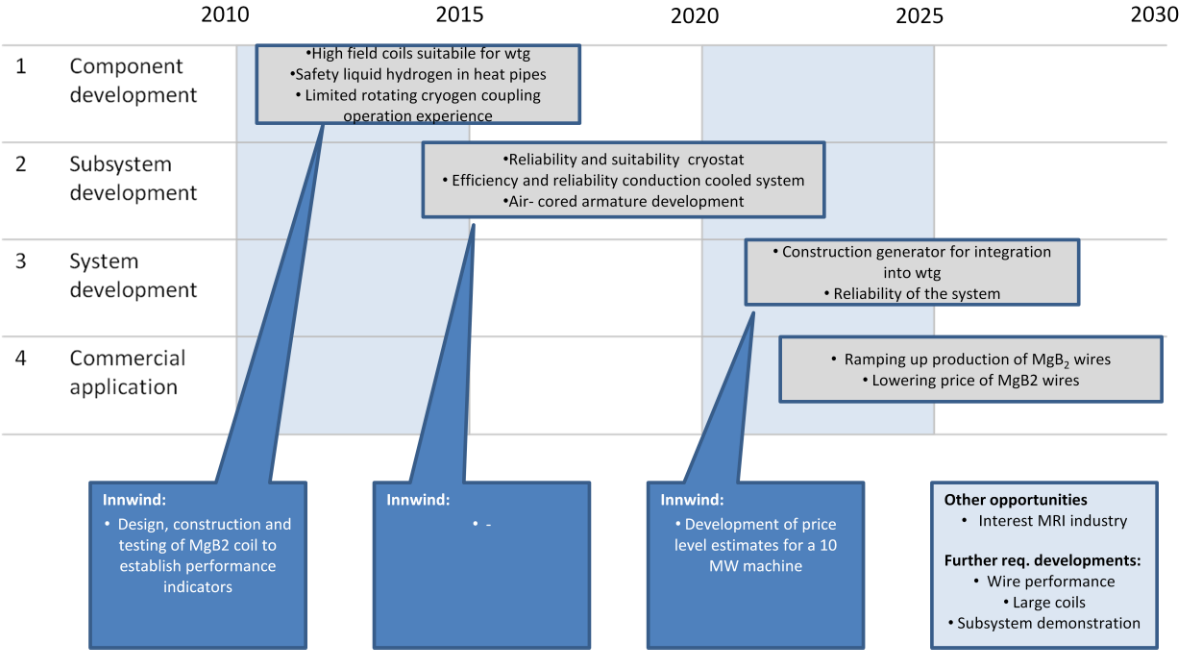

Figure 3-5 Technology roadmap of MgB_2 wire choice.

TECHNOLOGY ROADMAP – YBCO HIGH TEMPERATURE SUPER CONDUCTOR GENERATOR
Challenges and Innwind.EU activities

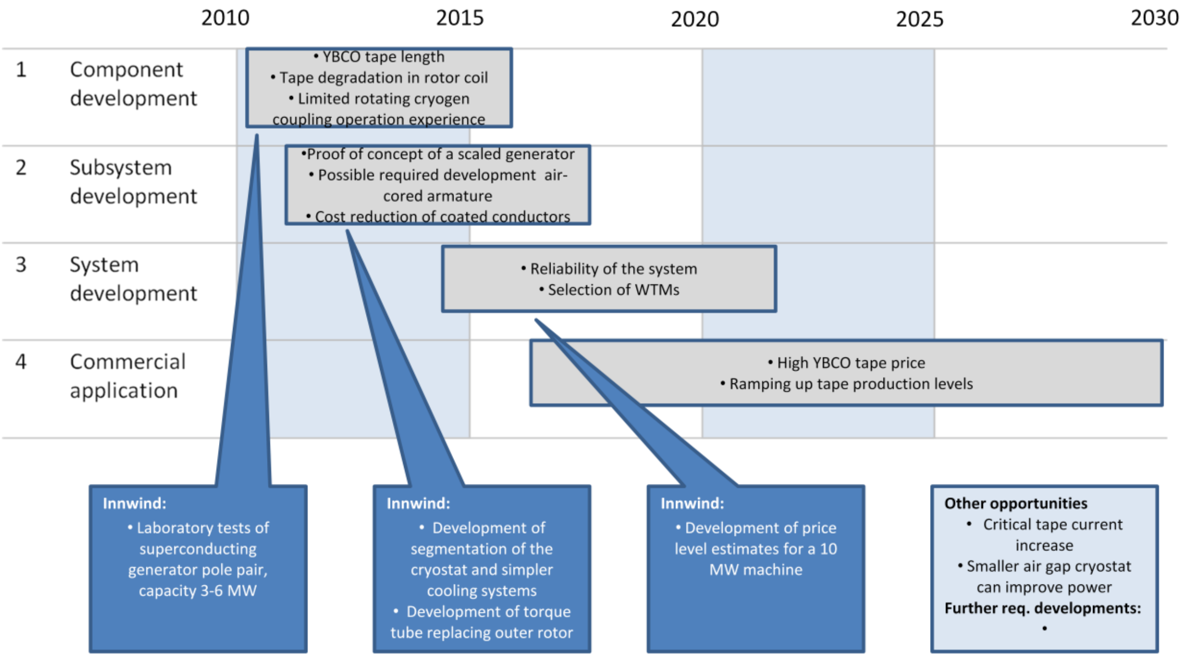

Figure 3-6 Technology roadmap of YBCO wire choice.

3.3 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 motors 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 twofold. 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 manufacture 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.

Timeline

Design of the major components of the demonstrator will be complete by 28/2/2014

The manufacture of the demonstrator will be completed by 3/11/2014

Testing of the demonstrator will be completed by 18/5/2014.

Market research into the potential of multi MW systems is on-going and will be completed by the end of 2013. Parallel marketing exercises on specific variations of this development are ongoing in response to specific customer enquiries.

Developed within Innwind.EU

Through the Innwind.EU programme a representative technology demonstrator will be designed, manufactured and tested by mid-2015. The design will be undertaken and verified using tools developed by the University of Sheffield and manufacturing and test via Magnomatics manufacturing facility. Based upon this work, it is envisaged that specific generators will be designed for specific large scale applications using the tools and techniques developed from the end of 2014 onwards.

The project will include the development of analytical software to allow rapid modelling of large machines. Based upon this development, design parameters for mechanical design and manufacture will be developed, leading to optimisation of the PDD in software. Once optimised, simulations will be undertaken under normal and fault conditions.

The software tool development will engender specific design for a proof of concept demonstration machine and subsequent build of the machine which will be scaled to demonstrate loads, frequencies, loss and thermal loading for a machine in the 10 to 20 MW range. A test programme will confirm actual performance against predicted design parameters.

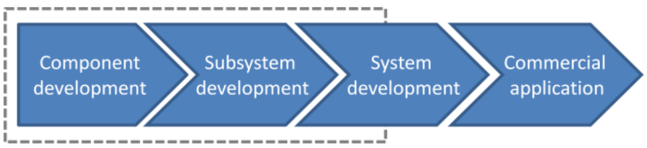

Figure 3-7: Innwind.EU scope for research into the pseudo-direct drive generator.

Expected final result

The design for a full scale 10-20MW machine will be realised as a scaled demonstrator based upon the software design, modelling and optimisation work, This demonstrator will be tested to provide experimental validation of the software based results.

Further developments

Once the larger scale machine has been validated (at scale) a programme to establish a definite osroute 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.

Preliminary roadmap

See Figure 3-8.

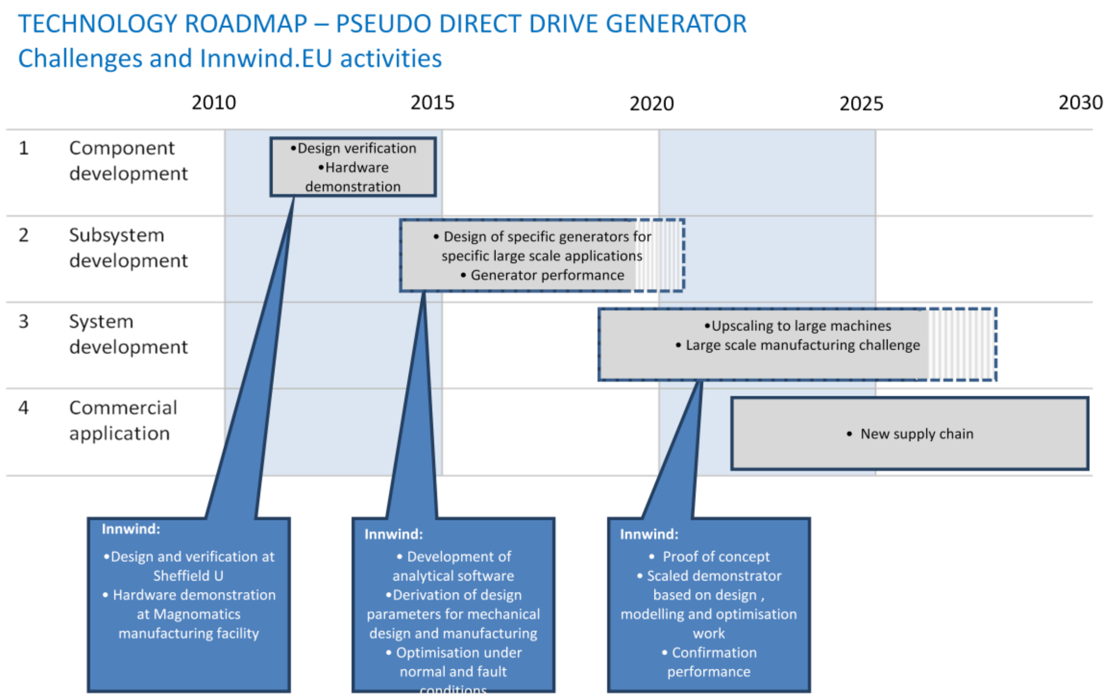

Figure 3-8: Technology roadmap Pseudo direct drive generator.

CHAPTER 4 INNOVATIONS FROM WORK PACKAGE 4

4.1 Introduction

Work Package 4: Support structures

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 phases

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

A support structure is not expected to influence the overall design and cost optimisation of the turbine. It should be noted that the tower is considered a part of the support structure. Therefore it may be 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 it’s 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.

An optimum support structure design needs to take BOP and O&M into consideration. Here the goal will be to develop support structures that 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.

System costs

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.

4.2 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, 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. 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 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 the sizes of some structural members are becoming massive and therefore new materials as well as other innovations are relevant to ensure low CAPEX.

Timeline

The expected timeline for the development phases is divided into developments for wind turbines up to 10MW within the first three years of the project and considerations of solutions for turbines at the scale of 20MW within the last two years of the project. The main milestones can be described as follows:

- Evaluation of current technology for jackets on a component level and development of necessary innovations to enable an overall cost-effective design. The development of a jacket-type support structure and compare it to other innovative designs, such as tubular towers with suction buckets or structures using hybrid-materials.

- Enable commercial application by ensuring knowledge transfer towards the industry
- Derive roadmap for support structure designs in the scale of 20MW wind turbines towards

Challenges and opportunities

The main challenge in this part of the project is the derivation of necessary innovations on the component level and the final combination of such developments within an overall structural application, even in an overall project consideration compromising design, fabrication, transport and installation. However, the opportunity on the other hand is that the project involves for each innovation package leading experts in that area and based on a detailed to be developed cost model it will be possible to evaluate the innovations and measure them against the initial defined goal to reduce costs by 20-30%.

A further opportunity is given by synergies to other R&D projects. Here the goal is to enable cross-project knowledge transfer and by using the industry partners within the work package also guarantee a close link to the future application in the industry.

Developed within Innwind.eu

For bottom-mounted structures, 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 actively be used to enable more cost-effective support structure designs. This is ensured by covering the turbine within an integrated design process in WP4 but as well by enabling a close link to the other activities within InnWind in the area of controls and load mitigation concept development.

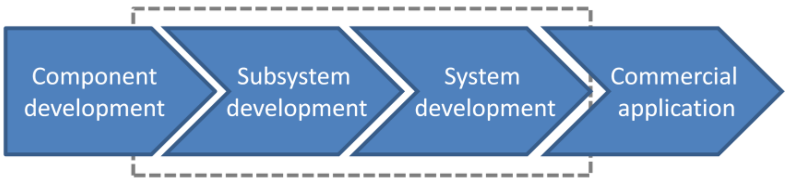

Figure 4-1: Innwind.EU scope for bottom-mounted support structures.

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 (20-30% compared to start of Innwind.EU). This also 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.

Preliminary roadmap

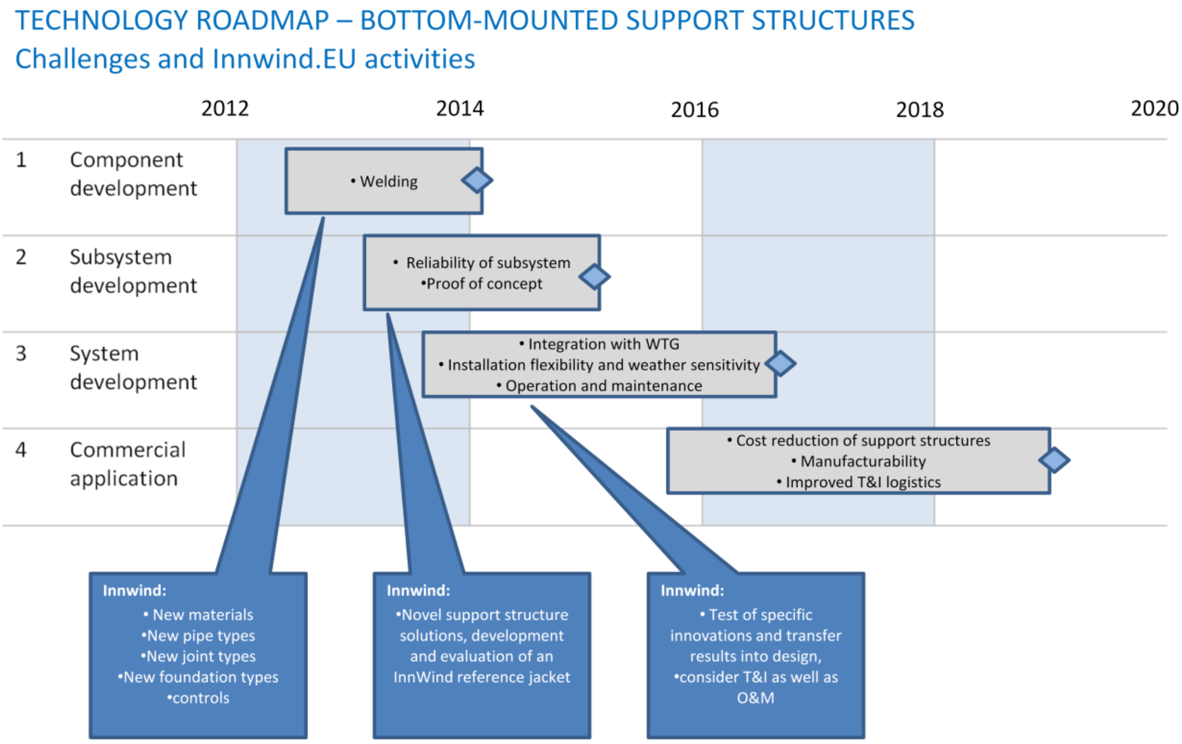

Figure 4-2: Technology roadmap bottom mounted support structures

4.3 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 yet available. Furthermore, the used design methods and standards have just been established and some 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 validation of methods for designing floating structures as well as derive based on that concepts that fulfil commercial criteria, such as reasonable costs compared to bottom-mounted alternatives and aspects like fabrication and installation.

Timeline

For floating structures, adequate conceptual solutions shall be available within the first 3 years; commercial solutions (including detailed engineering) at the end of the project (year 5). The detailed engineering will be supported by scaled-tests of certain promising concepts. The milestones can be defined as follows:

- Evaluation of current design methods for floating structures and development of necessary innovations to enable commercial designs. Conceptual development of two floating designs suitable for commercial application. Integration of the turbine as active element within the design process by considering the overall system dynamics and optimisation (i.e. stability control, load mitigation)
- Backup design methods and the design itself with tests of scaled-models in wave tanks
- Detailed engineering of selected concepts towards a commercial application in large numbers

Challenges and opportunities

The main challenge within this project is the large amount of involved partners and thus methods, which is at the time a large opportunity, as major stakeholders in that technology are cooperating within this work. In addition, close collaborations to other ongoing projects are available. Another opportunity in this project is that the turbine itself is another focus area and thus synergies in relation to controls can be used to enable key factors like stability and low load levels for floating structures. A further challenge is the link towards detailed engineering of a floating structure, including concepts for fabrication and installation, as the experience in this area is still limited. However, this can again Be an opportunity for InnWind to contribute to the development of these structures, as the link to commercial applications are so far often missing in latest R&D projects.

Developed within Innwind.eu

For floating structures, focus will be to enable the right design environment (tools and processes) followed by a direct application within a concept development. Final outcome shall be 1-2 concepts applicable for large turbines.

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

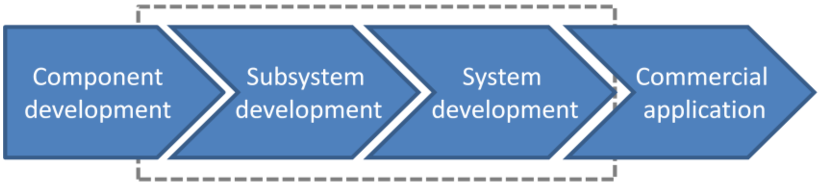

Figure 4-3: Innwind.EU scope for floating support structures.

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.

Preliminary roadmap

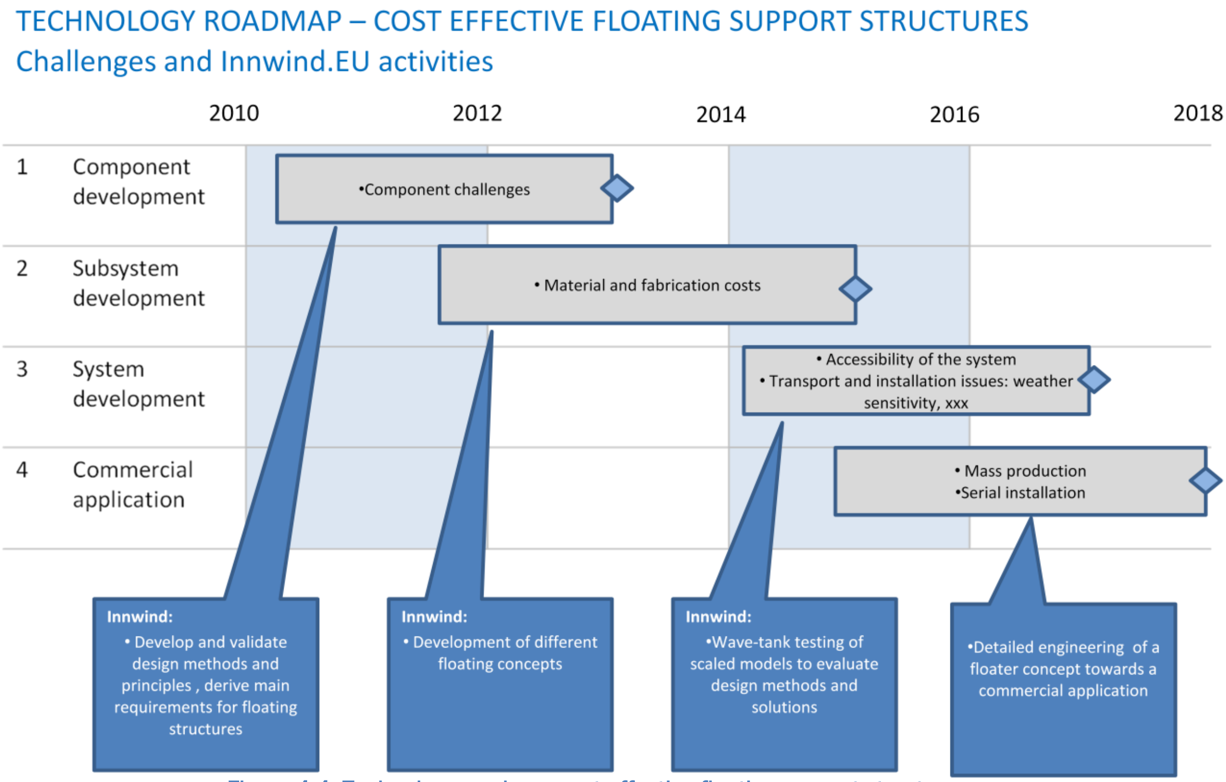

Figure 4-4: Technology roadmap cost effective floating support structures

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

Initial technology roadmaps for all major innovations in the project have been defined. These technology roadmaps have been defined in sufficient detail to facilitate discussions on how to reduce the time-to-market of these innovations, to have further cooperation in the overall project and to reduce risks. Within work package 5 the technology roadmap will be used as a starting point for identification of requirements for standards and guidelines in the task 5.2.

The technology roadmaps will be developed further in the remainder of the project. A number of recommendations for further improvement of the document has been identified:

- The requirements and needs for the innovation, what problems do we need to overcome, can be specified in more detail;
- The definition of the different phases can be made clearer and less ambiguous. It has been decide to adopt a set of design phases defined for aerospace; technology readiness level (TRL). A first evaluation shows that these TRLs can be used to further define the present phases without the need to replace the present development phases completely. Further the use of manufacturing readiness level will be evaluated. The TRL may not include sufficient criteria for mass production with is essential for the wind turbine industry.
- After defining these TRLs specifically for our wind turbine application the timeline of the roadmaps will be reviewed and where needed adapted.
- More detail will be added to the technology roadmaps:
    - Other innovations in the project like advanced control making use of wind sensing with a lidar will be included in the technology roadmaps of WP2 and possibly WP4.
    - Distinction between different options within the innovation will be detailed. Eg in case of the innovation “Passive control and structural optimisation for lightweight rotors”: twist-bend coupling is available now, while coupling of camber change with bending is not.
    - In case bottom mounted support structures separate roadmaps for 10MW and 20MW will be drafted. The scale of a support structure for a 20 MW wind turbine gives more challenges in the economic manufacturing, assembly and transport of the support structure than for a 10 MW turbine.