“NEXT GENERATION OF MATERIALS FOR MANUFACTURING OF BIG COMPONENTS IN OFFSHORE WIND ENERGY”

Contractor: **Fundación Asturiana de la Energía**

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1 INTRODUCTION

This document compiles the study for a "NEXT GENERATION OF MATERIALS FOR MANUFACTURING OF BIG COMPONENTS IN OFFSHORE WIND ENERGY" research report.

Led by Scotland and the Basque Country, the Vanguard Initiative pilot project in Advanced Manufacturing for Energy-Related Applications in Harsh Environments (ADMA Energy) brings together ten European regions (Scotland, the Basque Country, Navarre, Lombardy, Norte, Flanders, Asturias, Dalarna, Scania and Emilia-Romagna) whose work together is based on complimentary smart specialisation priorities, and whose aim it is for Europe to be the global leader in the manufacture of robust, high-integrity components and systems for marine renewable and offshore energy applications.

Based on a road-mapping exercise undertaken between partners, since 2016 the ADMA Energy has identified several industrial challenges and technology opportunities commonly faced by companies in their regions among which is the recently identified "New materials and manufacturing methods" challenge.

Regarding this topic, and in order to further explore its trends and opportunities both at a technological and strategical level, ADMA energy, represented by its partner FAEN (Fundación Asturiana de la Energía) is interested on compiling all these information into a research report that has been developed by IDONIAL Technology Centre.

2 DESCRIPTION OF THE STUDY

2.1 OBJECTIVES

This report includes the results of the study and analysis on "The next generation of materials for the manufacture of large components in offshore wind energy". It includes the following aspects:

- ✓ A summary of state of art of next generation of materials and their manufacturing methods of big components in offshore wind, key findings and challenges.
- ✓ A study of key activities, projects and initiatives happening in the challenge area.
- ✓ An analysis regarding areas of greatest interest, strengths and opportunities of ADMA regions.
- ✓ A study related to recommendations and conclusions for future actions (demonstration cases) based on available demonstration areas linked to the strengths and priorities of ADMA regions.
- ✓ An analysis of potential funding opportunities and opportunities for international linkages within wider ADMA Energy partnership for developing the demonstration case.
- ✓ An analysis and evaluation the project's strategic fit with strategies and policies at the regional, national, EU and international level with regards to the Blue Economy and related technology areas.

2.2 METHODOLOGY

The report has been developed from both a technical and strategic approach. Therefore, the methodology (detailed at Figure 1) was based on the following phases to carry out the consultation and the report preparation:

- Preparatory phase, dedicated to:
  a) establish the table of contents
  b) define of the information to be gathered,
  c) prepare of the specific tools (forms, questionnaires,..) for data collection.
  d) identify ADMA pilot project partners to be contacted.
- Intermediate phase: to gather and analyse the information through consultation of public documentation (web pages, scientific publications, patents, databases, etc.), mapping further key initiatives, projects, entities to be contacted of and questionnaires to ADMA partners.
- Final phase: The information coming from the previous phases was analysed, processed, and different outputs, recommendations and conclusions were extracted and presented in the final report.

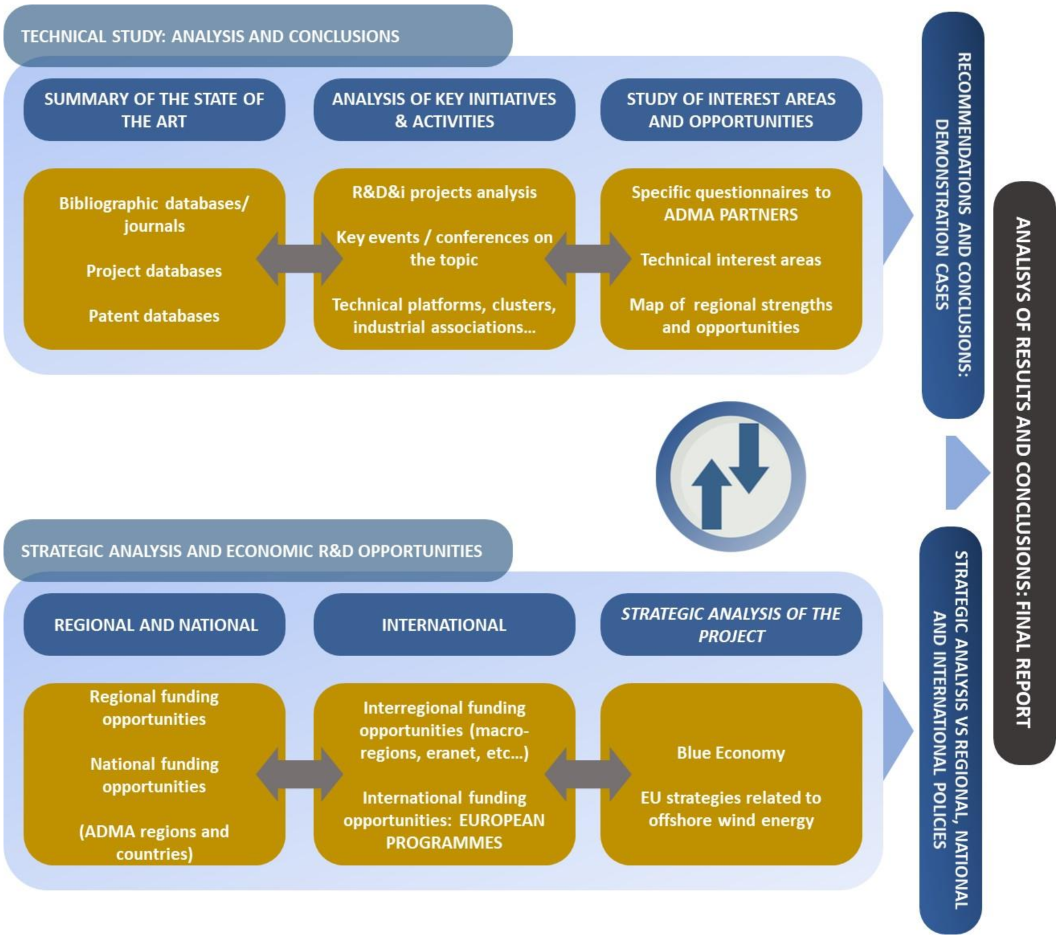

Figure 1. Methodology of the study

3 TECHNICAL STUDY: STATE OF THE ART

In this section, a detailed review on the State of the Art of next generation of materials and their manufacturing methods of big components in offshore wind has been performed. In addition, key activities, projects and initiatives in relation with the topic were also explored. To some extent, consultation with ADMA partners was done for the definition of the areas of greatest interest, to perform a matching analysis based on strengths and opportunities.

3.1 INTRODUCTION

Wind energy is one of the fastest growing sources of new electricity generation. The recent growth of the wind energy industry has been stimulated, in part, by innovation and consequent cost reductions, together with the support of state policies.

Looking ahead, further cost reductions are expected to be key to maintaining economic competitiveness. This is partly due to the competitive pressure of low-cost natural gas and photovoltaic solar energy. However, with a continuous reduction in costs, the economic deployment of wind energy up to 2050 could be greater than 430 GW and possibly up to 550 GW, with a wind energy supply of between 38% and 46% of total US electricity generation [1]. In addition, the amount of wind resources available is such that the opportunity to capture thousands of terawatt-hours of clean, low-cost wind energy remains of great interest.

The European offshore wind industry has been in existence for more than 20 years and its practices and know-how are very high.

Market data serves as a basis for assessing market potential and trends worldwide. Since 2010 it has increased its fleet from less than 3000 MW to a total fleet of more than 11700 MW by 2016.

Figure 1 shows the average nominal capacity (4.7 MW) of the turbines installed in 2016 worldwide, representing a 14% increase over 2015. The average diameter weighted by rotor capacity and hub height increased slightly to 127 m (8% growth over 2015) and 93 m (5% growth over 2015), respectively. These 2016 capacity weighted averages are in line with long-term industry trends. Data suggest that turbines increased from up to 3 MW in 2010 to over 4 MW from 2015, with some year-to-year fluctuations. The average rotor diameter also increased from 94 m in 2010 to over 127 m in 2016. An increase in rotor diameter increases the amount of energy that a turbine can draw from the wind at a given site and contributes to improved energy production throughout the offshore wind industry.

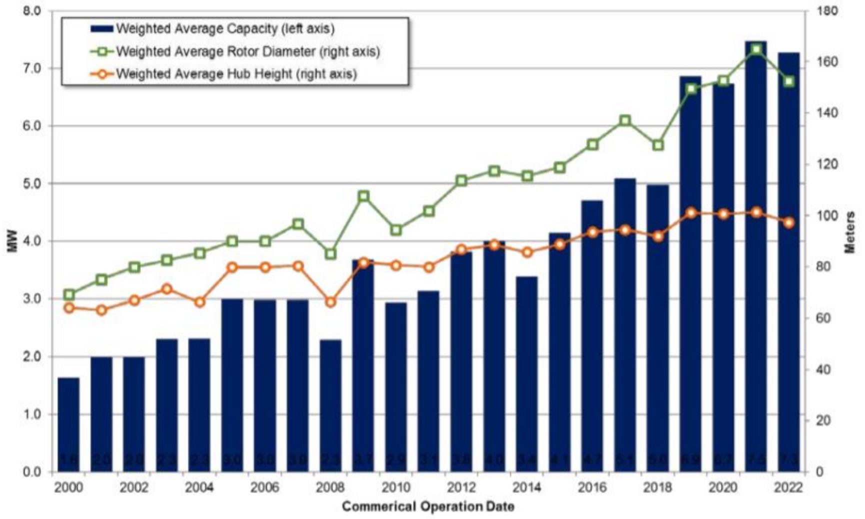

Figure 2. Average nominal capacity of the turbines that are installed worldwide. The values for expected turbine capacities, rotor diameters and tower heights from 2017 to 2022 are the weighted average capacity determined from projects that have announced turbine supply agreements. Source: NREL.

Oil and gas exploration and offshore wind power production are growing sectors internationally. There is therefore a great need to investigate the behaviour of these structures under severe offshore conditions.

Materials used in marine environments are subject to chemical, physical and biological degradation. These factors make material selection and design critical in ensuring effectiveness and safe operation.

Offshore structures are subject to cyclic loading conditions (due to waves, winds and currents) as well as corrosion. In other words, they work in a severe environment in which corrosion in marine atmospheres is combined with the dynamic loads that cause fatigue damage.

3.2 INVESTMENTS AND DEVELOPMENT FOR THE USE OF RENEWABLE OFFSHORE ENERGIES.

While the cost of building offshore structures is higher and more complex than onshore structures, the combination of increased plant size, technological improvements, infrastructure and associated R&D investments, as well as favourable market, political and economic conditions, has led to a downward trend in the expected prices of offshore wind power generation in Europe. This is demonstrated by the results obtained in auctions to obtain more competitive prices for the installation of offshore renewable energies carried out in countries such as Denmark, the United Kingdom, the Netherlands and Germany.

The development program for the generation of an average of 3700 MW per year from 2017 to 2022 covers the market needs to sustain a viable supply chain. The volume of production associated with this process has several benefits for the industry that support cost reduction, including increased economies of scale, improved infrastructure and manufacturing facilities, increased competition within the supply chain, and the promotion of a skilled workforce.

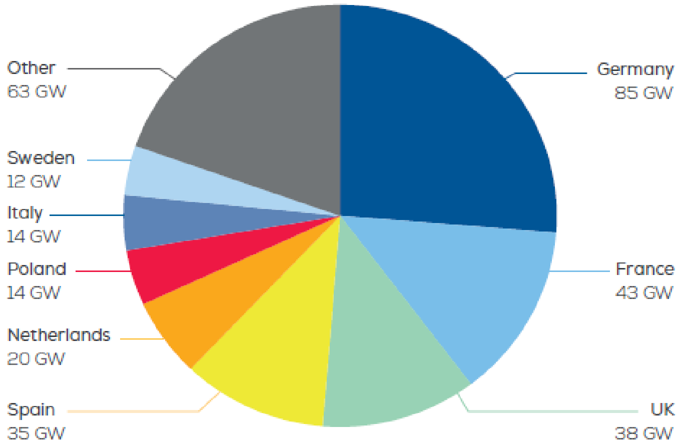

Figure 3. 2030 wind energy installed capacity by country according to Central Scenario in the EU (GW)[6]

Based on the demand announced to date, the European market has recently adopted larger technology platforms, with nominal powers increasing from 6 MW to 8.4 MW, resulting in fewer wind turbines for the same size wind farm.

Innovations are also being made in the design of foundations, installation techniques and electrical infrastructure.

In order to meet the European Union's commitment of 20% renewable energy by 2020 and 32% by 2030, European policy-makers have developed regulatory policies designed to minimize the cost of projects.

Figure 3 shows the Capex (Capital Expenditure) over time both for operational offshore projects and for those at different stages of development in the short term. The Capex is an important indicator of the life cycle in which the company is at a given time. Each bubble represents the estimated cost for a single project and the size of the bubble represents the nominal capacity of the project. The orange line shows the Capex capacity weighted average and provides an indication of the overall trend from 2000 to 2025.

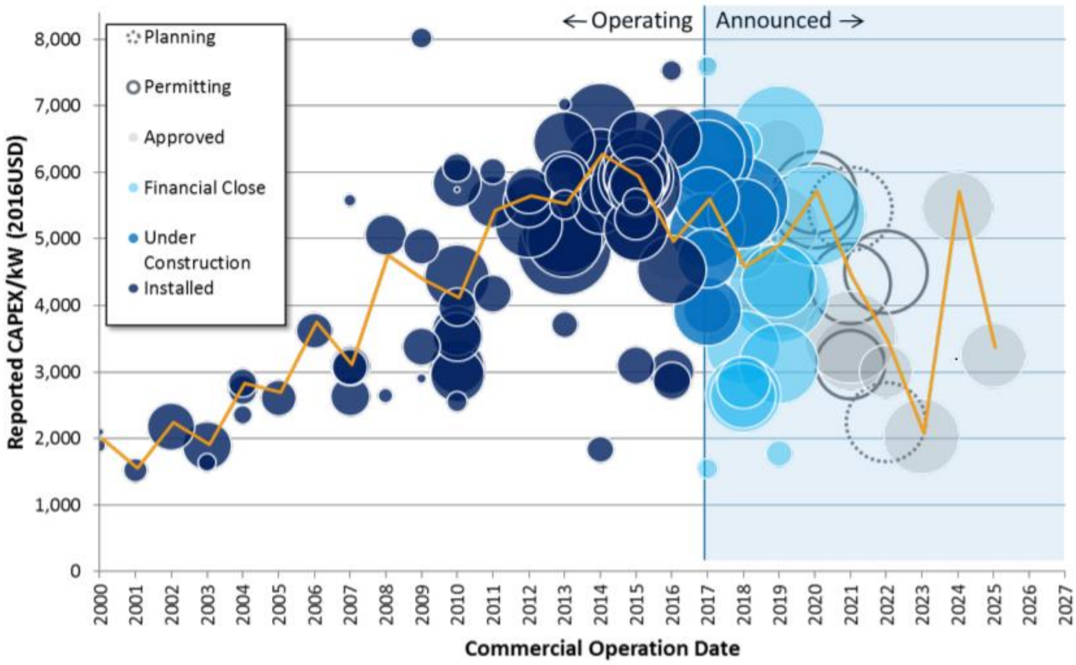

Figure 4. Capex (Capital Expenditure) over time for offshore projects. Source NREL.

Figure 4 shows in the form of bubbles the trend of offshore wind projects (which, as a minimum, are in the study phase of the location) depending on the depth of the water and the distance to the coast. The bubbles have different colours and sizes depending on the phase in which the project is located and the size of the bubbles. As can be seen, there is a trend towards larger projects (i.e. larger bubbles) located further from the coast (in the graph, moving to the right of the x-axis).

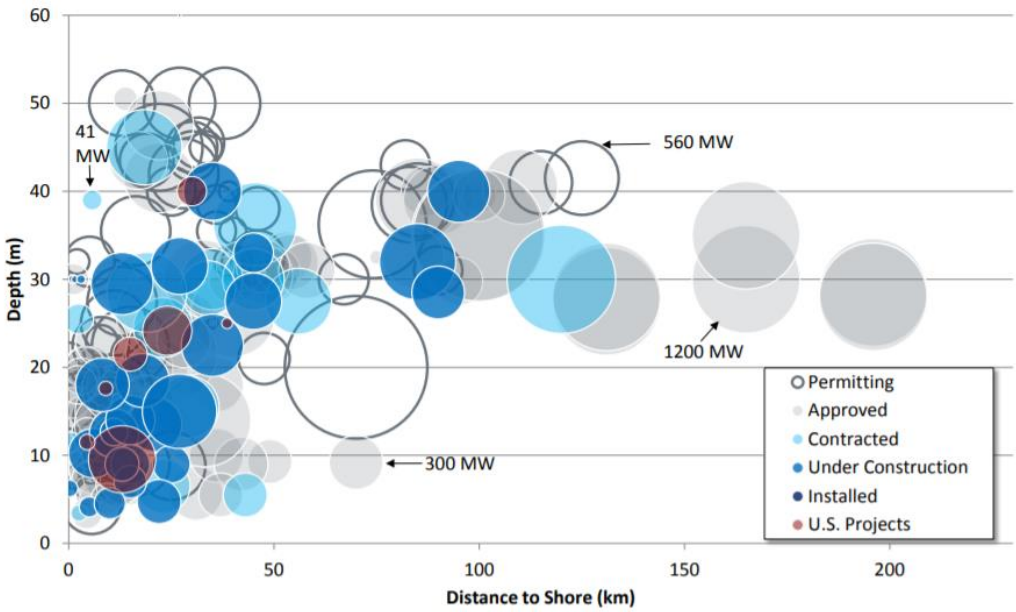

Figure 5. Offshore Wind Project Trend vs. Water Depth and Distance to Coast. Source: NREL.

3.3 LIFE CYCLE OF A WIND TURBINE

The life cycle of a wind turbine can be divided into the following five phases [31]:

Construction: the acquisition of all the raw materials and the production of the components that make up the wind turbine, as well as the auxiliary materials necessary for the development of the site.

- Transport: the equipment and supplies necessary to transport the raw materials from the extraction, processing, manufacturing and manufacturing facilities; the transport of the manufactured components to the wind turbine site; and the transport of maintenance supplies and spare parts during the operation of the turbine.
- Installation: assembling the wind turbine on site and connecting it to other turbines in the power plant and to the electricity grid.
- Operation: operation and maintenance of the turbine on a utility scale over its expected lifetime of 20 to 30 years; a turbine can be renewed to extend its lifetime by an additional 15 years or more, making the expected lifetime of a wind turbine comparable to 30 to 50 years for coal-fired power plants and 40 to 50 years for nuclear power plants.
- Dismantling and disposal: dismantling of the turbine and subsequent disposal of its components; this phase includes the transport of equipment to recycling or remanufacturing facilities or to landfills.

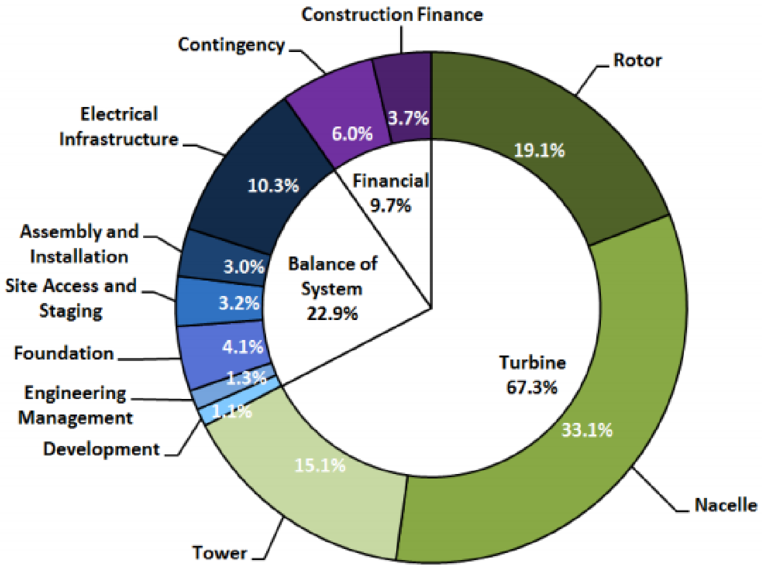

Figure 6. Capital expenditures for the land-based reference wind power plant project [8].

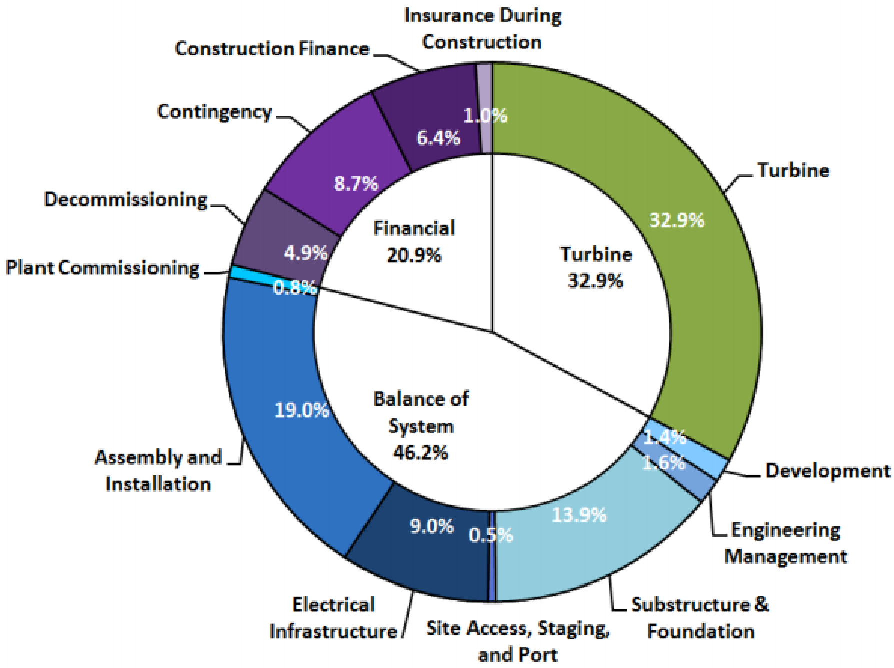

Figure 7. Capital expenditures for the fixed-bottom offshore reference wind power plant project [8].

3.4 DESCRIPTION OF A TYPICAL WIND TURBINE

Wind turbines consist of three main components, the nacelle, rotor and tower. The nacelle compartment is connected to the rotor hub by a shaft and contains the generators, gears and control mechanisms that maximize energy capture and conversion. The rotor, which usually consists of of three wing-shaped blades connected to a central hub, converts the kinetic energy of the wind into rotational energy. The tower, including the supporting foundations, provides the the height required to access the wind resource and the duct to transfer the electricity generated by the turbine to the collection system of the wind turbine in which the electricity of all wind turbines is often fed into the power grid.

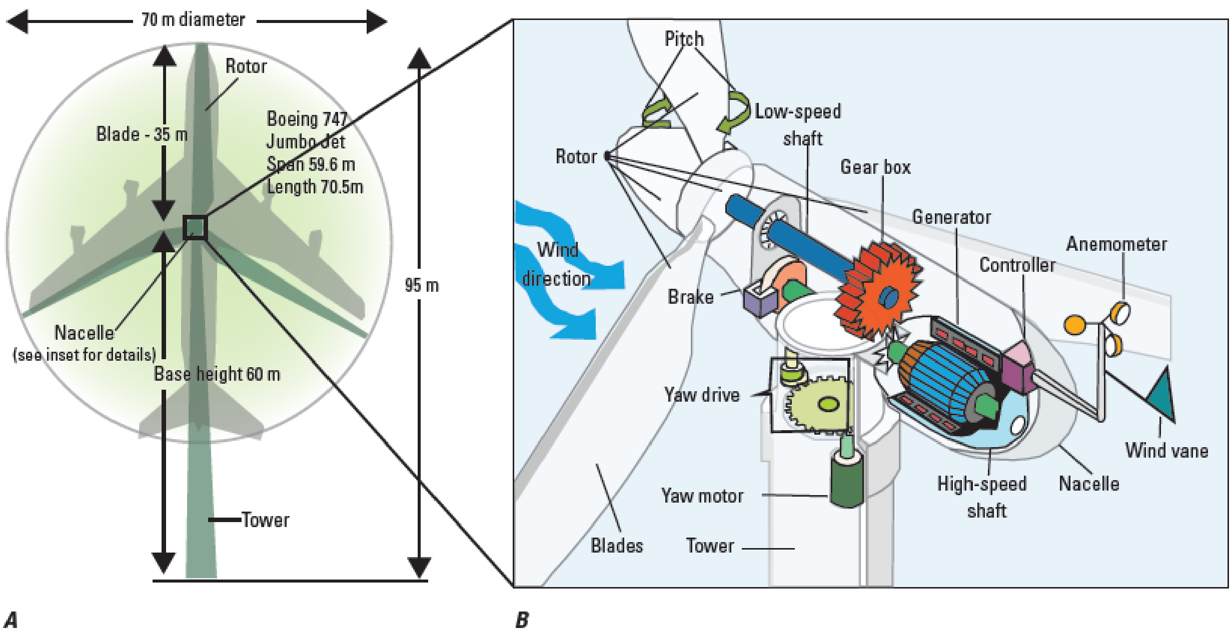

Figure 8. Diagrams of (A) a typical large wind turbine and (B) major components [31].

3.5 OBJETIVE OF THE TECHICAL STUDY

A typical wind turbine contains 89.1 percent steel, 5.8 percent fiberglass, 1.6 percent copper, 1.3 percent concrete (primarily cement, water, aggregates and steel reinforcement), 1.1 percent adhesives, 0.8 percent aluminum and 0.4 percent basic materials (primarily foam, plastic and wood) by weight [31]. As the use of wind turbines increases and research leads to the development of new technologies, the material requirements for wind turbines are likely to change, and the cumulative amount of these materials required.

The aim of this study is the bibliographic review of the materials used in the manufacture of the heaviest components of a wind turbine, those that support the most severe efforts and on which research is focused in order to reduce manufacturing costs.

Therefore the study will focus on the materials used for the manufacture of: foundations and towers, rotor hugs, rotor shafts, main frames and blades.

3.6 MATERIAL REQUIREMENTS OF WIND TURBINES

3.6.1. FOUNDATIONS AND TOWERS

The wind-energy technology does not stop evolving in search of cheaper and cheaper wind turbines that generate more energy, thus positioning itself as an alternative in price to conventional technologies.

One of the areas with great potential is offshore wind energy. The sea has more constant and less turbulent winds, ideal for wind generation. Furthermore, as the best places to install wind turbines on land are exhausted, it is necessary to begin to explore the sea in search of more productive positions.

Whether on land or at sea, one of the ways to reduce the costs of wind energy is to make wind turbines bigger and bigger both in height and diameter of blades, which can generate more energy at a lower price. It is estimated that for every metre that the size of the turbine increases, power generation rises by 0.5-1% per year.

Since the construction of the first commercial offshore wind farm in the world on the Danish coast in 1991 (which had only a tower of 35 meters, a rotor diameter of 35 meters and a nominal power of 0.45 MW), european countries including the United Kingdom, Germany and Denmark have been dominating the offshore wind market. Twenty six years later, in 2017, the German company Max Bögl Wind AG built a 178 m wind turbine with a total height (including the blade) of 246.5 m. The wind turbine is located in Gaildorf, Germany, and is part of a project where there will be four other equal wind turbines with tower heights ranging from 155 to 178 meters.

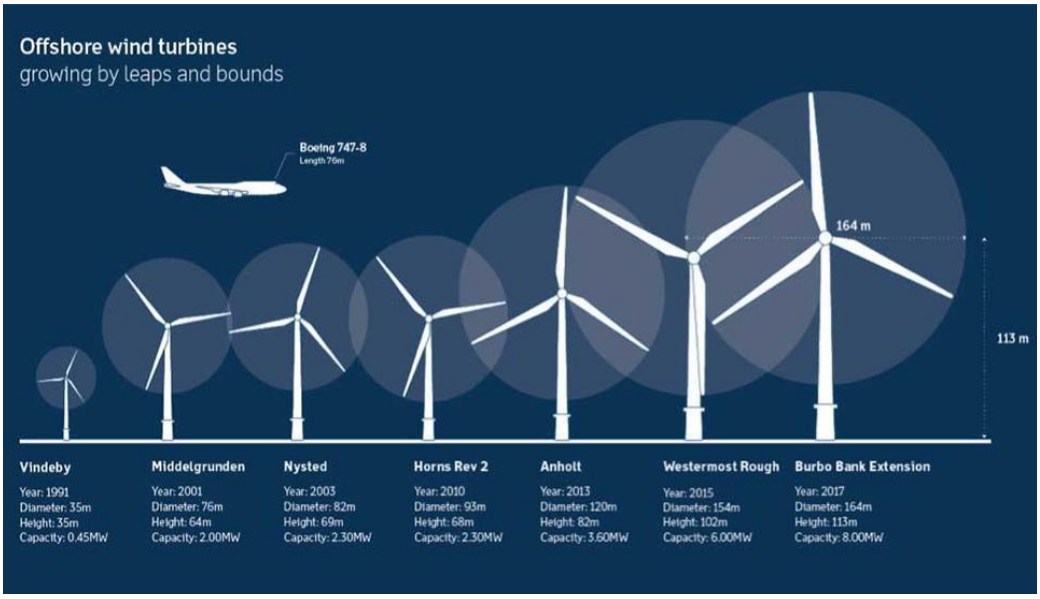

Figure 9. Offshore wind turbines height from 1991 to 2017

The average capacity of the new offshore wind turbines installed in Europe has increased from 3 MW in 2010 to 6 MW in 2017. The capacity of the largest commercial turbine currently in operation is 8 MW, and in the next two or three years we will witness the emergence of the 10 and 12 MW

turbines. One example is the 12 MW GE Renewable Energy turbine (Haliade-X project), with a 220 m rotor that reaches 260 metres above sea level, which is expected to start operating in 2021. Even the expectation for new offshore wind station in Europe measures up to about 50 GW by 2030. This implies the capacity yet to be installed over the next 13 years will more than triple that already established over the past 26 years.

As stated by the International Renewable Energy Agency (IRENA), the global offshore wind equivalent cost (LCOE: Levelized Cost of Electricity) for 2016 is about 20% lower than 2010, and expected to drop by up to 60% in the year 2022.

Consequently, structural dynamics, frequency response, fatigue and fracture toughness properties of materials, as well as soil-structure interactions, become increasingly important.

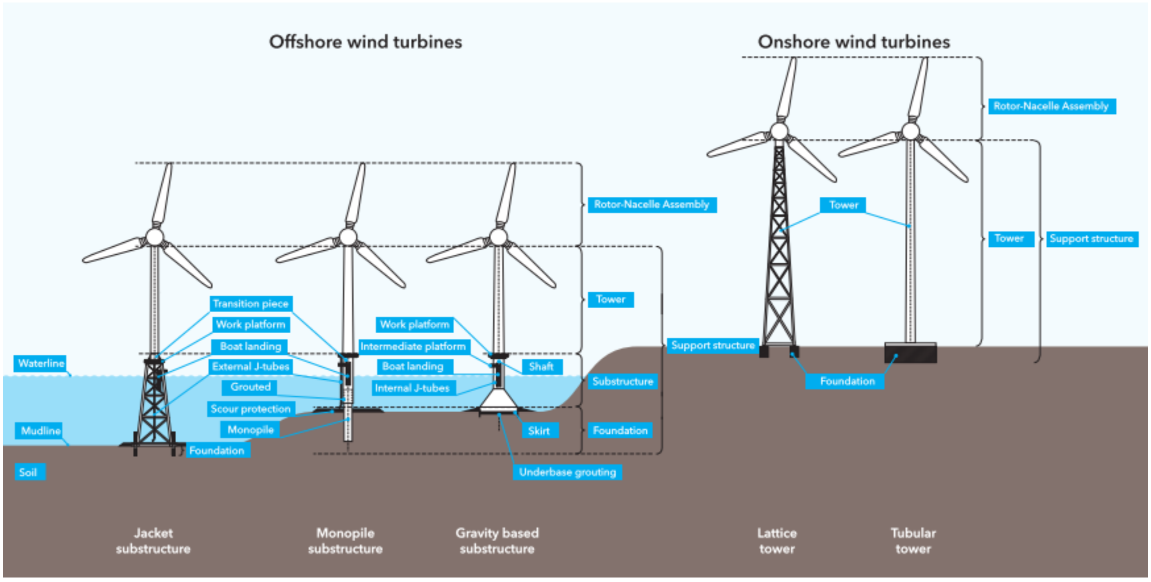

Figure 10. Wind Tower Scheme. Offshore wind turbines-Onshore wind turbines [5].

The water depth range at the site under consideration is usually the most important criteria for the type of support structure. But soil conditions, wind turbine size and experience from the designer also have major influence. As a rule of thumb, monopile-like structures are most suitable for shallow waters and jacket like structures are suitable for deeper waters. Unfortunately, it is not possible to define these limits exactly. In recent years the transition was approximately around 35-40 m. The allowable range for each support structure concept regarding the water depth is changing because technology advances continuously and further influential parameters such as soil conditions, met-ocean conditions and the size of the wind turbine result in variable limits. For example, a site with 50 m water depth and very stiff soil and small wave heights might still allow a competitive monopile design for 10 MW wind turbines, but shallow waters with soil in loose sand with extreme occurrence of scour and large wave heights will require solutions beyond a monopile. The design of the foundation always needs to follow an integrated approach considering many influential parameters of the site and the wind turbine appropriately. The most prevalent foun-dation design today is the monopile (82% of offshore wind turbines in European waters founded on monopiles at the end of 2018; EWEA, 2019). Where site conditions do not allow for an efficient or practical MP design, a number of alternative foundation solutions are available, including the suction bucket jacket (SBJ), piled jacket, gravity base or even a floating solution [35].

Gravity foundations: It is the oldest available foundation system for wind turbines and it comes under shallow foundation category. The first gravity base foundation (GBS) was installed in 1973 in the North Sea. The material used for its production is only concrete. The maximum depth achieved by this system can be 10 m. The gravity base must provide sufficient resistance against sliding and sufficient vertical bearing capacity. The weight of a gravity base has to be sufficient to avoid uplift, tilting and sliding, while at the same time avoiding failure of the subsoil. The main parameters to achieve this balance are the diameter and height of the gravity base.

- Suction bucket jacket: It is a flat foundation with skirts around the periphery; rather like an upturned bucket Suction caissons have been extensively used as anchors, principally in clays, and have also been used as foundations for a small number of offshore platforms in the North Sea. Right now it is a very popular foundation option in the offshore oil industry. They are currently being considered as possible foundations for offshore wind turbines also. The first possible use of caissons as wind turbine foundation was described in 1995 [59].Before 2002, all wind turbine foundations were mostly GBS or monopiles. Nowadays, due to its limited depth application, use of GBS is minimal. Due to increased capacity of wind turbines, it is necessary to go deeper in sea, where monopiles are preferred though no well-defined methods are available for design of monopiles having diameter more than 6m. Under such circumstances, the need arises for new foundation concepts. It seems that these pitfalls can be overcome by using suction caissons as wind turbine foundation. Depending upon the size of turbine, caissons may be single or multiple. In principle its behavior can be considered as a combination of gravity base and pile foundation systems. There are two aspects to the engineering design of this foundation: installation method, and in-service performance. During installation the skirt is partially embedded under the self-weight of the caisson and structure. The installation is completed by reducing the water pressure inside the caisson, thus forcing the skirts into the seafloor. In clay the net downward force caused by the pressure differential inside and outside the caisson drives the bucket into the ground. In sand, the hydraulic gradients set up in the soil around the bucket skirt also contribute to the process, as they reduce the soil resistance at the skirt tip, and within the caisson, to almost zero, allowing the bucket to penetrate easily into even very dense sand. The depth limitation for suction caissons is typically 25 m. However, investigation is continuing for increasing the depth applications [55].The cylindrical suction caisson has a cap that is sealed after installation. Since no active suction is applied after installation of the bucket, the geotechnical principles of axially loaded piles also apply here: skin friction and point resistance. Thus, the bearing capacity comprises of these two parameters. The point resistance of the pile tip is typically negligible, but the cap of the bucket causes very significant bearing capacity by pressing on the soil plug inside the bucket. Furthermore, it is assumed that the suction force is always sufficient to withstand dynamic loads, and that the relatively large static wind loading on the rotor and tower dominate the geotechnical design.

- Floating solution: Till now whatever foundation systems are available for wind turbines, maximum depth can be up to 50 m. But nowadays there is requirement to go beyond this limits and the problem to this solution is replacement of fixed foundation with floating platform. The vision for large-scale offshore floating wind turbines was introduced in 1972 [65]. But it was not until the mid 1990's, after the commercial wind industry was well established, that the topic was taken up again by them an instream research community. The floating structure must provide enough buoyancy to support the weight of turbine and to restrain pitch, wave as well as roll motion within acceptable limits. The floating platform configurations may vary widely. Typically, the overall architecture of a floating platform will be determined by a first-order static stability analysis, although there are many other critical factors that will determine the size and character of the final design. However, once the platform topology has been established, a crude economic feasibility analysis becomes possible. Therefore, a classification system was developed that divides all platforms into three general categories based on the physical principle or strategy that is used to achieve staticstability:
    - Ballast: Platforms that achieve stability by using ballast weights hung below a central buoyancy tank which creates a righting moment and high inertial resistance to pitch and rolland usually enough draft to offset heave motion. Spar-buoyslike the one shown in Figure 10 apply this strategy to achievestability.
    - Mooring Lines: Platforms that achieve stability throughthe use of mooring line tension. The tension leg platform (TLP), as shown in the centre of Figure 10, relies on mooringline tension for righting stability.
    - Buoyancy: Platforms that achieve stability through theuse of distributed buoyancy, taking advantage of weightedwater plane area for righting moment (see Figure 10).

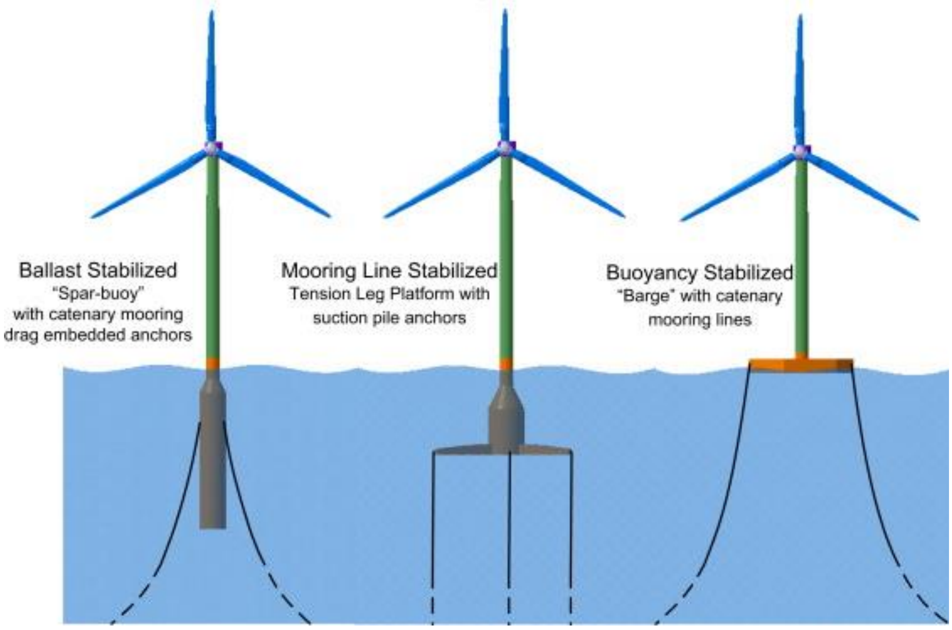

Figure 11. Floating platform concepts [16].

- Jackets structure: The jacket foundation concept is widely used in the oil and gas industry, and has also found use in the offshore wind industry, e.g. in the Beatrice Offshore Wind Farm, Scotland [40]. The jacket foundation concept consists of three parts: piles, jacket and transition piece [51]. The jacket is characterized by three or four legs stiffened with K-, N- or X-braces. It appears that the 4-legged jacket stiffened by X-braces and supported by main piles is particularly suitable for the offshore wind industry. The design therefore includes a 4-legged jacket and a concrete transition piece in the tower interface. The behavior of jacket foundation is similar to behavior of fixed offshore structures. The advantage of jacket substructures is that they are not very sensitive to wave loading as the structure attracts only small wave loads and is very stiff.
  The benefits of using the jacket foundation concept are found to be a lower wave load, a higher level of stiffness and lower soil dependency. The design will therefore be suitable for installations in deeper water or in waters with high waves and at sites with poor soil. It is assumed that by using jacket structure as foundation, greater maximum depth application is feasible compared to all other foundation options available for wind turbines.

Figure 12. Wikinger offshore wind farm (IBERDROLA) was inaugurated in October 2018. 280 piles were driven into the sea bed to hold the foundations. Measuring 40 metres in length by 2.5 metres in diameter, and a unit weight of 150 tonnes, they were all built by Spanish company Windar.

Different innovations at the components level for the advanced jacket sub structure have been developed and tested under laboratory conditions:

- Adhesive joints were tested as an alternative for welded connections in jacket members and further developments needed to develop this technology have been proposed.
- Sandwich tubes for jackets were also tested to determine the performance of composite materials in jackets. These are rod-like structural components consisting of three components:

two relatively thin steel tubes and a core made of ultra-high performance concrete (UHPC) [7].

Wind turbine towers are mainly made of steel. Due to their size they are constructed in welded sections. Overload problems limit transport to the site. Research is ongoing to overcome transportation problems and the high cost of erection, focusing on onsite tower fabrication, truss tower sections, and self-erecting tower technologies.

The tower provides the support system for the turbine and nacelle blades and serves as transmission line for electrical and electronic transmission and grounding. The most commonly used tower configuration steel sections with a foundation. A tower, including the foundation, typically represents 30 to 65 percent of the total weight of the wind turbine [9].Tower height is selected to optimize wind energy capture.

The increase in wind energy production is due to the increase in tower height and rotor size. Research and development, together with industry innovation, has allowed the height of turbine towers and rotors to grow and increase energy production, while eliminating excess material in manufacturing, improving production processes and maintaining reliability, allowing this increase in energy to be achieved with a low or no capital cost charge.

The growth of the offshore wind industry depends essentially on the reduction of energy costs. Many studies have shown that more cost-efficient and greener wind energy can be produced by increasing the size of turbines. On the other hand, as already mentioned, towers in marine environments are subject to very severe working conditions, mainly due to dynamic loads due to the effects of wind and waves, combined with marine corrosion.

When selecting the most suitable material to manufacture the wind turbine tower, several factors must be taken into account.

The final objective is to reduce the manufacturing and assembly costs by lightening the weight of the tower. For this purpose, it will be necessary to select materials with high mechanical properties (tensile strength and yield strength) that allow the manufacture of towers of lesser thickness. On the other hand, it must be borne in mind that the materials selected must behave well in the face of fatigue stresses and also have a good welding aptitude. As thickness and strength increase, cold cracking may occur. Cold cracking can be caused by a combination of the following factors:

- Diffusible hydrogen content in the weld metal.
- Fragile structure in the heat-affected zone (ZAT).
- Residual tensile stresses.

The frequency distribution is a significant factor in the structural fatigue life of wind turbine components. The natural frequency with which the tower moves is often referred to as the Eigen-frequency. The value of the natural frequency depends on the structural dimensions: height of the tower, the diameter of the support structure, the wall thickness of the tower shells, the weight of the top mass, weight of the nacelle, weight of any installation and maintenance platforms on the wind turbine, soil-structure interaction and water depth [3].

Resonance phenomena may implicate deformations and stresses exceeding the structural capacity and may lead to a total damage of the structure. Even if not doing so, resonance phenomena are most likely to implicate a considerable amount of fatigue being quite rapidly accumulated in members and joints [5].

Fatigue failure results from loads less than the design stresses. Loads causing fatigue damage originate from a variety of sources: steady loads from high winds, wind shear, yaw error and motion, stochastic loads from turbulence, transient loads from such events as gusts, operational starts and stops loads, and resonance-induced loads from vibration of the structure [32].

One of the most important variables to consider is temperature. Temperature has a direct influence on the mechanical fatigue and fracture behaviour of steels. As the temperature decreases, a substantial decrease in fracture toughness resistance is observed.

The fracture toughness is dependent on temperature and material thickness. In general, lower temperatures and thicker materials demand for higher toughness. These parameters are accounted for separately in selection of material. The resulting fracture toughness in the weld and the heat affected zone is also dependent on the fabrication method. Thus, to avoid brittle fracture, first a material with suitable fracture toughness for the actual service temperature and thickness is selected. Then a proper fabrication method is specified. A suitable amount of inspection should be carried out to remove planar defects larger than those considered acceptable [5].

Most of the steels used in the manufacture of wind turbine towers are steels defined by international standards and classification societies, such as: UNE EN 10025, UNE EN 10225, API, DNVG or NORSOK.

For the manufacture of these components, mainly weldable fine-grained structural steels defined by the standards UNE EN 10025-3 [46] and UNE EN 10025-4 [43] are used.

Grain size has a significant effect on the mechanical properties of steel. Fine grain steels have higher tensile strength, greater hardness and are less distorted during tempering, as well as being less susceptible to cracking.

Part 3 of the UNE EN 10025 standard specifies the requirements for hot-rolled flat and long products, for fine-grained structural steels in the normalized or normalized rolling state, for thicknesses less than 250 mm for types S275, S355 and S420 and for thicknesses less than or equal to 200 mm for type S460. These steels are suitable for use in highly demanded construction structures, at room temperatures and low temperatures.

S275 and S355 steels are unalloyed steels, while S420 and S460 must be classified as special alloyed steels.

Currently the main types of steel used are S235, S355.

Although the use of higher steel grades means a decrease in the thickness and therefore in the weight of the structure, these steels have more demanding weldability requirements. Their price is higher and there is not enough information in the current regulations on their behaviour in service.

Transport and installation costs are a factor to be taken into account. While the cost of S460 steels is slightly higher than that of S355 or S235 steels, the price of steels such as S690 is very high compared to S460 steel. Unless the weight is a severe problem, it would not be economical to use S690 steel.

With regard to the fatigue behaviour of welded joints, it should be pointed out that the influence of the tensile mean stress is not normally known, and so a tensile mean stress equal to the yield stress of the material must be assumed in a conservative manner, implying fatigue behaviour similar to that of lower grade steels.

On the other hand, the recent application of niobium in high strength offshore wind towers is evolving in Europe, offering possibilities for use in U.S. offshore wind tower projects. Through the optimized addition of niobium as utilized for onshore wind towers, these Nb-containing structural support steels provide fatigue and operational performance in critical wind, wave and oceanic conditions.

As the heights of the towers increase, the bottom of the tower reaches a point where highway transport is no longer possible due to width restrictions. The maximum allowed diameter of the tower base corresponds to an 80 m high tower. However, there is a steel solution for newly constructed taller towers. If high-strength niobium microalloyed steels are used in the design of the 100 m towers, it would be possible to to comply with the diameter restrictions at the bottom of the towers. In addition, there is the possibility of moving to a four-segment design instead of the current three-segment design. If steel manufacturers and designers consider upgrading towers from current grades S275 and S355 to S355, S420 and/or S460MPa grade steel cobinations, the lower segment transport plate width restriction would no longer be a problem. In addition, the known fatigue and fracture toughness performance is well established for lower elevation towers constructed of niobium microalloyed steel towers [4].

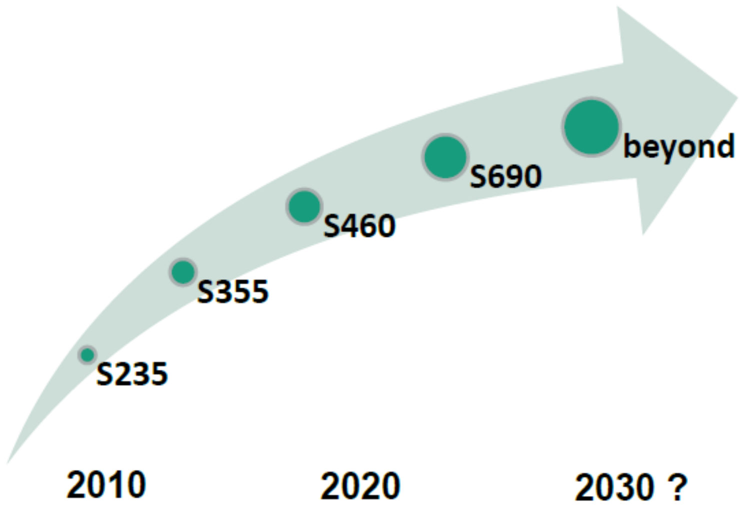

Figure 13. Trend in the application of structural materials

In turn, these steels can be supplied in different grades (N or NL) according to the requirements of the resilience test (Charpy test) at -20ºC and -50ºC respectively.

These steels have a fine-grained structure and a sufficient content of nitrogen-fixing elements.

Although the most commonly used quality is S355 and lower the tendency is to lighten weights trying to use higher qualities such as S420 or S460 (see tables 1 and 3).

In addition to these qualities and grades mentioned above, the M series (e.g. S355M and S355ML) is often used in the offshore industry, according to UNE EN 10025-4. See tables 2 and 4.

Table 1

General composition wt%. Normalized rolled structural steels. UNE EN 10025-3

Grades	C	Si	Mn	P	S	Nb	V	Al	Ti	Cr	Ni	Mo	Cu	Ni
	max	max		max	max	max	max	max	max	max	max	max	max	max
S275N	0.20	0.45	0.45-1.60	0.035	0.030	0.06	0.07	0.015	0.06	0.35	0.35	0.13	0.60	0.017
S275NL	0.18			0.030	0.025									
S355N	0.22	0.55	0.85-1.75	0.035	0.030	0.06	0.14	0.015	0.06	0.35	0.55	0.13	0.60	0.017
S355NL	0.20			0.030	0.025									
S420N	0.22	0.65	0.95-1.80	0.035	0.030	0.06	0.22	0.015	0.06	0.35	0.85	0.13	0.60	0.027
S420NL				0.030	0.025									
S460N	0.22	0.65	0.95-1.80	0.035	0.030	0.06	0.22	0.015	0.06	0.35	0.85	0.13	0.60	0.027
S460NL				0.030	0.025									

Table 2

General composition wt%. Thermomechanical rolled structural steels. UNE EN 10025-4

Grades	C	Si	Mn	P	S	Nb	V	Al	Ti	Cr	Ni	Mo	Cu	Ni
	max	max	max	max	max	max	max	max	max	max	max	max	max	max
S275M	0.15	0.55	1.60	0.035	0.030	0.06	0.10	0.015	0.06	0.35	0.35	0.13	0.60	0.017
S275ML				0.030	0.025									
S355M	0.16	0.55	1.70	0.035	0.030	0.06	0.12	0.015	0.06	0.35	0.55	0.13	0.60	0.017
S355ML				0.030	0.025									
S420M	0.18	0.55	1.80	0.035	0.030	0.06	0.14	0.015	0.06	0.35	0.85	0.23	0.60	0.027
S420ML				0.030	0.025									

S460M	0.18	0.65	1.80	0.035	0.030	0.06	0.14	0.015	0.06	0.35	0.85	0.23	0.60	0.027
S460ML				0.030	0.025									

Table 3

Mechanical properties at room temperature. Normalized rolled structural steels. UNE EN 10025-3

Grades	Minimum Yield strength ReH [MPa]								Tensile strength Rm [MPa]			Minimum Strain [%]					
	Nominal thickness [mm]								Nominal thickness [mm]			Nominal thickness [mm]					
	≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤150	>150 ≤200	>200 ≤250	≤100	>100 ≤200	>200 ≤250	≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤150
S275N / S275NL	275	265	255	245	235	225	215	205	370-510	350-480	350-480	24	24	24	23	23	23
S355N / S355NL	355	345	335	325	315	295	285	275	470-630	450-600	450-600	22	22	22	21	21	21
S420N / S420NL	420	400	390	370	360	340	330	320	520-680	500-650	500-650	19	19	19	18	18	18
S460N / S460NL	460	440	430	410	400	380	370	-	540-720	530-710	-	17	17	17	17	17	-

Table 4

Mechanical properties at room temperature. Thermomechanical rolled structural steels. UNE EN 10025-4

Grades	Minimum Yield strength ReH [MPa]						Tensile strength Rm [MPa]					Minimum Strain [%]
	Nominal thickness [mm]						Nominal thickness [mm]					
	≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤120	≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤120	
S275M / S275ML	275	265	255	245	235	225	370-530	360-520	350-510	350-510	350-510	24
S355M / S355ML	355	345	335	325	315	295	470-630	450-610	440-600	440-600	430-590	22
S420M	420	400	390	370	360	340						19

S420ML							520-680	500-660	480-640	470-630	460-620	
S460M S460ML	460	440	430	410	400	380	540-720	530-710	510-690	500-680	490-660	17

Currently, there is limited information on the corrosion fatigue behavior of grades of high yield strength steels.

Studies show that for instance the S355 TMCP offer higher fatigue strength than standard S355. However, the rate of crack growth in marine environments (where the material is subject to corrosion fatigue) is similar in TMCP and normalized steels. This suggests that a range of material choices are available for economic selection of S355 steel for wind farm support structure development [3].

On the other hand, the UNE EN 10225 standard specifies requirements for weldable structural steels to be used in the fabrication of fixed offshore structures in the form of plates up to and including 150 mm thick. It also specifies sections up to 63 mm thick (or as-rolled condition up to 25 mm). Seamless hollow sections up to and including 40 mm thick and high frequency electric resistance welded (HFW) hollow sections up to and including 20 mm thick are specified.

For low temperature a minimum elastic limit of 460 MPA is specified for temperatures below -40ºC (North Sea).

This standard does not apply to pipelines. For sheets, the thickness limitations are:

- S355G2 +N / +M up to and including 20 mm.
- S355G3 +N / +M up to and including 40 mm.
- S355G7 / G8 / G9 / G10 +N up to and including 150 mm.
- S355G7 / G8 / G9 /G10 +M up to and including 100 mm.
- S420G1 +QT / +M up to and including 100 mm.
- S420G2 +QT / +M up to and including 100 mm.
- S460G1 +QT / +M up to and including 100 mm.
- S460G2 +QT / +M up to and including 100 mm.

Where the letter “G” followed by the relevant digit characterizes the steel grade and the letters “+N”, “+M” y “+QT” indicate the delivery condition: normalizing rolling, thermomechanical rolling or quenching and tempering, respectively.

- Plates of group 1.
  - Delivery conditions +N o +M up to and including 40 mm.
  - Grades:
    - S355G2+N.
    - S355G3+N.
    - S355G5+N.
    - S355G6+N.
- Plates of groups 2 and 3.
  - Delivery conditions +N up to and including 150 mm.
  - Delivery conditions +M o +QT up to and including 100 mm.
  - Grades:

Group 2

- S355G7 +N/+M.
- S355G9 +N/+M.
- S420G1 +QT/+M.
- S460 G1 +QT/+M.

Group 3

- S355G8 +N/+M.
- S355G10 +N/+M.
- S420 G2 +QT/+M.
- S460G2 +QT/+M.

- Sections
  - As-rolled, +M o +N (at the manufacturer’s discretion). The as rolled delivery condition is limited to a maximum thickness of 25 mm.
  - Grades:

Group 1

- S355G1.
- S355G1+N.
- S355G4.
- S355G4+M.

Group 2

- S355G11.
- S355G11 +N / +M.
- S420G3.
- S420G3+M.
- S460G3.
- S460G3+M.

Group 3

- S355G12.
- S355G12 +N/+M.
- S420G4.
- S420G4+M.
- S460G4.
- S460G4+M.

- Hollow sections
  - Supplied in the normalizaed/normalized rolled (+N) or quenched and tempered (+QT). S420 and S460 grades are normally only available in circular form.
  - Welded, grades:

Group 1

- S355G1+N

Group 2

- S355G13 +N / +QT
- S420G5 +QT
- S460G5+QT

- Seamless, grades:

  Group 1

  - S355G1+N

  Group 2

  - S355G14 +N / +QT
  - S420G6 +QT
  - S460G6+QT

  Group 3

  - S355G15 +N / +QT

The table below shows chemical composition requirements.

Table 5.

Chemical composition for plates wt%. UNE EN 10225

Group	Steel Name	C	Si	Mn	P	S	Cr	Mo	Ni	Al(Total)[b]	Cu	N	Nb	Ti	V	Cr+Mo+Ni+Cu	Nb+V	Nb+V+Ti
		máx.			máx.	máx.	máx.	máx.	máx.		máx.	máx.	máx.	máx.	máx.	máx.	máx.	máx.
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Ladle analysis																		
1	S355G2+N	0,20	0,50 máx.	0,90 a 1,65	0,035	0,030	0,30	0,10	0,50	0,020. min	0,35	0,015	0,060	0,030	0,12	–	–	–
1	S355G3+N	0,18	0,50 máx.	0,90 a 1,65	0,030	0,025	0,30	0,10	0,50	0,020. min	0,35	0,015	0,060	0,030	0,12	–	–	–
1	S355G5+M	0,14	0,50 máx.	1,60 máx.	0,035	0,030	–	0,20	0,30	0,020 mín.	–	0,015	0,050	0,050	0,10	–	–	–
1	S355G6+M	0,14	0,50 máx.	1,60 máx.	0,030	0,025	–	0,20	0,30	0,020 mín.	–	0,015	0,050	0,050	0,10	–	–	–
Ladle and product analysis																		
2	S355G7+M[c] S355G7+N[c]	0,14	0,15 a 0,55	1,00 a 1,65	0,020	0,010	0,25	0,08	0,50	0,015 a 0,055	0,30	0,010	0,040	0,025	0,060	0,90	0,06	0,08
3	S355G8+M[c] S355G8+N[c]	0,14	0,15 a 0,55	1,00 a 1,65	0,020	0,007	0,25	0,08	0,50	0,015 a 0,055	0,30	0,010	0,040	0,025	0,060	0,90	0,06	0,08
2	S355G9+N[c] S355G9+M[c]	0,12	0,15 a 0,55	1,65 máx.	0,020	0,010	0,20	0,08[d]	0,70[e]	0,015 a 0,055	0,30	0,010	0,030	0,025	0,060	–	0,06	0,08
3	S355G10+N[c] S355G10+M[c]	0,12	0,15 a 0,55	1,65 máx.	0,015	0,005	0,20	0,08[d]	0,70[e]	0,015 a 0,055	0,30	0,010	0,030	0,025	0,060	–	0,06	0,08
2	S420G1+QT[c] S420G1+M[c]	0,14[f]	0,15 a 0,55	1,65 máx.	0,020	0,010	0,25	0,25	0,70	0,015 a 0,055	0,30	0,010	0,040	0,025	0,080	0,90	0,09	0,11
3	S420G2+QT[c] S420G2+M[c]	0,14[f]	0,15 a 0,55	1,65 máx.	0,020	0,007	0,25	0,25	0,70	0,015 a 0,055	0,30	0,010	0,040	0,025	0,080	0,90	0,09	0,11
2	S460G1+QT[c] S460G1+M[c]	0,14[f]	0,15 a 0,55	1,65 máx.	0,020	0,010	0,25	0,25	0,70	0,015 a 0,055	0,30	0,010	0,040	0,025	0,080	0,90	0,09	0,11
3	S460G2+QT[c] S460G2+M[c]	0,14[f]	0,15 a 0,55	1,65 máx.	0,020	0,007	0,25	0,25	0,70	0,015 a 0,055	0,30	0,010	0,040	0,025	0,080	0,90	0,09	0,11

Table 6.

Mechanical properties for plates. S355 grades. UNE EN 10225

Group	Steel name	Tensile strength Rm		Minimum yield strength ReH for thickness t (mm)						Minimum elongation A on gauge length of $5,65\sqrt{S_0}$	Minimum average Charpy V-notch impact test value		Thick. Max.
		Thickness t (mm) ≤ 100	> 100	$t \leq 16$	$16 < t \leq 25$	$25 < t \leq 40$	$40 < t \leq 63$	$63 < t \leq 100$	$100 < t \leq 150$		Temp.	Energy	
		MPa[c]	MPa[c]	MPa[c]	MPa[c]	MPa[c]	MPa[c]	MPa[c]	MPa[c]	%	°C	J	mm
1	S355G2+N	470 a 630		355	345	–	–	–	–	22	-20	50	20
1	S355G3+N	470 a 630		355	345	345	–	–	–	22	-40	50	40
1	S355G5+M	470 a 610		355	345	–	–	–	–	22	-20	50	20
1	S355G6+M	470 a 610		355	345	345	–	–	–	22	-40	50	40
2	S355G7+N	470 a 630	460 a 620	355	355	345	335	325	320	22	-40	50	150[b]
3	S355G8+N	470 a 630	460 a 620	355	355	345	335	325	320	22	-40	50	150[b]
2	S355G7+M	470 a 630	–	355	355	345	335	325	–	22	-40	50	100[b]
3	S355G8+M	470 a 630	–	355	355	345	335	325	–	22	-40	50	100[b]
2	S355G9+N	470 a 630	460 a 620	355	355	345	335	325	320	22	-40	50	150[b]
2	S355G9+M	470 a 630	–	355	355	345	335	325	–	22	-40	50	100[b]
3	S355G10+N	470 a 630	460 a 620	355	355	345	335	325	320	22	-40	50	150[b]
3	S355G10+M	470 a 630	–	355	355	345	335	325	–	22	-40	50	100[b]

Table 7.

Mechanical properties for plates. S420 grades. UNE EN 10225

Group	Steel name	Tensile strength Rm		Minimum yield strength ReH for thickness t (mm)					Minimum elongation A on gauge length of $5,65\sqrt{S_0}$	Minimum average Charpy V-notch impact test value		Thick. Max.
		$t \leq 40$	$40 < t \leq 100$	$t \leq 16$	$16 < t \leq 40$	$40 < t \leq 63$	$63 < t \leq 80$	$80 < t \leq 100$		Temp.	Energy	
		MPa	MPa	MPa	MPa	MPa	MPa	MPa	%	°C	J	mm
2	S420G1+QT	500 a 660	480 a 640	420	400	390	380	380	19	-40	60	100
2	S420G1+M	500 a 660	480 a 640	420	400	390	380	380	19	-40	60	100
3	S420G2+QT	500 a 660	480 a 640	420	400	390	380	380	19	-40	60	100
3	S420G2+M	500 a 660	480 a 640	420	400	390	380	380	19	-40	60	100

Table 8.

Mechanical properties for plates. S460 grades. UNE EN 10225

Thickness ranges (mm)	≤ 16	> 16 ≤ 25	> 25 ≤ 40	> 40 ≤ 63[a]	> 63 ≤ 80[a]	> 80 ≤ 100[a]
Minimum yield strength R_{eH} MPa [b]	460	440	420	415	405	400
Tensile strength R_m MPa [b]	540 to 700	530 to 690	520 to 680	515 to 675	505 to 665	500 to 660
Minimum elongation on gauge length $5{,}65\sqrt{S_o}$ %	17	17	17	17	17	17
Minimum average Charpy V-notch impact test value	60 J at –40 °C					

[a] Charpy V-notch mid-thickness tests are also required for thicknesses over 40 mm.
[b] 1 MPa = 1 N/mm^2.

Table 9.

Yield to tensile strength ratios for plates excluding steels of group 1. UNE EN 10225

Grade	Yield to tensile strength ratios	
	Thickness	max.
All S355+N grades	≤ 16 mm > 16 mm	0.87 0.85
All S355+M grades	≤ 16 mm > 16 mm	0.93[a] 0.90
All S420 grades	≤ 16 mm > 16 mm	0.93 0.90
All S460 grades	≤ 16 mm > 16 mm	0.93 0.90

[a] For plates ≤ 10 mm, alternative yield to tensile strength ratios may be agreed.

Other applicable standards for weldable steels for OFFSHORE structures are: API RP 2A-WSD, NORSOK Structural Steel Fabrication and the DNV-GL-OS-B101.

The steels recommended by API RP 2A-WSD [54] are classified according to the yield strength and minimum impact value requirements into three groups and classes, as shown in the following tables.

Table 10.

Recommended steels according to API RP 2A standard

Group	Yield strength Re [MPa]	Equivalent carbon content CE (max)	Additional requirements
I	<280	0.40	AWS D1.1
II	280<Re<360	0.45	Low hydrogen welding
III	Re>360	-	Special welding care. Fatigue and fracture toughness analysis.

Table 11.

Recommended steels according to API RP 2A standard

Class	Minimum average Charpy V-notch impact test value.		Additional requirements
	Temp. [ºC]	Energy [J]	
C	20	27	Non-essential parts
B	0	20-34	Structural parts subject to stress concentrations or impacts.
A	-40	27-34	Essential components

Table 12.

Recommended steels according to API RP 2A standard. Group I. Class A,B,C.

Group	Class	Specification and Grade	Yield Strength ksi	Yield Strength MPa	Tensile Strength ksi	Tensile Strength MPa
I	C	ASTM A36 (to 2 in. thick)	36	250	58–80	400–550
		ASTM A131 Grade A (to $^1/_2$ in. thick)	34	235	58–71	400–490
		ASTM A285 Grade C (to $^3/_4$ in. thick)	30	205	55–75	380–515
I	B	ASTM A131 Grades B, D	34	235	58–71	400–490
		ASTM A516 Grade 65	35	240	65–85	450–585
		ASTM A573 Grade 65	35	240	65–77	450–530
		ASTM A709 Grade 36T2	36	250	58–80	400–550
I	A	ASTM A131 Grades CS, E	34	235	58–71	400–490

Table 13.

Recommended steels according to API RP 2A standard. Group II. Class A,B,C.

Group	Class	Specification and Grade	Yield Strength ksi	Yield Strength MPa	Tensile Strength ksi	Tensile Strength MPa
II	C	ASTM A572 Grade 42 (to 2 in. thick)*	42	290	60 min.	415 min.
		ASTM A572 Grade 50 (to 2 in. thick; S91 required over $^1/_2$ in.)*	50	345	65 min.	450 min.
		API Spec 2MT2 Class C	50	345	65–90	450–620
		ASTM A992	50–65	345–450	65 min.	450 min.
II	B	API Spec 2MT1	50	345	70–90	483–620
		API Spec 2MT2 Class B	50	345	65–90	450–620
		ASTM A709 Grades 50T2, 50T3	50	345	65 min.	450 min.
		ASTM A131 Grade AH32	45.5	315	68–85	470–585
		ASTM A131 Grade AH36	51	350	71–90	490–620
II	A	API Spec 2H Grade 42	42	290	62–80	430–550
		Grade 50 (to $2^1/_2$ in. thick)	50	345	70–90	483–620
		(over $2^1/_2$ in. thick)	47	325	70–90	483–620
		API Spec 2W Grade 42 (to 1 in. thick)	42–67	290–462	62 min.	427 min.
		(over 1 in. thick)	42–62	290–427	62 min.	427 min.
		Grade 50 (to 1 in. thick)	50–75	345–517	65 min.	448 min.
		(over 1 in. thick)	50–70	345–483	65 min.	448 min.
		Grade 50T (to 1 in. thick)	50–80	345–522	70 min.	483 min.
		(over 1 in. thick)	50–75	345–517	70 min.	483 min.
		API Spec 2Y Grade 42 (to 1 in. thick)	42–67	290–462	62 min.	427 min.
		(over 1 in. thick)	42–62	290–427	62 min.	427 min.
		Grade 50 (to 1 in. thick)	50–75	345–517	65 min.	448 min.
		(over 1 in. thick)	50–70	345–483	65 min.	448 min.
		Grade 50T (to 1 in. thick)	50–80	345–572	70 min.	483 min.
		(over 1 in. thick)	50–75	345–517	70 min.	483 min.
		API Spec 2MT2 Class A	50	345	65–90	450–620
		ASTM A131 Grades DH32, EH32	45.5	315	68–85	470–585
		Grades DH36, EH36	51	350	71–90	490–620
		ASTM A537 Class I (to $2^1/_2$ in. thick)	50	345	70–90	485–620
		ASTM A633 Grade A	42	290	63–83	435–570

Table 14.

Recommended steels according to API RP 2A standard.Group III. Class A,B,C.

Group	Class	Specification and Grade	Yield Strength ksi	Yield Strength MPa	Tensile Strength ksi	Tensile Strength MPa
III	A	ASTM A537 Class II (to $2^1/_2$ in. thick)	60	415	80–100	550–690
		ASTM A678 Grade B	60	415	80–100	550–690
		API Spec 2W Grade 60 (to 1 in. thick)	60–90	414–621	75 min.	517 min.
		(over 1 in. thick)	60–85	414–586	75 min.	517 min.
		API Spec 2Y Grade 60 (to 1 in. thick)	60–90	414–621	75 min.	517 min.
		(over 1 in. thick)	60–85	414–586	75 min.	517 min.
		ASTM A710 Grade A Class 3 (quenched and precipitation heat treated)				
		through 2 in.	75	515	85	585
		2 in. to 4 in.	65	450	75	515
		over 4 in.	60	415	70	485

The NORSOK Structural Steel Fabrication [33] recommend, among others, the steels mentioned in the standards EN 10025 [46] and EN 10225. This NORSOK standard covers the requirements for fabrication and inspection of offshore steel structures with yield strength< 500 MPa and with a minimum design temperature down to -14 °C.

As additional requirements should be noted:

- There are stricter requirements for sulphur and phosphorus content.
- There are limitations of use in terms of qualities and thicknesses.
- It includes the use of the grade S355J2, limiting (by toughness) the content of sulfur and phosphorus.
- CTOD (crack tip opening displacement test) requirements are indicated for thicknesses greater than 40 mm.
- For some grades the maximum nickel content is limited.
- S500 grade materials not covered by EN10225 are included. For instance, steel Grade S460G2+Q/G2+M shall be modified to Grade S500G2+Q/G2+M as specified in the Norsok M-101 Material Data Sheet Y50, provided the requirements of that standard are met.
  - S500G2+Q/G2+M: plates.
  - S500G4+M: rolled sections.
  - S500G6+Q: seamless tubulars.
  - S500G1+Q/G1+M: plates.
  - S500G3+M: rolled sections.
  - S500G6+Q: seamless tubulars.

If the structure is designed and analysed according to Eurocode the selection of steel grades shall be in compliance with the requirements stated in EN 10025 series or EN 10225. Where other codes or standards have been specified in the design basis and utilised in the specification of steels, the application of such steel grades within the structure shall be specially considered. The steel grades selected for structural components shall be related to calculated stresses and requirements to toughness properties. Requirements for toughness properties are in general based on the Charpy V-notch test and are dependent on service temperature, structural category and thickness of the component in question. 4.2.4.5 The material toughness may also be evaluated by fracture mechanics testing (CTOD test) in special cases [5].

Within the DNVGL-OS-B101 [15] standard three groups of steels are shown according to their strength: normal strength (NS), high strength (HS) and extra high strength (EHS). See the table below.

Table 15.

Definitions of steel grades. DNV-GL-OS-B101

Strength group	*Impact testing*			*Tensile properties*	
	Symbol x		*Test temperature °C)*	*Symbol y*	*Minimum yield stress1) MPa*
	Normal weldability	*Improved weldability*			
NS	A B2) D E	- BW DW EW	- 0 −20 −40	Omitted	235
HS	A D E F	AW DW EW -	0 −20 −40 −60	27 32 36 40	265 315 355 390
EHS	A D E F	- DW EW -	0 −20 −40 −60	420 460 500 550 620 690	420 460 500 550 620 690

1) For steels of improved weldability the required minimum yield stress is reduced for increasing material thickness.
2) Charpy V-notch tests are not required for grade B with thickness of 25 mm or less.

The NS steel, is defined as steel with specified minimum yield stress of 235 MPa. The HS steel, is defined as steel with specified minimum yield stress of 265 MPa and up to and including 390 MPa. The EHS steels, is defined as steel with specified minimum yield stress of 420 MPa and up to and including 690 MPa. The steels of this last group shall be killed and fine grain treated.

Several factors will be taken into account when selecting the most suitable grade of steel:

- Design temperature: The lowest average temperature the structure can experience (above sea level - Lowest Astronomical Tide).
- The design temperature of the submerged parts will be 0 ºC. For thicknesses less than 10 mm in submerged structures, the design temperature will be 2 ºC.
- Grades VL A, B and D require minimum Charpy toughness values of 27 J up to thicknesses t = 50 mm, for higher thicknesses higher values are required.
- VL A/D 36 grades require minimum Charpy toughness values of 34 J up to 50 mm, 41 J up to 70 mm and 50 J for thicknesses greater than 70 mm.
- The mechanical properties in DNV are maintained with the thicknesses.
- Within each group there are two subgroups: normal weldability and improved weldability. The two series are intended for the same applications. However, in addition to leaner chemistry

and better weldability the improved weldability grades have extra margins to account for reduced toughness after welding. These grades are also limited to a specified minimum yield stress of 500 MPa.

- For the use of steels of grade S550 and higher, special considerations will be made in cases where corrosion may exist (due to the appearance of microcracks).
- For critical applications, a hydrogen induced stress cracking (HISC) susceptibility study will be performed.
- Steel resistant to pitting damage will always be selected.

The alphanumeric designation of the steel grade is:

- VL xy for steels of normal weldability
- VL xWy for steels of improved weldability.
- VL = designation of a steel grade according to the DNV GL offshore standards.
- x = a capital letter corresponding to a specified impact toughness test temperatura.
- W = letter included to designate a steel grade of improved weldability
- y = a figure designating the strength group according to the specified minimum yield stress.

The following tables show a summary of some of the steels recommended by DNV and their mechanical properties.

Table 16.

Mechanical properties for normal strength steel. DNV-GL-OS-B101

Grade	*Yeld stress R_{eH} minimum (MPa)*	*Tensile strength R_m (MPa)*	*Elongation A_5 minimum (%)*	*Impact energy, average minimum (J)*						
				Temperature (°C)	*$t \leq 50$ (mm)*		*$50 < t \leq 70$ (mm)*		*$70 < t \leq 150$ (mm)*	
					L	T	L	T	L	T
VL A	235	400 to 520	22[3]	+20	-	-	34[2]	24[2]	41[2]	27[2]
VL B				0	27[1]	20[1]	34	24	41	27
VL D				-20	27	20	34	24	41	27
VL E				-40	27	20	34	24	41	27

1) Impact tests are not required for grade B steel with thickness of 25 mm or less.

2) Impact tests for grade A over 50 mm thickness are not required when the material is produced using fine grain practice and supplied in either N or TM conditions.

3) For full thickness flat test pieces with width 25 mm and gauge length 200 mm, the minimum elongation (%) is reduced to the following values:

Thickness, mm	$t \leq 50$	$5 < t \leq 10$	$10 < t \leq 15$	$15 < t \leq 20$	$20 < t \leq 25$	$25 < t \leq 30$	$30 < t \leq 40$	$t > 40$
All grades	14	16	17	18	19	20	21	22

Table 17.

Mechanical properties for high strength steel. DNV-GL-OS-B101

Grade	Yeld stress R_{eH} minimum (MPa)	Tensile strength R_m (MPa)	Elongation A_5 minimum (%)	Impact energy, average minimum (J)						
				Temperature (°C)	t ≤ 50 (mm)		50 < t ≤ 70 (mm)		70 < t ≤ 150 (mm)	
					L	T	L	T	L	T
VL A27S VL D27S VL E27S VL F27S	265	400 to 530	22 1)	0 -20 -40 -60	27	20	34	24	41	27
VL A32 VL D32 VL E32 VL F32	315	440 to 570	22 1)	0 -20 -40 -60	31	22	38	26	46	31
VL A36 VL D36 VL E36 VL F36	355	490 to 630	21 1)	0 -20 -40 -60	34	24	41	27	50	34
VL A40 VL D40 VL E40 VL F40	390	510 to 660	20 1)	0 -20 -40 -60	39	26	46	31	55	37

1) For full thickness flat test pieces with width 25 mm and gauge length 200 mm, the minimum elongation (%) is reduced to the following values.

Table 18.

Mechanical properties for extra high strength steel. DNV-GL-OS-B101

Grade	Yield stress ReH minimum (MPa)	Tensile strength Rm (MPa)	Elongation A5 minimum (%)	Impact energy, average minimum (J) 1)		
				Temperature (°C)	t ≤ 150 (mm)	
					L	T
VL A420 VL D420 VL E420 VL F420	420	530 to 680	18 2)	0 -20 -40 -60	42	28
VL A460 VL D460 VL E460 VL F460	460	570 to 720	17 2)	0 -20 -40 -60	46	31
VL A500 VL D500 VL E500 VL F500	500	610 to 770	16 2)	0 -20 -40 -60	50	33
VL A550 VL D550 VL E550 VL F550	550	670 to 830	16 2)	0 -20 -40 -60	55	37
VL A620 VL D620 VL E620 VL F620	620	720 to 890	15 2)	0 -20 -40 -60	62	41
VL A690 VL D690 VL E690 VL F690	690	770 to 940	14 2)	0 -20 -40 -60	69	46

The following table shows the equivalences between some steel grades of EN 10025 and DNVGL-OS-B101 standards.

Table 19.

Steel grade conversions. DNVGL-ST-0126

	EN 10025-2	*EN 10025-3*	*EN 10025-4*	*VL grade*	*Test temperature VL grade (ºC)*
Normal strength steel (NS)	S235JR	–	–	VL A	-
	S235J0	–	–	VL B	0
	S235J2+N	–	–	VL D	-20
	–	–	–	VL E	-40
High strength steel (HS)	S275J0	S275N	S275M	VL A27S	0
	S275J2+N	S275N	S275M	VL D27S	-20
	–	S275NL	S275ML	VL E27S	-40
	–	–	–	VL F27S	-60
	(S355J0)	S355N	S355M	VL A36	0
	S355K2+N, (S355J2+N)	S355N	S355M	VL D36	-20
	–	(S355NL)	S355ML	VL E36	-40
	–	–	–	VL F36	-60
Extra high strength steel (EHS)	–	S420N	S420M	VL A420	0
	–	S420NL	S420ML	VL D420	-20
	–	(S420NL)	(S420ML)	VL E420	-40
	–	–	–	VL F420	-60
	–	S460NL	S460ML, (S460M)	VL A460	0
	–	(S460NL)	S460ML	VL D460	-20
	–	(S460NL)	(S460ML)	VL E460	-40
	–	–	–	VL F460	-60

The conversions are based on comparable requirements for strength and toughness. VL grades are, in general, better steel qualities than comparable EN 10025-2 grades. For example, most VL grades are killed and fine grain treated. This is the case only for the J2+N and K2+N grades in EN 10025-2. Because EN 10025-3 specifies requirements for fine grain treatment, the EN 10025-3 grades are in general better grades than corresponding grades listed in EN 10025-2 and can be considered equivalent with the corresponding VL grades [5].

3.6.2. MAIN FRAME, ROTOR HUB AND ROTOR SHAFT.

The nacelle contains most of the components necessary for the operation of the wind tower, so its weight is considerable (between 25 and 40% of the total weight of the wind turbine). In it are located bearings, coupling, gears, generator, and shafts, and the analytical and auxiliary equipment (anemometer, brakes, controller, convertor, cooling system, sensors, and yaw drive system. The materials used for these components are mainly steel and steel alloys, aluminium, cast iron, copper and plastic [31].

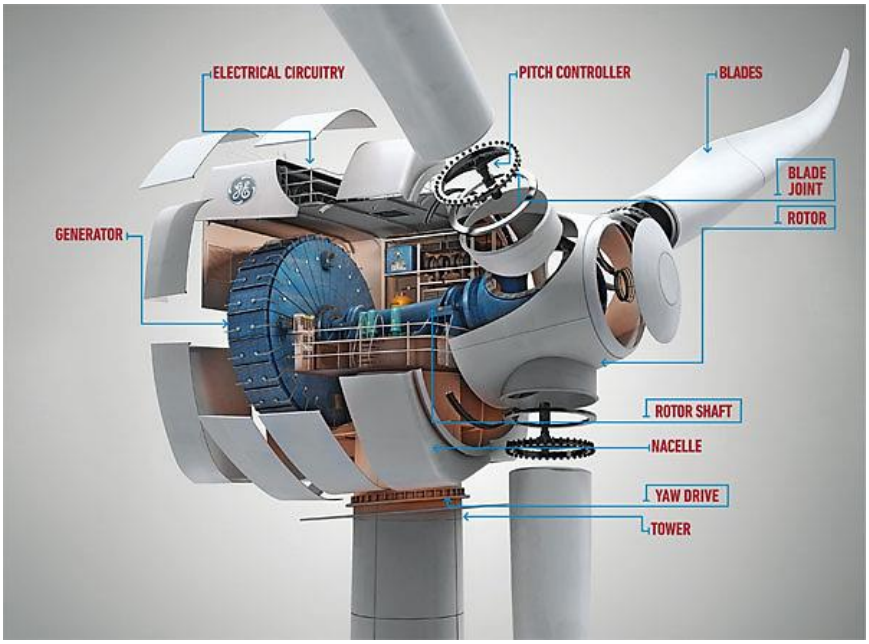

Figure 14. Nacelle detail

The torque is converted into electrical energy by means of a generator and a gearbox. By the action of the wind the blades turn the main shaft that connects the rotor with the gearbox. The gearbox increases the rotation speed of the shaft and drives the generator which transforms the rotational energy into electrical energy. Gearboxes are mainly made of cast iron and stainless steel.

The heaviest components and where it is most important to lighten the weight are: the rotor shaft, the hub and the main frame.

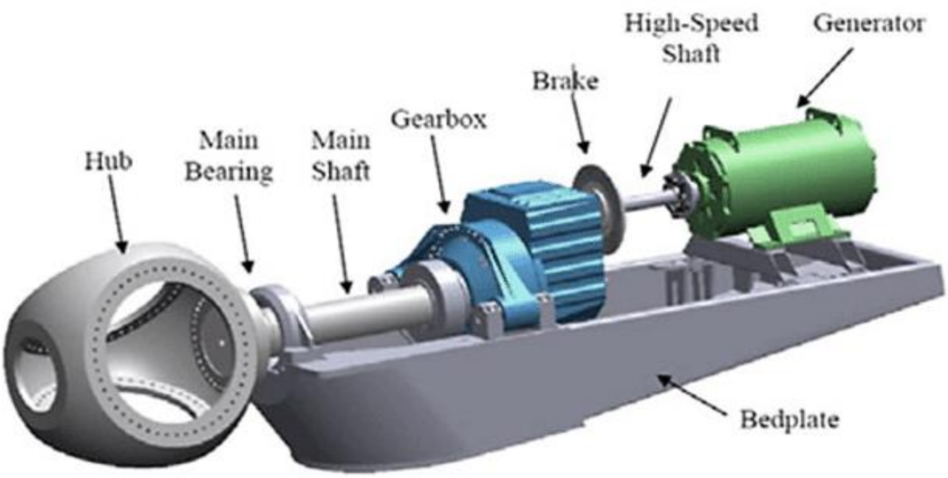

Figure 15. Detail of the hub and rotor shaft location.

Most of the structural components of the nacelle as: main frames, rotor hubs, blade root and tower top adapters, torque supports, planet carriers of the gearbox, brake disks as well as rotor axles and stator elements in direct-drive turbines are made of normal strength spheroidal graphite cast iron. One of the exceptions among the main components (apart from bearing housing and gearbox which are manufactured in lamellar graphite cast iron) is the rotor shaft, which is normally made out of forged steel [10].

The rotor shaft is a very important component in the safety and operation of a wind turbine, as it connects the rotor hub to the multiplier. Considering the tendency to increase the diameter of the rotors and the height of the nacelles, the loads to which the shaft is subjected increase considerably.

To counteract these phenomena, more compact drive designs are being developed, with shorter, hollow rotor shafts. However, these designs can cause relative movements between the rotor shaft and the inner ring, generating fretting fatigue phenomena, which means that surfaces deteriorate and premature shaft failure occurs [11].

These shafts are subject to stress concentration factors, fretting driven fatigue stress concentration, effects and vibration natural frequency.

On the other hand, to save costs, it is necessary to evaluate the possibilities of optimization with respect to the weight of the components. If the weight of a drive train component decreases, the use of material from the following structure and therefore the costs could also be reduced.

The main shaft for wind power generators, is manufactured by casting or forging. The weight of the main shaft, depending on the design, is generally 10 to 20 tons. One of the steels most used in the manufacture of these shafts is 42CMo4.

It has been shown that while the cast iron rotor shaft has better fatigue behaviour at low loads, the forged steel shaft performs better at high load levels. Fracture mechanics studies show that forged steel shafts are highly resistant to fatigue crack propagation. Although, at stresses below the endurance limit cast iron is also a good behaviour.

Table 20.

Materials for possible rotor shaft application [4].

Material	Tensile strength R_m (t < 30 mm)	Application in a wind turbine
42CrMo4s	1100 MPa	Rotor shaft mostly made of forged steel.
EN GJS-400-18-LT	400 MPa	Normal strength ductile iron often used for wind turbine components (Shirani et al. (2011)).
EN GJS-600-3, EN GJS-700-2	600 MPa, 700 MPa	Higher strength ductile iron, rarely used in wind turbines, so far almost exclusive for the planet carrier (Pollicino (2006)).
EN GJS-800-8, EN GJS-1000-5	800 MPa, 1000 MPa	Austempered ductile iron, no application for wind turbine main components so far (Herfurth (2003)).
GJSF-SiNi30-5	410 MPa* *(60 < t < 200 mm)	Si-solid solution strengthened ductile iron especially developed for wind turbine application (Mikoleizik et al. (2014)).

The rotor hub and the main frame are usually manufactured in spherical graphite castings mainly in SSF and ADI castings. The research is mainly based on the search for materials that are increasingly lighter and at the same time have excellent fatigue behaviour. In this type of castings, the shape and size of the graphite nodules as well as their distribution within the matrix are very important, because the properties of the casting depend on it.

A spheroidal graphite cast iron is a cast alloy, iron, carbon and silicon based, where carbon is present in the form of spheroidal graphite particles. They are also called ductile iron or nodular cast iron.

The properties of spheroidal graphite castings depend on their structure. EN 1563 [28] divides castings into two groups:

- Spheroidal graphite ferrito-pearlitic cast iron.

  Spheroidal graphite cast iron with a matrix containing ferrite or pearlite, or a combination of both. Perlite can be totally or partially replaced by bainite or martensite tempered in grades with higher strength.

- Solid solution strengthened ferritic ductile iron (SSF).

  Smelting with a matrix that mainly contains ferrite, strengthened by a solution mainly of silicon.

Both groups have specific properties:

- The ferritic grades in the first group have the highest impact energy.
- Grades containing perlite are more suitable for wear-resistant applications.
- Ferritic grains strengthened by solid solution have a higher yield strength and elongation than ferrito-perlitic grades. In addition, have a reduced variation of hardness, which implies a better machinability.

The grades of solid solution strengthened ferritic ductile iron, appear in the standard EN 1563 in 2011, and are listed below:

- EN GJS-450-18.
- EN-GJS-500-14.
- EN-GJS-600-10.

Probably the most used in these structures is the EN GJS-450-18. However, EN GJS-450-18 is similar to GJS-400-15, but EN-GJS-500-14 has great advantages over EN GJS-500-7. Same tensile strength, from 320 MPa to 400 MPa raised yield strength and from 7% to 14 % doubled elongation after fracture [2].

As far as EN-GJS-600-10 is concerned, it presents more application problems, as the silicon content to achieve the required strength is so high that the risk of ferrite brittleness, even at room temperature, is high.

The following table shows the approximate chemical composition values for these materials. A maximum manganese content of 0.30 improves machinability and elongation.

Table 21.

Guideline values for chemical composition. Solid solution strengthened ferritic ductile iron (SSF). EN 1563.

Material designation	**Si** % aprox.	**P** % máx.	**Mn** % máx.
EN-GJS-450-18	3,20	0,05	0,50
EN-GJS-500-14	3,80	0,05	0,50
EN-GJS-600-10	4,30	0,05	0,50

The following tables show the mechanical properties and Brinell hardness values for these materials.

Table 22.

Mechanical propertie measured on test pieces machined from cast samples (SSF). EN1563

Material designation	**Relevant wall thickness of the casting** t mm	**0.2% proof strength** $R_{p0,2}$ MPa mín.	**Tensile strength** R_m MPa mín.	**Elongation** A % mín.
EN-GJS-450-18	$t \leq 30$	350	450	18
	$30 \leq t \leq 60$	340	430	14
	$t > 60$	bajo acuerdo entre el fabricante y el comprador		
EN-GJS-500-14	$t \leq 30$	400	500	14
	$30 \leq t \leq 60$	390	480	12
	$t > 60$	bajo acuerdo entre el fabricante y el comprador		
EN-GJS-600-10	$t \leq 30$	470	600	10
	$30 \leq t \leq 60$	450	580	8
	$t > 60$	bajo acuerdo entre el fabricante y el comprador		

Tabla 23.

Guideline values of Brinell hardness. Spheroidal graphite ferrito-pearlitic cast iron and SSF. EN 1563.

Material designation	Brinell Hardness HBW	
	$t \leq 60$ mm	60 mm $< t \leq$ 200 mm
EN-GJS-350-22	< 160	< 160
EN-GJS-400-18	130 a 175	130 a 175
EN-GJS-400-15	135 a 180	135 a 180
EN-GJS-450-18	170 a 200	160 a 190
EN-GJS-450-10	160 a 210	160 a 210
EN-GJS-500-14	185 a 215	170 a 200
EN-GJS-500-7	170 a 230	150 a 230
EN-GJS-600-10	200 a 230	190 a 220
EN-GJS-600-3	190 a 270	180 a 270
EN-GJS-700-2	225 a 305	210 a 305
EN-GJS-800-2	245 a 335	240 a 335
EN-GJS-900-2	270 a 360	270 a 360

Austempered ductile iron castings (ADI castings) are a cast alloy, iron and carbon based, carbon being present mainly in the forma of spheridal graphite particles.

Compared with the spheroidal graphite cast-iron grades, this material combines higher strength and toughness properties as a result of the austempering heat treatment.The mechanical properties depend on their structure (the form of the graphite, the structure of the matrix…).

This heat treatment, which is an integral part of the production process, consists of an austenitising treatment at a temperature between 820ºC and 950ºC and an austempering treatment in the temperature range between 250ºC and 400ºC to form a predominantly austenitic-ferritic structure.

Heat treatment parameters and chemical composition have to be selected as a function of casting size (relevant wall thickness) and required grade.

The figure below shows a comparison between spheroidal graphite (SG) iron, cast steels and ADI castings in terms of tensile strength and elongation.

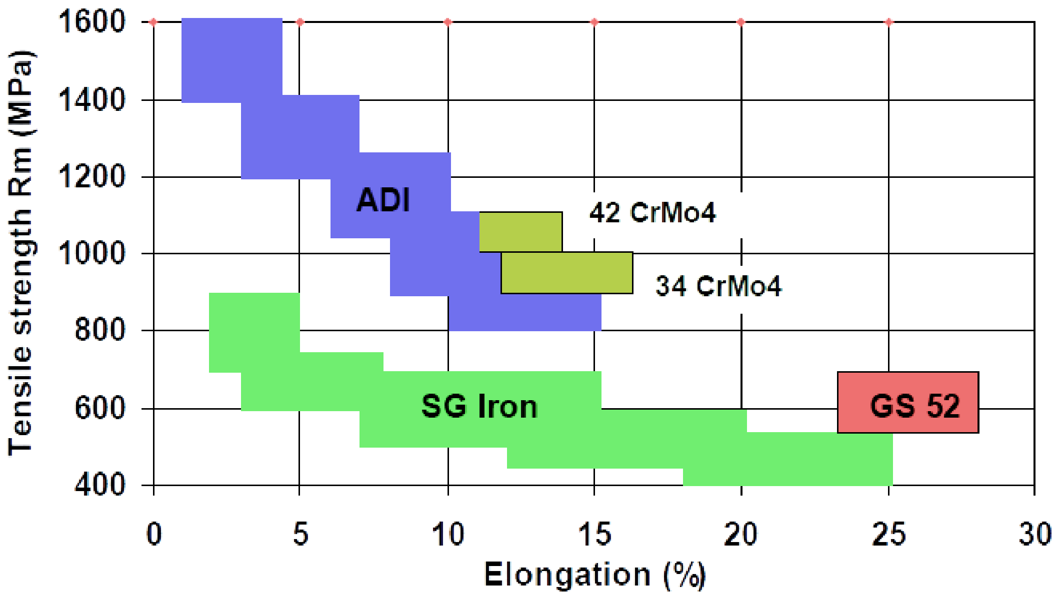

Figure 16. Comparison of tensile strength and elongation for SG irons, Cast steels and ADI.

Figures 16 and 17 show comparative graphs (relative weight per unit of 0.2% proof stress and fracture toughness KIC) between ADI castings and different materials.

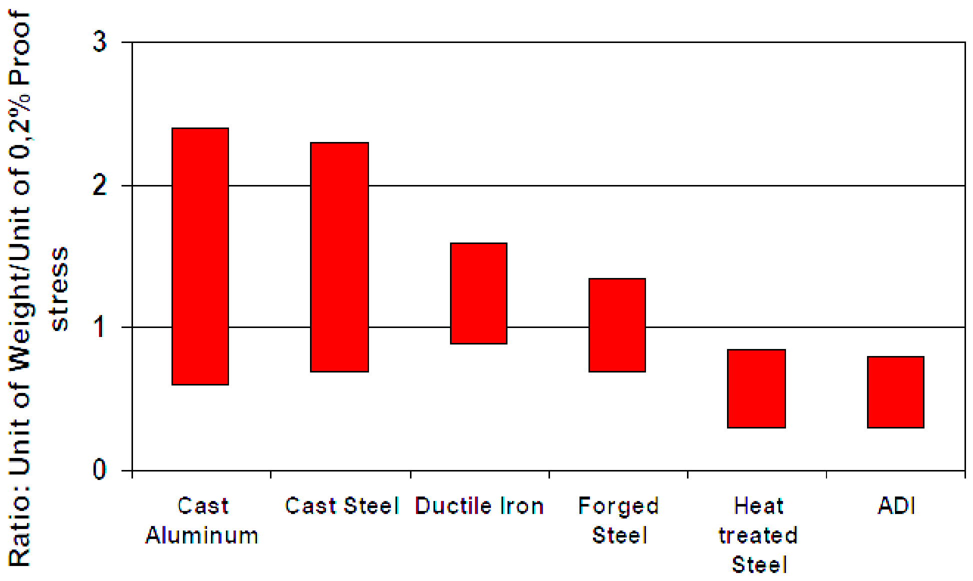

Figure 17. ADI, relative weight per unit of 0.2% proof stress.

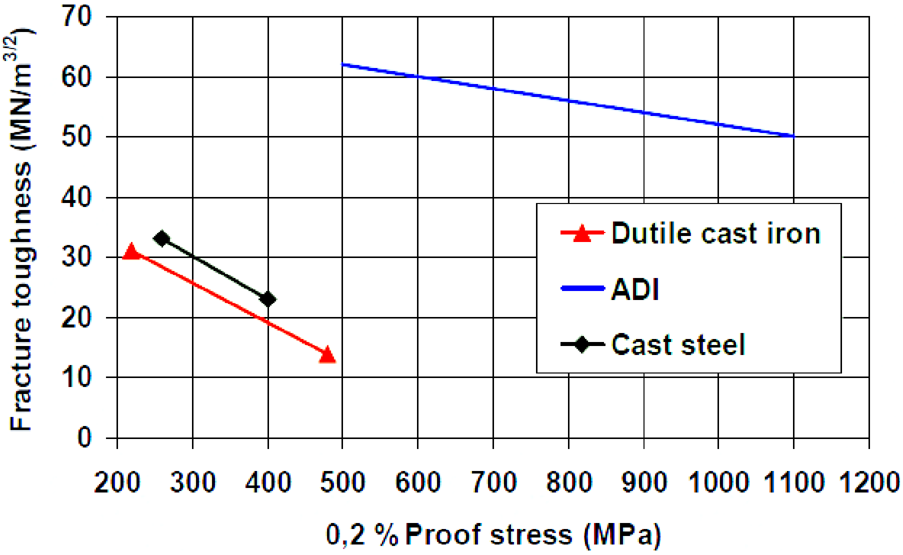

Figure 18. Comparison of fracture toughness KIC for ductile cast irons, sast steels and ADI.

Ductile irons show some technical and commercial advantages over cast and forged steels, and these advantages have become more visible as ADI castings have begun to replace some of the higher-strength forged steels.

- Replacement of various materials, mainly forged steels, by simultaneously combining high mechanical strength and toughness.
- Versatility in the manufacturing process.
- Excellent resistance weight ratio. ADI components are 10% lighter than forged-steel components of the same dimensions.
- High wear resistance, because graphite nodules on the surface provide a lubricating effect.
- Excellent machinability.
- Low deformation to thermal treatment.
- Low sensitivity to notching compared to other steels which implies that discontinuities on the component surface are of less significance.

Bainitic matrix and globular graphite castings combine high strength (Rm=800-1500 MPa) load and fracture toughness with excellent wear resistance. This allows them to be used instead of heat-treated steels, due among other things to savings in production costs.

The use of ADI castings in manufacturing of a safety-relevant components requires a good knowledge of the fatigue and fracture behaviour of these materials.

If the properties of ADI castings are compared with, for instance, a pearlitic cast iron EN GJS 600-3, it can be seen that although the ratio of yield strength to tensile strength of ADI is very high, the elongation of fracture in an ADI is larger than in EN GJS 600-3. This is due to the fine microstructure and austenite content in ADI (30%). It is also observed that the fatigue life (at strain amplitude up to 1%) is higher than EN GJS 600-3 [53].

Table 24 shows the values of tensile strength and yield strength of some of the most commonly used ADI grades and Table 25 shows similar grades according to other standards. Table 24.

Mechanical properties measured on test pieces machined from separately cast samples or cast-on samples. ISO 17804.

Material designation	Relevant wall thickness of the casting t mm	Tensile strength R_m N/mm² min.	0,2 % proof strength $R_{p0,2}$ N/mm² min.	Elongation A % min.
ISO 17804/JS/800-10 ISO 17804/JS/800-10RT	$t \leqslant 30$	800	500	10
	$30 < t \leqslant 60$	750		6
	$60 < t \leqslant 100$	720		5
ISO 17804/JS/900-8	$t \leqslant 30$	900	600	8
	$30 < t \leqslant 60$	850		5
	$60 < t \leqslant 100$	820		4
ISO 17804/JS/1050-6	$t \leqslant 30$	1 050	700	6
	$30 < t \leqslant 60$	1 000		4
	$60 < t \leqslant 100$	970		3
ISO 17804/JS/1200-3	$t \leqslant 30$	1 200	850	3
	$30 < t \leqslant 60$	1 170		2
	$60 < t \leqslant 100$	1 140		1
ISO 17804/JS/1400-1	$t \leqslant 30$	1 400	1 100	1
	$30 < t \leqslant 60$	1 170	To be agreed between the manufacturer and the purchaser	
	$60 < t \leqslant 100$	1 140		

Table 25.

Cross-references of similar grades. ISO 17804

ISO 17804:2005[a]	ASTM A897-02	ASTM A897M-02	EN 1564:1997	JIS G5503-1995	SAE J2477 May 2004
—	—	—	—	—	AD750
JS/800-10	—	—	EN-GJS-800-8	—	—
JS/800-10RT	—	—	—	—	—
—	125/80/10	850/550/10	—	—	—
JS/900-8	—	—	—	FCAD 900-8	AD900
—	—	—	EN-GJS-1000-5	FCAD 1000-5	—
JS/1050-6	150/100/7	1050/700/7	—	—	AD1050
JS/1200-3	175-125/4	1200/850/4	EN-GJS-1200-2	FCAD 1200-2	AD1200
JS/1400-1	200/155/1	1400/1100/1	EN-GJS-1400-1	FCAD 1400-1	AD1400
—	230/185/–	1600/1300/–	—	—	AD1600
JS/HBW400	200/155/1	1400/1100/1	EN-GJS-1400-1	FCAD 1400-1	AD1400
JS/HBW450	230/185/–	1600/1300/–	—	—	AD1600

[a] The complete ISO grade designation includes the ISO standard number (undated), e.g. ISO 17804/JS/800-10.

3.6.3. BLADES

Composite materials are used typically in blades and nacelles of wind turbines. Blades are the most important composite based part of a wind turbine, and the highest cost component of turbines despite being less than 15% of its weight. Reducing blade weight has a dramatic weight-saving effect throughout the rest of the wind turbine. However, a careful balance must be achieved between reductions in blade weight and the higher costs typically associated with specialized lightweight materials. The use of lighter materials becomes a necessity when trying to scale to larger blades, and thus more efficient turbines. In scaling rotor blade sizes from 40 m to 60 m in length, commercial blades at the upper end of the current size range are already nearing the limit of conventional designs from the standpoint of size, strength, and durability in operation over time.

A wind turbine blades consists of two faces (on the suction side and the pressure side), joined together and stiffened either by one or several integral (shear) webs linking the upper and lower parts of the blade shell or by a box beam (box spar with shell fairings) (see Schema on Figure 18) [22].

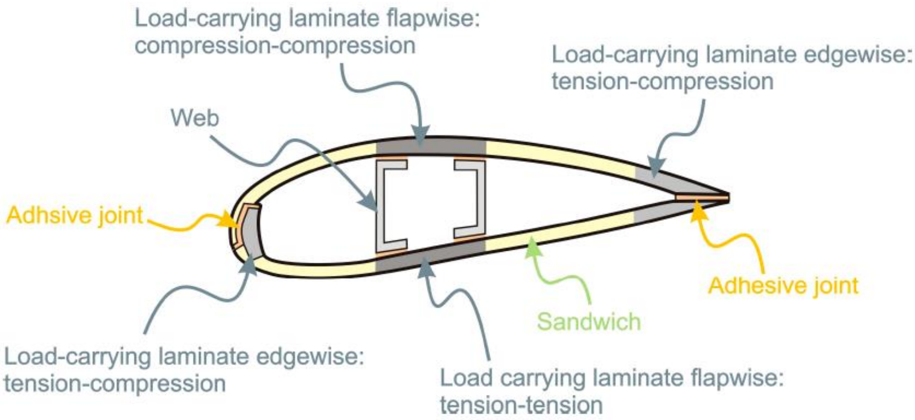

Figure 19. Schema of the section of the blade.

The flapwise load is caused by the wind pressure, and the edgewise load is caused by gravitational forces and torque load. The flapwise bending is resisted by the spar, internal webs or spar inside the blade, while the edges of the profile carry the edgewise bending. From the point of loads on materials, one of the main laminates in the main spar is subjected to cyclic tension-tension loads (pressure side) while the other (suction side) is subjected to cyclic compression-compression loads.

The laminates at the leading and trailing edges that carry the bending moments associated with the gravitation loads are subjected to tension-compression loads. The aeroshells, which are made of sandwich structures, are primarily designed against elastic buckling. The different cyclic loading histories that exist at the various locations at the blades suggest that it could be advantageous to use different materials for different parts of the blade.

Therefore, lightweight of the blades should be focus on:

- Reducing the mass of the blade skin.
- Reducing the mass of inner structure by mean of the design of the structure and/or the used of new materials.
    - Internal truss structure; whereby the spar box and 3rd web of the original configuration is replaced by a truss structure made of composite materials, and, see Figure 19 (a);
    - Grid reinforced skin; whereby the sandwich panels of the trailing edge are replaced by grid-stiffened panels, keeping the rest of the blade structure as per traditional designs. A scaled prototype was manufactured and can be seen in Figure 19 (b);
    - Rib reinforced skin; whereby the load-carrying structure of the blade is completely replaced by a truss structure having composite material members. The outer surface of the blade is no longer designed to carry the loads, but rather only to form the aerodynamic shape needed for the operation of the blade, see Figure 19 (c).

A reduction to the blade mass is possible when implementing each of those innovative solutions.

However not all aspects of the introduced concepts have been covered; for example, structural details such as the joints between truss members have not been considered in the design process.

Further research is needed to ensure the feasibility of the proposed concepts.

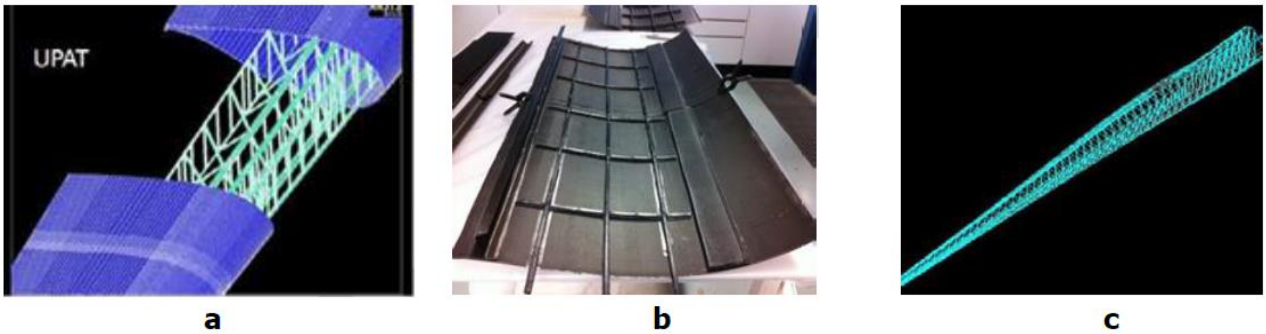

Figure 20. Different solutions for lightweight based on new design of internal structure. Source: Innwind.eu

A major trend in wind turbine development is the increase in size and offshore placements. Increasing size is motivating by the desire to reduce of the leveraged cost of energy. With increasing size, the weight of the rotor blades increases, so that gravitational loads become design drivers. Also longer blades deflect more, so that structural stiffness (to ensure tip clearance, i.e., to avoid the blade to hit the tower) is of increasing importance. Thus, from a materials perspective, the stiffness-to-weight is of major importance. In addition, with the turbine designed to be in operation for 20–25 years, the high-cycle fatigue (exceeding 100 million load cycles) behavior of composites and material interfaces (sandwich/composite interfaces) is of major importance.

During the first decades of the wind energy development, wind turbine blades were often produced using the wet hand lay-up technology, in open molds. The glass-fiber reinforcement was impregnated using paint brushes and rollers. The shells were adhesively bonded together to the spars. This technology was used mainly to produce small and medium size blades (up to 35 and 55 m, respectively). For larger blades, the same technology was used, but the web were inserted and adhesively bonded between two sides, and the plies with more fiber content were used. The disadvantages of the open mold technology are high labor costs, relatively low quality of products and environmental problems. In 1970s, several companies and institutes explored the applicability of filament winding technology, seeking to improve the quality of turbine and to reduce labor costs [23].

The introduction of vacuum infusion and prepreg technologies allowed improving the quality of manufacturing [36]. The prepreg technology, adapted from the aircraft industry, is based on utilizing "pre-impregnated" composite fibers, which already contain an amount of the matrix material bonding them together. Prepreg (widely used, for instance, by the Danish wind turbine producer Vestas) allows the industrial impregnation of fibers, and then forming the impregnated fibers to complex shapes.

The most widely used technology to produce the wind blades, especially longer blades, is the resin infusion technology. In the resin infusion technology, fibers are placed in closed and sealed mold, and resin is injected into the mold cavity under pressure. After the resin fills all the volume between fibers, the component is cured with heat. The resin infusion technologies can be divided into two groups: Resin Transfer Molding (RTM) (resin injection under pressure higher than atmospheric one) and Vacuum Assisted Resin Transfer Molding (VARTM) (or Vacuum Infusion Process) (when resin is injected under vacuum or pressure lower than atmospheric, typically, under a vacuum bag) [44]. A variation of VARTM called SCRIMP™ (i.e., Seemann Composite Resin Infusion Process) was developed in late 1980s and is quite efficient for producing large and thick parts. Currently, vacuum assisted resin transfer molding (VARTM) is the most common manufacturing method for manufacturing of wind turbine rotor blades. With his method, layers of fabrics of dry fibers, with nearly all unidirectional fibers, aligned in the direction along the length of the blade, are position on mold parts along with polymer foams or balsa wood for sandwich structures (for the aeroshells). In order to form a laminate that is thick by the root and gradually becomes thinner towards the tip, most plies run from the root only partly toward the tip; the termination of a ply is called ply-drop.

The fabrics and subsequently covered by a vacuum bag and made air-tight. After the application of vacuum, low-viscosity resin flows in and wets the fibers. After infusion, the resin cures at room temperature. As said in most cases, wind turbine rotor blades are made in large parts, e.g., as two aeroshells with a load-carrying box (spar) or internal webs that are then bonded together. Sometimes, the composite structure is post cured at elevated temperature. In principle, this manufacturing method is well suited for upscaling, since the number of resin inlets and vacuum suction points can be increased. A challenge with upscaling is however, than quite many layer of dry fabrics must be kept in place and should not slip relative to each other. The composite is quite thick by the root section, typically exceeding 50–60 mm in the consolidated state. In practice, it can be a challenge to avoid the formation of wrinkles at double-curved areas and areas with un- wetted fibers and air bubbles can be entrapped in the bondlines. After manufacturing, the blades are subjected to quality control and manufacturing defects are repaired. Since a large blade represents a large value in materials, increasing sizes means that it becomes less and less attractive to discard blades with manufacturing defects. Thus, with increasing size the requirements towards materials go towards easier processing and materials should preferably be more damage tolerant so that larger manufacturing defects can be tolerated.

The infusion process is usually cheaper that the prepreg process. However, the prepreg composites have more stable, better and less variable mechanical properties than the composites produced by resin infusion. This technology is relatively environmental friendly, and makes it possible to achieve higher volume content of fibers, and to control the materials properties. Further, the prepreg technology allows higher level of automation and better choice of resins.

The stiffness of composites is determined by the stiffness of fibers and their volume content. Typically, E-glass fibers (i.e., borosilicate glass called “electric glass” or “E-glass” for its high electric resistance) are used as main reinforcement in the composites. With increasing the volume content of fibers in UD composites, the stiffness, tensile and compression strength increase proportionally, yet, at high volume content of fibers (after 65%), there might be dry areas without resin between fibers and the fatigue strength of the composite reduces [66]. Typically, the glass/epoxy composites for wind blades contain up to 75 weight % glass. Many investigations toward the development of fibers, which are stronger than the usual E-glass fibers, have been carried out. The high strength fibers (which are still used seldom in practice, but represent a promising source of the composite materials improvement) include glass fibers with modified compositions (S-glass, R-glass, etc.), carbon fibers, basalt and aramid fibers. S-glass (i.e., high strength glass, S means “Strength” here) developed in the 1960s, shows 40% higher tensile and flexural strengths, and 10–20% higher compressive strength and flexural modulus, as compared to E-glass. The S-glass is much more expensive than E-glass. S2 glass was developed in the 1968 as a commercial version of S-glass. S glass and S2 glass fibers have the same composition (magnesium alumino-silicate). The main differences are in sizing (fiber coating) and certification procedure. The price of S2-glass is around 10 times of that of E-glass. R-Glass fibers, introduced in 1968, are produced with a calcium aluminosilicate glass with less silica and added oxides [47]. Some other special glasses developed by Owens Corning are ECRGLAS, Advantex and most recently WindStrandTM glass fibers. The WindStrandTM glass fibers show 15 percent higher stiffness and up to 30 percent higher strength when compared to E-glass [41].

Carbon fibers are considered to be a very promising alternative to the glass fibers. They show much higher stiffness and lower density than the glass fibers, thus, allowing the thinner, stiffer and lighter blades. However, they have relatively low damage tolerance, compressive strength and ultimate strain, and are much more expensive than the E glass fibers [42, 63]. Carbon fiber reinforced composites are sensitive to the fiber misalignment and waviness: even small misalignments lead to the strong reduction of compressive and fatigue strength. Carbon fiber composites are used by the companies Vestas (Aarhus, Denmark) and Siemens Gamesa (Zamudio, Spain), often in structural spar caps of large blades [42].

Further, an interesting alternative is using non-glass, high strength fibers first of all, aramid and basalt fibers. Aramid (aromatic polyamide) fibers demonstrate high mechanical strength, and are tough and damage tolerant, but have low compressive strength, low adhesion to polymer resins, absorb moisture, and degrade due to the ultraviolet radiation [48].

Basalt fibers show good mechanical properties, are 30% stronger, 15–20% stiffer and 8–10% lighter than E-glass, and cheaper than the carbon fibers [42]. The application of basalt fibers in small wind turbines have been demonstrated in [19, 17] and the results were very encouraging.

For large blades to avoid the near cubic weight increase with size, carbon, or carbon/glass hybrid composites and manufacturing processes that yield better mean properties and/or reduced property scatter through improvements in fiber alignment, fiber volume fraction, and void reduction are required [56]. Hybrid reinforcements (E-glass/carbon, E-glass/aramid, etc.) represent an interesting alternative to the pure glass or pure carbon reinforcements. Ong and Tsai [57] demonstrated that the full replacement would lead to 80% weight savings, and cost increase by 150%, while a partial (30%) replacement would lead to only 90% cost increase and 50% weight reduction for 8 m turbine. A wind turbine rotor blade of 88.4 m long blade from LM Wind Power was made of carbon/glass hybrid composites [64].

While carbon fiber reinforced plastics (CFRP) have superior properties compared to “traditional” glass fibers, such as approximately three times the stiffness with significantly better fatigue properties, it also has a much higher specific cost. While commonly used E-glass costs less than 2.20 USD$/kg, standard modulus carbon fiber costs on the order of 13.00 $/kg to 44 $/kg, depending on type, tow-size, and volume. In general, the cost advantage or disadvantage of carbon fiber replacement will depend on the cost ratio of labor to materials. In order to take advantage of carbon properties compared with the currently common composites, new designs and manufacturing methods must provide reduced labor time and therefore reduced costs, which permit CFRP rotor blades to be manufactured at a commercially competitive cost [58]. From an industrial point of view, advantages of carbon fiber reinforced plastics/composites in blades include:

- Thinner and more efficient profiles resulting in higher energy output.
- Stiffer blade resulting in shorter nacelle.
- More slender blades resulting in lower extreme loads on tower and nacelle.
- Lower blade mass resulting in easier handling in production and mounting.

In a number of works, the strength and damage mechanisms of hybrid composites were studied [52–61]. It was reported, among others, that the incorporation of glass fibers in carbon fiber reinforced composites allows the improvement of their impact properties and tensile strain to failure of the carbon fibers [62] observed an enhancement of the failure strain of the carbon fiber reinforced phase when "carbon fiber is combined with less-stiff higher-elongation glass fiber in a hybrid composite". However, in [20], it was shown on the basis of computations that the dependency of the composite strength on the ratio glass/carbon is V-shaped, with a minimum at the content of the order of 60% carbon, i.e., the hybrid strength can be under some conditions be lower than the strength of both pure glass or pure carbon composites. This observation was confirmed experimentally in [24]. Thus, while the hybrid composites seem to be a very promising group of composites for wind energy, additional investigations are required for the optimal composition of the materials.

Lately, the automated tape lay-up, automated fiber placement, two-pieces or segment wind blades, enhanced finishing technologies are expected to come into use to improve quality and reduce costs of the composite blade manufacturing. A big challenge, in comparison with e.g., automatization of composite structures for aerospace, is the much larger thicknesses and the much larger amount of materials to be places in the molds for wind turbine rotor blades. For some parts of the blades, 3D woven composites represent a promising alternative to producing fiber reinforced laminates. Mohamed and Wetzel [49] suggested producing spar caps from 3D woven carbon/glass hybrid composites. It was demonstrated that this technology allows producing spar caps with higher stiffness and lower weight, than the commonly used technologies manufacturing of a wind turbine rotor blade by assemblage and bonding of two aeroshells and two shear webs.

The second "part" of a composite is the matrix: Typically, thermosets (epoxies, polyesters, vinylesthers) or (more seldom) thermoplastics are used as matrices in wind blade composites.

Thermosets based composites represent around 80% of the market of reinforced polymers [45, 37]. The advantages of thermosets are the possibility of room or low temperature cure, and lower viscosity (which eases infusion and thus, allowing high processing speed). Initially, polyester resins were used for composite blades. With the development of large and extra-large wind turbines, epoxy resins replaced polyester and are now used most often as matrices of wind blade composites. Still, recent studies (e.g., by Swiss company DSM Composite Resins) support arguments for the return to unsaturated polyester resins, among them, faster cycle time and improved energy efficiency in the production, stating that the newly developed polyesters meet all the strength and durability requirements for large wind blades. Further, the development of matrix materials which cure faster and at lower temperatures is an important research area.

Thermoplastics represent an interesting alternative to the thermoset matrices. The important advantage of thermoplastic composites is their recyclability. Their disadvantages are the necessity of high processing temperatures (causing the increased energy consumption and possibly influencing fiber properties) and, difficulties to manufacture large (over 2 m) and thick (over 5 mm) parts, due to the much higher viscosity. The melt viscosity of thermoplastic matrices is of the order 102–103 Pa s, while that for thermosetting matrix is around 0.1–10 Pa s. Thermoplastics (as differed from thermosets) have melting temperatures lower than their decomposition temperatures, and, thus, can be reshaped upon melting. While the fracture toughness of thermoplastics is higher than that of thermosets, fatigue behavior of thermoplastics is generally not as good as thermosets, both with carbon or glass fibers [45].Other advantages of thermoplastics include the larger elongation at fracture, possibility of automatic processing, and unlimited shell life of raw materials [60] .

In several works, the possibilities of improvement of composites properties by adding nanoreinforcement in matrix were demonstrated. Additions of small amount (at the level of 0.5 weight %) of nanoreinforcement (carbon nanotubes or nanoclay [25]) in the polymer matrix of composites, fiber sizing or interlaminar layers can allow to increase the fatigue resistance, shear or compressive strength as well as fracture toughness of the composites by 30–80% [12,21]. Loos, Manas-Zloczower and colleagues developed various wind turbine blades with secondary carbon nanoparticles reinforcement (vinyl ester, thermoplasts, epoxy composites containing CNTs) and demonstrated that the incorporation of small amount of carbon nanotubes/CNT can increase the lifetime up to 1500% [29]. Koratkar and colleagues [26, 38] studied graphene as a secondary reinforcement for the nanomodification of wind turbine composites, and showed experimentally that the graphene reinforcement is very promising in the development of stronger, long-life turbine blades for the wind industry. Merugula and colleagues [30, 39] estimated theoretically that the addition of 1–5 wt % of carbon nanofibers (CNF) to the interfaces of glass fiber reinforced epoxy composites for blades in 2 MW and 5 MW turbines leads to improved tensile stress and modulus, and allows 20% weight reduction of the blades, leading to the increased lifetime. One should note that transferring property improvements obtained in specific polymer-nanocomposites (without fiber reinforcement) as matrix material to laminates with reinforcing fibers remains an issue, especially with respect to volume fraction of the nano-fillers and the lower bound of the scatter in improvements obtained [13].

In some cases, improvements from using nano-modified polymers as matrix (e.g., for improved strength or toughness) come with intrinsically lower property values in other areas (e.g., glass transition temperature) limiting the processability or the applicability of nano-modified polymers [27-In [18–14] the applicability of hierarchical composites for wind energy applications is analyzed, using the computational modelling. Also, the feasibility of using hybrid and nanoreinforced composites in wind blades, as a replacement for the currently used glass fiber/epoxy composites is evaluated in [18]. It was demonstrated in numerical studies that the gains in the lifetime of the composites justify additional investments to produce the wind turbine blades from hybrid and nanoreinforced composites. Still, as noted in [34] there remains a lot of practical and economical challenges before the nanoengineered wind turbines are used.

In the final engineering structure, core materials (typically varying from 60 – 150 kg/m3) form part of a sandwich structure comprising of resin (epoxy or polyester) and reinforcement (glass and/or carbon) on either side. The most important properties for core materials for blade applications are typically the shear modulus and density. Higher shear modulus is beneficial for improved buckling capacity and, of course, density is important to minimize blade weight. Cost and manufacturability are, of course, critical considerations, and Young’s modulus is also important as well. The core primarily is a means to reduce the weight of the laminate while sustaining the out-of-plane strength and rigidity.

The use of core material in composite applications is nothing new. Foam, balsa and honeycomb core have been mainstays of sandwich construction in boat hulls and decks for more than three decades, and can be found in hundreds of parts used in construction, energy, infrastructures and transportation applications. The last years, however, have seen explosive growth in wind turbine blade manufacturing, which promises to make unprecedented use of core in a variety of sandwich constructions. The expansion of this market — and the influence it exerts — is changing how core is made and applied in composites construction. In response, core manufacturers are working to develop new core materials that meet wind’s demand for strength, light weight and low cost.

The appeal of core is well known. In all its forms, it offers low density and, therefore, low mass, and does so at relatively low cost. In a sandwich construction — core material faced on each side with a reinforcing glass/resin skin offers greater mechanical strength and stiffness, pound-for-pound, than any other structural option, regardless of the materials used. Further, the great variety of available core material types, ranging from balsa to foams to honeycombs, provides a broad spectrum of material densities, geometries, processing options, costs and physical attributes.

Simplistically, the load carrying members of a typical blade today consists of structural webs connected to monolithic girders to form an approximation of a crude ‘boxed beam’ which in turn is joined to the root end. The surrounding two-part shell is transferring wind loads to the load carrying members while providing the optimum aerodynamic shape. Core material is normally used in both the spars and the shells, differently tailored in each component to provide ultimately the optimum level of design performance. The blade root and its immediate adjoining spar/girder area is often referred to as the primary structural element of the blade, as it is here that the considerable forces and loading come to bear in service life.

Blade manufacturers are, like all composites processors, balancing many variables against each other, each picking and choosing different combinations to meet cost and performance goals. Core type affects several metrics: thickness of sandwich construction, mechanical strength of sandwich construction, blade durability and blade cost. Some core types offer better mechanical strength, but are costly. Others are economical, but lack mechanical strength, in which case a thicker sandwich might be needed to meet a specific requirement. Some cores are only suitable for flat surfaces, while others, such as honeycombs, don’t lend themselves easily to infusion. Further, blade manufacturers are relying increasingly on CAD/CAM, finite element analysis (FEA) and simulation to understand what materials work best where in a blade, so they can optimize material use to match requirements at different locations along the blade’s length. Some manufacturers favor balsa over foam, while others prefer foam or, more increasingly, a combination of different cores.

Each wind energy company has its own unique blade design, which is usually subcontracted to blade manufacturers. Often, several blade manufactures are involved in providing an identical blade to a single wind energy company on a global basis. It is the global nature of wind energy, as much as the volume of production that requires the use of multiple blade manufacturers by a single wind energy company. The materials used in each blade design are considered proprietary and a closely held secret. Still, material variation from manufacturer to manufacturer is not substantial, so it is possible to get a general sense of what type of core material is used, and where, and how this use might be changing. One thing is clear, however: Wind blades have become much more hybridized over the last five years, meaning that choice of core material type can vary significantly within a single design, depending on material, weight, structural, production and cost requirements at different locations along the blade shell and within the shear web.

The last few years have seen four core material types emerge as the most widely used in wind energy applications: end-grain balsa, styrene acrylonitrile (SAN) foam, polyvinyl chloride (PVC) foam and polyethylene terephthalate (PET) foam. End-grain balsa is popular, first, because it is inexpensive; second, because its end-grain “honeycomb” structure provides robust mechanical properties — 5-lb/ft^3 to 15-lb/ft^3 density; and third, because it is derived from a sustainable and renewable resource, the fast-growing balsa tree. In hybrid blade construction, because of its higher strength and stiffness, it is most often used in the root section (approximately the first 10m/33 ft of a 40m/131-ft blade), although it can be used throughout the entire length of the blade.

It is most common to find core materials in the 130-150 kg/m3 range used, be they predominantly balsa or PVC, such as ProBalsa and H/HP130 respectively. The remaining webs will, like the shell then typically use a much lighter core in the 60-80 kg/m3 density range, such as H60, H80 and second-generation materials like Matrix 7-7 and 10-8, which transitions to the tip of the blade. Balsa and PVC have been (and still) is the engineering material of choice today, providing as it does an unrivalled balance of properties, weight and cost. The market has seen the use of SAN and PET material enter as alternatives during the high-growth years, when supply chain focus was on securing materials, however they have not penetrated the market as widely as PVC has done. Looking forward, with such a wide range of material options available, structural design engineers could tailor the use of core in a more optimum way if design allowables could be opened up.

Whilst the use of thickness (against global buckling) and density (for local buckling) have optimized designs, other opportunities exist. One could for example foresee the use of 45 kg/ m3 material towards the tip end, transitioning to 60, then 80, 100 and 130/150 kg/m3 at the root end, with a corresponding reduction in materials cost. Whilst adding such complexity brings issues with optimizing waste during the process of cutting a preformed kit, this is manageable by a combination of effective material utilization, reuse and nesting by the material supplier.

Balsa’s mechanical properties are derived mainly from its end-grain structure, but if used throughout the blade, its higher density can introduce a weight penalty when compared to foam cores. Although the density of the lumber within a sheet of balsa may vary, the average density of a sheet is held within tight tolerances. However, when it comes to infusion, balsa’s end-grain structure can boost resin uptake, adding weight to the blade. As with all cores, balsa and foam must be scored or segmented to create hinges that allow it to conform to curved surfaces. This scoring creates gaps, or kerfs, in the surface of the core where one segment angles away from another. The kerfs may help facilitate resin flow, but also fill with resin, which adds weight. Fortunately, in the infusion process the kerfs fill with resin, eliminating unwanted voids in the core structure.

Core made of SAN and PVC is less dense than balsa (about 4 lb/ft^3), but also tends to be more expensive. Both SAN and PVC are thermoset formulations that provide structural support, but would have to be about twice as thick as balsa to match balsa’s higher physical properties. As a result, foams tend to be used in areas that benefit from weight savings, but still require some strength and stiffness — primarily the middle 20m/66 ft or so of the blade shell, and in the shear web.

In infusion processes, use of any core type requires careful management of resin flow to ensure wet out. This can include machining of flow channels and other mechanical structures in the surface of the core to facilitate resin transport and to make sure resin flow fronts move evenly over the core surface on both sides of the core. One of the drawbacks of PVC is that it can outgas during the cure process when overlaid by prepreg, which can lead to delamination of the sandwich construction. Like balsa, SAN and PVC must be scored or segmented to conform to tooling surfaces and thus add weight via increased resin uptake in the kerfs.

Among the newest players in the foam core market is PET, which is in the high-potential, early-development phase of its wind energy maturation. PET is attractive for a number reasons, owing to the fact that, unlike PVC, it is a thermoplastic and, therefore:

- It is recyclable and is made with recycled content (typically, from waste PET bottles).
- It is manufactured via the extrusion process and thus provides more consistent density control and mechanical properties.
- It does not outgas when in contact with prepreg during cure.
- It is thermocuttable via either a hotwire or laser process, a fact that permits development of novel surfaces.
- It is remeltable, and therefore, can be fused with most face sheet laminates during heated cure, without use of an adhesive.
- It is, for the same reason, thermoformable and, thus, can be preformed to specified shapes/dimensions without the need for scoring or segmentation.

As a structural foam, PET requires a slightly higher density to match the mechanical strength and stiffness of SAN and PVC, and a substantially higher density to match balsa. PET is employed primarily in semistructural applications, in the last 10m/33 ft (the tip) of a wind blade shell. But PET is said to have the potential, following a few more developmental iterations, to find significantly greater use in turbine blade construction.

There is at least one material type working the fertile ground between balsa and traditional core. WebCore Technologies LLC (Miamisburg, Ohio) introduced to the market a core material positioned to offer the mechanical and cost benefits of balsa, with the weight benefits of a foam. WebCore's TYCOR W comprises closed-cell polyurethane "sticks" helically wound with glass fiber tows, with the space between tows variable and dependent on the application — the closer the spacing, the greater the strength and stiffness. The sticks are assembled and held together with fiberglass surface veils, creating 4 ft by 8 ft (1.2m by 2.4m) sheets of core. Because it is not a structural foam, the low-density polyurethane acts only as a carrier for the wound glass fiber, which — after resin infusion and cure — is the material's primary source of strength and stiffness. Moreover, the material is inherently flexible and, thus, requires no scoring or kerfing. TYCOR ranges from 12 to 78 mm thick (0.47 to 3.1 inches) and can match balsa's mechanical performance at the same price, with substantial weight and resin savings. TYCOR also can be used in the middle section of the blade shell, as well as in the shear web, where SAN and PVC traditionally take precedence.

3.7 CONCLUSIONS OF TECHNICAL STUDY

In order to lighten the weight of offshore wind towers, several components have been selected, whose weights are an important percentage of the total weight of the wind tower. The conclusions obtained are summarized below.

3.7.1. TOWER

- **Key Challenge**

Reduce the manufacturing and assembly costs by lightening the weight of the tower.

- **Materials used**

Weldable fine-grained structural steels.

Mainly: S275, S355, S420 in different grades (N or NL) according to the requirements of the resilience test (Charpy test) at -20ºC and -50ºC respectively. In addition to these qualities and grades mentioned, the M series, thermomechanically rolled plate, (e.g. S355M and S355ML) is often used in the offshore industry. UNE EN 10025-3 and UNE EN 10025-4 standards.

- **Technology trends**

Due to their size they are constructed in welded sections. Overload problems limit transport to the site. Research is ongoing to overcome transportation problems and the high cost of erection, focusing on onsite tower fabrication.

For this purpose, it will be necessary to select materials with high mechanical properties (tensile strength and yield strength) that allow the manufacture of towers of lesser thickness. On the other hand, it must be borne in mind that the materials selected must behave well in the face of fatigue stresses and also have a good welding aptitude. As thickness and strength increase, cold cracking may occur.

Although the most commonly used quality is S355 and lower the tendency is to lighten weights trying to use higher qualities such as S420 or S460

Transport and installation costs are a factor to be taken into account. While the cost of S460 steels is slightly higher than that of S355 or S235 steels, the price of steels such as S690 is very high compared to S460 steel. Unless the weight is a severe problem, it would not be economical to use S690 steel.

Some qualities can be improved by introducing alloying elements that improve the properties of steel such as the application of niobium in high strength offshore wind towers. These Nb-containing structural support steels provide fatigue and operational performance in critical wind, wave and oceanic conditions.

3.7.2. FOUNDATIONS

- **Key Challenge**

Reduce the manufacturing and assembly costs by lightening the weight of foundations.

- **Materials used**

Weldable fine-grained structural steels.

Some of the most used steels in the manufactured of jackets are:

  - S355NL/ML, S420NL/ML, S355G9+N/G9+M, S355G10+N/G10+M, S420G1+QT, according to UNE EN 10025-3, UNE EN 10025-4, UNE EN 10225 standards.
  - NV36D, NV36EZ according to DNV-OS-B101.
  - AH36, DH36 y EH36 according to ABS.

- **Technology trends**

High mechanical strength materials are required to lighten the weight of the structure, with good weldability and to resist corrosion- fatigue in both welded and bolted joints.

Different innovations at the components level for the advanced jacket sub structure have been developed and tested under laboratory conditions:

  - Adhesive joints were tested as an alternative for welded connections in jacket members and further developments needed to develop this technology have been proposed.
  - Sandwich tubes for jackets were also tested to determine the performance of composite materials in jackets. These are rod-like structural components consisting of three components: two relatively thin steel tubes and a core made of ultra-high performance concrete.

3.7.3. MAIN FRAME, ROTOR HUB AND ROTOR SHAFT

The nacelle contains most of the components necessary for the operation of the wind tower, so its weight is considerable (between 25 and 40% of the total weight of the wind turbine).

- **Key Challenge**

Reduce the costs by lightening the weight of this components (improve their fatigue and mechanical strength properties, while at the same time reducing the size of these components).

- **Materials used**

They are usually manufactured in spherical graphite castings mainly in SSF (solid solution strengthened ferritic ductile iron) and ADI (austempered ductile iron castings casting).

One of the most used castings is EN GJS-450-18.

One of the steels most used in the manufacture of the rotor shaft is 42CMo4 (mostly made of forged Steel).

- **Technology trends**

The research is mainly based on the search for materials that are increasingly lighter and at the same time have excellent fatigue behaviour. In this type of castings, the shape and size of the graphite nodules as well as their distribution within the matrix are very important, because the properties of the casting depend on it.

The rotor shafts are subject to stress concentration factors, fretting driven fatigue stress concentration, effects and vibration natural frequency, so the development of materials with a good fatigue behavior that increases the life cycle to fatigue of the component is a priority.

3.7.4. BLADES

- **Key Challenge**

Reduce the costs by lightening the weight of the blades.

- **Materials used**

Fiberglass and reinforcing products, such as epoxy resin with steel.

- **Technology trends**

Trend is toward lighter and stronger blades. Increased use of composite materials including carbon fiber reinforced plastic, steel and fiberglass.

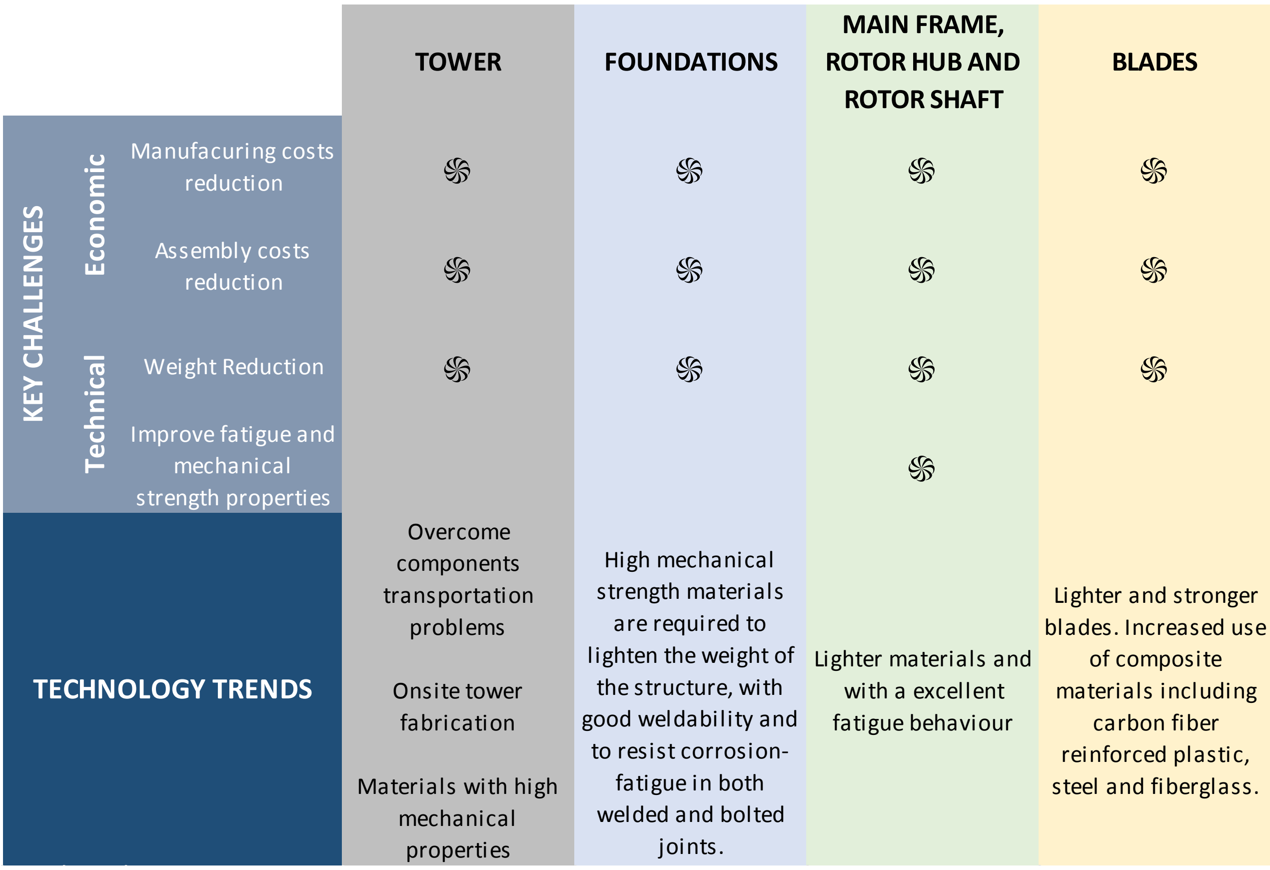

Figure 21. Resume of the principal key challenges and technology trends.

4 AREAS OF INTEREST AND OPPORTUNITIES FOR ADMA REGIONS

In order to know the areas of interest and opportunities for ADMA Regions, related to "NEXT GENERATION OF MATERIALS FOR THE MANUFACTURE OF LARGE COMPONENTS IN OFFSHORE WIND ENERGY", a survey (Annex I) was conducted between different regional entities. Thus, the study focused on knowing the areas of specialization of the regions, both at the level of companies and research centers, related to materials, tests, characterization, development of components for offshore, projects, etc.

A questionnaire was developed and circulated among the key participants in ADMA regions. Based on the received information and on a study of RIS3 priorities and collaborative programmes, the status for each region is presented below.Regions replying to survey were the following: Basque Country, Andalucia, Flanders, Skane and Asturias.

4.1 SURVEY ANALYSIS

Below they are a variety of diagrams and analysis on the main results of the study. However, the full results of the surveys can be found in Annex I.

Question 1. In which main big components of offshore systems are the entities (companies, RTO, others) of your region specialised?

The following graphics shows the main lines of specialization in terms of large components of offshore systems. The main elements and systems are included: assembly and engineering, wind turbine rotor, tower, nacelle, power conversion systems, foundation, connection to grid and offshore substation, remote control, others (recycling)

The first image shows the percent of regions that work on this specialization lines:

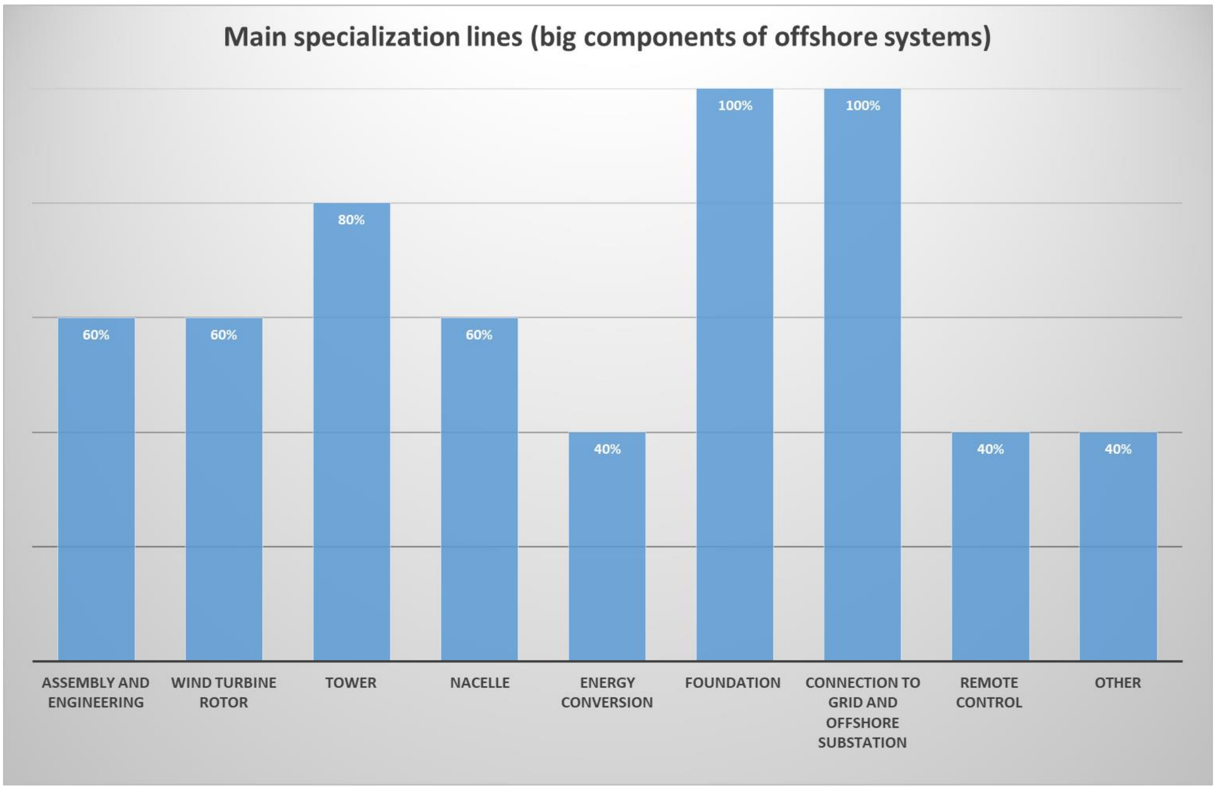

Figure 22.- Main specialization lines.

As a summary, the main lines of specialization of the different regions are the foundation, followed by the tower and connection, and later the assembly - engineering and nacelle and wind turbine rotor. Remote control and energy conversion are lines in which regions work less.

The following diagram shows a detail of which regions work in each of the specialization lines.

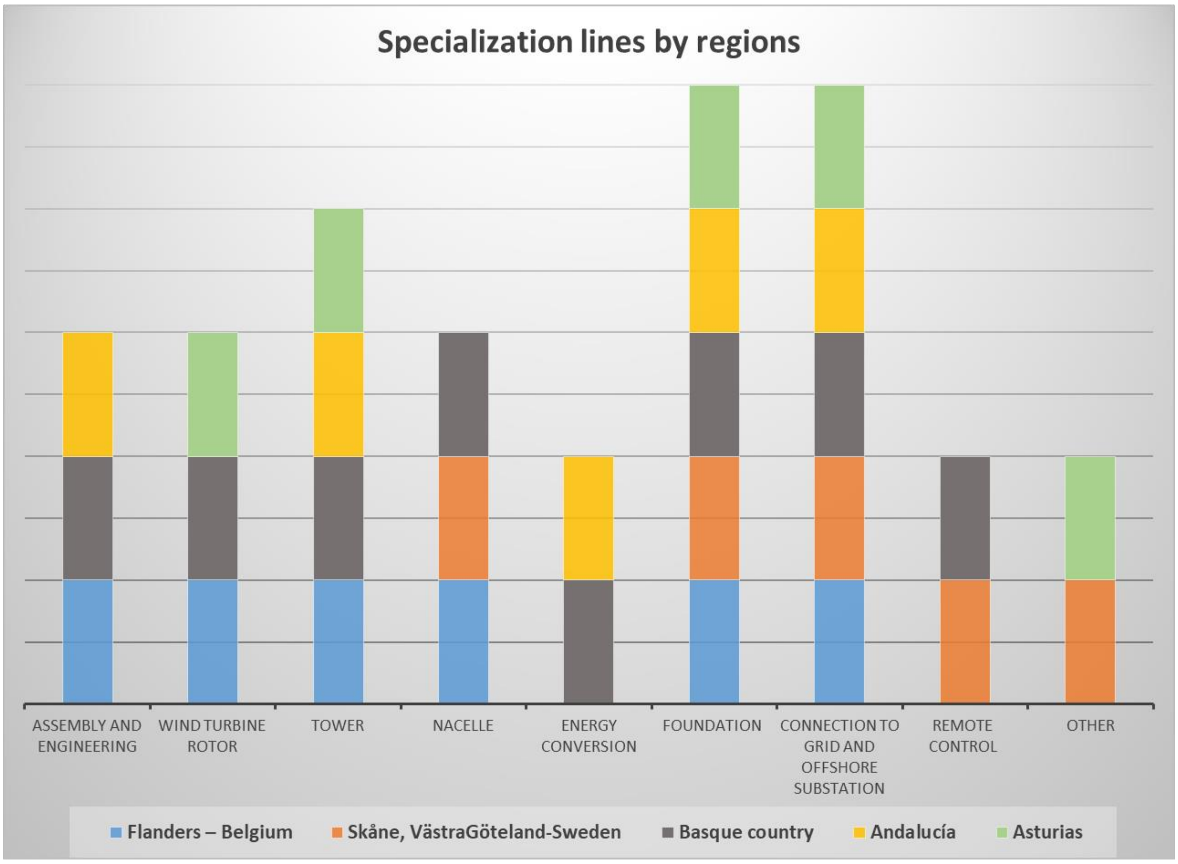

Figure 23.- Specialization lines by regions.

As shown in the graph, the regions have capabilities throughout the entire value chain in the development of offshore systems. The main lines of work are: foundation, connection to grid and offshore substation, and tower followed by wind turbine rotor, assembly – engineering and nacelle. Finally there are the energy conversion, remote control and others (Asturias: Wind turbine stator, sea-bed mooring. Skåne, VästraGöteland-Sweden: recycling).

Question 2. In your region area, are there any company with expertise in materials development? Main lines of development.

Question 3. In your region, are there any RTO with expertise in materials development?

These questions (2 and 3) evaluate the capacities of the regions in terms of development and study of materials (related to offshore systems). Companies and research centers have been analysed. The main materials defined have been metals, composites, coatings and others (concrete, nanoparticles).

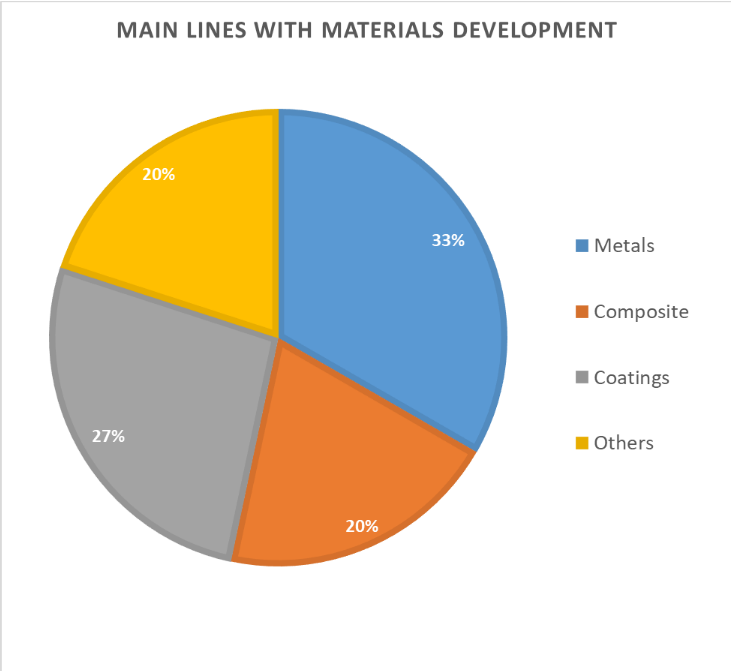

Figure 24.- Main lines with materials development.

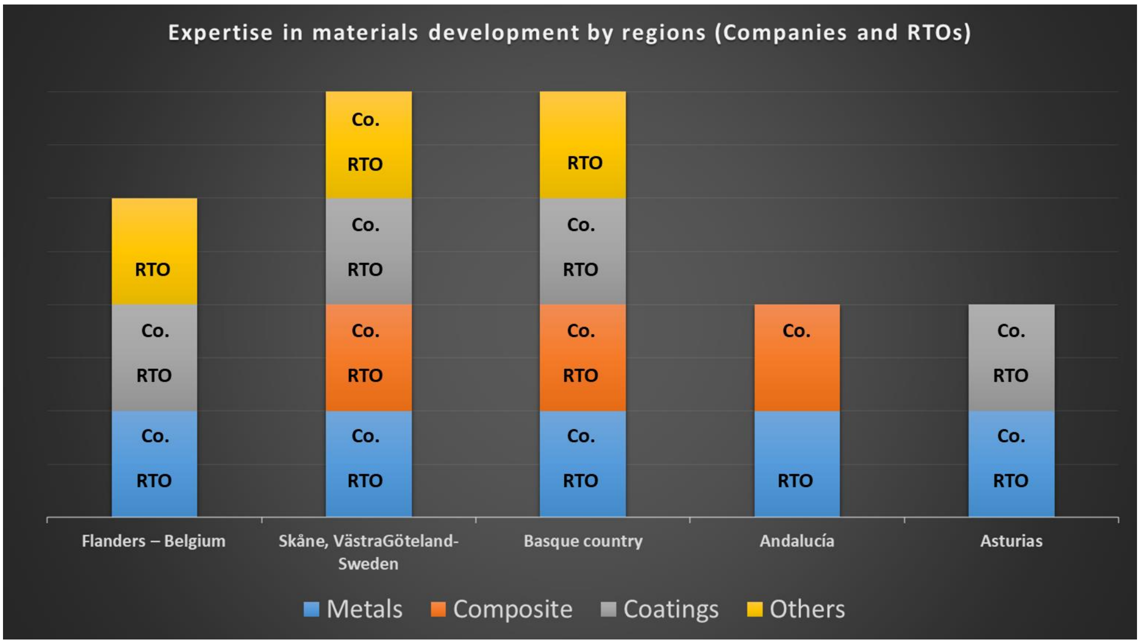

Figure 25.- Expertise in materials development by regions and by type of entity (Companies and/or RTOs)

Based on the results of the study, the main lines of development focus on metallic materials and coatings, followed by composites and others. It is also observed that there are capacities in both companies and RTOs.

Question 4. Regarding workforce, are there in your region qualified human resources with skills in materials development for big components in offshore wind energy.

The following diagram shows the capacities of each region in terms of qualified human resources in the field of materials development for big components in offshore wind energy, both at industry and RTO level.

	At Scientific and technological (R&D) level	At Industrial level	Any Specific Training related to the subject.
Flanders – Belgium	YES	YES	
Skåne, VästraGöteland-Sweden	YES	YES	Safety training for offshore workers
Basque country	YES	YES	https://www.master-rem.eu
Andalucía	NO	NO	
Asturias	YES	YES	

Figure 26.- Qualified human resources with skills in materials development for big components in offshore wind energy

Question 5. Have you identified any specific infrastructure (e.g. pilot lines, OITBs, testing labs….) related with materials for manufacturing of big components in offshore wind energy?

Regarding pilot plants, they have been identified in three regions of the five consulted, as shown in the following diagram:

Region	Specific infrastructure		Detail
	Yes	No	
Flanders – Belgium	x		OCAS, testing of large welds in fatigue, for example jacket nodes, University of Ghent, extensive test infra, for example for fatigue testing at high loads
Skåne, VästraGöteland-Sweden	x		RISE -testing labs
Basque country		x	
Andalucía		x	
Asturias	x		Complete cycle of metallic materials development. Industrial scale pilot. (ARCELOR and IDONIAL) http://www.idonial.com/en/blog/the-steel-square

Figure 27.- Specific infrastructure by regions related with materials for manufacturing of big components in offshore wind energy

In the Flanders and Skane regions, there are plants for component testing. In Asturias region, there is an infrastructure for development metallic materials at the pre-industrial plant level.

Question 6. In your region area there, any RTO or Company with expertise in testing materials for manufacturing of big components in offshore wind energy?

An analysis of the regions that have expertise to testing materials has been carried out. The following capacities have been evaluated:

- Corrosion
- Fitness For Service
- Characterisation
- Mechanical Testing (tensile test, fatigue test, fracture toughness)
- Residual stress measurement
- In Situ Non-Destructive tests
- Others

The following diagrams shows a detail of the regions with expertise in testing materials.

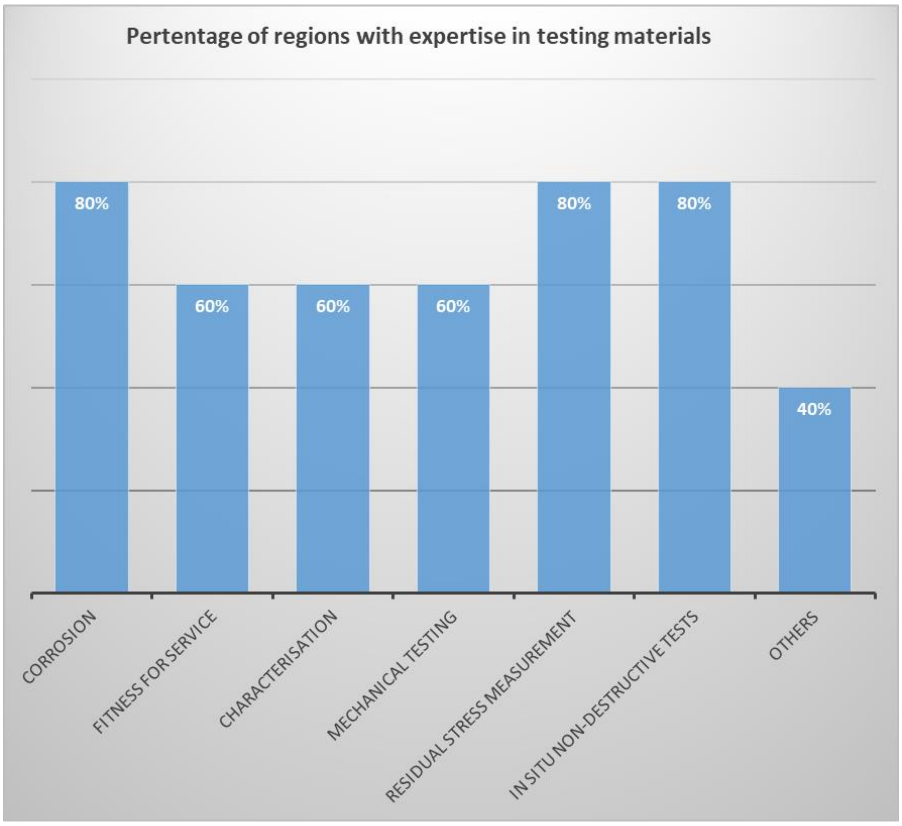

Figure 28.- Importance of expertise in testing materials.

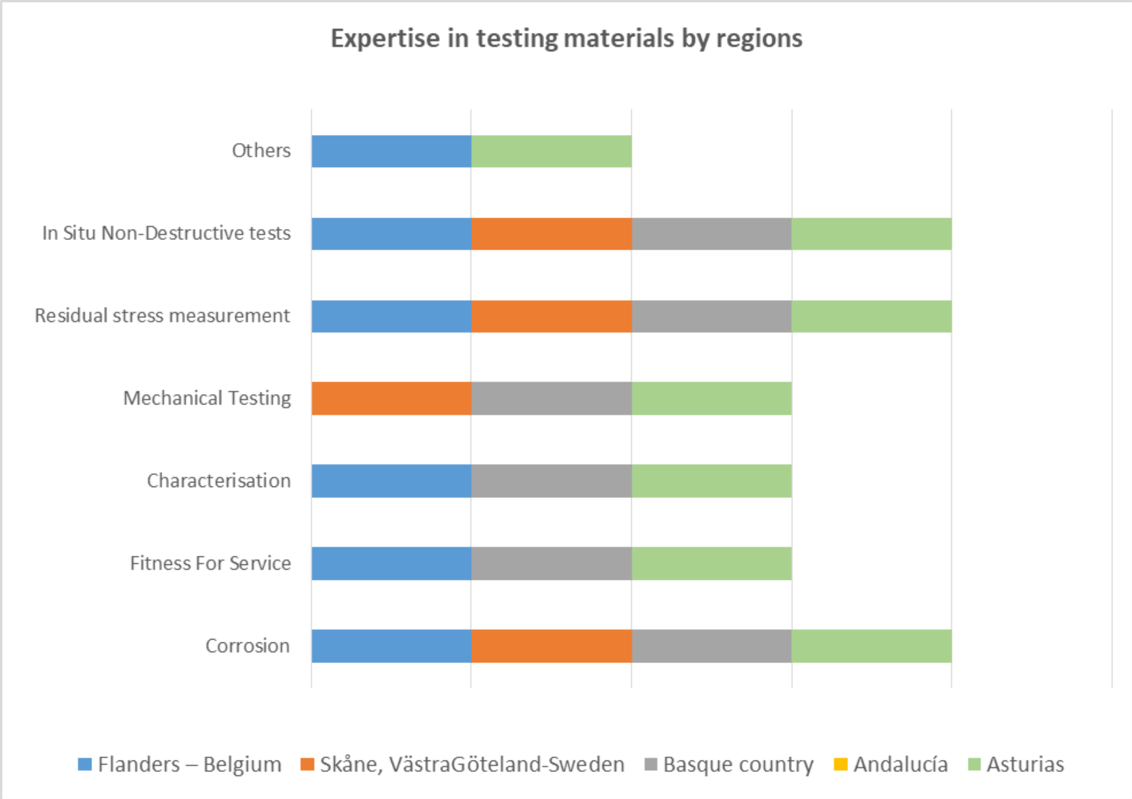

Figure 29.- Expertise in testing materials by regions.

As you can see in the graph, the main lines of specialization in materials testing are:

- Corrosion
- Residual stress measurement
- In Situ Non-Destructive tests

Followed by:

- Characterisation
- Mechanical Testing
- Fitness For Service
- Others

Of the five regions that have responded to the survey, four have expertise in the testing of offshore materials (Basque Country, Flanders, Skane and Asturias).

Question 7. Which of the main trends, related to materials for manufacturing of big components in offshore wind energy, are of interest. If you have identified any other, please indicate it.

Together with the capacities of each region, the main trends of future development interest have been evaluated. The results of the study are presented below:

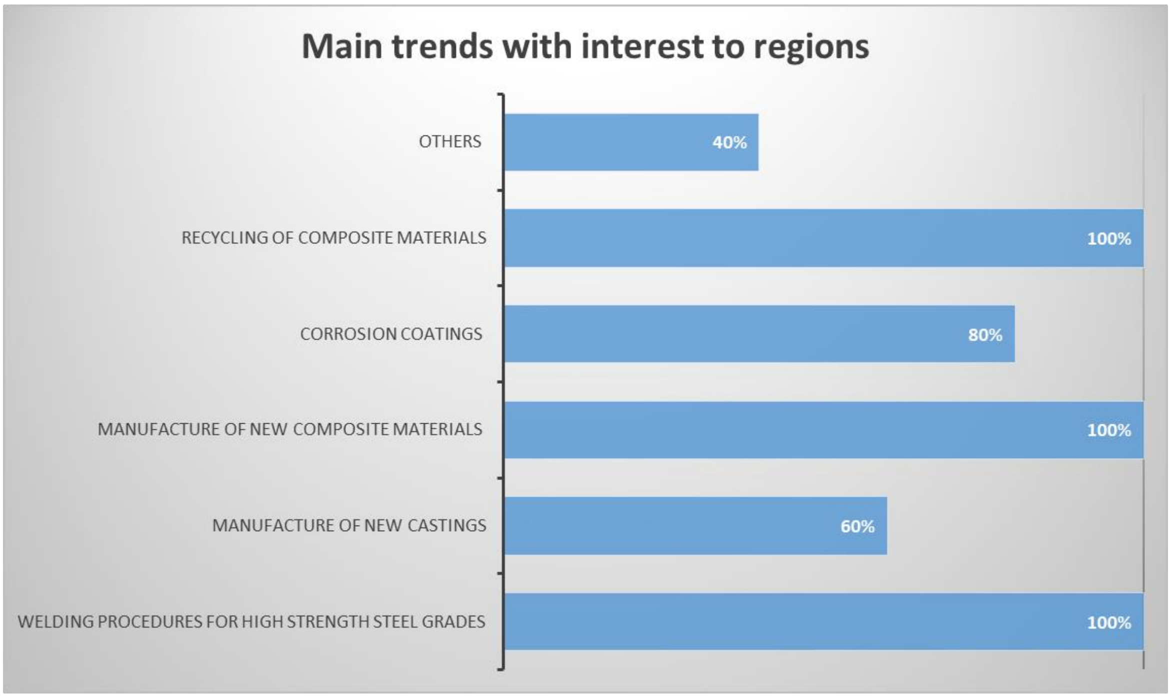

Figure 30.- Main trends with interest to regions.

The main trends of interest in the regions focus on:

- Welding procedures for high strength steel grades
- Manufacture of new composite materials
- Recycling of composite materials
- Corrosion coatings

Question 8. What regional strategies/policies support such materials development? And specifically with regards materials for manufacturing of big components in offshore wind energy?

Based on the results of the survey carried out, the regional policies to support the development of materials are:

Regions	Strategies / policies
Flanders	Strategic Initiative Materials in Flanders (https://www.sim-flanders.be/) Blue Cluster (https://www.blauwecluster.be/about-us)
Basque Country	EnergiBasque strategy
Skåne, VästraGöteland-Sweden	Maritime strategy, National strategy on wind energy
Andalucía	RIS3Andalucia: R&D in new materials

Asturias	RIS3 program: Naval and Wind Offshore Advance Manufacturing.

Figure 31.- Regional strategies/policies support such materials development

Question 9. Are you aware of any finished or ongoing R&D&I projects linked to the topic of material development for big components in offshore wind energy? If so, please provide a short description and link to webpage.

Regarding developments related to material development for big components in offshore wind energy have been identified the next projects:

NeSSIE	**http://www.nessieproject.com/**
NeSSIE project will tap into the existing knowledge of anti-corrosion technology / novel materials solutions in the maritime sector supply chain to develop demonstration projects for offshore renewables in the North Sea. The corrosion solutions, when developed and commercialised, will provide global growth and job creation opportunities in remote regions in the EU.	

i4Offshore	**https://i4offshore-project.eu/**
Siemens Gamesa Renewable Energy and Aalborg University in Denmark are leading the i4Offshore research and development project focused on significantly reducing the cost of offshore wind power. The project has received funding from the European Union's Horizon 2020 research and innovation programme with a grant of nearly 20 million euro.	

ReSHEALience	**https://uhdc.eu/**
The main goal of the project ReSHEALience is to develop an Ultra High Durability Concrete (UHDC) and a Durability Assessment-based Design (DAD) methodology for structures, to improve durability and predict their long-term performance under Extremely Aggressive Exposures (EAE: XS-chloride induced corrosion, XA-chemical attack).	

WINDSTEP	**http://www.demowind.eu/pages/funded-projects-8.html**
The main goal of the project is develop integrated Health Management System to optimise wind turbine performance through balance between power production and the rate of damage accumulation	

KBS-Weld (Manunet)	**http://kbs-weld.ro/**

Welding is an essential manufacturing process performed in almost every major industry. Therefore, weld quality and integrity are critical to safety in an extensive range of products and structures.

The KBS-Weld project aims to develop a knowledge-based system functioning as a computational support for the planning of the welding process, allowing the end-users to choose the best combination of welding materials, welding technologies and welding parameters to produce a welded structure with the required properties.

Being designed to reduce the lead-time and the direct influence of the human factor in the welding processes, as well as to increase the credibility of the results, this system will address some of the main needs of the SMEs involved in the manufacturing activities specific for the domain of interest that are highly demanding and with long term significant consequences on product's quality and safety.

XL-BLADE - DemoWind **https://www.era-learn.eu/network-information/networks/demowind/joint-call-2015/cost-of-energy-reduction-driven-development-manufacturing-and-in-field**

Achieving the ambitious EU target of 27% renewable penetration by 2030 requires step-change technological innovations across all sectors of renewables, paving the way for industrialization and scale. Within this context, offshore wind has proven its viability as a mature utility-scale contributor to the EU energy mix, with substantial cost reductions achieved over the past decade, and a similar trajectory as onshore wind towards grid parity. Within an offshore wind turbine system, the rotor set is one of the most influential ways to reduce total cost of energy. The overarching program objective of the consortium is to reduce the overall offshore wind cost of energy by merging the technological leadership of three offshore industry leaders across three participating countries to design, validate and deploy the world's largest offshore wind turbine blade. Specific technological objectives are design, manufacturing and in-field validation of blade approaching 90m in length with aggressive weight targets.

ODB Offshore Demonstration Blade (DemoWind 2) **http://www.demowind.eu/pages/funded-projects-8.html**

The objetivo of this project is to reduce the Cost of Energy of offshore wind by demostrating a set of blade technoloies aimed at increasisn the rotor energy perfomrance an dreducing its O&S cost.

JaCo - Improved Fatigue Life of Welded Jacket Connections **https://www.carbontrust.com/offshore-wind/owa/demonstration/jaco/**

NeSSIE project will tap into the existing knowledge of anti-corrosion technology / novel materials solutions in the maritime sector supply chain to develop demonstration projects for offshore renewables in the North Sea. The corrosion solutions, when developed and commercialised, will provide global growth and job creation opportunities in remote regions in the EU.

ReaLCoE (H2020) **https://www.realcoe.eu/**

ReaLCoE is a project supported by the EU research and innovation programme Horizon 2020 with the clear target to create better performing and more efficient offshore wind energy converters. The offshore WECs that ReaLCoE aims to develop will not only provide clean energy subsidy free, but will be competitive in comparison to conventional electricity sources. The innovated WECs will provide electricity to the lowest prices in comparison to the other conventional electricity sources, even the other renewable ones. By enhancing the operational capacity of the regular offshore WECs to 14-16 MW, ReaLCoE would achieve the electricity price of €35-50/MWh, which is just a third of the baseline price of similar projects. This will contribute to a more sustainable energy mix Europe-wide and bring growth and more job opportunities in the sector.

TELWIND **https://www.esteyco.com/projects/telwind/**

Coordinated by ESTEYCO, the TELWIND project is a 3-year project co-financed by the European Commission under the H2020 program for Research and Development. Started in December 2015 and with a total budget of 3.498.530 €, the project also counts with the collaboration of other seven European partners leaders in their respective fields such as: ALE HEAVY-LIFT (R&D), MECAL, Environmental Hydraulics Institute UC-IHC, CEDEX, COBRA ACS, DYWIDAG SYSTEMS INTERNATIONAL (DSI) and TECHNISCHE UNIVERSITÄT MÜNCHEN (TUM)

TÜV SÜD is responsible for the certification of design of the Floating Wind Turbine, comprising substructure design, verifications of motions and stability, mooring design, transport and installation phases and manufacturing specifications. The certification of design will provide the basis for a successful development of the concept and a safe deployment of the Floating Wind Turbine at sea.

Most of these developments are large collaborative projects framed in R&D calls such as (H2020, DemoWind, manunet, etc.). These initiatives include various parts and systems of offshore wind power such as nacelle, tower, foundation, etc..

Question 10. Have you identified any specific event (congress, meeting, others) related to the subject (Offshore Wind Energy)?

The results of the survey conducted indicate two main events. Both are international and with high impact:

- WindEurope Offshore event at Copenhagen https://windeurope.org/offshore2019/
- IPF 2020 in the US https://www.offshorewindus.org/2020ipf/

4.2 CONCLUSIONS

As a summary, the main lines of specialization of the different regions are the foundation, followed by the tower and connection, and later the assembly - engineering and nacelle and wind turbine rotor. Remote control and energy conversion are lines in which regions work less.

The regions ADMA have capabilities throughout the entire value chain in the development of offshore systems. The main lines of work are: foundation, connection to grid and offshore substation, and tower followed by wind turbine rotor, assembly – engineering and nacelle. Finally there are the energy conversion, remote control and others (Asturias: Wind turbine stator, sea-bed mooring. Skåne, VästraGöteland-Sweden: recycling).

Regarding developments related to material development for big components in offshore wind energy have been identified some projects (R&D, demostration scale, etc.)

It have been identified pilot plantsin three regions of the five consulted

The main trends of interest in the regions focus on:

- Welding procedures for high strength steel grades
- Manufacture of new composite materials
- Recycling of composite materials
- Corrosion coatings

5 STRATEGIC ANALYSIS

5.1 POLICY AND TRENDS

The following section allows defining the key research lines and actions promoted from key platforms or networks around the topic analysed. This will lead to a clear definition on how the next generation of large components for offshore wind energy fits in each different case.

6.1.1. EUROPEAN STRATEGIES AND ALLIANCES

At European level, the following cases have been explored:

- **SET PLAN**

The integrated SET Plan indentifies ten actions for research and innovation. The actions addresses the whole innovation chain, from research to market uptake, and tackles both financing and regulatory framework. To ensure an effective interaction with all partners, the plan has an overall governance structure for measuring key performance indicators (KPIs), including level of investment or cost reductions.

These are the 10 key action areas:

- Integrating renewable technologies in the energy systems
- Reducing costs of technologies
- New technologies and services for consumers
- Resilience and security of energy systems
- New materials and technologies for buildings
- Energy efficiency for industry
- Competitiveness in global battery sector and e-mobility

- Renewable fuels and bioenergy
- Carbon capture and storage
- Nuclear safety

Europe is the world leader in offshore wind installation, with almost 88 % of worldwide installed capacity. The UK has the largest offshore wind capacity in Europe, representing 41 % of all installations, followed by Germany (32 %) and Denmark (10 %). I***n line with the SET Plan targets, latest technology developments are focused on the upscale of wind turbine components with the aim of increasing energy capture, optimising operation and eventually reducing the cost of energy***. Cost reductions are driven by increasing economies of scale, more competitive supply chains and a variety of technology improvements – the latter also leading to higher capacity factors. These developments make wind energy highly competitive in medium and low-wind speed sites, expanding opportunities in new markets. Today, turbine supply accounts for about 33-40 % of total project costs, followed by installation costs (20-25 %) and foundation supply (15-18 %).Transmission expenditure outside the plant's boundary, which usually includes offshore and onshore transformers, export cable(s) and onshore connection, is estimated to represent 10-20 % of total investment costs. Costs were expected to gradually decrease towards a target of €100/MWh by 2020, but in 2017 a dramatic development took place thanks to reverse auctions. Leading energy companies won three projects in such auctions in Germany by placing bids of zero euro per MWh, meaning they will not receive any subsidy on top of the wholesale electricity price. The projects are planned to be commissioned in 2024 and 2025, although the final investment decision is pending in 2021. One of the cost drivers enabling these zero subsidy bids is the expectation of significantly bigger turbines by 2024.Then, taking into account the underlined key action areas, the next generation for manufacturing of big components in offshore wind energy will be aligned in this sense.

- **EERA**. The European Energy Research Alliance

The European Energy Research Alliance (EERA) is the largest energy research community in Europe**.** Organised in 17 Joint Research Programmes, EERA coordinates energy research to achieve more efficient and cheaper low carbon energy technologies.

With more than 50,000 experts, EERA brings together around 250 research centres and universities across 30 European countries.

This Alliance is the research pillar of the EU Strategic Energy Technology Plan (**SET-Plan**)**, for the acceleration, development and market uptake of low carbon technologies**. Working closely with industry and decision makers, it contributes to all 10 SET-Plan key actions**.**

EERA covers the whole range of low-carbon energy technologies and addresses systemic topics as well. To organise work within the association and realise its strategy, EERA operates different so-called **Joint Programmes**, the EERA Joint Programmes (JPs). They are clustered along different technologies but also more cross-cutting issues. All topics are aligned with the EU SET-Plan. To date, there are 17 JPs. Each EERA member organisation participates in at least one JP, but often they join several.

The mission for **EERA JP Wind is to provide strategic leadership for medium to long-term research and to support the European wind energy industry and societal stakeholders**. The joint programme brings together all public research organisations in Europe with substantial research and innovation efforts in wind energy.For Europe, EERA JP WIND aims to be:

- a one-stop shop for public wind energy R&D
- a platform for coordination of research facilities, data and human resources
- a driving force in maintaining Europe's role as home to the world's largest and most advanced wind turbine manufacturers and sub-suppliers

The current subprogrammes within the JP WIND in EERA include dedicated efforts on:

- **Structures, materials and components** (SP7). In the last decades, wind turbines have grown to be amongst the largest and highest loaded structures. Coupled with a need for lower energy costs, this means that the requirements, materials, and structures are extremely high. This SP aims to bring together the leading European research organizations in order to support the industry fulfilling these requirements. In turn, this implies a full understanding of structural response and increased knowledge of material behaviour in order to develop the appropriate tools and lay the basis for standards for designing such large structures, undertaking very high fluctuating loads, with increased reliability and reduced maintenance needs, while complying with all constraints of the wind turbine system. This combination of requirements is not encountered in any other structural sector (oil & gas, aeronautics, naval structures, civil works) and certainly presents a challenge for the engineering community. Materials, including better knowledge of properties, new and improved materials and their degradation and failure mechanisms provide new opportunities for weight and cost reductions, higher reliability and improved manufacture of blades, structures and mechanical components, where all future developments regarding manufacturing of large components for offshore wind are likely to be part of discussions and collaborative proposals. **This is the most interesting subprogramme for the potential developments in this field.**

- **Research Infrastructure, testing and standards** (SP2). Its main objective is to progress the research and technology agenda in these areas. The sub-programme brings together a collection of world leading academic and research organisations, many of which have access to world leading research infrastructures. In progressing the associated research and technology agenda, the sub-programme addresses a number of themes including: best use of existing portfolio of research infrastructures, exploring the needs for new ones, how to standardise activities, recommendations for verification or validation methods.

- **Aerodynamics, loads and control** (SP4). Coordinated by CENER, a public research institute based in Navarra region, one of the regions involved in ADMA Energy initiative. The fields of research include: Wind turbine aerodynamics; the modelling of the wind flow around the rotor, the energy extraction from the wind flow, the design of rotors and the impact of the rotor on the wind power system. Loads and structural design; the design of the turbine is a combination of aerodynamics, aeroelasticity, structural dynamics, wind turbine control and material response. Wind turbine control; handling loads and optimising power production by advanced control, in an integral wind turbine design control is an essential ingredient that ensures cost effective solutions.

- **BLUE GROWTH**. Blue growth is the long term strategy to support sustainable growth in the marine and maritime sectors as a whole. Seas and oceans are drivers for the European economy and have great potential for innovation and growth. It is the maritime contribution to achieving the goals of the Europe 2020 strategy for smart, sustainable and inclusive growth. In relation with renewable energy, a clear support is dedicated to ocean energy deployment as part of the overall aim of keeping the global leadership in renewable energy by the EU.

-**DG MARE**. DG for Maritime Affairs and Fisheries. The Commission's Directorate-General for Maritime Affairs and Fisheries is responsible for the policy area of fisheries, the Law of the Sea and Maritime Affairs. Key reports are generated within this DG, including the **EU Blue Economy Report** that analyses the scope and size of the Blue Economy in the European Union, solidifying a baseline to support policymakers and stakeholders in the quest for a sustainable development of oceans, sea and coastal resources. The report includes a chapter on regional analysis, which provides an overview of the main socioeconomic features of all EU sea basins and some examples of smart specialisation. Finally, the Report develops the analysis of the underlying factors driving the evolution of the EU Blue Economy. Aside from details for each sector, an overview of the general macroeconomic situation as well as the influence of global financial markets over the trends in financing and investments has been incorporated. The report focuses on the evolution of the EU Blue Economy over time. The differences in the figures with respect to last year's report can be explained by a combination of real growth and the statistical effect of including additional sectors. For instance, last year showed 3.5 million jobs for the EU Blue Economy established sectors and this year the data showed 4 million jobs. This is partly due to an increase in scope and improved methodology and partly due to actual economic growth. Differences for aggregated turnover are larger as a result of double counting effects within the various value chains of the Blue Economy (e.g. fishing – processing – commercialisation, marine equipment and machinery – shipbuilding – maritime transport). The Blue Economy's long-term potential in terms of jobs, growth and investments can only be completely realised if more effective and coordinated steps are taken to bring together environmental, economic and social aspects of ocean management. This assessment of the state and scope of the Blue Economy and investment opportunities is intended to support policy and decision-making, and provide direction in ocean stewardship and governance.

Within the Blue Economy report, a dedicated chapter deals with the topic of "Blue Energy". Starting with a small number of demonstration plants, the EU offshore wind energy has grown to a capacity of 18.5 GW by the end of 2018, with an increase of 2.65 GW in the last year. Offshore wind energy is gaining importance with respect to onshore wind energy: in 2016 new offshore wind capacity represented 11.5% of the new wind capacity installed reaching 23% of the new wind capacity in 2018. Offshore wind represents about 10% of the total installed wind energy capacity in the EU, growing from 8% in 2016. It represents over one third of the wind energy capacity installed in the UK and Belgium. In the short to medium term, a further growth of the offshore wind energy sector is foreseen, driven by the significant reduction in cost of offshore wind technologies and by decarbonisation policies and the implementation of the National Energy and Climate Plans. **The impact of such expected growth will be linked to addressing technical challenges through R&D Collaborative projects, and to job creation.**

6.1.2. EU TECHNOLOGY PLATFORMS AND INDUSTRIAL ASSOCIATIONS

During the analysis processs, a set of Technology Platforms and Industrial Associations have also been studies, given the activities and research lines that are highlighted and that represent a cross-cutting issue for the aim of this study.

. - **ESTEP**.

The European Steel Technology Platform (ESTEP) brings together all the major stakeholders in the European steel industry. The membership includes major steel manufacturers; universities and research institutions active in steel research; major users of steel such as car manufacturers; and public bodies like the European Commission and national governments – which have great interest in this vital industrial sector that is so important for Europe's future.

ESTEP's mission aims to engage in collaborative EU actions and projects on technology, which are tackling EU challenges (notably on renewable energy, climate change (low-carbon emission), circular economy) in order to create a sustainable EU steel industry.

Different Focus groups are already in place, representing the interests and helping in the definition of future needs. In this sense, the one dealing with Energy Market Applications and Engineering, emphasises the interests in structures and equipment used by wind installations, whereas the Low Carbon & Energy Efficiency highlights the need to shorten the time-to-market for innovative products and processes coming out of European Steel R&D.

- EUMAT.

The European Technology Platform for Advanced Engineering Materials and Technologies has been launched in order to assure optimal involvement of industry and other important stakeholders in the process of establishing of R&D priorities in the area of advanced engineering materials and technologies. EuMaT should improve coherence in existing and forthcoming EU projects, in the field of materials R&D.

EuMaT covers all elements of the life cycle of an industrial product, regardless if it is a component, a system or a final good:

- design, development & qualification of advanced material
- advanced production, processing and manufacturing
- material and component testing
- material selection and optimization
- advanced modelling on all scales
- databases and supporting analytical tools
- life cycle considerations, including impacts, decommissioning, reliability, hazards, risks and recyclability

EUMAT is also arranged in different Working Groups, where WG2 "Materials for Energy" deals with materials for power generation including renewables: e.g. novel materials for next generation powerplants, high temperature and corrosion resistant materials for vessels and heat exchangers; lightweight, high temperature-resistant and wear-resistant materials, high-performance materials for fuel cells, new advanced materials for windmill propellers and gears and for other power generation

sources, e.g. hydro and geothermal; novel materials for photovoltaics, renewable materials for biofuels and bioproducts; advanced materials for steam engines and stirling motors.
So, large component manufacturing for offshore wind will be endorsed by this technology platform. In this sense, Eumat, together with other relevant institutions (Alliance for Materials, A4M) have signed a Memorandum entitled “Materials provide solutions for tomorrow´s challenges”, promoting a relevant role in Horizon Europe for supporting calls that may fit for developments related to the aim of this study.

- EMIRI.

Energy Materials Industrial Research Initiative. an industry-oriented grouping complementary to established actors, uniquely positioned to span the innovation cycle and focusing solely on advanced materials for low carbon energy & energy efficiency technologies. The aim of this initiative is to achieve industrial leadership, aligned with the European policy framework through a set of strategy pillars (R&I across Europe, EU Value Chain Development and End-Market development in Europe). In this sense 1 of the 5 lines of activities is dedicated to Wind & Marine, with a clear vision of achieving the upscaling from lab to market. Participants in this Initiative are likely to be potential partners in future consortia dealing with the field of offshore wind manufacturing.

- **EFFRA**.

The European Factories of the Future Research Association (EFFRA) is a non-for-profit, industry-driven association promoting the development of new and innovative production technologies. It is the official representative of the private side in the 'Factories of the Future' public-private partnership.

The key objective of EFFRA is to promote pre-competitive research on production technologies within the European Research Area by engaging in a public-private partnership with the European Union called 'Factories of the Future'. This calls are included in H2020 Calls and have already been highlighted in the H2020 Funding Opportunities part.

EFFRA was established to shape, promote and support the implementation of the ‘Factories of the Future’ public-private partnership.

The partnership aims to bring together private and public resources to create an industry-led programme in research and innovation with the aim of launching hundreds of market-oriented cross-border projects throughout the European Union. Such projects will produce demonstrators and models to be applied in a wide range of manufacturing sectors.

The Factories of the Future Roadmap provides a vision for a manufacturing partnership in Horizon Europe, highlighting key priorities of interest for this study, namely:

- Advanced, smart material and product processing technologies, and process chains (additive manufacturing, joining, shaping, structuring, surface tailoring, etc.)
- Smart mechatronic systems, devices and components.
- Intelligent and autonomous handling, robotics, assembly and logistic technologies

Manufacturing challenges defined in the roadmap fit also with the aim of this study, in order to include the challenge of manufacturing offshore wind components using the most advanced technologies through collaborative proposal in *Factories of Future* Calls.

6.1.3. NATIONAL STRATEGIES

Based on the contribution received from participants, information on national strategies and associated funding schemes is explained in the following bullet points:

- **Spain**. The National R&D Plan states a set of challenges where Secure, Clean and Efficient Energy is present. The same multiannual plan provides information on the funding mechanisms available for facing such R&D challenges. This involves the launch of annual calls like *Retos Colaboración*, *Retos Investigación* or *Innterconecta* Calls.

In addition to this, further calls are arranged by the Centre for Industrial Technology Development (CDTI), including *CIEN* calls for large consortia, R&D projects, or other international schemes that are managed internally like Eureka, Eurostars or Eranet Schemes.

- **Sweden**. Different strategies defined at National level are setting the framework for funding programmes applicable to this study. These are the Maritime strategy and the National strategy on wind energy.

- **Denmark**. At National level, and based also in RIS3 priorities, within the maritime sector the blue Denmark strategy has been defined. It allows supporting the policy objective linked to blue renewable energy, by means of specific National Funding Programmes.

Strategies from the other participant countries (Portugal, UK, Italy, Belgium and Finland) are missing in the questionnaire).

6.1.4. REGIONAL STRATEGIES

Regional level funding programmes are linked with RIS3 priorities for each participating region, so an analysis of each region in **Eye@RIS3**, was performed leading to specific information about potential funding programmes aligned with the topic of materials for manufacturing of big components in offshore wind energy.

6.1.4.1. Scotland

RIS3 priorities for this region include:

- Energy: Sustainable energy & renewables.
- Marine energy: Blue renewable energy

An analysis of the Interreg schemes applicable for this region is presented in this section, although the precise description of such funding programme is presented in section 3 in this document. Applicable Interreg schemes for Scotland Northern periphery and Arctic, Interreg NorthWest Europe, Interreg North Sea region, Interreg Atlantic Area, Urbact, Espon, Interact andInterreg Europe.

6.1.4.2. Basque Country

RIS 3 priorities for this region include:

- Renewable energy. Renewable energy particularly regarding to marine offshore energy testing, energy storage systems, integrated systems and residual heat exploitation.
- Advanced manufacturing to transform Basque industry. Also advancement of offshore manufacturing.

Efforts dedicated to RIS3 and use of ESIF are summarised in an strategy called Energibasque. **Energibasque** is the strategy for the technological and industrial development of the Basque Country, and one the areas of deployment of the energy strategy for estrategia Euskadi by 2020 (3E2020). As a result of the development of such regional strategy, wind energy and associated key challenges like cost reduction, corrosion or manufacturing of large components are explicitly supported in regional funding schemes.

Applicable Interreg schemes for the Basque Country:

- Interreg Poctefa, Interreg SUDOE, Interreg Atlantic Area, Urbact, Espon, Interact,and Interreg Europe.

6.1.4.3. Navarre

RIS 3 priorities for this region include:

- Renewable energy. Sustainable energy & renewables

Applicable Interreg schemes for Navarre: Interreg Poctefa, Interreg SUDOE, Interreg Atlantic Area, Urbact, Espon, Interact,and Interreg Europe.

6.1.4..4. Lombardy

RIS 3 priorities for this region include:

- Advanced Manufacturing. KETs & Advanced manufacturing systems.

Applicable Interreg schemes for Lombardy: Interreg Central Europe, Interreg Alpine Space, Interreg Mediterranean, Interreg Adrion, Urbact, Espon, Interact,and Interreg Europe.

6.1.4.5. Norte

RIS3 Priorities for this region include:

- Marine and Maritime Technologies. Link applied engineering technologies with marine resources and economic activities (blue growth)
- Advanced Manufacturing Technologies. Key Enabling Technologies notably Advanced Manufacturing Systems, nanotechnologies, materials and ICTs

Applicable Interreg schemes for Norte: Interreg POCTEP, Interreg SUDOE, Interreg Atlantic Area, Urbact, Espon, Interact,and Interreg Europe.

6.1.4.6. Flanders

RIS 3 Priorities for this region include:

- Specialised manufacturing solutions. Advanced production technologies and additive manufacturing. Structural materials, nano-materials, self-healing materials, recyclable materials and materials for energy and light.

- Sustainable living. Sustainable energy technologies with focus on hydrogen, wind energy and electrical vehicles.

Applicable Interreg schemes for Flanders: Interreg Vlaanderen-Nederland, Interreg France-Wallonie-Vlaanderen, Interreg 2 Seas, Interreg NorthWest Europe, Interreg North Sea Region, Urbact, ESPON, Interact,and Interreg Europe.

In addition, two major, strategic initiatives in Flanders have funds to support research on these topics:

Strategic Initiative Materials in Flanders (https://www.sim-flanders.be/)

Blue Cluster (https://www.blauwecluster.be/about-us)

Furthermore, relevant initiatives like “Invest in Flanders” foster setting up R&D Activities in Flanders, providing the following examples of funding schemes:

- Feasibility studies, up to 50.000€.
- SME innovation projects, up to 250.000€.
- R&D programs of more than EUR 100,000 for the development of new innovative products. Up to 250.000€.
- **‘Sprint’ projects** to gain new (technological or other types of) knowledge to realize an important innovation. Up to 250.000€.

6.1.4.7. Asturias

RIS 3 Priorities for this region include:

- Steel and maritime industry. Blue Growth. Blue renewable energy.
- Advanced manufacturing.

Asturias has deployed a set of funding programmes, managed by IDEPA (Regional Development Agency). The proposals must be aligned with RIS3-related priorities, including “Maritime industries: Naval and Wind Offshore”.

In addition to RIS3-related calls, further European initiatives managed by IDEPA where Wind Energy proposals can be presented, are also annually launched. These are EraNet schemes, such as Manu-Net and M.Eranet, and Interreg Schemes that are listed below. Note that dedicated explanation of each funding mechanism is presented in section 3 in this document.

Applicable Interreg schemes for Asturias: Interreg Sudoe, Interreg Atlantic Area, Urbact, Espon, Interact, and Interreg Europe.

6.1.4.8. Dalarna

RIS 3 Priorities for this region include:

- Advanced Industry. KETs, Advanced Manufacturing Systems, Advanced Materials.

Applicable Interreg schemes for Dalarna: Interreg Nord, Interreg Sverige-Norge, Interreg Baltic Sea Region, Urbact, Espon, Interact,and Interreg Europe.

6.1.4.9. Scania

RIS Priorities for this region include:

- Smart Materials. KETs & Advanced materials.

Applicable Interreg schemes for Scania: Interreg Oresund-Kattegat-Skagerrak, Interreg South Baltic, Interreg Baltic Sea Region, Interreg North Sea Region, Urbact, Espon, Interact,and Interreg Europe.

6.1.4.10. Emilia-Romagna

RIS 3 Priorities for this region include:

- Mechatronics and the motor industry. New technologies and materials for the motor industry and other production systems.

Applicable Interreg schemes for Emilia-Romagna: Interreg Central Europe, Interreg Mediterranean, Interreg Adrion, Urbact, Espon, Interactand Interreg Europe.

6.1.4.11 Andalucía

Smart Specialisation Strategy in Andalusia (RIS3Andalucia) identified a Priority focused in Industry connected to transport that included an Action Line focused in R&D in new materials. Connected with this strategy, there is a financial instrument supported with EU funds that gives grants to companies to develop R&D projects. This instrument is global and indeed it is not regarding offshore wind energy specifically.

Applicable Interreg schemes for Andalucia: Interreg Poctep, Interreg Mediterranean, Interreg SUDOE, Interreg Atlantic Area, Urbact, ESPON, Interact,and Interreg Europe.

6.1.4.12 Ostrobotnia

RIS3 Priorities for this region include:

- Energy and advanced manufacturing.
- Advanced materials.

Applicable Interreg schemes for Ostrobotnia: Interreg Botnia-Atlantica, Interreg Baltic Sea Region, Urbact, ESPON, Interactand Interreg Europe.

6.1.4.13. Syddanmark

RIS 3 Priorities for this region include:

- Sustainable Energy. Sustainable Energy & Renewables.

Applicable Interreg schemes for Syddanmark: Interreg Germany-Denmark, Interreg Baltic Sea Region, Interreg North Sea Region, Urbact, Espon, Interactand Interreg Europe.

5.2 FUNDING R&D OPPORTUNITIES

According to information from S3 Platform, linked to the Joint Research Centre (JRC), during the programming period 2014–2020, EU Structural and Investment Funds (ESIF) play an essential role in promoting innovation in the field of energy, developing ICT applications in the field of energy, supporting SMEs and boosting the shift towards a low-carbon economy in all sectors. Around € 40 billion are allocated by the Cohesion Policy funds (ERDF, ESF and CF) to these objectives in the energy field. They include interventions in energy efficiency, renewable energy, smart distribution grids and sustainable urban mobility, as well as R&I in these areas, in complementarity with Horizon 2020.

Cohesion Policy is thus making an increasingly important contribution towards EU challenges for clean, efficient and secure supply of energy. The allocated amounts for low-carbon economy represent more than a doubling of funding compared to the previous programming period. Although Cohesion Policy funds will offer significant opportunities, their substantial extension will also represent an important challenge in terms of the readiness in the Member States and regions for their uptake. The absorption capacity of regions will become an issue. Moreover, the combination of Cohesion Policy funds with research financing, like Horizon 2020, will require learning and creative thinking. Finally, it is important to make sure that EU funding will leverage additional national public and private co-financing.

In addition to the need of making effective use of ESIF and further Cohesion Policy funds, there are some well established funding schemes that are of interest for the aim of this study, namely:

EUREKA.

EUREKA is a publicly-funded, intergovernmental network, involving over 40 countries. EUREKA’s aim is to enhance European competitiveness by fostering innovation-driven entrepreneurship in Europe, between small and large industry, research institutes and universities.

EUREKA is a leading open platform for international cooperation in innovation. It remains to this day the only initiative of its kind committed to the ‘bottom-up’principle - ensuring that any R&D project with a good business plan receives the support it deserves, independent of its technological nature, or the type of organisations involved. Different funding programmes are available under Eureka’s frame:

EUROGIA.

EUROGIA2020 aims to support and promote transnational, low carbon energy technology projects. EUROGIA2020 covers the entire energy mix from all forms of primary energy sources (except nuclear), through transportation and distribution, all the way to efficiency in end-use whether industrial or for individual consumers. It also includes transverse technologies such as materials, IT or manufacturing technologies that support the energy system. A call for proposals is arranged annually, being in 2 phases. In 2019, the deadline is Dec 9th. Funding is committed from certain countries, in the case of ADMA Energy partners, only Spain, Portugal and UK have funds available for this call.

SMART.

SMART is a flexible, industry-driven EUREKA Cluster program in Advanced Manufacturing. Its aim is to promote collaborative, international & close-to-market R&D&I projects. As a EUREKA Cluster, SMART is grounded in Europe and open to worldwide participants from the Eureka Network. Manufacturing is a vital sector in Europe, fundamental to European development towards a competitive sustainable globalization. Advanced manufacturing is strongly addressed in most political agendas as a key enabler that will lead European society towards a higher industrial competitiveness, sustainable growth and job creation. All countries present in ADMA Energy except Italy have committed funds to this initiative. Call for proposal is arranged at least once every year, being Nov 11th 2019 the last one.

METALLURGY EUROPE.

Metallurgy EU is a fascinating field, full of modern discoveries, commercial opportunities and industrial utility. To help solve the grand challenges facing society, it is imperative to continue investing in high-value metal products and their manufacture.European industry, academia and funding agencies now have seized a once-in-a-generation opportunity to establish a vibrant, well-coordinated and large-scale ‚Metallurgy Europe Research‘ Programme that can design, develop and deploy the next set of revolutionary alloys and composites for key industrial applications, including energy, renewables, mobility and health. Research topics addressed: Material Discovery, Novel design, metal processing and optimisation, Materials for green energy and renewables, Recycling technologies. Metallurgy Europe has a two step project proposal process and organises one call for projects to fund every year. Finland, Belgium, Portugal and Spain are involved in this initiative.

EUROSTARS.

Eurostars supports international innovative projects led by research and development- performing small- and medium-sized enterprises (R&D-performing SMEs). With a bottom-up approach, Eurostars supports the development of rapidly marketable innovative products, processes and services that help improve the daily lives of people around the world. Eurostars has been carefully developed to meet the specific needs of SMEs. It is an ideal first step in international cooperation, enabling small businesses to combine and share expertise and benefit from working beyond national borders.

Eurostars is a joint programme between EUREKA and the European Commission, co-funded from the national budgets of 36 Eurostars Participating States and Partner Countries and by the European Union through Horizon 2020. In the 2014-2020 period it has a total public budget of €1.14 billion.

The role of SMEs for the economy has never been so important. Eurostars aims to bring increased value to the economy, higher growth and more job opportunities. Calls for application are open twice every year. Funding rules are Country-specific.

ERA-NET. European network of public agencies related to funding programmes at regional and national level with the support of the European Commission. It aims fostering coordination of R&D Programmes of Member States, so as to provide resources to jointly deal with strategic technological challenges on a harmonised, effective and coherent way. This funding scheme was originally launched under the 6th FP and has evolved to the current Cofund scheme under H2020 Framework Programme. It is considered a key instrument for supporting research, knowledge transfer and international cooperation towards the establishment of the European Research Area. Details of Era-net schemes of interest for this study are listed below:

OCEANERA-NET COFUND.

The Ocean Energy ERA-NET Cofund is an initiative of eight national and regional government agencies from six European countries, which has received funding from the European Union under the Horizon 2020 Programme for Research and Innovation until 2021. The participating countries / regions are: the Basque Country, Brittany, Ireland, Pays de la Loire, Portugal, Scotland, Spain and Sweden.

The aim is to coordinate support for research and development in ocean energy, to encourage collaborative projects that tackle some of the key challenges identified for the sector as it progresses towards commercialisation.

Key objectives are to maintain and grow Europe's world leading position in ocean energy, to help bring innovative low carbon energy solutions closer to commercial deployment, drive down the levelised cost of energy (LCoE), create growth and jobs and reduce the environmental impact of the energy system

MARTERA ERANET COFUND.

MarTERA is an ERA-NET Cofund scheme of Horizon 2020 of the European Commission. The overall goal of the MarTERA is to strengthen the European Research Area (ERA) in maritime and marine technologies as well as Blue Growth.

MarTERA consortium, consisting of 16 collaborating countries, organise and co-fund, together with the EU one joint call for transnational research projects on different thematic áreas in order to contribute to the national priorities as well as to the Strategic Research Agenda of JPI Oceans and WATERBORNE.

The focus of development in MarTERA is given to technologies (instead of sectors) due to their potentially large impact to a wide range of application fields. Priority areas in call 2019 included:

- Priority Area 2: Novel materials development and structures
- Priority Area 4: Advanced manufacturing/production

Another call in year 2020 is expected.

MANUNET.

MANUNET supports innovation-driven, close-to-market research and development projects in manufacturing. It aims to encourage cross-border value chains that emerge from advancing technologies. During every first quarter of every new year, MANUNET opens a call for proposals to co-fund manufacturing research projects by preferably small and medium-sized enterprises (SMEs) and their strategic partners. Any short-term projects with small-medium consortia are expected. Funding is dependent on national and regional programmes. More than a decade of yearly calls has proven MANUNET as an ideal complementary programme halfway between Horizon 2020 and the national/regional funding programmes.

The MANUNET project is active for 5 years to facilitate the development of new value chains by setting up geographical poles of activity across Italy, Belgium, Luxemburg, Germany, Norway, Romania, Turkey, Israel, Spain, the Netherlands, Ireland, and Russia (meaning that 3 countries belonging to ADMA Energy are involved in the initiative). 24 national/regional funding programmes participate in MANUNET Initiative.

Base don the topics present in MANUNET Call 2019 for proposals, collaborative projects focussed on:

- Knowledge-based engineering, information and communication technologies for manufacturing, including technologies for Industry 4.0 (for example industrial robotics, computer-aided engineering and design, automated manufacturing, zero defect manufacturing, product lifetime management, cyber-physical systems, IoT, control, big-data, analytics, connectivity and mobility, augmented reality, cyber security for processes, etc.).
- Manufacturing technologies for environmental and energy applications including resource efficiency, recycling (reuse, remanufacturing, etc) and circular economy in manufacturing processes.
- Adaptive manufacturing technologies including processes for removing, joining, adding, forming, consolidating, assembling and related advanced industrial machinery.
- Additive manufacturing (for example technologies, materials, products etc.)
- New materials for manufacturing (alloys, lubricants, coatings, textile fibres, construction, composites, insulation, multi-functional multi-materials etc.).
- New manufacturing methods, components and systems (development of demonstrators, devices, tooling and equipment, logistic systems, etc.).
- Other technologies, products and services related to the manufacturing field (logistic, supply chain, etc.)

This Eranet funding scheme is seen as a candidate for elilgible regions to promote collaborative proposals in the topic in the future call expected in the first quarter in 2020.

M.ERANET.

M-ERA.NET for materials research and innovation, is an EU funded network which has been established to support and increase the coordination of European research programmes and related funding in materials science and engineering. Between 2016 and 2021, it continues to contribute to the restructuring of the European Research Area (ERA) by operating a single innovative and flexible network of national and regional funding organisations. M-ERA.NET contributes to EU policies and is complementary to funding schemes at regional, national and European levels, supporting the exploitation of knowledge along the whole innovation chain from basic research to applied research and innovation. Advanced materials technologies have been classified as Key Enabling Technologies (KET) with a wide range of product applications such as developing low carbon energy technologies and improving energy and resource efficiency.

A Call for proposals is launched every year, with a first deadline in Q2. The aim is to fund ambitious transnational RTD projects addressing materials research and innovation including materials for low carbon energy technologies and related production technologies. M-ERA.NET aims to strengthen the contribution of materials R&D to energy-related applications where applicable.

The Call 2019 included the following thematic areas:

- Modeling for materials engineering and processing
- Innovative surfaces, coatings and interfaces
- High performance composites
- Functional materials
- New strategies for advanced material-based technologies in health applications
- Materials for additive manufacturing

Participating countries (regions) in 2019 included Spain, Italy and Belgium. Based on the participation of the involved regions in Call 2020, topic may fit for collaborative proposal in the frame of the aim of this study.

INTERREG.

Interreg is one of the key instruments of the European Union (EU) supporting cooperation across borders through project funding. Its aim is to jointly tackle common challenges and find shared solutions in fields such as health, environment, research, education, transport, sustainable energy and more. Interreg is one of the two goals of the EU Cohesion Policy in the 2014-2020 period and it is funded by the European Regional Development Fund (ERDF). It has a budget of EUR 10.1 billion invested in the several cooperation programmes responsible for managing project funding. It has three types of programmes: Interregional, Transnational and Cross-Border cooperation. A more detailed analysis of the ones applicable to this study are described below.

Interreg Interregional Programmes include INTERACT, URBACT and ESPON, which are out of the scope for this study, and the one of relevance for the next funding period:

INTERREG EUROPE.

Interreg Europe helps regional and local governments across Europe to develop and deliver better policy. By creating an environment and opportunities for sharing solutions, we aim to ensure that government investment, innovation and implementation efforts all lead to integrated and sustainable impact for people and place. Interreg Europe aims to get maximum return from the EUR 359 million financed by the European Regional Development Fund (ERDF) for 2014-2020. All funds have been allocated to projects, so no more calls are expected for this period. However, this programme is expected to continue for the next period (2021-2027) following European Regional Cooperation.

Interreg Europe exists to assist three types of beneficiaries**:**

- **Public authorities –** local, regional and national
- **Managing authorities/intermediate bodies** - in charge of the Investment for Growth and Jobs programmes or European Territorial Cooperation
- **Agencies, research institutes, thematic and non-profit organisations** – although not our main target group, these types of organisations can also work with Interreg Europe

by *first* engaging with their local policymakers in order to identify options for collaboration with Interreg Europe

Any actions developed with financial support from Interreg Europe must fall into one of the following four categories:

- Research and innovation
- SME competitiveness
- Low-carbon economy
- Environment and resource efficiency

Interreg Europe will co-finance up to 85% of project activities that you carry out in partnership with other policy organisations based in different countries in Europe. Through interregional cooperation projects, you and your partners must identify a common interest and then work together for 3-5 years.

Depending on the number of partners involved, duration of interregional learning etc., the average total ERDF budget of a project is expected to be **EUR 1-2 million**.

Interreg Transnational and Cross Border Programmes with presence of 2 or more regions:

INTERREG ATLANTIC AREA.

Interreg Atlantic Area supports transnational cooperation projects in 36 Atlantic regions of five countries: France, Ireland, Portugal, Spain and the United Kingdom, contributing to the achievement of economic, social and territorial cohesion. The Programme overall objective is to implement solutions to answer to regional challenges in the fields of innovation, resource efficiency, environment and cultural assets, supporting regional development and sustainable growth. With a total budget of EUR 185 million, which comprises a fund allocation above EUR 140 million from the European Regional Development Fund (ERDF), the Programme focuses on four main priorities axes and specific objectives related to Stimulating innovation and competitiveness, Fostering resource efficiency, Strengthening the territory's resilience to risks of natural, climate and human origin and Enhancing biodiversity and the natural and cultural assets.

Regions from ADMA Energy: Norte, Asturias, Basque Country, Navarre, Andalucia, Scotland.

On November 13th 2019, an annual event will be held in Porto (Portugal). This programme may still launch another call for proposals. Several regions participating in ADMA Energy are present in this área, so it represents another opportunity for collaborative proposals.

- **INTERREG SUDOE**.

Interreg Sudoe Programme is part of the European territorial cooperation objective known as Interreg, which is financed by one of the European structural funds: the European Regional Development Fund **(ERDF)**. The current programming period covers from **2014 to 2020**. The Interreg Sudoe Programme supports regional development in Southwestern Europe, financing **transnational projects** through the **ERDF**. The Programme promotes **transnational cooperation** to solve common problems in the covered territory, such as low investment in research and development, weak competitiveness of the small and medium-sized enterprises and exposure to climate change and environmental risks.

It is divided in 5 priority axis, namely: Research & Innovation, Competitiveness of SMEs, Low Carbon Economy, Combating Climate Change and Environment and Resource Efficiency.

Regions from ADMA Energy involved: Norte, Asturias, Basque Country and Navarre.

Application for first stage call for proposals has closed in October 25th 2019. It is uncertain whether more calls will be open in 2020 or not.

INTERREG NORTH SEA.

The overall aim is to support development and foster sustained economic growth across the region. It helps enterprises, institutions, public administrations, NGOs and others to pool their expertise, share their experience and cooperate to develop realistic solutions to problems shared across the region. Priorities include: Thinking Growth, Eco-Innovation, Sustainable North Sea Region and Green Transport and Mobility.

Regions from ADMA Energy involved: Flanders, Syddanmark, Skane and Scotland.

A call for applications was closed in October 11th 2019. It is uncertain whether more calls will be open in 2020 or not.

INTERREG BALTIC SEA.

The Interreg Baltic Sea Region Programme 2014-2020 supports integrated territorial development and cooperation for a more innovative, better accessible and sustainable Baltic Sea region. Partners from countries around the Baltic Sea work together in transnational projects on common key challenges and opportunities. Projects have to involve at least three partners from three different countries from the Programme area. Total project budgets typically range between EUR 1.5 and 4.5 million for seven or more partners working together for two to three years.

The Programme offers funding for four thematic priorities: Capacity for Innovation, Management of natural resources, Sustainable transport and EU Strategy support.

Regions from ADMA Energy involved: Syddanmark, Skane, Dalarna and Ostrobotnia.

Several calls are arranged, Project platform call, regular Project call and Seed Money call, being the latter the only currently open (until December 9th 2019. It is uncertain whether more calls will be open in 2020 or not.

INTERREG CENTRAL EUROPE.

Interreg CENTRAL EUROPE improves capacities for regional development in innovation, carbon dioxide reduction, the protection of natural and cultural resources as well as transport and mobility. There are currently 129 cooperation projects funded across central Europe. In total, around 231 million Euro from the European Regional Development Fund (ERDF) will be transferred to transnational partnerships in the coming years. The projects address shared regional challenges in the fields of innovation, low-carbon economy, environment, culture and transport.

Regions from ADMA Energy involved: Emilia-Romagna and Lombardy.

The final call closed on July 5th 2019. Future calls will be launched in the period 2021-2027.

INTERREG ADRION.

The ADRION programme is a European transnational programme that invests in regional innovation systems, cultural and natural heritage, environmental resilience, sustainable transport and mobility as well as capacity building. By bringing together eight Partner States, ADRION aims to act as a policy driver and governance innovator for the benefit of more than 70 million people in the Adriatic and Ionian region.

Regions from ADMA Energy involved: Emilia-Romagna and Lombardy.

Calls for proposals were arranged in September 2019 for S3 on Blue Growth, Social Innovation, Maritime Transport and City Transport. It is uncertain whether more calls will be open in 2020 or not.

INTERREG MEDITERRANEAN.

Partner States from 13 countries are working together in the transnational European Cooperation Programme for the Mediterranean area, The Interreg MED Programme 2014-2020. The transnational setup allows them to tackle challenges beyond national borders, such as the rise of low carbon economy, the protection of natural and cultural resources and the strengthening of innovation.

The main objective of the Interreg MED Programme is to promote sustainable growth in the Mediterranean area by fostering innovative concepts and practices and a reasonable use of resources and by supporting social integration through an integrated and territorially based cooperation approach. Priority 1 (Innovation) promote actions related to Blue Growth, Green Growth and Social/Creative. In priority 2 (Low Carbon Economy), a dedicated objective is located for Renewable Energy.

Regions from ADMA Energy involved: Andalucia, Emilia-Romagna and Lombardy.

Calls for modular, horizontal and strategic projects were arranged in 2019. It is uncertain whether more calls will be open in 2020 or not.

Further Interreg schemes have been analysed in order to know more about transborder cooperation, just 2 examples have been explored, POCTEP for Spain&Portugal and POCTEFA for Spain&Andorra&France, but a reference to existing transborder funding schemes are mentioned in regional level analysis in section 2.1.

HORIZON 2020.

Horizon 2020 programme is running from 2014 to 2020 with a €80 billion budget. It provides research and innovation funding for multi-national collaboration projects as well as for individual researchers and supports SMEs with a special funding instrument.

An analysis was performed in order to find funding opportunities within different Work Programmes. In this sense, 2 Work Programmes concentrate most of these opportunities. Namely:

- **Leadership in Enabling and Industrial Technologies – Nanotechnologies, Advanced Materials, Biotechnologies, and Advanced Manufacturing and Processing (LEIT-NMBP)**. The Leadership in Enabling and Industrial Technologies (LEIT) part of Horizon 2020 will support the development of technologies underpinning innovation across a range of sectors. Horizon 2020 will have a strong focus on developing European industrial capabilities in Key Enabling Technologies (KETs). This part of the programme covers different areas :
    - Nanotechnologies
    - Advanced materials

- Advanced manufacturing and processing
- Biotechnology

Activities of the work programme will address the whole innovation chain with technology readiness levels spanning the crucial range from medium levels to high levels preceding mass production, and helping to bridge the gaps ("valley of death") in this range. These activities will be based on research and innovation agendas defined by industry and business, together with the research community, and have a strong focus on leveraging private sector investment. For the higher technology readiness levels, dedicated support will therefore be provided for larger-scale pilot lines and demonstrator projects to facilitate industrial take-up and commercialisation. There will be a strong focus on the contribution of Key Enabling Technologies to societal challenges.

- **Societal Challenge 3: Secure, Clean and Efficient Energy.** To make the transition to a competitive energy system, we need to overcome a number of challenges, such as increasingly scarce resources, growing energy needs and climate change. The Energy Challenge is structured around seven specific objectives and research areas:
    - Reducing energy consumption and carbon footprint
    - Low-cost, low-carbon electricity supply
    - Alternative fuels and mobile energy sources
    - A single, smart European electricity grid
    - New knowledge and technologies
    - Robust decision making and public engagement
    - Market uptake of energy and ICT innovation.

  Low Carbon Technologies: It is important to develop and bring to market affordable, cost-effective and resource-efficient technology solutions to decarbonise the energy system in a sustainable way, secure energy supply and complete the energy internal market. Research activities within this area will cover: Photovoltaics, Concentrated Solar Power, Wind energy, Ocean Energy, Hydro Power, Geothermal Energy, Renewable Heating and Cooling, Energy Storage, Biofuels and Alternative Fuels, Carbon Capture and Storage.

In addition to these WorkProgrammes, further opportunities have been explored in other H2020 using the Participant Portal Website (Funding and Tenders search engine).

The Programme has also defined a set of Focus Areas that have allowed to centralise the actions to be performed during the H2020 period. One of these Focus Areas is "Low-Carbon Research & Innovation". The focus area 'Building a low-carbon, climate-resilient future' brings together and coordinates the activities of several thematic areas of Horizon 2020 — the European Union's research and innovation funding programme. It will include research and innovation activities on climate change science, **energy**, transport, **industry**, agriculture, the built environment and Earth observation. Regarding energy, on the supply side, cheaper and better-performing renewable energy generation technologies which are better integrated across the energy system are explicitly mentioned. Note that call acronims starting with LC are included in this focus area.

The results from this analysis is presented below:

- **LC-SC3-RES-31-2020**. **Offshore wind basic science and balance of plant**. RIA. Deadline April 21st 2020. Specific Challenge: The contribution of offshore wind power to the energy mix is expected to increase significantly by 2030. Better knowledge of basic wind energy science and related areas contributes to the cost reductions required to achieve that goal. Several research areas for offshore wind present in the implementation of the SET Plan are mentioned, such as "Development and validation of models of structural damage and degradation for offshore wind turbines and/or for their components as functions of loads and environment;" or "Numerical and test methods for accurate assessment of system and component reliability when introducing new materials and technologies". The proposals are expected to bring new technologies/models/methods to TRL 4-5.

- **LC-SC3-RES-19-2020**: **Demonstration of innovative technologies for floating wind farms**. IA. Deadline December 11th 2019. The first commercial-scale floating wind farm has recently come into operation and other floating wind farms initiatives are ongoing. Floating wind farms have significant potential but further efforts are needed to drive the costs down and to fully commercialise and industrialise the technology. Proposals will focus on the demonstration of floating offshore wind innovations (such as blades, floaters, moorings, electrical subsystems and cabling, monitoring systems, and/or integrated systems, including whole wind turbines specifically conceived for floating offshore), in view of scaling-up power rating to >10 MW. Proposals are expected to bring the technology (ies) to TRL 6-8.

- **DT-FOF-09-2020**: **Energy-efficient manufacturing system management** (IA). Deadline February 5th 2020. Specific Challenge: Improving industrial energy efficiency requires the integration of energy data, such as historical data, real-time data and real-time predicted energy cost, into the production management systems. Manufacturing systems are complex because many parameters, related to environment, components, usage of materials, machines, cells, lines and supply chains, collectively influence the energy performance of production processes. Different technologies of energy-efficient manufacturing have already been studied in the past. However, the challenge is now to combine all these technologies in a holistic, intelligent and interoperable approach to ensure a comprehensive implementation, providing significant energy savings. Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

- **DT-FOF-10-2020**: **Pilot lines for large-part high-precision manufacturing** (IA 50%). Deadline February 5th 2020. Specific Challenge: The production of large-scale parts has achieved so far a relatively low level of mechanisation and automation because standard machines and design procedures are not suitable for these parts and specific equipment is too slow and too expensive. Moreover, repairing large parts requires operating in difficult spaces. All this causes problems of quality and repeatability. Therefore, industry needs more automated production and in-situ repair methods for new innovative and multi-functional products. Recent research in the large-scale parts production has delivered high quality demonstrators, although generally quite specific and with a too limited impact. Full-scale, reconfigurable, modular and flexible pilot lines including different processing facilities, thermal treatment, control and characterisation could demonstrate comprehensive highly visible prototypes. Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

- **DT-FOF-11-2020**: **Quality control in smart manufacturing** (IA). Deadline February 5th 2020. Specific Challenge: Smart factories are characterised by processes involving interlinked work pieces and associated tools as well as logistics operations. These are generating large amounts of data, which can be used for analysis and prediction as well as to optimise the quality of manufacturing operations and manufactured products. However, a major challenge for manufacturing is the reliability of data. Certification, regulatory and standardisation activities related to the proposed solutions should be included in the proposal. Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

- **LC-SPIRE-08-2020**: **Novel high performance materials and components** (RIA). Deadline February 5th 2020. Specific Challenge: Energy intensive industries will require a radical transformation of their production processes to reach carbon neutrality by 2050. Future low carbon technologies and processes should address fluctuating and extreme conditions, such as high temperature or corrosive environments, materials and components that will need to be able to be sustained. In the same way, they also need to be designed for high-energy performance. Existing components materials and any combination thereof have however inherent limitations to meeting new extreme conditions. Stress resulting in degradation, corrosion, wear and/or deterioration can in particular lead to reduced plant efficiency even plant shutdowns or entire equipment failures. The challenge is therefore to develop new, or overhaul the performance of, materials and combined components. Activities should start at TRL 3 and achieve TRL 5 at the end of the project.

- **LC-NMBP-31-2020**: **Materials for off shore energy** (IA). Deadline December 12th 2019. Specific Challenge: The next generation of large offshore wind energy generators and tidal power generators will help to reach climate goals and CO2 reduction levels and are likely to secure Europe’s technical and economic competitiveness. Accordingly, new challenges related to materials or multi-material architectures must be addressed, to increase operational performance and allow an appreciable reduction of the overall cost of offshore energy generation, taking into account capital expenditure as well as, running and maintenance costs. The challenge is therefore to improve the operational performance of the next generation of offshore wind energy generators (larger than 8MW) and tidal stream power generators through better performance of their functional (e.g. wind energy generator rotor blades) and/or structural components (e.g. floating or bottom fixed base structure). Activities should start at TRL 4 and achieve TRL 6 at the end of the project.

- **BG-07-2019-2020**: **The Future of Seas and Oceans Flagship Initiative**. Deadline January 22nd 2020. Specific Challenge: Our future is intimately linked to the future of the seas, oceans and coasts. The seas, oceans and coasts provide multiple ecosystem services and a wealth of resources, influence climate and provide many economic opportunities. To fully profit from the seas and oceans also in the future, we have to preserve those valuable resources and ensure that their exploitation is sustainable. Furthermore, without appropriate ocean observations for forecasting and for the protection of property and human activities, the global economy would lose hundreds of billions of euros annually. For this, we need to have the technologies for observations, integrated ocean observing systems, data management systems, and appropriate models and services. This action will contribute to make ocean observations and data management in European seas and the Atlantic Ocean fit for the future, in line with the G7 Future of the Oceans Initiative (Tsukuba Communiqué of the G7 Science Ministers. It will also support the Collaborative Research Action on Oceans of the Belmont Forum and the International Ocean Governance Communication. Similarly, ocean observation data must be available to effectively address local, national and global challenges such as the forecasting of ocean conditions and climate change, to take stock of biomass and biodiversity, to mitigate the impact of climate change and ocean acidification, to ensure food security and food safety (also in fresh water), and to contribute to the UN 2030 Sustainable Development Agenda, notably UN SDGs 2, 13, 14 and 15, and monitoring their targets for 2020 and 2025.

- **MG-3-7-2020**: **Improved Production and Maintenance Processes in Shipyards**. Deadline April 21st 2020. Specific Challenge: European Ship building, repair, modification and maintenance has been founded upon a technology based competitive advantage which has enabled it to build, improve and maintain the world’s most advanced ships. However, competitors are also becoming more advanced and seeking to enter European high technology markets. Many ship types developed within Europe are now built elsewhere. Also European marine equipment, including environmental technologies are often retrofitted to ships within non-European shipyards. Europe is still a global leader for very high technology ships such as large passenger vessels, but this is a niche and competitors have a strategy to also enter these markets. The market is particularly challenging for smaller shipyards across Europe who can be agile to develop and maintain niche products or to be integrated within smart supply chains yet do not have significant resources to undertake research and innovation. Consequently, continuous innovation is needed for the sector to remain competitive and in this respect, lessons and technologies can be drawn for other sectors including automotive, aerospace and IT. For example taking advantage of the latest developments within digital production, advanced robotics and co-bots, machine vision, internet of things, flexible production systems, 3D printing, supply chain integration across multiple sites, skills development and deployment strategies.

- **LC-SC3-RES-32-2020**: **New test rig devices for accelerating ocean energy technology development.** Deadline April 21st 2020. Specific Challenge: By 2050 ocean energy can contribute significantly to the renewable energy mix in Europe. As stated in the SET-Plan Ocean Energy Implementation Plan ocean energy costs must be reduced through, but not only, increased performance and reliability in order to meet its full potential. Researchers and industries are presenting innovative solutions, but to accelerate the development pathway to the market, new testing methodologies will help industries to take more quickly go/no-go decisions. For this a better understanding of basic ocean energy sciences is required to develop the research competences and the underpinning scientific knowledge for the testing methodologies.

Following this reference funding programme, another research and innovation framework programme is being shaped for the next period (2021-2027), called **Horizon Europe**. The preliminary structure of Horizon Europe includes three pillars (Pillar 1 Excellence Science, Pillar 2 Global Challenges and European Industrial Competitiveness and Pillar 3 Innovative Europe).

Further information about such preliminary structure is presented in the next figure.

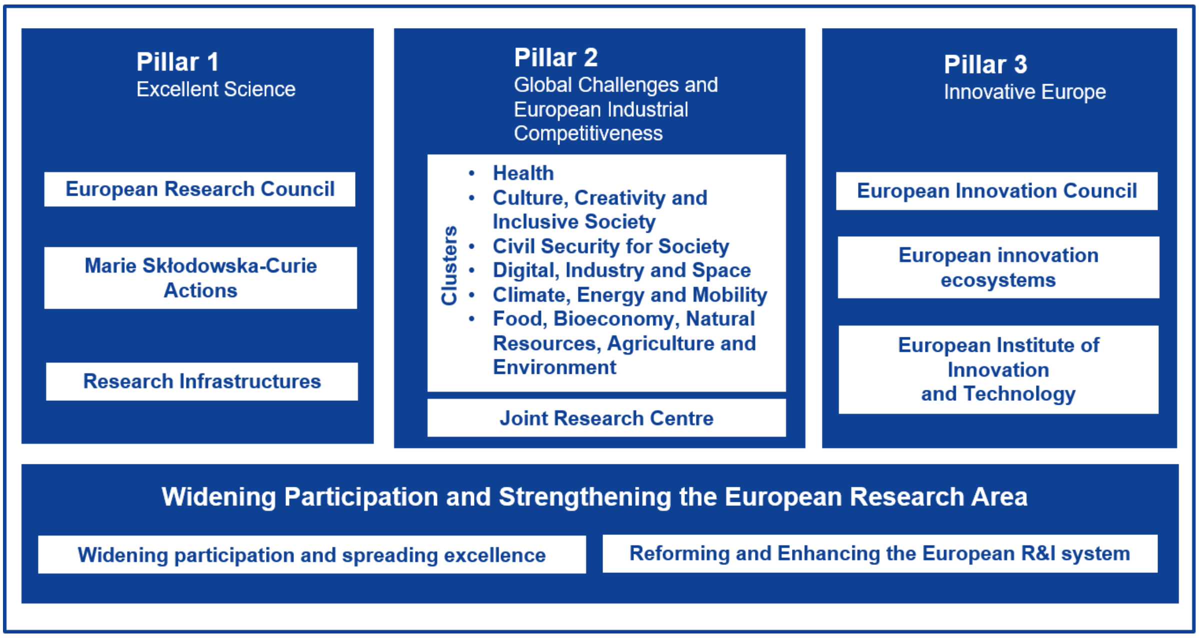

Figure 32.- Horizon Europe Prelliminary Structure (Source EC)

Based on the existing information, most of the funding opportunities will be located in Pillar 2, where the Clusters "Digital, Industry and Space" and "Climate, Energy and Mobility" are likely to play a key role for the "Next generation of materials for manufacturing of big components in offshore wind energy".

To shape the strategic objectives of the programme, the Commission invited public and private stakeholders to have their say on the programme's design. This feedback will help prepare the "Strategic Plan" for Horizon Europe and guide the research & innovation investments for the first four years of Horizon Europe (2021-2024). The strategic priorities laid out in that plan will be cemented in future work programmes and calls for proposals.

To deliver on its ambitious climate and energy targets, Europe needs strong and fit-for-purpose industrial and innovation programmes. These will develop and improve technology solutions and applications, and support existing European supply chains. Horizon Europe is a crucial instrument to boost the competitiveness and development of the wind energy sector. The programme should allocate substantial budgets and targeted calls for proposals to:

a) improve performance and reduce cost of utility-scale renewable energy production and bring new concepts faster to market;

b) enhance sustainability and promote circularity within European industries; and

c) accelerate a renewables-based electrification (direct and indirect) of hard-to-abate sectors (e.g. steel)

A fit-for-purpose Horizon Europe programme should have more open calls, with multi-annual deadlines. Open calls will promote bottom-up engagement and increase participation and interest from private stakeholders, especially industry. Furthermore, the expert opinion of European Technology & Innovation Platforms (ETIPs) should be fully considered in the design and evaluation process of the work programmes, and ETIP WIND (The European Technology and Innovation Platform for Wind Energy) actively participated in the definition of Horizon Europe, supporting the role of Wind Energy in future calls.

-RFCS.

Research Fund for Coal and Steel. The Research Fund for Coal and Steel (RFCS) supports research and innovation projects in coal and steel sectors. Every year around €40 million is made available to universities, research centers and private companies to fund projects. These projects cover:

- production processes
- application, utilisation and conversion of resources
- safety at work
- environmental protection
- reducing CO2 emissions from coal use and steel production

It has an annual Call in mid September, for collaborative projects. Within the Steel programme, a set of priorities are defined, improvements in manufacturing of large components for wind offshore based on steel fit in different Technical Groups, namely:

- TGS 6 Physical metallurgy and design of new generic steel grades. It includes the development of steel with improved properties at low and high temperatures such as strength and toughness, fatigue, wear, creep and resistance against fracture. Also, new steel grades for demanding applications.
- TGS 8. Steel products and applications for building, construction and industry. Technologies relating to the forming, cutting, welding and joining of steel and other materials. Design of assembled structures to facilitate the easy recovery of steel scrap and its reconversion into usable steels and techniques for recycling.

LIFE.

The LIFE programme is the EU's funding instrument for the environment and climate action created in 1992. The current funding period 2014-2020 has a budget of €3.4 billion. Indicative dates for 2020 Calls are as follows: June 2020 for submitting the concept notes in the Environment sub-programme, and September 2020 for submitting full proposals of the climate action subprogramme.

COSME.

COSME aims to make it easier for small and medium-sized enterprises (SMEs) to access finance in all phases of their lifecycle – creation, expansion, or business transfer. Thanks to EU support, businesses have easier access to guarantees, loans and equity capital. EU ‘financial instruments’ are channelled through local financial institutions in EU countries

In the following table, a matrix compiling the regions involved in the study and the different funding mechanism is presented:

Funding Programme	RIS 3 Calls	National Calls	Interreg EU	Interreg Atlantic Area	Interreg Northern Sea	Interreg Baltic Sea	Interreg Mediterranean	Interreg Adrion	Interreg NW Europe	Interreg Sudoe	Interreg Central EU	Interreg Poctep	Interreg Poctefa	Martera	OceanEranet	Manunet	Meranet	Eurogia	Eureka Smart	Metallurgy EU
Scotland	X	X	X	X	X				X										X	
Basque Country	X	X	X	X						X			X	X	X	X	X	X	X	X
Navarre	X	X	X	X						X		X	X	X	X	X		X	X	X
Lombardy	X	X	X				X	X			X			X						
Norte	X	X	X	X						X				X	X			X	X	X
Flanders	X	X	X		X				X					X	X		X		X	X
Asturias	X	X	X	X						X				X	X	X	X	X	X	X
Dalarna	X	X	X			X									X				X	
Scania	X	X	X		X	X									X				X	
Emilia-Romagna	X	X	X				X	X			X			X						
Andalucia	X	X	X	X			X			X		X		X	X		X	X	X	X
Ostrobotnia	X	X	X			X													X	X
Syddanmark	X	X	X		X	X													X	

Figure 33. - Different funding mechanism (by regions).

Recommendations and Conclusions for Demo Cases

After a complete analysis on the mapping of existing funding opportunities at regional, national and international/European scale, and once all strategies for RIS3 priorities of each involved regions, National plans on Energy, Maritime and R&D, and key international policies, the study concludes the following conclusions:

- The topic is seen as one of the key drivers for supporting the deployment of several industries (materials development, manufacturing, wind offshore-related activities) that will help supporting the position of **Europe at the forefront of the global leadership in renewable** energies, including Offshore Wind.
- The analysis of the different funding mechanisms allows the deployment of a **tiered approach**, from regional-scale projects (RIS3 regional and national calls), to interregional collaboration (Interreg and Eranet Schemes), leading to large scale projects (Horizon 2020, Horizon Europe, Eureka Calls).
- Technical challenges for substructures, towers, nacelle and blades are demanding **industrial involvement to upscale the most promising outcomes** from existing and running R&D Projects.
- **Certification agencies** should play an active part in validating future developments.
- (Nacelle) Casting materials for key components like the motor frame should be lightened. Close to market solutions can be **tested in relevant demo sites** on a collaborative basis, following EERA requirements in JP Wind subprogrammes.
- The expected growth in Wind Energy at European level will **support several EU priorities related to SET Plan and Blue Economy**, namely **Job Creation** and Keeping the global **leadership of EU in Renewable Energies**.
- **Structural dynamics, frequency response, fatigue and fracture toughness properties** of materials, as well as soil-structure interactions, become increasingly important from a technical perspective for future solutions.
- **Materials and Manufacturing challenges** regarding the topic implies **selecting materials** with high mechanical properties (tensile strength and yield strength) that **allow the manufacture of towers of lesser thickness**, with good **weldability** and resistance against **harsh environments**.
- **Limited information on the corrosion fatigue behavior of grades of high yield strength steels. Opportunity for further R&D activities.**
- **Fatigue Phenomena** is considered a key issue when manufacturing larger parts and/or replacing materials. **Large potential for research** in the coming years, especially for **nacelle-related** parts.
- Several EU Funding Schemes are available to deal with the topic, including explicit support from relevant EU strategies. **Dedicated topics in H2020 set the basis for collaborative proposals between ADMA regions partners**.
- Regional Strengths are aligned all along the value chain, from materials development to advanced manufacturing, including crosscutting issues. **Specific opportunities under Eranet and Interreg schemes should be explored**.

6 CONCLUSIONS OF THE STUDY

Achieving the ambitious EU target of 27% renewable penetration by 2030 requires step-change technological innovations across all sectors of renewables, paving the way for industrialization and scale.

Wind energy is one of the fastest growing sources of new electricity generation. The recent growth of the wind energy industry has been stimulated, in part, by innovation and consequent cost reductions, together with the support of state policies.

While the cost of building offshore structures is higher and more complex than onshore structures, the combination of increased plant size, technological improvements, infrastructure and associated R&D investments, as well as favourable market, political and economic conditions, has led to a downward trend in the expected prices of offshore wind power generation in Europe.

The development program for the generation of an average of 3700 MW per year from 2017 to 2022 covers the market needs to sustain a viable supply chain. The volume of production associated with this process has several benefits for the industry that support cost reduction, including increased economies of scale, improved infrastructure and manufacturing facilities, increased competition within the supply chain, and the promotion of a skilled workforce.

Despite the potential of technologies, there are a number of technological challenges to overcome the face of improving competition and the cost of offshore infrastructure. Below are the main key challenges and technological trends in offshore systems.

TOWER

Key Challenge

Reduce the manufacturing and assembly costs by lightening the weight of the tower. Certification agencies should play an active part in validating future developments or materials with a yield strength higher than 500MPa.

Technology trends

Due to their size they are constructed in welded sections. Overload problems limit transport to the site. Research is ongoing to overcome transportation problems and the high cost of erection, focusing on onsite tower fabrication.

For this purpose, it will be necessary to select materials with high mechanical properties (tensile strength and yield strength) that allow the manufacture of towers of lesser thickness. On the other hand, it must be borne in mind that the materials selected must behave well in the face of fatigue stresses and also have a good welding aptitude. As thickness and strength increase, cold cracking may occur.

Although the most commonly used quality is S355 and lower the tendency is to lighten weights trying to use higher qualities such as S420 or S460

Transport and installation costs are a factor to be taken into account. While the cost of S460 steels is slightly higher than that of S355 or S235 steels, the price of steels such as S690 is very high compared to S460 steel. Unless the weight is a severe problem, it would not be economical to use S690 steel.

Some qualities can be improved by introducing alloying elements that improve the properties of steel such as the application of niobium in high strength offshore wind towers. These Nb-containing structural support steels provide fatigue and operational performance in critical wind, wave and oceanic conditions.

FOUNDATIONS

Key Challenge

Steel grades used on the foundations are similar to the steel grades used on towers. Reduce the manufacturing and assembly costs by lightening the weight of foundations. Certification agencies should play an active part in validating future developments or materials with a yield strength higher than 500MPa.

Technology trends

High mechanical strength materials are required to lighten the weight of the structure, with good weldability and to resist corrosion- fatigue in both welded and bolted joints.

Different innovations at the components level for the advanced jacket sub structure have been developed and tested under laboratory conditions:

- Adhesive joints were tested as an alternative for welded connections in jacket members and further developments needed to develop this technology have been proposed.
- Sandwich tubes for jackets were also tested to determine the performance of composite materials in jackets. These are rod-like structural components consisting of three components: two relatively thin steel tubes and a core made of ultra-high performance concrete.

MAIN FRAME, ROTOR HUB AND ROTOR SHAFT

The nacelle contains most of the components necessary for the operation of the wind tower, so its weight is considerable (between 25 and 40% of the total weight of the wind turbine).

Key Challenge

Reduce the costs by lightening the weight of this components (improve their fatigue and mechanical strength properties, while at the same time reducing the size of these components).

Technology trends

The research is mainly based on the search for materials that are increasingly lighter and at the same time have excellent fatigue behaviour. In this type of castings, the shape and size of the graphite nodules as well as their distribution within the matrix are very important, because the properties of the casting depend on it. Nowadays developments are been focused on improving of grade GJS400 and GJS450.

The rotor shafts are subject to stress concentration factors, fretting driven fatigue stress concentration, effects and vibration natural frequency, so the development of materials with a good fatigue behavior that increases the life cycle to fatigue of the component is a priority.

BLADES

Key Challenge

Reduce the costs by lightening the weight of the blades.

Technology trends

Trend is toward lighter and stronger blades. Increased use of composite materials including carbon fiber reinforced plastic, steel and fiberglass.

In order to know the areas of interest and opportunities for ADMA Regions, related to “NEXT GENERATION OF MATERIALS FOR THE MANUFACTURE OF LARGE COMPONENTS IN OFFSHORE WIND ENERGY”, a survey was conducted between different regional entities. Thus, the study focused on knowing the areas of specialization of the regions, both at the level of companies and research centers, related to materials, tests, characterization, development of components for offshore, projects, etc.

As a summary, the main lines of specialization of the different regions are the foundation, followed by the tower and connection, and later the assembly - engineering and nacelle and wind turbine rotor. Remote control and energy conversion are lines in which regions work less.

The regions ADMA have capabilities throughout the entire value chain in the development of offshore systems. The main lines of work are: foundation, connection to grid and offshore substation, and tower followed by wind turbine rotor, assembly – engineering and nacelle

Regarding developments related to material development for big components in offshore wind energy have been identified some projects (R&D, demostration scale, etc.), and it have been identified pilot plantsin three regions of the five consulted

The main trends of interest in the regions focus on:

- Welding procedures for high strength steel grades
- Manufacture of new composite materials
- Recycling of composite materials
- Corrosion coatings

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