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Joining of Large Components in a Harsh Environment

Research report for the Vanguard Initiative ADMA Energy Pilot – Challenges and outlook

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1 Introduction

Joining of large components in renewable energy devices has been identified by the ADMA Energy pilot as a potential topic for research, development and demonstration within a European collaboration. ADMA Energy is a pilot project of the European Vanguard Initiative in Advanced Manufacturing for Energy-Related Applications in Harsh Environments. The aim of this report, which has been ordered by the ADMA Energy pilot, is to assess the state of the art, in order to identify key issues, challenges, existing projects, lessons learned and potential for future collaboration on research and demonstration projects.
ADMA aims to support companies across the entire Offshore Renewable Energy (ORE) value chain by initiating collaborative research and demonstration projects related to the joining of large components in ORE devices. The information contained in this report should allow ADMA to assess the possibility to launch one or more research and/or demonstration projects, as well as provide the necessary information to define a project scope and partnership or specify which further actions are needed in order to obtain this information.

The three main chapters of this report are:

- Chapter 3: Large components and joining technologies in current designs
- Chapter 4: Challenges in current designs
- Chapter 10: Ideas for Collaborative projects

In chapter 3 an overview is given of the different offshore renewable energy technologies and what the focus points are in terms of joining technology. Chapter 4 takes a closer look at the specific challenges related to joining of large components in a harsh environment. In chapter 10, the challenges are translated into ideas for collaborative projects.

Supporting information to establish collaborative projects is contained in the other chapters. This includes information about possible partners throughout the ADMA regions, potential test sites and funding opportunities.

The report is concluded in chapter 11 with a short recommendation on which projects could be taken forward within the ADMA Energy pilot. These are the authors' own suggestions and are meant to serve as a starting point for a discussion within the ADMA Energy pilot.

2 Report Scope

Devices under study:
Fixed and floating wind
Wave and tidal energy

Type of joints:
Bolted connections
Adhesive bonding
Alternative mechanical connections (e.g. slip joint, grouting)

Materials:
Metallic materials (Focus on Construction steel and Stainless steel)
Fibre reinforced composites

Technical challenges:
Design challenges
Understanding and preventing degradation (combined mechanical and environmental loading)
Inspection and monitoring

Definition of large components joining:
Focus on components where joint failure has a critical impact on structural integrity and device functionality, i.e. a critical impact on system level

Welding and the connection of mooring lines/chains have been excluded from the scope of this report.
Welding technology and the study of the fatigue performance of welds in a harsh environment is an entire field of study on its own, which requires specific expertise and knowledge. It was not possible to include this within the scope of work. The connection of mooring lines/chains has also not been considered as this is a very specific technology and merits dedicated attention. This connection will to some extent be covered in a separate research report on 'Mooring systems', ordered by the ADMA Energy pilot.

3 Large components and joining technologies in current designs

In the following, a high-level overview is given of which large components are being joined together and are considered in this research report. Most information is available on wind energy devices, as these are relatively standardised designs and all have more or less the same connections in them.
For floating wind and tidal energy, important additional elements or major differences are discussed. For wave energy, the large variety in design concepts makes it difficult to give a general overview. It is likely that many of the problems TEC developers encounter will be similar to the ones encountered in either wind or tidal devices. It is therefore important to raise awareness about the possible challenges, so that they can be addressed in an early stage of the design.

3.1 Fixed wind

Components and joining types

In this section, the most important structural joints present in wind turbine devices will be identified. The four main structural components of the turbine are here considered to be:

- M1: Rotor
- M2: Nacelle
- M3: Tower
- M4: Substructure

Each of these components is connected to another by means of a structural joint. Additionally, within a single main structural element, there are also structural joints between subcomponents. For each main component, the subcomponents, assembly and joints are summarised in a table. In the 'Assembly' section, the joints are indicated. 'MJ' stands for main joint, i.e. a joint that 'exits' the main component. 'J' stands for structural joints within the main component. In the 'Joints' section, the joint type is described.

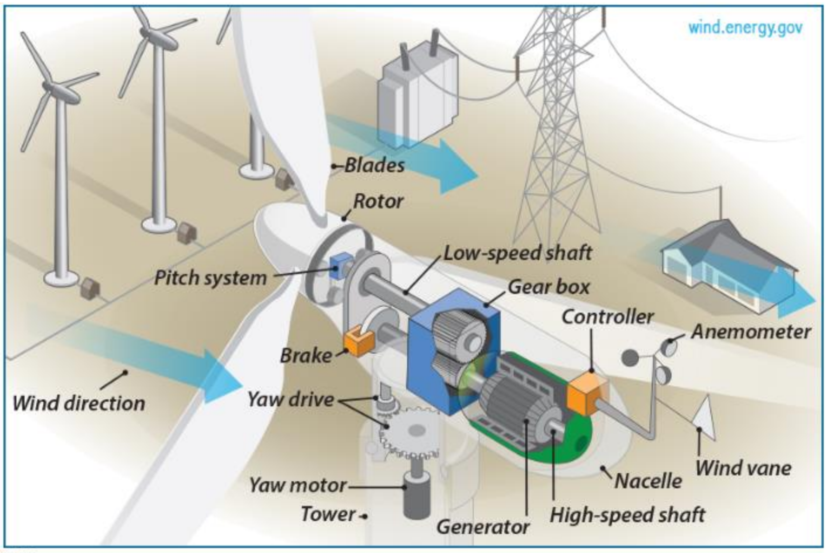


Figure 1: Overview of the general design of a wind turbine rotor and nacelle.[1]

Main component	**M1: Rotor**
Subcomponents	▪ Blades ▪ Blade Bearings ▪ Hub ▪ Spinner (i.e. the cap around the hub)
Assembly	J1: Blade root > Blade Bearings J2: Blade Bearings > Hub MJ: Hub (in M1) > Main shaft (in M2)

[1] Source: wind.energy.gov

Joints	MJ: Conventionally, the rotor is flange-connected to the main shaft using a single or double row of structural fasteners. [6] J1: Typically M30 or M36 grade 10.9 bolts or studs. Differing arrangements are used to provide threaded connection for fasteners connecting the blade root to the bearing: ▪ A ring set into the root of the blade ▪ Inserts bonded into holes drilled in the root ▪ Inserts infused during manufacture ▪ Single or double row of "IKEA-type" threaded bars, set perpendicular to the direction of orientation of studs (T-bolt) -> up to ±60m blades J2: Typically M30 or M36 grade 10.9 bolts or studs
Additional Information	▪ The blade to hub bearing connection is the only one that is made during on-site installation. ▪ Blade root: The blade root acts as the interface between the main composite section of the blade and the steel blade bearing. The root of the blade must be sufficiently flat so as not to apply excessive uneven load to the blade bearing. ▪ Loading of the root-end and fasteners at the blade root is critical due to the complex geometry, especially of the hub and bearing under load. Development testing of root end strength is common. ▪ Generally, the spinner is made from fibreglass in sections and bolted together on a galvanised steel frame. ▪ T-bolt or barrel nut connections have long been the commonly used blade root connection. For larger blade lengths, inserts are becoming the new standard (see section 4.1.6). ▪ Inserts can also be infused into the root section. This allows higher bolt densities and thus higher load transfer, in conjunction with thinner root laminates. Insert solution is relatively strong plus efficient on mass and cost. Therefore, higher loads go towards insert solutions. [20] ▪ Using more but smaller size bolts is preferred, as this uses less material (mass & cost) [20].

Figure 2: Wind turbine hub being installed.[1]

[1] Source: By Paul Anderson, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=13457166

Figure 3: Fiberglass-reinforced epoxy blades of Siemens SWT-2.3-101 wind turbines. The blade size of 49 meters[43] is in comparison to a substation behind them at Wolfe Island Wind Farm.[1]

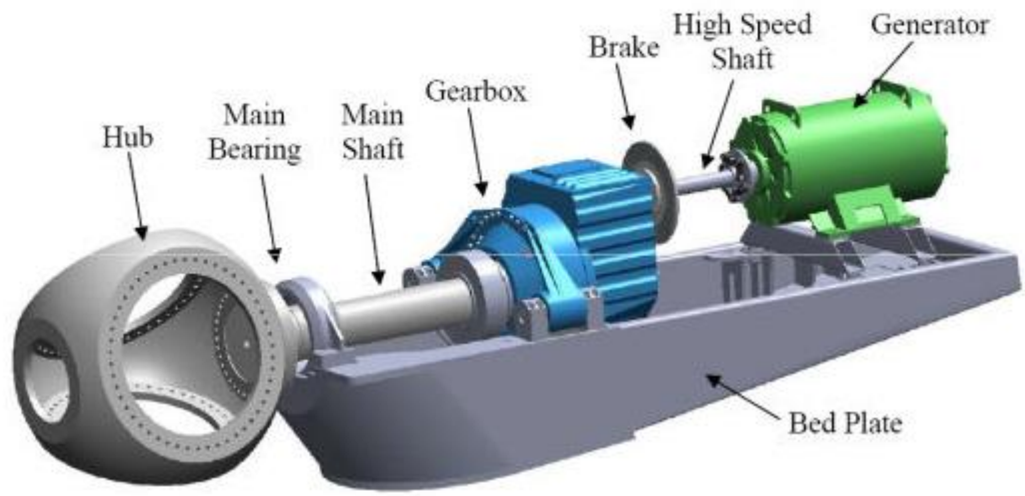


Figure 4: Overview of the main components in the nacelle and connection to the rotor hub.

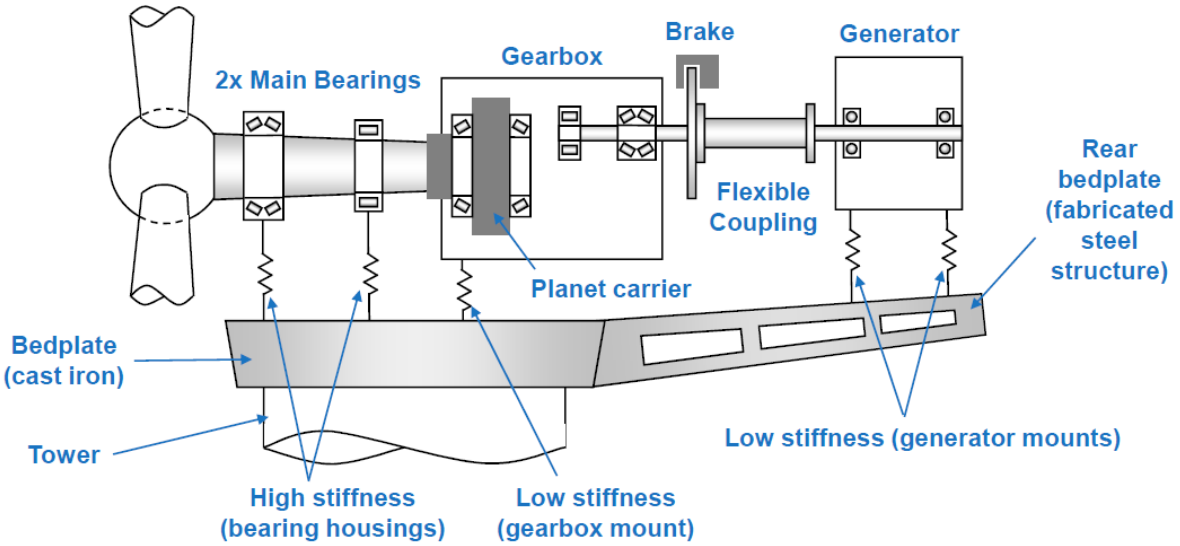
Main component	**M2: Nacelle**
Subcomponents	▪ Bedplate ▪ Main bearing ▪ Main shaft: Transfers torque from the rotor to the gearbox or, for some direct drive designs, to the generator. Supported at the rotor end by the main shaft bearing and at the other end either by the gearbox/generator or separately mounted bearing. [6] ▪ Gearbox ▪ Generator ▪ Yaw Bearing
Assembly	(The following is considered for a traditional high-speed drivetrain, see below this table for a short overview of current innovations with an impact on the joints incorporated into the assembly. [12]) J1: Gearbox > Bedplate J2: Generator > Bedplate J3: Generator > Gearbox J4: Bedplate (underside) > Yaw bearing J5: Main bearing housing > bedplate MJ: Yaw bearing (in M2) > Tower top flange (M3)
Joints	J1: Flexibly mounted J2: Flexibly mounted J3: Not a real 'joint', the coupling that connects the generator to the gearbox is able to cope with substantial misalignment. J4: Typically M36 or larger, grade 10.9 bolts or studs J5: Typically M36 or larger, grade 10.9 bolts or studs MJ: Yaw bearing connected to a flange on the top of the tower. Requires a flat mounting surface, so the tower flange will be machined after welding.

[1] Source: By Z22 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=28994238

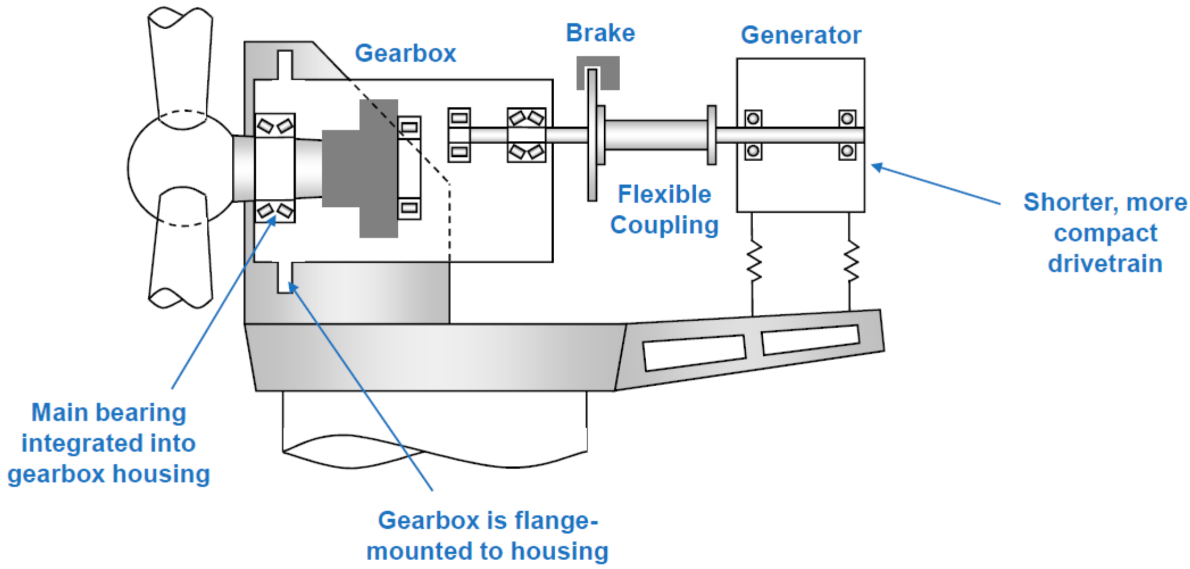
Additional Information	▪ Most of the joints within the nacelle can be realised in a workshop environment. Only the yaw bearing connection is performed on-site. ▪ There are a large number of bolts in the nacelle/rotor or a wind turbine. The total quickly amounts to a few hundred bolts. ▪ New designs of offshore turbines place a high emphasis on maintainability. This is being achieved through modular designs for large components so more subcomponents can be replaced using the nacelle crane. ▪ Main shaft: Forged and machined from high-grade steel such as 42CrMo4 or cast hollow from EN-GJS-400-18U-LT. Different turbine concepts require quite different main shaft designs. Fatigue loading is important. It is critical to minimise stress concentrations. [6] ▪ Planned maintenance should typically be only on an annual basis. ▪ To protect all nacelle components from corrosion, the nacelle is well sealed and the whole area is served by a local air conditioning system. ▪ Many offshore wind developers are moving towards direct drive technology. This vastly improves reliability and reduces offshore maintenance.

Drive train innovations with an impact on joints in the nacelle assembly [12].
Three types of drive trains can be distinguished: the traditional high speed drive rain, a medium speed drivetrain and a direct drive system.

High speed drivetrain.
The image below illustrates the joints between major subcomponents, in particular the high stiffness joint (bolted) between the main bearings and the bedplate and the flexible mounting of gearbox and generator to the bedplate.

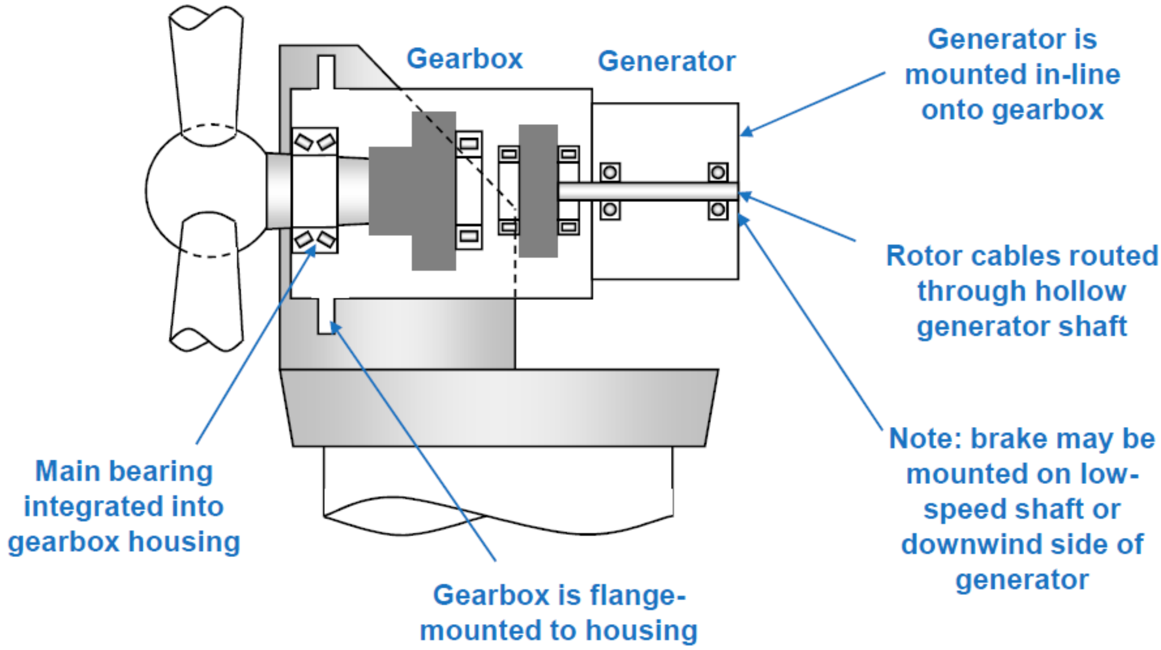


High speed drivetrain with integrated main bearing and integrated mainframe.
In this design, the flexible mounting between gearbox and bedplate is no long present. The entire assembly of main bearing and gearbox is mounted with a bolted flange to the housing/bedplate.



Medium speed drivetrain concept with integrated generator, main bearing and mainframe.

It can be seen on the image below that the number of joints between major subcomponents as defined in the table above is further reduced. In particular, the generator no longer requires a flexible mounting to the bedplate.



Main component	**M3: Tower**
Subcomponents	▪ Tower sections
Assembly	J1: Tower section n > Tower section n+1
Joints	J1: Bolted flange: In general, tower flanges of wind turbines are connected using hot-dip galvanized high strength bolting assemblies for preloading according to national or European standards. [16] Sizes M36-M72. (These connections are also called tower splices.)
Additional Information	▪ Towers are manufactured by cutting and rolling steel plate, welding to make typically 3m “cans” then welding these to make tower sections of say 40m, with bolted flanges each end. ▪ Tower top flanges are machined post welding to ensure top flange flatness is within tolerances required for the yaw bearing.

	▪ Innovations in tower design could allow for the development of single section towers by 2025, allowing a more streamlined manufacturing and a reduced need for bolt inspections (lower OPEX). [10]

Main component	**M4: Substructures**
Design types	▪ Monopile/TP (±80%) ▪ Jacket (±15%) (does not have a separate TP) ▪ Gravity Base ▪ Tripod ▪ Tripile ▪ Suction Bucket (does not require a separate TP) ▪ Self-installed gravity base foundation
Subcomponents	▪ Transition Piece (in MP designs this is a separate TP, in jacket and gravity base designs, the TP is included in the foundation structure): finished at the top with a flange that will mate to the flange at the base of the turbine tower ▪ Pin piles (in Jacket designs)
Assembly	J1: Monopile > Transition piece (only for the MP design) J1': Alternative joint: Monopile > Turbine Tower J2: Pin piles > Jacket base MJ: Transition piece > Turbine Tower (M3)
Joints	J1': Slip Joint (Tested in 2018-2019 at the Delft Offshore Turbine, DOT) [9] or bolted. J1: Grouted or Bolted ▪ Grouted: Typically a long joint, either cylindrical, with shear keys, or conical (extensively used since 2009 [16]), filled with grout. Jacking points allow adjustment to ensure that the transition piece is vertical before the grout is poured. ▪ Bolted: Flange welded on the top of the MP and a flange on the TP/Tower are bolted together with a large number of bolts and nuts. The flange is sealed to prevent moisture ingress. (First used in 2013 at the Humber Gateway and Amrumbank West Wind Farms.) Bolt of upto M72 are used and are typically galvanised as a means of corrosion protection. The flanges are typically coated. J2: Installation usually involves pre-piling the pin piles. The jacket is then lowered into place over the pin piles and grouted. Post-piling may alternatively be used, in which the pin piles are driven (or lowered into pre-drilled sockets) through a sleeve on the jacket legs. MJ: Bolted flange (The bottom of the tower is bolted directly to the MP or to the top of the transition piece (TP) by the use of flanges pre-welded to the tubular shells.)
Additional Information	▪ Settlements of the TP on several offshore wind farms (OWF) in 2010 with the traditional cylindrical grouted connection led to the development of today's most widely used conical grouted connection and alternatives such as the bolted ring flange connection or slip/double slip joints. Current tendencies are that an increased number of offshore wind farms are moving towards the bolted flange solution between the MP-TP. [13] ▪ Grouts and grouted connections are well covered by offshore standards, for bolted connections, a number of issues arise with respect to standardisation, especially for bolts larger than M72. ▪ For larger turbines and in deeper water, the cost of monopiles rises substantially. At around 35m water depth, jacket designs become cost competitive. It is easier to design a stiffer jacket structure for turbines of 10MW and above in order to meet natural frequency requirements, giving such structures the edge over monopiles. However, further developments in monopile designs may make them cost effective at larger water depths. ▪ Jackets can be used in a wider range of ground conditions, where the ground is either too hard or too soft to suit monopiles. ▪ A separate transition piece (in combination with MPs) avoids pile driving on the flange below the turbine tower, and allows secondary steelwork to avoid pile-driving loads. Innovations in design and installation are also working towards designs

	without transition piece. If secondary steel can be attached directly to the MP, without need for a TP, this greatly reduces cost. Additionally, if the tower is connected directly to the MP, and the joint can be moved to a location above the splash zone, the corrosion risk to the joint is also reduced considerably. ▪ Suction buckets have the advantage of little or no piling noise. They can only be installed in certain soil conditions, preferably sand or clay that is neither too dense or hard nor too loose or soft. Sites with shallow bedrock or the presence of boulders in clay soils are not suited to suction buckets. ▪ The top of the transition piece needs to be approximately 20m above the highest astronomical tide (HAT) to keep the working platform above the worst expected combination of wave height, splash height, tide height and storm surge. ▪ The tower interface level is typically around 20m above water level. ▪ Corrosion protection: Flange and washer contact surfaces are thermal spray metallized, all other areas are corrosion protected by epoxy coating (Amrumbank Wind Farm). Fasteners (bolts and nuts) are typically hot dip galvanized. [16] ▪ Pile driving can cause plastic deformation and/or fatigue loading of the MP flange. This can be avoided by introducing a small nominal tilt of the flange to the bottom to ensure that the anvil-flange contact area is limited to the projection of the MP wall. [16]

Additional information

Specifications	▪ Fasteners for critical structural joints within large turbines are typically of size M30 or M36 and grade 10.9. ▪ Often, the fasteners are specified to have threads rolled after heat treatment to improve fatigue properties. ▪ All critical structural fasteners are preloaded either using hydraulic torque tooling or (in the case of studs) hydraulic tensioning. Increasingly, preload indicators or other visual checks on tightness are used. ▪ Coatings provide corrosion protection. Multi-layer corrosion protection systems have not had any serious issues as far as publicly known. [3] One-layer corrosion protection, when applied correctly and without faults, can be very cost effective. However, in case of faults, the maintenance costs can be very high.
Inspection and monitoring	▪ Typical maintenance includes inspection, ***checking of bolted joints***, and replacement of worn parts. Typically there is a combination of limited yearly checks and more extensive inspections every 3-5 years. ▪ Drones are increasingly being used for inspection work. They can be equipped with a digital camera, a thermographic camera or a combination. A digital camera provides proof of the visual failures and damages to the tower, nacelle, rotor blades and ***bolt jointing***. ▪ Inspections and surveys include monopile internal ***inspections of*** the grouted or ***bolted connections***.
Economic considerations	▪ The structural fasteners cost for a 10MW wind turbine is about £70,000 (for all fasteners in rotor and nacelle). ▪ Typical inspection scheme: inspection on a 2-yearly interval, approximately 5000 EUR per inspection per turbine. According to industry, a reduction by 50% should be envisaged and feasible. ▪ Total Operations, Maintenance and Service (OMS) cost: About £75 million per annum for a 1GW wind farm (100 10MW turbines), including insurance and internal asset owner costs. ○ £25 million per annum goes into operations ○ £50 million per annum goes into maintenance and service (£33 million for turbines, £17 for balance of plant) ▪ The blade root it represents between seven percent and 20 percent of the total blade cost. [18]

3.2 Floating wind

Floating wind devices are typically installed in deeper water (>60m), or in shallow water where there are poor seabed conditions (e.g. unstable or very hard rock). There are more than 40 different concepts, with around 20 in active development. [1] The most common floating substructures are illustrated in Figure 5:

- Spar
- Semi-Submersible
- Barge
- Tension Leg Platform

A floating substructure is typically constructed in blocks which are welded together in a single product. Bolted connections in the submerged and splash zone are avoided as much as possible as these zones are most prone to the occurrence of problems in terms of longevity. As a result, most issues are related to predicting and improving the fatigue life of welds, similar as for fixed wind foundations. The major difference in comparison to fixed foundations are the different loads experienced by floating foundations, which are expected to be high due to the dynamic response of the floater. Especially the peak loads experienced by floating foundations during emergency breaking of the turbine can be very high. Because of the different loads on the structure, also the joints will be stressed differently. The forces experienced by floating wind foundations are also expected to be an order of magnitude larger as compared to floating wave or tidal devices.
The challenges related to welds will not be considered further within this report, as discussed in the description of the report scope.

Floaters can have either a TP between the floater and the tower, or have the tower directly bolted to the platform. In any case, the connections is typically a bolted flange, similar to the ones used in fixed wind. However, the loads experienced by these joints will be much larger than those faced in fixed wind. An important consideration is for example emergency breaking, which causes large tower inclination and corresponding loads on the bolted flange joint(s). There is still some uncertainty how this influences the durability of the joint.

Floating foundations are mostly constructed from steel. Composite materials are currently not yet used for structural elements. However, the industry is considering how and where new materials could contribute to a reduction of cost in terms of manufacturing, installation and maintenance.
Frontier Technical Ltd. developed and patented MARLIN, a Modular Floating Platform. Compact and easily transportable modules are used as building blocks, facilitating offshore installation and reducing costs. This illustrates that future developments may move away from the large welded structure, increasing the need for durable and cost effective connections that can survive for extended periods in the splash and submerged zones.

Some of the challenges related to floating foundations as identified by ORE Catapult in [1] are:

- There is a lack of available operational performance data (which makes floating wind a high-risk investment).
- There is limited collaboration between substructure developers and wind turbine OEMs (in part because there are not enough OEMs to partner with each substructure concept developer).
- Difficulty of performing on-site inspections and repairs due to the inherent dynamics of floating wind turbines (continuous vibrations and possibly large accelerations and displacements). Development of substructures and wind turbines with reduced maintenance requirements could therefore be a significant added value, in light of this report topic, that means reduced maintenance needs of for example bolted joints (pre-loading, corrosion).

Floating structures are kept in place by a mooring system. The mooring lines/chains are connected to the floater. In the case of chains, shackles can for example be used to connect the chain to a ring welded to the floater. Many different commercial solutions exist for various types of mooring. Although this can be considered as joint between two large components of the device, it will not be considered in this report, because this type of joint deviates a lot from other joints and uses a dedicated connector. This connection will to some extent be covered in a separate research report on ‘Mooring systems’, ordered by the ADMA Energy pilot.
One of the challenges: Multiple connections and disconnections of the mooring system should be possible in order to allow major maintenance at port. There is a significant commercial need to develop connectors which are faster, lighter and easier to assemble in order to increase reliability, productivity, whilst also reducing maintenance costs and improving safety of the device.

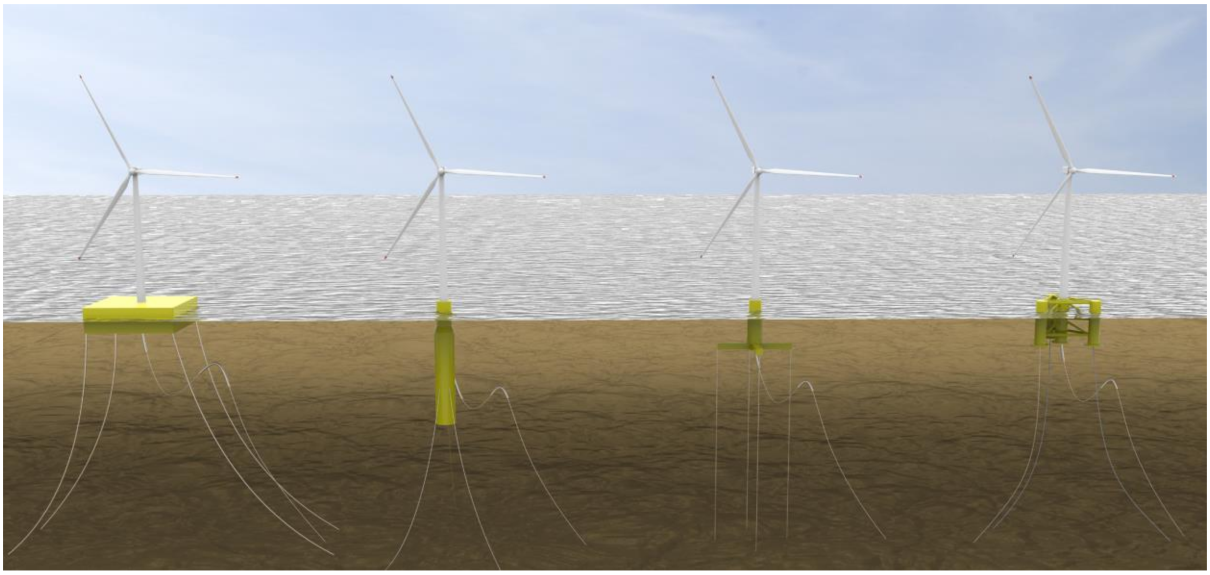


Figure 5: Schematic illustration of the most common Floating wind typologies (left to right: barge, spar, tension leg platform (TLP), semi-submersible). [1]

3.3 Tidal Energy Convertors (TEC)

The vast majority of TECs being developed or close to commercialisation are horizontal axis turbines (see Figure 6). Horizontal-axis turbines also represent tidal converters with highest technology readiness levels (TRLs). These operate much like wind turbines, but instead of getting power from the wind, they get power from tidal flows. The rotor and nacelle of horizontal axis tidal turbines close to commercialisation, consist largely of the same components as wind turbines:

- A rotor made up of two, three or more blades, connected to a hub.
- The hub connected to a main shaft entering the nacelle, where power is generated either through a direct drive generator or a combination of a gearbox and generator.

The blades are generally made from composite materials (glass fibre and/or carbon fibre), but are of a significantly smaller size than those for wind turbines, with rotor diameters up to 25m.

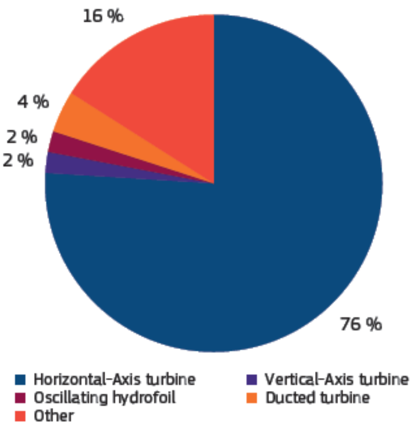


Figure 6: Distribution of R&D efforts in TECs types. (Source: 2014 JRC Ocean Energy Status Report)

Tidal devices can be installed on fixed structure, such as monopiles, pods and gravity foundations, or floating and moored to the seabed by tethers. Whilst a convergence can be seen in the type of tidal technology, the same cannot be said with regards to foundations: about 40% of tidal devices require floating connections, and 60% require fixed foundations.

In the case of a tidal kite, the nacelle is attached beneath the kite. [8] A number of examples of tidal energy convertors is shown in the figures below. For a more complete list of TEC developers, the reader is referred to the website of EMEC[1].

SIMEC ATLANTIS ENERGY | sabella ride the tide | NOVA INNOVATION

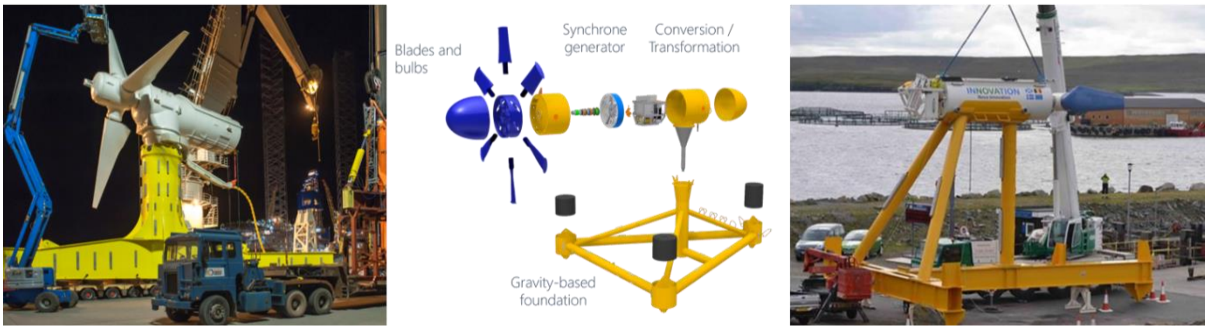


Figure 7: Examples of bottom fixed turbines.

Magallanes Renovables | ORBITAL MARINE POWER

Figure 8: Examples of floating tidal turbines.

[1] http://www.emec.org.uk/marine-energy/tidal-developers/

Figure 9: Example of Tidal Kite.

Whilst the tidal sector exhibits a certain level of design consensus, the picture looks slightly different when components and subcomponents of TECs are taken into account [8]. As a result, the design and type of joints used in the TECs is also different.

One major joint that is encountered in all devices is the connection between rotor blades and the hub. In case of composite blades, the design of the connection is similar to that for wind turbines. Encountered connection types are the T-bolt principle, a steel ring adhesively bonded into the blade root or adhesively bonded inserts in which studs are placed. A major difference with respect to wind turbines, is the fact that the tidal blades are submerged in seawater, which has an impact of the degradation mechanisms to which this joint is exposed (see sections 4.1.7 and 4.2.4).

Individual parts of the steel structure are either welded or bolted together. In contract to wind energy devices, the bolted flanges are located either underwater or in the splash zone. As a result, protection of these bolted connections against corrosion and leakage presents a much greater challenge (see section 4.2.4).

The importance of installing the bolts with the correct pre-load and maintaining this preload is comparable to that for offshore wind, although many devices have not yet been long enough in the water to observe issues related to loss of pre-load. Additionally, because technology developers are aware of the importance of pre-loading and the fact that for TECs inspection is extremely costly, great care is given to the installation. An additional concern is the impact of biofouling, which can have a big impact on the feasibility and cost of inspection of submerged joints.

An additional consideration for submerged bolted joints is the material usage. Submerged systems are typically protected using cathodic protection. As a result there is a risk on hydrogen evolution. Therefore, lower strength bolts (grade 8.8) are typically prescribed for submerged applications. Also the risk on corrosion mechanisms like crevice corrosion, pitting corrosion and stress corrosion cracking is increased. To manage the risk of for example stress corrosion cracking, bolts can be overdesigned in order to reduce the stress levels. However, this again introduces unwanted additional costs. If these risks cannot be properly managed, it is likely that bolts will have to be changed every 5-10 years, which would introduce a significant maintenance cost.

As is the case for wind energy turbines, horizontal axis tidal turbines can have pitch and yaw systems in order to align the rotor and blades so as to maximise energy generation or break the system. However, as these systems are submerged, sealing of these systems and the joints between the major components against water ingress (for example blade to pitch bearing to hub) is an important challenge, along with protection against degradation due to sea water. Because these submerged bearings provide potential failure modes, certain systems are also designed without them.

Next to pitch and yaw bearings, tidal energy devices may have other mobile joints to allow relative movement of two components. Because these joints are either in the splash zone or submerged, protection of these joints against corrosion poses an additional challenge.

Some bottom fixed structures, utilise a unique joint type between the foundation and the nacelle to allow easy recovery of the nacelle. The foundation has a large socket on its top, on which the nacelle can be lowered and is kept in place (either by gravity alone or in combination with a fixture). The nacelle has a large pin/protrusion at its bottom, which slides into the female type socket on top of the foundation. A major concern here is protection of both sides of the connection against wear/damage during installation and subsequent corrosion.

Floating structures are kept in place by a mooring system. The mooring lines/chains are connected to the floater. In the case of chains, shackles can for example be used to connect the chain to a ring welded to the floater. Many different commercial solutions exist for various types of mooring. Although this can be considered as joint between two large components of the device, it will not be considered in this report, because this type of joint deviates a lot from other joints and merits dedicated attention. It will also to some extent be covered in a separate research report on 'Mooring systems', ordered by the ADMA Energy pilot.

3.4 Wave Energy Convertors (WEC)

The large variety in design concepts for WECs makes it impossible to give a general overview of the structural elements of Wave Energy Convertors and how they are joined together. In this section, a few specific points of attention will be highlighted and a few examples given. The problems that will be encountered in terms of joining, are likely to be similar as for tidal devices, although the solutions will need to be adapted to specific WEC designs. A lot could be learned from solutions currently used in the Oil&Gas sector.

Different types of WEC have been proposed over the years, differentiated mainly by the way the devices would react to the force exerted by waves. According to the JRC Ocean Energy Status Report [8], most R&D effort is undertaken on the development of point absorber type of devices, as is illustrated in Figure 10. Wave energy presents the form of ocean energy with the highest deployment potential in European waters, associated with a global potential 30 times higher than that of tidal energy. IRENA has shown that 64 % of WECs have been designed for offshore operation and 36 % for near-shore and onshore operation (IRENA 2014b). [8]

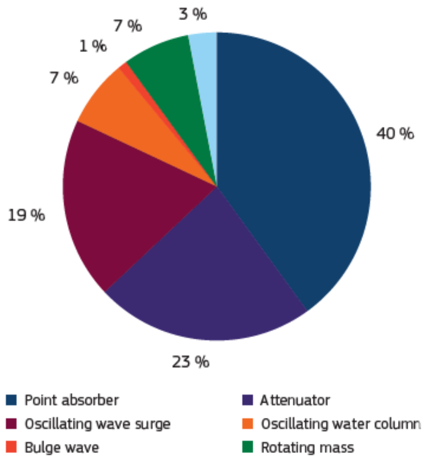


Figure 10: Distribution of R&D efforts according to wave energy technology type. Source: JRC 2014 [8]

The structural requirements necessary to ensure the survival of a wave energy converter (WEC) in extreme sea states are a key cost driver in WEC design and represent a central challenge to the development of WECs into a reliable, cost-efficient source of renewable energy. [8] Depending on the type and design of the WEC, the joints between key structural elements will play an important role in the survivability of the device and should therefore be considered with great care, including the degradation due to the sea water environment.

Wave energy developers have focussed on designing WECs that could harness directly the most powerful resources offshore, adding further complexity to the design challenges of a reliable wave energy conversion device. Regardless of type, each WEC comprises the following three elements [8]:

- A prime mover: a structural component reacting to the incoming wave power, activating a PTO or inducing the movement of other structural components.
- Moorings or foundations, according to the location and application of the device.
- Power take-off: single or multiple PTOs that can be embedded within the device or located on the seabed/shore.

As for tidal energy devices, WECs may have mobile joints to allow relative movement of two components. If these joints are exposed either in the splash zone or submerged, protection of these joints against corrosion poses an additional challenge. Some designs manage to avoid external moving parts, which are prone to degradation, by totally enclosing all the moving parts (mechanical, hydraulic, and electrical) inside a closed, waterproof shell, thereby sheltering them from the action of the sea. However, this is not possible for all types of wave energy convertors.

Currently, there are still very limited amounts of long-term operating data available. Many WEC developers also have not yet been confronted with problems related to fatigue and corrosion of joints because the prototype devices haven't been operational for sufficiently long periods of time. Wave devices are often using traditional joining solutions, which are easily available on the market. Focus is still on development of the power take-off, power generation efficiency, etc. Many of the devices are not yet cost optimised and are therefore not yet in a stage where long-term reliability is a major design driver (for first prototypes), first the technologies ability to generate electricity has to be proven. In engaging with WEC developers, the focus could therefore mainly be placed on awareness raising, so that joints are designed with the necessary care in an early design stage. By learning from well-established sectors such as O&G, and even the more advanced Tidal Energy Devices, costly design iterations in terms of joint design and protection can be avoided.

The most used material in WECs is steel. The use of composite materials is still limited. Weight is less of a concern for most wave devices (most devices even need to ballasted), so the major benefit of composites is in terms of corrosion protection. But, same as with the joints, most project are not yet in a stage where material optimisation studies have been performed.

Below, a number of example devices are described (after [23]). This illustrates that while some devices have limited external joints, others do have external joints, moving parts and flexible connections exposed to the sea water.

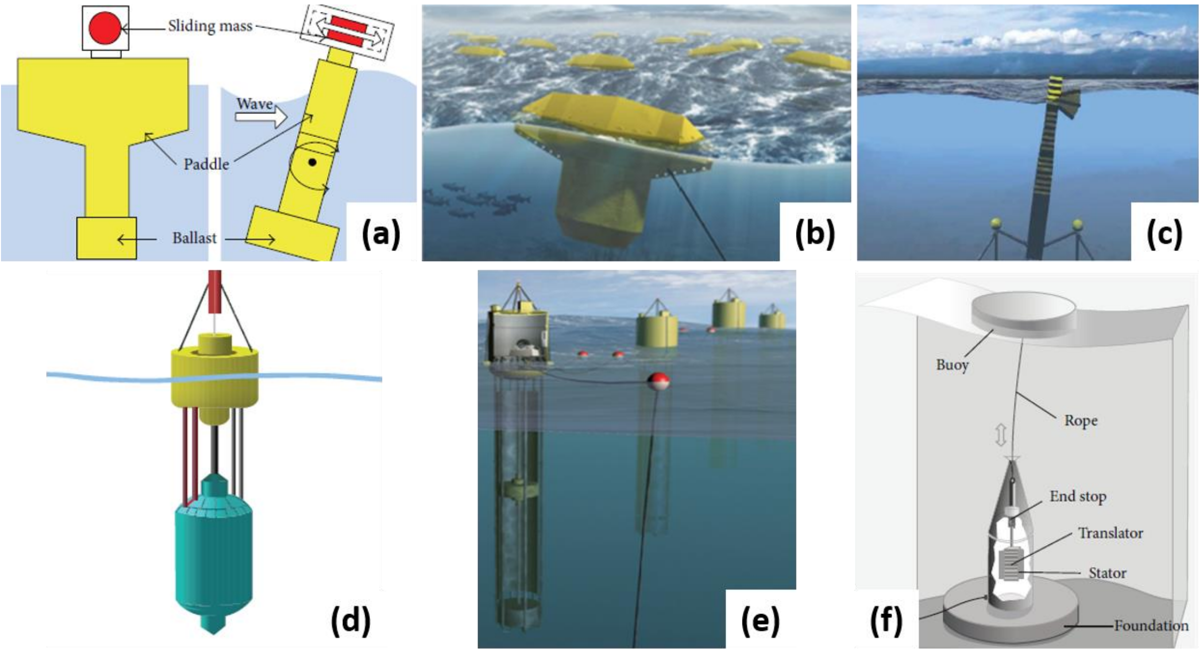


Figure 11: Examples of WECs, after [23]. (a) PS Frog MK 5 (b) Searev (c) WET-NZ (d) Wavebob (e) Aquabuoy (f) Uppsala

The PS frogMK5 is a point absorber that consists of a large buoyant paddle with a ballasted handle hanging below it. The waves act on the paddle. When the WEC is pitching, power is extracted by partially resisting the sliding of a power-take-off mass, which moves in guides above sea level. This device is totally enclosed in a steel hull with no external moving parts.
The Searev WEC is a point absorber that encloses a heavy horizontal axis wheel. The centre of gravity of the wheel is off centred and this allows it to behave like a pendulum. The rotational motion of this pendular wheel relative to the hull activates a power take-off (PTO) system. All the moving parts (mechanical, hydraulic, and electrical) are sheltered from the action of the sea inside a closed, waterproof shell.
The WET-NZ extracts energy from the differential motion of two bodies of different mass: a reactive hull and an active float. The reactive hull is sufficiently long to extend below the wave motion, whilst the float is at the surface, where maximal wave energy is located. The energy is absorbed through a single pivot rotating motion.
The Wavebob consists of two oscillating bodies that are controlled by a damping system: an inner float and an outer ring. The inner float undergoes heaving motion slowly in the outer ring. The energy of this motion is captured to generate electricity through a high-pressure oil system.
The Aquabuoy consists of a floater which keeps the system afloat. A large cylinder called the accelerator tube is connected below the floater. A piston is housed in the centre of the accelerator tube and is connected to the

top and bottom section of the buoy using a hose pump. The relative motion between the buoy and the piston stretches and compresses the hose pump, which in turn drives the water through a Pelton turbine to generate electricity.
The Uppsala Point Absorber has a linear direct drive generator placed on the seabed. A buoy is connected to the moving part of the generator using a line and a piston. Springs are attached beneath the translator of the generator to store energy and act as a restoring force during wave troughs.

4 Challenges in current designs

Generally speaking, four main classes of connections can be identified for large components in offshore energy devices:

- Bolted joints
- Adhesively bonded joints
- Grouted connections (MP/TP, jacket pin-piles)
- Mechanical contact joints (e.g. slip-joint)

An attempt has been made to map the challenges related to joining of large components in offshore energy devices through a combination of literature reports and interviews with industry experts. The following is a summary of the findings and should give a good overview of the challenges that are currently driving the industry. This document does not however claim to present an exhaustive list, and individual asset owners, technology and project developers may be faced with other issues. The current authors are however confident that most of the major elements are to a certain extent covered. It will however become clear that bolted joints take up the biggest space. This is a reflection of the fact that this is indeed the most used type of connection (next to welding, which is not within the scope of this document) and that most of the identified challenges relate to this type of connection.

The challenges and difficulties identified have been subdivided in three main sections:

- Design challenges
- Understanding and preventing degradation
- Inspection and monitoring

4.1 Design challenges

4.1.1 Large flanged joints

A major issue that can impact the durability of large flanged joints is ***the tolerance on the opposing flanges***. With ever increasing sizes of components, precision manufacturing of these components is a real challenge. The tolerances on fabrication (and accumulated during installation), have an impact on the load bearing capacity of bolted flanges (both in maximum load and fatigue loading) [13]. In [16] an example is given for the production of a flange connection with an outer diameter of 5.2m. Criteria for flange flatness state an allowed deviation of 1 mm over a segment of 30°. Additionally, only gaps of up to 3 mm are allowed to be closed by tightening the bolts. This is a challenge when producing flanges with ever increasing diameters.
A typical example of a large flanged joint is the bolted connection between the MP and the TP of offshore wind turbines. The authors of [16] advise that ***flange flatness tolerance guidelines should be reviewed*** for the case of MP foundations. This should be supported by advanced modelling work that includes the influences of fabrication and installation tolerances on static and dynamic load calculations [13]. Even with larger tolerances allowed, it will remain challenging to fabricate large flanges (up to 10m diameter) within the specified criteria.

A problem specific to the MP-TP connection is the horizontal storage of the MPs prior to installation. Prolonged periods of storage can lead to ***the MP cross-section becoming slightly oval instead of perfectly circular***. This will lead to small mismatches between the MP and TP flange. As a result not all bolts are perfectly in place leading to a small amounts of slack. In combination with the complex loads to which wind turbines are subjected, even very small deviations (< 1mm) may lead to some bolts being loaded more than other and can influence the long term fatigue behaviour of the bolted joint. It is yet unclear just how big this effect can be and whether or not it needs to be considered.

Current designs of large flanged joints still use assumptions from 20 years ago which were applicable to smaller diameter flanges. It is uncertain that these assumptions are still valid for larger flanges and that these tolerances can be met in production. There are two approaches to solving this issue. A first solution is to improve manufacturing processes so that they can deliver large components with very tight tolerances. However, this may proof impossible and/or very costly for the ever increasing device sizes. Another approach is to allow for larger imperfections, and take this into account in the design stage. The latter will require development of new design methods and modelling tools.

4.1.2 MP/TP connection

As mentioned in the previous section, a specific example of a large flanged joint is the bolted connection between the MP and TP of an offshore wind turbine (this can be either on a fixed or floating platform). In Figure 12 an example of a bolted flange connection is shown. It should be remarked that this particular connection uses a combination of bolting and grouting. However, the grout used here is meant to prevent the ingress of seawater (see also Figure 19 in section 4.2.4) and provide additional protection against the corrosion of bolts, but doesn't have a load bearing function. This should not be confused with the 'grouted connection', where the grout is used to keep the TP in place (see section 3.1 for more information).

Figure 12: Bolting and grouting in progress, source: Boskalis[1].

The trend in the offshore foundations seems to go towards flanged connections between the MP and TP since installations can be faster and more cost-efficient. If the current trend continues, the bolted flange will become the new standard for MP/TP connections.
Corrosion and pre-loading issues associated to flanged connections can lead to an increase in maintenance costs over the lifetime of the wind turbine. On the other hand, MPs with grouted connections have in the past lead to slippage problems, but may effectively be used after implementation of the newest design guidelines. For a more extensive list of pros and cons of bolted connections and grouted connections, the reader is invited to consult windpower-international.com[2]
As there is a trend towards using bolted connections, in the following, a number of challenges related to flanged connections are mentioned:

- Hammering directly on the flange of the MP may result in **possible physical damage to the flange** and negative effect on the fatigue resistance, both from **material damage and flange misalignment**. This is **not taken into account in established design procedures**. [13] Research effort should be undertaken in order to minimize MP flange tilting, used to avoid flange-anvil collisions while driving, in order to minimize the necessity of shims. [16]
- The flange is also prone to coating damage during hammering.

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[1] Source: Presentation by André Andringa, Boskalis, at Society for Underwater Technology, October 10th 2018 https://www.sut.org/wp-content/uploads/2017/09/Andre-Andringa-ETM-10-Oct-2018_web-approved-.pdf
[2] Monopile foundations with flanged connections, consulted on 29/10/2019, http://www.windpower-international.com/contractors/world-wind-technology/monopile-foundations-with-flanged-connections/

- **High corrosion risk**: The bolted connections need special attention because the highly corrosive environment of the seawater causes steel corrosion of the normally galvanised components.
- Misalignment of bolt holes can lead to a reduced fatigue life.
- Bolts need to be **pre-loaded** to the correct load in order to ascertain the fatigue life. This also brings with it high maintenance and inspections costs (see section 4.2.2 for more information).
- Transition pieces with bolted joints require the monopile to be installed to within a small deviation from vertical. Driving the MP into the seabed can result in the MP not being perfectly vertical and the mounting flange being inclined. This is **not covered in existing design procedures**. [13] Imperfections in verticality may need to be corrected using foundation-specific solutions, such as adapter rings. If an adapter ring is used to correct verticality, the bolts need to be longer than the standard bolts, leading to higher costs and longer waiting periods. [14]
- **Installation procedures** are not always entirely clear, or not followed to the letter, for example on which type of grease to use (may influence corrosion resistance and bolt pre-load), which type of pre-load measurement to apply, etc.
- Monopile foundations are getting bigger to handle the loads of larger turbines, which would require bigger and more bolts in the flanged connection. Therefore, **larger bolt sizes** will need to be standardised (see also section 4.1.3). Other material grades may also need to be considered which are not currently covered by design standards and guidelines.
- It is not always easy or possible to verify that design assumptions are being respected (i.e. no corrosion, correct pre-load, flange positioning, experienced loads, etc.)

4.1.3 Large bolt sizes

The largest bolt size currently used in offshore wind MP/TP connections is an M72 bolt. With the ongoing trend of ever increasing turbine sizes (12MW+ turbines), there is also a demand for larger diameter monopile foundations (8-10m). As a consequence, larger bolts will also be needed to transfer the increased load from the turbine to the foundation. ***However, there are currently no standards for fatigue lifetime assessment of bolts at size larger than M72.*** I.e. what are allowed tolerances on geometrical accuracy, ovality, surface roughness, etc. to allow for a 30 year fatigue lifetime? Such standards will be required in order to be able to certify and get insurance for projects using larger turbines.
Although the above focusses on monopile foundations, larger turbine sizes will lead to larger diameter connections to the foundation, regardless of the type of foundation being used. This therefore also applies to jacket structures and in the future potentially also floating foundations.

4.1.4 Modular design

The ADMA Prioritisation study 'ADMA Energy Analysis and Priority Setting' undertaken by Optimat undertaken in 2019 mentions as an option for prioritisation an 'Increasing Modular Approach to Systems'. Modular design provides the possibility to implement standardised designs and adopt a modular approach to process units, thereby reducing design, schedule and cost uncertainty. Modular design offers opportunities for savings and the options for onsite fabrication and offsite shop modular fabrication in order to add engineering accuracy and quality efficiency.
The development of a modular approach to system fabrication necessitates the introduction of larger amount of structural joints between large components. Two examples are:

- Modular construction of floating platforms for offshore wind. Using the concept of compact easily transportable modules as building blocks. Such building blocks could be standardised welded cans which can be joined together through bolted flanges. The amount of cans required could then be adapted based on the required size of the floating platform. The bolted flange connection could in many respects be similar to the MP/TP bolted joint, although possibly with a different orientation (vertical vs. horizontal) and different applied load spectrum. The impact of the potentially large loads at emergency breaking on the design and durability of bolted joints should be investigated. Also the potential on-site realisation of the joint could be very challenging, with a preference to perform assembly on a construction yard.
- Developments in substation installation include the use of modular structures so that the individual lifts can be undertaken by a vessel with a lower crane capacity. This will require the on-site realisation of joints between large components. Depending on the design different types of joints (not necessarily

bolted) could be envisaged. Operational experience, focused on ease of on-site assembly (including time requirements) and durability of the joints will be required to evaluate alternative designs.

4.1.5 Segmented blades

Difficulties in manufacture, testing, transportation and installation are associated to the production of increasingly long blades (> 100m). Therefore, the concept of segmented blades is being investigated. These segments will need to be connected to one another in a reliable and cost effective way. (Little or no maintenance need, good fatigue resistance, corrosion resistance, etc.) **Adhesive bonds** are expected to provide structural and economic efficiency, but **in-field assembly poses a big issue** (see also section 4.1.7). Prototype segmented blades using T-bolt joints, studs and spar bridge concepts have proven successful, as well as aerodynamically-shaped root and hub extenders. [18]

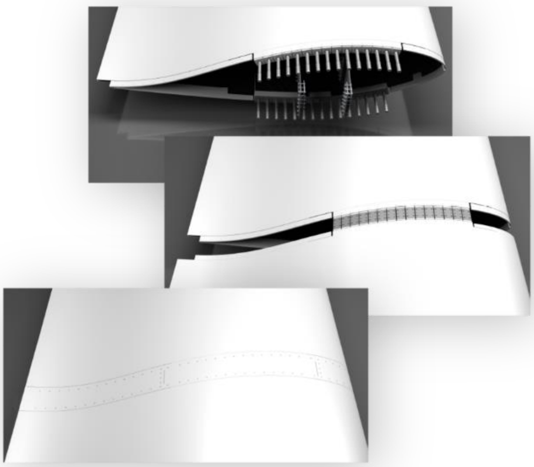


Figure 13: The Nabrajoint, as an example of an approach to segmented blades. Developed by Nabrawind.[1]

Current status [20]:

- Tip replacements designed and implemented
- Various design assessments' and prototypes in the business
- Steel to composite solutions applied

Maintaining the original blade specs (mass, stiffness, freq.) and the joint between the segments (spar cap joint) still provide challenges. Alternative joining solutions are still being proposed and developed further. One example could be thermoplastic welding of composite material[2].

Companies like GE and Siemens are developing prototypes with segmented blades (also for onshore turbines, where the challenges related to logistics are even larger).

4.1.6 Blade to hub connection

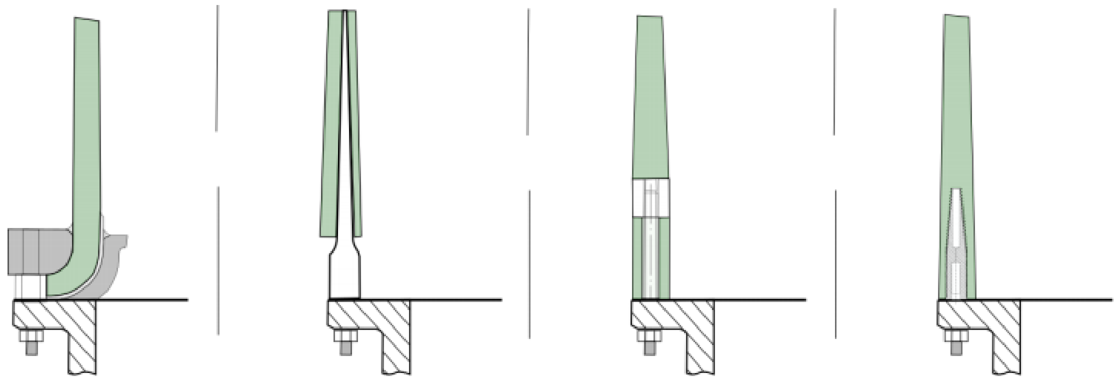
Wind Turbines

The composite wind turbine blades need to be joined to the steel hub (in effect the blade bearing). Today this is achieved by means of a bolted connection. The most commonly used way to integrate the bolts/studs in the composite laminate is by means of a T-bolt connection. The use of T-bolts has its limitations when moving towards larger blades, as will be discussed below. As a result, another type of connection, based on inserts with an internal thread (stud root connection) is becoming more popular. The challenge on how to transfer large loads at the composite/steel interface remains a topic of investigation and continuous development, with the ever increasing size of offshore wind turbines driving the developments forward.

[1] Source: https://www.nabrawind.com/nabrajoint/ (consulted on 30/10/2019).

[2] Source: Interview with Dirk-Jan Kootstra, Quattra-P.

The weight of the joint is less important, since it is added close to the hub and the centre of rotation. As a consequence, it does not have a big impact on the blade's eigenfrequencies, and edge-wise and dynamic loads. This is different for blade segmentation joints, which are placed further outboard. Due to the superior fatigue performance of T-bolts and studs, other blade root designs have become rare. [18]



Blade Root Connection	Advantages	Drawbacks	Implementations
Flange type	-	Inferior fatigue behavior	-
Hub type	-	Heavy	-
T-bolt type	Inexpensive and simple	Packing limitation of the T-bolts	[45,52,100]
Stud/insert type	Allows for the lightest joint	cost	[49,55]

Figure 14: An overview of bladed root joints. (a) Flange root connection. (b) Hub-type root connection. (c) T-bolt root connection. (d) Stud root connection. Source: [18]

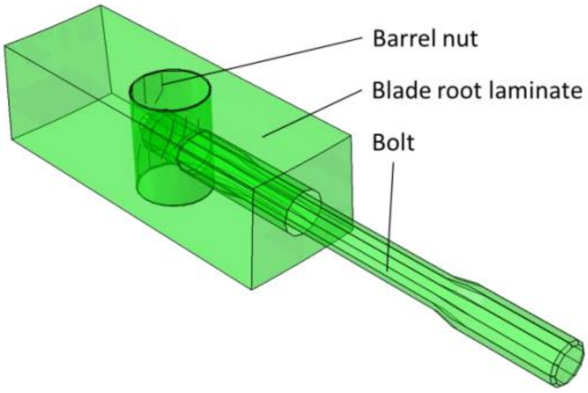


Figure 15: Elementary T-bolt parts. Source: [17]

The T-bolt connection is the most commonly used root connection because it has a lot of advantages. It does not rely on adhesives, its cost is lower than other connection types, it has a good reproducibility and when a bolt or barrel nut is broken, it can easily be removed and replaced. However, it needs a high drilling accuracy in order not to introduce unnecessary bending, but this is not a big problem with current machining tools. The T-bolt joint is reliable and inexpensive, but has a low structural efficiency, resulting in a high weight compared to other solutions such as inserts. Packing limitations exist and lead to a significant laminate build-up.

The barrel nut is a steel cylinder which is placed in a drilled hole in the composite shell of the blade at a certain distance from the end side, with its axis normal to the shell. The barrel nut is glued to the laminate but this glue has little stiffness. Its purpose is just to hold the barrel nut in place and not to transfer the forces. The forces are always transferred by bearing of the laminate against the barrel nut. In order to allow this bearing and because the forces are the highest at the blade root connection, the laminate is a lot thicker at the root. This thickness is oversized due to an absolute lack of information related to the bearing strength of very thick laminates with a hole in the middle of the bearing area for the bolt. Guidelines suggest a thickness of about 1.5 times the barrel nut diameter. [17]

This high material usage due to the introduction of high stresses in the composite around the T-bolt is the biggest disadvantage of this type of connection. [17] At the blade root, the loads are highest and the cross-section comparatively small, which necessitates the use of thicker laminates. Additionally, the hole in which the barrel nut is positioned acts as a stress concentrator. Because very high loads need to be transferred from the composite laminate to the bolt at this location, this further increases the required laminate thickness. The biggest challenge is the lack of knowledge on how such thick laminates behave. Moreover, this is a challenge which is unique to the wind industry, as such thick laminates are not used in any other business. Because wind energy is pioneering in this field, there is no knowledge from other sectors that can be used. In order to understand the behaviour of these connections and predict their lifetime, ***accurate modelling and testing of the connection is necessary***.

As blade lengths increase, the load that needs to be transferred increases faster than the blade root circumference. As a result the T-bolts need to be placed closer together. In order to be able to transfer the load from the barrel nut to the laminate, the laminate thickness needs to increase further. Eventually, this increases the risk on undesired failure modes (Figure 17). Further increasing the laminate thickness therefore doesn't result in any additional gain. Essentially, the T-bolt is reaching its limit, because the centre-to-centre-distance over hole diameter ratio is becoming undesirable and the favoured failure mode can no longer be imposed.

The size of the barrel nut is also large compared to the stud diameter. As the number of studs required to be able to bear the load increases, the barrel nuts would eventually need to 'overlap'. This is evidently not possible and again illustrates the limitations of this design. One possibility could for example be not to have all the barrel nuts on a single line, but distributed over two lines.

Composite materials are sensitive ***to damage through moisture uptake***. To prevent this, the composite is coated with a barrier coating. The position of the barrel-nut presents a critical location for degradation due to moisture uptake. The holes are drilled in the laminate, meaning that at this location the fibres are exposed to the environment. It is essential to provide good, long term protection at this location, which can be a challenge.

Figure 16: Image of a blade being connected to its hub. The T-bolt principle is used. The barrel nuts can clearly be seen around the circumference of the blade root.[1]

[1] http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201209/PN201209-01_300dpi.jpg

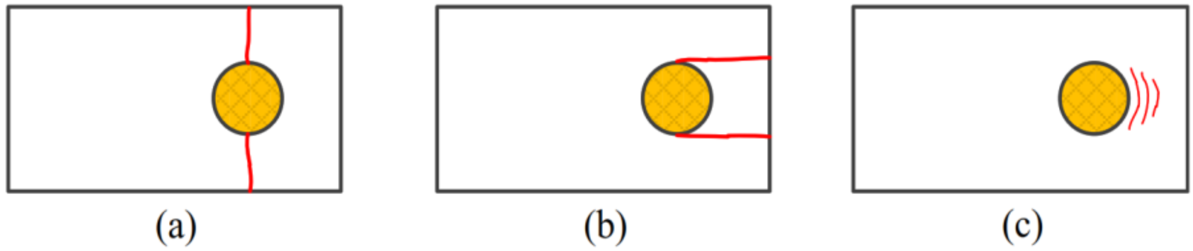


Figure 17: Failure modes of pin-loaded composites. (a) Net-Tension. (b) Shear Out. (c) Bearing. Bearing is the desired failure mode as this occurs gradually, while (a) and (b) may result in sudden failure. Source: [20]

Another solution being applied is the use of ***inlaid inserts*** which are essentially adhesively bonded to the laminate. The diameter of these inserts is smaller than that of the barrel nuts, allowing more bolts to be incorporated within the same blade root circumference. The stress concentrations around such an insert are also greatly reduced, allowing the use of thinner laminates. Therefore, this type of connection is much easier to upscale to larger blades. The principle of this type of connection, developed by WE4CE[1], is illustrated in Figure 18. Failure of this type of connection could occur due to shear-out of the insert. This is prevented by having a sufficiently large surface area (length of the insert), and potentially mechanical interlocking. The inserts are tapered to reduce stress concentrations at the end of the insert.
The stud or insert root joint relies on longitudinal bolts attached to studs or inserts. Typically, the inserts are female threaded and made of steel, causing a thermal and flexural mismatch. Often, the studs are glued into the blade. In wood composite blades, the studs are placed in holes that are drilled, while in glass fibre blades, the holes are preferably formed during fabrication. Positioning of the stud is vital to the quality of the joint as a non-uniform adhesive thickness causes stress concentrations. In general, to provide sufficient pull-out strength, inserts have to be long. Various improvements have been suggested to increase the pull-out strength, allowing shorter, lighter inserts. [18]
Input from the industry suggests that the design with inserts currently performs well from a load bearing/transfer perspective and that this technology provides a solution for the next generation of larger turbine blades.

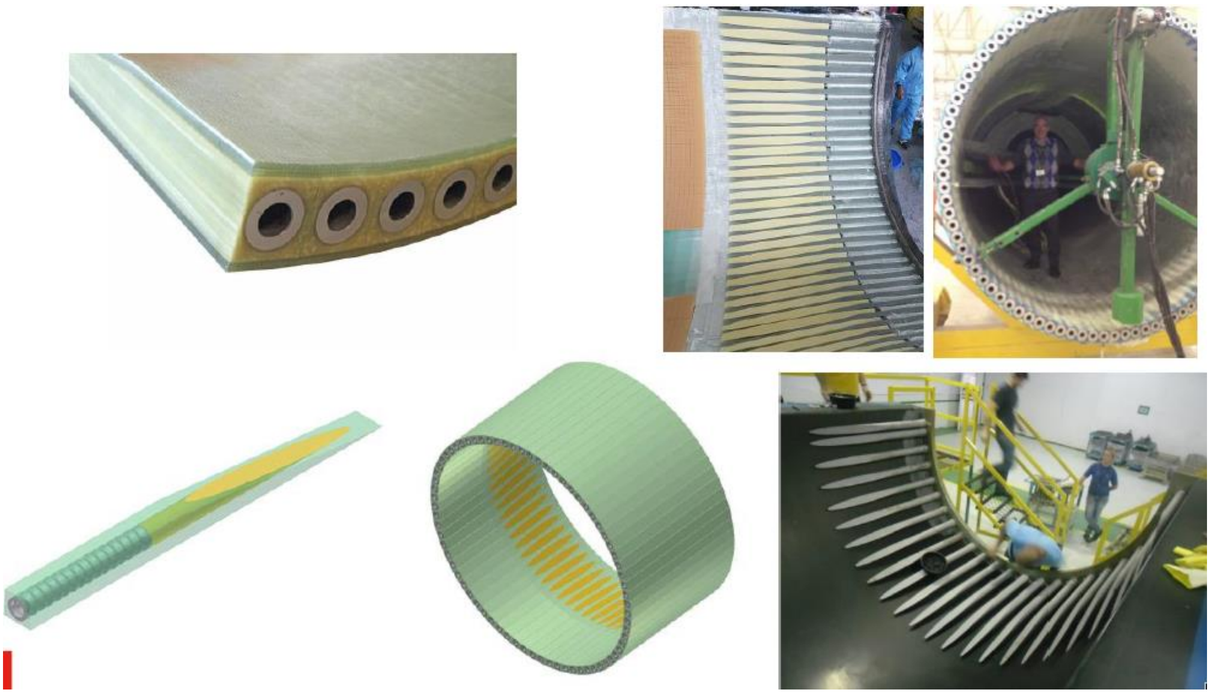


Figure 18: Illustration of the concept of inserts to connect composite blades to the hub. Source: [20], Fiberline, We4Ce.

With longer inserts, larger loads can be transferred from the composite to the steel. With further upscaling of such a solution, the limits of strength of the steel could eventually be reached. Today steel grade 10.9 is used

[1] https://www.we4ce.eu/en/innovations/we4ce-blade-root-connection

for the bolts/studs. It might be necessary to consider ***higher strength materials for the studs***. For designs using T-bolts, this could also open the way to using less bolts and reducing laminate thicknesses.

Inspection of blade/hub connection can also be a challenge. This includes, the condition of the bolts/studs, the pre-load, but also of the composite laminate. For the T-bolt connection this involves inspecting or monitoring the laminate region around the barrel nuts for cracks. For the inserts, the condition of the bond/interface between the studs and the laminate needs to be monitored. Techniques like ultrasound inspection of imbedding of optical fibres could potentially be used to inspect/monitor this interface.

All current blade designs start from the principle that the connection to the root/hub needs to be a detachable connection. The reasons can for example be the need for easy replacement, onshore testing (for which blades need to be attached and detached) and/or easy on-site installation. As such, the choice for mechanical joints is unavoidable. This also brings with it some level of stress concentration and a need for thicker laminates. This can be avoided by using adhesive bonding, although adhesive bonding also has its own limitation and challenges, as discussed in section 4.1.7.

Alternative design concepts have also been presented, where the connection between the blade and hub is moved to another location on the blade where the cross-section is higher. As a result the load that needs to be transferred per unit of circumference is reduced.

Tidal Turbines

Similar design concepts can be used for Tidal Turbine blades. A major difference with respect to wind turbines is the material of choice (depending on the design carbon fibre composites may be used) and the environment in which they operate. Tidal turbines blades are submerged in seawater, which adds a challenge regarding corrosion protection of the metallic parts of the connection (section 4.2.4), as well as bio-fouling. Additionally, preventing water uptake by the composite, particularly at the contact with steel is of great importance (section 4.2.3).
Where the blade is connected to the hub, a pitch bearing may also be present in tidal turbines. This bearing needs to be sealed against water ingress, which can also pose challenge.

4.1.7 Adhesive bonding

Currently, composites are being assembled using fasteners. This represents a huge weight penalty for composites, since holes cut through the load carrying fibres and destroy the load path. Adhesive bonding is the most promising joining technology in terms of weight and performance. However, its lack of acceptance is limiting its application to secondary structures, whose failure is not detrimental for the structural safety. In primary (critical-load-bearing) structures, fasteners are always included along bond lines, as “back-up” in case the bond fails. The main reasons for this lack of acceptance are the ***limited knowledge of their key manufacturing parameters, non-destructive inspection techniques, damage tolerance methodology and reliable diagnosis and prognosis of their structural integrity***.[1]

The use of adhesive bonding could be an option for the structural joint between composite blade sections or the connection between the blade and the blade bearing, as has been discussed in section 4.1.6. Also for non-structural joints, between for example walkway gratings and steel supports this could be an option. In the latter case, use of adhesive bonding circumvents current problems and maintenance costs associated to corrosion of the bolts used to fix the gratings to their steel supports. Furthermore, future developments will likely see the introduction of load-bearing composite components in the structure, for example replacing the steel support for the gratings by a composite support. This avoids corrosion issues. Bonding between composite components using adhesives has great potential to reduce both cost and weight as compared to bolted connections between composite components. Different composite components of a blade which cannot be manufactured as a single part (due to cost or technical constraints) can be bonded using adhesives. As blade sizes increase in wind turbines, the need for joining of components will likely only increase.

Adhesive joints can be structurally efficient, light and inexpensive. They have low stress concentrations and good damage tolerance. [18] However, ***the use of adhesive bonds also present a number of challenges***:

[1] Source: https://www.cost.eu/actions/CA18120/#tabs|Name:overview

- Lack of inherent self-alignment of adhesive joints which makes on-site installation very challenging [18].
- Difficulty of producing a high quality bond on-site compared to under controlled conditions [18].
  - Surface preparation, temperature and humidity affect the quality of adhesive joints.
  - Good control over the bond thickness is important to avoid stress concentrations.
  - Air entrapment can drastically reduce the strength of adhesive joints.
- Because of the large number of factors influencing the quality of an adhesive joint, proper control of the joining process and thereby achieving a high quality joint with good repeatability is still a major challenge. Also for post-installation inspection of the joint to ascertain the quality, there are not many techniques available and no standardised procedures.
- The durability of adhesive joints in a harsh environment is currently not well understood. UV, water, humidity, salinity, etc. can all have a negative impact on the durability of adhesive bonds and little is known about how various adhesives behave in a marine environment or submerged in seawater. An additional difficulty is that the adhesive often loses strength first in regions which are difficult to access or inspect.
- Modelling of large adhesive joints currently still presents a lot of challenges.
- Adhesive bonds are non-reversible, i.e. they cannot be opened and closed in the same way as bolted connections. This has implications with respect to maintenance. For example, if one were to use adhesive bonding to join the blade to the hub, it cannot be easily replaced.

In contrast, mechanical joints for composite blade connections are heavy and expensive, but are fast and easy to assemble. Furthermore, they are easier to inspect but require some maintenance. [18]

The above difficulties related to adhesive joining also make that it is difficult to know what strength and fatigue properties can be allowed in the design phase of adhesive joints. Under a complex fatigue loading condition, there are still a lot of questions on how the non-degraded adhesive behaves. Adding to that degradation due to environmental influences makes a correct estimation of design values even more challenging. ***The lack of understanding and limited research done on this topic so far, may be limiting the market uptake of adhesive bonding.***

Not only the adhesive itself, but also the (mechanical) design of the components to be bonded should be carefully considered. The largest challenges are not necessarily at a technological level, but the fact that end-users, designers and customers are not familiar with how to design a good adhesive joint, especially for large hybrid connections (e.g. steel/composite).

Adhesive Joint Issue		Suggested Remedies
Time of assembly	Alignment of the segments	-Alignment using laser-positioning -Brackets attached to spar cap -Alignment pins -Overlapping portions
	Curing of the bonds	-Resistance heated bonds
Bond-quality	Bond thickness	-Bonding grid -Shims -Producing the segments in a single mold
	Air entrapment	-Flooding of a cavity -Infusion

Table 1: Overview of issues with the use of adhesive joints for segmented blades and the suggested remedies. [18]

4.1.8 Testing and certification

The introduction of innovations in the offshore renewable energy sector, where maintenance costs are very high, is often difficult. Materials and components need to be extensively tested prior to being used offshore, because the costs of remediation in case of unexpected failures is very high.

A number of specific issues with respect to testing:

- A combination of large scale laboratory/workshop testing and field exposure is typically required. In order to reduce the time to market, as well as the costs, accelerated testing is often needed. However, establishing a direct link between accelerated testing and the real lifetime of a material or component is not straightforward.

- There is a lack of standardised accelerated test procedures for connections (bolted, welded, adhesive) in an aggressive environment (corrosion, fouling, UB), often in combination with fatigue loading.
- There is a lack of fatigue test data, especially for large bolts (>M72). Also in combination with corrosion. Standardised test procedures should be developed to approve and certify the use of certain types of bolts, also on full scale.
- Fatigue testing of M36 and M42 bolts is already very expensive. In order to make extensive fatigue testing on M72 bolts and larger feasible (which is required in order to update the design standards), new and cheaper accelerated testing methods will be required.
- Combined testing of corrosion/fatigue. No clear understanding of how corrosion and fatigue loading influence each other, therefore also no guidelines on standardized testing. Fatigue and corrosion can both be accelerated, but processes are taking place on a different timescale and fatigue is accelerated more than corrosion. Therefore, there are questions on how representative the results of such tests are for real exposure conditions.
- Large scale fatigue testing of composites, steel structures and joints is expensive and time consuming.
- The costs for large and full scale testing in a representative environment (i.e. offshore), can be very high. Often funding is not readily available, because these are not necessarily research issues, but can often be classified as engineering challenges.

4.2 Understanding and preventing degradation

Two major types of failure mechanisms need to be considered when designing offshore energy devices [24]:

- for Survivability: Immediate failure caused by exceedance of material ultimate strength, and
- for Durability: Fatigue failure caused by repeated mechanical loads below the ultimate material strength.

Both mechanisms depend on material strength in hot spots in the structure and on external loads. The strength may change as a result of degradation during usage by [24]

- corrosion, changing load carrying material content and geometry,
- wear, also changing load carrying material content and geometry,
- marine growth causing changed mechanical behaviour.

In this section of the report, a number of challenges related to understanding and preventing degradation of joints will be discussed. The topic of adhesive joining has mainly been addressed in section 4.1.7.

It is important to keep in mind that:

1. Costs in offshore operations are very different from onshore. Offshore, needs more reduction in assembly time and has a higher drive to reduce maintenance than in onshore.
2. Many problems have already been encountered in O&G, however the pressure on reducing costs is very higher in renewable energy. There is a perception that some of the solutions which are working well in O&G may simply be too expensive for renewable energy. Relative costs related to offshore inspection and maintenance are also higher for offshore renewable energy, because these devices are unmanned. An objective study of cost of ownership of joining solutions available from O&G should be performed in order to evaluate which solutions from O&G can or cannot be used in the offshore renewable energy sector.

4.2.1 Bolted connections

As is already clear from the previous sections in this document, the bolted connection is a frequently used type of connection. There are bolted connections of different sizes, depending on the components being joined. A lot of questions remain on the degradation and damage mechanisms to which bolts are exposed and how these influence their lifetime.

Understanding bolt degradation and preventing it, are important issues not only for wind energy, but also for wave and tidal. However, there is a clear distinction both in degradation processes and protection needs in the atmospheric zone as compared to splash and submerged zones. The latter two pose a much higher degradation risk and are of major importance to wave and tidal devices, where the entire structure is contained in these two zones.

The issues related to bolt degradation and protection need to be tackled taking into consideration different possible circumstances:

- Installation in submerged vs splash zone vs atmospheric conditions.
- Bolted connections with continuous/frequent usage (i.e. opening and closing of flanges) vs connections checked only routinely (i.e. every 5 or 10 or 15 years).
- Connections between same metals vs different metals vs metal/composite connections.

A number of possible root causes for breaking of bolts have been identified in [21], which is mainly for bolts in ***the atmospheric zone***:

- Fabrication and Installation
  - poor lubrication, ineffective contact between bolt and nut, connection undone
  - improper bolting sequence, uneven stress distribution, stress concentration, overutilization
  - missing washers, improper stress transferral, loosening of connection
- Design: poorly specified pretension force, loosening of connection at one bolt, more bolts to loosen
- O&M
  - excessive loading during testing of bolts, exceeding elastic limit, loss of pre-load
  - insufficient sealing against water through grease caps, corrosion
  - internal climate control broken, high humidity, corrosive environment,

In the submerged zone, other risks can be added to this list, such as a risk of hydrogen embrittlement when combined with cathodic protection, especially if higher strength bolts are used. Also the risk on corrosion mechanisms like crevice corrosion, pitting corrosion and stress corrosion cracking is increased. To manage the risk of for example stress corrosion cracking, bolts can be overdesigned in order to reduce the stress levels. However, this again introduces unwanted additional costs. ***A better understanding of the risks, possible failure modes and alternative solutions, should allow to optimise designs and reduce costs.***

Also for joints within subcomponents, the challenges related to bolting play an important role. For example, direct drive machines require very large welded structures to support the generator. These are become so large, that the support structure will have to be split in sectors and joined with bolts. Also here the issues related to flatness tolerances, pre-loading and fatigue degradation play a role.

4.2.2 Pre-load

Importance of pre-load

In order to increase the fatigue life of bolts, they are pre-loaded to a high percentage of their tensile strength. If the bolts are loaded correctly, they only experience a small percentage change in load as external loads occur, and the fatigue life of the bolts is practically infinite. If the pre-load reduces over time, this will drastically reduce the fatigue life of the bolts. That's why the installation tightening procedure and achieved pre-load are so important. [19] If a too low or high load to the bolt is applied during new construction or maintenance, it will lead to a direct influence on the fatigue life of the bolts in the operational phase, resulting in a loss of load or, worse, bolt failure. [22] Over 90% of all bolted joint failures can be attributed to low bolt tension on installation tightening. Achieving and maintaining the correct installed design load will eliminate failures.[1]
Offshore wind parks are still relatively new, and the first wind turbines had larger safety margins built into the design. Since wind turbines are getting bigger and heavier, the safety margins become smaller. With a 70% spread in load, it is assumed that a wind turbine will not achieve its expected lifespan of 25-30 years without costly repairs or bolt replacements. Most companies in the offshore wind industry are now aware of the fact that the quality of the bolted connections is a serious concern. [22]
When the bolts are installed and maintained at the correct load, less maintenance is needed and they do not need to be replaced at a later stage. When the old school torque procedures are used (for example the DASt norm), the bolts in the flange connection will experience enormous fluctuations in loads (see also section 4.1.1) and should be replaced once every 2-7 years. [22]

[1] Source: https://www.rotabolt.co.uk/

Applying and maintaining the correct pre-load

There are two main categories of bolt pre-loading: torque methods and tension/pull methods. In the torque method, the load is applied by rotating the bolt to a certain degree. In the tension methods, a load is applied axially by gripping one or both ends of the bolt and pulling on it. Within the torque methods, various mays of controlling the pre-load exist. The control variable may be the applied torque, the rotation angle or a combination of both. The latter is also called yield control tightening, because if the measured rotation increases with a reduced increase in the torque, this means the bolt material is yielding.

The quality of a bolted connection depends very much on the load in the bolts. Torque wrenches are not a good way to achieve or determine the correct load. In fact, torque (in Nm) and load (in kN) have no direct predictive relation to each other. Using torque tools, the wrench stops when the bolt or nut offers a certain resistance. In the laboratory, the resistance of each bolt seems the same, but there may be up to 40% deviation, which in offshore practice can lead to a spread in bolt tension up to 70%, affecting the entire flange. [22]
It is generally accepted that applying pre-load to the bolt in an accurate and repeatable way should be done using tensioning tools rather that torque tools. However, most tensioning tools require longer bolts (access to the bolt thread is required to apply the tension), and sufficient space around the nut to operate.[1] Where access is more restricted, torque tools are often the only solution. In order to be able to tension all bolts using tension tools, ***the space required to operate these tools needs to be taken into account in the turbine design stage***.
Applying pre-load correctly is a slow process and requires the use of heavy and cumbersome hydraulic equipment within the nacelle (during installation and maintenance operations). Hydraulic power packs and hoses are difficult to use in the often confined or difficult to reach spaces in the turbine. There is also a risk of spilling of hydraulic fluid. Work is being done on the development of new tools to apply pre-load easier, faster and with fewer people, such as the development of electrical tools. Electrical tools are also faster to deploy than hydraulic tools, which is of great importance to the Offshore Renewables Sector.
Electrical wrench tools are already on the market, but do not yet provide the same level of accuracy and repeatability as hydraulic tools. It is expected that this technology will continue to develop to improve accuracy. Another solution could be to monitor the load in the bolt itself instead of through the installation tool. No indications were found for the existence of electric tension tools.
The key to developing successful installation and inspection tools is that they need to reduce assembly and maintenance times and provide a closely controlled and homogeneously distributed pre-load.

In addition to the technology used to apply the pre-load, also the procedures of tightening and load spreading are important [22]. This involves for example the order in which bolt tightening is done, whether or not several bolts can be loaded simultaneously, etc. Pre-loading a bolt will change the pre-load of adjacent bolts. As a result, the pre-load may be non-uniform along the circumference of the flange. Therefore, in order to have a high quality of pre-loading and knowing the exact pre-load, a pre-load measurement system should be used during installation. ***It is yet unclear what the impact of different pre-loading methods and devices is on the homogeneity and loss of pre-load.***

The design calculations of the flanges clearly indicate what the required pre-load is. However, the procedures to apply, verify and maintain the pre-load are not yet clearly established. In case of a lack of installation guidelines or unclear guidelines, there can be a lot of uncertainty from the very beginning of the lifetime of the bolt.

- When using torque tools, use of type and amount of grease can influence the achieved pre-load, as well as the environmental conditions under which the bolt was installed. Presence of water can affect the lubricant of the nuts, leading to increased friction in the contact surfaces of the joint[2] and a different pre-load.
- It is not always clear how pre-load was measured (torque or tension). If torque is measured, it is not clear if the required tension is also achieved. And if measured directly, there can be a question about whether the tension was measured correctly. The latter is related to proper training of personnel. Considering the importance of pre-load and the cost of maintenance in offshore installations, highly trained personnel should be and are used in this sector.

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[1] Source: https://www.enerpac.com/en-us/training/e/tensioning
[2] Source: http://www.windaction.org/posts/46369-vestas-wind-turbine-collapse-in-lemnhult-sweden#.XY4dL0YzaUk, consulted in October 2019.

- For older installations, it is often not known whether the bolts were installed with the correct pre-load. In new installations, it seems that constructors and owners have realised the importance of pre-load and greater care is being taken to correctly install bolts and measure pre-load after or during installation.
- During installation of the bolts, the structure is already subjected to external loads. It is unclear to what extent these external loads influence the measured pre-load, and when the external loads are removed or change, how this influences the pre-load on the bolt.

Also during maintenance, there is source of uncertainty. If bolts loosen, and are replaced and/or re-loaded, it is unclear if and how many of the neighbouring bolts also need to be inspected. This brings with it a high cost, so economic considerations factor into the decision process.

Pre-load is a major concern for all bolted connections exposed to fatigue loading. The challenges outlined above are therefore not unique to wind energy applications. Although the current WEC and TEC devices may not have been in operation for long enough for serious issues to have surfaced, also for these technologies, maintaining pre-load under fatigue loading will be a challenge[1]. Many developers are well aware of this importance and take great care in the design of the connections, for example by using longer bolt lengths. This is especially true for permanently submerged devices, where inspection is practically impossible.

Loss of pre-load

Both literature sources and contacts with various stakeholders confirm that loss of pre-load is currently one of the major issues concerning bolted connections for wind turbines (both on and off shore). In order to maintain pre-load in the bolts, they need to be regularly inspected or monitored to determine the load in the bolts, and if necessary maintenance needs to be scheduled to perform re-loading or replacement. This brings with it high costs.

During the first day after pre-loading, bolts can lose 10-15% of the applied preload. This can for example be due to temperature increases during tightening, followed by the temperature decreasing again. Over time an additional 10-20% or more may be lost. ***The root cause of loss of pre-load is still not fully understood. It is not clear under what circumstances and how fast bolts lose pre-load***:

- Does creep of coating materials influence loss of pre-load?
- Do temperature variations introduce loss of pre-load? (There is evidence that bolts need to be re-loaded much more frequently in cold climates.)
- How does corrosion influence pre-load?
- What is the influence of the use of grease?

A major issue is also the collection of data about bolts, pre-load, loss of pre-load, failure rates and failure modes. A thorough investigation of the mechanisms behind loss of pre-load, the time on which pre-load is lost and the impact of loss of pre-load on a system level (the entire joint) could help to establish guidelines and good practices for design, installation procedures and maintenance of bolted joints. ***However, there is currently insufficient data available to perform such a study.***

What problem owners essentially want is a 'maintenance free bolt', that doesn't lose pre-load. After a period of testing and certification, this could greatly reduce the maintenance costs by reducing costs associated to inspection, monitoring and re-loading work. In particular for the bolted ring flange connections, several R&D programs are running on the development of maintenance free bolts. In a JIP, led by DNV-GL, a definition of what a maintenance free bolted joint is has been established, along with what the checks are that need to be carried out to determine whether a bolted joint is indeed maintenance free (JIP 'Integrated Design, Installation and Maintenance of Bolted Joints'). A major concern is the occurrence of corrosion. In corrosive environments, bolts may never become completely 'maintenance free'. For example, for the MP/TP connection to date, no flawless anti-corrosion system has been found yet.

4.2.3 Fatigue performance

Fatigue performance of materials in the harsh marine environment is not well understood. This is also true for bolts, and other types of joining like ***adhesive joining***. The interaction with the sea water is especially important

[1] Source: https://www.nord-lock.com/nl-nl/insights/customer-cases/2017/converting-sea-wave-motion-into-energy/, consulted in October 2019.

for the MP/TP connection of wind energy devices and for tidal and wave energy, as these devices are closer to the water (i.e. submerged or in the splash zone).

The design is nowadays very conservative, based on old standards and fatigue information. It is expected that there is significant margin to reduce costs by optimising new designs, based on more accurate information about the fatigue life of bolts, composites and adhesives in a sea water environment. For example, using higher strength bolts could reduce costs, but is limited because of a lack of standardization. In terms of fatigue lifetime, not only the interaction between corrosion and fatigue loading is of concern, but also the fracture toughness of the material and behaviour under low temperatures.
Research is needed on ***service life assessment of bolted joints*** (including fatigue and effect preloading of bolts)

- Effect of corrosion on the fatigue strength of bolts
- Effect of corrosion on preloading and load distribution
- Monitoring preloading
- Effect of structural imperfections on fatigue
- Effect of loss of pre-load on service life

The ***fatigue performance of the composite materials***, submerged in seawater is also not fully understood. Fibre reinforced polymer composites are prone to moisture uptake, which reduces the fatigue lifetime. Especially around the connection between the blade and the hub this can be an issue. In general, composite materials are coated to prevent or limit the uptake of water. However, around the composite steel/interface this can be challenging, especially if holes need to be drilled in the composite laminate.

4.2.4 Corrosion

Corrosion of the joint between components can be an issue in the aggressive offshore environment. A distinction can be made between joints on the inside of devices, and those on the outside. The atmosphere inside the devices is generally conditioned to reduce humidity and chlorine contents. As a consequence, corrosion is often not a severe issue in these locations. On the other hand, joints which are outside of this conditioned zone, are exposed to the aggressive marine environment and are at a higher risk of corroding. Horizontal flanges are also of greater concern than inclined flanges, as water may accumulate on these flanges.

For wind turbines, this means that no indications of major corrosion issues where found for the bolted connections between tower sections or for bolted connections within the nacelle (this includes the bed plate to yaw bearing to tower assembly). Two major joints which are exposed to more aggressive conditions are the MP/TP connection and the blade to hub connection. When the MP/TP connection is a bolted flange, corrosion may be an issue. This is addressed further on in this section of the report.
The blade to hub connection is an external connection. However, no corrosion issues for this joint have been identified by the current authors. To some extent, this connection is protected by a shroud. The combination with corrosion resistant bolts/studs (typically double-dip galvanised and finished with a Ni-base coating) appears to be sufficient to prevent corrosion.

For tidal devices, external connections are either submerged or in the splash zone. The latter is of concern for floating devices, not for bottom fixed installations. The two types of connections which are of most concern are large (external) flanged joints and the composite/steel hybrid joint when composite blades are used. Both are addressed in more detail in this section.

The first concern is to avoid the occurrence of corrosion. Depending on the situation and the type of corrosion protection used, it can be difficult to inspect for corrosion (for example under non-transparent coatings). ***If corrosion does occur, issues with respect to quantification are raised. I.e., how much corrosion did occur, how much does it increase from year-to-year and what is the impact on the (fatigue) strength of the joint. Answering the latter question could allow to determining and hopefully reduce inspection frequencies and to decide whether a corroded components needs to be replaced immediately or whether it can wait to the next scheduled maintenance.***
A problem in answering these question is that corrosion of bolts is not well understood:

- What are the relevant local corrosion mechanisms (does stress corrosion, pitting, crevice and/or uniform corrosion occur)?
- What are the associated corrosion rates?

- Are bolts susceptible to hydrogen embrittlement, including various types of bolts and strengths (possible sources of hydrogen are cathodic protection, MIC, hydro-carbon based grease, etc.)
- Is MIC an issue for bolted connections (and in what applications/environments)? If MIC is an issue, how can it be prevented?

The type of corrosion and the corrosion rate depend on many different parameters, application and environmental conditions, material properties, stress and strain effects and effectiveness of the protective measures. The focus on corrosion resistance of fasteners is increasing as the commercial aspects of having corroded fasteners are pushing towards smarter solutions. [11]

Another topic is corrosion of major component interfaces. Some examples are:

- In the nacelle, many major components have lubrication systems, such as the gearbox and main bearing. When replacing or maintaining these components, corrosion is sometimes seen at the interfaces, which can lead to lost time during remedial works. Components may need to be lowered to a jack-up vessel and polished before being re-fitted. No solutions have been offered for this to date.[1]
- Corrosion of the hydraulic systems for yaw and pitch movement on offshore turbines can be an issue. Especially the threaded connection by which the hydraulic system is connected to the turbine is susceptible to corrosion. This is a challenge for hydraulic system manufacturers, who are looking for solutions with a long lifetime in order to meet the requirements of the turbine manufacturers.[2]

Corrosion at the MP/TP Interface

To date, no flawless corrosion protection for MP/TP flange has been found. The MP/TP flanged connection is typically protected from corrosion by the application of a seal in combination with barrier coatings. An example is shown in Figure 19. There is evidence that the seal (in various designs) is unable to fully prevent ingress of moisture, leading to bolt corrosion and hydrogen embrittlement (see 4.2.5). This is possibly linked to the large loads exerted on the joint. Water ingress could be an issue for many L-flange designs, because the connection may open and there may not be enough pressure to provide sufficient sealing. The seal is typically close to the wall, while the bolts are in the flange itself. As a result, tightening the bolts tends to result in a small opening of the part with the seal. There are also questions as to whether the seals can withstand the large loads in combination with salt water (and sun if you take away the skirt and grout seal).
In other offshore sectors, there is ample experience with this type of sealing of bolted connections. Testing and evaluation of different designs to effectively seal the joint for a 30 year lifetime would help to standardize the way in which flanged connections are realized and reduce maintenance costs.
The bolts used in the MP/TP bolted flange are typically hot-dip galvanized. It seems that so far, this has provided the best corrosion resistance, with other types of coatings also tested. However, galvanizing also introduces a risk of reducing the mechanical properties (H-embrittlement issues). If other types of efficient coatings could be found, maybe smaller bolts could also be used (smaller, cheaper, faster).

At a corrosion workshop organised in Ghent, Belgium, by the Innovative Business Network for Offshore Energy[3] and the NeSSIE project, a number of additional challenges with respect to the bolted MP/TP flange were put forward:

- How to inspect and monitor bolted flanges at the MP/TP for the occurrence of corrosion, without having to remove each individual bolt, as this would be a costly and time consuming operation?
- How to monitor corrosion in bolthole MP/TP connection without removing the bolts?
- How to quantify the amount of corrosion on the MP/TP bolted connection? It is not enough to answer the question ‘Is there corrosion?’, the question ‘How much corrosion is there?’ needs to be answered.
- What are the optimal materials and/or coatings to prevent corrosion? The flanges are normally coated, but during use, vibrations and applied forces can cause slight displacements of the flanges with respect to one another, resulting in coating damage. In new designs, the flanges are often metallized. This appears to be a good solution. Is it the best solution?
- What types of grease can be used or may help to prevent corrosion?

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[1] European NeSSIE project, ‘Taming NeSSIE’ – International conference on Anti-corrosion solutions for Offshore Renewable Energy, *the Offshore Wind Industry: SSE’s story*, January 24, 2019.
[2] Input from industry experts, Tecnalia.
[3] http://www.offshoreenergycluster.be/

It should be stressed that the problem is not always the bolt itself, but concerns the entire flange assembly. Corrosion at the interface between two flanges has also been observed. The contact point between flanges is often an initiation site for crevice corrosion.[1] There are possibly also issues with the seal, as discussed above.

In all cases, there is a need for corrosion protection systems that still allow easy inspection of the bolted flange (see also below). This is important, because it has to be possible to assess the integrity of the structures at all stages of the lifetime. This includes visual inspection (for example with transparent coatings), but may also involve more advanced inspection techniques like ultrasound to quantify corrosion. Finally, there is also a link to pre-load: How to inspect/monitor pre-load when a barrier coating is applied over the bolt/flange assembly?

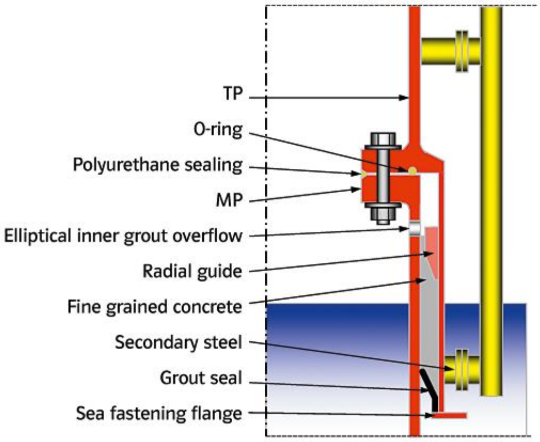

Figure 19: Schematic Illustration of concept Amrumbank connection TP to MP [16]

External flanged joints

External flanged joints are bolted flanges which have their bolts on the outside of the device. This type of joint is avoided as much as possible, due to the higher risk of corrosion associated with it, but is sometimes unavoidable. Examples are:

- Bottom fixed tidal turbines where section of the device such as the nacelle and gearbox are connected using external flanges.
- Yaw systems of tidal turbines.
- Lifting cranes on the exterior deck of wind turbines.

A lot of the issues discussed in the section on 'Corrosion at the MP/TP Interface' are also of relevance for the external flanged joints. In the following a few points will be elaborated further.

Corrosion protection of bolted flanges or other connections from corrosion can be performed by completely sealing them off from the environment. For submerged bolted connections, cathodic protection can also be employed. In this case, special consideration needs to be given to the evolution of hydrogen at or near to the bolt assembly, which can cause hydrogen embrittlement of the high strength bolt (see section 4.2.5). Also the effectiveness of cathodic protection to prevent crevice corrosion needs to be considered.

A specific issue presents itself when it is necessary to get access to the joint, for example for inspection, or because they need to be opened for maintenance or component replacement. As an example, the flange connection between nacelle and gearbox in certain TEC designs can be considered. In order to open the connection, the applied protective coating/sealing needs to be removed and re-applied afterwards. Often, the corrosion protection after re-applying, is not as good as on the primary protection. This is especially true when the coating is re-applied on-site or on service vessels, under non-ideal conditions (humidity, salinity, temperature). Various corrosion protection solutions for joints that need to be opened and closed exist, at different stages of commercialisation. End-users are however often not aware of their existence, or unwilling to invest in these often more expensive solutions, because the total cost of ownership is not clear. By comparing various solutions (including 'traditional' coating), and evaluating the total cost of ownership, the most

[1] Input from industry experts.

appropriate solution could be identified. While this is a general concern, it is of special concern to WEC and TEC devices which are either submerged or have topside completely exposed to the splash zone.

Most problems are related to bolted connections with larger bolt size (> M30). Smaller bolts seem to present less issues in terms of corrosion protection. There is also a question with respect to ***durability of O-rings in large connections***. Design lifetime are on the order of 25 years. Although it is expected that O-rings can survive these 25 years, such a long lifetime is generally not guaranteed. This means they need to be inspected at some time during the lifetime of the device, and possibly replaced. The solution would be to develop O-rings with high durability and methods to test and certify their lifetime. Alternatively, O-rings which can easily be inspected and or replaced could be used. On this topic, there is a lot of expertise from the Oil&Gas sector which could be tapped into.

Joining of dissimilar metals

When joining dissimilar metals, galvanic corrosion is an issue. Various solutions to deal with this exist, for example from experience in O&G. However, these solutions may be too expensive to be used in renewable energy devices, where there is a much bigger drive on cost reduction. As a result, tidal and wave developers need to spend more effort on for example the design of an effective cathodic protection system. ***There is a challenge both with regards to awareness raising and finding or developing more cost-effective solutions.***

Corrosion at composite/steel connections

With optimising the use of different materials for different components, also comes the consequence that dissimilar materials need to be joined in some locations. The most important example is the composite/steel hybrid joint. Although steel inserts in the composite laminate may be well protected inside the material, other steel elements in the joint may suffer from corrosion.

Crevice corrosion of stainless steel at the interface with glass fibre composites is a known issue. Crevice corrosion is likely to occur when the parts clamped by stainless steel bolts/nuts contain non-metallic materials like polymer composites. The phenomena can occur when moisture is present in a small crevice and can lead to a highly corrosive microenvironment, especially in combination with the presence of chloride ions. Known solutions for this issue are correct material choice for the bolt/nut, using grease/wax to protect the interface or complete sealing of the joint interface. For TECs and WECs, where composite/steel joints may be submerged, this issue of corrosion may be even more severe, this includes stainless steel corrosion in sea water. Popular materials like 316, are susceptible to pitting and crevice corrosion when exposed to sea water.

Another challenge is presented when using carbon fibre composites submerged in seawater, as is often used for tidal turbine blades. ***Carbon fibres are found in the galvanic series amongst the most noble metals. When in contact with steel, even stainless steel, galvanic corrosion of the steel can occur and lead to rapid failure.*** Different methods to prevent this type of corrosion are being applied, with varying levels of success. Possible solutions include:

- Apply cathodic protection to the steel. A disadvantage with this approach, which is often used in submerged conditions, is that it has been shown to lead to cathodic disbondment at the composite/steel interface.
- Preventing electric contact between the carbon fibres and the steel.
    - A sufficiently thick polymer layer at the edge of the laminate.
    - In case of a hole drilled in the laminate in which a steel insert is placed, coat the edges of the hole with a barrier coating.
    - Have an insulating layer of glass fibre laminate in the region of contact with the steel. A disadvantage with this approach is that the region in contact with the steel is often the region of highest load transfer, where the strength of the carbon fibre is required. Also in regions where there is a risk of the joint interface getting wet, this solutions may not suffice. Moister uptake by the polymer may result in enough conductivity to cause corrosion and/or cathodic disbondment.
- Prevent closing the electronic circuit through the electrolyte, either by completely coating the carbon fibre composite with a barrier coating, or the steel.

What the best approach is to preventing corrosion and cathodic disbondment when using carbon fibres is likely to be application dependent and an important challenge to be addressed. There is currently still a lack of understanding regarding the corrosion behaviour of combined metal/composite components.

Combined corrosion-fatigue

Corrosion may lead to nucleation and/or accelerate growth of fatigue cracks. There are two ways to deal with this:

- Use fatigue strength curves that take this effect into account in the design stage.
- Prevent corrosion, allowing to use less conservative design curves.

Fatigue strength curves should be developed for unprotected, free corroding bolts in seawater. Additionally, the effect of protecting bolts against localised corrosion should be evaluated. As mentioned before, the entire flange assembly is of concern. As such there is also an interest to investigate the influence of corrosion on pre-load.
If the clamped material corrodes, this will, from a bolting perspective, increase the risk of loss of preload that could result in premature fatigue failure. On the other hand, if the bolt assembly would corrode, this could result in corrosion fatigue of the bolted assembly. The solution to minimize the rate of corrosion is to choose a coating which is equivalent to the corrosion protection system of the construction. [11]

Socket of easy-lift Tidal Turbines

Some bottom fixed structures, utilise a unique joint type between the foundation and the nacelle to allow easy recovery of the nacelle. The foundation has a large socket on its top, on which the nacelle can be lowered and is kept in place (either by gravity alone or in combination with a fixture). The nacelle has a large pin/protrusion at its bottom, which slides into the female type socket on top of the foundation. A major concern here is protection of both sides of the connection against wear/damage during installation and subsequent corrosion. As the nacelle with its pin is lowered into the foundation socket, the pin can impact the socket. Any corrosion protection coatings that were applied are at risk of being damaged and subsequently corroding.

Corrosion protection of mobile joints

Wave and Tidal devices may have mobile joints to allow relative movement of two components. Because these joints are either in the splash zone or submerged, protection of these joints against corrosion poses an additional challenge, because the movement introduces a wear component. Solutions for these types of joints exist from the O&G sector, but often involve the use of expensive materials and/or coatings. ***The challenge for offshore renewable energy, is to find solutions which are more cost effective in order to reduce the LCoE.***
An example of this type of joint is a pin-joint. The pins can be made from stainless steel or carbon steel with a stainless lining. However, also stainless may degrade in seawater, unless more expensive grades are used. Another solution might be to use carbon steel with a very hard coating.

4.2.5 Hydrogen embrittlement

Issues with the flange connection between MP/TP during construction and first year of operation have been reported, with significant numbers of broken nuts reported. There is reason to believe that hydrogen embrittlement is the cause of observed nut fracture at the MP/TP connection. The MP/TP joint is typically sealed to prevent ingress of moisture between the flanges and into the bolt/nut assembly. This means that the sealing of the joint is likely not entirely reliable. Apart from issues with hydrogen embrittlement, this could also cause general corrosion issues.
Other sources of hydrogen also need to be considered, such as the degradation of grease due to vibrations, and hydrogen coming from the cathodic protection of the MP foundation. While it is generally assumed that the steel of the foundation itself is not subject to hydrogen embrittlement (low strength steel), this is not the case for the high strength steel used in bolts and nuts. Especially galvanized bolts and nuts are at risk of hydrogen embrittlement, because of the possible introduction of hydrogen during the galvanization process. However, to date, galvanized bolts remain the standard because no other solutions provides the same level of corrosion protection for a low cost.
The combination of a hydrogen source, tensile loads, material choice and the condition of the material, leads to failure. ***The challenge is to understand the failure and source of hydrogen, and prevent future issues.***

Whether or not there is a risk for hydrogen embrittlement will be application and situation dependent, e.g. different for wind and tidal devices. Submerged systems are typically protected using cathodic protection. As a

result there is a risk on hydrogen evolution. Therefore, lower strength bolts (grade 8.8) are typically prescribed for submerged applications.
If there is a risk, it may be difficult to ***predict/model the reduction in lifetime due to (a risk on) hydrogen embrittlement***. In combination with monitoring of moisture and hydrogen levels this may be possible. However, it is likely that a great deal of research is still required to answer these questions.

4.2.6 Reliability database

For offshore wind energy devices, a vast amount of information already exists on the operational performance of different types of connections or design variations of the same type of connection. This data is generally owned by companies and not publicly shared, because data can be of great commercial value. While a lot of work has already been done on analysing (large) subsets of data (for example in the ROMEO project), a structured and centralised repository of operating and reliability data could help to move to a standardised design of large joints, based on the objective evaluation of different design approaches. However, this brings with it issues related to IP and confidentiality of data. Examples on ways to approach this challenge are DNV GL's Veracity portal and the OPERA project (for wave energy).
In contract to offshore wind energy, the amount of data available on the reliability of tidal energy and especially wave energy devices is very limited. Individual developers or companies do not have sufficient data in order to perform statistical analyses or compare various solutions. Collaboration and data sharing on a larger scale could help to more quickly advance these technologies to successful market integration.

A reliability database, combining information on different types of designs, environmental and use conditions could be build up in order to feed information into the design of the next generation of offshore renewable energy devices. Some examples of what could be included in such a database (not necessarily limited to joints):

- Used corrosion protection measures
- Applied pre-loading on bolts and methods of pre-loading
- Time to loss of pre-load on bolts
- Observed failures and failure modes
- Cost and frequency of maintenance/replacement

Making operational data publicly available, would also facilitate cross-sector learning and avoid the same mistakes from being made in new designs of for example wave and tidal devices. Additionally, such data could be used by start-ups, research organisations and established companies developing new tools/services to reduce O&M costs, such as for example through monitoring solutions.
Finally, making such data publicly available and applying AI techniques to large amounts of operational data could help to identify which are the most costly failure modes and critical areas of devices, where there is potential to reduce the LCoE.

There are already some initiatives in wave energy, like the WES Knowledge library[1]. Also the newest update of ETIP Oceans Strategic Research and Innovation Agenda[2] mentions plans for an open-data repository. The focus of this initiative should be on developing a structured databases, in order to increase the usability of the data for design optimisation, O&M, etc.

4.3 Inspection and monitoring

Inspection and monitoring is an important topic of development, with the aim of reducing O&M costs, evaluating the integrity of devices and optimizing future designs. This is relevant for many elements of the offshore energy devices, also for joints. For the purpose of this report, inspection is considered as requiring manual intervention (i.e. someone needs to go on-site), whereas monitoring can be done from the control room (or anywhere with computer access) using remote sensors.

This topic has already been brought up in the ADMA Energy Analysis and Priority Setting analysis in the beginning of 2019 [5]. There it was stated that the reliability and survivability of ocean energy devices can be improved by developing monitoring systems for real conditions and identifying potential failure modes to subsequently improve designs. The ***development of new tools and sensors for condition monitoring systems, along with***

[1] https://library.waveenergyscotland.co.uk/, consulted on 27/11/2019.
[2] Draft report presentation, Live Webinar, 27/11/2019.

O&M models to improve predictive and preventive maintenance processes, was indicated as a priority. The latter element clearly indicates that it is not sufficient to develop sensors and measurement devices. The necessary knowledge, algorithms and computer models to interpret and use the data need to be developed simultaneously.

It is also important to think about a back-up plan if the monitoring system fails, especially for critical components on remote and hard to access assets. Is there secondary data that can be used to analyse whether failure of the monitoring system is linked to critical failure of the device? How long can the monitoring system be allowed to remain out of operation? Should redundancy be built into the system?
An analysis of integration cost should also be performed for on-site testing in order to quantify expected benefits. Once, the system is proved satisfactory in real conditions, and cost-efficient, then it can be deployed on commercial devices. [21]
Monitoring can be expensive, therefore hotspots to be monitored should be defined using finite element calculation. Such calculation would also provide valuable information on the operating range of the sensors that should be chosen. [21] Sufficiently accurate FE models and software that are capable of correctly predicting possibly strongly localised 'hot zones' will be required to accomplish this. Existing operating data should also be used to identify critical zones and possible failure modes in order to engineer an efficient and effective monitoring system. Such data is not easily publicly available, making cross-sector learning more difficult. (See also section 4.2.6.)

Joints of interest to be monitored in off shore wind turbines, as identified in the Romeo project [21], include the MP/TP grout connection, the integrity of the connection between the jacket legs and the pin piles, bolted connections in general and the tensioning of the TP-tower bolted connection in particular. As an additional element, the composite/steel joint at the root of the blades could be added.
The technology developed in wind energy for monitoring of bolts and composites could potentially be introduced in ocean energy (wave and tidal) devices. Currently the most advanced wave and tidal technologies are entering a (pre-)commercial stage with increasingly long deployment times and are therefore also starting to consider the implementation of remote monitoring technologies in order to assess the structural integrity without a need for manual inspections. Additionally, by monitoring how current designs behave, future designs could also be optimised.

4.3.1 Bolt inspection and monitoring

Bolt inspection and monitoring is focussed on two major aspects: pre-load and corrosion. More detailed investigations into the structural integrity may also look for the presence of fatigue cracks or other faults but are not part of routine investigations and O&M practices.
Inspection involves an inspector going on-site, whereas monitoring utilises sensors or devices that can measure or perform inspections without the need for on-site manual intervention. While inspection is a concern for all marine devices, monitoring is currently only being considered by the more mature offshore wind sector. However, developments in the offshore wind sector can evidently be transferred to wave and tidal devices, where the business case for monitoring may be even stronger due to the often increased difficulty of inspection (depending on device design).

The biggest concern for offshore wind is currently to guarantee the pre-load on all the bolts, as this has a major impact on the fatigue lifetime of the bolts. Questions relate to:

- Finding the ideal combination of inspection and monitoring tools,
- Determining the correct inspection interval and strategy in order to reduce the amount of inspections (cost) without compromising safety and structural integrity,
- Checking whether design assumptions are being respected.

Specifically for bolts and bolted connections at MP/TP interface, the issue of inspection/monitoring of corrosion presents an additional challenge.

Load inspection/monitoring

Pre-loading a bolt will change the pre-load of adjacent bolts. As a result, the pre-load may be non-uniform along the circumference of the flange. Therefore, in order to have a high quality of pre-loading and knowing the exact pre-load, a pre-load measurement system should be used during installation. Various techniques for measuring the load in bolts are available [16, 21] at different stages of development/commercialisation:

- Strain gauge mounted on the body of the bolt
- Centric applied strain gauges
- Ultrasonic based method (the velocity of the ultrasonic waves depends on the axial load in the bolt)
- Vibration-based damage assessment of bolted structures. Post-processing of vibration signal is complex and it can be difficult to detect bolt looseness using this technique.
- Acoustoelastic effect based method
- Piezoelectric active sensing method
- Piezoelectric impedance method.
- Load measurement washers.

While these systems can be used for inspection, it may be difficult to use such systems as monitoring systems, especially if frequent recalibration or maintenance of the measurement systems is required. It might also be very expensive and not cost-efficient to monitor all bolts [21]. ***One of the main issues when dealing with bolt monitoring would therefore be to determine which bolts should be monitored.*** This is a topic under consideration in the ROMEO project [21]. The question also remains, whether monitoring of subset of bolts will give sufficient information for risk management, i.e. whether loosening of non-monitored bolts can be detected with sufficient accuracy.
Many organisations are working on developing and testing various pre-load measurement devices. However, there is ***no consensus as to which technologies work best in terms of cost, accuracy, handling, etc.*** One question which needs to be considered is whether it is cost-effective to incorporate monitoring/measurement devices in the bolts/washers, or if this should be limited to load measurement installation tools.

An additional element of consideration mentioned in [16] is that not all measurement methods may be able to deal with bolt bending as a result of non-perfect flanges. This remark was aimed specifically at the development of stable ultrasonic bolt force measurement suitable for bolt bending up to min 1-2%, but is likely to also be applicable to other techniques.

Bolt loosening, when reaching a certain extent, can be responsible for a slack between the two parts, which could, possibly, induce a change in vibration properties of the structure. Hence, a good solution to detect a possible bolt-loosening would be to perform a vibration or modal analysis of the area of concern in order to detect a deviation from the original state, using accelerometers. This would, be much less expensive than installing bolt-loosening monitoring systems on bolts. However, once again, other phenomenon might interfere and it could be interesting to install two systems, e.g. bolt-tension measurement and accelerometers, for comparison and to have a better understanding of the physics. [21]

Assuming that either individual bolts or entire bolt assemblies can be monitored, ***a real challenge also remains in correctly interpreting the data in terms of structural integrity***. Large amounts of data need to be analysed. This will involve the development of a combination of FE models and/or Artificial Intelligence based algorithms.

A number of practical challenges with respect to monitoring have also been identified:

- Wireless monitoring of bolted connections is a challenge: making a wireless, battery based connection work, that is robust enough to survive harsh offshore conditions, with acceptable costs.
- Specifically for wave and tidal devices, monitoring of bolts in submerged conditions presents a challenge.

Using the data from inspection/monitoring of bolts is not only valuable in order to plan O&M activities, but also to optimize the joint design itself. Additionally, an improved joint design may also contribute to optimizing the surrounding structure. E.g. change of the hub design, reduction of safety factor on other components, etc.

Corrosion inspection and monitoring

Specifically for the MP/TP bolted joint of wind turbines, inspection and monitoring of corrosion has also been raised as an issue. This is a challenge which may also be transferred to wave and tidal devices as the operational periods become longer and the effects of corrosion become more sever.

Inspection of bolts in the MP/TP connection for corrosion is expensive and labour intensive, as bolts need to be removed in order to visually inspect the bolts. Additionally, it is difficult to quantify the amount of corrosion on-site and even more difficult to evaluate the year-by-year evolution. In case corrosion is observed, current practise is often limited to making a photo-report and replacing the affected bolts. The challenge can be summarised in the following question: ***How to quantify corrosion on the MP-TP bolted connection without loosening every bolt?***

Techniques for monitoring corrosion of bolted joints are still in an experimental phase. There has been mention of various methods:

- Methods based on acoustic emission (monitoring),
- Ultrasonic mapping of the bolt cross section (inspection),
- Potential and/ or current measurements,
- Electrical Resistance sensors installed in the bolt hole or between the flanges.

Other questions relate to determining and adjusting inspection intervals. Risk based inspection of bolts, possibly in combination with environmental monitoring should allow to determine an economic and safe inspection regime and to ascertain whether design assumptions are being respected.

4.3.2 Grout inspection/monitoring

A challenge is to assess the integrity of grout used in offshore wind turbines: Detection of cracks and general degradation of grout in the TP/MP connection and the jacket foundation (fixation of pin piles).

With regards to the grouted connection at jackets, the issue mainly lies on the confinement of this connection and the total lack of access. Also, how cyclic loading can ultimately affect the upper section of the connection and lead to early grout degradation. ***At present there are no suitable inspection techniques.*** Should inspection be required the only way forward at present is coring, i.e. taking a material sample by drilling. [21]

A solution was developed for grouted MP/TP connections by Uniper in answer to the Carbon Trust's Subsea Inspection competition: a system which uses interfering low frequency ultrasound waves to detect gaps in the layer of grout between the inner and outer steel tubes. An ROV is used to position the ultrasound device (inspection from the inside). [15]

Acoustic Emission could be used for monitoring, but a lot of challenges remain. There are a lot of interfering signals from the surrounding environment which need to be filtered out. One of the problems in using AE in a brittle material such as the grout is that it is a heterogeneous material due to cracking occurring during drying, which leads to a non-uniform wave speed in the material. Although it is difficult to determine the exact type and size of damage, acoustic emission can be used for damage localization and combined with other techniques to get a more accurate damage interpretation. The application of this method is being investigated in the H2020 project ROMEO. [21]

It could also be interesting to measure the relative displacements between the TP and the MP by using strain gauges or displacement sensors. In [21] the use of accelerometers (installed on the nacelle of many wind turbines) to monitor failure of the grout connection was considered. It was concluded that damage could potentially be detected in the grout by monitoring the natural frequency of the structure (Operational Modal Analysis). Therefore, it could be interesting to install accelerometers on the mast to determine whether there is a slack between the mast and the TP.

It should be remarked, that for MP/TP connections, the trend is towards using bolted connections. There can still be grout between the TP skirt and the MP to prevent ingress of seawater, however this is no longer a structural joint.

4.3.3 Operational Modal Analysis

Operational Modal Analysis is a technique based on measuring the vibrations of the structure or parts of a structure and by analysing these vibrations, obtaining information about the state of the structure. In the sections above, this has been considered both for bolt monitoring and grout monitoring.

An important challenge is to be able to signals related to detect damage within noise generated due to changes in Environmental and Operational Conditions. Currently, the signal processing techniques are not always sufficiently powerful to deal with a full scale operational environment. Furthermore, it can be difficult to identify which is the phenomenon responsible for the deviation from the normal behaviour. Identifying the cause of abnormal response requires a model for which it can be difficult to identify all the parameters. [21]

An example of vibrational analysis for Tidal Turbines can be found in the REMO project (see section 6).

4.3.4 Monitoring of composite/steel joints

Inspection of the blade root to hub connection is a challenge. This includes the condition of the bolts/studs, the pre-load, but also of the composite laminate. For the T-bolt connection this involves inspecting or monitoring the laminate region around the barrel nuts for cracks. For the inserts, the condition of the bond/interface between the studs and the laminate needs to be monitored. A key question is 'What is the condition of the interface at the laminate/insert after 15 years of operation?'. Techniques like ultrasound inspection or imbedding of optical fibres could potentially be used to inspect/monitor this interface. However, currently there appears to be no standard practise on how to inspect or monitor the critical interface between composite and steel. Similar to other parts of the structure, vibrational analysis of the blades could also provide information about the connection, but will likely not indicate exactly which bolt/stud is concerned.

The above challenge currently exists both for wind turbine blades and tidal turbine blades, but may be even more critical for tidal turbine blades using adhesive bonding. It ***is unclear how the seawater affects the adhesive and what strength loss there is over time***. Additionally, the adhesive is often located in a position with is difficult to inspect. Currently, there appear to be ***no standard techniques for inspection of adhesive bonds*** between composite/steel. The problem may also be expanded to inspection of composite/composite adhesive bonds.
Inspection of adhesive bonds is not only an O&M challenge, but also relates to quality control during installation. It has already been indicated that on-site installation using adhesives presents specific challenges (section 4.1.7). In order to ascertain the quality of installation and repeatability of the process, accurate inspection techniques will be a crucial element of the installation procedure.

4.3.5 Cost of Monitoring

Operators have started appreciating the importance of investing in Structural Health Monitoring. However, although monitoring has many proven advantages, it is expensive. This makes that it is generally impossible to instrument all devices with an extensive sensor arrangement. Therefore, hotspots to be monitored should be defined using finite element calculation and digital twin methods could be developed in order to reduce the cost of monitoring.

5 Stakeholder companies

During the work done in preparation of this report, relevant supply-chain companies that were encountered have been noted down. A list of these companies can be obtained by contacting the author. As these are companies encountered while working on this report, this list is not meant to be an exhaustive list of supply-chain companies.

6 Current and past projects

This section of the report gives some examples of current and past projects related to the topic of joining of large components in harsh environments. The goal of this section is not to provide an exhaustive list of all projects that have a connection to the topic of the current report, but rather to illustrate what types of projects have been or are being undertaken. These examples can serve as reference points when developing new projects from within ADMA.

European databases listing EU projects can be found online, such as https://ec.europa.eu/info/research-and-innovation/projects/project-databases_en

Floating wind prototype projects: Hywind, WindFloat, FLOATGEN, TetraSpar, Ideol, SeaTwirl.

O&M Centre of Excellence		
Start date: -	*End date: -*	*Status: Ongoing*
Website: https://ore.catapult.org.uk/operation-performance/strategic-programmes/omce/		
A joint initiative between the ORE Catapult and the University of Hull bringing together key offshore wind stakeholders to focus on the industry's priority O&M challenges and accelerate the development and deployment of innovative solutions. The OMCE has completed six scoping projects of which the most relevant for the current topic are: - Monopile Foundations: Remaining Useful Life Assessment - Reducing Mandatory Inspections		

Interreg Qualify		
Start date: 13/07/2017	*End date: 31/07/2020*	*Status: Ongoing*
Website: https://www.interreg2seas.eu/en/qualify		
Enabling Qualification of Hybrid Structures for Lightweight and Safe Maritime Transport The drivers to reduce weight in traditionally heavy loaded structures such as ships demands the development of durable, lightweight solutions that can withstand such loads under extreme conditions. The combination of steels and composites in adhesively bonded structures can reduce weight while preserving strength, leading to lighter and stronger ships. 10% weight reduction triggers a reduction of up to 7% in fuel consumption. The potential savings, along to the manufacturing advantages, have motivated the shipbuilding industry to explore the use of adhesively bonded hybrid joints in primary structures, capable to withstand high loads and guaranteeing safety. Currently, no certification guidelines exist to orient the industry when certifying new designs using such hybrid assemblies, which limits their use to secondary structures. QUALIFY will provide the necessary knowledge to remove these technological and regulatory barriers, enabling their use in primary structures in shipbuilding.		

FS FOUND		
Start date: 2018	*End date: -*	*Status: Ongoing*
Website: https://ore.catapult.org.uk/stories/fs-found/		
Led by ORE Catapult. Demonstrated the design, manufacture, installation and maintenance of five innovative float-and-submerge gravity based foundations at EDF's Blyth Offshore Wind Farm. One of the project's key elements, a custom instrumentation system designed by our engineers, collects operational data from the turbines that is being used to optimise future foundation design and validate its cost model.		

H2020 OPERA project		
Start date: 01/02/2016	*End date: 31/07/2019*	*Status: Finished*

Website: http://opera-h2020.eu/ https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/opera
Open Sea Operating Experience to Reduce Wave Energy Cost (OPERA), led by Tecnalia: Delivering, for the first time, open access, high-quality open-sea operating data to the wave energy development community (device performance, survivability and reliability). Research project, involving field demonstration with reduced power prototype (not full scale). 4 industrial innovations validated: - Novel biradial air turbine - Advanced control strategies - Elastomeric mooring teether - Shared mooring configuration

H2020 ROMEO project		
Start date: 01/06/2017	*End date: 31/05/2022*	*Status: Ongoing*
Website: https://www.romeoproject.eu/ https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/wind/romeo		
Develop advanced technological solutions that enable the operation and maintenance costs of offshore wind power facilities to be reduced. The main objective is to develop a platform for the analysis and management of the data obtained from the offshore wind power generation plants during their operation and use the data collected in the design of strategies that enable the operation and maintenance of the wind farms to be improved. - Increase wind farm reliability and decrease the number of failures leading to downtime - Increase the life time of key turbine components - Reduce the WT O&M costs through the reduction of the resources required for annual inspections of the turbine - Reduce the O&M costs associated to foundation through reduction in jacket substructures inspections		

COST Action CA18120 - Reliable roadmap for certification of bonded primary structures		
Start date: 04/04/2019	*End date: 03/04/2023*	*Status: Ongoing*
Website: https://www.cost.eu/actions/CA18120/#tabs|Name:overview		
The Action aims to deliver a reliable roadmap for enabling certification of primary bonded composite structures. Despite the motivation being aircraft structures, which is believed to have the most demanding certification, it will directly involve other application fields in which similar needs are required. This Action will tackle the scientific challenges in the different stages of the life-cycle of a bonded structure through the synergy of multi-disciplinary fields and knowledge transfer.		

Fieldlab Zephyros		
Start date: 2018	*End date: -*	*Status: Ongoing*
Website: https://www.worldclassmaintenance.com/project/fieldlab-zephyros/		
This initiative unites the Dutch offshore wind sector (industry, education and knowledge institutes) in achieving better offshore wind energy performance. The goal of Fieldlab Zephyros is to develop, test and demonstrate innovations and to develop knowledge and skills. The ultimate goal: no unnecessary downtime and no need for on-site maintenance of the offshore wind energy system. Within this FieldLab, there is a project on O&M of bolts: Offshore Wind Bolting. (Partners: Stork, Lubo International, Arvick, InHolland and TNO.)		

H2020 RAMSSES		
Start date: 01/06/2017	*End date: 31/05/2021*	*Status: Ongoing*
Website: https://www.ramsses-project.eu/ https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/waterborne/ramsses		
For a broad variety of ship types, RAMSSES develops, produces and assesses thirteen industry led and market driven demonstrator cases, which cover applications from structural components and equipment up to ship integration. Of relevance for the current report, is that large hybrid structures are also considered. Innovations implemented and rested in RAMSSES could potentially also be valuable for offshore renewable energy devices.		

BONDSHIP		
Start date: 01/04/2000	*End date: 30/06/2003*	*Status: Finished*
Website: https://cordis.europa.eu/project/rcn/51636/factsheet/en		
The BONDSHIP project was a major European initiative to introduce into shipbuilding the use of adhesive bonding for joining lightweight materials. Main tasks: - studying the structural behaviour of bonded joints, including long-term performance in a marine environment - designing, building, testing and repairing prototypes involving superstructures of patrol craft, secondary attachments to cruise ship superstructures and load bearing connections in superstructures - preparing guidelines for use of adhesive bonding in such applications The main results are guidelines for the design and modelling of bonded joints; acceptance tests and criteria; inspection methods; documented application cases and joint designs; production and repairs procedures.		

FAUSST		
Start date: 01/04/2000	*End date: 30/06/2003*	*Status: Finished*
Website: https://www.fausst.com/ https://www.hyconnect.de/en/		
FAUSST is a hybrid fabric with a metallic and non-metallic part. Tailored knitted fabrics made out of steel and e.g. glass fibres permit the construction of a laminate, that can be welded on one side. FAUSST is a ready to use constructive element, that integrates into the fibre reinforced part a steel sheet that can be easily welded to the ship structures! The project ended by having found a new way to join metal and composites that is currently being commercialised by HYCONNECT.		

FloTEC		
Start date: 01/01/2016	*End date: 30/06/2019*	*Status: Finished*
Website: https://orbitalmarine.com/ https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/flotec		
Led by Orbital Marine Power, this project aims to demonstrate the potential for floating tidal stream turbines to provide low-cost, high-value energy to the European grid mix. The FloTEC project has 5 core objectives: 1. Demonstrate a full-scale prototype floating tidal energy generation system for optimised energy extraction in locally varying tidal resources; 2. Reduce the Levelised Cost of Energy of floating tidal energy from current estimated €250/MWh to €200/MWh, through both CAPEX and OPEX cost reductions in Scotrenewables Tidal Technology; 3. Develop potential of tidal energy generation towards flexible, baseload generation, through the integration of energy storage; 4. Demonstrate the potential for centralised MV power conversion to provide a generic, optimised low-cost solution for tidal arrays; 5. Progress tidal energy towards maturity and standard project financing by reducing cost and risk, improving reliability, and developing an advanced financing plan for first arrays. This will be realised through the construction of a M2-SR2000 2MW turbine which will incorporate the following innovations: 50% greater energy capture through enlarged rotors with a lower rated speed; Automated steel fabrication; Centralised MV power conversion; Integrated Energy Storage; Mooring load dampers; Composite Blade Manufacturing.		

REMO project		
Start date: 01/12/2012	*End date: 30/11/2014*	*Status: Finished*
Website: http://remo-project.eu/ https://cordis.europa.eu/project/rcn/106287/factsheet/en		
Online Remote Condition Monitoring of Tidal Stream Generators This aim of this project was to develop a system for the remote and permanent monitoring of the structural integrity of all the rotating components in a tidal stream generator so that advanced warning of potential structural failure is obtained well in advance and thereby avoiding potential damage and allowing all necessary component repairs or replacements to be performed at scheduled maintenance intervals. REMO technology is based on the monitoring of structural vibrations throughout the entire frequency spectrum generated by the rotating components and so combines a suite of accelerometer sensors for the low frequency regime and acoustic emission sensors for the high frequency regime. The REMO technology		

permanently monitors tidal wave generators and determines the vibrational signature of a healthy turbine and the evolution of that signature during the turbine life cycle. It then highlights any significant change in that signature that could be a symptom of a structural health problem or the build-up of marine fouling at any point in the life cycle and then issue an automatic warning.

JIP - Integrated Design, Installation and Maintenance of Bolted Joints		
Start date: 09/2016	*End date: 09/2019*	*Status: Finished*
Website: -		
Led by DNV-GL. Focus on bolted joints in the nacelle. WP1: collecting evidence and data on bolted joints in general, most data collected on MP/TP, still relatively limited openness about sharing of operational data WP2: modify design methods to allow for imperfections of flanges WP3: definition of what a maintenance free bolt is and what checks need to be performed in order to certify such a bolt WP4: investigation and adjusting of design factors in light of newly developed features, check whether less conservative designs are now possible WP5: recommended practices		

BlueGift		
Start date: 03/2019	*End date: 03/2022*	*Status: Ongoing*
Website: http://bluegift.eu/ *https://www.wavec.org/en/research-development/projects/bluegift*		
This project will help Atlantic Arc companies test the next generation of Marine Renewable Energy (MRE) technology in real sea environments and prove power can be economically generated from the ocean. Blue-GIFT will result in a minimum of 8 MRE floating wind, wave or tidal precommercial demonstrations, over 24,000hrs of operation, work with over 20 SME's, sustaining 30+ jobs and helping to secure €15M investment into MRE companies.		

7 ADMA Regions' Strengths and Interests

General themes highlighted by Basque Country:

- Sensorization of critical and auxiliary systems
- Connectivity and cybersecurity of components
- CMS systems for offshore O&M
- New materials and coatings for harsh environments

Table below: specific input from questionnaires on companies and RTO's potentially interested in participating on projects related to the topic of joining of large components in harsh environments.
Completed questionnaires were received from five regions: Andalusia, Basque Country, Flanders, Lombardy and Scotland. No responses were received from other ADMA regions: Navarre, Norte, Asturias, Dalarna, Scania and Emilia-Romagna.

Andalusia		
Cluster Marítimo Naval Cadiz	Cluster	
EnerOcean	RTO	in design and development of floating platforms, very interested in demonstration projects that can scale up its design with large components
Navantia	RTO	Manufacturer of offshore foundations: fixed structures like jackets, floating structures and offshore substations.
Basque Country		
Tecnalia	RTO	Investigation of corrosion-fatigue, development of bolt monitoring, Expertise in corrosion protection, Experience with Ocean Energy Convertors, Experience with large European projects
Ikerlan	RTO	Structural reliability, pre-loading of bolts, adhesive joining, structural integrity of large devices, extensive experience in offshore renewables. Experience with adhesive bonding of composites, including degradation due to environmental condition and mechanical loading. Condition monitoring systems.
Nautilus	Company	floating platform developer
Saitec Offshore Technologies	Company	floating platform developer
Erreka Fastening Solutions	Company	working on the development of bolt load measurement and installation tools, are working their way into offshore, have produced bolts for the Heliade X wind turbine. Are designing a fatigue test machine for large bolts, searching for partners to develop this further.
Euskal Forging	Company	Manufacturer of seamless rolled rings, these constitute the flange of bolted flange connections.
NabraWind	Company	Segmented blade design
Flanders		
University of Ghent	RTO	Composite materials, corrosion and fatigue degradation of materials, modelling and testing
University of Brussels	RTO	Research on load monitoring, vibrational analysis of offshore structures, structural integrity analysis
IBN Offshore Energy	Cluster	Cluster and networking organisation for the Belgian Offshore Energy Value-Chain
24SEA	Company	Monitoring of offshore structures, load monitoring, vibrational analysis
Com&Sens	Company	Monitoring using optical fibres
Force Technology	Company	Installation, maintenance and service inspection of bolted connections, both onshore and offshore.
Smulders	Company	Manufacturer of offshore foundations (TPs and Jackets)
DEME	Company	Installation of offshore energy devices

Jan De Nul	Company	Installation of offshore energy devices
Lombardy		
Università di Bergamo	RTO	
Cescor	Company	An engineering company that operates in the fields of corrosion prevention, cathodic protection, inspections and asset integrity (including corrosion monitoring). Is aware of the interest of Oil&Gas industry in the field of joining of medium and large components, from which past experiences, failures and solutions can be derived, and rearranged for structures used in renewables.
Donelli Alexo	Company	An engineering company that operates in the fields of corrosion prevention, cathodic protection, inspections and asset integrity. A lot of experience in offshore structures, e.g. O&G. Also provides dedicated corrosion protection solutions for bolted connections. Can also provide contacts to company working on inserts bonded in composites.
Scotland		
University of Strathclyde	RTO	Structural integrity of Offshore Energy Devices.
University of Edinburgh	RTO	Development of composite materials for wind and tidal blades
National Subsea Research Initiative (NSRI)	RTO	Dedicated to advancing underwater technology and sharing cross industry knowledge within the subsea domain. Matchmaking organization. Decades of experience in O&G sector. Solutions used in O&G could be transferred to joining of large components in Offshore Renewables.
Advanced Forming Research Centre (AFRC)	RTO	World leading metal forming and forging research: hot forging and forming, cold forming, materials characterisation, metallography, metrology, furnaces and machining.
Composites UK	RTO	Composites UK is the Trade Body for the UK composites industry. (UK composite capabilities database)
Subsea UK	RTO	not-for-profit industry body that champions the UK's underwater supply chain
Wave Energy Scotland	RTO	support a range of projects focused on the key systems and sub-systems of Wave Energy Converters
ORE Catapult	RTO	The UK's leading technology innovation and research centre for offshore renewable energy.
Nova Innovation	Company	TEC developer
Orbital Marine Power	Company	TEC developer
SIMEC Atlantis Energy	Company	TEC developer
European Marine Energy Centre (EMEC)	RTO	Offshore test-site
SSE	Company	Offshore windfarm owner

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8 Test sites

In the following, a number of test sites that could be relevant for the development and demonstration of joining technologies are listed:

Blade testing		
ORE Catapult	blade test site, fatigue testing	https://ore.catapult.org.uk/testing-validation/facilities/blades/
Siemens Gamesa	is building world's largest wind turbine blade test stand in Aalborg, Denmark	
Fraunhofer IWES	Full-scale blade testing upto 83m	https://www.iwes.fraunhofer.de/en/test-centers-and-measurements.html
University of Edinburgh	will commission a Tidal Blade test rig FASTBlade in 2020/21	
Components and materials		
Fraunhofer IWES	Site for testing of windturbine components and materials • 1:10 scale testing of foundations • nacelle test rig for complete nacelles	https://www.iwes.fraunhofer.de/en/test-centers-and-measurements.html
OCAS, CRONOS	large scale testing of flanged bolted connections, possibly in combination with a corrosive environment	https://www.ocas.be/
Basin testing		
COB	The 'Coastal and Ocean Basin', wave tank in short, is a large concrete construction filled with water (30 m x 30 m x 1,4 m deep) in which controlled waves, currents and wind can be generated. Unique is that its features allow wind, waves and currents to be manipulated independently. Scale models of offshore constructions, constructions for coastal protection, floating wind turbines, golf energy converters,… are placed in this tank, where their design and behaviour under the influence of waves, currents and wind are being studied.	http://www.aqua.ugent.be/coastal-ocean-basin-cob-or-wave-tank-new-flanders-maritime-laboratory-ostend-belgium
Field testing		
EMEC	Multi-berth, purpose-built, open sea test facilities for wave and tidal energy converters.	http://www.emec.org.uk/
Harsh Lab Tecnalia	Advanced floating platform for the evaluation of standardized probes and components in real offshore environment. Harsh Lab v1.0 is suitable to test new materials and solutions against corrosion, ageing and fouling in real and monitored offshore conditions.	https://www.tecnalia.com/en/energy-and-environment/infrastructure-a-equipment/harsh-lab-v10-en/harsh-lab-v10-en.htm
UN-SEA-MD Test-Center	Testing platform in marine environment. The capacity to test all materials (composites, concrete, iron, …) in simulated natural and accelerated condition for: deep sea, immersion area, splash and tidal zone and spay area, coupled with mechanical loading (abrasion and static or cyclic loading)	https://www.weamec.fr/en/blog/record_technology/testing-platform-in-marine-environment/
BIOCOLMAR	BIOCOLMAR is an offshore measurement station to provide the real data base from the intended MRE installing site. It has been designed to measure the physico-chemical parameters of the water as well as the sampling of the organisms colonizing offshore structures.	https://www.weamec.fr/en/blog/record_technology/biocolmar/

Sem-Rev offshore test site	SEM-REV is the first European site for multi-technology offshore testing that is connected to the grid. It has all the equipment - offshore and on land - to develop, test and improve energy recovery systems (mainly from wind and wave sources). It will play a decisive role in meeting the challenge of Marine Renewable Energy development in France. It is operated by Centrale Nantes, with the aim of helping industrialists develop new energy production capacities.	https://www.ec-nantes.fr/research-facilities/sem-rev-offshore-test-site/sem-rev-offshore-test-site-153194.kjsp
Galway Bay Test Site/ SmartBay	The Galway Bay ¼ scale wave energy test site has been in operation since 2006. The site is situated on the North side of Galway Bay, 1 mile East of Spiddal. The site is 37 Hectares in depths of 20-23m. The area is marked by navigation markers on each corner. The site has provided test and validation facilities for a number of devices to date. Real time oceanographic data are available on the Galway Bay dashboard. Time series data and full spectral data set are available through the Marine Institute's Data Request service.	https://www.marine.ie/Home/site-area/infrastructure-facilities/ocean-energy/galway-bay-test-site-0 https://www.smartbay.ie/facilities

Funding Ocean Renewable Energy through Strategic European Action (FORESEA) [30] is an 11M euro project, funded through Interreg North West Europe, which helps to bring offshore renewable energy technologies to market by offering free access to a world-leading network of test centres.

9 Funding opportunities and gabs

It is impossible to give a complete overview of all funding opportunities within the EU and the various regions. Furthermore, the funding landscape is continuously changing. Upon selection of a certain topic for a project, it is advisable to get in touch with the National Contact Points of interested partners to find the most suitable funding regime.

In the following, a brief summary of a number of main EU funding schemes is given, along with a short discussion on strategic fit with the EU Ocean Energy policy. The section is concluded by pointing out a number of funding gabs identified from the questionnaires send out to the ADMA partners.

Main Funding mechanisms at EU level[1]

- European Structural and Investment funds (ESIF) ESIF consist of five funds[2]:
    - European Social Fund (ESF)
    - European Regional Development Fund (ERDF): Interreg program falls under ERDF, as well as the Vanguard Initiative and funding for the prioritisation of regional research and innovation smart specialisation strategies (RIS3)
    - European Maritime and Fisheries Fund (EMFF)[3]
    - Cohesion Fund (CF)
    - European Agricultural Fund for Rural Development (EAFRD)
- European Investment Bank (EIB)
    - InnovFin Energy Demo Projects (EDP)
- NER 300 Initiative: NER 300 is a funding programme pooling together about EUR 2 billion for innovative low-carbon energy demonstration projects. The programme has been conceived as a catalyst for the demonstration of environmentally safe Carbon Capture and Storage (CCS) and innovative renewable energy (RES) technologies on a commercial scale within the European Union. The program mainly focusses on large demonstration projects.[4]
- Horizon 2020 programme: This is the EUs framework program that ran from 2014 to 2020 and had a wide range of call topics and actions. Two very specific ones which could be applicable to the topics considered within this report are given below. It should be remarked that the H2020 program is ending and no new calls are expected. A follow-up program will be established by the EU, currently given the name 'Horizon Europe'[5].
    - OCEANERA-NET COFUND: 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 R&D in OE, to encourage collaborative projects that tackle some of the key challenges identified for the sector.
    - MANU-NET: is a specific support action to move towards a European regionally-based Research Area on manufacturing. It supports innovation-driven, close-to-market research and development projects in manufacturing.
- COST Actions: Funding to set up interdisciplinary research networks.[6]
- Research Fund for Coal and Steel (RFCS)[7]: Might be applicable for smaller projects on the use of high strength steels or other innovative steels (e.g. corrosion resistant) in the maritime industry. Success rates are typically somewhat higher when compared with for example H2020 applications.
- Interreg Europe[8]: Funding for Interregional Cooperation Projects. Program runs from 2014-2020, with funding coming from European Regional Development Fund (ERDF). It is unclear whether there will be a follow-up program.

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[1] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities_en, consulted on 11/10/2019.
[2] https://ec.europa.eu/regional_policy/en/funding/, consulted on 17/10/2019.
[3] https://ec.europa.eu/fisheries/cfp/emff, consulted on 25/11/2019.
[4] https://ec.europa.eu/clima/policies/innovation-fund/ner300_en, consulted on 25/11/2019.
[5] https://ec.europa.eu/info/node/71880, consulted on 25/11/2019.
[6] https://www.cost.eu/funding/what-do-we-fund/, consulted on 07/11/2019.
[7] https://ec.europa.eu/info/rfcs_en, consulted on 05/11/2019.
[8] https://www.interregeurope.eu/, consulted on 27/11/2019.

EU Strategic Fit

The EU is the leading region in the world for the development and application of offshore renewable energy technologies. Maintaining a world leading position in this field is of major importance to the EU, both in terms of reaching climate and sustainability goals and to continue the growth of the economic potential and jobs in the Blue Economy. From all of the available documentation on priorities and strategies, two major drivers can be extracted which are considered by the EU as crucial in order to maintain a world leading position, and compete with countries like China and the USA that have an increasing interest in Ocean Energy:

- ***Development of systems, subsystems and components with added functionality*** (e.g. smart systems, sensitisation) ***and increased reliability*** (longer lifetime, less maintenance requirements, less down time). This should allow European companies active in the development and manufacture of systems for Ocean Energy devices to remain competitive against low cost manufacturing in other countries.
- ***Reduction of the LCoE.*** This can be done both through a ***reduction in CAPEX***. One example is the introduction of are new technologies for lighter weight subsystems or new joining techniques that allow faster and lower cost installation procedures. ***Reduction of OPEX*** is also considered, which typically comes from a reduction in inspection and maintenance costs. Here, there is a clear link to the increased functionality (sensors) and reliability of systems, subsystems and components.

The Ocean Energy Forum has identified main technology focus areas. The most relevant ones for the topic under consideration in this report are:

- Testing and modelling – which covers validation of concepts and development of high definition modelling through to demonstration in real conditions and deployment. It includes modelling on sub-systems, components and the entire device in real and in controlled environments.
- Reliability and survivability – to increase the reliability of ocean energy devices by developing monitoring systems for real conditions and to identify potential failure modes to subsequently improve designs.
- Installation and logistics - a new generation of waterborne and sub-sea solutions is needed to match the specificities of ocean energy devices and reach the targeted costs per kWh.

The European Technology and Innovation Platform for Ocean Energy (ETIP Ocean) is funded by the European Commission to define research and innovation priorities for the ocean energy sector. The two most relevants topics for the current report are:

- Focus on the development of systems and test-rigs that allow data for condition monitoring algorithms to be obtained and optimise
- Determine component failure rates by testing full scale systems with accelerated lifetime testing from test rigs and feed into the design of ocean energy converters

Funding gabs

Although there are a wide range of funding mechanisms available, a number of funding gabs have been indicated by the ADMA partners that replied to the questionnaire:

- ***Funding for pre-normative research***, i.e. research focussed on the definition of new or updated standards. This typically requires significant research and demonstration programs, but has no immediate return in terms of job creation. Additionally, individual companies are not likely to invest in such work themselves, as the results are by definition shared with the entire sector and therefore do not result in a commercial advantage. Nevertheless, research to update existing standards or create new standards is of major importance to forward industry as a whole and has the potential for major cost savings and design improvements on an EU-wide level. It prevents mistakes from being made multiple times, results in efficiency gains both in research and development work, and makes sure that advances in technology are captured for future generations and easily dessiminated to entire value-chains.
- ***Large scale demonstration of disruptive innovations:*** There are EU calls to very large demonstration projects (for example new generations of large turbines), but this funding is not well fitted to demonstrate disruptive concepts. The funding is mainly aimed at higher TRL levels, and doesn't support large scale demonstration at lower TRL levels, where the risk is much higher (although potential gains in terms of succes may on the mid-long term be higher aswell). Still, in order to advance disruptive innovations more rapidly, large scale demonstration is required. Under the motto 'Fail Fast' (and learn

quickly), this may in the long run be less expensive than a long and slow development process that drags on.

- ***Large scale demonstration with a research component:*** In line of the above, it has been noted that the lastest EU calls are oriented to demonstration of very large wind turbines, to demonstrate viability of already existing turbines (for example for floating), but that there are not much calls for collaborative demonstration projects where there is also a research component involved. Especially in the maritime sector, research often requires demonstration in the field, because the real maritime conditions are difficult to mimic in the lab. This type of in-field research, often also requires large investments in testing equipment, which are difficult for research organisations to bear at funding rates of 50-60%.
- ***Cross-sector knowledge transfer and engineering:*** Many technology developers have problems identifying solution providers and assessing the various technologies/solutions available. Specifically for offshore renewable energy, many solutions are available from the Oil & Gas sector. However, a real engineering effort is required to adapt solutions to the renewables sector and specific devices, where there is a different market mechanism, cost drive and O&M environment. Because of the very challenging environment and need to reduce costs and therefore work with 'cheap' solutions, it is unclear whether solutions for other sectors will also work when they need to be adapted for offshore renewable energy devices. Searching for potential solution providers, assessing all the different solutions on the market, adapting where necessary and testing various solutions is a time and capital intensive job. Because this is often conceived as 'engineering work' and not 'at the right TRL level', it is difficult to find government funding. On the other hand, it is also difficult to do this kind of work in a JIP, because if the technology developers pay for it, they don't want other technology developers to benefit from it, i.e. they want to keep the competitive benefit. However, if a solution is developed together with solution providers, it is also unreasonable to expect these solution providers to not sell the technology to anyone else. Therefore, this kind of work has the biggest chance of success and impact when performed in an open innovation approach. This however, requires government support because the benefits belong to a wide range of companies along the value chain (and potentially also other value chains such as aqua-culture, etc. where margins are potentially also smaller).
- ***Revenue support for marine energy (Wave and Tidal):*** There is no revenue support for marine energy projects which makes it difficult for projects to compete in the UK Governments Contracts for Difference auction rounds (in which offshore wind is making traction due to significant cost reductions). There was ring-fenced funding to be allocated to innovative energy generation but this has been removed. Renewable UK/Scottish Renewables and the Marine Energy Council (comprised of a number of mostly tidal developers) are making a coordinated effort to lobby UK Government in this regard.

10 Ideas for Collaborative projects

In this chapter, the challenges identified in chapter 4 will be used to define a number of collaborative project ideas. The specific challenges will not be discussed in detail, because this was already done in chapter 4. When preparing a project based on the ideas in this chapter, it is recommended to read the relevant sections in chapter 4.

10.1 Bolted connections

Bolted connections are the major type of joint being used in renewable energy devices. Each wind turbine potentially requires in excess of 20,000 bolts[1] and also Wave and Tidal devices use large numbers of bolts. Some challenges are generic for all devices, like pre-loading, while others may be device specific, like corrosion.

10.1.1 Pre-load

Over 90% of all bolted joint failures can be attributed to low bolt tension on installation tightening. Better control of pre-load can allow a reduction of design safety margins, leading to cost reductions. New methods of applying pre-load can reduce installation costs. An improved understanding of loss of pre-load can also help to reduced O&M costs.

Bolt Installation tools: pre-loading	
Type of activity	Development
Problem statement	
Two main types of applying pre-loading exist: torque tools and tension tools. It is generally accepted that tension tools result in a more reliable application of the correct level of pre-loading. However, these tools require more space for installation, which is not always available. A combination of innovative tooling and taking into account the space required for pre-loading in the design of renewable energy devices could help overcome the barriers to the general use of tension tools. Currently, hydraulic tools are generally used. These can however be cumbersome to use. There is a demand for fast, accurate and reliable methods that are easy to use and have no risk on oil spills. Electrical tools could be the answer to this, but a lot of development work is still needed to optimise this type of tooling. The key to developing successful installation and inspection tools is that they need to reduce assembly and maintenance times and provide a closely controlled and homogeneously distributed pre-load.	
Key Activities	
- Engineering and development of fast, accurate, easy to use and repeatable pre-loading tools. - Close collaboration between bolt manufacturers, installation tool developers and renewable energy technology developers to incorporate the bolt installation procedures in the entire design and installation process.	
Challenges in reaching the market	
Development of new types of tooling is underway. Technology developers are also realising that the space required for pre-loading should be factored into designs. There appears to be no market-failure. In the coming years, the technology will continue to evolve and the best solutions will likely find their way to the market. Joint Industry Projects could be established, led by an RTO or cluster organisation to accelerate the development of these tools and perform an objective comparison of various technologies.	

Maintaining bolt pre-load	
Type of activity	Research and demonstration
Problem statement	
The root cause of loss of pre-load is not understood. As a result, there are no clear guidelines on what are the best installation and maintenance procedures. A better understanding of why and how pre-load is lost, may also result in technological developments of innovative bolting systems that require less and preferably no maintenance in terms of pre-load.	
Key Activities	
Investigation of mechanisms leading to loss of pre-load	

[1] http://www.clydefasteners.com/energy/, consulted on 31/10/2019.

- Influence of various environmental conditions (wind/wave loads, temperature variations, corrosion, etc.) - Investigate the reduction of pre-load over time - Combination of large scale demonstration in a controlled lab environment and data collection from in-service installations. Investigate influence of different installation procedures - Influence of forces exerted on the structure during installation (e.g. wind and waves) - Influence of bolt loading sequence and loading method - Influence of manufacturing and installation tolerances on flanges - Combination of large scale demonstration in a controlled lab environment and data collection from in-service installations. Investigate ways to inspect/monitor pre-load in a cost-effective way - Objective comparison of existing technologies (accuracy, repeatability, need for a reference at installation, or can also be used on existing structures, possibility to monitor, cost, speed of measurement, etc.) - Development of new technologies - Determine if and how monitoring of a subset of bolts can provide sufficient information to determine the state of the entire joint system Interpretation and collection of data - Collection of data about bolts, pre-load, loss of pre-load, failure rates and failure modes - Develop methods for data interpretation in terms of structural integrity - Investigate the impact of loss of pre-load on a system level (the entire joint) ***Demonstration Idea:*** - ***For MP/TP connection: In collaboration with a project developer, the bolt-load after installation of multiple turbines could be investigated (in first 12 hours, first days, etc.), with different installation procedures followed on different turbines. During installation, the bolt load of multiple bolts should be monitored, allowing to see how tightening of one bolts influences another.*** - ***For blade/hub connection: A similar demonstration could be done onshore in a blade testing facility, where fatigue loading is accelerated and the effect of pre-load investigated.*** Development of installation and maintenance guidelines - Correct installation, inspection after installation and training of personnel (i.e. quality control) - Required inspection frequency - Optimal method of inspection/monitoring - Knowledge transfer and awareness raising (incorporate in existing standards)
Challenges in reaching the market
Investigation of the fundamental mechanisms leading to loss of pre-load requires applied academic research, a large amount of data and dedicated demonstration projects. The outcomes of such research are likely to lead to advances in technologies, however, the research itself requires sector wide collaboration, supported by government funding. For monitoring/inspection systems: various developments underway. No support needed in technology development, but rather in data interpretation and best way to apply the technology (e.g. monitoring of a subset of bolts). One possible issue in term of monitoring/inspection systems: currently, a lot of different technologies are being developed. A Joint Industry Project, lead by an RTO, cluster of certification body, could help to develop a more standardized technology and result in more collaboration along the value chain, instead of having a lot of non-compatible solutions. Research effort required in terms of data interpretation. Applied academic research requiring in-field data and possibly dedicated demonstrators. Methods and algorithms from which entire sector benefits. Large effort required, possibly too much for a single company. Collaboration required to collect sufficient data.

10.1.2 Bolt degradation in a maritime environment

Improving the understanding of bolt degradation mechanisms in a maritime environment	
Type of activity	Research and demonstration
Problem statement	
The degradation mechanisms of bolts exposed to a maritime environment are not well understood:	

- What are the relevant local corrosion mechanisms (pitting, crevice and/or uniform corrosion, stress corrosion cracking)?
- What are the associated corrosion rates?
- Are bolts susceptible to hydrogen embrittlement, including various types of bolts and strengths (possible sources of hydrogen are cathodic protection, MIC, hydro-carbon based grease, etc.)?
- Is MIC an issue for bolted connections (and in what applications/environments)? If MIC is an issue, how can it be prevented?
- How do corrosion and fatigue loading interact? ***What is the impact on the expected fatigue lifetime?***

An improved understanding of these mechanisms will lead to design improvements, better maintenance procedures and protection measures. Results from research on this topic can be incorporated in existing standards to guide future designs.

Many devices are currently over-engineered, especially for submerged connections, because of the large uncertainty associated with these connections, which introduced unwanted costs. A better understanding of the risks, possible failure modes and alternative solutions, should allow to optimise designs and reduce costs.

Additionally, there is a lack of standardised and affordable accelerated test procedures for connections (bolted, welded, adhesive) in an aggressive environment (corrosion, fouling, UB), especially in combination with fatigue loading. This makes market uptake of innovative solutions more difficult, because it is hard to prove the effectiveness of these solutions in an objective way (i.e. certify), without expensive and very long in-field test campaigns.

Key Activities

Research to improve the understanding of the fundamental degradation mechanisms of bolts operating in a maritime environment and exposed to a combination of stresses (both mechanical and environmental).

- Study the low temperature fatigue behaviour of bolts.
- Study the corrosion mechanisms on bolts after a number of years in-service.
- Study the behaviour of high strength bolts
- Study the potential risk on hydrogen embrittlement (various sources of hydrogen need to be considered)
- Study the interaction between different degradation mechanisms

Improved lifetime prediction of bolted connections.

- Investigate the impact of corrosion on the fatigue strength and lifetime of bolted joints.

Development of standardised and affordable accelerated test procedures for a combination of corrosion and fatigue in a maritime environment.

- Specific procedures for bolts should be developed, also for full-scale testing.
- Developed test methods should allow certification of technological innovations in terms of joining technology (e.g. the use of high strength bolts) or protection of joints from the environment.
- Accelerated tests should be validated using long exposure field tests or, if available, high quality historic data.

Incorporate the new insights in existing standards to allow for optimisation of future designs.

- Including the behaviour of high strength materials.
- Optimised S/N curves for bolts, also taking into account large bolts (>M72).

Corrosion inspection and quantification of bolts in-service should also be considered

- Development of monitoring and/or inspection technologies that allow to quantify corrosion as well as the structural health of bolts and bolt holes in a bolted connection, preferably without having to remove every bolt.
- Development of technologies that allow monitoring and/or inspection without having to remove protective coatings.

In all activities, a clear distinction should be made between the submerged and atmospheric zones. Both degradation mechanisms and testing procedures will be different.

Challenges in reaching the market

The research activities required to better understand the fundamental degradation mechanisms are academic in nature. The results will feed into new technological developments, but the research work should be performed by RTOs. Because the return on investment is not clearly defined, it is difficult to obtain private funding for this type of work.

Development of test procedures requires collaboration between RTOs, certifying bodies and end-users in order to make sure that the results from testing will be accepted by all parties involved. Also here, there is no

clear return on investment for individual companies, but rather for the sector as a whole. Therefore, government funding is better suited to this development work. An additional difficulty is that a relatively long funding period is required in order to validate/correlate the accelerated tests with field tests.
For the development of new technologies for inspection/monitoring of bolted connections, collaboration should be sought between companies that develop and commercialise inspection equipment and RTOs that can provide support in terms of data interpretation. Because of the many technological challenges involved with the development of inspection/monitoring technologies and the relatively high risk, a combination of government and private funding should be established.

10.1.3 Large flanged joint

Supporting the development of the next generation of large flanged joints	
Type of activity	Development and Demonstration
Problem statement	
Large flanged joints (diameters of several meters) have imperfections associated with the flanges (flatness, roundness, hole alignment). These imperfections can influence the long term fatigue behaviour of the bolted joint. However, it is yet unclear just how big this effect can be and if and how this needs to be considered in the design stage. The flatness tolerance guidelines currently being used by the industry are not adapted to the size of the flanges being used today, meaning that it is sometimes impossible to meet the requirements. Larger joints also means transfer of higher loads. Therefore, the use of larger bolts and/or high strength bolts is being considered. However, there are no standards for fatigue lifetime assessment of these bolts, especially in a maritime environment. Additionally, sealing and corrosion protection of large flanged joints, both in the submerged and splash zones still presents a challenge. To date, no flawless, maintenance free corrosion protection systems have been found for example for the MP/TP connection. But also large bolted joints in Tidal and Wave energy devices, often in the submerged zone, suffer from imperfect sealing and corrosion protection.	
Key Activities	
Flange tolerances - Improve understanding of the effect flange tolerances have on the design life of a bolted flange connection, through a combination of modelling and testing. - Investigate the feasibility and potential benefits of precision manufacturing of large flanges. - Large scale demonstration involving manufacturing and installing large flanges, measuring all the relevant tolerances and validating models for fatigue lifetime, possibly through a large scale accelerated fatigue test. - Review and update flange tolerance guidelines for large flanged joints. Using larger bolts (>M72) and/or high strength bolts - Fatigue testing of large bolts and high strength bolts, possibly in combination with environmental influences (see section 10.1.2). - Development of innovative fatigue testing methods that are more affordable and/or faster. - Develop standards for large bolts and high strength bolts. Sealing and corrosion protection of large flanged joints - Implementation and demonstration of alternative sealing and corrosion protection. Preliminary testing of solutions could potentially be performed by means of accelerated testing. However, because of the very specific in-service conditions, final proof of a protection system can only be performed on real-life installations, with results only becoming evident after a few years of exposure. - New methods are being tried and implemented by the industry with each new project. - More sharing of information within the industry could accelerate the adoption and standardisation of efficient solutions. This means sharing information on solutions being tested, and how well they perform.	
Challenges in reaching the market	
Fatigue testing of large bolts is very expensive. This means industry wide collaboration is required to be able to cover the costs. Additionally, the benefits are not for a single company, but industry wide, which means there is no commercial advantage over other companies. Rather the advantage is for the society, with the development of a new generation of larger and more efficient renewable energy devices (specifically offshore wind). Therefore, a very strong consortium, in which all major technology developers are involved should be	

established in order to be able to tackle this issue. A certain amount of government funding could help to facilitate this, especially considering the advantage for society as a whole. Similarly, solving issues related to the flange tolerances benefits not just a single company, but the entire offshore energy industry. Also here, the costs related to a demonstration campaign will likely be large. Additionally, part of the work on understanding the impact of flange tolerances on fatigue lifetime can be considered as applied research to be performed by RTOs or universities. Therefore, a combination of private and government funding will be required to tackle these challenges. Sealing and corrosion protection: no real market failure, but difficult to get industry wide collaboration and sharing of best-practices or successful solutions, because of the commercial benefits often associated with this information. To some extent this is covered by the scale enlargement of existing companies and consolidation in a small number of companies active world-wide, i.e. a single company may have enough data and funds to keep on working towards a good solution that will than be applied in a large number of devices world-wide. The downside to this is that other upcomming sectors like wave and tidal may not be able to profit from the learnings in offshore wind.

10.1.4 Submerged bolted connections

Corrosion and leakage prevention of submerged bolted connections	
Type of activity	Development and Demonstration
Problem statement	
Corrosion and leakage prevention of submerged bolted connections presents a challenge to tidal and wave energy developers. Many problems have already been encountered in O&G and other maritime sectors, however the pressure on reducing costs is much higher in renewable energy. There is a perception that some of the solutions which are working well in O&G may simply be too expensive for renewable energy. Relative costs related to offshore inspection and maintenance are also higher for offshore renewable energy, because these devices are unmanned.	
Key Activities	
Knowledge transfer from existing sectors like O&G to offshore renewables - An objective study of cost of ownership of joining solutions available from O&G should be performed in order to evaluate which solutions from O&G can or cannot be used in the offshore renewable energy sector and how cross-sector knowledge transfer can lead to a reduction of the LCoE. - Further developing and adapting existing solutions to better suit the needs of the offshore renewables industry. - Demonstration: Evaluate a number of selected solutions during field testing at relevant test sites. Investigate the possibility to use high strength and/or corrosion resistant materials - High strength steels: combination with cathodic protection and risk on hydrogen embrittlement. - Evaluate the life cycle cost of using more expensive materials Evaluate maintenance and inspection procedures - Evaluate the use of remote monitoring or automated inspection for submerged devices which are expensive and difficult to inspect. - Evaluate the possibility for underwater maintenance, for example using ROVs for cleaning (fouling), underwater paint application, etc.	
Challenges in reaching the market	
A large amount of potential solutions is already available on the market. However, for the relatively small companies developing wave and tidal devices, it is difficult to evaluate which solutions would work best. Additionally, there is high development and engineering costs associated with testing a large amount of solutions in order to find the optimum one for a specific device. Furthermore, there is a high pressure towards cost reduction and lack of funding for wave and tidal development because of the successes of offshore wind. Especially for the type of work described above, which is at a high TRL level (i.e. adaption and evaluation of existing solutions), there is not much government funding available. A Joint Industry Project could potentailly be set up to learn from existing maritime sectors.	

10.2 Composite/Steel Joint

Composite/Steel Joints in Marine applications	
Type of activity	Development and Demonstration

Problem statement
There is a trend towards using more composite material in the design of offshore renewable energy devices, either because of the benefits associated to lower weight, or because of the improved corrosion resistance. This means that the amount of composite/steel joints will also increase. Much of the technology required to realise a good joint already exists. There is however a lack of experience and track record. End-users, designers and manufacturers don't know what is possible and how to best design large hybrid joints. The best known composite/steel joint is the blade root connection. Bonded inserts are accepted as the solution of choice for large blades. Nevertheless, more accurate modelling tools are required to support in the design of large scale hybrid structures, with a focus on very thick laminate sections around the composite/steel joint. It is expected that more and more other components will also be made from fibre reinforced composites in the near future. A wider range of joining techniques will be required to have a cost-optimised solution for these different components. Designers and manufactures will therefore need to build up the necessary know-how on joining of composite and steel sections. Additionally, there are concerns about reliability of hybrid joints in terms of for example corrosion, but this is also mainly awareness raising (i.e. solutions are on the market). Coupled with engineering and demonstration work to prove the viability of innovative designs. Inspection of composite/steel joints presents a real challenge. Innovative technologies need to be developed to be able to inspect and/or monitor these joints. (For joining using adhesives, see section 10.3.)
Key Activities

- Awareness raising and knowledge build-up on various types of composite/steel joining.
- Investigate the use of adhesives for hybrid connections, taking into account that adhesive bonds are not detachable, which has an impact on design, installation and maintenance, i.e. this is a system engineering aspect of the choice of connection type.
- The joining technology cannot be considered separately, but depends on the components being joined. A project should therefore also look at the economic benefits of using composites and identify what components could result in a reduction of LCoE when made from fibre reinforced polymers. Synergies should be sought with recommendations from the report on new materials, ordered by ADMA. A potential project should:
    o Identifying potential components to be made from composites
    o Evaluate potential joining technologies
    o Chose the best candidates in terms of joining technology, considering manufacturing cost, reliability, installation costs and maintenance costs.
    o Adapt designs in order to accommodate for this type of joining
- Evaluate the use of higher strength bolts in T-bolt or insert connections in order to reduce laminate thickness.
- Develop and evaluate solutions for corrosion protection of hybrid joints (mainly for submerged zone, e.g. tidal blades, and splash zone, e.g. working platforms).
- Development of inspection/monitoring technologies.
- Large scale demonstration: testing of the connection is necessary to improve reliability and market uptake, this includes installation and decommissioning procedures and costs.

Challenges in reaching the market
The main challenge is related to awareness raising. Designers and developers are still searching for potential candidate components to be made from composites. This requires multi-disciplinary knowledge on manufacturability, manufacturing costs, mechanical performance, durability, etc. The joining of composite and steel components is only a small part of the bigger picture. Networking effort is required to bring different actors together. A project focussing on evaluating various candidate components for example for offshore wind turbines could be useful. The RAMSSES project can be seen as an example for shipbuilding (see chapter 6). Technological challenges in terms of inspection/monitoring of the joint. New solutions will need to be developed. Collaboration should be sought between companies that can commercialise inspection equipment and RTOs that can support in the technological development. Radical design changes may be required in order to profit from innovative joining techniques (for example adhesive joining). In order to better understand the consequences and demonstrate whether the expected benefits are indeed achievable (for example in terms of installation cost and speed), large scale

demonstration projects may be required. Because there may be large risk of failure associated with such a demonstration, it may be difficult to find private investment.

10.3 Adhesive bonding

Adhesive bonding in Marine applications	
Type of activity	Research, Development and Demonstration
Problem statement	
Adhesive bonding holds great potential, but a lot of work is required to make them generally accepted for manufacturing/joining of large components. Adhesive bonding can be used for joining of composite and steel components, but also for joining of individual composite sections or even steel to steel. The two main barriers to wider uptake of adhesive joining are: - A lack of experience and knowledge on the potential benefits of adhesive joining and in which applications they can be used. The potential positive impacts of using adhesives is not well understood, especially because design adaptations may be required which brings with it significant costs. The complete cost of ownership of innovative designs employing adhesive bonding needs to be evaluated and understood. - Limited knowledge of their key manufacturing and installation parameters, non-destructive inspection techniques, damage tolerance methodology and reliable diagnosis and prognosis of their structural integrity. There is a lot of uncertainty about the performance and durability of adhesive joints exposed to a combination of environmental degradation (temperature, humidity, UV) and mechanical loading (extreme loads, fatigue loads).	
Key Activities	
Research on the durability and fatigue performance of adhesive joints exposed to a combination of environmental degradation and mechanical loading. - A combination of laboratory and field testing. - Development of test procedures that can be standardised. - Investigation of degradation mechanisms. A better understand could allow the development of dedicated adhesives for maritime applications. Identification of potential applications for adhesive joining - A collaboration of engineering companies and RTOs with knowledge on the use of adhesive bonding can identify potential applications for adhesive joining. - Adaptation of current designs to make optimal use of adhesive joining: different installation procedures, maintenance is different, adhesively bonded parts cannot necessarily easily be dis-bonded again if individual parts need to be replaced. - Evaluation of the cost of ownership of devices incorporating adhesives, i.e. impact on the LCoE. An LCA should also be performed. - Large scale demonstration to evaluate whether the envisaged benefits are achievable and what problems may be encountered in terms of manufacturing and installation. Depending on the results of above activities, new adhesives dedicated to maritime applications may be required - Improved durability under the influence of seawater - Development of reversible bonding or adhesives that can easily be removed (for maintenance purposes) Development of techniques to inspect adhesive bonds - Techniques for quality control after installation - In-service inspection and/or monitoring in combination with data processing and analysis to evaluate the structural integrity and remaining life of adhesive bonds.	
Challenges in reaching the market	
There is a combination of technological challenges and a lack of knowledge/experience on the use of adhesive bonding. Technological challenges associated to the question of performance and durability in a maritime environment should be answered by means of research projects lead by RTOs and universities. These projects should include a significant awareness raising and knowledge transfer element in order to convince the industry of the potential benefits of adhesive joining. A large collaborative demonstration project, supported by government funding, could help to accelerate the market uptake of adhesive joining for large components in a maritime environment. By means of large scale	

demonstration, advances in terms of manufacturing and installation procedures can also be made. These steps need to be taken in order to be able to more accurately assess the potential economic benefits of adhesive joining. Wider market uptake doesn't only depend on proving the durability of the adhesives, but also on a better understanding of how adhesive joining impacts the design, manufacturing and installation procedures.

10.4 Reliability database for joints

Reliability database for joints	
Type of activity	Development
Problem statement	
A lot of information on used joining types, failure modes, failure rates and inspection costs exist at individual companies. Such data is not easily shared amongst companies, because it either gives a commercial advantage or because it might reflect badly on a company. Not sharing this information inevitable leads to the same solutions being tested multiple times. By sharing, development and selection of optimal solutions would be accelerated considerable. A reliability database, combining information on different types of designs, environmental and use conditions could feed information into the design of the next generation of offshore renewable energy devices. Making operational data publicly available, would also facilitate cross-sector learning and avoid the same mistakes from being made in new designs of for example wave and tidal devices. Additionally, such data could be used by start-ups, research organisations and established companies developing new tools/services to reduce O&M costs, such as for example through monitoring solutions. Finally, making such data publicly available and applying AI techniques to large amounts of operational data could help to identify which are the most costly failure modes and critical areas of devices, where there is potential to reduce the LCoE.	
Key Activities	

- Identification of required data
- Develop an approach to deal with IP and data sharing issues
- Data collection and structuring (what data should be collected and how can it be ordered in a database so that it can be used to feed into AI algorithms)
- Development of algorithms to extract information from the data in terms of for example:
    o Failure Mode and Effects Analysis
    o Optimal installation procedures
    o Optimal corrosion protection
    o Optimised inspection and maintenance procedures
- Demonstration: A reliability database can be considered as a digital demonstrator.	

Challenges in reaching the market	
The major challenge are IP and data sharing issues, which may be an insurmountable obstacle.	

11 Recommendations and further actions

From the above project ideas, those that fit best with the ADMA Energy goals and approach should be selected to be taken forward The essence of what ADMA Energy has set out to accomplish can be captured by the following quotes and will be used as a guidelines in this assessment.

> "The Pilot aims to make Europe the global leader in ***manufacturing of robust high integrity components and systems*** for marine renewables, subsea and offshore energy applications, by ***creating new business opportunities and increased growth for the sector***, and helping larger companies strengthen their supply chains by working with innovative SMEs all over Europe, whilst providing smaller companies with new, high-demand customers to grow their businesses."
>
> "ADMA Energy also aims to create new value chains across the growing offshore energy and subsea industries***, through the provision of support for advanced manufacturing technologies*** across traditional and emerging sectors and technologies – as well as ***disruptive innovations*** related to design, functionality, integration, automation, material, communication, etc. of components and systems in the "Blue Growth" and subsea domains. These innovations will enhance the quality and efficiency of products, services and processes."
>
> "Our fields of activity include marine renewable energy, traditional offshore energy sectors, as well as components and systems for ***application in harsh, subsea, and deep-underground environments***."

In terms of research, the most interesting challenges are:

- Bolt degradation in a maritime environment
- Adhesive bonding
- Interpretation of bolt pre-load data and impact on structural integrity and fatigue life

In terms of (large scale) demonstration, the following topics are considered to be most interesting:

- Large flanged joints (precision manufacturing of large components and impact of tolerances on design lifetime).
- Adhesive bonding, possible in combination with composite/Steel joint: focus on identification and evaluation of possible applications, followed by large scale demonstration. Adhesive bonding and the composite/steel joint could be combined in a single project because adhesive bonding could be a good choice for composite/steel joining.
- Development of guidelines on bolt installation and pre-load inspection/maintenance.

Companies interested in participating in a project related to the topics described above are invited to contact the ADMA Energy Pilot (www.s3vanguardinitiative.eu) or the author of this report.

Appendix A – Bibliography

List of consulted sources and companies contacted (interviews).

Consulted Reports

1	Floating Wind_Key risks and how to mitigate them_ORE Catapult	2017
2	ORE-Catapult-Innovation-Highlights-2018-19	2018/19
3	Substructures for offshore wind turbines current trends and developments	2014
4	Offshore wind in Europe-key trends and statistics 2018_Wind Europe	2018
5	ADMA Energy Analysis and Priority Setting	2019
6	guide-to-offshore-wind-farm-2019	2019
7	IRENA_Innovation_Outlook_Offshore_Wind_2016_summary	2016
8	2014-JRC-Ocean-Energy-Status-Report	2015
9	Slip Joint Turbine Completes Offshore Tests	2019
10	InnoEnergy - Future renewable energy costs: Offshore wind	2017
11	Fasteners - Corrosion protection systems and durability	2018
12	Wind Turbine Drivetrain Technology and Cost Drivers_JohnCoultate_Romax	2011
13	Analytical and numerical investigation of bolted steel ring flange connection for offshore wind monopile foundations	2017
14	Monopile foundations with flanged connections	2019
15	Innovative inspection for offshore turbine foundations	2018
16	Flanged foundation connection of the Offshore Wind Farm Amrumbank West – Concept, approval, design, tests and installation	2014
17	Detailed modeling of connections in large composite wind turbine blades	2013
18	The concept of segmented wind turbine blades - a review	2017
19	Wind generator tower splice bolts - the problems in north america	2008
20	Mechanical Joints in Composites - Experiences from the Wind Industry	2019
21	ROMEO project D4.1 - Monitoring technology and specification of the support structure monitoring problem for offshore wind farms	2018
22	Boltlife extends lifespan of wind turbines	2018
23	A Design Outline for Floating Point Absorber Wave Energy Converters	2014

Interviews

Company/organisation	Type	Interviewed on
ENGIE	Project Developer	07/10/2018
Tecnalia (Materials Department)	Research Institute	08/10/2019
Quattra-P	Engineering company	08/10/2019
Force Mechanics	O&M	10/10/2019
Donelli Alexo	O&M	11/10/2019
SSE	Project Developer	14/10/2019
Simec Atlantis	Technology Developer	14/10/2019
Tecnalia (Wave Energy)	Research Institute	16/10/2019
Ikerlan	Research Institute	17/10/2019
Erreka	Structural Fastener Supplier	17/10/2019
DNV GL	Certification and standardisation	25/10/2019
Magallanes	Technology Developer	25/10/2019
Navantia	Technology Developer	31/10/2019
EMEC	Research Institute	31/10/2019
Orbital Marine Power	Technology Developer	05/11/2019