NeSSIE
North Sea Solutions for
Innovation in Corrosion for Energy

State of the Art Study on Materials and Solutions against Corrosion in Offshore Structures

North Sea Solutions for Innovation in Corrosion for Energy

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The NeSSIE project (2017-2019) seeks to deliver new business and investment opportunities in corrosion solutions and new materials for offshore energy installations. The project aims to draw on North Sea regional expertise in traditional offshore sectors (i.e. oil and gas, shipbuilding) in order to develop solutions for emerging opportunities in offshore renewable energy sources (wave, tidal and offshore wind energy).

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1   Abbreviations and Acronyms

CCP	Corrosion Cathodic Protection
CFRP	Carbon Fibre Reinforced Polymers
DO	Dissolved Oxygen
FRP	Fibre Reinforced Polymers
LCoE	Levelized Cost of Energy
MIC	Microbiologically Influenced Corrosion
OE	Ocean Energies
O&G	Oil&Gas
O&M	Operations & Maintenance
OWE	Ocean Wave Energy
OW(S)	Offshore Wind (Structures)
SCC	Stress Corrosion Cracking
TCE	Tidal Current Energy
TCT	Tidal Current Turbine

2   Executive Summary

Operation and Maintenance (O&M) costs are typically around 15 - 30% of the total life-cycle cost of an Offshore Wind (OW) farm. Within the O&M budget, a large element is due to replacement parts caused by corrosion problems to metal structures. This document (deliverable 2.1) will map the current activities, research, standards and norms on corrosion solutions and materials currently used in the offshore energy field and will consider in more detail the impact of corrosion on offshore renewable energy structures in wave, tidal and offshore wind. This deliverable will be used as a current state of the art study in the offshore industry and will form the baseline for further work in WP2, WP3 and WP4.

The report will set the context by listing and defining the main technical concepts and materials that are used in marine environments and the main challenges of the offshore renewable energy field. This is followed by a description of the main corrosion phenomena occurring in offshore environments with attention given to their relationship with the characteristic areas of an offshore structure. The report will then review the materials and innovative solutions adopted in corrosion protection in the offshore sector and will present them together with the main industrial protection strategies for offshore wind structures.

In the last chapters, international standards and guidelines on the methods of design and operation of the main offshore renewable energy structures, materials and protection strategies from mainly corrosion and fatigue damages are summarized before some conclusions are drawn.

3   Introduction

3.1   Report aims and outline

The aim of this report is to present the state of art in terms of corrosion solutions and corrosion resistant materials suitable for application in offshore renewable energy structures. The report is the

result of a desktop study (scientific literature and standards) and is mainly focused on offshore wind and tidal energy structures. The report is complemented with input from industry experts.

In this chapter, first a number of terms used throughout the report are defined. In section 3.3 the materials used in marine environments are summarized. Some attention is paid to composite materials and concrete. However, these will not be discussed further in the report. This report focuses on corrosion issues and therefore is mainly concerned with metallic materials. The introductory chapter continues with a short exploration of corrosion and other challenges in the offshore wind and ocean energy sector.

The main corrosion phenomena occurring in offshore environments are described in detail in chapter 4. A distinction is made between the various areas of an offshore structure, in which different intensity of corrosion attack takes place. A review of corrosion resistant materials and innovative as well as commercially applied protection strategies for offshore wind structures is presented in chapters 5 and 6. In chapter 7 an overview of current corrosion mitigation strategies, used in offshore wind structures is given. This is complemented with remaining corrosion issues that were identified and possible innovative anti-corrosion strategies. Finally, international standards and guidelines relevant for the design and operation of offshore renewable energy structures, materials and protection strategies for corrosion and fatigue mitigation are presented in chapter 8. Chapter 9 collects the main conclusive remarks of this report.

According to current projections of the world electricity demand, electricity is set to remain the fastest-growing final form of energy worldwide, growing by 2.1% per year over the 2012-2040 period. Total global demand is expected to reach 34900 TWh in 2040, from 19400 TWh back in 2012. In this fast-growing movement, **offshore renewables are estimated to play a major role**, driven by both political and economic factors. The renewables-based electricity generation is projected to triple over 2013-2040, overtaking coal to become the largest source of electricity. According to the new policies scenario, 33% of the world electricity generation by source will come from renewables in 2040 (IEA, 2014) [1]. A significant part of this renewable energy comes from wind turbines, of which a large share of is located offshore. This has advantages in terms of predictability and availability of wind, as well as availability of development sites. Ocean wave and tidal energy generation are, by their very nature, also located offshore. The aim of this report is therefore to contribute to the development of renewable energy by focusing on these offshore structures.

Forecasts from 2009 indicated that by 2020 the total installed offshore wind capacity could be 40 GW, meeting 4% of the EU's total electricity consumption. However, at the end of 2015 the total installed capacity reached only about 11 GW, covering 1.5% of the EU's total energy consumption [2]. This may be explained by the complexity involved in the Offshore Wind sector, and the fact that supply chains are not yet established, leading to higher costs of energy generation than other methods of generating green electricity. Offshore wind has an average production cost of 110-130 €/MWh, nonetheless, there already are parks that will be commissioned after 2020 that have closed prices ranging 65-95€/MWh [3]. To continue the development of offshore renewable energy, the cost of installing and maintaining these structures needs to be decreased further. A significant part of the costs is the result of the harsh conditions in which these structures need to operate and, more specifically, the resulting corrosion. By presenting an overview of new and existing corrosion mitigation strategies, this report will prepare the way to find innovative solutions that will reduce the cost of renewable energy.

The UK has the largest amount of installed offshore wind capacity in Europe representing 40.8% of all installations, as reported in Figure 1a. Germany follows with 32.5%. Despite no additional capacity in

2016, Denmark remains the third largest market with 10.1% and the Netherlands (8.8%) displaces Belgium (5.6%) to have the fourth largest share in Europe, as highlighted in Figure 1a [4]. More in general, installation in the North Sea account for 72% of all offshore wind capacity in Europe, as reported in Figure 1b. In detail, the Irish Sea has 16.4% of installed capacity followed by the Baltic Sea with 11.5% [4]. In comparison, the development of other forms of renewable offshore energy (wave and tidal energy) is only in a start-up stage. Therefore, this desktop study is mainly focused on offshore wind structures in the North Sea basin. However, because the environment and corrosion phenomena are comparable, solutions for offshore wind structures can also serve as solutions for wave and tidal energy devices.

(a)   (b)
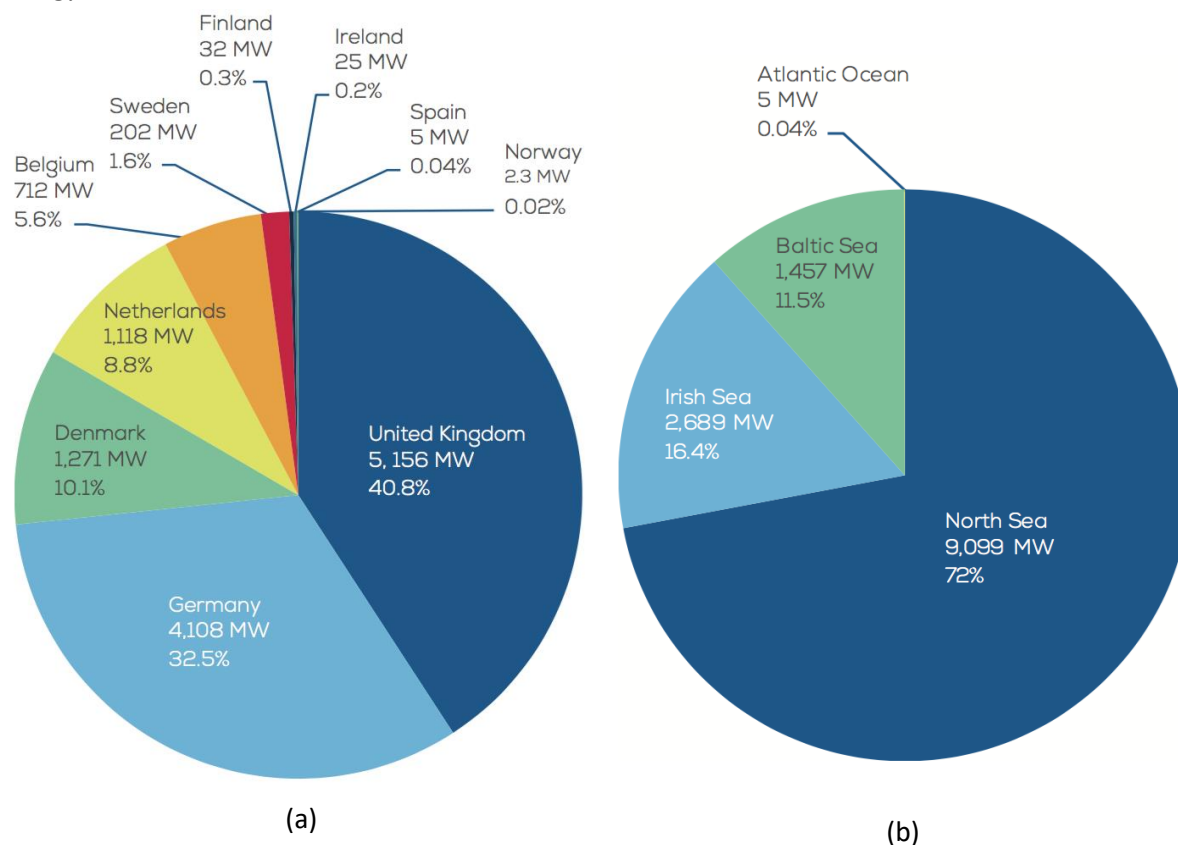
Figure 1: installed capacity up to 2016: (a) cumulative share by country (MW); (b) cumulative share by basin (MW) [4]

3.2   Definitions

In this paragraph all the technical concepts discussed in this report are defined as follows:

Marine Environment: The ocean, seas, bays estuaries and other major water bodies, including their surface interface and interaction, with the atmosphere and with the land seaward of the mean high-water mark. Seas and oceans act as a coherent ecosystem, within which all species and habitats are active and essential components. In addition, an enhanced appreciation on the interconnection between marine ecosystem and human communities is increasing. In particular, humans have been operating with and within marine environment for millennia, causing change through complex interactions. The consequences of human activities are now so profound that there are negative impacts on the structure and function of marine ecosystems around the globe. At the same time exploitation of the seas continues to grow [5].

Offshore renewable energy: which can be extracted by tides, wave and winds. In particular, offshore wind structure (OWS) uses energy from the wind to drive a turbine to generate electricity. Renewable ocean energy mainly consists of tidal and wave energy. Tidal current energy (TDE) is derived from twice-daily changes in water flow. Ocean wave energy (OWE) devices generate electricity by using water motion caused by winds at the sea surface. As world population grows at an average rate of 0.9% per year to an estimated 8.7 billion population in 2035, the energy consumption will sharply increase when more peoples move to urban areas.[6]. Future energy demands are hard to meet without burning fossil fuels or depending on nuclear power. Exploration of renewable energy is one of the expected solutions to achieve the sustainable development [7].

Corrosion: "Physiochemical interaction between a metal and its environment which results in the changes in the properties of the metal and which may often lead to impairment of the function of the metal, the environment or the technical system of which these form a part" [8]. Corrosion can be generally described considering the corrosion system, a three system phases: medium, material and interphase. The predominant media acting in offshore structures are air and seawater. In addition, condensation water in internal spaces and soil on foundations can be considered as additional media. As for offshore energy sector, the main ambition is to facilitate to European companies the best partnerships in order to address and solve specific technical challenge, corrosion in seawater is a fundamental issue to take into consideration in the different technological process steps. In particular, for offshore Oil&Gas one of the main challenge includes operation in deeper seas, higher pressures and temperatures with an increased level of corrosive and erosive materials, while for offshore wind energy the main challenge is to mitigate corrosion of towers and foundations, with a resultant increase in logistical challenges for installation and operation and maintenance [1]. So, achieving high quality results in an offshore environment is a major challenge. Corrosion on offshore structures highly depends on site-specific factors such as water temperature, salinity, chlorinity, water depth and current speed. The application process and the specificity of the corrosion protection system are extremely important and should be suitable for the substrate and the environment.

Operation: refers to activities contributing to the high-level management of the asset such as remote monitoring, environmental monitoring, electricity sales, marketing, administration and other back office tasks. Operations represent a very small proportion of Operations and Maintenance (O&M) expenditure, the vast majority of which is accounted for directly by the wind farm owner or the supplier of the wind turbines.

Maintenance: accounts for by far the largest portion of O&M effort, cost and risk. Maintenance activity is the up-keep and repair of the physical plant and systems. It can be divided into: i) preventive (proactive repair to, or replacement of, known wear components based on routine inspections or information from condition monitoring systems also including routine surveys and inspections) and corrective (reactive repair or replacement of failed or damaged components) maintenance and ii) remote/unmanned or with personnel.

3.3   Materials used in Marine Environments

A wide range of materials is applied in offshore systems. In particular, different **metals** are used [9]:

- Unalloyed and low-alloyed steel;

- Unalloyed and low-alloyed cast steel;
- Cast iron;
- Stainless steel;
- Stainless cast steel;
- Copper and copper alloys;
- Aluminium alloys.

All these metallic materials are regulated by the standard DNVGL-OS-B101 which provides technical requirements, production techniques and guidance for metallic materials to be used in the fabrication of offshore structures and equipment [10]. Metallic materials, mainly steel alloys, are often protected from the harsh environment of the seawater by coatings. In submerged and buried sections of offshore structures cathodic corrosion protection (CCP) can be also applied.

Composite materials have also attracted lots of attention in the offshore sector, due to excellent mechanical and durability properties. Composite materials are made of an assemblage of different parts with peculiar mechanical and chemical properties in order to produce a new material whose performance is superior to that of the individual parts taken separately [11].

Composite materials are usually classified in fibre composites, particle composite and laminated composites. In particular, fibre reinforced polymers (FRP) have been used extensively worldwide in both onshore and offshore applications, applied on secondary structures, such as railing grating walkway, cable tray, but also for turbine blades for both wind and ocean energy [12].

In addition, composite materials show potential as fire protectors in offshore structure. Carbon fibre reinforced polymers (CFRP) can also be used to repair steel structures. Galvanic corrosion could occur between the carbon and the steel. To prevent this, a layer of E-Glass FRP material can be used to electrically insulate the two materials [11]. Finally, the adhesive that shows good durability under marine environment condition is the epoxy resin and bonding is enhanced when the surface is treated with silane [13].

Particularly the ocean energy field is naturally turning to use composite materials because of their perceived non-corrosive properties in the harsh marine environment as well as their high specific strength and stiffness. However, the durability of this type of materials is considerably lower to metals in terms of erosion. This especially important for tidal turbines [7].

DNVGL-ST-C501 [14] provides an international acceptable standard for safe design with respect to strength and performance by defining minimum requirements for design, materials, fabrication and installation of load-carrying Fibre Reinforced Plastic (FRP) laminates and sandwich structures and components.

Offshore foundation structures, mainly in the O&G, are made of **reinforced concrete** due to low installation cost and good durability. These may be floating or gravity-based structures. DNVGL-ST-C502 regulates the principles, technical requirements and guidelines for the design, construction and in service inspection of offshore concrete structures [15]. However, in the aggressive chloride contaminated marine environment, susceptibility of the steel-reinforced concrete to corrosion attack can occur. In particular, chloride ingress into the concrete affects concrete durability through the destruction of the thin passive oxide layer protecting the concrete steel-reinforcement from corrosion degradation [16]. Rusts, the by-product from chloride attacks of concrete steel-rebar, are expansive within the concrete structure leading to cracks, spalling, delamination and loss of structural integrity

of concrete. The use of corrosion inhibitor admixtures in concrete for offshore structures has been identified as a potential solution, not just for improving strength, but also for improving its corrosion resistance. Well-known substances for inhibiting steel rebar corrosion in chloride contaminated environment include compounds of chromate and of nitrites, as well as innovative, non-toxic and environmentally-friendly admixtures [16].

As corrosion is the main issue for metallic alloys related to durability in offshore environments this report is mainly focused on corrosion mechanism of metallic alloys as well as corrosion solutions in order to optimize the durability of offshore structures.

3.4   Corrosion in Offshore Wind Structures (OWS) case study

An offshore wind structure (OWS) consists of a station-keeping system, foundation, foundation/tower interface structure, tower, nacelle, rotor blades and any other secondary steel structures (boat landings, platforms, walkways, …) [2]. Currently, offshore wind structures are particularly abundant compared to other types of marine based devices, such as waves or current energy converters [17]. In general, OW farms are planned for operational lives exceeding 20 years. For this reason, they must be designed to meet or exceed the operational and environmental loads expected to occur during the design life of the farm. In particular [18,19]:

- OWS should be designed to operate for stated design life without requirements for large-scale repairs, replacement or refurbishment;
- OWS should be designed to resist mechanical damage, physical and environmental loads and chemical deterioration while aiming at minimizing the total life cost of the structure;
- inspection, maintenance and repair (O&M) should be performed on a schedule in accordance with project specifications;
- structure and structural components should be designed with ductile resistance to applicable loads;
- structural connections should be designed as to minimize stress concentrations and complex stresses flow patterns;
- The structure should be designed considering several loading types, such as wind and tidal loads, hydrodynamic loads induced by waves and currents, snow and ice loads, impact by floating ice and other mechanical loads.

Offshore wind structures are exposed to a harsh environment, including [20]:

- Corrosion (accelerated by the presence of chlorides and microorganisms in seawater);
- Physical loads and impact (see above);
- Exposure to UV-radiation;
- Extreme sub-zero temperatures;
- Marine growth and biofouling;
- Bird droppings (can chemically degrade coatings).

One of the most probable failure and degradation mechanisms for OW steel structures are corrosion and fatigue. Corrosion can be described very clearly through a corrosion system, consisting of the three system phases: medium, material and interphase. In offshore wind energy structures, the main media are air and seawater. Seawater differs in composition depending on the geographical location;

however generally it is considered to be composed of 3.5 wt% of sodium chloride (NaCl) and its pH ranges from 7.8 to 8.3 and is considered as mildly alkaline [9]. In addition, as geographical locations induce different values of corrosion rates [9], difficulties exist in providing mean values of corrosion rates in the different geographical locations.

Two corrosivity categories must be considered for OWS according to ISO 12944-5:2007. Firstly, C5-M is for marine, coastal and offshore areas with high salinity for tidal, splash and atmospheric zones. Secondly, Im2 is for the zones permanently submerged in seawater [2].

Finally, regarding fatigue damage due to rapid development in the wind sector, offshore steel manufacturers now use standardized materials and fabrication techniques for the production of thicker plates for monopiles and other types of support structures. Therefore, the behaviour of the innovative materials with respect to the area of application needs to be understood. Also, fabrication techniques, such as the types of welding process employed nowadays, significantly influence crack growth behaviour in the materials in air and seawater environments. This is because of possible changes in the microstructure of the weld materials and level of weld induced residual stresses as a result of material thickness, material type, welding input parameters, and levels of restraints employed particularly during welding [21].

Different types of corrosion attack, relevant for ORE-structures, are described in chapter 4. For offshore wind structures, a more detailed overview of specific corrosion issues remaining today is presented in section 9.2.

3.5   Current challenges with offshore wind development

A rapid development of offshore wind structures occurred from 2000 to 2015 due to the targets set by the European Union (EU), but also due to OWS units of larger capacity being installed in larger farms [22]. In particular, in 2015 wind energy contributed to meet 11.4% of the EU's electricity demand, against only the 2.4% calculated in 2000 [22]. Since 2011, the United Kingdom has the largest amount of installed offshore wind powered structures in Europe, followed by Germany with both these countries showing a significant increase from 2011 to 2015. Denmark is the third largest producer of offshore wind power in the EU [2]. In addition, for offshore wind energy the main challenges include increased water depths, more remote and distant site locations, corrosion of towers and foundations and larger size of components, with a resultant increase in logistical challenges for installation, operation and maintenance.

Onshore wind farms have shown an outstanding level of development in the last few decades; however this has led to a decreased amount of available, high energy onshore sites remaining [23]. Offshore wind structures have available physical space with deep ocean waters representing 70% of the world's area [22]. In addition, OWS can be also placed at greater distance from the coast to reduce onshore visual impact and reduce social planning conflicts. Even though OWS costs are higher compared with onshore, OWS are placed in locations where wind speeds are much higher than onshore locations. For all of these reasons, offshore wind energy is a promising option for clean energy production in Europe.

OWS are subjected to several structural damage mechanisms including corrosion and fatigue; protective strategies should be considered because they are essential to reach the expected service life for which a structure was designed. Different protection systems can be used to delay and mitigate

corrosion initiation and its related consequences such as safety, structural integrity and service life [2]. A simple approach for protecting offshore wind structures can be to adapt coating systems developed for offshore Oil&Gas (O&G) platform. The coating industry has, over the years, developed special coating systems to protect offshore structures from corrosion. This approach of transferring the technology used for O&G industry would also allow the use of existing standard assessments schemes developed by the industry and regulatory bodies [9]. However, there are critical differences to be considered between oil platforms and wind towers. In particular, few systematic relationships between companies and organizations across these industrial sectors are currently set. In addition, considering conventional offshore O&G structures, some technical differences are reported in Table 1.

Table 1: Main critical differences between offshore O&G platforms and OW structures [9]

O&G platforms	OW structures
Corrosion protection systems generally under permanent inspection	Unmanned structures with highly restricted access (accessibility < 60%) [24]
Areas of deteriorated coating can be recognised and repaired	Deteriorated coating repairs are not feasible
No strong influence of loading in corrosion phenomena	Structural design and corrosion fatigue as crucial issue

Corrosion protection is always the last step during a production process. When a job is behind schedule, there is often pressure on the paint shop and the solution to compromise the application painting process to solve these time-related problems can create an extremely expensive situation [25]. In fact, the costs for the repair of corrosion protection systems of offshore wind energy structures are 5-10 times as high as the initial application costs. If repair must be carried out directly in OWS, costs are assumed to be 50 times higher than the costs considered during the initial application of the corrosion protection systems during the production of the tower [9]. For this reason, corrosion protection systems must **show a higher reliability** considering the harsh environment and must be **capable to protect the structure for a sufficient period of time** even if the corrosion protection system is mechanically damaged (expected service life for OW structure is 25 years). Finally, an **internationally acceptable level of safety** should be defined in accordance with the minimum requirements for corrosion protection systems, as suggested by [26].

Offshore repair of coatings is more expensive than painting onshore, due to logistic of getting men and materials to the job site and the limited access to the structures created by offshore weather conditions [25]. The main differences between onshore and offshore exposure are that in onshore conditions, usually there is cyclic due/condensation with or without minor salinity and moderate exposure to sunlight, resulting in moderate corrosion, whereas in offshore environment a long-term exposure to humidity with high salinity, intensive influence of UV light, wave action and the presence of splash zone area occur and high corrosivity stress give rise to dramatic and very fast corrosion [25]. Moreover, **achieving high quality results in an offshore environmen**t is a major challenge. Corrosion on offshore structures is highly dependent on site-specific factors such as water temperature, salinity, chlorinity, water depth and current speed. The application process and the specificity of the corrosion protection system are extremely important and should be suitable for the substrate and the environment. Effective, unambiguous, feasible and achievable specifications should be prepared by experts with a good understanding of the technology involved in protective coating systems. Expert judgment is primarily important when coatings systems are applied in very specific conditions such as

harsh offshore environment [2].

In particular, in the scenario of offshore applications in North Sea region protective systems will face a greater number of challenges, mainly caused by the harsh environment [27]. The environment is characterised by violent wind, high waves, very low air temperatures, infrared radiation, floating and pushing ice, rime and snow. It is known that steel corrosion will not be accelerated in low-temperature seawater or low-temperature atmosphere [28], although the water may show increased oxygen contents. It is not an increase in corrosivity, but rather the question how surface protective coatings will respond to the harsh environment, that will determine the performance of organic coatings, including the corrosion protection capacity, icing and de-icing behaviour and the response to mechanical loads [27,29]. In terms of corrosion protection capacity, the low air temperatures may be a special challenge to the coatings. Temperatures as low as − 60 °C can be expected in North Sea region [27,29]. Standard testing scenarios for offshore coatings [30,31] require air temperatures up to −20 °C only, and it is not known how organic coatings may perform at lower temperatures. The response to mechanical loads, namely to impact, will also be affected at low temperatures. It is known that the response of organic materials changes from plastic to elastic, or elastic–plastic response [32], and to higher rigidity modulus at low temperatures.

3.6 Current challenges in Ocean Energies (OE) development

Oceans have a tremendous natural resources, which are able to make significant contribution to our future energy demands [7]. In particular, ocean energy (OE) offers a renewable resource with the advantage of being predictable several days in advance, consistent throughout the day and night and significantly higher in its energy density compared to wind and solar energies [33]. Several types of ocean sources have been defined as potential sources to generate electricity, including tidal barrage, tidal current energy, wave energy, ocean thermal energy, and salinity gradient energy [34]. The challenge of ocean energy global market is 337GW of installed capacity by 2050 and in Europe the aspiration stated by the ocean energy sector is to install up to 100 GW [1]. So, ocean energy has significant potential, but related technologies require further improvement to drive down costs. Investments in research activities for wave and tidal developers show a clear interest to mobilise resources for strategic markets. However, the cost of tidal and wave energy generation is less competitive than other methods of generating green electricity. In particular, tidal energy has production costs around 350€/MWh and wave energy, has higher costs at some 450 €/MWh [35], though these figures are rough estimates, due to the emerging nature of these technologies. The OE markets represent for Europe a progress towards a resource-efficient economy, with great projection in terms of economic growth and job creation. However, they are still far from the forecasted scale and commercial deployment. This increase in the Ocean energy installed power will be only possible if a dramatic reduction of the Levelized Cost of Energy (LCoE) of these renewable sources is achieved, estimated to be at around 130-150 €/MWh for wave and tidal generation within 2020.

Tidal current energy (TDE) is one of the most advantageous resources, which can be extracted from the rise and fall of sea levels caused by the gravitational force exerted by the moon and sun and the rotation of the earth [7]. It is more predictable and easier to be quantified compared to wind and wave energies. For this technology, extreme sea conditions have to be considered for the survivability of tidal current turbines (TCT), which is the biggest current challenge for ocean energy [1,7]. In particular, sea environment is harsh due to the intrinsic nature of the sea state. The underwater conditions are more predictable and calmer compared to the water surface in sea. Atmospheric hurricane does not

exist underwater. Less action needs to be taken to the tidal current power compared to the wind power technologies. However, extreme events occur frequently, such as hurricane, typhoon, tsunami and storm, and bring along the extreme wave and strong wind, which could have severe impacts on the survivability of TCTs. So, the surface wave generated by the extreme events may have negative influences on the performance of TCTs.

Tidal current turbines are vulnerable to the damage of seabed scour, fatigue failure of blades and corrosion failure due to saline water attack and the hydrodynamic failure of biofouling at the blades [7]. In particular, The TCTs face corrosion issue in their lifetime and the corrosive environment bring uncertainty to the reliability of TCTs. TCTs operate in such environment with the presence of large suspended solids which may possibly lead to erosive damage over lifetime of the device [36]. The loss of materials on the overall TCTs system may cause severe negative effect on the durability of TCTs. Some of the TCTs are partially submerged, such as Seaflow and SeaGen. The upper part of the TCTs is affected by aggressive atmospheric environment, which contain high content of chloride, oxygen and other corrosive species. In addition, the seawater arising from wave effects could spray on the upper part of TCTs. Salts may be detected in the air due to salt spray blown by wind. Moreover, carbon dioxide (CO_2), hydrogen sulphide (H_2S), sulphur dioxide (SO_2), and sulphur trioxide (SO_3) are the gases contained in the air. They accelerate the corrosion rate through activating the thin layer of electrolyte [37]. On the other hand, the submerged structure of TCTs could experience immersion corrosion.

The ocean energy field is naturally turning to use composite materials as their perceived non-corrosive properties in the harsh marine environment as well as their high specific strength and stiffness. For example, Seaflow (300 kW) and SeaGen (1.2 MW) tidal turbines are the ocean energy devices partially made by composite material [38]. However, the durability of composite material is considerably inferior to metals in terms of erosion [7,36]. In particular, the blades of turbines may operate in turbulent slurry flows. The cavitation may interact with corrosion processes. Plastic deformation of the surface or puncture of the corrosion-resistant passive films on unprotected metallic surface may take place. The particles in the flow can even strip protective paints from metallic surfaces [7,36]. The loss of materials on the structural components of TCTs may influence their structure capacity. So, the potential sites for TCTs have fast flow, which could wash away the corrosion-resistant passive films on the metallic surface of TCTs' components. The painting against corrosion and fouling on the surface of TCTs' components also face the same issue. The degradation of coatings of TCTs should be investigated in order to know the optimum schedule for maintenance. Also marine fouling could increase the hydrodynamic loading significantly due to increasing of marine structure's surface roughness and dimensions of submerged parts of marine structures [39]. Furthermore, underwater operation and inspection could be impeded by the assemblage of marine organisms due to obscuration of underlying substratum. It affects further maintenance and monitoring of TCTs.

4   Types of corrosion

4.1   Introduction

Several zones exposed to different environmental conditions are usually considered in offshore renewable energy structure. In particular, a schematic representation of the five typical zones of OWS is shown in Figure 2 and the typical zones can be defined as follows:

1. *Buried zone* that includes any structural parts buried in sea floor sediments or covered by disposed solids.
2. *Submerged zone*, where the structure is permanently submerged. Corrosion cathodic protection (CCP) is generally used in this zone, often in conjunction with coating.
3. T*idal zone* or *intermediate zone*, between the minimum and the maximum level of tides and governed by their variations. This region is subjected to wetting and drying cycles. In this area, degradation occurred due to chemical attack, abrasive action of waves and the attack of microorganisms. This zone is often coated.
4. *Splash zone*, immediately above the maximum level of the intermediate zone. In this zone, the surface is directly affected by water splash. The height of the splash zone is a function of the wave height, as well as of the speed and wind direction and is subjected to cycles of wetting and drying. This zone is often coated using a multi-layer scheme involving glass flakes-reinforced polymer to help protect against mechanical damage. Corrosion becomes more significant as water evaporates, and salts remains on the surface of the substrate.
5. *Atmospheric zone*, above the splash zone where the steel tower and topside structure suffers actions from marine aerosol, however, unlike the splash zone the structure is not directly attacked by water splashes. The winds carry the salts in the form of solid particles or as droplets of saline solution. The quantity of salt present decreases as a function of height distance from the mean water line. Also this zone is typically coated [2,7,9,20,26].
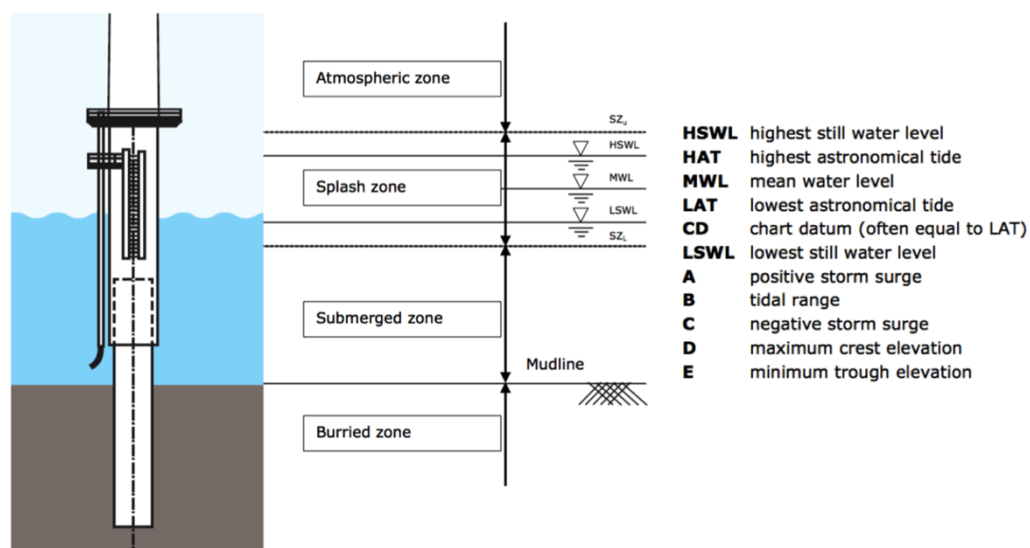
Figure 2: Schematic representation of levels and zones in seawater environment [26]

As carbon steel is usually applied for both OWS and OE industry (especially for constructing the supporting structure of TCTs), some authors report that the corrosion rates of carbon steel in the

harsh offshore environment can be greater than 2.5 mm per year, depending on the location [40]. In addition, corrosion rate of carbon steel increases with increase of water velocity at an exponentially decreasing rate [7]. In particular, for North Sea region a corrosion rate mean value of 0.2 mm/y for carbon steel (one of the most used materials in OWS) was measured from experimental studies [9,41]. However, from experimental studies, corrosion rates were measured with mean values reported in Table 2 and corrosion rates of steel are the highest in correspondence of the splash zone of offshore construction, as reported in Table 2 [20]. So, splash zone requires particular attention for corrosion protection.

Table 2: Corrosion rates (mm/y) of carbon steel in offshore service [40]

Environmental zone	Corrosion rate (mm/y)
Buried in soil	0.06-0.10
Submerged zone	0.10-0.20
Intermediate zone	0.05-0.25
Splash zone	0.20-0.40
Atmospheric zone	0.050-0.075

In addition, the design practice DNVGL-RP-0416 states higher minimum values for corrosion rates on primary structural parts in splash zones. In particular, for temperate climate region (annual mean surface temperature of seawater ≤ 12 °C) corrosion rate should be considered as 0.30 mm/y for external surfaces, while for subtropical and tropical climate region 0.4 mm/y is the minimum value [26].

Corrosion can be classified according the appearance of the corrosion damage or the mechanism of attack as [2,42]:

- **Uniform or general corrosion:** accounts for the greater proportion of metal deterioration in terms of mass and of metal converted to corrosion products. It is predictable on the basis of laboratory and field testing;
- **Pitting corrosion:** localised corrosion attack in which only small areas of the metal are corroded, whilst the remainder is largely unaffected. Pitting is insidious, as it frequently results in perforation of the metal with consequently loss in physical and mechanical performance;
- **Crevice corrosion:** intense localised corrosion than can occur within narrow crevices that may be formed by the geometry of the structure (e.g. riveted plates, welded fabrications and threaded joints), by contact of metal with non-metallic solids or by deposit of sand, dirt or permeable corrosion products on the metallic surface;
- **Filiform corrosion:** characterised by the formation of a network of threadlike filaments of corrosion products on the metallic surface usually coated, as a result of exposure to a humid atmosphere;
- **Galvanic corrosion:** occurs when metals or alloys with different practical nobility, are in physical (and electrical) contact in the presence of a corrosive electrolyte;
- **Erosion-corrosion:** includes all the forms of accelerated attack that induce the removal of metallic materials due to the abrasive action of movement of a fluid (liquid or gas) at high velocity;
- **Intergranular corrosion:** where the region immediately adjacent to the grain boundaries are preferentially attacked;
- **De-alloying:** selective dissolution of one metal can occur in certain alloys under certain environmental conditions and can result in perforation or in a more uniform attack;

- **Environmental assisted cracking, including stress corrosion cracking (SCC), corrosion fatigue and hydrogen damage:** combined effect of the chemical attack and mechanical stresses (e.g. corrosion fatigue, tensile stress with specific corrosive environments).

Table 3 shows the corrosion zones previously defined of an OW structure and the mostly liked form of corrosion for each zone.

Table 3: Corrosion zones and form of corrosion in OWS [18,19]

Corrosion zones	Main form of corrosion
Atmospheric zone	
External and internal areas of steel structure	Uniform and erosion-corrosion, Stress-corrosion cracking (SCC)
Internal surfaces without control of humidity	Uniform and pitting corrosion
Internal surfaces of structural parts	Crevice, pitting and galvanic corrosion, SCC
Splash and tidal zone	
External and internal areas of steel structure	Uniform, crevice, pitting corrosion, SCC
Internal surfaces of critical structures	Uniform, crevice, pitting corrosion
Components below mean water level (MWL)	Uniform corrosion, MIC
Components below 1.0 water level of the MWL	
External surfaces in the splash zone below MWL	
Submerged zone	
External and internal areas of steel structure	Uniform corrosion and erosion-corrosion, MIC
Internal surfaces of steel structure	Uniform, crevice and pitting corrosion, MIC
Critical structures and components	Uniform and/or pitting corrosion, MIC, SCC

In addition, considering the deep-sea environment additional considerations should be stated. In particular, this environment is very different from the sea at the surface, as it is characterised by total absence of sunlight, high hydrostatic pressure (increase of 1 atm for each 10 m in depth) and a low water temperature of about 3 °C [43]. As the business community increasingly request great performances for structure materials (*e.g.* metals and alloys) in deep-seawater, laboratory experiments were performed under controlled conditions. It was found that the available literature on this topic is scarce, deep-sea experiments are expensive and technically demanded and the results comparison is difficult as they are influenced by experimental features and local effects. However some main issues can be highlighted: concentration of dissolved oxygen (DO) in sea-water (oxygen level increases at higher depth of 100 mm due to cold, dense, oxygenated water sinking in polar regions), low sea-water temperature (usually about 3 °C) and microbial communities (composition of bacteria present in deep-sea biofilm appears to be as complex as the coastal bacteria biofilm community and very diverse even at great depth) [43].

4.2   *Microbiologically influenced corrosion (MIC)*

Microbiologically influenced corrosion (MIC) occurs in seawater and in soils. It is often seen as pitting attack. A great variety of organisms can be associated with MIC. Some can be easily observed such as barnacles, algae, mussels and clams while others are microscopic (bacteria). These microorganisms tend to attach to and grow on the surface of structural materials, resulting in the formation of a

biofilm. The microorganisms and bacteria may directly cause corrosion, or influence other corrosion processes of metallic materials [2]. In the case of OWSs, heavy encrustations of hard-shelled fouling organisms form on the surface of the metallic structure. These organisms change the environmental variables including the oxidizing power, temperature and the concentration of any aggressive species. Therefore, the value of a given parameter on the metallic/seawater interface under the biofilm can be different from that in the bulk electrolyte away from the interface. This difference may result in corrosion initiation under conditions in which there would be none if the film was not present. Presence of the biofilm may also yield changes in the form of corrosion (from uniform to localized) or an increase in the corrosion rate [2].

MIC refers to corrosion that is induced by the presence and activities of microorganisms and the products produced in their metabolism in anaerobic conditions and stagnant fluids. The mechanism by which sulphate reducers (SRB) accelerate metal corrosion is the topic of various research projects, but details of the process are still inadequately understood. In addition to SRB also Iron-reducing bacteria (IRB) or Iron-oxidizing bacteria (IOB) can play in relevant role in MIC. Especially the sulphate reducing bacteria (SRB), which occur under anaerobic conditions can play a major part in soil corrosion. The reaction product of SRB metabolism is sulphide ions, which react with the metal surface allowing corrosion. The environmental conditions under which these microorganisms normally operate are temperatures from 20 to 30 °C and pH from 6 to 8 [44].

This is a very specific site problem depending very much on the environmental conditions and is hard to predict or even detect. Biofilm morphology plays a critical role in MIC pitting [45]. MIC usually takes place around the mud line, outside and inside the foundation structure and is influenced strongly by the nutrients levels in the water [46]. The probability for MIC is increasing with the availability of organic matter in the soil. MIC is also possible in an oxygen free environment, making the concept of airtight substructures even more questionable.

MIC could be detected using coupons as test samples in the suspected areas to monitor the corrosion processes and examining these during the inspection program. Changes in the pH value of the internal water column (mainly localized at the bacteria/metal interface) can also indicate relevant bacteria growth [47]. Objective evidence on the impact of the corrosion processes and the integrity of the structure will only be attained by local inspection and wall thickness measurements by Remotely Operated Vehicle (ROV) or diver [48].

4.3   Fouling and biological growth

Marine biological fouling, usually called marine biofouling, can be defined as the undesirable accumulation of microorganisms, plants, and animals on artificial surfaces immersed in seawater [49]. The adverse effects caused by this biological settlement are the following:
- High frictional resistance, due to generated roughness, which leads to an increase of weight;
- Influence on increased drag and hydrodynamic loading;
- Deterioration of the coating so that corrosion, discolouration, and alteration of the electrical conductivity of the material are favoured [50];
- Increase of the O&M costs mainly linked to the regular operations of removal of this biological settlement.

The imminent ban of environmentally harmful tributyltin (TBT)-based paint products has been the cause of a major change in the antifouling paint industry. In the past decade, several tin-free products have reached the commercial market and claimed their effectiveness as regards the prevention of

marine biofouling on ships in an environmentally friendly manner.

From the analysis of the factors affecting the biofouling process, the interference with the settlement and attachment mechanisms is the most promising environmentally benign option. This can be accomplished in two main ways: imitation of the natural antifouling processes and modification of the characteristics of the substrate. The potential development of broad-spectrum efficient coatings based on natural anti-foulants is far from commercialisation. However, exploitation of a weakening of biofouling adhesion by means of the non-stick and fouling-release concepts is at a rather advanced stage of development [49].

4.4   *Stress corrosion cracking*

The term stress corrosion cracking (SCC) describes a premature service failure of engineering materials that occur as consequence of crack propagation induced by the simultaneous and synergistic presence of an aggressive environment and a mechanical tensile stress. Static loading is usually associated with SCC, while crack propagation due to cyclic loading in the presence of an aggressive environment is referred to as corrosion fatigue. Both are considered as "environmentally induced cracking".

SCC is highly specific and is observed only for a definite material/environment combination, as neither factor can produce the same effect if acting independently. In fact, if the stress or the specific environment is removed, the crack propagation will stop or the SCC will not occur.

The stress values required to induce SCC are small, usually well below those of yield stress (*i.e.* lower than the stress required to produce a purely mechanical failure).

Under the action of SCC, most of the structure is only affected by general corrosion, while, on the contrary, SCC will not normally occur if a strong general corrosion is present. On the other hand, situations of local attack, such as pitting, favour the establishment of SCC. This form of corrosion is particularly insidious, because it can affect critical components or structures and a general inspection may not reveal any evidence of attack as microcracks are formed at a microscopic level. The main aspects to be considered in SCC are environmental conditions, stress state and the selected materials.

In a marine environment, the main aggressive species are chloride ions; however, during operation, conditions where sea water can be contaminated with other chemicals, such as process fluids, are possible. The materials surface conditions, the local concentration of aggressive species and solution temperature in contact with stressed materials will influence the likelihood of SCC in a complex way, making the estimate of the attack probability very difficult.

Stresses in metallic structures can be caused by the type of assembly or by residual stress resulting from the fabrication process, such as cold working or welding. In high strength alloys, locked-in stresses can arise internally when heat treatment or aging induce precipitation at grain boundaries with consequent internal strain. The residual stresses caused by fabrication can be relieved by annealing or by post weld heat treatment. In the case of stainless steels, these treatments are important not only for relief of the residual stresses, but also to homogenise the composition in order to minimize the risk of sensitization and impart the highest corrosion resistance. The main option for reducing the risk of the chloride-induced SSC consists in an accurate design of the critical parts to prevent the accumulation of high chloride concentration levels and to avoid high temperatures . After optimal designs, the risk of Cl-SCC can be reduced by choosing more resistant alloys.

Ordinary carbon steels are not susceptible to SCC in marine environments, while high strength-steels can suffer from hydrogen-induced stress corrosion as consequence of hydrogen penetration in the materials during pickling processes, electroplating or cathodic protection. In marine environment aluminium alloys like Al/Zn/Mg, Al/Mg, Al/Cu and austenitic stainless steels are susceptible to SCC.

The susceptibility of ferritic and duplex stainless steels depends on environmental conditions and on the steel composition and structure. In ferritic stainless steels, small nickel additions result detrimental to SCC resistance in the presence of chlorides. Laboratory tests, carried out on different types of stainless steels and alloys, highlighted the effect of nickel content on SCC susceptibility (Figure 3) and suggested that nickel amounts between 30-40 wt% are necessary to avoid SCC [51]. Duplex stainless steels generally have considerably higher threshold stress levels for chloride SCC than austenitic ones [52] and show higher resistance to SCC because of the presence of the ferrite phase. Concerning aluminium alloys, the SCC is limited to high strength alloys. ASTM and the Aluminium Association developed a system to rate the SCC resistance for high-strength aluminium alloys in chloride environment [53]. This classification covers ratings of the relative resistance to SCC of various wrought heat-treated aluminium alloys and the procedure for determining them. The ratings do not apply to metal where the metallurgical structure has been altered by welding, forming, or other fabrication processes. The documents MIL-HANDBOOK-5 MIL-STD-1568, NASC SD-24 and MSFC-SPEC-552A can be useful for design purpose.
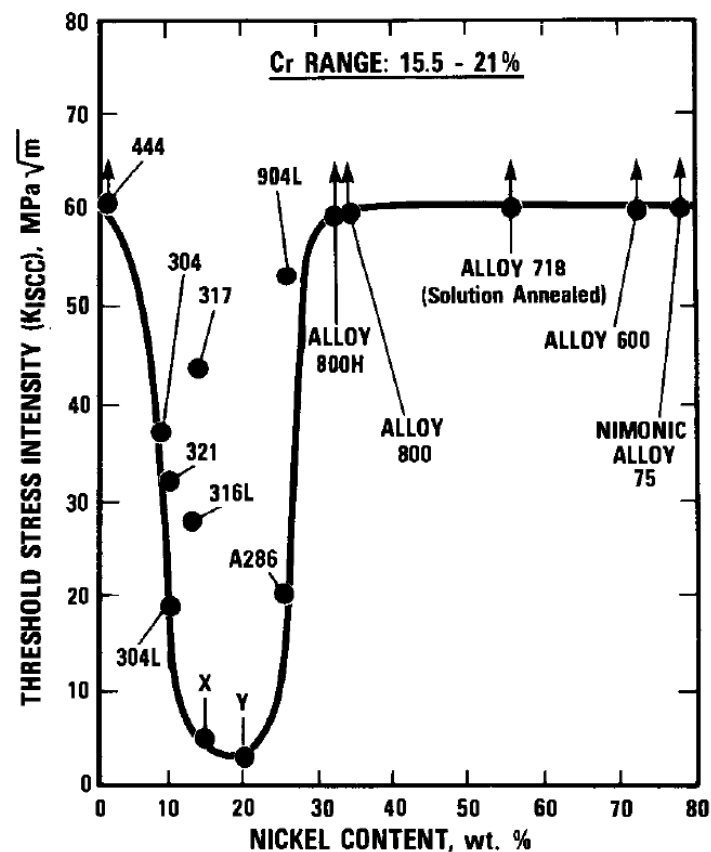
Figure 3: Effect of nickel content on the stress corrosion threshold for different alloys [54]

4.5   Corrosion fatigue

Fatigue consists of a process of localized, cumulative and permanent damage resulting from the action of cyclic loading. Repeated loading and unloading of a structure, mainly in tension can result in failure. The permanent action of cyclic loading can lead to crack initiation. Fatigue strength mainly depends on the number of cycles of loading, the range of service load stresses and the presence of high stress

concentrations. In addition, the main parameters influencing the fatigue life of a structure are the materials properties, the geometry and properties of the element, the environmental effects and the loading [2].

The corrosion crack growth mechanism can be amplified under fatigue loading due to the synergistic interaction of the applied cyclic loads and the influence of the corrosive environments. This is the case of the mechanisms may occur in the offshore structures due to the cyclic loading on the structure from harsh offshore environments [21].

Fatigue behaviour can be significantly influenced by variation in temperature, pH, dissolved oxygen and salinity and in particular by seawater composition. For this reason, significant differences in test conditions may also results in appreciable variations in crack growth behaviour of the materials.

Fatigue cracks can progress from existing defects that may be introduced by manufacturing, fabrication, transportation and installation. In particular, welded parts are very susceptible to fatigue cracking generally due to stress concentration and residual stresses, as well as microstructural defects and heterogeneities induced by discontinuities linked to welding execution. In addition, poor design can increase stress concentration increasing its susceptibility to fatigue cracking also in case of simultaneous actions of fatigue and corrosion. For these reasons, defects or cracks in offshore structures need to be reliably inspected and monitored to ensure that the structure meet the service design life [21].

In addition, fatigue design is considered for offshore steel structures, in accordance with the recommended practice DNVGL-RP-C203 [55]. This standard is valid for Carbon Manganese steel materials in air with yield strength less than 960 MPa, while for the carbon and low alloy machined forgings for subsea applications the S-N curves are valid for steels with tensile strength up to 862 MPa in air environment. In addition, for steel (C-Mn) in seawater with cathodic protection or steel with free corrosion, the recommended practice is valid up to 690 MPa. Finally, DNVGL-RP-C203 is also valid for bolts in air environment or with protection corresponding to that condition of grades up to 10.9, ASTM A490 or equivalent [55].

Consideration of the fatigue limit state is a major part of the design of offshore wind foundations, as wind turbines induce high fatigue loading into the foundations. The resistance against fatigue is normally given in terms of an S-N curve that reports the number of cycles N versus the stress range S. In particular, the design fatigue life for structural components should be based on the specified service life of the structure. The S-N curve are provided for the following environmental conditions: "in air" for surface with coating, "in seawater" for surfaces with cathodic protection, "free corrosion" for surface protected by only corrosion allowance [48]. In correspondence of tidal zone, the S-N curves approach reveal some uncertainty in the internal monopile due to the fact that these areas that are not constantly submerged do not receive adequate CCP.

5   Use of corrosion resistant materials

Corrosion is a primary issue for metallic materials. Although concrete, polymers and polymer composites also suffer from degradation under the influence of environmental conditions, these material classes will not be considered in this report. The aim of this report is to provide a basis to reduce costs due to corrosion in offshore energy structures. These costs are mainly linked to structures for which the use of metallic materials is required.

5.1   Materials selection

A notable number of materials are being utilized for offshore structures, including the following materials [9]. In particular, for OWS different corrosion rate values were measured in the North Sea for different materials. In particular, zinc shows an annual corrosion rate of 0.0031 mm, while copper and steel annual corrosion rate values of 0.0053 mm and 0.119 mm, respectively [9]. However, for cost reasons, OWS are mainly made of corrosion sensitive construction steels. For this reason, the corrosion protection strategies play a strong role in the service life of offshore wind energy structures.

Two corrosivity categories must be considered for OWS according to ISO 12944-5 [56]. Firstly, C5-M is for marine, coastal and offshore areas with high salinity for tidal, splash and atmospheric zones. Secondly, Im2 is for the zones permanently submerged in seawater. Corrosion rates for construction steel below sea level average 0.2 mm/y. In the tidal and splash zones, the corrosion rates may fluctuate between 0.4 to 1.2 mm/y [41,57]. Other authors have reported that the corrosion rate of construction steel in offshore environments can be as high as 2.5 mm/y depending on the location [40].

5.1.1   Carbon manganese Steel

Carbon manganese steel is not corrosion resistant and must be protected by means of cathodic protection, coatings or other systems. This type of steel is still included in the current review, because it is the most commonly used material for pipelines in the North Sea. More specifically, material grades X46, X52 and X60 have widely been used. Later more high strength steel types as X65, X70 and higher were developed and used [58]. Table 4 shows the chemical composition of these unalloyed steels. The index refers to the minimal yield strength expressed in KSI (x 6.89 to convert in MPa). Other more corrosion resistant steel as duplex and super duplex steel and 13%Cr stainless steels have been used as material for pipelines. During the last years few pipelines were made of C-Mn steel internally lined (mechanical bonding) or clad (metallurgical bonding) with corrosion resistant alloys such as 316L, Incoloy 825 and Inconel 625. For external protection, coatings based on asphalt enamel or fusion bonded epoxy covered with other types of plastic, such as PE or PP were applied for mechanical protection or heat insulation. Besides these coatings the corrosion is controlled by cathodic protection in case of coating damages.

Table 4: Composition of steel grades for pipes according to API

Grade	Max %C	Max %Si	Max %Mn	Max %P	Max %Cr	Min Yield (MPa)
API 5L X46	0.16	0.45	1.5	0.025	0.3	316
API 5L X52	0.16	0.45	1.6	0.025	0.3	358
API 5L X56	0.16	0.45	1.6	0.025	0.3	385
API 5L X60	0.16	0.45	1.6	0.025	0.3	413

| API 5L X65 | 0.16 | 0.45 | 1.65 | 0.025 | 0.3 | 447 |
| API 5L X70 | 0.16 | 0.45 | 1.7 | 0.025 | 0.3 | 482 |
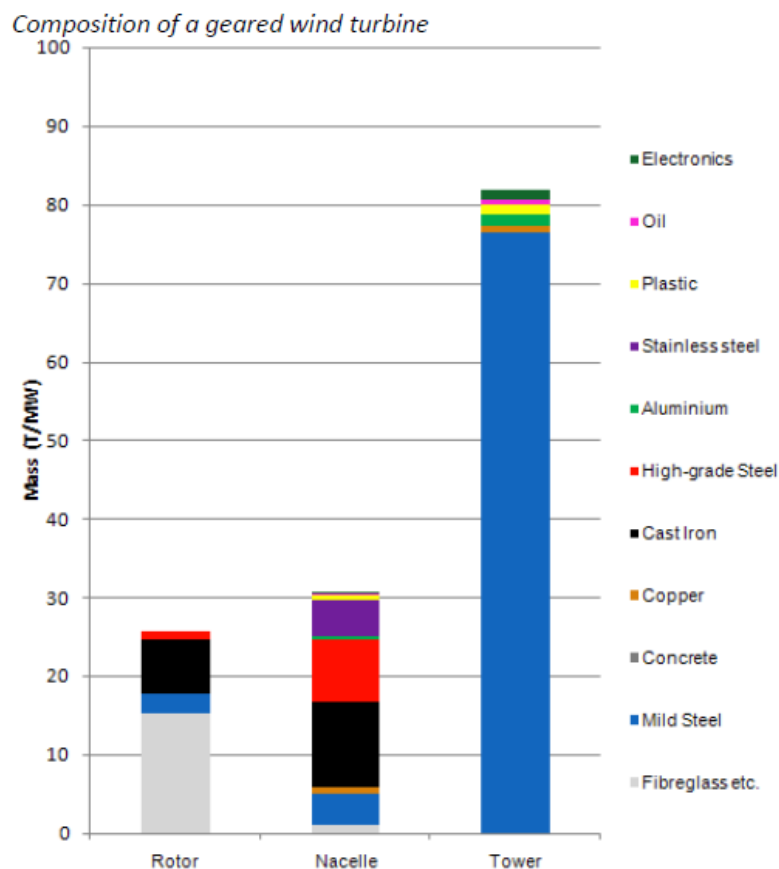
Figure 4: Different materials used in geared wind turbines

In the '60s and '70s, the construction of offshore platforms for the production of oil and gas in the North Sea required heavy plate properties that significantly exceeded the requirements of conventional constructional steels [59]. Due to stringent requirements on the safety and reliability of the platforms under very extreme external conditions (low temperatures, severe storms, high waves, and corrosion by seawater), as well as the necessity of partial assembly on-site at sea, heavy steel plates with especially high ductility, high resistance against crack growth and good fabrication properties had to be developed. These steels involved substantial developments from **fine-grained steels** to special offshore grades. These offshore steels like S355G10+M according to EN 10225 [60] were introduced. The plates can be delivered in either a normalized (+N) or in thermo mechanical-rolled condition (+M) with thicknesses of up to 250 mm. In particular, the TM-rolled heavy steel plates show very good toughness properties after welding and can be processed in a cost-effective manner [59]. Recent platform constructions are characterized by a higher overall height due to deeper sea levels. When applying the classical S355 steel grade in these constructions, the necessity of large cross-sections considerably increases the total weight of the structure. Therefore, **high-strength steel** plates like the steel grade S460 [61] have gained recognition in the North Sea platform applications. These plates are delivered in thicknesses of up to 120 mm in the TM-rolled condition. Plates with greater thicknesses are normally used in the quenched and tempered condition (+Q). Tests with higher

strength steel like S690 are currently under investigation [61] to reduce the plate thickness but maintaining or increasing the bending moment of the tower. Figure 4 gives an overview of the different materials used in modern wind turbines [62].

The tower is mainly composed of mild steel, aluminium and plastics whereas the nacelle contains high grade steel, stainless steel and cast iron (Figure 4). Regarding the use of high strength steel (yield strength > 450 MPa) in offshore and marine environments, hydrogen embrittlement (HE) and corrosion fatigue is mentioned as problems [58,63]. The principal sources of hydrogen in steel are from corrosion reactions and cathodic protection (CCP). Welding can also cause high hydrogen contents if, for example, the consumables are not dry and without applying preheat. It has been shown that the uptake of hydrogen by steel in the marine environment is strongly influenced by the combined effects of CCP and sulfate reducing bacteria (SRB). CCP produces hydrogen on the steel surface and its absorption is promoted by the biogenic sulphides produced by the sulphide reducing bacteria (SRB). When sulphides are present, as in sour oil and gas environments, it is often termed sulphide stress corrosion cracking (SSCC). In both cases, these are forms of hydrogen embrittlement (HE). They are quite distinct from hydrogen induced cracking (HIC), usually associated with pipeline steels, in which hydrogen generated by internal corrosion in sour oil or gas is absorbed by the steel and collects at elongated manganese sulphide inclusions where it leads to stepwise cracking. The mentioned mild carbon manganese and high strength steels have no resistance against general, local and specific corrosion in harsh marine environments and must therefore be coated or painted. However **special steels** or low-alloyed construction steels were developed containing small amounts of copper, chromium and nickel with increased corrosion resistance. The so-called **weathering steels** (*e.g.* Cor-Ten steel) are an example of this group [64]. However most of these CorTen steels are not suited for exposure in marine atmospheres because the presence of high chlorine concentration will locally attack the surface and destroy the natural protective layer as formed in urban environments. Table 5 shows the composition of low-alloyed construction steel that can be used against corrosion. In most cases the surface of these steels must be painted to protect the steel against local corrosion.

Table 5: Chemical composition of unalloyed and low alloyed structural steel with improved corrosion resistance

Steel grade	% C	% Mn	% Cr	% Ni	% Cu	% N	%Al	% P
X60 (S420)	< 0.16	< 1.60	-	-	-	-	-	< 0.025
Cor-Ten B	< 0.19	0.8-1.25	0.40-0.65	< 0.4	0.25-0.40	-	0.02-0.06	0.035
S355J0WP	< 0.12	< 1.0	0.30-1.25	-	0.25-0.55	0.009	-	0.06-0.15
ASTM A690	0.22	-	-	0.75	0.50	-	-	0.15
AMLoCor	0.11	0.87	1.0	-	-	0.007	0.65	-

A new construction steel, *i.e.* **AMLoCor**, was recently developed by the Arcelor Mittal Group in Luxemburg for sheet piling [65]. The composition of this steel can be found in the Table 5. The mechanical properties of this steel are equivalent to the S355 but its composition contains 0.8 % Cr, 0.4 % Al and 0.011 % N. There are three types available depending on the strength level *i.e.* Blue 320, Blue 355 and Blue 390. Comparative corrosion tests with S355 showed that the new (uncoated) steel has a lower corrosion rate in the splash- and immersion-zones (Figure 5).
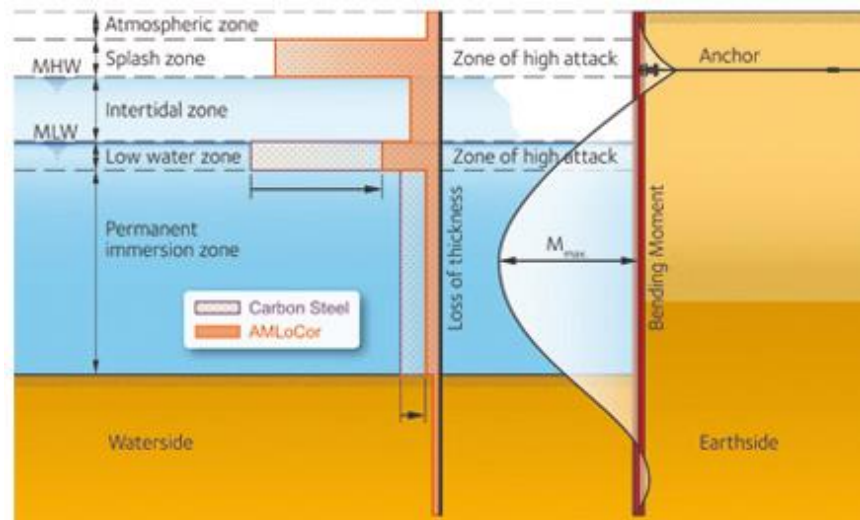
Figure 5: Loss of thickness due to corrosion and bending moment of steel in sheet piling

5.1.2   Cast iron

Although most cast iron grades have a good corrosion resistance to water and atmospheric conditions, they are not resistant to chlorine containing environments. The nodular cast iron grade EN-GJS-400-18-LT is for example mentioned as substrate for nacelle bedplates [62].

As for steel, alloying cast iron with chromium and nickel increases the corrosion resistance significantly. Ni Resist cast iron type II containing 3 % C, 20 % Ni and 2 % Cr was mentioned as a material used in marine environments for pumps, pipes etc. Another reference [66] mentions the use of high silicon cast iron containing 14 % Si as a material for anodes in suppressed anodic current systems instead of graphite, lead or other expensive metals like platinum etc.

5.1.3   Stainless steel

Stainless steel can also be used in offshore components although the material cost is much higher than the unalloyed and alloyed steels that are commonly used for structural and piping solutions. The stainless steels are corrosion resistant because of the high chromium content (> 12% Cr) besides other elements, like nickel and molybdenum etc. The chromium is especially responsible for the corrosion resistance of steel because of the formation of a thin but adhering chromium oxide layer at its surface that reduces corrosion. However most austenitic stainless steels like EN 1.4301 (AISI 304) have a moderate corrosion resistance, depending on the environment. Two cases can happen: sensitization after welding and local corrosion (*pitting*) due to free chlorine and sulfate ions [44]. Some stainless steels like EN 1.4307 (AISI 304L) and EN 1.4404 (AISI 316L) can be welded without sensitization but their resistance against chlorine is quite low. Steels with higher chromium and especially molybdenum contents, like EN 1.4539 (AISI 904L) have a higher resistance against chlorine attack and pitting.

Pitting resistance equivalent numbers (PREN) are a theoretical way of comparing the pitting corrosion resistance of various types of stainless steels, based on their chemical compositions (EN 1994-1). The PREN (or PRE) numbers are useful for ranking and comparing the different grades but cannot be used to predict whether pitting will occur for a specific combination of stainless steel and corrosive environment. The higher the number is, the better the pitting resistance against chlorine. A number of slightly varying formulas for the calculation of PREN are in use. The most used version of the formula

26

is [67]:

$$PREN = Cr + 3.3Mo + 16N$$

In the tungsten bearing super-duplex types, for example 1.4501, tungsten is also included in the molybdenum-rating factor to acknowledge its effect on pitting resistance [67]:

$$PREN = Cr + 3.3(Mo + 0.5W) + 16N$$

PREN values for a selection of stainless steels are given in Table 8.

The Euro Codes 1-4 (EN 1993-1-4) provide a procedure for selecting the appropriate grade of stainless steel for a certain environment. A **Corrosion Resistance Factor (CRF)** [68] is calculated and used to assess the corrosive environment. The CRF is the sum of three factors: risk of exposure to chlorides (F1), risk of exposure to SO_2 (F2) and the influence of cleaning and rain (F3):

$$CRF = F1 + F2 + F3$$

The value of the CRF can range from 1 to below -20. A more negative CRF value indicates an environment with a higher corrosion risk. The various stainless steel grades are classified in Corrosion Resistance Classes (CRC) I, I, III, IV & V, suitable for specific CRF value.

The risk factors used in the CRF calculation are detailed in Table 6. The designation of CRF values to Corrosion Resistance Classes is shown in

Table 7 [69]. CRC classes for a selection of stainless steels are given in Table 8.

Table 6: Risk factors used in the calculation of Corrosion Resistance Factors [70]

F1: Risk of Exposure to Chlorides	
Note: M is distance from the sea and S is distance from roads with de-icing salts.	
1	Internal, Controlled Environment
0	Low Risk of Exposure: M > 10 km or S > 0.1 km
-3	Medium Risk of Exposure: 1 km < M ≤ 10 km or 0.01 km < S ≤ 0.1 km
-7	High Risk of Exposure: 0.25 km < M ≤ 1 km or S ≤ 0.01 km
-10	Very High Risk of Exposure: Road Tunnels where de-icing salts are used.
-10	Very High Risk of Exposure: M ≤ 0.25 km. North sea coast of Germany & All Baltic Coastal Areas.
-15	Very High Risk of Exposure: M ≤ 0.25 km. Incl. all other European/UK Coastal Areas.
F2: Risk of Exposure to SO_2	
Note: for European coastal environments the sulphur dioxide value is usually low. For inland environments the sulphur dioxide value is either low or medium. The high classification is unusual and associated with particularly heavy industrial locations or specific environments such as road tunnels. Sulphur dioxide deposition may be evaluated according to the method in ISO 9225.	
0	Low Risk of Exposure: 10 average deposition
-5	Medium Risk of Exposure: 10-90 average deposition
-10	High Risk of Exposure: 90-250 average deposition
F3: Influence of cleaning and rain	
0	Fully exposed to washing by rain
-2	Specified cleaning regime
-7	No washing by rain or specified cleaning regime

Table 7: Designation of CRF values to Corrosion Resistance Classes

CRF	CRC
CRF=1	I
0 ≥ CRF > -7	II
-7 ≥ CRF > -15	III
-15 ≥ CRF ≥ -20	IV
CRF< -20	V

In Figure 6 three groups of stainless steel can be distinguished: ferritic, austenitic and duplex steels [68]. Above the horizontal line of seawater at 20°C only 6 alloys can be selected with PREN higher than 30. The only ferritic steel that complies is the so-called Sea-Cure produced by Plymouth US [71]. Most of the steels that have sufficient high corrosion resistance against seawater contain high chromium and nickel contents combined with high molybdenum and nitrogen contents. The composition of a selected number of stainless steel alloys, along with their PREN value and the CRC class for which they are suited, are given in Table 8.
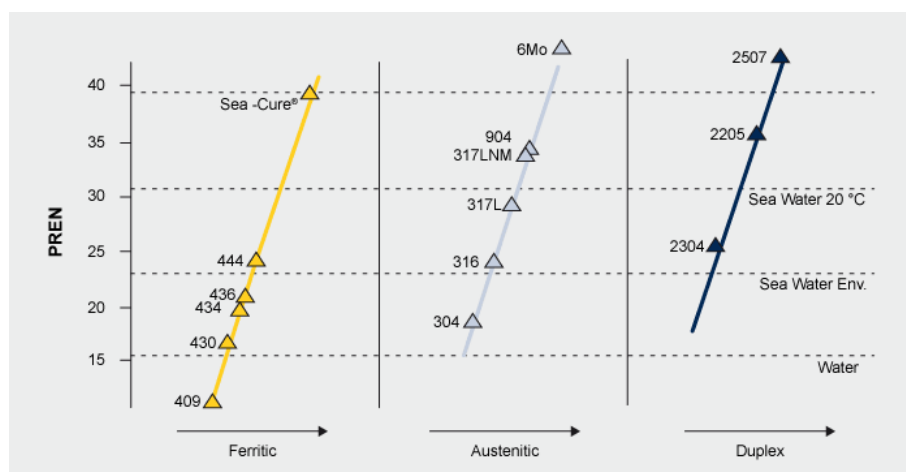
Figure 6: PREN number for different types of stainless steel

Table 8: Composition of a selected number of stainless steel alloys, their PREN value and the CRC class for which they are suited (*Note: Sea-Cure and Zeron 100 are commercial names, not AISI designations)

EN	AISI/Name	Symbolic	Type	C	Cr	Mo	Ni	N	PREN	CRC
1.4016	430	X6Cr17	F	< 0.12	16-18	-	-	-	16.0-18.0	I
1.4113	434	X6CrMo17-1	F	< 0.12	16-18	0.9-1.4	-	-	19.0-22.6	
1.4512	409	X2CrTi12	F	< 0.08	10.5-11.75	-	-	-	10.5-12.0	I
1.4521	444	X2CrMoTi18-2	F	< 0.03	17-20	1.8-2.5	-	<0.03	23.0-28.7	
1.4526	436	X6CrMoNb17-1	F	< 0.12	16-18	0.9-1.4	-	-	19.0-22.6	
	Sea-Cure*		F	< 0.03	25-28	3-4	1-3,5	< 0.04	35.5-42.0	
1.4301	304	X5CrNi18-10	A	< 0.08	17.5-19.5	-	8.0-10.0	<0.11	17.5-20.8	II
1.4307	304L	X2CrNi18-9	A	< 0.03	17.5-19.5	-	8.0-10.0	<0.11	17.5-20.8	II
1.4311	304LN	X2CrNiN18-10	A	< 0.03	17.5-19.5	-	8.0-10.0	0.12-0.22	19.4-23.0	II
1.4401	316	X5CrNiMo17-12-2	A	< 0.08	16.5-18.5	2.0-2.5	10.0-14.0	<0.11	23.1-28.5	III
1.4404	316L	X5CrNiMo17-12-2	A	< 0.03	16.5-18.5	2.0-2.5	10.0-14.0	<0.11	23.1-28.5	III
1.4406	316LN	X2CrNiMoN17-11-2	A	< 0.03	16.5-18.5	2.0-2.5	10.0-14.0	0.12-0.22	25.0-30.3	

1.4439	317 LMN	X3CrNiMoN17-13-5	A	< 0.03	16.5-20	3-4	10.5-15	0.10-0.22	28.0-36.7	IV
1.4539	904L		A	< 0.02	19-23	4-5	23-28	< 0.15	32.2-39.9	IV
1.4547	254SMO	X1CrNiMoCu20-18-7	A	< 0.02	19.5-20.5	6.0-6.5	17.5-18.5	0.18-0.22	> 40	V
1.4362	2304		D	< 0.03	21.5-24.5	0.05-0.6	3.0-5.5	0.05-0.20	23.1-29.2	III
1.4410	2507	X2CrNiMoN25-7-4	D	< 0.03	24-26	3-5	6-8	0.24-0.35	> 40	V
1.4462	2205	X2CrNiMoN22-5	D	< 0.03	21-23	2.5-3.5	4.5-6.5	0.10-0.22	30.8-38.1	IV
1.4501	Zeron 100*		D	< 0.03	24-26	3-5	6.0-8.0	0.20-0.30	> 40	V

The Finnish company Outokumpu claims to deliver its Forta 2205 duplex steel (EN 1.4462) for the construction of 66 wind turbines in the North Sea near the German coast.

'Jacketed' tubes composed of a stainless steel sleeve over unalloyed steel tubes have been reported as an alternative solution for corrosion of pipes and tubes.

In the non-tidal zones the chloride concentrations are much higher than inland locations (up to 1500 ppm Cl) [44]. Euro-Inox recommends for these aggressive environments to use molybdenum containing stainless steels such as EN 1.4401 or EN 1.4521. In the tidal zone, the 2% molybdenum containing stainless steels (austenitic and ferritic) are evaluated as unsatisfactory. Instead EN 1.4547 and EN 1.4410 can be used without signs of corrosion.

Concerning *soil corrosion* recommendations from Euro-Inox are based on the results of different experiments in soils. In a soil for which the resistivity is less than $1.000\ \Omega \cdot cm$, the chloride content is higher than 500 ppm, and the pH less than 4.5 should be considered as aggressive.

Table 9 summarizes the stainless steel selection criteria and indicates the types of stainless steel that can be employed without any coating and/or cathodic protection in the absence of stray current.

Table 9: Stainless steel selection according to soil conditions [44]

Stainless steel grade		Soil conditions
Name	**Number**	
X5CrNi18-10	1.4301	Cl < 500 ppm
X5CrNi17-12-2	1.4404	Resistivity > 1000 Ω·cm
X5CrMoTi18-2	1.4521	pH > 4.5
X5CrNi17-12-2	1.4404	Cl < 1500 ppm
X2CrMoTi18-2	1.4521	Resistivity > 1000 Ω·cm pH > 4.5
X2CrNiMoN25-7-4	1.4410	Cl < 6000 ppm
X1CrNiMoCu20-18-7	1.4547	Resistivity > 500 Ω·cm pH > 4.5

The resistance of construction steel to MIC corrosion is low and severe corrosion will occur. Stainless steels however have a higher resistance that increases with the amount of the alloying elements, which are also beneficial for resistance to pitting corrosion and crevice corrosion [72]. As for chloride contamination, pitting and tunnelling is formed during MIC especially around welds.

The standard austenitic steels like EN 1.4307 (AISI 304L) and EN 1.4404 (AISI 316L) are quite vulnerable to micro-biologically influenced corrosion. Duplex steels like EN 1.4462 (AISI 2205) are reported as borderline materials, whereas hyper-duplex, super-duplex and high-alloy austenitic stainless steel grades like EN 1.4547 (254 SMO) can be regarded as immune to microbiologically influenced corrosion (MIC) in seawater [72].

5.1.4   Non-ferrous alloys

Non-ferrous alloys like aluminium, copper-nickel, nickel and titanium can be used in offshore construction despite their lower mechanical properties and higher cost compared to steel.

5.1.4.1   Nickel alloys

Nickel and nickel-based alloys have the best corrosion resistance for almost every chemical product, especially for sulphate and chloride containing environments. Several commercial nickel alloys exist, as those produced by the Haynes Company. These alloys are not subject to chloride stress corrosion cracking as compared to other stainless steels and their pitting resistance is extremely high making these alloys suitable for fasteners and other fixing equipment in extreme harsh conditions. The high price of these alloys however makes them rather unsuitable as a substrate for constructive elements like pillars and girders. Table 10 gives some alloys mentioned in literature [73] for marine applications.

Table 10: Composition of nickel superalloys used in marine environments (wt%)

Grade	Ni	Cr	Mo	Co	W	Other
Inconel 625	> 77	20-23	-	< 1	-	3-4 Nb/Ta
Hastelloy C-276	57	16	16	< 2.5	4	-
Incoloy 825	38-46	19-23.5	2.5-3.5	-	-	> 22 Fe
Rene 41	> 50	18-20	9-10.5	10-12	-	-

Figure 7 shows the galvanic series of different metals in seawater [73]. The nickel alloys are located at the bottom of the diagram near inert materials like platinum and graphite.
From this figure it can be seen that metals with different potential can generate galvanic corrosion when connected to each other. In [74] it is explained that sometimes galvanic couples are permitted if the surface of the anodic metal (less noble) is larger than the surface of the cathodic metal (most noble) for example stainless steel bolts in aluminium plates. In other cases, galvanic separation using joints and seals are needed to prevent corrosion of the less noble part of the construction.
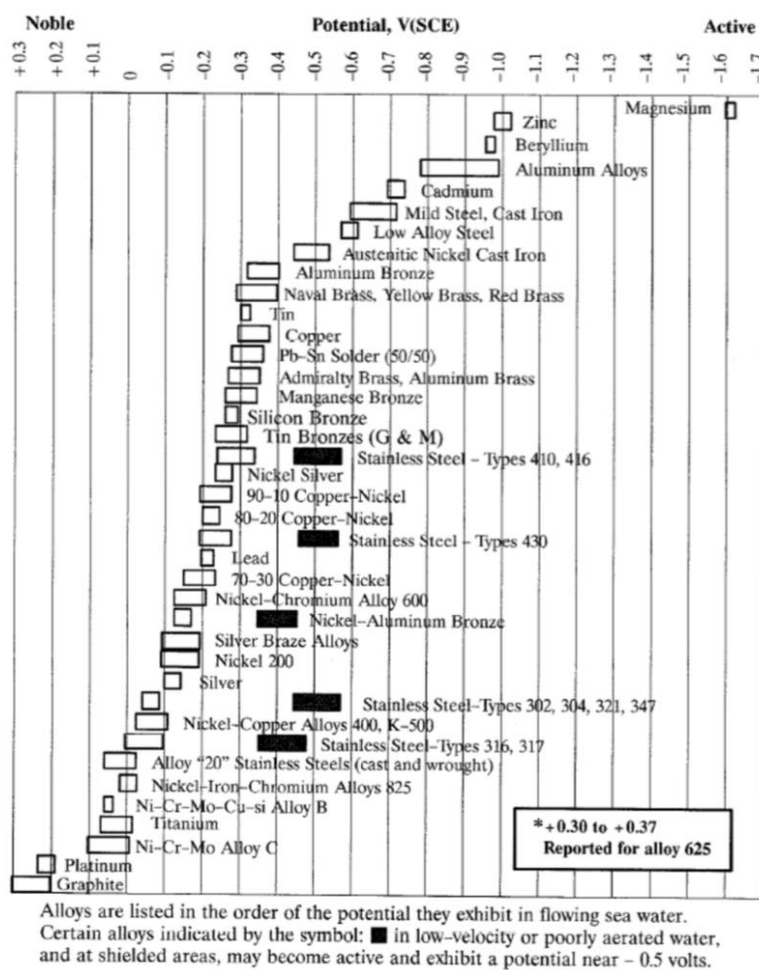
Figure 7: Galvanic series of metals and alloys in seawater [73]

5.1.4.2 Titanium Alloys

Titanium has increasing applications in marine structures over the last years despite its higher cost compared to steel and stainless steel [75]. The four principal areas of application have been its strength per weight advantage (highest of all metals), its complete immunity to corrosion by seawater (0.01 mm/year), its heat transfer capability, and its high corrosion fatigue limits in both low and high cycle fatigue. Titanium alloys are lighter than steel and have excellent mechanical properties making them useful for constructive parts with high corrosive demands. The applications in offshore are stress joints, pipes, water tanks, sleeves, manholes etc. The hardenable alloys Ti-3Al2.5V (grade 9) and Ti-6Al4V (grade 23) are most used but also pure Ti (grade 2) can be applied [75].

The excellent corrosion performance (see Figure 7) is due to a very thin and highly protective surface oxide film. If scratched or damaged the surface oxide will immediately restore itself in the presence of air or seawater. Welds and castings of the common titanium marine grades exhibit corrosion resistance comparable to wrought materials, eliminating a concern over heat affected zones or a need to upgrade alloying in weld metal or castings.

The fatigue properties and toughness of common marine grade titanium alloys are unaffected by seawater exposure. The alloys are immune to seawater stress corrosion cracking. Unalloyed titanium (grade 1 and 2) is susceptible to crevice corrosion pitting in some severe seawater environments, such as at gasketed mechanical joints [76] grade 7 (Ti-0.15Pd) can solve this problem.

5.1.4.3 Copper and copper alloys

According to the Copper Development Association copper alloys like 90-10 CuNi and Monel 400 (67-33 NiCu) can be used for piping and valves in gas and oil platforms [77,78]. Corrosion rates from 0.5 to 1.5 mm/year can be expected in seawater. Also copper-nickel-silicon alloy and naval brass (59 %Cu – 40 %Zn – 1 %Sn) are used as materials in marine environment.

These metals are also used for so called 'sheathing' (protection sheets) of steel piles and ship hulls [78]. Whereas sheathing of ship hulls for corrosion and biofouling resistance is a concept waiting for a definitive demonstration and test, sheathing of a variety of offshore structures is a proven application for copper-nickel alloys and the nickel-copper alloy like Monel 400.

5.1.4.4 Aluminium alloys

According to the Norwegian company Hydro, aluminium alloys can be used for offshore and wind platforms to reduce total weight [74]. The use of aluminium for anodes in cathodic protection and for thermal spray coatings and cladding is one of the applications besides its structural use. As for stainless steel, aluminium is protected by a superficial and natural oxide layer. This layer can also be applied by a special surface treatment called 'anodizing'. Anodizing is an electrochemical method of making a protective aluminium oxide film Al_2O_3 at the surface. Cladding is a method of coating of Al-alloys products by thin layer of pure Al or Al-alloys. If the cladding layer is anodic in comparison to the base Al alloy, the products are called alclad products. Alloy 7072 is used as cladding for Al-Mg and Al-Mg-Si alloys

Pure aluminium (1000 series) and aluminium-magnesium alloys (5000 series) have good general corrosion resistance and is used for sheet and plates. The hardenable alloy 6082 has also be reported [79] as alloy for extrusions in shipbuilding.

The presence of high chlorine concentrations can however destroy the protective layer and cause intergranular and stress corrosion. Therefore, coating aluminium with paints will also be necessary against severe corrosion attack depending on the location to the sea level. Table 11 show the composition of corrosion resistant aluminium alloys for offshore applications. Figure 8 shows some protection measures for aluminium components used in marine atmospheres [74].

Table 11: Aluminium alloys for marine applications

Alloy	% Mg	%Cu	%Mn	% Fe	% Zn	% Si
1050	< 0.05	< 0.05	< 0.05	< 0.4	< 0.05	< 0.1
5083	4-4.9	< 0.1	0.4-1	< 0.4	< 0.1	< 0.1
6082	0.6-1.2	< 0.1	0.4-1	< 0.5	< 0.2	0.7-1.3
7072	< 0.1	< 0.1	< 0.1	< 0.1	0.8-1.3	< 0.1
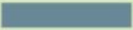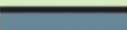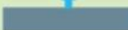
ZONE	NO PROTECTION	PASSIVE PROTECTION	ACTIVE (CATHODIC) PROTECTION	TO BE CONSIDERED
above sea level	uncoated surface	coating	not applicable	avoid galvanic corrosion, assure air ventilation, allow for natural cleaning by rain where possible
		anodizing		for decorative surfaces
below sea level	insufficient	insufficient	anodes	avoid galvanic corrosion
		coating + anodes		

Figure 8: Corrosion protection measures for aluminium in marine environments [74]

Although aluminium alloys can be used in marine environments without coatings sometimes a supplemental protection is needed (Figure 9). When painting aluminium structures, pre-treating the surface is essential. In addition to degreasing, the oxide layer has to be removed either chemically (pickling) or mechanically (blasting, sweeping or grinding) prior to coating. This is the only way to permanently prevent paint delamination in a marine atmosphere. Figure 9 gives two different approaches for painting aluminium components.

	NORSOK STANDARD M-501	GSB GUIDELINE AL631
Cleaning	Sweep blasting => anchor profile 25-45µm	Degreasing with ~1g/m² material removal
Passivation		Conversion layer < 1g/m² (Cr-VI, Cr-III or Cr-free) or pre-anodisation 3-8µm
Coating	epoxy primer 50µm two-component epoxy 100µm one coat topcoat 50µm	one coat 75µm (wet or powder)
Total thickness	225µm	75µm
Schematic		

Figure 9: Coating concepts for aluminium in the marine environment [74]

5.1.4.5   HEA

In recent years, a new class of alloys has gained great interest from research and application point of view. In contrast to the traditional approach of the physical metallurgy centred on the base-element concept, in which one or two principal elements are mixed with minor alloying elements to enhance the alloy properties, a new multi-principal element design was adopted for this new alloy family. These multicomponent alloys were named "high entropy alloys" (HEAs), multi-principal element alloys (MPEAs) or complex concentrated alloys (CCAs). The main purpose in developing these new materials is to explore and exploit the very large number of alloys in the central region of hyper dimensional composition space [80–83].

More than 400 different alloys were studied in the last decades in which almost all non-gaseous or non-radioactive elements were used in different alloys and in various combinations. Some elements are very common in MPEA: Al, Co, Cr, Cu, Fe, Mn, Ni and Ti are used in more than 100 alloys while Co, Cr, Fe, Ni are present in more of 70% of CCAs. These alloys were classified in seven distinct MPEA families: 3d transition metal CCAs, refractory metal CCAs, light metal CCAs, lanthanide (4f) transition metal CCAs, CCA brasses and bronzes, precious metal CCAs and interstitial compound (boride, carbide and nitride) CCAs. Alloys in the 3d transition metal family can be considered extensions of stainless steels and superalloys and are the most studied HEA. The refractory metal CCA family consists of alloys containing at least 4 of the 9 refractory elements Cr, Hf, Mo, Nb, Ta, Ti, V, W, with the addition of Zr and Al. The other families were developed because of the need for new low density structural alloys for aerospace and transportation applications [84,85] or to study single-phase high entropy alloys with the HCP crystal structure (two families DyGdLuTbY and DyGdLuTbTm) [86]. For an extensive analysis of the MPEA families see [83]. The stable formation of simple solid solution in HEAs is mainly due their large configurational mixing entropy that increases the solubility (especially at high temperature) and decreases the tendency to segregation, by suppressing the formation of intermetallic compounds.

Many research studies highlighted that these alloys are characterized by high fracture toughness, improved fatigue resistance, high strength, high thermal stability and significant corrosion resistance. The corrosion behaviour of HEAs containing passivating elements was reported to be equivalent or superior to traditional alloys, so the combinations of these unique properties make HEAs attractive for applications in critical environments as offshore and marine atmosphere [87]. As already stressed, HEAs are a large family of new alloys, that have not yet been completely studied and exploited. Some patent applications have recently been submitted. In particular, the alloys $Fe_aNi_bMn_cAl_dCr_eC_f$ (with a=37-43at%, b=8-14at%, c = 32-38at%, d =4,5-10.5%, e=2,5-9at% and f=0-2at%) were proposed as a candidate to replace austenitic stainless steels in applications where higher strength and higher oxidation resistance are required at both room and elevated temperatures [88]. Despite the high number of principal elements and the composition complexity, HEAs form relatively simple FCC or BCC structures (or structures combining both). Recently, several techniques have been proposed to strengthen HEAs by introducing non high-entropy secondary phases [89]. A method was proposed to enhance the antifouling properties of HEAs without the need to use chemical treatments (such as antifouling paints). The method uses a severe plastic deformation to reduce grain size and thereby suppress the attachment of marine organisms. These HEAs are proposed for applications in marine structures [90].

In general, the combination of high corrosion resistance and high cavitation–erosion resistance in saline environments make HEAs strong candidate materials for critical offshore and marine

applications, even if, from an economical point of view, they currently have high production costs. Their use as coating materials could overcome this problem.

5.2 Corrosion allowance

Corrosion allowances are active corrosion protection strategies and represent material sections that are allowed to corrode without compromising the function (safety, stability, strength) of the construction. This approach can be considered when general corrosion is expected to occur and in particular for OW structures corrosion allowance is recommended mainly for the splash zone (SZ) [9]. The design of the corrosion allowance value depends on the material, expected mechanical loads, corrosivity category and corrosion zone. Generally, it is recommended to combine corrosion allowance with coating, in order to have a more reliable structure but also for costly reasons.

6   Corrosion protection – Technology overview

In chapter 5, an overview of corrosion resistant metal was presented. However, using high corrosion resistant materials is not always possible for all constructive parts because of high production cost. In fact, the use of low alloy steels far exceeds that of any other alloys in offshore and marine applications. Even when corrosion resistant materials can be used, they may still degrade or require additional protection as a safety measure. In this chapter, various strategies to prevent corrosion are therefore discussed. This chapter should be considered as an overview of what technologies for corrosion protection exist. Not all of the presented solutions are currently used in offshore applications, although the authors have aimed to select those solutions that have potential in the offshore sector. The scope has been kept fairly wide on purpose and invites the reader to be open to new and innovative ideas for corrosion protection in the offshore sector. For an overview of what are currently the most used corrosion protection solutions in offshore wind turbines, the reader is referred to chapter 7. The corrosion protection is a complex task which requires a multidisciplinary approach. The corrosion protection system must be designed to taking into account materials, geographic and local environments, corrosivity class, the geometry of components to be protected, mechanical load and required durability of the protection system. From a formal point of view, the corrosion protection methods can be classified into active or passive methods, though it is important to stress that most protection systems use both methods of protection.

6.1   Active corrosion protection: cathodic corrosion protection (CCP)

Cathodic corrosion protection (CCP) can be defined as "electrochemical protection by decreasing the corrosion potential to a level at which the corrosion rate of the metal is significantly reduced", according to the International Standard ISO 8044 [8]. For carbon and low-alloy steels, cathodic protection should be considered as a technique for corrosion control, rather than to provide immunity [48]. Cathodic protection can be provided by Galvanic Anode Cathodic Protection (GACP) using anodes to sacrifice themselves in order to protect the main structure or by Impressed Current Cathodic Protection (ICCP) using an external DC power source [9]. CCP is a method for the protection of uncoated and coated sections which are permanently subject to seawater acting as electrolyte. When combining CCP with a coating system, a coating must be selected which is compatible with CCP (see section 6.2.2). Steel reinforcement bars in reinforced concrete can also be protected with CCP for OW structures. Cathodic protection can be provided by Galvanic Anode Cathodic Protection (GACP) using anodes to sacrifice themselves in order to protect the main structure or Impressed Current Cathodic Protection (ICCP) using an external DC power source [9]. Attention must be paid to numerous criteria when designing CCP system, as protection potential and protection current density must be chosen in accordance with the operational conditions.

For this reason, DNVGL-RP-B401 [91] gives requirements and guidelines for cathodic protection design, anode manufacturing and installation of galvanic anodes. For offshore wind structures, galvanic anodes (GACP) are generally preferred. Galvanic anodes must meet certain criteria in terms of materials and composition. Galvanic anodes usually consist of zinc or aluminium alloys. However, magnesium alloys are not allowed for maritime applications.

These installations are very robust and reliable once the functionality has been established. Costly offshore maintenance can be expected to be minimized with these systems. However, the recommendations in the DNVGL-RP-B401 [91] are not specifically provided for the requirements of

offshore wind farm with monopile foundations, but for jacket foundations. In general, for a correctly designed galvanic anode CCP system, the protection potential shall be in the range of -0.80 to -1.10 V in aerobic conditions, while the range of -0.90 to -1.10 V in anaerobic conditions is required for the main structural parts in carbon steel or cast iron. Jacket structures for Oil & Gas industry have the possibility to spread the anodes over large parts of the structure, but monopoles themselves cannot be equipped with anodes easily due to the installation with pile driving processes [48]. Therefore, the anodes are frequently equipped to the transition piece (TP) and installed together with this TP structure. The use of anode systems can offer versatile solutions specially for retrofitting cathodic protection systems of offshore structures to extend their service life or to implement an additional protection system [92]. Anode carriers with many sacrificial anodes attached and electrically connected to the structure to be protected can be placed on the ocean floor above the mud line. Otherwise, the anode assembly with protective housing can be easily placed the near structure pile and anchored to the ocean floor with weights [93].

Impressed Current Cathodic Protection (ICCP) is becoming more popular in the OW industry, particularly for external protection and there have been discussions about the use of this type of cathodic protection internally. In particular, design and installation of CCP systems working with external current require special attention as it is more susceptible to environmental damage and third-party mechanical damage than galvanic anodes systems, as suggested in DNVGL-RP-0416 [26]. In addition, ICCP requires more maintenance and inspections, which are costly to provide for OW structures. Nevertheless ICCP systems can offer some advantages with respect the traditional GACP methods. In addition to being more economical and easier to install, ICCP systems can be controlled and automatically tuned from a remote and on-shore control system, which provides a real-time verification of the protection status. The opportunity to check and tune the driving voltage enables an extension of the corrosion protection to the foundations the prevention of the microbiological influenced corrosion. Recently interesting solutions were proposed for offshore wind turbine energy implants. Some configurations use at least one turbine unit or a power supply associated with a turbine to apply an impressed current to the electrochemically coupled anode and to protect all wind turbine in the field. This solution allows both adapting the settings of the protection system to the changing corrosion condition and extending wind turbine lifetime. [94].

6.2   Passive corrosion protection

6.2.1   Barrier coatings

Passive corrosion protection with barrier coatings works by separating the metal to be protected from the corrosive environment. Barrier coatings must have excellent barrier properties (to prevent the ingress of corroding species such as oxygen and water); sufficient adhesion to the metal surface to effectively resist under-film migration of moisture; be sufficiently ductile to resist cracking; have sufficient strength to resist damage; and, if used in conjunction with cathodic protection (CP), have properties that are compatible with CP (see section 6.2.2). Additionally, if the external protective coating is an electrically insulating type, it must also have low moisture absorption and high electrical resistance. In general, an electrically insulating protective coating with insulation resistance of 10^6 Ω-m² is good; and, depending on the service conditions, a coating with a minimum resistance of 10^4 Ω-m² is acceptable [95]. Passive corrosion protection systems may consist of several layers of different types of coatings, in that case, the compatibility between the coats (layers) must be ensured.

The coating process involves the application of non-metallic coatings (including organic or inorganic layers), metallic coatings, or the combinations of these two types of coatings on the steel surface, to form a multilayer protective system (named duplex or triplex)[96]. Metallic coatings are generally composed of non-ferrous metals, commonly zinc, aluminium and its alloys. These metallic coatings provide protection to steel structures against corrosion by both galvanic action and barrier. Moreover, the metallic coatings protect steel sacrificially at damaged areas or at small pores in the coatings [2]. Sprayed metals are usually applied to flange connections, frames and platform railings. However they are also frequently applied to the whole tower sections (usually in combination with organic coating systems) [9].

The ideal coating system should assure the proper performance of the structure during its service life without requiring structural repairs. The major factors to be considered in the selection of a coating system are: the type of structure and its importance, environmental conditions, service life, required durability, coating performance, and costs including its application and surface preparation. For a coating system to achieve the optimum performance, the following steps should be followed [25]:

- Selection of the most suitable protective system according to the particular environmental conditions;
- Coating requirements;
- Assessment of the structure design to optimize coating system application;
- Detail clearly and unequivocally the specifications of the system;
- Use adequate and suitable techniques for coating deposition;
- Respect the requirements of the coating system;
- Rigorous quality control of the specified and supplied materials;
- Inspection at all phases during coating system application.

So for OWS, in particular, the coatings should be resistant to high corrosive stress due to elevated salt concentration in both water and air, impact loading due to ice drift (particularly for North Sea region) or floating objects, biological stress, namely under water, notable variations in temperature of both water and air [97]. Algae (plants), animal and bacteria life on site causes biological stress on the structural components in the submerged and in the splash zones. Algae and animal growth adds weight to the structural component and influences the geometry and the surface texture of the component. The marine growth may therefore impact on the hydrodynamic loads, the dynamic response, the accessibility and the corrosion rate of the structure [7]. Inspections, at all phases, are essential to make sure that all requirements of the coating specification are satisfied. An unambiguous and adequate quality control system should be implemented. Quality control of the entire coating process will ensure that the applied systems will reach their full potential. Protection of steel by painting is generally ensured by the application of several coats of different paints, each having a specific role. The different types of coats are defined by the order of application on the substrate, namely: The primer (first coat), undercoat (any coat between the primer and the finishing coat) and the topcoat (finishing coat). The different layers should have different colours to ease its identification. Generally, the coating system is characterized by the number of layers (coats) involved and is known by the name of the paint binder used in the topcoat. There are also systems without undercoats [2]. Inadequate adhesion may promote failure of the coating and expose the substrate to the environment (aggressive species) and therefore cause corrosion. Most organic-based coating failures such as cracking, delamination, fouling damage, mud cracking and dirt under paint can only be resolved by sandblasting the surface or removing the coating mechanically, cleaning the surface and applying a

new coat. In case of fouling damage, the damaged paint should be replaced by a tougher and more adherent coating with antifouling properties. The primer that is applied on the steel surface should provide adequate adhesion and anticorrosive protection. Undercoats are generally used to increase the overall thickness of the coating system. The top coat protects the layers below from environmental agents such as UV light from the sun and provides primary abrasion resistance and decoration when necessary.

Appropriate surface preparation is crucial for the performance of paint systems. In certain cases, surface preparation is very expensive and/or difficult to carry out leading to the development of coatings known as *surface-tolerant* [98–100]. This type of system consists of introducing hydrophilic solvents or surface-active agents in the coating that when combined with the moisture on the surface will cause moisture dispersion through the film paint. Nevertheless, this type of coatings should only be used as last resort.

6.2.2   Compatibility with Cathodic Protection

Cathodic protection and barrier coatings are often used simultaneously in order to provide an additional degree of protection. The barrier coating provides the first line of protection. When the coating is damaged or deteriorates (ages) under influence of environmental conditions, and the bare steel is exposed, cathodic protection is provided to prevent corrosion.

When combining the use of cathodic protection (CP) and barrier coatings, the selected coating should be compatible with CP. Every coating system has finite life and eventually degrades or is damaged, allowing oxygen, water, and chemicals to reach the substrate. At this point, two problems can occur:

1. Cathodic disbondment of the coating.
2. Inadequate CP of the steel due to shielding.

Cathodic disbondment is the destruction of adhesion between a coating and the coated surface due to cathodic reaction products. In the absence of defects, cathodic disbondment will normally not occur. However, if there is a coating defect, CP current will pass into the metal at the coating defect, resulting in a highly alkaline environment due to the formation of hydroxyl groups at the steel surface. The highly alkaline environment coupled with the polarized potential can cause the coating to lose adhesion and disbond from the substrate. As the defect gets larger, the current flow increases and more of the coating is pushed away from the metal. This can result in rapid disbondment and coating breakdown. It is thus important to select coatings resistant to alkaline environments and CP current flow [95].

Another problem presents itself when the coating is damaged or becomes permeable (and allows corrosive species to reach the steel substrate) but prevents the CP current to flow to the steel substrate at the location of the defect. The steel will then not be protected and corrosion will occur. This is called **'shielding'** and can be defined as "as high-resistance or nonconducting materials preventing CP current from reaching the structure to be protected, or low-resistance material diverting the current away from the structure to be protected" [95].

For a coating to be truly compatible with CP, the coating should allow the CP to provide protection to the structure if disbondment occurs and water penetrates. The CP current should be able to pass through a coating which has become permeable. Additionally, the coating should not prevent the CP current from reaching the steel substrate at defects with very small dimensions such as pinholes and hairline fractures. As such, when CP-compatible coatings degrade or water contacts the steel, the surface will still protected from corrosion and SCC because the CP current can reach the steel [101].

6.2.3   Surface preparation and cleaning

It is important that the surface of an object to be coated against corrosion is free of contaminants such as oxide (rust), oil or grease and dust [102]. Any external contamination will decrease the adhesive strength between the coating and the substrate, and the corrosive protection will fail.

In ISO 8501and NACE several cleaning methods are recommended. The most effective method is blasting and its effectiveness is expressed as an Sa value ranging from 1 to 3. The lowest value Sa 1 corresponds with a surface where loose contaminants were removed by brushing. In most cases Sa2 ½ is used for preparation of coatings for harsh environment [103]. To obtain this cleanliness almost all oxides and oil are removed by blasting, whereas Sa 3 is a surface that is completely free of oxides and other contaminants. Figure 10 shows the visual aspect of this Sa scale. For offshore structures it is recommended [104] to use steel with an initial rust grade not worse than B (Norsok M501) or not worse than C (EN ISO12944). The service life of a coating system depends on the rust grade of the initial steel and the degree of preparation.

Figure 10: Surface aspects of cleaned surfaces in function of the rust grade according to ISO 8501-1

Besides blasting using grid, shot or soda the cleaning of contaminated surfaces can be executed by other methods like brushing, grinding even dry ice cleaning, high pressure waterjet and laser ablation can be used [105]. However, some of these methods generate some practical issues when metal parts and huge constructions like offshore platforms must be repaired and treated in open air against corrosion. The easiest way is to use manual brushing and grinding [104].

Dust removal is very important because loose non-adherent particles will affect the adhesion of the coating. Cleaning with solvents is mostly effective before painting or coating. Nevertheless, some metal particles and even salt particles can still be present on the surface after cleaning. To measure the amount of residues (sum of all soluble salts expressed as mg/m²) the so called Bresle test was

developed (EN ISO 8502-6). With this simple chemical test, the amount of soluble salts including chlorine is measured after removing them with a patch. Some contamination can be introduced during blasting because the grit can adsorb salt particles as well [103]. In offshore applications the amount of chlorine however is very high so that high concentrations of salt can be expected in the blasting grit as on the cleaned surface. The residual salt is hygroscopic and will generate an osmotic force in the paint layer and blistering. Normally a maximum concentration of 20 mg/m² is considered as acceptable [103].

Another important parameter for the surface preparation is the quality and the finish of edges in metal parts and constructions. In EN 1090-2, ISO 8501-3 and ISO 12944-2 the specification for corrosion environments higher C2 like CX (offshore environment) are described. For welded structures special attention must be paid at the finish and imperfections of the welds [2,104]. This specification is expressed as preparation grades P1 (lowest), P2 and P3 (highest). For offshore structures preparation grade P2 and P3 should be specified depending on the relevant details of the construction. For P2 no sharp edges are allowed and for P3 rounding with a radius of greater than 2 mm is needed before coating or painting.

6.3   Metallic coatings

Two main groups of coatings can be applied on off shore and oil and gas constructions: hot dip zinc coatings and thermal spray coatings [102,106–108].

6.3.1   Hot Dip Galvanizing

Steel constructions can be galvanized onshore after assembly and welding according to the conventional hot dip galvanizing practice. This means that the steel structure is dipped in a molten zinc bath. Depending on the immersion time the zinc layer will grow to a certain thickness. The thickness of the galvanized coating is influenced by various factors including the size and thickness of the workpiece and the surface preparation of the steel. Thick steels and steels which have been abrasive blast cleaned tend to produce relatively thick coatings. Additionally, the steel composition has an influence on the coating produced.

Silicon and phosphorus can have a marked effect on the thickness, structure and appearance of galvanized coatings (so called Sandelin effect). The thickness of the coating is largely dependent on the silicon content of the steel and the bath immersion time. These thick coatings (circa 200 µm) sometimes have a dull dark grey appearance and can be susceptible to mechanical damage. The galvanized layer is composed of several sublayers with increasing iron content and hardness towards the substrate. This property is important for the abrasive resistance compared to other coatings.

Since hot-dip galvanizing is a dipping process, there is obviously some limitation on the size of components which can be galvanized. Double dipping can often be used when the length or width of the workpiece exceeds the size of the bath. Some aspects of the design of structural steel components need to take the galvanizing process into account, particularly with regard the ease of filling, venting and draining and the likelihood of distortion. To enable a satisfactory coating, suitable holes must be provided in hollow articles (e.g. tubes and rectangular hollow sections) to allow access for the molten zinc, the venting of hot gases to prevent explosions, and the subsequent draining of zinc. Further guidance on the design of articles to be hot dip galvanized can be found in EN ISO 14713 [102].

The Zinc Info Center Benelux [109] specifies a minimum thickness of 80 µm for moderate environments and > 120 µm for severe environments. According to Momber [9] the minimal thickness

depends also on the thickness of the substrate and 85 µm seems to be a minimum value for massive constructions (> 6mm) as used in offshore.

The benefit of zinc is its anodic nature towards iron giving the so-called the sacrificial or cathodic protection (CCP). This means that exposed substrate areas, due to porosities or damages in the zinc coating, will be protected by the galvanic coupling with the more active metal and the corrosion rate of exposed iron will be strongly reduced. Moreover, damages to the zinc coating will be restored (self-healing reaction) by the formation of zinc corrosion products (white rust formation), so protecting the bat steel surface from red rust corrosion. The dimensions of the coating defects which still allow the cathodic protection of the underlying substrate depend on the conductivity of the aggressive environment and on the component geometry. In the marine environment, where, electrolyte electrical conductivity is high, the protective action remains effective in the presence of large uncovered areas (> 1 mm^2). In most cases galvanized steel structures are painted (duplex systems) to increase their resistance in a synergetic way. For repair the zinc layer must be cleaned of white rust before applying a new paint. Sometimes adhesion problems with the paint can occur because of remaining white rust. Zinc phosphating of galvanized surfaces is also a method to improve the coating adhesion of paint layers.

Hot dip metallizing is not only performed with pure zinc. Hot dip layers containing Aluminium and Magnesium are also applied. This provides advantages both in terms of mechanical properties and corrosion resistance.

The FeZn intermetallic which forms when zinc and iron react is a hard, but brittle layer. This can lead to cracking of the galvanized layer. With the addition of aluminium, a more ductile, non-brittle FeZnAl layer is formed instead.

The addition of Al and Mg also increases the corrosion protection in harsh environments. Evidence for this can be found in corrosion test data, courtesy of Bekaert NV [110]. Steel wire was coated with pure zinc, Benzinal® (ZN, 5% Al), Benzinal 2000® (Zn, 10% Al) or Benzinal 3000® (Zn, 10% Al, <1% Mg) and immersed in real ocean water. The percentage of red and black rust was monitored as a function of time. At the time of writing, the test was still ongoing, but it is clear that after 20 months of exposure, the Benzinal® coated wires performs drastically better, with virtually no rust observation.
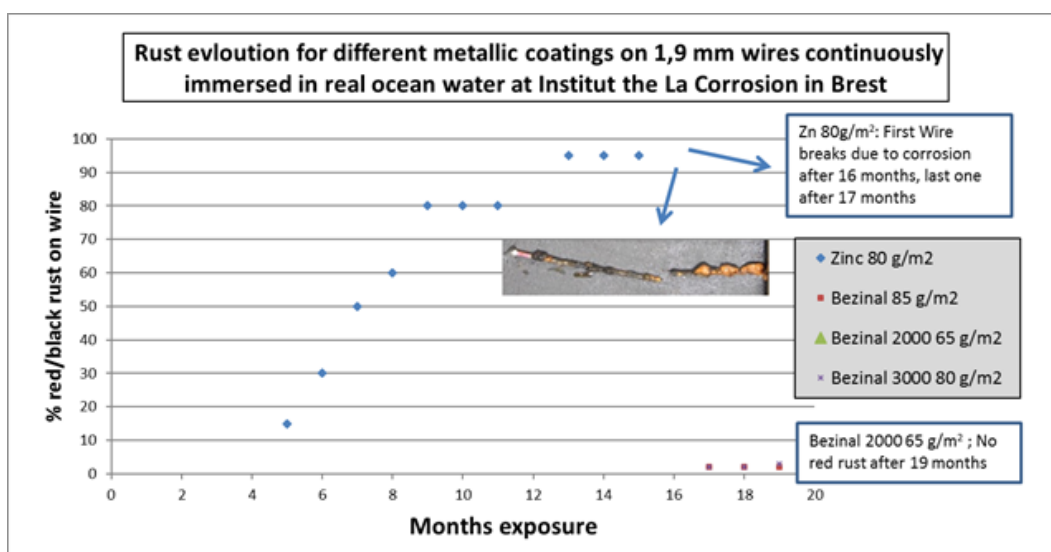
Figure 11: Comparative study of Zn and ZnAl coated steel wire, immersed in ocean water. Courtesy of Bekaert NV [110]

It should be remarked that the coating thicknesses used in the test described above (80g/m² ≈ 11 µm Zn) are very small. This was required in order to see differences between the various coatings within a reasonable time frame. For offshore applications, coating thicknesses on steel wire are generally in the range of 30-50 µm (250 g/m²) or more.

The addition of aluminium and magnesium also increases the cathodic protection of the steel in areas where the galvanizing layer is damaged. This is illustrated on steel wire by making a clean cut and exposing the wire cross-section to the atmosphere. It is clear that the ZnAlMg coating provides the best cathodic protection [111].

Figure 12: Pictures of cut edges of 4 mm steel wires with Zinc, Benzinal and Benzinal 3000 coatings after 3 years of exposure in Belgium [111]

Galvanized steel wire is used in many marine and offshore applications, including fishing ropes, offshore hoisting ropes, wire and rope for suspended structures and ROV cables. Even when the wires and ropes are sheathed in polymer, they are often galvanized in order to provide an additional layer of protection in case the polymer sheathing is damaged.

6.3.2   Thermal Spraying

The most applied technique for the application of metallic coatings on steel structures in the offshore sector, is thermal spraying [104]. It is particularly suited for protecting articles which are too large to be dipped in a galvanizing bath and for repair [102]. In case of sprayed metals, it is also called 'metallizing'. This technique described in ISO 2063 sprays metal particles that are heated to temperatures near or above the melting point, onto a surface. The coating particles are heated by electrical (plasma or arc) or chemical means (combustion flame) and projected at high velocity by air or other gasses.

Thermal spraying can provide thick coatings ranging from 20 micrometres to several mm, depending on the process and feedstock (powder or wire). It can cover a large area at higher deposition rates than other coating processes such as cladding. The materials suitable for thermal spraying include pure metals, alloys, ceramics, even plastics and composites.

The materials are fed in powder or wire form, heated to a molten or semi-molten state and accelerated towards substrates in the form of micrometre-size particles. Combustion or electrical arc discharge is usually used as the source of energy for thermal spraying. The resulting coatings are made by the accumulation of numerous sprayed particles.

Thermal sprayed coatings often contain **porosity** due to particle impingement, insufficiently heated and undeformed particles, gas inclusion, formation of oxide etc. The surface of the substrate may not

heat up significantly, so that the mechanical properties of the substrate is not influenced by the heat input. Generally, the coating quality increases with increasing particle velocities.

The most common thermal spray methods [107] are **Wire Arc and Plasma Spraying**. However, a number of other methods also exist:

- Detonation spraying;
- Plasma Transferred Arc (PTA);
- Flame spraying;
- High velocity oxy-fuel coating spraying (HVOF);
- High velocity air fuel (HVAF);
- Cold spraying.

In classical used processes such as flame spraying and wire arc spraying, the particle velocities are generally low (< 150 m/s), and raw materials must be molten to be deposited. Plasma spraying uses a high-temperature plasma jet generated by arc discharge with extreme high temperatures, which makes it possible to spray refractory materials such as oxides, molybdenum etc.

Cold spraying is a more 'exotic' type of thermal spraying, and in fact the metal powder used as a raw material is not heated, but accelerated towards the surface at very high velocities. Although its current uses are rather limited, cold spraying has a number of interesting properties. Cold spraying and its possible application in offshore is discussed in somewhat more detail below.

In the Offshore sector, pure zinc, zinc-aluminium alloy (15% Al), pure aluminium (TSA) and aluminium-magnesium (AlMg5) alloys are applied by Thermal Spraying [126]. Grit blasting is the preferred surface pre-treatment for most TS coating because it creates a higher roughness on the substrate (grade P3 and Sa3). Special attention should be paid to the treatment of weld areas where flux residues and sharp edges can occur [102].

The spraying equipment gives some physical limits to the application of TS coatings. An operator can use a brush for painting in difficult to access areas but for TS there is no alternative even with a spray gun with an angle-head nozzle. This means that the design must be adapted so that TS can be applied (EN ISO 14713).

Zinc-based TS coatings are traditionally sealed to fill the pores either with thin organic (*e.g.* Dichtol from Diamant Co) or silicone sealants, or by painting over the TS coating [102]. This is necessary to increase corrosion protection duration. Without this sealing, the zinc metal corrodes at an elevated rate, and once all sacrificial zinc has oxidized, the steel below will no longer be protected. The inclusion of Al and Mg can result in self-sealing of the TS coating, by the corrosion products which form during exposure. Some Danish wind farms of 15 to 22 years old were coated with zinc (resp. 60 and 80 μm) followed by a Hempel Paint system and are still in good condition [106].

Other references [102,127] indicate 100-150 μm thickness for zinc and 150-200 μm for aluminium. Ref [126] indicates that a coating thickness less than 150 μm signs of rust can occur so that this value can be stated as an absolute minimum.

Environment	5-10 years	10-20 years	20-40 years	>40 years
Rural Atmosphere	-	-	50 – 200 (2-8)	-
Industrial Atmosphere	-	150 – 200 (6-8)	250-300 (10-12)	300 (12)
Marine Atmosphere	150-200 (6-8)	200-250 (8-10)	250-300 (10-12)	300 (12)
Seawater Immersion	200-250 (8-10)	250-300 (8-10)	300-350 (12-14)	-
Fresh Water Atmosphere	150-200 (6-8)	200-250 (8-10)	250-300 (10-12)	-
High Temperature (300°-660°C)	200-250 (8-10)	250-300 (10-12)	-	-

Figure 13: Thickness range of TSA (µm-mils) as function of the estimated service time and atmosphere [128]

According to Praxair [127] and Canadoil [128], the thickness of 150 µm mentioned in Figure 13 is too low to guarantee a service life of 20 years in marine environments and is definitely inadequate for immersion in seawater. The minimum thickness should be at least 250 µm when no additional paint layer is applied.

As mentioned with hot dip zinc most thermal spray zinc layers are also painted producing a longer life than that of the sum of the individual lifetimes of zinc and paint. The **duplex** lifetime in marine area is estimated according to ref [106] at 1.8-2 times the sum of the lifetimes of zinc and paint and 1.5 to 1.6 times the sum for immersion in seawater. The time to first maintenance of the duplex coating for extreme environments is between 7 and 23 years.

A study by SINTEF in Norway showed that the life-time cost a three-layer paint system was higher than that of a system consisting of a TS zinc coating plus a three-layer paint system, due to reduced maintenance cost required over a period of 30 years. A study at the Aachen University pointed out that a three-layer paint system (primer, middle and top coat) on zinc was even better than a four-layer paint without zinc. Frank Goodwin [129] developed an excel based life-cycle cost comparator CorrWind for calculating the maintenance costs of constructions for a life cycle of 20 years. For a 3.6 MW wind turbine the savings are estimated at 0.8 Eurocent per kWh produced during the considered lifetime.

Case Study: TS(x) A coatings for offshore corrosion protection

Thermally Sprayed Aluminium (TSA) is widely used in the offshore oil and gas industry, on platforms, in pipeline applications, on tension leg elements and on production risers in deep water. Unpainted TSA coatings can be used for atmospheric and submerged areas reducing the need of sacrificial anodes [126]. TSA provides an alternative to the use of conventional coatings and anodes on foundations [130,131]. In offshore wind, TSA has so far primarily been used as corrosion protection for smaller steel components under water or for larger components above water, for example in offshore substations [132]. However, it has recently (2017) been used for the first time in European waters to protect the foundations of Offshore Wind Energy (OWE) devices of the Arkona Windfarm [133] and has also been used in China [134]. At the time of writing, TSA is still not a standard solution for corrosion prevention of OWE foundations. The CROWN-project therefore worked on removing some barriers keeping TSA from being applied on OWE foundations, on a larger scale [130,132,133,135]. The Welding Institute (TWI) also performed significant research in the area of TSA coatings [131].

A robot with arc spray guns deposits a 350μm thick layer of molten aluminium onto the foundations [133]. In the permanently submerged zone (monopile/jacket foundation), TSA provides cathodic protection. The corrosion protection is twofold – it firstly acts as a barrier to the seawater between the steel and seawater. However, the coating is slightly porous and so where steel is exposed (on a micro-scale), the coating acts sacrificially to provide cathodic protection. This cathodic protective action results in the formation of aluminium oxides and the deposition of calcareous minerals from the seawater, which acts to seal the pores of the coating. Therefore, sealant is not necessarily required. However, if sealant is used (for example on transition pieces to provide colour), it should be applied in such a manner to not interfere with the cathodic protection function of the underlying TSA. Previous work has shown poor performance when thick epoxy top-coats have been used in conjunction with TSA due to unfavourable electrochemical interactions [135,136].

Some barriers need to be overcome to facilitate the large-scale application of TSA. Uncertainties in the application process and electrochemistry, paired with misleading testing of epoxy coated TSA created mix perception of its offshore performances. In addition, there is no standard covering the DESIGN of a CP system based on the use of TSA. The perceived risk and lack of standardization make the risk too high for investors [135].

The CROWN project has already taken important steps to removing some of these barriers:

- Some light has been shed on electrochemistry and like-for-like performances against most commonly used epoxy coatings and cathodic protection systems (corrosion testing and modelling).
- The ability of TSA coatings to protect bare steel at locations where the TSA coating is damaged has been found to be very good [137].
- TSA cost efficiency has been modelled and compared to sacrificial anodes and ICCP (life-cycle cost modelling).
- The process efficiency of TSA has been increased, resulting in a significant cost reduction.
- The best way to spray the nodes of jacket foundations was investigated (Universal Coatings).

With respect to standardization and certification, the CROWN project team is working to add the use of the TS(x)A in the list of possible corrosion protection solution in their corrosion standard. The standard is expected to be ready by the second quarter of 2018 [135].

Within the CROWN project, three metal systems were tested: pure Al, AlMg, ZnAl. It was found that ZnAl is highly protective of exposed steel but consumed at a relatively high rate when used in seawater [135]. In contrast the corrosion rates of Al and AlMg are much lower, yet the coatings are still able to provide excellent protection to exposed steel.

While TSA can be applied on-site, it is currently not being considered as a retrofitting solution for existing wind turbines. Above the water line, retrofitting is technically feasible, but the recoating of external surfaces is challenging due to their exposure to the elements.

6.3.3 Nickel coatings

As for nickel alloys, nickel-based coatings have an excellent corrosion resistance to different

chemicals.

Electroless nickel (ELN) plating is a process for depositing a nickel alloy from aqueous solutions onto a substrate without the use of electric current. It differs, therefore, from electroplating which depends on an external source of direct current to reduce nickel ions in the electrolyte to nickel metal on the substrate. ELN plating is a chemical process, which reduces nickel ions in solution to nickel metal by chemical reduction [138].

There are major differences between electrodeposited nickel and ELN coatings. For instance, the uniformity of the deposit of ELN is higher that of with electro-nickel. The great uniformity achievable with electroless plating makes it an ideal process for components with complex geometries or with a high number of holes, threading, cleavages and bends.

The purity of electrodeposited nickel is typically greater than 99% but when sodium hypophosphite is used as a reducing agent in electroless nickel plating, a typical composition for the deposit is 92% nickel and 8% phosphorus. The phosphorus content has a great effect on deposit properties and it can be varied over a wide range, typically 3 to 12%. The industry normally identifies electroless nickel coatings according to their phosphorus content, e.g.:

- Low phosphorus 2 - 5% P;
- Medium phosphorus 6 - 9% P;
- High Phosphorus 10 - 13% P.

There are distinct differences in the corrosion resistance and hardness properties of low and high phosphorus deposits. The structure of electroless nickel is responsible for some of its unique properties. It differs greatly from the crystalline structure of electro-deposited nickel and it can normally be described as having an amorphous structure. The absence of a well-defined crystal structure eliminates the possibility of intergranular corrosion that can be a problem with crystalline deposits, such as electrolytic nickel. Electroless nickel, therefore, provides a more effective barrier coating in protecting a substrate from corrosive attack.

Heat treatment of nickel-phosphorus deposits at about 400°C causes significant changes in properties especially its hardness (up to 1000 HV) due to the precipitation of nickel phosphide (Ni_3P) making the coating resistant to wear.

ELN offers very good corrosion resistance, it is not susceptible to stress corrosion cracking and can be deposited with a range of compositions and thicknesses, thus extending the life of coated parts and reducing the repair costs and limiting the part replacements. The use of nickel coatings in offshore applications is however rather to small components like valves, heat exchangers and pumps. Unlike galvanic coatings based on zinc, aluminium or cadmium, nickel coatings do not offer cathodic protection to the substrate but act as a barrier between the aggressive environment and the substrate. Consequently, the coating thickness, its uniformity and the absence of porosity are the key factors for an excellent corrosion resistance. In aggressive environments, such as the off shore one, and on components subjected to large elastic deformations, such as springs, the nickel coating is in turn protected by an anodic zinc-based coating [139].

6.4   Organic coatings

Organic coatings are protective systems whose primary components are derived from carbon-rich compounds of natural or synthetic origin. They are the main component (binder) of modern paints and are used to provide additional protection for the materials on which they are applied. Paints are complex and heterogeneous protective systems containing the binder, the pigments (or active and protective additive), extenders, solvent, driers and anti-skinning agents. The binder is the film former

and mainly contributes to the protective system durability. The pigments, when present, are dispersed in the binder and their proportion to the binder is a critical factor in paint formulation since their presence in the film increase the UV resistance but affect the rheological properties [140].. The pigments contribute to hardness and abrasion resistance of the film and can reduce its permeability to oxygen and water. Some particles (inhibitive pigments) such as zinc phosphate, metallic aluminium and zinc flake or lamella offer active protection to the substrates and improve their durability. Pigments can be used to give to the paint a specific colour, as well as anti-fouling and anti-bacterial properties. Extenders are present in small amounts and are generally used to modify the coating properties. Anti-skin agents prevent the formation of a rigid film on the coating surface. In some paints a thixotropic agent is added to control sagging of the paint and to allow the application of a greater coating thickness [141].

Organic coatings can be monolithic (consisting of only one layer) or containing multiple layers. Typically, a multilayer system consists of a primer, 2-3 intermediate coats and a topcoat. The primer can be based on an organic coating, but often metallization is also used as a 'primer' layer.

The primer is applied directly onto the cleaned steel surface. Its purpose is to wet the surface, to provide adhesion for subsequently applied coats and, in some cases, to provide corrosion inhibition. Undercoats (intermediate coats) are applied to 'build' the total film thickness of the system, possibly with multiple layers of paint. A higher total dry film thickness of the coating system (DFT) generally results in a longer protection life. Finally, a topcoat can be applied to provide the required appearance and surface resistance to the coating system. The topcoat is also the first line of defences against weather, sunlight, corrosion, mechanical damage and biological influences (bacteria, fungi, algae, etc.). The various superimposed coats within a painting system must to be compatible with one another [102].

Organic coatings act as a protective barrier against corrosion and oxidation and their effectiveness depend primarily on their chemical inertness and impermeability. As already mentioned, the total DFT of the coating system has an important influence on the durability of the corrosion protection system. Paints are not completely impervious to oxygen, moisture and salt penetration. These corrosive media diffuse through the applied paint barrier very slowly. The thicker the coating, the longer it takes for the corrosive media to reach the steel below the paint. This is also one of the reasons why a primer with good corrosion inhibitive properties is often required. In addition to DFT, a higher coating density and degree of cross-linking can slow down the diffusion process and prolong the protection lifetime. Modern paints have been developed to provide improved protective properties, but these can be achieved only through careful surface preparation, correct paint application and the proper paint selection for the exposure conditions.

The organic protective systems are usually designated on the basis of the binder (*i.e.* epoxy paints) and by the pigments as both have a strong influence on coating properties. An overview of the most important binders and hybrid systems for offshore applications is described in the following pages.

6.4.1   *Epoxy coating systems*

Epoxy together with polyurethane (PUR) based paint systems are the most frequently used anti-corrosion solutions in many industries, including the offshore sector. The epoxy resins are compounds that contain hydroxyl groups and reactive epoxide end-groups in the molecule chain, which, by reaction with cross-linking agents, form highly cross-linked structures with high chemical resistance. The cross-linking agent (such as polyamide, aromatic or aliphatic or cycloaliphatic amine, amidoamine, amine adduct or polyamine curing agents) can be added to the resins at the time of application. **Epoxy**

primers [102] are usually two-pack materials. However, epoxy resins can also react at high temperatures with amine or phenolic resins. The epoxy formulations are supplied ready for use without the need to add the cross-linking agent and film formation only requires solvent evaporation as reactive processes are not involved. They are called a single-component systems or one-pack compositions [142].

Zinc phosphate epoxy primers are the most frequently encountered and give the best durability within the group. Zinc phosphate refers to the type of corrosion inhibitor used in the primer. **Zinc-epoxy primers** [102] can be either zinc-rich or reduced zinc types, where metallic zinc (dust) is used as a corrosion inhibitor. Zinc-rich primers produce films which contain at least 80% by weight of metallic zinc powder [143] while corresponding figures for the reduced zinc type are as low as 55% by weight. Epoxy based paints are typically used for the intermediate coats. They have good abrasion and chemical resistance and are very good barrier layers. Epoxy paints are generally also less expensive than the PUR paints, which are used as topcoats.

In early 2016, six organic coating systems were investigated according to their performance under Arctic offshore conditions [27,29]. The studied coating systems were epoxy and polyurethane based, but differed in coating material, hardener, number of layers, dry film thickness and application method. The corrosion performance of the coatings was assessed under test conditions adapted to Arctic offshore conditions [27,29]. The results indicated that if exposed to very low temperatures (-60°C), the coatings change their response to corrosive and mechanical impact loads:

- Corrosion protection resistance decreased.
- Coating adhesion increased (pull-off strength).
- Impact resistance and abrasion resistance decreased.

Hoarfrost accretion changes with coating type. Improved behaviour was obtained for a three-layer system with high thickness (1400μm), consisting of two glass-flake reinforced epoxy coats and a polyurethane topcoat [27,29].

The incorporation of laminar pigments, such as micaceous iron oxide, reduces or delays moisture penetration in humid atmospheres and improves tensile strength. This illustrates that a large variety of epoxy and PUR based paints is available on the market, with exact formulations being the property of the coating manufacturers.

By means of a wide possibility of formulations, epoxy resins allow the preparation of paints with different characteristics suitable for various applications. Therefore, there are many systems based on epoxy resins.

It is important to mention coal tar epoxy resins. These systems are a combination of epoxy resin and coal tar, which can be applied in a high film thickness in one coat. The epoxy resin is usually supplied separately from the curing agent. The coal tar is in the form of a semi-liquid pitch that can then be blended with the epoxy resin. The curing agents for coal tar epoxies may be amines or polyamides. The coal tar has the function of filler within a cross-linked epoxy matrix, but, some additional crosslinking could be obtained through the reaction between some hydroxyl group of phenolic compounds in coal tar and hydroxyl groups on epoxy. These systems offer excellent resistance to salt water and are highly resistant to cathodic disbondment. They are primarily used in pipe coatings and protection of offshore facilities and coats of 300 to 400 μm thickness are generally used.

Still nowadays, the most common epoxy paints that are particularly resistant to marine or industrial atmospheres, contain solvents. Paint thinners improve the workability by reducing the viscosity of the system, but a balance between viscosity and volatility is required for satisfactory application of paints. Under pressure of environmental regulations, there is a trend to search for paints with lower VOC

contents (Volatile Organic Compound), which are considered as air pollutants. There are basically three possible products: a high-solids low-solvent-borne product (this is achieved with high amounts of small primary amines in the curing component [144] or the use of a special formulation of amine-based hardener [145]), a solvent-free product or a water-borne product.

The water-based epoxy coatings are usually two-package systems based on epoxy polyamide or non-yellowing acrylic resin and a water-soluble or water dispersed epoxy resin. The epoxy component could be a proprietary mixture of epoxy and aliphatic-epoxy monomers emulsified in water. The curing agents completely dissolve in hydroxyl-free water-miscible solvent (e.g. ethylene glycol monoethylether acetate) and other solvents. These formulations can contain some organic co-solvents and undergo poly-condensation or polymerization reactions. Waterborne coatings can be applied with conventional techniques: spraying is one of the best solutions for porous material.

Care should be taken in the application of these products, as they can be difficult to apply at the specified nominal dry film thicknesses. More information regarding the use of low-VOC paints can be found in the International Standard ISO 12944, part 5 [143].

Single layer, solvent free epoxy coating [146] are environmentally friendly coating solutions. Some of these solvent-free epoxies exist as single layer coating systems. Such coatings can be applied directly to the bare steel and do not require a primer. As a result, the application time is short and there are no wait times between subsequent coats. This is a big advantage for maintenance work, as the shut-down period is drastically shortened.

Single layer, solvent free epoxy coatings are used to stop underwater heavy marine corrosion and can withstand very aggressive environments, including Accelerated Low Water Corrosion (ALWC) and MIC. The solvent free characteristic of the coating plays an important role in this. As solvents evaporate from traditional paints, they leave microscopic porosity, through which MIC inducing organisms can find their way to the steel. Anti-fouling formulations of single layer, solvent free epoxy coatings also exist. The cost per litre of single layer, solvent free epoxy coatings is generally higher than that for traditional coating systems, but reduced application and maintenance costs can result in a reduction of the total cost of ownership. This type of coating is currently used on tidal turbines in the Netherlands. As maintenance of tidal turbines is very challenging, the high durability of the coating can outweigh the higher cost.

Once such paint is Humidur®, a two-component, solvent free epoxy coatings. The specific chemistry of the Humidur ® coating makes that its corrosion resistance is not degraded under influence of UV. This means that a topcoat is not required to provide adequate corrosion protection. The paint is primer, intermediate and top coat, all in one. However, the colour of the coating can degrade under UV. Therefore, for applications where colour coding is important, a topcoat may be necessary.

The solvent free epoxy can cure under water, which is an added advantage for maintenance works. The repaired zone doesn't have to be shielded during curing and can even be submerged. As a result, the window of opportunity (in terms of weather conditions) for repair work is enlarged. The coating can also be applied and cure at sub-zero temperatures.

A further advantage with respect to maintenance work is the surface tolerance of the coating. Humidur® performs well on surfaces prepared by water jetting or by means of hand tool or mechanical tool cleaning. The grit blasting step can be omitted. In offshore environments, care must still be taken to remove salts from the steel surface.

The higher viscosity of the paint gives it good edge protection properties. The coating thickness (single

layer) can range from 400 to 2000 μm (on sharp edges). The product lifetime effectiveness is 20-50 years.

Single layer, solvent free epoxy coatings can be used both in submerged and atmospheric zones. They are currently used in a large number of applications. Some relevant applications for the Offshore Energy Sector are:

- Construction of waterway walls with sheet piles. The sheet piles are first coated and subsequently hammered into the ground. It has been shown that the applied coating is not damaged and also provides corrosion protection below the mudline;
- Corrosion protection of maritime steel, with proven resistance after 30 years of exposure (jetty piles, mooring piles, tubular piles);
- Corrosion protection of offshore structures (complete O&G platforms, FPSO's, maintenance of offshore wind turbines, support structures, coating repair of ships);
- As a coating on concrete structures;
- Applications in the Great Lakes (USA), exposed to floating ice;
- Petrochemistry sector: used in maintenance campaigns.

6.4.2   Polyurethane coating systems

Polyurethane resins (PUR) are obtained by reaction of acrylics, polyesters or polyethers, containing reactive hydroxyl groups (polyols), with organic isocyanates (hardener) which can be aliphatic or aromatic. The latter is obtained by condensation of aromatic poly-isocyanic derivatives with polyfunctional hydroxyl compounds: in this way a polymer is obtained which avoids the effects of the isocyanic derivative (generally volatile and toxic). The properties of polyurethane are greatly influenced by the types of isocyanates and polyols used to make it. The aliphatic isocyanates produce the most durable and light-stable coatings but they react slowly and are more expensive than the aromatic isocyanates. Long or flexible chains produces elastic polymers, while high cross-linked chains produce tough or rigid polymers [140]. Acrylic polyurethanes are widely used for atmospheric corrosion protection but are not used on parts immersed in water where the more chemical resistant polyester urethanes are preferred. Acrylic urethanes are used as a top coat or intermediate coat in atmospheric environments.

PURs are available as single or two pack materials. Two-pack resins are similar to epoxies but with improved atmospheric durability. PUR paints have a better UV resistance than epoxy paints, making them good topcoats for offshore environments with high resistance to UV exposure. These resins are used in the formulation of anticorrosion paints with excellent resistance to abrasion and to chemical aggressive agents (typically a little better than that of epoxy paints). Moisture should be avoided during application in order prevent the reaction between isocyanate and the hydroxyl water group. However, this reaction is exploited for the curing of a special class of polyurethane resins known as moisture-cured urethanes (MCU). MCU are supplied as single or two components containing pigments that are nonreactive with isocyanate. It is possible to add a number of pigments but aluminium leaf or zinc particles are commonly used. Because of rapid curing reaction, aromatic isocyanates are mainly used in MCU. Moisture-cured isocyanates are used as primers and/or intermediated coats under epoxy coatings or aliphatic polyurethane to minimize yellowing and darkening [147]. An interesting coating material containing MCU with unreacted and active -NCO groups can be applied to a rust covered surface. The free -NCO groups in the coating material react with the moisture in the rust, dehydrating it and producing a strong protective barrier against outer water and oxygen [148].

6.4.3 Polyurea coatings

Polyurea systems are obtained from a polyaddition reaction of an aliphatic or aromatic isocyanate with a resin blend. The isocyanates can be monomers, polymers or pre-polymers, while the resin blend contains amine-terminated polymers and/or amine-terminated chain extenders. The resin blends also can also contain some additives such as polyol dispersed pigments.

The quality of the coating is not determined by the presence of amines or another curing agent but by the type and nature of the isocyanate and by the quality of the resins and additives that contain the polyols. In fact, the polyurea coatings (PC) are charged with pigments or substances that contain hydroxyl groups that favour cross-linking and provide excellent resistance to the substrate corrosion and to chemical agents. The polymerization reaction with the amines is particularly fast and this characteristic is especially important with regard to spray applications in the presence of very low temperatures and humidity. Polyurea coatings have exceptional physical properties such as very good flexibility, good tear strength, tensile strength, chemical and water resistance. Moreover, PCs are very tough, combining high elasticity with high surface hardness, resulting in very good abrasion resistance. They also can have very good barrier properties due to the high density of the film. Therefore PC combine a very good corrosion protection with excellent weathering and abrasion resistance [149].

An important characteristic of this type of coatings is their versatility. In fact, they can be applied to a wide range of substrates, including concrete, steel and even polymers and a wide range of coatings are available, suitable for different applications ranging from roofing to anti-explosion protection, to the rear lining of a truck, to parking decks and bridges.

PCs are also used in Offshore Applications (shipping, oil platforms) on decks, superstructures, ballast tank liners, chain wells, etc. These are all areas subjected to impact and heavy abrasion, which are exposed to harsh chemical agents such as salts [150]. The high abrasion resistance of polyurea coatings and the possibility for applying it in thicknesses of up to 6mm makes them suitable for wind turbine boat landings, ladders, rails, walkways, etc. Additionally, the high flexibility and elongation of the coatings make them suitable for the bridging of dynamic cracks. These coatings can also expand and contract with the underlying structure as temperature changes (due to flexibility), which could be beneficial for offshore applications. Certain polyurea systems can also be applied on polymers [151]. They could therefore be used on the blades of tidal turbines, where erosion plays an important role.

Some applications methods are currently used for PU coatings. A high-pressure hot spray is suitable for very high-volume coatings. Isocyanate is mixed under high pressure and temperature (up to 200bars and 80°C) with amine-based solutions at low viscosity. Under these conditions, the polyurea system undergoes a more immediate curing process and the application is faster: polyurea coatings are often referred to as a "spray and go" coatings. Before application, the surface substrate should be cleaned from oil contamination, dirt or rust to ensure adhesion and durability. This application method requires specialized equipment and specifically trained operators.

Warm spray coating is used for medium volumes and the polyurea formulation maintains low viscosity at temperatures below 60°C while low pressure spray coatings are used when slower speed applications are permitted and a hot-spray, high-pressure application is not needed. Roller or brush methods are also used for interior coatings or for areas that are difficult to reach with a spraying apparatus. Polyurea coatings have a high tolerance for humidity, both from the environment and from the substrate, and temperature (will cure even at temperatures well below 0°C).

They cure very rapidly to a solid surface, in a matter of seconds [149,150]. The fast curing can for example be an advantage for pier protection, which needs to be fully cured before high tide.

Combined with the tolerance to humidity and temperature, this could make polyurea coatings suitable for on-site repair jobs.

PC are considered to be a modern technology. They have been commercially developed in the US and Asia since 1990. It is only since 2000 that commercial development also focused on Europe [152]. In the past 15 years, the technology has known a rapid development [150].

Recently, some classes of polyurea and poly(urethane-urea)s coatings showed self-healing properties [153,154].

In fact, these materials that also include inexpensive commercially available compounds show the ability to heal back together, at room temperature, after a crack or cut, with almost the same strength they exhibited before. This property was obtained without the need for a catalyst or high temperatures by designing hindered urea bond (HUB) with a specific substituent on the amine group. The reversibility of a hindered urea bond can be controlled by changing the bulkiness of the substituents [153,154].

The technology was first developed for polyurea coatings but can be applied and integrated into a variety of polymers, such as polyurethanes, polyesters, polyamides, polycarbonates, polyamines, and polysaccharides to make linear, branched, and cross-linked polymers. Polymers incorporating these HUBs can be used in self-healing polymers for corrosion protection and in a wide variety of other applications including environmentally compatible packaging materials and biomedical applications, such as drug delivery systems and tissue engineering [153,154].

6.4.4 Powder coatings

Powder coating is an organic coating that is applied as a free-flowing, dry powder. The main difference between a conventional liquid paint and a powder coating is that the powder coating does not require a solvent to keep the binder and filler parts in a liquid suspension form. This has several environmental benefits, as no VOC's are required. The powder is typically deposited electrostatically and then cured under heat (150-200 °C).

Powder coatings offer a number of benefits compared to liquid coatings. In many cases, they perform better and last longer than traditional wet paints. Powder coatings are very durable and corrosion resistant. Powder coatings provide corrosion protection by being very good barrier layers. Compared to liquid coatings, most powder coatings are also more resistant to chips, scratches, wear and fading, and they retain their brightness and vibrancy longer [155].

The powder can be either a thermoset or a thermoplastic material. Thermosets are mostly insoluble and will not melt, making them suited for high temperature service and chemical resistance. However, they cannot be repaired and are difficult to maintain. Thermoplastics can be melted and remelted. They can be repaired and the thickness of the coating may be increased with the addition of more material. There are no delamination problems, as sometimes associated with liquid paint systems. The most common polymers used are polyester, polyurethane, polyester-epoxy (known as hybrid), straight epoxy (fusion bonded epoxy) and acrylics [156].

Powder coating is also suitable for coating structures that end up in the offshore environment. Offshore powder coatings are found for example on pipelines and components on floating production units, fixed platforms, mobile rigs and drill ships.

The use of powder coatings is traditionally limited because the coating is applied in the shop (due to the need for oven curing). However, technological development in the last 20 years has made it possible to apply powder coatings with a type of thermal spray process. This makes it possible to

deposit and cure powder coatings simultaneously, eliminating the application restrictions of traditional powder coatings [156,157].

Fusion-bonded epoxy coatings for offshore applications [158].

The most common powder coating in offshore applications is fusion-bonded epoxy coating (FBE coating), which is suitable for use alone or in a dual powder coating system. The FBE coating system is a thermosetting resin for external surfaces of, for example, offshore pipelines. These FBE coatings provide external metal surfaces with extremely strong corrosion protection. A typical coating thickness is in the range of 400-600 µm. Very good adhesion is achieved, even in humid environments. These coatings come with at least 20 years warranty.

High performance fusion bonded epoxy powder is also suitable for use in a three-layer system which provides even better corrosion resistance than the FBE alone:

- Layer 1: Fusion bonded epoxy coating;
- Layer 2: Co-polymer adhesive;
- Layer 3: Polypropylene (suitable for operating temperatures between -40 °C and 110 °C).

The last layer is the one that defines the thickness of the coating system.

6.4.5 Rubber linings

Rubber linings have been extensively used for protecting carbon steel equipment against corrosion and abrasion since the very beginning of the 20th century [159] and they are still used in the most aggressive processes of chemical industry. Rubber compounds show strong adhesion to carbon steel, which makes them adapted for being used as coatings and linings. There are many different types of rubbers depending on its chemical structure and properties. One of the most prominent is chloroprene rubber (most known by its commercial name neoprene) due to its flexibility and outstanding resistance against ozone, sea water and weathering [160]. Due to its remarkable mechanical properties and outstanding resistance to weathering, chloroprene rubber is nowadays one of the most adapted material for mechanical and anticorrosion protection of clamps and supports of offshore secondary steel (J-tubes, grouting, Boat-landing stairs and other). Recently, special qualities of chloroprene (GN-60 and GN-60 EM) have been used in the following windmill parks: HYWIND, EAST-ANGLIA, NISSUM and DEUTSCHE BUTCH for IBERDROLA and STATOIL mainly. Besides, chloroprene rubber linings are potential candidates for protection of carbon steel in the splash zone.

6.4.6 Epoxy – Aluminium oxide composite coatings

Composites of epoxy novolac polymers and silanized micro-ceramic aluminium oxides charges are emerging coatings with good adhesion and flexibility for anticorrosion on both carbon steel and concrete with even poor substrate preparation, nevertheless using an epoxy primer the adhesion normally becomes outstanding. This family of solvent free coating can be applied by airless spray pump or by roller usually in 2 layers of ≈ 250 µm. The combination of high chemical resistance and ease of application make them suitable for many industries with highly corrosive environments. In particular, such composite coatings are being used in offshore environments with excellent results such as the one achieved in the monobuoy for CEPSA Company in Cadiz Spain.

6.4.7 Ongoing research on organic coatings

In the last few decades, several types of organic-based coatings have been developed [161], including anti-fouling paints [162–167], composites and nano-coatings [168,169], self-healing coatings [170–

173], and hybrid sol-gel materials [171,174,175] among others. However, very few studies were performed on OW structures using self-healing and hybrid sol-gel coatings. This may be explained by the fact that these types of coatings are not well established in the market and the most of them are still under optimization studies. Frei et al. [176] in 2013, reported that the TRL of most applications in self-healing topics is in classes 2 to 4. Nevertheless, smart coatings are regarded as the future of coatings and the applications of functional or smart strategies are actually the most promising routes to realize high performance protective systems. Not surprisingly, the coatings industry in the last decades has invested many resources in this direction [177–179].

Smart materials are able to dynamically adapt their properties to the environment and initiate a specific response to a change in the external environment. The strategy adopted in smart coatings is to provide an additional corrosion protection on demand when the coating is mechanically (scratch, cut cracks) or chemically (pH change due to corrosion onset) damaged or when an external trigger (electrical or chemical) is applied to the coating. Two main routes are used to introduce the required smart functionality into the coating: microencapsulation (or loading) of active species in nano/micro carriers or direct introduction into the polymer chains (in bulk and/or surface) of specific groups or functionality. Micro or nano carriers include a wide range of hollow or mesoporous particles, clays (halloysite), Zeolites, nanotubes, polymeric microcapsules. The microencapsulation technology has been widely exploited in the chemical, pharmaceutical, cosmetic, agricultural and food industries to produce delivery systems and is considered the most promising option [180]. The main requirements of these carriers are the simultaneous compatibility with the host coating and active content, long shelf-life, mechanical strength and chemical resistance to survive the coating production and application. The carriers operate as reservoirs of specific chemical species that are released under specific stimuli. The carriers embedded in polymeric protective coatings can deliver or contain corrosion inhibitors [181–183], antifoulings or biocides [184], , corrosion indicators, healing agents or all of these. The carriers are dispersed in the polymeric matrix and the encapsulated corrosion inhibitors are released when the corrosion reaction induces a pH change that opens the microcapsules [185,186]. Calle and co-worker showed a successful application of multifunctional smart coatings for corrosion control and protection of the launch pad metallic structure at the Kennedy Space Center (Florida) in a strongly corrosive marine environment [187]. The authors developed new microcapsules [188] that can deliver corrosion inhibitors and pH indicators at the onset of the corrosion process, in order to monitor the status of steel structures and to protect them from corrosion. Smart coatings can also be used to protect submerged structures under cathodic protection. In this case, the protective system includes polymer embedded micro-capsules containing compounds sensitive to the electric field generated by the cathodic protection. The microcapsules react in the presence of an alkaline medium at the coating discontinuity where the metallic substrate is in direct contact with a corrosive medium and the released content forms a protective layer on the exposed surface [189,190]. Some other smart coatings incorporate micro-capsules containing polymerizable species. When these microcapsules are broken because of cracks propagations through the coating matrix the content is released and the polymerizable species (healing agents), can heal or repair damage either alone or in the presence of a dispersed catalyst, without any external intervention [191,192].

Self-healing materials containing microcapsules will remain working as long as unbroken capsules are present. By contrast, as reported before, dynamic polyurea can heal itself, as it relies solely on its molecular structure when HUB is specifically designed.

The HUB approach can be applied to polyurethanes, polyesters, polyamides, polycarbonates, polyamines, in order to produce self-healing coatings [153].

In recent years, new systems of paints have also been developed in which the anticorrosive function and other required properties are ensured by the same paint, thus reducing the number of coats applied and the costs associated with its application [193].

For corrosion protection coating systems, the research focus is on new environmentally friendly coating systems with the ability to behave and adapt in response to environmental demands [164,167,194,195]. Coatings with pre-emptive healing abilities may become one of the main targets in the coating industry [170,173]. Combined systems (multilayers) that associate different layers with distinct functions will be improved and/or developed in order to achieve the most efficient protection possible against corrosion [9,25,174,175]. These coatings may be comprised of metal-rich coatings, containing zinc or magnesium particles or other inhibitor particles.

There are many epoxy coatings commercially available for corrosion mitigation, but research for contemporaneous polymers or hybrid materials have been gaining market niches. Additionally, several coatings with anti-fouling properties have also been studied. Recently, Palanichamy and Subramanian reported a study where bacteriocin incorporated epoxy-based paint exhibited an antifouling property in natural seawater [166]. Azemar et al. [165] recently reported the development of hybrid antifouling paints. The authors reported the use of a copolymer binder, producing a paint that associates hydrophobicity and biodegradable properties. The reported paints prevented fouling settlement and proliferation by erosion, biocides release, and high and constant hydrophobicity. Carteau et al. [164] reported the development of environmentally friendly antifouling paints using biodegradable polymer and lower toxic substances showing that it is possible to obtain antifouling activity with lower toxic substances. Studies using composite coating materials have also been performed [168].

6.5   Hybrid and other coating systems

6.5.1   Phosphate conversion coatings

Phosphate conversion coatings are extensively used as primer layers in many industries, especially the automotive industry, to improve the adhesion of organic coatings to ferrous metals [196,197]. There are three types of phosphate conversion systems: amorphous iron phosphate, crystalline manganese and zinc phosphate.

The most used conversion coatings for high demanding corrosion protection are the zinc phosphate-based coatings (tri-cation phosphate systems). These coatings can be applied either by spray or by immersion and require several process stages.

No references were found regarding the use of zinc phosphate in the offshore sector. However, in theory new offshore constructions could be phosphated by using spray systems. This phosphate conversion layer would than serve as a replacement for the traditional primers used today.

Traditional organic primers can contain zinc particles or zinc phosphate as a pigment. These phosphate pigments also act as corrosion inhibitors, but do not give the same bond strength to the steel substrate as obtained with phosphate conversion coatings. The latter result from a chemical reaction with the steel surface and are thus chemically bonded to the steel substrate.
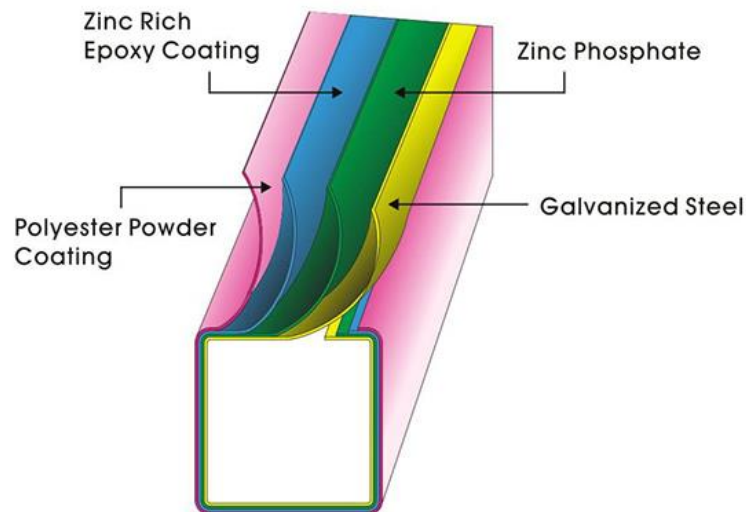
Figure 14: A complete corrosion protection system for steel substrates

In some **iron phosphate** coating applications, the cleaning and coating steps are combined (iron phosphate washing). This process is most used for powder coating of steel parts (see section 6.4.4). Otherwise each process step is typically separated by a rinse step to remove residual chemistry (Figure 14).

Iron phosphate coatings can be applied by **hand wiping**, with a handheld spray wand, by immersion, or a spray washer. The number and type of process stages is directly dependent on finished part requirements. A cleaner/coater combination followed by a rinse is the minimum chemical cleaning and phosphating process used. The addition of stages in the process can provide enhanced performance. Unlike the iron phosphate, a zinc phosphate coating cannot clean and coat simultaneously. In a conventional three-stage process, a separate cleaning stage is required between each pre-treatment stage [196].

Wipe application iron phosphating is the simplest method of phosphating. The easy application and its working ability at lower temperatures make wipe application iron phosphating very feasible. Metal parts can be wiped, brushed or cleaned with a sponge. It is preferred for such large metal pieces which do not fit into phosphating baths and also when working area is not enough to set up a continuous line or immersion line of phosphating [198].

Henkel developed a new dry-in-place phosphate system that does not need a final water rinse. The commercial products Bonderite 1455-W (Wipe) and Bonderite 7400 according to the manufacturer should be used on either steel, galvanized steel or even aluminium substrates [197].

After phosphating, a final post treatment can be applied to passivate the phosphate layer. In the past chromate rinse was used but due to stringent environmental rules other alternative products are developed based on zirconium oxide [199].

In order to reduce the heavy metals content and the production of phosphate-rich waste, a new class of environment-friendly conversion coatings have been developed based on a zirconium coating technology and not containing phosphates, nickel or manganese. Some products (TecTalis®, Oxsilan®, Zircobond®) are already available from different industries Although these new treatments provide adequate protection in most applications, in some critical applications, they are not as effective as the old zinc - phosphate based coatings. Nevertheless, new products with improved properties, still based on zirconium but with reduced phosphate content, have recently been developed [200].

6.5.2   Chemically Bonded Phosphate Ceramic coatings

Chemically Bonded Phosphate Ceramic (CBPC) coatings are corrosion protection coatings for carbon and mild steels. CBPC is a two layer system that is applied in a single coating step [201]. The coating is applied by spraying of an acid/base mixture. The acid reacts with the steel to form a 2 µm thick iron magnesium phosphate layer, which is chemically bonded (covalent bond) to the steel substrate. This alloy layer effectively prevents corrosion of the steel [202,203].

The second layer of protection is a 300-900 µm thick ceramic shield that serves as a phosphate reservoir. The hardness of the ceramic top layer provides good abrasion and impact resistance. The ceramic layer is chemically bonded to the iron phosphate alloy layer. If the ceramic shell and alloy layer below are breached, the ceramic will bleed phosphate into the breach and continuously re-passivating the steel to ensure that the alloy layer remains intact. This illustrates that the CBPC coating is not a barrier coating, but a self-healing conversion coating [202,204].

If the area of the breach is too large, the phosphate may not be able to reach and re-alloy the entire damaged area. However, because of the chemical bonding between the alloy layer and the substrate, and between the ceramic and the alloy layer, corrosion promoters like oxygen and humidity cannot get behind the coating. Damage to the coated substrate will not spread because the carbon steel's surface is turned into a layer of stable oxides [202,203]. Corrosion will therefore effectively be blocked at the start of the coated area.

Evidence for this is provided by a test performed by EonCoat according to NASA standards: deeply gouged samples are cyclically exposed to 4 hours of salt spray, followed by 4 hours of UV light. Most tested industrial corrosion protection coatings failed in 45 days or less (samples on the right side). The Eon Coat CR sample (samples on the left side) does not suffer from corrosion, even after 120 days. The EonCoat CR coating is expected to have a service lifetime of 30 years [201]. It has undergone a salt spray ASTM B117 test for more than 10.000 hours, without evidence of corrosion [203].

Figure 15: Comparative study on a gouged sample subjected to a cyclic corrosion test [201]

Apart from its operational properties, also its forgivingness towards application conditions makes it an interesting coating technology. Only a minimum surface preparation is required. A commercial blast to SSPC-SP6/NACE3 is generally sufficient. In fact, the presence of slight surface oxidation improves the reactions between the coating and the substrate. EonCoat can easily be applied over a flash-rusted surface, making blasting conditions less stringent. The CBPC coating can be applied on humid surfaces and is 100% salt tolerant. This makes that the coating can be applied on-site, in offshore conditions. The coating dries in 10-15 minutes after application and is service-ready in one

hour.

CBPC coatings can also be used for local repairs. No masking of adjacent, coated areas is needed. If sprayed over existing paint, the CBPC coating can simply be washed-off.

Important with respect to application in offshore conditions is also the slightly alkaline surface of the 100% inorganic coating. This makes the coating resistant to micro fouling. EonCoat is a white coating, but it can be covered with a coloured topcoat if necessary.

EonCoat protective coating [205,206] is currently used in a large number of applications such as submarine vessels, fuel oil storage tanks (inside and outside), coastal bridge structures and pipelines, and is currently gaining a foothold as a the coating for offshore structures [204]. Similar coatings with improved surface characteristics like surface toughness and smoothness, better abrasion and acid resistance, less erosion and longer durability have recently been proposed. [207]. These coatings consisted of pore free phosphate-bonded glass-ceramics with a translucent and dense surface. They could be applied by single spraying providing both passivation and protective coating formation.

Specifically for Offshore Wind structures, CBPC coatings could potentially be used on every part of the structure (MP, TP and tower, both inside and outside). For the coating of structures exposed to heavy abrasion and impact (such as the boat landing), a CBPC coating could be used as a primer, followed by a tough polyurea topcoat.

6.5.3   Chemically Bonded Silica Ceramic coatings

Ceramic silica-based coatings can be used to protect a variety of metal substrates from corrosion (stainless steel, carbon steel, high alloys, aluminium, copper, etc.). The coatings are produced by a controlled melting process of inorganic raw materials, which are first sprayed on the surface. The coating process involves mixing the raw materials, a pre-treatment of the workpiece (usually sandblasting) in order to remove impurities from the metal surface, followed by the deposition of the ceramic formulation. Common deposition technologies are Spray coating, Dipping, Flow coating, Electrophoretic deposition and Powder electrostatic deposition. After the coating application a thermal treatment at approximately 800 °C is needed in order to consolidate the ceramic silica-based coatings on the metal substrate [208,209]. By using a laser to perform the heat treatment, the technique can also be used for large constructions.

Controlled application of ceramic silica-based coating formulations allows to obtain a very smooth surface finishing and excellent edge coverage in all the areas of the product, even where the access is limited. In addition, redox reactions occurring during the thermal treatment enhance the chemical bonding between the ceramic coating and the metallic substrate. The solubility of some components like Ni and Cr in iron is used to create a diffusion layer at the interface [210,211].

Despite all of these advantages, the thermal treatment required to sinter the ceramic coating may lead to a substantial change in the mechanical properties of the metal substrate, such as hardness and resistance to fatigue. This has, up to now, been a severe handicap that limited the scope of the ceramic silica-based process for a large number of substrates, restricting the access to big components such as offshore structures.

In order to be able to apply such coatings to big carbon steel structures, a laser sintering process is under development by Kera-Coat Company [212], trying to get a productivity of the coated area of 1 m^2/min. The development is expected to be ready within 3 years (2021). The ceramic silica-based

coating is applied as a monolayer coating using a spray robot. The coating has to be cured/vitrified by heating, which can be achieved using a laser. The heat input from the laser source is very localized, preventing unwanted heating of the substrate. The developed technology allows performing spraying and laser-curing in a single process step. The envisaged productivity of 1m²/min would be much faster than today's polymeric multilayers coating. Offshore Wind structures can take advantage of this technology, especially focused to the harsh exposed area of the tower, the splash zone, but also deployed to other parts of the structure due to "tailor-made" silica-based formulations developed.

In order to overcome a number of disadvantages, Kera-Coat has been working for several years in three technical lines trying to solve this drawback:

1. First one related to the ceramic silica-based formulations by the improvement of the chemical resistance [213] and durability on seawater media compared with multilayer polymeric paints protection. This effect connected to its low roughness surface ($R_a < 0.1$), able to lead to a vitreous and glassy surface, helps prevent fouling and biofouling adhesion, without including toxic and lixiviant compounds, becoming a great and eco-friendly approach for the protection of offshore metal structures. Apart from this property, the 150 µm monolayer coating present a hardness of 64 HRC and high abrasion resistance under a low tightening torque according to EN ISO 5470-1 standard (58 mg metal substrate vs. 0.9 mg from the coated sample, related to material loss). Despite the high hardness, the coating cannot be used for metal-metal contacts under high pressure, due to a low compression resistance. These functional results have been validated in seawater conditions (Plentzia bay) over the last 5 years [214].

2. Secondly, the use of a laser source to make a selected thermal treatment over the ceramic silica-based coating was investigated and the coating adapted for such laser technology. The laser technology allows to precisely target a selected area, generating enough power for sintering of the coating and to create a chemical bond with the surface. Thus, by controlling parameters as the energy of the laser-shot and the displacement speed of the beam over the coated sample, the ceramic coating achieves the melting temperature throughout its thickness without modifying the core of the substrate.
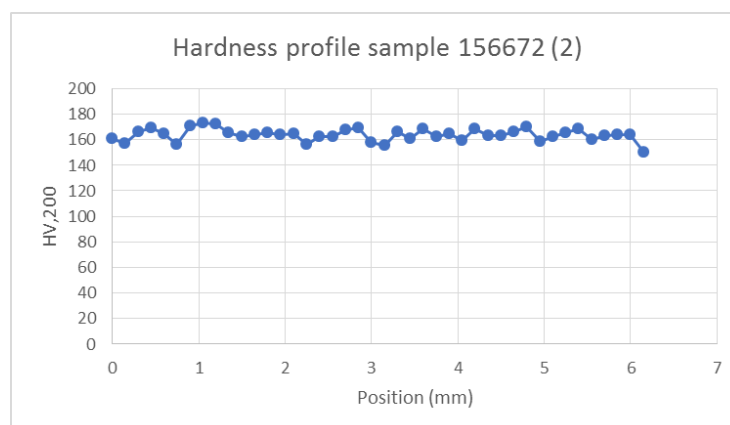
Figure 16: Carbon Steel hardness profile after laser treatment

3. Offshore maintenance represents a difficult task involving exorbitantly high costs. Despite the ceramic silica-based performance, some maintenance operations could be needed during its lifetime or assembly operations. In this sense Kera-coat Company is also investigating on-site repair technologies in order to offer a full turnkey solution. This approach consists on a ceramic silica-based formulation adapted to a wet spraying technology combined with a local

thermal treatment (portable electric resistance and induction thermal technology)

6.5.4 Film Galvanizing Systems

Film galvanizing systems can be used to deposit a metallic zinc coating on surfaces that need to be protected from corrosion. The zinc layer can be applied as a paint, with brush, roller or by spraying (with a spray gun, or simply from a spray can). The result however, is a metallic coating containing 96% high purity zinc dust in its dry film. It is thus a metallic coating, providing cathodic protection to steel substrates, on top of the passive barrier protection it offers.

Commercialized under the name ZINGA® [215], this type of coating provides cathodic protection, similar to hot-dip galvanizing, but with the advantage that it can easily be applied to large structures or on-site. It can thus not only be applied to new structures, but can also be used for repair operations, for instance for the repair and reloading of galvanized structures.

The resulting zinc-coating consists of 96% zinc, the other 4% being an organic binder. The organic binder improves the coating-substrate adhesion. Additionally, the binder provides supplementary barrier protection, reducing the depletion of zinc and increasing the protection lifetime in comparison with for example thermal sprayed zinc coatings. As the corrosion process commences, insoluble zinc salts are formed which provide an additional degree of protection.

An important advantage of the film galvanizing system is its ease of application. It can be applied with brush, roller or spray (gun or spray can). The film is touch dry in 10 min, can be overcoated with a second layer after 1 hour or with a compatible top coat after 4-6 hours. Painting is possible on surfaces with temperatures ranging from -15 °C to +40 °C and in atmospheres with humidity up to 95%.

When painting on a new surface, high pressure wash-down, followed by blasting to Sa 2.5 is required. Recoating/reloading of previously galvanized surfaces requires a cleaning to remove grease and other contaminations followed by a light sweep blast to remove zinc salts. The remaining zinc layer can simply be overpainted with the film galvanizing system to reload it.

Typical zinc layer thickness is 80-180 μm, depending on the atmospheric conditions and required lifetime. The galvanizing film can be used stand-alone and has already proven to provide adequate corrosion protection in marine environments (see below). The zinc coating has a light grey colour but can be coloured by applying an additional topcoat. The film galvanizing system can also be used as a primer, with a thickness of 60μm, after which compatible epoxy and PU coatings can be applied on the structure.

Properties and advantages:
- Single component system;
- Unlimited shelf life;
- A degree of cathodic protection which cannot be achieved with traditional Zn-rich paints. As a result no under creep corrosion is possible, even at damage sites;
- Can be applied like a paint, both on large structures and for small, quick repair jobs (brush painting or can spraying);
- A sealant is not required (which is the case for porous thermally zinc sprayed, which depletes relatively fast if no sealant is applied).

Film galvanizing systems can be used both to coat new structures (where it can replace hot-dip,

traditional paint systems or thermal spray zinc coatings) and for the repair of existing structures. Some current uses are:

- Recharging and repair of galvanized structures;
- Replacing complete paint systems on O&G platforms;
- Local protection of nuts and bolts, corners, difficult to access areas, etc. where coating application and inspection are difficult and risk for damage and corrosion is larger;
- Marine: ship decks, steel pier legs (in use since 2000), offshore high voltage pylons, offshore charging cranes;
- Offshore wind: used for the repair of galvanized components in turbine housing;
- Desalination plants (complete steel structure).

It could be used on offshore wind structures as a duplex system, i.e. with top coats on the transition piece and tower. For the inside of the monopile and around the mudline a stand-alone galvanizing film could be used. Testing is underway to proof the MIC resistance of the galvanizing film, as this could provide significant added value to the coating.

6.5.5   Silane coatings

Metal surfaces are usually pre-treated before the application of a corrosion protection coating in order to improve the overall protection capability. For many years, chromium conversion coatings have been used on steels as a pre-treatment because their use strongly increases both the corrosion protection and adhesion of organic coatings. In an attempt to replace the use of chromate conversion coating because of the carcinogenicity and toxicity in the last decades several different green pre-treatments were developed. Sol-gel films based on hybrid silicon alkoxide precursors are emerging as efficient pre-treatments capable of providing good corrosion resistance and coating adhesion without heat [199,216]. Organofunctional silanes are silane based chemicals containing organic as well as inorganic moieties in a single molecule. Silanes are used as coupling agents between inorganic and organic materials in many formulations in order to promote the adhesion between metallic substrates and organic coatings in hybrid corrosion protection systems. Treatments based on water-borne silane coating are used on aluminium or chromium plated metal parts or on zinc alloys. Aqueous mixtures of different silanes have been proposed as pretreatments with corrosion inhibiting properties on various substrates such as Al alloys, steels and zinc alloys [217].

Water-borne hybrid silane systems are also used in commercial products as binders for two pack zinc dust paints in order improve the corrosion protection of parts exposed to marine envinronment.

Silane-based products can be used in conventional three-stage pre-treatment systems (and not for on- site applications) and may be able to use typical city water instead of demineralized water. More stages and higher-purity water may be necessary, however, for finished products that require higher standards of corrosion resistance. Like zirconium-based pre-treatments, these formulations also save waste disposal and maintenance costs by reducing sludge. There may also be savings in rinse water consumption, because the rinse following the treatment is cleaner than the rinse following a phosphate treatment.

6.5.6   Sol-gel coatings

Sol-Gel does not refer to a specific material type, but to a process. Material is deposited as a liquid, loaded with nano-scale solid particles (called a Sol), which solidifies after in-situ crosslinking between the nano-particles. In case of coating deposition this means cross-linking happens after deposition on the substrate.

Sol-Gel coatings can be purely inorganic in nature (for example pure Si-O coatings), but these are limited to very thin films (typically < 500 nm). These films are very dense and provide excellent barrier properties. However, they require high temperature curing which, together with their limited thickness and brittle nature, makes them unsuited for offshore corrosion protection applications [218].

Hybrid Sol-Gel coatings on the other hand consist of alternating inorganic and organic polymeric chains linked in a single covalent network. These coatings can be built up to larger thicknesses (up to 10 µm) [112], but more importantly, they are more flexible and abrasion and impact resistant. Recent developments make it possible to deposit these coatings electrolytically, by brushing and even by spraying. Curing of these hybrid coatings can be performed at lower temperatures (80-150 °C) or by UV-light. In some cases, curing can even be omitted. As such, the practical barriers for application of these coatings on large structures can be overcome [218].

To the authors' knowledge, there are currently no large-scale corrosion solutions commercially available that are based on the Sol-Gel technique. However, the use of hybrid Sol-Gel coatings does offer a number of advantage that could result in a break-through in the near future [112,174,218]:

- Relatively insensitive to moisture on the substrate (depending on coating chemistry).
- Formation of a covalent bond with the substrate, resulting in excellent adhesion.
- Excellent adhesion with additional organic coating layers (for example epoxies). If the organic part of the hybrid coating is tuned correctly, a covalent bond with organic overcoats is possible.
- Excellent barrier properties due to a higher density than traditional organic paints.
- Corrosion inhibitors such as zinc particles or certain chemicals can be incorporated in the coating.
- Sol-Gel coatings with self-healing properties can be synthesized.
- Many Sol-Gel based coatings can be realized based on VOC-free solvents, which makes it an environmentally friendly process.

Sol-Gel coatings can be applied to a wide range of substrates, including polymers, aluminium, stainless steel and construction steels. In the following, two possible application examples will be described.

Self-healing Sol-Gel coating on aluminium components and structures [174]

To increase the corrosion resistance of aluminium, the surface can be coated by paints. The aluminium surface must be pre-treated to ensure good coating adhesion and corrosion resistance, for which chromates have long since been used. However, environmental and worker safety issues associated with hexavalent chrome have driven the market to look for alternatives.

One possible alternative is the use of thin (50-500 nm) Sol-Gel films. According to the supplier, it does not form a crystalline layer, there is no dwell time and require removal of oxides is not required prior to film deposition. By forming a covalent bond directly with aluminium oxide, the chemical produces a thin, hydrophobic barrier coating capable of protecting aluminium from further oxidation by

blocking corrosive materials to the surface [175]. The pre-treatment molecules are designed to penetrate deep into the nano-pores of the aluminium oxide and self-assemble up to 100 layers of highly cross-linked polymers. Figure 17 shows a system under investigation for a so-called 'self-healing' sol gel coating on aluminium. Nano-particles doped with an inhibitor passivate exposed aluminium where the coating is damaged.
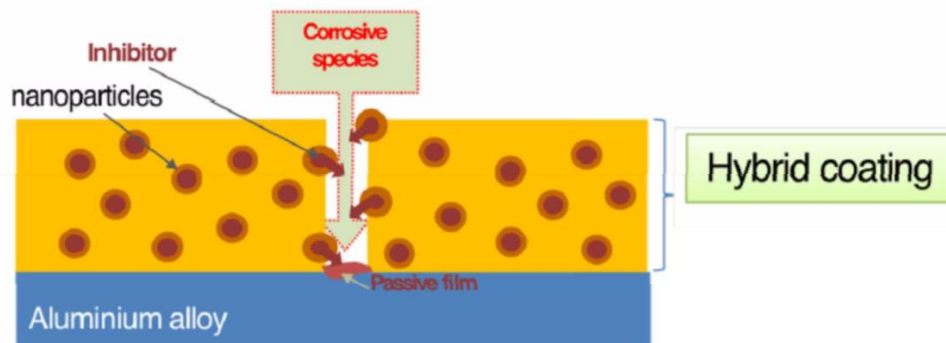
Figure 17: Corrosion healing mechanism of a hybrid sol gel coating with nanoparticles [174]

Sol-Gel based primer on steel structures [218]

The good adhesion, which can be achieved to both the substrate and subsequent paint layers, makes Sol-Gel coatings good candidates for primers. A hybrid epoxy-Si-O film (1-10 µm) can be sprayed on a steel substrate and cured under UV-light. By tuning the chemistry of the coating, a covalent bond between the sol-gel film and the steel can be achieved. The epoxy chains in the film should result in a good adhesion of a subsequent epoxy-based paint. Nano-scale zinc particles can be incorporated in the coating as corrosion inhibitors.

It is expected that future developments will focus on the investigation of more environmentally friendly precursors/reagents, as well as VOC-free systems. Metal-rich sol-gel coatings, containing zinc or magnesium particles, or coatings including other inhibitor particles will also be developed in order to further improve the corrosion protection. This should allow to combine the excellent barrier properties of sol-gel layer with and cathodic protection of sacrificial particles [174].

6.6   Alternative corrosion control measures

6.6.1   General precautions

The design and detailing of a structure affects the corrosion durability of any protective coating applied on constructions [9]. Structures designed with many small components and fasteners are more difficult to protect than those with large flat surfaces. The key issues to consider include:

- Access for coating application and maintenance
- Avoidance of moisture and debris traps
- Avoidance or sealing of crevices
- Drainage and ventilation to minimize the 'time of wetness'
- Careful management of galvanic contact with other materials

General guidelines for the prevention of corrosion by good design detailing can be found in EN ISO 12944-3, and some typical do's and don'ts for steel framed buildings are shown in Figure 18. Most of

these guidelines include the avoidance of entrapped water, dust (sand/salt).
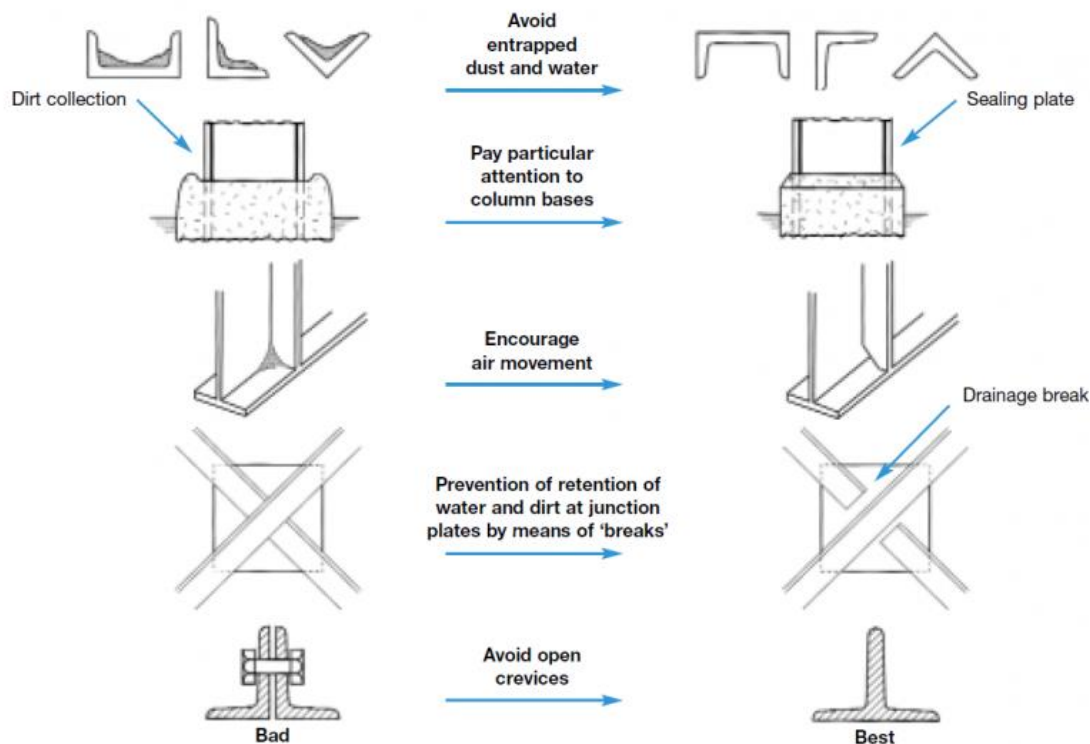
Figure 18: General design detailing of constructive elements

Bolts, rivets and welds are often used in joints for offshore constructions made of steel.
Using different materials can lead to crevice corrosion, galvanic corrosion as well as stress corrosion cracking. In most cases the weld filler material is selected according to the type of steel.
Bolted steel connections are always vulnerable to corrosion. Bolts made of carbon steel can be used but often stainless steel bolts are used. When using stainless steel bolts in flanges it is important to protect the bolts from corrosion. This can be done by applying paint layers or by the following innovative solutions.

6.6.2   Protective caps and shields

BoltShield® developed metal-made protective caps in aluminium, stainless steel and zinc coated steel for bolts and nuts against corrosion [219]. For bolted connections between tubular steel parts, the company *Alocit* developed special clamps made up from two halves surrounding the connection [220]. One of these clamps is connected to the platform by a stub piece, they are hinged and/or bolted together around the pile (Figure 19). By using these special clamps corrosion can be slowed down and even stopped after using sealing products.
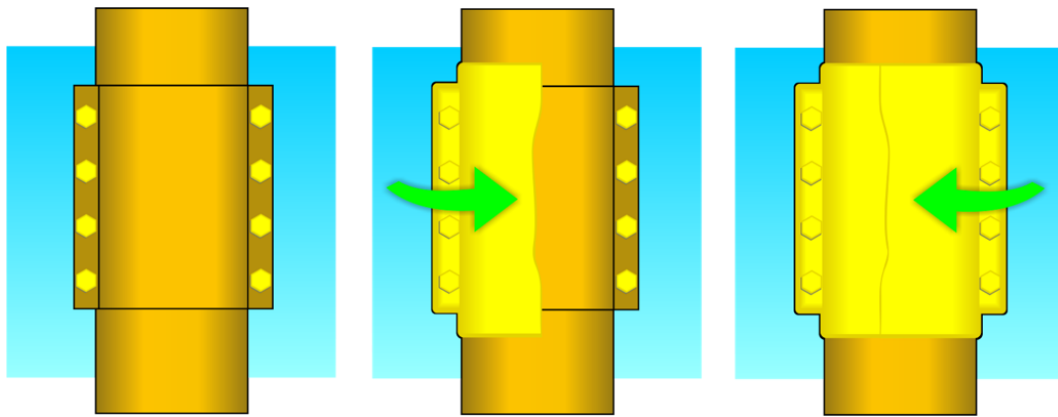
Figure 19: Protection of bolted steel connections by special clamps [220]

If welding is carried out after the application of the metal coating or when severe damage occurs, it is difficult to accomplish the same standard of protection in those areas compared to the rest of the structure. Welded joints are generally critical because of their susceptibility to stress concentration and residual stresses. Discontinuities linked to the execution of welding can induce defects and heterogeneities in the microstructure [2].

6.6.3   Sheathing

Protection of steel structures like platforms and ship hulls can also be obtained by the so called 'sheathing' [78] components with thin metal sheets and plates. These plates can be connected by welding or adhesives. Special attention is needed to prevent crevice and galvanic corrosion when using different materials (see above).

6.6.4   Dehumidifiers

The company *Cotes* patented compact dehumidifiers and overpressure systems to be installed in offshore wind towers to keep the inside of the nacelle and tower dry [221]. By this action penetrated seawater or salt will be removed from the inside and corrosion will be prevented. A method to prevent the equipment corrosion in an offshore wind turbine by minimizing the air pressure difference across the outside and inside faces of the seals was patented by Adwen Offshore SL [222]. The proposed system includes a slotted, streamlined plenum over each of these interfaces that helps moderate the air pressure on the outside of the seals. On the inside, the air pressure over the seals is controlled by a variable air flow resistance system that consists of two circulars, coaxial perforated plates that can rotate relative to each other.

6.6.5   Sealing and joints

Seals are used in wind towers to prevent penetration of seawater. They are mostly consisting of rubber-based materials.
As mentioned above the galvanic contact between two metals like stainless steel and galvanized steel can create bimetallic or galvanic corrosion on the less noble part of the junction (anodic cell). In addition crevice corrosion between the junctions can occur.

Typical examples are bolts, screws and nuts but also welds can react as galvanic couples when the welding material is different from the parent material. To prevent this type corrosion for bolted connections, isolation with neoprene seals can be used [74]. Coating of couplings with paint can also prevent the corrosion of galvanic couples.

7   Corrosion protection of Offshore Wind (OW) structures

In section 7.1 the coating systems which are currently used most often on Offshore Wind Structures are presented. To a large extend, these correspond to the coating systems prescribed in norms and standards. Paragraph 9.2 lists a number of corrosion issues that remain today in the Offshore Renewable Energy sector. An attempt is made to link some of the corrosion protection technologies presented in this report to remaining corrosion issues.

7.1   *Coating systems currently in use*

The selection of coating systems for OW structures is not straightforward. The approach for coating system selection for OWSs is similar to that for other offshore structures designed for oil and gas production. Procedures for selection and minimum paint system requirements are given in guidelines and standards [26,30,31,143], but often corporate experience and guidelines also influence the final decision.

Information on the coatings systems of specific wind farms is difficult to obtain. However, it is safe to say that most offshore wind turbines will be coated according to the specifications in the relevant standards (NORSOK M-501, ISO 12944-5, ISO 20340, DNVGL-RP-0416). The limited information on site specific coating systems that were found, confirms this. Nevertheless, deviations from the standards do occur, especially if construction of the wind farms is done in cooperation with for example Oil&Gas companies that have experience in the offshore sector and apply this experience in tuning the coating system. Such information is generally kept confidential, as it can give an important economic advantage. An overview of the coating systems specified for use on carbon steel in the aforementioned standards, for the outside of OW structures, is given in Table 12.

Table 12: Overview of coating systems specified for use on carbon steel in standards ISO 12944-5, ISO 20340 and NORSOK M-501, for the outside of OW structures. Coating systems are subdivided according to exposure category

Standard	Primer		Subsequent coat(s)	Total Paint System	
	Type	NDFT [μm]		No. of coats	NDFT [μm]
Corrosion category C5-M High *Atmospheric zone*					
ISO 12944-5	EP, PUR	80	EP, PUR	3-4	320
	EP, PUR	250	EP, PUR	2	500
	EP, PUR (ZnR)	60	EP, PUR	4-5	320
ISO 20340	EP (ZnR)	≥ 40	EP	≥ 3	≥ 280
	EP	≥ 60	EP	≥ 3	≥ 350
NORSOK M-501	EP (ZnR)	≥ 60	EP	≥ 3	≥ 280
Combined Corrosion categories C5-M High and Im2 High *Splash and Tidal zones (2)*					
ISO 12944-5	-	-	-	-	-
ISO 20340	EP, PUR (ZnR)	≥ 40	EP, PUR	≥ 3	≥ 450
	EP, PUR	≥ 60	EP, PUR	≥ 3	≥ 450
	EP, PUR	≥ 200	EP, PUR	≥ 2	≥ 600
NORSOK M-501	(1)	(1)	EP, PE	≥ 2	≥ 600

Corrosion category Im2 High					
Submerged zone (2)					
ISO 12944-5	EP (ZnR)	60	EP, PUR	3-5	540
	EP	80	EPGF, EP, PUR	3	500
	EP	800	-	-	800
	EP	80	EPGF	3	800
ISO 20340	EP, PUR (ZnR)	≥ 40	EP, PUR	≥ 3	≥ 350
	EP	800	-	-	800
	EP	≥ 150	EP, PUR	≥ 2	≥ 350
NORSOK M-501	(1)	(1)	EP (3)	≥ 2	≥ 350
NOTES					
NDFT = Nominal Dry Film Thickness EP = Epoxy; PUR = Polyurethane; EPGF = Glass Flake Epoxy; PE = Polyester; ZnR = Zinc Rich (1) Not specified (2) In the submerged, tidal and splash zone, a coating system is often used in combination with cathodic protection (CP). In this case, attention should be paid to selecting a coating system that is compatible with the use of CP. (3) Coating system shall always be used in combination with CP.					

The specification 'High', next to the corrosion category, indicates that the coating systems should have a lifetime of at least 15 years in the environment under consideration. With respect to the splash zone, DNVGL guideline (DNVGL-RP-0416) states that "for coating systems based on epoxy and meeting the requirements for coating materials and quality control of surface preparation and coating application in NORSOK M-501 Coating System No. 7A (min. DFT 600 µm) with a useful life of up to 15 years may be assumed in the splash zone. For an equivalent system based on glass-flake reinforced epoxy or polyester (min. DFT 700 µm), the useful life may be assumed to be up to 20 years in the splash zone." In a presentation by SINTEF (2010) [223], it was pointed out that a paint system according to the NORSOK specifications for the atmospheric zones (60 µm EP ZnR, 150 µm EP, 70 µm PU) generally requires a first major maintenance after 10 years. In the splash zone a lifetime of > 20 years can be achieved with a two coat polyester systems (NDFT > 1000 µm).

A classic system that meets the requirements for OW structures in the atmospheric zone consists of a zinc-rich, epoxy-based primer coating (60 µm), three successive epoxy mid-coats, and one PU topcoat, with a total nominal dry film thickness of 400 µm [2].

The above only considers organic coating systems and does not include the detailed application of metal coatings, which are not un-usual on OW structures [97]. Paint systems for metallized steel substrates are included in the standards ISO 12944-5, ISO 20340 and NORSOK M-501, albeit to a lesser extent. An overview is given in Table 13.

Table 13: Overview of coating systems specified for use on metallized carbon steel in standards ISO 12944-5, ISO 20340 and NORSOK M-501, for the outside of OW structures

Standard	Sealer coat		Subsequent coat(s)	Total Paint System	
	Type	NDFT [µm]		No. of coats	NDFT [µm]
Corrosion categories C5-M High and Im2 High					
ISO 12944-5	EP	NA (1)	EP	3	450
	EP, PUR	NA (1)	EP	3	320

| ISO 20340 | - | - | EP | ≥ 2 | ≥ 200 |
| NORSOK M-501 | (2) | (2) | (2) | ≥ 2 | ≥ 200 (3) |

| **NOTES** |
| (1) NA = not applicable. The dry film thickness of the sealer coat will not significantly contribute to the total dry film thickness of the system.
 (2) Not specified.
 (3) NORSOK M-501 specifies 100µm of thermal sprayed zinc or zinc alloys as metallization. |

Previously used coating systems included a Zn/Al-85/15-metallization (60-100µm), organic pore filler, two intermediate epoxy-based coats (2x 100-120µm) and a PU based topcoat (50-80µm) [2,97,104]. However, it is stated in [104] that, "due to the demands for less time spent on painting, cost reduction, and good experience over years with paint systems, wind turbine structures may be metallized less often. More and more, high quality paint systems without metallizing (according to DIN EN ISO 12944, C5- Marine) are going to be used for external protection."

Environmental conditions inside the towers are less severe than on the outside. Therefore, pure paint systems can be used, according to corrosion class C4. In the lower parts of the tower, some specifications do require the use of metallization plus paint [104].

In principle, many chemical resistant coatings could be selected such as urethanes, epoxies, chlorinated rubber and vinyl polymers. In [2], a number of alternative coating systems are mentioned that are used on OW Structures. These are indicated in Table 14, along with a number of other corrosion control systems. It should be noted that the current authors are not aware of any current uses of (chlorinated) rubber or neoprene coatings on OW structures in the NSB.

Table 14: Alternative coating systems which could be used on OW structures, classified according to exposure zone

| **Atmospheric zone** |
| Vinyl systems (3-4 layers) |
| Zn phosphate pigmented two-pack epoxy primer (1 layer) |
| Two-pack epoxy (2 layer) [2,20,27,29] |
| Chlorinated rubber system (3-4 layers) |
| **Submerged zone** |
| The main control is CCP. The use of coating systems is optional, generally EP based coatings, and these should be compatible with CCP. When coatings are used fewer anodes are necessary and the corrosion protection system is expected to last longer |
| **Splash and Tidal zone** |
| Coatings similar to those for the atmospheric zone are used. Higher film thickness is employed |
| The steel thickness is increased (to act as corrosion allowance) and is coated with the same coating system of the rest of the structure |
| Thick rubber or neoprene coating up to 15 mm of thickness |
| Polymeric resins or glass-flake reinforced polyester materials are often used to protect against mechanical damage [2,27,29] |

Repairing the coating of structures in offshore environments can be very difficult and expensive. The steel surface is likely to be moist or even wet and contaminated with chloride ions during the repairing

procedure. Therefore, the corrosion resistance of paint systems applied on contaminated steel substrates should be investigated. In 2011, Shi et al. [224] reported a study on the influence of salt deposition at the steel/paint interface. The authors found corrosion products under the paint. It was suggested that the exposure time of steel substrate before paint application should be as short as possible to avoid degradation due to salt deposition.

Next to proper coating selection and application, the cost of OW structures and their maintenance can be decreased by optimizing systems for Structural Health Monitoring (SHM). This would also increase the output and reliability of current wind energy system technologies. Optimization of SHM can lead to reducing labour costs of wind turbine inspection by the prevention of unnecessary replacement of components or early repairing interventions such as repainting of affected components [22].

7.2 Corrosion issue on Offshore wind structures

Corrosion protection solutions have been in place since the installation of the first offshore wind turbines. However, corrosion of offshore wind structures remains a challenge and new solutions are still sought after. In the following, a number of these corrosion issues are presented. The result is the authors' attempt to describe the corrosion challenges faced in the construction and maintenance of offshore wind structures. The list is compiled based on literature and a selected number of interviews with industry experts and is therefore not to be considered as an exhaustive account.

Along with listing a number of issues, some suggestions are made where innovative solutions could be used to tackle the identified corrosion problems. The authors' suggestions are not an attempt to present a conclusive answer to the remaining corrosion issues, as this would surely fail. Rather, it is an attempt to invite the reader to think about new, innovative and creative solutions for existing problems.

In the following, a distinction is made between primary and secondary steel structures. Primary steel includes structural components such as the foundation and tower. Failure of a primary steel component could threaten integrity of the entire structure. Secondary steel structures are components which are important, but whose failure will not result in a total collapse of the structure.

7.2.1 Primary steel

In the **atmospheric zone**, no significant corrosion issues have been reported. The currently used coatings provide adequate protection for the required lifetime. There are no signs of overall coating failure.

In the **splash zone**, coating damage and corrosion is observed. In general, the coating damages are not the result of coating failure. The used coatings (i.e. the product) are of high quality, comply with the relevant standards and provide the required protection to corrosion. If a coating is locally damaged, this can almost invariably be linked to either mechanical damage (impacts by floating objects or service boats) or improper coating application.

It has also been observed that the coating thickness in the splash zone may decrease over time, as a result of the grinding action of waves. However, this can easily be taken into account in the design

stage.

As coating damage and corrosion in this zone are mainly due to mechanical damage, a more flexible and damage tolerant coating could be a solution. Powder coatings or polyurea paints, which generally have better mechanical properties, could be used. In both cases the cost effectiveness has to be compared to existing solutions (including repair costs). Alternatively, forms of active protection like galvanizing film, zinc thermal spraying or the use of chemically bonded phosphate ceramic coatings could be used, with a colored topcoat.

To reduce the LCoE, attempts are made to reduce the cost of the coating system, without compromising the durability. Only reducing the coating thickness doesn't reduce the cost much, as the labor cost is much higher than the paint cost. Therefore, a reduction in the number of layers in the coat system would be much more effective. However, this brings with it a question of reliability. In a multi-layer system, a defect in an individual layer does not necessarily result in a through coating defect, making the multi-layer system relatively tolerant to application defects. In a single layer system, a layer defect evidently results in a through coating defect.

Moving to coating systems with less layers is therefore not a matter of proving that the coating can prevent corrosion. Existing single layer systems can provide the necessary certificates to proof this. It is rather a matter of quality control. Making the use of single layer coatings generally acceptable, would require the development of a control mechanism that allows to verify that the coating is defect free over the complete extend of the coated structure (i.e. not just spot checks).

In the **submerged zone**, the foundation structure is protected by cathodic protection (with or without an additional coating). If properly designed, this effectively prevents corrosion. There are however two points that should be highlighted:

- A presumed risk of MIC around the mudline.
- Corrosion on the inside of monopile foundations.

It is generally believed that MIC around the mudline (up to 1m into the soil) could pose a threat. However, no data has been found to clearly establish the severity of MIC and whether or not it indeed poses a threat. Investigation of decommissioned foundations could shed more light on this issue.

If MIC indeed poses a threat, it is also unclear how foundations could be protected against it. There is no conclusive evidence showing whether or not ICCP helps to prevent MIC. Coatings may be a solution. But foundations are hammered into the ground, often through the layer of scour protection deposited on the sea bed. The question remains whether the coating integrity is not compromised after such an aggressive treatment.

Corrosion on the inside of monopile foundations was first believed not to occur. Monopiles were sealed and considered airtight. In such an enclosure, oxygen would rapidly be used up, preventing corrosion. However, it has been shown that fresh seawater and oxygen do penetrate into the monopile, necessitating some form of corrosion protection. This can be a coating, cathodic protection or a combination of both.

In case aluminum alloy anodes are used for cathodic protection, the seawater pH can drop to acidic levels, making the cathodic protection ineffective. To avoid this, it should be made sure that the seawater in the monopile can be refreshed by tidal action [225].

As corrosion inside the monopile does occur, special attention should be paid to welds where weld cracking and pitting can occur [226].

7.2.2   Secondary steel

The importance of secondary steel corrosion is often underestimated. Nevertheless, secondary steel structures are more susceptible to corrosion and are constantly being repaired. A large part of the corrosion maintenance costs can be allocated to secondary steel structures.

Boat landing	The coatings currently used on boat landings cannot cope with the impact and mechanical loading due to service boats. As a result the boat landings show severe coating damage and corrosion, making constant maintenance necessary. The only coating solution is to use a damage tolerant coating. An example could be the use of polyurea coatings, which are also used in the Offshore O&G sector for damage sensitive areas. As an additional precaution, a chemically bonded phosphate ceramic coating could be used as a primer to provide a more active protection. Alternatively, corrosion protection with a coating can be abandoned and higher corrosion allowances taken into account.
Railings, platform borders, hatches	Also these components are often subject to damage due to frequent use for inspection and maintenance activities, and hoisting of material. Also here polyurea coatings or powder coating could be considered.
Bolted connections, corners and difficult to reach areas	These difficult to coat areas are prone to early coating failure. As a solution, a form of active protection could be used. Film galvanizing could be performed with a brush or spray as a form of local protection. Certain types of flexible, thermoplastic anti-corrosion paints may also perform well in these areas.
Grating fixation	Gratings are often fixed to the support structure with bolts that are screwed in stainless steel blocks, welded to the carbon steel supports. These welds are difficult to prepare in terms of surface roughness, resulting in poor coating adhesion. A coating with a better adhesion to less rough surfaces would provide a solution. Alternative connection solutions are also being used, such as Hilti® studs. In fixations with nuts and bolts, contact corrosion may be observed.
Temporary accessories	Some secondary steel attachments are only used during installation (ex. cable pull-off). To reduce costs, less stringent corrosion protection measures are often taken on these accessories. As the accessory is no longer needed, corrosion of these structures may not be considered an issue. However, run-off corrosion products that cover the coated structure below may promote coating degradation of more important primary or secondary steel structures.

Although often neglected in the wider corrosion debate, also electrical components suffer from corrosion. The costs due to standstill and replacement parts can be significant. In order to reduce the LCoE, also these components need to be considered.

7.2.3   Repair solutions

No matter how performant the selected coating system, it will never be possible to completely

prevent all damages. Therefore, efficient coating repair solutions are also required. Mainy coating products specify very strict surface conditions for applications, including surface roughness, humidity and salt concentration. In the offshore environment in which repairs have to be conducted, it is often very difficult, if not impossible to comply with these requirements (certainly for humidity and salt). Coating systems, which have a high tolerance to the surface condition, have the potential to facilitate maintenance jobs.

Commercial products such as ZINGA®, Humidur®, Alocit® and others claim properties that make them suitable for repair jobs. A wide range of suppliers of such products is already available on the market, however, there are no recommendations or guidelines specifying which products should be used in which situation.

8   Normative standards and guidelines

Several normative references are currently used for designing of offshore structures with the main focus on offshore wind and ocean energy, selection of materials and corrosion protection strategies in offshore conditions. The main normative standards and guidelines are reported as follows:

- Offshore structures:
  - **DNVGL-OS-C401**: "Fabrication and testing of offshore structures" [227];
  - **DNVGL-OS-E301**: "Position mooring" [228];
  - **DNVGL-SE-047**: "Risk Based Verification of offshore structures" [229];
  - **DNV-OSS-121**: "Classification Based on Performance Criteria Determined from Risk Assessment Methodology" [230];
  - **DNVGL-ST-C502**: "Offshore concrete structures" [15];
  - **DNVGL-OS-D101**:" Marine and machinery systems and equipment" [231];
  - **DNVGL-OS-D201**: "Electrical installations" [232];
  - **DNV Classification notes no.30.6** "Structural reliability analysis of marine structures" [233];
  - **DNVGL-SE-0420**: "Certification of meteorological masts" [234];
  - **DNVGL-ST-0145**: "Offshore substations" [235].

- Offshore wind farms - methods of design and operation:
  - **DNV-OS-J201**: "Offshore substations for wind farms" [19]
  - **DNVGL-RP-B401**: "Cathodic protection design" [91];
  - **DNVGL-RP-0416**: "Corrosion protection for wind turbines" [26];
  - **DNVGL-RP-J101**: "Use of remote sensing for wind energy assessment" [236]
  - **DNVGL-SE-0073**: "Project certification of wind farms according to IEC 61400-22" [237];
  - **DNVGL-SE-0074**: "Type and component certification of wind turbines according to IEC 61400-22" [238];
  - **DNVGL-SE-0190**: "Project certification of wind power plants" [239];
  - **DNVGL-SE-0441**: "Type and component certification of wind turbines" [240];
  - **DNVGL-ST-0126**: "Design of support structures for wind turbines" [241];
  - **DNVGL-ST-0361**: "Machinery for wind turbines" [242];
  - **EN 50308**: "Wind turbines – Protective measures – requirements for design, operation and maintenance" [243].

- Ocean energy systems - methods of design and operation:
  - **DNVGL-ST-0164**: "Tidal turbines" [244];
  - **DNV-OSS-312**: "Certification of tidal and wave energy converters" [245];
  - **DNVGL-SE-0163**: "Certification of tidal turbines and arrays" [246];
  - **IEC/TS 62600-1:** "Marine energy - Wave, tidal and other water current converters - Part 1: Terminology" [247];
  - **IEC/TS 62600-100:** "Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters - Power performance assessment" [248];

- **IEC/TS 62600-101:** "Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization" [249];

- **IEC/TS 62600-200:** "Marine energy - Wave, tidal and other water current converters - Part 200: Electricity producing tidal energy converters - Power performance assessment" [250];
- **IEC/TS 62600-201:** "Marine energy - Wave, tidal and other water current converters - Tidal energy resource assessment and characterization" [251];
- **IEC/TS 62600-10:** "Marine energy - Wave, tidal and other water current converters - Part 10: Assessment of mooring system for marine energy converters (MECs)" [252].

− Materials requirements - metallic alloys, metallic coatings, paints and varnishes:
  - **EN 1090-1**: "Execution of steel and aluminium structures – Part 1: Requirements for conformity assessment of structural components" [253];
  - **EN 1090-2**: "Execution of steel and aluminium structures – Part 2: Technical requirements for steel structures" [254];
  - **EN 10204**: "Metallic products – types od inspections documents" [255];
  - **EN 10225:** "Weldable structural steels for fixed offshore structures – technical delivery conditions" [60];
  - **EN 12473**: "General principles of cathodic protection in seawater" [256];
  - **EN 12495**: "Cathodic protection of fixed offshore structures" [257];
  - **EN ISO 12944**: "Paints and varnishes – Corrosion protection of steel structures by protective paint systems" [56];
  - **EN ISO 14713**: "Zinc coatings – Guidelines and recommendations for the protection against corrosion of iron and steel structures – Part 1: general principles of design and corrosion resistance" [258];
  - **ISO 8501**: "Preparation of steel substrates before application of paints and related products – visual assessment of surface cleanliness" [259];
  - **ISO 8502**: "Preparation of steel substrates before application of paints and related products – Tests for the assessment of surface cleanliness" [260];
  - **ISO 8503**: "Preparation of steel substrates before application of paints and related products – Surface roughness characteristics of blast-cleaned steel substrates" [261];
  - **ISO 20340**: "Paints and varnishes – Performance requirements for protective paint systems for offshore and related structures" [30];
  - **NORSOK M-501**: "Surface preparation and protective coating" [31];
  - **DNVGL-OS-B101**: "Metallic materials" [10];
  - **DNVGL-OS-C101**: "Design of offshore steel structures , general - LRFD method" [262];
  - **DNVGL-ST-C501**: Composite Components [14].

Obligatory standards for testing and selection of corrosion protection systems, mainly for coatings and linings, for offshore structures are in force for some years now. This includes in particular ISO 20340 and Norsok M-501 [30,31]. The testing procedure consists of three individual tests, cathodic disbonment test and seawater immersion test. The ageing resistance test procedure consists of 7-day

cycle, whereby the coating system is exposed to three loading mechanisms, which must be passed through 25 times (4200 h). Assessment criteria include adhesion strength (pull-off testing), coating deterioration, scribe corrosion and delamination during the cathodic disbondment.

9 Conclusions

In this literature review a special attention was given to the presentation of the main corrosion mechanisms and forms that usually occur in offshore systems, material selection, surface preparation and metallic and organic coatings of constructions for offshore systems, mainly focused on wind, tidal energy structures.

The main conclusions can be drawn as follows:

- Offshore renewables are estimated to play a major role, driven by both political and economic factors. The renewables-based electricity generation is projected to triple over 2013-2040, overtaking coal to become the largest source of electricity. According to the new policies scenario, 33% of the world electricity generation by source will come from renewables in 2040 (IEA, 2014).

- Offshore structures in general are subjected to several damage mechanisms including corrosion and fatigue; so protective strategies should be considered as are essential to reach the expected service life for which a structure was designed. Different protection systems can be used to delay and mitigate corrosion initiation and its related consequences such as safety, structural integrity and service life.

- Cleaning of substrates before coating is still a very fundamental operation as it strongly influences the adhesion of the protective layers and coatings on the substrate. Grinding and blasting is mostly performed but other methods like high-pressure water jet can be used.

- Modern offshore constructions are more and more made of special alloys including high strength steel, stainless steel, aluminium and even titanium alloys. Low and unalloyed steel however must always be protected because of their low corrosion resistance to marine atmosphere. The best results are obtained by thick thermal spray aluminium or zinc-aluminium coatings with or without additional paint layers. Smaller parts can be made of uncoated special stainless steels, nickel alloys etc. The number of innovative corrosion resistant alloys however is restricted: only the AMLoCor was found to be a new alloy for offshore applications.

- Finally, a survey of the main standards and guidelines is reported in order to collect all the reference for the materials, procedures that can be used in offshore systems.

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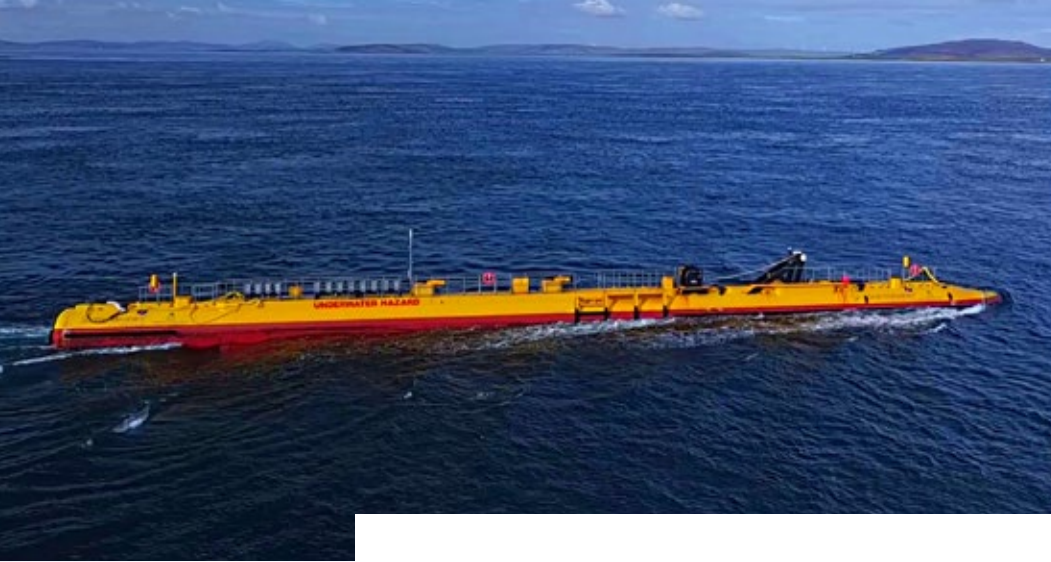[129]   F. Goodwin, Corrwind: A Life-cycle cost comparator, www.zinc.org, n.d.

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