RECOMMENDATIONS FOR THE CHEMICAL RISK ASSESSMENT OF CATHODIC PROTECTION SYSTEMS IN THE MARINE ENVIRONMENT

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RECOMMENDATIONS FOR THE CHEMICAL RISK ASSESSMENT OF CATHODIC PROTECTION SYSTEMS IN THE MARINE ENVIRONMENT

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Acronyms

Al Aluminium
Al-GACP Aluminium-based galvanic anode
Bi Bismuth
CBP Chlorination by-products
CP Cathodic protection
DOM Dissolved organic matter
DPF Day post fertilisation
DPH Day post hatching
EC_{10} Effect concentration 10
EC_{50} Effect concentration 50
EU European Union
Fe Iron
Ga Gallium
GACP Galvanic anode cathodic protection
GW Gigawatt
In Indium
IC_{10} Inhibition concentration 10
ICCP Impressed current cathodic protection
LC_{10} Lethal concentration 10
Mn Manganese
NOEC No observed effect concentration
OMIC Omics-based approaches (e.g., genomics, proteomics, metabolomics) used to study biological responses
ORE Offshore renewable energy
OWF Offshore wind farm
PEC Predicted environmental concentration
PIS Passive integrative samplers
PNEC Predicted no effect concentration
SSD Species sensitivity distribution
TiMMO Titanium mixed metal oxide
V Vanadium
Zn Zinc

Acknowledgements

This report was written as part of the collaborative ECOCAP project (ECOtoxicology analysis of CAthodic Protections to assess the chemical risk of elements released from Galvanic Anode (GACP) and Impressed Current (ICCP) on the marine environment and its food webs), led by France Energies Marines and the University of Caen Normandie. The ECOCAP project received funding from France Energies Marines, its members and partners, as well as support from the French State managed by the National Research Agency under the France 2030 Investment Plan (ANR-10-IEED-0006-34). We would like to thank the 21 project partners (France Energies Marines, University of Caen Normandie, University of South Brittany, French Office for Biodiversity, Qair, Cedre, French Corrosion Institute, EDF Renouveblables, Ocean Winds, Shell, RWE, Ifremer, RTE, University of Aix-Marseille, University of Toulon, INRAE, Mediterranean Insitute of Oceanography, INERIS, Saipem, Smel, Skyborn) for their contributions throughout the ECOCAP project.

Introduction

Offshore wind has rapidly become one of the most dynamic technologies in the global energy mix. Starting with 3 gigawatts (GW) of installed capacity in 2010, Europe has added 3.8 GW of new offshore wind capacity by 2023. This growth is in line with the EU's regional offshore energy targets (excluding the UK) of around 111 GW of cumulative capacity by 2030 and 317 GW by 2050 (European Commission, 2023). In France, the first offshore wind farm (OWF) began operations in 2022, followed by the inauguration of two additional OWFs in 2023. These developments have brought the total nominal capacity of offshore renewable energy (ORE) in France to just under 1.5 GW. Additionally, 1.5 GW is currently under construction, and 1.85 GW has been awarded. The market is growing rapidly, with development prospects accelerating. The French ''Programmation pluriannuelle de l'énergie'' target up to 10 GW by 2035. In the context of massive deployment of ORE in France, the potential impact of cathodic protections (CP) was highlighted as an environmental concern due to the chronic release of chemicals in the water column. Based on this issue, the ECOCAP R&D project, was launched in 2021 and completed in 2024. It has produced a knowledge base to enhance the definition of environmental pressures and potential associated impacts related to the chronic releases of elements from galvanic anode (GACP) and impressed current (ICCP) cathodic protections. This document synthesises the results obtained in the ECOCAP project by producing a report with conclusions and recommendations addressed to offshore wind stakeholders. Based on bibliographic analysis, experimental ecotoxicological results (Blanc-Legendre et al., 2025) and assessment of the risk of elemental contamination (i.e. metals and ICCP compounds) to the environment, the recommendations report also propose, where appropriate, adapted protocols for environmental water quality monitoring.

1 - Defining the environmental pressure

In order to estimate the environmental pressure associated with the release of chemical substances into the environment, it is essential to determine the frequency of these releases as well as their concentration. By assessing these two parameters, we can better understand the intensity of this environmental pressure.

1.1 Elements released from aluminium-based galvanic anodes

Depending on the commercial formulations, galvanic anodes can contain at least 94% of Aluminium (Al) and around 5% of Zinc (Zn). It is estimated that, to protect a monopile wind turbine foundation, 13 tons of anode is required during the 25 years of the wind turbine's life cycle (Kirchgeorg et al., 2018). This quantity decreases to 6 tons if the structure is additionally protected by an anticorrosion coating. At least, 85% of the anode mass would be degraded and therefore released during the OWF's life cycle (DNV-RP-B401, 2010) (Figure 1). According to Reese et al. (2020), it is estimated that for a coated monopile (6 m diameter, 26 m submerged in water), up to 2200 kg of Al, 130 kg of Zn, 5.2 kg of Manganese (Mn), 3.6 kg of Iron (Fe), 1.4 kg of Bismuth (Bi), 0.5 kg of Indium (In), 0.29 kg of Gallium (Ga), 0.28 kg of Vanadium (V) will be released from the Al-GACP during a 27-year period. Extrapolating these results to a hypothetical 50 turbine OWF, it can be estimated that up to 110 tons of Al, 6.5 tons of Zn, 260 kg of Mn, 180 kg of Fe, 70 kg of Bi, 25 kg of In, 14.5 kg of Ga, 14 kg of V could be released from the Al-GACP during the OWF's life cycle. Watson et al. (2025) estimated that the current 30 GW OWF activity in Europe releases 3219 t Al y^{-1}, 1148 t Zn y^{-1} and 1.2 t In y^{-1}. Based on a 9 to 12 fold increase in European OWF capacity by 2050, these released could reach 30,148 – 37,980 t Al y^{-1}, 10,756 – 13,550 t Zn y^{-1} and 10.9–13.7 t In y^{-1} (Watson et al., 2025).

Fig. 1 : *A galvanic anode at different stages of degradation.*

Although the quantities of these metals released have been considered, the behaviour and fate of these trace elements in the environment at different spatial and temporal scales remain the main obstacle to defining the best environmental risk assessment for Al-GACP. It should also be considered that metals are widely distributed in the environment through natural processes and numerous anthropogenic activities. For example, atmospheric fallout and river discharges of suspended matters rich in alumino-silicates enrich coastal waters with Al. Similarly, urban leaching, production of fertiliser and pesticides and coatings contribute to the Zn distribution. However, the transfer of these metals into water does not necessarily lead to the formation of the same physical and chemical forms (speciations) that can lead to their bioavailability to living organisms. During the degradation of the anode, the metallic elements transition from a solid state known as metallographic to a crystallographic state, in the form of metal oxide, and to a dissolved state. These trace elements emitted into the environment tend to quickly interact with dissolved organic matter (DOM), suspended matter and living organisms. The speciation of these elements will therefore be driven by the physico-chemical parameters of the environment, such as pH, salinity, DOM, suspended matter and organic ligands. In seawater (pH 8.2), the principal forms of dissolved inorganic aluminium are 68% aluminate ($Al(OH)_4^-$) and 32% colloidal neutral aluminium hydroxide

$Al(OH)_3$ (Millero et al., 2009). Importance of alkali (Sodium (Na), Potassium (K) and alkaline-earth (Calcium (Ca), Magnesium (Mg)) aluminate complexes are also considered in other studies resulting in 46.4% aluminate ion $Al(OH)_4^-$, 38.2% Mg-aluminate ion $MgAl(OH)_4^+$, 11% Na-aluminate ion $NaAl(OH)_4^-$, 3% Ca-aluminate ion $CaAl(OH)_4$ and < 0.01% Al^{3+}(Markich, 2021). The ECOCAP project investigated the question of dissolved Al state by considering the assessment of labile fraction. This fraction (which constitute a part of the total dissolved fraction) is considered as the most bioavailable to organisms living in the water column. As the chemical forms present in this fraction are difficult to identify, assessing the level of Al concentration of the labile fraction in the Al dissolved fraction enabled us to estimate more precisely the impact of the present chemical forms on organisms. ECOCAP was based on the principle that all elements degrade and solubilise uniformly. This principle aimed to establish a maximised approach to the enrichment of the water column as part of a worst-case scenario for chemical risk analysis using the REACH methodology. However, the issue of the accumulation of released elements from GACP must be examined within the sedimentary compartment (Reese et al., 2020; Ebeling et al., 2023).

To this end, experiments will need to be conducted to understand the physico-chemical interactions between the elements released by wind farms and suspended matter. These studies will also aim to assess the potential accumulation of these element-enriched suspended matter in sedimentation areas. Another issue concerns the fate of elements from the Al-GACP in the presence of biofouling on offshore structures particularly with selected suspension feeders such as bivalves of the *Mytilus* genus and crustaceans of the *Jassa* spp. genus (Mavraki et al, 2020), which can lead to a local enrichment in organic matter around the foundations of OWFs.

1.2 Elements produced by impressed current cathodic protection (ICCP)

It is acknowledged that ICCP systems produce an electrolysis reaction when seawater comes into contact with the anode. Despite this, ICCP system is often described as resulting in no significant emissions (Kirchgeorg et al., 2018), but to our knowledge empirical data is lacking to support this claim. However, the electrolysis of seawater which contains chloride and bromide ions, generates chlorine (Cl_2) and bromine (Br_2) which can react with natural organic matter in seawater to form chlorination by-products (CBP). These by-products vary in volatility and persistence within the marine environment. The ECOCAP project has enabled an initial evaluation of molecules produced by ICCP in a laboratory setting. Several compound families of CBP were identified experimentally: volatile compounds, such as trihalomethanes, which can be transferred into the atmosphere, and non-volatile compounds, including haloacetonitriles, haloaldehydes, and haloacetic acids, which can persist in water. During the project, protocols and equipment for measuring the volatility of CBP were optimised to determine the volatilisation constants in seawater for two main volatile compounds identified: tribromomethane and dibromochloromethane. Over time, all these compounds (volatile and non-volatile) can degrade through processes such as photolysis. Investigating their lifespan in seawater and comparing the measured concentrations with water samples from an ICCP-protected OWF could provide valuable insights. Indeed, defining the environmental impact of ICCP is a challenging task. Among this challenge, accurately characterise the production of chlorine during seawater electrolysis resulting from the use of an ICCP system appears as a first step. An approach should be developed to link chlorine production with the impressed current in the system being protected. The impact of the type of anode used in ICCP system (Titanium mixed metal oxide (TiMMO) for example) on the Cl_2 production should also be considered. Finally, a better characterisation of CBP and their potential accumulation in water, sediment, or biota must be addressed. This last point requires the development of specific analytical protocols.

2 - In situ assessment

2.1 Environmental monitoring

Ecological quality in OWF needs to be monitored in three key matrices: the water column, sedimentation zones, and biota. For the water column, *in situ* assessments carried out in the ECOCAP project revealed the need to use passive integrative samplers (PIS) to provide temporal information on chemical concentrations **(Figure 2)**. These PIS must be adapted to the families of molecules being researched and should be coupled with water sampling during installation and recovery of PIS. They should be positioned as close as possible to the structures protected by GACP or ICCP. Ideally, these sensors should be deployed twice a year to detect any seasonal effects on the quality of the OWF's water.

Furthermore, systematic analysis of targeted compounds in the sedimentary matrix is essential when the nature of the seabed allows it. Samples taken from the immediate vicinity of the OWF structures and along a distance gradient will provide crucial information for identifying potential chemical enrichment factors. Additionally, passive biomonitoring (monitoring of natural populations of organisms) should be conducted within the OWF, targeting concentration levels of CP compounds. If possible, different trophic levels of sessile species constituting the biofouling community present on the structures should be studied. Temporal analyses will help identify potential accumulations of these compounds. To refine our understanding on relations between environmental pressures from OWF and biological responses, a study site where the foundations are protected by ICCP and a site for the GACP should be the subject of intensified monitoring. These sites could also be used for a spatio-temporal active biomonitoring by deploying caging systems containing sentinel organisms such bivalves, shrimps or juvenile fish. This active biomonitoring could be combined with accurate measurement of the seasonality of water quality through the use of automated monitoring devices with passive sensors. Beyond a simple bioconcentration assessment, a biomarker approach could be performed, focusing on several levels of biological organisation and various biological functions to assess physiological state of the organisms. This would help to determine causal links between the various pressures associated with OWF activity and potential biological responses.

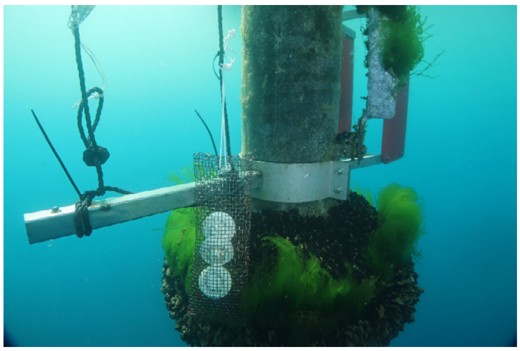

Fig. 2 : *Passive integrative samplers deployed on the APPEAL buoy in the Atlantic.*

2.2 Defining tracers for GACP and ICCP in water, sediment and biota column

In order to better understand the chronic discharges of endogenous chemicals of OWF, it is essential to differentiate them from those considered exogenous. The ECOCAP project, through its hydrodynamic modelling work, has highlighted significant inputs from rivers of compounds such as aluminium to future OWFs. Of the six OWF case studies modelled in ECOCAP, five had a higher proportion of river inputs in the modelled aluminium contents. It is therefore essential to define chemical tracers specific to the discharges of OWF. These tracers must therefore be representative of discharges from the OWF while being absent from other anthropogenic discharges. They must be relevant to the different target compartments, i.e. the water column, sediment and biota. Ideally, each tracer should be specific to a function (cathodic protection) or to an element of the OWF structure (paints, mooring lines, etc).

For Al-GACP, Al, Zn, Ga, and In are four potential candidates for tracers in the water column due to their high proportion in the anode and low proportion in the water column (Reese et al., 2020). To date, only In has been reported as an efficient tracer for water column in the German OWF of the North Sea (Ebeling et al., 2025). Due to their high proportion in the anode and their low theoretical proportion in the sediment, Zn, Ga and In are three candidates for tracer in the sediment (Reese et al., 2020). There is less evidence available to identify a tracer of Al-GACP in biota. As a first step, it is recommended to analyse the levels of the four elements mentioned above in the different species that can be subject to passive biomonitoring at proximity of the OWF. The work of Bell et al. (2020) conducted under controlled conditions highlighted, for example, a high bioconcentration of In and Al in the benthic crustacean *Corophium volutator* exposed to GACP during laboratory work, with respectively enrichment factor of 136 times and 5 times. These results must nevertheless be considered with caution due to the exposure concentrations of Al-GACP used in this study which were not environmentally realistic.

To date, the definition of tracers specific to the use of an ICCP system is more challenging to establish due to the transient nature of some molecules and the volatility of others. Among the compounds identified in ECOCAP, non-volatile compounds such as haloacetonitriles, haloaldehydes, haloacetic acids and haloadehydes appear to be promising candidates. However, further experimentation is needed to confirm their relevance as tracers.

3 - Biological impact of aluminum, Al-GACP and ICCP

3.1 Ecotoxicity of Al-GACP

ECOCAP's experimentations assessed the responses of various marine species following exposures (chronic or acute) to aluminium chloride ($AlCl_3$, 6 H_2O) and to a solution obtained from the dissolution of an aluminium-based galvanic anode (Al-GACP). Table 1 present the main results of these experimentations.

	Taxa		Species	Life stage	Endpoint	Time of exposure	Endpoint	Al total concentration (µg.L^{-1})	
								$AlCl_3$	GACP
Algae	Bacillariophyta (diatom)		*Phaeodactylum tricornutum*	-	Growth inhibition	72h	IC_{10}	226	284
Animal	Crustacean	Branchiopod	*Artemia salina*	Larvae	Mortality	48h	NOEC	>10573	>12709
		Decapod	*Palaemon elegans*	Adult	Mortality	96h	NOEC	>5928	>4346
				Embryo-larvae	Mortality 20 dph	30d	LC_{10}	200	64
				Embryo-larvae	Hatching	7d	EC_{50}	>6413	≥2674
	Echinorderm	Sea urchin	*Paracentrotus lividus*	Embryo-larvae	Embryo development	72h	EC_{50}	383	355
				Embryo-larve	Effect on spicule length	72h	EC_{10}	>6829	>8258
				Juvenile	Growth	70d	EC_{10}	152	174
				Juvenile	Feeding	70d	EC_{10}	67	152
	Mollusc	Bivalve	*Crassostrea gigas*	Larvae	Embryo development	48h	EC_{10}	62.7	46.5
		Cephalopod	*Sepia officinalis*	Embryo-larvae	Hatching	>35d	EC_{10}	>1745	289
				Juvenile	Growth	45d	EC_{10}	>1561	127
				Juvenile	Feeding	45d	EC_{10}	>1561	>1297
	Fish	Teleost	*Oryzias melastigma*	Embryo-larvae	Mortality 12 dpf	12d	NOEC	>3536	≥1111
				Juvenile	Mortality 60 dpf	60d	NOEC	>333	≥394
				Larvae	Mortality 90 dpf	90d	NOEC	>333	≥394

Tab. 1: *Ecotoxicological endpoints of model species after exposure to $AlCl_3$ or Al-GACP solution*

- *day post fertilisation (dpf)*
- *day post hatching (dph)*
- *No Observed Effect Concentration (NOEC)*
- *Inhibition Concentration 10 (IC_{10}): 10% inhibition concentration compared to control group.*
- *Effect Concentration 10 or 50 (EC_{10} and EC_{50}): concentration of a substance that causes a 10% or 50% effect compared to control group.*
- *Lethal Concentration 10 (LC_{10}): chemical concentration that causes 10% mortality in a test population over a specified period.*

These threshold values evaluated by conducting ecotoxicology experiments are all higher than the projected aluminium concentrations determined by modelling approaches in the water column. Consequently, the results of the ECOCAP ecotoxicology experiments indicate a low risk posed by Al-GACP elements when considering only the water column (details are presented in Section 4.1). However, to fully exclude any environmental risk associated with Al-GACP, several issues need to be addressed. A major challenge will be to address the interaction of these chemicals with sedimentary components by studying the accumulation, bioavailability, and toxicity of elements from the anodes in this matrix. Additional ecotoxicological studies on various model species representative of benthic habitats are therefore necessary. The trophic accumulation of Al-GACP components also needs to be addressed. This work should focus on elements other than Al, particularly Zn and trace elements of the anode such as In and Ga. Furthermore, investigating the potential cocktail effects of anode elements interacting with other chemicals, both exogenous and endogenous to OWF (Bell, thesis 2021), would be relevant. Lastly, it is crucial to investigate the changes in speciation and bioavailability of Al-GACP elements due to variations in certain abiotic parameters (such as salinity, pH, temperature, and turbidity) over the coming decades as a result of global change (Millero et al., 2009).

3.2 Ecotoxicity of ICCP

The ECOCAP project initiated the study of the potential acute toxicity of ICCP-derived elements and compared it with results from Al-GACP exposures. However, it is important not to draw premature conclusions due to the limited data on ICCP toxicity, variability in ICCP-derived element concentrations, and the low integration levels of the bioassays used. This initial step needs to be expanded with additional approaches in both ecotoxicology and general chemistry to understand the fate and behavior of these compounds in various marine compartments, including water, sediment, and biota. The ecotoxicological issues associated with the various CBP generated by ICCP deserve particular attention, especially concerning the less volatile molecules that are the most persistent in the water column or potentially accumulative in sedimentary and biological matrices due to their high lipophilic *log Kow*. Analysis of the literature on these compounds reveals that the data are too fragmentary to enable a relevant chemical risk assessment. Therefore, it is essential to define a roadmap for future studies addressing the chemical risk assessment of ICCP systems.

The question of carrying out a chemical risk assessment in accordance with the REACH directives for the various compounds produced by ICCP systems in the context of environmental risk assessment needs to be addressed. If such work is undertaken, what should be the objective? An exhaustive chemical risk assessment specific to each compound generated by the ICCP, or a chemical risk assessment focused on the most persistent compounds? This work involves determining seawater Predicted No Effect Concentration (PNECs) with the lowest assessment factors achievable in order to understand the toxicity of each compound more effectively. Another approach could be to focus on a chronic sub-lethal assessment by targeting representative model species of the targeted ecosystem. Further work in ecotoxicology should be undertaken to highlight the responses at different levels of biological organisation when exposed to realistic concentrations of ICCP compounds.

4 - Chemical risk assessment characterisation

4.1 For Aluminium-based galvanic anode

The refinement of the PNEC for dissolved Al in seawater column ($PNEC_{seawater}$ Al) was achieved using the Assessment Factor method. In this approach, the PNEC is calculated by dividing the lowest observed effect concentration, such as NOEC (No Observed Effect Concentration), ECx (Effect Concentration), ICx (Inhibition Concentration), or LCx (Lethal Concentration), by an assessment factor that reflects the quality and quantity of available data. Thanks to various studies carried out on different trophic levels (algae, crustaceans, fish, echinoderms and molluscs) and at different levels of toxicity (acute and chronic), ECOCAP studies allowed to lower the assessment factor for PNEC determination to 10, corresponding to the lowest level (when Species Sensitivity Distribution - SSD - curve is not applicable) in the methodology. The $PNEC_{seawater}$ is based on the ecotoxicological endpoints, such as mortality or growth inhibition, of the most sensitive species for Al in the literature, in our case the diatom-type microalga species *Ceratoneis closterium*. Three studies aimed to determine an algal growth inhibition concentration for this species with IC_{10} defined at 14 $\mu g.L^{-1}$ Al (Harford et al., 2011), 16 $\mu g.L^{-1}$ Al (Golding et al., 2015) and 80 $\mu g.L^{-1}$ total Al (Gillmore et al., 2016). The mean value of these three studies is 37 $\mu g.L^{-1}$ Al for IC_{10}, so the $PNEC_{seawater}$ is therefore 3.7 $\mu g.L^{-1}$ considering the assessment factor of 10.

The chemical risk characterisation on the six OWF case studies of the ECOCAP project (Bay of Seine considering only the OWF of Courseulles-sur-Mer, St-Nazaire, Yeu-Noirmoutier, AO5 -750MW, GOL Area 1 - 750MW and GOL Area 2 - 750MW) has been performed based on simulations of Predicted Environmental Concentration (PEC) modelled in ECOCAP. The ECOCAP study is worst-case scenario assuming the modelling hypothesis that all the OWF studied are protected from corrosion by the use of Al-GACP (despite the fact that some are actually protected by ICCP) and that all the Al from the anode remain in the water column without any interaction with suspended matter, sediment or biota. Furthermore, no inputs from other offshore activities, such as marine traffic, were considered in the scenario. The results of the risk characterisation ratios in the seawater column ($PEC_{seawater}$ / $PNEC_{seawater}$) for each case studies are shown in Table 2. For each case study, the risk ratio was determined based both on the PEC specific to OWFs (PEC_{OWF}), the PEC specific to river inputs (PEC_{river}) and the Al cumulative PEC ($PEC_{cumulated}$) considering several inputs of Al in the area (the maximum Al concentration induced by galvanic anodes, the maximum Al concentration from river discharge over the farm area, and an ambient Al concentration from an area without river influence).

Case studies with GACP scenario	$PNEC_{seawater}$ for Al ($\mu g.L^{-1}$)	PEC_{OWF} for Al ($\mu g.L^{-1}$)	PEC_{river} for Al ($\mu g.L^{-1}$)	$PEC_{cumulated}$ for Al ($\mu g.L^{-1}$)	PEC_{OWF} / PNEC	PEC_{river} / PNEC	$PEC_{cumulated}$ / PNEC
Bay of Seine	3.70	1.11	2.00	3.48	**0.30**	**0.54**	**0.94**
Saint-Nazaire		0.56	21.00	21.56	**0.15**	**5.68**	**5.83**
Yeu-Noirmoutier		1.10	7.00	8.10	**0.30**	**1.89**	**2.19**
AO5 - 750 MW		1.37	4.00	5.37	**0.37**	**1.08**	**1.45**
GOL Area 1 - 750 MW		1.83	1.12	6.95	**0.49**	**0.30**	**1.88**
GOL Area 2 - 750 MW		1.54	4.2	9.74	**0.42**	**1.14**	**2.63**

Tab. 2: *Risk assessment calculation in seawater ($PNEC_{seawater}$, $PEC_{seawater}$ and PEC/PNEC ratio) for total aluminium considering two levels of inputs. Modelling hypothesis: 1/ all the OWF studied are protected from corrosion by the use of Al-GACP ; 2/ Al from the anode remain in the water column*

- *PEC_{OWF}: maximum Al concentration induced by OWF GACP*
- *PEC_{river}: maximum Al concentration induced by river discharge*
- *$PEC_{cumulated}$: the maximum Al concentration induced by OWF GACP, the maximum Al concentration from river discharge over the OWF area, and an ambient Al concentration from an area without river influence*

Considering only Al inputs from OWF, none of our study cases exceeds a risk index of 1. Therefore, under these specific hypothesis, there is no environmental risk for the water column associated with Al from Al-GACP. However, when accounting an ambient Al concentration from an area without river influence and potential aluminium inputs from river, risks appear in all configurations except for the Bay of Seine highlighting the need to consider cumulative effect of environmental pressure in the risk assessment methodologies. Aluminum inputs from rivers significantly influence the PECs estimated in our study areas. Consequently, OWFs closest to these discharges, such as the one at Saint-Nazaire, will have high PECs. Similarly, rivers such as the Rhône with high aluminum concentrations will markedly increase aluminum levels in the zone of influence of their plume, as observed in the Gulf of Lion as shown in **figure 3** (Michelet et al., 2025).

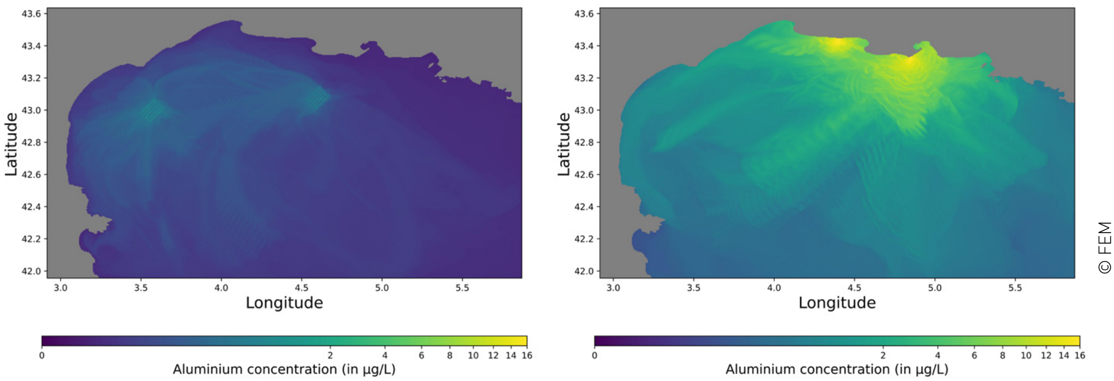

Fig. 3 : *Modellised maximum aluminium concentration (in µg L^{-1}) in the Gulf of Lion, over time and depth, induced by two 750 MW offshore wind farms (left) versus by the Rhône river discharge (right).*

4.2 For impressed current cathodic protection

The chemical risk analysis for the water column was conducted in the same case studies than Section 4.1 (the Bay of Seine, the north of the Bay of Biscay, and the Gulf of Lion) considering all the OWF studied could be protected from corrosion by ICCP. The studies were focused on five compounds generated by ICCP use (Tribromomethane, Dibromoacetonitrile, Dibromochloromethane, Bromochloroacetic acid, and Tribromoacetic acid). Results did not indicate significant risk, as all ratios were lower than 1. However, caution is advised for several reasons. First, the PNECs for the five compounds have very high assessment factors, ranging from 500 to 10,000 (ECHA; Delacroix et al., 2013), indicating a lack of ecotoxicological data and limiting the interpretation of the results. Furthermore, the PECs, derived from modelling assessment conducted in ECOCAP, were based on controlled laboratory experiments to assess production kinetics. However, scaling up these production kinetics to real- *in situ* conditions is now required to provide better insights into the characterisation of ICCP releases. Finally, as for GACP and Al, future works should also consider the risk associated with the sediment matrix.

4.3 Cocktail of chemicals

Bibliographic studies on cocktail effects highlight the importance of considering the entire chemical exposome in chemical risk analysis. Unlike Al-GACP, where the content of the anode is known and therefore the associated ecotoxicity is easier to predict, the chemical compounds produced by ICCP are site-dependent and transient based on environmental parameters. This disparity makes it difficult to perform a relevant cocktail risk assessment for ICCP based on the non-exhaustivity in the identification of CBP.

Concerning Al-GACP, focusing at a minimum on Al and Zn is relevant due to their high proportion in the anodes. Trace elements in the anode composition such as Fe, Ga, In or V must be considered with caution in a chemical mixture risk assessment as they could artificially increase the risk associated with these chemical substances due to the absence of robust PNEC for the elements.

5 - Knowledge requirement and perspectives

5.1 Refining the environmental pressure and the scale of assessments

Based on the chemical risk analysis protocols set out in the REACH guidelines, ECOCAP's studies have provided initial information on the chemical risk for water column associated with the release of metals from GACP along the French coastlines. They also have provided an initial estimate of the compounds released by the electro-chlorination process induced by ICCP systems. This research deserves to be taken further by targeting, on a local scale, the chemical risks associated with the chronic release of elements from various components or systems of an OWF, in particular cathodic protection (Al-GACP and ICCP). It is essential to:

- **Extend knowledge of the characterisation and quantification of releases** induced by these systems, in particular those from ICCP.
- **Enhance understanding of their behaviour and fate in the marine environment** (water column, benthic compartment and biota).

In addition to this work, it is essential to address new issues concerning the release of substances from OWF. This includes leaching from anticorrosion coatings and even synthetic mooring lines for anticipating future floating OWF releases, considering the specific environmental conditions in which they are applied or used. It is also crucial to account for the different ageing processes of these compounds, such as hydrolysis, UV exposure, and mechanical stress.

5.2 Defining environmental survey in OWF

The various controlled studies and *in situ* measurements initiated by the ECOCAP project need to be further developed and used as a basis for developing knowledge on the potential environmental impact of the use of corrosion protection systems (ICCP, Al-GACP and paints). This environmental assessment requires the development of new transdisciplinary approaches from chemistry to *in situ* biomonitoring.

Firstly, it is essential to characterise the levels of exposure to chemical elements at OWF sites. This involves implementing various actions and protocols to achieve the following objectives:

- **Identify existing chemical elements:** Before the installation of OWF, we need to identify the chemical elements already present in the water column and sediment.
- **Estimate levels and differentiate inputs:** Within these compartments, we must differentiate between endogenous chemical elements (originating directly from cathodic protection systems and other structural elements of the OWF) and exogenous chemical elements (such as those from rivers).

As mentioned in Section 2.2, achieving these objectives will require defining a list of chemicals representative of OWF activity. It is then crucial to develop various ecotoxicological approaches to establish a comprehensive link between biological responses observed in laboratory experiments and those from *in situ* areas. These approaches must involve:

- **Bioassay/risk assessment approaches**: Bioassays will make it possible to predict, under controlled conditions, responses at different levels of biological organisation following exposure to one or more mixtures of chemicals. These approaches will help to understand the mechanisms of toxicity for a specific chemical or a cocktail of chemicals.
- **Biomonitoring approaches:** The use of bioassay results obtained under controlled conditions should provide a better knowledge base needed to detect potential ecosystem disturbances by supporting complementary active or passive biomonitoring approaches. Active biomonitoring will make it possible to monitor the ecological status of OWF by assessing the potential biological effects of a contaminant (or an exposome) in different micro-habitats within a OWF (benthos or water column, close to structure, a peripheral or central in the OWF, etc.) using model species belonging to taxonomic groups such as bivalves, decapods and fish. This protocol will allow to work *in situ* on standardised organisms (species, size, age, sex, etc.) with a known level of exposure thanks to a controlled duration and the use of environmental parameters probes and PIS. Biomonitoring approaches currently use biomarkers analysis to assess levels of stress, whether or not related to exposure to a chemical substance. This *in situ* approach is increasingly using OMIC tools, particularly proteomics, in coastal or riverine contexts. These OMIC approaches should also be considered in the context of OWF, as they could provide a comprehensive overview of biological processes and responses to potential cumulative environmental stress within the studied site.

Conclusion

The ECOCAP project has provided a comprehensive assessment of the chemical risks associated with cathodic protection systems in OWFs along the French coastlines. Through a combination of bibliographic analysis, controlled ecotoxicological and chemical experiments, and environmental modelling, the project has clarified the main sources, quantities, and environmental toxicity of metals released by galvanic anode cathodic protection, particularly aluminium. It has also initiated the first investigations on the compounds generated by impressed current cathodic protection systems.

The results indicate that, based on future deployment scenarios and on worst-case modelling assumptions, the risk to the water column from aluminium-based galvanic anodes from OWF remains low. However, the cumulative effects of riverine inputs and other anthropogenic sources must be considered in future risk assessments, especially for sites located near major river plumes. The ECOCAP project also draws attention to the generation of chlorination-by-products by ICCP systems, whose identification and quantification remain challenging. Further research is needed to assess their rate of production, persistence, accumulation, and potential toxicity in marine environments.

The report highlights the importance of developing robust environmental monitoring protocols, including the use of chemical tracers specific to OWF system such as cathodic protection, passive samplers, and biomonitoring approaches, to better characterise exposure and biological effects *in situ*. Finally, the project underlines the need for transdisciplinary research to address key knowledge gaps, particularly regarding the fate of released elements in sediments and biota, the potential effects of chemical mixtures, and the influence of global change on metal speciation and bioavailability. These recommendations aim to support offshore renewable energy stakeholders in implementing best practices for environmental risk assessment and management, ensuring the sustainable development of offshore wind energy while minimising impacts on marine ecosystems.

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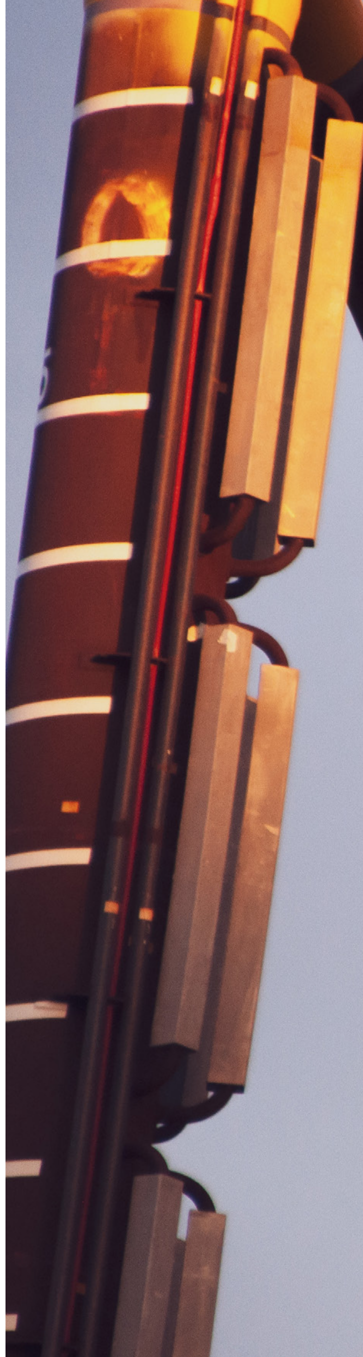

As offshore wind energy expands rapidly in France and Europe, understanding and managing the environmental impacts of corrosion protection systems is crucial. This synthesis report, produced by the ECOCAP project, provides an integrated assessment of the chemical risks associated with aluminium-based galvanic anode (Al-GACP) and impressed current (ICCP) cathodic protections in offshore wind farms.

Combining experimental ecotoxicology, environmental modelling, and field monitoring, the report offers clear recommendations for identifying, quantifying, and monitoring the release of metals from anodes and by-products from impressed current systems into the marine environment. It addresses key challenges such as the cumulative effects of multiple sources, the fate of chemical compounds in water, sediments and biota, and the need for robust, site-specific monitoring protocols.

Intended for offshore wind stakeholders, environmental managers, and policymakers, this report delivers actionable scientific data to support the sustainable development of offshore wind energy while preserving marine ecosystems.

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