



# Moving Toward a Sustainable Society: Corrosion Issues and Challenges

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French alternative energies and atomic energy commission - [www.cea.fr](http://www.cea.fr)

## SYNOPSIS




Intro – Green chemistry – Renewable energies

- ▶ **Introduction** – context & definitions
- ▶ **Corrosion protection and green chemistry principles**
  - Declination of the 12 principles
- ▶ **Corrosion and low carbon energies**
  - Corrosion and renewable technologies
- ▶ **Conclusive remarks**




## Few words about the World Corrosion Organisation - WCO




Intro – Green chemistry – Renewable energies

- ▶ **The WCO is a non-profit charitable organization** and is accredited by the United Nations (UN) as a non-governmental organization (NGO).
- ▶ **The WCO has members from around the world** and fall into two categories: General Members (national not-for-profit organizations) and Affiliate Members (governmental organizations, industrial enterprises, or other profit-oriented organizations).
- ▶ **Our Mission:** to promote education and best practices in corrosion control for the socio-economic benefit of society, preservation of resources, and protection of the environment.
- ▶ **Our Goals**
  - **To raise public awareness** of corrosion and corrosion control as well as develop and implement an internationally recognized Corrosion Awareness Day, similar to the way we recognize Earth Day.
  - **To identify international best practices** in corrosion management.
  - **To facilitate the provision of corrosion control expertise** to governments, industries, and communities to make this information available, especially to the developing world.
  - **To normalize** corrosion related standards worldwide and to harmonize the standards already used.




World Corrosion Organisation – [www.corrosion.org](http://www.corrosion.org)
Damien Féron
Lehigh University / 21 April 2022
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## What are we talking about? - Sustainable



Intro – Green chemistry – Renewable energies

- ❑ Multiple facets of sustainability
- ❑ From the UN World Commission on Environment and Development: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”
- ❑ 2012 working IPCC report: « Toward a sustainable and resilient future »
  - “the importance of considering **‘hard’ (engineering) and ‘soft’ (social and administrative) technology**”
  - “Both hard and soft technology systems must be responsive”
  - “Technology development and use are necessary for reducing vulnerabilities to climate extremes”
- ❑ The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015. Among the 17 SDGs, some are clearly linked to engineering (6- clean water & sanitation, 7- affordable & clean energy, ...)



Focus on engineering (**‘hard’ technology**) issues and challenges and more precisely on the behavior of metals and alloys in low carbon-energy systems

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## What are we talking about? - Energy

A global transition towards more sustainable, affordable and reliable energy systems is being stimulated by the Paris Agreement and the United Nation's 2030 Agenda for Sustainable Development

Low-carbon energies, as proposed by the Intergovernmental Panel on Climate Change (IPCC) of United Nations



- ▶ **Renewable energies**
  - Solar & wind energies
  - Hydro & tidal powers
  - Geothermal & biomass energies
- ▶ **Nuclear energy**
- ▶ **Carbon capture and storage**



<https://www.vox.com/energy-and-environment/2017/3/27/15043522/nuclear-power-future-innovation>

Clean / Green energies, as described in media



- ▶ **Environmentally friendly ("clean")**
- ▶ **Sustainable**
- ▶ **Renewable**



<https://www.vox.com/energy-and-environment/2017/9/27/16365290/renewable-energy-standards-are-working>

## What are we talking about? - Corrosion

- ❑ ISO 8044 – 2020

Corrosion: Physicochemical interaction between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part

- ❑ The annual direct cost of corrosion was estimated in 2013 between 1% to 5 % of the gross domestic product, following the country (2.7% in US, 1% in Japan, 4.2% in Europe and China, ...)
- ❑ Application of existing corrosion control technologies would save at least 30%



**Raise public awareness**  
**Promotion education**  
**Identify world best practices**



## Toward a White Paper



- ▶ Climate-resilient energy systems and infrastructures bring with them a long-term direction, so as a result the long-term behaviour of structural materials (mainly metals and alloys) becomes a major prospect.
- ▶ Low carbon energy technologies have emerged as a strategic priority to reduce the global carbon footprint, decrease CO<sub>2</sub> emissions and improve air quality.
- ▶ These investment in new technologies underlines the importance of corrosion protection of metals and alloys in the development of energy production



Corrosion protection evolution toward environmentally friendly systems  
Importance of corrosion protection in the development of low-carbon energy



## Corrosion Challenges Towards a Sustainable Society

Editors:

Roman Bender, Damien Féron, Douglas Mills, Stefan Ritter

## CORROSION PROTECTION &amp; ENVIRONMENT



- ❖ To be environmentally friendly, corrosion protection has to take care of the environment.
- ❖ Does corrosion protection fit with the principles of the Green Chemistry ?

1. Prevention of waste
2. Atoms economy
3. Less hazardous conditions
4. Design safer chemicals
5. Benin solvents
6. Design for energy efficiency
7. Use of renewable feedstocks
8. Reduce derivatives
9. Catalysis
10. Design for innocuous degradation
11. Pollution prevention
12. Safer for accident prevention

**Green Chemistry Pocket Guide**

**The 12 Principles of Green Chemistry**

Provides a framework for learning about green chemistry and designing or improving materials, products, processes and systems.

1. Prevent waste
2. Atom Economy
3. Less Hazardous Synthesis
4. Design Benign Chemicals
5. Benign Solvents & Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis (vs. Stoichiometric)
10. Design for Degradation
11. Real-Time Analysis for Pollution Prevention
12. Inherently Benign Chemistry for Accident Prevention

[www.acs.org/greenchemistry](http://www.acs.org/greenchemistry)



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From P.T. Anastas & J.C Warner, "Green Chemistry: theory & practice, 1998, Oxford University Press, New-York, USA & S. Sarrade, La chimie d'une planète durable, Editions Le Pommier, 2011.

## Principle 1...

**Prevention:** “it is better to prevent waste/pollution than to treat and clean up after it has been done”

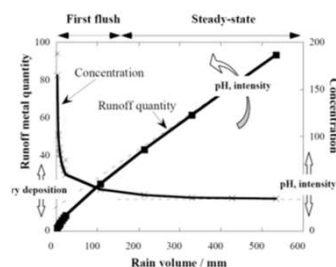
### Illustration - Pollution linked to the copper roofs

In many cities, copper roofs are used since centuries, but with the recent requirements regarding the polluted waters, raining waters on these roofs are becoming too concentrated in metallic cations ...



#### Solutions :

- More resistant alloys
- Pre-oxidized copper surfaces



C. Leygraf & al., Atmospheric corrosion, ECS series, 2000

## Principle 2...

**Atoms economy:** *economy of “raw materials”*

### Illustration – extension of exploitation time of industrial equipments

Initial nuclear power plants were planned for 30 years, new ones are planned for 60 years of operation and the exploitation of some old ones have been extended to 60 years or more, one reason being a very good corrosion resistance of the alloys.

#### Atoms economy:

- 7 000 tonnes for the confinement building,
- 550 tonnes for the steam generator,
- 330 to 510 tonnes for the vessel, ...



Beznau nuclear power plant (1969, 365 Mwe, initially planned for 40 years, the oldest nuclear power plant in operation today in Europe)

## Principle 3...

**Less hazardous conditions:** “working and living in safer conditions with less hazardous chemicals”

**Illustration – corrosion management and control are needed for safe operation of plants and civil structures**



Highway bridge over the Mississippi, Minnesota, 2007 (40 years old, corrosion)



Viaduc de Polcevera, Genova, 2018 (09-1967)

### Actions:

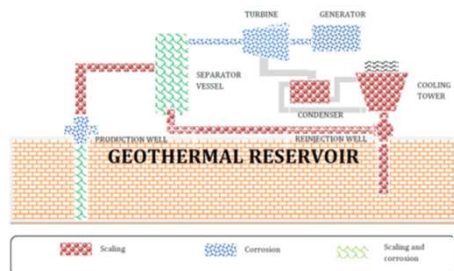
- Information: “flash info” in February 2022 “Ageing: all the equipments are concerned” (vieillessement: tous les équipements sont concerné”) 2450 events

Ministère de la transition écologique <https://www.aria.developpement-durable.gouv.fr>

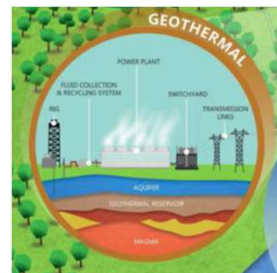
## Principle 4...

**Design safer chemicals:** “chemical products should be designed to affect their design function while minimizing their toxicity”

**Illustration – Corrosion inhibitors (Directive REACH)** - Many compounds are now known environmental and public health hazards. A number of dangerous compounds used in anti-corrosion are being phased out due to regulations



From P.A. Remoroza & al, World Geothermal Congress 2010 and G. V. Tomaroc & al., World Geothermal Congress 2015



From EDC annual report, 2013

**Solutions:** Use of “natural” corrosion inhibitors in Geothermal waters like clays (Montmorillonite – corrosion rates divided by a factor of 100 with 1% of MMT in acid geothermal brine)



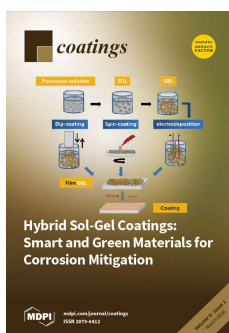
## Principle 5...



**Benign solvents:** “the use of auxiliary substances (e.g., solvents) should be made unnecessary wherever possible and, innocuous when used.”

### Illustration – protective coatings for anticorrosive purposes

International and national legislation aiming at reducing the emission of volatile organic compounds (VOCs) have caused significant changes in the anticorrosive coating industry



### Solutions

- Solvent-free coatings and sol-gel coatings are designed for long-term protection of wind turbines including offshore
- Water-borne anticorrosive paints are acquiring increasing relevance for the anticorrosive protection of steel surfaces exposed to the atmosphere...



www.tikkurila.de

## Principle 6...



### Design for energy efficiency

### Illustration – Efficiency of electricity production

Thermal electricity generation process is limited by the Carnot efficiency =  $(T_{\text{source}} - T_{\text{sink}}) / T_{\text{source}}$ . High temperatures of  $T_{\text{source}}$  lead to a better efficiency, but corrosion is thermally activated.



A supercritical coal plant in Germany achieves thermal efficiency of 46%



Concentrating solar power plant (CSP) Thémis, France

### Challenges:

- Thermally resistant alloys
- High temperature corrosion

<https://www.gen-4.org>

[https://www.actu-environnement.com/ae/news/renaissance\\_centrale\\_themis\\_5233.php4](https://www.actu-environnement.com/ae/news/renaissance_centrale_themis_5233.php4)

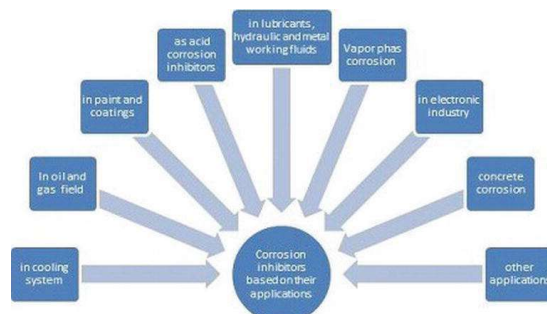
## Principle 7...

**Use of renewable feedstocks:** “A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable”.

**Illustration – “Green Corrosion inhibitors”, coming from plants, bacteria, fungi,... (gums, tannins, extracts...)**



Green Corrosion Inhibitors, Past, Present and Future, O. S. Shehata & Al., Intech, 2018 - DOI: 10.5772/intechopen.72753



## Principle 8...

**Reduce derivatives:** “Try not to have too many steps in the reaction because this means more reagents are needed and it can generate waste”

### Illustration – galvanizing

- Galvanization is the process of coating iron and steel with zinc is widely used in applications where corrosion resistance is needed.
- Electro-galvanization used high chemical electrolytes (cyanides, caustic or acid solutions with several types of preparation)
- Hot-dip galvanization is used more and more during which the steel is dipped into molten zinc and so less chemical reagents are used.

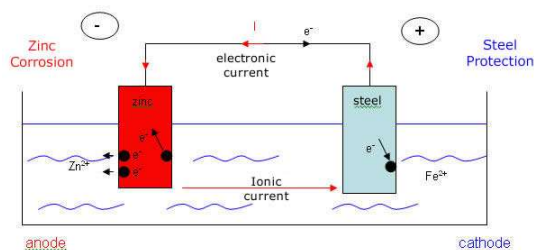




## Principle 9...

### Catalysis

#### Illustration – cathodic protection



Impressed Current Cathodic Protection (ICCP) for Offshore Wind

- Cathodic reaction is increased on the « cathode », where is the metal to protect
- To avoid cationic metallic pollution, imposed current has to be favored

## Principle 10...

**Design for innocuous degradation:** “*design a product including for its final degradation.*”

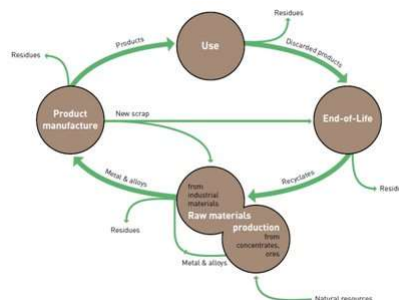
#### Illustration - recycling metals and alloys

Metal	Global recycling rate, %
Aluminum	40
Copper	38
Iron steel	47
Lead	47
Nickel	34
Zinc	36

Table 1. Indicative global recycling rates of some metals – values depend on the measure used and should usually be defined as a range due to the complexity of recycling systems (INOR) & (REU2)

#### Evolution

- Life cycle management
- Include other metals (Mo, Co, Sn, In...)



Challenges of metals recycling, Markus A. Reuter, Ilkka V. Kojo

## Principle 11...

**Pollution prevention:** “real-time, in-process monitoring and control prior to the formation of hazardous substances”.

### Illustration – corrosion monitoring

Metallic cations are pollutants for natural environments  
Corrosion Monitoring is a process that evaluates and monitors equipment components, structures, process units, and facilities for signs of corrosion. It is a way to know corrosion rates and releases of metallic ions in aqueous environments  
It is a way to control structure integrity and environmental pollution



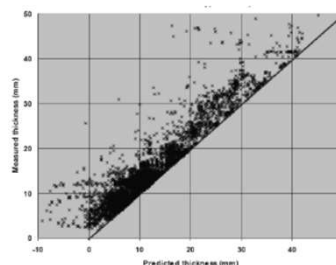
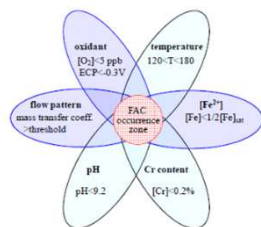
“Green Workshop”, Eurocorr 2018

## Principle 12...

**Safer for accident prevention:** “process should be chosen to minimize the potential for accidents, including chemical releases, explosions, and fires”

### Illustration - modelling of flow accelerated corrosion (FAC)

FAC leads to several accidents with causalities in all steam-water systems including nuclear power plants  
In France BRT-Cicero code is used



“Green Workshop”, Eurocorr 2018

## CORROSION PROTECTION &amp; GREEN CHEMISTRY IN SUMMARY



- ❖ Corrosion protection has to take care of the environment.
- ❖ Already corrosion protection fits with the 12 principles of “Green Chemistry”



- ❖ Several areas are still challenging:

- Awareness
- Design
- Monitoring
- Prevention
- Knowledge

- ❖ Development of low carbon energy technologies

- Issues and challenges: application of the knowledge, long term, new developments
- White Paper
- Focus on few renewable energies
  - Solar energy
  - Wind and sub-seawater turbines
  - Geothermal energy



## LES BIOCARBURANTS



## EFC &amp; WCO White Paper



- ▶ “Corrosion Challenges Towards a Sustainable Society” White Paper presents a series of cases showing the importance of corrosion protection of metals and alloys in the development of energy production to further understand the science of corrosion, and bring the need for research and the consequences of corrosion into public and political focus.

## Foreword – Executive Summary - 17 chapters

- |  |  |
|--|--|
| 1 Corrosion in the Solar Energy Sector   | 9 Robustness against Climate in Electrical Engineering/Electronics                             |
| 2 Corrosion in the Geothermal Energy Sector  | 10 Corrosion in the Oil & Gas Production Sector  |
| 3 Corrosion in other Renewable Energy Sectors  | 11 Infrastructure – Corrosion of Reinforced Concrete   |
| 4 Corrosion Challenges in Decarbonisation: the Crucial Role of Safe Batteries and Hydrogen Technologies                                    | 12 Corrosion and Additive Manufacturing  |
| 5 Corrosion in the Nuclear Energy Sector   | 13 Self-Healing Coatings   |
| 6 Materials and Corrosion Considerations in Carbon Capture Utilization and Storage Applications  | 14 Corrosion of Metallic Biomaterials  |
| 7 Sustainable Production: Impact of Reduction of Greenhouse Gas Emission in Metal Production and its Consequences on Corrosion Performance | 15 Protection of Cultural Heritage   |
| 8 Light Weight Design in Transportation to Reduce CO <sub>2</sub> Emissions: Impact on Corrosion Performance                               | 16 Finite Element Modelling and Artificial Intelligence for Corrosion Prediction the Way to Go |
|  | 17 Corrosion and Environment: the Release of Metal Ions to the Environment                     |



## Application of corrosion knowledge in solar energy



Intro – Green chemistry – Renewable energies

**Solar thermal energy (STE) :** high temperature corrosion & corrosion of reflectors

**Photovoltaic energy (PV) with solar panels**

- Corrosion of the structural materials
- Oxidation of electric contacts
- Degradation of photovoltaic panels

Atmospheric corrosion



Solar pannel degradation from El-Gharabawy, Int. J. of smart grid, 2, 4, December 2018

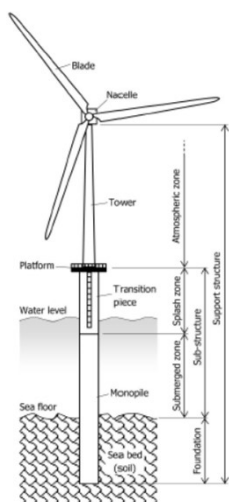


## Application & development of corrosion knowledge in wind turbines (off shore)



Intro – Green chemistry – Renewable energies

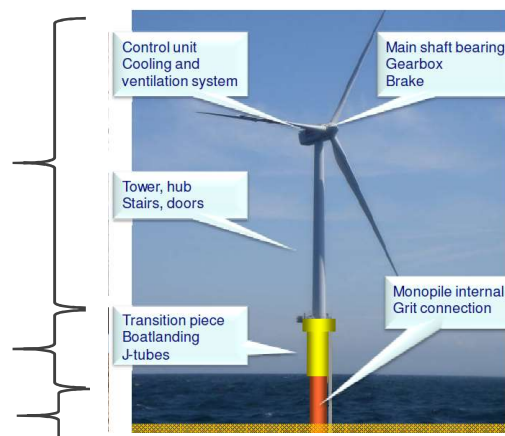
External and external surfaces are divided into corrosion zones



Atmospheric corrosion

Splash zone

Submerged zone  
(sea / floor)



**Various corrosion phenomena and protection technologies not far from off shore oil platforms**

(FROM EUROCRR 2021 WORKSHOP)

## Application & development of corrosion knowledge for sea water turbine (near & off shore)



### Sub seawater turbines are destroyed by corrosion

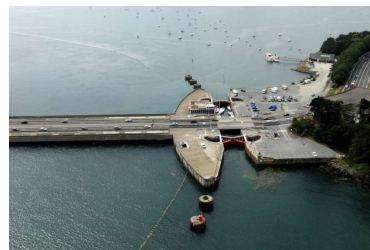
#### Les hydroliennes de Paimpol-Brehat attaquées par la corrosion

ENERGIE & ENVIRONNEMENT | ENERGIES RENOUVELABLES | HYDROLIEN | NAVAL | EOLIEN | EDF  
PAR BAPTISTE CESSIEUX PUBLIÉ LE 10/11/2017 À 10H42



La corrosion a attaqué les deux hydroliennes du site d'essai de Paimpol-Brehat. Celles-ci ont été retirées de l'eau en mai et juillet dernier. Immergées en 2014, ces deux prototypes n'ont jamais atteint l'un de leurs objectifs : produire de l'électricité pour 3000 foyers. Explications.

En mai et juillet dernier, les deux hydroliennes du site d'essai de Paimpol-Brehat ont été retirées de l'eau. Malgré leurs raccordements au réseau, les machines qui avaient été immergées en 2014 n'ont jamais atteint l'un de leurs objectifs : produire de



TIDAL ENERGY: Since 1966 a plant built across the estuary of the La Rance River in Brittany, France, produces around 500 GWh/year (turbines blades in titanium, all metallic parts are cathodically protected by imposed current since the beginning)

Main issues: seawater corrosion, including corrosion-erosion phenomena

## Geothermal energy

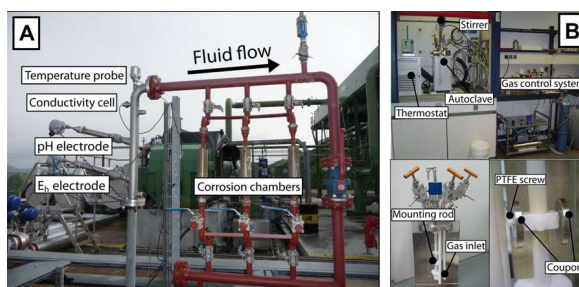


Geothermal energy is already well developed in some countries (Island, Philippines, ...).

Brine chemistry is the key point for corrosion resistance



- Some have low salt content “General corrosion rates in the geothermal district heating systems in Iceland are generally low, of the magnitude  $1 \mu\text{m}/\text{y}$ . The reason is high pH (9.5), low-conductivity ( $200 \mu\text{S}/\text{cm}$ ) and negligible dissolved oxygen”, from S. Richter, L.R. Hilbert, R.I. Thorarinsdottir, *Corrosion Science* 48 (2006) 1770–1778.
- But often, many brines are very corrosive environments (temperature, sulfur, high salt concentrations including chlorides, ...). Corrosion investigation and monitoring are then needed to select the alloys.



Monitoring system used for to a better understanding of corrosion and scaling in an operating geothermal power plant (Soultz-sous-Forêts, France), from N. Mundhenk & al., *Corrosion Science* 70 (2013) 17–28.



## Conclusive remarks & events



### Low carbon energies need to pay more attention to corrosion issues to be strongly sustainable and renewable (more attention to the “hard” technologies)

- To raise awareness of corrosion and corrosion control
- To identify international best practices
- To develop knowledge

### 2020&21: WCO workshops and forum on “low-carbon energies & corrosion”

- Workshops during Virtual Eurocorr 2020 & 2021
- WCO webinars on Corrosion Awareness days
- Workshop in China (17<sup>th</sup> – 18<sup>th</sup> November 2020)
- Forum during NACE CORROSION (2021)
- Workshop during the 21<sup>st</sup> ICC in Sao Paulo (Brazil), on July 2021

**=> 2022 White Paper**

## Conclusive comments (from the EFC and WCO White Paper)



- Like hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damage to everything.
- For future generations, obtaining a thorough understanding of corrosion and prevention of corrosion is vital. Approaches such as augmented and virtual reality or artificial intelligence are crucial.
- Sustainable development of low-carbon technologies embrace technologies of corrosion prevention.
- More than ever, raising awareness about corrosion and corrosion protection is a necessity.





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THANK  
YOU!

☺

THE WORLD  
CORROSION  
ORGANIZATION

April 24<sup>th</sup> – Corrosion Awareness Day

French alternative energies and atomic energy commission - [www.cea.fr](http://www.cea.fr)

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