

Article

Outdoor-Indoor Atmospheric Corrosion in a Coastal Wind Farm Located in a Tropical Island

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Abstract. Atmospheric corrosion is important to consider for energy production and transmission. Important and valuable information have been accumulated in this subject; however, the application of new knowledge obtained is not completed. In order to contribute to a decrease in economic losses caused by atmospheric corrosion in wind farms, studies toward application of this knowledge should be carried out. One of the most common reasons for the failure of coastal structures and infrastructures is deterioration failure which is the result of structure deterioration and lack of project maintenance. Atmospheric corrosion was evaluated at outdoor and indoor exposure sites located at different distances from the sea in a wind farm region. Carbon and galvanized steel, copper and aluminum specimens were exposed. Main pollutants and atmospheric parameters were measured. Significant differences between outdoor corrosivity determined by dose response functions established on ISO standard respecting direct weight loss evaluation were found. Estimation carried out using dose response functions overestimate corrosivity (excepting copper). Main factors causing outdoor corrosion are different to indoor. Very high outdoor and indoor corrosivity classifications were determined.

Keywords: Atmospheric corrosion, carbon steel, copper, aluminum, wind farm.

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1. Introduction

Atmospheric corrosion classification is an important aspect to consider before building a wind farm for power generation in a coastal zone. High levels of wind speed flow may cause salinity deposition high (Chloride deposition rate (Cl^-DR) and, consequently, fast deterioration of metallic materials. In the wind farms, most of the elements, technology and infrastructure are composed by metallic materials. As it is known, corrosivity categories of the atmosphere are a technical feature that provides the proper selection of metallic materials and protective measures depending on the specific application [1]. It allows increasing the durability and useful life of the infrastructure, as well as extending the maintenance and repairing works. Wind farm emplaced in coastal zone and those are intended to build should consider this reality.

Many atmospheric corrosion reports carried out under high and extreme corrosivity categories of the atmosphere in the last years have been linked to analysis and morphological characterization and microstructure of corrosion products [2-5]. Important projects dealing on atmospheric corrosion have been performed in recent years [6-9].

Important and valuable information in this subject have been accumulated; however, the application of new knowledge obtained is not completed. In order to contribute to a decrease in economic losses caused by atmospheric corrosion, studies toward application of this knowledge already reported should be carried out [10].

One of the most common reasons for the failure of coastal structures and infrastructures is deterioration failure which is the result of structure deterioration and lack of project maintenance. Deterioration is a gradual aging of the structure and its components over time; it can progress slowly, and often goes undetected because the structure continues to function as originally intended. However, if left uncorrected, continuous deterioration can lead to partial or complete failure of the structure.

Atmospheric corrosion studies allowing increasing the durability and useful life of infrastructure and technological resources used in transmission and distribution of electrical energy from any type of generation source are almost inexistent today. A report about the influence of atmospheric corrosion on transmission and distribution electricity lines in the coastal zone of São Luis; Maranhão at northeastern of Brazil was carried out during two years [11]. It was based in determining models to predict the atmospheric corrosion behavior of carbon steel, copper and aluminum as a tool to increase the durability and the service life of infrastructure.

Few atmospheric corrosion studies in wind farms before and after its construction have been reported. Only one study performed at Cabo Vilano wind farm, Camariñas, Spain has been found. This research was performed at six outdoor exposure sites located at different distances from the sea where carbon steel specimens were exposed during one year. A clear relationship between wave heights in the nearby sea, run of marine winds and Cl^-DR was determined. Monthly average spectral wave height values (1.5–2.0 m) are sufficient to produce high monthly average salinity values (Cl^-DR in the ranges 60-300 and 300-1500 mg m⁻²d⁻¹ Wet Candle Method). Total run of marine winds (instead to average wind speed as expected) was the parameter having greater influence on determining the atmospheric salinity of the test site [12-14].

Very few atmospheric corrosion researches have conducted an analysis related with meteorological factors influencing on Cl^-DR in coastal zone. Factors with higher influence on Cl^-DR were wind speed flow and distance from the sea or to the shoreline.

Changes in Cl^-DR versus distance from the sea at different coastal sites have been determined [15-21]; however, they have not been linked directly to corrosivity categories of the atmosphere under outdoor and indoor exposure conditions. No attention to Sulphur compounds deposition rate (SO_x^-DR) by airborne salinity and how it changes respecting distance from the sea has been given produced. In general, only SO_x^-DR (considered as sulphur dioxide deposition) and Cl^-DR is taken into account to predict corrosivity classification under outdoor exposure condition. In a coastal zone, not only SO_2 is an important parameter in determining atmospheric corrosivity, but also the presence of sulphur compounds such as sulphate coming in marine aerosol. SO_2 is one of the most aggressive gases respecting atmospheric corrosion, but other sulphur compounds may also influence on corrosion rate. The analysis of SO_x^-DR and Cl^-DR behavior respecting distance from the sea is a good tool in atmospheric corrosion research.

Two types of Chloride deposition on surfaces may occur. When salt particles are generated, they rapidly become equilibrated with the environment in marine aerosol and, depending on temperature and relative humidity (RH) conditions; they can turn into saline solution or salt crystals [22]. If RH is higher than 70%,

aerosol particles on surfaces as saline solution and not as crystals are deposited. It may increase atmospheric corrosivity. Chloride salts hygroscopicity increase particles size and promotes their deposition.

Washout effect (caused by rainfall) is more effective at higher *RH* levels. It is concluded that salinity wetting increases salt particles sizes and rainfall removes a great amount of salt aerosol [23-25].

The effect caused by a decrease of air temperature on salt particles existing on *Cl⁻DR* is usually not considered. ISO 9223: Second edition 2012-02-01 standard establishes: "The airborne salinity, based on chloride deposition, is strongly dependent on the variables influencing the transport inland of sea-salt, such as wind direction flow, wind speed flow, local topography, distance of the exposure site from the sea". It does not consider the influence of air temperature in marine aerosol penetration on land [1].

Atmospheric corrosion in Cuba, as well as in other areas of the Caribbean, has been characterized by studies carried out during the last decades. Most of them have been dedicated to determine factors influencing on the atmospheric corrosion of different metallic materials like carbon steel, copper, zinc and aluminum, that is to say, metallic materials more used in the construction industry. Investigations were executed at different exposure conditions (outdoor, indoor, including closed storehouses and under heat trap effect). A good data fit was obtained for copper and carbon steel under parallel outdoor exposure conditions in coastal zone in Havana (Cuba) and Medellin City (Colombia) using cumulative models including Chloride deposition rate and rain characteristics. The importance of Chloride deposition rate–rain regime complex in determining of copper and carbon steel mass loss was confirmed. Acceleration rate by chloride ions was caused on atmospheric corrosion of carbon steel and copper depended on the characteristics of rain regime. For a place having high amount and time of rain, a lower acceleration on corrosion rate should be expected for a given *Cl⁻DR* [26-28].

Higher corrosion of carbon steel under outdoor exposure conditions in Cuba for time of wetness at air temperatures between 5 and 25°C and lower for time of wetness at temperatures between 25 and 35°C was determined. In case of copper, factor more influencing on corrosion rate was the complex Chloride deposition rate–Time of rainfall (h) [29, 30].

Regarding Zinc and Aluminum in outdoor exposure conditions in coastal Cuban zones, the complex Chloride deposition rate –Time of rainfall was the factor more influencing in corrosion rate determined by mass loss. In general, *Cl⁻DR* was always present as important parameter in statistical analysis [31].

For other corrosion stations in the Caribbean under outdoor exposure conditions (Venezuela and Mexico), after one year of study, the predominant factor determining changes on steel corrosion rate was *Cl⁻DR*. A different effect of *Cl⁻DR* between Eastern Caribbean regions (Venezuela) and Western Caribbean regions (Cuba and Mexico), due to different atmospheric conditions was observed. In the Caribbean coastal regions, it is common to find extreme corrosivity categories of the atmospheres (CX) established in ISO 9223 Standard [32].

Respecting indoor atmospheric corrosion in coastal zones, the influence of dust deposition in determining the magnitude of carbon steel corrosion has been reported. The position of the specimens in the corrosion behavior was very important. The role of ventilation and the use of air conditioner parameters in determining corrosion rate of carbon steel in indoor conditions were also important [33, 34]. A model of indoor carbon steel corrosion with time including the influence of dust deposition (DD), *Cl⁻DR* and *SO_x⁻DR* has been proposed and shows a good statistical significance for the conditions tested. Respecting indoor corrosion in coastal zone, determined under heat trap effect, a significant effect of *SO_x⁻DR* on carbon steel corrosion have been reported [28].

The main objectives of the present paper are: (1) The establishment of corrosivity categories of the atmospheres (according to ISO standards) under outdoor and indoor exposure conditions in a wind farm region. (2) Determine the factors influencing on atmospheric corrosion of different metallic materials commonly used in construction in the coastal insular Cuban tropical climate, (3) Validate the usefulness of ISO 9223: 2012 and ISO 11844 procedures to predict or determine corrosivity categories of the atmosphere classifications in conditions corresponding to a wind farm located in an insular tropical coastal site and (4) Identify main environmental factors influencing on marine aerosol penetration evaluated by *Cl⁻DR* under outdoor exposure conditions. All these objectives are important in order to design a correct maintenance and corrosion protection program for wind farm.

2. Materials and Methods

2.1. Exposure Sites

Five outdoor exposure sites located at different distances from the sea (m) were selected (S1-60 m, S2-100 m, S3-400 m, S4-700 m and S5-1 360 m). Two indoor exposure sites (T1 and T6) were located within two wind turbine generators. Both wind turbine generators selected are located at 60 m from the sea in the extremes of the six ones comprising the wind farm.

The win farm, located in the north coast of the Holguin Province Cuba (21°06'34" NL and 76°07'54" WL) is considered the one showing higher generation of wind energy in Cuba (Fig. 1).

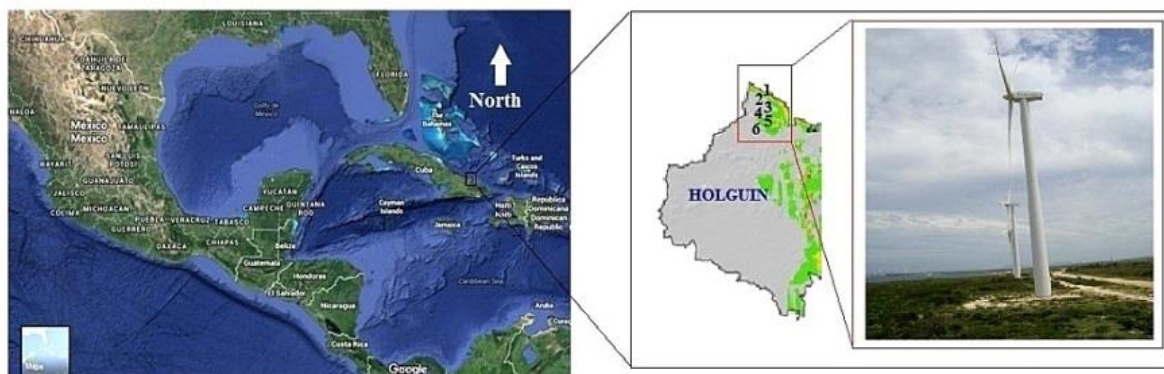


Fig.1. Location of wind farm at the East of Cuban Isle, distribution of outdoor exposure sites in experimental zone in Holguin province and general view of wind farm.

Every outdoor exposure site was composed by:

- Wooden rack with four atmospheric pollutants devices: Two dry plate devices (320 x 220 mm) for Cl^-DR determination and two cellulose filters plates (150 x 100 mm) for SO_x^-DR determination (device is sensible to all sulphur compounds presented in air). The wooden racks were oriented toward the sea and were placed at minimum height of 3m from the ground, under a shed to avoid the washing effect of rain (Fig. 2).
- Wooden racks for annual average outdoor corrosion rate determination: three specimens of four metals: carbon steel, galvanized steel, copper and aluminum (size 150 mm x 100 mm) were exposed (Fig. 2).



Fig. 2. Outdoor exposure sites with four atmospheric pollutants devices and three specimens of four metals: carbon steel, aluminum, copper and galvanized steel placed in the wooden racks.

Indoor exposure sites within wind turbine generator were composed by:

- Wooden racks for atmospheric pollutants devices (the same as for outdoor exposure sites).
- Wooden racks for average annual outdoor corrosion rate determination: three specimens of two metals: carbon steel and galvanized steel.
- Petri dishes for dust deposition indoor determination, as well as Electronic data logger sensor calibrated Tinytag Ultra brand manufactured in the UK. *HR* range (0-100%) and *T* range (-30 until 50°C) to measure air relative humidity and temperature.

Materials compositions:

- Carbon steel: unalloyed carbon steel (C: 0.15-0.2%, Cu 0.03% to 0.10%, P < 0.07%).
- Galvanized steel: Hot deep galvanized, coating thickness $\approx 21 \mu\text{m}$ of zinc.
- Copper: copper 99.85%. Main impurities: S (0.01%), Bi (0.003%), Pb (0.005%), Sb (0.05%).
- Aluminium: 99.5 % min.

2.2. Outdoor Pollutants

Cl^-DR ($\text{mg m}^{-2} \text{d}^{-1}$) based on Cuban standard using Dry plate device method was determined [35]. Dry plate device consisted in a piece of absorbent cloth sizing 320 mm x 220 mm located at 45 degrees to the horizontal and in front to the sea. Two pieces of cloth for every site, perfectly cleaned and washed with distilled water were used (Fig. 2). Clothes were exposed monthly during one year. Chloride deposited on the clothes was determined by chemical analysis. After retired, clothes into plastic bags up to chemical analysis were kept. Two values of Cl^-DR for every month of exposure (in the period September/2009 - August/2010) were obtained: one for device 1 and other for device 2, for every outdoor exposure site (total = 24). The principle of this method is the same than Wet Candle described on ISO: 9225:2012 [36]. Outdoor monthly average data (12), as well as annual average data (5 sites) with respect to distance from the sea were plotted and data was statistically processed.

SO_x^-DR ($\text{mg m}^{-2} \text{d}^{-1}$) based on Cuban standard using alkaline plate method was determined [37]. Alkaline plate device consisted in a piece of absorbent cellulose paper sizing 150 mm x 100 mm located at 45 degrees to the horizontal and in front to the north direction (Fig. 2). Pieces of cellulose paper in NaCO_3 70% were immersed and subsequently dried at a temperature of 60°C on the stove. Two specimens for test site were used. After drying, plates on each test site were exposed. After retired, specimens into plastic bags were kept up to chemical analysis. Two data of SO_x^-DR for every month of exposure was obtained: one for device 1 and other for device 2 for every exposure site, for a total of 24 in one year. The principle of this method is described on ISO: 9225:2012. Average monthly data (12) and average annual data (5) were plotted respecting distance from the sea.

Annual average deposition rate for both atmospheric pollutants in conjunction with the annual average of relative humidity (*RH* in %) and temperature (*T* in °C) to every outdoor exposure site can be used as an indirect estimation of the corrosion rate (r_{corr} in $\mu\text{m y}^{-1}$) of basic metals (carbon steel, copper, aluminum and zinc) using dose-response functions established in ISO 9223:2012 standard to estimate corrosivity categories of the atmosphere under outdoor exposure sites [1].

2.3. Indoor Pollutants

Indoor atmospheric devices at the same time that outdoors (September/2009-August/2010) were placed. At these test sites there is wind inflow caused by wind turbine generators. Monthly pollutants deposition rate data was plotted with respect to time of exposure. Taking into account ISO 11844-1:2006 uses SO_2 concentration for calculation of Indoor Corrosivity categories [38], SO_2 concentration was calculated from SO_x^-DR through the established relation: $P_d = 0.8P_c$ where P_d : SO_x^-DR and P_c : SO_2 concentration [1].

Regarding dust deposition, this atmospheric pollutant as cumulative quarterly was determined, that is to say, in the four quarters included in the year of evaluation. Given the low amount of dust deposition, it was necessary to extend exposure period up to three months. Inorganic dust (ID), organic dust (OD) and total dust (TD) deposition within the wind turbine generator was determined [39]

2.4. Corrosion Rate

Chemical cleaning procedure of specimens before placing in outdoor and indoor exposure condition [40], as well as to remove corrosion products to determine corrosion rate (mass loss per unit area over time) were carried out using established standards [41]. Specimen's thickness was considered equal and constant.

Three individual corrosion rate data (r_{corr} in $\text{g m}^{-2}\text{y}^{-1}$) for every group of specimens placed during the year of evaluation were determined. Average data to determine corrosivity categories of the atmosphere for each outdoor exposure site can be used. Three data for each metal tested (total number of data = 15) in order to determine the factors that could influence on the infrastructure deterioration and metallic technology in the zone of higher generation of wind energy in Cuba were statistically processed.

Regarding indoor exposure sites, corrosion rate (r_{corr} in $\text{mg m}^{-2} \text{y}^{-1}$) data for every specimen was determined. Data was used to determine corrosivity categories of the atmosphere in two indoor exposure sites within wind turbine generator.

2.5. Meteorological Parameters

Relative humidity (RH %), temperature (T °C) and wind speed flow (WS m s^{-1}) monthly data were measured using sensors located in the measuring mast of the control system installed in the wind farm. The wind speed flow at 50 m (WS_{50m}), 30 m (WS_{30m}) and 10 m (WS_{10m}) height from east-northeast to west-northwest directions was determined (wind speed flow coming from the sea).

All monthly data of climatic parameters were statistically processed to determine the factors influencing on Cl^-DR and corrosion rate of metals exposed. Step wise regression models in both cases were used. It was necessary to calculate three average data for every four months of the year for Cl^-DR and SO_x^-DR , for a total number of 15 data.

Monthly RH and T data to calculate time of wetness was used (TOW h y^{-1}) at different relative humidity intervals. Under indoor exposure site within wind turbine generator, where electronic data logger sensor was located, accumulated data was downloaded every month. Finally, TOW was estimated according to ISO 9223 as the time during which RH is over 80% and Temperature is above 0°C (temperature below zero is never reached in Cuban insular tropical climate).

3. Results and Discussion

3.1. Time of Wetness (TOW)

TOW under indoor exposure conditions within wind turbine generator respecting outdoor exposure conditions was higher (Fig. 3). It is in agreement with results obtained in other atmospheric corrosion studies carried out in the coastal insular tropical climate of Cuba for closed store houses and under heat trap conditions, as well as with the prediction of ISO 9223 standard [25-32]. At the range 80-90% of RH , TOW reaches higher values because it is a heavily forested coastal zone.

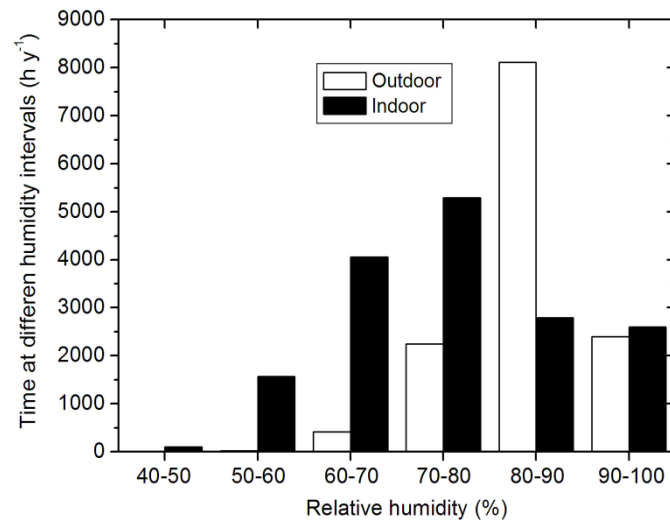


Fig. 3. Distribution of TOW at different intervals of RH under outdoor and indoor exposure conditions. TOW is considered the time when $RH \geq 80\%$ and $T > 0^\circ\text{C}$ (Temperature in Cuba is always higher than 0°C).

Under indoor exposure conditions (indoor of the button tower section) maxima and average monthly RH data respecting outdoor exposure conditions is higher or equal (Fig. 4a) and 4b). Time in the RH intervals 60-70%, 70-80% and 90-100% respecting outdoors is higher indoors (Fig. 3).

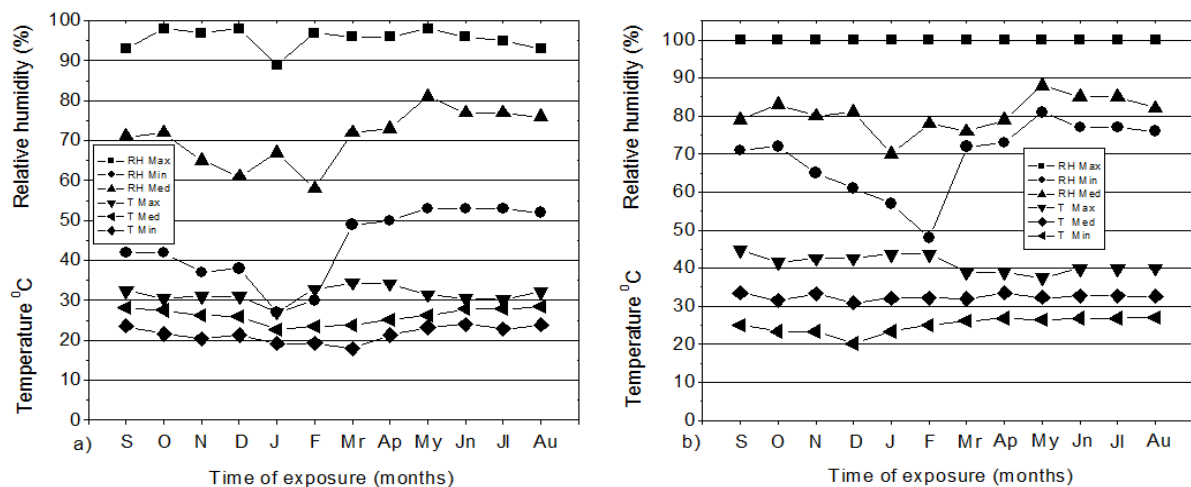


Fig. 4. Behavior of relative humidity-temperature complex, a) outdoor exposure site, b) indoor exposure site.

For outdoor exposure conditions, TOW is considered as the time when RH is higher than 80% and temperature above 0°C , it includes liquid precipitations because it is at the open atmosphere.

Metals exposed indoors are not submitted to liquid precipitations or sun radiation and the influence of wind speed is very low. It is a significant difference respecting outdoor exposure conditions. Temperature data show that water condensation is probable due to a significant difference between maximum and minimum values of temperature (Fig. 4b).

Average RH is over 70% under indoor exposure (Fig. 4b). Classification of RH level respecting ISO 11844-1:2006(E) is IV (See Annex D in standard) [38]. At a RH over 70% corrosion aggressivity IC4 (high indoor) or IC5 (very high indoor) is predicted. Conditions described for IC4 are the following: “heated spaces with fluctuation of humidity and temperature, elevated levels of pollution including specific pollutants, e.g. electrical service rooms in industrial plants”, “Unheated spaces with high relative humidity ($> 70\%$) with some risk of condensation, medium levels of pollution, possible effect of specific pollutants,

e.g. churches in polluted areas, outdoor boxes for telecommunication in polluted areas”. For IC5: “heated spaces with limited influence of relative humidity, higher levels of pollution including specific pollutants like H_2S , e.g. electrical service rooms, cross-connection rooms in industries without efficient pollution control”, “unheated spaces with high relative humidity and risk for condensation, medium and higher levels of pollution, e.g. storage rooms in basements in polluted areas”.

By using TOW concept established in ISO9223:2012 standard, it is possible to predict high atmospheric corrosion for indoor conditions, that is to say, within wind turbine generator, due to probabilities of higher retention of liquid water film on the metallic surface. However, it has been shown that under outdoor exposure, atmospheric corrosion is still higher due to high atmospheric pollutants deposition (mainly chloride ions) and the presence of liquid precipitations [27-29, 31-34].

In spite of the differences between TOW for both exposure conditions, when RH average data is over 70%, the most probable TOW classification category is $T_4(2\ 500 < T \leq 5\ 500)$. It means that indoor atmospheric conditions within wind turbine generator are very aggressive. It indicates the presence and permanence of a humid climate conducive to the existence of high levels of atmospheric corrosivity categories depending on the level of atmospheric pollutants deposition.

3.2. Outdoor Atmospheric Pollutants

3.2.1. Comparison between behaviors of Cl^-DR and SO_x^-DR

Cl^-DR and SO_x^-DR rate data taking into account a significant different behavior was analyzed separately (Fig. 5 a, b, c and d).

Regarding Cl^-DR , higher deposition in the site close to the sea (60 m) in winter period (November to February) was determined. During winter and summer seasons, Cl^-DR was always over $60\ mg\ m^{-2}\ d^{-1}$ up to a distance from the sea around 60 m. Top values in winter period were reached (Fig. 5 a and b). Cl^-DR shows small changes at a distance range of 400-1400 m from the sea. At a distance longer than 400 m from the sea, it is lower or equal to $3\ mg\ m^{-2}\ d^{-1}$ during summer season. Corrosivity category at distances larger than 1400 m could decrease because Cl^-DR reaches lower values.

Respecting SO_x^-DR , a different behavior is observed. A significant decrease in function of distance from the sea in winter season is appreciated. Higher values in the exposure site close to the sea were determined. More frequent changes are observed during summer (Fig. 5 c and d). SO_x^-DR decreases with distance from the sea in winter is observed. However, no significant decrease in summer is observed. Cl^-DR is always higher than SO_x^-DR excepting when distance from the sea is over 1360 m during winter and 700 m in summer.

Cl^-DR could be one of the main factors causing a significant corrosion of infrastructure in the wind farm. It is important to note that SO_x^-DR does not significantly decrease with distance from the sea in summer period. Corrosivity categories of the atmosphere could change.

Annual average Cl^-DR and SO_x^-DR versus distance from the sea are represented (Fig. 6 a and b). Data was fitted to the models: $(Cl^-DR = Cl^-D_0R + Ae^{-x/t})$ and $(SO_x^-DR = SO_x^-D_0R + Ae^{-x/t})$ respectively. These models are based on a decreasing exponential function of deposition versus distance from the sea. When $Cl^-D_0R = 0$ in case of Chloride deposition, it means that big salt particles originated in the breaking wave's zone are deposited at short distances from the sea in the region under study (Fig. 6a). It also means that small particles formed in the ocean can travel longer distances and deposited in the land. Parameter A can be considered as Cl^-DR in the breaking wave zone, in the coast line.

Similar results respecting Cl^-DR versus distance from the sea in several coastal zones in the world have been reported [15-21]. They did not establish corrosivity categories of the atmosphere. Cl^-DR behavior obtained is similar to reported for Havana City north coast. The City is characterized by screening structures [20].

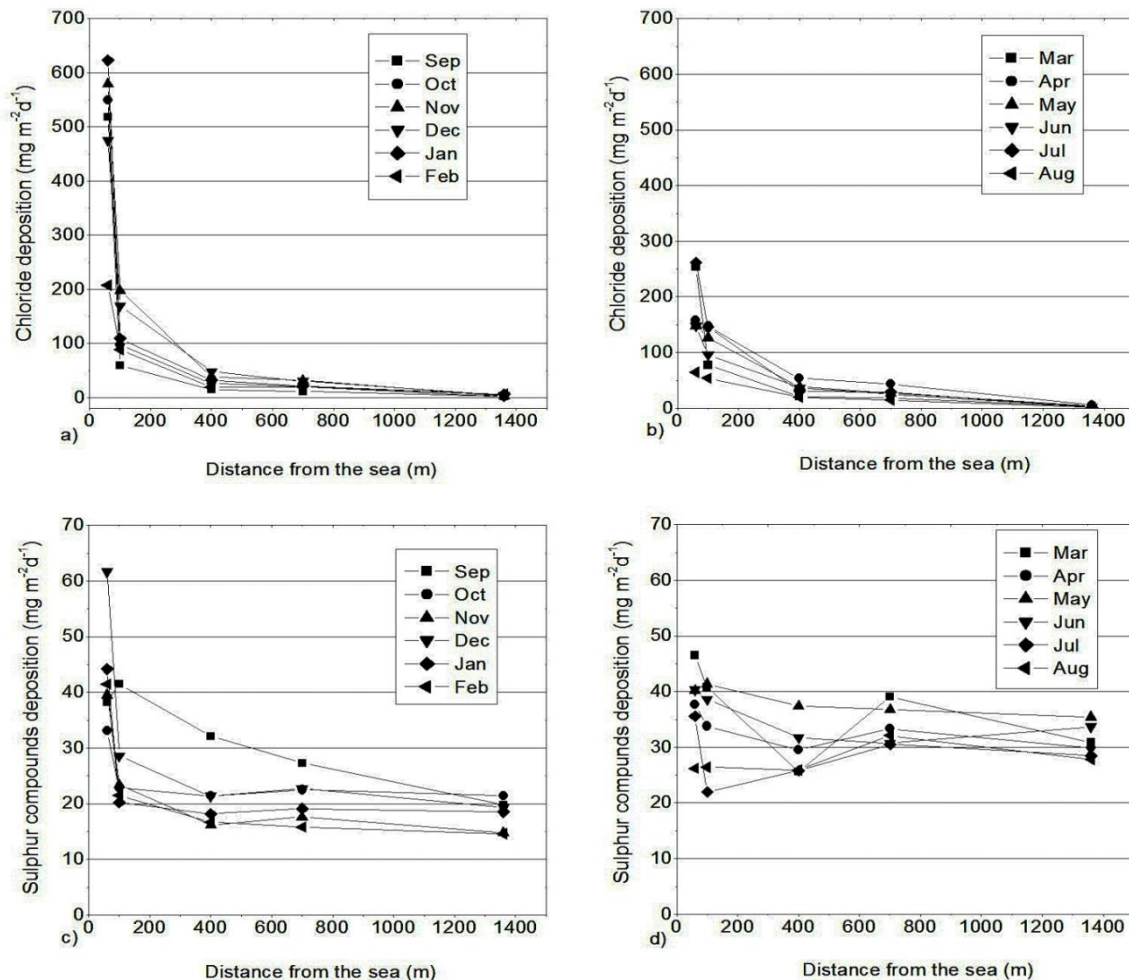


Fig. 5. Behavior of Cl^-DR and SO_x^-DR respecting distance from the sea in summer and winter seasons. Cl^-DR (a and b) and SO_x^-DR (c and d).

Cl^-DR at different distances from the sea shows a different behavior at Cabo Vilano wind farm, Camariñas, Spain. The evaluation lasted six months about Cl^-DR by wet candle method was determined. Cl^-DR versus distance from the sea obeyed a decreasing exponential function; however, two values of Cl^-D_0R each quarter in the period from April to September 2013 were obtained for ($Cl^-D_0 = 108.40$ and 83.03 mg m⁻² d⁻¹). It means that big salt particles originated in the breaking wave's zone are deposited at higher distances from the sea. Both data are higher than 60 mg m⁻² d⁻¹ and are indicative of very high corrosivity categories of the atmosphere. There is predominance of the coastal atmosphere in the zone under study; hence the importance to determine its influence on indoor exposure site. No previous information about indoor corrosion inside wind turbine generator is reported.

SO_x^-DR is usually produced by industrial or urban sources (mainly composed by SO_2 , very aggressive acid gas), dependence between SO_x^-DR and distance from the sea is not obtained frequently. No reports on this subject have been found. It means that one of the main sources of SO_x^-DR is the sea (mainly composed by sulphate aerosol). In case of this type of pollutant (Sulphate, SO_2 , SO_3 , SH_2 and other Sulphur compounds can be included in SO_x^-DR) sulphate ions can be produced by the sea. When $SO_x^-D_0R = 25.66$ it could mean that it is the average deposition determined at a distance starting from 200 m from the sea (Fig. 6b). It also implies that Sulphate coming from the sea is an important contribution to sulphur compounds deposition determined in the zone. The incorporation of sulphur compounds to horizontal flow of marine aerosol coming from the sea is what really occurs. Sulphate particles show a lower weight and size respecting Chloride. It causes them to travel and settle at higher distance from the sea respecting Chloride particles.

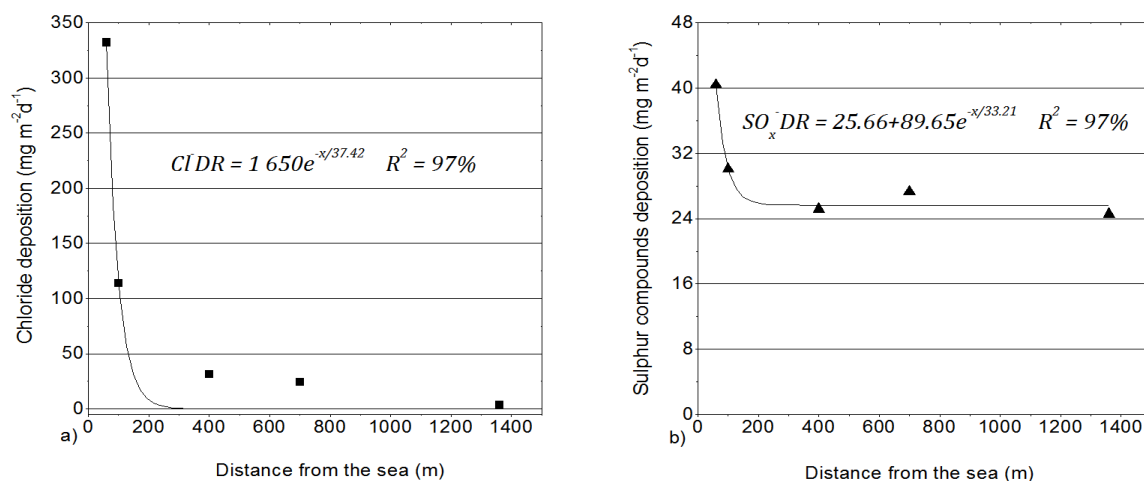


Fig. 6. Annual average Cl^{-}DR a) and SO_x^{-}DR b) versus distance from the sea. Regression equation obtained and model fitness.

This effect is called negative deposition, deposition wasn't caused by a source or natural effect [21]. The device used is sensitive to Sulphate deposition from marine aerosol and other sulfur compounds coming from other sources like industry and urban activity. No industries in the zone are located. It is characterized by a heavily forested coast surrounded by mountains. Other sources of Sulphur compounds (not Sulphate, but Sulphur oxides, significantly more corrosive) could be car traffic. Heavy vehicles move near the wind farm. In addition, Sulphur compounds could be originated in population settlement of Gibara, located relatively near to the wind farm. SO_x^{-}DR ($\text{SO}_x^{-}\text{D}_0\text{R} = 25.66$) is not in the range of an urban atmosphere; because the place is not an urban site. Rather it may be considered as industrial site. In sites close to the sea (distance to the shoreline = 60 and 100 m) SO_x^{-}DR is higher than $24 \text{ mg m}^{-2} \text{d}^{-1}$. The same behavior is kept from distance of 400 m from the sea. According to ISO standard, they could be classified as industrial zone; however, there are no industries. It means the main composition of SO_x^{-}DR is sulphate ions coming in marine aerosol (Fig. 6b). Atmospheric classification of sites close to the sea could be coastal-industrial. When distance from the sea is longer than 1 400 m, the zone can be classified as industrial. An atmosphere combining Cl^{-}DR and SO_x^{-}DR should probably produce very high corrosivity outdoors (C4, C5 or CX) and indoors (IC4-IC5).

SO_x^{-}DR data in Cuban conditions should represent mainly sulphate deposition coming in marine aerosol; however, some presence of SO_2 should exist produced by human activity such as shipping and traffic.

The average annual Cl^{-}DR data in the outdoor exposure site close to the sea (60 m), that is, site where wind farm was built (WF-60m) were compared with the six highest average annual Cl^{-}DR data obtained in the 75 outdoor exposure sites corresponding to Ibero-American Map of Atmospheric Corrosion Project (MICAT Project), it is noted that only in the exposure site located in Fortaleza Brazil (Br-3) annual average Cl^{-}DR data was higher [42]. These outdoor exposure sites in coastal regions (Brazil: Br-1, Br-2, Br-3; Uruguay: Uru; Costa Rica: CR and Portugal: Port) were located at a distance around or perhaps less than 60 m from the sea (Fig. 7).

The average annual SO_x^{-}DR data in these exposure sites was lower than $24.0 \text{ mg m}^{-2} \text{d}^{-1}$. Therefore, atmospheres can be classified as coastal and not as coastal-industrial; with the exception of the exposure site located at Sines, Portugal where the average annual SO_x^{-}DR data was $27.0 \text{ mg m}^{-2} \text{d}^{-1}$ and the atmosphere can be classified as coastal-industrial [42].

Regarding to average annual SO_x^{-}DR data, only in five Iberoamerican sites located at longer distances from the sea (Fig. 8), data was higher in comparison with the outdoor exposure site close to the sea (WF-60m). These outdoor exposure sites (Brazil: Br-4, Br-5; Spain; Panama: Pan; Chile and Portugal: Port) are located in cities with the presence of industries and intense automotive traffic.

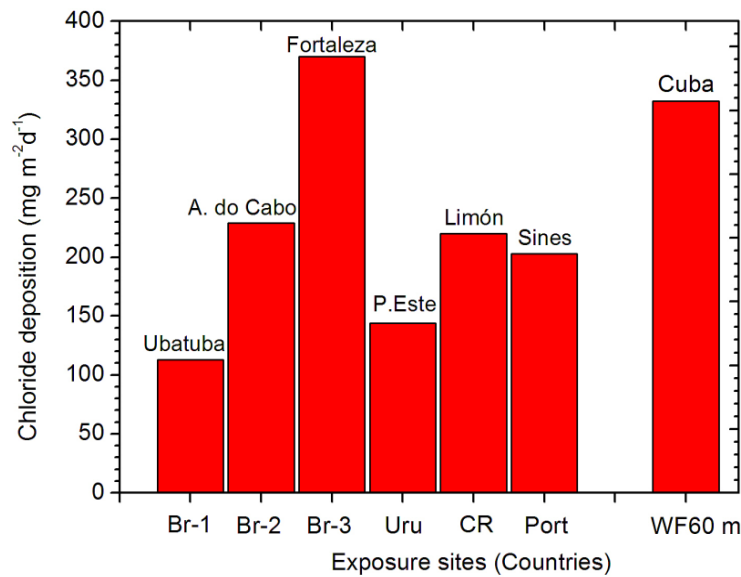


Fig. 7. Comparison between the average annual values of Cl^-DR for different Iberoamerican sites.

According to data reported, the coastal zone of Cuban wind farm can be considered as one with higher corrosivity category into Iberoamerican countries. It confirms why it is necessary to know how outdoor conditions influence indoors in the exposure site within wind turbine generator.

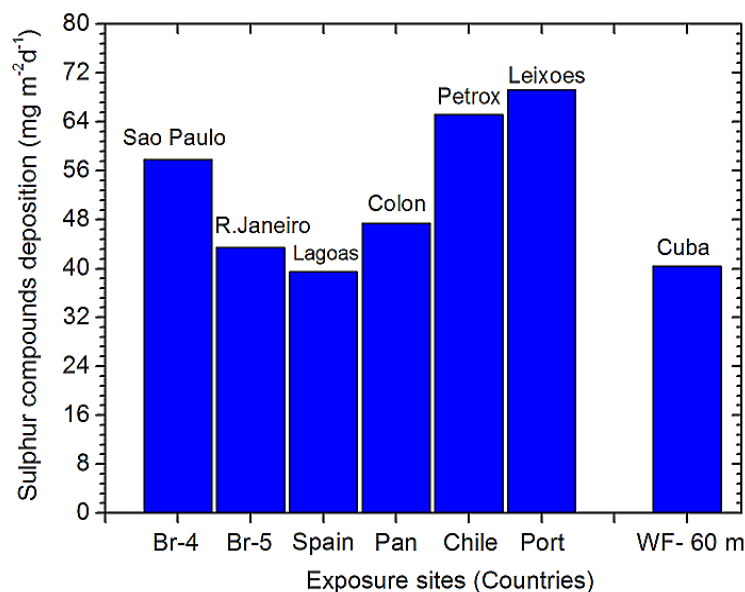


Fig. 8. Comparison between the average annual values of SO_x^-DR for different Iberoamerican sites.

3.3. Influence of Wind Flow and Temperature Humidity Complex on Cl^-DR .

The analysis of the influence of wind speed flow and temperature humidity complex on Cl^-DR has not been taken into account in Cuba and worldwide in atmospheric corrosion studies. ISO 9223 standard establishes that airborne salinity is strongly dependent on the variables influencing transport inland of the sea-salt, such as wind speed flow and direction. For outdoor exposure sites close to the sea, according to the fitness of multilinear model, wind speed flow (at 10 and 50 m height) is the most influencing factor in determining Cl^-DR . When wind speed flow at a height of 50 m increases, Cl^-DR decreases, but at 10 m height, Cl^-DR increases (Table 1).

Heavy aerosol particles generally do not reach 12 m height when they are carried by the wind in the horizontal flow [22]. Hence, an increase of the wind speed flow up to 10 m height causes an increase in Cl^-DR .

It means that most of the chloride aerosol particles come in the wind speed flow at a height of 10 m or lower. Annual average wind speed flow at a height of 10 m in this zone is 5.5 ms^{-1} . Threshold value for Cl^-DR reported for many coastal zones in the world is 3 ms^{-1} [17-19]. It means that an intense marine aerosol formation and Cl^-DR is possible for this zone. At a distance of 400 m from the sea, it is not only wind speed flow influencing, but also relative humidity temperature complex, that is, an increase in RH and a decrease in temperature (Table 1).

Table 1. Regression equations, probability and square correlation coefficient obtained by fitting data to the multilinear model showing the dependence of Cl^-DR on RH , T , Wind speed flow rate at 50 m height (WS_{50m}), at 30 m (WS_{30m}) height and 10 m height (WS_{10m}).

Distance from the sea (m)	$Cl^-DR = a \pm b(RH) \pm c(T) \pm d(WS_{50m}) \pm e(WS_{30m}) \pm f(WS_{10m})$ n=12	P	R ² (%)
60	$Cl^-DR = 1573.46 - 1065.96(WS_{50m}) + 1048.18(WS_{10m})$	0.0012	73
400	$Cl^-DR = 137.09 + 3.10(RH) - 5.04(T) - 65.13(WS_{50m}) + 86.50(WS_{10m})$	0.0050	53
1360	$Cl^-DR = 23.50 - 0.77(T)$	0.0014	62

At exposure sites placed at longer distances from the sea (1360 m), where the atmosphere can be classified as industrial, the main factor influencing on Cl^-DR is a decrease in temperature. When air temperature decreases, water condensation may occur. Aerosol particles formed within ocean increase their weight by absorbing water and makes deposition more probable. Annual average relative humidity is over 70% in the zone, it means that Cl^-DR is in the form of saline solution and not as salt crystals.

No significant regression equations were obtained for sites located at 100 and 700 m from the sea. These places were in a very intricate zone and at higher height respecting sea level.

Cl^-DR is affected not only by wind flow, but also by a decrease in temperature. Chloride deposition under such conditions takes place as saline solution, causing a high, very high or extreme corrosivity category of the atmosphere.

Respecting SO_x^-DR , no statistical significant influence was obtained. Perhaps different sources of these compounds are presented in the zone.

3.4. Corrosivity Category Classification

Corrosivity categories of the different exposure sites estimated according to dose-response functions presented in ISO 9223 standard are shown (Table 2). High corrosivity categories of the atmospheres are estimated.

To estimate corrosivity categories the relationship already established between Cl^-DR determined by dry plate and wet candle methods was used. That relation can be approximately expressed as: $S_{d,c} = 2.4S_{d,p}$ where $S_{d,c} = Cl^-DR$ determined by wet candle and $S_{d,p} = Cl^-DR$ determined by dry plate method [34]. To use dose-response functions presented in ISO 9223 standard, data of annual average Cl^-DR by wet candle method should be obtained [1].

Aluminum is not included on ISO 9223 standard to calculate the corrosion rate from dose-response functions. Aluminum experiences uniform and localized corrosion. The corrosion rates shown are calculated as uniform corrosion. Maximum pit depth or number of pits can be a better indicator of potential damage. It depends on the final application.

Corrosivity categories of the atmospheres for carbon steel, Zinc and Copper increase when distance from the sea decreases, from C3 to CX for Carbon steel and Zinc, as well as from C2 to C4 for Copper (Table 2). They show similar behavior.

It appears that, from the values of corrosion rate obtained of dose-response functions established by ISO 9223:2012, Copper should be the metallic material less affected. For a distance from the sea of 1 360 m (atmosphere can be classified as industrial) corrosivity categories of the atmosphere calculated was medium and low (Table 2).

Changes in corrosivity categories classification determined by direct measurement of corrosion rate of specimens is different to the estimation made based on dose-response functions. Sharp decrease in corrosivity categories of the atmospheres is observed for Carbon steel and Zinc (Galvanized steel). Copper does not show the same behavior (Table 3).

Table 2. Corrosivity categories of the atmospheres estimated for different sites using dose-response functions established by ISO 9223:2012 for three of the materials evaluated.

Distance from the sea(m)	Carbon steel		Zinc(Galvanized Steel)		Copper	
	r_{corr} ($\mu\text{m y}^{-1}$)	Categories (C)	r_{corr} ($\mu\text{m y}^{-1}$)	Categories (C)	r_{corr} ($\mu\text{m y}^{-1}$)	Categories (C)
60	210.92	CX Extreme	13.37	CX Extreme	2.50	C4 High
100	115.86	C5 Very high	7.32	C5 Very high	1.71	C4 High
400	60.39	C4 High	3.58	C4 High	1.04	C3 Medium
700	54.65	C4 High	3.18	C4 High	0.96	C3 Medium
1 360	26.89	C3 Medium	1.14	C3 Medium	0.33	C2 Low

Table 3. Corrosivity categories of the atmosphere determined by weight loss for Carbon steel, Galvanized steel, Copper and Aluminum.

Distance from the sea (m)	Corrosion rate ($\text{g m}^{-2}\text{y}^{-1}$)		Corrosivity categories (C)	
	Carbon steel	Galvanized steel	Copper	Aluminum
60	1035.21 (C5) Very high	28.83 (C4) High	85.53 (CX) Extreme	1.98 (C3) Medium
100	874.98 (C5) Very high	22.56 (C4) High	74.17 (CX) Extreme	0.21 (C1) Very low
400	455.57 (C4) High	9.30 (C3) Medium	37.83 (C5) Very high	1.51 (C3) Medium
700	73.76 (C2) Low	4.94 (C2) Low	33.08 (C5) Very high	0.22 (C1) Very low
1 360	29.07 (C2) Low	4.88 (C2) Low	32.67 (C5) Very high	1.48 (C3) Medium

Dose-response functions using data from many countries but mainly corresponding to temperate climate have been obtained. Data for tropical countries are not abundant in data base used for obtaining dose-response functions. It means that dose-response function over estimate corrosivity categories of the atmosphere for Cuba and perhaps for tropical climate (excepting Copper). In a previous report concerning copper atmospheric corrosion in Cuba the increase in corrosion rate in coastal zones is attributed to the formation of atacamite as main corrosion product having high hygroscopic properties [43, 44].

Galvanized steel is not included on ISO 9223 standard [1]. Hot deep zinc coating 21 μm thicknesses was exposed. Corrosivity categories classification was made based on pure Zinc according to data presented on ISO standard. Galvanized and carbon steels had very similar behavior in relation to corrosivity categories starting from 700 m of distance from the sea in the study zone (Table 3). Regarding to copper it is important to note very high corrosivity categories of the atmospheres determined (C5 to CX).

Images of specimens at different distances from the sea exposed illustrate changes in corrosivity categories for the different metals tested (Fig. 9).

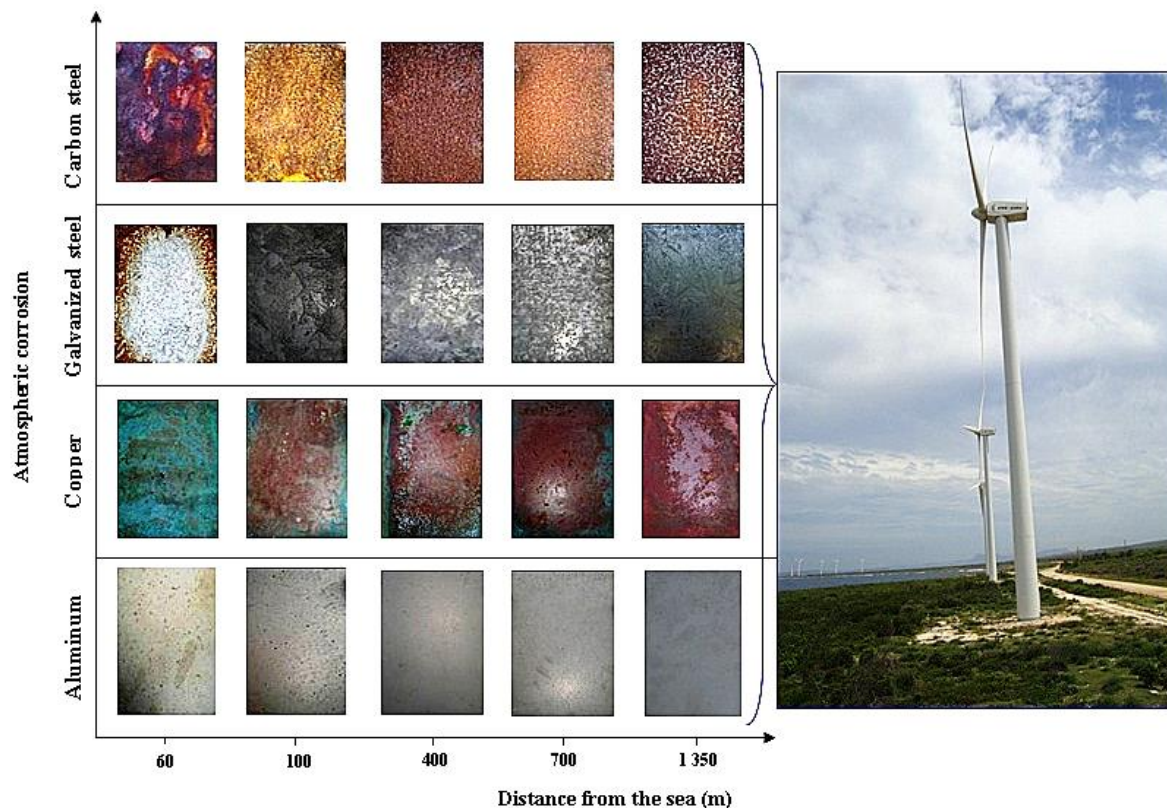


Fig. 9. Atmospheric corrosion observed on specimens exposed under outdoor exposition conditions during one year at different distances from the sea. Carbon steel, Galvanized steel, Copper and Aluminum.

Similarities are observed for corrosivity categories of Carbon and Galvanized steel for different exposure sites depending on distance from the sea. Copper shows higher corrosivity respecting carbon steel; aluminum shows lower corrosivity (Table 3). Estimated corrosivity categories of the atmospheres based on dose-response functions does not coincide with determination carried out by weight loss. It is confirmed by visual observation of specimens exposed on each site (Fig. 9).

Corrosivity category determination is a requirement to proceed to wind farm construction. Corrosion products on the surface of carbon steel specimens exposed during one year at 700 m and 1360 m do not cover completely the surface (Fig. 9), it is a confirmation of low corrosivity. Corrosion products of Carbon steel are uniform and compact, but are not heavily contaminated with chloride ions. A more intense corrosion is observed in exposure sites close to the sea confirming the existence of high and very high corrosivity categories of the atmosphere.

Galvanized steel specimens show corrosion near the edges when are close to the shoreline; however at a distance of 400 m from the sea only a slight loss of metallic gloss is observed on zinc surface (Fig. 9).

A green patina on copper specimens is observed (Fig. 9). Corrosion products like paratacamite or atacamite ($\text{Cu}_2(\text{OH})_3\text{Cl}$) could be formed as main constituents of the patinas due to direct action of Cl^- [43, 44]. Specimens located at 60 m from the sea are almost covered with green patina, exposed between 100 and 700 m from the sea show green patina near the edges, but specimens exposed at 1360 m from the sea do not show green patina but red brown color. It should mean that the influence of Chloride ions is not significant at this last distance to the shoreline, but the high deposition of sulphate ions could cause a high corrosion rate. Brochantite ($\text{Cu}_4\text{SO}_4(\text{OH})_6$) and posnjakite ($\text{Cu}_4\text{SO}_4(\text{OH})_6 \cdot \text{H}_2\text{O}$) could be also present in corrosion products composition due to presence of SO_4^{2-} in coastal and industrial atmospheres [43, 44].

Aluminum corrosion does not significantly change as function of distance from the sea. It is only used for indoor structures because of its relatively weak mechanical strength. Pitting corrosion of aluminum in

specimens located near from the sea (60-100m) can be observed. Pit density seems to be high because presence of pitting is very abundant (Fig. 9). Pitting are very close to each other, indicative of high corrosion rate, however, corrosivity categories do not show high levels. Determination of maximum pit depth and pit density could be a better index of potential damage.

Undoubtedly, corrosivity categories of the atmosphere determined by weight loss offer more valuable information than estimation using dose-response functions.

3.5. Factors Influencing on Outdoor Atmospheric Corrosion

In addition to Corrosivity category of the atmospheres, it is also necessary to determine the main environmental factors influencing in atmospheric corrosion process. Under atmospheric corrosion conditions in coastal zone, a competitive adsorption process between Cl^-DR and SO_x^-DR could take place. The term $([Cl^-DR][SO_x^-DR])$ can be considered as an interaction between Cl^-DR and SO_x^-DR during atmospheric corrosion process. If this term is statistically significant, it is possible to confirm the existence of competitive adsorption process between ions presented in the marine aerosol

Interaction between Cl^-DR and SO_x^-DR during atmospheric corrosion process is statistically significant according to multilinear model proposed between corrosion rate as dependent variable and RH , T , Cl^-DR , SO_x^-DR and interaction $([Cl^-DR][SO_x^-DR])$ as independent ones (Table 4). In addition to an increase in corrosion rate when Cl^-DR increases, a possible competitive adsorption process could occur in atmospheric corrosion process of carbon steel and galvanized steel. In the case of aluminum the regression coefficient affecting $([Cl^-DR][SO_x^-DR])$ interaction has a positive sign so it could be considered as a synergism causing an increase in corrosion rate. It is noticing a direct influence of SO_x^-DR on copper corrosion (Table 4) appearance not seen in the coastal insular tropical climates as Cuba.

For a better statistical significance, RH and T can be eliminated to obtain a more accurate and precise result based on the influence of Cl^-DR and $([Cl^-DR][SO_x^-DR])$. This does not mean that climatic factors (RH and T) does not influence in atmospheric corrosion in metallic materials tested, but their influence could be considered constant.

Table 4. Regression equations obtained for metallic materials tested. Statistical fitness to the model proposed.

Metallic materials	$r_{corr} = a \pm b(RH) \pm c(T) \pm d(Cl^-DR) \pm e(SO_x^-DR) \pm ([Cl^-DR][SO_x^-DR])$ n=15	P	R ² (%)
Carbon steel	$r_{corr} = 14.40 + 19.76(Cl^-DR) - 0.41([Cl^-DR][SO_x^-DR])$	0.0001	91
Copper	$r_{corr} = -49.15 + 3.45(SO_x^-DR)$	0.0008	85
Galvanized steel	$r_{corr} = 2.97 + 0.40(Cl^-DR) - 0.007([Cl^-DR][SO_x^-DR])$	0.0000	96
Aluminum	$r_{corr} = 0.74 + 0.12(Cl^-DR) + 0.004([Cl^-DR][SO_x^-DR])$	0.0000	98

The increase of sulphate ions in marine aerosol in coastal site tends to inhibit atmospheric corrosion by chlorides in carbon steel surface. Therefore, an increase in SO_x^-DR could cause a decrease in corrosion rate of Carbon and Galvanized steel at the same level of Cl^-DR . It explains why both metallic materials show similar behaviour in the exposure site farthest from the sea (SO_x^-DR is higher than Cl^-DR , atmosphere can be classified as industrial). If necessary, protective measures for galvanized steel could be similar to those required for carbon steel. These materials are widely used in the construction industry, mainly in the construction of wind farm.

3.6. Indoor Atmospheric Corrosion

Indoor corrosivity categories (IC) determined within wind turbine generators T1 and T6 is IC5 (very high) for Carbon steel and IC4 (high) for Galvanized steel (considered as Zinc) (Table 5).

Wind turbine generators selected were located at 60 m from the sea, that is, outdoor corrosivity classification ranges between C4 and CX. Although corrosion rate determined outdoor and indoor is different for Carbon and Galvanized steel, indoor and outdoor corrosivity classification is high or very high. It means that outdoor environment influences on corrosion indoors. This technical feature should be taken into account for designing and building new wind turbine generators.

Average relative humidity exceeded 70% within one of the wind turbine generators. It indicates level IV (RH > 70%) for this climatic parameter. Concerning annual average SO₂ concentration it was always higher than 10 µg m⁻³ corresponding to level IV characteristic of high corrosivity categories according to ISO standard (Fig. 10) [38].

Table 5. Indoor Corrosivity categories determined within wind turbine generator numbers 1 and 6 (according to ISO 11844-1 standard).

Indoor Exposure site	Carbon steel (mg m ⁻² y ⁻¹)				Galvanized steel (mg m ⁻² y ⁻¹)			
	Specimen 1	Specimen 2	Specimen 3	Average data (Categories)	Specimen 1	Specimen 2	Specimen 3	Average data (Categories)
T1	76 170	76 930	77 740	76 946 (IC5) Very high	2 460	2 220	2 824	2 340 (IC4) High
T2	75 680	74 724	78 860	76 421 (IC5) Very high	2470	2 410	2420	2433 (IC4) High

It is important to note that higher SO₂ concentrations are determined for summer period (March-August). It is possible due to a higher anthropogenic generation in summer because in this case no sulphate is determined, only gaseous SO₂. Access doors within wind turbine generators are located back to the sea. Every wind turbine generator tower has two windows covered by a filter mesh. Doors are frequently opened due to intrinsic workings of the wind farm. As expected, *Cl*⁻*DR* is low as commonly occurs in indoor environments.

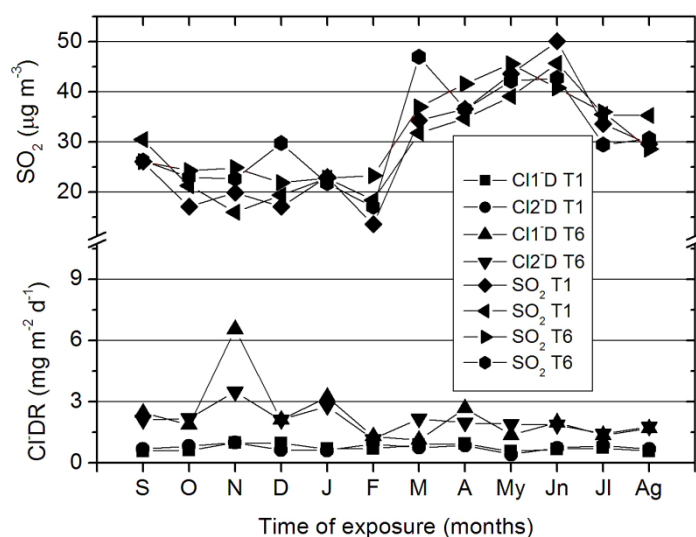


Fig. 10. Indoor *Cl*⁻*DR* and annual average SO₂ concentration within both wind turbine generator (T1 and T6).

Wind turbine generator exhibits a good penetration resistance not only to *Cl*⁻*DR* but also DD (Fig. 11). Not the case with respect to SO₂ concentrations or *SO*_x⁻*DR*. As it is very well known, aerosol particles

impact on surfaces and remain over them. That is why Cl^-DR and dust deposition (Fig. 11) appreciably decreases inside turbine generators. It is not the case for SO_2 , as a gas, it can enter to indoor environments almost freely. Similar results are reported under heat trap and storehouses in Cuban conditions. Sulphate aerosols particles are usually smaller than chloride ones, so they can enter to indoor environments in higher amount. It is an aspect to take into account for designing and building wind turbine generators near or in the sea.

Although statistical analysis have not been executed (data was not sufficient to obtain statistical significance), main factors determining the magnitude of indoor atmospheric corrosion within wind turbine generator for both metallic materials should be RH and SO_2 concentration due to the high levels determined. Indoor corrosion process is obviously very different to outdoor corrosion because conditions and factors influencing significantly differ; however it is important to remark a very high indoor corrosivity within wind turbine generator room.

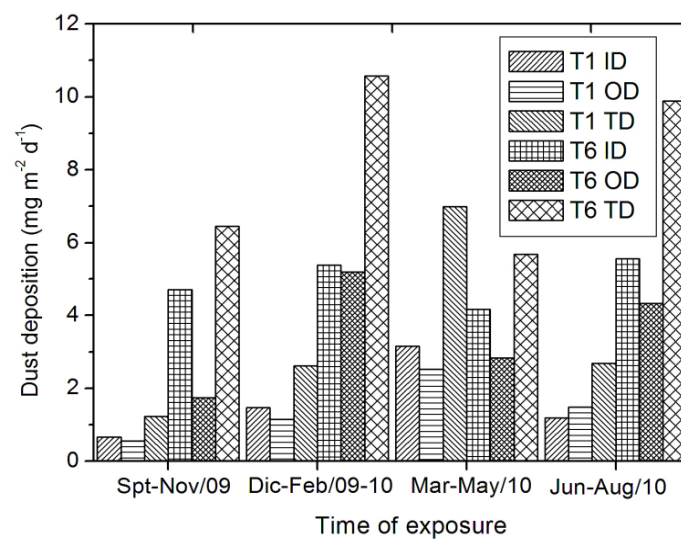


Fig. 11. Dust deposition within both wind turbine generators (T1 and T6), ID=Inorganic Dust Deposition. OD = Organic Dust Deposition. TD: Total Dust Deposition.

Carbon steel indoor corrosion rate during one year in store houses located in the coastal atmosphere in Cuba was $9\,000\text{ mg m}^{-2}\text{y}^{-1}$ and $27\,400\text{ mg m}^{-2}\text{y}^{-1}$. Corresponding indoor corrosivity categories were IC3 (medium) and IC4(high), respectively. Storehouses were closed (no windows) [33, 34]. Under indoor heat trap conditions, corrosion rate of carbon steel was about $80\,000\text{ mg m}^{-2}\text{y}^{-1}$ (IC5) [28, 29]. Therefore, indoor corrosivity within wind turbine generator is similar to heat trap conditions. Heat trap indoor exposure conditions consisted in introducing samples in galvanized steel metallic boxes designed and manufactured as containers (class 3.4 according to International Standard, ETS 300-019-1-0) [45]. Every metallic box has a front door and two small windows on each side for ventilation. Each window has a filter mesh made of galvanized steel for wind filtration as also occurs in the access door in the wind turbine generators. Boxes were located in a position where small windows are placed in the dominant wind direction, that is, very similar to indoor exposure conditions within wind turbine generator.

4. Conclusions

The following are the most relevant conclusions of this work:

1. High outdoor corrosivity categories of the atmospheres are determined in the wind farm zone. Significant differences are observed between corrosivity categories predicted using dose-response functions and determined by weight loss according to ISO-9223:2012 standard. Dose-responses function should be revised for use in coastal insular tropical climates as Cuba. Nevertheless, there were not differences between corrosivity categories determined from description of typical atmospheric environment and the classification determined by weight loss.

2. High indoor corrosivity category is determined within wind turbine generators. Outdoor and indoor corrosivity categories are coincident (although corrosion rate is different) for carbon and galvanized steel. Main factors influencing on indoor corrosion changes respecting outdoors. Cl^-DR is the main factor determining corrosion in outdoor conditions. SO_2 and RH are the main factors determining corrosion under indoor conditions. Indoor corrosivity within wind turbine generator is similar to heat trap conditions.
3. Decisive influence of Relative humidity-temperature complex and wind speed flow on Cl^-DR is observed, particularly for exposure sites located relatively far from the sea. Cl^-DR increases when air temperature decreases. Sulphate ions coming from the sea are a significant part of SO_x^-DR .
4. Some particular effects in atmospheric corrosion, such as an interaction between Cl^-DR and SO_x^-DR during corrosion process for Carbon steel, Galvanized steel and Aluminum were determined, as well as direct influence of SO_x^-DR on copper corrosion. These effects have not been reported previously.

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