CAUSES AND MECHANISMS OF CORROSION FOR SUPPORTING STRUCTURES OF ROOFTOP PHOTOVOLTAIC SYSTEMS

URSACHEN UND MECHANISMEN DER KORROSION BEI TRÄGER-KONSTRUKTIONEN VON AUFDACH-PHOTOVOLTAIKANLAGEN

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SUMMARY

This article describes the function and detailing of the support structure of rooftop photovoltaic systems. Components of the supporting structure are often manufactured using aluminium and stainless steel. The corrosion exposure and the corrosion behaviour of the components in the atmosphere are treated, taking into account the self-corrosion and bimetallic corrosion. From the point of view of corrosion technology, atmospheric conditions close to the sea are particularly problematic. Increased attacks by aluminium in contact with stainless steel cannot be ruled out here. Possible corrosion problems are also explained on the basis of a damage case.

ZUSAMMENFASSUNG

Der Beitrag beschreibt die Funktion und den Aufbau der Trägerkonstruktion von Aufdach-Photovoltaikanlagen. Die Bauteile werden häufig aus Aluminium und nichtrostendem Stahl hergestellt. Behandelt werden die Korrosionsbeanspruchung und das Korrosionsverhalten der Bauteile in der Atmosphäre unter Berücksichtigung der Eigen- und Bimetallkorrosion. Aus korrosionstechnischer Sicht problematisch sind vor allem die Verhältnisse in Meeresnähe. Hier sind verstärkte Angriffe von Aluminium im Kontakt mit nichtrostendem Stahl möglich.

KEYWORDS: Photovoltaics, supporting structure, fasteners, atmospheric self-corrosion and bimetallic corrosion, contact with timber, aluminium, stainless steel

1. FUNCTION AND STRUCTURE OF A ROOFTOP PHOTOVOLTAIC SYSTEM

A rooftop photovoltaic system (PV-system) is a solar power system in which solar cells convert part of the solar radiation into electrical energy. In this energy

conversion, the photoelectric effect of solar cells is exploited. The electricity generated by the solar cells can be used directly by the user. Very little current flows in a single solar cell. Therefore, several solar cells are interconnected to form a solar module. On roofs, solar modules are fastened to the load-bearing substrate via a supporting structure.

The rooftop-mounted system on tiled roofs, in which the building carries the PV-system, is widely used. "On roof" means that the PV-system is mounted on the inclined roof surface on a support structure parallel to the roof (Fig. 1). Roof hooks in a variety of designs, known as rafter anchors, are used to fasten the supporting structure. These are attached to the substructure of the roof after temporary removal of the tiles, preferably using wood screws on the wooden rafters of the roof truss (mostly spruce). In the next step, mounting rails are fastened to the roof hooks using fasteners (usually screw connections), depending on the system horizontally, vertically or both. The solar modules are then assembled. The mostly framed modules are often fixed to the mounting rails with special clamps whose screws are accessible from the front.

The metallic fasteners of a rooftop system are exposed to atmospheric corrosive exposure. Depending on the type and intensity of this stress, the possibility of self-corrosion and bimetallic corrosion must be taken into account, depending on the design and the selected corrosion protection. For corrosion protection and weight reasons, but also from the point of view of fast and easy assembly, the following metals and corrosion protection measures have proven reliable for the individual components of the carrier system:

- The roof hooks are usually made of stainless steel (material no. 1.4301) or aluminium AlMgSi 0.7.

- As a rule, the roof hooks are fastened to the wooden rafters with hexagon wood screws made of stainless steel material no. 1.4301 and 1.4567. Extruded aluminium profiles (e.g. AlMgSi 0.7) are almost exclusively used as materials for the mounting rails of the substructure, while stainless steel rails are rarely used.

- The screws, nuts and washers for connecting the aluminium mounting rails to each other and to the roof hooks are usually made of stainless steel.

- Framed photovoltaic modules are fixed to the mounting rails of the material AlMgSi 0.7 using specially shaped aluminium clamps, which are fixed to the rails with stainless steel screws.

1 Rafter   Spruce
2 Roof hooks   Stainless steel, corrosion resistance class II (1.4301)
                           Aluminium (AlMgSi0,7),
3 Wood screw   Stainless steel, corrosion resistance class II (1.4301, 1.4567)
4 Mounting rails   Aluminium (AlMgSi0,7), stainless steel, corrosion resistance class II
5 Screw connection Stainless steel, corrosion resistance class II
6 Retaining clamps Aluminium (AlMgSi0,7),
7 Screw connection Stainless steel, corrosion resistance class II
8 PV modules   Special glass (outside)

Fig. 1: Installation of a rooftop photovoltaic system on an inclined tiled roof (example)

Fig. 2: Photovoltaic modules mounted on a trapezoidal sheet metal roof (left) and mounting detail (right): flat profile made of AlMgSi 0.7 and fastening system made of 1.4301

The majority of flat roofs with corrugated or trapezoidal sheet metal roofing on a wooden substructure only offer limited load reserves to carry the weight of a PV-system. In such cases, the carrier system and the modules can be fixed with a hanger bolt mounting system (Fig. 2). The hanger bolts are screwed through the roof covering to the wooden roof construction. In the systems shown in Fig. 2, the profiles and brackets of the frame construction are made of aluminium. The load-bearing hanger bolts (threaded rods) and screw connections are made of stainless steel, e.g. made of the material 1.4301. The overlying retaining clamps of the PV

modules are made of aluminium AlMgSi0.7; they are screwed to the aluminium frame construction using stainless steel screws.

2. POSSIBLE PROBLEMS FROM THE CORROSION POINT OF VIEW

Supporting structures of rooftop photovoltaic systems are mixed structures with components made of aluminium and stainless steel. These are exposed to atmospheric corrosion. They can be in contact with wood (wood screws for fixing the roof hooks in rooftop-mounted systems). In the case of corrosion exposure there are several possibilities of bimetallic corrosion in addition to the self-corrosion of the components: Combinations of stainless steel (wood screws, roof hooks, mounting rails, screw connections/threaded rods) and aluminium components (roof hooks, mounting rails, clamps). The majority of the materials or material combinations exposed to the atmosphere are not directly irrigated, which can be advantageous in a low-pollutant atmosphere, but disadvantageous in a high-pollutant atmosphere (marine atmosphere) because the pollutants can accumulate.

3. CORROSION EXPOSURE TO BE EXPECTED

3.1 CORROSION EXPOSURE IN THE ATMOSPHERE

Under atmospheric corrosion conditions, the metallic components and fasteners of the PV-system exposed to the atmosphere can only be subject to damaging corrosion attacks if moisture and specific pollutants are present in sufficiently high concentrations at the same time [1, 2]: Above 60% relative humidity, corrosion increases with increasing humidity and the content of gaseous and/or solid impurities in the air.

Humidity/Rain. Corrosion requires moisture (water) on the metal surface. A special feature of the atmospheric stress of metals is the formation of only extremely thin electrolyte films on the component surface above certain air humidities and the regular course of wet/dry cycles due to condensation and precipitation. Rain can have very different effects on corrosion processes. In the case of outdoor corrosion, irrigation can promote corrosion by supplying an electrolyte and removing corrosion-inhibiting corrosion products. However, irrigation also removes dirt and salt deposits, which prevents corrosion.

Sulphur dioxide. Gaseous substances contained in the air promote a corrosion attack in dissolved form. Above all, sulphur dioxide act corrosive; SO_2 can form sulphurous acid at high humidity, which is converted to sulphuric acid by further

oxygen uptake. Over the past two decades, the SO_2 content of the air has been drastically reduced, especially in urban and industrial agglomerations. Nowadays, SO_2 concentrations of less than 5 µg/m^3 are measured on an annual average in large Central European cities, which have hardly any influence on metal corrosion.

Chloride salts. The chloride-containing aerosols, which are particularly active in regard to corrosion, are formed near the sea or through the use of de-icing salt. In the atmosphere of coastal areas, seawater is carried by the wind onto the land in the finest distribution as "aerosols" (solid and liquid particles of about 0,1 to 100 µm in diameter) and is deposited on structures. High, corrosion-promoting contents of aerosols, however, can only be found in the immediate vicinity of the coast. Sea salt consists predominantly of sodium chloride NaCl, in smaller quantities also the strongly hygroscopically reacting salts calcium chloride $CaCl_2$ and magnesium chloride $MgCl_2$ are contained, which has to be considered from a corrosion-chemical point of view in support systems for PV-systems.

In outdoor areas that are not directly irrigated (e.g. in structural gaps below the module surfaces of PV-systems), components do not come into contact with rainwater. It is therefore characteristic for such areas that substances harmful to corrosion from the surroundings of the building can accumulate here. Due to the hygroscopic behaviour of salts, highly concentrated aqueous salt solutions are formed even in non-weathered outdoor areas, which attack the surfaces of components. Calcium and magnesium chloride, which are proportionally contained in sea salt, have a so-called saturation humidity of little more than 30%. This means that they already form highly concentrated and thus extremely corrosive salt solutions in very dry air. With a saturation moisture of 78%, sodium chloride has a less pronounced hygroscopic behaviour. This salt forms solutions only in a more humid climate or when water enters. Because of such relationships, the irrigation of the components of PV-systems plays an important role.

Chlorides in concentrations that have a corrosive effect can also occur close to roads and bridges with heavy traffic that have been treated with de-icing salt. Sodium chloride (NaCl) is scattered above all. The maximum extent of the so-called splash water area next to busy roads is about 10 m in the inner-city area, the range of the significantly less polluting spray mist area is assumed to be about 10 to 30 m from the scattered road, although the intensity decreases with increasing distance from the road.

3.2 CORROSION EXPOSURE IN CONTACT WITH TIMBER

The wood screws used to fasten the roof hooks in roof systems on tiled roofs (Fig. 1) are screwed into the wood below the tiled roof. The so-called hanger bolts for fastening PV-systems to trapezoidal roofs (Fig. 2) are also anchored in wood beneath the roof. When metallic components come into contact with porous building materials such as wood, the moisture content of the building material and, if sufficient moisture is present, also the content of harmful substances (acids, salts) determine its corrosiveness [3].
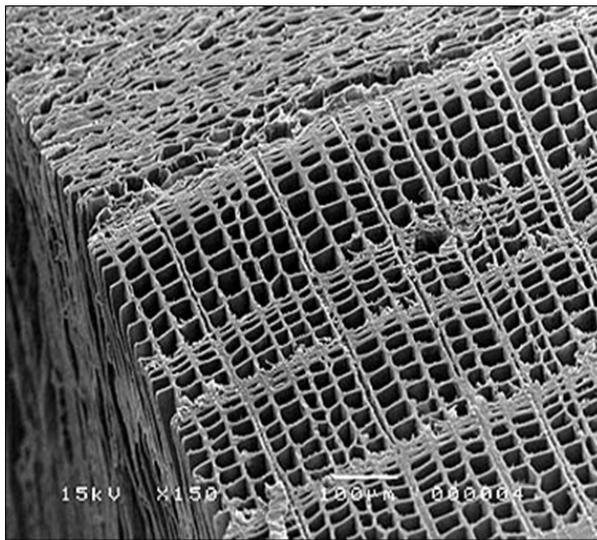
Fig. 3: Wood in a scanning electron microscope
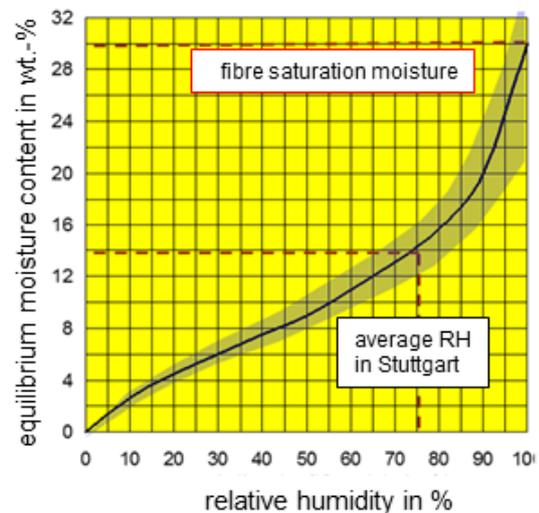
Fig. 4: Sorption isotherm for spruce wood at 20°C

Wood is a porous building material (Fig. 3). It can absorb liquid water capillarily and gaseous water via water vapour diffusion, bind it and release this moisture again with decreasing relative humidity. Fig. 4 illustrates the water content of wood as a function of relative humidity using the example of spruce wood at 20°C. With increasing humidity, bound water first accumulates in the cell walls of the wood and the moisture content of the wood increases. Free water is present in the cell cavities above the fibre saturation moisture (about 30 wt.-% water in conifers). With an average annual relative humidity of 75%, only a humidity of about 14 wt.-% is reached in the not weathered (not irrigated) outdoor area. In the case of weathering with repeated irrigation, which does not take place with PV-systems, moisture around 20 wt.-% would be possible.

Timber can react more or less acidically when wet and supported by increased temperatures: Timber contains parts of acetic acid, which are initially bound to cellulose as esters. In the presence of unbound water, the esters can hydrolyse and release acetic acid. Thus the humidity (the free water) in the timber is always

weakly acetic acid. Acetic acid formation is wood-specific. Aqueous extracts of construction timber have the following pH values, depending on the wood species [3]: E. g. spruce 4.8 to 5.3 and oak 3.3 to 3.9. In combination with moisture, oak has a more corrosive effect on metals than spruce. However, it should be noted: Acidification is only possible in sufficiently moist woods (equilibrium moisture content > 30 wt.-%). In rather dry timber, which is especially typical for non-weathered outdoor areas, i.e. also for photovoltaic systems, these interrelationships therefore do not play a significant role. Some timber preservatives also have a corrosion-intensifying effect. Chloride-containing and copper-containing timber preservatives have a corrosive effect on metallic zinc-based coatings in the presence of moisture. The process of acidification as well as the corrosion intensification by timber preservatives does not play a significant role in rooftop photovoltaic systems, as a high moisture content > about 30 wt.-% water cannot be achieved in practice.

3.3   STANDARDS TO BE OBSERVED FOR ROOFTOP PHOTOVOLTAIC SYSTEMS

Classification of atmospheric corrosiveness

Aluminium. DIN EN ISO 9223 [4] and the resulting DIN EN ISO 12944 (Part 2) [5] deal with the classification of important environmental conditions to which metallic components, including aluminium components of PV-systems, may be exposed and subdivide atmospheric corrosion stress into corrosivity categories (Table 1).

This determination of corrosiveness is the basis for the design of the required corrosion protection. The evaluation of corrosiveness shall be based on criteria such as climate and humidity, exposure to chlorides (from marine atmospheres and de-icing salt) and sulphur dioxide (from polluted cities and industries). With increasing category C2 to C5, the corrosion load due to these parameters alone or in combination increases. PV-systems are built under corrosion conditions corresponding to corrosivity categories C2 to C4, so only these categories are mentioned in Table 1. However, increased sulphur dioxide emissions in accordance with a corrosivity category C3 and above all C4 are rather rare or do no longer occur in Europe due to the reduction of industrial emissions. Table 1 applies primarily to free weathering. Influences from non-irrigation of surfaces and possible concentration of pollutants are not taken into account. However, such an influence can be assumed for photovoltaic systems. The chloride load also corresponds

more to a corrosivity category C2 to C3 near the sea if the surface of the components is repeatedly irrigated and deposited chloride salts are repeatedly washed away by the rain. On the other hand, a considerable concentration of deposited chlorides can be assumed for non-irrigation near the sea. During the investigations in [6], chloride coverings of 10 to 30 mg/m² were measured on the island of Helgoland at a distance of 50 m from the sea for irrigated surfaces and 300 mg/m² for non-irrigated surfaces. It can be deduced from the above data that stronger attacks are possible with aluminium and also stainless steel near the sea, especially if the components, which is the case with support structures of photovoltaic systems (below the modules), are not irrigated and chloride salts can concentrate. In urban areas, increased attacks could only be expected directly next to roads with heavy traffic and treated with de-icing salt. The latter is rarely the case with PV-systems, especially since the systems are arranged on roofs in urban areas and the distance to the road is usually more than 10 m.

Table 1: Corrosivity categories for outdoor areas according to [4, 5] in modified representation

CC	corrosion load	humidity/ climate	chloride exposure		SO₂ - exposure	
			typical environment	content in $\mu g/m^3$	typical environment	content in $\mu g/m^3$
C2	low	temperate climate, rarely condensation water	> 10 km from the sea	< 5	low polluted rural areas and cities	< 5
C3	intermediate	temperate climate, occasionally condensation water	10 - 3 km from the sea	5 - 10	moderately polluted areas (cities and industrial areas)	5 - 30
			spray mist beside the road (10-30m)			
C4	high	subtropical, tropical climate, frequent condensation water	3 - 0,1 km from the sea, no spray mist	10 - 100	heavily polluted industrial areas, tunnels	30 - 90
			splash water beside the road (0 to 10 m)			

CC = corrosivity categorie

Stainless steel. For the selection of materials from the point of view of resistance to corrosive influences, the building authority approval [7a] in combination with DIN EN 1993-1-4 [7b] regulates the safety-relevant requirements for statically stressed components and fasteners. The above rules and regulations use a points based system to evaluate corrosiveness and to determine a required steel from five possible corrosion resistance classes (Table 2). Corrosivity is determined taking into account exposure to sulphur dioxide, chloride pollution (distance from the sea and to roads treated with de-icing salt in cities) and the possibility of concentration of pollutants in non-irrigated areas (which increases corrosion, see section

3.1). From the sum of the possible exposures an exposure risk is derived and from this in turn the necessity to use stainless steel of a certain resistance is deduced. Taking into account the possible conditions in supporting structures, the following exposure risks and required types of stainless steel can be derived:

- **Rooftop photovoltaic systems in urban areas:** Taking into account the
  - very low sulphur dioxide levels in urban atmospheres today,
  - the comparatively rare use of de-icing salts in residential areas,
  - the rather low driving speed of cars in residential areas (low whirling up of salts)
  - and the mostly greater distance of the facilities to the road (> 10 m),

a low to medium exposure risk can usually be assumed in the case of systems in urban areas on roofs of residential buildings, which justifies the use of stainless steels of corrosion resistance class II (Table 2).

- **Rooftop photovoltaic systems near the sea:** Due to their immediate proximity to the sea (e.g. buildings on the spa promenade of Helgoland) and the expected high concentration of salts in the non-irrigated area (see Section 3.3), a high exposure risk is to be assumed for these plants, which after approval justifies the use of stainless steels of a corrosion resistance class III, better corrosion resistance class IV (Table 2).

Corrosiveness of timber

Metallic connections and connections to load-bearing timber always have direct wood-contact and at the same time, at least in sections, are also in contact with the surrounding atmosphere. With regard to durability, aspects of atmospheric corrosion (see above) and corrosion in contact with timber must therefore be considered. Information on corrosiveness in contact with timber can be found in DIN EN 1995 (Part 1) [8] (a design standard) and DIN EN 14592 [9] (a product standard). Specifically, for stainless steel fasteners in contact with timber, notes are given in [7a, 7b].

Depending on the structural situation and moisture exposure, DIN EN 14592 distinguishes between the following with regard to the risk of corrosion of fasteners for timber structures

- timber classes 1 to 5 for the wood-contacted area

- and corrosivity categories (Table 1) for the air-contacted area.

Table 2: Classification of stainless steels into corrosion resistance classes CRC (examples for fasteners in fastening technology and for attachments) [7a]

Structure	Material no.	Short name	CRC
ferritic ferritic ferritic	1.4003 1.4016 1.4512	X2CrNi 12 X6Cr 17 X2CrTi 12	I low
austenitic austenitic	1.4301 1.4567	X5CrNi 18-10 X3CrNiCu 18-9-4	II moderate
austenitic austenitic austenitic	1.4401 1.4404 1.4571	X5CrNiMo 17-12-2 X2CrNiMo 17-12-2 X6CrNiMoTi 17-12-2	III intermediate
austenitic ferrit.-austenit.	1.4439 1.4462	X2CrNiMoN 17-13-5 X2CrNiMoN 22-5-3	IV high
austenitic austenitic	1.4565 1.4529	X2CrNiMnMoN 25-18-6-5 X1NiCrMoCuN 25-20-7	V very high

For non-irrigated outdoor constructions, i.e. also for components of the support structures of rooftop photovoltaic systems, a wood class 2 applies. This is characterized by a climate with approximately 20°C and a relative humidity, whose height exceeds a value of 85% only for few weeks per year. Under such conditions, experience has shown that the average moisture content of wood is only about ≤ 16 wt.-% (Section 3.2). The timber is therefore relatively dry and is not sufficient to cause significant corrosion in contact with building metals [10].

For stainless steels in contact with timber, there are no special restrictions for not irrigated outdoor areas [7a, 7b]. Only for contact with timber which may have higher moisture content due to weathering (irrigation), at least corrosion resistance class CRC II (Table 2) must be selected for the steel if the timber then reacts strongly acid (pH < 4) (e.g. oak, Section 3.2).

4. ASSESSMENT OF CORROSION BEHAVIOUR OF THE COMPONENTS OF CARRIER SYSTEMS

Subsequently, the metals aluminium and stainless steel used for rooftop photovoltaic systems will be assessed with regard to their behaviour under the possible corrosive exposure (Section 3), taking into account self-corrosion and bimetallic corrosion. Possible problems of aluminium and stainless steel components of the support structures of rooftop photovoltaic systems are mentioned in Section 2.

4.1 SELF-CORROSION OF ALUMINIUM [1, 11]

Atmosphere. Copper-free aluminium alloys such as the AlMgSi0,7 used here are very resistant to atmospheric corrosion. This advantageous behaviour can be attributed to the formation of very dense oxide cover layers. An additional obstacle to the cathodic partial reaction is based on the low electrical conductivity of the oxidic passive layers. This hinders the flow of electrons or the reaction with atmospheric oxygen. Due to the resistance of the surface layers to diluted acids, aluminium is only corroded very slightly in the normally polluted atmosphere. Chloride-induced pitting corrosion occurs in the marine atmosphere or when de-icing salt mists have direct access to the surface. The holes that form always have a very limited depth, which can be attributed to the sealing effect of the corrosion products that form. As a rule, there is no influence on the load carrying capacity. In the case of aluminium, the more local corrosion attack increases in the order of land, urban, industrial and marine atmosphere. In the atmosphere of a corrosivity category C2/C3 or C4 (sea atmosphere), maximum attack depths below 100 µm respectively 200 µm after 50 years can be assumed [11].

Contact to timber. In non-irrigated outdoor areas, the corrosion of aluminium in contact with timber is not increased compared to atmospheric corrosion. On one hand, the corrosion-promoting constituents of relatively dry wood (section 3.2) are not effective. On the other hand, corrosion-promoting deposits (such as chloride aerosols near the sea) can only diffuse into the timber together with (non-existent) water [6].

4.2 BIMETALLIC CORROSION OF ALUMINIUM [12]

In support systems for rooftop photovoltaic systems, under certain ambient conditions, there is the possibility of bimetallic corrosion of aluminium components in contact with stainless steel (see also section 1). Bimetallic corrosion is a so-called galvanic corrosion in which a corrosion element is formed in an aqueous medium by two differently noble metals in contact with each other. This can result in accelerated corrosion of the less noble material. The total corrosion of the less noble material results from the sum of the self-corrosion and bimetallic corrosion. Necessary prerequisites for bimetallic corrosion are:

- The metals show a different corrosion potential in the attacking electrolyte.

- They are electrically (metal contact) and electrolytically (via a conductive aqueous medium) connected to each other.

However, the actual risk of bimetallic corrosion to a composite structure depends on other influencing factors. This includes the materials used, the environmental conditions determining the corrosion intensity and the design. The main influencing variables are:

- The potential difference U_C - U_A in the acting electrolyte,

- the "aggressiveness" of the acting aqueous medium (the conductivity of the electrolyte W) and the duration of humidification,

- the surface ratio cathode/anode F_C (noble metal) / F_A (active metal).

Practical electrochemical series - Potential difference. The so-called electrochemical series of metals are used to estimate the hazard due to bimetallic corrosion. The "practical electrochemical series" shown in Fig. 5 take into account the behaviour of material pairings in two typical environments, namely chloride-free, slightly acid rain and condensation water (in an urban atmosphere, corrosivity category C2/C3, the electrolyte would in the worst case be low chloride, slightly acidic water), and neutral seawater (also applies to atmospheric waters near the sea, corrosivity category C4).

From the point of view of a potential difference, the following situation applies to the carrier systems of interest here:

In an urban atmosphere, aluminium has a comparatively high electric potential due to its passivity, and there is only a small potential difference between components made of stainless steel and aluminium components. In a marine atmosphere or in the presence of chloride-rich aqueous solutions, however, a high potential difference between aluminium and stainless steel is possible. On the side of potential conditions, the requirements for bimetallic corrosion would thus be present in the marine atmosphere, but hardly in the urban atmosphere.
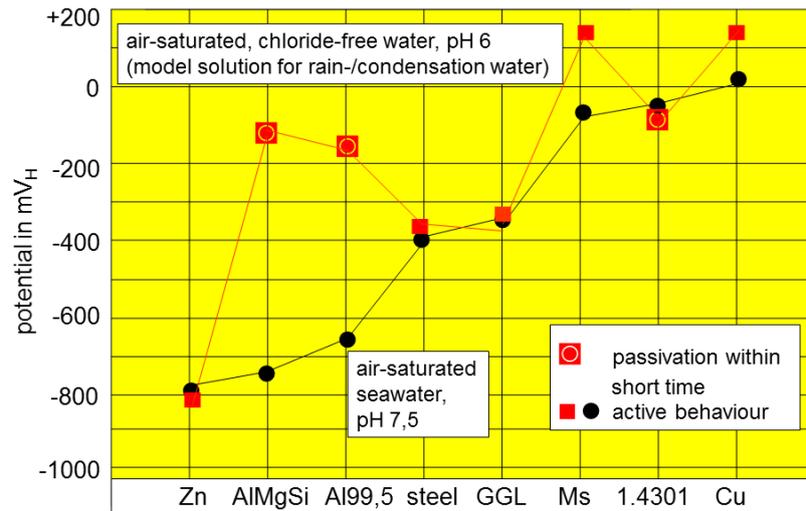
*Fig. 5: Practical electrochemical series of selected metals in model solutions
(water: according to Elze, seawater: according to Audi Ingolstadt)*

Conductivity of electrolytes. The strength of the amount of metal wastage depends on the conductivity of the electrolyte. Only highly conductive electrolytes cause significant bimetallic corrosion. Atmospheric waters (rain and condensation water in rural and urban atmospheres) are rather pure electrolytes with a low conductivity < 100 µS/cm. In salty waters (sea water, condensation water near the sea) the conductivity is some powers of ten higher; values > 10,000 µS/cm are possible.

Area ratio cathode/anode. With an increasing quotient of cathode area (area of the more noble metal) and anode area (area of the less noble metal), bimetallic corrosion is promoted as long as the above two prerequisites (sufficiently high potential difference, high electrolytic conductivity of a wetting aqueous medium) are met. Under atmospheric corrosion conditions, any area ratios are always low, since the "range" of a corrosion element is limited due to the lack of wetting of the surface with a thicker, electrolytically well conducting water film. Therefore the metal removal due to bimetallic corrosion is limited under such conditions, even if the other conditions are fulfilled.

Conclusion. The main hazard for corrosion-stressed aluminium components is therefore in contact with other noble metals such as stainless steel, as bimetallic corrosion can occur. The cathodic partial reaction, which is severely impeded by the aluminium itself, can then take place on the contact material. However, strong bimetallic corrosion is only to be expected in support structures for PV-systems if the electrolyte has a high conductivity, i.e. is "aggressive", and if the components in contact are extensively wetted by the electrolyte [11]:

- Since in atmospheric weathering and especially in the shielded area below the module surfaces of photovoltaic systems only small amounts of electrolytes and, as a rule, only pure electrolytes have a maximum temporary effect on the surfaces of structures, the risk of an acceleration of corrosion of aluminium by bimetallic corrosion away from the sea is usually very low.

- With PV-systems, bimetallic corrosion can only be expected if saline aerosols act on the fasteners and connection means near the sea. As the case of damage described in section 5 shows, the fact that salts can accumulate in non-irrigated areas has a detrimental effect on PV-systems near the sea. Due to the strongly hygroscopic behaviour of the magnesium chloride contained proportionally in the salts, the required electrolyte is also available.

4.3 STAINLESS STEEL [1]

Stainless steels are highly alloyed steels in which, in contrast to unalloyed and low-alloyed steels, no uniform corrosion and rust formation occur under natural environmental conditions and in aqueous, almost neutral aqueous media if the alloy content is sufficient. Therefore, additional protection is usually not necessary for these steels. For this behaviour the steel requires a chromium content (Cr) of at least about 11 wt.-% as well as an oxidizing agent such as oxygen in the surrounding medium. This prerequisite is given by contact with the atmosphere and with oxygen-containing waters. In the presence of oxygen, the surface is passivated and thus corrosion protection against a large number of chemically aggressive substances is achieved. The corrosion resistance of the steel to the possible types of corrosion is further improved by increasing the chromium content and/or adding other elements such as nickel (Ni) and/or molybdenum (Mo) and nitrogen (N).

For metallic fasteners and adjacent components, mainly stainless steels are used which have increased contents of the alloying elements chromium, nickel and molybdenum and, depending on the type and content of these elements, can be assigned to a certain corrosion resistance class (Table 2). Chromium stabilises the passive layer, molybdenum improves the corrosion behaviour in the presence of chlorides and nickel is primarily responsible for the resistance to acids. Since in structural crevices in the presence of iron chloride ($FeCl_2$), for example, acidification of the electrolyte as a result of hydrolysis is also possible, nickel also increases resistance to crevice corrosion and, at higher contents, resistance to stress corrosion cracking.

Passive steels with insufficient alloy content are sensitive to certain types of corrosion when specific media attack. Chlorides dissolved in aqueous media (e.g. in seawater) are the main cause of corrosion:

- This includes above all the so-called pitting corrosion. It is a local attack that takes place under the formation of rust.

- Pitting corrosion is increased when stainless steel components form a crevice with each other or in contact with other materials. This is called crevice corrosion.

- There is also stress corrosion cracking and intergranular corrosion; these are types of corrosion that occur through cracking.

Rain or condensation water is completely harmless for stainless steels. Even the low sulphur dioxide content of the atmosphere alone does not harm this material, since the passive layer is resistant to diluted acids.

Stainless steels of corrosion resistance class II (1.4301) are used in carrier systems for PV-systems. As already pointed out (see section 3.3), this material is not approved for applications in moderately heavily polluted industrial atmospheres and near the seashore according to the building supervisory approval [4]. This, however, is contradicted by practical experience:

This steel of corrosion resistance class II, which is widely used in construction technology, has been repeatedly investigated in the past with regard to its behaviour under atmospheric corrosion conditions. In literature evaluations [1,13] it was found that in a more heavily polluted urban atmosphere of earlier years, the corrosion attack is insignificant and can only be recognised with the naked eye as discolouration. Fine pitting corrosion attacks were only detectable, if at all, at a higher magnification. In the case of such steels, an attack associated with rust formation and proceeding via pitting corrosion can only be expected in a more heavily polluted industrial atmosphere (which no longer exists in Europe) and also in a marine atmosphere (distance from the coast < 1 km). However, the attack depths determined in these more aggressive climates are still below 100 μm even after decades and as a rule have no influence on the load-bearing capacity of structural parts. Fig. 6 illustrates these statements by means of a literature evaluation of the corrosion behaviour of various stainless steels in different climates. When evaluating sheet metal, the bottom areas in particular were taken into account. Any pollutants present here (comparable to the conditions in PV-systems) may tend to concentrate, as washing off by atmospheric water is impossible.

Material-no.	1.4016	1.4301	1.4401	1.4439	1.4529
resistance class	I	II	III	III	IV
pitting resistance equivalent	17	18	24	36	42
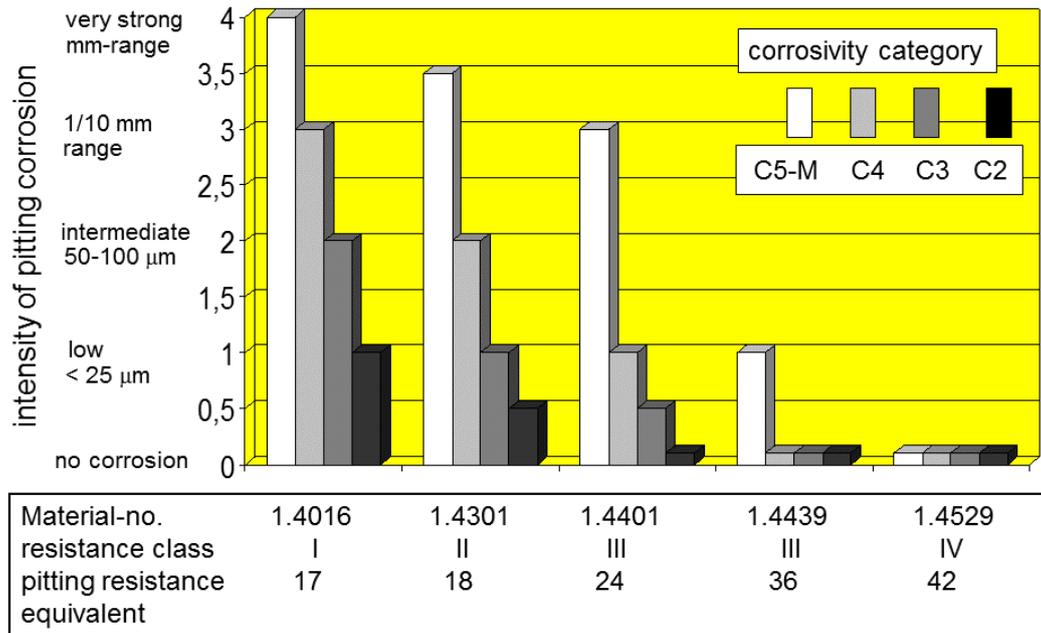
Fig. 6: Pitting corrosion on the bottom side of surface-ground and cold-rolled sheets in different atmospheres (literature evaluation), corrosion after about 10 years (according to literature results in [1])

5. BIMETALLIC CORROSION IN A ROOFTOP SYSTEM

On a property 2 km from the sea, a PV-system was installed on a trapezoidal sheet metal roof. The modules are mounted on a substructure of aluminium profiles and flat bars (material AlMgSi0,7) at an angle of 20 degrees. This substructure (Fig. 7) is in turn mounted on stainless steel threaded rods (material no. 1.4301). The flat bar and threaded rod (Fig. 7, right) are connected by means of slightly pretensioned screws and nuts with under-head toothing made of stainless steel 1.4401.

Already after about 1 year, corrosion phenomena occurred on the not directly weathered construction underneath the module surfaces, which increased with time. The most striking feature was the increased corrosion of the aluminium underneath the nut with under-head toothing. Here, the flat aluminium steels showed voluminous white corrosion products of aluminium in a striking manner (Fig. 8). These products are the result of bimetallic corrosion between the stainless steel screw and the aluminium profile. After chemical removal of these corrosion products, it was obvious that the aluminium was significantly attacked in the contact area between under-head toothing and flat steel (Fig. 9). Outside the contact area between aluminium and stainless steel, the attack of the aluminium was negligible.

Fig. 7: Substructure of the photovoltaic system and detail marked with a yellow circle

Fig. 8: Aluminium flat steel with cor-
rosion products in the contact area

Fig. 9: Flat steel after removal of
the corrosion products from
the contact area

A quantitative X-ray analysis of the aluminium corrosion products showed that they contained about 7.9 wt.-% chlorine (chloride). The very high chloride content is responsible for the early and quite intensive bimetallic corrosion of aluminium. This is due to aerosols carried by the wind from the nearby sea. The chlorides are carried by water (condensation etc.) into the gap and accumulate there. Marine aerosols contain magnesium chloride in addition to sodium chloride as main component. This salt has a very low saturation humidity of little more than 30% and is therefore highly hygroscopic (section 3.1). It therefore forms saturated and thus extremely corrosive salt solutions even in very dry air. Sodium chloride has less pronounced hygroscopic behaviour. This salt forms saturated salt solutions only above 80% relative humidity in contact with air. However, such higher humidities occur more frequently in a coastal climate.

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