

RESEARCH ARTICLE

Categorization of weathering stresses for photovoltaic modules

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Abstract

Solar energy conversion requires permanent outdoor operation of essential components such as photovoltaic modules, solar collectors, or reflectors. They are exposed to weathering stresses. The stress levels depend on the local climates. Monitoring of climatic properties and sample properties in different climatic zones (alpine, arid, maritime, moderate, and tropical) during several years provided the base for categorization of these climates. The local climate does not differ very much from year to year in terms of frequency distributions, but big differences are found for different regions or climatic zones. Especially, the solar irradiation is very location-dependent. The alpine location shows the highest UV irradiation. The UV fraction of the solar irradiation is varying between 2.2% (tropics) and 4.7% (alps). The temperature histograms can be modeled by Gaussian distribution functions. The maritime histogram is very slim and high, showing the cooling by the sea and the wind. Several approaches for a categorization of these local climates can be applied: Mean temperatures, effective temperatures, or the corresponding constant testing time for fictive degradation processes with arbitrary activation energy. The categorization of the relative humidity revealed humid climates in the alpine and the tropical test site, when considering the time of wetness ($rh > 80\%$). Obviously, the humidity stress or the corrosivity would be very different at those sites. Therefore, a more holistic approach considering more stress factors simultaneously would be more appropriate for the categorization. The interaction between the samples and the climate creates the so-called micro-climate which is the real stress on the samples, such as surface temperature, daily temperature cycles, surface humidity, or temperature-enhanced photo-degradation. The conditions for accelerated life testing (ALT) modeled on the base of monitored climatic data and sample temperatures are different for the different locations. They offer another possibility for categorization of the climatic stresses and the option for designing climate-adapted components.

Introduction

The most important components of solar systems, such as solar absorbers, glazing, reflectors, or PV modules are subjected to weathering. Weathering causes aging—changes of the performance over time—by degradation of the materials of the components. The weathering stresses depend very much on the local climate where the solar systems are operated. There is a big difference

of the intensity of the single stressors such as solar and UV irradiation, ambient temperature and humidity, wind—and snow loads, thermomechanical stresses, and effects of air pollutants (including salt, sulfur dioxide, soil) between potential locations for solar systems. The designs of solar systems and the selection of materials must enable a service life in the order of 20–30 years. An actual question is whether it is reasonable to aim for worst-case conditions including all possible stress

conditions or to optimize the durability of a solar system for special climatic conditions such as for moderate urban, arid, tropical, or maritime locations to avoid over-engineering and reduce costs. Presently, the standardization committee for PV modules started a new working item proposal for climate-depending stress testing.

Both approaches require knowledge about weathering data. The climatic data (irradiation, ambient temperature, ambient humidity, wind speed, etc.) are not independent from another but correlated (temperature and irradiation) or anti-correlated (relative humidity and temperature) and varying with time. Therefore, complete sets of data in form of time series for defined locations are needed for the description of the local climatic stresses.

Climatic data are recorded by many national or private weather services and historical data are available commercially or publicly for free. Usually, hourly or daily averages are available easily but no highly resolved time series. A lot of data are available from metro-stations or from satellites, but the big question is their lateral and time resolution. The most common intervals yield time series with hourly integral values which have smoothed the most dynamic changes introduced by clouds completely. They are mostly good enough for estimating the average annual yield of solar systems for these locations, but not appropriate for the assessment of the stresses on the materials. Satellite-based data usually do not provide complete sets of data, have an insufficient lateral resolution, or can only provide high-noon data, but worldwide.

We installed test sites in very different climates for the outdoor exposure testing of solar components with simultaneous monitoring of the climatic conditions and of sample properties (e.g., performance, surface temperatures, internal micro-climate) with a high time resolution to find correlations between the external climate, sample stresses, and long-term performance.

Two other publications focusing more on the PV-module performance at different climates were issued during the reviewing process of this paper [1, 2] underlining the general interest in this topic.

Monitoring of climatic data

The monitoring of climatic data and sample properties enables the development of models for the correlation of the sample stresses (micro-climate) and the ambient weathering (macro-climate) which can be used for the predictive modeling of stresses for any given climatic data.

Usually, the following meteorological parameters are measured as one minute averages day and night (see e.g., Fig. 1):

- Global irradiance horizontally and in plane-of-array using standard calibrated pyranometers from Kipp & Zonen
- Sample temperatures are measured by platinum resistance thermometers
- Atmospheric pressure
- Three-dimensional wind speed via a 3D ultrasonic anemometer
- Relative ambient humidity
- Ambient temperatures

Total ultraviolet (UV) radiation

These data are measured every 15s via agilent 34970A data acquisition systems and 1 minute averages are stored.

Salt concentration is measured by the so-called “wet-candle” method as monthly integrals, corrosivity is evaluated using metal-coupons exposed to weathering for 1 year according to ISO 9226:2012 (Corrosion of metals and alloys—Corrosivity of atmospheres—Determination of corrosion rate of standard specimens for the evaluation of corrosivity).

Locations

The solar irradiation strongly depends on the location, especially on the latitude and the geographical border conditions. The other climatic parameters vary accordingly. The stress for samples exposed to weathering depends strongly on the local irradiation, especially the UV radiation, the ambient temperature, the humidity, and other corrosive pollutants in the atmosphere and dust and wind. The sample temperature changes cause thermomechanical stress in addition.

Here, we present exemplarily results from an 8-year research project partly funded by the German Government (No. 0329978 and 0329978A). The test sites were selected

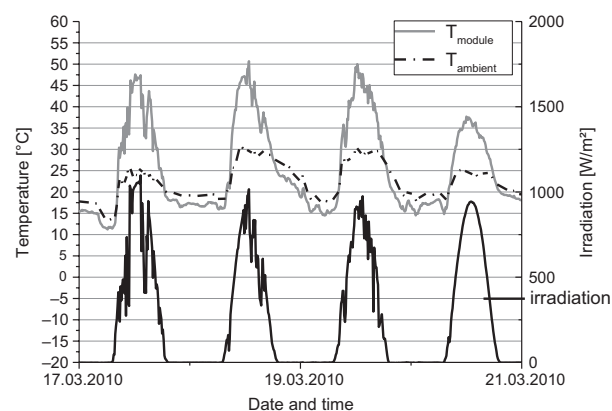


Figure 1. Example for monitoring module temperature, ambient temperature, and solar irradiation in plane of array at four consecutive sunny days at the location Freiburg.

to represent different extreme climates and were equipped with similar climate- and sample monitoring systems, but were partly not in operation in the same time periods. A big advantage was that the test sites have been operated by well-established research institutes providing good technical infrastructure and support. Identical sets of commercial PV modules were exposed.

An alpine test site was established at Schneefernerhaus (Zugspitze, Germany) at latitude of 47.5° and an elevation of 2656 m above sea level with a tilt angle of 45° to the south. The main purposes are the investigations of the degradation effects of snow-loads, big temperature differences, and high UV loads. The arid test site in Sde Boqer in the Negev desert (Israel) at 30.8° latitude with an array tilt angle of 31° to the south has also big temperature differences and a high irradiance but in a dry ambient. The urban reference is located at our institute in Freiburg (Germany) at 48° with a moderate climate without impact of pollutants at an array tilt angle of 45° to the south. The saline impact can be studied at the maritime test site with a tilt angle of 22.5° to the south at latitude of 28° on the Canary Islands (Spain) together with increased soil-ing risk caused by dry periods, dusty soil, salty aerosols, and strong winds. These strong winds have a big impact on the sample temperature, too. Serpong (Indonesia) at 6.3° was temporarily used as a tropical test site (operated by TÜV Rheinland).

Monitoring results

Solar irradiation

The variation of the irradiation histograms from 1 year to another (Fig. 2) is much smaller than between the different locations (see Fig. 3). The night values (irradiation below 50 W/m²) are omitted. The noon data around 1000 W/m² come from clear sunny days and show maxima depending on the number of clear days.

The German sites (Fig. 2A and D) show more periods at irradiation below 400 W/m², while the southern locations have clear maxima at high irradiation around 1000 W/m². However, the highest solar radiation values were measured at the alpine site. Figure 2: Yearly frequency histograms of the global irradiation in plane of array for the locations Freiburg (A), Gran Canaria (B), Negev (C), and Zugspitze (D). The values for irradiation below 50 W/m² are neglected because of better visualization of the stress-relevant high irradiation.

The integral insolation was not varying very much from year to year as shown in Table 1. The irradiation at southern locations is higher and more constant than at the central European places resulting in a plus of more than 50% solar energy.

Ultraviolet irradiation

The measurements of the UV radiation are not as simple and accurate as those of the total solar irradiation. Low-intensity levels are dominating in moderate climates (Fig. 4A), but the maximum values are in the same order as for maritime (Fig. 4B) and arid (Fig. 4C) climates, but with less probability. The highest values were measured in the mountains (Fig. 4D). The histograms show characteristic shapes and high similarities from year to year again. Only the measurements in the desert (Fig. 4C) reveal some technical problems.

The comparison of the average UV histograms from the different locations shows clear differences (Fig. 5) in the maximum UV intensities (from 30 to 70 W/m²) and in the frequency of the main UV contributions. The evaluation of suitable accelerated service life tests for UV stresses might face some problems when taking into account the non-reciprocity of UV doses.

The comparison of the integral annual doses with the global solar irradiation (see Table 2) shows clearly the high UV load at the southern test sites—up to a factor of 2 more than at moderate, urban climates—and the expected higher level in the mountains, where the highest fraction of UV from the global irradiation could be found. The reason for the low UV level (Fig. 5) at the tropical site could be absorption of UV by pollutants and aerosols. In general, an average UV fraction between 4% and 5% of the global irradiation seems to be a good assumption for locations without UV monitoring aiming for worst-case conditions. Note that this assumption does not reflect the daily and seasonal variations in this factor.

Ambient temperature

The ambient temperature with its direct influence on the sample temperature is important for the reaction speed of the degradation processes on one hand. The sample temperature causes the thermomechanical stresses caused by differences in the thermal expansion coefficients of joint materials on the other hand (see figure 6), but it varies strongly from location to location (figure 7).

The annual reproducibility of the frequency distributions is very high again. They can be modeled by Gaussian distribution functions (see Fig. 8):

$$y = A * \exp(-0.5 * ((T - T_c)/w)^2) \quad (1)$$

where the number of events depends on an amplitude factor A , median temperature T_c , and the shape factor w (see Table 3).

The histogram for the tropical site is different from the others because it seems to be composed of two

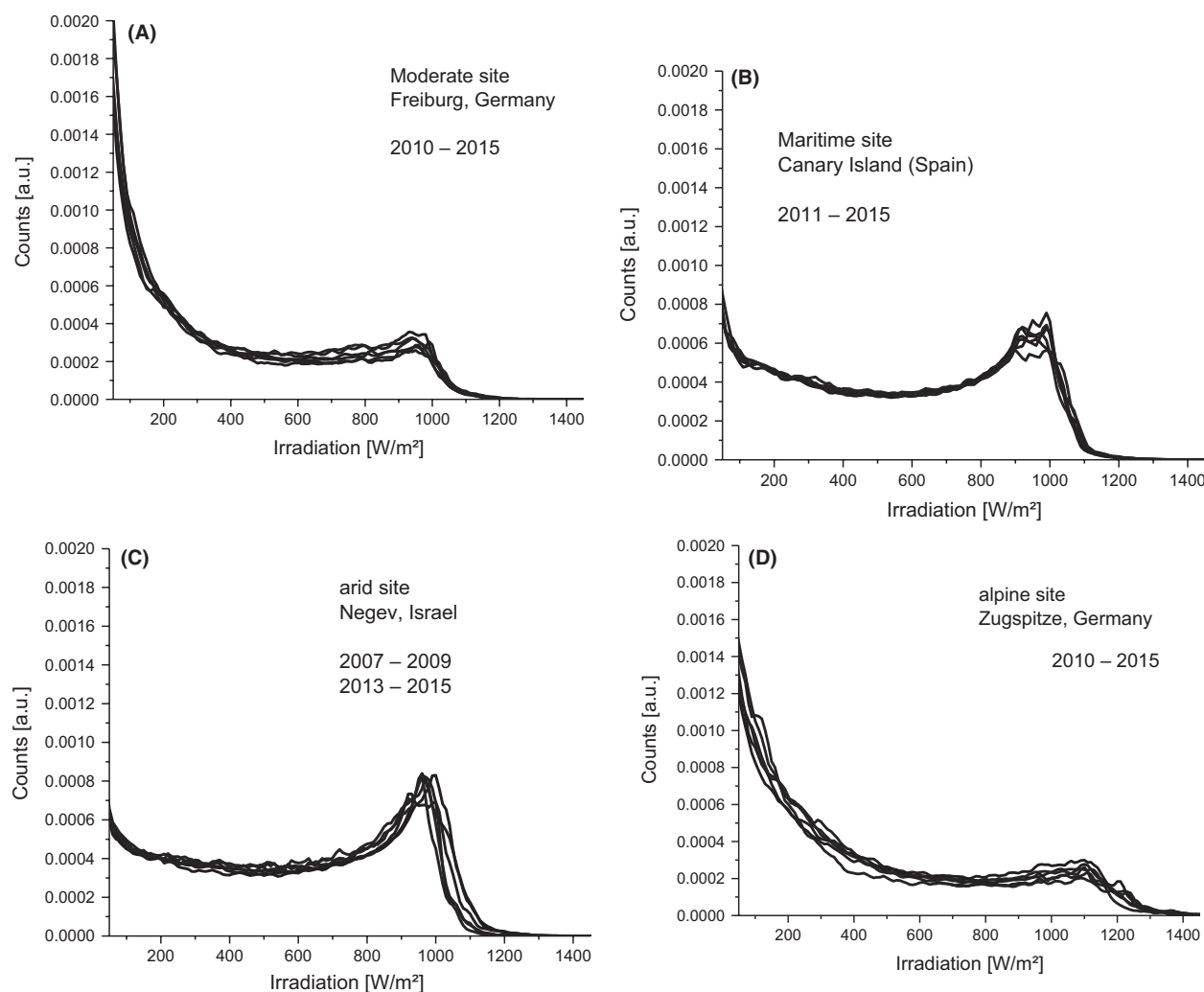


Figure 2. Yearly frequency histograms of the global irradiation in plane of array for the locations Freiburg (A), Gran Canaria (B), Negev (C), and Zugspitze (D). The values for irradiation below 50 W/m² are neglected because of better visualization of the stress-relevant high irradiation.

Table 1. Integrated annual insolation and the average and the variance in kWh/(year*m²).

Dimensions	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average	Variance
Freiburg	1403	1308	1180	1313	1189	1395	1298	97
Canary Island	2235	2160	2205	2196	2186	2173	2192	26
Negev	2373	2334	2269	2247	2238	2195	2276	66
Zugspitze	1775	1660	1603	1465	1386	1674	1594	144

Gaussian distributions. The one with the higher amplitude and the maximum at 24°C results from the night, morning, and evening periods, whereas the second peak represents the sunny days with a maximum at 31.5°C.

The histogram from the maritime site is unusual, too. The temperature range is more narrow than for the other

sites, indicating the buffer effect of the Atlantic ocean. The remaining three curves differ mainly in the mean temperature between 0°C for the alpine location, about 12°C in the moderate Freiburg, and 18°C for the Negev desert. The maximum temperatures are shifted proportionally, since the FWHM (full width at half maximum), the amplitude, and the shape factor are very similar.

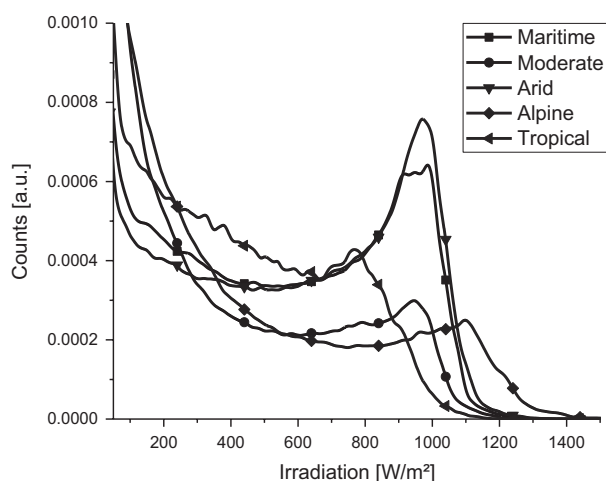


Figure 3. Average yearly frequency histograms of the global irradiation in plane of array for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), Serpong (tropical), and Zugspitze (alpine).

The temperature is usually not a stress factor by itself (except of the thermomechanical stress), but acting as accelerator for degradation processes with temperature-dependent kinetics. The most simple and most common temperature dependence of the acceleration factor a is called Arrhenius law [3]:

$$a(T) = t_1/t_2 = \exp \left[-(E_a/R) \cdot (1/T_2 - 1/T_1) \right] \quad (2)$$

The degradation process has to be proceeded to the same stage at temperature T_1 after the time interval t_1 as after t_2 at temperature T_2 . The process-dependent parameter E_a is called activation energy. The bigger it is, the greater is the acceleration of the process by a given temperature increase. The exponential dose-response function has also the effect that a temperature increase accelerates much more than an increase in the exposure time by the same factor. Therefore, the stresses are very much depending on the peak temperatures,

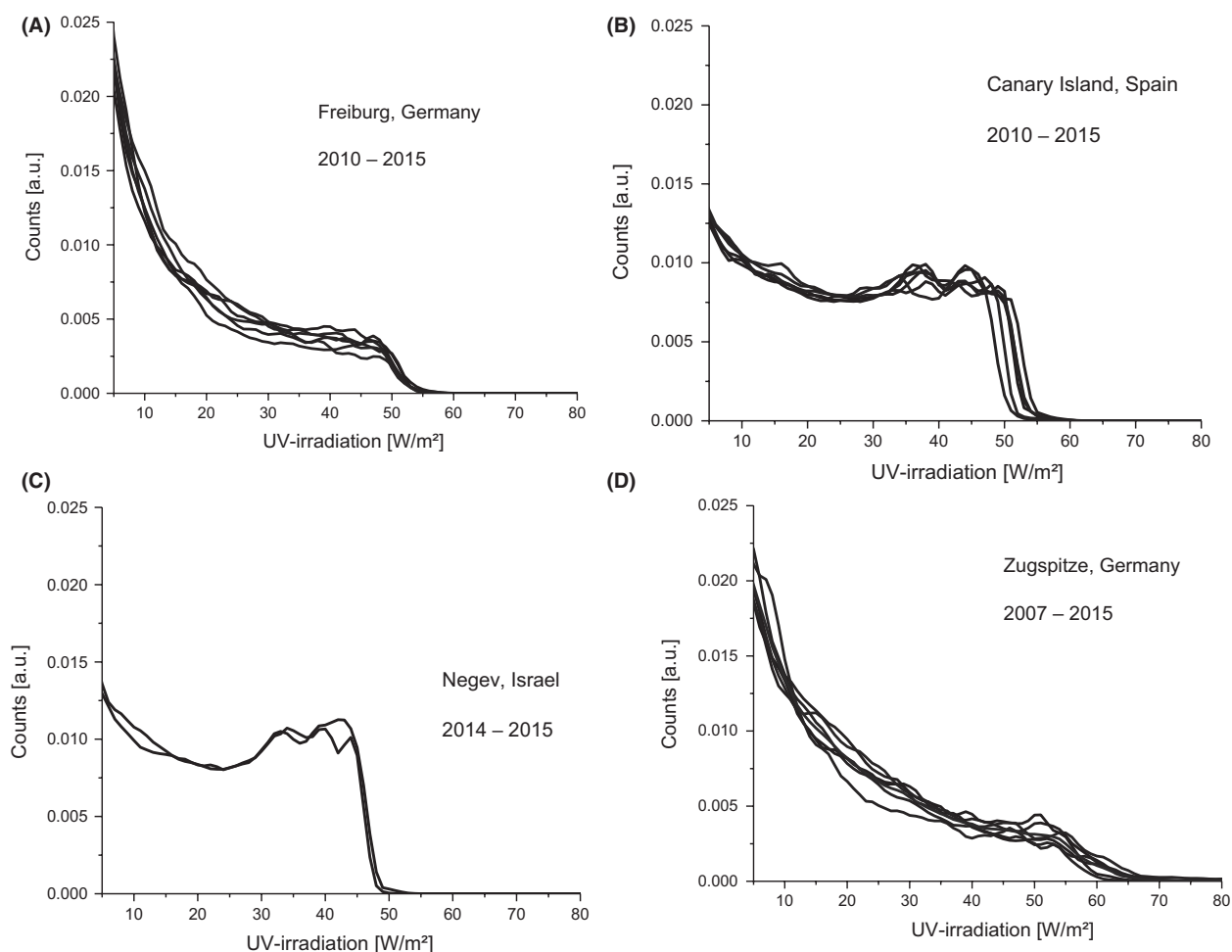


Figure 4. Frequency histogram of the ultraviolet irradiation in plane of array for the locations Freiburg (A), Gran Canaria (B), Negev (C), and Zugspitze (D).

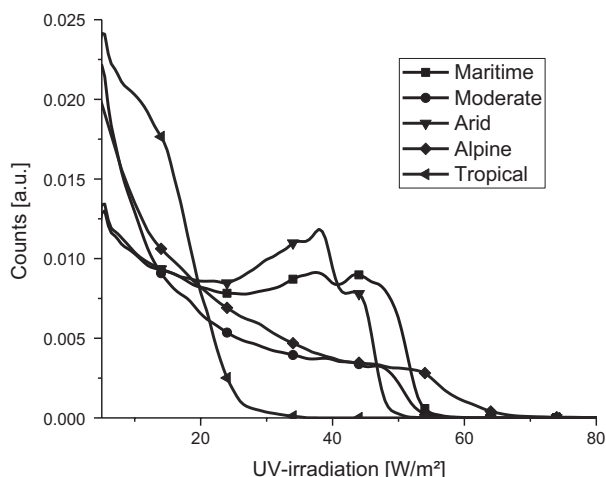


Figure 5. Average yearly frequency histograms of the ultraviolet irradiation in plane of array for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), Serpong (tropical), and Zugspitze (alpine).

which are often smoothed by reducing the time resolution.

The question is how to find the right property for a categorization of locations and for the design of accelerated life tests for qualifying samples for the respective application. One way is the computation of the so-called effective temperature [4] based on the most appropriate models (equation 2) for the degradation kinetics. This characteristic temperature would be the testing temperature for a 1-year constant temperature test corresponding to the transient temperature stress for 1 year. The problem is the usually unknown activation energy, but it is easy to vary this parameter by modeling. The practical way is the transformation of the duration of the measurement interval of the monitored temperature to a constant

temperature according to equation 2 and the integration of the complete time series for 1 year.

Finally, the time transformation (equation 2) is used once more for calculating the effective temperature, which is the constant temperature corresponding to the considered year. The integrated testing times in Table 4 were computed for a testing temperature of 85°C because this is the usual testing temperature in IEC 61215. The effect of the activation energy is obvious. The testing time t_{test} (for a selected activation energy) could be used for designing categories, as well.

The effective temperatures are very close to the median temperature of the time series for stable climatic conditions covering a small temperature range like in the tropical and maritime locations. A possible definition of categories could be:

Cold: $T_{\text{eff}} < 10^{\circ}\text{C}$, or testing time (@85°C for 60 kJ/mol) < 48 h

Moderate: $10^{\circ}\text{C} < T_{\text{eff}} < 18^{\circ}\text{C}$, or testing time (@85°C for 60 kJ/mol) < 96 h

Hot: $T_{\text{eff}} > 18^{\circ}\text{C}$, or testing time (@85°C for 60 kJ/mol) > 96 h

“Moderate” and “cold” climatic zones could be merged, since no big temperature impact is expected at these locations because of the exponential temperature dependence. The integration of samples into a building envelope results in a higher temperature of the devices [5, 6] and a detailed consideration of temperature categories and testing conditions might be appropriate for this kind of application.

These test conditions based on the ambient temperatures are much too weak because they do not take into account the heating of the samples by the solar irradiation. Those micro-climatic aspects are discussed in chapter 5.1.

Table 2. Average annual global irradiation and UV irradiation from the periods of measurements indicated in Figures 3 and 5 and the fraction of UV irradiation in percent.

	Maritime	Moderate	Arid	Alpine	Tropical	
Global Irradiation	2192	1298	2276	1594	1564	kWh/a/m ²
UV irradiation	97	57	88	75	34	kWh/a/m ²
UV/G	4.44	4.37	3.89	4.69	2.21	%

Table 3. Parameters (amplitude factor A , median temperature T_c , and the shape factor w) of the Gaussian models for the temperature histogram for different locations.

	Moderate	Maritime	Arid	Alpine	Tropical night and day		
T_c	12	20	18	−0.1	24	32	°C
w	9.1	3.4	8.3	7.7	1.7		°C
A	0.05	0.12	0.05	0.05	0.16	0.06	
FWHM	21	8	20	18	4	5	°C

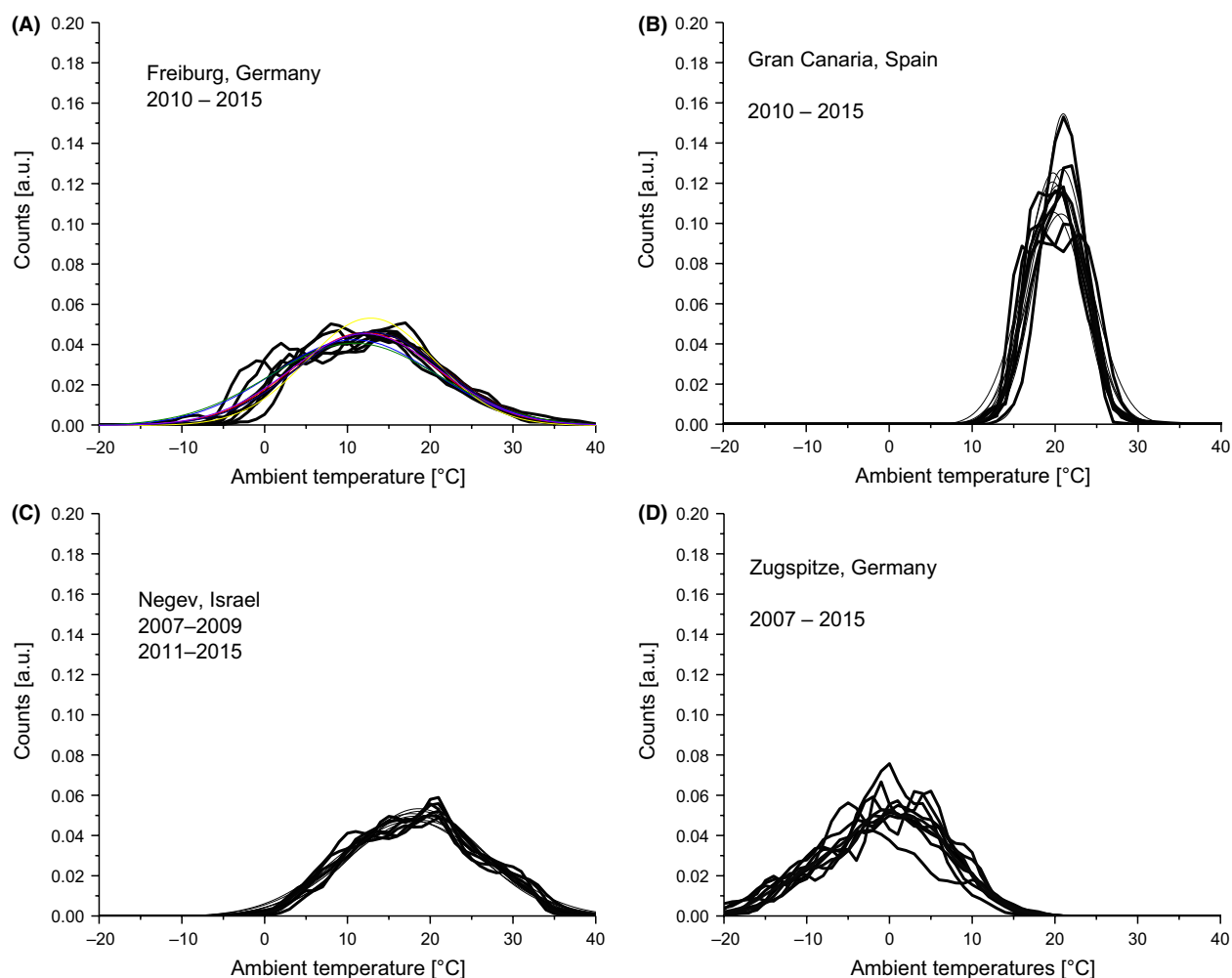


Figure 6. Frequency histogram of the ambient temperatures for the locations Freiburg (moderate A), Gran Canaria (maritime B), Negev (arid C), and Zugspitze (alpine D).

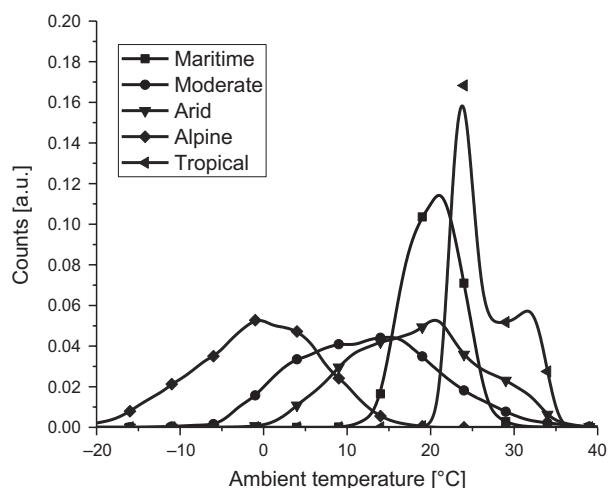


Figure 7. Average yearly frequency histograms of the ambient temperature for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), Serpong (tropical), and Zugspitze (alpine).

Ambient humidity

The absolute humidity is the amount of water vapor molecules in the atmosphere. Its partial pressure depends on the total air pressure and the temperature. It is more convenient and common to work with the relative humidity defined as the water vapor partial pressure related to the saturation water pressure at the same thermodynamic conditions (temperature, total air pressure). The relative humidity depends strongly on the temperature because of the temperature dependence of the saturation water pressure. The effect of decreasing temperature or air pressure is an increasing relative humidity until the saturation pressure is reached and condensation or even rain starts. The opposite effect of the increasing temperature leads to a low relative humidity for the same absolute amount of water describing the potential for up taking much more water from humid surfaces or samples. Therefore, the

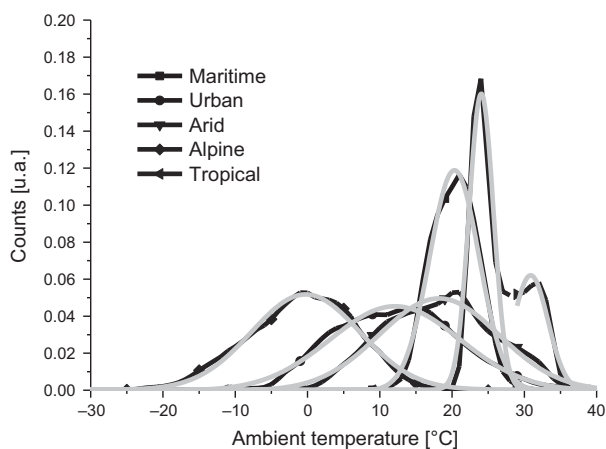


Figure 8. Average yearly frequency histograms of the ambient temperature for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), Serpong (tropical), Zugspitze (alpine), and Gaussian models (grey).

relative humidity is considered as the more relevant property in weathering. On the other hand, the temperature plays a paramount role for accelerating degradation processes and a high humidity at low temperatures (see the alpine site) is not a very corrosive condition.

Temperature differences between the solar components and the ambient atmosphere have to be taken into account when discussing the humidity levels at the sample surfaces [7]. The histograms (see Figs. 9 and 10) show again characteristic patterns for the different sites that

are repeated more or less every year. The histograms for the arid and the moderate site look very similar with two characteristic humps representing the day-time at low relative humidity around 40% and the night-time at the higher values above 80% r.h. whereas the maritime location shows only one peak at 70% r.h., indicating the buffering impact of the ocean. The cold and dry alpine site (Fig. 9D) shows high relative humidity levels above 80% because the saturation pressure around the freezing point at 0°C is very low (Fig. 11).

The categorization in humid and moderate/dry locations seems to be not easy and needs to include the temperature levels (see alpine conditions) because the humidity as degradation factor needs a big concentration gradient between the ambience and the material and a high temperature for achieving high partial pressure differences for an enhanced diffusion of water in the polymeric components of the module 3. Therefore, the calculated surface humidity at the Nominal Module Operating Temperature (NMOT) using the median temperature (T_{amb}) from Table 4 and the 50% value of the cumulative relative humidity in Table 5 and equation 3 for calculating the relative humidity might be a reasonable property for the characterization of the humidity impact at a given location.

$$\text{rh}(T_{\text{NMOT}}) = \text{rh}_{50\%}(T_{\text{amb}}) * p_{\text{sat}}(T_{\text{NMOT}}) / p_{\text{sat}}(T_{\text{amb}}) \quad (3)$$

The values for p_{sat} which is the saturation water vapor pressure for a given temperature can be found in https://en.wikipedia.org/wiki/Vapour_pressure_of_water (2017).

Table 4. Testing time in hours for accelerated life testing at 85°C temperature for an assumed activation energy E_a corresponding to 1 year operation at the different test sites modeled by an Arrhenius law and the effective temperature for the test sites compared with the median temperature from the monitored histograms.

	Maritime	Moderate	Arid	Alpine	Tropical	
Median temperature	20.3	12.1	18.2	−0.3	24.0	°C
Effective temperature	20.7	15.3	20.4	1.1	27.0	°C
t_{test} for $E_a = 40$ kJ/mol	458	320	436	136	647	h
t_{test} for $E_a = 60$ kJ/mol	106	67	104	18	178	h
t_{test} for $E_a = 80$ kJ/mol	25	15	26	3	50	h
Category	Hot	Moderate	Hot	Cold	Hot	

Table 5. Fraction of the time at high humidity (above 60% r.h.) and of the Time of Wetness (above 80% r.h.), the threshold when 50% of the cumulated rh values are reached and the relative surface humidity at an average Nominal Module Operating Temperature (NMOT) and a possible characterization of the climate.

	Maritime	Moderate	Arid	Alpine	Tropical	
Fraction of r.h. above 60%	71	58	56	74	78	%
Fraction of r.h. above 80%	10	30	32	57	55	%
50% rh value for cumulated rh	65	65	65	82	81	%
r.h. at 47°C (NMOT)	14	9	13	5	23	%
Category	Humid	Dry	Humid	Dry	Wet	

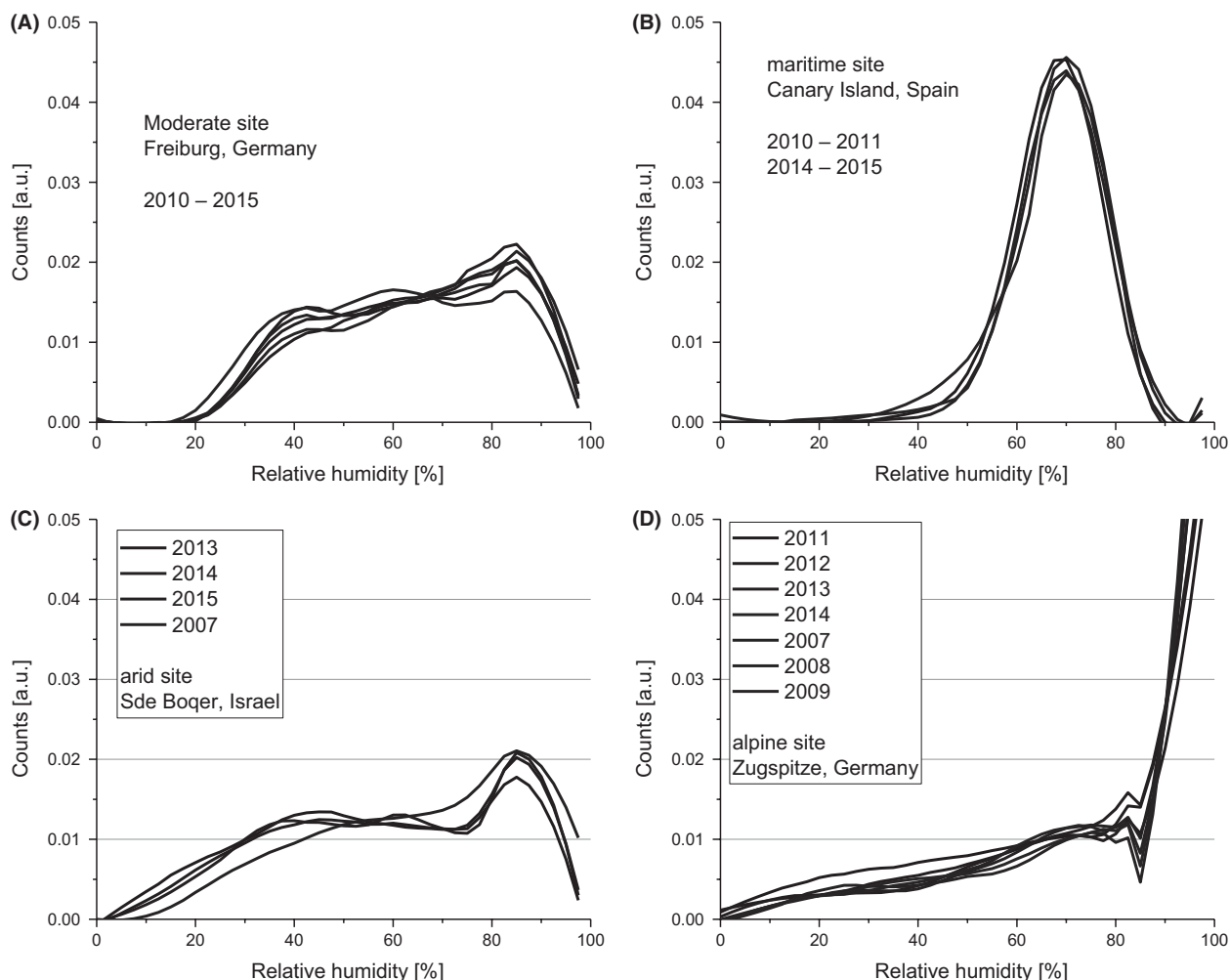


Figure 9. Frequency histograms of the relative ambient humidity for the locations Freiburg (A), Gran Canaria (B), Negev (C), and Zugspitze (D).

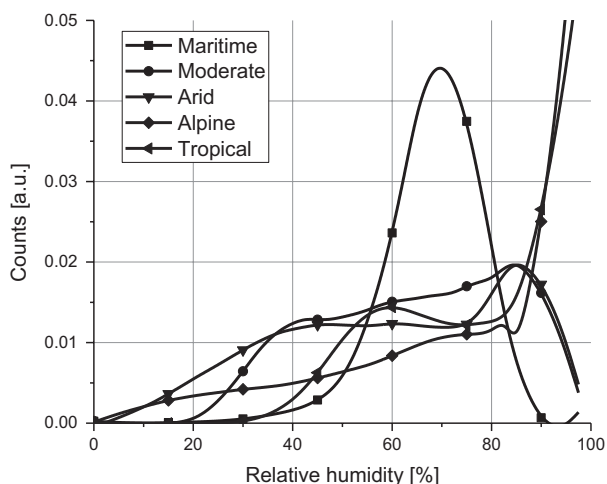


Figure 10. Average yearly frequency histograms of the relative ambient humidity for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), Serpong (tropical), and Zugspitze (alpine).

This approach does not recommend considering the arid climate as dry in general. The morning dew combined with the high temperature during day-time might result in a moisture impact for corrosion comparable to the maritime site with higher humidity, but more moderate temperatures.

Wind

The wind influences the solar systems in three ways. Wind as forced convection can cool solar devices [5, 8]. Lower PV-module temperatures are usually positive, since the electrical performance is improved and the degradation rates are decreased. Solar-thermal systems will perform worse because of the higher thermal losses.

The other effect is the mechanical load caused by steady winds or by strong wind gusts causing big pressure differences between front and back of flat panels.

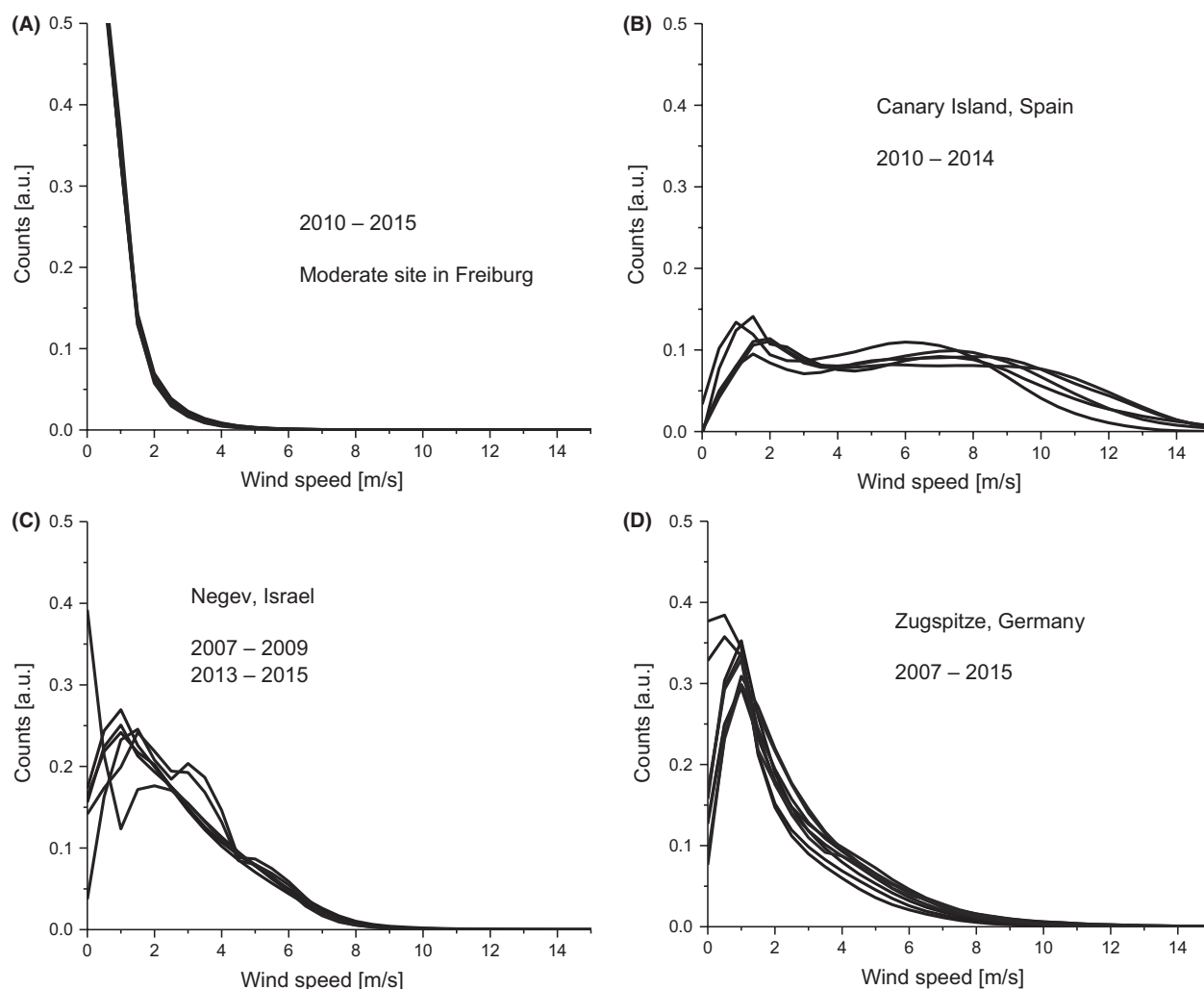


Figure 11. Frequency histograms of the wind speed (1 min average of readings every 15 sec) for the locations Freiburg (A), Gran Canaria (B), Negev (C), and Zugspitze (D).

Finally, even the excitation of vibrations could be observed [9] (see chapter 5.4).

A general problem of monitoring the wind properties is the interaction of wind with the solar systems and their environment that can disturb the wind direction and the wind speed. Measurements according to the standards 3 m or 10 m above ground or buildings should be used for statistical investigations, but the wind conditions at the sample could be very different from the measured data. The anemometer in Canary Island is located 6 m above ground, while the anemometer in Freiburg is located in plane of array which is shaded by a building behind. Therefore, the monitored wind speed was very low in Freiburg (see figure 11).

The result of the wind speed monitored in the vicinity of the exposed samples shows the exceptional conditions on the Canary Islands. Strong winds between 4 and 14 m/s

are very likely (see Fig. 12) and the average wind speed is clearly higher than at other places (Table 6).

Summary

Continuous monitoring of climatic data at different test sites has shown that the differences from one year to another year at the same location are very small and especially very small compared with the differences between the locations. The yearly solar irradiation varies nearly by a factor of 2, the average wind speed even by a factor of 10. The range of the effective ambient temperature goes from 1°C up to 27°C yielding a corresponding effective PV-module temperature in a range from 9.5°C to 37.5°C. The humidity classes need defined operating sample surface temperature. The resulting average values of the stress parameters shown in Table 6 might be used as a

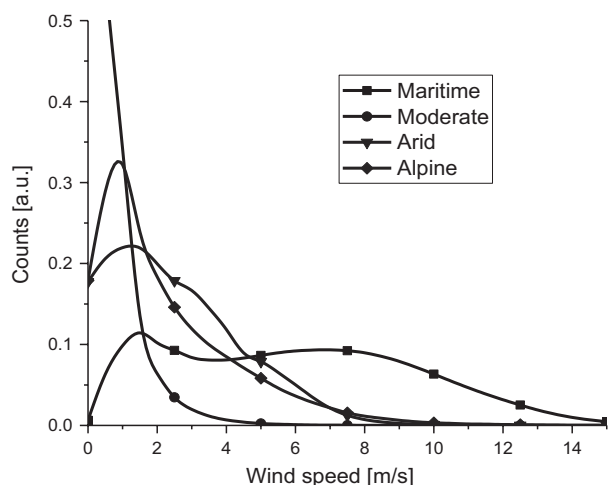


Figure 12. Average yearly frequency histograms of the wind speed for the locations Freiburg (moderate), Gran Canaria (maritime), Negev (arid), and Zugspitze (alpine).

base for a definition of climate classes for solar components exposed to weathering such as PV modules or solar-thermal collectors.

Micro-climate and combined stresses

In chapter 4, the monitoring of the climatic conditions as weathering stresses was discussed. The stresses on the samples are not only directly depending on the ambient climatic conditions, but also on the interaction between sample and the climatic degradation factors and the geometric exposition conditions including the ambient shading, thermal border conditions (e.g., building integration) or albedo conditions. The stressors depend on the climate and the sample properties, both, and are mostly not directly measurable. Some of the stressors can be modeled as function of the ambient climate.

Sample temperature

The solar irradiation heats the sample depending on the relation between angle of incidence and sample orientation, the solar absorptance of the sample that is complementary to the sum of reflectance and transmittance of

the irradiation and the thermal energy losses by conversion into electricity, usage of the thermal energy or heat transfer to the ambience by conduction as well as forced or thermal convection. The radiative heat losses during night-time can cool the sample below ambient temperature. This effect is mainly important for the formation of dew on the sample surface as can be observed at the wind screen of cars after clear nights.

The temperature is also very important for the degradation of the PV modules because it determines at least the reaction rate for the degradation processes caused by the other degradation factors (e.g. hydrolysis by humidity and photo-degradation by UV light, e.g.). Modeling of the service life of modules applied in different climatic regions requires time series of the measured or modeled module temperature (see Fig. 13).

A model which allows calculating the module temperature as function of the ambient temperature, the global irradiation and the wind speed, would facilitate the use of time series of climatic data for a climatic region of interest, which could be provided by weather services or test reference years (e.g. <https://meteotest.ch/en/product/meteonorm>).

The difference between module temperature and ambient temperature is nearly a linear function of the irradiation with a slope depending on the wind speed [5]. A comparison of measured and modeled photovoltaic module operating temperatures under different climatic conditions can be found in the literature [5, 8]. Here, we apply a very simplified model for a fictive average module temperature based on the Faïman model [10], which might be sufficient for a temperature categorization:

$$T_{\text{mod}} = T_{\text{eff}} + H / (U_0 + U_1 \nu) \quad (4)$$

where H is the integral solar energy irradiation per m^2 and year, ν is the average wind speed (see 4.6), and the coefficients U_0 and U_1 are specific for the PV-module type. Here, we assume $U_0 = 30 \text{ kW/m}^2/\text{°C}$ (typical for a module composed of crystalline silicon cells [8]) and $U_1 = 6 \text{ kW/m}^3/\text{°C}$ as used for the computation of the nominal module operating temperature in IEC 61215. The results are listed in Table 7. Now, the categorization might be different from Table 4 because the strong wind on

Table 6. Characteristic average climatic properties at the different test sites.

Property/test site	Maritime	Moderate	Arid	Alpine	Tropical	Dimensions
Integral irradiation	2192	1298	2276	1594	1564	kWh/a/m^2
Average wind speed	5.5	0.5	2.0	1.3	1.0	m/s
Effective amb. temperature	20.7	15.3	20.4	1.1	27.0	$^{\circ}\text{C}$
Eff. module temperature	26.7	31.0	35.4	9.5	37.5	$^{\circ}\text{C}$
r.h. at 47°C (NMOT)	14	9	13	5	23	%

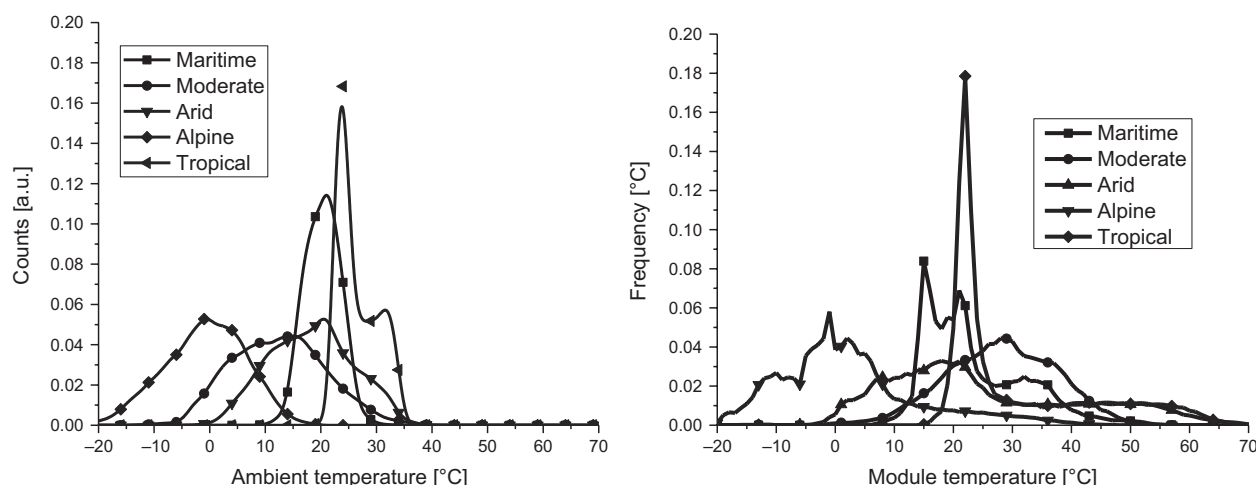


Figure 13. Histograms of the average ambient and the average module temperature measured at different locations.

the Canary Islands cools down the modules much more than in the moderate climate in Germany (Table 7).

The effect of the climate on the module temperature can be modeled using characteristic yearly average data [5, 8] allowing a categorization of the climatic regions. The maximum module temperature is achieved by roof-integration providing between 20 and 40 K temperature enhancement related to free-rack exposure [6].

Mechanical stresses

The differences between the day and night temperatures cause thermomechanical stresses because of the different thermal expansion coefficients of the glazing material, silicon cells, and encapsulants. Fig 14 shows the frequency distribution of the daily temperature differences. Obviously, the tropical site does not exhibit big climatic changes resulting in a

narrow peak around 42 K while the Atlantic ocean and the high winds decrease the daily maxima and increase the daily minima at the maritime site (see Table 8). The biggest temperature differences can be found in the desert.

The mechanical stresses such as static pressure from wind or snow, thermomechanical stresses caused by module temperature changes, or vibrations excited by wind gusts or turbulent wind flow at the module perimeter cause deflections of the modules and therefore mechanical stresses on the module components. These stresses are not easily measured directly. However, the deflection of the module pane can be detected by means of laser triangular sensors (Fig. 15).

The comparison of the characteristic vibration frequencies resulted from a Fourier analysis of the 50 Hz deflection and wind data from outdoor exposure on Canary Island (see Fig. 16) confirmed the laboratory investigations. A fundamental vibration at a frequency of about 11 Hz

Table 7. Fictive module temperature for the different test sites modeled by equation 4 with the properties listed in the table and the effective temperature from Table 4.

	Maritime	Moderate	Arid	Alpine	Tropical	
Integral irradiation	2192	1298	2276	1594	1564	kWh/a/m ²
Average wind speed	5.5	0.5	2.0	1.3	1.0	m/s
Effective amb. temperature	20.7	15.3	20.4	1.1	27.0	°C
Eff. Module temperature	26.7	31.0	35.4	9.5	37.5	°C
T_{mod} (free rack)	55	55	75	43	70	°C
T_{mod} (roof integrated)	87	77	112	70	97	°C

Table 8. Maxima of the frequency distribution of the daily temperature differences.

	Maritime	Moderate	Arid	Alpine	Tropics	
Maximum Delta T	17	44	48	40	42	K

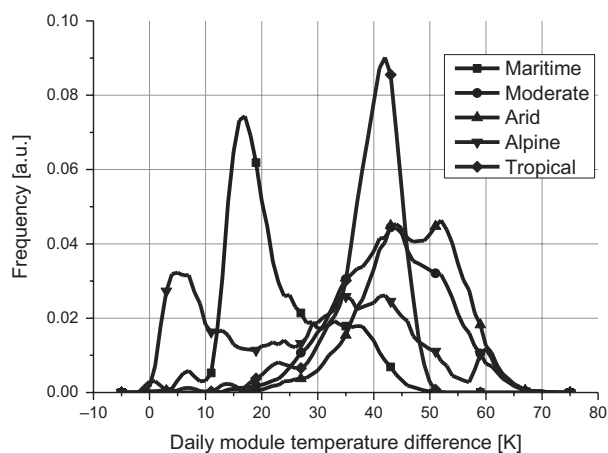


Figure 14. Histograms of the differences between monitored daily minimum and maximum module temperatures at different locations (averages of several years and several modules).



Figure 15. Two Laser deflection sensors and a pressure gauge mounted below a PV module.

[11] could be found, but the module deflection did not exceed 4 mm at a wind speed above 20 m/s (70 km/h), which corresponds well to the wind-tunnel results [12].

The mechanical deflection is clearly correlated with the module temperature and is superimposed by fluctuations at higher frequency excited by wind gusts (see Fig. 16). The overall deflection is in the order of 1–2 mm, while the vibrations have amplitudes of 0.2 mm. Unfortunately, we have not been able to perform these measurements at the other test sites.

Surface humidity

More efforts are needed to calculate the transient moisture impact taking into account the sample temperature, especially, as we have previously presented [13]. A suitable

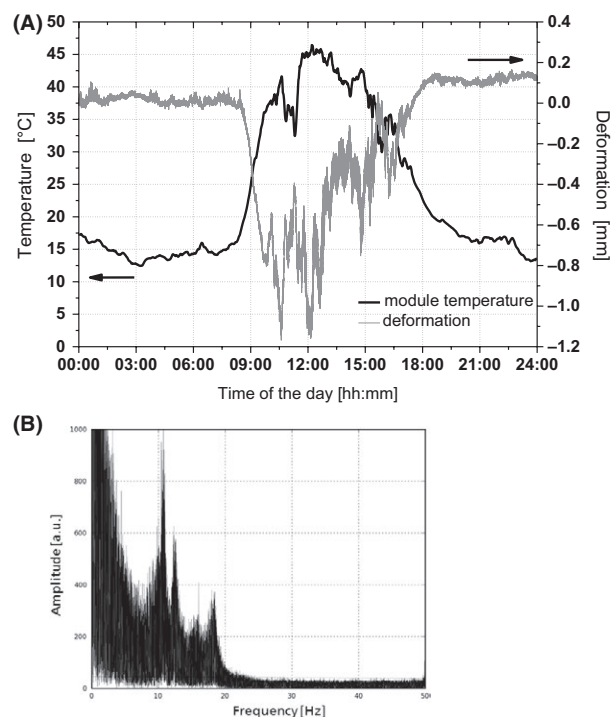


Figure 16. Deflection and module temperature during 1 day at Canary Island (A) and the spectral power distribution resulted from Fourier analysis of the deflection.

way is the calculation of the corresponding testing times for accelerated life testing. The single steps are the following:

1. Measurement or modeling of the temperature of the sample surface [8]
2. Computing of the surface humidity $rh(T_{mod})$ according to equation 3
3. Modeling of the effective surface humidity as function of the module temperature $rh_{eff} = 1/(1 + 98 \exp(-9.4 rh(T_{mod})))$ Figure details can be found in the literature [7]
4. Transformation of the surface temperature for achieving an effective relative surface humidity of 85% for the expected range of activation energy values (see Table 9)
5. Transformation of surface temperature and monitoring time interval to 85°C test conditions and integration for 1 year. Multiplication with the number of required service life years yields equivalent accelerated life testing times.

Figure 17 shows how the moisture load is decreased by taking into account the drying by surface temperature increase and neglecting medium levels of the relative humidity because of the low water vapor concentration gradient (effective surface humidity). The times of high wetness can be found at low surface temperatures because

of condensation and high ambient humidity and low temperature gradients between surface and ambience.

The difference between different climate zones is obvious (Fig. 18). The longest periods of high effective relative surface humidity were around the freezing point in the alpine site, while the distribution in the desert was broader than at the maritime site with smaller temperature range.

Ultraviolet radiation

The main effect of UV irradiation is the photo-degradation of polymeric materials. These materials can be the front glazing (directly exposed to the irradiation) or encapsulants behind the front glazing or materials at the back-site that are hit by UV either through transparent materials at the sunny side or facing backwards getting the diffuse part of the radiation or from the albedo, such as back-sheets, junction boxes, casings. Figure 19 shows the typical transmittance spectra for low-iron glass filtering the very short wavelength range and PMMA filtering nearly the complete UV part. Encapsulants or back-sheets behind such filters will see very different UV radiation.

Table 9. Estimated testing times for constant temperature testing at 100°C for 25 years lifetime based on the different module temperatures (micro-climates).

Activation energy	Maritime	Moderate	Arid	Alpine	Tropical	
40 kJ/mol	8741	11,136	12,290	2935	14,316	h
60 kJ/mol	1932	2715	3861	445	4472	h
80 kJ/mol	460	693	1386	80	1573	h
T_{eff}	26.7	31.0	35.6	9.5	37.5	°C
Category	Moderate	Moderate	Hot	Cold	Hot	

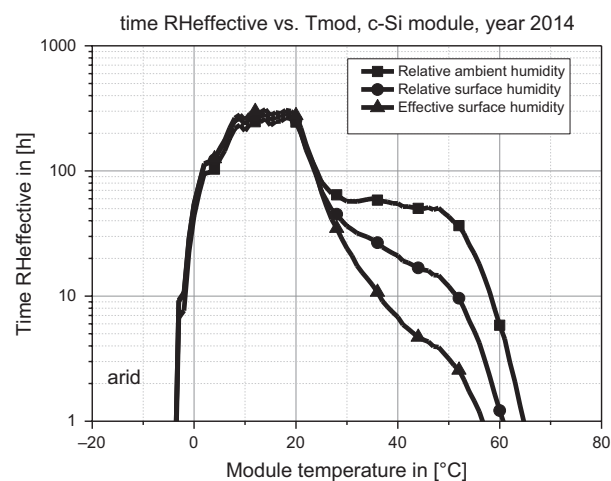


Figure 17. Histograms of the moisture loads based on the ambient humidity, the calculated surface humidity and the modeled effective relative surface humidity as function of the module temperatures in the arid location for illustrating steps 1–3.

Modeling of the accelerated life testing conditions

The monitored and modeled micro-climatic stress data can be used as base for the evaluation of accelerated service life testing conditions. The basic models for the time transformation functions based on the kinetics of the chemical or physical degradation processes in the module can be found in numerous textbooks dealing with reliability, accelerated life testing (ALT), and service life prediction (SLP) [9, 14]. They should provide the possibility to integrate the stress factors by transforming the time intervals to a given set of degradation factor values as described in equation 5

$$t_{\text{test}}(S_{\text{test}}) = \sum_0^N f(S_n, S_{\text{test}}) \Delta t \quad (5)$$

where n is the incrementing index, $f(S_n, S_{\text{test}})$ is the time transformation function, S_n the respective stress factor vector (micro-climatic data) during the time interval Δt for the module, and S_{test} the stress factor vector during the accelerated testing with the duration t_{test}

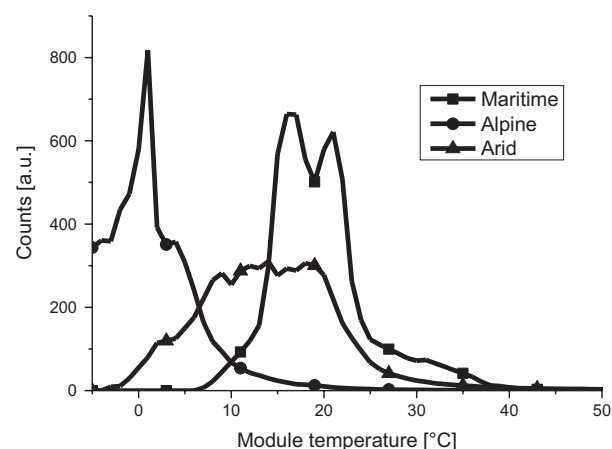


Figure 18. Histograms of the effective relative surface moisture loads as function of the module temperatures at the alpine, arid, and maritime test site averaged over several years of monitored climatic data.

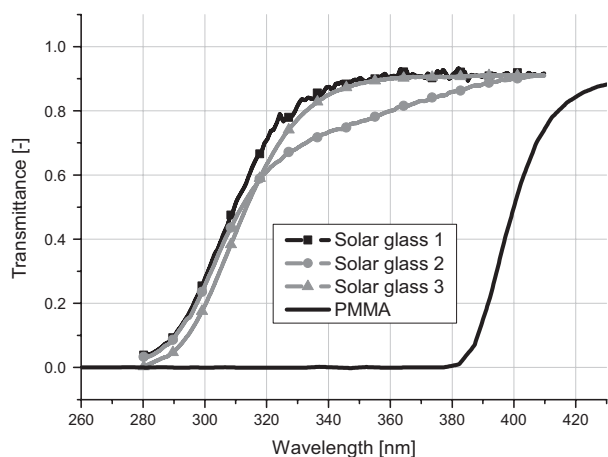


Figure 19. Spectral transmittance of different cover glazing.

corresponding to the operational stresses during the total measuring time interval $N \cdot \Delta t$, for example, 1 year.

Temperature stress

The most simple and often suitable time-transformation function describing the acceleration by temperature enhancement from T_1 to T_2 is the so-called Arrhenius law that was already used in chapter 4.3:

$$t_2 = t_1 \cdot \exp \left[- (E_a/R) \cdot (1/T_2 - 1/T_1) \right] \quad (6)$$

Integration of the outdoor load T_{mod} yields corresponding indoor test conditions

$$t_{\text{test}} = \sum_i \{ \Delta t_i \cdot \exp \left[- (E_a/R) \cdot (1/T_{\text{test}} - 1/T_{\text{mod},i}) \right] \} \quad (7)$$

The activation energy E_a for the rate dominating degradation process is a material-specific parameter that has to be determined by comparing the degradation progress of a suitable property during accelerated indoor tests at two or more temperature levels. Figure 20 shows the testing times for constant temperature tests resulting from the integration of the averaged module temperatures measured at different test sites and the transformation to a test temperature of 100°C and Figure 21 the effect of varying the test temperature. Table 9 shows the another way of categorization of the climates for the degradation factor temperature based on the required duration of the service life testing of PV modules.

Thermomechanical stress

The thermomechanical stress depends mainly on the temperature difference and the number of cycles. A rough estimation is the difference between minimum temperature

during night-time and maximum temperature during day-time, yielding one temperature cycle per day by neglecting effects from clouds resulting in higher frequency and lower temperature differences. The simplest model for temperature cycles is the Coffin–Manson Model [15] for the acceleration factor between different temperature cycles ΔT_1 and ΔT_2 :

$$a = (\Delta T_1 / \Delta T_2)^c \quad (8)$$

The exponent c depends on the materials. The frequency of the cycles is not taken into account as well as the average temperature level. Both effects could be used for an additional acceleration. First, the temperature differences evaluated from the outdoor monitoring at the

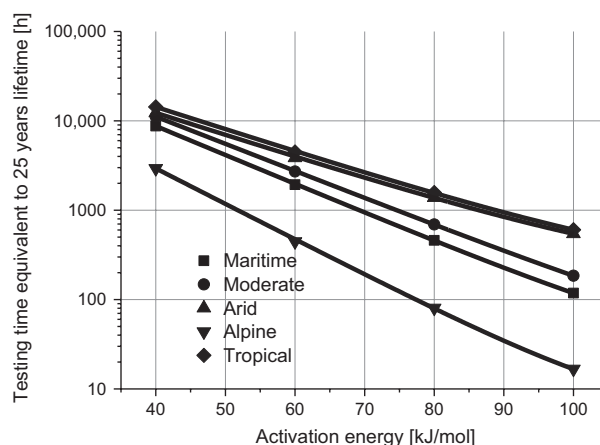


Figure 20. Equivalent testing times at 100°C for temperature stresses at different locations modeled as function of the activation energy using data of one averaged year from monitored climatic data and module temperatures for several years.

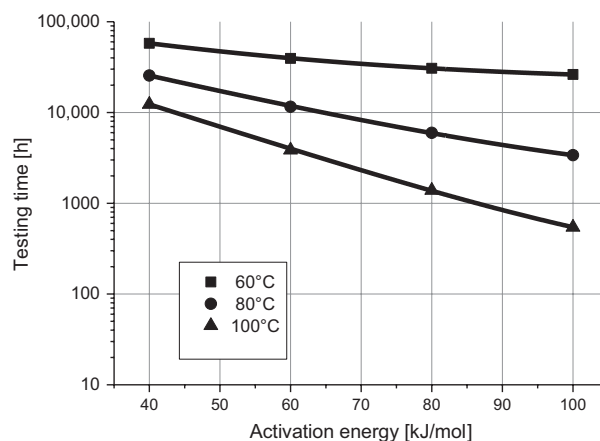


Figure 21. Equivalent testing times at different testing temperatures for temperature stresses at the arid location modeled as function of the activation energy.

different locations (see Fig. 22) are transferred to the usual temperature cycling conditions according to IEC 61215 (-40 to 85°C means $\Delta T_2 = 125$ K). The resulting number of cycles still depends on the unknown parameter c (see Fig. 22). The difference between the locations with the highest and the lowest dynamic is about a factor of 2 in maximum for the parameter $c = 1$ up to a factor of 4 for $c = 2$. The required number of test cycles must be in the order of thousands (note that the traditional thermal cycling test in IEC 61215 requires only 200 cycles), if there was no further acceleration possible by increasing the ΔT . More sophisticated modeling of the thermomechanical effects can be found in the literature [16].

Moisture stress tests

In case of humidity testing and humidity-borne degradation in general, two properties are contributing: the water vapor transport into the module (permeation) [17] and the temperature-dependent reaction rate of the degradation processes. These processes are usually hydrolysis of the polymeric encapsulant (especially in the case of ethylene-vinyl-acetate (EVA)) and corrosion of metallic life parts for electrical contacts of the cells. The initial permeation process needs a big water vapor concentration gradient between the module surface, especially of the polymeric back-sheet, and the metallization and grids of the embedded cells. Drying out reverses the gradient and the water will be diffusing out of the module. Therefore, the model of the effective surface humidity was introduced for evaluating the micro-climatic conditions (see chapter 5.3). The integration of the effective surface humidity and transformation to the test temperature and the relative

humidity yields corresponding accelerated life testing conditions [13]:

$$t_{\text{test}} = \text{Lifetime} \cdot \sum_i \left\{ \frac{\Delta t_i}{\text{rh}_{\text{test}}} \cdot \left(\frac{1}{1 + 98 \exp(-9.4 \text{rh}_i)} \right) \cdot \exp \left[-\left(\frac{E_a}{R} \right) \cdot \left(\frac{1}{T_{\text{test}}} - \frac{1}{T_{\text{mod},i}} \right) \right] \right\} \quad (9)$$

The relative surface humidity rh_s is calculated using equation 3. The humidity during damp-heat testing rh_{test} is usually 0.85. This humidity level should not drop below 70% to keep a high moisture level in the polymeric components of the PV module. The modeled test conditions mirror the big differences between the stress levels at the different considered locations (Fig. 23 and Table 10). There is about a factor of 4 between the dry cold alpine climate and the tropical climate for degradation processes with an activation energy of 60 kJ/mol and more than a factor of 10 between the test conditions for processes with activation energies of 40 and 80 kJ/mol in the tropical climate.

Low activation energy around 40 kJ/mol, which is typical for water-diffusion-dominated processes, does not allow a high acceleration by increasing the testing temperature to 85°C . A categorization would obviously result in

- wet climates with required testing times above 6000 h
- moderate and arid locations above 4000 h
- dry climates below 3000 h

Much shorter testing times but similar ranking can be found for an activation energy of 60 kJ/mol:

- wet climates with required testing times above 1500 h
- moderate and arid locations above 750 h
- dry climates below 250 h

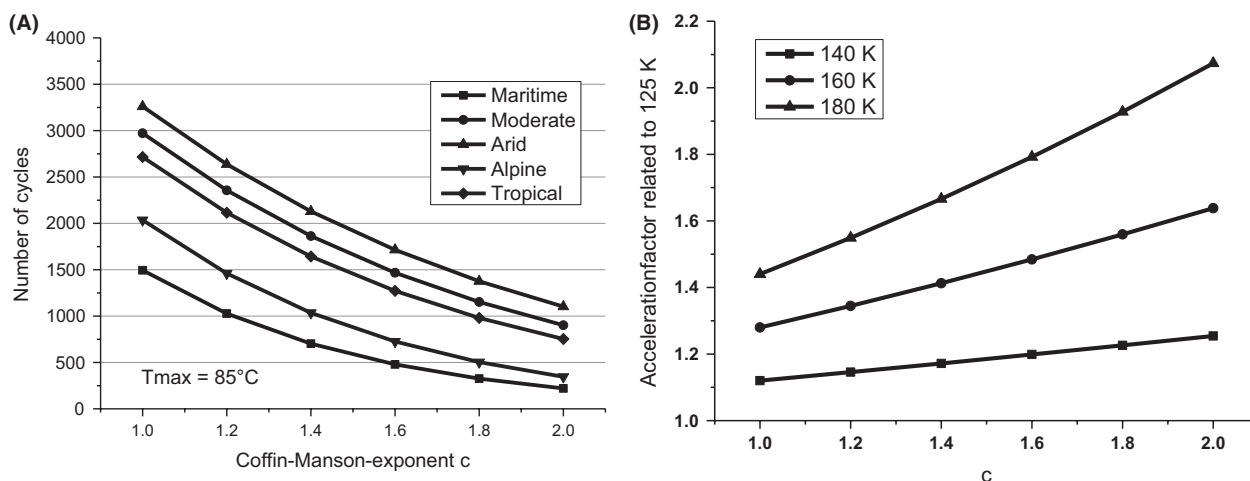


Figure 22. Number of test cycles for 125 K temperature difference corresponding to daily temperature differences during 25 years at different locations as function of the exponent in the Coffin–Manson relation (A) and acceleration by increased testing temperature differences (B).

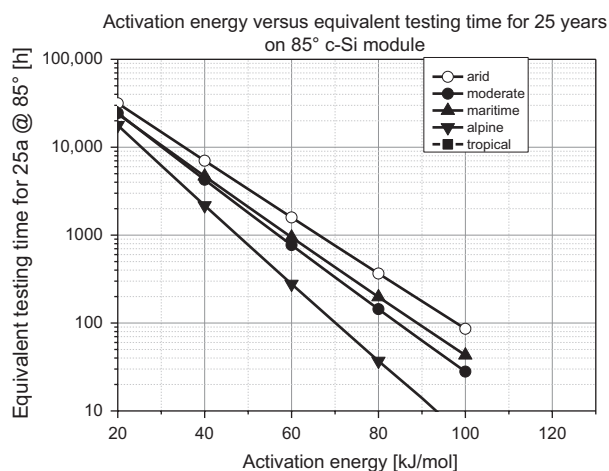


Figure 23. Equivalent testing times at different testing temperatures for moisture stresses at the different location modeled as a function of the activation energy using data of one averaged year from monitored climatic data and module temperatures for several years.

Suitable categories and test conditions have to be defined as well as procedures for the evaluation of the activation energy for the rate dominating parameter of the degradation process.

UV stress

The UV radiation with wavelengths below the threshold representing the minimum energy needed for photo-degradation [18] is simulated by testing with artificial UV-radiation sources. The acceleration needed for ALT can be obtained by either increasing the irradiation or by enhancing the sample/process temperature. Unfortunately, the reciprocity law, which assumes that the UV dose implies a linear relation between irradiation and duration, is not always valid. The exponent n of the relation between two levels of the irradiation in equation 10 is not unity in this case of non-reciprocity.

A value of 0.7 was found for the photo-degradation of back-sheets [15]. In this case, an increase to 10 times the natural UV radiation would be needed for an acceleration factor of 5.

$$t_{\text{test}} = \text{Lifetime (years)} \cdot \sum_i \{ \Delta t_i \cdot (I_{\text{uv},i} / I_{\text{uv,test}})^n \cdot \exp [- (E_a / R) \cdot (1/T_{\text{test}} - 1/T_{\text{mod},i})] \} \quad (10)$$

The sample temperature plays a role for photo-degradation as well. The acceleration by temperature can be described by an Arrhenius relation, but the activation energy is low. About 40 kJ/mol was found for back-sheets. An estimation of the UV dosage based on climate monitoring in the desert for a service life test at a sample temperature of 85°C as a function of the activation energy is shown in the diagram in Figure 24. A much lower stress could be expected if the sample temperature would not exceed the ambient temperature resulting in a low dosage for the ALT. The activation energy is a measure for the temperature impact. The higher the activation energy, the stronger the real-world stress when the temperature is increasing, as could be noticed at the strongly increasing dosage for the higher sample temperature T_{mod} . The total ALT dosage decreases with increasing activation energy because the testing temperature of 85°C is much higher than T_{mod} and provides a higher acceleration.

These effects can be found in the comparison of the different locations again (Fig. 25). The stronger decrease in the dosage in the alpine and maritime climate with increasing activation energy is caused by the lower module temperatures (see Fig. 20) compared to the moderate and arid location. The acceleration during testing dominates the temperature impact during exposure and reduces the required UV dosage drastically (Table 11). ALT at 85°C sample temperature might need 540 kWh/m² for a PV application in the Negev desert. The four test sites differ by a factor of 4. Testing in 120 kWh/m² steps would allow a gradual qualification of PV modules.

Table 10. Testing times in hours for damp/heat tests at 85°C and 85% relative humidity as accelerated service life tests corresponding to 25 years of service life evaluated for different climatic locations based on monitored climatic data for varied activation energies of the degradation processes. White numbers on grey back-ground indicate conditions already covered by the type approval testing according to IEC 61215.

Activation energy [kJ/mol]	Maritime	Moderate	Arid	Alpine	Tropical
20	31,650	24,453	23,960	17,743	29,442
30	14,885	10,166	10,540	6180	13,620
40	7030	4262	4678	2175	6385
50	3334	1802	2094	773	3029
60	1588	769	946	278	1453
70	760	331	431	101	704
80	366	144	198	37	344
90	177	63	92	14	170
100	86	28	43	5	85

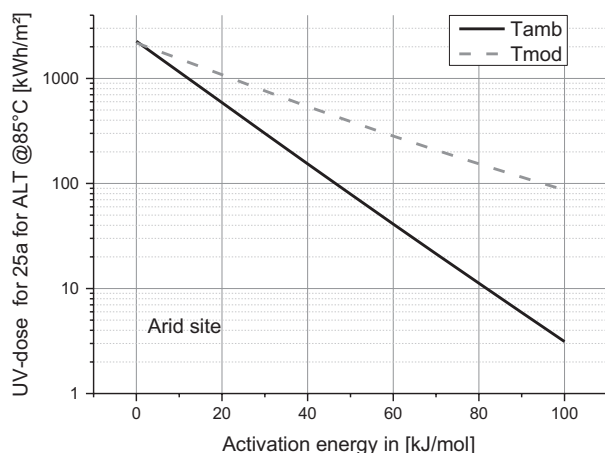


Figure 24. UV dosage for tests at 85°C as accelerated service life tests corresponding to 25 years of service life for the arid location based on monitored climatic data for sample temperatures at ambient temperature or module back-side temperature, respectively.

Conclusion

Monitoring of climatic properties and sample properties in different climatic zones (alpine, arid, maritime, moderate, tropical) during several years provided the base for categorization of these climates. The local climate does not differ very much from year to year in terms of frequency distributions, but big differences are found for different regions or climatic zones.

The histograms of the solar irradiation and the yearly sum of the insolation seem to be very location-dependent, especially. The alpine location shows the highest UV irradiation. The UV fraction of the solar irradiation is varying between 2.2% (tropics) and 4.7% (alps).

The temperature histograms can be modeled by Gaussian distribution functions. The maritime histogram is very slim and high, showing the cooling by the sea and the wind. The temperature distribution of the tropical location consists of two superimposed functions.

Several approaches for a categorization of these local climates can be applied: Mean temperatures, effective temperatures, or the corresponding constant testing time for fictive degradation processes with arbitrary activation energy.

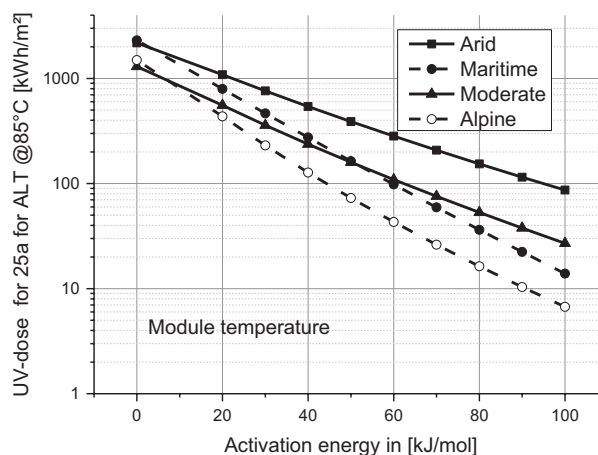


Figure 25. UV dosage for tests at 85°C as accelerated service life tests corresponding to 25 years of service life evaluated for different climatic locations based on monitored climatic data for varied activation energies of the degradation processes.

The categorization of the relative humidity revealed humid climates in the alpine and the tropical test site, when considering the time of wetness ($rh > 80\%$). Obviously, the humidity stress or the corrosivity would be very different at those sites. Therefore, a more holistic approach considering more stress factors simultaneously would be more appropriate for the categorization. The interaction between the samples and the climate creates the so-called micro-climate which is the real stress on the samples, such as surface temperature, daily temperature cycles, surface humidity, and temperature-enhanced photo-degradation.

The conditions for accelerated life testing (ALT) modeled on the base of monitored climatic data and sample temperatures are different for the different locations. They offer another possibility for categorization of the climatic stresses and the option for designing climate-adapted components.

Acknowledgments

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Table 11. UV dose for tests at 85°C as accelerated service life tests corresponding to 25 years of service life evaluated for different climatic locations based on monitored climatic data and module back-side temperatures. A very high dosage is required if there is no temperature impact ($E_a = 0$), low sample temperature (at ambient temperature) with moderate temperature dependence ($E_a = 40$ kJ/mol) reduces the required dosage while a higher sample temperature (T_{mod}) needs higher test loads.

	E_a (kJ/mol)	ARID	Maritime	Moderate	Alpine	
T_{amb}	0	2261	2368	1388	1294	kWh/m ²
	40	154	135	77	34	kWh/m ²
T_{mod}	40	541	275	237	127	kWh/m ²

the industrial partners Bosch, Schott Solar, Solarfabrik, Solarwatt, Solar World, and Solon.

Conflict of Interest

None declared.

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