

## Review Article

# Simulation of Water Vapor Ingress into PV-Modules under Different Climatic Conditions

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This work deals with the simulation of water vapor ingress into wafer-based PV-modules for long-term exposure under different climatic conditions. Measured material parameters together with climatic data sets from four test sites (tropic, moderate, alpine, and arid) were used to calculate the water concentration inside of the encapsulant between solar cell and glass for a lifetime of 20 years. Two back-sheet materials (PET-based and PA-based) combined with EVA as encapsulant were used in respect to their influence on water ingress. The results show faster water ingress for warmer regions, but the highest concentrations were found for the moderate test site. The water ingress was additionally influenced by the used encapsulant and back-sheet combination. In particular the temperature dependency of the mass transfer, which differs from material to material, was the focus of this investigation.

## 1. Introduction

PV-modules are globally installed and, thus, exposed to different climates with continuously changing environmental conditions as, for example, UV-irradiation, temperature cycles, or snow loads over a life time of 20 years and more.

The ambient atmosphere and its containing air humidity constitute one of these loads. Polymers interact with the water vapor in a manner of absorption and desorption. Therefore, water can enter a PV-module and causes hydrolysis of the polymers [1, 2] or corrosion of metallic components, but it can also be part of other chemical reactions, for example, acetic acid production [3]. In addition, also mechanical properties of the encapsulation and back-sheet materials (polymers) such as viscoelastic behavior can be changed by water uptake [4].

The absorption of air humidity is primarily controlled by the microclimate at the interface PV-module to ambient atmosphere and by specific temperature controlled material parameters such as water vapor transmission rate (WVTR) and diffusion coefficient ( $D$ ). Water vapor therefore enters the PV-module via the whole surface of the back sheet and molecules diffuse through the encapsulation polymer until

they reach the area between solar cell and front glass [5]. Depending on the water concentration inside of the polymers and the air humidity of the microclimate at the surface, the mass transfer of water molecules will be directed towards the inside or the outside of the PV-module.

The present paper deals with the investigation of water concentration behavior inside polymeric materials used in PV-modules, depending on different climates, and over a planned lifetime of 20 years. Due to the geometrical structure of wafer-based cSi-PV-modules and the long-lasting life time, measurements of water concentration inside the module are viable. Therefore, a combination of real measured data and 2-D FEM-simulation (finite element method) was used to solve this problem. The measurements include the determination of the temperature dependent permeability of water vapor through different encapsulation and back-sheet materials, but also the microclimate which was measured at four test sites representing different climates (moderate, alpine, tropic, and desert). Compared to prior publications addressing this issue [6], this paper focuses on the behavior of microclimates and on how different polymeric materials, respectively, their diffusion properties, (back sheet and encapsulant) influence the water uptake with respect to geometrical situation by using 2-D FEM simulations.

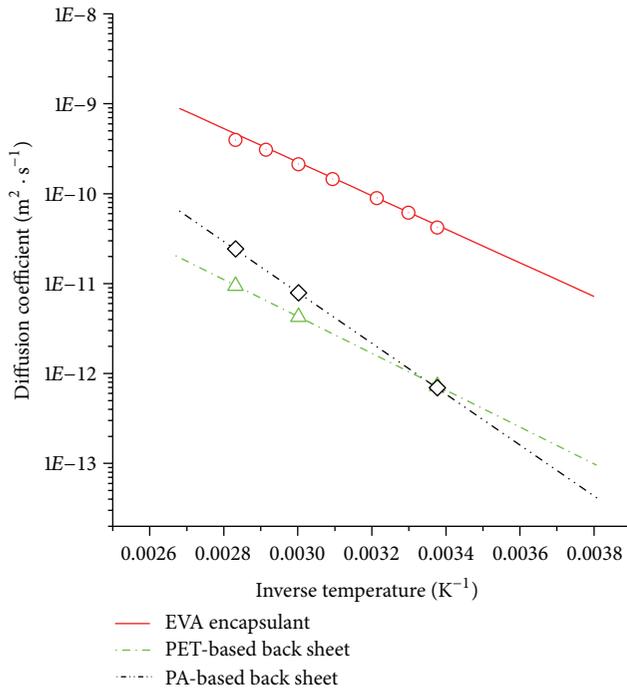


FIGURE 1: Measured effective diffusion coefficients of the materials used in the simulation [6-modified].

## 2. Measurements

**2.1. Materials.** In this study, three commercial products—one encapsulant and two back sheets—were chosen for the analysis of their influence on water vapor ingress. The encapsulant was a standard EVA (fast cure) which is well established on the market.

Back sheets generally consist of three layers of polymeric films which are glued together by adhesives. The core material between the two outer layers is, because of its thickness, the dominant part regarding the permeability of gases. Results of a prior work [6] show that back sheets can be distinguished by their core material with respect to its temperature dependency of the permeability. Here, two polymeric material groups were analyzed. One represents polyethylene-terephthalate- (PET-) based back sheets, and the other one represents a polyamide- (PA-) based material group. The PET back sheet consists of a  $250\ \mu\text{m}$  thick PET core glued between two outer layers of PVF (polyvinyl-fluoride) all in all having a total thickness of  $350\ \mu\text{m}$ . The same thickness ( $350\ \mu\text{m}$ ) can be stated for the PA back sheet.

**2.2. Measured Parameters.** Two material parameters, permeability ( $P$ ) and diffusion coefficient ( $D$ ), were determined by a permeation test device that was developed by Fraunhofer ISE. This test setup is capable of measuring the permeation of water vapor and other gases through polymeric films or laminates over a wide range of temperature [7]. In this manner, the temperature dependency of mass transport was quantified and, therefore, the activation energy  $E_A$  for this process was calculated (see Table 1).

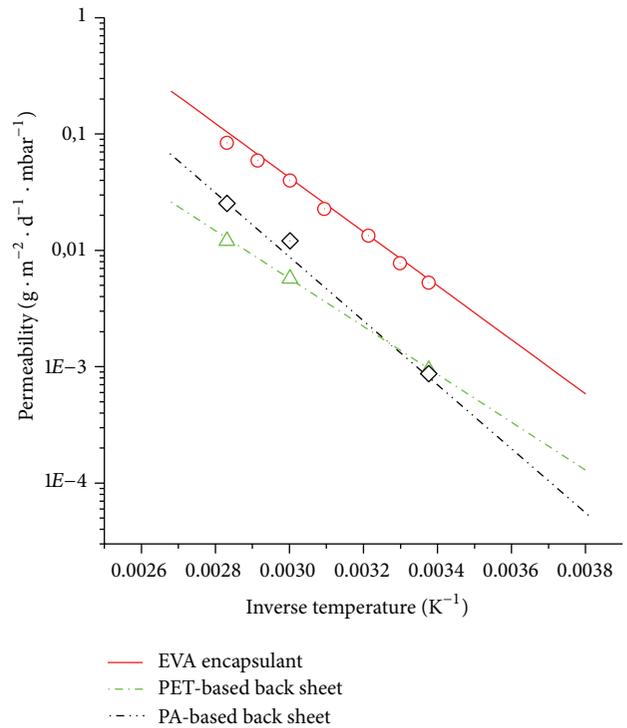


FIGURE 2: Measured permeability of materials used in the simulation of water ingress [6-modified].

The results of  $P$  and  $D$  measurements for various polymeric materials were published in an earlier paper [6]. Here, the results for the materials used in the simulation are shown below in Figures 1 and 2. Both graphs show the measured values and an Arrhenius fitted extrapolation to a temperature range PV-modules can be exposed to. The back-sheet materials were measured as a laminate that consists of the core and both outer layers. Therefore, Figure 1 shows effective diffusion coefficients for the back sheets.

**2.3. Climate Data.** To simulate the water ingress under realistic climatic conditions, knowledge of the local climate the PV-module is exposed to is needed. Therefore, the climate data such as air temperature ( $T_{\text{air}}$ ), relative air humidity (rH), and the PV-module temperature ( $T_{\text{module}}$ ) were measured at four outdoor test sites which are located in different climate zones:

- (i) Freiburg, Germany (moderate climate),
- (ii) Negev desert, Israel (arid climate),
- (iii) Zugspitze (altitude: 2650 m), Germany (alpine climate),
- (iv) Serpong, Indonesia (tropic climate).

Figures 3, 4, 5, 6, 7, 8, 9, and 10 show the development of the measured climate parameters for the year 2008 at the four test sites in 5-minute increments. For each test site, the

TABLE 1: Calculated activation energies  $E_A$  of the diffusion process of water vapor for the materials used in the FEM simulations. The values of the back sheet-materials are effective  $E_A$  measured for the layered structure.

Material	Thickness ( $\mu\text{m}$ )	$E_A$ of diffusion process [ $\text{kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ ]
PET-based (back sheet)	350	39,2
PA-based (back sheet)	350	54,1
EVA (encapsulant)	1000	35,7

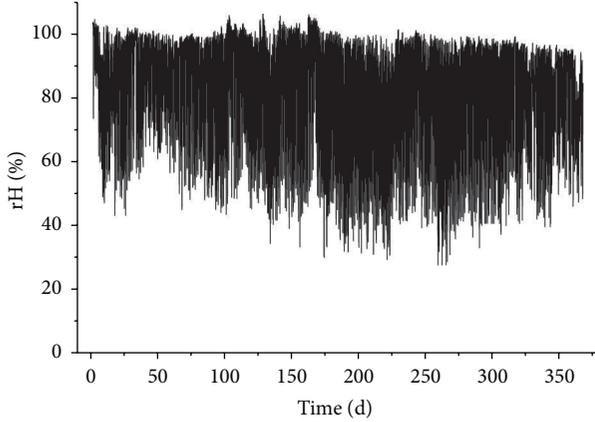


FIGURE 3: Relative air humidity: tropic.

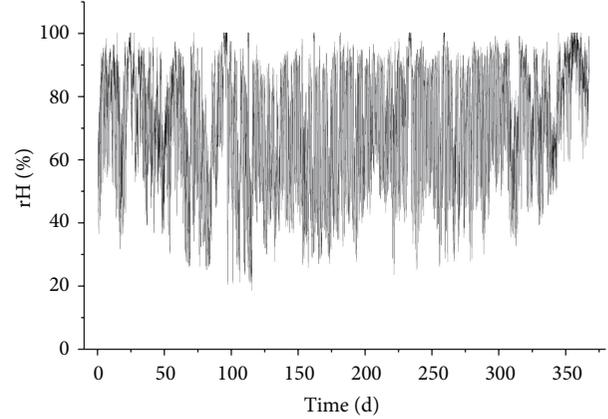


FIGURE 5: Relative air humidity: arid.

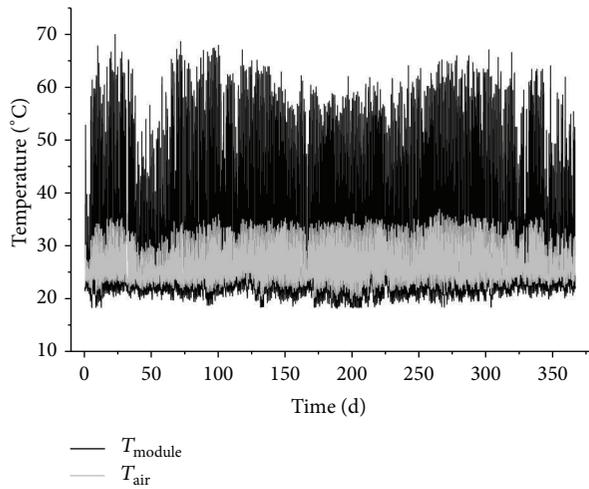


FIGURE 4: Module and air temperature: tropic.

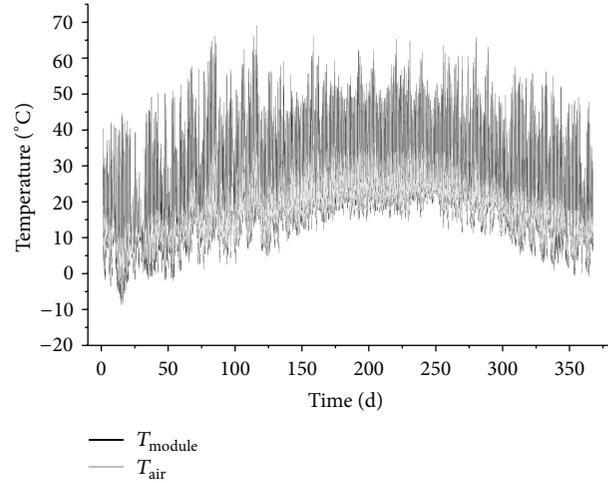


FIGURE 6: Module and air temperature: arid.

air humidity of the microclimate was calculated from these data sets via the so-called Magnus-formula [8].

Microclimate is defined in this study as the boundary layer between the atmospheric side of the back sheet and the ambient air. This air layer with a thickness of approximately 1 mm holds a temperature balance with the PV-module whose temperature is, compared to the ambient air temperature, elevated by solar irradiation during the day and lowered by thermal emission during the night. Thus, the humidity a PV-module is exposed to at its back sheet is determined by the humidity of the microclimate, which provides dryer

conditions at day and wetter conditions at night because of the temperature deviation between PV-module and air.

Figures 11 and 12 show, by way of example, a closer view on the diurnal cycles of the climate data derived from the arid test site in the Negev desert (Israel). The strong deviation of module temperature and ambient temperature can cause very dry conditions during day and wet conditions at night (Figure 12). Here, also condensation of air humidity can be observed. To sum up, daytime presents faster diffusion conditions, while at night, the mass transport of water vapor and also other gases is slowed down.

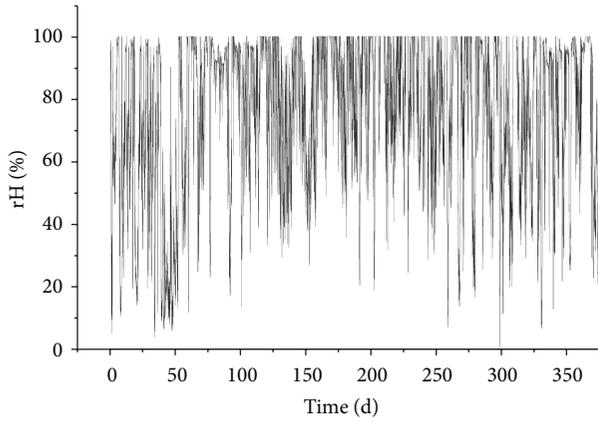


FIGURE 7: Relative air humidity: alpine.

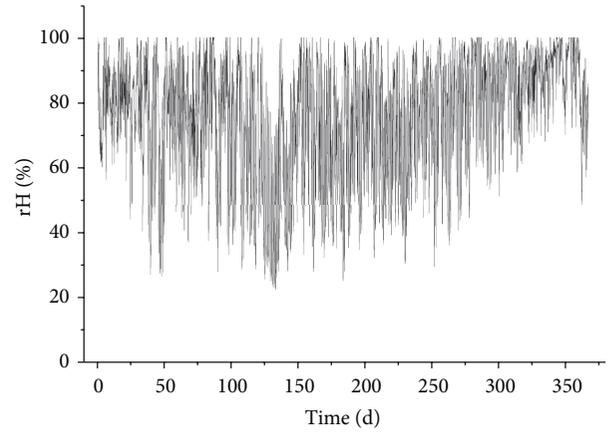


FIGURE 9: Relative air humidity: moderate.

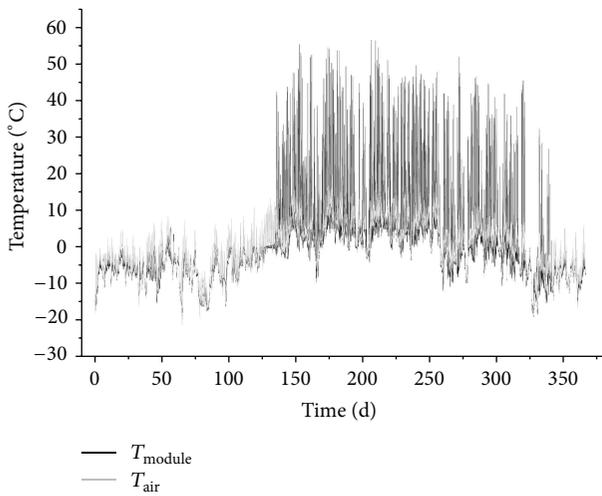


FIGURE 8: Module and air temperature: alpine.

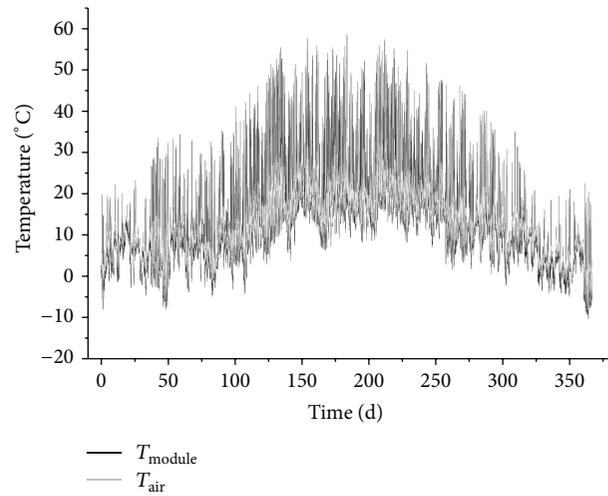


FIGURE 10: Module and air temperature: moderate.

### 3. Simulation

The FEM-based simulation was carried out with a commercial software tool. The following sections discuss geometry and layout of the used model including boundary conditions and discuss the results of the simulation.

**3.1. Geometry and Boundary Conditions.** The geometry used for the simulation presents a simple, symmetrical, and 2-dimensional constructed model (Figure 13). It is composed of a back-sheet layer, followed by the encapsulation integrated with two half-sized solar cells (6-inch cells) which show a gap of 3 mm in between them. The atmospheric side of the back sheet layer provides the feed-in zone for the water molecules. This layer is infinitely thin and, therefore, permanently in sorption equilibrium with the air humidity of the microclimate.

The possible pathway of a water molecule is illustrated by plotted arrows in Figure 13. A molecule will follow a concentration gradient and diffuse either deeper into the PV-module or back to the feed-in zone (atmospheric side of the

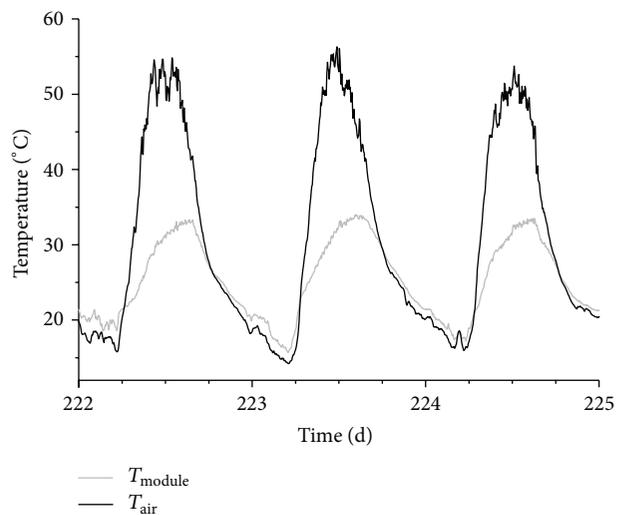


FIGURE 11: Diurnal cycles of measured air and module temperature: arid.

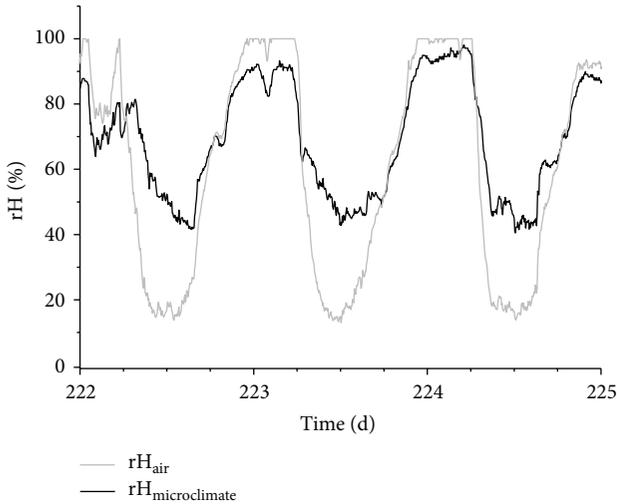


FIGURE 12: Diurnal cycles of measured air humidity and calculated microclimate humidity: arid.

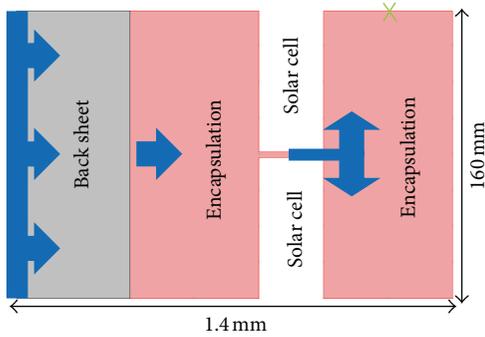


FIGURE 13: Assembling and geometry of the simulated model including pathway of water molecules.

back sheet), depending on the gradient. At the beginning, the molecule will diffuse perpendicular to the module level, passing the back sheet, followed by the first encapsulation layer, and has then to turn onto the module level past the small gap between the cells. Then, it continues until it reaches the center area between solar cell and front glass. All in all, the maximum possible way of diffusion adds up to approximately 80 mm in this geometry.

The main advantage of using a 2-D model is that also permeated cross-sectional areas are considered which is given, for instance, by the ratio of space between the cells (here, 3 mm) and the distance of cell to glass (here, ~0.4 mm). Please, mind the unequal dimension of the  $x$ - and the  $y$ -axis in Figure 13.

The input parameters used for this simulation were given by the measured temperature dependency of permeability of the encapsulation and back-sheet materials which were described in Section 2.2, including the already published data [6] and the climatic data sets from the outdoor test sites shown in Section 2.3. These one-year data sets were assembled to time series of 20 years by means of repetition.

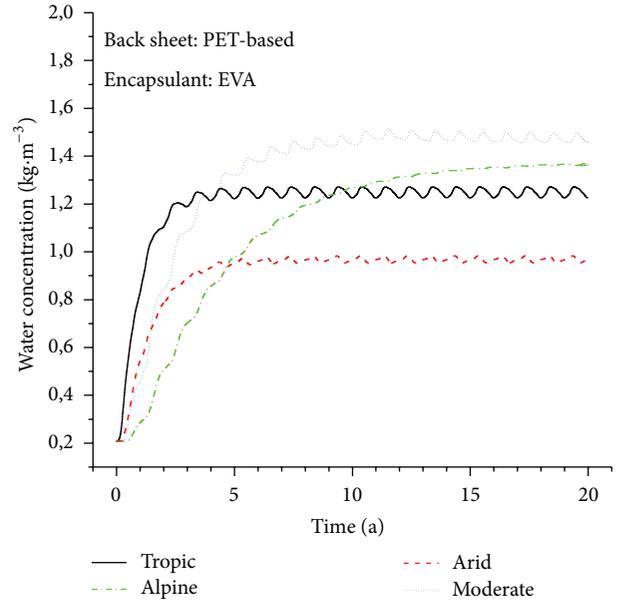


FIGURE 14: Simulated water ingress into a PV-module for different climates. Here, an EVA encapsulant and a PET-based back sheet were used.

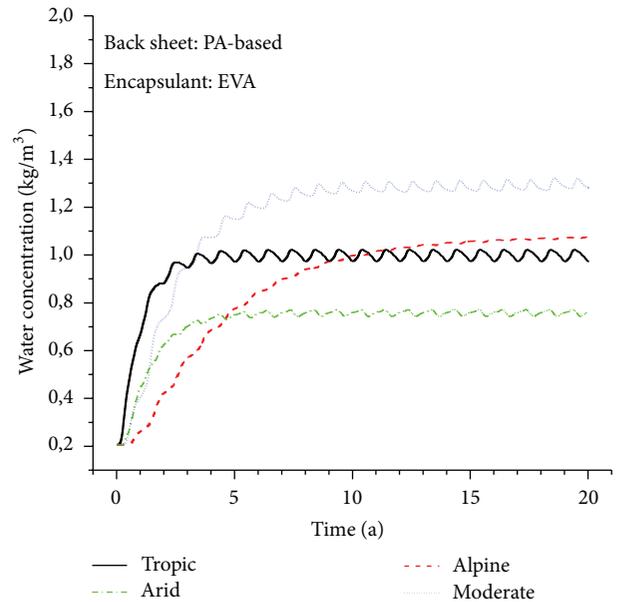


FIGURE 15: Simulated water ingress into a PV-module for different climates. The use of the PA-based back sheet causes significantly lower water concentrations.

This way, it was possible to simulate the slope of the water concentration inside a PV-module over a planned life time of 20 years and for different climate zones under continuously changing ambient temperature and humidity conditions. Additionally, a small initial concentration of water was to be considered in the encapsulant even after lamination process.

3.2. *Results and Discussion.* The water ingress was simulated for various back-sheet and encapsulant material combinations which are listed below:

- (i) PET-based back sheet/EVA (fast cure) encapsulant,
- (ii) PA-based back sheet/EVA (fast cure) encapsulant.

Figures 14 and 15 show the development of simulated water concentration inside the encapsulant over a time period of 20 years. The place inside the encapsulant represents the maximum diffusion length a water molecule can achieve in a PV-module. It is marked by an “x” in Figure 13 in the upper right corner.

Both graphs (Figures 14 and 15) show an increase of water concentration which runs faster in warmer climates, for example, at tropic sites, and much slower in colder regions (e.g., alpine). This effect is based on the acceleration of the mass transfer by temperature, the so-called temperature dependency [7, 9]. In detail, this effect causes differences in the time lag, which represents the time a molecule needs to diffuse from the outside of the back sheet towards the space between cell and glass, and is also visible in a sharper gradient of the concentration. The alpine site, for example, shows a time lag of more than ten years until equilibrium (Figure 14) whereas at the other test sites molecules will diffuse much faster because of higher temperatures (also Figure 14). Besides the local climate (temperature), also the encapsulant influences the time lag and the slope on concentration increase.

In addition to the speed of water ingress, also the maximum water concentration that is reached after several years depends on the climate (Figures 14 and 15). The arid test site shows the lowest concentration which also provides the driest climate. Interestingly, the tropic site features a lower water concentration after 20 years than the alpine and the moderate sites. This phenomenon is caused by the transient microclimate at each test site which provides drying and moisturizing conditions as a diurnal cycle. Depending on ratio between dry and wet conditions in cooperation with temperature and its effect on transport mechanism higher or lower water concentrations are reached inside the encapsulant before the center of the cell.

The influence of the back sheet can be determined by focusing on the concentration that is in equilibrium after several years but oscillates around a mean concentration. The mean equilibrium concentration differs from site to site (see above). But within the same site, the equilibrium concentration is significantly influenced by the used back sheet (Figure 16). It can be stated that this concentration is lower in samples with a PA-based back sheet (see Figures 15 and 16). This effect can be explained by a higher  $E_A$  of PA compared to PET (see Table 1), together with a transient microclimate. PA and PET have a comparable permeability for water vapor at 30°C, but PA has the higher temperature dependency which leads to a higher permeability at elevated temperatures and to a lower permeability at temperatures below 30°C. As presented in Section 2.3, the microclimate offers dry conditions and high temperatures during the day and wet and cold conditions (condensation) at night. The

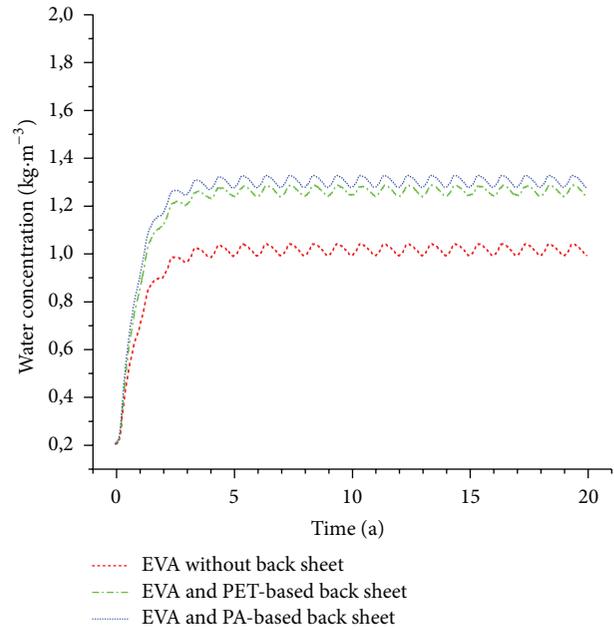


FIGURE 16: Simulated water ingress for the tropic test site and the effect of different back sheets.

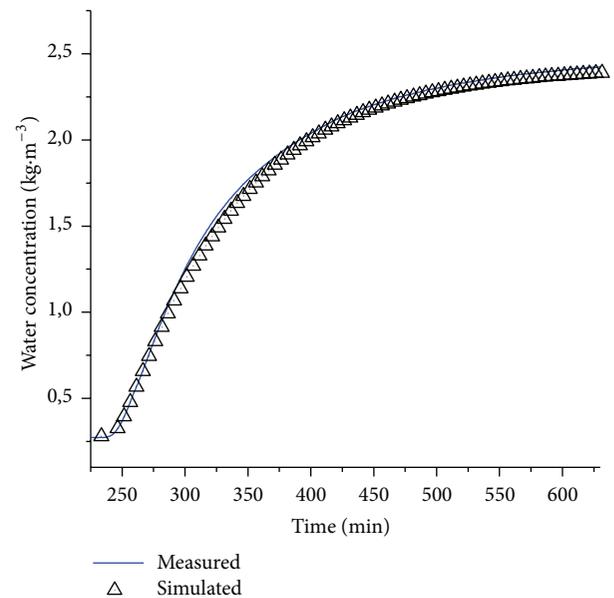


FIGURE 17: Simulated versus measured permeation through a 1 mm EVA film (at 38°C) which shows a very good agreement.

higher temperature dependency of the PA provides a more breathable back sheet in dry conditions (day) and a better barrier in wet conditions (night).

3.3. *Validation.* A first validation of the simulation of water ingress is shown in Figure 17. In this case, the permeation through a 1 mm thick EVA sample was measured with the test device mentioned in Section 2.2, followed by a simulation

using the same geometry and boundary conditions. The simulation agrees very well with the measured values, also in regard to the time lag and the slope of concentration increase.

#### 4. Summary and Conclusion

In this study, the water ingress into PV-modules was simulated for an outdoor exposure of 20 years in different climates. Real measured parameters such as permeability of encapsulant and back sheets, together with monitored data sets of four climatic sites were used as basis for this simulation. The results show the influence of different climates on water concentration inside the encapsulant between solar cell and glass. Interestingly, the tropic test site does not thereby provide the highest concentrations. But also the effect of using different encapsulants in combination with different back-sheet materials on water ingress was shown. In particular the temperature dependency of the mass transfer influences the water ingress, depending on the material combination that is used. Results show, for example, for PA-based back sheets, that a higher  $E_A$  in combination with a transient microclimate (humidity and temperature) causes lower water concentrations over long periods of outdoor exposure.

In summary, a method was presented, existing of measured parameters and simulation, which is well suited for material and design studies regarding water ingress—not only for PV-modules.

#### Acknowledgments

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