Conclusions

Systematic fire tests of fire behavior and fire resistance of PV modules including emissions in case of fire and development of a test procedure on the influence of PV modules to the roofing

Systematic fire tests were conducted on photovoltaic (PV) modules in this study. Different fire scenarios with different levels of fire exposure have been investigated with commercially available PV-modules and their fire behavior, resistance to fire as long as the fire by-products have been analyzed.

For the assessment of the fire behavior and the fire resistance we only refer to the modules investigated in this study. But since the actual market is really large, we had to choose a selection of representative modules for each available category. The modules investigated in this study include thick-film silicon panels, with the construction type glass sheet on the front and plastic sheet on the back (glass/plastic), and also thin-film modules with the construction type glass/glass (amorphous silicon, cadmium telluride and copper indium gallium selenide) as long as the construction type glass/plastic and plastic/plastic. For deeper and broader generalizations, substantial series of tests need to be carried out.

Firstly, the solar modules have been submitted to the lowest level of fire exposure, a flammability test for building materials (building materials class B2) according to EN 13501-1 or the German DIN 4102-1 standards. The fabrication of the needed small samples was there problematic. Glass breakage could happen during the cutting of the modules and there is also an influence of the temperature on the untoughened glasses. A favorable experience has been made with water jet cutting procedure. It can also be noted that a test of the whole module according to the corresponding standard conditions (length of the flame, distance to the module etc.) gives the same results, as a test with a module sample cut according to standard. The advantage of a test with a real module in its original material structure is that the overall performance is reflected and the easier handling.

In further steps the PV modules have been tested with the wire basket test (“Drahtkorbtest”) according to CEN TS 1187/Test method 1 standard. None of the investigated modules showed flaming droplets or flaming particles, opening or burning-through in accordance with the standard. The damage areas were small. Additionally the wire basket test was modified, in which the incendiaries (incendiary compositions) were placed on the lower edge of the module and also under the elevated (tilt-mounted) module. The lower edge ignition causes no further damages. In the case of the ignition from underneath the module, a burning-through with glass breakage after 4 minutes was registered only for one module (amorphous thick-film silicon module). After the end of the test, the electric power for all the investigated modules was between 12-95%.

In an increasing level of fire exposure, the PV-modules were tested in the Burning Brand Test in compliance with the IEC 61730/UL 790 standard. All the investigated modules fulfill the minimal requirements of fire resistance (class C) after exposure to the smallest fire load (wood crib of 10 g). In this case all the investigated modules showed no damage and kept 100% of the electrical performance. With an exposure to the next biggest fire load (wood crib of 500 g) of the class B all the considered panels of the glass/plastic construction type showed a strong smoke production, flaming droplets (drop down) or flaming particles (fall down) after a few minutes and a burning-through after 2-8 min. The investigated modules of the glass/glass construction type, however, showed no flaming droplets and there were no burning-through. The electrical power after the test was under 10% for all of them. On the contrary, all the modules showed extensive damage area and an electrical power of 0% after the fire tests with the biggest wood crib (2 kg) of the class A test. The burning-through took place after around 2 min., associated with the falling down of flaming parts and flaming droplets. The fire extinguished after 8-10 min. Corresponding fire tests with tar paper (roofing felt) as underlying roofing material showed no modification of the fire behavior of the PV-module. After the falling down of flaming droplets from the burning modules there was no propagation of the flame to the tar paper and the fire extinguished. A comparison between the performed fire tests of modules from relative low price segment and from relative high price segment (from China) showed no significant influence on the reaction to fire. The investigated Chinese modules exhibited in comparison to the other considered modules a quite higher fire resistance.

Single Burning Item (SBI) fire tests according to DIN EN 13823 were carried out with different fire exposures to test the resistance to fire of vertically mounted PV modules. Glass breakage and falling down of small parts occurred when exposed to a fire load of 30 kW according to the standard, but the vertical construction on the wall stayed stabile during the 30 min of the test. On the opposite, when exposed to a fire load of 130 kW, the module already fall down from the fixations on the wall after 6 min and continued to burn further 7 min. Electrical power could still be measured on the investigated modules after the fire tests.

Furthermore a new test was developed to assess the fire behavior of the PV-modules under variable fire conditions in a simple test apparatus. The conditions that can be adjusted are the output of the gas burner, where a particular fire scenario can be reconstructed, as long as the configuration of the burner, that can simulate a fire from outside or inside (above or underneath the module). The advantages of this test are the variable fire conditions, which can be adjusted to particular requirements and the ease of handling. No incendiaries like wood cribs need to be produced and the fire load level can be suited in an easy way by the burner output. Fire tests with a burner output of 16, 30 and 46 kW were carried out, what approximately correspond to the fire exposure level of the different fire classes of the burning brand test in compliance with IEC 61730/UL 790 and the wire basket test (“Drahtkorbtest”) according to CEN TS 1187/Test method 1 standard. Depending on the fire levels of these tests, small to extensive damages were obtained.
In the case of a burner output of 16 kW no burning-through occurred for all the investigated PV-Module during the 15 min of the test. The modules of the glass/plastic construction type showed however already after 2 min a strong production of smoke and it came to flaming droplets. In contrast, the modules of the construction type glass/glass did not show this behavior, but it came to glass breakage of the upper glass sheet. The electrical power of the investigated PV-modules was between 17-26% after the fire tests.
With a 30 kW burner output bigger damages are recorded, with strong smoke production and a burning through after 6-8 min. The thin-layer modules (glass/glass) differentiated form the thick-layer modules as they showed during all the gas burner

tests a glass breakage, which happened after nearly 1 min, independently of the burner output. The thin-layer modules of the glass/glass construction type showed no burning droplets after exposure to the 30 kW burner. The thick-layer modules (glass/plastic) exhibited on the opposite a strong burning off of the plastic back sheet with flaming droplets and flaming falling down of parts. The electrical power after the 30kW gas burner tests were still about 10% of the one before the test. Further tests showed that the use of tar paper as underlying roofing material did not propagate the fire, despite the strong flaming droplets of the PV-modules the tar paper did not ignite.

Modules tested with a burner output of 46 kW showed a similar fire behavior than during the tests with 30 kW, only the damage areas were somehow partly bigger after the tests.

Furthermore a new test procedure was developed, that simulate a fire from inside, were the burner is placed in this case underneath the module. With a burner output of 30 kW, set as default output for this test procedure, the modules showed significantly larger damages in comparison with a fire exposure from outside, both with the investigated thin-layer and thick-layer panels. The module with the glass/plastic configuration type showed a strong smoke production and flame generation already after 25 seconds. The module was extensively damaged at the end of the test, even if no burning through happened. On the contrary, the thin-layer module (glass/glass type) investigated here showed a burning-through already after 2 min as long as relative small damaged area, but the electrical performance was 0% after the test. Conversely all the other exposed modules during the other gas burner tests showed a residual electrical power until 26% in the outside exposure burner configuration.

The performed standard testing methods and the fire tests with the new self-developed test procedure mainly addressed the evaluation of the fire behaviors and fire resistance of the modules and that is why to the assessment of mechanical, electrical and energy damages which can come from PV-modules during a fire.

Furthermore, smoke production was also evaluated to get an estimation of the visibility during the fire test. The risk assessment of the substance that means the toxicity of the fire by-products mainly occurred in bench-scale tests in the smoke density chamber according to ISO 5659-2, in the cone calorimeter according to ISO 5660-1and in the Single Burning item (SBI) test in compliance to DIN EN 13823.

Chemical analysis has been used on the one hand to evaluate the gas composition of the smoke in order to assess the toxicity of the smoke, and on the other hand on the fire residues in view of the toxicity of fire by-products like heavy metals.

The smoke production is relatively low during the bench-scale fire test in comparison to e.g. some common plastics. The ignition happened in the closed smoke density chamber 4 to 6 min after the start of the test, on test duration of 20 min. The transmission of the CdTe-, CIGS- and a-Si thin-film modules decrease from around 95% to 40% within two minutes after the ignition of the samples. In an open well ventilated system like the cone calorimeter test, the reduction of the transmission by smoke is lower. In this case the thin-layer modules of the glass/glass type exhibited better results, with the lowest transmission values between 70-80%. The total smoke release over the 15 min of the test is approximately 200 m² smoke per m² of module. The values between the glass/glass type modules are similar. The ignition of the samples in the cone calorimeter occurred after ca. 2 min and the smoke production ended after 4 min. On the opposite, the Si thick-layer module of the glass/plastic type

ignited already after 1 min and produced higher amount of smoke with a total smoke production of 380 m²/m².
The composition of the smoke gases have been continuously measured with a FTIR spectrometer during the fire bench-scale tests in the smoke density chamber and in the cone calorimeter.
A quantitative evaluation of the concentrations in some toxic gases was possible thanks to calibrations of the spectrometer. Additionally a new calibration method was developed to quantify acetic acid, which was a main product of the pyrolysis of EVA foils (encapsulating material of the wafers).
The combustion of the laminating film produced mainly CO_2 and water, as long as CO from incomplete combustion. Additionally acetic acid could be detected in large amount in the bench scale tests. Other gases could also be detected in small amount such as methane, formaldehyde and ethylene, whereas the presence of other investigated gases such as SO_2, NO, NO_2, NH_3, HCl, HCN, HBr, benzene and phenol could not be clearly proved in our detection range.
The smoke gas composition is similar for all the investigated modules and differentiates only on the quantity of the gases. The modules of the glass/plastic type showed higher CO and CO_2 concentrations than glass/glass type due to the additional burning of the plastic back sheet. The investigated CIGS modules showed generally higher concentrations than the CdTe and a-Si thin-layer modules during the bench-scale test.

The maximal concentrations of the gas components emitted during the bench-scale tests have been compared with toxicologically significant threshold limit values to evaluate the hazards with regard to the relevant substances (see chapter 4). However threshold data on toxicology are various, and depending on the time of exposure and exposure scenario, so only a trend can be drawn from this comparison. Thick-film silicon modules produced CO in the Cone Calorimeter test in high concentrations (approx. 800 ppm). Furthermore all the investigated PV modules released during the bench-scale tests high concentrations of acetic acid (between 50-120 ppm in Cone Calorimeter and 220-290 ppm in the Smoke Density Chamber. Further on high concentrations of formaldehyde evolved during fire tests of CIGS modules in the smoke density chamber (ca. 24 ppm). However a direct transfer of the results obtained in the bench-scale tests to the large scale test has to be made only with caution, since normally PV-modules are mounted on a roof and in open air conditions, and the gas concentrations drop down depending on the distance to the modules [5].

To further evaluate the toxicity of the fire by-products, the bench-scale and real fire residues have been chemically analyzed to find out if the contained heavy metals of the thin-film modules are released in the environment. The heavy metal content in the unburned and burned residues has been evaluated with atomic spectrometry methods (ICP-OES inductive coupled plasma optical emission spectrometry and AAS atom absorption spectrometry). The difference between both concentrations indicated if a release of the elements cadmium, tellurium, gallium, selenium, copper or indium occurred. The fire residue samples of CdTe and CIGS thin-layer modules produced in the bench-scale test (smoke density chamber, 50 kW/m², pilot flame) as long as in roof test (burning brand test with wind) have been first mechanically milled and chemically extracted. The concentrations in the heavy metals have been determined from their extracts with atomic spectroscopy.

For all the investigated CdTe modules the main amount of the initial heavy metals stay in average in the residue during and after the fire. The percentage of the element in the residue lies between 94-100% of the original amount for cadmium and around 96% of the original tellurium. It is supposed that these elements are encapsulated during the fire in the melted glass and for this reason is not released. Comparable results were independently published for other fire tests in [47].

The investigated CIGS modules showed after the fire test a loss in the investigated elements between 12 to 18% compared to the unexposed samples (copper -18%, gallium -12%, indium -17%, selenium -14% and cadmium -13%). A part of the elements could have been emitted in the form of smoke. However the measurements exhibited a large scatter of the results in the elemental concentrations for both the unexposed samples (standard deviation 5%) and the burned samples (standard deviation 10-13%). For this reason no definitive conclusions can be drawn but only a trend to release in the atmosphere during fire can be seen. The spread of the obtained concentrations may result on the one hand from the inhomogeneous repartition of the elements in the modules, but also from systematical errors during the chemical preparation of the fire residues samples. Additionally the reproducibility of the fire scenarios is also subjected to systematical errors. For this reason the statistical standard deviation of the element concentration in the residue is somehow higher than the one of the unexposed samples. The analytical methods usually exhibit only an error of ± 1%.