Impact of installation handling on cell cracks and power loss of PV modules

Testing | PV modules are subjected to various loads during installation handling. Research teams from the Institute for Solar Energy Research Hamelin (ISFH) and Hanwha Q CELLS attended the installations of PV modules in order to develop various test sequences for quantifying the effects of handling loads on the modules. As a result of these observations, lab tests have been designed to evaluate the impact of module-handling loads on cell cracking in the modules. Some rules for module handling are subsequently proposed

In previous publications, transportation has been discussed as a source of solar cell cracking in PV modules [1]; this cell cracking may reduce the reliability of the modules [2,3]. However, the correlation between cell cracking and power loss trends after the cracking damage is still not clear. Very often a direct impact on module power is below the detection limit for absolute power measurements (<2.5%) [2]. It is only after some additional load, such as thermo-cycling or further mechanical loads, that the cell cracking causes a relevant power loss. Kasewieter [4] found that the most significant mechanism for a permanent power loss is the electrical isolation of the aluminium metallization of the cell rear side. The aluminium rear metallization forms bridges over the crack, with no change in resistance taking place during the first load. After further mechanical loads, however, these bridges break and randomly reconnect, causing isolated cell parts to appear and disappear.

Olschok [5] has already shown that a handling failure – such as dropping the entire PV module from the carrying height, dropping a cordless screwdriver on the module, or stepping on the module – may cause cell cracks. Some very severe handling failures and corresponding tests have already been described in one proposal for a transportation standard [1], but these are not included in the corresponding IEC standard (IEC 62759: Photovoltaic (PV) modules – Transportation testing – Part 1: Transportation and shipping of module package units).

In this paper some typical situations that seem to be the most challenging for the mechanical integrity of solar cells in a PV module are identified. Simple tests are subsequently created for simulating the handling of solar modules and for analysing the cell cracks. The goal of these tests is to answer the following questions:

1. How does a specific handling step affect cell cracking in a PV module?
2. Does the ambient temperature during installation influence cell cracking in a PV module?

The test results will lead to recommendations for PV module handling. In this paper the focus is on modules containing 60 cells, with a cell size of 15.6cm × 15.6cm, embedded in ethylene vinyl acetate (EVA), a glass cover and a backsheet foil.

Field observation

To answer question 1, three PV module installations were attended, and test procedures were extracted from the observed handling. During these installations, the ambient temperatures were between –5°C and +25°C. The handling tests are therefore conducted at–5°C and +25°C in order to address question 2. Table 1 documents all the handling steps during the installation that are suspected to cause cell cracks.

Test set-up

In Table 1 the handling steps 1 to 6 are accidental and therefore excluded from the test set-up. Olschock et al. [5] have already

Handling step	Observed handling loads
1	Overturning from vertical onto the glass side
2	Overturning of a pallet (vertical transport)
3	Inadequate pallet for modules (horizontal transport)
4	Horizontal dropping from the carrying height
5	Vertical dropping from the carrying height
6	Scratching of a module's backsheet by the corner of another module during destacking
7	Pulling the module rear side over a ladder
8	Stepping on the module frame
9	Crossing a generator area
10	Dropping a tool on the module
11	Fall of one side of the module caused by sticking of the stacking corners
12	Non-gentle laying-down of a module on the module substructure during de-stacking
13	Overhead handling (module backsheet lying on top of a helmet)

Table 1. Critical handling loads observed by Olschock et al. [5] and used in this paper: 1–6 are accidental handling; 7–10 are prohibited, but sometimes occur; 11–13 are normal handling.

Test number	Test description	Temperature [°C]	Number of modules
1	Loading on the frame corner, with increasing weight	–5 / +25	2
2	Loading on the long edge of the frame, with increasing weight	–5 / +25	2
3	Loading on the module centre, with increasing weight	–5 / +25	2
4	Dropping a skittle ball on the module centre/corner above the centre of the cells, with increasing drop height	–5 / +25	2
5	Dropping a module over its short edge, with increasing drop height, sunny-side down	–5 / +25	2
6	Dropping a module over its short edge, with increasing drop height, sunny-side up	–5 / +25	

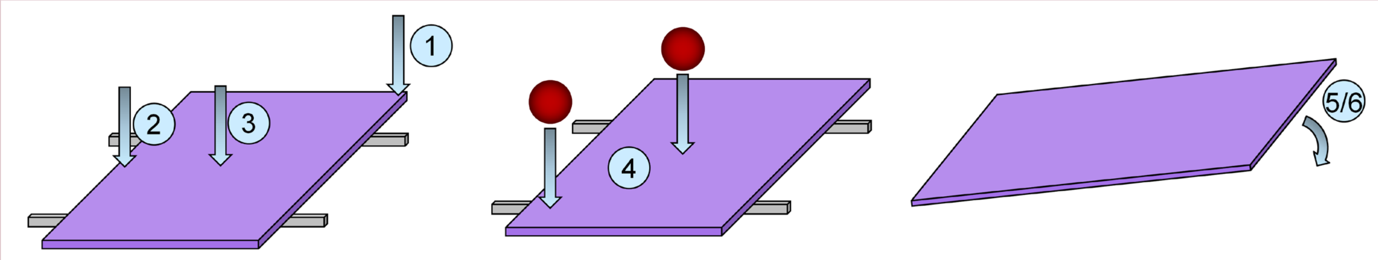


Table 2. Overview of the installation handling tests.

shown that overhead handling (i.e. module backsheet lying on a helmet) is not harmful to PV modules [5]; this type of handling is therefore also excluded from the tests. All the other observed handling types form the basis of the following test set-up. A shortlist of the tests inspired by the observations in the field is shown in Table 2.

Tests 1–3 are derived from stepping on a mounted PV module. The dropping of a cordless screwdriver on a PV module is simulated by Test 4. The tipping test in Test 5 is created to simulate the situation of destacking a module from a module stack; during destacking, the next module in the stack may be lifted up because of the sticking of the module stacking corners, and subsequently fall back onto the stack after a certain height. Test 6 simulates the non-gentle laying-down of a module onto a pallet or a mounting substructure.

Each test is conducted at –5°C and +25°C in order to examine the temperature sensitivity of the modules; for each temperature a new module is used. Before and after each test step, electroluminescence (EL) images are taken and the module power is measured. The output power of the PV module is measured by a flasher with a reproducibility of ±0.3% in module power for repeated measurements at standard test conditions.

Cell cracks are counted by using the differential EL method, which reveals even small cell cracks in multicrystalline solar cells. The EL image of the PV modules is recorded in the initial state and after any test procedure.

For each test a new module is used, apart from Test 6, for which the corresponding module of Test 5 is reused, since it is virtually undamaged after Test 5. In total, 20 modules (10 per type) are used for all tests.

"Cell cracks are counted by using the differential EL method, which reveals even small cell cracks in multicrystalline solar cells"

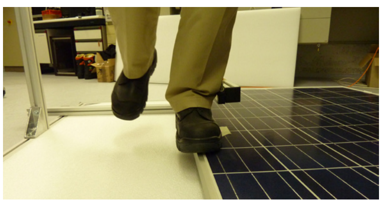
Tests 1–3

For Tests 1–3 the modules are mounted on a two-rail mounting system using four clamps, as suggested by the module manufacturer; the rail system is fixed on a rigid substructure. A laser distance sensor measures the deformation of the module surface, as shown in Fig. 1. The desired weight for the load tests is adjusted by adding weights to a rucksack carried by a person. From one test to the next, the weight of the load is increased: 25kg, 35kg, and then from 50 to 120kg in steps of 10kg. The person steps on the module slowly (1 sec) with one foot, remains for 5 sec, and then removes the foot again slowly (1 sec) (see Fig. 1). The module is loaded at the module corner for Test 1, at the centre of the module long edge for Test 2, and at the module centre for Test 3. For Tests 1 and 3, the module clamps are adjusted for the maximum distance between the clamps and the neighbouring module corners; for Tests 2 and 4, the clamps are adjusted for minimum distance between the clamps and the neighbouring module corners. These configurations result in a maximum deflection of the module in Tests 1 to 3.

Test 4

An internet survey of 2,687 cordless screwdrivers was performed; of these, 1,369 (50%) had a weight in the range 1–2kg (September 2014). A 'C-Jugend' (German youth athletic group C) skittle ball with a diameter of 130±0.2mm and a weight of 1.515kg was therefore chosen for the tool drop test (Test 4). The surface hardness of the skittle ball was 75±5 on the Shore D scale at 20°C [6]; the weight and the hardness corresponded to typical values for cordless screwdrivers.

The 20°C tempered ball is fixed by a pneumatic suction cap on a beam above the centre of a cell at each drop position, as shown in Fig. 2. The centre (o) and corner (x) fall positions on the PV module are indicated in Fig. 3. The distances between the drop positions are maximized in order to reduce any interaction of the drop tests. For each position, the fall test is repeated



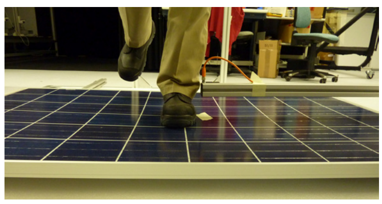


Figure 1. The top, middle and bottom pictures show the loading set-up for Tests 1, 2 and 3 respectively. The local bending of the module is measured by a laser distance measurement close to the loading point (black box in the images).

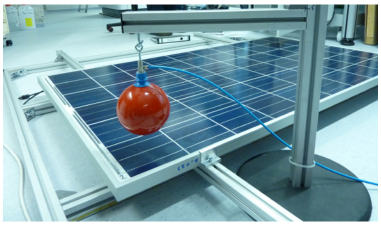


Figure 2. Set-up for Test 4 – tool drop test.

with increasing drop height, from 5cm to 20cm in steps of 5cm and from 30cm to 90cm in steps of 10cm, until the impacted solar cell breaks. Cell cracks below the point of impact are classified as primary cell cracks, and cell cracks elsewhere are secondary cell cracks. When the directly hit cell is broken, the next test is started at a 5cm drop distance in a new position, until all the marked positions of Fig. 3 have been tested. For Test 4, the clamps of the module are placed as close to the module corner as permitted by the manufacturer. These configurations allow the evaluation of the effect of the most rigid mechanical support at the corner position and the least support at the centre position.

Test 5

Test 5 simulates the drop of a PV module onto a module stack during destacking. Because most modules are stacked with their sunny-side down, the modules are dropped back onto a second module, both sunny-side down, as illustrated in Fig. 4. The short side of the module is dropped in order to test the case of the maximal drop energy. This side is jacked up with a stick, which is then pulled away at the start of the test. To adjust the exact drop height, several sticks of the following lengths were prepared: 5cm to 20cm in steps of 5cm, and 30cm to 50cm in steps of 10cm. The opposite side of the module is taped so that it cannot slide horizontally; this avoids an irreproducible jump-out of the module stack.

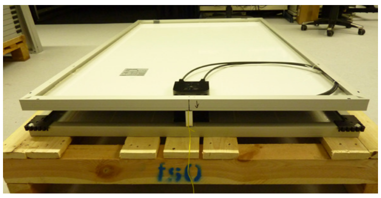


Figure 4. Set-up for Test 5.

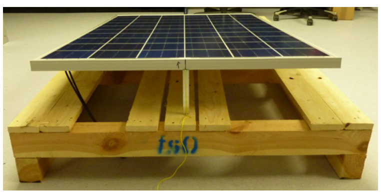


Figure 5. Set-up for Test 6.

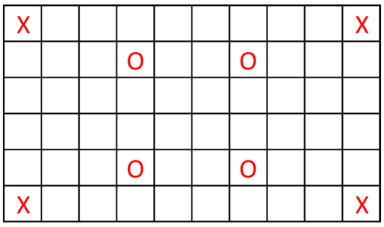


Figure 3. Pattern of the positions chosen for the drop test. The square grid indicates the cells in the module (x = corner drop locations; o = centre drop locations).

Test 6

Test 6 simulates a non-gentle laying-down or the dropping of a module onto the substructure of a PV system, or the laying-down of a module onto a pallet. This test is executed in the same way as Test 5, except that a rigid pallet is used as the bottom surface (rather than another module), as shown in Fig. 5. The chosen pallet and the module frame must not be deformed by the module drop. Furthermore, the pallet must have a partly open surface; this allows the air between the module and the pallet to escape, thus avoiding an airbag effect.

Results

Tests 1–3

Figs. 6 and 7 show the results of Tests 1–3 for module types I and II. The effective weight m_{eff}, which affects the module bending in the direction of the normal of the module glass plate surface, is calculated for a rooftop with an angle α of 45°. This effective weight is indicated on the top axis in Figs. 6 and 7 as the orientation for the loading effect on rooftop installations.

The bowing of the module caused by stepping on the module centre and on the module edge is similar for both module types. The bowing of the module corners by stepping on the corners, however, differs by 10mm. The much higher bending of the module corners for the type II module than for the type I module is due, at least in part, to the greater distance (+6.1cm) allowed from the mounting point to the neighbouring module corner.

Stepping on the module corners and edges does not result in cell cracks for either module type under 25°C test conditions. Stepping on the module centre, however, does cause cell cracks for both module types. For module type I, cell cracks occur at 90kg and above, and for module type II, from 50kg. In the case of both module types, the total number of cracked cells initiated by Tests 1–3 at –5°C is at least double the number of cell cracks at +25°C.

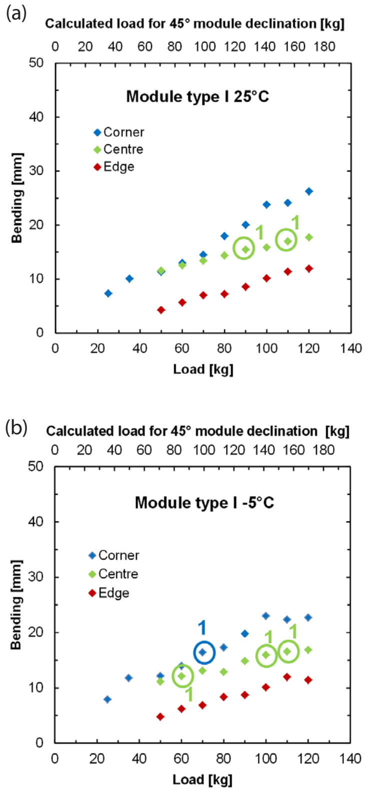


Figure 6. Results for Tests 1–3. Measured bending of a type I PV module close to the load position as a function of the applied load weight and temperature (a) +25°C; (b) –5°C. The circles show the loading steps that result in a cell crack; the number next to the circles indicates the number of cells cracked during this step.

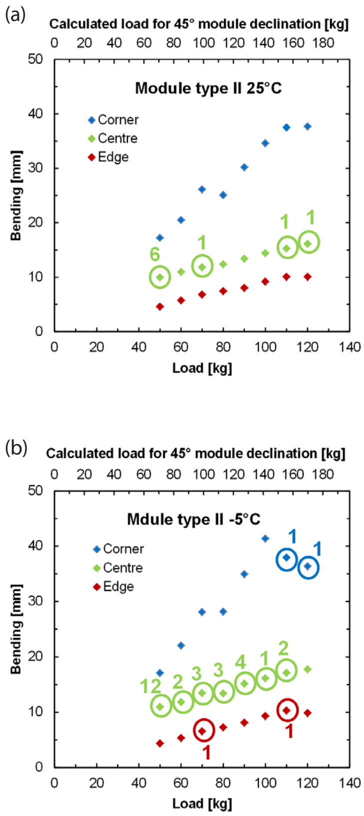


Figure 7. Results for Tests 1–3. Measured bending of a type II PV module near the load position as a function of the applied load weight and temperature: (a) +25°C; (b) –5°C. The circles show the loading steps that result in a cell crack; the number next to the circles indicates the number of cells cracked during this step.

Test 4

Fig. 8 shows the results of the drop test (Test 4) for both module types. The effective height, which affects the impact energy of the ball in the direction of the normal of the

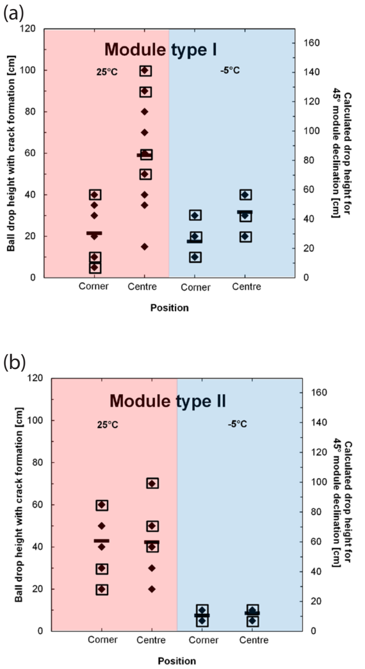


Figure 8. Dependency of cell crack occurrence on the impact position and on the temperature for (a) type I and (b) type II modules. The symbols inside squares indicate a crack of the cell direct below the point of impact of the ball. The other symbols represent secondary cell cracks of surrounding cells. The bars show the mean ball drop height for each test.

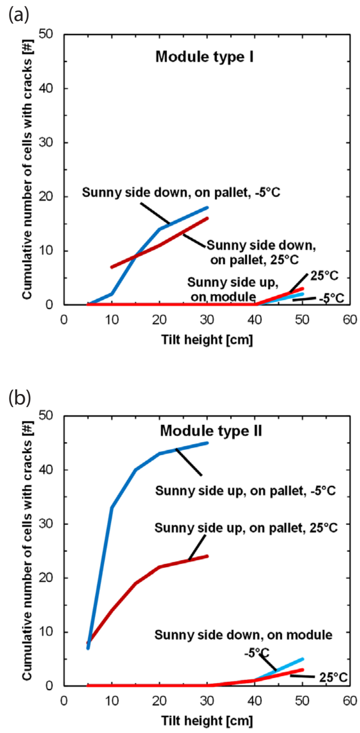


Figure 9. Cumulative cell breakage as a function of the tipping height of the short edge of (a) module type I and (b) module type II. The results for Test 5 (sunny-side down) and Test 6 (sunny-side up) at +25°C and –5°C are shown.

module glass plate surface, is calculated for a rooftop with an angle of 45 degrees. This effective height is indicated on the right axis in Fig. 8 as the orientation for the corresponding impact on a rooftop installation.

It was found that no safe dropping distance exists in the drop test; in some cases, even a drop height of 5cm resulted in a cell crack. Below a 15cm drop height, the resulting cell cracks were predominantly sustained by the directly hit cell. Of the 16 cells cracked by a direct hit, 14 demonstrated a star-shaped crack pattern.

Fig. 8 shows that the greater the ball drop height, the greater the chance of secondary cell breakage. None of the secondary cracks exhibit a star-shaped crack pattern. Secondary cell cracks are found up to two-thirds of the module length away from the direct hit location. Modules of both types are more sensitive to ball drops at –5°C than at +25°C: all directly hit cells survive at most a drop height of 30cm at –5°C , wheras some cells may survive even up to a drop height of 90cm at 25°C.

Tests 5 and 6

Fig. 9 shows the cumulative number of cells cracked in Tests 5 and 6 for both module types. The results in Fig. 9(a) and (b) demonstrate that tipping a module with the sunny-side down onto a module stack does not lead to cell cracks for a tipping height of up to 30cm. Even a tipping height of up to 50cm only leads to a maximum of six broken cells.

In contrast, the tipping of modules with the sunny-side up onto a pallet results in numerous cell cracks. For a module type I cell and at 25°C, cracking starts at a dropping height of 10cm, with seven cell cracks reported, while module type II shows seven cell cracks already at a drop height of 5cm. Although module type I exhibits a similar number of cell cracks at 25°C and –5°C, the number doubles in the case of module type II at the colder test temperature.

Impact on module power

		ΔP [%]				
Test		1	2	3	5	6
Module I	25°C	–0.2	–0.2	–0.4	0.0	–1.2
	–5°C	–0.2	–0.2	–1.7	–0.2	–0.4
Module II	25°C	0.1	0.0	0.1	0.0	–1.2
	–5°C	–0.3	0.0	–1.0	–0.3	–0.8

Table 3. Relative power loss of the tested PV modules. Relative values below |ΔP|= 0.3% are below the reproducibility of the test system, and are indicated by a darker background.

Table 3 shows the module power changes after Tests 1–3, 5 and 6, relative to the initial power; the power loss in all cases is less than 2%. For Test 4, a module power comparison makes no sense, because the number of ball drops is different for all modules since the drops are continued until the cell below the drop position breaks, whereas other cells in the module may break at intermediate test steps.

Discussion

Cell cracks typically cause only a small immediate power loss [3]. In the tests carried out, all the modules lost less than 2% of their initial power (Table 3), which indicates that the handling-induced cell cracks are not immediately relevant when considering the total power of a PV installation. The defects might get worse, however, during the service life of the PV system.

Despite the significantly greater bending of the module corner during the loading in Tests 1 and 2, many fewer cell cracks occur than when the module centre is loaded in Test 3. As a result of the down-bending of the corners, the cells are compressed in the laminate. However, solar cells are much more resistant to compression than to tension loading, which occurs when the edge and centre are loaded.

The load situations in Tests 2 and 3 result in both compression and tension of the solar cells in the module. However, the total bending by stepping on the module edge (Test 3) is the lowest of all three test scenarios, and therefore the number of broken cells is also low. Stepping on the module centre means that the cells in the module centre are strained in tension; as a consequence, and because of the relatively high bowing that occurs, a greater number of cells are cracked.

> "The most critical handling failure is the dropping of a sunny-side up module, even for short distances of a few centimetres"

The loads at –5°C lead to cell cracks at lower loads than at +25°C, because the EVA lamination material is one order of magnitude stiffer at –5°C than at the higher temperature [7].

The impact tests on the centre cells lead to many secondary cell cracks in the modules. During a hit in the module centre, the cells crack because the glass bends over a long distance and consequently stretches the cells. The bending of the glass can crack cells far away from the point of impact, because the strike causes a wave to pass along the entire glass plate. This effect carries the impact energy away from the point of impact, which may explain the high number of secondary cell cracks found in the case of drop tests in the middle of the module. The glass may locally deform if a support structure is close; this is true for corner cells, which break mostly with a star crack.

The type II module demonstrates cell cracks at lower ball drop heights in the module centre than the type I module. The type II module demonstrates similar mean crack heights in the centre and in the corner, whereas the mean drop height for type I is much higher for the centre compared to the corner. It is thought that the mounting is the reason for this effect, because for module type I the mounting points are 6.1cm closer to the corners than for module type II. The closer the drop point is to a rigid fix point, the higher is the cell crack impact of the drop, because the glass cannot bend down as a whole and must deform locally.

It is considered that the relatively low cell-breakage rate of the modules tipping with the sunny-side down compared with the sunny-side up case is due to the bending of the module's front glass after the touch-down. The sunny-side down module bends and so the cells are in compression, which is much less harmful to the cells than tension. Furthermore, in Test 5 the module directly under the tipping module prevents the air below the dropping module from escaping; an airbag effect might therefore reduce the touchdown speed of the tipping module.

In contrast, in Test 6 the sunny-side up tipping module bends after the touchdown and thus the cells are in tension, which increases the cracking – for example, from zero cracks for the sunny-side down test for a 10cm tipping height, to 2–33 cell cracks for the sunny-side up test. Moreover, an open pallet is chosen as the touchdown surface in Test 6; this allows the air under the tipping module to escape through the slits in the pallet, and so the module can reach a higher speed shortly before touchdown. The situation in Test 6 is similar to a typical module-mounting substructure.

Summary and conclusion

From earlier work [5] it is known that the handling of a vertical module is not critical with regard to cell breakage; for example, a module might have dropped vertically from a raised height of 20cm with no breakage of cells (although the frame may show some scratches and dents). For this reason, PV modules in the field, or especially calibration modules in the lab, should always be handled and stored vertically. For horizontal test equipment using modules sunny-side up, one should have specially supported modules that prevent bending of the laminate.

The dropping of modules with the sunny-side down onto a module stack is quite safe for a single-side drop distance of up to 30cm. However, if modules are dropped on stony ground, the glass plate may crack, and this handling failure should therefore be avoided.

The installation instructions from the module manufacturer with regard to not stepping on PV modules must be taken seriously; even stepping on the frame might crack cells in the module. To help avoid stepping on the PV modules during installation, service and repair, there are currently many solutions on the market; for example, special commercially available crossbars, which are placed on the module frame, may be used to step on a module.

Heavy tools, such as a cordless screwdriver, should be secured at the wrist with a tool lanyard during any work undertaken on PV modules, because no safe drop height exists for this situation. The most critical handling failure is the dropping of a sunny-side up module, even for short distances of a few centimetres, which must therefore always be avoided. This caution should be taken seriously, especially during the placement of the modules on the roof/substructure. If possible, the module should be laid down directly onto the roof/substructure without any dropping distance. In the authors' opinion, this step is more important than most other typical transport and handling issues, because it is a frequent and typical step during a module installation. The handling of cold PV modules, especially in temperatures below freezing, should be avoided if possible. Furthermore, a 5cm drop test could be performed (even on a building site) using EL imaging equipment to check the crack sensitivity of a PV module. A well-processed module should not show new cell cracks after a 5cm drop of one edge with the sunny-side up.

The effects of handling failures on module power are initially very low: even the worst handling test demonstrates a power loss of less than 1.7%. However, any solar cell cracks that are initiated might increase the degradation rate of carelessly handled modules compared with carefully handled ones. Installers should be fully conversant with module-handling rules in order to ensure a long service life for the PV system. ■

Acknowledgements

We thank F. Haase for fruitful discussions about this paper. Funding was provided by the German Federal Ministry for Economic Affairs and Energy under Contract No. 0325295A.

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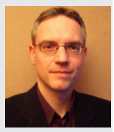

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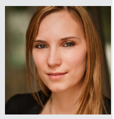

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