Increase of PID susceptibility of PV modules under enhanced environmental stress

Module degradation | Potential-induced degradation (PID) is still one of the main reasons for unpredictable power losses in PV power plants. Volker Naumann, Otwin Breitenstein, Klemens Ilse, Matthias Pander, Kai Sporleder and Christian Hagendorf of Fraunhofer CSP examine how the PID susceptibility of PV modules is influenced by environmental stress. It is found that PID may develop in originally PID-resistant modules after a period of one to three years of unsuspicious operation, depending on climatic conditions

Credit: Fraunhofer CSP

Potential-induced degradation (PID) of PV modules containing silicon solar cells is an issue with high relevance to the long-term reliability of PV systems [1]. Despite knowledge of methods for mitigation of PID for standard module technologies, there are still new cases of PID arising related to new technologies such as bifacial solar cells or cheaper packaging materials. It was observed that even PV modules designed and specified to be "PID-free" can develop PID under particular outdoor conditions. Especially humid and hot climates in combination with soiling can lead to a change of the electric properties of the module encapsulation, which results in PID degradation of initially "PID-free" modules, in particular when they exhibit a conventional metal frame and a polymeric back sheet, which is to some extent water permeable. This is attributed to the change of the electric conductivity of the glass surface and of the encapsulating materials [2] causing increased leakage currents on the path from the frame across the glass surface and through the module encapsulation layers and thus change of the electric field in the anti-reflective coating (ARC) of the solar cells.

State-of-the-art assessment of PID susceptibility and leakage currents of aged modules under accelerated test conditions, using the PIDcheck test device

In a PV power plant, many modules (each delivering a voltage of about 35V) are switched in series, leading to voltages to ground up to several hundred volts. Both the module glass and the polymer back sheet are no absolute insulators, therefore tiny leakage currents may flow between the cells in the modules and ground. The leakage current that flows under high-voltage stress of 1,000 V amounts to typically some 10µA/m² for solar modules with soda-lime front glass and EVA encapsulation. This can be measured outdoors e.g. using the PIDcheck test device, as shown above.

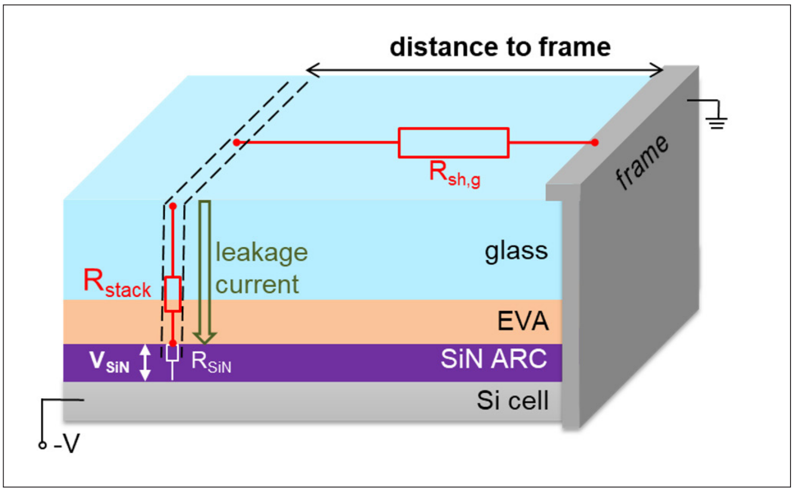

Figure 1. Equivalent circuit for the leakage current path at the front side of a framed PV module (voltage divider model). $R_{sh,g}$ and R_{stack} are subject to changes due to environmental influences like soiling and moisture. The voltage across the SiN ARC of the solar cells determines the strength and rate of PID and depends only on the local leakage current (density) through the encapsulating layer stack and the electric properties of the SiN layer (R_{SiN})

PID may occur if the voltage drop across the insulating SiN anti-reflective coating (ARC) layer at the top of the cells V_{SiN} exceeds a certain limit, driven by the leakage current. In this work, PID of the shunting type [1] (also called "PID-s") is addressed since currently it is the most detrimental type of PID.

Figure 1 illustrates the leakage current flow in a module. The Si cell is assumed to lie on a high negative voltage $-V_c$, since only negative cell voltages are known to lead to PID of the shunting type [1], and the metallic frame is assumed to lie on ground potential. Then, for enabling leakage current to flow to the cell at a certain lateral position of the module, first the current must flow horizontally to this position via the glass surface sheet resistance $R_{sh,g}$, and then it flows vertically through the stack of glass and the encapsulating polymer ethylene vinyl acetate (EVA) to the cell having a resistance of R_{stack}. Note that for this stack the EVA layer represents the limiting resistance, since the resistance of the glass is relatively low. On top of the cell there is an anti-reflective coating (ARC) made by amorphous silicon nitride (SiN), which is an excellent insulator. However, this layer is very thin (below 100 nm) and thus does not contribute significantly to the resistance across the layer stack R_{stack}. If the voltage across this layer V_{SiN} exceeds 5-10 V, which is well below the cell voltage to ground $-V_c$, leakage current J_{leak} flows through, which may lead to PID. It is known that V_{SiN} depends logarithmically on J_{leak} [3]. Thus, the circuit shown in Figure 1 represents a voltage divider [3], where the leakage current density J_{leak} and thus the voltage V_{SiN} (being critical for PID) becomes the larger, the lower the sum of $R_{sh,g}$ and R_{stack} is. In this work, the specific variations of the resistors $R_{sh,g}$ and R_{stack} are to be determined quantitatively in dependence of soiling and the humidity soaking process.

In the approximation of ohmic resistors the voltage across the SiN ARC V_{SiN} along a specific current path or location at the module, respectively, is given by

$$V_{SiN}=V_c\, R_{SiN}/(R_{sh,g}+R_{stack}+R_{SiN}) \propto J_{leak} \qquad (1)$$

Experimental approach

Thirty-six single-cell mini modules with three different commercial EVA encapsulation materials (A, B and C) were manufactured. The solar cells are special PID-susceptible multicrystalline silicon PERC cells with dimensions of 156.75 x 156.75 mm^2. The layer stack of the mini modules comprises (from front to rear): 3.2 mm low-iron float glass, EVA foil, solar cell, EVA foil and the back sheet. In addition to the mini modules, EVA-glass laminates with dimensions of 10 x 10 cm^2 were prepared using the same glass and EVA foil.

For acquisition of the electrical resistance of the clean and dusted glass surface as a function of the surface humidity, the surface humidity was increased from ~30% to ~100% by cooling of the mini module at constant air temperature and humidity. The temperature of the surface was measured with a precise thermocouple while the chuck was cooled from ~30°C to about 1 K below the dew point (~7°C), which represents 100% RH. The temperature profiles are recorded and used for calculation of surface humidity values.

The sheet resistance as a function of the relative surface humidity is calculated by measuring the current between two adhesive metal electrode strips on the glass surface before and after the soiling test by using a Keithley 2601A source measure unit. The applied voltage was 40 VDC.

"Soiling" means the unintended deposition of dust particles at the surface of solar modules during operation, which leads to additional

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light absorption and to a decrease of the glass surface sheet resistance, as mentioned above. One of the mini modules has been subject to soiling tests in a self-constructed soiling chamber, which is capable of controlled dust deposition at defined environmental parameters. For this, Arizona Test Dust A2 fine was used. The dust settled from the dust aerosol at about 40% relative humidity (RH) and 22°C ambient and 30°C surface temperature over 30 minutes, so that a surface coverage (area covered with dust) of about 20 % was reached.

For assessment of the influence of water ingress in the polymeric encapsulation foils, damp heat soaking of the mini modules is performed in a damp heat chamber at 85°C, 85% RH for 500, 1,000 and 2,000 hours. At each

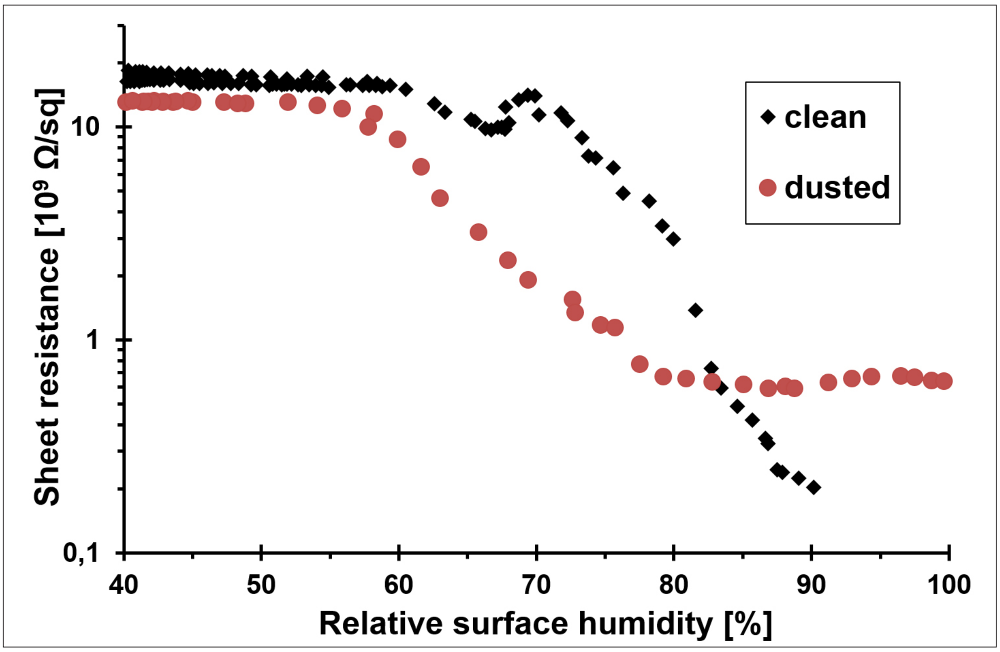

Figure 2. Glass surface sheet resistance $R_{sh,g}$ measured at the clean state (black) and after a well-defined soiling test (Arizona Test Dust) with a final dust surface coverage of ~20 % (red)

condition, including the dry (initial) state, PID tests and characterisation of the EVA have been performed at similar mini modules. For measurement of the water uptake of the EVA by so-called Karl Fischer titration, ~4 cm^2 sized pieces of the front side EVA are delaminated out of the mini modules at the centre and at the corner of the solar cells.

PID tests are performed using four PIDcon test devices by Freiberg Instruments, equipped with mini module test capabilities. The high electrical potential of +1,000 V is applied to the electrode that contacts the front glass of the mini modules on an area equal to the cell area. During the PID tests the shunt conductance of the cells is measured. In addition, the leakage current that is flowing through the glass and EVA layers is recorded.

The water content-dependent electric behaviour of two EVA samples is additionally measured at glass-EVA laminates, using a voltage source up to 1,000 V and a Keithley 2601A source measure unit for current measurements in the nA…μA range. The 10 x 10 cm^2 sized glass-EVA laminates are covered with a perforated Al foil on the EVA with small (sub-mm) holes in the Al foil at a pitch of 1 cm. They are tested at initial (dry) condition after lamination as well as after a one-week damp heat cycle, when the water uptake was presumably saturated.

Influence of soiling on surface sheet resistance

In Figure 2 the measured dependence of the glass surface sheet resistance is shown as a function of relative humidity level for two surface conditions: clean and dusted. We see that already for low humidity (below 50%) the dusted surface shows a slightly lower sheet resistance than the clean one. This difference becomes much stronger for humidity above 55%. Interestingly, the resistance of the dusted surface saturates for humidity above 80%, whereas that of the clean surface does not. This finding could be explained by the formation of a closed ultra-thin water film in the case of the clean sample above 80% humidity, but the proof requires more research. The basic result of Figure 2 is that the glass surface sheet resistance starts to reduce significantly at humidity levels well below the dew point of 100%. Note that the Arizona test dust used here does not contain any salts and only minor fractions of other hygroscopic contents. We attribute this behaviour to capillary condensation at the surface, which may happen both for the dusted and the clean surface already at lower humidity levels.

Moisture ingress to EVA

Figure 3 shows the water content (measured by weight) of the front side EVA in mini modules for the three investigated EVA foils, extracted from the centre and the corner in front of the solar cell after 0, 500, 1,000 and 2,000 hours of damp heat soaking. At the

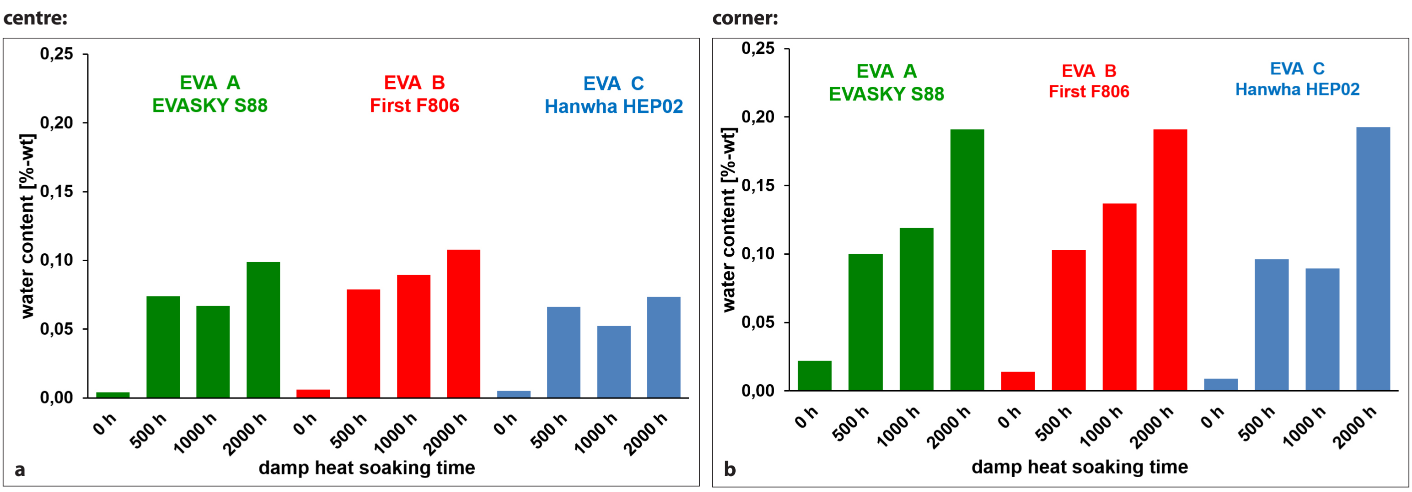

Figure 3. Water content of the front side EVA within mini modules as a function of damp heat soaking time (left) at the centre of the mini module; (right) at a corner of the cell

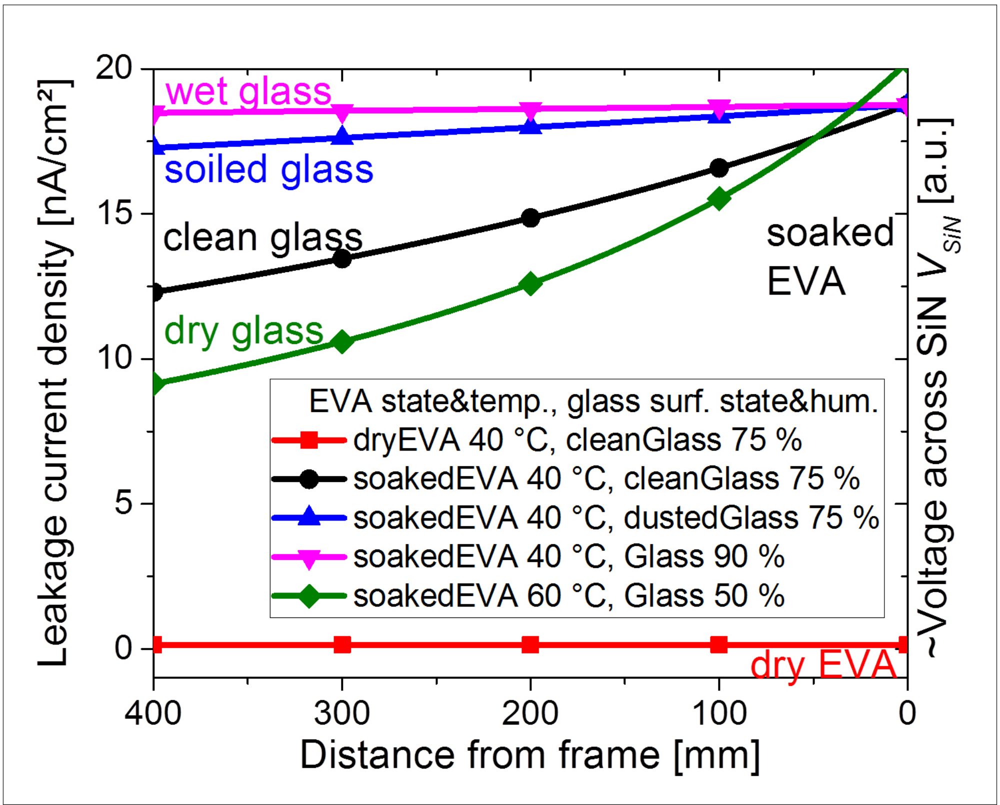

Figure 4. Calculated leakage current density as a function of the distance from the module frame based on measured electrical properties of the front glass surface (clean vs. soiled) and EVA (dry vs. damp heat soaked, here: EVA C)

centre position, the initial water content (in dry condition after lamination) is measured to be lower than 0.01% for all three EVA foils.

The damp heat conditions expedite the water ingress that will happen over time in the field [4]. As can be seen from Figure 3, the water content at the centre of the cell is lower compared to the corner just because of the different lengths of the diffusion paths. With increasing soaking time, the water content increases, but at different rates for the three EVAs. EVA A and B have quite similar soaking behaviour while the water uptake rate in EVA C is lower.

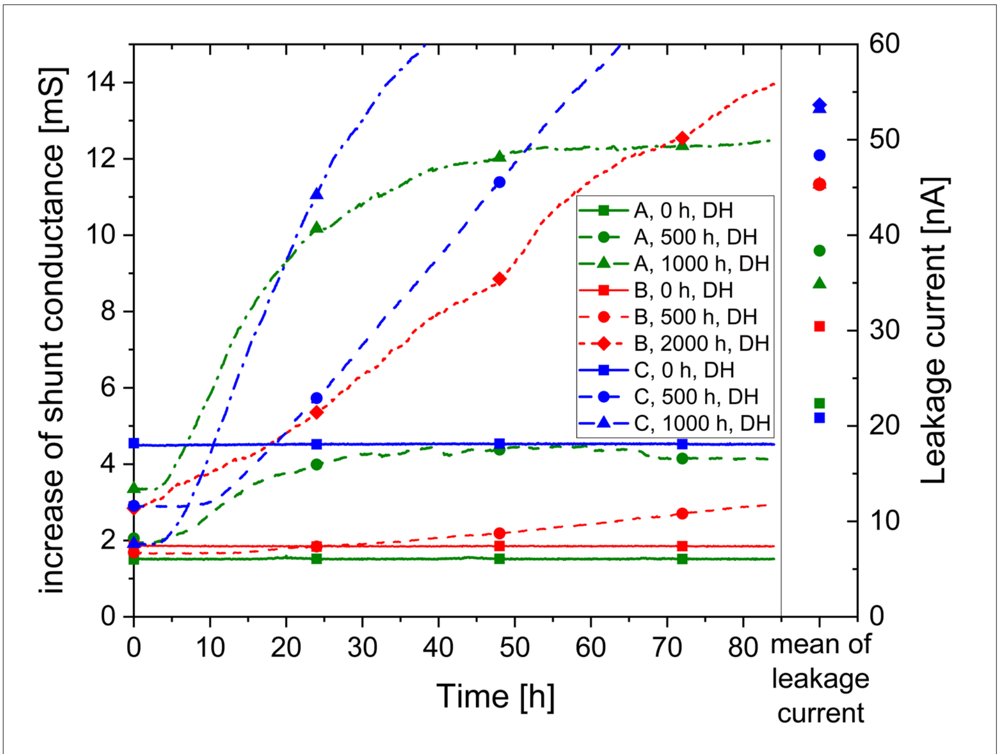

Figure 5. PIDcon PID tests at mini modules after different durations of damp heat soaking exhibit a significant increase of the PID (shunting) susceptibility of modules due to increasing water content of the front EVA

From the corner results (Figure 3b) after 2,000h, it seems that all materials will reach the same saturated value. Even if 2,000 hours are not representative for all climates, the significant increase of water content even after 500 hours of damp heat soaking, being equivalent to one to three years of outdoor weathering in tropical to arid climates [4], is remarkable. Consequently, brand-new modules, which are normally supplied for PID testing, generally have much lower moisture content than will later be the case in operation. Therefore, the PID testing on such modules may lead to false-negative results, since in operation the modules may absorb water and thus become PID-susceptible at some point.

Leakage current modelling

Based on the voltage divider model presented in Figure 3, the leakage currents can be calculated as a function of the distance from the frame. The leakage currents follow the electrical potential distribution from the metal frame across the glass surface and through the encapsulation polymers. The resulting voltage across the SiN ARC is the driving force for PID [3]. The leakage current density J_{leak} can be obtained for both full-scale and mini modules, respectively. As variable parameters in our model we used the measured resistivity values of the EVA material C after different pre-soaking durations, the glass surface sheet resistance values from the soiling tests at different humidity conditions and the distance to the frame. As a fixed parameter, the voltage V_c is set to 1,000 V.

Thus, different soiling and water soaking conditions as well as the resulting PID stress states of the solar module are deduced from the measured resistance values for the glass surface and the EVA-glass laminates. This is exemplarily shown in Figure 4 for the EVA material C in the dry condition (red graph) and in the soaked condition (other graphs). For the dry EVA a constant leakage current density of 0.14 nA/cm² is calculated for a temperature of 40°C, regardless of the glass surface condition (not shown here). This is attributed to the low contribution of the glass surface to the overall resistance along the leakage path. In the case of the soaked EVA (saturated water content of presumably 0.2 %) the regime of the strongly increased leakage current density level with a calculated maximum of 19 nA/cm² at 40°C depends on the condition of the glass surface. For the wet glass surface (90% RH), again, the resistance of the glass surface has a low contribution, leading to a flat behaviour of the leakage current. For the dry glass surface (50% RH) there is a pronounced drop of the leakage current density with increasing distance from the module frame. For moderate humidity levels (75% RH) the dependency of the leakage current on the surface state (clean vs. soiled) is clearly visible.

Even these comparably small differences in the leakage current density that are caused by soiling, can have a strong impact on the evolution of PID. Since the threshold of the voltage across the SiN ARC of the solar cell for beginning of significant PID (of the shunting type) is expected to be in the range of 10 V [5], the threshold for the leakage current density is in the range of 10…30nA/cm², according to [3]. Therefore, it is concluded that the soiling state of modules can have a strong impact on the evolution of PID by adding a small amount of leakage current stress to cells that are further away from the module frame.

PID tests at mini modules

The modelled leakage current densities and thereof implied voltage level across the solar cells' SiN ARC are compared with degradation rates measured through PID tests on the mini modules with the three different EVA materials after increasing damp heat soaking durations.

The increase of shunt conductance of the mini modules is shown in Figure 5 as a function of PID test time, together with corresponding average leakage current values also measured during the PID tests. The shunt conductance at the beginning of each PID test, which is governed by the parallel resistance of the non-degraded cells, has been set to 0 by subtraction of an offset. In the initial state (with 0 hours of damp heat soaking), all mini modules with the three tested EVA materials exhibit no increase of the cell shunt conductance (i.e. PID) during and after the PID tests performed with a high voltage of 1,000 V at 40°C for 84 hours each. After damp heat soaking of 500, 1,000 and 2,000 hours, respectively, there is a significant PID susceptibility measurable, which increases with the duration of damp heat soaking. It is interesting that even after comparably short damp heat duration of 500 hours there is a pronounced PID susceptibility, especially for the EVA material C. This might be a hint that not only the plain water content, but also the chemical formulation of the EVA has an influence on its resistivity at elevated water content levels.

Conclusion

A systematic investigation of the change of electric properties of the front glass surface and the polymeric encapsulation materials upon soiling and moisture ingress, respectively, is used for modelling basic dependencies. The impact on PID sensitivity is exemplarily measured for the case of water uptake of three commonly used EVA materials. Even though the modules exhibit PID resistance in the initial condition, all EVA products develop increasing PID susceptibility due to prolonged damp heat testing. Extrapolated to field conditions, this means that PID may develop after a period of one to three years of unsuspicious operation, depending on climatic conditions.

Furthermore, it was shown that soiling leads to boosted areal grounding of the glass surface at moderate humidity levels, thus promoting PID of the whole module area. This aspect will be part of future research, since soiling will become more and more relevant given the rising installation shares in the sunbelt regions of the world. ■

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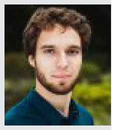

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