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RESEARCH ARTICLE

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Effects of solar cell group granularity and modern system architectures on partial shading response of crystalline silicon modules and systems

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Abstract

Partial shading is widely considered to be a limiting factor in the performance of photovoltaic (PV) systems applied in urban environments. Modern system architectures combined with per module deployment of power electronics have been used to improve performance especially at heterogeneous irradiance conditions. In this work another approach is used to combine modern system architecture with alternate module designs. The granularity of cell groups in PV modules is investigated together with the so-called Tessera concept, in which single cells are cut in 16 parts. Typical meteorological year yield calculations show that these alternate module designs in combination with modern system architectures can retrieve up to half the shading losses compared to standard modules and string inverters under identical shading conditions.

KEYWORDS
solar cell granularity, Tessera module, module level power electronics, bypass diodes

1 | INTRODUCTION

Photovoltaic (PV) energy technologies are becoming increasingly prominent in the global energy mix. Global cumulative capacity rose from 3 GW in 2003 to 500 GW in 2018 and SolarPowerEurope further foresees a more-than-doubling of capacity to 1 TW by 2023 with continuation of market growth toward 2030.[1] What is more, PV is considered to be one of the fastest-growing industries worldwide.[2] These trends are thought to be closely related to vast PV cost reductions over the last years.[3]

Furthermore, the adoption of PV systems is not only concentrated in large ground mounting systems but it has a fair share in residential systems and in the urban environment in general. Adoption of PV systems in the urban environment comes with a yield sacrifice due to partial shading from various objects in close proximity such as chimneys, dormers, trees, and neighboring buildings. If the irradiance on shaded cells is low compared to the irradiance on un-shaded cells in the same series connection, the shaded cells can be forced to support current levels exceeding their characteristic short-circuit current. This may push the shaded cells into reverse voltage regimes where they start behaving as rectifying diodes.[4] As a consequence, thermal power dissipation by the cells in question causes excessive power losses, the formation of localized "hot spots" and possible permanent cell damage.[5]

New products have been introduced on the market in recent years. This is caused by the commercial development of per-module PV power electronics. Generally, these products fall into the categories of (1) DC-DC conversion power optimizers connected to central inverters, and (2) AC micro-inverters.[6] These types of devices are also referred to as distributed power electronics or module-level power electronics (MLPE). This is because power optimizers (POs) and micro-inverters (MIs) optimize the maximum power point (MPP) of the module and distributed power per module instead of for the entire PV system at once, as is generally the case for central inverters. In a previous study we showed some yield increase under partial shading conditions using MLPE.[7]

Similar studies for shading optimized module designs have shown promising results. Specifically, cell granularity and the use of power electronics laminated in the module are considered to be beneficial for power output during partial shading. Golroodbari et al.[8,9] has shown that a typical c-Si module with 60 series connected cells (three groups of 20) has been re-arranged in 10 groups of six cells. Each cell group was connected to a DC/DC buck converter which can adjust the current on the shaded cell groups by limiting the voltage output. In this way the power output can be significantly improved under partial shading but due to the working efficiency of the DC/DC converters power output is suffering under non heterogeneous irradiance conditions. A differential power processing architecture has been proposed by Olalla et al.[10] which employs distributed low power processing sub module converters. Another approach[11] is to use "cool BPDs" per group of solar cells. These newer diodes resemble the typical Schottky diodes used in standard PV modules but the

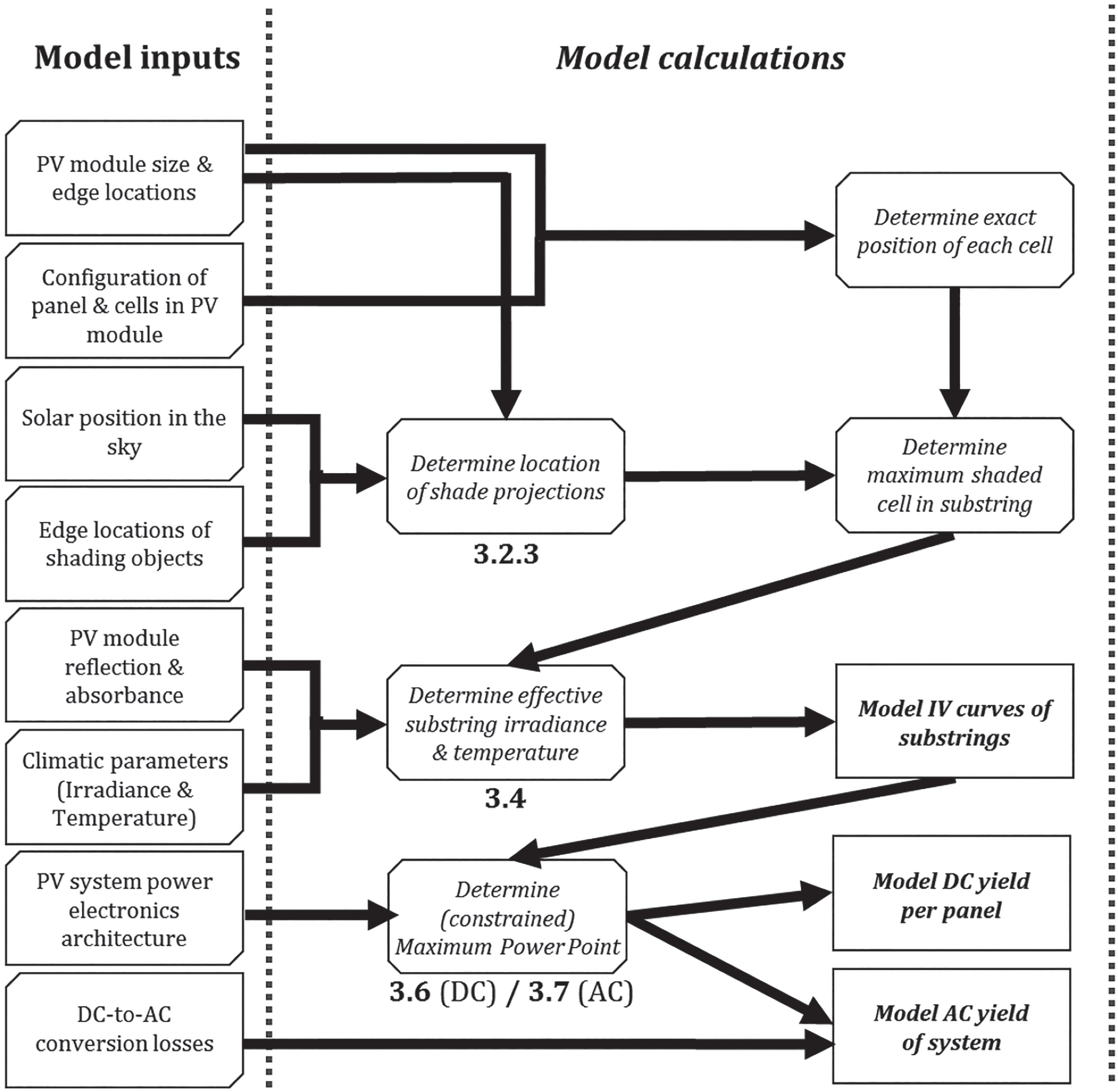

FIGURE 1 Flowchart of the complete model for each timestamp

power and heat dissipation of these diodes is far superior. Literature thus concludes[12] that the module and system design are the limiting factors in an effort to decrease partial shading losses. In this paper several module designs will be evaluated, mainly the insertion of additional by pass diodes and thus resulting in smaller c-Si cell groups and beyond cell level to sub cell level with the Tessera module technology. Lately several companies[13,14] are launching half-cell or even quarter cell modules. The benefit of such module architectures is the lower series resistance losses occurring especially in high irradiance conditions and the improved shade response of these modules due to the parallel connection of the sub modules. In this paper the Tessera module takes this technology a step further by introducing back contact Metal Wrap Through (MWT) mini cells. The mini cells are cut from 6-inch full size MWT cells in 16 mini cells which are then connected in series forming blocks which are then connected in parallel. These module designs will be evaluated with modern system architectures to determine the most beneficial combination.

2 | METHODOLOGY

To properly evaluate the module and system designs a simulation model was developed by the authors in the past.[15] The model includes a shading evaluation of the installation by means of 3D modeling, irradiance calculations, PV cell modeling and finally an empirical power conversion model based on previous outdoor analysis.[7] In this paper, the model has been adapted to accommodate several module designs by means of smaller group cells or smaller cell sizes and adapting the series and parallel connections between the cells. An overview of the model flowchart can be seen in Figure 1. The partial shading conditions opted for in this research is set to match typical shading objects on a representative "reference" south-facing rooftop. The rooftop reference (Figure 2) is determined for The Netherlands because the Dutch documentation on the housing stock is extensive.

For the system design mono-crystalline silicon (c-Si) panels were used that are well documented from previous experiments by the

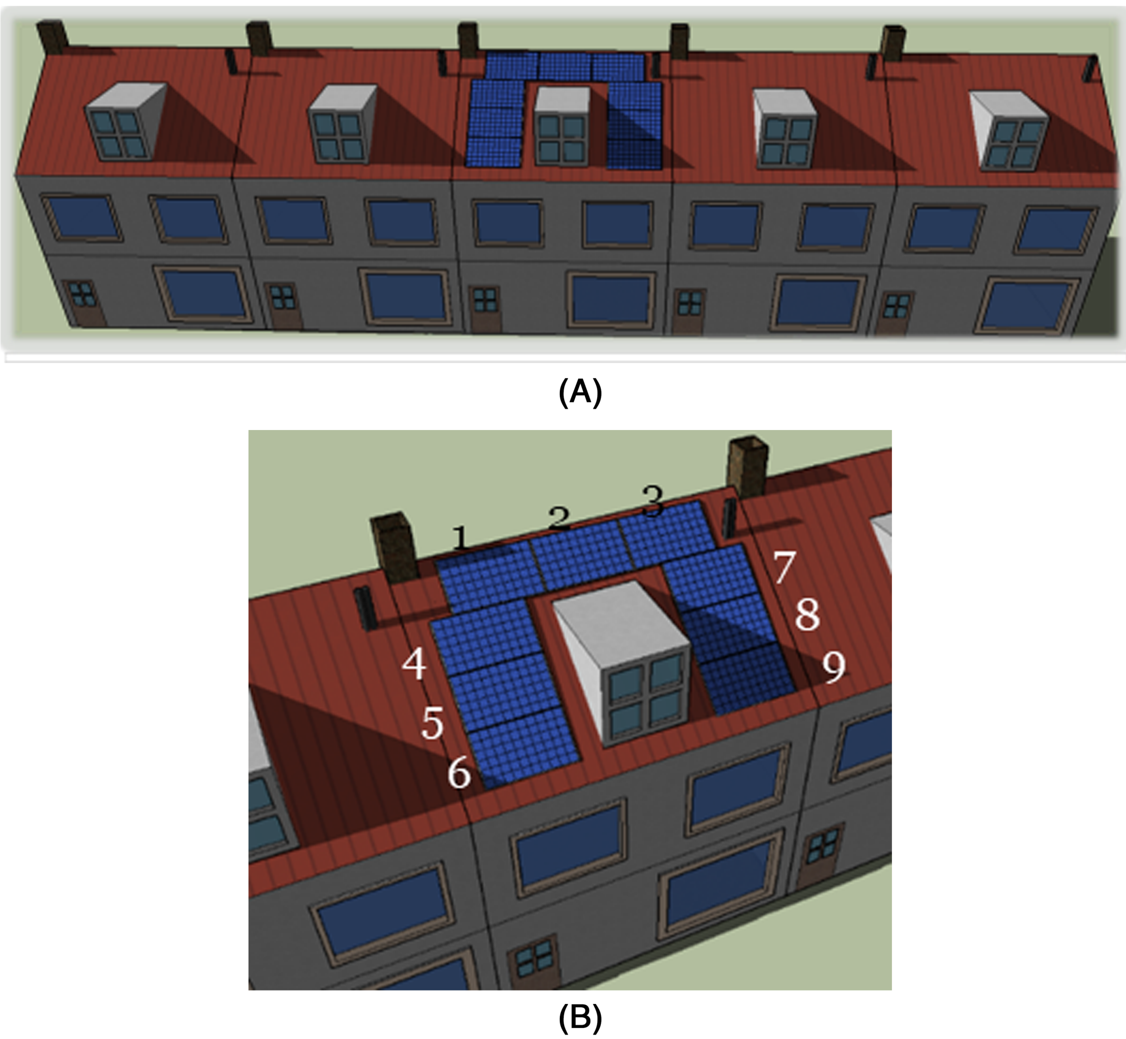

FIGURE 2 Sketch up representation of the (A) modeled house in a row of similar houses including shading elements such as dormer, chimney, and ventilation exhaust pipe, (B) detailed view with the photovoltaic (PV) modules numbered for later reference

authors.[7] Through the model the cell groups within a panel could be modified by grouping them to groups with smaller amounts of cells. Furthermore, three different PV system architectures were used in the research.

a. String inverter with shadow mode
b. Micro inverters
c. Power optimizers

The shadow mode of the inverter is a hybrid Perturb and Observe MPPt algorithm which allows frequent voltage sweeps. In this way the global MPP can be found. The shadow mode is delivered as standard in most of the commercial inverters and should be activated via the inverter settings interface.

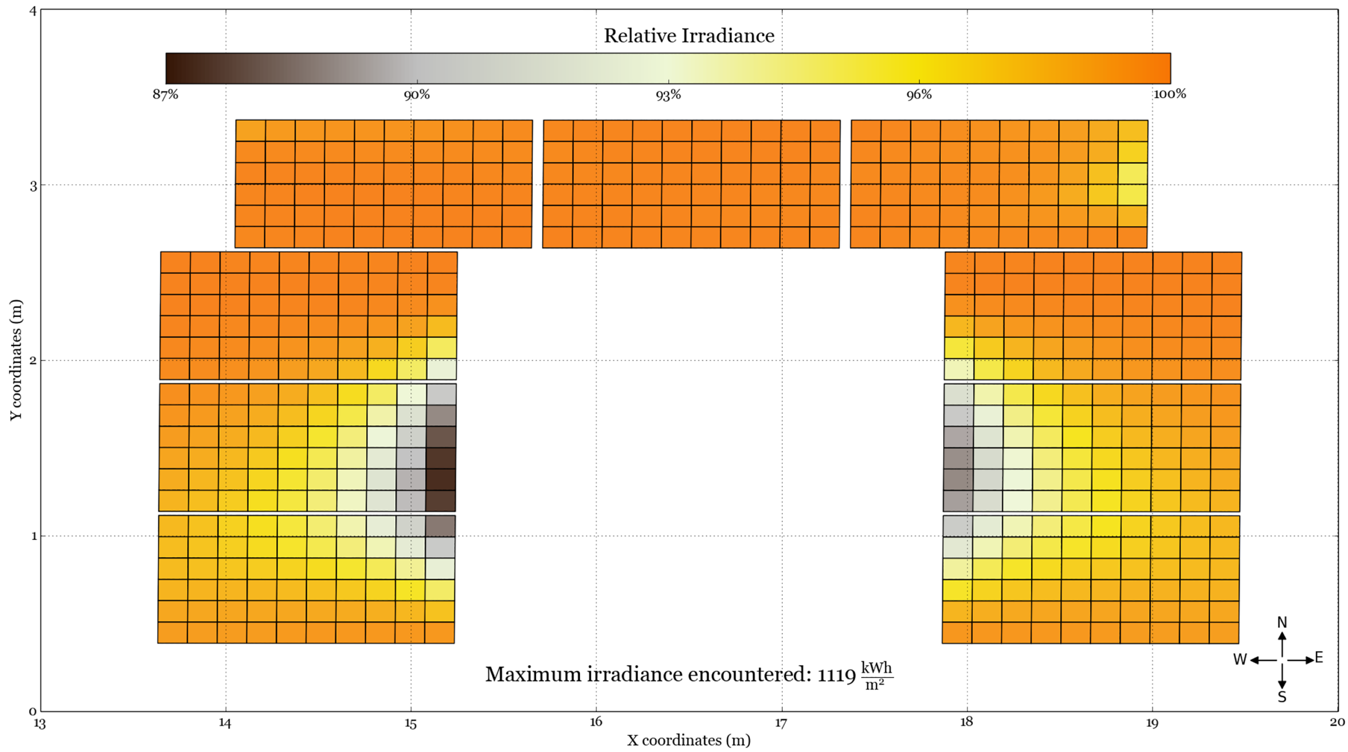

FIGURE 3 Annual relative irradiance losses per cell of a nine module system

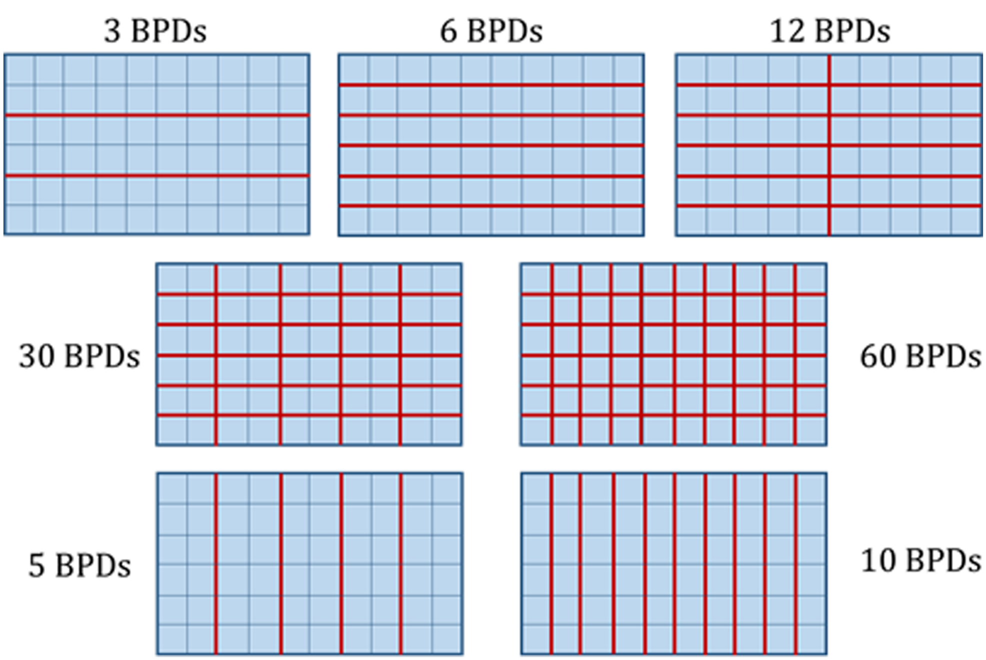

FIGURE 4 Substring granularities or variation of per-module bypass diodes (BPDs) investigated in this research. The 3, 6, 12, and 30 BPD cases are referred to as horizontally aligned substrings; the 5 and 10 BPD cases as vertically aligned substrings. BPDs per cell are assumed in the 60 BPD case

The model employs a time step of 1 hr and uses typical meteorological year (TMY) data from Meteonorm[16] for Eindhoven in The Netherlands. In Figure 3 the annual reduction of irradiance per cell can be seen. The heaviest shaded modules are the ones close to the dormer with up to 13% lower irradiance. Smaller effects can be seen in modules close to the chimney and exhaust poles. The total annual irradiance reduction averaged across the whole surface of the PV system is around 2%.

3 | GRANULARITY OF CELL GROUPS

Nowadays most PV modules are equipped with bypass diodes (BPDs) per substring of 12–24 cells connected in series to avoid hotspots. It has been proven[15] that 50%–60% shading of a single cell in the substring is sufficient to activate the bypass diode and thus loose one third of the power output of a module. By applying the previously developed simulation model[15] cell group granularity is investigated. The module designs that are investigated can be seen in Figure 4. The three BPD module is the industry standard in the past years. In this work we evaluate various scenarios of solar cell granularity ranging from the industry standard to an extreme of a single BPD per cell, totaling 60 diodes in a module. The effect of shading on the cells surface is illustrated in Figure 5. In Figure 6 the IV curves of the module designs can be seen. It can be concluded that the increased cell group granularity of each cell protected by a pass diode can extract up to 130% more power at a given shading scenario.

The effect of shading on the DC energy production of the total system of nine panels in the simulated environment is shown in Figure 7. Note that the DC results exclude the effects of system architecture. These are incorporated in the AC results which are shown later. The reference case, as depicted by the dark-yellow bars,

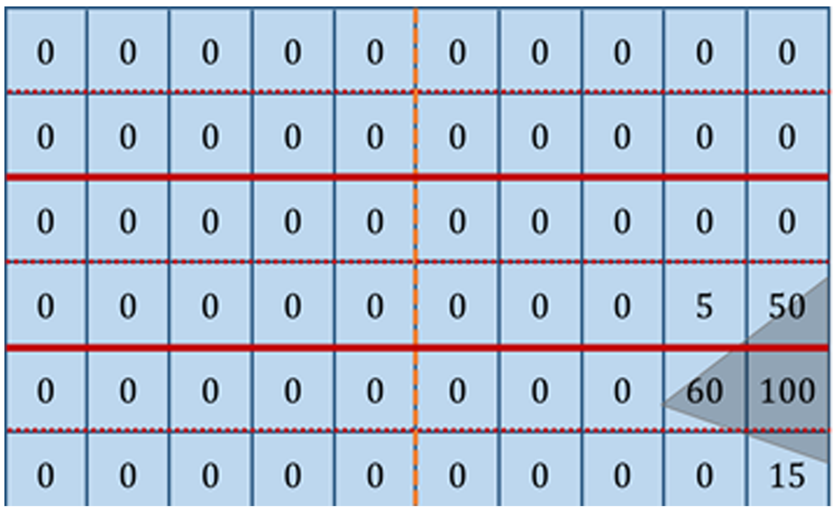

FIGURE 5 Partially shaded photovoltaic (PV) module with shaded cell percentages. The red thick horizontal lines indicate the edges between substrings if 20 cells per substring (three bypass diodes, BPDs) are used. Thin dashed horizontal red lines do so for substrings of 10 cells or six BPDs, and the dashed vertical orange line does so for substrings of 5 cells or 12 BPDs in this example

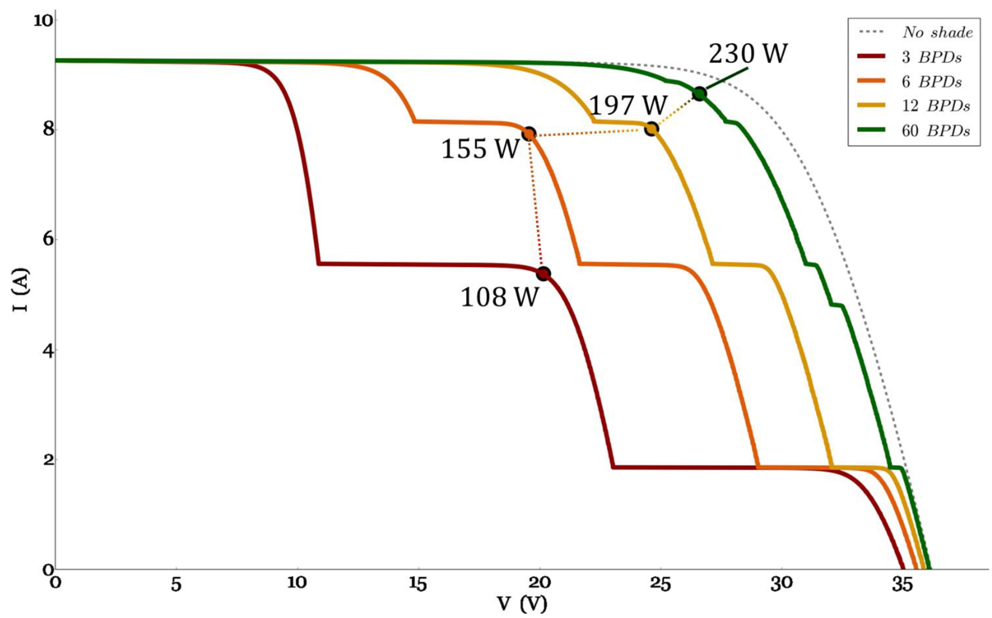

FIGURE 6 IV responses of example module under partial shading as in Figure 5. The cases of 3, 6, 12, and 60 per-module bypass diodes (BPDs) are shown. All increases in number of BPDs lead to increases in extractable power, as can be seen from the highlighted maximum power point (MPP) values

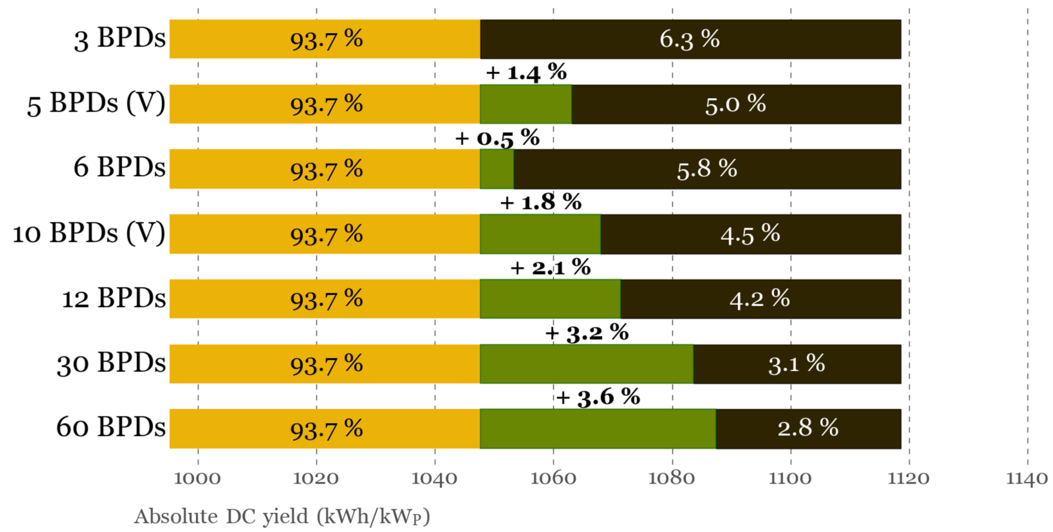

FIGURE 7 Annual DC energy yield for various cell granularities for a full system of nine panels (Figure 2) exluding the system architecture

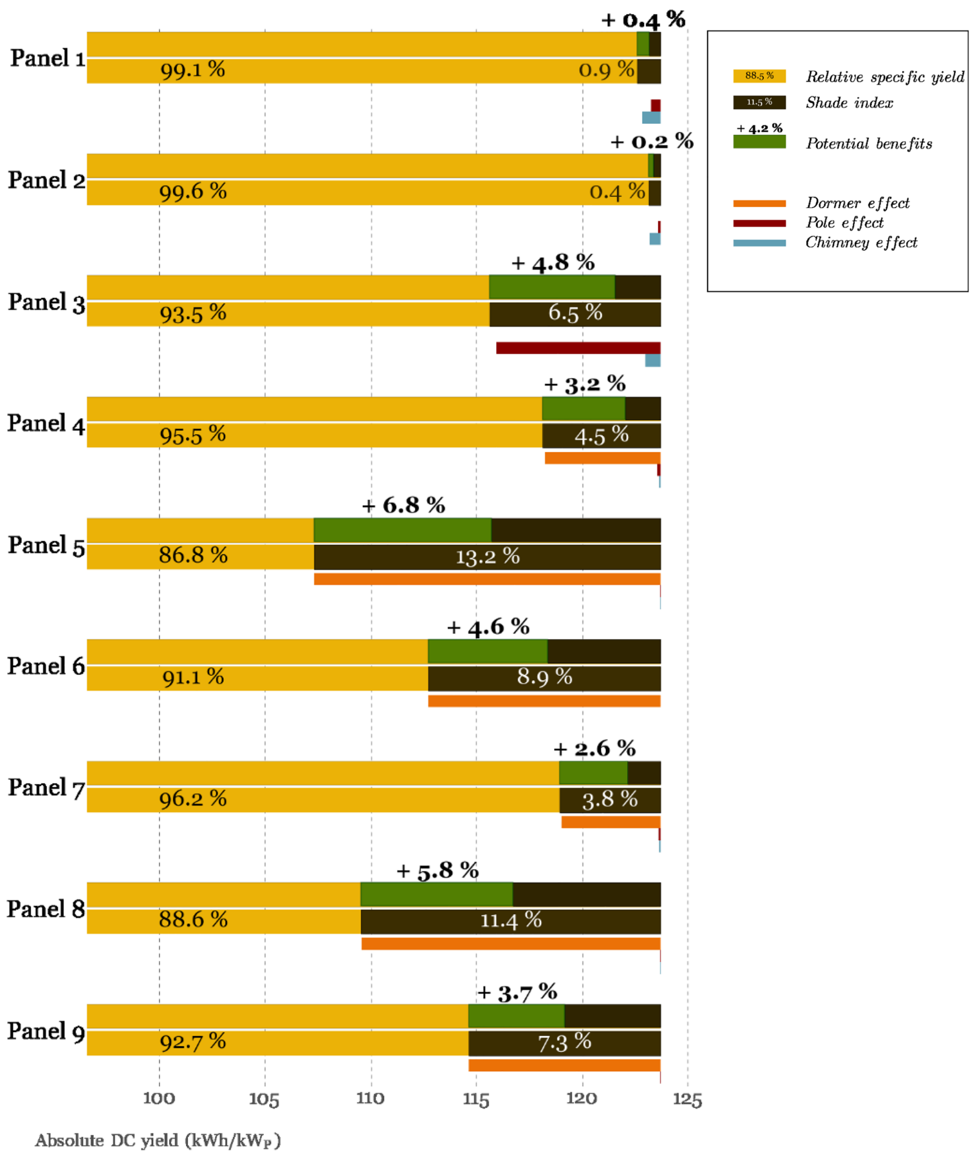

FIGURE 8 Per panel annual DC energy yield. Individual panel losses can be attributed to the dormer, chimney, and pole shading effects

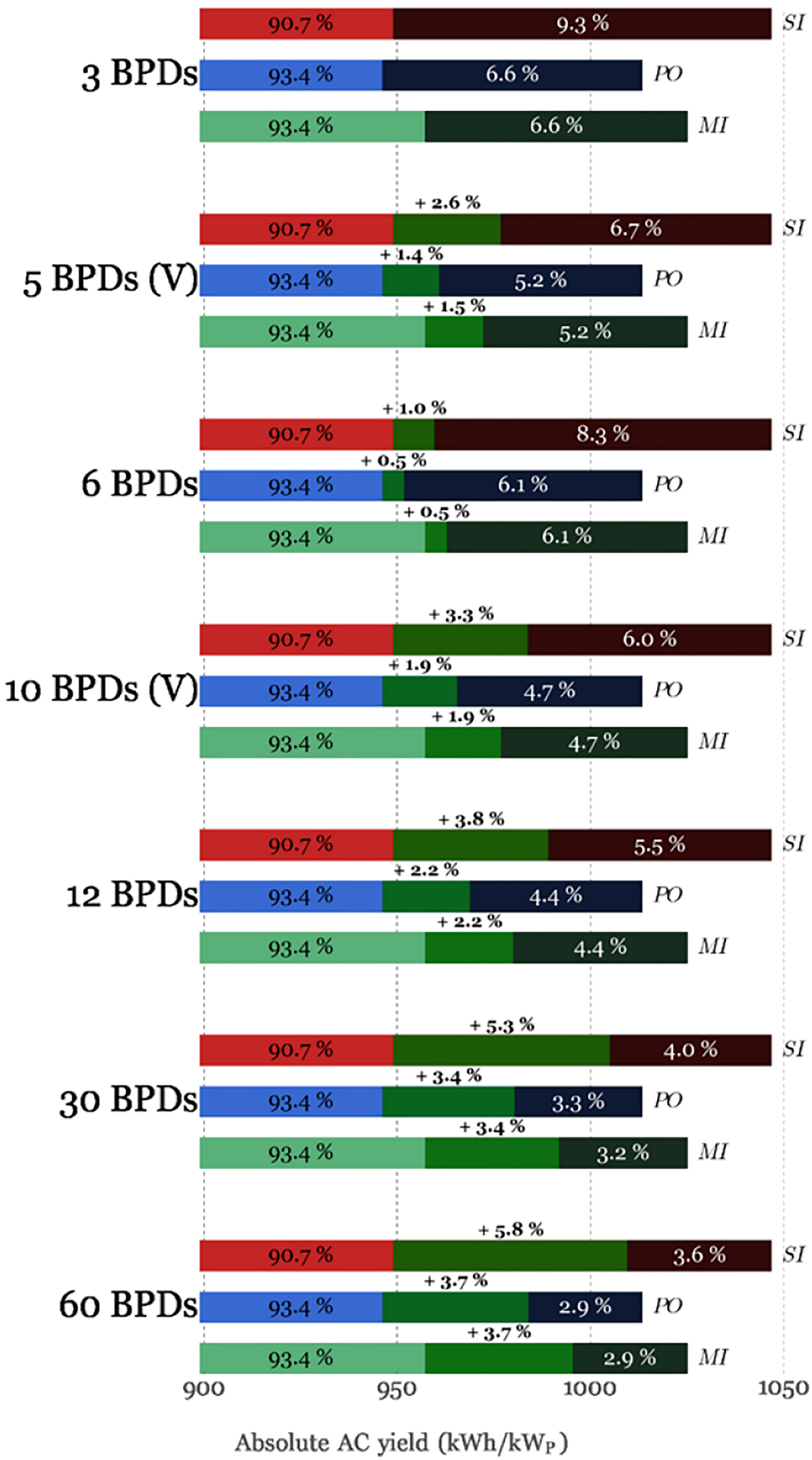

FIGURE 9 Typical meteorological year (TMY) AC yield results for a variation of cell granularities and system architectures. The architectures depicted are SI (string inverter), PO (power optimizer) and MI (micro inverter)

includes three BPDs per module. The accompanying percentage score shown in black illustrates the relative specific system yield compared to the un-shaded case. Un-shaded situations would lead to a relative yield percentage score of 100%. The three BPD module thus suffers from shading lowering its annual DC yield to 93.7%. Black bars indicate the shading index which is defined as the annual shading losses, as a result of the shading scenario applied (Figure 2). Green bars and the percentage scores placed directly above show the potential benefits attained by increasing the amount of per-module BPDs from 3 to 60. This can be interpreted as the maximum recovery potential that can be attributed to applying more BPDs in each module.

Simulation of the nine-panel system also included the effects of dormers, poles and chimneys. These are shown by the use of thin orange, dark-red and light-blue bars placed below each panel's performance indication bars, in Figure 8. The per-module DC results illustrate that the shading index values related to chimneys are relatively modest (<1%) for the south-oriented roof. The exhaust pipes only significantly affect top-right panel 3. Dormers have a thorough influence on panels 4 through 9. The left- and right-middle panels numbered 5 and 8 experience the most intense yield losses with shading index values of 13.2% and 11.4% respectively. It can be interpreted that the maximum recovery potential that can be attributed to increasing the solar cell granularity is above 50% for several cases.

The annual energy losses of the standard module system at the given scenario are around 6.3%. By increasing the solar cell group granularity there is an improvement in absolute annual yield up to 3.6% for the case of the 60 BPDs module (Figure 7). The losses than can be retrieved with this specific module design are around 60%.

In Figure 9 the system architecture is also taken into account where SI is the string inverter system, MI is the micro inverter and PO is the power optimizer system (DC/DC boost parallel connection topology). While there are yield differences based on the chosen architecture of the system, an overall improvement regardless of the system design can be observed. Specifically the string inverter system benefits most with the increased granularity. This is due to the large MPP voltage window of string inverters which are capable to bypass more cells than the micro inverter and the power optimizer systems when shade is localized in few panels. Moreover, the efficiency of the string inverter is not as voltage sensitive as is the micro-inverter's.[8] Additionally, the string inverter supports a shadow function which scans the power voltage curve of the string in frequent intervals and

TABLE 1 European efficiency of power electronic devices used for the simulation model

Device	Euro ETA
String inverter	95.7
Micro inverter	94.5
Power optimizer, central inverter	97(PO), 95(inv)

Note: Efficiencies are confirmed by outdoor tests.

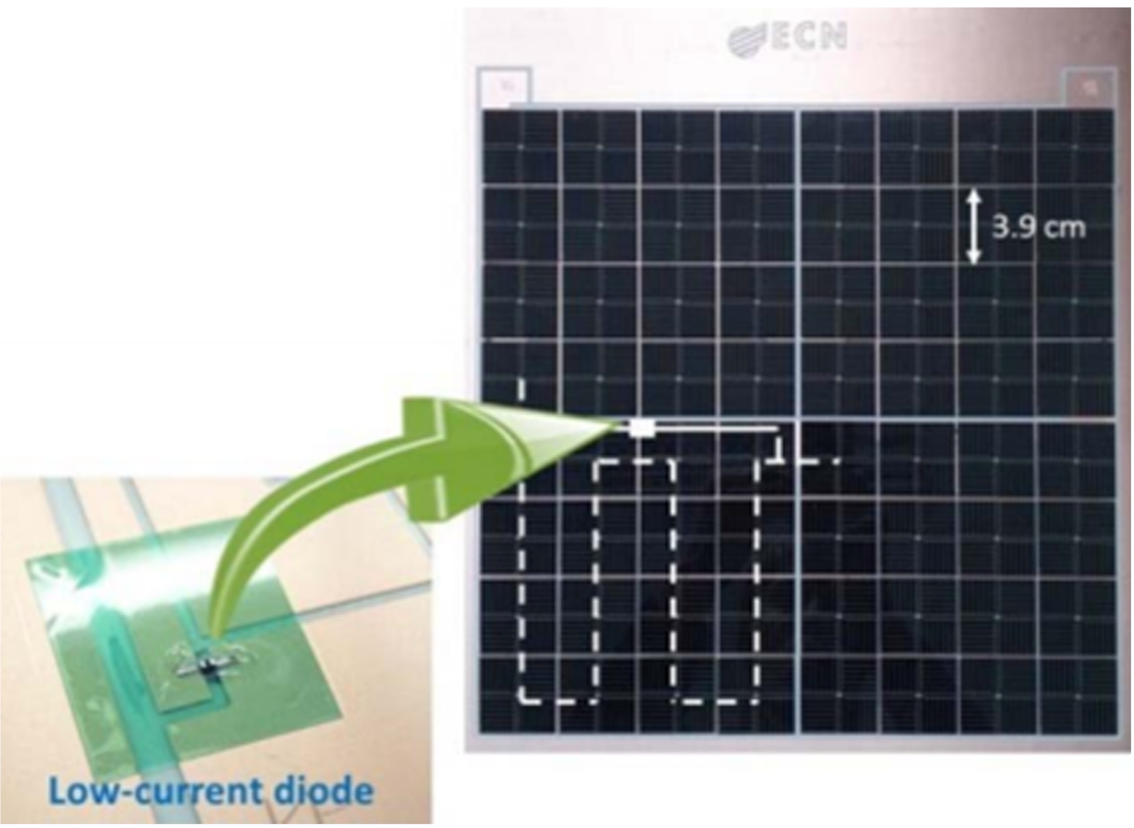

FIGURE 10 Picture of a module building block with 64 mini cells in series and low current diode per 16 mini cells[14]

thus always finds the global MPP. The power optimizer system is the least efficient system in our study due to the lower overall efficiency from the double conversion of the DC/DC optimizers followed by the DC/AC inverter. In Table 1 the rated European efficiency of the power electronics can be seen.

4 | TESSERA MODULE, SIMULATIONS, AND OUTDOOR DATA ANALYSIS

The insertion of additional BPDs in solar module designs seems to be beneficial in terms of power output under partial shading conditions. On the other hand manufacturability of such modules is difficult and expensive due to the size of the BPDs which have to be laminated in the solar module. The size of the BPD can be significantly smaller if the current would be lower than the typical 7.5–9 A that 6-inch cells generate under full-sun conditions. The Tessera module design consist of 6-inch Metal Wrap Through (MWT) back contact technology c-Si cells which are cut in smaller pieces, thus leading to lower currents. Out of one 6-inch cell, 16 smaller cells are cut with 16 times lower current and connected in series in a sub cell group (SCG).[17] Subsequently four SCGs are connected in series forming a module building block (MBB) with 64 mini cells proving almost the same voltage as a typical c-Si module (Figure 10). Fifteen MBBs are then connected in

FIGURE 11 Picture of the Tessera system, with six Tessera full size modules. Partial shading applied by a pole situated in the middle of the system

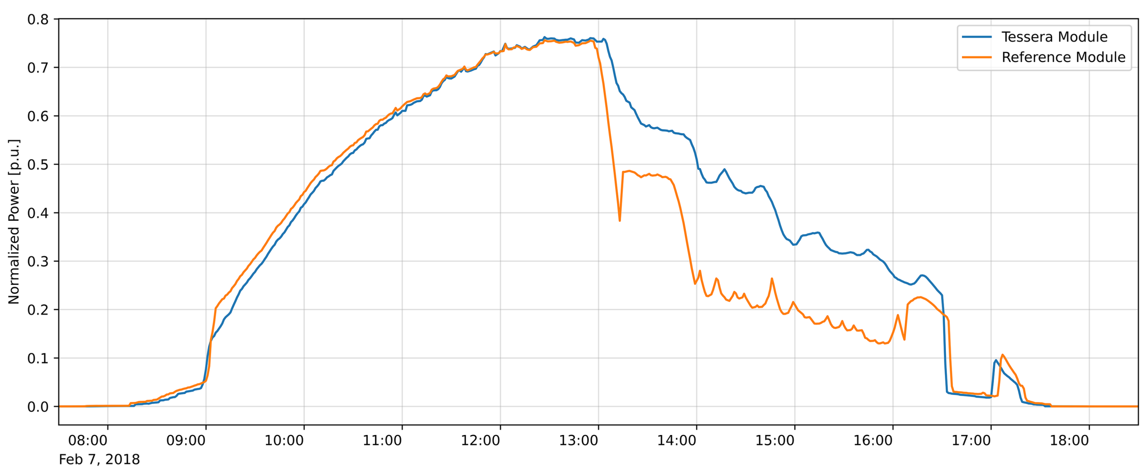

FIGURE 12 Normalized power output of a Tessera and reference standard module under the same partial shading conditions

parallel forming the Tessera module. In total 960 mini cells are used for one full size module.

The same simulation methodology used above was used to validate the results of the Tessera module. The only difference in the Tessera simulation model is that the solar cell size on the 3D design and the respective IV curves of the diode model are different than standard size solar cells that were used above. Additionally, six Tessera full size modules have been manufactured and tested in an outdoor set up (Figure 11) along with reference systems.

a. Reference system 1: Six standard modules connected to six micro inverters
b. Reference system 2: Six standard modules in series and then connected to a string inverter
c. Tessera system: Six Tessera modules connected to six micro inverters

The reference systems used the same module type (265Wp mono c-Si) while all systems used the same inclination and orientation. Monitoring of electrical parameters is measured with high accuracy power analyzers from Yokogawa. Irradiance is measured via a secondary standard pyranometer from Kipp and Zonen. All data are scanned per second and then averaged to minute values which are saved in a data base. By means of a pole, partial shading was applied in the same way for all three systems.

In Figure 12 the normalized power output of a Tessera and reference module under the same partial shading conditions can be seen. During the sunny day shown the Tessera module produced 15% more energy throughout the day.

While the DC production of the Tessera seems to outperform the reference panel, it is interesting to see that the micro inverter efficiency is marginally better with the Tessera module (Figure 13). This is due to the fact that the voltage output of the Tessera module stays relatively stable regardless of the shading effect. The reference module which includes 3 substrings of 20 cells is reducing the voltage output of the module and thus the efficiency of the micro inverter. This can also be observed in Figure 14 where the relation of voltage, power output and micro inverter efficiency can be seen. For the reference module a second cloud of points can be observed in the 20 Volts range, while in general the voltage range is larger as well. As a result, the Tessera module performs approximately 2%–3% better in terms of DC/AC conversion efficiency when a micro inverter is used.

The overall performance of the 3 systems is expressed with the Performance Ratio (Equation 1) and can be seen in Table 1.

$$PR = \frac{Y_f}{Y_r} = \frac{\sum_{t_o}^{t_{end}} P_i}{P_{STC}} \times \frac{G_{STC}}{\sum_{t_o}^{t_{end}} G_{POAi}} \quad (1)$$

where:

Y_f = produced energy

Y_γ = theoretical yield

P_i = Power produced

G_{stc} = Irradiance at STC conditions (1000 W/m^2)

P_{stc} = Installed capacity of the PV system

G_{POA} = Irradiance on the plane of array of the system

In total 8 months of outdoor measurements were analyzed. The Tessera system seems to outperform both reference systems for the measured period (Table 2). The largest difference lies between the reference 2 and the Tessera system while reference system 1 with micro-inverter is closer to the Tessera system.

After the analysis of the measured results a simulation was performed based on TMY irradiance data (Figure 15) in a similar partial shading scenario which is described Section 3. Results show that the Tessera system has comparable losses with the 60 BPDs design of around 3%.

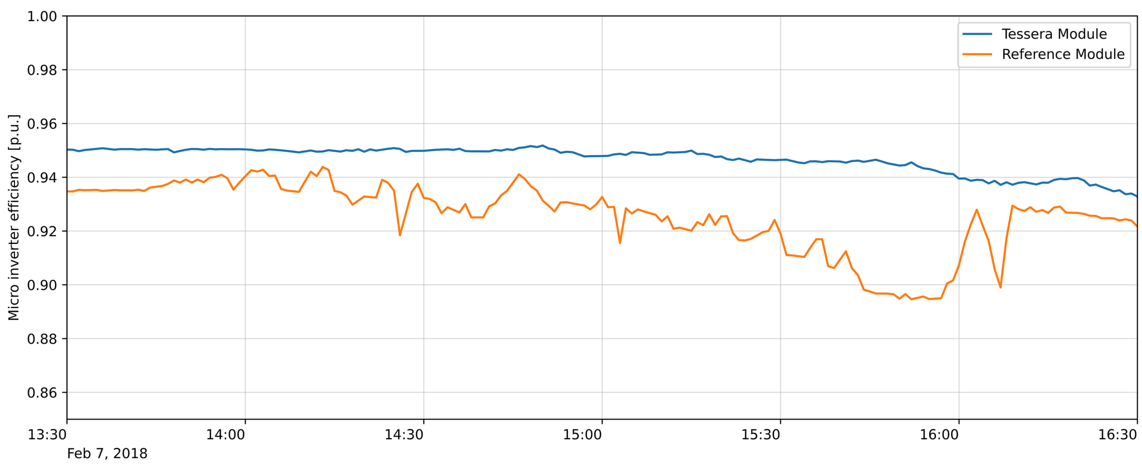

FIGURE 13 Efficiency of identical micro inverters while operating under the same partial shading conditions with a Tessera and the reference module

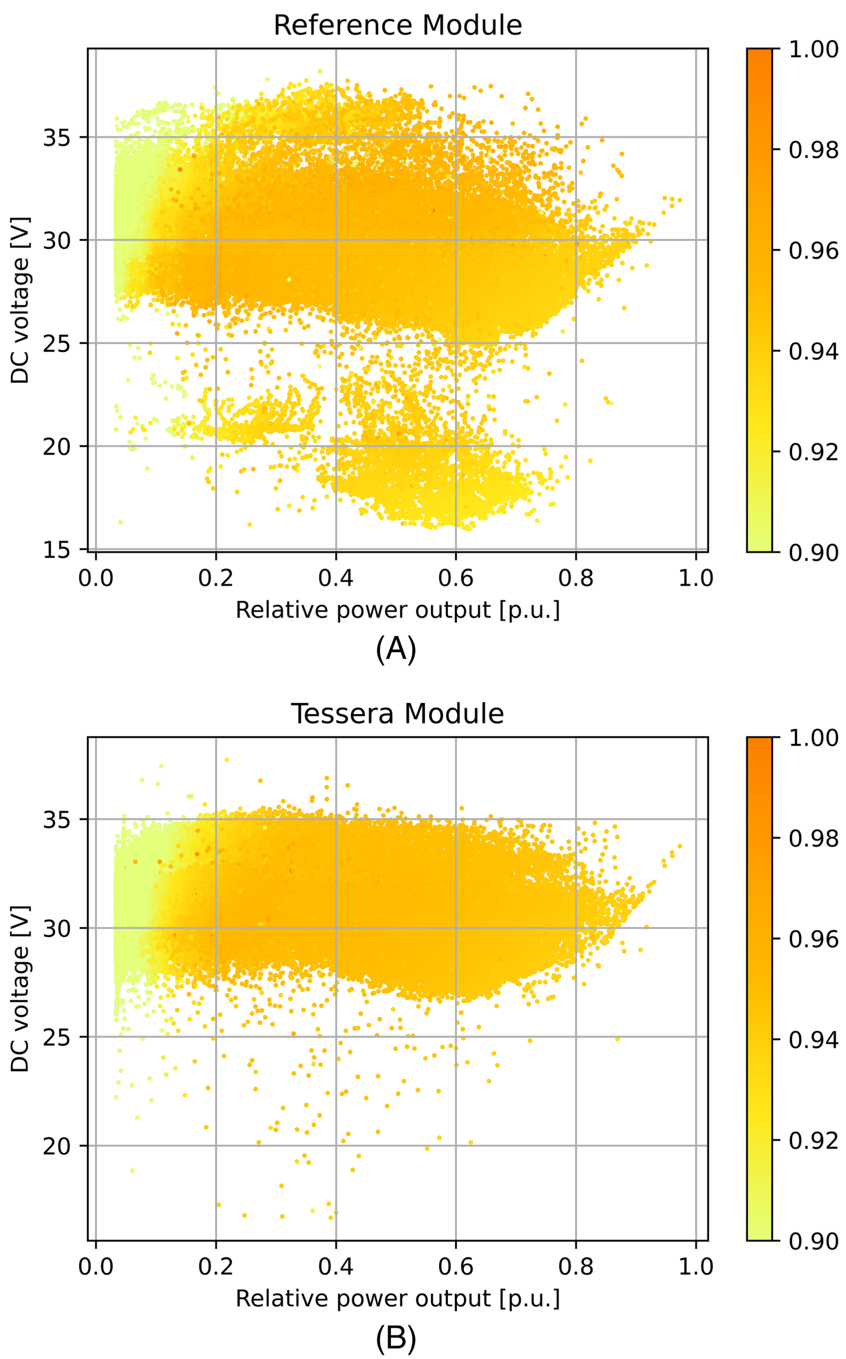

FIGURE 14 Relation of voltage, power and efficiency of the micro inverters for the reference (A) and Tessera system (B)

TABLE 2 PR DC and AC for 8 months of outdoor testing

	Feb	Mar	April	May	Jun	Jul	Aug	Sep
DC PR								
TESSERA	0.96	0.94	0.90	0.89	0.88	0.86	0.81	0.89
Reference1	0.94	0.94	0.89	0.85	0.91	0.86	0.78	0.87
Reference2	0.80	0.89	0.85	0.82	0.88	0.82	0.72	0.82
AC PR								
TESSERA	0.91	0.88	0.85	0.84	0.83	0.81	0.76	0.84
Reference1	0.88	0.87	0.83	0.80	0.85	0.81	0.73	0.82
Reference2	0.76	0.84	0.81	0.77	0.84	0.78	0.68	0.78

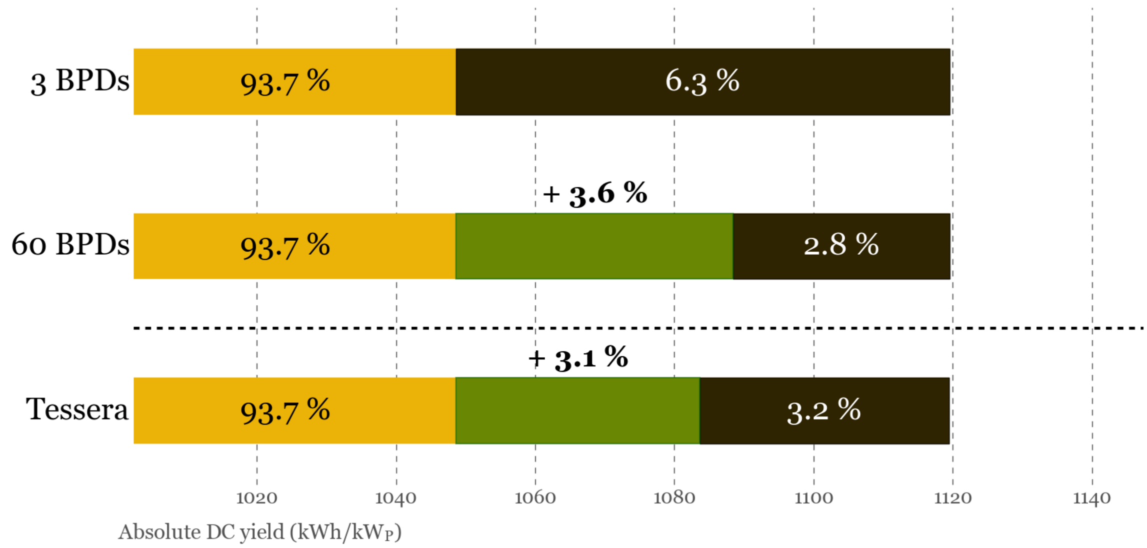

FIGURE 15 Simulation results for a TMY in Eindhoven

5 | CONCLUSION

It has been shown that a combination of smart module designs and system architectures can be very beneficial for mitigating effects of shade on PV performance. Specifically the granularity of the module design is of paramount importance to increase the annual yield output of a partially shaded PV system. While instantaneous losses from partial shading can be considered very high at around 50% (Figure 6), the impact on the annual yield is in the order of 6% DC based on the reference system design on a typical Dutch roof. In the past a common practice of installers and system designers was to avoid installing modules in places where partial shading was present. We have shown that even in residential roofs with several shading objects, the yield losses with standard system configurations (standard module design and string inverter) are in the order of 9% annually (inclusive DC/AC conversion). This can be further reduced to 6%–7% with the use of MLPE. Innovations in module design in combination with modern system architectures show that this can be further reduced to 3% with the same partial shading profile.

While all described solutions seem to be beneficial in terms of energy yield improvement, one has to evaluate the financial consequences for such designs. At the moment MLPE systems add a 10%–15% of the initial investment when compared to a string inverter and thus the additional annual yield is not enough to increase the return of the investment.[18] On the other hand MLPE offer a lot of flexibility in system design by being able to install different module types in a single string or using different orientations and inclination angles. Furthermore, safety issues have arisen the past years regarding high DC voltages present on residential roofs that can cause arcing when cable insulation is compromised. New safety standards in the USA (NEC2017 690.12) dictate that all conductors within 30 cm of a solar module should be able to shutdown rapidly (within 30 s). MLPE is complying in a safe way with the new installation standards for residential roofs and allows first responders in case of fire or other calamity to act safely. Detailed monitoring of single modules is another benefit of MLPE devices, promoting a faster and easier fault analysis in modern PV systems.

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