Towards new module and system concepts for linear shading response

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***Abstract* — Large scale implementation of PV in urban areas asks for more shadow tolerant modules and more size flexibility. Power optimizers and micro inverters can be used to improve shadow tolerance of standard c-Si modules but the electrical interconnection and the size of cell groups in the standard module design is a limiting factor when it comes to further increase shadow tolerance. In this work another approach is used in which the cells in the module are smaller and series connected in building blocks. The resulting lower currents allow the use of small in laminate diodes and the building blocks give access to more size flexibility and improved shadow robustness. Yearly yield calculations will be shown and compared to a standard 3-sub-string module with either power optimizers or micro inverters. It is shown that for a typical Dutch house the TESSERA concept outperforms the other by up to 6%.**

I. INTRODUCTION

Solar photovoltaic (PV) systems today play a significant role in the energy mix and their penetration is forecasted to keep growing in the future [1]. Particularly the application of building integrated PV (BIPV) and building added PV (BAPV) systems are projected to thrive in the following years as a result of increasing electricity prices for the residential sector and decreasing PV component costs. Residential and small commercial PV systems are typically installed in an urban environment. Roofs and terraces are often affected by shade coming from the close proximity of buildings, poles, antennas, dormers, etc. introducing electrical and thermal mismatch losses between cells and modules. Solar modules are connected in series and thus sharing the same current in a string. This topology is prone to power losses if the solar cells in the module are not operating under the same conditions thereby reducing the current of the module and consequently of the whole string. Partially shaded solar cells may become reverse biased because of the series connection and thus act as a load consuming the power that is generated by the unshaded cells. Two negative effects occur from partially shaded operation of a PV system: power loss and increased temperature of the shaded cells (hot-spot). By-pass diodes have been applied in solar modules to prevent power consumption from shaded cells and to prevent hot-spots by by-passing the shaded substrings of the solar module. Most of the solar modules include one by-pass diode connected anti parallel per 16–24 cells [2]. However, it is known that increased granularity of cell groups can increase performance under partial shading conditions [3].

The TESSERA concept makes use of this knowledge and offers increased granularity. It includes 6 inch Metal Wrap Through (MWT) c-Si cells which have been cut to produce 16 mini cells. The mini cells are connected in series and protected with an in-laminate low current by-pass diode (Fig. 1a). In total 64 mini cells are connected in series forming an maximum power point (MPP) voltage of around 31V at standard test conditions (STC). Blocks of 64 mini cells are then connected in parallel forming modules with custom size and thus custom current levels. A full size TESSERA module has been built based on ECN's back contact technology and is shown in Fig. 1b. The module consists of a white Tedlar backsheet with Cu foil on top. The cells make contact to the

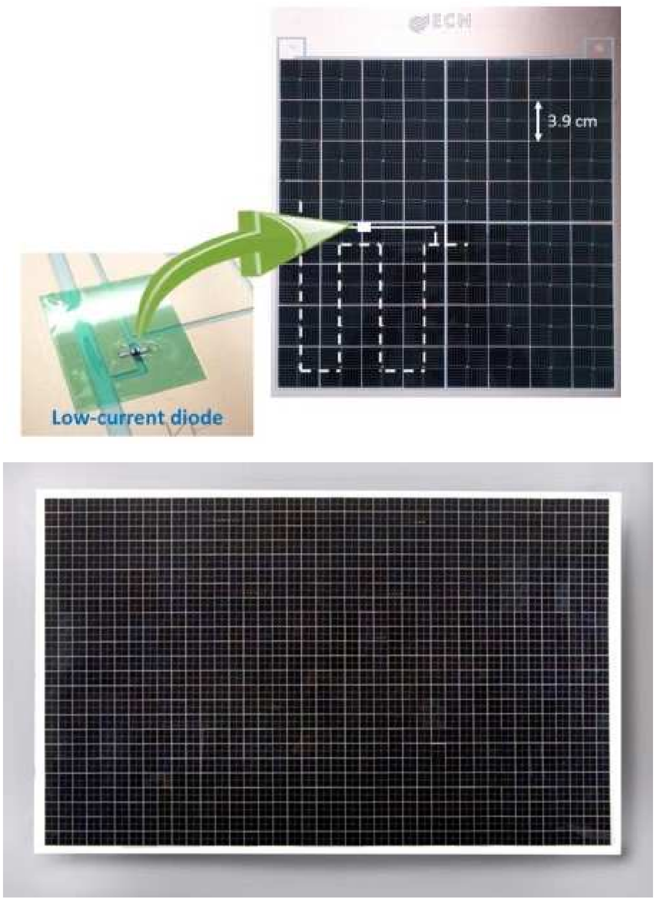

Figure 1a: A building block of the TESSERA concept consisting of 64 mini cells connected in series and protected by 4 low current in laminate diodes; 1b: a full size TESSERA module.

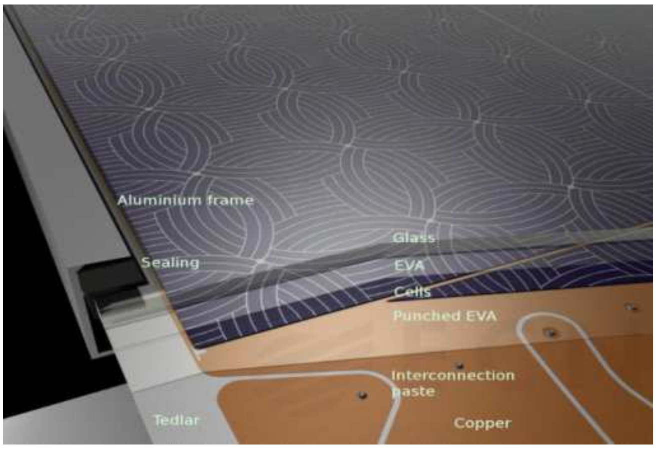

Figure 2: Presentation of the build-up of a MWT back contact module using an interconnecting backsheet.

patterned Cu foil via an electrically conductive adhesive. Outside the dots, the cells are isolated from the foil by white EVA. Transparent EVA is used as the encapsulant between the cells and the front side glass. A schematic representation of the module stack is shown in Fig. 2.

The use of module level power electronic devices (MLPE) has been proposed to mitigate electrical and thermal mismatch losses [4-6] in the field by tracking the maximum power point of individual modules. In general MLPE devices consist of two main categories: micro inverters and power optimizers. In this paper micro inverters (MI) and power optimizers (PO) (boost DC-DC converter) are considered for the TESSERA system.

II. METHODOLOGY

A simulation model is developed [7] to quantify the benefits and drawbacks of different PV system architectures. The simulation model takes into account different module designs (standard cells with 3, 6, 10 by-pass diodes, and TESSERA) and different system architectures (string inverter shadow mode on-off (SI+), micro inverters (MI), power optimizers

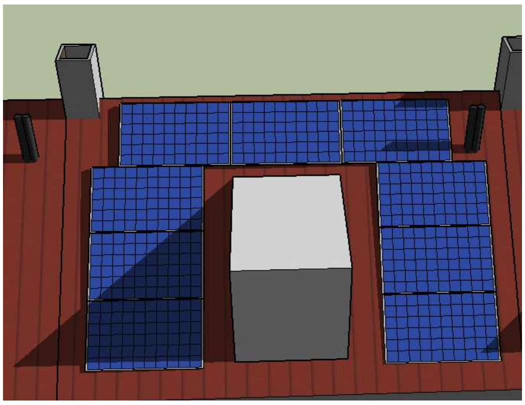

Figure 3. System layout for the yearly yield calculations. A typical Dutch roof including a dormer, chimney and exhaust poles,

(PO)). The characteristics of the inverters and power optimizers used in the calculations are shown in Table I.

In Fig. 3 the 3D design of the roof can be seen including the shading obstacles of the roof (dormer, chimney, exhaust poles). By providing input on the orientation and the inclination of the PV panels as well as the PV module configuration, the determination of the exact position of all the cells in the system can be achieved. This is combined with information on the geographical characteristics and object shading from the location. This determines the shading on all the cells, see Fig 4a, and placed in a lookup table as shading fraction per cell for a specific date and time. The resulting blocked irradiance on an annual level is around 1.7%, see Fig 3b. Next the PV module characteristics and the irradiance (direct and diffuse ratio is taken into account using the Reindl-2-model [8]) and temperature information is added to determine the IV curve of the substrings. The IV curve is generated using a simplified double diode model. To reduce the calculation time it was assumed that the saturation current

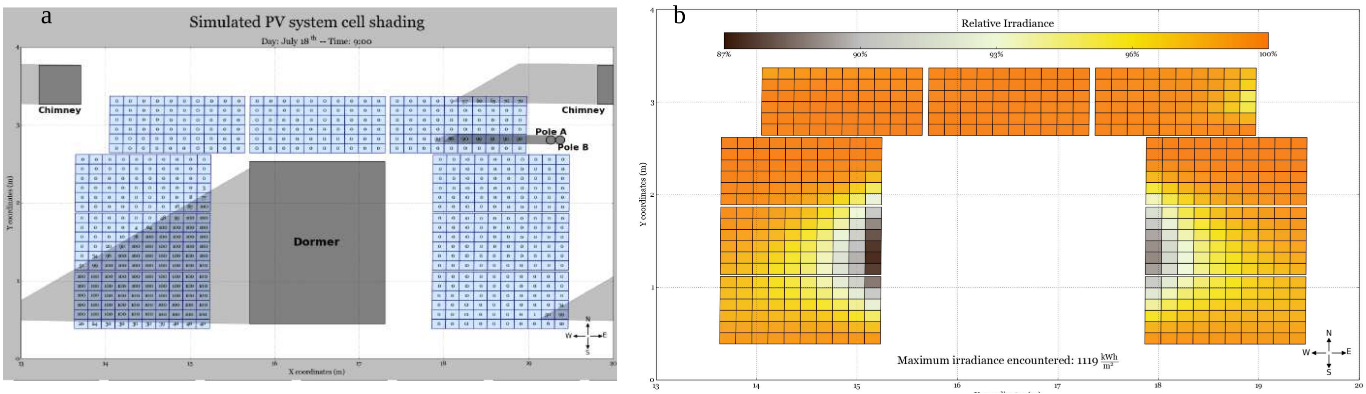

Figure 4. a. Placement of modules on a typical Dutch roof including a dormer, chimney and exhaust poles, b. Effective irradiance reaching the modules in a typical meteorological year for NL.

density of the first and second diode are equal as described in [9]. The resulting diode equation is:

$$I = I_{ph} - I_o\left(e^{\frac{V_S+IR_S}{V_{th}}} + e^{\frac{V_S+IR_S}{2V_{th}}} - 2\right) - \left(\frac{V_S + IR_S}{R_{sh}}\right)$$

Subsequently the DC output is determined and after including the conversion losses of the specific AC converter, the AC output is derived. Further settings for the model are given in Table I.

Table I: parameters used in the model.

Parameter	Value
Simulation interval	*10 minutes*
TMY data interval	*60 minutes*
TMY data resampling method	*Simple interpolation*
IAM model	*(Snell's and Bougher's laws*
Effective cell temperature	*Faiman model*
Albedo factor	*0.15*
Irradiance separation model	*Perez model (in Meteonorm)*
Tilt (in-plane) radiation model	*Perez model (in Meteonorm)*
Irradiance data period	*1991-2010*
Ambient temperature data period	*2000-2009*
POA azimuth tilt angle	*180°; 40° (o°; 40° in Meteonorm)*
Latitude, longitude, elevation	*51.4° N; 5.5°E; 30 m*
Other meteorological output	*Local wind speed (for temperature)*

TMY: Typical Meteorological Year, IAM: Incident Angle Modification, POA: plane of array.

The energy yield of three leading architectures is confirmed (string inverter (SI), power optimizer, micro inverter) for clear and partial shading conditions by means of an outdoor field test [8] and IV curves from a solar simulator [9]. For this work the model has been tuned to accommodate different module and PV system designs in an effort to compare the partial shading response of the TESSERA concept with standard c-Si design of three substrings of 20 cells.

III. RESULTS-DISCUSSION

By using the typical meteorological year's irradiation data of Meteonorm [10], a full year simulation for unshaded and partially shaded scenarios has been performed. Meteonorm provides measured irradiance data for a variety of locations. Moreover, the data can be decomposed and trans-positioned by using known irradiance models. A constant albedo factor of 0.15 has been used for the simulations. The simulation model takes into account different module designs (standard cells with 3, 6, 10 and 60 by-pass diodes, and TESSERA) and different system architectures (string inverter shadow mode on-off, micro inverters, power optimizers). The characteristics of the inverters and power optimizers used in the calculations are shown in Table II.

Table II: characteristics of the inverters and power optimizers used in the calculations.

	MI	PO	SI
Power electronic devices	*Heliox SMI-300*	*Femtogrid PV300+Kratos Inverter 2400*	*SMA Sunny Boy SB 2500 TLST-21*
Voltage range	*16V- 48V*	*8V – 42V*	*180V – 500V*
European efficiency	*93.6%*	*93.1% (97%*96%)*	*95.6%*
MPP granularity	*Module*	*Module*	*System (9 modules in series)*
Input power/current constraints	*> 5.0 W*	*> 0.03 A; > 6.7 A*	*> 32 W*
Output power/current constraints	*< 285.0 W*	*< 10.5A*	*< 10.9A*
Efficiency determination methodology	*Linear-interpolation of V-dependent efficiency curves (MLPM data)*	*Linear-interpolation of V-dependent efficiency curves (MLPM data)*	*Double linear interpolation of P, V-dependent efficiency curves (PV Syst)*
System elements	*9*(4S * 15P)*	*9*(4S * 15P)*	*36S * 15P*

In Fig. 5 the simulation results can be seen in specific yield kWh/kWp per annum. The total length of the bars indicate the total kWh/kWp that can be generated per year if no shading is present. Under these circumstances, the string inverter system (Fig. 5a). seems to be the best performing system. This is due to the higher efficiency of the string inverter compared to the power optimizer and micro inverter. However, when partial shading is introduced, then the performance drops due to the shading losses. This drop is indicated in Fig. 5 by the black bars. As can be seen, in this case the performance of the power optimizer and the micro inverter are substantially better. The shading losses reduce with about 50% compared to a 3BPD system. The higher granularity of cell groups seems to benefit the string inverter more than the power optimizer or micro inverter due to the wider operational voltage. For the TESSERA concept we can observe an improvement of around 6% when used in combination with a micro inverter or power optimizer in comparison with a typical PV system consisting out of modules connected in series and attached to a string inverter. The performance behavior of the TESSERA concept is similar with that of a standard 60 by pass diode module.

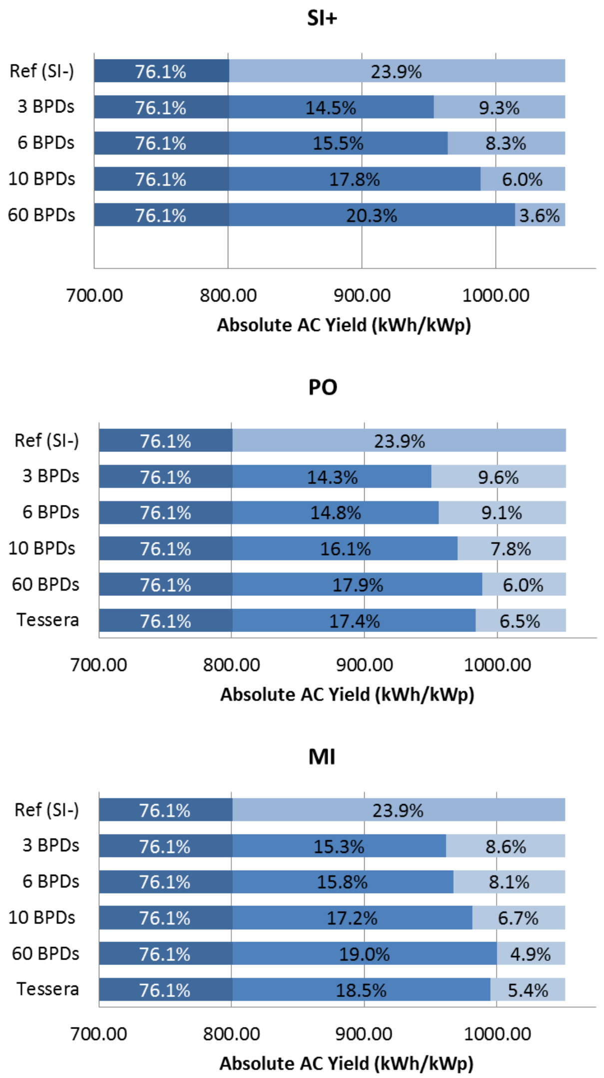

Figure 5: Simulation results for various module and system designs. The total bar length gives the AC yield of a reference 3 string module with string inverter without shadow in the module

indicates the annual AC yield of a 60 cell module with string inverter (without shadow option) with shadow on the module

is the gain in annual AC yield with respect to the reference due to improved shadow tolerance

loss due to shadow

shadow loss and electrical loss

Furthermore the TESSERA module manages to keep a steady MPP voltage throughout the year and independent of the partial shading conditions. Figure 6 shows the number of occasions during a year in which a specific Vmpp/Voc is obtained for the TESSERA module and for a 3 by-pass diode module (3BPD) for a system with MI and for a system with PO. The module with 3 bypass-diodes shows 1 or two additional Voc/Vmpp ranges at which the system is operating during the year. Although they are relatively low compared to the main operating condition around 0.8, it still amounts to 2.3% of the year for the MI system and 2.8% for a PO system. For TESSERA only 0.5% of the time the system operates at a different Vmpp.

IV. CONCLUSIONS

This works describes a shadow tolerant module concept that is based on standard back contact foil technology. It consists of small cells connected in series to form a modular block. These blocks are connected in parallel to form the module. This dedicated interconnection makes the module much more shadow tolerant. Annual yield modeling of the power output for a typical Dutch house is compared with the output of standard 3 sub-string modules with string inverters, power optimizers or micro-inverters. It is shown that the presented concept outperforms the others by 3-6%.

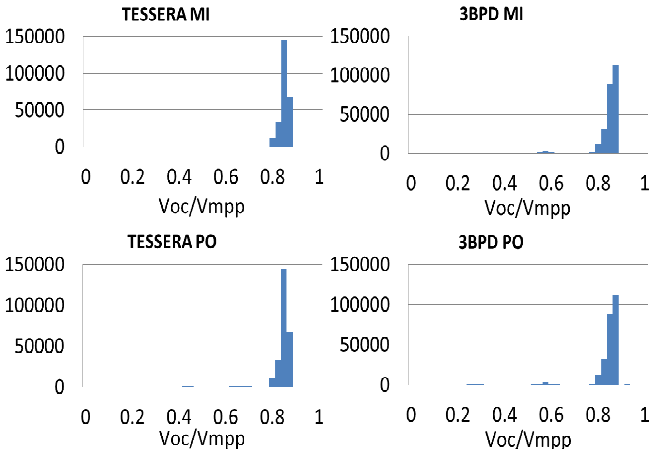

Figure 6. Vmpp/Voc for a 3BPD module with micro-inverter or power optimizer and a TESSERA module with micro-inverter or power optimizer

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