Annual energy losses due to partial shading in PV modules with cut wafer-based Si solar cells

Kristijan Brecl*, Matevž Bokalič, Marko Topič

Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, SI-1000, Ljubljana, Slovenia

1. Introduction

In the last decade the gap between the record solar cell efficiencies in the lab and that in the production is getting smaller and smaller [1,2]. Record efficiencies of crystalline silicon (c-Si) photovoltaic (PV) modules is close to 20% and close to 25% for interdigitated back contact (IBC) (c-Si and c-Si heterojunction) modules [1]. However, the use of highly efficient full size wafer-based solar cells means also high currents and thus higher series resistance (Joule) losses. To reduce the Joule losses several innovative cell designs have been developed from multi busbar solutions [3,4], smart-wire [5] to IBC designs. In addition to reducing Joule losses, innovative interconnection designs also reduce busbar shading and improve module efficiency. A current standard c-Si PV module consists of 60 solar cells connected in series and protected by three by-pass diodes [6]. The PV module dimensions are not standardized but are usually slightly below 1.7 × 1.0 m² for a 60 cell module. The active area share of a 60-cell module with 156 × 156 mm² square cells therefore results in around 86% of a total module area (area fill-factor). To lower the internal current and enhance the active area, designs with cut solar cells that are aligned with a minimum gap between them (or even shingled) were introduced. The first half-cell module was introduced in 2014 by REC [7]. Today the market share of the half-cell PV module is close to 15% and it is expected to grow to over 60% in 2030 [8]. Also, PV modules with smaller cells (1/4 or 1/6) are already on the market, however their share in 2030 is expected to be still below 10% [8]. Smaller cells are more interesting for shingled cell design [9]. SunPower introduced their high performance PV module with shingled cells in 2015 [10] followed by some other big producers [11].

Energy yield of PV modules is a key performance parameter that gives information about how good a module performs under given circumstances in operation. Next to the elevated module temperature, energy yield is most affected by complete and partial shading. While complete uniform shading reduces only energy yield [12], partial shading may also lead to phenomena that may accelerate degradation of the modules and lead to a premature failure [13]. Shading analysis of shingled modules has been recently reported [14,15], some studies of partial shading have also been
published [15–17], however a detailed study of annual energy yield of partially shaded modules has, to the best of our knowledge, not been published yet.

To evaluate the annual performance of a shaded PV module the shape of the shade has to be calculated for each hour in the year. Thus, a 3D profile of the shading object has to be defined in addition to the 2D horizon profile of distance objects/landscape shape. In this paper we investigate how PV modules with cut c-Si cells using different topologies perform under different partial shading conditions. We evaluate their performance compared to the performance of a standard 60-cell c-Si module. In the methodology section we present five module topologies, corresponding electrical Spice model, introduce three shading scenarios, explain shading analysis at five locations and disclose details of solar irradiance and energy balance models. We develop a comprehensive annual energy performance model for partially shaded modules with different cell topologies, introduce a 3D shading profile for detailed shading analysis on cell level and examine the cell thermal condition by using the PV module energy balance model. We present results first under the worse condition on the shortest day of the year and followed by that over the whole year. We finish the paper with discussion of the results and conclusion.

2. Methodology

We use five different module topologies together with three shading objects. We execute two analyses (single situation around noon time and annual energy yield simulations). For the single situation analysis, we choose the shortest day of the year to check the worse influence of the shade. The analysis is supported by the energy balance model of the shaded cell. The annual energy yield simulations were run for five locations.

In the simulations we use several mathematical models which are described in details in the following subsections. Nowadays, several sources with measured or modelled solar irradiation data on a national or global level are available [18–23]. They differ on accuracy and spatial resolution, two parameters which are crucial when year-to-year PV system performance is calculated. In our study, typical meteorological year (TMY) data are used. The hourly irradiation data on flat surface at chosen locations was taken from previous studies [24] for Slovenia or from PVGIS [22], for other locations. For the plane-of-array irradiation we used the established Perez model [25]. For the shading analysis we used a newly developed 3D shading profile presented herein. For the electrical simulations we built a one-diode Spice model of solar cells which allows us to preform annual simulations of shaded modules. For the evaluation of circumstances in the shaded cell we use energy balance model [26,27].

2.1. Module topologies

We have chosen five different wafer-based Si PV module topologies:

- A standard 60 full-size squared 156 × 156 cm² cell module as a reference with 2 bypass diodes (T1)
- Three modules of one sixth area (1/6) rectangular cells with vertical cell connections with 6 strings in parallel and different number of strings in series:
  - 2 strings in series of 6 × 32 1/6 cells strings, 2 bypass diodes (T2)
  - 3 strings in series of 6 × 21 1/6 cells strings, 3 bypass diodes (T3)
  - 4 strings in series of 6 × 16 1/6 cells strings, 4 bypass diodes (T4)
- One module of 1/6 cells with 10 strings in parallel made of 38 cells in series, 1 bypass diode (T5)

The module topologies and their electrical characteristics are presented in Table 1. No edge effects that would reduce the cell performance were taken into account. The number of cells was selected in a way to maximize the area fill factor of a module. Modules T2, T3 and T4 are connected in such a way that their external electrical parameters are similar to the conventional 60 full-size cell PV module and can thus be used with established system components. The T5 module is of different topology that results in a higher short-circuit current of almost 15 A, and lower open-circuit voltage of slightly under 30 V.

2.2. Electrical spice model

The electrical simulations are done with LTSpice [28] simulator with a one diode model for a full-size or cut solar cell presented in Fig. 1. Since the aim of the simulations is to investigate behaviour around maximum power point or strongly in the reverse polarity, the usage of one diode model is sufficient and justified. During the shading simulations, all parameters in the module were kept the same except the photogenerated current, which was changed with regard to the shading situation. The full-size cell parameters were obtained from a measured solar cell and scaled accordingly to represent the cut cell size.

The simulation for specific time was made with a Spice OP analysis. The annual simulation of the module was made with a Spice DC analysis where the hourly values of photogenerated current of each individual cell were given as a table of a voltage controlled current source. The control voltage was defined by a second voltage source in the circuit that presented the hour of simulation.

2.3. Shading

The shading analysis of PV systems is usually done by using horizon profiles. Horizon profiles can be generated from elevation profiles [29] or from a measurement [30]. In both cases the horizon file is usually given as points of azimuth/elevation angle pairs of the obstacles. Such an approach is suitable when the shading objects are far away and when a module is treated as one entity. However, it cannot describe the exact position, shape and movement of a sharp shade on the module that is caused by an object close to the module. Therefore, we developed a new approach that takes into account the information of the distance between the observed point on the module and the points of the shaded object.

To simulate the shading influence of the nearby object a 3D horizon file with the information of the azimuth, elevation and horizontal distance has to be prepared. When preparing the 3D horizon file we have to keep in mind that the visible shape of an object changes from the viewing point, which means that not all edges of the object are always visible.

In our study we define three shading objects: two chimneys with different heights (1 m and 2 m) and a pole with a height of one meter above the lowest point of the module and situated one meter in front of the bottom-left corner of the module. In the case of chimney, the 3D horizon file defines all edges of the top surface. In the case of pole, only 2D are taken into account. Afterwards, a conventional 2D horizon is defined for each point of view separately. Dimensions of the shading objects are collected in Table 2 and the visualisation of the chimney is presented in Fig. 2.

To simulate the shading impact correctly, we divide the module in small areas of around 5 × 5 cm² at the largest. Thus the full-size cell is divided into 9 subareas (of 5 × 5 cm²) and the 1/6-size cell to
Table 1: Parameters and topology of simulated modules.

|       | T1 – standard module | T2 | T3 | T4 | T5 |
|-------|----------------------|----|----|----|----|
| Cells | 384 1/6 cells        | 378 1/6 cells | 384 1/6 cells | 384 1/6 cells | 380 1/6 cells |
| 60 full-size cells connected in series | 32 cells per string | 21 cells per string | 16 cells per string | 38 cells per string | 38 cells per string |
| 2 strings in parallel | 6 strings in parallel | 3 strings in parallel | 6 strings in parallel | 4 strings in parallel | 10 strings in parallel |
| $I_{sc}$ | 8.8 A | 8.8 A | 8.8 A | 8.8 A | 14.7 A |
| $V_{oc}$ | 44.0 V | 46.9 V | 46.2 V | 46.9 V | 27.9 V |
| $P_{mpp}$ | 303 W | 319 W | 324 W | 319 W | 320 W |

Fig. 1. One diode Spice model of a solar cell in the PV module and parameters of a full-size solar cell ($I_s$ – diode saturation current; $N$ – diode quality factor; $R_s$ and $R_{sh}$ – series and shunt resistance, respectively; $BV$ – break down voltage).

Table 2: Parameters of shading objects.

| Object  | Chimney 1 m | Chimney 2 m | Pole |
|---------|-------------|-------------|------|
| dimensions (WxDxH) | 0.3 x 0.3 x 1.0 m³ | 0.3 x 0.3 x 2.0 m³ | 0.03 x 0.03 x 1.0 m³ |
| distance to the left bottom edge of the module | 1 m | 1 m | 1 m |

Fig. 2. Location of a chimney (left) and pole (right) as a shading object in front of the observed module.
3 subareas (of 2 × 5 cm²). The horizon of the shading object is calculated at the centre point of each subarea. At the same point we calculate the solar irradiance. The observed solar cell’s total short circuit current is then defined as the sum of currents in the subareas.

2.4. Solar irradiance modelling

All simulations were carried out for five locations: Ljubljana-Slovenia, Freiburg-Germany, Helsinki-Finland, Cairo-Egypt and Denver-USA. The solar irradiation for Ljubljana was calculated by the in-house developed software [24] while for the other locations the typical meteorological year (TMY) data from PVGIS was used [18]. The PVGIS TMY for Ljubljana gives close to 3% higher annual irradiation value compared to average measured data from national meteorological agency [23]. The TMY for Ljubljana is based on measurements [23] from 2000 to 2010 while the PVGIS data are based on measurements from PVGIS from 2006 to 2015. For the plane-of-array irradiation we used the well-established and most cited Perez [25] model.

In the shaded areas of the module only the diffuse light was taken into account. In the case when the sun position was less than 1° apart from the shading object (looking from the simulation point), we consider that beside the diffuse light also half of the direct light can hit the solar cell.

2.5. Energy balance model

The influence of the shading on temperature of individual solar cells within a module is calculated with the energy balance model [26]. The energy flow in a solar cell or in a module can be described with four equations of the solar energy (Psolar), generated electrical power (Pele), infrared radiation (Pirr) and convection of the heat (Pcon):

\[ P_{\text{solar}} = S_{\text{cell}}(1 - \alpha_{\text{PV}})G_{\text{poa}} \]  
\[ P_{\text{el}} = -S_{\text{cell}}\eta_{\text{cell,STC}}(1 + \gamma(T_{\text{ref}} - 25^\circ\text{C}))G_{\text{poa}} \]  
\[ P_{\text{irr}} = -2S_{\text{cell}}\sigma\left(\frac{e_f + e_b}{2} + \frac{e_f + e_b}{2} \right) \]  
\[ P_{\text{con}} = -2S_{\text{cell}}(k_{\text{con,1}} + k_{\text{con,2}})(T_{\text{cell}} - T_{\text{amb}}) \]

where \( S_{\text{cell}} \) is the solar cell surface area, \( \alpha_{\text{PV}} \) is the albedo of the PV module surface, \( \eta_{\text{cell,STC}} \) is the cell efficiency at standard test conditions, \( G_{\text{poa}} = 1000 \text{~W/m}^2 \), \( T_{\text{cell}} = 25^\circ\text{C} \), \( \gamma \) is the relative power temperature coefficient, \( \sigma \) is the Stefan-Boltzmann constant, \( e_f \) and \( e_b \) the module emissivity of the front and the back, respectively, \( e_{\text{sky}} \) and \( e_{\text{ground}} \) are the emissivities of sky and the ground, respectively, \( k_{\text{con,1}} \) and \( k_{\text{con,2}} \) are free and forced cooling coefficients, respectively, and \( v \) the wind speed.

2.6. Worst-case and annual analysis

We performed two analyses. In the first analysis, all module topologies were simulated on the shortest day of the year in the northern hemisphere (December 21) when the shade is the longest. Since the shape of the shade does not depend on the location but only on the azimuth and elevation/zenith angle of the sun, the simulations are presented only for Ljubljana. Longitude for Ljubljana is 14.52°, which means that the solar noon almost coincides with the CET noon. However, since the shade of an object defined in Table 2 is parallel to the module edges at noon time we decided to make the simulation at 12:30 when the solar azimuth angle in Ljubljana is 7.4° west.

With simulations at a single moment we present the influence of the shading object on the energy output of different PV module topologies. To examine the shaded cell condition with regard to their temperature we made a comprehensive energy balance investigation.

In the second analysis, we calculate the total annual energy yield of the shaded module at the five locations. As pointed out in the introduction, during partial shading, not only the total module generated output energy is relevant. The most important result of the single simulation of a shaded module is to analyse the situation of each individual solar cell in the module. The shaded solar cells might get reversed biased and in the worst case even reach the breakdown voltage. With annual simulations we obtain also the information of the frequency of the cell’s reversed biased occurrence.

In the simulations of the total annual energy yield of the shaded module at different locations, the modules were always oriented south with an inclination angle of 30°. We are aware that the optimal inclination angle depends on the location, however simulating at different angles would introduce another parameter that would influence the simulation results.

3. Results

3.1. Worst-case simulations on the shortest day of the year

The simulations were carried out for the shortest day in the year when the zenith angle of the sun at noon is the largest. The simulations were made for Ljubljana at 12:30 to avoid shades in parallel to the module edges. The whole I–V curve was simulated for each case while the presented results are showing maximal power point (MPP) condition.

The losses of partially shaded modules with three different shading objects are presented in Fig. 3. From the results, it is visible that in general the standard module with full-size cells performs the worst. All the other modules with cut cells are less affected to the selected partial shading scenario. T2, T3 and T4 modules have lower shading losses than the standard module or even the T5 module in portrait orientation. We can also observe that T5 module always performs best in landscape orientation, but mostly worst in portrait orientation. The reason is that T5 module has 10 strings in parallel where cells are serially connected in vertical, when the module is in landscape orientation. In this situation, the shade covers only a part of one or two strings, while the other nine or eight strings in parallel can still operate at full capacity. Similarly, we can observe that T2 to 4 modules produce lower losses when in portrait orientation. In this case the shade only affects one or two out of six strings in parallel reducing the power output of this group of six strings proportionally. But since this group with reduced capacity is in series with one to three other groups, it will reduce the capacity of the other groups as well.

In general, the simulations show that the shorter the strings are and the more parallel connections we have the better the module responds to the shading scenarios. In contrary, looking at the reverse bias of the shaded cell we would expect a larger influence at smaller cells since the shade covers the whole cell earlier. However, due to smaller cells and lower currents in the strings of solar cells connected in series, PV modules with smaller cells in general outperform the modules with full-size cells. Table 3 presents the number of reversed biased cells and the largest reverse bias voltage for all shaded modules in Ljubljana.

Except of the T1 module and T5 module in case of pole as a shading object, in all modules more cells experience the reverse bias in the landscape orientation because when the shade goes over...
the whole module all strings in parallel are affected which is similar to the situation of one covered cell in the standard module (where all cells are connected in series). The shading situation of the “chimney 2 m” object for three module types is best visible from Fig. 4, where it is also evident why the reverse bias voltage is lower at T3 module than at T4 module. At T3 module in one string only one cell is reverse biased and therefore also most affected.

3.2. Temperature in the reverse biased cell

From the electrical simulations on the shortest day of the year we found out that the maximal reverse voltage of a cell in the module (cut or full-size) was close to –15 V which is around half of the breakdown voltage of the modelled cells (32 V). We have got the same voltage when only one cell in the standard module was completely covered (Isc = 0 A) while the other cells were exposed to STC conditions, which is in accordance with other studies [15].

To look at the temperature behaviour of the shaded cell we evaluated the worst case scenario, assuming that the module is operating under 1000 W/m² and an ambient temperature of 20 °C (NOCT) while one shaded cell is illuminated only with the diffuse light of 200 W/m², which results in a reverse bias of –15 V. The wind speed was assumed to be zero. The energy flow of one solar cell is presented in Table 4. The model assumes a steady-state situation neglecting the heat transfer to/from the neighbouring unshaded cells. If the temperature of the solar cells in an unshaded monocrystalline Si module is 44.7 °C and the temperature of the cells in completely shaded module 23.2 °C, the temperature of a single shaded cell with a reverse bias of –15 V in an unshaded module will reach 64 °C (20 °C over the cell in unshaded module). At this condition, the power which is dissipated on one full-size shaded cell is 26.5 W.

### Table 3

Maximal reverse bias voltage of a solar cell in the shaded module in with regard to the shading object and module orientation (portrait/landscape) for Ljubljana on December 21 at 12:30.

| Ljubljana chimney 1 m | chimney 2 m | pole |
|----------------------|------------|------|
| Module type          | Module orientation | no. of rev. biased cells | max reverse bias voltage (V) | no. of rev. biased cells | max reverse bias voltage (V) | no. of rev. biased cells | max reverse bias voltage (V) |
| T1 - portrait        | standard landscape | 3 | –13.84 | 15 | –13.7 | 0 | 0 |
| T2 - portrait        | landscape | 0 | 0 | 0 | 0 | 0 | 0 |
| T3 - portrait        | landscape | 3 | –0.12 | 88 | –0.95 | 6 | –0.9 |
| T4 - portrait        | landscape | 1 | –0.95 | 89 | –14.58 | 6 | –0.58 |
| T5 - portrait        | landscape | 0 | –0.08 | 0 | 0 | 0 | 0 |

### Table 4

![Diagram of Power losses due to shading - portrait orientation](image1)

![Diagram of Power losses due to shading - landscape orientation](image2)

**Fig. 3.** MPP losses due to partial shading of different modules on clear-sky December 21 at 12:30 in Ljubljana.

**Fig. 4.** Shading situation in the standard T1, T3 and T4 modules in the portrait and landscape orientation. (on Dec. 21 at 12:30 in Ljubljana for “chimney 2 m” shading object).
The high temperature is not such a severe problem if the heat is dissipated homogeneously/uniformly over the whole solar cell. The problem occurs due to the material deviations in the cell [31], which localize heat dissipation into a few small areas which in turn experience very high temperatures.

3.3. Annual simulation

While the single simulation of partially shaded module for the worst shading situation is important to emphasize the effects of shading, the annual energy yield for different locations is an important key performance indicator. As mentioned before, we selected three locations in Europe (Ljubljana, Freiburg and Helsinki) and one in North Africa (Cairo). At all locations, the same shading scenario (location of the shading objects) is used as also the same mounting position of the modules (oriented south with an inclination of 30°).

Monthly energy yield profiles for all locations and two modules in landscape orientation are presented in Fig. 5 and Table 5. As expected the losses are visible only in half of the year from September to March. In the summer time the Sun is so high in the sky that the shading objects do not shade the module. The same reason is in Cairo for lower shading objects. The values of energy losses for all situations and locations are collected in Table 6.

The energy loss due to the shading object is relatively low (up to 12.5% in worst case for the 2 m chimney at Helsinki), however the main concern about the shading influence is the reverse bias of individual solar cell.

In Table 7 the number of reverse biased cells, number of reverse biased occurrences at the most affected cell and the maximal negative voltage are presented. It must be noted, that the numbers do not occur at the same time, but at different times throughout the year.

The most negative voltage of a cell in the module is close to −15 V regardless of the shading object type. In some cases, all or the majority of the cells in the module feel the negative bias at least once a year. The highest number of negative voltage occurrences in one cell is 97, which is 2.3% of the time in a year. Additionally, the simulation reveals that in some cases almost all cells can experience the reverse bias at least once in a year.

4. Discussion

The shading conditions in big field PV systems are usually not problematic since self-shading [12] can be mitigated by correct PV module positioning. Additionally, the shade from the previous row of modules shades the whole bottom part of the module and not only one cell and thus spreads reverse bias over several cells and limits the high reverse bias voltage. However, in residential areas the partial shading of neighbouring objects like chimneys, dormers, antennas or vegetation cannot be avoided, therefore it is very important which module type is less sensitive to partial shading conditions. Usually the shading occurs during morning or evening hours and does not largely affect the energy production. But, we have to keep in mind that the same shade can influence the production day by day. Usually the same cell or part of the module is shaded. Although a single event usually does not damage the module, a repeatable shade can lead to a faster degradation of affected area in the module and even failure of the whole module.

Our simulations show that the new type of modules with cut cells, regardless whether the module has a shingled or a classical cell interconnection design, behave better or are less sensitive to partial shading (see Table 5). The reason is not in the cell size, since a smaller cell can get totally shaded sooner, but in the parallel connection of the cells. The shade over the cell largely affects the short circuit current, namely the response is almost linearly dependent on the solar irradiance, but less the solar cells voltage. In the shading situation, a parallel connection of solar cells is therefore preferred.

However, a combination of the type of the shade and the

| Irradiance (W/m²) | T_air (°C) | P_con (W) | P_solar (W) | P_el (W) | P_ir (W) | T_cell (°C) |
|------------------|-----------|-----------|-------------|---------|--------|------------|
| unshaded cell    | 1000      | 20        | −8.7        | 21.9    | −4.6   | −8.6       | 44.7       |
| shaded cell      | 200       | 20        | −1.1        | 4.4     | −1.0   | −2.2       | 23.2       |
| shaded cell in reverse bias | 200 | 20        | −15.4       | 4.4     | 26.5   | −15.5      | 64.0       |
| shaded cell in reverse bias | 200 | 30        | −14.7       | 4.4     | 26.5   | −16.2      | 72.0       |

Fig. 5. Monthly energy yield for standard T1 and T4 module for Ljubljana, Freiburg, Helsinki, Cairo and Denver in landscape orientation.
Table 5
Annual energy yield for standard T1 and T4 module for Ljubljana, Freiburg, Helsinki, Cairo and Denver in landscape orientation.

| Location          | T1    | T4    |
|-------------------|-------|-------|
| Ljubljana         |       |       |
| unshaded          | 1354  | 1351  |
| chimney 1m        | 1332  | 1340  |
| chimney 2m        | 1252  | 1287  |
| pole              | 1345  | 1344  |
| Freiburg          |       |       |
| unshaded          | 1352  | 1349  |
| chimney 1m        | 1309  | 1329  |
| chimney 2m        | 1217  | 1273  |
| pole              | 1332  | 1334  |

| Location          | T1    | T4    |
|-------------------|-------|-------|
| Helsinki          |       |       |
| T1                | 1170  | 1167  |
| chimney 1m        | 1133  | 1148  |
| chimney 2m        | 1023  | 1087  |
| pole              | 1156  | 1155  |
| Cairo             |       |       |
| unshaded          | 2467  | 2461  |
| chimney 1m        | 2467  | 2461  |
| chimney 2m        | 2308  | 2375  |
| pole              | 2467  | 2461  |
| Denver            |       |       |
| unshaded          | 2113  | 2108  |
| chimney 1m        | 2074  | 2094  |
| chimney 2m        | 1869  | 1965  |
| pole              | 2091  | 2097  |

Table 6
Annual energy losses for T1 and T4 modules, shading situations and locations (red colour of the table cell represents the highest losses and green colour the lowest losses with regard to the shading object).

| Location          | portrait | landscape |
|-------------------|----------|-----------|
| Ljubljana         |          |           |
| chimney 1m        | 1.3%     | 1.6%      |
| chimney 2m        | 4.8%     | 7.5%      |
| pole              | 0.4%     | 0.7%      |
| T1                |          |           |
| chimney 1m        | 2.0%     | 3.2%      |
| chimney 2m        | 5.5%     | 10.0%     |
| pole              | 0.8%     | 1.5%      |
| T4                |          |           |
| chimney 1m        | 1.5%     | 1.5%      |
| chimney 2m        | 3.3%     | 5.6%      |
| pole              | 0.3%     | 1.1%      |

| Freiburg          |          |           |
| chimney 1m        | 2.1%     | 3.1%      |
| chimney 2m        | 7.9%     | 12.5%     |
| pole              | 0.8%     | 1.2%      |
| T1                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 4.0%     | 6.4%      |
| pole              | 0.0%     | 0.0%      |
| T4                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 2.4%     | 3.5%      |
| pole              | 0.0%     | 0.0%      |

| Helsinki          |          |           |
| chimney 1m        | 1.6%     | 1.7%      |
| chimney 2m        | 5.4%     | 6.9%      |
| pole              | 0.3%     | 1.0%      |
| T1                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 4.0%     | 6.4%      |
| pole              | 0.0%     | 0.0%      |
| T4                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 2.4%     | 3.5%      |
| pole              | 0.0%     | 0.0%      |

| Cairo             |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 4.0%     | 6.4%      |
| pole              | 0.0%     | 0.0%      |
| T1                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 2.4%     | 3.5%      |
| pole              | 0.0%     | 0.0%      |
| T4                |          |           |
| chimney 1m        | 0.0%     | 0.0%      |
| chimney 2m        | 2.4%     | 3.5%      |
| pole              | 0.0%     | 0.0%      |

| Denver            |          |           |
| chimney 1m        | 1.1%     | 1.8%      |
| chimney 2m        | 6.3%     | 11.5%     |
| pole              | 0.4%     | 1.0%      |
| T1                |          |           |
| chimney 1m        | 1.2%     | 0.6%      |
| chimney 2m        | 3.5%     | 6.8%      |
| pole              | 0.2%     | 0.5%      |
| T4                |          |           |
| chimney 1m        | 1.1%     | 1.8%      |
| chimney 2m        | 6.3%     | 11.5%     |
| pole              | 0.4%     | 1.0%      |
orientation is very important. In shading conditions, it is important that the cell strings in the module are short to avoid large negative cell voltages and consequent power dissipation in the affected cell. A higher temperature of the reversed biased cell, even if the voltage is still only at half of the breakdown voltage, can provoke faster cell degradation.

A conclusion can also be drawn regarding the orientation of series connected cells in substrings. If the orientation of the series connected substrings is in line with the orientation of the shape of the shade, the power loss will be reduced. This means that the orientation of the modules for a given installation should be considered, taking into account both, the orientation of series connected cut cell strings and the specific shape of the shades at the exact installation location. For the best result, they should be aligned as much as possible.

Additionally to the module/shade orientation alignment, also the PV system location plays a significant role. Locations with lower diffuse light share (higher share of the direct light) during the shading hours are more exposed to energy loss, which is evident from monthly energy yield values (Fig. 5). If winter month values are compared between Ljubljana and Cairo or Denver we can see the large influence of shading object at lower sun angles. If a 2 m chimney is responsible for 32% energy loss in December in Ljubljana, it lowers the yield in Denver for 45%. The share of the direct light in December in Ljubljana and Denver is 30% and 63%, respectively.

Also, from the energy production/system performance side it is important to maximize the energy output also during the shading phase. Thus, a smart, fast and efficient MPPT tracking algorithm is very important, especially in small residential systems using optimizers or micro inverters.

5. Conclusion

With a rise of the PV module efficiency and power, new designs are taking advantage of cut solar cells to reduce the current in substrings and consequently lower the Joule losses in the module. Lower current enables also the use of narrower busbars, which reduces the front-side shading and increases the output power. Lowering the gap between the cut cells and ultimately the shingled design is used to further maximize the power. If modules with cut cells are to have similar electrical properties than the standard 60-cell PV module, the substrings have to be connected also in parallel. A parallel connection of solar cells is beneficial in shading conditions, since the solar cell voltage is less affected by a shade than the current.

In this work, we simulated five different types of PV modules with cut solar cells and evaluated shading losses by three different shading objects. Additionally, we checked their behaviour at five locations from Helsinki in the north to Cairo in the south. The module performance was calculated on the shortest day of the year when the shade is the longest and over the whole year. In the worst case scenario simulations, the losses of PV modules with cut cells can be reduced to as much as half of the losses in a conventional 60-full-size cell PV module. However, the reverse bias voltage of a single shaded cut cell can still reach close to ~15 V. At this voltage and in full sunshine, the solar cell can heat up to temperatures above 70 °C, which can be dangerous for degradation if it occurs periodically and for longer times.

In the annual simulations of the “chimney 2 m” shaded T1 and T4 PV module, the maximal energy loss varies from Cairo 4.0% and 2.4%, respectively, to Helsinki 12.5% and 6.9%, respectively.

Based on the simulations presented herein, we conclude that there is no clear best module configuration. The best configuration depends on the specific installation conditions of the modules and micro shading conditions. In general, the orientation of the cells connected in series should be aligned with the shape of the shade as much as possible to reduce energy loss and to minimise cells' reverse voltage. With an optimised configuration the annual energy losses can be reduced up to 50% if compared to a standard 60-cell module.

CRediT authorship contribution statement

Kristijan Breci: Simulations, Methodology, Software, Writing.
Matez Bokalic: Discussions, Reviewing, Marko Topi: Reviewing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The Authors acknowledge the financial support of the Slovenian Research Agency (Research Programme P2-0197). This work has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 857793.

References

[1] M.A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A.W.Y. Ho-Bailie, Solar cell efficiency tables (Version 55), Prog. Photovolt. Res. Appl. 28 (1) (2020) 3–15, https://doi.org/10.1002/pip.3228.
[2] Best Research-Cell Efficiency Chart. https://www.nrel.gov/pv/cell-efficiency. html. (Accessed 4 May 2020).
[3] S. Braun, G. Hahn, R. Nissel, C. Pönsch, D. Habermann, Multi-busbar solar cells and modules: high efficiencies and low silver consumption, Energy Procedia 38 (Jan. 2013) 334–339, https://doi.org/10.1016/ eegypro.2013.07.286.
[4] S. Braun, G. Micard, G. Hahn, Solar cell improvement by using a multi busbar design as front electrode, Energy Procedia 27 (Jan. 2012) 227–233, https:// doi.org/10.1016/j.egypro.2012.07.056.
[5] C. Ballif, et al., SmartWire solar cell interconnection technology, 29th Eur. Photovolt. Sol. Energy Conf. Exhib. (Nov. 2014) 2555–2561, https://doi.org/ 10.4229/EUPVSEC2014-2014-5D0.16.3.
[6] R.C. Vieira, F.M.U. de Araújo, M. Dhimish, M.I.S. Guerra, A comprehensive review on bypass diode application on photovoltaic modules, Energies 13 (10)
What is a half cell solar panel and how does it work? Solar Power World (2018). Oct. 24, https://www.solarpowerworldonline.com/2018/10/what-is-a-half-cell-solar-panel/. accessed May 05, 2020.

[7] What is a half cell solar panel and how does it work? Solar Power World (2018). Oct. 24, https://www.solarpowerworldonline.com/2018/10/what-is-a-half-cell-solar-panel/. accessed May 05, 2020.

[8] ITRPV, International Technology Roadmap for Photovoltaic, eleventh ed., ITRPV, Apr. 2020. Accessed: May 05, 2020. [Online]. Available: http://itrpv.net/Reports/Downloads/.

[9] D. Tonini, G. Cellere, M. Bertazzo, A. Fecchio, L. Cerasti, M. Galiazzo, Shingling technology for cell interconnection: technological aspects and process integration, Energy Procedia 150 (Sep. 2018) 36–43, https://doi.org/10.1016/j.egypro.2018.09.010.

[10] SunPower, Performance Series (P-Series) Commercial Solar Panels, SunPower, United States, Sep. 09, 2016. https://www.sunpower.com/solar-panels-technology/p-series-solar-panels/, accessed May 05, 2020.

[11] LONGi Solar Jumps on ‘shingled’ Module Train with New Seamless Soldering Technology, Solar Power World, May 31, 2019. https://www.solarpowerworldonline.com/2019/05/longi-solar-jumps-on-shingled-module-train-with-new-seamless-soldering-technology/ accessed May 05, 2020.

[12] K. Brecl, M. Topić, Self-shading losses of fixed free-standing PV arrays, Renew. Energy 36 (11) (Nov. 2011) 3211–3216, https://doi.org/10.1016/j.renene.2011.03.011.

[13] A.A. Elbaset, M.S. Hassan, Design and Power Quality Improvement of Photovoltaic Power System, Springer International Publishing, 2017.

[14] H. Zhou, L. Zhou, Shading and hot spot performance of shingled cell array module, in: 33rd Eur. Photovolt. Sol. Energy Conf and Exhibition, Nov. 2017, pp. 1744–1747, https://doi.org/10.4229/EUPVSEC2017-SDV.3.2.

[15] O. Kunz, R.J. Evans, M.K. Juhl, T. Trupke, Understanding partial shading effects in shingled PV modules, Sol. Energy 202 (May 2020) 420–428, https://doi.org/10.1016/j.solener.2020.03.032.

[16] S. Guo, J.P. Singh, I.M. Peters, A.G. Aberle, T.M. Walsh, A quantitative analysis of photovoltaic modules using halved cells, Int. J. Photoenergy 2013 (2013) 1–8, https://doi.org/10.1155/2013/739374.

[17] J.R. Lim, et al., Analytical study of the electrical output characteristics of c-Si solar cells by cut and shading phenomena, Energies 11 (12) (Dec. 2018), https://doi.org/10.3390/en11123397, Art. no. 12.

[18] T. Huld, R. Müller, A. Gambardella, A new solar radiation database for estimating PV performance in Europe and Africa, Sol. Energy 86 (6) (Jun. 2012) 1803–1815, https://doi.org/10.1016/j.solener.2012.01.006.

[19] Copernicus Climate Change Service (C3S), ERAS: fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus climate change service climate data store (CDS); copernicus climate change service (C3S). https://cds.climate.copernicus.eu/cdsapp#!/home accessed Oct. 07, 2020.

[20] NSRDB, National solar radiation database. https://nsrdb.nrel.gov/ accessed Oct. 07, 2020.

[21] Meteornorm, Meteornorm: irradiation data for every place on Earth. http://www.meteornorm.com/en/, Mar. 05, 2018 accessed Mar. 05, 2018.

[22] JRC’s Directorate C, Energy, transport and climate - PVGIS – European commission. http://re.jrc.ec.europa.eu/pvgis/ accessed Mar. 05, 2018.

[23] Slovenian Environment Agency - ARSO. http://www.arso.gov.si/en/ (Accessed 14 May 2020).

[24] K. Brecl, M. Topić, Development of a stochastic hourly solar irradiation model, Int. J. Photoenergy 2014 (2014) 1–7, https://doi.org/10.1155/2014/376504.

[25] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Modeling daylight availability and irradiance components from direct and global irradiance, Sol. Energy 44 (5) (Jan. 1990) 271–283, https://doi.org/10.1016/0038-092X(90)90055-H.

[26] J. Kurnik, M. Jankovec, K. Brecl, M. Topić, Outdoor testing of PV module temperature and performance under different mounting and operational conditions, Sol. Energy Mater. Sol. Cells 95 (1) (Jan. 2011) 373–376, https://doi.org/10.1016/j.solmat.2010.04.022.

[27] A.D. Jones, C.P. Underwood, A thermal model for photovoltaic systems, Sol. Energy 70 (4) (Jan. 2001) 349–359, https://doi.org/10.1016/S0038-092X(00)00149-3.

[28] LTspice | design center | analog devices. https://www.analog.com/en/design-center/design-tools-and-calculators/ltspace-simulator.html# accessed Jul. 14, 2020.

[29] N.G.D. Center, ETOPO1 global relief. https://www.ngdc.noaa.gov/mgg/global/ accessed May 05, 2020.

[30] Horicatcher - Meteonom (de), Meteonom (en). https://meteonom.com/en/product/horicatcher accessed May 05, 2020.

[31] O. Breitenstein, et al., Understanding junction breakdown in multicrystalline solar cells, J. Appl. Phys. 109 (7) (Apr. 2011), https://doi.org/10.1063/1.3562200, 071101.