Theoretical Limits of Internal Shading Effect on Electricity Production of Roof-Top PV Plants

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Abstract

This paper deals with a problem of internal shading within roof-top PV plants based on c-Si technology. The internal shading results from limited spacing between parallel rows of PV modules and represents the situation when a row of modules is shaded by the previous one. A procedure to determine theoretical limits of internal shading effect for a typical roof-top PV plant is presented. The procedure is based on the concept of average clear sky day specified for every month, for which a difference in daily electricity production between shaded and unshaded module is calculated. Finally, knowing the monthly distribution of equivalent clear sky days, the effect of internal shading is determined.

1. Large area roof-top PV plants and the problem of internal shading

Large area flat roofs with sufficient structural capacity are particularly suitable for PV plants.
A common design maximizing annual production assumes preferably southern orientation of PV modules sloping app. 30° for central European latitudes. The spacing between the respective rows of modules is designed according to a commonly accepted rule saying that any internal shading shall be avoided at local noon at winter solstice. The term internal shading in this case expresses the situation when a row of modules is shaded by the previous one, or more generally, when modules are source of shading for other modules.

Unlike PV plants on terrain, the roof-top ones usually consist of single-module rows. The reason lies in effort to minimize wind loads acting on the modules and structural elements of the installation.

Fig. 1. Typical layout of a roof-top PV plant with the modules mounted horizontally.

The question is, what spacing between the rows is still suitable to avoid significant production losses while allowing dense coverage of a limited roof area at the same time. This paper deals with PV plants based on crystalline silicon (c-Si) modules which are especially vulnerable to partial shading. Thin-film modules are generally more resistant to this influence.

2. Modeling the influence of internal shading

2.1. Approach to the problem

The internal shading occurs only during sunny hours with a sufficient amount of direct solar radiation that casts shades. When the sky is overcastted the internal shading is not present. Of course, the sunny hours can be scattered over time.

To handle this problem in a simple manner and to keep the calculation time short, the concept of equivalent clear sky days has been developed. It is assumed that these days equivalently comprise all the sunny hours for each month and therefore, the problem of internal shading can be concentrated in them as well. It follows, that electricity production can be calculated on monthly basis for the equivalent clear sky days with and without the internal shading effect. The difference is then subtracted from monthly electricity production obtained from a standard PV model (for example PVGIS, Sandia etc.). In this way the monthly DC production of PV plant incorporating the influence of internal shading is obtained.

Solar radiation during clear sky days is modeled using mathematical clear sky irradiance model presented by Muneer [1]. It takes into account, besides location characteristics, Linke turbidity factor representing atmospheric conditions.

In order to calculate the magnitude of internal shading during clear sky days a shading model has been developed. It is based on standard stereometrical relations between position of the sun and the geometry of PV installation [2]. Output of the model is shaded length measured from the bottom of the module from which the number of shaded cells is derived. This is the key factor since the number of shaded cells determines the drop of the output power of the module. The shading model is considered to be one dimensional since it does not cover the edge effects as is shown in Fig. 2 (left) .

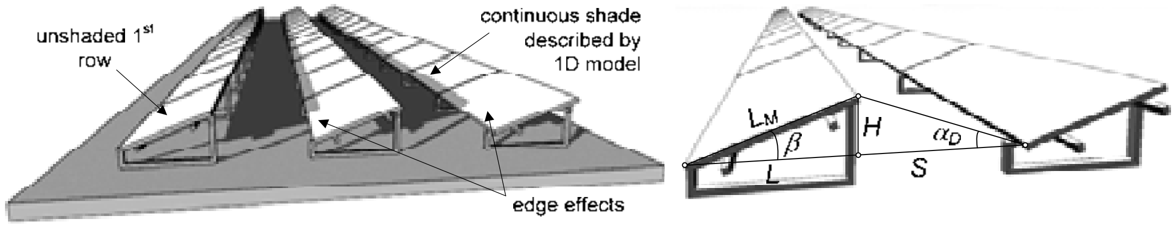

Fig. 2. The principle of 1D shading model (left) and the design angle α_D (right).

Regarding the geometry of roof-top PV installations, an important quantity called the design angle, α_D, has to be introduced, see Fig. 2 (right). The design angle make it possible to describe the influence of internal shading on PV plants with various geometries in a unified manner. In most projects it is equal to height of the sun at local noon at winter solstice. For Prague (+50N) it would be 17°. Module spacing, S, is then derived from the design angle, slope, β, and size of the modules, L_M.

2.2. Influence of partial shading on output power of c-Si PV modules

A typical c-Si PV module consists of a number of cells in series(-parallel) connection. When a part of these cells is shaded, the output power of the module drops. Furthermore, the decrease is not linearly proportional to the shaded area. It is due to the electrical nature of the cells connected into series. The shaded cells behaves a sink and even one shaded cell can disable the whole string.

In a typical c-Si PV module all the cells are connected in series creating one long string. In order to lower the influence of partial shading the manufacturers equip the modules with by-pass diodes, mostly with 3 of them that divides the module into 3 sections. Every diode acts as a bridge - it switches of the respective section under partial shading, while the other sections remain unaffected. Structure of a typical commercial module and connection of the diodes is shown in Fig. 3.

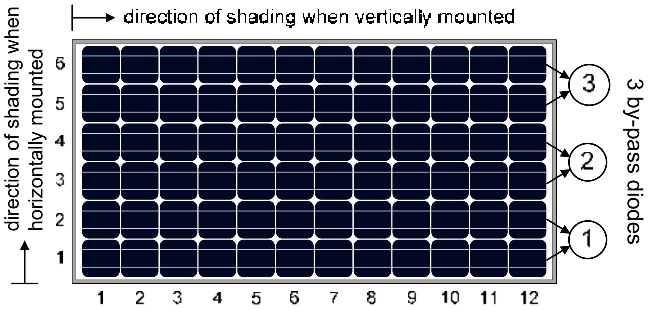

Fig. 3. By-pass diodes connected within a typical commercial c-Si PV module.

It is obvious that the position in which the module is mounted plays an important role in calculating the effect of internal shading. Horizontally mounted modules can use the advantage of by-pass diodes whilst vertically mounted modules cannot. A simple experiment to express this effect was designed, in which two different commercial c-Si PV modules were used with equal result. During a clear sky day the modules were gradually shaded from a distance of 1,5 m with a step of 1/4 of the cell. The shade always spanned from edge to edge which corresponds to the situation of internal shading. The output power at every step was measured by Mini-KLA PV I-V Curve Analyser. The results for both mounting positions in form of a dimensionless output power reduction coefficient are shown in Fig. 4.

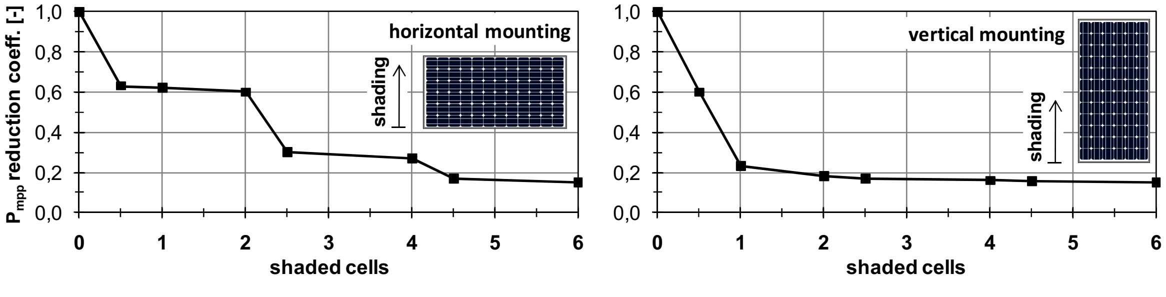

Fig. 4. Reduction coefficient expressing the influence of partial shading on P_{mpp} of a c-Si PV module (based on experimental data and applies for clear sky conditions).

The difference between the horizontal and vertical mounting position is obvious. While the output power of horizontally mounted module decreases in steps as the respective sections are switched off by by-pass diodes, in the case of vertical mounting the whole module is switched off immediately after the first row of cells is shaded.

2.3. Characteristic day and number of equivalent clear sky days for each month

Firstly, a characteristic day is assigned to each month. This is not done randomly but the approach developed by Klein is used [2]. Secondly, the concept of an equivalent clear sky day is brought in. Every equivalent clear sky day is assumed to have the same sun path as the characteristic day for that month. Simply, it is a sunny characteristic day. Finally, the number of equivalent clear sky days is estimated for each month based on sunshine duration defined in [3] and meteorological data [3, 4].

The calculations in the following sections are done for the geographic location of Prague (+50N, -14E) using hourly climatic data from Meteonorm [4].

Table 1. Equivalent clear sky days derived from sunshine duration and length of day for each month.

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**year**
Characteristic day	**17**	**16**	**16**	**15**	**15**	**11**	**17**	**16**	**15**	**15**	**14**	**10**	
Sunshine duration [h]	42	84	131	185	228	229	203	221	152	122	63	40	tot. 1700
Length of day [h]	8.4	9.9	11.6	13.5	15.2	16.1	15.7	14.2	12.4	10.5	8.8	8.0	av. 12.0
Equival. clear sky days	**5.0**	**8.5**	**11.3**	**13.7**	**15.0**	**14.3**	**13.0**	**15.5**	**12.3**	**11.7**	**7.2**	**5.0**	tot. **132**

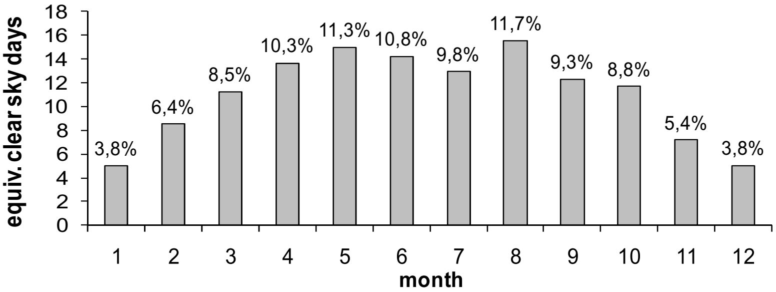

Fig. 5. Annual distribution of equivalent clear sky days for the location of Prague based on Meteonorm data [4].

Obviously, the magnitude of internal shading effect depends strongly on the annual distribution of clear sky days (see Fig. 5). The fewer of them falls on winter months with low sun, the weaker is the influence of internal shading on annual electricity production.

2.4. Influence of internal shading during equivalent clear sky days and annual losses

This section shows an example of calculation of internal shading influence on annual electrical production of a typical roof-top PV plant. It is done using (1) the shading model, (2) known electrical behavior of c-Si modules under partial shading and (3) the concept of equivalent clear sky days, as presented in the previous sections.

The input parameters are:

geometric location and hourly meteorological data:	Prague (+50N, -14E)
design angle determining the spacing between rows:	18°
slope and azimuth of the modules:	30° and 0° (south)

For each equivalent clear sky day, the solar radiation reaching the surface of the modules is calculated using mathematical clear sky irradiance model [1]. Based on this solar input, the DC output power of the unshaded module is determined including optical, low-irradiance and temperature losses [5]. Then the number of cells shaded by the previous row is calculated. Next, the DC output power of the shaded module is determined using P_{mpp} reduction coefficient shown in Fig. 4. Knowing the difference in daily electricity production between the shaded and unshaded module for equivalent clear sky days, the monthly decrease in delivered energy is calculated taking into account their number.

Fig. 6 shows nondimensionalized DC output power during equivalent clear sky days for three months with the highest influence of internal shading for both horizontal and vertical mounting position.

horizontal ↓	mounting position of PV modules	↓ vertical

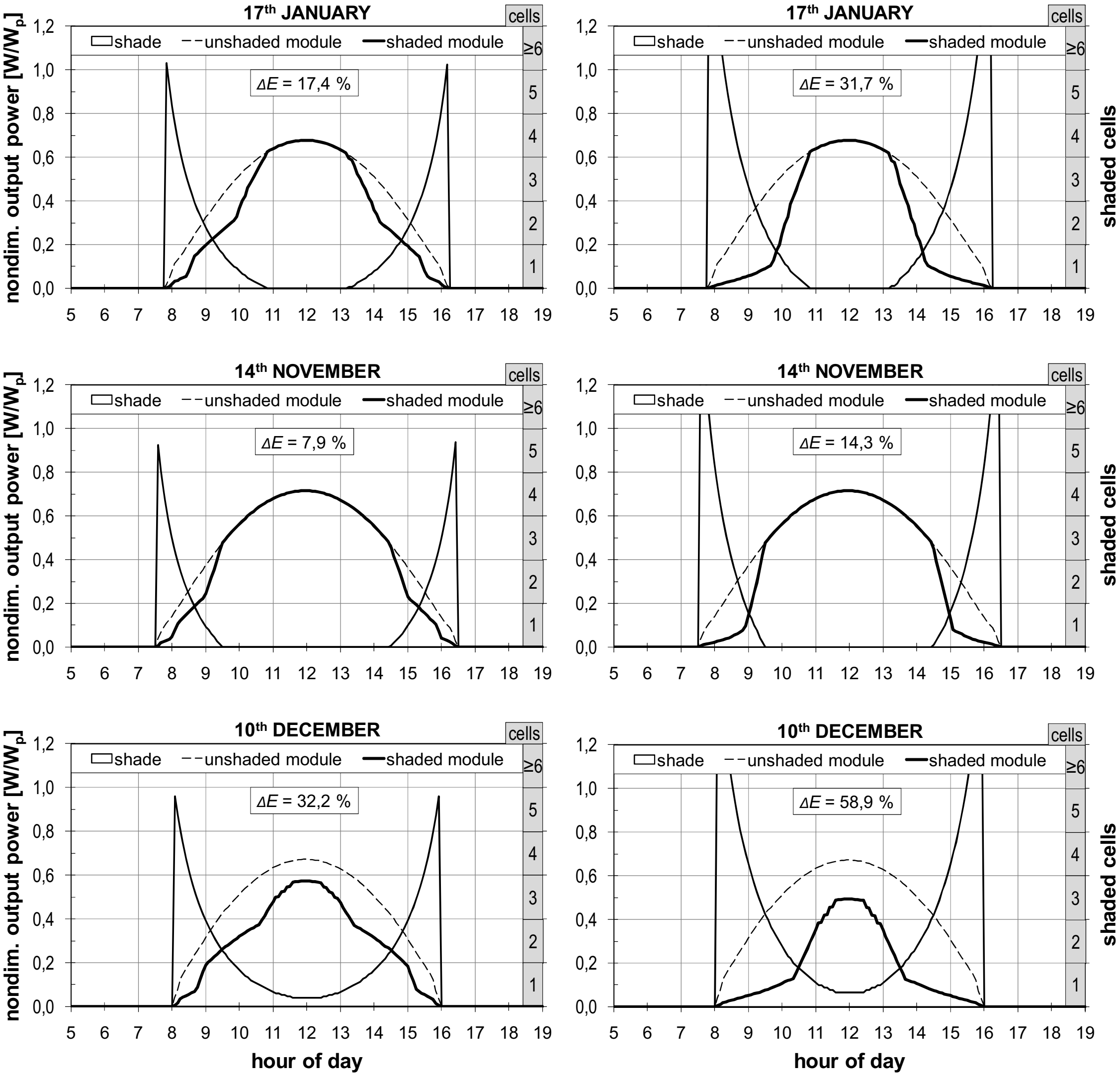

Fig. 6. Influence of internal shading on output power of a c-Si PV module during characteristic days in Jan, Nov and Dec (months most affected by internal shading).

Table 2. Determination of monthly and annual production losses due to internal shading.

Month	Global radiation [kWh/m^2]		Clear sky days	DC production of the modules [kWh/kW$_p$]						**Monthly losses [%]**	
				Monthly	1equivalent clear sky day			Monthly			
	Horiz.	Tilted		unshaded	unshaded	shaded horiz. mount.	shaded vert. mount.	shaded horiz. mount.	shaded vert. mount.	horiz. mount.	vert. mount.
1	21	30	5,0	**28**	3,8	3,1	2,6	**25**	**23**	11,5%	20,9%
2	37	51	8,5	**49**	4,9	4,8	4,7	**48**	**48**	1,8%	3,2%
3	72	89	11,3	**85**	5,9	5,9	5,9	**85**	**85**	0%	0%
4	114	129	13,7	**121**	7,0	7,0	7,0	**121**	**121**	0%	0%
5	149	155	15,0	**140**	7,4	7,4	7,4	**140**	**140**	0%	0%
6	146	147	14,3	**131**	7,4	7,4	7,4	**131**	**131**	0%	0%
7	145	146	13,0	**130**	7,3	7,3	7,3	**130**	**130**	0%	0%
8	136	149	15,5	**132**	6,7	6,7	6,7	**132**	**132**	0%	0%
9	87	102	12,3	**92**	6,0	6,0	6,0	**92**	**92**	0%	0%
10	57	76	11,7	**71**	4,9	4,9	4,9	**70**	**70**	0,4%	0,7%
11	25	37	7,2	**35**	4,2	3,8	3,6	**32**	**30**	6,8%	12,4%
12	15	24	5,0	**22**	3,7	2,5	1,5	**16**	**11**	26,6%	48,7%
year	1 004	1 134	132,4	**1 036**	69	67	65	**1 024**	**1 013**	**1,23%**	**2,24%**

A difference in annual losses due to internal shading between the horizontal and vertical mounting position is obvious. It results from the electrical behavior of the modules equipped with by-pass diodes.

3. Results and application

3.1. Annual loss in electricity production due to internal shading for various situations

The same procedure as in section 2.4 is used to calculate annual losses due to internal shading for roof-top PV plants with single-module rows with various

mounting positions of the modules:	horizontal and vertical
design angles:	14° to 24°
slopes:	20° and 30°
orientations:	SE to SW

The results (see Fig. 7) can be interpreted in the following way:

1) **The annual losses due to internal shading:** the losses for common conditions ranges from 0,3 to 4,2 % for horizontally and from 0,6 to 7,2 % for vertically mounted modules.

2) **Mounting position of modules:** roof-top PV plants with horizontally oriented modules are less vulnerable to internal shading. The annual loss in electricity production ranges from 55 to 60 % compared to vertically mounted modules almost independently of their slope and orientation.

3) **Design angle and orientation of modules:** the design angle equal to height of the sun at local noon at winter solstice well applies for installations with orientation of the modules from SSE to SSW. When the orientation significantly differs from south, a lower design angle should be chosen to avoid excessive losses due to internal shading.

4) **Slope of modules:** Lowering the slope of PV modules to 20° can further decrease the annual losses due to internal shading. This effect almost balances the decrease in production due to deviation from the optimum slope for maximum annual production (35° for +50N). The total decrease in annual production is then less than 2 % compared to the optimum. However, the lower slope makes it possible to install more W_p, not to mention structural benefits due to lower wind loads.

horizontal ↓	mounting position of PV modules	↓ vertical

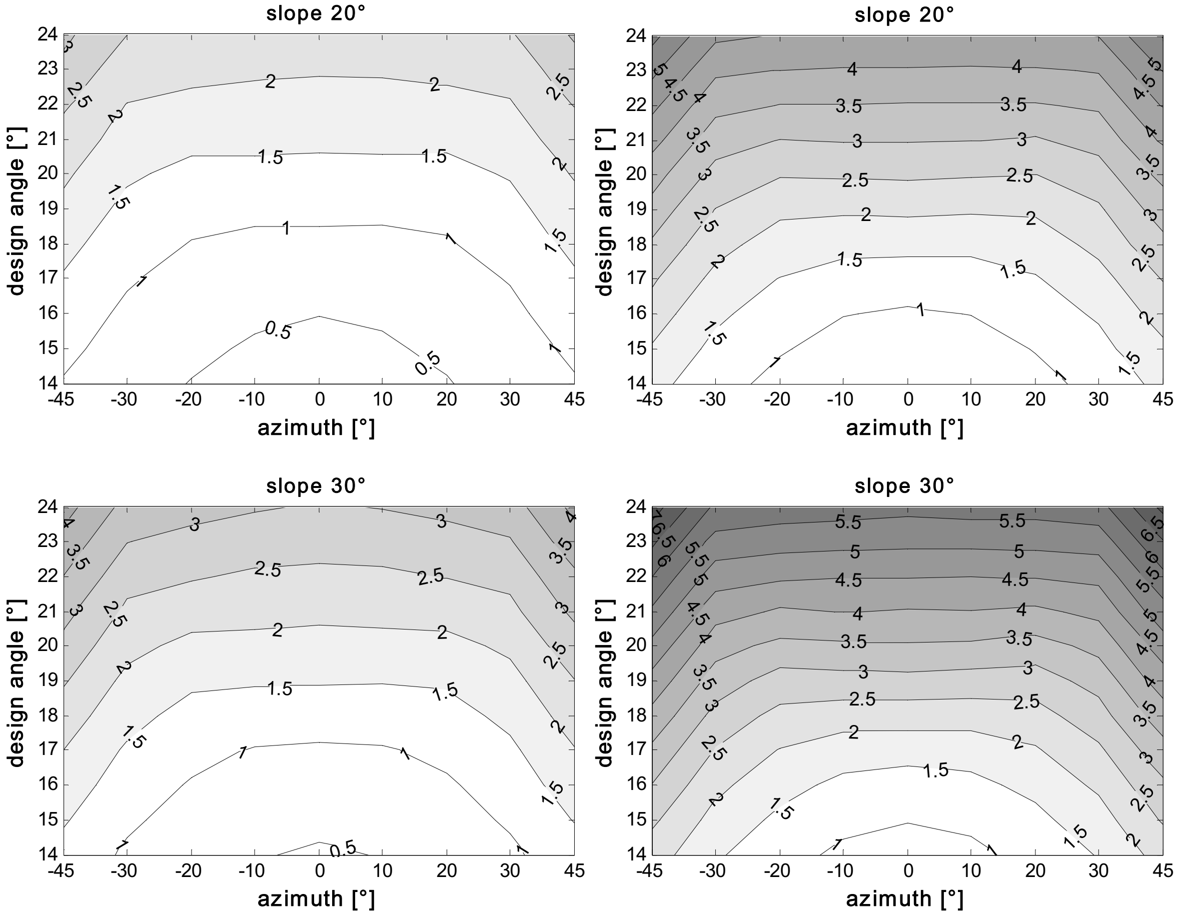

Fig. 7. Percentage losses in annual electricity production of c-Si PV modules due to internal shading as a function of design angle and azimuth angle of the modules (0° S, -45° SE, +45° SW). Shown for 20° and 30° slope and horizontal and vertical mounting position of the modules. Calculated for the location of Prague.

The results presented in Fig. 7 depend on the annual distribution of clear sky days (see Fig. 5).

3.2. Case study

Let's have a flat roof of an industrial building located in Prague and oriented 20° westerly. The goal is to compare two installation options:

Case1: Vertically mounted PV modules, inclined 30°.

Case 2: Horizontally mounted PV modules, inclined 20°.

The design angle in both cases is 17°. The DC production is virtually measured right behind the modules (i.e. cable and other technological losses are not calculated).

Table 3. Results of the case study.

Case	Annual DC production per installed power [kWh/kW$_p$]		Installed power per roof area [W$_p$/m^2]	**Annual DC production per roof area** [kWh/m^2]
	without int. shading	with the effect of internal shading		
1	1 024 (100 %)	1 004 (100 %)	57,3 (100 %)	**57,5 (100 %)**
2	1 006 (98,2 %)	998 (99,4 %)	68,7 (120 %)	**68,6 (119 %)**

4. Conclusion

The problem of electricity losses due to internal shading within roof-top PV plants based on c-Si technology has been described. These losses are predictable and their magnitude is comparable to optical, inverter or cable losses, most commonly ranging from 1 to 4 %. They can be also minimized by a proper design. The mounting position of PV modules should be preferably horizontal in order to use the advantage of by-pass diodes. Also lower than optimum inclinations of the modules (20° instead of 35° for +50N) can be used without additional loss in electricity production. Besides this, the lower angles enable higher installation density and thus better coverage of often limited roof space. Furthermore, the influence of design angle on magnitude of internal shading has been studied. A standard rule saying that the design angle should be equal to height of the sun at local noon at winter solstice (17° for +50N) proved to be right for southerly oriented installations, or even too conservative especially for horizontally mounted PV modules. On the other hand, this rule can lead to production losses due to internal shading higher than 3 % for PV plants oriented SE or SW with vertically mounted modules. Regarding horizontally mounted modules, it has been proved that there is a potential to lower the distances between rows without excessive decrease in electricity production.

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