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Analysis of spatial fixed PV arrays configurations to maximize energy harvesting in BIPV applications

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Abstract–This paper presents a new approach for efficient utilization of building integrated photovoltaic (BIPV) systems under partial shading conditions in urban areas. The aim of this study is to find out the best electrical configuration by analyzing annual energy generation of the same BIPV system, in terms of nominal power, without changing physical locations of the PV modules in the PV arrays. For this purpose, the spatial structure of the PV system including the PV modules and the surrounding obstacles is taken into account on the basis of virtual reality environment. In this study, chimneys which are located on the residential roof-top area are considered to create the effect of shading over the PV array. The locations of PV modules are kept stationary, which is the main point of this paper, while comparing the performances of the configurations with the same surrounding obstacles that causes partial shading conditions. The same spatial structure with twelve distinct PV array configurations is considered. The same settling conditions on the roof-top area allow fair comparisons between PV array configurations.

The payback time analysis is also performed with considering local and global maximum power points (MPPs) of PV arrays by comparing the annual energy yield of the different configurations.

Keywords: BIPV systems; PV configurations; Partial shading; Virtual reality; Payback time

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1. Introduction

Physical placement of the photovoltaic (PV) modules on the planned installation surface is one of the major steps for efficient utilization of PV systems in building integrated photovoltaic (BIPV) applications. One of the most important advantages of PV modules is their modular structure, hence they can be simply adopted in existing buildings and can be installed anywhere [1]. However, PV system performance is affected by several environmental and physical factors such as shading effects of the environmental obstacles, specifications of the PV array area, tilt and azimuth angles of the mounting surface [2-4]. The partial shading effect is one of the most important issues in terms of power reduction in BIPV systems. It is difficult to avoid partial shading effects along the year due to the neighboring obstacles around BIPV systems. Under partial shading conditions, the PV arrays present highly nonlinear power-voltage (P-V) curves depending on the irradiance values and the number of shaded PV modules. In this situation, the conventional maximum power point tracking (MPPT) methods cannot track the global maximum power point on the P-V curve. Therefore, there are a number of studies on development of advanced global MPPTs methods to reduce the power losses due to partial shading effects [5-9]. On the other hand, another approach for reducing partial shading effect is to find out available installation areas where the PV modules are minimally affected by partial shading effect. In the literature, different techniques have been presented in order to estimate available area for the installation of PV modules [10, 11]. In these studies, software packages are used to find the non-shaded areas or minimum shaded areas during the day. Loulas et al. studied on the estimation of the potential PV systems on buildings by using Google Sketchup and PVsyst for detailed shading analysis in Greece [10]. Strzalka et al. worked on the 3D modeling of large city areas to estimate the PV energy generation by using Geographic Information System (GIS) in Germany [10]. These studies focused on the estimation of the suitable area to avoid the shading effect in PV array due to the surrounding obstacles. However, it is not always feasible in BIPV systems because of the lack of spaces for installing the PV modules to a different place. Another approach to reduce the mismatch losses due to the shading effect is the using of different PV array configurations [12-14]. Rani et al. reconfigured the physical location of the PV modules in the PV array according to a Su Do Ku puzzle pattern to improve the performance of the system under partially shaded conditions without altering the electrical connection [14]. On the other hand, it is possible to change the global MPP on the P-V curve by different PV array configurations without changing the physical location of PV modules. In conventional series-parallel (SP) configuration, the MPPs usually move to the short circuit point on the P-V curve under partial shading conditions. Therefore, if the global MPP of P-V curve can be kept near the open circuit voltage by only changing the configuration type, the harvested energy from PV array can be increased by using a simple conventional MPPT method in a narrow voltage window [13]. Generally, PV modules are connected to each other by SP configuration. However, a new configuration called as the total cross tied (TCT) can be more advantageous than the SP configuration [12, 13].

This study evaluates different electrical configuration types without changing the physical location of PV modules considering realistic partial shading conditions in BIPV systems. In this study, PV array is built up by 24 PV modules and electrical configurations of the PV array are designed as 2x12, 3x8, 4x6, 12x2, 8x3, and 6x4 for TCT and SP types. The locations of PV modules are kept stationary, which is the main point of this paper, while comparing the performances of the configurations with the same surrounding obstacles that causes partial shading conditions. The payback time analysis is also performed by comparing annual harvesting energies in different configurations of the PV arrays.

2. Methodology

The proposed methodology has three main phases. The first phase deals with the spatial behavior of the shadow on the PV array. This phase includes the identification of the shadow of surrounding obstacles, detection of the shadow on the PV module surfaces, and solar irradiance calculations. The partial shading analysis of fixed located PV array configurations presented in this work is based on the previous study [15] that presents the structure of trigonometric equations and procedures of the shadowing model for a PV array. When evaluating the performance of PV systems, solar irradiance data is required to determine the potential energy yield over the year. In this study, the solar irradiance values are taken from ASHRAE formulations [16].

In the second phase, the electrical behavior of PV array is analyzed. The second phase consists of two stages: constructing equivalent circuit based model of PV arrays and assigning of solar irradiance values to the PV modules according to the shadow conditions. In this study, the model of BP 3125J PV module is used on virtual reality simulations. The PV module parameters are given in Table 1. The module consists of 36 solar cells, and 18 cells are equipped with one bypass diode. Since each PV module has two bypass diodes, one PV module shows two PV module characteristics. The single PV module can be divided into two parts to reduce the computational efforts and each part behaves as a single module [17]. It allows that two one-diode equivalent circuit models are enough to represent the behavior of a single PV module characteristic. The model of a PV module is given in Fig. 1. Each bypass diode part of a PV module is named by the left side and right side as shown in Fig. 1.

Table 1
Typical electric characteristic of BP 3125J

Parameters	Standard Test Condition
Maximum power	125 W
Voltage at P_{max} (V_{max})	17.40 V
Current at P_{max} (I_{max})	7.20 A
Short circuit current	8.10 A
Open circuit voltage	22.0
Module efficiency (%)	12.3
Diodes	2 Bypass diodes
Module dimensions	1510x674x50 mm

For a realistic simulation in PV systems, the physical dimension of PV module is a very important parameter as well as electrical parameters for observation of the partial shading effects on the harvested energy. In simulation studies, PV cell based model can be used for detailed PV analysis. However, it causes to increase computational time significantly because a PV module consists of multiple individual solar cells connected in series. In a typical module, solar cells are connected in series to increase the power and voltage. Moreover, in a PV array, individual PV modules are connected in both series and parallel. For this reason, bypass diode based model can be used to reduce the computational efforts [17, 18]. Karatepe et al. [17] present an analysis method to reflect the mismatch effects as well as solar cell based analysis without increasing computational time, in a simple manner and with sufficient degree of precision. In this study, PV array consists of 24 PV modules and each module has two bypass diodes to avoid from hot spot effect of partial shading.

In the third phase, the harvested energy is calculated at local and global MPPs in order to determine payback time of different PV array configurations. In this phase, the performance analyses of the different electrical configurations are compared by payback time under the same partial shading conditions. In addition, the MPP is also observed under uniform irradiance condition for comparison purposes by removing the surrounding obstacles that cause partial shading conditions.

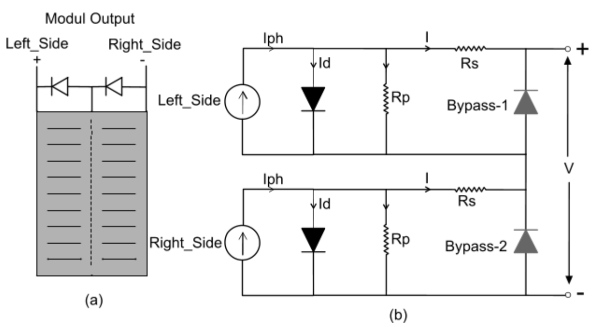


Fig. 1. PV module model (a) physical structure (b) electrical structure.

3. Shadowing Model

The PV modules can be shaded due to the different reasons through the year. However, all reasons are not schedulable by using deterministic methods, such as cloud passing, dust or bird dropping. On the other hand, the effect of surrounding obstacles around the PV array can be observed and analyzed by suitable virtual reality simulations. In this study, two chimneys are considered for partial shading observations on the PV array which are placed on the rooftop of a building. The installations of PV modules and two chimneys are represented in Fig. 2.

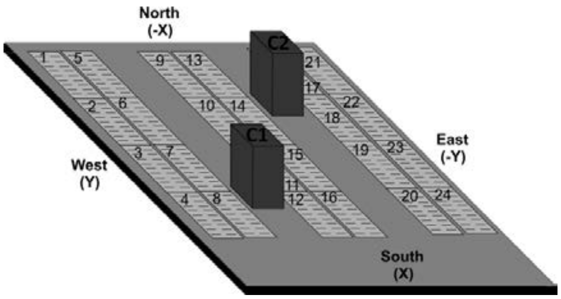


Fig. 2. BIPV rooftop PV array and chimneys

Identical installation conditions are considered for each array configuration when observing the shading effects by taking into account the sun path. The same settling and surrounding operating conditions on the roof-top area allow fair comparisons between payback times of the different PV array configurations.

Shadowing model involves complex trigonometric equations which are based on the 3D imagination of the sun moving and geometric structures [19]. The geometric information of the PV modules and obstacles is necessary for virtual reality simulations. Besides that solar angles which represent the movement of the sun are needed to study in the virtual reality world [19]. The illustration of shadowing process is depicted in Fig. 3.

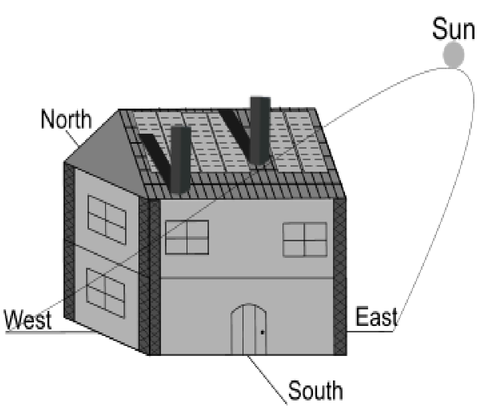


Fig. 3. BIPV system shading method

The shadowing calculations are performed based on the previous study [15] that presents the structure of trigonometric equations and procedures of the shadowing model for a PV array. The methodology is summarized in Fig. 4. The process is based on the time of the day and the geographic location of the examined area (latitude angle). Shadow lengths are determined by using obstacle lengths and the solar angles which are determined by the time and latitude angle. After calculation of the shadow lengths, shaded PV modules are determined by the comparison of the PV module location and shadow location on the surface of PV modules. If shadow points are observed between the edges of the PV modules, then "PV module is shadowed" decision is assigned. The same process is repeated for all PV modules in the field and then the electrical characteristics of PV array configurations are observed [15]. The physical variables for calculation of the shadows are given in Table 2 in this study.

Table 2
Physical variables of the system for partial shading analysis

Parameters	**Values**
Roof Tilt Angle	30°
Roof Azimuth Angle	0° (South faced)
Chimney Lengths	750x750x2000 mm
Module Lengths	1510x674x50 mm
Distance Between Modules	100 mm
Distance Between Chimney and a Module	100 mm
Latitude Angle	38.42° E

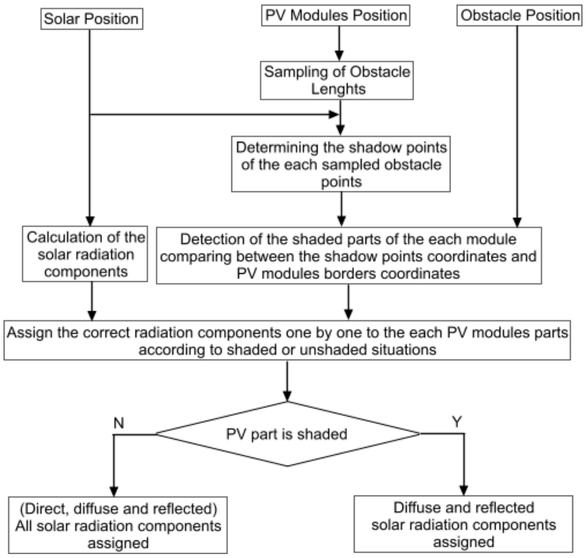


Fig 4. Flowchart of shadow detection [15]

4. SP and TCT Configurations

In this section, the basic electrical behaviors of SP and TCT configurations are presented. The SP and TCT configuration types are represented in Fig. 5 for 2x2 PV array.

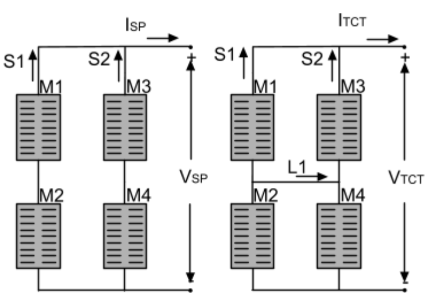


Fig. 5. SP and TCT configurations for 2x2 PV array

When both PV array configurations are operating under the same irradiance conditions, the different current and output power values are obtained at the global MPP. They are given in Table 3.

Table 3

The current and power at the global MPP for 2x2 SP and TCT configurations

(Irradiances of four PV modules in [W/m^2]: G1=1000, G2=200, G3=500, G4=1000)

Configurations	Current [A]					Power [W]
	M1	M2	M3	M4	L1	
SP	1.5	1.5	3.9	3.9	---	57
TCT	6.7	1.5	2.7	7.9	-5.2	167

The value of the current L1 is the tie line current in TCT configuration. In the SP configuration, the irradiance differences on the PV modules force the current flow through bypass diodes. However, L1 line in TCT configuration offers an alternative path for the current flow. In Fig. 6, the P-V curves are given for both SP and TCT configurations. The global MPP of the TCT configuration occurs at the near open circuit voltage as seen in the figure. This means that the configuration types strongly affect the output power of the PV array.

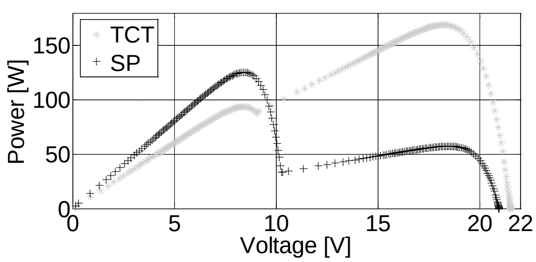
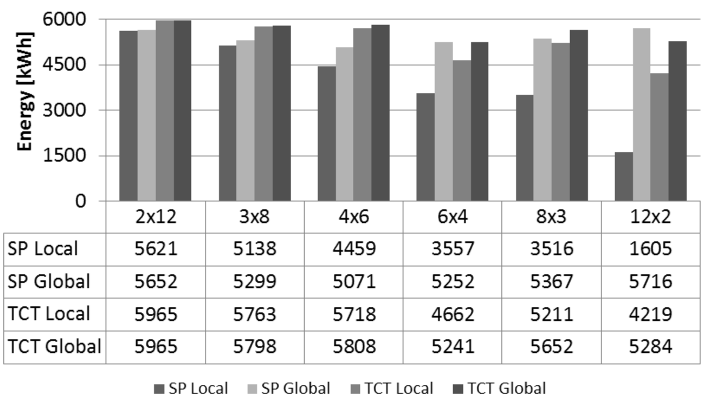


Fig. 6. P-V curve of TCT and SP configurations

5. Energy Yield and Payback Time

In this section, the performance analyses of the different electrical configurations are compared by payback time under the same partial shading conditions. First, the harvested energies are given in Fig. 7 for the locations of the PV modules and chimneys which are given in Fig. 2.



	2x12	3x8	4x6	6x4	8x3	12x2
SP Local	5621	5138	4459	3557	3516	1605
SP Global	5652	5299	5071	5252	5367	5716
TCT Local	5965	5763	5718	4662	5211	4219
TCT Global	5965	5798	5808	5241	5652	5284

Fig. 7. Harvested energies calculated with “10 min” intervals during the year

Two distinct payback times are defined depending on the local and global MPPs under partial shading conditions. In addition, the MPP is also observed under uniform irradiance condition by removing the obstacles that cause partial shading conditions. The uniform irradiance condition means that there are no shaded PV modules (5968 kWh) due to the surrounding obstacles on the field. If there is no partial shading condition, the SP and TCT configurations show the same characteristic. The payback times are determined for a grid connected PV system and the parameters are taken as PV module costs (1 $/Wp), inverter costs (1 $/Wp), charge controller cost (0.5 $/Wp), balance of the system cost (0.2 $/Wp), engineering cost (%10 of initial capital cost), installation cost (%13 of initial capital cost), operation and maintenance cost (%1 of initial capital cost), and the price of solar energy (0.5 $/kWh for Turkey) [20]. Total investment is calculated as 10,044 $. The payback times of each configuration are presented in Table 4.

The ρ_1 and ρ_2 are the payback times for harvested local and global energies which are harvested from local and global MPPs of the PV array, respectively. The ρ_o is the payback time without considering surrounding obstacles. The payback times give information about the field quality depending on the harvested energy type under the partial shading conditions. In this paper, the harvested local energy is supposed to be output energy value determined by the conventional perturbation & observation (P&O) MPPT technique which is generally track to the first MPP near the open circuit voltage on the P-V curve.

Table 4
Payback times of electrical configurations

	ρ_1 [years] (Local MPP)		ρ_2 [years] (Global MPP)	
$N_S x N_P$	SP	TCT	SP	TCT
2x12	2,30	2,17	2,29	2,17
3x8	2,52	2,24	2,44	2,23
4x6	2,90	2,26	2,55	2,22
6x4	3,64	2,77	2,46	2,47
8x3	3,68	2,48	2,41	2,29
12x2	8,06	3,06	2,26	2,45
ρ_o (Payback time without partial shading): 1,67 years				

Furthermore, the harvested global energy is determined by a global MPPT technique which is able to track the global MPP successfully on the P-V curve under partial shading conditions. Thus, the ρ_1 and ρ_2 payback times can also be used to evaluate the field quality when using a conventional or global MPPT techniques. Moreover, this approach can be used when comparing the performances of novel MPPT techniques. Results show that there is a significant difference between configuration types. In the next section, the results will be analyzed in detail.

6. Simulation Results

Some interesting results have been observed on the harvested energies of different configurations without changing the physical location of PV modules. The partial shading conditions cause nonlinear characteristics on the P-V curves of PV arrays. The general expectation is that the number of series connected PV modules should be as minimum as possible to reduce the partial shading effects. However, this expectation is observed only in the SP local energy in this study. While 12x2 SP local energy is the worst case, 2x12 SP local energy is the best case as expected when considering local energies. On the other hand, when global energy is considered the connection of 12x2 SP is the best case among SP configurations. Moreover, TCT configurations show positive impacts on reducing the power losses due to the partial shading conditions according to the local energies. TCT configurations generated more energy than SP configurations except in a particular case of global energy in 12x2 connection. However, it cannot be generalized because it is strongly dependent on partial shading patterns. For this reason, environmental obstacles should be included in the analysis of PV arrays for any BIPV system. The configuration types show different characteristics even if they have the same shading pattern. Therefore, a more detail observation is necessary to understand the reasons of these results.

6.1. *Shading Pattern and Power Values on 6th April*

In this section, one day shading pattern is investigated to reveal the differences between configuration types. The P-V curves of SP and TCT arrays are presented for 6th April at 11:00 in Fig. 8. The shaded PV module parts are presented in Table 5 for 6th April at 11:00 according to placements of the PV modules and obstacles in Fig. 2. In this section, one hour results are examined because of the lack of space to present all the results of every hour. Nevertheless, it is a good example to understand the relationship between shading effects and configuration types. In this example, according to the given PV modules and chimneys placements in Fig 2, the left and right side of module 7 and the right side of module 8 are shaded by the chimney 1. In addition, the left and right side of module 13 and the right side of module 14 are shaded by the chimney 2.

As seen in Fig. 8, 2x12 SP and TCT configurations show the same characteristics under the given shading pattern. The local and global MPP points are at the same point on the P-V curves in both configurations. In 3x8 connection, there is a slight difference between SP and TCT curves and also the local and global MPPs are located at almost the same voltage. On the other hand, there is an obvious difference between SP and TCT curves in 4x6 connection. Even so, in 2x12, 3x8, and 4x6, the local and global MPPs are observed almost at the same voltage level and the P&O MPPT is able to catch the global power point.

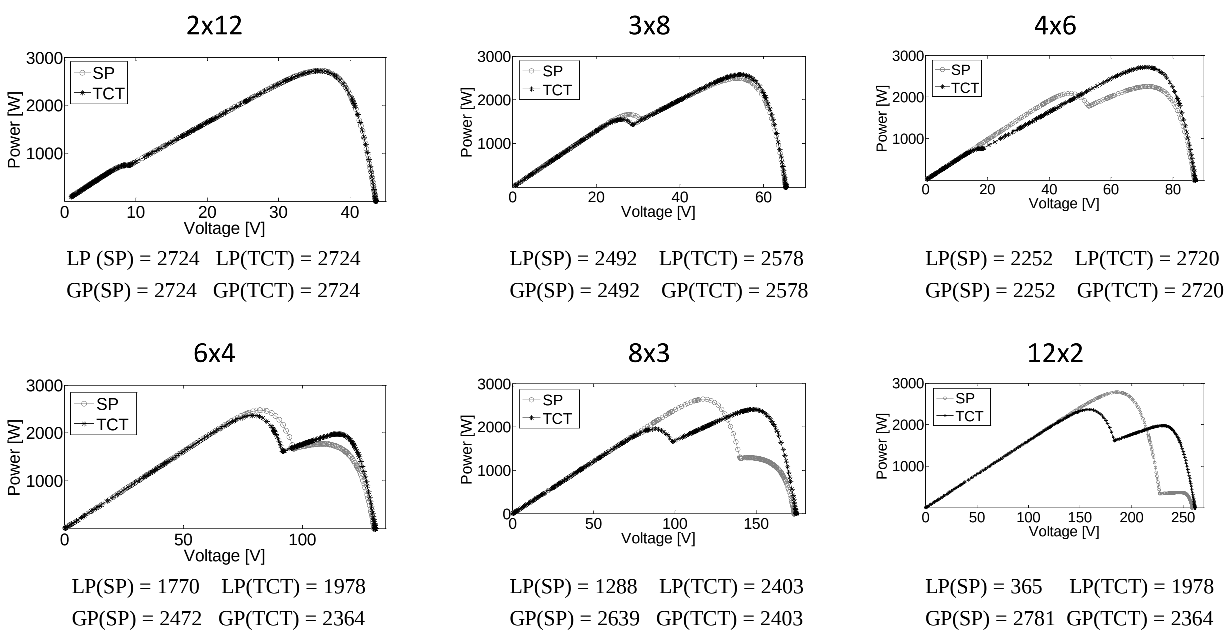


Fig. 8. P-V curves of SP and TCT configurations on 6th April at 11:00 (LP and GP are local and global MPP powers in [W])

Table 5

Shaded PV modules on 6th April at 11:00 in Fig. 2

Shaded PV module parts		**Irradiances [W/m^2]**	
PV left side	PV right side	(non-shaded PV modules)	(shaded PV modules)
7, 13	7, 8, 13, 14	997	92

However, in 6x4, there is a significant difference between local and global MPPs for both configurations. While the TCT shows better performance by 208 W when considering local MPP, the SP is surprisingly better than TCT connection when considering global MPP, with a 108 W power difference. In 8x3, the SP and TCT curves can be distinguished clearly. In this connection, the SP configuration fails in catching global MPP with the P&O MPPT because the global MPP of SP configuration is closer to the short circuit current point. On the other hand, the P&O MPPT can catch the global MPP in the TCT configuration. However, when global MPP is considered in 6x4, the SP configuration shows better performance. Surprisingly, 12x2-SP configuration shows better performance than the TCT configuration too when taking into account of global MPP. Therefore, the current flows in the arrays will be observed in the next section to understand the impact of the same partial shading conditions on the electrical configurations.

6.2. *Current based analysis*

This section presents the current flows in the lines for SP and TCT configurations in 6x4 and 8x3 PV array connections under the same irradiance conditions (on 6th April at 11:00). In Figs. 9 and 10, the electrical connections of the PV arrays are given with partial shading representation which both sides of modules 7 and 13 and the right side of modules 8 and 14 are shaded in both connections. The shaded PV modules are the same in every configuration because the physical location of PV modules are not changed when changing the electrical connections. In Figs. 9 and 10, output currents of the PV modules are represented with "C" and tie line currents are represented with "L". The figures are given for TCT configuration, but it can be turned into SP configuration without considering tie lines.

In Table 6, the output string currents of the SP configuration are given for 6x4 and 8x3 connections. LP and GP represent the current values at local and global MPPs on the P-V curve, respectively. In the same string, the current of all PV modules are the same in SP configurations because of the Kirchhoff current law.

Table 6
String current values of 6x4 and 8x3 SP configurations at local (LP) and global (GP) MPPs

		String-1 [A]	String-2 [A]	String-3 [A]	String-4 [A]	Output Voltage [V]
6x4	LP	7.43	0.75	0.75	7.43	108
	GP	8.05	6.99	6.99	8.05	82
8x3	LP	0.75	0.75	7.38	---	145
	GP	7.26	7.26	7.38		117

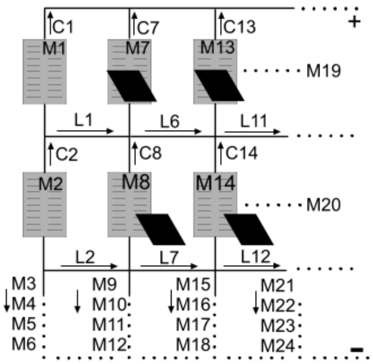


Fig. 9. 6x4 PV array connection with shading effect

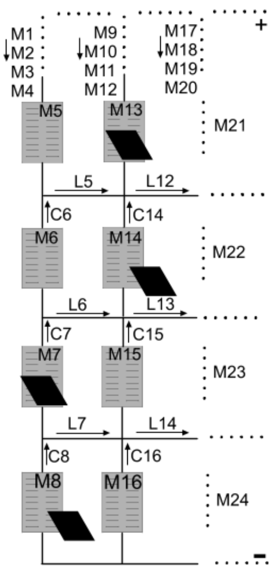


Fig. 10. 8x3 PV array connection with shading effect

In Tables 7 and 8, the output currents of the PV modules and tie line currents are given for TCT configurations. In 8x3 TCT configuration, the currents at local and global MPPs are the same.

Table 7
Module current values of 6x4 and 8x3 TCT configurations at local (LP) and global (GP) MPPs

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
6x4	LP	7.95	7.86	4.30	4.30	4.30	4.30	0.65	0.74	4.30	4.30	4.30	4.30
6x4	GP	11.15	8.08	7.48	7.48	7.48	7.48	3.81	6.88	7.48	7.48	7.48	7.48
8x3	LP/GP	5.40	5.40	5.40	5.40	7.83	7.74	0.56	0.74	5.40	5.40	5.40	5.40
		C13	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**	**C21**	**C22**	**C23**	**C24**
6x4	LP	0.65	0.74	4.30	4.30	4.30	4.30	7.95	7.86	4.30	4.30	4.30	4.30
6x4	GP	3.81	6.88	7.48	7.48	7.48	7.48	11.15	8.08	7.48	7.48	7.48	7.48
8x3	LP/GP	0.56	0.74	7.83	7.74	5.40	5.40	5.40	5.40	7.83	7.74	7.82	7.74

Table 8
Link current values of 6x4 and 8x3 TCT configurations

		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14
6x4	LP	-0.09	-3.56	0	0	0	0	0	0	0	0	0.09	3.56	0	0
	GP	-3.07	-0.60	0	0	0	0	0	0	0	0	3.07	0.60	0	0
8x3LP/GP		0	0	0	2.42	-0.08	-7.18	0.17	0	0	0	-2.42	0.08	-0.08	0.08

When local MPPs of SP connections are considered, it can be clearly seen that 6x4 connection type shows better performance than 8x3 connection. While the half of the string of 6x4 connection is shaded, the string of in 8x3 connection 2/3 of the string is shaded. It means that more PV modules are affected from shadowing in 8x3 connection. This impact can be seen on the local MPPs clearly. In all cases, TCT configurations show better performance when considering powers at local MPPs. The reason of this result is due to the tie lines that support alternative current paths. These alternative paths help to avoid limiting the currents in same string due to the partially shaded PV modules. In TCT connection, tie lines have a significant effect on the current flows. It causes to change the individual MPP of each PV module and this result in the change of the output power of PV arrays.

7. Discussion

Small scale PV systems have rapidly increased in urban areas over the past decade. In urban areas, a large amount of empty rooftop spaces are ideal locations for PV modules. However, shadows of neighboring objects significantly cause to decrease performance of the PV system. The impact of shadow changes due to the movement of the sun. In this study, chimneys which are located on the residential roof-top area are considered to create the effect of shading over the PV array. The locations of PV modules are kept stationary, which is the main point of this paper, while comparing the performances of the different electrical configurations with the same surrounding obstacles that causes partial shading conditions. The purpose of this study is to investigate the potential for improving the long-term efficiency of PV arrays by finding out the best electrical configuration under the partially shaded conditions by analyzing annual energy generation of the same BIPV system, in terms of nominal power, without changing physical locations of the PV modules in the PV arrays. For this purpose, the spatial structure of the PV system including the PV modules and the surrounding obstacles is taken into account on the basis of virtual reality environment. On the other hand, utility poles, trees, other buildings, and other parts of the same building may also cause shadows on the PV modules in urban areas. In addition to that, PV systems are not only installed on the rooftop of the buildings, but also all surfaces of the high rise buildings [21]. So, the PV modules can be shaded by different type of objects. Depending on the building rotation and structure, tilt and azimuth angles of PV modules are important parameters for PV systems. As a result, geometric details of the rooftop and surrounding obstacles affect calculation of the shadows on the PV arrays [22]. Because of different installation parameters, annually energy output of the PV arrays will be different [23]. In the present study, results show that it is possible to improve the long-term performance of the partially shaded PV array by considering different electrical connections of PV array. It is worth noting that advanced and detailed simulation analysis will be more important to estimate the harvested energy from PV arrays in urban areas. This kind of analysis must be applied before mounting the PV modules on the buildings considering surrounding shadow factors.

8. Conclusions

In this paper, different electrical connected PV arrays are analyzed under realistic partial shading conditions without changing physical locations of PV modules in the PV arrays. The power-voltage characteristics of PV array strongly depend on which PV modules are shaded in the electrical connection of PV array. The performance analyses are performed by two different payback times to compare economic advantages of the PV electrical configurations. The main aim of this study is to show that if the field area of PV modules is restricted and it is not possible to change the location of PV modules due to the partial shading effect, it is possible to improve the system efficiency by only changing the electrical configuration of PV array. It is possible to determine which connection type is the best for the interested PV installation field by taking into account of the surrounding obstacles such as chimney on the roof before installation of PV systems. In this study, 24 PV modules are used on the rooftop area and the connection of the PV modules is changed such as 2x12, 3x8, 4x6, 6x4, 8x3, and 12x2 for configuration types of TCT and SP. The spatial shadow behaviors are incorporated to the location of PV modules on the rooftop area with the chimneys. The results show that the different configurations and connection types of PV arrays have a significant impact on the partially shaded PV arrays and the payback time. It is important to note that shading conditions is a vital important factor on the performance of BIPV systems.

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