Design and Performance of Landscape Adaptable PV Structures

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Abstract

This paper presents an investigation of the electrical output associated with change in shapes of stand-alone adaptable PV structures. The PV structures presented in this work consist of PV plates of different fixed orientations, but adaptable tilt angles according to the time of the day and year, and the orientation of the plates themselves. Adopting fixed but different orientations allows to capture the maximum of solar radiation at different time of the day by a fraction of the structure, without a continuous movement of the plates. The study is carried out for a cold northern climate. The results of the study indicate that it is possible to significantly increase the yearly electrical output of an adaptable PV structure as compared to fixed design.

Keywords: PV structures, Landscape, Adaptable structures, Fixed PV

1. Introduction

Efforts to design and build resilient and low environmental impact communities are multiplying, worldwide. These efforts will become even stronger in the wake of climate related disasters and uncertain economic situations. Reducing reliance of communities on fossil fuels and associated emissions is an important step toward achieving more sustainable and resilient communities. The integration of renewable clean energy, especially solar collectors, including photovoltaic systems, within urban development is attracting considerable interest, in both research and applications, due to their numerous advantages.

Integration of PV in buildings is however limited due to shortage of building surfaces for such integration, potential shading from surrounding buildings, and other architectural and functional considerations. To increase the potential of urban areas to generate solar energy, different methods of integration of PV technologies need to be exploited, including employing PV in urban landscape and open public areas. landscape-integration of PV (Scognamiglio 2016) can be implemented either in agricultural land and remote PV farms, or, on smaller scale installation within urban landscape.

Some issues and opportunities arise in designing landscape integrated PV technologies, both in remote land and in urban areas. A massive and uncontrolled expansion of large-scale PV systems on agricultural land can negatively impact the ecosystem, agricultural productivity of the land, as well as site hydrology (e.g. McDonald et al, 2009; Prados, 2009; Turney and Fthenakis, 2011). In urban setting, significant challenges are posed by the selection of urban landscape to offer adequate solar potential, while avoiding shade from the surrounding buildings. On the other hand, landscape can offer spatial solutions for the installation of PV systems to increase renewable energy generation in remote and urban areas, while presenting environmental co-benefit opportunities.

Although there are some applications of PV technologies in urban landscape, research on landscape PV is mostly targeting large-scale applications, integrated within agricultural or other remote sites. Integration of PV structures in the public landscape provides the opportunity to improve the outdoor thermal comfort of the built environment. PV structures can be designed as integrated part of the spatial design of neighborhoods and its street network to fulfill various supplemental environmental functions, such as weather protection and noise barrier.

Coupling PV electricity generation technologies with structural form finding and deployment methods can improve the overall energy generation throughout the year. The use of moveable and adaptable structures for PV support

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allows compensation for daily and seasonal variations of solar radiation, as well as for the impact of shading by surrounding buildings in high-density environment. In addition, standalone landscape PV structures can offer flexibility of design, presenting an opportunity to enhance the aesthetics of PV structures, and their acceptability in the built environment. One of the obstacles facing the implementation of PV deployment is the reluctance by designers, architects, planners and the public. Public acceptability can be stimulated by enhancing the aesthetic aspect of PV structures, through appropriate design of their components and choices of color and material while maintaining their performance (e.g. Kapetanakis et al, 2014; Scognamiglio, 2016; Tsantopoulos et al, 2014), Reducing the intrusion of PV structures on landscape, especially in public areas (See Fig.1), can play a key role in increased social acceptance.

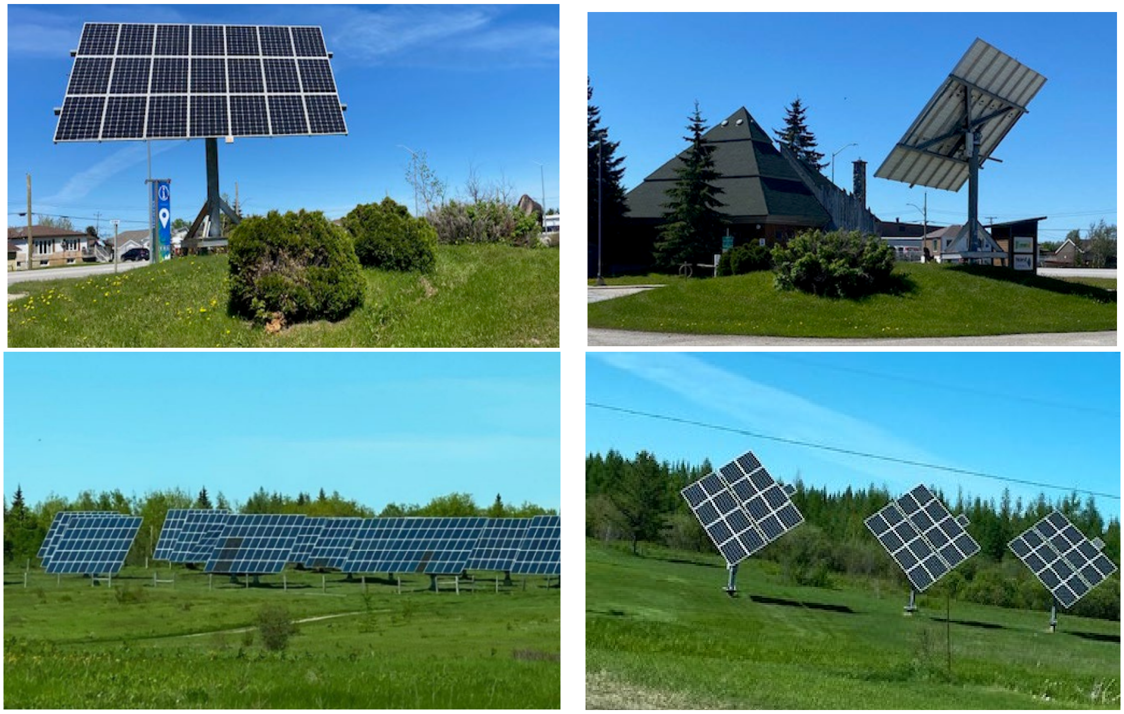

Figure 1, examples of PV stand-alone structures, (a) and (b) in public areas, (c) and (d) in farm lands.

A number of methods and approaches are employed in solar tracking, including passive tracking, active tracking and chronological tracking (Khalil et al, 2017). Active trackers employ motors and gears to drive the panels. Two main techniques of solar trackers – single axis and dual axis – are broadly used in PV power systems. While dual axis tracking system is highly accurate, it is associated with high costs and low reliability (e.g. due to wear and tear). Single axis tracking system is associated with lower cost and more reliability; however it is less accurate than the dual axis tracking system. Research on various types of PV technologies employed in tracking systems shows that crystalline or thin film PV cells are not significantly affected by a deviation of the orientation by up to 10° from the sun true location due to diffuse light (Tania and Alam, 2014).

Single axis tracking system is mostly used to track the movement of the sun during the day, by changing the orientation of the panel, so it aligns with the location of the sun. Several studies have been conducted on such systems. For instance, Anuraj et al. (2014) designed a PV prototype with a single degree of freedom solar tracker, which employs Light Dependent Resistors to detect sun light, and to position a PV panel so it receives maximum irradiance. Vertical tracking is usually combined with horizontal tracking in a dual axis tracking system. Mahmood et al. (2013) studied a dual axis solar tracker which employs a programmable logic controller. Optimal vertical and horizontal angles for each day of the year are extracted from numerical models and employed to track the sun, throughout the year. A power gain of 38% is obtained with the proposed system. Afrin and Titirsha (2013) proposed an azimuth-altitude dual axis solar tracker, which allows an overall increase of 50-60% in energy generation as compared to a fixed PV system. In addition, some research had focused on reduced movement of the trackers to reduce the energy consumed by the structure itself (Khalil et al, 2017). Such research aims at proving that increased costs associated with movable PV-arrays can be justified by the increased electrical output (Moghbelli and Vartanian, 2006).

This paper presents the first stage of designing adaptable landscape PV structures (ALPVs) to be implemented in various urban areas. A number of designs are developed and their energy output is simulated to determine the optimal configuration for different times of the year.

2. Methodology

This study investigates two main configurations of adaptable structures, the first design is a single level structure, while the other configuration consists of 2 levels of panels mounted on top of each other. A distance equal to twice the length of the panels is set between the two levels to eliminate shading. For each of these configurations several design alternatives are proposed, comprising different orientations of panels. The designs, within each of these configurations, adopt fixed orientation ranging from full south to full east and west, and variable tilt angles, employing single axis tracking (see below). The study is conducted for a Northern cold climate (51° North).

Conventional PV panels, such as those commercially available are employed in the design. The deployment of PV panels may employ mechanisms of varying complexity, ranging from individual hydraulic pistons to more complex systems, such as cable control, mobile components (e.g. scissors), and others. This work focuses on the PV performance within each design rather than the deployment mechanisms. Figure 2 presents illustrations of the studied single- level adaptable landscape PV structures (ALPVs), while Figure 3 presents an example of application of the basic structure in urban setting. Figure 4 presents a schematic of 2-level ALPVs. The general approach and assumptions in the design of these ALPVs are described below.

2.1. Design approach

The designs explored in this study are described in the following, for the single and 2-level configurations. The total area of PV within the design variations of each of the configurations (i.e. single or double levels) remains fixed. The double-level configurations have double the PV area of the single level configurations.

Single- level design. Three different designs are explored, for the single level configurations, as shown in Figure 2. These designs are the basic structure, a variation on this basic design, and an 8- petals (8P) flower design. The characteristics of each of these designs are summarized below.

- Basic design: consisting of 2 south PV panels, in addition to one east and one west panel (Fig. 2a).
- Variation: consisting of 2 PV panels oriented south and 2 panels oriented 45° from south towards east and west (Fig. 2b). The two south facing PV panels (S1 and S2, Fig 2b), are located on the south and north of the structure, respectively. S2 (located on the north) is tilted toward south, to maximize solar radiation. It is also placed at a higher level than the other panels to reduce potential shading.

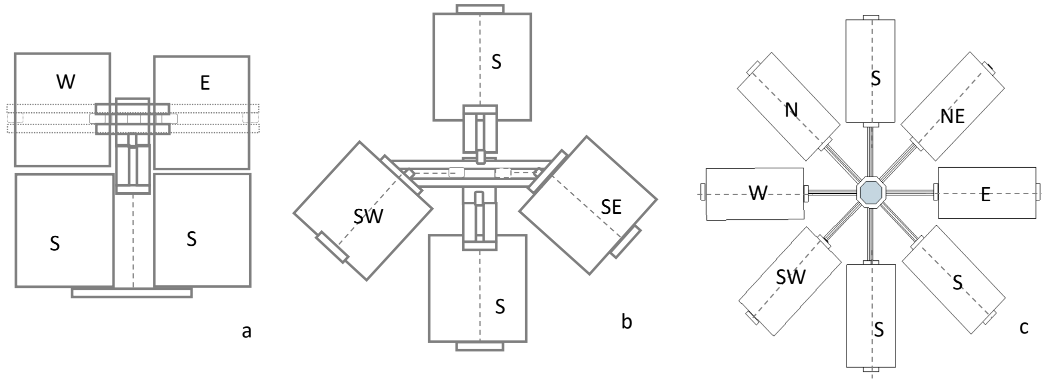

Figure 2, Illustration of the plan view of the single level configurations, (a) basic 4-plates, (b) variation of the basic structure, (c) 8-petal (8P) flower

- Flower design with 8 petals, consisting of 8 rectangular panels. The area of each of these panels is equivalent to half of the panel area employed in the configurations presented above. Panels are oriented south, east and west as well as 45 º from east and west (Fig. 2c). All panels placed on the north (including north east and north west) in the plan are tilted toward south.

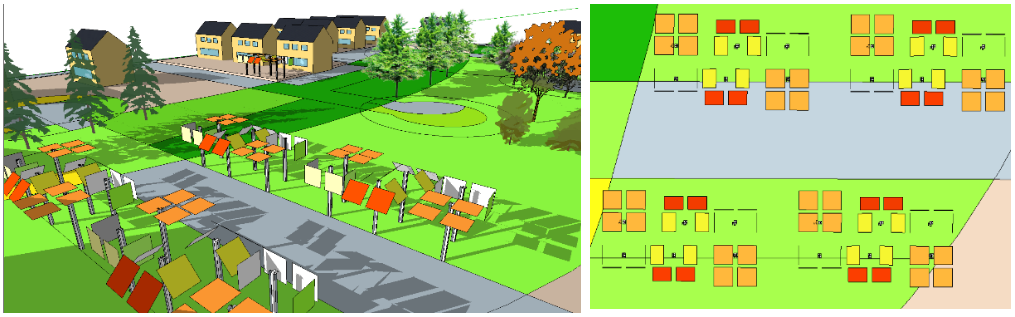

Figure 3, application of the basic structure in urban setting

Two-level designs. The two-level designs combine one or more of the designs developed for the single level configuration, described above. A distance equal to twice the length of the panels is designed between the two levels, to eliminate shading effect. The three design variations are summarized below.

- Basic design consists of the basic 4-plates design (Fig. 2a), employed in both the lower and upper levels (Fig4 a).
- Variation of the basic design (see Fig.4b), employing the variation of 4-plates design described above (Fig 2b) in both levels.
- Combination of basic and variation, consisting of the basic design on the bottom level and the variation on the upper level (Fig.4c).

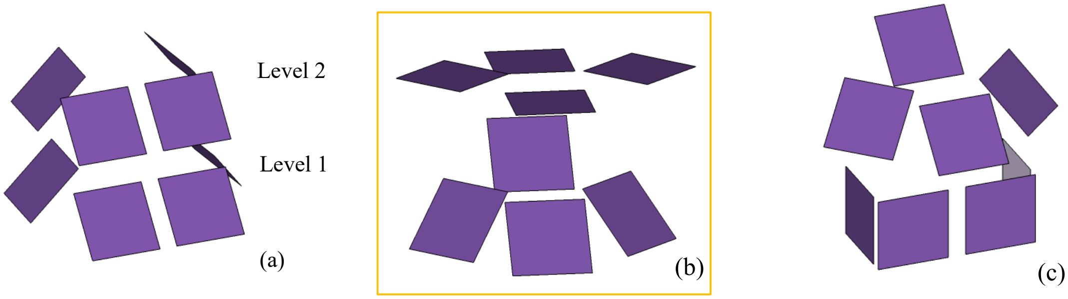

Figure 4, illustration of the PV plates in the 2-level studied structures, (a) Basic, (b) Variation, (c) basic- variation

3. Analysis and Results

The electrical output of these adaptable landscape PV structures (ALPVs) are simulated employing EnergyPlus (Crawly et al, 2000), in conjunction with Scketchup Pluggin (Ellis et al, 2000), employed to generate various geometric shapes. Three main positions of each of the PV panels are analysed – horizontal (0º), inclined (45 º tilt), and vertical (90º). Weather data of Calgary (Canada, 51ºN) is used in the simulations, to obtain daily, monthly and yearly generation. The results are presented for the single level configurations, followed by the 2-level configurations. The results present the yearly, monthly and hourly optimal configurations.

3.1. Single level design

Basic design. Table 1 presents the total yearly generation of the basic 4 plates structure (Fig. 2a), associated with a fixed tilt angle, where the 4 panels of the structure (3 main orientations, south, east and west) assume the same tilt angle year-round (not controlled). Among the main studied positions – horizontal, tilted (45 °) and vertical – the optimal fixed tilt position is at 45 °, as expected for the studied location. Controlling the position of the plates to obtain the optimal monthly positions, allows increasing the yearly generation by about 5% as compared to the same structure design with a fixed optimal tilt (of 45°), and by 16% and 36% as compared to the horizonal (0°) and vertical (90 °) positions, respectively. The hourly control allows an increase of generation by 18%, as compared to the 45° tilt, and by 31% and 53% as compared to the horizontal and vertical positions, respectively.

Table 1[1]: Yearly generation of the basic structure, associated with fixed positions and monthly and hourly change.

Fixed position	Yearly generation	Comparison to optimal	Controlled positions	Generation	Comparison to optimal fixed position (45 °)	Comparison to horizontal position (0 °)	Comparison to vertical position (90°)
0 °	5.24E+09	0.90	**Yearly Optimal**	5.8E+09	1.00	1	1
45 °	5.80E+09	1.00	**Monthly - Optimal**	6.1E+09	1.05	1.16	1.36
90 °	4.49E+09	0.77	**Hourly - Optimal**	6.86E+09	1.18	1.31	1.53

Variations of the basic 4-plates designs are studied for a fixed tilt position, a monthly controlled and hourly controlled positions. The results are presented in Table 2, and Figs. 5a and 5b. Considering the optimal fixed position (45 °), the design variation that combines south, south-east and south-west orientations (Fig. 2b), allows an increase of 11%, as compared to the basic design, while the 8P-flower (Fig. 2c) allows a 4% increase.

Table 2: Generation of all single level ALPVs, associated with fixed positions, and monthly and hourly changes

Yearly generation at a fixed position				Yearly generation with controlled positions		
Position	**Basic**	**Variation**	**Flower-8P**	**Configuration**	Monthly -Optimal positions	Hourly - Optimal positions
0	5.24E+09	5.24E+09	5.24E+09	**Basic**	6.10E+09	6.86E+09
45	5.80E+09	6.41E+09	6.04E+09	**Variation**	6.53E+09	7.07E+09
90	4.49E+09	4.96E+09	4.53E+09	**8P-Flower**	6.21E+09	6.95E+09

The comparison of the monthly and hourly optimal positions for all the configurations, to the fixed position (where all plates have the same angle) is presented in Fig. 6a. A monthly change- allowing to change the position only once a month to obtain the optimal generation of the whole month- is significant when compared to the horizontal and vertical fixed position. The increase of generation for the design variations is 25% and 31% as compared to the horizontal and vertical positions (respectively). An increase of generation by 18% and 37% is observed for monthly variation, of the 8P-flower, as compared to the horizontal and vertical position (respectively). The monthly variation of all configurations is not significantly higher than the optimal fixed position (of 45 ° tilt), corresponding to an increase of 5%, 2% and 3% for the basic design, variations and 8P flower respectively.

The hourly change -capturing the optimal generation at each hour of the year- shows a significant increase of generation, for all studied configurations, as compared to all fixed positions. The increase is about 18%, 10% and 15% for the basic, variation and the 8P flower (respectively) as compared to the fixed optimal position. This increase is much more significant when compared to the horizontal and vertical position (reaching difference of 54% for the 8P flower) (see Fig. 5a).

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[1] Energy generation is measured in units of Joules (J) in this document.

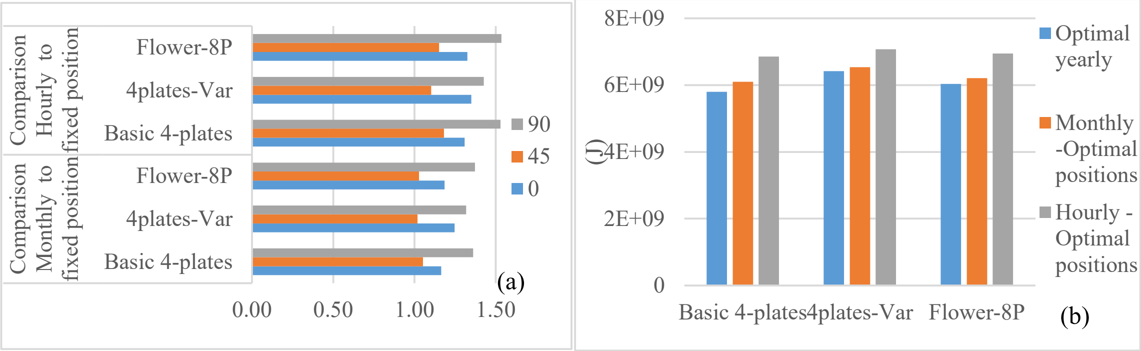

Figure 5, (a) comparison of generation associated with the hourly and monthly change of each structure to the fixed optimal position, (b) total generation of all studied configurations and their positions.

An example of the monthly optimal positions of the plates of the basic configuration is presented in Table 3. It can be observed that while the optimal tilt position of the south plates changes for the different months of the year, the east and west plates have an optimal horizontal position. A vertical position is optimal for the south plates during November-January, and a horizontal position is optimal from May-July. A tilt of 45 º is optimal for the remaining 6 months of the year (Feb-April, and August to October).

Table 3: Monthly variation of energy generation of each panel of the basic 4-plates structure, presented by its position (tiltº) and orientation. The colors indicate the optimal values.

Date/Time	0 º -S [J]	45 º -S [J]	90 º -S [J]	0 º -E- [J]	45 º -E [J]	90 º -E- [J]	0 º -W- [J]	45 º -W	90 º -W
January	3.9E+07	1.0E+08	1.1E+08	3.9E+07	3.6E+07	3.5E+07	3.9E+07	3.7E+07	3.5E+07
February	6.0E+07	1.1E+08	1.1E+08	6.0E+07	5.4E+07	4.6E+07	6.0E+07	5.5E+07	4.7E+07
March	1.0E+08	1.5E+08	1.3E+08	1.0E+08	8.9E+07	6.9E+07	1.0E+08	1.0E+08	8.1E+07
April	1.3E+08	1.6E+08	1.1E+08	1.3E+08	1.3E+08	9.7E+07	1.3E+08	1.2E+08	8.9E+07
May	1.7E+08	1.7E+08	9.9E+07	1.7E+08	1.6E+08	1.2E+08	1.7E+08	1.5E+08	1.1E+08
June	1.8E+08	1.7E+08	9.3E+07	1.8E+08	1.7E+08	1.2E+08	1.8E+08	1.5E+08	1.1E+08
July	2.0E+08	1.9E+08	1.1E+08	2.0E+08	1.8E+08	1.3E+08	2.0E+08	1.8E+08	1.3E+08
August	1.6E+08	1.8E+08	1.2E+08	1.6E+08	1.5E+08	1.1E+08	1.6E+08	1.5E+08	1.1E+08
September	1.1E+08	1.5E+08	1.2E+08	1.1E+08	1.0E+08	8.1E+07	1.1E+08	1.0E+08	8.1E+07
October	8.0E+07	1.5E+08	1.4E+08	8.0E+07	7.4E+07	6.4E+07	8.0E+07	7.9E+07	6.9E+07
November	4.3E+07	9.3E+07	9.6E+07	4.3E+07	3.9E+07	3.4E+07	4.3E+07	4.1E+07	3.6E+07
December	3.1E+07	7.8E+07	8.5E+07	3.1E+07	2.8E+07	2.6E+07	3.1E+07	3.0E+07	2.8E+07

Examples of hourly energy generation of each panel (south (S), East (E)and West (W)) of the 4-plates basic structure, associated with different tilt positions, are presented in Tables 4-7, for the solstice and the equinox days of the year. Since the two south plates yield the same energy generation, only the generation of one of the plates is reported in the tables. In contrast with the monthly results, east and west plates show greater variations of the optimal position during a day while the south plates show less variations.

Table 4: Energy generation variation during the spring equinox

	South (S)			**East (E)**			**West (W)**		
Time	**0 º**	**45 º**	**90 º**	**0 º**	**45 º**	**90 º**	**0 º**	**45 º**	**90 º**
7:00:00	3.1E+03	3.0E+03	2.2E+03	3.1E+03	1.2E+04	1.5E+04	3.1E+03	2.2E+03	1.7E+03
8:00:00	3.1E+04	3.8E+04	2.9E+04	3.1E+04	8.6E+04	9.8E+04	3.1E+04	1.8E+04	1.4E+04
9:00:00	7.6E+04	9.3E+04	7.2E+04	7.6E+04	1.3E+05	1.3E+05	7.6E+04	4.0E+04	3.2E+04
10:00:00	1.5E+05	1.7E+05	1.3E+05	1.5E+05	1.9E+05	1.6E+05	1.5E+05	8.2E+04	6.2E+04
11:00:00	2.2E+05	2.6E+05	2.0E+05	2.2E+05	2.4E+05	1.7E+05	2.2E+05	1.2E+05	9.0E+04

12:00:00	2.6E+05	3.1E+05	2.4E+05	2.6E+05	2.4E+05	1.6E+05	2.6E+05	1.7E+05	1.1E+05
13:00:00	3.1E+05	3.8E+05	2.9E+05	3.1E+05	2.4E+05	1.3E+05	3.1E+05	2.3E+05	1.2E+05
14:00:00	3.5E+05	5.0E+05	4.1E+05	3.5E+05	1.9E+05	1.0E+05	3.5E+05	3.4E+05	2.0E+05
15:00:00	4.1E+05	6.1E+05	5.0E+05	4.1E+05	1.3E+05	1.0E+05	4.1E+05	5.1E+05	3.8E+05
16:00:00	3.4E+05	5.0E+05	4.1E+05	3.4E+05	8.3E+04	8.7E+04	3.4E+05	5.4E+05	4.7E+05
17:00:00	2.3E+05	3.3E+05	2.7E+05	2.3E+05	6.2E+04	6.3E+04	2.3E+05	4.8E+05	4.9E+05
18:00:00	1.1E+05	1.5E+05	1.2E+05	1.1E+05	4.2E+04	3.8E+04	1.1E+05	3.3E+05	3.7E+05
19:00:00	1.5E+04	1.6E+04	1.2E+04	1.5E+04	9.6E+03	7.2E+03	1.5E+04	5.3E+04	6.4E+04

Table 5: Energy generation variation during the summer solstice

	South (S)			East (E)			West (W)		
Time	**0°**	**45°**	**90°**	**Date/Time**	**0°**	**45°**	**90°**	**Date/Time**	**0°**
5:00:00	7.1E+03	4.1E+03	3.5E+03	7.1E+03	3.6E+04	4.6E+04	7.1E+03	4.0E+03	3.5E+03
6:00:00	5.9E+04	2.0E+04	2.1E+04	5.9E+04	2.2E+05	2.6E+05	5.9E+04	1.9E+04	2.1E+04
7:00:00	1.9E+05	7.7E+04	5.4E+04	1.9E+05	4.7E+05	5.0E+05	1.9E+05	4.9E+04	5.4E+04
8:00:00	3.7E+05	2.6E+05	8.6E+04	3.7E+05	7.2E+05	7.0E+05	3.7E+05	7.0E+04	8.5E+04
9:00:00	5.0E+05	4.5E+05	1.8E+05	5.0E+05	8.2E+05	7.1E+05	5.0E+05	7.3E+04	1.0E+05
10:00:00	6.7E+05	6.7E+05	3.3E+05	6.7E+05	9.2E+05	6.8E+05	6.7E+05	1.2E+05	1.1E+05
11:00:00	7.5E+05	8.1E+05	4.5E+05	7.5E+05	8.7E+05	5.4E+05	7.5E+05	2.9E+05	1.3E+05
12:00:00	6.6E+05	7.3E+05	4.3E+05	6.6E+05	6.4E+05	3.0E+05	6.6E+05	3.7E+05	1.2E+05
13:00:00	3.6E+05	4.1E+05	2.5E+05	3.6E+05	3.0E+05	1.1E+05	3.6E+05	2.9E+05	9.8E+04
14:00:00	3.7E+05	4.1E+05	2.5E+05	3.7E+05	2.3E+05	8.9E+04	3.7E+05	3.6E+05	1.8E+05
15:00:00	5.8E+05	6.3E+05	3.6E+05	5.8E+05	2.4E+05	1.1E+05	5.8E+05	6.7E+05	4.1E+05
16:00:00	5.7E+05	5.8E+05	2.9E+05	5.7E+05	1.1E+05	1.0E+05	5.7E+05	7.7E+05	5.7E+05
17:00:00	4.6E+05	4.2E+05	1.8E+05	4.6E+05	7.1E+04	9.6E+04	4.6E+05	7.4E+05	6.3E+05
18:00:00	2.7E+05	2.0E+05	8.0E+04	2.7E+05	8.0E+04	7.9E+04	2.7E+05	4.9E+05	4.5E+05
19:00:00	2.1E+05	8.1E+04	5.5E+04	2.1E+05	4.8E+04	5.5E+04	2.1E+05	5.3E+05	5.6E+05
20:00:00	1.1E+05	2.9E+04	3.2E+04	1.1E+05	2.8E+04	3.2E+04	1.1E+05	4.3E+05	5.1E+05
21:00:00	1.7E+04	7.6E+03	7.2E+03	1.7E+04	7.4E+03	7.2E+03	1.7E+04	1.1E+05	1.4E+05

Table 6: Energy generation variation during the Fall equinox

	South (S)			East (E)			West (W)		
Time	**0°**	**45°**	**90°**	**Date/Time**	**0°**	**45°**	**90°**	**Date/Time**	**0°**
7:00:00	2.1E+04	2.5E+04	1.9E+04	2.1E+04	1.5E+05	2.0E+05	2.1E+04	8.1E+03	8.2E+03
8:00:00	1.6E+05	2.4E+05	1.9E+05	1.6E+05	6.1E+05	7.1E+05	1.6E+05	3.2E+04	3.9E+04
9:00:00	3.2E+05	4.8E+05	3.9E+05	3.2E+05	7.5E+05	7.7E+05	3.2E+05	5.7E+04	7.1E+04
10:00:00	4.6E+05	7.0E+05	5.7E+05	4.6E+05	7.8E+05	7.0E+05	4.6E+05	7.1E+04	9.4E+04
11:00:00	5.6E+05	8.6E+05	7.0E+05	5.6E+05	7.3E+05	5.4E+05	5.6E+05	1.4E+05	1.2E+05
12:00:00	6.3E+05	9.6E+05	7.9E+05	6.3E+05	6.2E+05	3.4E+05	6.3E+05	3.0E+05	1.3E+05
13:00:00	6.6E+05	1.0E+06	8.3E+05	6.6E+05	4.5E+05	1.4E+05	6.6E+05	4.8E+05	1.6E+05
14:00:00	6.3E+05	9.8E+05	8.0E+05	6.3E+05	2.7E+05	1.2E+05	6.3E+05	6.5E+05	3.8E+05
15:00:00	5.6E+05	8.6E+05	7.0E+05	5.6E+05	1.1E+05	1.1E+05	5.6E+05	7.6E+05	5.8E+05
16:00:00	4.4E+05	6.7E+05	5.5E+05	4.4E+05	6.9E+04	9.1E+04	4.4E+05	7.9E+05	7.2E+05
17:00:00	2.9E+05	4.4E+05	3.5E+05	2.9E+05	5.3E+04	6.5E+04	2.9E+05	7.2E+05	7.6E+05
18:00:00	1.3E+05	1.8E+05	1.4E+05	1.3E+05	3.3E+04	3.6E+04	1.3E+05	4.9E+05	5.8E+05
19:00:00	1.2E+04	1.2E+04	8.5E+03	1.2E+04	6.0E+03	5.4E+03	1.2E+04	7.8E+04	1.0E+05

Table 7: Energy generation variation during the winter solstice

Date/Time	South (S) 0°	45°	90°	East (E) Date/Time	0°	45°	90°	West (W) Date/Time	0°
9:00:00	5.8E+03	2.1E+04	2.7E+04	5.8E+03	2.3E+04	2.9E+04	5.8E+03	4.0E+03	3.1E+03
10:00:00	6.3E+04	2.1E+05	2.4E+05	6.3E+04	1.7E+05	2.0E+05	6.3E+04	3.2E+04	2.6E+04
11:00:00	1.6E+05	4.5E+05	5.1E+05	1.6E+05	2.7E+05	2.8E+05	1.6E+05	5.9E+04	5.3E+04
12:00:00	2.4E+05	6.9E+05	7.6E+05	2.4E+05	2.6E+05	2.3E+05	2.4E+05	7.2E+04	6.5E+04
13:00:00	2.5E+05	6.8E+05	7.4E+05	2.5E+05	1.5E+05	9.1E+04	2.5E+05	1.5E+05	9.1E+04
14:00:00	1.9E+05	3.8E+05	3.9E+05	1.9E+05	1.0E+05	7.4E+04	1.9E+05	1.9E+05	1.5E+05
15:00:00	1.3E+05	2.3E+05	2.4E+05	1.3E+05	7.6E+04	5.4E+04	1.3E+05	1.6E+05	1.5E+05
16:00:00	5.9E+04	1.5E+05	1.6E+05	5.9E+04	3.6E+04	2.7E+04	5.9E+04	1.3E+05	1.4E+05
17:00:00	4.6E+03	1.1E+04	1.3E+04	4.6E+03	3.5E+03	2.4E+03	4.6E+03	1.2E+04	1.4E+04

The generation profiles of various tilt positions of the basic configuration, on the four solstice/equinox days are presented in Figure 6. The daily optimal control allows higher generation at each hour of the day, producing, in some cases, substantial increase at specific hours such as mornings and evenings, as compared to the fixed positions.

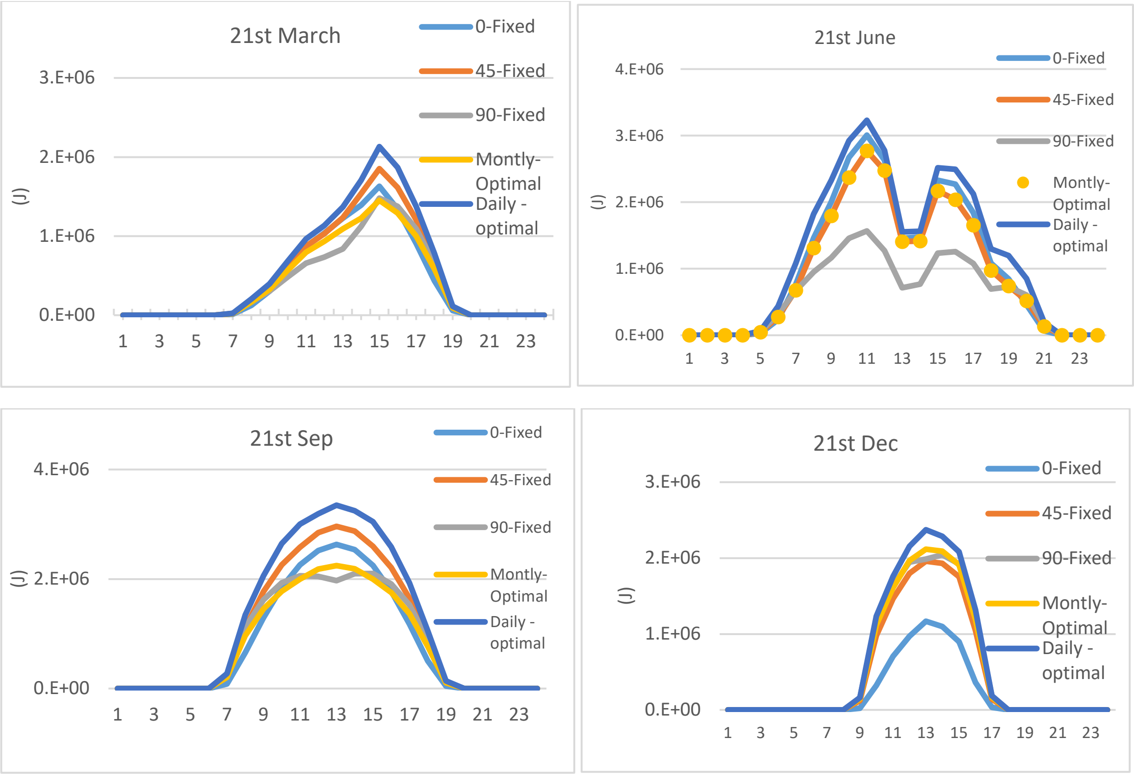

Figure 6, generation of different configurations on the equinox and solstice days

3.2 2-Level configurations

The results of the three studied 2-level configurations –basic, variations, and basic- variation are presented below. Table 8 shows the results of the fixed position of each configuration, as well as the comparison between these configurations. It should be noted that for the fixed positions, the two levels are studied at similar as well as different positions.

The comparison of the variation and basic-variation to the basic design shows that in the majority of cases, these variant configurations outperform the basic configuration. The increase in electrical output reaches 11% for with the 2-level variation with the bottom plates horizontal and the upper plates inclined or vertical. Significant increase (>5%) is highlighted in Table 8.

Table 8: yearly generation of all 2-level configurations associated with various fixed positions of each of plate of the 2 levels, and comparison of these configurations

Position (1st level, 2nd level)	Yearly generation			Comparison	
	Basic	Variation	Basic- variation	Variation/Basic	Basic-Variation/Basic
0° -0°	9.80E+09	9.56E+09	9.63E+09	0.97	0.98
0° -45°	9.48E+09	1.05E+10	1.06E+10	1.11	1.11
0° -90°	8.64E+09	9.38E+09	9.47E+09	1.09	1.10
45° -0°	1.08E+10	1.10E+10	1.09E+10	1.01	1.01
45° -45°	1.14E+10	1.19E+10	1.21E+10	1.04	1.06
45° -90°	1.01E+10	1.10E+10	1.08E+10	1.08	1.06
90° -0°	9.61E+09	9.82E+09	9.66E+09	1.02	1.00
90° -45°	1.01E+10	1.07E+10	1.09E+10	1.06	1.08
90° -90°	8.94E+09	9.24E+09	9.47E+09	1.03	1.06

The yearly generation for optimal monthly and hourly positions for all configurations is presented in Table 9. The comparison of the hourly generation to the optimal fixed position (45°) shows an increase of generation of 13%, 12% and 8% for the basic configuration, the variation and basic-variation configurations, respectively. The optimal monthly position yield less significant change as shown in Table 9. The hourly change as compared to horizontal and vertical fixed position of both levels is about 46% and 56% respectively, for the variation configuration.

Table 9: generation associated with monthly and hourly change, for each configuration and comparison to the generation by the optimal fixed position

Configuration	Generation		Comparison		
	Monthly optimal	Hourly optimal	Monthly to yearly	Hourly to yearly	Hourly to monthly
Basic	1.18E+10	1.32E+10	1.04	1.17	1.13
Variation	1.25E+10	1.38E+10	1.06	1.18	1.12
Basic- variation	1.25E+10	1.33E+10	1.03	1.12	1.08

An example of change of tilt position between the bottom and upper level of the 2-level basic configuration is shown in Table 10. Although the values of the hourly electricity production refer to the panels of the 1st level, the optimal position of the two levels are indicated. For examples a 45° -90° E (in the top row of Table 10) corresponds to the east panels, with the first level (bottom) at 45° and the 2nd level (top) at 90°.

It should be mentioned that in some cases, several possibilities can be obtained. Although south oriented panels are optimally at vertical position in the winter months, they are subject to more hourly variations during other months of the year. This is also shown for the single level variation presented above (Tables 4-7).

Table 10: Hourly energy generation of the panels with different orientation (S, E and W) of the 2-level basic design during the winter solstice

	Tilt position of the bottom and upper level panels (of the same orientation)						
Time	90°-90° -S	0° -0° -E	45°-90°-E	90°-0° -E	90°-90°-E	0°-0° W	45°-90°W	90° -0°-W
09:00:00	2.65E+04	5.24E+03	2.30E+04	2.93E+04	2.93E+04	5.20E+03	3.81E+03	3.10E+03
10:00:00	2.43E+05	5.84E+04	1.78E+05	2.05E+05	2.05E+05	5.81E+04	3.03E+04	2.65E+04

11:00:00	5.04E+05	1.50E+05	2.90E+05	2.82E+05	2.82E+05	1.50E+05	5.66E+04	5.26E+04
12:00:00	7.61E+05	2.30E+05	3.08E+05	2.34E+05	2.34E+05	2.30E+05	8.10E+04	6.55E+04
13:00:00	7.40E+05	2.41E+05	1.97E+05	9.08E+04	9.08E+04	2.40E+05	1.96E+05	9.06E+04
14:00:00	3.89E+05	1.77E+05	1.02E+05	7.42E+04	7.42E+04	1.76E+05	2.06E+05	1.52E+05
15:00:00	2.36E+05	1.16E+05	7.22E+04	5.41E+04	5.41E+04	1.15E+05	1.69E+05	1.51E+05
16:00:00	1.63E+05	5.40E+04	3.48E+04	2.69E+04	2.69E+04	5.37E+04	1.29E+05	1.43E+05
17:00:00	1.27E+04	4.12E+03	3.30E+03	2.45E+03	2.45E+03	4.09E+03	1.18E+04	1.41E+04

The comparison between the performance of the 2-levels configurations is presented in Figure 7 for the winter solstice and fall equinox days. While the configurations perform similarly for the summer and spring days, the 2-level variations present more advantageous design for the winter and fall days.

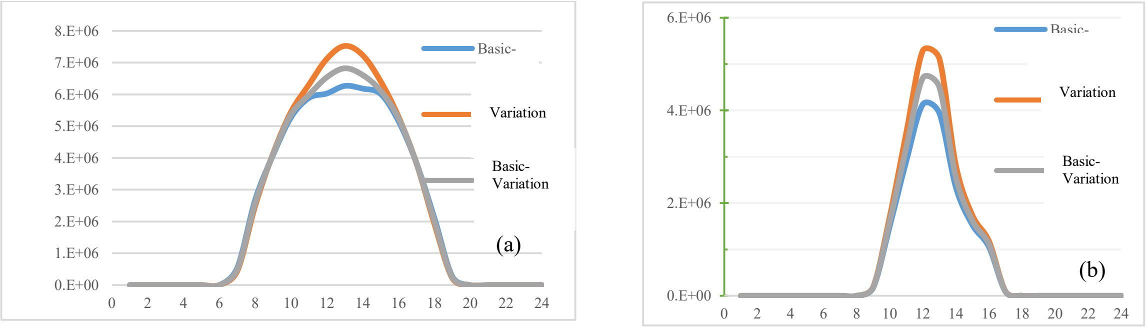

Figure 7, generation profile of all 2-levels configurations: a) Fall equinox; b) Winter solstice.

4. Discussion and Conclusion

This work presents an investigation into the potential of adaptable landscape PV structures (ALPVs), and their performance as compared to fixed structures. Several configurations are designed and their performance in terms of electrical output is analyzed. The designs include a single level structures and 2-level structures, with PV panels stacked on top of each other with a distance in between equal to double of the length of the basic plate of PV. An innovative approach of changing only the tilt of the PV plates, with determined fixed orientation is adopted in this research, in contrast to methods of tracking the sun path all day long. This approach is adopted to reduce the frequency that the plates need to change position and thus reduce associated energy consumption, as well as fabrication and maintenance costs. This investigation is aiming at developing structures that can be incorporated within urban landscape, and can present some architectural and visual interest, while providing multi-functional benefits. The main observations of this investigation are discussed below.

- Monthly variation of the ALPVs, where the plates of different orientations take the optimal position for a specific month, is more beneficial for south plates, while east and west plates are optimal at a 45° tilt. Monthly change increases the performance as compared to a fixed state of optimal tilt (45° tilt) slightly (by up to 5%), but allows a significant increase as compared to the horizontal and vertical PV (16% and 36% respectively). Such design of PV structures can offer supplemental energy generation in existing urban areas where the potential to integrate PV systems in buildings is restricted due to non-optimal surface areas, associated with existing orientation and tilt angles.
- The hourly change of the plates position increases the generation significantly as compared to the fixed tilt position. The fact that the change only happens 3 to 4 times per day and does not occur at every hour as in the case of a rotational motion that follows the daily sun path, reduces the amount of energy required to move the structure. The increase of generation can be very significant, especially if compared to fixed non-optimal position (e.g. horizontal or vertical). This increase in generation ranges between 30-35% for different configurations as compared to the horizontal fixed position and by up to 54% as compared to a

fixed vertical position.

- The concept of designing two levels of PV plates mounted on top of each other, provides an opportunity to increase available areas for PV panels, while occupying the same land area. This concept can be applied to multiple levels, providing significant potential to generate renewable energy in urban areas, where land can be scarce and expensive.
- These ALPVs can present an interesting design especially in public areas, allowing to be better integrated with the landscape and with outdoor comfort. The flexibility of design and changing the shape of the structure reduce the massive aspect that PV structures might take, and therefore their intrusion on the landscape (See Fig 1). This research shows that an improved position for south facing panels is vertical in winter, allowing solar radiation to reach the ground (and people using the space), providing thus more warmth, while in the summer a near horizontal position provides shade to the surrounding. The concept of changing tilt angle of the panels has the potential to adapt to non-optimal situation due to shadow cast by buildings.

This study is a conceptual demonstration of the design of Adaptable Landscape PV structures (ALPVs). Simple designs are presented in this work, to investigate the potential of these structures and flexibility that can be obtained. Variations of the design to respond to various aesthetic and architectural values can be studied in more elaboration, in the future, in order to reduce intrusion on the landscape, both visually and functionally.

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