Reconfigurable three dimensional photovoltaic panel architecture for solar-powered time extension

Donghwa Shin[1], Naehyuck Chang[2], Yanzhi Wang and Massoud Pedram[3]
[1]Yeungnam University, Gyeongsan, Gyeongbuk, Korea (donghwashin@yu.ac.kr)
[2]KAIST, Daejeon, Korea (naehyuck@kaist.ac.kr)
[3]Univ. of Southern California, Los Angeles, CA, USA ({yanzhiwa, pedram}@usc.edu)

***Abstract*—Photovoltaic (PV) power generation systems are usually accompanied by battery to bridge the gap between the generation and load demand. Solar tracking is also used to enhance the power stability and increase the amount of collected energy from the Sun. However, battery and tracking devices significantly increase the system cost, and they are subject to wear and tear, which makes maintenance-free installation challenging. In this work, we conduct the design optimization of a twofold three dimensional PV panel for solar-powered systems. With the proposed three dimensional arrangement, we extend the solar-powered time of the target application that is powered only with solar power. Experimental results show that the proposed architecture and control method extend the service time of the target system by up to 23% compared to a non-reconfigurable flat panel with the same PV panel area.**

***Index Terms*—Photovoltaic, solar tracking, reconfiguration**

I. Introduction

Photovoltaics (PV) convert sunlight into direct current electricity using materials that exhibit the photovoltaic effect. The sunlight is one of the most plentiful renewable energy source, and, therefore, solar PV power generation has been regarded as a sustainable energy source for various applications. It is widely used for the various applications from portable application to large-capacity and grid-connected PV power generation facilities in these days [1].

The solar irradiance on the Earth's surface and, in turn, the amount of generated power vary significantly with time and locations. In realty, we should overcome the effect of such variations of solar irradiance due to the following reasons. First, we should bridge the gap between the amount of generated PV power and load power demand. Solar PV systems are often accompanied by energy storage to charge the excessive energy during daytime and supply the load power during night. However, the battery and charger circuits significantly increase the system cost. The cost of the battery is considerably higher than that of the PV panel in the commercial products [2], [3], [4]. It also requires expensive charger to handle the peak power during peak irradiance time. Furthermore, batteries require periodic maintenance.

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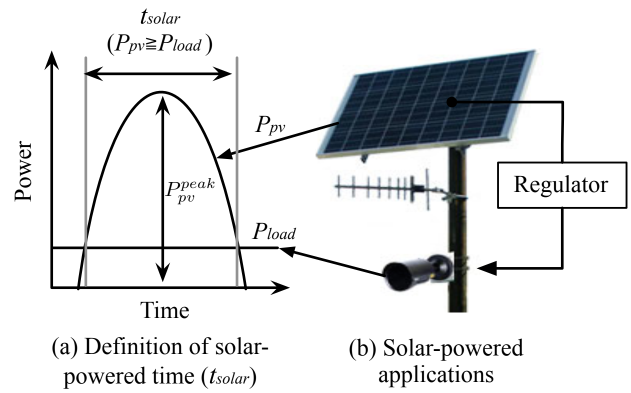


Fig. 1. (a) Load power demand (P_{load}), PV panel power capacity (P_{pv}), Solar-powered time (t_{solar}) and peak PV panel power capacity ($max(P_{pv})$) with (b) solar-powered applications.

A solar tracking is a method that adaptively changes the orientation of the PV panel following the optimal panel angle according the Sun's position to extend the solar-powered time and increase the amount of collected energy over time. It is reported that solar tracking generally enhances the power and energy capacity of PV power systems by up to 25% with the same-size PV panel [5]. However, the cost of tracking facilities is often much more expensive than that of the PV panel. The cost of commercial solar tracking solutions is much higher than that of the supported PV panel. [5]. Furthermore, the tracking system involves mechanical moving parts, which are subject to wear and tear. It is also challenging to self-start the tracking without external power source or energy storage.

Solar PV generation have been regarded as an appropriate power sources in remote places. Even though various methods have been introduced to enhance the PV energy harvesting efficiency, we still need to invest a considerable amount of money to construct off-grid power systems that is completely powered by the Sun. The power systems based on solar energy should be cost efficient. We should consider the various aspect of the solar-powered systems such as power, energy, cost to equip energy storages and tracking facilities, maintenance requirement, and so on.

In this work, we aim at prolonging *solar-powered time* t_{solar} PV-powered applications in remote location such as a pole camera (Fig. 1 (b)) without expensive and complicated solar tracking equipments. The proposed method also will reduce the maintenance cost thanks to its simplicity. For the applications without storage elements, t_{solar} is important rather than the peak power capacity of the PV panel (P_{pv}^{peak}) because the excessive energy is meaningless without the energy storages. Fig. 1 (a) shows the definition of the solar-powered time t_{solar}, which is the length of time duration satisfying $P_{pv} \geq P_{load}$ where P_{pv} and P_{load} represent the *power capacity* and *load power demand* of the PV panel, respectively.

We obtain the most effective size of the flat PV panel, and then, we find the optimal angle of a twofold three dimensional PV panel consisting of equal-size sub-panels. We deal with the panel geometry-induced partial shading problem with a single power converter by applying a sub-panel switching method to properly combine the power capacity of each sub-panel. The experimental result shows that the proposed twofold three dimensional setup extend the solar-powered time of the pole camera up to 23% with the proposed re-configurable architecture while we need 2.61× larger area of the PV panel the conventional flat setup to achieve the same solar-powered time.

The rest of the paper is organized as follows. Section II introduces relevant studies. Section III introduces models of solar irradiance and PV panel conversion efficiency. Sections IV and V explain the proposed three-dimensional PV panel arrangement and reconfiguration schemes to extend t_{solar} for target applications. Sections VI introduce the proposed heuristic to derive the optimal angle for the twofold panel with reconfiguration. Section VII presents experimental results, and then, we conclude the paper.

II. Related work

Combinations of a reflector and PV cells have been investigated as an alternative method of mechanical tracking. The reflector is deployed to suppress the variation of solar irradiance according to the angle between the Sun and PV panel. It is known that a tubular shaped panel and reflector are highly effective to mitigate the variation of solar irradiance over time [6]. Recently, a more complicated three dimensional arrangement of PV panels has been introduced to achieve the similar effect to the solar tracking without significant cost increase. Multiple PV modules are deployed with different solar irradiance incidence angles to mimic the output of solar tracking, and the total surface area of those PV modules is larger than the occupied ground area because of the three dimensional structure. This work claims that a more economic solution can be achieved than solar tracking in spite of the increase in total PV surface area [7]. However, these approaches mainly focus on overcoming the variation of the solar irradiance rather than explicit t_{solar} extension.

A reconfiguration of the PV panel is also intensively studied so far. The partial shading problem with a single power converter has been well-known in the design of large-size panel system. Conventionally, commercial PV panels usually have been composed by connecting the cells in series with bypass diodes to protect the cells from a reverse voltage in case of abnormalities such as partial shading. In this case, the power-current characteristics of the panel with partial shading have the multiple number of peak. A reconfiguration of the PV panel has been introduced to extract the maximum power with partial shading condition by using a switch network [8].

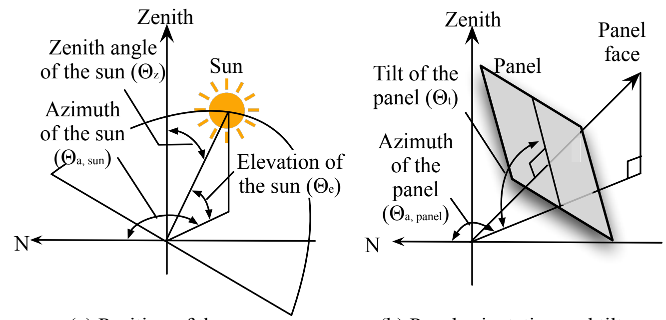


Fig. 2. (a) Solar position model and (b) panel orientation and tilt model.

A technique has been proposed to extend the solar-powered time of different systems without storage elements [9]. This work focused on the control of the target microprocessor to perform a maximum power point tracking (MPPT) without the aid of the storage elements.

III. PV panel and solar irradiance models

PV cells exhibit different efficiencies with different solar irradiance levels. We use a widely-accepted PV cell model introduced in [10] and the parameters of A-300 PV module [11] to calculate the power capacity of the PV panel (P_{pv}) with a given solar irradiance. Note that we do not consider an intra-panel irradiance variation. We assume that the irradiance in a sub-panel is uniform.

We consider two major factors to estimate solar irradiance: geographical factor and air mass effect. We consider the position of the Sun and air mass effect to calculate the solar irradiance on the Earth's surface during a day. Fig. 2 (a) shows the geometry of Sun's position. The *air mass coefficient AM* is approximated by

$$AM = \frac{1}{cos(\theta_z) + 0.50572 \cdot (96.07995 - \theta_z)^{-1.6364}}, \quad (1)$$

where θ_z is the *zenith angle of the Sun* as described in Fig. 2 (a) [12]. And then, the solar irradiance on the Earth's surface is estimated by the following equation:

$$I_d = 1.353 \cdot 0.7^{AM^{0.678}}. \quad (2)$$

This equation is valid when the altitude of the location of interest is lower than a few kilometers above the sea level [13].

θ_z is calculated as follows depending on the seasonal and geographical parameters:

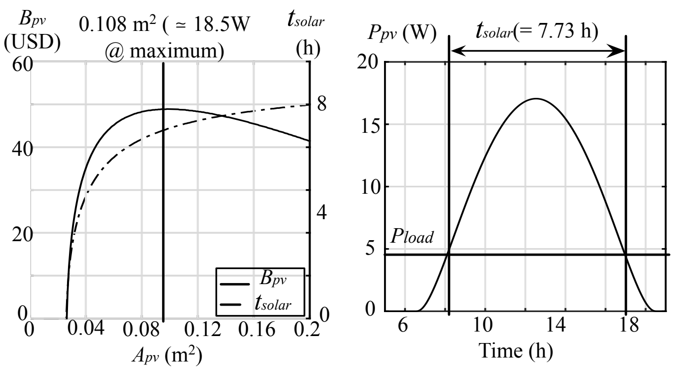
$$\begin{aligned}\theta_z =& 90^\circ - \theta_e \\ =& 90^\circ - sin^{-1}[sin\delta sin\phi + cos\delta cos\phi cos(HRA)],\end{aligned} \quad (3)$$

where ϕ is the *latitude of the location of interest*. The *declination angle* δ and *hour angle HRA* are determined by the following equations:

$$\begin{aligned}\delta =& sin^{-1}[sin(23.45^\circ)sin(360 - 365(d - 81))], \\ HRA =& 15^\circ \cdot LST,\end{aligned} \quad (4)$$

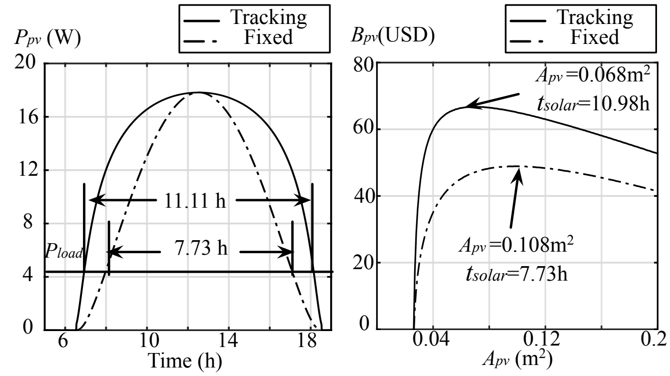
where LST is the *local solar time*, and d is the *day of year* (d = 1 at Jan. 1).

The panel orientation is represented by the *azimuth angle that the panel faces* ($\theta_{a,panel}$) and *tilt angle of the panel* (θ_t)



(a) B_{pv} w/ different A_{pv} (b) P_{pv} with the maximum benefit

Fig. 3. (a) B_{pv} for target application with different size of panel and (b) t_{solar} with maximum B_{pv}.



(a) t_{solar} w/ and w/o tracking (b) B_{pv} w/ and w/o tracking

Fig. 4. t_{solar} with and without solar tracking.

as described in Fig. 2. Finally, we obtain the *solar irradiance* S_{module} on the surface of an arbitrarily oriented solar panel considering the air-mass effect using the following equation.

$$S_{module} = I_d \cdot sin(\theta_e + \theta_t) \cdot cos(\theta_{a,panel} - \theta_{a,sun}), \quad (5)$$

where $\theta_{a,sun}$ is the *azimuth of the Sun* defined as follows:

$$\theta_{a,sun} = cos^{-1} \cdot \left(\frac{sin\delta cos\theta_z - cos\delta sin\theta_z \cdot cos(HRA)}{cos\theta_e} \right). \quad (6)$$

We use the presented models to estimate P_{pv} over time and eventually obtain t_{solar}.

IV. Solar-powered time extension

A. Panel sizing and solar tracking

One of the most straightforward method to extend the solar-powered time is a PV panel sizing. We should be aware the ultimate benefit of the PV panel in cost when we choose the size of the PV panel. The size of the PV panel can be determined from the perspective of the cost and benefit. The *benefit of the PV panel* (B_{pv}) is evaluated by obtaining the energy cost saving over 20 years (typical lifetime of PV pane) if we use the energy from the PV panel instead of the grid.

$$B_{pv} = C_{grid} t_{solar} P_{load}, \quad (7)$$

where the grid energy cost C_{grid} is set to 0.22 \$/kWh [5]. In realty, the exact result of cost-benefit analysis depends on various other factors such as government subsidies. Note that we use a simplified cost in this work, but the the presented approach can be extended to the other cost models without loss of generality.

Fig. 3 (a) shows B_{pv} for the target application, a remote pole camera with a cellular connection [14]. We use the path of the Sun at the location at the autumn equinox 2014. The zenith angle of the panel is set to the same as the latitude of the location of interest (34.05° N, 118.25° W), and the azimuth is set to 180°. The maximum B_{pv} is achieved when t_{solar} is 7.73 h with PV panel size of 0.108 m^2 that provides 18.5 W $max(P_{pv})$ as shown in Fig. 3 (b). As we increase the *PV panel area (A_{pv})*, the increment of t_{solar} gradually decrease, and, in turn, the effectiveness of the invested PV panel cost accordingly decrease after the peak point. *We use this panel size as a baseline to compare the proposed method and the conventional flat PV panel in the following sections.*

The solar tracking is an ideal solution to enhance t_{solar} with a given PV panel size. Fig. 4 shows the solar irradiance on the panel's surface with and without the solar tracking method. The zenith angle of the panel is set to the same as the latitude of the location of interest for the case without solar tracking. With the same load and solar conditions as the case presented in Fig. 3, t_{solar} increases 42% by using solar tracking even with a smaller size of panel compared to the fixed panel without solar tracking. It turns out that we need about ×3 larger PV panel to achieve the same t_{solar} without solar tracking.

However, it is not enough to be economic solution in our case where the cost of commercial typical tracking solutions is up to three times of the PV panel cost [5], [4]. We can fully exploit the advantages of the solar tracking when we store all the energy to the storage. Even though, it is an ideal solution to extend t_{solar}, it is not an economic solution for the storage-less applications. Therefore, *we only use the result of the solar tracking as an ideal case with the given size of PV panel to evaluate the effectiveness of the proposed method.*

B. Twofold three-dimensional PV panel

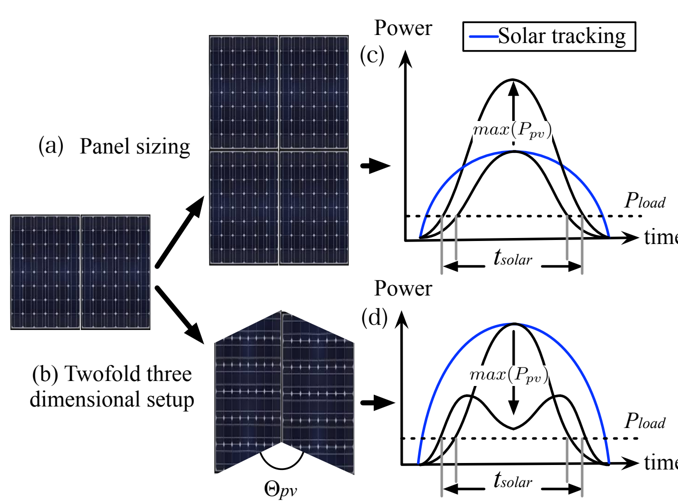


Fig. 5. Change of P_{pv} and t_{solar} with (a) Panel sizing, solar tracking, and (b) Twofold three dimensional setup.

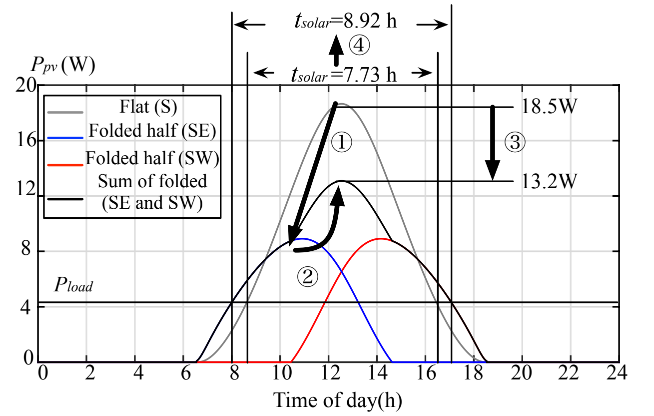


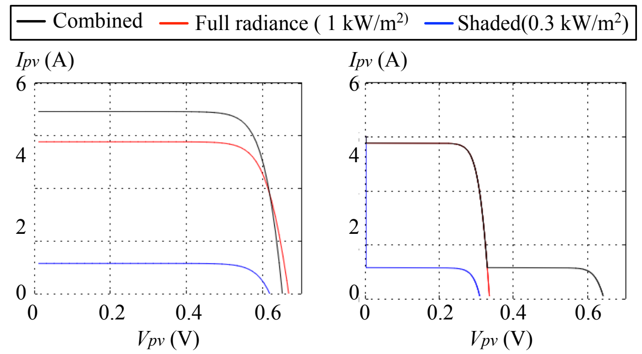
Fig. 6. Power capacity of the fixed flat solar panel and fixed folded solar panel during a day.

The third way to prolong the solar-powered time is to mount (and fix) different parts of the PV panel in different angles. This idea does not increase the peak power of the PV panel where the maximum amount of collected energy is achieved by aligning the panel to face towards the equator. Fig. 5 describes the principles and effects of the panel sizing, solar tracking, and proposed three dimensional setup to extend t_{solar}. The panel sizing increase both P_{pv}^{peak} and t_{solar} as shown in Figures 5 ① and ③. On the other hand, we obtain a longer t_{solar} while decreasing P_{pv}^{peak} by dividing the PV panel into two sub-panels and assigning different azimuth angles to the sub-panels as shown in Figures 5 ② and ④.

The extension of t_{solar} is strongly dependent on the extension of boundary over P_{load}. We need relatively larger size of PV panel to supply P_{load} with lower solar irradiance in the morning and evening. The fixed angle PV panel facing to the Sun at noon produces enough P_{pv} even with a faction of the PV panel while it produces much smaller P_{pv} in the morning and afternoon. Therefore, it is worthy to dedicate a large portion of the PV panel area for the morning and afternoon. The generalized three dimensional PV panel is a very complicated problem. This paper limit s the focus to the case such that the number of sub-panels and their orientation are limited to a *twofold* shape. In this context, the problem setup of this work is summarized as follows.

Problem:*find the optimal angle between the sub-panels (Θ_{pv}) in twofold PV panel to achieve the maximum t_{solar} where the size of PV panel is determined based on the cost-benefit analysis of the conventional flat panel*

The twofold three dimensional setup corresponds to the shifting of the P_{pv} curves. The boundary of the P_{pv} curve is expanded selectively by assigning different the azimuth angles to the sub-panels. The proposed twofold three dimensional setup allows the boundary expansion without any increase in the size of the PV panel. Fig. 6 shows an motivational example of the twofold three dimensional PV panel setup in details. We divide the panel evenly and assign different azimuth values (135° (South East, SE) and 225° (South West, SW) at 34.05° N, 118.25° W) to the two sub-panels, which makes P_{pv} curves of sub-panels shifted and scaled (Fig. 6 ①) from the original curve with 180° azimuth. If we have a method to properly aggregate the power from the sub-panels, we will get a summed power as presented in Fig. 6 ②.



(a) V-I in parallel (b) V-I in series

Fig. 7. Combined characteristics of sub-panels in series and parallel with different solar conditions.

The result shows the lower $max(P_{pv})$ (Fig. 6 ③), but longer solar-powered time t_{solar} (Fig. 6 ④). The twofold setup shown in Fig. 6 achieves 15.5% longer t_{solar} with the same size of panel with 90° for Θ_{pv}. We use the optimal size calculated from the fixed and flat panel case presented in Fig. 3. We set a tilt angle to the same as latitude.

V. Aggregation of sub-panel power

A. Series and parallel connections

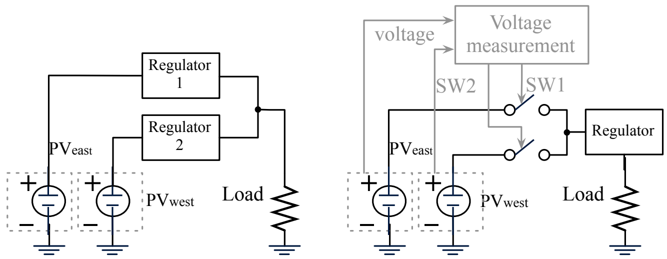
The three dimensional arrangement of PV panel involves partial shading in nature because of the different angle for the sub-panels. If we simply connect the sub-panels with different angle in parallel or series and connect them to the single power converter, a sub-panel in an opposite side of the Sun would be a bottleneck of the system as shown in Fig. 7. The current limit of the shaded cell would be the bottleneck when sub-panels are connected in series (Figures 7 (b)), and the voltage limit of the shaded cell would be the bottleneck when sub-panels are connected in parallel (Figures 7 (a)).

In general, the maximum voltage of the panel rapidly decrease when the solar irradiance is small. Otherwise, the voltage is less flexible with respect to the change of the current. As a result, panel voltage is likely to be a bottleneck if one of the sub-panel is in full or nearly full shade, and panel current is likely to be a bottleneck when the sub-panels in similar solar condition.

B. Micro inverter

If power from each sub-panel is independently converted and delivered by using dedicated converters, we can easily aggregate the power from the sub-panels. In series and parallel connections, sub-panel current is determined by its internal resistance and current-voltage characteristics. On the other hand, the dedicated converters allow us to control the power form each sub-panel as we want. It is called as micro-inverter (or converter) architecture as described in Fig. 8 (a), which is regarded as an ideal solution for the large-size PV systems to handle the imbalance of the sub-panels due to the partial shading problem and so on. There are no direct connection and uncontrolled power flow among each sub-panels, but they are only connected through a power converter to the load.

Unfortunately, the micro-inverter architecture is not generally affordable for the small applications due to the cost of



(a) Micro interview for twofold PV panel
(b) Sub-panel switching of twofold PV panel

Fig. 8. (a) Micro inverter architecture and (b) Sub-panel switching architecture for twofold PV panel.

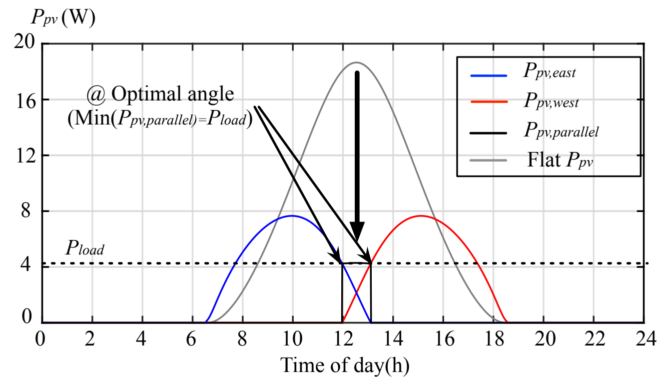


Fig. 10. Concept of heuristic to obtain the maximum t_{solar}

converter circuits. Another problem is efficiency. Even though the conversion efficiency of modern DC-DC converters is even higher than 98%, but it is guaranteed only for the designed input and output range. The voltage and current of the shaded sub-panel vary from zero to the maximum value. It is difficult to design the converters efficiently to deal with such a wide range of condition. In the following section, we introduce a sub-panel switching scheme for the proposed twofold PV panel setup as shown in Fig. 8 (b). The proposed architecture is simple but is able to fully utilize the power from the twofold setup.

C. Reconfigurable architecture

We devise a sub-panel switching scheme to accomodate the proposed twofold three dimensional PV panel into a single power converter. Fig. 8 (b) shows the proposed sub-panel switching architecture to connect the sub-panels selectively. We change the connection of the sub-panels to handle this change of the bottleneck. We only connect the sub-panel when the panel voltage is enough to be connected to the other sub-panel. Because we arrange the sub-panels symmetrically to east and west, which leads us to connect the sub-panels according to the sequence of the east-facing sub-panel in the morning, in parallel around noon, and the west-facing sub-panel in the evening.

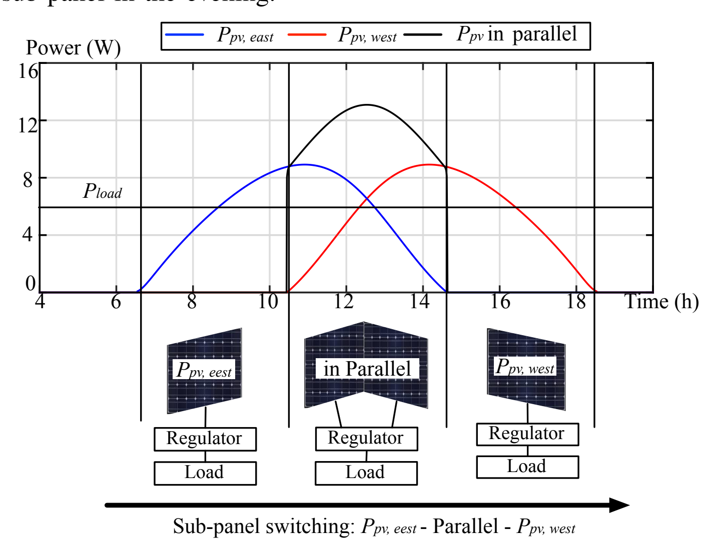


Fig. 9. Change of sub-panel connection according during a day.

Figures 9 shows the behavior of the proposed sub-panel switching. $P_{pv,east}$ and $P_{pv,west}$ represent the P_{pv} *of East-facing sub-panel* and P_{pv} *of west-facing sub-panel* in Fig. 9. The power capacity of the sub-panels in parallel is bounded by fully shaded sub-panel in the morning and evening. Therefore, at that moment, we only utilizes the power from the sub-panels with good solar condition even with the shaded sub-panel. At the intersection of $P_{pv,east}$ and $P_{pv,west}$, we combine the power from each sub-panel in parallel when the solar-conditions of the sub-panels are similar around noon.

VI. Optimal Angle Derivation

We use a heuristic to find the optimal angle considering the sub-panel switching based on the observations from the design space exploration. We assume that the power capacity of each sub-panel is combined by the proposed sub-panel switching architecture. The *combined capacity of the sub-panels in parallel* ($P_{pv,parallel}$) decrease in width and height as the intersection of the sub-panels decreasing as we decreasing Θ_{pv}. That is because t_{solar} of each sub-panel tends to decrease starting from the flat panel (Θ_{pv} = 180°) where the solar irradiance decrease as the distance from the peak point (noon) increasing. Therefore, the maximum t_{solar} is achieved by shifting $P_{pv,east}$ and $P_{pv,west}$ until $P_{pv,parallel}$ is enough to supply P_{load} in the intersection of r$P_{pv,east}$ and $P_{pv,west}$ around noon as shown in Fig. 10. Consequently, the maximum t_{solar} is obtained by finding the smallest Θ_{pv} satisfying the following condition:

$$\mathrm{Min}(P_{pv,parallel}) = P_{load}. \quad (8)$$

Where Min($P_{pv,parallel}$) represent the *minimum value of* $P_{pv,parallel}$. Note that we do not consider the change of solar spectrum and air condition within a day, and, therefore, the solar irradiance is symmetric with respective to the peak point. We numerically obtain the intersection of $P_{pv,east}$, P_{pv}, and P_{load}.

VII. Experiment

We have performed a design space exploration by the simulation of t_{solar}. Fig. 11 shows the P_{pv} of the twofold PV panel with different Θ_{pv} during a day. A grey surface is the power capacity of flat panel and a black surface is the power capacity of twofold panel with different angle. As Θ_{pv} decreasing, the power capacity profiles of the sub-panels move to the boundary in time domain. At the same time, the *max*($P_{pv,parallel}$) (white plot indicated in Fig. 11 (a)) rapidly decrease. As a result, the black region is observed

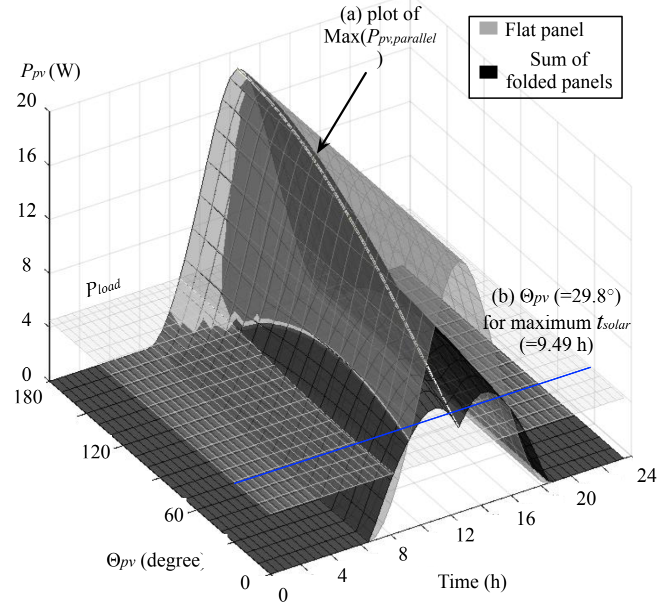
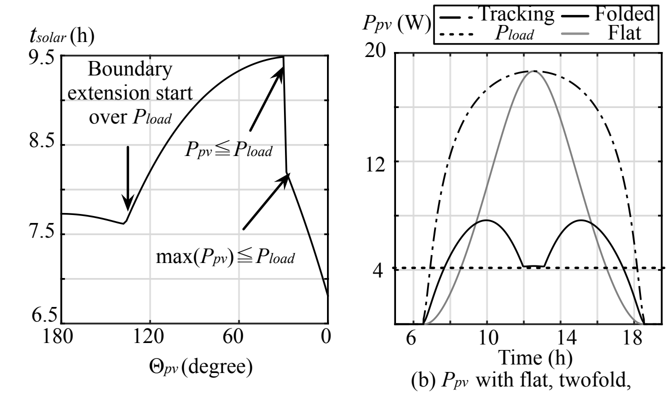


Fig. 11. Estimated P_{pv} with different Θ_{pv} and during a day.



(a) t_{solar} with different Θ_{pv}

(b) P_{pv} with flat, twofold, and tracking PV panel

Fig. 12. (a) t_{solar} with different Θ_{pv} and (b) a comparison of flat, twofold, and solar tracking PV panels at the maximum t_{solar} with a twofold PV panel.

over the grey surface and a deep valley n the middle of the black surface in Fig. 11. We find that the maximum t_{solar} is observed at just before the valley goes down the P_{load} surface, which confirms that the heuristic presented in Section VI is corresponds to the characteristics of the design space.

Fig. 12 (a) shows the t_{solar} of the twofold PV panel with different Θ_{pv} during a day. It shows three points of change. The first point shows the moment that t_{solar} of the twofold PV panel exceeds that of the flat panel. The second point shows that P_{pv} meets P_{load}, which results in a sudden t_{solar} decrease in both directions at the valley of P_{pv}. The decreasing rate slow down when the peak of P_{pv} meets P_{load} and t_{solar} decreases in just one direction.

It turns out that 29.8° is the optimal for the target application with the given size of PV panel in terms of t_{solar}, which achieves 23% of t_{solar} extension compared to the flat PV panel with the same size. We need about 2.61× larger PV panel to achieve the same t_{solar} with the flat panel. Fig. 12 (b) shows the t_{solar} with the flat, twofold, and solar tracking PV panels. t_{solar} of the flat and twofold PV panel without solar tracking are 7.73 and 9.49 hours respectively. The maximum t_{solar} with solar tracking is 11.11 hours. The proposed twofold three dimensional setup achieves up to 85.4% of t_{solar} compared to the solar tracking.

VIII. Conclusions

In this work, we propose a practical, cost effective and maintenance-free solution to extend solar-powered time of the target systems with the same size of PV panel. We fold the panel into two parts to achieve the similar effect to the tracking without much cost. It extends solar-powered time by dividing the PV panel while sacrificing the peak power capacity of the PV panel.

We conduct a design space exploration of the twofold three dimensional PV panel setup for an application that equips PV panel at remote location without any backup power. We propose a heuristic to find the optimal angle maximizing the solar-powered time based on the observations on the design space. We also propose a sub-panel switching method to combine the power capacity from the sub-panels with a single power converter. The experimental result shows that the proposed method extends the solar-powered time up to 23% for target application with the same size of flat PV panel. It corresponds to 85.4% of t_{solar} compared to that of the solar tracking. As for the future work, we will also extend the design space considering more complicated three dimensional structure of the PV panel to find a true optimal structure.

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