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A Research Study to Increase Usage of PVs in Residential Areas

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Self-generation of energy by residential houses has been met with many obstacles. When PV Solar energy technology is considered, the barriers manifest in problems related to the location, slope, strength, and shade exposure of house roofs are the most common. Therefore, it is not possible to meet daily energy needs from PV panels placed on the existing roofs of many houses. Solar Tracking Systems keep PV panels perpendicular to the Sun throughout the day, providing a significant increase in their efficiency. But the application of these systems on the roofs or houses is not suitable for many reasons, especially in terms of aesthetic appearance. This article is aimed at effectively showing how the slope and direction inconsistencies in the existing roofs of houses in residential areas cause great losses in the performance of PVs; also a research and design study is presented to find a solution to the application of Sun tracking systems in residential areas without creating aesthetic appearance problem. As a solution, combining a dual axis Sun tracking system with an aesthetic looking Gazebo has been considered. A design study was carried out for the targeted system, and the dimensions of a movable platform/roof such a system should have in order to meet the electricity needs of a house from the Sun throughout the year was investigated. How much energy the PV panels can collect annually is determined by a simulation program called “PV performance tool”.

Keywords: solar energy, PV, sun tracking system, active building, energy efficiency

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INTRODUCTION

Extending the use of renewable energy sources can be considered a very important development towards a cleaner world, but an even better solution can only be achieved by obtaining energy from renewable energy sources while also consuming this same energy straight from the point of production. Because in this solution, many losses and problems associated with energy transmission and distribution lines can also be eliminated.

A significant part of energy consumption takes place in residential areas. In the evenings, especially, this consumption increases considerably (Anderson et al., 2017; Validzic, 2017). The fact that people produce the electricity they need in their own homes as much as possible provides many benefits in terms of the energy network. Some of this benefits include reduction in the need for centrally-operated large power plants, increase in the usage of renewable energy sources, ease of the burden on energy transmission and distribution lines, and reduction in both losses and maintenance-breakdown expenses (Zahedi, 2011). Efforts to increase these benefits also contribute to the protection of nature as well as a slow-down in the spate of global warming (Panwar et al., 2011; Rabaia et al., 2021).

However, houses in residential areas face many obstacles in generating their own energy. When these obstacles are considered with focus on PV Solar energy, the most common problems that arise include the direction, slope, strength, and shadow exposure of house roofs (Kouhestani et al., 2019). Likewise, some other similar problems are: the lack of sufficient space for the use of PV panels in the gardens, shadow problems, distortion of the aesthetic appearance of the gardens, or the PV panels creating anxiety in people due to electric phobia. However, even if all the mentioned problems are solved, deeper considerations of the total roof areas of the city residences reveals that the total that can be produced from roof-mounted solar PV will be insufficient to meet the energy needs of those cities even if all available roof areas are used (Jurasz et al., 2020). In this case, attention must be pointed to solar energy systems that enable us to obtain higher performance from a limited area. Besides, studies in Active Building which have experienced significant developments in recent years also show the importance of this subject. One of the important targets of Active Building works is that a building should generate and manage all the energy it needs (Bulut et al., 2016; Fosas et al., 2020; Strbac et al., 2020).

For houses that cannot meet the energy they need from the Sun, the increase in the performance of PVs depending on the developments in the material structure can produce an effective solution in the long term. For instance, it is hoped that the performance of PV panels can be doubled with GaNP-based photovoltaic device integrated on Si substrate (Dvoretckaia et al., 2020). Similarly, it is hoped that the performance of solar cells can be increased to 42.5% with GaAsP/Si tandem technology. (Kim et al., 2018). Or, due to the very cheap price of PVs, another solution may be placing the PV panels not only on the roofs but also on the walls and thus ignoring the losses due to unsuitable positions or shadow problems. For instance, it is hoped that the Perovskite solar cell technology will make PV prices considerably cheaper. (Huckaba, 2016; Fagiolari and Bella, 2019).

However, in this study, a research has been made to produce a solution under today's conditions and it is aimed to benefit from the performance increase of around 30% provided by Sun Tracking Systems (STS). There has been a lot of research for a long time into the performance improvement provided by STSs. For instance, Nadia AL-Rousan and her colleagues from University Sains Malaysia examined many Sun Tracking systems in their article named "Advances in solar photovoltaic tracking systems: A review" and showed that the efficiency gains of these systems compared to Fix position PV panels can vary between 20 and 50%. (Nadia et al., 2018).

The most important roadblock to the use of STS on roofs is the problem of aesthetic appearance. In addition, if there is a shadow problem on a roof caused by adjacent buildings or trees, it will not be beneficial to use STS there. Within the scope of this study, which has been going on for several years, it was aimed to combine an STS with a Gazebo in an aesthetic fashion, and a single axes novel design STS-Gazebo system was presented at a conference in 2019 (Kiray, 2019). The developed system was named as Rotating Roof Gazebo System (RRGS).

In this phase of the research, it was shown how effective the losses due to slope and direction on roofs and how large these losses are compared to the performance provided by STS systems. In addition, a design study was presented to prove that the aesthetic image problem can be solved by combining an STS with a Gazebo. The width of the mobile platform that will follow the Sun and the power of the PVs that can be placed on this platform were determined by the design study.

The performance calculations were made for the determined total PV power by using the "PV performance tool" offered by the science and information service on the European Commission's website. Cities in Warsaw and Madrid were selected for performance tests and the data obtained were presented under a separate heading. RRGS performance, and whether this performance can meet the annual energy of a normal home, are discussed in the Discussion section.

In the literature study for the research and design study presented, it was first investigated whether the dual axis novel STS has similar electromechanical equivalents. Then, scientific studies that take solar energy systems or materials in an aesthetic concept have been examined.

A review of the literature reveals two studies that can be considered the closest to RRGS, which use the logic of creating Sun Tracking using a rotating platform. The first of these studies is seen in a Patent Application named "Rotating lattice solar tracking platform". However, in this study, the use of a Gazebo was not considered, and a design was not made to eliminate the shadow problem that occurs when the Sun rays are not vertical, and its mechanical system is completely different from the RRGS (Bill, 2010). The other close study involves single-axis solar tracking platforms placed on a very wide platform that rotates in a horizontal plane. This study differs from RRGS both in terms of its mechanical system and the fact that it does not use a single-piece platform (Lim et al., 2020).

When the literature is examined, many scientific studies related to solar tracking systems were found to have been consucted (Hafez et al., 2018a; Hafez et al., 2018b; Nsengiyumva et al., 2018; Singh et al., 2018; Awasthi et al., 2020), but since the RRGS has a novel design that combines a Gazebo with a Solar Tracking System, there is no similar study in the literature yet. However, since the Sun Tracking Logic is handled with an aesthetic understanding in RRGS design, the research and design study presented has gained a different dimension. When the literature is viewed from this point of view, the flower-looking Smart Flower design, which deals with the use of PV panels in an aesthetic manner, stands out (Mulyana et al., 2018). Besides, the Tesla Roof, consisting of Solar tiles, can be considered as another design study that deals with the use of solar energy in an aesthetic outlook (Choi et al., 2018; Hire et al., 2020).

SLOPE AND DIRECTION PROBLEMS DEPENDING ON THE STRUCTURE AND POSITION OF THE ROOFS

It is very difficult to change the roofs of houses built years ago in favour of solar energy systems. However, depending on the slope (tilt) and direction (azimuth) of the roofs, significant changes occur in the performance of PV Solar Energy systems. The effect of tilt and azimuth factors can be understood from the formulas given below. Solar energy to be harvested from a PV panel is generally expressed in the following formula (Suthar et al., 2013; Hailu and Fung, 2019).

$$HT = HB + HD + HR \tag{1}$$

The monthly average daily total radiation on a tilted surface (HT) is obtained from the direct beam (HB), diffuse (HD), and reflected components (HR) of the radiation on a tilted surface (Suthar et al., 2013; Hailu and Fung, 2019).

Tilt and Azimuth factors are effective over *(HB)* in this formula.

$$HB = (Hg - Hd)Rb \tag{2}$$

where *Hg, Hd,* and *Rb* are the monthly mean daily global, the monthly mean daily diffuse radiation on a horizontal surface, and the ratio of the beam radiation on a tilted surface to that on a horizontal surface, respectively. *Rb*, the ratio of the beam radiation on the tilted surface to that on a horizontal surface.

$$Rb = \cos\theta i / \cos\theta Z \tag{3}$$

$$\cos\theta i = (\cos\Phi\cos\beta + \sin\Phi\sin\beta\cos\gamma)\cos\delta\cos w + \cos\delta\sin w\sin\beta\sin\gamma + \sin\delta(\sin\Phi\cos\beta - \cos\Phi\sin\beta\cos\gamma) \tag{4}$$

$$\cos\theta Z = \sin\delta\sin\Phi + \cos\delta\cos\Phi\cos w \tag{5}$$

where Φ is the latitude of location, β is PV module surface slope from horizontal called tilt angle, γ is the surface azimuth angle, w is the angle from the local solar noon called hour angle and δ is the declination angle (Suthar et al., 2013; Hailu and Fung, 2019).

In addition, it is possible to see the effect of tilt and azimuth angles on the performance of PV panels by using various simulation programs. The simulation results of this research study are presented in *Discussion* Section. When the results are examined, it is seen that the slope and direction problems of the roofs have considerable impact on the performance of the PV Solar energy systems.

AN ALTERNATIVE SOLUTION TO ROOFS IN TERM OF PV PANEL PLACEMENT

For houses whose roofs are not suitable for the placement of PV panels, the use of gardens, if any, and the use of solar tracking systems for higher efficiency is the most practical solution that comes to mind. Gardens can be considered as more advantageous areas than roofs for the deployment of PV panels. However, the lack of sufficient space in the gardens, the disruption of the garden aesthetics by fixed PV panels or solar tracking systems and the concerns of people with electric shock phobia also constitute different problems.

The fact that Solar Photovoltaics (PV) show the sharpest cost decline over 2010–2019 at 82% also reduces the attractiveness of solar tracking systems (Irena Report, 2019)[1]. However, in today's conditions, solar tracking systems maintain their importance for situations where high performance from a limited area is aimed. However, solar tracking systems are not aesthetically suitable either for roofs or for gardens. The use of solar energy in a certain aesthetic level in residential areas is an issue that maintains a high degree of importance. Smart flower design (Hafez et al., 2018a) and Tesla roof also support the studies in this concept (Mulyana et al., 2018; Hire et al., 2020).

Considering all these, it was thought that converting a Gazebo into an STS can minimize the mentioned problems. Within the scope of the research, a single axis STS was obtained by rotating the roof of the gazebo in the first plan and a real-size prototype application was realized. Two important problems were identified in this application (Kiray, 2019). First, the roof material creates a significant weight and the motors selected to rotate the roof had to have high power and thus high energy consumption. Second, because only the sun-facing side of the roof is used and the roof angle is constant, there is a significant performance loss. In this research phase, it was thought that the roof would be completely canceled, a wide-area platform following the Sun would be used instead of the roof, and the loss of aesthetic appearance would be minimized with a symmetrical system. In addition, again in relation to the aesthetic appearance, the body structure of the Gazebo was prepared in a structure like a cylinder.

ELECTRO-MECHANIC STRUCTURE OF RRGS

Unlike other STSs, the RRGS is designed by using a second platform that makes angular motion on the vertical plane on a main platform that makes circular rotation on the horizontal plane.

The main platform is supported by three carriers connected to each other with iron profiles (**Figure 1A**). The platform moves on a disc placed on top of side walls of the Gazebo. The platform is rotated with motors placed at the end points instead of rotating from the center (**Figure 1B**), but thanks to the unique design, the platform makes a circular rotation movement as if it is rotated from the center point (**Figure 1C**). While the main wheels of the carriers move on the disc, the other wheels of the carriers also move under the disc and on the side wall of the disc to prevent the platform from tipping or shaking in windy weather (**Figure 1B**).

Movement on the vertical plane is provided by the angular movement of the platform carrying the PV panels. Therefore, when the whole system is considered, a unique dual-axis Solar tracking system is obtained (**Figure 1D**).

In the framework of this research presented, two design studies were made for the optimal placement of the second platform on the RRGS. In the first design, it was thought that the platform, which should be perpendicular to the Sun, should be divided into two parts in order not to spoil the aesthetic appearance of the system and not be affected by the wind, but it was seen that there would be a huge loss of efficiency in the calculations. Because, in the case of using platforms consisting of two rows, a large gap must be left in order not to affect the rear platform from the shadow created by the front platform (**Figure 2A**). Therefore, this design option was not chosen.

[1]https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019 (Visited at 08/04/2021, 10:55) https://re.jrc.ec.europa.eu/pvg_tools/en/#PVP (Visited at 08/04/2021, 10:57) https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels (Visited at 08/04/2021, 10:57) https://ec.europa.eu/jrc/en/PVGIS/docs/methods (Visited at 16/05/2021, 10:50) https://www.globalpetrolprices.com/Spain/electricity_prices/ (Visited at 16/05/2021, 10:53) https://www.made-in-china.com/products-search/hot-china-products/Solar_Panel.html?gclid=EAIaIQobChMI4-r8nfrO8AIVVgWRCh2MNAGbEAAYAyAAEgLCofD_BwE (Visited at 16/05/2021, 10:57) https://www.made-in-china.com/productdirectory.do?word=power+inverter+charger&file=&subaction=hunt&style=b&mode=and&code=0&comProvince=nolimit&order=0&isOpenCorrection=1 (Visited at 16/05/2021, 11:11) https://www.made-in-china.com/productdirectory.do?word=dual+axis+tracking&file=&subaction=hunt&style=b&mode=and&code=0&comProvince=nolimit&order=0&isOpenCorrection=1&log_from=1 (Visited at 16/05/2021, 11:23).

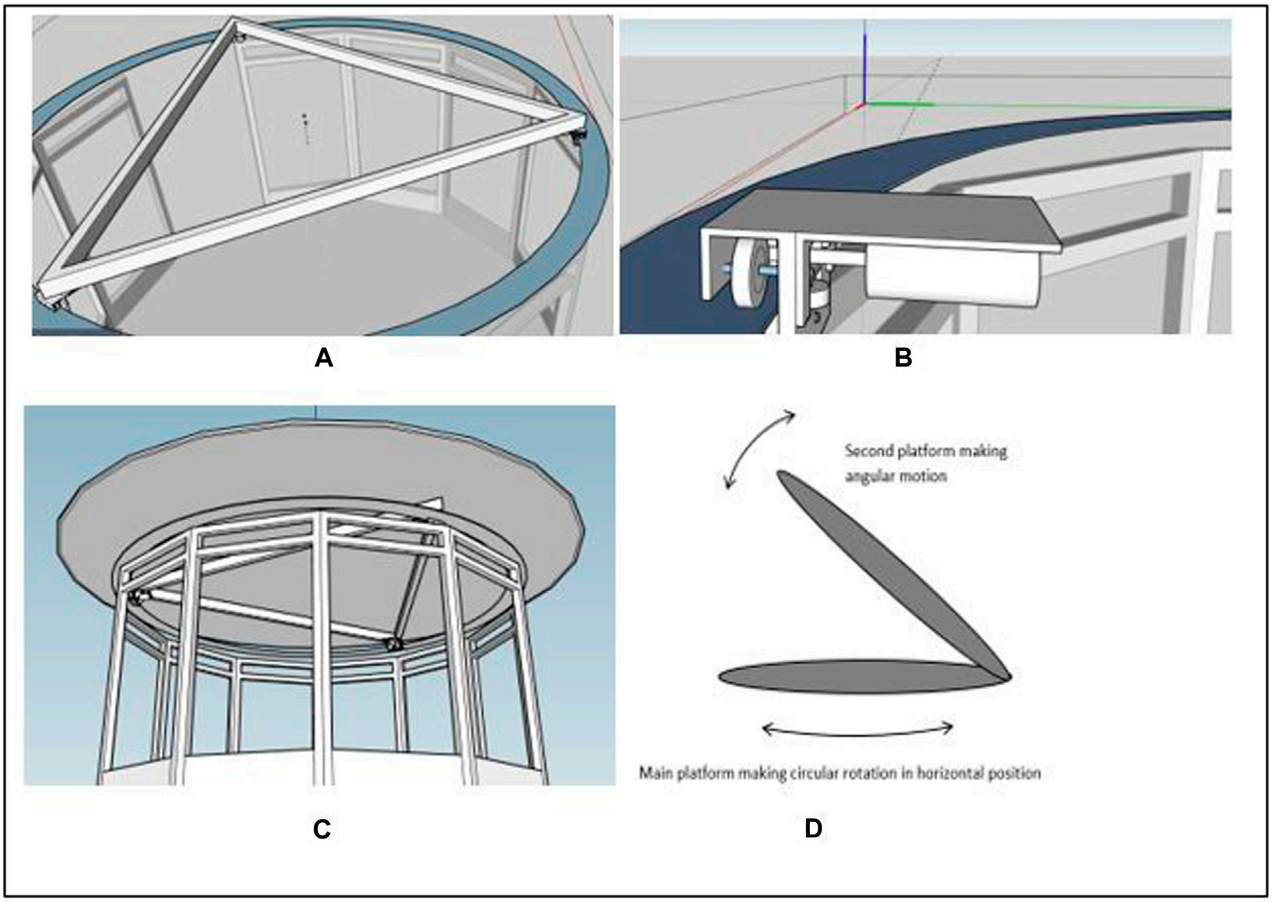


FIGURE 1 | Electro-mechanic structure of RRGS. **(A)** Disc and Movable triangular carrier. **(B)** Disc and one of the carrier's motor. **(C)** Main platform on moving carrier. **(D)** Main and Second platform.

In the second design study, the platform moving in a vertical plane is designed as a single piece (**Figure 2B**). It was thought that this platform could be larger than the platform that rotates in the horizontal plane to make the area where the PV panels will be placed as wide as possible. In this design, three important problems were encountered: Aesthetic appearance, Wind effect, and the necessity of a special electromechanical system. At this study some changes have been made to the design to minimize these problems.

Aesthetic appearance: To partially restore the roof image that our eyes are accustomed to, a back platform made of light material, which will create symmetry to the mentioned platform, is added to the design. In addition, the symmetrical image is strengthened with the two arms extending from the rear platform.

Wind Effect: To reduce the wind effect, it is used not only to create symmetry from the rear platform, but also to increase its mechanical stability. In addition, it is thought that the position of the platform in windy weather could be adjusted to a zone with the least wind effect with the aid of a wind sensor.

Electromechanical system: Depending on the problems in question, a special Electromechanical system was added to the design: In the developed design, both platforms are articulated at their lower ends. The rear platform with two arms has channels in these arms. While the main platform arranges its position to the Sun, the protrusions of the front (main) platform moving in these channels allow the rear platform to move symmetrically (**Figure 2B**).

Both platforms are articulated at their lower ends. The rear platform has two arms each of which has channels. The protrusions of the front platform moving in these channels allow the rear platform to move symmetrically (**Figure 2**). In addition to creating an aesthetic appearance, the rear platform also contributes to the strengthening of the system and to the reduction of negative wind effect.

The electro-mechanical system design presented in this study is modelled quite realistically as it was based on a previously made prototype study.

Sizes of Platforms

The Gazebo, whose structure resembles a cylinder, has a diameter of 4 m. The platform, which rotates in the horizontal plane and completely covers the top of the gazebo and protects it from rain, is set to 5 m in diameter and an area of approximately 20 m^2 is obtained. The area of the platform following the Sun is expanded a little more and determined as 23.66 m^2. It is not possible to cover the entire area with PV panels because PV panels come in fixed dimensions predetermined by the manufacturer.

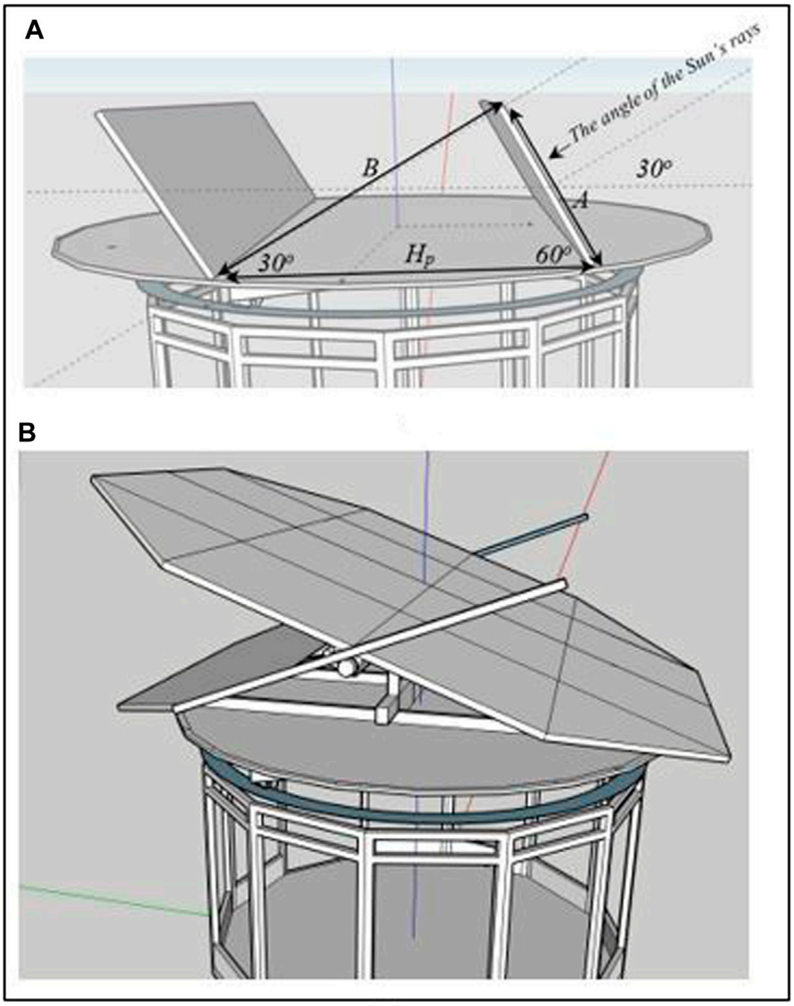


FIGURE 2 | Two different design studies of RRGS. **(A)** First design with low efficiency. **(B)** Second design with high efficiency.

Types of the PV's and Optimal Placement of the PV Panels

Half-cut cell PV module technology is a good alternative for RRGS, as the RRGS aims to get high performance from limited space.

Half-cut cell PV module technology makes it possible to harvest more energy from the same area (Akram et al., 2020). It seems possible to obtain 250 Wp energy from one m2 with commodified products that are produced using this technology existing as of 2021 (www.Cleanenergyreviews.info/). For this reason, it is decided to use PV panels with 78 cells (156 HC) with dimensions of 2.2 m × 1.1 m for RRGS. The average peak power (Wp) of these panels varies between 450 and 600 Wp. So, it seems possible to obtain an average power of 2,700–3600 Wp by placing six high-performance PV panels with a power of 450–600 Wp and dimensions of 2.2 m × 1.1 m in this area. (**Figure 3**). Under ideal conditions, it seems possible to obtain 5,750 Wp energy from an area of 23 m^2, but depending on the standard PV panel sizes, the usable active area is limited to 14. 52 m^2 and so, the average total peak power is limited to 3,300 Wp.

THE PV PERFORMANCE TOOL AND SIMULATION RESULTS

The "PV performance tool" offered by The European Commission's science and knowledge service on its website (https://re.jrc.ec.europa.eu/pvg_tools/) is used in the performance calculations of RRGS.

"PV performance tool" is a simulation program that calculates the monthly and annual possible energy harvest performance of fixed position PVs or those PVs mounted on single axis/dual axis STS. The location where the PVs will be deployed is determined on the map. The energy harvest performance of PVs placed on the roof of a house can be simulated by entering Slope and Azimuth angle values for fixed position panels.

The total power of the PVs placed on the RRGS is specified as 3,300 Wp. Since RRGS has a dual-axis STS feature, simulation results are first obtained for a 3,300 Wp STS. The performance of this value is accepted %100.

The "PV performance tool" program also takes into account the PV module efficiency in the calculations.

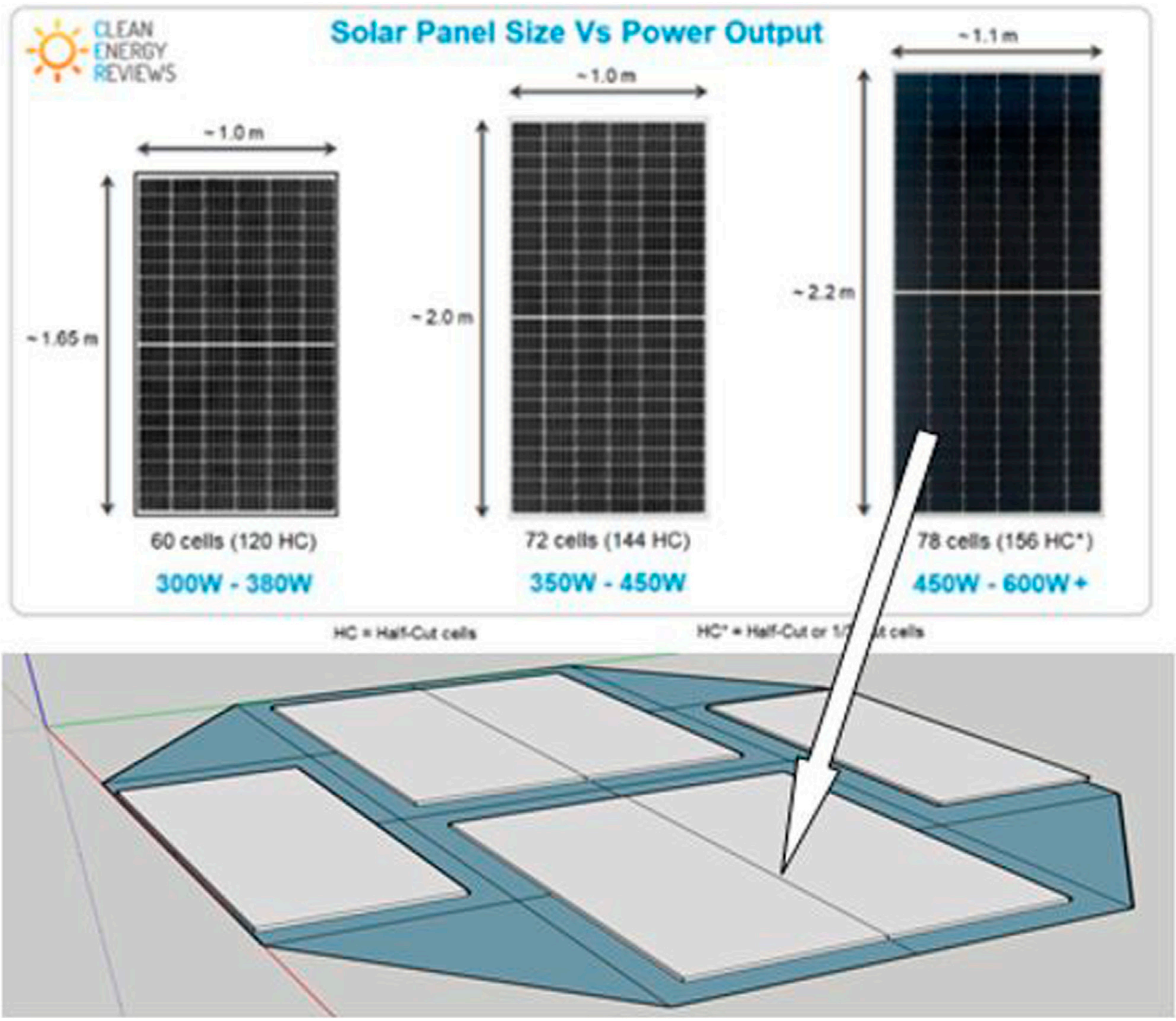


FIGURE 3 | Placement of PV panels on the platform.

Accordingly, the efficiency loss for PV modules was determined to be 14%. The factors taken into account in efficiency calculations and the formulas used are presented in the documentation section of the relevant website (ec. europa.eu/…/methodes).

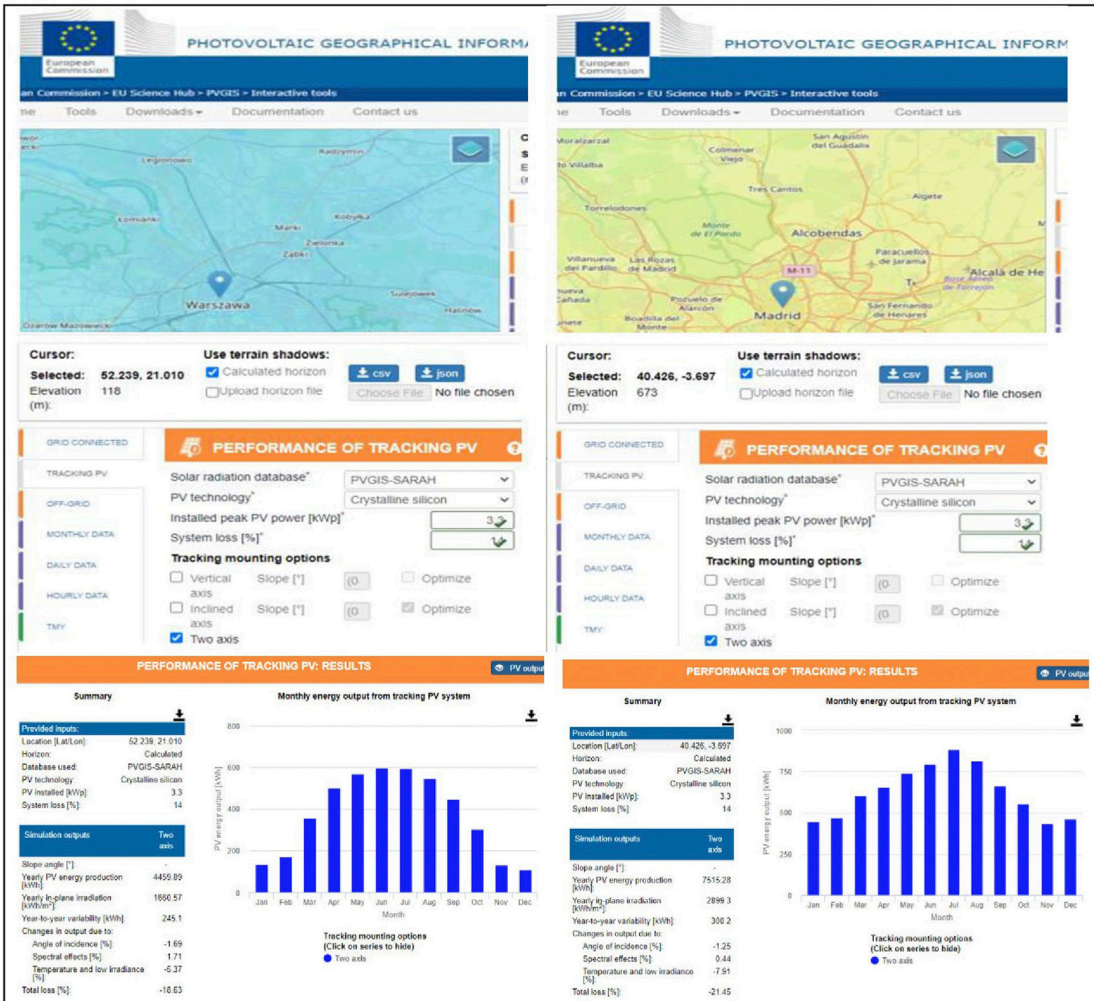
DISCUSSION

At first glance, the values obtained with the PV performance tool can be perceived as comparing Fixed PVs with PVs placed on STS. However, the 3,300 Wp power value obtained was obtained at the end of a design study. The performance values given in **Table 1** show how the performance decreases as the unconformity increases and the importance of the RRGS increases for the houses with slope and direction problems on their roofs.

The simulation program used can calculate the optimal slope and Azimuth values. According to these values, even if the slope and Azimuth angles of the roof of a house in Warsaw are at the optimum level and the power of the PV panels installed on it is equal to the total power of the panels above RRGS, its performance will be on average 27% lower than the performance of the RRGS. In similar manner, if a comparison is made for Madrid, the estimated performance loss would be 32%. However, it is very unlikely that the slope and azimuth angles on the roof of a house built years ago are at an optimal level.

To see more realistic results, if the roof slopes of the house in question are assumed to be 20 degrees different in both cities, there is a possible loss of efficiency of 30% in the house in Warsaw and 34% in the house in Madrid. If there is a small deflection of 30 degrees in the direction of the roofs, not in the slopes of the roof, 35% loss occurs in Warsaw and 39% in Madrid. If there is a 20-degree slope deflection and a 30-

TABLE 1 | Annual possible energy (kWh) amounts that RRGS can produce for Warsaw and Madrid.



PLACE	Total PV Area (m^2)	Total PV Power (Wp)	Yearly PV Energy Production (kWh)					
WARSAW	14.52	3300		Fix position				
			Dual axis	Slope: 39 Azimuth: -2 **(Optimal)**	Slope: 59 Azimuth: -2	Slope: 39 Azimuth: 58	Slope: 59 Azimuth: 58	Slope: 65 Azimuth: 90
			4459	**3267**	**3117**	**2910**	**2701**	**2202**
			Performance: % 100	Performance ratio: % 73	Performance ratio: % 70	Performance ratio: 65	Performance ratio: % 60	Performance ratio: % 49
MADRID	14.52	3300		Fix position				
			Dual axis	Slope: 36 Azimuth: -3 **(Optimal)**	Slope: 56 Azimuth: -3	Slope: 36 Azimuth: 57	Slope: 56 Azimuth: 57	Slope: 56 Azimuth: 90
			7515	**5183**	**4961**	**4649**	**4341**	**3714**
			Performance: % 100	Performance ratio: % 68	Performance ratio: % 66	Performance ratio: % 61	Performance ratio: % 58	Performance ratio: % 49

degree deflection in the direction on the roof, this time there is a 40% loss of efficiency in the house in Warsaw and 42% in the house in Madrid.

An exaggerated scenario has been added to the simulations to show the losses caused by the slope and direction problems of the roofs more effectively. Although this scenario did not make much change in the slopes of the roof, it was assumed that the direction of the house was facing east or west rather than south. In this case, it has been shown that the efficiency can fall below 50%.

Is the Performance Achieved Sufficient?

When the annual energy amount of 7,515 kWh obtained for Madrid is divided into 356 days in a rough calculation, it is seen that daily energy of 20.58 kWh can be obtained. This amount obtained shows that a house with a daily energy need of 15 kWh can be met all year round with a small battery bank supplement. For countries that have a good energy infrastructure and can buy all the energy produced by the end user, the need for a battery bank can be eliminated by using grid energy when needed and then making an offset. Even with a 3,300 Wp PV power RRGS, it may be possible to earn income from energy sales.

If the same calculation is made for Warsaw, it is seen that an average of 12.21 kWh of energy can be obtained per day. From a rough calculation, 80% of 15 kWh daily energy need of a house can be met.

Rough Economic Analysis

The economic analysis of the RRGS will be discussed in the next study. However, the following can be said to give a general idea.

Since the Gazebo part of the RRGS will also be used as a Gazebo, there is no need for the gazebo cost to be included in the economic analysis. However, a significant modification is needed to make the upper part of the gazebo follow the Sun, and the cost of this modification can be assumed to be equal to the cost of a dual-axis STS.

In this case, the cost of PV panels, on-grid inverter/Charger cost (new generation inverters include MPPT function), dual-axis STS cost and 20% miscellaneous expenses cost can roughly determine the overall cost of the system. In the market research conducted within the scope of this idea, the cost of PV panels is 1,200 USD (hot-china-products/PV), 3.3 kWp invertor/charger cost 2,000 USD (hot-china-products/Inverter) and Dual-axis STS price 3,300 USD (hot-china-products/tracker) and in this case, the total investment cost of the system is 5,500 USD and the total investment cost of the system can be considered as 6,600 USD, together with the cost of miscellaneous expenses of 20%.

The price of electricity for 2020 in Poland is seen as 0.199 USD and for Spain as 0.244 USD (www.globalpetrolprices.com). If it is assumed that all the electricity produced is purchased by the state, the annual production of 4,450 kWh in Poland saves 885.55 USD and the RRGS itself is amortized in 7.45 years. Likewise, in Spain, annual electricity production of 7,515 kWh saves 1833.66 USD and RRGS amortizes itself in 3.59 years.

Why Gazebo?

First of all, Gazebos are aesthetic and useful structures that add beauty to gardens. Gazebos can be turned into a STS with a special electro-mechanic system design on the roof parts. Thus, the Novel system obtained can be used both as a Gazebo and as an STS. And Because Gazebos can be moved to the desired location of the gardens, the shadow problems can be minimized.

The direct use of STSs on roofs or in gardens is not aesthetically appropriate, but it seems possible to overcome this problem with an STS integrated into a Gazebo. The fact that the PVs are mounted on the gazebo offers a distinct advantage for those with electric phobia besides the advantage of aesthetic appearance.

AUTHOR'S NOTE

VK received his Ph.D. degree from the Electrical and Electronics Engineering department of the Institute of Science, Sakarya University, Turkey 2003. He completed his Post-doctoral experience in the Technopark research office of Hochschule fur Technik, Zurich, 2006. His current research interests include Renewables, Smart Grid, Micro-Grid, and energy management systems. He has got also experiences and publications on FPGA-based Digital Design. He has been on the executive board of IEEE-ICECCO conferences since 2013. He is currently working as a researcher and academic staff at the Vistula University, Energy Management program, Warsaw, Poland.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the author, without undue reservation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.680304/full#supplementary-material

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