



Research Article

Impact of vehicle integration sections on photovoltaic performance: A case study for Türkiye

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ABSTRACT

The integration of photovoltaic systems into vehicles raises the question of how different sections of the car body can be used to generate solar energy. This question is becoming increasingly important as electric vehicle technologies seek more efficient and sustainable energy sources. The potential of solar energy was analyzed using a region-independent methodology based on one year of irradiance data from three cities in Türkiye representing low, medium, and high solar radiation levels. The analysis was made with data obtained from the Photovoltaic Geographical Information System, and it was applied to five vehicle surfaces with different inclinations and azimuth angles: the roof, the front hood, the rear hood and both doors. The results indicate that the door sections collectively contribute the most to the energy reception (26.67%), followed by the front hood (26.47%), the roof (24.22%) and the rear hood (22.64%). The study also shows that irradiance values for differently oriented surfaces can be inferred from a single pyranometer measurement, greatly reducing the complexity and cost of data collection for future applications. This study is novel compared to existing literature in that it presents a new method for assessing section-based irradiance contributions irrespective of the photovoltaic surface area, thus enabling more generalizable and scalable insights for future vehicle designs. The comparison with experimental results was made to confirm the reliability of the methodology, with a deviation of only $\pm 4.83\%$.

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INTRODUCTION

In contemporary societies, the degree of development and economic prosperity is frequently gauged by the indices of energy generation and consumption. This energy is derived from two sources: primary and secondary. Primary

sources are fossil fuels (oil, coal and natural gas) and renewable sources (solar [1], wind [2] and hydroelectric power [3]). Secondary sources, such as electricity, are derived from primary sources through various conversion processes, making them ready for direct consumption [4]. However,

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the production and consumption of energy are among the major determinants of environmental degradation, mainly through carbon dioxide (CO₂) emissions. In the past, these emissions have come from fossil fuels, combustion and industrial processes. They differ between regions, and have grown with industrialization. Figure 1 presents the emissions of CO₂ by certain sources, such as coal, natural gas, oil, combustion activities, and cement production, worldwide and in Türkiye [5, 6].

Despite efforts to reduce CO₂ emissions since the 17 Sustainable Development Goals [7] launched by the United Nations in 2015 and the 2015 Paris Agreement, levels

continue to rise, worsening the effects of climate change and making it harder to achieve global climate goals. In response, many countries are increasingly investing in zero-emission and sustainable energy alternatives [8]. Solar energy, one of these sources, is abundant, environmentally friendly, versatile, easily accessible, and easy to utilize, while also offering a low average cost [9]. Due to these advantages, global solar energy production has increased by an average of 25.9% annually since 2013, while Türkiye has experienced an average annual growth rate of 22.7%. This expansion is also evidenced by the rising number of installed solar panels [10].

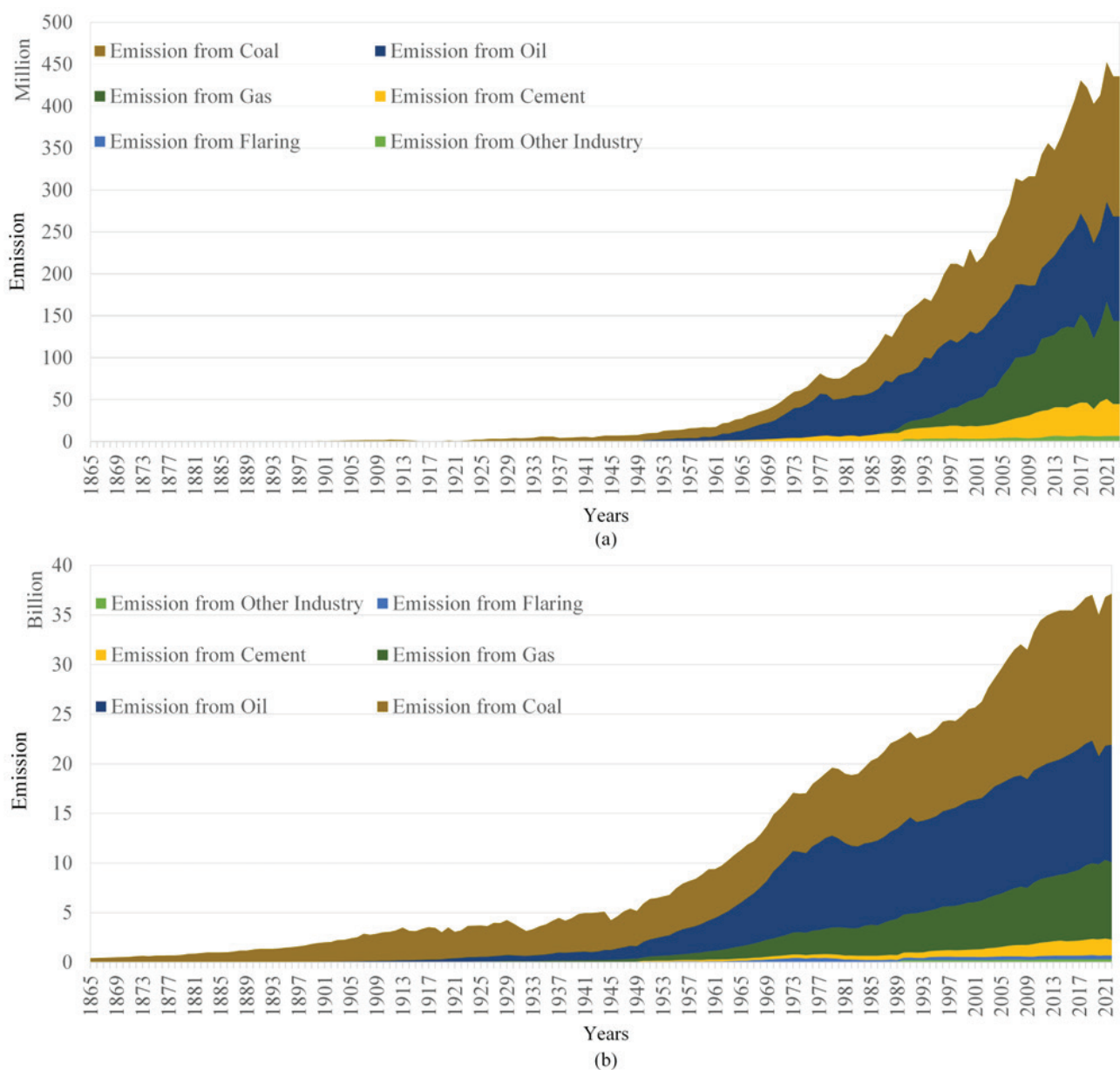


Figure 1. CO₂ emissions by coal, natural gas, oil, combustion processes, and cement production a) Türkiye, b) Globally. [Created by the authors using open-access data from the Global Carbon Project [6]].

The production of electricity from solar energy is based on the basic function of photovoltaic (PV) panels. Photons from sunlight hit the semiconductor material in the PV panels and transfer energy [11]. In this process, electrons in the semiconductor material are released and start moving, which provides direct current electricity production. This electrical energy produced by PV systems is used in buildings [12], agricultural areas [13], lighting/air conditioning [14–16] systems, and vehicles [17–19]. In addition, the applications of solar-powered vehicles have witnessed a significant surge, with the global market size valued at USD 456.6 million in 2023. This market is expected to increase from USD 545.0 million in 2024 to USD 2,526.2 million by 2032, at an estimated CAGR of 21.1% during the forecast period [20]. The main advantages of expanding PV applications in electric vehicles (EVs) are extending the vehicle's range, reducing carbon emissions by charging with renewable energy, decreasing dependence on the electrical grid and saving money [21]. The benefits of PV integration into EVs have also been highlighted in the literature. Sagaria et al. [22] demonstrated through tests on various vehicle segments that the integration of solar panels effectively extends the range of EVs. Similarly, Centeno Brito et al. [17] conducted a case study in Lisbon, confirming comparable outcomes. Kanz et al. [23] demonstrated in their studies that PV integration in EVs significantly reduces carbon emissions. Hoth et al. [24] demonstrated in their research that integrating PV technology reduces costs by decreasing the frequency of grid-dependent charging. These benefits of PV technology in vehicles can be improved by expanding the PV-covered area of the vehicle [25]. Expanding the PV-covered area is feasible only by integrating PV cells into additional sections of the vehicle's surface. Therefore, it is important to evaluate the impact of vehicle integration sections on PV performance.

There are studies in the literature comparing the power generation of vehicle-integrated PVs (VIPVs) incorporated into various vehicle sections. According to [26], the front hood VIPV generates approximately 43% of the potential of the roof VIPV. According to [27], during a midday home drive, the combined time-averaged solar irradiance received on the vehicle's side and rear surfaces corresponds to approximately 53% of the irradiance received on the roof but, under stationary conditions such as parking and PV charging, the sum of the irradiance on the sides and rear even exceeds that of the roof. Similarly, [28] performed high-time-resolution measurements on a moving vehicle and found that, on average, 54.3% of the total irradiance was received by the roof and 45.7% by the side surfaces. Under specific conditions, such as sunny winter days, the irradiance on the sides was similar to or even higher than that on the roof owing to the lower solar altitude and favorable angles of the vertical surfaces. In [29], it is reported that the rear hood VIPV generates 42% of the energy produced by the roof VIPV, while the doors contribute 27%. In contrast, [30] indicates that the front hood VIPV achieves up to 86%

of the roof VIPV's production potential, whereas the rear hood and the doors generate 25% and 67%, respectively. Current literature reveals the power generation potential of PVs integrated into different vehicle sections under various scenarios. However, these literature results are far from consistent. The primary reason for this is that the PV area, which has a major impact on the PV output, varies with the different vehicles used in the studies. Additionally, because the results are largely related to the PV area, analyses of the impact of integration sections on PV performance cannot be generalized.

This study aims to fill the gap in the current literature by evaluating the effect of vehicle integration sections on PV performance independent of PV area, and thus providing insights into the power contribution of PVs in different sections of the vehicle. In addition, the study uses one year of solar irradiance data from three different cities in Türkiye, which are classified as low, medium, and high irradiance, to enhance the consistency of the analysis by not limiting the study to one location. The key contributions of the paper can be summarized as follows:

- An area-independent analysis was carried out by evaluating the performance of different PV sections independent of the panel area, allowing a fair comparison between different vehicle surfaces.
- A complete seasonal analysis was performed by investigating the energy contribution of each vehicle section across all four seasons, which results in a more representative picture of annual performance.
- To account for the different climatic conditions and improve the generalizability of the results, multi-regional irradiance data were utilized from three different regions of Türkiye, namely Mardin, Ankara, and Rize.
- The proposed methodology was verified by comparing the calculated results with experimental data reported in the literature.
- A simplified data acquisition model is introduced, in which data of irradiance in one vehicle section (e.g., roof) can be used to estimate the irradiance in other sections, reducing the number of measurement points needed.

Following the introductory information, Section 2 presents a thorough review of VIPV, covering application areas and integration approaches for PV panels in EVs. Section 3 presents the methodology used to analyze VIPV systems, including panel positioning, regional performance evaluation, and power output analysis based on solar irradiance data. Section 4 presents the results and discussion, and Section 5 summarizes the main findings and conclusions.

Review of Vehicle-Integrated Photovoltaics

In recent years, trends in energy and environmental policies have accelerated the adoption of EVs and decline in the use of internal combustion engine vehicles. Figure 2 shows the number of EVs and non-EVs sold from 2010 to 2024 [31]. Worldwide EV sales grew from under 1 million in

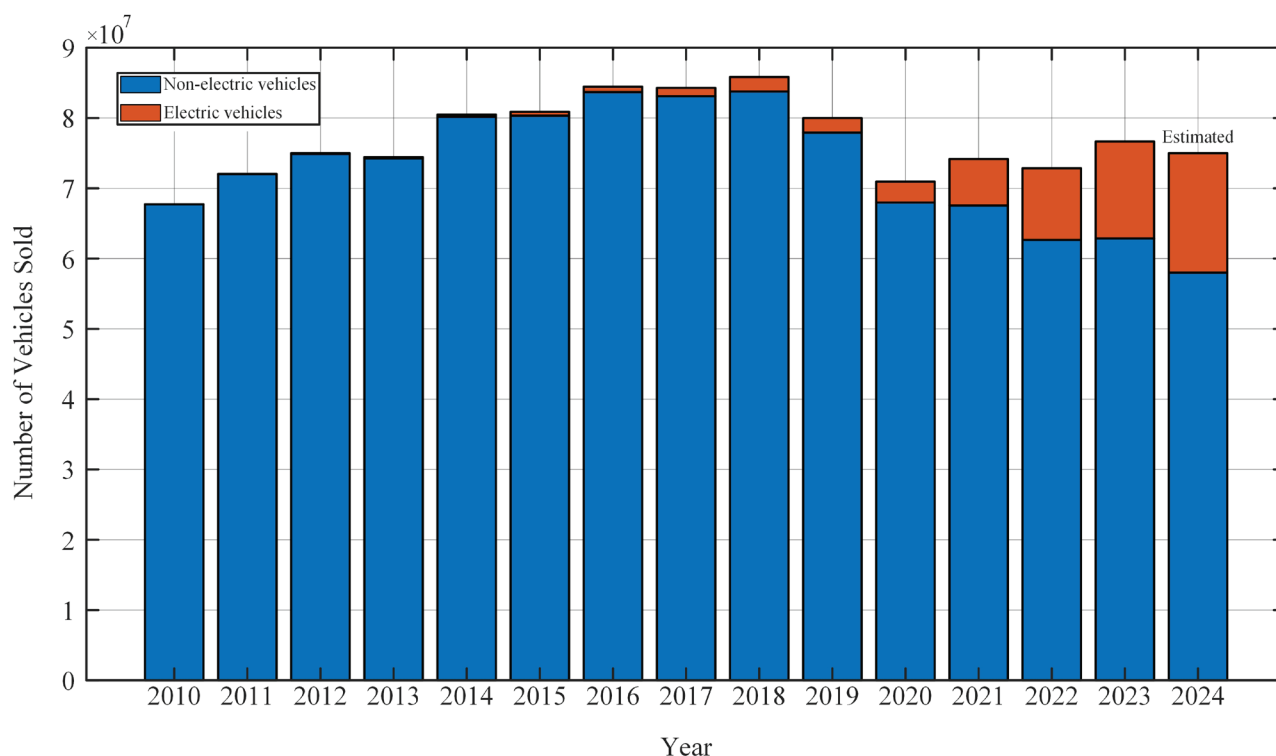


Figure 2. Number of new vehicles sold from 2010 to 2024 by type. [Created by the authors using open-access data from the International Energy Agency [31]].

2015 to over 10 million in 2022. Sales of EVs are estimated to reach 17 million worldwide by 2024 and represent more than 21% of all auto sales. This growth, up 25% compared to 2023, has been particularly strong in key markets such as China, Europe and the US. In China, EVs are projected to account for 45% of car sales by 2024, while Europe and the US are forecast to have shares of 25% and 11% respectively. In 2023, EV sales alone hit nearly 14 million, up 35% from the previous year.

The decline in the use of internal combustion engine vehicles can be attributed to a number of factors, including stringent regulations to reduce carbon emissions, rising fuel prices and growing environmental awareness. In contrast, growth in EVs has been driven by government incentives, decreasing battery prices, and investments in new technologies and regulations, such as the European Union's goal to reduce carbon emissions by 55% by 2030. However, it is also worth noting that EVs are not entirely emission-free, since some of the electricity used to charge them still comes from fossil fuels. This reduces the environmental benefits of EVs and highlights the need for alternative solutions. Technologies such as VIPV can help to reduce charging frequency, indirectly reduce emissions, and reduce operating costs [25].

The first VIPV examples came with solar-powered cars built for competitions. Prominent examples are the Sunmobile (1955), the GM Sunraycer (1987) and later

entries in the World Solar Challenge, such as the Nuna series by Delft University (2001) and the Tokai Challenger (2009). These vehicles were initially engineered for efficiency in controlled environments, but proved the feasibility of incorporating PVs into automotive systems. As PV technology evolved, VIPVs were increasingly used to support broader applications, like powering secondary systems (e.g. steering, air conditioning) and supplementing the main drivetrain. Mallon et al. [32] investigated the impact of on-board PVs on the performance of the electric bus. The simulation results based on the suburban bus cycles and the yearly weather data in Davis, California, showed that the roof-mounted panels provided an average annual increase of 4.7% on the driving range, and the combination of roof and side panels provided an increase of 8.9%. The economic and environmental viability of VIPV systems was studied by Kronthaler et al. [33] for different locations, vehicle types and PV types. They demonstrated a saving of 1600 kg of CO₂ per square meter of VIPV. However, these assessments do not include commercial passenger vehicles and are largely conducted for commercial vehicles with high utilization rates and relatively large roof surface areas. Sagaria et al. [22] examined the feasibility of VIPV in EVs and found that onboard PV systems could have a significant effect on the range, 30–50% for micro-cars and 30–100% for 5-seaters, for private driving profiles, while there is no real benefit for fuel cell powertrains. Their

analysis also showed economic benefits, with VIPV reaching cost parity before the half-life of the vehicle. Yamaguchi et al. [34] investigated the potential of high-efficiency solar modules for VIPVs. They showed that modules with efficiencies above 35% can realize over 30 km/day of PV driving under typical irradiance conditions ($4 \text{ kWh/m}^2/\text{day}$) without external charging. They also emphasized the need for cost reductions, estimating cost targets of $\$2.6/\text{Wp}$ for 20% efficiency and $\$3.7/\text{Wp}$ for 40% efficiency to ensure economic viability, based on charging cost savings and CO_2 emission reductions. Diahovchenko et al. [35] evaluated the feasibility of using commercial PV technologies to enhance EV mileage, and concluded that solar panels on the roof could produce up to 6.32% of the range on sunny summer days and 1.16% on sunny winter days, providing energy for propulsion or auxiliary systems with low investment. Such literature studies have shown the practical applicability of VIPVs leading to their integration into market vehicles [36].

MATERIALS AND METHODS

Determining the Position of the Photovoltaic Panels

The positioning of PV panels in terms of slope and azimuth is critical for improving solar energy capture and power generation efficiency [37]. The slope angle refers to the tilt degree of PV panels relative to the horizontal plane, or in other words, the angle the panel makes with the ground. The azimuth angle, on the other hand, indicates the direction a surface faces on the horizontal plane. To accurately model VIPVs, appropriate slope and azimuth angles must be defined for the relevant sections of the vehicle. To ensure realistic positioning, a reference passenger vehicle

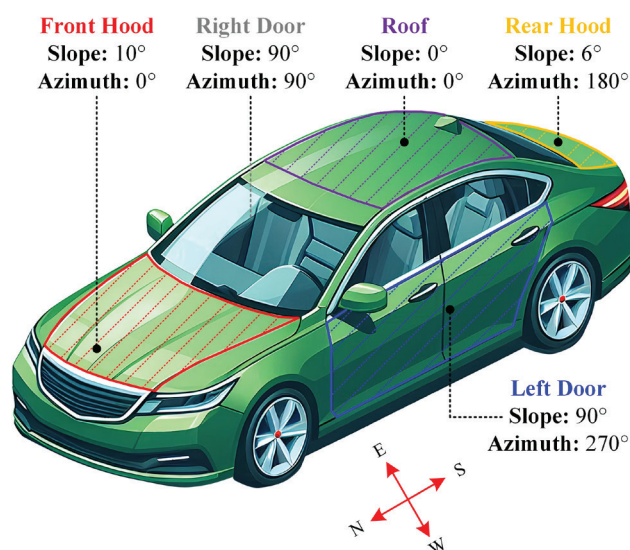


Figure 3. Positioning parameters of VIPVs relative to the reference vehicle.

[30] has been selected. Figure 3 presents the positioning parameters of the VIPVs relative to this vehicle. In addition, the orientation of each PV surface (i.e., slope and azimuth) is assumed to be fixed relative to the vehicle body, representing a static parked condition with a predefined heading. The analysis does not consider the dynamic changes in the vehicle orientation, for instance, while driving or when the vehicle is parked at different angles. Such a simplification enables a controlled comparison between vehicle sections.

Most vehicle roofs and even some other parts are curved [38] for purposes such as increasing the vehicle's aerodynamic performance, reducing air resistance and improving fuel efficiency. PV panels integrated on curved surfaces may not receive optimal sunlight and could experience performance degradation due to issues such as partial shading and accumulation of pollutants. It is important to note that this study assumes PVs are integrated on flat surfaces, thus any potential effects resulting from curved surfaces are not considered.

Determination of Analysis Regions Based on Solar Exposure

It is known that the results of PV studies are more generalizable in distinct four-season locations compared to summer or winter-dominant locations [39]. This is because summer or winter-dominant locations provide performance analyses under only specific conditions, making it difficult to fully assess the adaptation of PV systems to varying conditions throughout the year. Therefore, Türkiye, a typical four-season country [40], has been chosen as the analysis location for this study. In Türkiye, the four seasons follow a different cycle. In spring the amount of precipitation decreases and the temperature rises. In summer the temperature is high and it is dry. In autumn the temperature drops and the amount of precipitation increases. In winter it is cold and rainy [41]. These patterns are shaped by the country's complex topography, where mountainous terrain and varied elevation contribute to significant regional climate differences. The topography, and particularly the more complex relief, causes a spatial pattern of climates in Mediterranean regions. This results in spatial variations of climate parameters such as air temperature, humidity, radiation, and precipitation [42, 43]. Consequently, the country's broad geographic and climatic diversity also causes its solar map to be quite variable. Figure 4 presents the solar map of Türkiye [44].

In this study, three different locations as marked in Figure 4 are considered. It is important to repeat the analysis in other solar radiation regions like these to understand the variability of energy generation depending on the regional conditions and to get more realistic and consistent estimates. The locations are classified as low, medium and high solar radiation regions according to the distribution of annual total solar energy potential of Türkiye in different regions [45]. The high solar radiation region can be used to test the upper limits in efficiency to maximize the energy

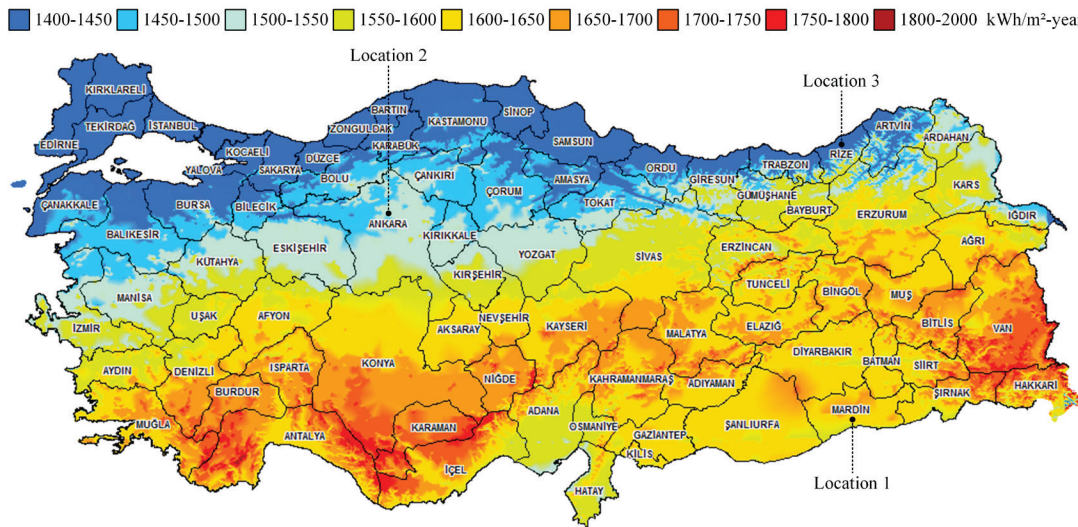


Figure 4. Solar map of Türkiye. [Adapted from the Solar Energy Potential Atlas [44]].

Table 1. Geographic coordinates of the three locations within the scope of the study

	Location 1	Location 2	Location 3
Solar Energy Potential	High	Medium	Low
Region	Southeastern Anatolia	Central Anatolia	Black Sea
Province	Mardin	Ankara	Rize
Latitude (°)	37.33	39.92	41.03
Longitude (°)	40.73	32.84	40.80
Elevation (m)	892	893	891

production of PV systems. The medium and low solar radiation areas allow for the assessment of the performance of PV under more common conditions and emphasize the potential for regional application. Geographic coordinates for the three sites are given in Table 1.

Analyzing the Performance of Vehicle-Integrated Photovoltaics

Obtaining solar irradiance data

The paper uses the solar irradiance data of the selected regions downloaded from the Photovoltaic Geographical Information System (PVGIS) [46]. The choice of the PVGIS system is due to its ability to provide high-resolution, site-specific irradiance data, integrating satellite observations, ground measurements and atmospheric modeling. Compared to on-site measurements, which require substantial instrumentation and are often limited to short time periods and specific locations, PVGIS offers a cost-effective, validated and widely used option for long-term solar resource assessment. Its proven accuracy and accessibility make it particularly suitable for academic studies involving different geographic regions and temporal scales. PVGIS

provides reliable estimates of irradiance for the assessment of PV potential but does not consider the small-scale shading effects due to local obstructions such as buildings or trees [47]. Thus, it is important to point out that similar effects are not considered in this paper as well.

The irradiance values provided by PVGIS are mean hourly values calculated over a multi-year period from 2005 to 2016. The selected values for each month are the average of all days of the month of the reference period. Such long-term averaging ensures that the irradiance data used in the study are statistically robust and representative of typical climatic conditions, minimizing the influence of short-term anomalies or atypical weather events. As mentioned in the previous chapters, the data collection process involves the collection of average daily irradiance data from the PVGIS system for 3 different locations (latitude and longitude), 5 different vehicle integration section positions (slope and azimuths), and 12 different months of the year. The 12 months for Türkiye are divided into four seasons [40]: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Figure 5 presents the

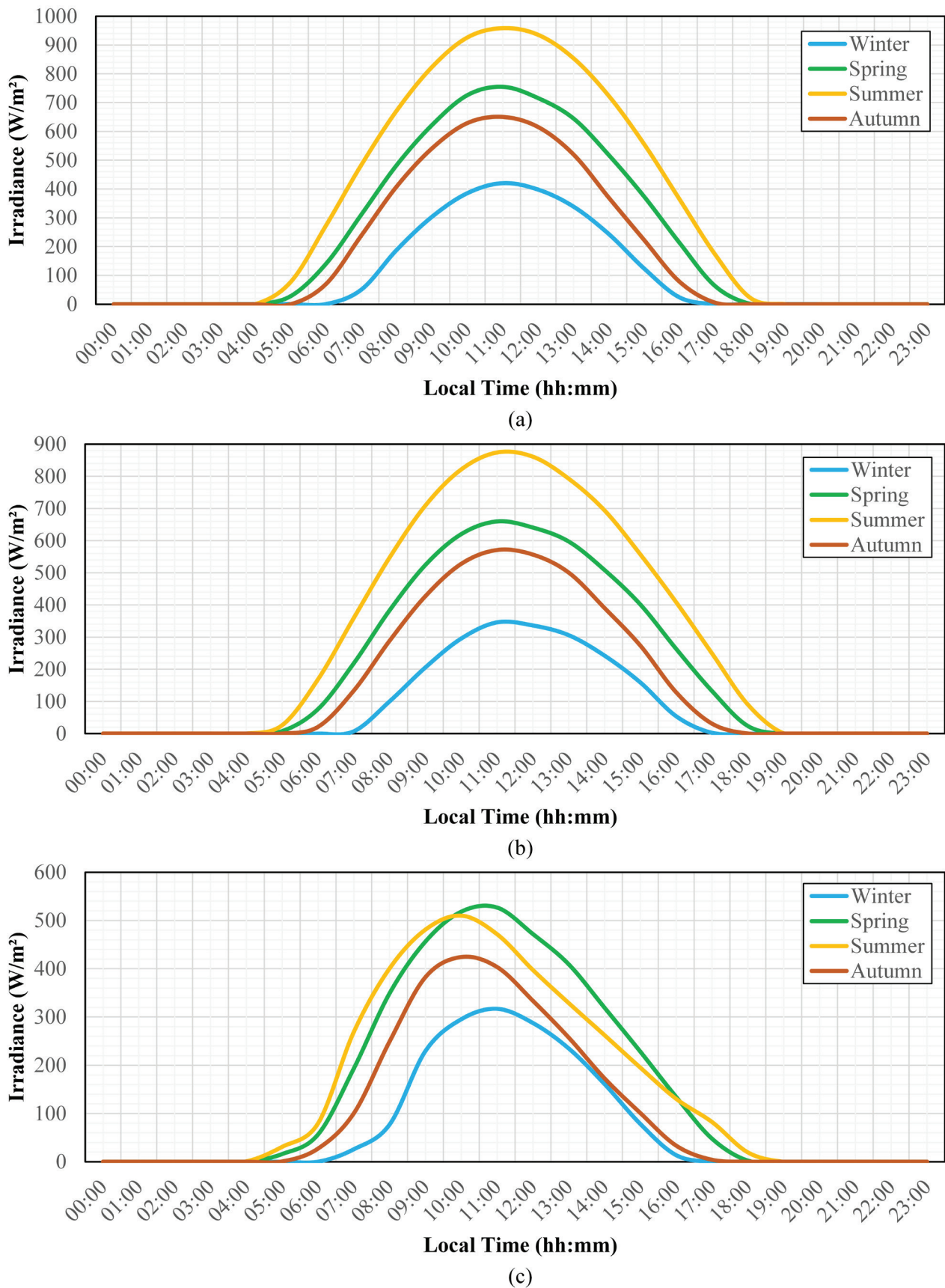


Figure 5. Location-based average daily global horizontal irradiance data a) Mardin, b) Ankara, c) Rize.

location-based average daily global horizontal irradiance data for these four seasons.

As shown in Figure 5, summer accounts for the largest relative share of the average daily solar irradiation in Mardin and Ankara, with 39% and 40%, respectively, followed by spring, autumn, and winter. In Rize, summer and spring show equal shares of approximately 32%, indicating a more balanced seasonal distribution. These results highlight the seasonal variability of solar energy and the influence of geographic location and regional climatic conditions on solar availability.

Determining the power output of photovoltaic panels

The power output of a PV panel P_{PV} can be simply expressed as follows [48]:

$$P_{PV} = A_{PV} \times G \times \eta \quad (1)$$

where A_{PV} is the area of the PV panel, G is the solar irradiance, and η is the efficiency of the PV. As previously mentioned, within the scope of this study, the power outputs of VIPVs will not be compared, but rather the power production potential (expressed by the received solar irradiance) of vehicle integration sections. Therefore, there is no need to use the conventional PV power output formula given in Equation 1. The power production data per square meter obtained from PVGIS (i.e. only G) for specific locations and positions will suffice for the analysis.

The solar irradiance G represents the average amount of solar irradiance falling on a surface every hour of each day during the relevant month. In other words, the total solar irradiance in the relevant month is divided by the number of days in the month to obtain an average value for each hour of each day. This series of values contains a total of 24 hours of data with one-hour intervals. The total amount of solar irradiance G_n^t received by the surface n during the day can be expressed as follows:

$$G_n^t = \sum_{i=1}^{24} G_n^i \quad (2)$$

where G_n^i is the total solar irradiance received by surface n during the i th hour. The surfaces indicated by n are the previously defined roof, rear hood, front hood, left door or right door sections. Equation 3 gives the total solar irradiance G^t received by all PV surfaces on the vehicle during the day.

$$G^t = \sum_{n=1}^5 G_n^t \quad (3)$$

Finally, the ratio P_n of the total solar irradiance received by surface n during the day to the total solar irradiance received by all VIPV surfaces can be calculated as follows:

$$P_n = 100 \times \frac{G_n^t}{G^t} \quad (4)$$

RESULTS AND DISCUSSION

The results of the analysis on the impact of vehicle integration sections on PV performance for Mardin province are given in Table 2, for Ankara province in Table 3 and for Rize province in Table 4. It should be noted that G^t is the average total solar irradiance received on any day of the relevant month.

In the case of Mardin, the front hood appears to be the most efficient section for power production, with a maximum contribution of 28.88%. This section performs particularly well during relatively low irradiance seasons, such as winter and autumn. In the summer months, it shows similar efficiency to the roof section, with an average contribution of 25%. Although the door sections individually

Table 2. Contribution rates of vehicle integration sections to daily potential power production (Mardin case)

Month	P_{roof} (%)	$P_{rear\ hood}$ (%)	$P_{front\ hood}$ (%)	$P_{left\ door}$ (%)	$P_{right\ door}$ (%)	G^t (W/m ²)
December	23.46	19.98	28.88	15.72	11.96	9088
January	23.66	20.67	28.26	15.65	11.76	9237
February	23.59	21.34	26.99	16.31	11.76	13143
March	24.08	22.59	26.19	15.58	11.57	17770
April	24.52	23.65	25.58	14.66	11.60	22731
May	24.97	24.49	25.35	14.16	11.04	27733
June	25.01	24.76	24.99	14.32	10.92	32435
July	24.91	24.55	25.07	14.24	11.24	32625
August	24.63	23.82	25.53	14.55	11.46	29542
September	24.13	22.63	26.20	15.82	11.24	25146
October	23.77	21.60	27.01	16.64	10.98	17329
November	23.31	20.21	28.09	17.47	10.92	12274

Table 3. Contribution rates of vehicle integration sections to daily potential power production (Ankara case)

Month	P_{roof} (%)	$P_{rear\ hood}$ (%)	$P_{front\ hood}$ (%)	$P_{left\ door}$ (%)	$P_{right\ door}$ (%)	G' (W/m ²)
December	22.98	19.68	28.12	14.44	14.79	7557
January	23.18	20.51	27.29	14.21	14.81	7605
February	23.56	21.34	26.90	13.96	14.24	11319
March	23.85	22.35	25.96	13.82	14.02	16129
April	24.32	23.41	25.46	13.74	13.06	21711
May	24.63	24.15	25.04	13.34	12.84	24560
June	24.88	24.56	24.98	13.52	12.06	28178
July	24.82	24.37	25.12	12.92	12.77	30749
August	24.49	23.60	25.53	13.00	13.39	27925
September	23.95	22.43	26.07	13.91	13.64	22586
October	23.59	21.34	26.95	14.30	13.81	15261
November	22.85	19.57	27.94	14.75	14.89	11082

Table 4. Contribution rates of vehicle integration sections to daily potential power production (Rize case)

Month	P_{roof} (%)	$P_{rear\ hood}$ (%)	$P_{front\ hood}$ (%)	$P_{left\ door}$ (%)	$P_{right\ door}$ (%)	G' (W/m ²)
December	23.85	20.66	28.78	13.65	13.07	6086
January	24.12	21.56	28.04	14.04	12.24	6236
February	24.49	22.47	27.48	12.88	12.68	8995
March	24.58	23.29	26.39	13.67	12.07	11728
April	24.82	23.95	25.90	13.38	11.96	15719
May	25.13	24.61	25.61	13.39	11.27	17527
June	25.04	24.73	25.20	13.92	11.10	16389
July	24.82	24.52	25.00	14.55	11.10	14278
August	24.56	24.05	25.10	15.55	10.75	13544
September	24.54	23.42	26.07	15.69	10.29	12764
October	24.43	22.56	27.18	14.34	11.48	10250
November	24.40	21.58	28.70	12.45	12.86	7506

seem to have the lowest performance (with a minimum of 14.16% for the left door and 10.92% for the right door), when considered together, they promise slightly higher efficiency than the front hood, with an average contribution of 26.80%. Notably, the left door is about 4% more efficient than the right door on average. The rear hood, on the other hand, consistently shows the lowest efficiency (with a minimum of 19.98%) for each month.

In the case of Ankara, similar to Mardin, the front hood appears to be the most efficient section for power production, with a maximum contribution of 28.12%. Winter, autumn, and spring are the most productive seasons for this section, respectively. During the summer, the four vehicle sections (with the doors considered together) contribute almost equally to power production. The rear hood section consistently shows the lowest efficiency in this case as well, with a minimum contribution of 19.57%. When the doors

are considered together, they promise approximately 1.5% higher efficiency than the front hood, with an average contribution of 27.52%.

In Rize, the front hood section is clearly the most efficient, with a maximum contribution of 28.78%. Even when the doors are considered together, they fall short by approximately 1% on average compared to the front hood. In this case, the doors perform worse than in other cases, with efficiency differences of up to 2% at maximum and 1% at minimum. This loss in door performance has resulted in an average efficiency increase of 0.5% for the roof section and 1% for the rear hood section compared to the other cases. Evaluating all cases together will yield more consistent and generalizable results. For this purpose, an average of the contribution rates obtained in all months for each section can be considered separately. Table 5 depicts the average contribution rates of the vehicle integration sections to the

Table 5. Average contribution rates of the vehicle integration sections to the daily potential power production for different locations

Province	P_{roof} (%)	$P_{rear\ hood}$ (%)	$P_{front\ hood}$ (%)	$P_{left\ door}$ (%)	$P_{right\ door}$ (%)
Mardin	24.17	22.52	26.51	15.43	11.37
Ankara	23.92	22.28	26.28	13.82	13.69
Rize	24.57	23.12	26.62	13.96	11.74

daily potential power production for different locations. Despite the numerical differences in solar energy potential across regions, the similar results for PV integration sections can be attributed to the percentage-based contribution of each panel to the total energy potential, which remains independent of location. The observed difference in performance between the right and left doors arises from their differing orientations with respect to the sun's daily path. Due to variations in azimuth angles, one side receives more direct sunlight during certain hours of the day. These orientation-related factors explain both the minimal variation across different locations and the asymmetry observed between the door performances.

An average of the analysis results for the three different locations presented in Table 5 could expand the scope of the analysis to Türkiye. Consequently, for a vehicle with VIPV in a country like Türkiye, which experiences four seasons, the final energy performance of the integration sections would be as follows: doors (26.67%), front hood (26.47%), roof (24.22%), and rear hood (22.64%). Despite the significant solar potential of the doors, only 10% of solar-assisted market vehicles over the past five years have PV on their doors, while roof PVs remain dominant compared to other sections [30]. The primary reasons for this could be as follows:

- The roof is the least self-shading section of the vehicle. The PV installation area is larger compared to other sections and, unlike the hood and doors, it is more durable since it does not have mobility. Additionally, it does not compromise the vehicle's aesthetics and aerodynamics as much as other sections.
- On the other hand, the hood and door sections always carry the risk of damage due to impacts. It is known that the efficiency of PVs integrated into the front hood of hybrid vehicles decreases due to heating along with the

engine [26]. Finally, the limited installation area of the rear hood can result in relatively low power outputs.

The roof is the most practical place to integrate PV, from a design perspective, especially for battery EVs. Further increase of the energy yield can be achieved by integrating PVs on the roof and front hood. However, for hybrid EVs, the efficiency of front hood PVs can be reduced due to the higher temperatures generated by the engine operation. Despite the great potential of the doors for capturing solar energy, their integration is currently constrained by issues such as mechanical vulnerability, shading due to the side position and the difficulty in ensuring structural durability. Although the rear hood contributes the least to total irradiance, it can still be a viable option for certain types of vehicles, such as sedans with large, flat rear surfaces, where additional PV coverage can be implemented without compromising design integrity. These results underscore the importance of a comprehensive assessment of not only irradiance potential but also practical integration constraints in the optimal deployment of VIPV systems.

Before concluding the study, the obtained results are compared with experimental studies in the literature. In [29], the authors presented a scenario where an EV, equipped with VIPV on its roof, rear window (referred to as the rear hood in this case), and left/right doors, moves along seventeen different routes with various slope and azimuth angles in Samcheok city, Gangwon-do, Korea. According to the results obtained throughout the route, the roof VIPV accounted for 59.17% of the total power generated by the VIPVs during the day, the rear hood VIPV for 24.85%, and the door VIPVs for 15.98%. The specifications of the PVs used in the study are given in Table 6.

Assuming that the total solar irradiance incident on the vehicle at any given time is 100 W/m^2 , according to the outputs of our study, the roof would receive 24.22 W/m^2 , the rear hood 22.64 W/m^2 , the doors 26.67 W/m^2 , and

Table 6. Specifications of PVs used in the literature study

	Roof PV	Rear Hood PV	Left Door PV	Right Door PV
Model	SMF 175W	SMF 100W	FS 40W	FS 40W
Efficiency	17.30%	15.49%	19.60%	19.60%
Integration Area	1 m^2	0.65 m^2	0.22 m^2	0.22 m^2

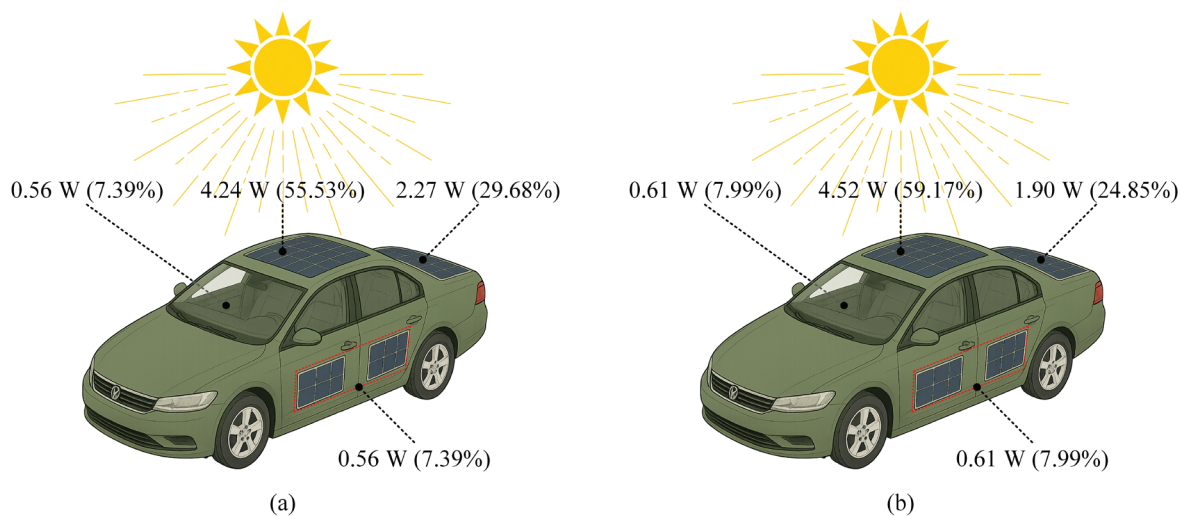


Figure 6. Comparison of the instantaneous power generation of the VIPVs in the scenario where the total instantaneous solar irradiance is 100 W/m^2 a) present study and (b) created by the authors using data reported in Park et al. [29] (Open Access).

the front hood 26.47 W/m^2 . If the vehicle is equipped with the PVs specified in Table 6, the instantaneous power generated by the VIPVs can be calculated using Equation 1. Figure 6 compares the results of this study with those of the literature.

The results demonstrated the accuracy of the outcomes obtained in the paper, with a reasonable deviation of $\pm 4.83\%$ compared to the outputs of the experimental study in the literature. The paper presents the relative contribution of each integration section to the vehicle's overall solar energy capture. With these findings, for example, solar irradiance data for different slope and azimuth angles (such as doors, front, and rear hood) can be estimated using a single pyranometer data point (such as from the roof). This would significantly simplify the measurement process and provide cost-effectiveness. Instead of installing multiple sensors, the need for extensive data collection infrastructure is reduced, as irradiance for various integration sections can be estimated from a single dataset.

CONCLUSION

With the world moving toward sustainability and energy efficiency, the combination of solar energy and EVs is increasingly important. However, the existing VIPV applications mainly remain on the roof surface, which limits the energy output due to the limited installation area. Thus, one of the key focuses is to investigate the optimal integration locations to increase the energy output of VIPVs, which is critical to increase the PV installation area. This study attempts to overcome this limitation by estimating the solar energy potential of five different vehicle integration sections (roof, front hood, rear hood, left door, and right

door) using high-resolution irradiance data obtained for three regions in Türkiye (Mardin, Ankara, and Rize) which are known as high, medium, and low solar radiation zones, respectively. The methodology considers seasonal variability and surface-specific orientation characteristics for an area-independent comparison of irradiance contributions. The results show that the roof (24.22%) and rear hood (22.64%) have slightly lower solar energy potential than the doors (26.67%) and front hood (26.47%). The roof is the most practical place to integrate due to its durability, minimal shading and larger surface area, but the high potential of other sections, especially the doors, points to an opportunity to expand PV coverage in future vehicle designs. The proposed methodology was validated with experimental data from the literature and showed a deviation of $\pm 4.83\%$, which emphasizes the reliability of the analysis. Additionally, the study proposes a simplified methodology for estimating the irradiance values on multiple vehicle surfaces from a single pyranometer measurement, which offers a significant advantage in terms of data collection efficiency and sensor cost reduction. These results can be directly applied by engineers in the early design stages of solar-assisted EVs to enable more efficient PV surface allocations beyond the traditional roof placements. Moreover, the ability to estimate irradiance for multiple surfaces of a vehicle from a single measurement source provides practical advantages in terms of sensor infrastructure costs for vehicle prototyping and testing. This study provides a quantitative basis for policymakers and sustainability planners to advocate for regulations or incentives promoting multi-surface solar integration in vehicles, particularly in areas with varying solar conditions, such as Türkiye.

NOMENCLATURE

Abbreviations

CO ₂	Carbon Dioxide
EV	Electric Vehicle
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
VIPV	Vehicle-Integrated Photovoltaic

Symbols

A_{PV}	Area of the photovoltaic panel (m ²)
G	Solar irradiance (W/m ²)
η	Efficiency of the photovoltaic panel (%)
P_{PV}	Power output of a photovoltaic panel (W)
P_n	Ratio of irradiance received by surface n to total irradiance from all surfaces (%)
n	Subscript denoting surface type (roof, front hood, rear hood, left door, right door)
G^t	Total solar irradiance received by all photovoltaic surfaces on the vehicle during the day (W/m ²)
G_n^i	Total solar irradiance received by the surface n at the i -th hour (W/m ²)
G_n^t	Total solar irradiance received by the surface n during the day (W/m ²)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

- [1] Gholami A, Amer M, Zandi M, Ghoachani RG. Dust accumulation on photovoltaic modules: A review on the effective parameters. *Sigma J Eng Nat Sci* 2021;39:45–57.
- [2] Sunil Kumar K, Muniamuthu S, Salunkhe S, Cep R, Abouel Nasr E. In-situ analysis on drop in thermal performance of wind turbine gearbox system: global challenges and sustainable ideas. *Eng Res Express* 2025;7:015556. [CrossRef]
- [3] Agiralioğlu N, Eris E, Andic G, Cıgızoglu HK, Coskun HG, Yilmaz L, et al. Practical methods for the estimation of hydroelectric power potential of poorly gauged basins. *Sigma J Eng Nat Sci* 2017;35:347–358.
- [4] Rashid MH. *Alternative energy in power electronics*. Butterworth-Heinemann; 2014.
- [5] CO₂ emissions by fuel 2024. Available at: <https://ourworldindata.org/emissions-by-fuel>. Accessed December 12, 2024.
- [6] Data supplement to the Global Carbon Budget 2024. Available at: <https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2024>. Accessed December 12, 2024.
- [7] Awogbemi O, Kallon DV Von, Kumar KS. Contributions of artificial intelligence and digitization in achieving clean and affordable energy. *Intell Syst with Appl* 2024;22:200389. [CrossRef]
- [8] Energy Outlook 2024. Available at: <https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html>. Accessed December 12, 2024.
- [9] Guangul FM, Chala GT. Solar Energy as Renewable Energy Source: SWOT Analysis. 2019 4th MEC Int. Conf. Big Data Smart City, IEEE; 2019, p. 1–5. [CrossRef]
- [10] Renewable capacity statistics 2024. Available at: <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>. Accessed December 12, 2024.
- [11] Güngör O, Yüksek Hİ. Modeling of boost and CUK converters and comparison of their performance in MPPT. *Sigma J Eng Nat Sci* 2020;11:83–101.
- [12] Skandalos N, Karamanis D. An optimization approach to photovoltaic building integration towards low energy buildings in different climate zones. *Appl Energy* 2021;295:117017. [CrossRef]
- [13] Liu W, Liu L, Guan C, Zhang F, Li M, Lv H, et al. A novel agricultural photovoltaic system based on solar spectrum separation. *Sol Energy* 2018;162:84–94. [CrossRef]
- [14] Sutopo W, Mardikaningsih IS, Zakaria R, Ali A. A Model to Improve the Implementation Standards of Street Lighting Based on Solar Energy: A Case Study. *Energies* 2020;13:630. [CrossRef]
- [15] Al-Yasiri Q, Szabó M, Arıcı M. A review on solar-powered cooling and air-conditioning systems for building applications. *Energy Reports* 2022;8:2888–2907. [CrossRef]
- [16] Salameh T, Assad MEH, Tawalbeh M, Ghenai C, Merabet A, Öztöpe HF. Analysis of cooling load on commercial building in UAE climate using building integrated photovoltaic façade system. *Sol Energy* 2020;199:617–629. [CrossRef]

- [17] Centeno Brito M, Santos T, Moura F, Pera D, Rocha J. Urban solar potential for vehicle integrated photovoltaics. *Transp Res Part D Transp Environ* 2021;94:102810. [\[CrossRef\]](#)
- [18] Araki K, Ota Y, Yamaguchi M. Measurement and Modeling of 3D Solar Irradiance for Vehicle-Integrated Photovoltaic. *Appl Sci* 2020;10:872. [\[CrossRef\]](#)
- [19] Heinrich M, Kutter C, Basler F, Mittag M, Alanis LE, Eberlein D, et al. Potential and challenges of vehicle integrated photovoltaics for passenger cars. *Present. 37th Eur. PV Sol. Energy Conf. Exhib*, vol. 7, 2020, p. 4229. [\[CrossRef\]](#)
- [20] Solar Vehicle Market Size 2020. Available at: <https://www.fortunebusinessinsights.com/solar-vehicle-market-104333>. Accessed December 12, 2024.
- [21] The Benefits of Powering Your EV with Solar Energy 2023. Available at: <https://www.energy.gov/eere/solar/articles/benefits-powering-your-ev-solar-energy>. Accessed December 12, 2024.
- [22] Sagaria S, Duarte G, Neves D, Baptista P. Photovoltaic integrated electric vehicles: Assessment of synergies between solar energy, vehicle types and usage patterns. *J Clean Prod* 2022;348:131402. [\[CrossRef\]](#)
- [23] Kanz O, Reinders A, May J, Ding K. Environmental impacts of integrated photovoltaic modules in light utility electric vehicles. *Energies* 2020;13:5120. [\[CrossRef\]](#)
- [24] Hoth P, Heide L, Grahle A, Göhlich D. Vehicle-integrated photovoltaics-a case study for Berlin. *World Electr Veh J* 2024;15:113. [\[CrossRef\]](#)
- [25] Parlak BO, Yavasoglu HA. Assessment of vehicle-integrated photovoltaics: a financial and environmental perspective. *Sustain Energy Technol Assessments* 2024;72:104042. [\[CrossRef\]](#)
- [26] Tiano FA, Rizzo G, Marino M, Monetti A. Evaluation of the potential of solar photovoltaic panels installed on vehicle body including temperature effect on efficiency. *ETransportation* 2020;5:100067. [\[CrossRef\]](#)
- [27] Peibst R, Fischer H, Brunner M, Schießl A, Wöhe S, Wecker R, et al. Demonstration of feeding vehicle-integrated photovoltaic-converted energy into the high-voltage on-board network of practical light commercial vehicles for range extension. *Sol RRL* 2022;6:2100516. [\[CrossRef\]](#)
- [28] Wetzel G, Salomon L, Krügener J, Bredemeier D, Peibst R. High time resolution measurement of solar irradiance onto driving car body for vehicle integrated photovoltaics. *Prog Photovoltaics Res Appl* 2022;30:543–551. [\[CrossRef\]](#)
- [29] Park C, Park H, Jeon H, Choi K, Suh J. Evaluation and Validation of Photovoltaic Potential Based on Time and Pathway of Solar-Powered Electric Vehicle. *Appl Sci* 2023;13:1025. [\[CrossRef\]](#)
- [30] Parlak BO, Yavasoglu HA, Ozcan HG. In-depth analysis of battery life enhancement in solar-assisted fuel-cell range-extender vehicles. *Int J Hydrogen Energy* 2024;67:1033–1043. [\[CrossRef\]](#)
- [31] Global EV Outlook 2024. Available at: <https://www.iea.org/reports/global-ev-outlook-2024>. Accessed December 12, 2024.
- [32] Mallon K, Assadian F, Fu B. Analysis of on-board photovoltaics for a battery electric bus and their impact on battery lifespan. *Energies* 2017;10:943. [\[CrossRef\]](#)
- [33] Kronthaler L, Maturi L, Moser D, Alberti L. Vehicle-integrated photovoltaic (ViPV) systems: energy production, diesel equivalent, payback time; an assessment screening for trucks and busses. *2014 Ninth Int. Conf. Ecol. Veh. Renew. Energies, IEEE*; 2014, p. 1–8. [\[CrossRef\]](#)
- [34] Yamaguchi M, Nakamura K, Ozaki R, Kojima N, Ohshita Y, Masuda T, et al. Analysis for the potential of high-efficiency and low-cost vehicle-integrated photovoltaics. *Sol RRL* 2023;7:2200556. [\[CrossRef\]](#)
- [35] Diahovchenko I, Petrichenko L, Borzenkov I, Kolcun M. Application of photovoltaic panels in electric vehicles to enhance the range. *Heliyon* 2022;8:e12425. [\[CrossRef\]](#)
- [36] Commault B, Duigou T, Maneval V, Gaume J, Chabuel F, Voroshazi E. Overview and Perspectives for Vehicle-Integrated Photovoltaics. *Appl Sci* 2021;11:11598. [\[CrossRef\]](#)
- [37] Talebizadeh P, Mehrabian MA, Abdolzadeh M. Prediction of the optimum slope and surface azimuth angles using the Genetic Algorithm. *Energy Build* 2011;43:2998–3005. [\[CrossRef\]](#)
- [38] Ota Y, Masuda T, Araki K, Yamaguchi M. Curve-correction factor for characterization of the output of a three-dimensional curved photovoltaic module on a car roof. *Coatings* 2018;8:432. [\[CrossRef\]](#)
- [39] Myong SY, Park Y-C, Jeon SW. Performance of Si-based PV rooftop systems operated under distinct four seasons. *Renew Energy* 2015;81:482–489. [\[CrossRef\]](#)
- [40] Kadioğlu M. Trends in surface air temperature data over Turkey. *Int J Climatol* 1997;17:511–520. [\[CrossRef\]](#)
- [41] Kadioğlu M. Regional variability of seasonal precipitation over Turkey. *Int J Climatol* 2000;20:1743–1760. [\[CrossRef\]](#)
- [42] Nikitidou E, Kazantzidis A, Tzoumanikas P, Salamalikis V, Bais AF. Retrieval of surface solar irradiance, based on satellite-derived cloud information, in Greece. *Energy* 2015;90:776–783. [\[CrossRef\]](#)
- [43] Teke A, Yıldırım HB. Estimating the monthly global solar radiation for Eastern Mediterranean Region. *Energy Convers Manag* 2014;87:628–635. [\[CrossRef\]](#)
- [44] Solar Energy Potential Atlas 2024. Available at: <https://gepa.enerji.gov.tr/>. Accessed December 12, 2024.
- [45] Biomass 2024. Available at: <https://enerji.gov.tr/eigm-renewable-energy-resources-biomass>. Accessed December 12, 2024.

-
- [46] Photovoltaic Geographical Information System (PVGIS) 2024. Available at: https://re.jrc.ec.europa.eu/pvg_tools/en/. Accessed December 12, 2024.
- [47] PVGIS data sources & calculation methods 2024. Available at: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis/getting-started-pvgis/pvgis-data-sources-calculation-methods_en. Accessed December 12, 2024.
- [48] Araki K, Ota Y, Lee K-H, Yamada N, Yamaguchi M. Curve Correction of the energy yield by flexible photovoltaics for VIPV and BIPV applications using a simple correction factor. 2019 IEEE 46th Photovolt. Spec. Conf., IEEE; 2019, p. 1584–1591. [\[CrossRef\]](#)