Heliyon 8 (2022) e12425

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Application of photovoltaic panels in electric vehicles to enhance the range

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A R T I C L E I N F O

Keywords:
Electric vehicle
Travel distance
Solar panel
Battery
Solar irradiance
Photovoltaic array

A B S T R A C T

There is a significant increase in the number of alternative energy sources and electric vehicles. Therefore, there is a growing need for new technical solutions to increase the distance that an electric vehicle can travel on a single charge. The aim of this study is to assess the possibility of mileage increasing of an electric vehicle by means of commercially available solar energy technologies that require minimal investment. The considered electric car can be recharged from solar panels mounted on its roof during parking stages. Photovoltaic modules can contribute to the vehicle's propulsion or energize its accessories, such as ventilation, air conditioner, heated passenger seats, interior lighting. The results demonstrate feasibility of the proposed solutions for both cases with and without sun-tracking adjustments of solar panels. The calculations show that the vehicle-integrated photovoltaic panels can provide energy for up to 6.32% of the range on a full charge of the battery during the sunniest summer months and up to 1.16% of the range during the least sunny winter months, for the given conditions.

1. Introduction

1.1. The essence of the problem

Concerns about the state of the environment due to greenhouse gas emissions emitted by traditional internal combustion engines (ICEs) are considered as major factors that will accelerate and support the growth of electric vehicles (EVs) in use [1]. With recent technological advances in batteries, power electronics, control and microelectronics, the share of EVs in the automotive industry is projected to increase by about 4.3 times by 2025 and by about 11.7 times, compared to the 2020 EV stock level [2]. This is evidenced not only by the dynamics of EVs' sales, but also the restrictions adopted by some countries on the with ICEs. For example, Norway has become the first country planning to limit sales of cars with ICEs from 2025. Similar initiatives for the near future are in the United Kingdom, France and several other states [3].

As of July 2020, according to the Ministry of Infrastructure of Ukraine, almost 23,000 EVs have been registered in Ukraine [4]. Over the past couple of years, the share of EVs has increased by 300%. In addition to EVs, other types of electric transport are becoming increasingly popular among the Ukrainians: electric bicycles, electric scooters, unicycles, scooterboards, segways etc., which in context of the possible risks of spread of infectious diseases, such as COVID-19, allows their owners to minimize the use of public transport and reduce contact with other people [5].

In parallel with the incrementing number of EVs, there is a growing need for new technical solutions to increase the distance that an electric car can run on a single charge. A rational solution in this perspective are solar modules, which convert renewable energy into electricity for recharging batteries of EVs. Solar energy is renewable, free and largely diffused, and photovoltaic (PV) panels are subject to continuous technological advances in terms of cell efficiency, while their cost is constantly decreasing [6]. At the same time, the limitations of PV technologies are clear: generation is intermittent and variable in time, due to weather conditions, which can be foreseen only partially and for relatively short periods of time, while cheap PV inverters can cause power quality problems in distribution power networks [7].

The implementation of solar-based on-board recharging mini-stations requires solving several issues linked with the establishment of technical conditions for mini-stations of this type, mathematical definition of energy conversion and storaging processes, with respect to the specifics of the EV charging process. Several research works are dedicated to applications of on-board PV modules for EVs and hybrid electric vehicles (HEVs) [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

Different aspects, challenges, and problems for solar vehicle development are reviewed in [8]. The article [9] presents a comparison of

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https://doi.org/10.1016/j.heliyon.2022.e12425
Received 29 June 2022; Received in revised form 16 September 2022; Accepted 9 December 2022

several commercial PV panels to power on-board EVs and suggests that monocrystalline silicon modules can be an optimal choice to for a low-speed and lightweight electric car. In [10] the authors investigated the impacts of weather, season and building density in an urban area on measured irradiance on the roof and the sides of a vehicle with integrated PV panels, concluding that environmental conditions have the highest effect on the measured irradiance on the roof, while the relative irradiance on the sidei is mostly season-dependent. The paper [11] proposes a solar power-assisted battery balancing system, which controls the charging/discharging process during EV driving and parking. In [12] the authors examined practical efficiency of monocrystalline silicon solar panels installed on EVs and concluded that losses of the PV panels and vehicle's power supply system should be assessed more accurately at the design stage. The paper [13] introduces techniques for modeling and measurement of solar irradiance for vehicle-integrated photovoltaics, using a shading model, a curve-correction model for the curved surfaces covered with PV cells, and a mismatching model for partial shading. In [14] a direct current air conditioning system powered by PV module is proposed to control temperature inside the vehicle. The impact of nonplanar panels on power generation in the case of PV panels mounted on an EV was studied in [15]. The results demonstrate that PV panels installed on the sides and tilted surfaces of EVs can significantly contribute to the total solar power generation [15]. Based on the roof shapes and sizes of several commercially available passenger vehicles, the authors of [16] calculated the PV coverage for various surfaces and estimated how the curvature can affect the power output. Feasibility of the integration of PV panels in HEVs to face energy saving and environmental issues is discussed in [17, 18]. And the work [19] assesses the flexibility of the EV battery charging system fed from a PV array irrespective of the irradiation conditions.

This work is focused on the use of PV panels for recharging batteries of EVs on the example of Ukraine. In contrast to the previous related studies, in this paper the chosen PV technologies are inexpensive and allow to make an upgrade of a common commercially available EV to its PV-assisted version with minimal investments, which makes the considered solutions available for regular drivers. The feasibility of the proposed solutions will be assessed with common economic indicators.

1.2. Initial conditions for the study

The design of a solar car is strictly limited by the amount of energy invested in it. Vehicles with solar panels face some significant obstacles to becoming a reality for car buyers right now. First, the amount of power that a car with solar panels can produce is likely to be insufficient to energize the entire vehicle. Given that the present photovoltaic modules convert sunlight into useful electricity by about 20%, a car covered with solar cells can receive enough energy every day to provide its own movement over a distance of 32–40 km [20]. This estimate assumes the presence of sunny weather during the day, the absence of clouds, the absence of dust that contaminates solar cells, and perfectly oriented solar panels. Also, the distance will depend on the geographic location, which refers to the solar irradiation and climate conditions [10], and on the vehicle's parameters.

For drivers travelling short distances in areas with a lot of sunny days per year, photocells integrated in a car can be a way to cover a few extra km on solar energy alone. Also, energy from solar cells can be used to power electrical appliances inside, such as radios, power windows, instrument panel, climate control system, heated passenger seats.

Energy consumption of a modern electric car is quite low, about 120–300 Wh/km, depending on the model, season, driving style and road quality. The average consumption of electric cars can be considered close to 200 Wh/km [21]. The range depends on battery capacity and consumption. It is usually expressed in the value obtained by one of the standard car tests: NEDC, WLTP or EPA. These tests are designed to simulate real conditions to determine the consumption and range of an EV. The NEDC standard is considered to be the oldest and too optimistic (gives high range, hardly attainable in real conditions), and therefore is rarely used. The WLTP is employed in Europe and is more accurately defines the range for mixed driving in summer (city and not expressway), while the EPA – the American standard – can be considered the closest to real conditions [21].

Solar panels work most efficiently when they face the Sun, and their surface is perpendicular to the Sun's rays. In this paper, it is assumed that the solar panels are mounted on the roof of Volkswagen e-Golf as flat and parallel to ground level. With this arrangement of the panels, the maximum energy efficiency can be provided only during the hours when the sun is at its zenith. Due to the movement of the Earth around the Sun, there are also seasonal variations. In winter the Sun does not reach the same angle as in summer. Ideally, solar panels should be located more horizontally in summer than in winter. Therefore, the optimal angle of inclination for summer is smaller than for winter. Given that solar panels on the roof of the EV may have a suboptimal angle of rotation to the Sun, especially in the winter months, consider adjusting this angle during parking by means of a special platform with guides on the roof of the EV.

The possibility and expediency of use of the PV panels placed on a roof of an EV for batteries subcharging during parking at an open stop will be estimated, basing on the additional distance the EV can travel on a single charge, according to the NEDC and the EPA car tests. Subcharging during driving in daylight is not considered, since the on-board controlling systems of a commercial EV, like the e-Golf, do not allow simultaneous charging and driving. The feasibility of a sun-tracking roof platform to maximize captured energy in parking phases will be also evaluated.

The rest of the article is organized as follows. Methodology and models are described in Section 2; the case study is presented, and the results are discussed in Section 3; the conclusions are stated in Section 4.

2. Methodology and models

2.1. Determining the amount of energy that can be generated by a photovoltaic array

The complexity of modeling of electricity generation by a photovoltaic array (PVA), E_{PVA}, is due to the variable nature of the intensity of solar irradiation, which acts as an energy source, and nonlinear algorithm for converting solar energy into electricity, which introduces additional uncertainty due to operational differences of PV panels, depending on climate and landscape peculiarities [22, 23].

Given this, a mathematical description of the autonomous PV charging station on the roof of an EV is needed. The intensity of solar irradiation is a random variable, respectively, the production of electricity by PVA is variable. Descriptions of the distribution of solar irradiation intensity are carried out by beta distribution, while using of exponential, geometric, lognormal and gamma distributions is also possible [23].

The power of the PVA is limited to a certain value, which is equal to the nominal (installed) power P_{PVA}, regardless to the intensity of solar irradiance. Analysis of typical volt-ampere characteristics shows a directly proportional dependence of the PVA's current on the intensity of solar irradiance (G, W/m^2). On the other hand, the nonlinearity of the $I_{PVA} = f(U)$ curves is obvious, which vary depending on the irradiance intensity and temperature. This will ultimately determine the nonlinear dependence $P_{PVA} = f(U)$, because the power output of the PVA, P_{PVA}, as a source of electricity, in the simplest case equals the product of voltage U_{PVA} and current I_{PVA}.

In a more detailed model, the output power of the photovoltaic array is expressed by the following equation [24]:

$$P_{PVA}(G,T) = \eta_{PVA} \cdot A_{PVA} \cdot G_t = \eta_r \cdot \eta_{pc} \cdot \left(1 - \beta\left(T_c - T_{ref}\right)\right) A_{PVA} \cdot G_t, \tag{1}$$

where A_{PVA} is the PVA's area, m^2; G_t is intensity of solar irradiance, W/m^2; η_{PVA} is the efficiency ratio, p.u., which can be calculated with Eq. (2):

$$\eta_{PVA} = \eta_r \cdot \eta_{pc} \cdot [1 - \beta(T_c - T_{ref})]; \tag{2}$$

η_r is the rated efficiency of the PV panels, p.u.; η_{pc} is the power efficiency, p.u. – equal to 1 when the maximum power point is reached; β is the temperature coefficient of efficiency, $°C^{-1}$, is considered constant for a specific type of semiconductor (for silicon photovoltaic cells it is equal 0.004–0.006 $°C^{-1}$); T_{ref} is the rated temperature of photocells, °C; T_c is the current temperature of photocells, °C, which can be defined by Eq. (3) [25]:

$$T_c = T_a + \left[\left(\frac{NOCT - 20}{800}\right)\right] \cdot G_t, \tag{3}$$

where T_a is the ambiance temperature, °C; $NOCT$ is the nominal operating temperature of photocells, °C.

Adoption of suitable maximum power point tracking (MPPT) techniques can considerably improve the impact of solar panels' contribution, since for an electric vehicle the MPPT and energy-management are more critical than in stationary solar power plants [17].

Since η_{pc}, β, $NOCT$ and A_{PVA} depend on the type of the PV panel and are set by the manufacturer, the independent random variables are the temperature and the intensity of solar irradiance. Analysis of Eq. (1) shows the linear dependence of the output power from the intensity of solar irradiance. The advantages of the model (1) include consideration of the influence of the ambient temperature, of the PV module's temperature, high accuracy of PV arrays simulation.

The efficiency of PVA use in autonomous power units is determined by climatic and meteorological conditions of the area. When choosing PV panels for autonomous energy supply, a preliminary energy assessment of the solar energy potential is performed, which determines the suitability of a specific area for PV installations.

Electric energy, which can be obtained by photoelectric conversion and defined as [22], Eq. (4):

$$E_{PVA}(G,T) = \tau_{PVA} \cdot K_{con.PVA} \cdot P_{PVA}(G,T), \tag{4}$$

where τ_{PVA} is the operation time of the PVA (i.e., the time during which the PVA generates power), h; $K_{con.PVA}$ is the ratio of the maximum possible power output of the PVA to the total installed power of the PVA, p.u., which takes into account the connection of separate solar panels (i.e., in series or in parallel) within the array.

2.2. Evaluation of the additional distance the EV can travel with roof-mounted solar panels

The specific energy consumption per 1 km of travel, ΔE_{tr}^{EV}, for contemporary commercial EV in EPA mode ranges from 0.133 kWh (BMW i3) to 0.261 kWh (Toyota RAV4 EV), i.e. from 13.3 kWh/100 km to 26.1 kWh/100 km, respectively [21]. The total energy capacity of batteries of modern EVs is in the range of (16–100) kWh, and its increase can be expected in future [2]. However, the announced value of batteries for EVs for the next 5 years does not exceed 100 kWh. The energy required to charge the battery of an EV is determined by Eq. (5) [22]:

$$E_{ch.bat}^{EV} = \frac{1}{\eta_{ch.bat}} \cdot U_{bat} \cdot \int_{C_0}^{C_{max}} C_{ch.bat} \cdot \psi(C) \cdot dC = \frac{E_{bat}^{EV}}{\eta_{ch.bat}}, \tag{5}$$

where $E_{ch.bat}^{EV}$ is the energy required to charge the EV, kWh; $\psi(C)$ is the function that takes into account the random nature and frequency of the process of the EV's battery charging; $C_{ch.bat}$ is the battery capacity of the EV, kWh; $\eta_{ch.bat}$ is the efficiency of the EV's battery charging, p.u.; U_{bat} is the voltage of the EV's battery, V; C_0 is the initial charge level, p.u., C_{max} is the maximum charge level, p.u. ($C_{max} = 1$). The function $\psi(C)$ can be determined heuristically, based on the adoption of certain assumptions, taking into account operational requirements for the operation of the EV's battery [22].

Given the above said, the distance that the EV can travel on the energy received from the PVA, for a day in the i-th month, can be determined as follows, Eq. (6):

$$D_{PVA}^{i} = \frac{E_{PVA}^{i}}{\Delta E_{tr}^{EV} \cdot \eta_{ch.bat}}. \tag{6}$$

Thus, the distance, that the EV can travel on the energy from the PVA on a typical day of winter/spring/summer/fall (according to the EPA standard), can be determined.

If solar panels are installed at an angle $\gamma > 0°$ to the horizon, then the conversion of solar irradiation from the horizontal surface to the slope [26], Eq. (7):

$$E_{slope} = R \cdot E_{hor}, \tag{7}$$

where E_{hor} is the average monthly daily total amount of solar energy coming to the horizontal surface, kWh/m^2; R is the ratio of the average monthly daily amount of solar irradiation received by the inclined and horizontal surface, p.u.

The conversion factor from the horizontal plane to the south-oriented plane equals to the summation result of the three components, which represent the direct, the scattered and the reflected solar irradiation [26], according to Eq. (8):

$$R = \left(1 - \frac{E_p}{E_{hor}}\right) \cdot R_п + \frac{E_p}{E_{hor}} \cdot \frac{1 + \cos\gamma}{2} + \rho \cdot \frac{1 - \cos\gamma}{2}, \tag{8}$$

where E_p is the average monthly daily portion of scattered solar irradiation coming to the horizontal area, kWh/m^2; E_p/E_{hor} is the average monthly daily share of scattered solar irradiation; $R_п$ is the average monthly conversion factor of direct solar irradiation from horizontal to inclined surface, p.u.; γ is the inclination angle of the PV panel to the horizon, deg.; ρ is the reflection coefficient (albedo) of the Earth's surface and surrounding bodies, p.u., which is generally taken as 0.7 for winter and 0.2 for summer.

The average monthly conversion factor of direct solar irradiation from horizontal to inclined area can be determined, using Eqs. (9), (10), (11), and (12) [26]:

$$R_п = \frac{\cos(\varphi - \gamma) \cdot \cos\delta \cdot \sin\omega_{zn} + \frac{\pi}{180} \cdot \omega_{zn} \cdot \sin(\varphi - \varphi) \cdot \sin\delta}{\cos\varphi \cdot \cos\delta \cdot \sin\omega_z + \frac{\pi}{180} \cdot \omega_z \cdot \sin\varphi \cdot \sin\delta}, \tag{9}$$

where φ is the latitude, deg.; δ is the inclination of the Sun (the angle between the line connecting the centers of the Earth and the Sun, and its projection on the plane of the equator) on the average day of the month, deg.:

$$\delta = 23,45 \cdot \sin\left(360 \cdot \frac{284 + n}{365}\right), \tag{10}$$

n is the serial number of the day, deducted from January 1 (number of the average settlement day for each month of the year); ω_z is hour angle of sunset (sunrise) of the Sun for the horizontal surface, deg.:

$$\omega_z = \arccos(-tg\varphi \cdot tg\delta); \tag{11}$$

ω_{zn} is the sunset hour angle for a south-oriented sloping surface, deg.:

$$\omega_{zn} = \arccos[-tg(\varphi - \gamma) \cdot tg\delta)]. \tag{12}$$

2.3. Profitability assessment

To assess the feasibility of investing in PV panels on the roof of EV, the following indicators are used:

1) Levelized Cost of Energy (LCOE) is the average estimated cost of electricity production over the entire life cycle of a power plant

(including all possible investments, costs and revenues) [27]. LCOE is calculated as follows:

$$LCOE_{PVA} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}, \tag{13}$$

where I_t is the investment expenditures in the year t, \$; M_t is the operations and maintenance expenditures in the year t, \$; F_t is the fuel expenditures in the year t, \$; E_t is the electrical energy converted in the year t, kWh; r is the discount rate, %; n is the expected lifetime of system or power station, years.

2) Payback Period is the time during which the initial investment costs are expected to be recovered from the cash flows generated by the investment. This is one of the simplest methods of valuing investments [28]:

$$PBP_{PVA} = A + \frac{B}{C}, \tag{14}$$

where A is the last period number with a negative cumulative cash flow, \$; B is the absolute value (i.e. value without negative sign) of cumulative net cash flow at the end of the period A, \$; C is the total cash inflow during the period following the period A, \$.

3. Case study and results

3.1. Solar irradiation potential of Ukraine

In this case study the applications of roof-mounted solar panels are considered for Ukrainian conditions. Ukraine's solar energy resources determine the country's overall potential for solar electricity generation. The average annual potential of solar energy in Ukraine (1 235 kWh/m^2) is considerably higher than, for instance, in Germany – 1000 kWh/m^2, in Poland – 1080 kWh/m^2 or in Latvia – 1000 kWh/m^2 [29]. Therefore, there are good opportunities for effective use of solar installations on the territory of Ukraine. Here, by the "effective use" it is implied that the solar system can operate with an output of 50% or more from its installed power, which is possible to achieve during 9 months in the southern regions of Ukraine (March to November), and 7 months in the northern regions (April to October). In winter the efficiency of PV panels increases due to lower temperatures, but the yield (i.e., the power generation) decreases due to lower solar irradiance.

The average daily values of total irradiation in Ukraine in MJ/m^2 according to direct measurements for the first half of the year (typical months of January and April) are shown in Figure 1(a), and for the second half of the year (typical months of July and October) are demonstrated in Figure 1(b) [29].

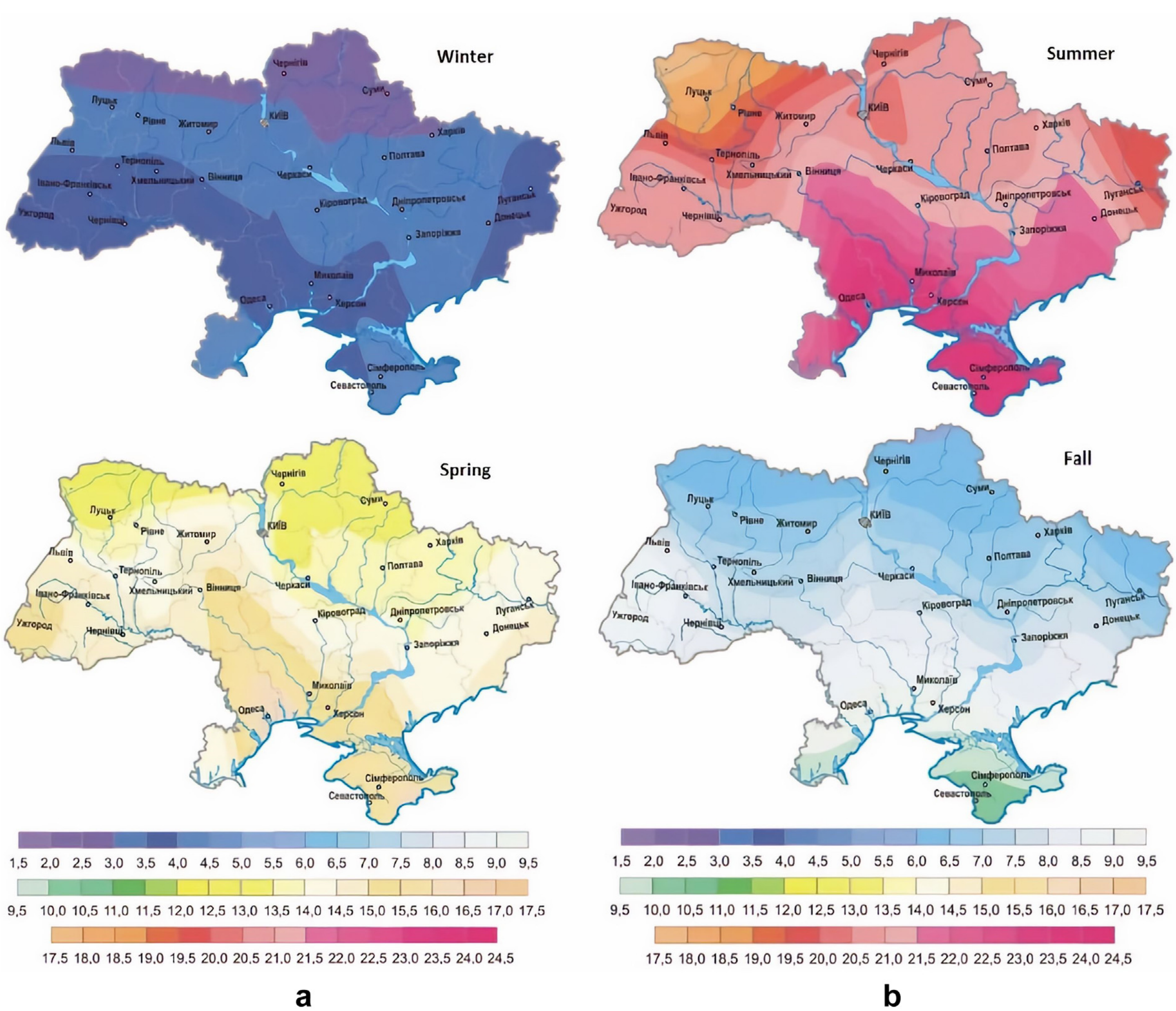

Figure 1. The average daily values of total irradiation in MJ/m^2 according to direct measurements: (a) for the first half of the year; (b) for the second half of the year.

3.2. Input data and assumptions

3.2.1. Choice of solar panels for the electric vehicle

The use of photovoltaic panels for recharging batteries is considered on the example of the 2017 Volkswagen e-Golf 7 series. It can be noted that a straightforward addition of PV panels to an existing EV is only the first step. To maximize the advantages associated with the integration of PV and EV technologies, it is necessary to re-design and optimize the whole vehicle-powertrain system, taking into account dimensions of an EV, reciprocal interactions between energy flows, sizing of propulsion system's components, adopting of power electronics, weight and costs [17].

In Volkswagen e-Golf engine performance and climate control are influenced by three driving modes – "Standard", "Eco" and "Eco+". The modes differ in running range of 5–7 km, which is not much, if the maximum range is considered. Also, the range depends on the driving style – 150–160 km with the fastest driving, and 200–250 km with moderate driving. Volkswagen e-Golf has the following energy consumption per 100 km: 12.7–13 kWh with usual driving, 15 kWh at high speed. According to the EPA standard, the value of the maximum mileage is more modest, but close to reality – 200 km [22]. Technical characteristics of the EV are given in Table 1.

Based on the geometric parameters of the EV, the roof area available for PV panels was determined, which is 1468 × 1135 mm. The roof of the car can accommodate two 120 W flexible solar panels Xinpuguang made of single-crystal silicon, dimensions 1170 × 540 × 3 mm, and one 50 W flexible solar panel Xinpuguang, dimensions 1060 × 277 × 3 mm [30]. Technical specifications of the selected panels are given in Table 2. Due to the panels' light weight and flexibility, their influence on the EV's aerodynamics and mileage with on charge is minimized.

It is known that when the panels are connected in parallel, the currents add up, and the voltage remains the same, and vice versa, when the panels are connected in series, the voltage adds up, and the current remains unchanged. The PV panels of 120 W and 50 W have similar maximum voltages, and their maximum currents differ significantly. Thus, all the three panels should be connected in parallel to obtain the maximum possible power. In this case the maximum power can be determined by the formula:

$$P_{PVA}^{\max} = U_{mp}^{\min} \cdot \Sigma I_{mp(i)}, \tag{15}$$

where U_{mp}^{min} is the minimal maximum power voltage in the PVA, V; $I_{mp(i)}$ is the maximum power current of the i-th PV panel in the array, A.

As a result, we get 257.92 W. In this case, two panels of 120 W, connected in parallel or in series, could give a maximum power of 234 W. Therefore, an additional 50 W panel adds another 23.92 W to the maximum possible power of the entire installation.

Other assumptions

The following assumptions and limiting conditions are taken into account:

(a) the power efficiency $\eta_{pc} = 0.98$ (efficiency of the MPPT controller);
(b) the efficiency of the EV's battery charge $\eta_{ch.bat} = 0.95$;
(c) temperature coefficient of efficiency $\beta = 0.006^{\circ}\mathrm{C}^{-1}$;
(d) the ambient temperature for Kyiv is according to [31];
(e) the average daily values of the total irradiation G_{day} in MJ/m^2, according to direct measurements for these months, can be determined from [29];
(f) consider the case when the inclination angle of the solar panels to the horizon $\gamma = 80^{\circ}$ during winter and fall, and $\gamma = 20^{\circ}$ during spring and summer;
(g) when calculating solar energy, the value in MJ/m^2 is converted to Wh/m^2, assuming 1 [MJ/m^2] = 277.8 [Wh/m^2];
(h) the latitude of $50^{\circ}27'$ is considered for solar energy estimations;
(i) the investment expenditures in the first year are \$307.89 and equal to the PVA's price [30];
(j) operating costs and maintenance costs are at the level of 5% of the PVA's price, no fuel costs;
(k) the discount rate is assumed to be 3%;
(l) each year solar panels' productivity decreases by 0.36%, based on the median degradation rate for mono-Si technology [32];
(m) the cost of EV charging in Kyiv is 0.22 \$/kWh [33].

Table 2. Solar panels' specifications [30].

Characteristic	Value	
Maximum power (P_{max})	120 W	50 W
Output tolerance	±3%	±3%
Maximum system voltage	700 V DC	700 V DC
Open circuit voltage (U_{oc})	21.6 V	19.2 V
Short circuit current (I_{sc})	6.8 A	3.43 A
Maximum power voltage (U_{mp})	18 V	16 V
Maximum power current (I_{mp})	6.5 A	3.12 A
Cell efficiency	21%	19.5%
Operating temperature (NOCT)	45 ± 2 °C	45 ± 2 °C
Temperature range	–40 … ~ +80 °C	–40 … ~ +80 °C
Number of cells	36 pcs	16 pcs
Weight	2200 g	1030 g
Size	1170 × 540 × 3 mm	1060 × 277 × 3 mm

3.3. Results and discussion

The calculation results of the energy amount obtained from the PVA, are shown in Table 3.

The calculation results of distances of EVs for typical days of January, April, July and October, according to EPA and NEDC standards, are summarized in Table 4.

The best results can be observed for summer, when solar activity is the highest (Table 4). The 1587.56 kWh of energy that the EV can receive to recharge the battery on a July day, allow to travel 7.98 km, according to the EPA standard, or even 12.64 km, according to the NEDC standard. These are 3.99% and 6.32% of the maximum range of the trip on a full charge of the battery, respectively. On the contrary, in winter the distance that EV can travel on energy from PV modules is the smallest. The energy of 291.32 kWh converted by solar panels on a January day will provide a range of 1.55 km according to the EPA standard or 2.32 km according to the NEDC standard, which is 0.77% and 1.16%, respectively, from the maximum range.

Table 1. Technical characteristics of Volkswagen e-Golf 2017 [22].

Engine type	Electric motor power		Type of onboard AB	Energy of onboard AB, kWh	Range		Maximum speed, km/h	Normal charge from the 220 V AC, h	Normal charge from the 380 V AC, h	Accelerated charge from 0.2 to 0.8 Cn, h	Specific energy consumption, kWh/km	
	hp	kW			EPA	NEDC					EPA	NEDC
Synchronous AC motor	136	100	Li-Ion	35.8	200	300	150	7–10	4–5	1	0.179	0.1193

Table 3. Calculation of energy converted by the PVA.

Typical month	G_{day}, MJ/m^2	G_{day}, Wh/m^2	T_a, °C	T_c, °C	$K_{con.PVA}$	E_{PVA}^{120}, Wh	E_{PVA}^{50}, Wh	E_{PVA}^{i}, Wh
January	3.2	889	-3.5	-2.49	0.89	119.81	51.70	291.32
April	13.7	3806	9.3	13.26	0.89	471.10	203.30	1145.51
July	20.5	5695	20.5	26.37	0.89	652.91	281.75	1587.56
October	7.3	2028	8.4	10.57	0.89	254.90	110.00	619.80

Table 4. Distance the EV can travel on the energy received from the PVA.

Typical month	E_{PVA}^{i}, Wh	D_{PVA}^{i}, km (EPA)	D_{PVA}^{i}, km (NEDC)	D_{PVA}^{i}, % (EPA)	D_{PVA}^{i}, % (NEDC)	R	$D_{cor.PVA}^{i}$, km (EPA)	$D_{cor.PVA}^{i}$, km (NEDC)	$D_{cor.PVA}^{i}$, % (EPA)	$D_{cor.PVA}^{i}$, % (NEDC)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
January	291.32	1.55	2.32	0.77%	1.16%	1.95	3.01	4.52	1.51%	2.26%
April	1145.51	5.76	9.12	2.88%	4.56%	1.07	6.16	9.76	3.08%	4.88%
July	1587.56	7.98	12.64	3.99%	6.32%	1.00	7.98	12.64	3.99%	6.32%
October	619.80	3.12	4.94	1.56%	2.47%	1.65	5.14	8.14	2.57%	4.07%
Average annual additional travel, km/%		4.6	7.25	2.3%	3.63%	-	5.58	8.77	2.79%	4.38%

From these results it can be inferred that the outcome of the PVA is highly dependent on the ambient conditions. In winter the efficiency of PV panels increases due to lower temperatures, but the yield (i.e., the power generation) decreases due to lower solar irradiance. During low solar irradiation periods, such as winter, roof-mounted PV panels provide little benefits, compared to the summer periods with high solar irradiation. The difference in range, which can be travelled with the energy from the PVA, between the sunniest summer months and the least sunny winter months is about 5 times.

The new calculation results of the distance that can be traveled on the energy obtained from the PVA, when installed on the sun-tracking roof platform, are shown in columns 8–11 of Table 4. It can be observed that, with the adoption of an adjustable solar roof (single axis tracking), there is an increase of incident energy and travelled distance. In terms of relative benefits, the moving sun-tracking platform with PV panels would improve the solar contribution from about 7% in spring up to 95% in winter. On a day of April, the EV can travel 6.16 km according to the EPA standard and 9.67 km according to the more optimistic NEDC standard. These are 3.08% or 4.88% of the maximum range of the trip on a full charge of the battery, respectively. In winter, the distance will be 3.01 km according to the EPA standard or 4.52 km according to the NEDC standard, which correspond to 1.51% and 2.26% of the maximum possible mileage on a single battery charge. Similarly, the PVA performance is noticeably better during the months with higher solar irradiation. However, the adoption of the moving platform can reduce the difference between the power output of PV panels in summer and in winter: to 2.64 times (EPA standard scenario) or even to 1.8 times (NEDC standard scenario) in favor of periods with high solar irradiation.

Note that the adoption of a moving platform could be feasible only for parking phases, where on the other hand many cars in urban environment spend most of their time. The real advantages can be lower than the ones provided in Table 4, due to the energy spent to adjust the sun-tracking roof platform and to possible constraints preventing perfect orientation.

The calculation results for LCOE (Eq. (13)) and PBP (Eq. (14)) results (are indicated in Table 5.

With the adoption of moving PV roof, the LCOE increases by 40%, while the PBP decreases only by 4.7%. The LCOE increase is due to the additional costs for the moving platform to adjust the inclination of the PVA. For the considered cases the negative cumulative cash flow is supervised during the first 5 years. Given the small difference in the PBP, an ordinary EV's driver can be satisfied with the system without inclination adjustment, since a sun-tracking roof platform requires significantly higher initial investment expenditures and makes more difficult the installation of the roof PVA.

Table 5. Calculation results of LCOE and PBP indicators.

PV panels inclination	$LCOE_{PVA}$, \$/kWh	PBP_{PVA}, years
Fixed $\gamma = 0°$	0.6654	5.32
Depending on the season $\gamma = 20°$ or $\gamma = 80°$	1.1013	5.07

4. Conclusions

This paper considers the use of PV panels mounted on the roofs of EVs as an additional means of improving their efficiency. The integration of solar energy sources would also contribute to battery recharging time reduction, which is a critical issue for plug-in electric vehicles. The considered vehicle integrated photovoltaic systems are inexpensive and commercially available, and the calculation method is straightforward and fast. Therefore, a regular EV can be upgraded to its PV-assisted version in short terms and with minimal investments, making the considered solutions available for regular drivers.

The characteristics of solar irradiation resources for Ukraine are given, and the total energy that the photovoltaic array can convert for the conditions of Kyiv is calculated. The most electric energy PV panels can convert during the summer months, while in winter the electricity generation is less. In July during the day the selected photovoltaic panels can provide energy for recharging the batteries of the electric car in the amount of 1587.56 Wh, while in January the energy return is only 291.32 Wh.

In summer the energy from the PVA can allow the EV to travel 7.98 km (EPA) or even 12.64 km (NEDC), while in winter the additional distance can be only 1.55 km (EPA) or 2.32 km (NEDC). Given that the PVA on the EV's roof may have a suboptimal inclination angle towards the Sun, the recalculation of the distance that the EV can travel on the energy from the PVA in the presence of an adjustable solar roof is performed. The adoption of moving sun-tracking platform for parking phases allows to enhance the trip distance in winter and fall significantly. The payback period of the PVA was assessed, taking into account the efficiency of batteries charging. The PBP of the project with flat PV panels on the roof is 5.32 years. When using a moving roof, the PBP will be reduced to 5.07 years, while the LCOE will increase from 0.6654 \$/kWh to 1.1013 \$/kWh. The results confirm feasibility of the photovoltaic array-based off-board charging of electric vehicles.

In the future work it is planned to incorporate modeling and analysis of the vehicle-integrated photovoltaic system, considering the effects of the PV panels' curvature, the driving patterns, the duration of parking and driving stages, and shadowing on the energy conversion efficiency.

Declarations

Author contribution statement

Illia Diahovchenko: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Lubov Petrichenko, Ihor Borzenkov: Analyzed and interpreted the data.

Michal Kolcun: Contributed reagents, materials, analysis tools or data.

Funding statement

Michal Kolcun was supported by Agentúra na Podporu Výskumu a Vývoja [APVV-19-0576].

Lubov Petrichenko was supported by European Regional Development Fund [1.1.1.2/VIAA/2/18/317].

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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