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A method of calculating CO_2 emission savings obtained by the use of innovative technology of photovoltaic roof of cars supporting battery charge

***Abstract**. Photovoltaic cells don't have to be associated only with the panels on the building roofs. The producers of renewable sources of energy are constantly looking for new solutions and conducting research on alternative materials for production of such energy. The solar systems are now applied in such vehicles as cars, trucks, buses, trains and ships. It is also a result of growing ecological consciousness and suggestions from the clients. In this article, the authors presented a method of calculating CO_2 savings obtained by the use of innovative technology of photovoltaic roof of cars supporting battery charge. Moreover, they presented examples of prototypical solar systems.*

Streszczenie.** Ogniwa fotowoltaiczne nie muszą kojarzyć się tylko z panelami na dachach budynków. Producenci odnawialnych źródeł energii wciąż szukają nowych rozwiązań i prowadzą badania nad alternatywnymi materiałami do ich produkcji. Zwiększa się tym samym zainteresowanie systemami solarnymi, które znajdują zastosowanie w pojazdach takich jak samochody, ciężarówki, autobusy, pociągi i statki. Wynika to również ze stale rosnącej świadomości ekologicznej oraz sugestii ze strony administracji czy też samych klientów. W artykule autorzy zaprezentowali metodę obliczenia oszczędności CO_2 uzyskanych dzięki innowacyjnej technologii dachu fotowoltaicznego samochodów osobowych wspomagającego ładowanie akumulatora. Ponadto przedstawili przykłady prototypowych instalacji systemów solarnych będących kompletnym rozwiązaniem dachu solarnego. **Metoda obliczania oszczędność emisji CO_2 wykorzystująca technologię fotowoltaicznych dachów wspomagających ładowanie akumulatorów

Keywords: CO_2 emission, Photovoltaic roof, Battery charging, Solar module.
Słowa kluczowe: Emisja CO_2, Dach fotowoltaiczny, Ładowanie akumulatora, Moduł solarny.

Introduction

For a long time, car companies did not want to produce pro-ecological cars. They produced vehicles powered by oil, petrol or gas. However, they are slowly introducing new ideas and pro-ecological products that make use of renewable energy [11,15]. The producers of cars noticed a potential niche and started production of cars that allow to protect natural environment [16,17,18,19]. Most of them are still the so-called concept models that make use of energy of sunrays obtained by photovoltaic panels mounted on the roof of vehicles [12,13,14]. Nowadays, new innovative technology of photovoltaic roof of cars that will support battery charge is being developed [6,7]. The producers of PV roofs must have an option of certifying the reduction of CO_2 by the use of energy-efficient innovations and certifying compliance in order to get approval for energy-efficient products supporting battery charge [8]. It is required to define a method of testing vehicles equipped with photovoltaic roof supporting battery charge and to select a reference vehicle, of which level of CO_2 emission is compared with the level of emission of a vehicle equipped with innovative technology, in accordance with art. 5 and 8 of the executive order (EU) no. 725/2011 [9]. In accordance with the requirements of this order, a reference vehicle should be a variant of a vehicle that is identical to eco-innovative vehicle, with the exception of photovoltaic roof and where appropriate, without additional battery or other devices needed to transform solar energy into electric energy.

In accordance with Article 2(2)(b) of Implementing Regulation (EU) No 725/2011 it is to be demonstrated that the battery-charging photovoltaic roof is intrinsic to the efficient operation of the vehicle. This means that the energy generated by the photovoltaic roof should not for example be solely devoted to a comfort-enhancing appliance.

In order to facilitate a wider deployment of battery-charging photovoltaic roofs in new vehicles, a manufacturer should also have the possibility to apply for the certification of the CO_2 savings from several photovoltaic roof systems by a single certification application. It is however appropriate to ensure that where this possibility is used a mechanism is applied that incentivises the deployment of only those photovoltaic roofs systems that offer the highest efficiency.

A confirmation of eco-innovation is entering the code no. 21 in a vehicle approval documentation in accordance with art. 11 sec. 1 of the executive order (EU) no. 725/2011.

Methodology to determine the CO_2 savings of battery charging photovoltaic roofs

In order to determine the CO_2 emission reductions that can be attributed to a battery charging photovoltaic (PV) roof for use in an M_1 vehicle, it is necessary to establish the following:

- The testing conditions and the test equipment,
- The quantities determining CO_2 savings by application of photovoltaic roof supporting battery charge.

A parameter necessary for determination of CO_2 savings is maximum output power and taking measurements of output power. The measurements of the peak power output shall be performed at standard test conditions as defined in the international standard IEC/TS 61836:2007 standard for „Solar photovoltaic energy systems – Terms, definitions and symbols" [5]. Initial stabilisation of the tested device is to be done in accordance with the methodology specified in the international standard IEC 61215-2:2016 standard for „Terrestrial photovoltaic (PV) modules — Design qualification and type approval" [4]. The measured average peak power output ($\overline{mP_p}$) of the PV roof is to be determined experimentally for each vehicle variant. A dismantled complete PV roof is to be used. The four corner points of the panel are to touch the measurement plane. The measurements of the peak power output shall be performed at least five times and the arithmetic mean ($\overline{mP_p}$) has to be calculated.

Calculation of the CO_2 savings

The CO_2 savings of the PV roof are to be calculated by formula (1) defined by Technical Guidelines for the preparation of applications for the approval of innovative technologies pursuant to Regulation (EC) No 443/2009 and

Regulation (EU) No 510/2011 [10]. Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles.

$$C_{CO_2} = S_{IR} \cdot UF_{IR} \cdot \eta_{SS} \cdot \frac{\overline{mP_p}}{S_{IR\_STC}} \cdot SCC \cdot \frac{V_{Pe}}{\eta_A} \cdot \frac{CF}{M} \cdot \cos\Phi - \Delta CO_{2m} \quad (1)$$

where: C_{CO_2} – CO_2 savings [gCO_2/km], S_{IR} – Yearly European mean solar irradiation [W/m^2], which is120 W/m^2, UF_{IR} – Usage factor (shading effect) [-], which is 0.51, η_{SS} – Efficiency of the photovoltaic system [%], which is 76 %, $\overline{mP_p}$ – Measured average PV roof peak power output [W], S_{IR_STC} – Global irradiation at Standard Test Conditions (STC) [W/m^2], which is 1 000 W/m^2, SCC – Solar correction coefficient [-] as defined in Table 1. Total available storage capacity of the battery system or the SCC value is to be supplied by the vehicle manufacturer, V_{P_e} – Consumption of effective power [l/kWh] as defined in Table 2, η_A – Efficiency of the alternator [%], which is 67 %, CF – Conversion factor (l/100km) — (g CO_2/km) [gCO_2/l] as defined in Table 3, M – Mean annual mileage [km/year] as defined in Table 4, Φ – Lengthwise inclination of the solar panel [°]. This value is to be supplied by the vehicle manufacturer, ΔCO_{2m} – CO_2 correction coefficient due to the extra mass of the solar roof and, where applicable, the additional battery and other appliances needed specifically for the conversion of the solar energy into electricity and its storage [g CO_2/km] as defined in Table 5.

Table 1. Solar correction coefficient

Total available storage capacity (12V)/ PV peak power [Ah/Wp]	0.10	0.20	0.30	0.40	0.50	0.60	≤ 0.666
Solar correction coefficient (SCC)	0.481	0.656	0.784	0.873	0.934	0.977	1

The total storage capacity includes a mean usable storage capacity of the starter battery of 10 Ah (12 V). All values refer to a mean annual solar radiation of 120 W/m^2, a shading share of 0.49 and a mean vehicle driving time of 1 hour per day at 750 W electric power requirement.

Table 2. Consumption of Effective power

Type of engine	Consumption of effective power (V_{Pe}) [l/kWh]
Petrol	0.264
Petrol/Turbo	0.280
Diesel	0. 220

Table 3. Fuel conversion factor

Type of fuel	Conversion factor (l/100 km) – (g CO_2/km) (WK) [gCO_2/l]
Petrol	2 330
Disel	2 640

Table 4. Mean annual mileage for M_1 vehicles

Type of fuel	Mean annual mileage (M) [km/year]
Petrol	12 700
Disel	17 000

Table 4. CO_2 correction coefficient due to the extra mass

Type of fuel	CO_2 correction coefficient due to the extra mass (ΔCO_{2m}) [gCO_2/km]
Petrol	0.0277 · Δm
Disel	0.0383 · Δm

In Table 5 Δm is the extra mass due to the installation of the photovoltaic system, composed by the PV roof and, where applicable, the additional battery and other appliances needed specifically for the conversion of the solar energy into electricity and its storage. In particular, Δm is the positive difference between the mass of the photovoltaic system mass and the mass of a standard steel roof. The mass of a standard steel roof is assumed equal to 12 kg. In case the weight of the solar system is lower than 12 kg, no correction for the change in mass has to be made.

Calculation of the statistical margin

The standard deviation of the arithmetic mean of the peak power output is to be calculated by formula (2):

$$s_{\overline{mP_p}} = \sqrt{\frac{\sum_{i=1}^{n}\left(mP_{p_i} - \overline{mP_p}\right)^2}{n(n-1)}} \quad (2)$$

where: $s_{\overline{mP_p}}$ – Standard deviation of the arithmetic mean of the peak power output [W], mP_{p_i} – Measurement value of the peak power output [W], $\overline{mP_p}$ – Arithmetic mean of the peak power output [W], n – Number of measurements of the peak power output, which is at least 5.

The standard deviation of arithmetic mean of the PV roof peak power output leads to a statistical margin in the CO_2 savings ($s_{C_{co_2}}$). This value is to be calculated in accordance with formula (3):

$$s_{C_{CO_2}} = \sqrt{\left(\frac{\partial C_{CO_2}}{\partial \overline{mP_p}} \cdot s_{\overline{mP_p}}\right)^2} = S_{IR}\frac{1}{S_{IR\_STC}} \cdot UF_{IR} \cdot \eta_{SS} \cdot SCC \cdot \frac{V_{Pe}}{\eta_A} \cdot \frac{CF}{M} \cdot \cos\Phi \cdot s_{\overline{mP_p}} \quad (3)$$

where: $\frac{\partial C_{CO_2}}{\partial \overline{mP_p}}$ – Sensitivity of calculated CO_2 savings related to the average solar PV roof peak power output.

It has to be demonstrated for each type, variant and version of a vehicle fitted with the battery charging PV roof that the minimum threshold of 1 gCO_2/km is exceeded in a statistically significant way, as specified in Article 9(1) of Implementing Regulation (EU) No 725/2011. As a consequence, formula (4) is to be used.

$$MT \le C_{CO_2} - s_{C_{CO_2}} \quad (4)$$

where: MT – Minimum threshold [g CO_2/km], which is 1 g CO_2/km, $s_{C_{co_2}}$ – Statistical margin of the total CO_2 savings [g CO_2/km]

Where the CO_2 emission savings, as a result of the calculation using Formula 4, are below the threshold specified in Article 9(1) of Implementing Regulation (EU) No 725/2011, the second subparagraph of Article 11(2) of that Regulation shall apply.

Photovoltaic modules applied on the roofs of the vehicles

Due to the sizes and curvatures of car roofs, typical photovoltaic modules are not accepted. An ideal solution to such installations is technology of thin-film or elastic solar modules. Thin-film (amorphous) solar modules differ in structure from typical technologies of silicic mono or polycrystalline modules. In this technology, thin layer of silicon is spread on the surface of other material, for example, glass. No single photovoltaic cells can be distinguished in such panels, they form one compact formation in the colours from dark claret to black. An advantage of thin-film modules is their relatively low price and lower loss of efficiency with temperature rise in a module. The disadvantages include lower efficiency in comparison with crystalline modules (about 20 % in laboratory conditions), which requires larger surface to achieve appropriate power of photovoltaic system. The following thin-film technologies are distinguished:

- **CIGS/CIS module –** a mix of copper, indium, gallium and selenium (CIGS) or copper, indium and selenium (CIS) is a semiconductor material in this module. Visually, there are no distinctive cells that form one compact black formation in this module. The module is characterized by relatively low price and moderate efficiency (high for thin-film modules and similar to crystalline silicon modules), low-energy scattered radiation is well developed.
- **CdTe module –** cadmium telluride CdTe is a semiconductor material in this module. Visually, there are no distinctive cells that form one compact black formation in the module. This type of solar batteries is characterized by relatively low price and moderate efficiency (high for thin-film modules and similar to crystalline silicon modules), it has also low rate of power decrease when the temperature rises. Despite the use of cadmium, it is safe to use such solar batteries. They must be properly utilized during the assembly

Fig.1. Roof of a car with solar modules and Fresnel system of lens [3]

There are solutions supporting solar modules mounted on the car roofs. Fresnel system of lens is made of very light plastics and works just like magnifying glass. System of lens may roll backwards and forward. It also follows the direction of incidence of sunrays and adapts to it. It enables to take the most intensive dose of sunrays at a given moment. Such cell system may take 50 % of more energy on the same surface than conventional solar panels. Based on conducted research, it was found that cars with such system may get about 8 kW during the day. [3] It means that it is enough to drive up somewhere without using gas or connecting to electrical power supply. However, such solution still doesn't fulfil the requirement of basic power source without traditional fuels. Car roof with solar modules and Fresnel system of lens is presented on Fig.1 [3].

Another interesting solution is innovative solar technology to direct use of renewable energy – directly in the cars, the so-called solar module as a car solar module. The system of solar roof of dimension 2.5 m x 1.3 m and curvatures > 40 made of double thin glass or light composites is the system of the highest efficiency with transparent or semi-transparent shapes to charge hybrid traction batteries or electric vehicles. An innovative technology enabled to create the largest photovoltaic module of spherically curved roof and power generation up to 200 watts [1,2]. The solar modules with the highest efficiency are presented on fig. 2.

Fig.2. Solar roof with a solar module of the highest efficiency 200W [1, 2]

Tested vehicle equipped with solar module and "plug-in hybrid" technology of drive system drove about 80 km. Total range was about 500 km without charging and refuelling. New solar roof turned out to be useful for a vehicle and reduced the costs of fuel and CO_2 emission. Solar roof 100 Wp enables to save CO_2 2.5 g CO_2/km/year in a vehicle with petrol engine and 1.6 CO_2/km/year in a vehicle with diesel oil engine [1,2].

Summary

The idea of using solar energy to power vehicles, as well as other alternative sources, is not new and dates back to the second half of the 20th century. However, due to high costs and not sufficient efficiency of these systems (up to 17% in the latest photovoltaic elements), it is a technology of the future. The vehicles using solar energy as fuel are in a phase of models and prototypes. Despite the fact that solar modules are imperfect, there will be more and more vehicles that will use electricity to power cars and their selected elements. There are many examples of the structures with aggregates powered by solar energy, or electric systems, in which classic alternator is supported by solar panels. In the delivery trucks, a sleeper cab of a driver and his/her rest will be guaranteed by the sun. Newly built prototypes of trucks have solar systems of spherical curvature above 40 and power of 270 W. It enables drivers not only to rest during stopover, but also allows to reduce fuel consumption even by 20 litres/100 km and makes road transport more efficient. New innovative solar roofs require one coherent method of calculating CO_2 emission savings. This method allows to estimate the level of emission of CO_2 in the vehicles with innovative photovoltaic roof and devices needed to transform solar energy into electric energy.

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