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Efficiency of photoelectric converters intellectual system application on ground electric transport

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Abstract. The development of environmentally friendly road transport is now directly related to the introduction of electric actuators, high-voltage storage systems and the accumulation of electricity in transport. Thus, a significant variety of hybrid traction drive circuits appears, which can be charged from an external power source. However, all of them use hydrocarbon fuel for charging and storage of electricity, which emits CO₂ while burning. Clean electric vehicles are the most efficient in terms of environmental indicators, since they use only electricity produced in power plants located far from the operation aureole of the electric vehicle, which allows to improve the environmental situation in megapolises significantly. As you know, energy complexes in different countries have different environmental efficiency and CO₂ emissions during power generation are also present. Transition to the use of renewable energy sources, such as solar power plants, can give its effect, since at present, their productivity in the world reaches 400 GW, but the transmission of energy over distances reduces the efficiency. Thus, based on the development trends of solar power plants, it is important to consider the use of photovoltaic cells, the so-called "solar cells" directly on the electric vehicle itself in order to improve environmental friendliness.

1. Introduction

In the era of electric drive development in motor vehicles, both in cooperation with internal combustion engines, with electrochemical fuel cells on hydrogen and in its pure form, the question sooner or later arises: what will be the next stage? The next step in the development of environmentally friendly transport can be considered the stage of energy replenishment systems development with the help of various converters that provide power generation, both from mechanical energy and from a renewable source, for example, the Sun [1,2].

Also, due to the worldwide struggle to reduce greenhouse gas emissions, a lot of research has been carried out [3], which showed that the energy produced by solar power plants has CO₂ emissions no more than 48 g/kWh. This quantity includes emissions over the entire life cycle. It means that solar energy is quite clean compared to other options that are available for installation on a vehicle, for example, oil or gas-fueled heat engines (Figure 1).



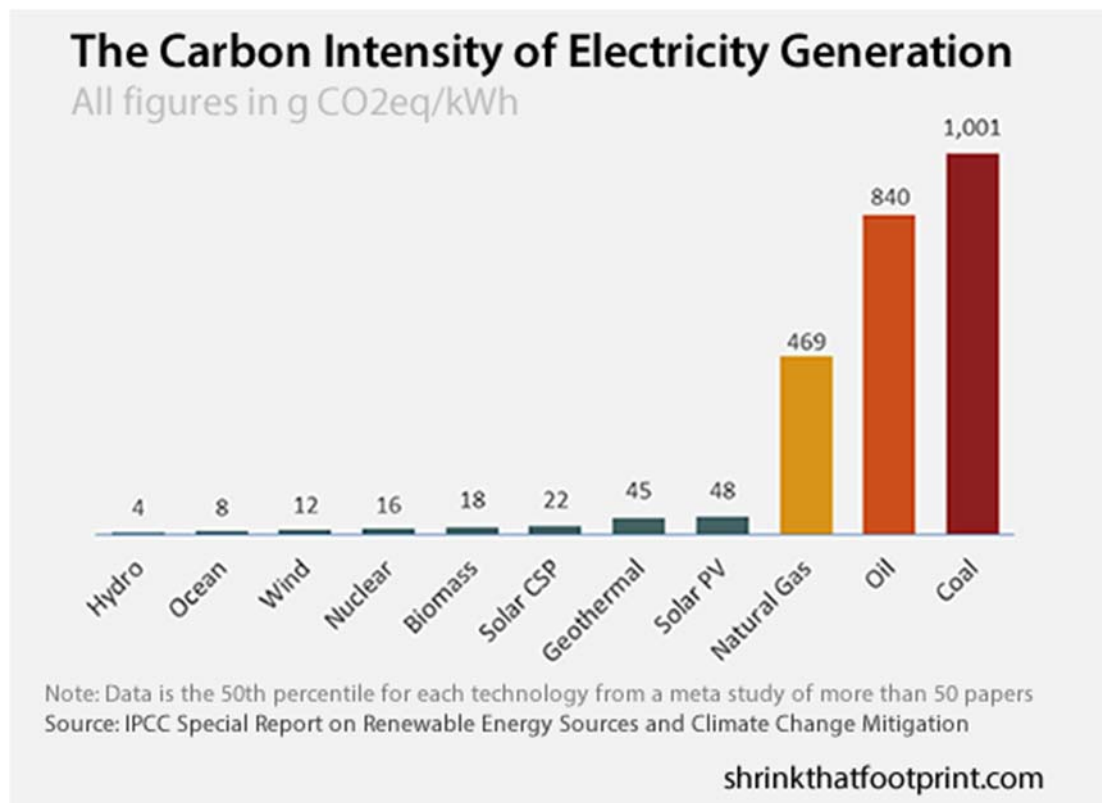


Figure 1. The level of greenhouse gas emissions at various ways of electricity generation.

The share of solar energy in total electricity generation is growing rapidly and, over the past five years, its capacity has increased almost four times. Solar power plants that were commissioned in 2017 increased electricity production by 97 GW, which increased the total power output of this method to 400 GW, which is 32% more compared to the end of 2016 [4].

2. Main part

In the field of photoelectric converters (PV), a lot of discoveries occur that lead to an increase in the efficiency of single-piece solar cells in laboratory conditions, as well as under operating conditions. Back in 2009, Spectrolab research company, part of the Boeing corporation, developed PV with a conversion efficiency of 41.6% [5], then in 2011, Solar Junction (USA) set a new level of PV efficiency – in the laboratory an efficiency of 43.5% was obtained on 5.5×5.5 mm sample which is 1.2% higher than the previous achievement.

In 2013, Sharp Company manufactured a three-layer PV with dimensions of 4×4 mm on an indium gallium-arsenide basis with an efficiency of 44.4% [6].

At the end of 2013, a new level was taken in the field of PV development: scientists from Soitec and CEA-Leti (France), together with the Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer Solar Power Systems, Germany) developed a PV with an efficiency of 46% [7].

A new milestone was set in November 2017 by Russian scientists from the Institute of Semiconductor Physics (ISP) named after Rzhanov. With the support of the ISP Screen company, they developed a new type of vacuum photodiodes, which will improve the efficiency of PV batteries, which, according to the developers of the device, can reach 50% or more, which, in the future, will allow vacuum photo cells to compete with the best multi-stage ones [8].

Thus, the use of PV in electric transport is becoming increasingly relevant and aspects of their usage in road transport need to be studied and researched.

In the FSUE “NAMI”, as a result of the work on the “Solar Battery” project, an electric vehicle was manufactured with a system of additional energy sources based on photovoltaic cells, which includes an electricity transmission channel to a high-voltage battery as well as a thermal control system for the main components of an electric vehicle (Figure 2).



Figure 2. General view of an experimental electric vehicle with PV, developed and manufactured in the FSUE "NAMI".

Calculations preceding the start of the work showed that at the latitude of St. Petersburg a similar PV system can generate up to 260 kWh per year, at the latitude of Moscow up to 280 kWh per year, at the latitude of Sochi and Astrakhan up to 380 kWh per year at the latitude of Vladivostok up to 400 kWh. Therefore, installation of an additional power source based on photovoltaic cells with an area of 1.8 m² on an electric vehicle is capable to reduce CO₂ emissions by 153,000 – 240,000 grams per year [9,10] compared to a similar electric vehicle with the same mileage, and this is not accounting for power transmission losses at the standard method of electric vehicle charging [11].

During the work, a mathematical model of an electric vehicle with a photoelectric converters battery was created, which was implemented on a computer in the Simulink environment (Figure 3).

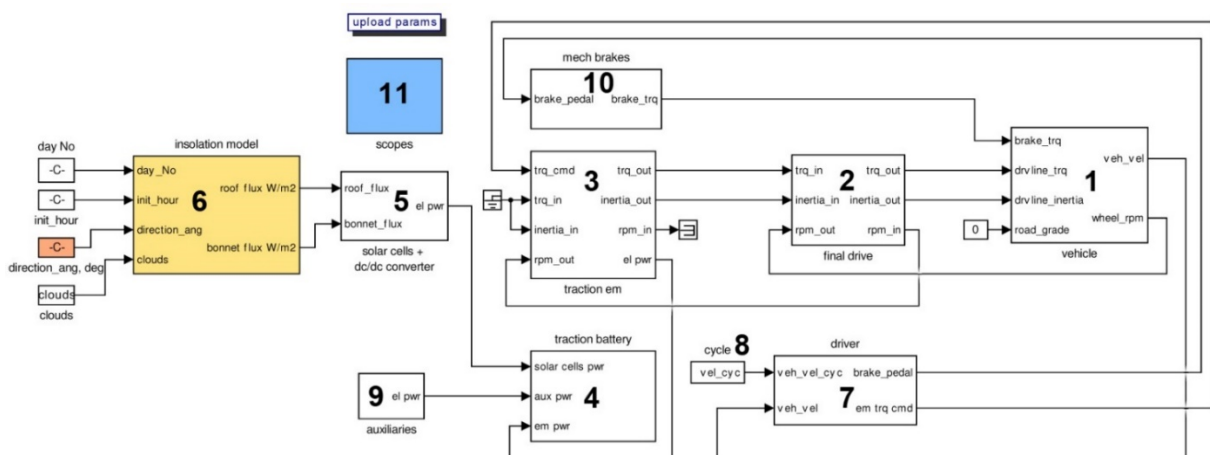


Figure 3. Implementation of an electric vehicle model with a PVs battery in the Simulink software environment (the upper level of the model).

Subsystem 1 contains the equation for the linear motion of the car and the equations for resistance calculation to the motion forces. Subsystem 2 is a model of the main transmission, which reproduces its

power and kinematic transfer functions. Subsystem 3 contains the model of the traction motor. Subsystem 4 represents the traction battery. Block 5 is a model of energy transformations. Sub-model 6 generates two signals: roof and hood surfaces density that enters the photocell battery block (5), 7 and 8 are sub-models of the vehicle speed control system. Block 9 simulates energy consumption by additional onboard devices; block 11 contains means for variables monitoring.

The model of the electric car included the following models:

- solar radiation model;
- driver model;
- power plant components model;
- vehicle movement model.

To determine the power generated by the photo cells, it is necessary to calculate the density of solar radiation when a car moves. It depends on a number of factors: time of day, season, angle of inclination and orientation of the light-receiving surface. These factors are taken into account in the model for an adequate assessment of the energy effect obtained from the use of photo cells. To calculate the density of solar radiation Bird's method was used [12], since it provides a good adequacy of the results using relatively simple dependencies for calculating the transmittance of solar radiation and requires a small amount of input data, which is important for design calculations.

The dependence underlying the calculations of all particular cases of surfaces and a solar radiation (SR) flux interaction is the expression of the SR density falling on a horizontal platform without taking into account the atmosphere (space SR):

$$\Psi_{hor}^0 = \Psi_{C\perp} \cdot \cos \theta_z [13] \quad (1)$$

where $\Psi_{C\perp} = 1367 \text{ W/m}^2$ – solar constant; θ_z – sunlight incidence angle.

The cosine of the sunlight incidence angle is calculated according to the equation:

$$\cos \theta_z = \cos \delta_n \cdot \cos \varphi_l \cdot \cos \omega_s + \sin \varphi_l \cdot \sin \delta_n \quad (2)$$

where δ_n – sun declination angle; φ_l – location latitude; ω_s – sun hour angle.

The geometric meaning of the parameters used in this expression is shown in Figure 4.

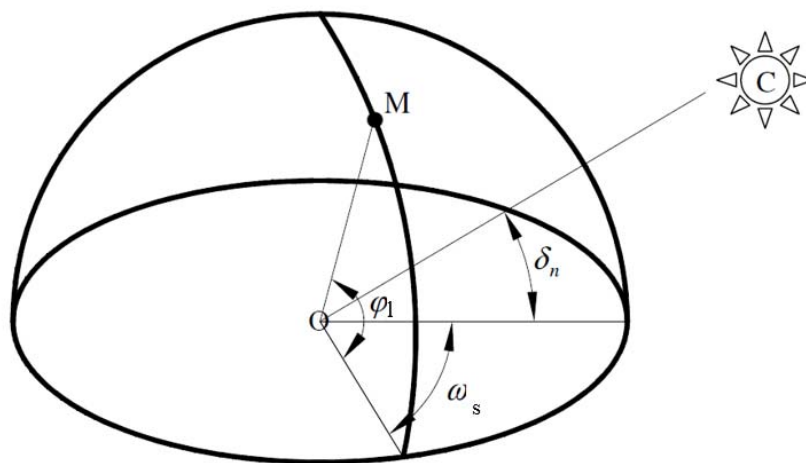


Figure 4. Scheme for determining the location latitude, the sun hour angle and the sun declination angle.

The sun declination angle is calculated using the equation

$$\delta_n = 23.5^\circ \sin\left(360^\circ \frac{n-81}{365}\right) \quad (3)$$

where n is the ordinal number of a day, counted from the 1st January.

To calculate the sun hour angle, the following expression is used:

$$\omega_s = \frac{15^\circ}{\text{hour}} (t_l - \Delta t_{\text{decr}} - 12 + t_t) + (\lambda_l - \lambda_m) \quad (4)$$

where t_l – local time; Δt_{decr} – amendment to the decree time used in the territory of the Russian Federation (1 h); t_t – time amendment; λ_l – longitude of the place; λ_m – longitude of the middle meridian of the time zone.

The time amendment is the difference between the true solar time and the average solar time on the considered meridian, which is associated with uneven movement of the Earth around the Sun due to the elliptical orbit of the planet:

$$t_t = 229.2 \cdot (0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.014615 \cdot \cos 2B - 0.04089 \cdot \sin 2B) \quad (5)$$

where $B = 360^\circ \frac{n-1}{365}$.

Cosmic radiation is absorbed and scattered by molecules of atmospheric gases (nitrogen, oxygen, carbon dioxide, water vapor, ozone). The degree of absorption and scattering is determined by the fundamental properties of these gases: the natural frequencies of atomic vibrations in molecules, the rotational-vibrational spectra in molecules and the frequencies ratio of these vibrations and the radiation frequencies in the solar spectrum. When calculating the radiation density with regard to the atmosphere, these properties are taken into account by empirical coefficients [14].

A common case is the determination of the solar radiation density perceived by the oriented surface on which it acts, passing through the atmosphere in cloudy conditions. Figure 5 shows the radiation components that are taken into account. The scattered part of direct SR is called diffuse solar radiation. If the light-receiving surface is at an angle to the horizon line, it is also affected by the SR, reflected from the Earth's surface. Modeling close to real climatic conditions requires the calculation of SR both in clear weather and in the presence of clouds, which reflects part of the SR, reducing its flux falling on the light-receiving surface.

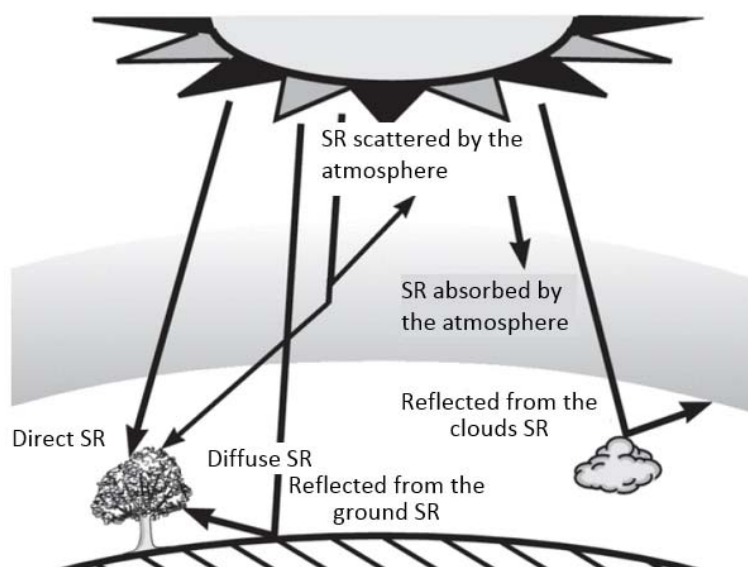


Figure 5. Components of solar radiation passing through the atmosphere of the Earth and falling on an oriented surface.

The initial version of the SR calculation taking into account the atmosphere is its definition for clear weather. The density of the direct SR, falling on a horizontal platform, taking into account the atmosphere, is calculated according to the equation:

$$\Psi_{hor}^{dir} = \Psi_{C\perp} \cdot \cos\theta_z \cdot \tau_{\Sigma} \cdot K_{hor}^{dir} \quad (6)$$

In this formula, the correction factor is used, the values of which for the territory of the Russian Federation were calculated by the authors of the article [12]. For direct SR, it is equal to 1.14 in winter and 0.91 in summer. In this paper, linear interpolation is used to calculate values between these seasons.

The designation τ_{Σ} is called the transmittance of direct solar radiation, the value of which depends on the absorption and light scattering in the atmosphere and defined as the product of several partial transmittances:

$$\tau_{\Sigma} = \tau_{O_3} \cdot \tau_{gas} \cdot \tau_{H_2O} \cdot \tau_R \cdot \tau_A \quad (7)$$

where, τ_{O_3} , τ_{gas} , τ_{H_2O} take into account the absorption of solar radiation by ozone, gas mixture (O_2 , N_2 , CO_2) and water vapor respectively; and take into account Rayleigh and aerosol dispersion. These coefficients are calculated using the formulas presented below.

$$\tau_R = \exp(-0.0903 \cdot (M^*)^{0.84} \cdot (1 + M^* - (M^*)^{1.01})) \quad (8)$$

where M^* is the atmospheric effective mass.

Atmospheric mass is a measure of the sunlight path length in the atmosphere. Unit of atmospheric mass is the path of the sun's rays in the atmosphere when the Sun is at its zenith:

$$M = \frac{1}{\cos\theta_z + 0.15 \cdot (93.885 - \theta_z)^{-1.25}} \quad (9)$$

In calculations, the atmospheric mass is used, taking into account the pressure correction:

$$M^* = \frac{p \cdot M}{p_0} \quad (10)$$

p_0 is the normal pressure of 1 atm.

$$\tau_A = \exp(-\tau_{A'}^{0.873} \cdot (1 + \tau_{A'} - \tau_{A'}^{0.7088}) \cdot M^*)^{0.9108} \quad (11)$$

where $\tau_{A'} = 1.832 \cdot \alpha$, $\alpha = 0.0314$ – spectral turbidity coefficient of Angstrom.

$$\tau_{O_3} = 1 - 0.1611 \cdot d_{O_3} \cdot M^* \cdot (1 + 139.48 \cdot d_{O_3} \cdot M^*)^{-0.3035} - 0.002715 \cdot d_{O_3} \cdot M^* \cdot (1 + 0.044 \cdot d_{O_3} \cdot M^* + 0.0003 \cdot (d_{O_3} \cdot M^*)^2)^{-1} \quad (12)$$

where $d_{O_3} = 0.0032$ m is the thickness of the ozone layer at normal temperature and pressure for middle latitudes.

$$\tau_{gas} = \exp(-0.0127 \cdot (M^*)^{0.26}) \quad (13)$$

$$\tau_{H_2O} = 1 - 2.4959 \cdot d_{H_2O} \cdot M^* \cdot (1 + 79.034 \cdot d_{H_2O} \cdot M^*)^{0.6828} + 6.385 \cdot d_{H_2O} \cdot M^* \quad (14)$$

where d_{H_2O} is the indicator of water vapor content in the vertical column of the atmosphere, equal to 1.3 g/cm² for winter and 3 g/cm² for summer. In this paper, linear interpolation is used to calculate values between these seasons.

The calculation of the diffuse solar radiation density incident to a horizontal area is performed using the following formula:

$$\Psi_{hor}^{dif} = \Psi_{C\perp} \cdot \cos\theta_z \cdot \tau_{O_3} \cdot \tau_{gas} \cdot \tau_{H_2O} \cdot \tau_{AA} \cdot (0.5 \cdot (1 - \tau_R) + B_a \cdot (1 - \tau_{AS})) / (1 - M^* + (M^*)^{1.02}) \cdot K_{hor}^{dif} \quad (15)$$

In addition to the coefficients presented above, it contains the transmittance coefficient τ_{AA} , which takes into account aerosol dispersion, the absorption coefficient τ_{AS} , which takes into account the scattering of dry air particles and B_a – the ratio of the scattered direct radiation to the total scattered radiation. The correction factor for diffuse SR is $K_{hor}^{dif} = 1.05$. Additional factors are calculated as follows:

$$\tau_{AA} = 1 - 0.1 \cdot (1 - M^* + (M^*)^{1.06}) \cdot (1 - \tau_A) \quad (16)$$

$$\tau_{AS} = \tau_A / \tau_{AA} \quad (17)$$

$$B_a = 0.5 \cdot (1 + \cos \theta_z) \quad (18)$$

The density of the total radiation incident to a horizontal area, taking into account the atmosphere, is determined by the sum of direct and diffuse SR:

$$\Psi_{hor}^{tot} = (\Psi_{hor}^{dir} + \Psi_{hor}^{dif}) / (1 - r_E \cdot r_A) \quad (19)$$

where r_E and r_A are the albedo (characteristic of the diffuse reflectivity of the surface) of the earth's surface (the surface along which the car moves) and the atmosphere respectively.

To assess the effect of the car hood using to accommodate photo cells, it should be noted that its surface is at an angle to the horizon, and when the car is moving, it is also oriented in azimuth direction. Taking into account these features, the cosine of the sunlight incidence angle is calculated as follows:

$$\begin{aligned} \cos \theta_{z,inc} = & \sin \delta_n \cdot \sin \varphi_l \cdot \cos \beta - \sin \delta_n \cdot \cos \varphi_l \cdot \sin \beta \cdot \cos \gamma + \cos \delta_n \cdot \cos \varphi_l \cdot \cos \beta \cdot \cos \omega_s + \\ & + \cos \delta_n \cdot \sin \varphi_l \cdot \sin \beta \cdot \cos \gamma \cdot \cos \omega_s + \cos \delta_n \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega_s \end{aligned} \quad (20)$$

where β is the angle of the light-receiving surface to the horizon inclination; γ – the astronomical azimuth of the light-receiving surface (measured from the direction to the south). The value $\cos \theta_{z,inc}$ is used to calculate the direct SR for the inclined platform (Ψ_{inc}^{dir}) according to the similar formula.

To calculate the density of diffuse SR in the case of an inclined surface, the value of diffuse SR for the horizontal surface, previously calculated from the above formulas, is used:

$$\Psi_{or}^{dif} = \Psi_{hor}^{dif} \left(\frac{1 + \cos \beta}{2} \right) \quad (21)$$

For an inclined surface is also determined by the density of the reflected SR:

$$\Psi_{or}^{ref} = \Psi_{hor}^{tot} \cdot r_E \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (22)$$

The total density of the SR for an inclined surface is determined by the sum of the direct, diffuse and reflected components:

$$\Psi_{or}^{tot} = \Psi_{or}^{dir} + \Psi_{or}^{dif} + \Psi_{or}^{ref} \quad (23)$$

To take into account the conditions of cloudiness, [11] proposed to use solar radiation correction coefficients calculated for clear weather. These coefficients are determined by the ratio between the observed (experimental) SR in cloudy ($\Psi_{ob,cloud}^{tot}$) and clear ($\Psi_{ob,clear}^{tot}$) weather:

$$K_{cor} = \frac{\Psi_{ob,cloud}^{tot}}{\Psi_{ob,clear}^{tot}} \quad (24)$$

Experimental SR values for a known geographic location and time of year can be obtained from climate guides or databases. Using the correction factor, the full SR for cloudy weather is calculated as follows:

$$\Psi_{theory,cloud}^{tot} = \Psi_{theory,clear}^{tot} \cdot K_{cor} \quad (25)$$

Based on the calculation of the electric vehicle mileage increase per NewEuropean Driving Cycle (NEDC), currently used in the certification procedures of UNO Regulation №101 and WLTC (WorldwideHarmonizedLightVehicleTestCycle) – a mixed driving cycle, which was developed as a replacement for the outdated NEDC through the use of a system based on PVs were obtained indicators presented in table 1.

Table 1. The results of computational experiments.

Configuration	NEDC. S, km	DS, %	NEDC-city. S, km	DS, %
Day 15 (January), to the South, 9 o'clock				
Basic electric car	152.2	0.00	225.4	0.00
Electric car + PV	153.5	0.82	229.8	1.95
Day 15 (January), to the South, 12 o'clock				
Electric car + PV	155.0	1.84	237.0	5.17
Day 15 (January), to the South, 15 o'clock				
Electric car + PV	152.7	0.29	227.4	0.89
Day 105 (April), to the South, 9 o'clock				
Electric car + PV	159.9	5.04	257.5	14.24
Day 105 (April), to the South, 12 o'clock				
Electric car + PV	161.5	6.13	266.8	18.37
Day 105 (April), to the South, 15 o'clock				
Electric car + PV	157.7	3.62	249.8	10.85
Day 105 (April), to the South, 18 o'clock				
Electric car + PV	152.6	0.24	227.0	0.74
Day 196 (June), to the South, 9 o'clock				
Electric car + PV	160.8	5.62	261.8	16.14
Day 196 (July), to the South, 12 o'clock				
Electric car + PV	162.3	6.64	270.5	20.03
Day 196 (July), to the South, 15 o'clock				
Electric car + PV	159.2	4.58	256.3	13.73
Day 196 (July), to the South, 18 o'clock				
Electric car + PV	153.9	1.13	233.1	3.44
Day 288 (October), to the South, 9 o'clock				
Electric car + PV	156.2	2.64	241.3	7.04
Day 288 (October), to the South, 12 o'clock				
Electric car + PV	157.3	3.37	247.3	9.70
Day 288 (October), to the South, 15 o'clock				
Electric car + PV	153.7	0.95	232.0	2.95
Day 288 (October), to the South, 18 o'clock				
Electric car + PV	152.2	0.00	225.4	0.00

The photovoltaic indicators system, made for an electric vehicle, consists of two solar panels with 84 elements on the roof surface and 36 elements on the hood surface, which together make up 1.85 m².

These batteries are protected from environmental influences by glass, which repeats the shape of the body elements of an electric vehicle. Solar cell battery was installed on a protective glazing to minimize the sun's loss occur when the beam overcome the air gap between the protective glass and the LET system. The back of the LET battery was sealed to prevent the contact with metal body elements, for this goal a special heat-resistant (up to + 250 °C) two-component compound - "Silagerm-2104" encapsulant was used. Thus, the air gap between the surface of PVs and protective glazing is completely excluded. The used compound has absolute resistance to UV light and allows the solar cell system to maintain full operation in an open air environment and conditions of high humidity (Figure 6).



Figure 6. Elements of a PV system mounted on a protective glazing.

A schematic diagram of the photovoltaic cells system components relationship on the vehicle is shown in Figure 7.

The scheme has two main modes of operation:

- stationary;
- dynamic.

The first option assumes that the charge of the high-voltage battery occurs when the vehicle is idle in automatic mode. A battery of photoelectric converters, using a controller that monitors the point of battery maximum efficiency, supplies a buffer lithium-ion drive with a nominal voltage of 12V. When the buffer drive is fully charged, the charging of a high-voltage battery occur.

In the dynamic version, when the vehicle is in motion, the circuit operates according to the following algorithm: the battery of PV feeds the buffer battery through the charge controller, which is the main battery of the entire low-voltage circuit of the experimental vehicle. With the help of a current sensor, the consumption of on-board low-voltage electronics is monitored and, with a lack of power produced by the PV battery, electricity is supplied from the high-voltage battery to the buffer drive through the DC converter, but in a smaller amount compared to the disconnected PV cell battery.

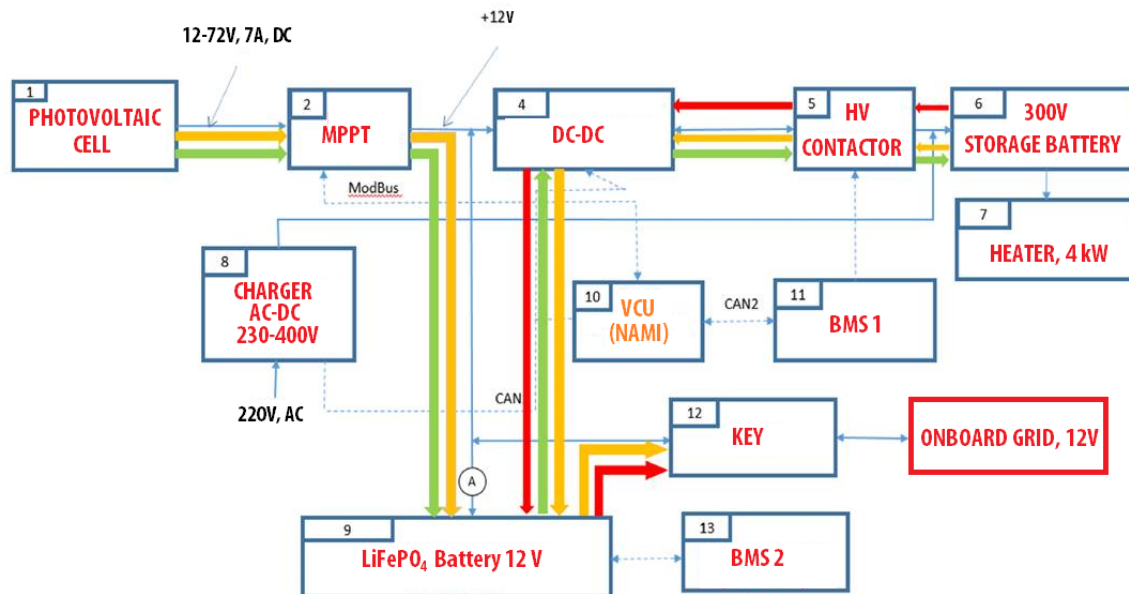


Figure 7. Scheme of an additional energy sources system based on solar cells.

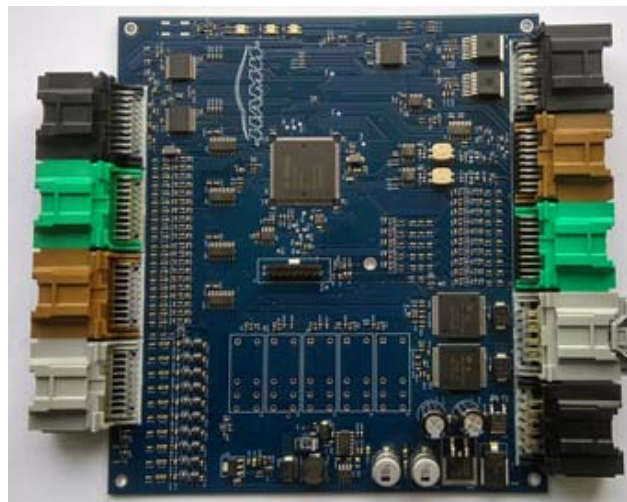


Figure 8. Main control unit.

Figure 8 shows the main control unit designed and manufactured as part of the Solar Panel project. The input and output interfaces of this unit meet the requirements for compiling into C++ code. The unit controls the following devices: an MPPT controller (control converter of the PV battery) and a DC/DC converter that exchanges energy between the buffer and traction batteries and also controls the elements of the temperature control system. To work as a part of a hardware controller, the control system was compiled into C++ program code. Compilation is performed by the built-in tools of the MATLAB/Simulink software environment.

To monitor and record the input and output parameters of an electric vehicle with a system of additional power sources based on photovoltaic cells in LabVIEW, an interface was developed, the working menu of which is shown in Figure 9. This interface provides for the manual mode of controlling individual devices in order to receive experimental data separately.



Figure 9. The system for indicators of electric vehicle with a PV system monitoring.

The obtained results at the FSUE “NAMI” testing ground (Figure 10) for the NewEuropeanDrivingCycle (NEDC) were partially shown in table 2. During field tests the solar energy density was about 600-750 W/m² (Figure 11), which is far from the maximum possible value for the climatic zone of Moscow city.



Figure 10. Road tests conduction at the FSUE "NAMI" testing ground.



Figure 11. Measuring of the solar energy intensity.

Table 2. Results of the road tests.

Configuration	NEDC S, km	DS, %	NEDC-city S, km	DS, %
Day 227 (August), to the South, 12 o'clock				
Basic electric car	142.4	0.00	211	0.00
Electric car + LET	149,6	5.08%	230,3	9,15%

3. Conclusions

The effect of increased mileage primarily depends on the intensity of traffic. In case of its increase, what characterizes WLTP cycles, which reproduce modern road traffic conditions, the advantages of using photocells are reduced by 5-10% compared with the outdated NEDC cycle, which has a low dynamics of the European movement of the 1980s. In mixed cycles in summer conditions, the increase in mileage is up to 6%.

Obviously, even now, with PV efficiency of 20-22%, the increase in the mileage of an electric vehicle can reach relatively high rates, and, at the large-scale development of electric transport with an additional power supply system based on PV, will provide an additional opportunity to reduce greenhouse gas emissions.

Undoubtedly, with the development of technologies that increase the efficiency of PV that can be used in the automotive industry, we will see significant advantages of this method for replenishment of energy over the currently used mileage multipliers, both in terms of environmental and energy efficiency. In addition using the vehicle according to the Vehicle-to-Grid protocol (V2G, car-electric grid) will allow returning excess electricity to the network, since, as a rule, most of the personal transport is not used throughout the daylight hours.

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