# Window Frame Installed Photovoltaic Module for Feeding of Low Power Devices

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**Abstract -** "Solar window" is one of the fastest growing areas of "building-integrated photovoltaics " technology. The use of standard silicon solar cells with high efficiency and low price is a compromise between obtaining of photovoltaic energy and maintaining the illumination in the room behind the window. The article presents the results of the development of solar photovoltaic module integrated into a standard double-glazed window frame 730x700 (mm) in size. New sealing method of silicon solar cells was applied, based on the use of polysiloxane gel, allowing to increase the module period of service by 1.5-2 times compared to standard silicon modules. The paper presents module design and describes the technology of its sealing. The module allows to charge the lithium-ion accumulator pack with the capacity of 6.8 Ah, output voltage of 5.25 V. This energy can be used to power any device with a USB 2.0 connector. The paper includes calculation of the necessary photovoltaic module power (the number of solar cells) for the vertical position of the module, measurements of optical characteristics of the photovoltaic module and the window frame. Authors describe electronic circuit of accumulator charging and power supply of devices and the charge current of the lithium-ion accumulator pack and the corresponding charge time of the required capacity measured under natural solar radiation in conditions of different solar radiation intensity.

**Keywords -** solar radiation, solar window, photovoltaic module, polysiloxane gel, power supply system, sealing technology.

## 1. Introduction

The use of photovoltaic (PV) energy began with low power systems. They were located in regions where there were no centralized power supply networks to provide minimal necessary energy supply to small social and industrial facilities. Further on, as a result of successful work to reduce the cost of energy, growing environmental problems and in order to ensure the energy security of countries, a rapid growth in the use of renewable energy sources has taken place in the last 15-20 years. Access to reliable and sustainable energy stimulates investments, including state investments, into the development of a wide range of renewable energy converters in energy consumption formats in order to fully realize the potential of renewable sources of energy of different countries. Solar energy holds the leading position in terms of growth rates among different types of renewable energy sources, giving an annual increase of 20-30%, reaching a total capacity of over 400 GW [1].

Photovoltaic energy production naturally developed from low-power systems to power plants with capacity of hundreds of megawatts and more. But at present, PV modules with the power of tens and hundreds of watts have not lost their relevance. These systems work separately [2] or in the microgrid network [3]. Autonomous power supply systems based on photovoltaic modules are widely used in the organization of traffic for the illumination of signs, traffic lights, as well as at public transport stops for charging various gadgets [4]. Such systems are widely used in agriculture [5] too, both in cattle breeding [6] and in crop production [7]. The use of low-power systems in urban environments is due to the successful development of energy-efficient electronics and lighting equipment at low direct current. Solar photovoltaic modules provide precisely this electric energy type without power losses for conversion. As a result, technology “building-integrated photovoltaics” [8,9] and its economics [10] are developing. In the framework of this technology a tendency of “solar panel window” has been formed, which uses windows of buildings to generate electricity from the solar radiation [11].

This tendency has several approaches. First of them – use of rare-earth luminophores for down-conversion of ultraviolet radiation of solar spectrum in near infrared range for photovoltaic conversion by $CuInSe_2$ cells. Up to 65% of the visible spectrum passes through the window [12]. Another approach is due to thermochromic transformation of the perovskites of different composition [13,14]. Under the influence of solar heating window loses its transparency, absorbs solar energy and generates electricity. These approaches have both advantages and disadvantages: small power-conversion efficiency, short life, environmental problems and others. For this reason, a simple solution remains relevant – to place standard silicon solar cells along the perimeter of the window [15]. Their number is determined by the needed photovoltaic power and it is necessary to take into account the direction (not always South) and position (not always optimal angle) and statistics of incoming solar radiation in region.

This paper presents the results of the study of the practical characteristics of the solar photovoltaic module mounted by a new sealing technology in the window frame and equipped with a block of lithium-ion batteries with a scheme of its charging from this module for the subsequent power supply of low-current electrical appliances. This design does not require a separate construction and attachment and has improved heat exchange parameters with the environment.

## 2. Design of the Window Solar Module

Technical requirements for the developed module include the following parameters:

- Output voltage 5.2 – 5.25 V;

- The capacity of the accumulator battery pack (ABP) 6.8 Ah;

- Position of the photoreceiver plane of the solar module – vertical;

- the peak power of the photovoltaic module should be enough to maintain the ABP charge level not less than 1/3 capacity during day light hours even in conditions of cloudy weather.

### *2.1. Analysis of the PV module required parameters*

One sided flexible Maxeon C60 (Sunpower corp.) solar cells (SC) of 125x125 (mm) with a peak power of 3.4 watts (insolation 1000 $Wm^{-2}$, temperature $25^oC$) were used as photovoltaic converters of solar radiation in the PV module.

The arrival of solar radiation on different oriented inclined surfaces is calculated with using of meteorological data and known methods for determining of the sunlight incidence angle θ on the plane in question at a given time [16]:

$$\cos\theta = \sin\delta \cdot \sin\varphi \cdot \cos S - \sin\delta \cdot \cos\varphi \cdot \sin S \cdot \cos\gamma + \cos\delta \cdot \cos\varphi \cdot \cos S \cdot \cos\omega + \cos\delta \cdot \sin\varphi \cdot \sin S \cdot \cos\gamma \cdot \cos\omega + \cos\delta \cdot \sin\gamma \cdot \sin S \cdot \sin\omega \quad (1)$$

where $\varphi$ – the latitude of the location; $\delta$ – the solar declination; $S$ – the slope of the surface of the module (the angle between the plane of the PV module and the horizontal plane); $\gamma$ – the azimuth of the receiving surface (for the receiving surface with South orientation $\gamma$=0, for the receiving surface oriented to the East (West), $\gamma$= – 90 ° ($\gamma$= 90°)), and to the North: $\gamma$=±180°); $\omega$ – hour angle ( angular displacement of the Sun measured from solar noon with respect to the local meridian due to the rotation of the Earth at a speed of 15° per hour).

Computer program in accordance with equation (1) was used to estimate total (direct and scattered) insolation and monthly photovoltaic energy generation of vertical photovoltaic panels, in kilowatt-hours per kilowatt of the installed peak power solar module, kWh│kW, (Table 1)

**Table 1.** Estimated photovoltaic power generation (kWh│kW) for vertical solar panels for the Moscow region

| Month (number) | South orientation | South-East (South-West) | East (West) |
|---|---|---|---|
| 1 | 13.5 | 12.3 | 9.8 |
| 2 | 36.1 | 30.9 | 22.1 |
| 3 | 66.0 | 58.7 | 45.8 |
| 4 | 60.1 | 58.0 | 49.1 |
| 5 | 71.2 | 74.9 | 71.8 |
| 6 | 66.5 | 71.9 | 73.2 |
| 7 | 70.7 | 74.7 | 73.3 |
| 8 | 66.4 | 66.3 | 58.8 |
| 9 | 54.3 | 48.8 | 37.8 |
| 10 | 36.7 | 30.6 | 20.3 |
| 11 | 24.9 | 19.7 | 10.8 |
| 12 | 15.9 | 12.9 | 7.4 |
| Annual amount | 582.3 | 559.8 | 480.3 |

In this case, the average long-term month amounts of solar radiation, entering the horizontal surface, for the Moscow region were used [17]. The program allows to estimate the amount of solar energy receipt on a panel surface with various schemes of orientation. Though the program allows to calculate other characteristics, for the purpose of this research only PV panel orientation was used. For comparison, Table 2 presents calculated data on the PV power generation of horizontal and inclined photovoltaic modules.

**Table 2**. Calculated photovoltaic energy generation (kWh│kW) for horizontal solar panels installed at an angle to the horizon for the Moscow region

| Month (number) | Horizontal surface | South orientation, tilt 35° – 40° |
|---|---|---|
| 1 | 11.5 | 13.5 |
| 2 | 24.2 | 33.6 |
| 3 | 55.5 | 70.2 |
| 4 | 77.7 | 86.4 |
| 5 | 112.9 | 115.3 |
| 6 | 116.7 | 114.3 |
| 7 | 116.4 | 116.2 |
| 8 | 91.0 | 98.4 |
| 9 | 58.0 | 69.1 |
| 10 | 29.0 | 39.5 |
| 11 | 13.0 | 22.2 |
| 12 | 8.2 | 13.6 |
| Annual amount | 714.2 | 792.4 |

For practical application and implementation of the specified technical requirements, the data of Table 1 were recalculated in accordance with equation (2) for the required area of the photovoltaic module (Fig. 1). The corresponding number of the above-mentioned solar cells is shown on the right axis.

$$S_{PV} = \frac{keU_{out}E_{st}s}{(E/n)p\eta} \quad (2)$$

In this equation:
e = 2.2 Ah – 1/3 of ABP capacity;
$U_{out}$ = 5.25V – electronic module output voltage;
E – PV power generation (in Wh) from Table 1;
$E_{st}$ =1000 W – standard peak power of the solar panel, which generate the energy E in the conditions of real insolation;
n – number of the days in the month;
p = 3.4 W – peak power of SC used;
s = $1.5 \cdot 10^{-2}$ $m^2$ – the area of SC used;
η – efficiency of the electronic module from Table 3;
k – the empirical coefficient of "building-integrated photovoltaics" technology, taking into account temperature change, misalignment of electrical parameters under different insolation, the height of the building, the floor where the window with PV panel is installed, the possible environment (trees, other buildings) and other factors that can change the average insolation in a given location and not amenable to analytical evaluation; in the absence of these factors obviously k≈1, in our calculations, taking into account these circumstances and preliminary studies, as well as the need for the output voltage of the module more than 9 V, we assumed k=3.

From Fig. 1 it can be seen that from March to September six solar cells provide the required power generation at the vertical position of the module regardless of the geographic orientation in the sector 180 degrees from East to West through the South. In other months these dependences are diverging significantly and in December the module of the South orientation must use 22 SC. But for the East (or West) directions vertical PV module must contain at least 47 SC.

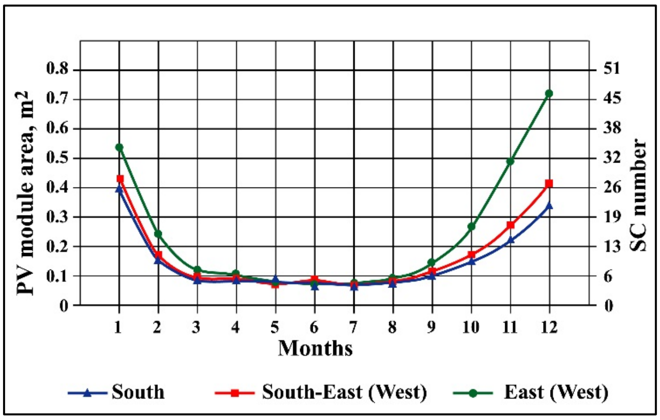


**Fig. 1.** Monthly dependence of the photovoltaic module area for the charge of 1/3 lithium-ion battery pack capacity during one day

Comparison of the Tables 1 and 2 data shows that for an attic window, the frame of which can be at a more favorable angle as regards the front of the solar radiation flux, the situation is considerably improved. In this case, you can proportionally reduce the area of PV module or get more photovoltaic energy.

The decision on the choice of the number of SC used obviously faces contradictory requirements – on the one hand, the need to maintain the ABP charge in winter months requires an increase in their number, but on the other – this reduces the light aperture of the window frame. In addition, to operate the ABP charging scheme with double voltage of the lithium-ion battery, it is necessary to have the output voltage of the PV module not lower than 9.0V, i.e. 16 elements must be connected in series. On the basis of such analysis, 16 SC of 125x62 (mm) were used for the window photovoltaic module, the total area of which is equal to 8 standard SC. This allowed, as can be seen from figure 1, to meet the requirement of ABP charging from February to

October for most of the orientations, with the exception of those close to the East and West.

*2.2. Sealing Elements of the Module*

The choice of sealing technology of the PV module mounted in the window frame is one of the most important design decision. The main factor here is the chemical composition of the sealing material (filler). This technology should ensure that the following requirements are met:

- reliable adhesion to the material surface of the SC to ensure quality of optical and thermal contact in order to minimize reflection from the front surface of the solar cells and effective heat elimination;
- light and heat resistance when exposed to sunlight and overheating;
- absence of structural elements and impurities in the filler, which have a destructive effect on the SC surface materials and contact elements, that shorten the life;
- protection of SC from mechanical damage and moisture;
- environmental safety of application.

At present the most widely used thermoplastic filler is based on the copolymer ethylene vinyl acetate. However, this material has disadvantages in almost all of the above requirements, either immediately (for example, in terms of ecology) or after a certain period of time (optical characteristics and destructive effects). For these reasons, the sealing using a two-component liquid polysiloxane compound, which is structured at room temperature in a low-modulus gel was used.

The basics of this technology were developed by I.S. Persits group under the leadership of D.S. Strebkov [18]. The research [19] showed the advantage of this technology over ethylene vinyl acetate. The essence of the proposed method of sealing (Fig.2) is that the polysiloxane compound (2) fills the space with solar elements (6) placed between the back side of the outer glass (1) of the window frame and the sheet of polycarbonate (3) which is attached to it by thermoplastic spacer (7). The inner glass (4) of the frame is tightly sealed (5). In the direction A the solar radiation falls on SC and in the direction B the solar radiation passes through the window.

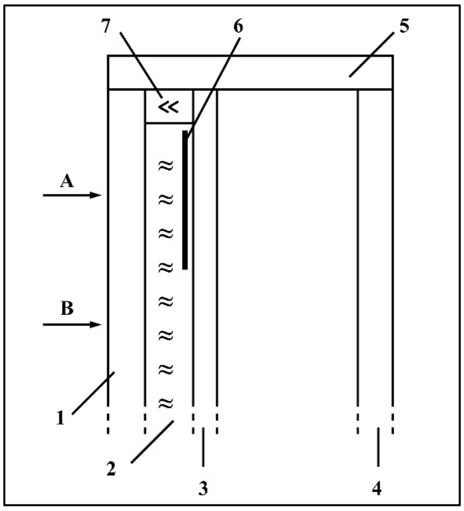


**Fig. 2.** Chart of the window frame design with photoelectric module

This makes it possible to provide a sufficiently efficient heat sink (thermal conductivity coefficient of polysiloxane gel 0.18 $Wm^{-1}K^{-1}$ against 0.13 $Wm^{-1}K^{-1}$ for ethylene vinyl acetate). The gel much better absorbs the mechanical stresses during thermal cycles – the linear coefficient of thermal expansion is of $2.5 \cdot 10^{-4}$ $K^{-1}$ and $4 \cdot 10^{-4}$ $K^{-1}$ respectively and Young's modulus (of elasticity) 0.006 N $mm^{-2}$ and 10 N $mm^{-2}$.

Fig.3 shows standard window frame with built-in solar cells (1, front and rear view) and devises on the rear of the frame: LED strip (2) and electronic unit with integrated ABP and USB connector (3).

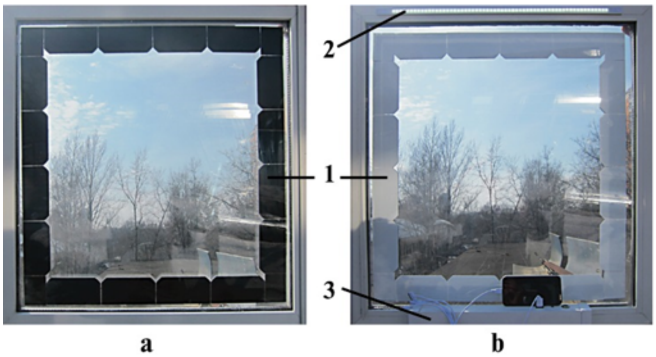


**Fig. 3.** Window frame with integrated photovoltaic module (a – external view, b – internal view)

*2.3. Optical properties of the glazing in the spectral range of solar radiation*

The optical characteristics of this multilayer structure are of obvious interest. For this purpose, the reflection coefficient in direction A (Fig. 2) and the transmittance coefficient in direction B were measured. The results of measurements on the SPECORD 205 spectrophotometer are shown in Fig. 4 and Fig. 5.

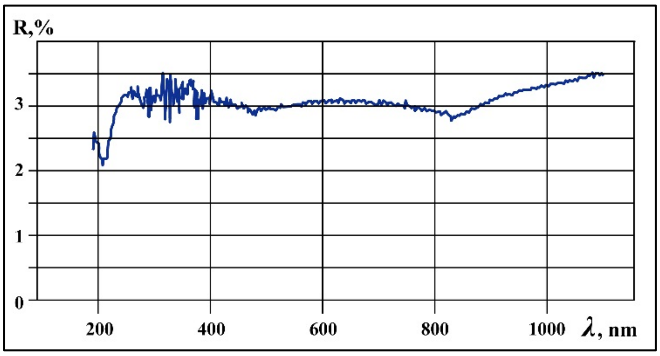


**Fig. 4.** Reflection spectrum in direction A of the window frame

It can be seen from the above spectral dependences that the reflection coefficient from the "outer glass-gel-SC" structure (Fig. 4) is about 3%, so more than 90% of the solar radiation energy is absorbed by the photoconverter (the long-wave edge of silicon absorption at room temperature is at the wavelength approximately λ=1050 nm).

Fig. 5 shows the transmission spectrum in direction B (curve 1) and the transmission spectrum of a standard single-chamber glass frame (two glasses, curve 2).

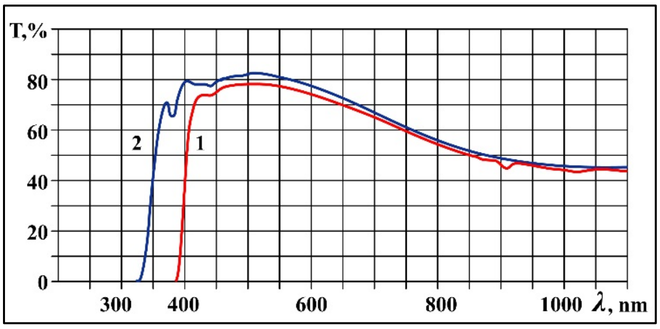


**Fig. 5.** Transmission Spectra of the window frame

The main difference between these curves is the shift of the short-wave edge of the spectrum in the long-wave direction in the region λ=400 nm for the structure with polysiloxane gel and polycarbonate. However, this does not affect the ambient illumination behind the window, because the shift occurs in the ultraviolet region of the spectrum, where the photosensitivity of the human eye is almost zero. Indeed, the sensitivity of the eye is a fraction of percentage at λ=400 nm, only 3-4% in the λ=450 nm region and increases to 100% in the green spectral region at λ=550 nm.

*2.4. Design of electronic circuits charging lithium-ion ABP and feeding the load*

In order to meet the technical requirements for ABP output voltage (pair of accumulator batteries in series) and capacity (two pairs connected in parallel) batteries type NCR 1850B were used.

To convert current and voltage of the photovoltaic module, an electronic circuit was developed and manufactured (Fig. 6). It consists of two electronic modules (with pulse conversion) [20] and ABP. The voltage of the PV module (1) is 9.0–9.3 V. It enters into the electronic module (2), the main function of which is to charge the ABP (3), working in buffer mode with the voltage level of 7.4-8.4 V. The electronic module (4) converts the constant voltage of the storage batteries to provide the load (5) with the stabilized output voltage of 5.25 V. The maximum load current is 3 A.

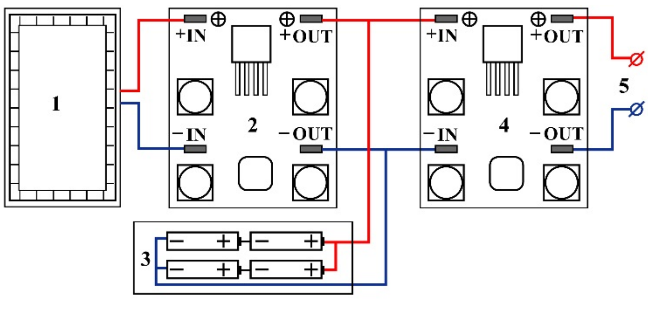


**Fig. 6.** Chart of electronics

Electronic modules 2 and 4 are made according to the same electric circuit (Fig.7) and are adjustable pulse stabilizers. The output voltage is regulated by the variable resistor R1.

The required charge level of the lithium-ion ABP, with a maximum voltage of 4.2 V per cell, is set by a resistor of 47 K.

For charging mobile phones, smartphones, tablets, etc. USB 2.0 connector is being used with output voltage in the range of 5.2 – 5.25 V. For this purpose, in the circuit of the electronic module 4 resistor R1 is used the nominal resistance 3.6 – 3.9 K.

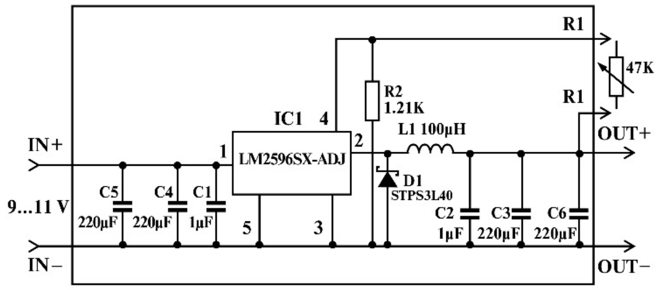


**Fig. 7.** The electric circuit of the electronic module 2 (4) with varying R1 resistor 47K (3.6–3.9K)

The electronic modules are made on a board with an aluminum substrate, which allows to have the output current up to 2 A for a long time without additional heat sink, unlike linear stabilizers. The device has thermal protection and output current limitation about 3A. The output voltage should not exceed the input voltage. The full technical characteristics of the electronic module are shown in Table 3.

**Table 3.** Technical characteristics of the electronic module

| | |
|---|---|
| Input voltage, (V) | not more 40 |
| Output voltage, (V) | 1.2 – 37 |
| Output current over the entire voltage range, (A) | not more 3 |
| Restrictions of the output current (A) | 3 – 4 |
| Conversion frequency, (kHz) | 150 |
| Efficiency (depends on input and output voltage and current; Li-ion ABP charge specific) (%) | 85 – 90 |
| Operating temperature range, (°C) | – 40 – 105 |
| Module dimensions, (mm) | 43×40×12 |
| The weight of the module, (g) | 15 |

After the assembly of the entire system, studies were carried out on the dependence of the charging current ABP on the nature solar illumination P ($Wm^{-2}$) at different levels of the initial voltage at ABP, U (V) (Fig. 8): 1 – U=6.3V ( ~ 20% of capacity); 2 – U=6.5V ( ~ 25%); 3 – U=6.9V ( ~ 40%); 4 – U=7.2V ( ~ 50%); 5 – U=7.5V ( ~ 60%); 6 – U=7.8V ( ~ 80%). The illumination was measured by Benning SUN2 tester. As expected, the charging current ABP decreases with increasing degree of initial charging state of the battery.

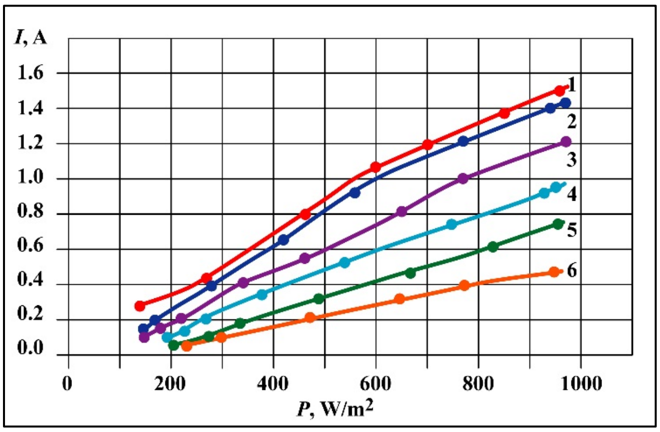


**Fig. 8.** Dependence of the charging current ABP on the illumination at different initial voltage at ABP

However, at the low charge level of ABP, even in low light conditions (150-200 $Wm^{-2}$, with dense clouds) the charging current (~ 0.3 A) is sufficient to maintain the charge level at 1/3 of the ABP capacity (2.2 Ah) within 7-8 hours of day time. Thus, the technical requirements are met. Based on these results, it can be concluded that the choice of the empirical coefficient k=3 in equation (2) is correct.

On the basis of the obtained experimental data for practical application, the dependence of the 1/3 capacity ABP charge time on the weather and season is constructed (Fig.9), that is the dependence of the energy storage time for one smartphone depending on the weather and season is added.

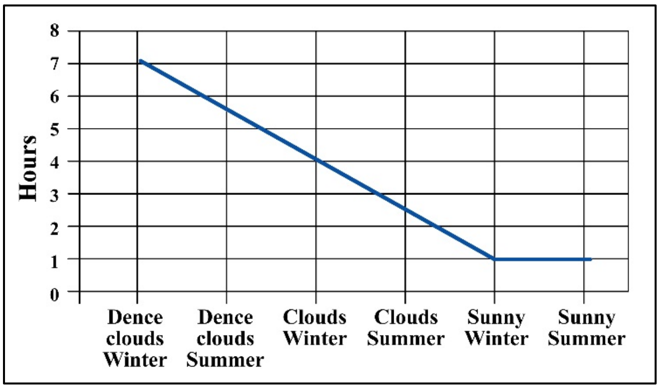


**Fig. 9.** The dependence of the 1/3 capacity ABP charge time on the weather and season

## 3. Results

The PV module constructed is a tape of solar cells mounted at the perimeter of the window frame using a new sealing technique. It charges the lithium-ion battery located in the electronic unit together with the electronic charging circuit. The LED tape on the frame is fixed. The switch push-button of the LED tape, ABP charge sensor and USB output jack are set on the electronic block.

The study of optical characteristics showed no losses in the visible spectrum compared to a normal window except for shading by solar cells. During the tests the system showed the following characteristics:

| | |
|---|---|
| Peak photovoltaic power, (W) | 27 |
| Maximum capacity of the AKP, (Ah) | 6.8 (~*3 smartphones*) |
| Output voltage, (V) | 5.2 – 5.25 |
| Shading of the light opening by the solar elements tape, (%) | 37 |

The power of the photovoltaic module is enough to maintain the ABP charge level not less than 1/3 capacity during day light hours even in conditions of cloudy weather.

## 4. Conclusions

The article presents the results of the development and research of the photovoltaic module design integrated into a standard window frame as part of "solar panel window" technology for building-integrated photovoltaics.

Basing on the theoretical approaches and best practices analyses of using this technology for low-power building-integrated photovoltaics systems, the design described allows to generate electricity from the solar radiation without losses for conversion.

The essential advantage of this design is that the photovoltaic module, being placed in a double-glazed frame, does not require additional constructions for sealing and decoration, as well as devices for placement and fastening. In addition, the service life of the window solar panel must correspond to the service life of the window (or building), which exceeds the service life of a conventional PV panel. The sealing method using a two-component liquid polysiloxane compound, structured at room temperature in a low-modulus gel provides increased service time [19], efficient heat sink and effectively absorbs the mechanical stresses during thermal cycles. This is the difference of window solar panel from the ordinary PV panel.

The measurements show flexible interaction of PV module with extended service time, electronic unit and accumulator battery pack operating in buffer mode, under different light conditions, the ABP degree of charge and energy consumption.

Though this paper describes a small-scale solar window structure, the algorithm used in this work for the development, creation and research of solar photovoltaic modules of built-in type can be used for other small-scale systems, taking into account different illumination intensity, room space, windows sizes and other parameters.

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