sciendo RIGA TECHNICAL UNIVERSITY 1862
Electrical, Control and Communication Engineering
ISSN 2255-9159 (online)
ISSN 2255-9140 (print)
2019, vol. 15, no. 1, pp. 30–38
doi: 10.2478/ecce-2019-0005
https://content.sciendo.com

Study of Load Characteristics of Various Types of Silicon PV Panels for Sustainable Energy Efficient Road Pavement

Antons Patlins[*] (*Leading Researcher, Institute of Industrial Electronics and Electrical Engineering, Riga Technical University, Riga, Latvia*),
Andrii Hnatov (*Professor, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine*),
Shchasiana Arhun (*Associate Professor, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine*),
Hanna Hnatova (*Student, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine*),
Vasiliy Migal (*Professor, Kharkiv Petro Vasylenko National Technical University of Agriculture, Kharkiv, Ukraine*)

***Abstract* – This paper presents a new approach to the creation of innovative roads having sustainable energy efficient road pavement as their basis. It is a new type of intelligent roads that is able to service itself and provide power, i.e. it is also a renewable source of electricity. It is planned to use the studies on the PV panels in sustainable energy efficient road pavement to determine their load parameters. The work used the methods of mathematical analysis and theoretical electrophysics to carry out the studies on load characteristics of various types of silicon PV panels in order to define the most effective panels from the point of view of generated electrical energy load resistance values. The analysis of the obtained results of the experimental research has shown that in order to make the operation of PV panels of series FS-100M and FS-110P most efficient, their load must be maintained within 3–3.5 Ω range. If load resistance exceeds the specified limits, the work of PV panels of this series will be ineffective. The road having a sustainable energy efficient road pavement is able to track road conditions, traffic, weather conditions and react quickly to their changes. It is shown how road markings can change dependance on road conditions.**

***Keywords* – Energy efficiency; Photovoltaic systems; Renewable energy sources; Solar energy; Solar panels.**

I. INTRODUCTION

According to the information of the international organization REN21 (Division of the International Renewable Energy Agency), 287.5 billion USD have been invested in RES only during 2016. Alternative energy is being actively developed in China, UK, USA, Japan, as well as in a number of European countries [1]. Many power plants operating on RES are commissioned every year. The share of alternative sources in the established annual capacity in the world in 2017 exceeded 50 %. According to “Global Energy” experts, by the year 2100 the share of oil and coal in the global fuel and energy balance will be 2.1 % and 0.9 %, respectively, and more than a quarter of the world’s electricity would be produced by the sun. According to the long-term forecasts of Bloomberg New Energy Finance (2017), it is expected that the share of wind and solar power generation by the year 2040 will increase six times and exceed all other types of energy.

Solar energy is one of the most dynamically developing branches of renewable energy. It is based on the transformation of solar radiation into electrical energy. Solar energy is ecologically clean, because it has no harmful effect on the environment. Its development is stimulated not only by the environmental but also by economic factors, namely, the constantly increasing prices for traditional energy sources (coal, oil, peat, gas), the reduction of the cost of equipment for solar stations with increased productivity. This generally leads to a reduction in the cost of electricity generated. Also, a significant reduction in the cost of electricity, which is generated from solar energy, is attributable to the improvement of the technology of photovoltaic modules. In more than 30 countries, the energy generated by the sun has become cheaper than that obtained from fossil sources. Tau Island (American Samoa) is the most remarkable example of success of the application of solar technologies. Previously, Tau was entirely dependent on the supply of diesel fuel, and after the installation of modern solar power plants became completely energy-independent [2].

In solar energy research, it is possible to distinguish two types of transformation of solar power: direct conversion of solar radiation into electric current and a multi-stage one (i.e. conversion of solar energy into heat, then into mechanical work, and then into electricity). So far, better results have been achieved in the second area – industrial solar units with concentrators, turbines or Stirling engines show quite a good performance (efficiency can reach ~31 %) [3].

Such solar units are extremely complicated and expensive. They are effective in the conditions of very high solar activity and are not yet very widely used in the world. Therefore, direct converters of solar radiation – Photovoltaic (PV) panels occupy the leading position in the world of solar energy by application. The productivity of standard industrial solar panels (SP), depending on the technology, ranges from 5 % to 22 % today. But technologies are being developed and enhanced – new solar cells (SC) with efficiency within ~40 % are being developed and tested [3].

---

[*] Corresponding author.
E-mail: Antons.Patlins@rtu.lv

The purpose of the work is to study load characteristics of different types of PV panels in order to determine the most effective value of load resistance from the point of view of the generated electric energy. The results of the research will allow using the panel data in the innovative sustainable energy efficient road pavement, which serves as a modern smart road and renewable energy source, with the maximum possible efficiency.

II. DIFFERENT TYPES OF PV PANELS

To date, scientists have invented a fairly large number of different types of PV panels. These panels differ both in terms of the manufacturing technology and materials from which they are produced.

PV panels based on silicon are the most common type of panels available in the modern market. The vast majority of cells of the solar transformers of modern standard PV panels (or photo modules) are made of mono-crystalline (c-Si), or polycrystalline (mc-Si) silicon. To date, such silicon photovoltaic modules occupy about 90 % of the market of photovoltaic converters, of which about 2/3 are polycrystalline silicon and 1/3 are mono-crystalline. Then there are solar modules, whose photocells are made using thin-film technology – the method of deposition, or spraying photosensitive substances on different substrates. The essential advantage of the modules of these elements is lower production cost, because they need about 100 times less material than silicon plates. Multi-transient SCs from the so-called tandem or multifunction cells are the least common [3].

Mono-crystalline PV panels are the silicon cells, which are joined together. The purest silicon obtained by the Czochralski method is used for their manufacture [3]. After solidification, the finished mono-crystal is cut into thin plates of 250–300 μm in thickness and permeated with a grid of metal electrodes (Fig. 1a). The technology is relatively costly, so mono-crystalline panels are more expensive than polycrystalline or amorphous ones. This type of PV panel is chosen because of high efficiency coefficient (about 17–25 %).

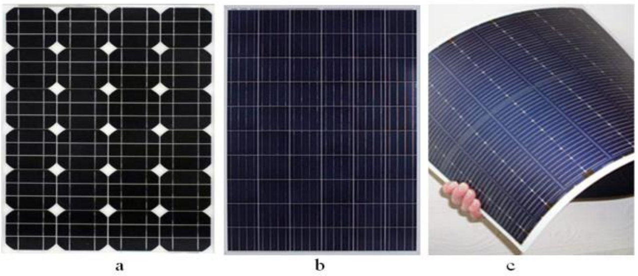


Fig. 1. Silicon PV panels: a – monocrystalline; b – polycrystalline; c – amorphous.

In order to obtain poly-crystals, silicon melt is slowly cooled. Such technology requires less energy input; hence, the cost of silicon obtained by it is lower. The only but significant drawback is that polycrystalline PV panels have lower efficiency coefficient (12–18 %), Fig. 1b. The reason is that inside the poly-crystal the spaces with granular boundaries are formed, which cause a decrease in the efficiency of the elements [5].

If the division is made depending on the material used, then the amorphous panels are made of silicon, and if they are divided according to the production technology, they belong to the film type (Fig. 1c). Thin-film technologies are often regarded as the future of photovoltaic power, despite the fact that at present about 83 % of all solar modules produced in the world are crystalline. Nevertheless, the technology of thin-film modules is developing very quickly and in several directions. The very first technology of thin-film modules, which received commercial distribution, is the film of amorphous silicon. Now the modules of the 3rd generation are already being developed. The first generation with single-transition solar cells had a small service life (up to 10 years) and efficiency of 4–5 %. The second generation also had single-transient elements, but their service life was almost equal to the life of the crystalline elements, and the efficiency was 6–8 %. The third generation can include the most modern multi-transient thin-film elements, which allow achieving even greater efficiency (up to 12 %) with long service life [3].

Flexible silicon-based photovoltaic cells in comparison with crystalline analogues have a number of advantages:

- better performance under elevated temperatures;
- ability to produce electricity at low level of illumination;
- possibility of concealed installation;
- lower cost of the unit of produced energy due to lower costs for the production of equipment;
- simplicity and manufacturability of the production process;
- simplified installation, replacement and maintenance at the expense of insignificant thickness and increased flexibility;
- reduced effect of shading.

The low efficiency indicator is the main negative feature of using amorphous panels. In ideal conditions, efficiency of panels on the basis of amorphous silicon is two times lower than that of similar polycrystalline modules.

In addition to the types of silicon PV panels described above, there are also their hybrids. So for a greater stability of the elements, a two-phase material is used, which is amorphous silicon with inclusions of nano- or micro-crystals. The properties of the obtained material are similar to the polycrystalline silicon.

The second point of the given classification is the film PV panels (classified according to the production technology). The development of film panels is explained by the need to reduce the cost of PV panels and improve their performance and technical characteristics. Since they are less widespread and less commonly used, in their description we will only enumerate their main types [3]:

- panels based on CdTe;
- panels based on copper-indium selenide;
- panels based on polymers.

The analysis of different types of PV panels allows making a conclusion that at the moment poly and mono-crystalline Photovoltaic modules are the most suitable constituent elements to be used in sustainable energy efficient road pavement. PV panels on the basis of data modules have received the greatest distribution and, as a result, are most acceptable by the triple ratio: price-quality-efficiency. Based on this, the same type of poly and mono-crystal panels, which currently are the most widespread in the market, was chosen for further research.

III. MAXIMUM POWER POINT

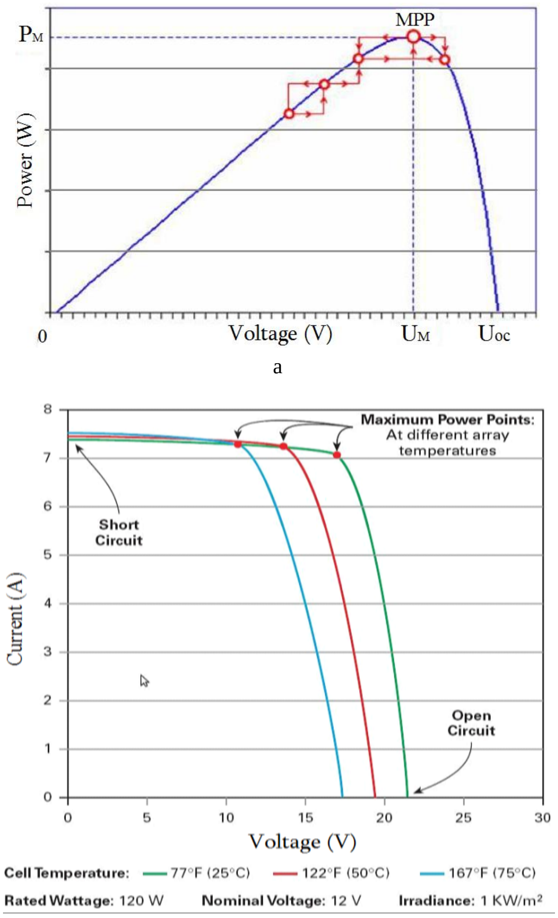
In [3], the basic requirements for efficient work of SC are formulated. First, in order to ensure the absorption of the maximum possible amount of radiation energy entering the SC, the optical absorption the coefficient of the photoelectric layer should be close to one. Secondly, photogenic carriers must effectively cumulate on the contact electrodes on both sides of the photovoltaic layer containing the p-n junction. Thirdly, the SC must have an optimal barrier height in the p-n junction, sufficient to provide a high voltage value of idling U_{oc}, but not very large. This is necessary in order to ensure that the solar spectrum photons are not absorbed. Fourth, the full resistance of the external circuit, connected serially with the SC, must meet the criterion of transmitting the maximum power to the load, i.e. be equal to the resistance of the SC itself.

Compliance and implementation of the first three conditions mentioned above mainly depend on the manufacturers of the PV panels. This is determined by both production technology and the choice of material for the production of panels. Execution of the last condition depends directly on the consumer. These are hardware and software tasks that control the load and performance characteristics of PV panels during their operation. That is, to satisfy the criterion of transmission of maximum power from PV panels to load, it is necessary to monitor the ratio of internal resistance of the panels and load. In ideal conditions they should be equal [3].

In view of the foregoing, it is clear that the issue of tracking PV panels load characteristics, which may be part of complex systems, is sufficiently relevant. Consequently, deviation from the optimal parameters, for example, regarding the mentioned ratio of active resistances, can significantly reduce the efficiency of the system as a whole. It should also be noted that the efficiency of PV panels as part of complex systems such as sustainable energy efficient road pavement will be influenced by a lot of other factors. Thus, in [7] the influence of pollution silicon PV panels on their textural, chemical and optical properties is studied. The authors of the article [8] consider the influence of different parameters on the efficiency of energy conversion by photovoltaic modules. It has been also shown that even dust brought by the wind can reduce the efficiency of the modules by ~2.2 %.

Of course, tracking external factors that affect the performance of PV panels is an important task. However, it is already quite well researched and appropriate methods and approaches to its solution have been developed, for example, in the quoted works [7], [8]. Therefore, we focus on the electrochemical processes that occur in the photovoltaic modules during their operation. From this point of view, to increase the efficiency of PV panels a solar controller with the Maximum Power Point Tracking (MPPT) should be used. Such controller will allow generation of more electric power compared to the Pulse Width Modulator (PWM) controllers. This is especially topical for solar high-power stations consisting of dozens (hundreds) of PV panels. The MPPT controller continuously monitors the current and voltage on a PV panel and determines a current-voltage pair which will guarantee the maximum power of a PV panel. The point of maximum power can be calculated in a number of ways. In the simplest case, the controller gradually decreases voltage from the point of idle run to the voltage on the battery. The Maximum Power Point (MPP) will be somewhere between these values [3], [6], [9], [10].

The position of MPP depends on several parameters: module lighting conditions, temperature, diversity of the modules being used, etc. The controller monitors the values of electric energy power generated by PV panels on each side of the MPP. If the power increases, it moves to work in this point, Fig. 2a [9].



a

b

Fig. 2. Maximum Power Point: a – determination of MPP; b – MPP depending on the temperature of a PV panel [9].

Fig. 2b shows how the voltage in MPP can change with different module temperatures. The higher the temperature of the solar module, the less voltage is on the module and, consequently, the generation of energy by PV panel. At certain moments, the point of maximum power can be lower than the voltage on the battery, and in this case the operation of MPPT controller will be ineffective (in terms of power generation) compared with the PWM controller. Shading of a PV panel has the same effect.

So, when using MPPT panel, a PV panel should be commutated to higher voltage. Most controllers can monitor the point of maximum power over the wide range. Such solution will also provide the opportunity to increase energy generation by PV panel at lowered lighting. However, big difference between input and output voltage must not be allowed, because it results in the decrease of the controller efficiency coefficient.

It is worth noting that using MPPT controller is efficient when the power of PV panel is over 200 W. It is stipulated by economic factors and proved by both the authors' research and publications [3], [10]. That is, when using low-power PV panels, load resistance should be monitored in order to maintain the operation of PV panel with high efficiency coefficient. Also, knowing how the load and, correspondingly, the generated power on the output of a PV panel changes, the necessary controller can be chosen. It can increase the PV panel operation efficiency and, consequently, will allow generation of more electric energy.

In this paper, we will present the results of the first of the planned studies, namely, the volt-ampere characteristics and the dependence of the generated electricity on the active load that is connected to the PV panels (it corresponds to the real conditions of their operation). This will allow determining the load value at which the highest value of the generated electric power will be observed, and therefore the criterion for transmitting the maximum power to the load will be implemented [3].

Experimental studies of mono-crystalline and polycrystalline PV panels were performed on the modules, the technical characteristics of which are presented in Table I. This type of PV panels is the most affordable in the modern market and can easily be integrated into sustainable energy efficient road pavement.

TABLE I

TECHNICAL CHARACTERISTICS OF PV PANELS

Parameter	Monocrystal	Polycrystal
Model	FS-100M/100W	FS-110P/110W
Weight, kg	8.45	9.18
Nominal power, W	100	110
Nominal voltage U_{nom}, V	17.50	17.50
Nominal current I_{nom}, A	5.72	7.72
Voltage at open loop U_{oc}, V	21.60	21.60
Short circuit current I_{sc}, A	6.46	7.10
Dimensions H × L × W, mm	1070 × 670 × 35	1170 × 670 × 35

Based on the given technical characteristics, the internal resistance of the investigated panels can be determined:

$$R_{\text{in}} = \frac{U_{\text{oc}}}{I_{\text{sc}}}. \quad (1)$$

According to (1), the internal resistance of the panels is $R_{\text{in (mono)}} = 3.34\ \Omega$; $R_{\text{in (poly)}} = 3.04\ \Omega$. Knowing the internal resistance of the studied PV panels, the required load resistance can be determined (considering their sequential-parallel connection). With their equality, the most efficient work of PV panels will be ensured.

A filling factor FF is another important parameter of the SC. It is a parameter which, in combination with short circuit current (photocurrent) and idle voltage, determines the maximum output power of the SC. FF is determined as the ratio of the nominal power of the SC to the product U_{oc} by I_{sc}, and is equal to the maximum square of the rectangle, which can be entered into the volt-ampere curve of the SC [3].

$$FF = \frac{I_{\text{nom}} \cdot U_{\text{nom}}}{I_{\text{sc}} \cdot U_{\text{sc}}}. \quad (2)$$

According to (2), the coefficient of filling of the panels under consideration equals $FF_{\text{(mono)}} = 0.72$; $FF_{\text{(poly)}} = 0.88$.

Volt-ampere characteristic and load characteristic (dependence of the power of the panel on the load current) are among the most important parameters of the PV panels, which consist of many parallel and consistently connected SCs. Manufacturers of the PV panels must determine these characteristics in accordance with the approved methods, which are given in [12], [13]. The calculation of the volt-ampere characteristic can be made by the expression:

$$I = I_f - I_0\left(\exp\left[\frac{q}{AkT}\left(U + IR_l\right)\right] - 1\right), \quad (3)$$

where: I_f – photocurrent, A; I_0 – saturation current, A; q – charge, C; A – coefficient obtained when comparing theoretical and experimental characteristics, takes the value from 1 to 5; k – Bolzman constant; T – absolute temperature, K; I – current in SC, A; U – voltage, V; R_l – successive resistance of SC, Ω.

IV. EXPERIMENTAL RESEARCH

1) A sunny day was chosen (July), the time corresponds to the higher intensity of solar radiation (city of Kharkiv), range 12.30–14.00 hours.
2) The active load was chosen for a PV panel. It corresponds to the real conditions of PV panel operation. The loads connected to the PV panel according to the circuit of the experiment (Fig. 3) change within the range from 2 to 10 Ω. The change step is 0.5 Ω.
3) The temperature on the surface of the PV panel is ~45 °C.
4) The measurements are made during the short-term locking of the load range of the PV panel, which allows getting rid of the dependence of the load resistance on the temperature.
5) Measurements of current and voltage in accordance with Fig. 3 are made by digital multimeters APPA 82.
6) The angle of inclination of the PV panel is 35–40° (the optimal angle for the given latitude is chosen).
7) Measurements were made cyclically – in forward and reverse directions (to reduce the error), which corresponds to the gradual increase and decrease of load resistance.

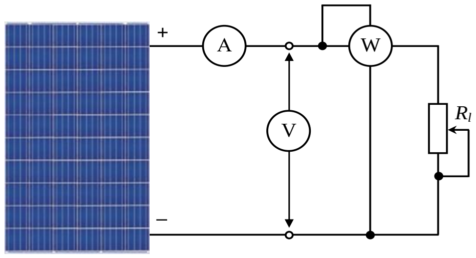


Fig. 3. The circuit of the experiment.

In the course of experimental research, a series of experiments on the measurement of volt-ampere and load characteristics on polycrystalline and mono-crystalline PV panels was performed. The averaged values of the measured characteristics are presented in the form of graphs in Fig. 4, where A, B are polycrystal (A corresponds to the direct measurement method, B – the measurements in the opposite direction); C, D – monocrysral (C corresponds to the direct measurement method, D – the measurement in the opposite direction)

The range of active load resistance ranged from 2 Ohms to 10 Ohms. Measurements outside this range are not practical, as the panels under study will generate low-efficiency electricity. The latter is quite clearly visible considering the measured characteristics, Fig. 4.

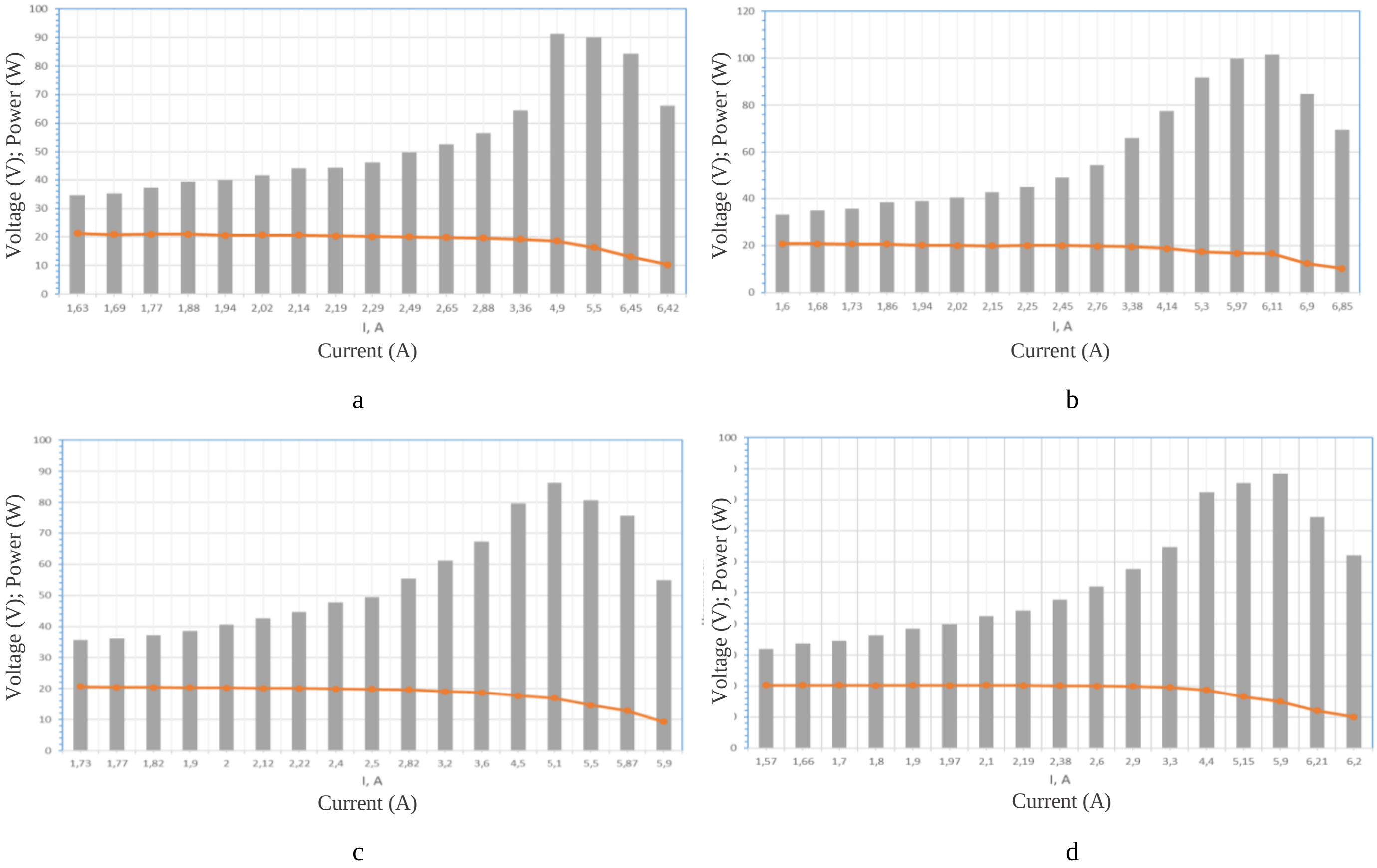


Fig. 4. Volt-ampere and load characteristics of the PV panel: a, b – polycrystal; c, d – monocrysral.

By analysing the measured volt-ampere and load characteristics (Fig. 4), it can be concluded that the photovoltaic panels being examined generate electricity with the greatest efficiency in the active load range from 3.0 Ω to 3.5 Ω. That is, if these types of PV panels are used for sustainable energy efficient road pavement, it is necessary to maintain the load in the specified range of resistances, considering the electrical circuits of their connection. If PV panels with a load that goes beyond the specified range are used, their work becomes ineffective. The latter is explained by the fact that going beyond the set limits of load resistance, a PV panel will work with low efficiency coefficient, meaning that it will generate much less electric energy (with respect to its nominal values).

The obtained results quite coincide with the above stated criterion of transmitting maximum power to the load. In accordance with the given technical characteristics, the internal resistance of the PV panel calculated for a single crystal battery is 3.34 Ω and for the polycrystalline – 3.04 Ω.

If the investigated types of PV panels should be grouped into the systems with the corresponding serial-parallel connection, then the internal resistance of the PV panel system must be determined. Then the load connected to such a system must meet the criterion of transmitting the maximum power and be calculated taking into account that one mono-crystalline PV panel has an internal resistance of 3.34 Ω and a polycrystalline PV panel – 3.04 Ω.

Summarizing the conducted analysis of experimental research, it is necessary to note, that heating of photovoltaic modules also influences the efficiency of generation of electric power, i.e. the higher the surface temperature of the PV panels, the lower its efficiency is [9].

It is also necessary to consider the fact that sustainable energy efficient road pavement will be in a horizontal state, i.e. the possibility to adjust the angle of the photovoltaic modules in relation to the solar radiation is not foreseen (of course, if only the terrain does not contribute to this, forming a certain slope of the road). To determine the volt-ampere and load characteristics of the PV panels studied (Fig. 4), the inclination angle was 35–40°. These measures have been taken specifically to obtain complete information on the electrical capabilities of this type of PV panels.

V. SUSTAINABLE ENERGY EFFICIENT ROAD PAVEMENT

The pace of development of innovative technologies is growing as science and technology develop. This is especially noticeable in recent times. And it may seem that new technologies cannot cardinally change anything in road construction any more, but modern realities show absolutely the opposite – new materials are invented, the existing materials are improved, and their creation and application technologies are developed. Technical possibilities allow achieving such practical results, which were unimaginable some years ago, for example, using new technologies it is possible to improve technical characteristics of the PV panels, to increase their efficiency and to reduce cost. This also concerns sustainable energy efficient road pavement.

As it is known, different technologies for road and road construction have already been presented.

For example, in the Netherlands a small section of the route (500 m) was built, where the road is marked with a special paint containing “photo-luminising” powder. During the day, this mark-up charges, and in the dark glows green. In this case, there is no need for street illumination [14].

No less interesting is the project of the Dutch company Volker Wessels, which is working on the project of plastic pavement [15]. This project embodies the concept of plastic waste roads. The plastic highway is analogous to the roads made of concrete. It is envisaged that this road should be quickly mounted on site from separate panels. In this case, some of them will be hollow. They will include cables, pipelines, collectors, and other infrastructure elements.

At the moment we know quite a lot of such solutions and technologies, the main ones are described in [4], [16]. However, the most promising, in our opinion, are the so-called smart roads [17], [18]. These roads are collected from individual slabs, which are combined into one single system and have great functionality, ranging from electricity generation to full self-service.

The results of the experimental studies and their analysis reveal one of the possible ways of using the sun energy for sustainable energy efficient road pavement.

The solution of sustainable energy efficient road pavement allows producing green energy for additional street lighting using LED technologies with acceptable monitoring. Measurement and monitoring of electrical energy consumption enable economical relationship between the consumer and electricity supplier. Development of local energy consumption monitoring system is offered in [19]. On the other hand, integration of renewable energy sources and LED luminaries in DC based street lighting grid is offered in [20] and after performing of some modifications could be used in the framework of the current solution.

Sustainable energy efficient road pavement offered by the authors refers to alternative sources of electricity and road construction. It can be used for prefabricated pavement building and for transforming the kinetic energy from the pressure of vehicles on the road and solar energy into electrical energy.

Sustainable energy efficient road pavement is integrated into a single system and assumes autonomous operation of the road irrespective of energy sources (see Fig. 5, Fig. 6). This system possesses quite wide functionality, which is not inferior to modern road coverings. This is described in more detail in paper [16]. In addition to standard road functions, sustainable energy efficient road pavement is capable of operating as an autonomous renewable energy source that not only provides its own power needs but is also capable of generating electricity for other (not related to the drone or its infrastructure) consumers [16].

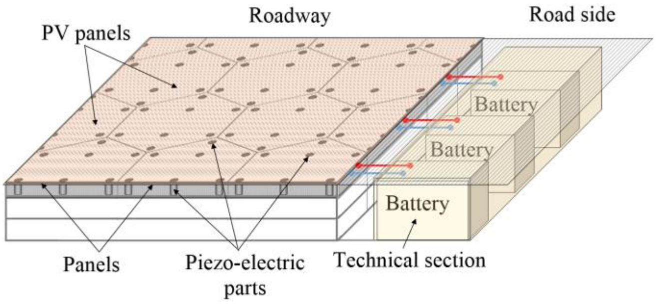
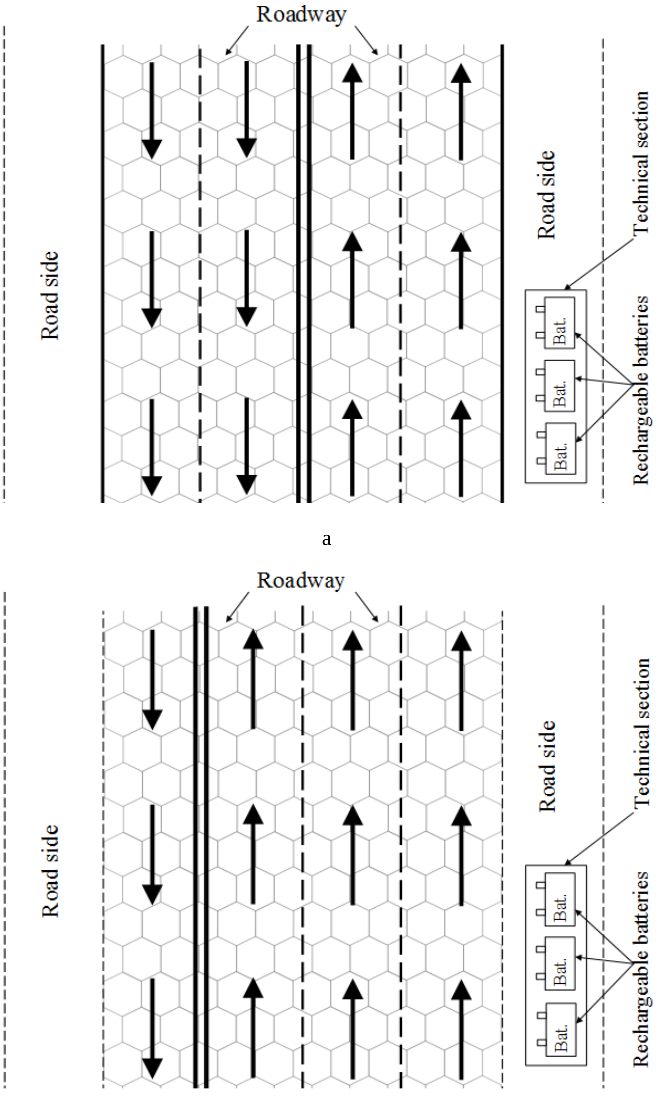


Fig. 5. The solution of sustainable energy efficient road pavement [26].

Each panel of the sustainable energy efficient road pavement consists of 3 basic components. The protective top cover is the first. This element of the panel is made of high-strength transparent plexiglas, on the inside of which there is an electric heating element in the form of heating fibres (analogous to car glass heating). At the basis of the supports, on which the protective top cover is located, piezoelectric elements (piezo-generators) are installed. They generate electricity when pressed. Solar panels (PV panels) with the built-in LEDs are the second element of the panel. In this element, the LEDs and PV panels are located on the entire plane of the panel. The base with electronic control boards and a cable channel is the third element of the panel. From five hundred to a thousand such panels are connected to the one accumulator batteries (battery). The battery is located in the technological compartment next to the sustainable road-pavement – on the roadside [3].

The main principles of operation of the sustainable road pavement system are well described in the authors’ research [4]. The assessment of the sustainable road pavement system electricity generation also has been considered as additional research result.

The above-mentioned analysis showed that the use of silicon PV panels is the most rational solution at the moment. This is due to their price and affordability in the market. In addition, modern technologies allow producing PV panels on a wide scale with a sufficiently high value of photovoltaic conversion coefficient. At the moment, the value of this coefficient in the silicon PV panels presented on the market can reach 25 %. The above-mentioned factors played a decisive role in the choice of photovoltaic module for sustainable energy efficient road pavement.



a

b

Fig. 6. Change of road marking on the road: a – before the change; b – after the change.

The current research conducted by the authors allows evaluating the efficiency of the silicon PV panels in the sustainable energy efficient road pavement depending on the electrical load conditions. As this load can change (it is connected, for example, with the change of weather conditions or the time of the day), it is offered to use solar controller MPPT for monitoring of conditions under which silicon PV panels will work with maximum efficiency [9].

As mentioned above, sustainable energy efficient road pavement performs the functions of not only the road surface, but also the renewable energy source (converting solar and kinetic energy into electric). The generated electricity partly goes to supply own needs of sustainable energy efficient road pavement, including the drawing of dynamic mark-up. This mark-up may vary depending on the road conditions. For example, in normal conditions the road has two lanes in each direction. At some point in time, the system captures a large number of vehicles that move in the same direction. According to the new data, the road markings are changed to ensure the greatest safety and throughput of the road.

For more visibility, as an illustrative example, let’s imagine the following situation – there is a large number of vehicles on the roads in the morning and evening during the rush hours. In addition, at different times of the day different lanes are loaded (for example, in the morning the most loaded is the strip leading from the residential areas to the centre of the village, where the offices of various companies are located, and in the evening on the contrary). In the daytime, the flow of vehicles in both directions is roughly the same. Functional sustainable energy efficient road pavement allows to automatically determine the road conditions and, depending on the situation, change the road markings (for example, expand the more loaded lane), drawing its LEDs. The illustration of this example is presented in Fig. 6.

It has been mentioned above that PV panels in sustainable energy efficient road pavement will be located horizontally and therefore depending on the location, their efficiency will be different. For example, for the average northern latitude of Europe, about 48 degrees (for North America this is part of the US territory on the border with Canada), the angle of incidence of the sun rays on the horizontally lying SP will be about 72 degrees [17]. Under such external operating conditions, the PV panel will operate at an efficiency of 69 %. These circumstances should be taken into account in the calculation and design of modern roads on the basis of sustainable energy efficient road pavement.

VI. CONCLUSIONS

The conducted research allows not only to define the value of load resistance for silicon PV panels, but also to create conditions under which these panels will work with maximum efficiency. This circumstance is especially important in the work of silicon PV panels as part of complex modern systems, such as sustainable energy efficient road pavement. In such systems, the load, and therefore its resistance, can dynamically change over time. Therefore, to ensure the effective operation of photovoltaic modules, it is necessary to constantly monitor the ratio of internal resistance of the PV panels considering their connection diagrams and load resistance. Maintaining the equality of these resistances can ensure the transmission of the maximum power to the load.

The analysis of the obtained results of the experimental research has shown that in order to make the operation of PV panels of series FS-100M and FS-110P most efficient, their load must be maintained within 3–3.5 Ω range. If the load resistance goes beyond the specified limits, the work of PV panels of this series will not be effective. In this case, it is necessary either to change the internal resistance of the PV panels system by changing their electrical wiring diagrams or to change the load resistance.

It is suggested to use the studied silicon PV panel series as a part of complex modern systems, such as sustainable energy efficient road pavement. It is obvious that their effectiveness due to the horizontal position will be somewhat smaller (an average of 31 %). For effective operation of PV panels as part of a single system of sustainable road-pavement, MPPT-type controllers must be used. These controllers can automatically provide the operation of PV panels as part of a complex system with the highest possible efficiency of power generation.

The results obtained from the presented studies form the basis for a completely new approach to road construction. The proposed sustainable energy efficient road pavement is not only a new innovative road that is capable of serving itself and providing power, but also a renewable source of energy. In other words, such roads can be perfectly considered as alternative green energy sources. Also noteworthy is the fact that the functionality of the new innovation road is greatly increased. Sustainable energy efficient road pavement is able to track road conditions, traffic, weather conditions and respond to them quickly. This can be manifested both in the change of road markings and in the highlighting of hazardous areas, as well as informing road users about these sites. And this is nothing more than safety of road traffic.

REFERENCES

[1] C. D. Ahrens, "Transition to very high share of renewables in Germany", *CSEE Journal of Power and Energy Systems*, vol. 3, no. 1, pp. 17–25, 2017. https://doi.org/10.17775/CSEEJPES.2017.0004

[2] Rentechno Group, "Solar PV power plants - development, design, construction | Rentechno". [Online]. Available: https://rentechno.ua/en/solar.html [Accessed: 22-Jun-2019].

[3] A. Patlins, S. Arhun, A. Hnatov, O. Dziubenko, and S. Ponikarovska, "Determination of the Best Load Parameters for Productive Operation of PV Panels of Series FS-100M and FS-110P for Sustainable Energy Efficient Road Pavement", *proceedings in IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2018)*, 12–14 November, 2018. https://doi.org/10.1109/RTUCON.2018.8659829

[4] A. Patlins, A. Hnatov, and S. Arhun, "Safety of Pedestrian Crossings and Additional Lighting Using Green Energy", *Transport Means 2018, Proceedings of 22nd International Scientific Conference*, Kaunas University of Technology, Kaunas, vol. 2, pp. 527–531, 2018.

[5] M. I. Oprea et al., "Detection of potential induced degradation in c-Si PV panels using electrical impedance spectroscopy", in *2016 IEEE 43rd Photovoltaic Specialists Conference* (PVSC), 2016, pp. 1575–1579.

[6] S. Arhun, A. Hnatov, O. Dziubenko, and S. Ponikarovska, "A Device for Converting Kinetic Energy of Press Into Electric Power as a Means of Energy Saving", *Journal of the Korean Society for Precision Engineering*, vol. 36, no. 1, pp. 105–110, 2019. https://doi.org/10.7736/KSPE.2019.36.1.105

[7] U. Mehmood, H. M. Irshad, F. A. Al-Sulaiman, S. Bashir, and B. S. Yilbas, "Effect of Accumulation of Environmental Dust and Subsequent Mud Formation on Textural, Chemical, and Optical Properties of Silicon Wafers for Photovoltaic Cells", *IEEE Journal of Photovoltaics*, vol. 8, no. 5, pp. 1274–1280, 2018. https://doi.org/10.1109/JPHOTOV.2018.2841498

[8] M. Gürtürk, H. Benli, and N. K. Ertürk, "Effects of different parameters on energy–Exergy and power conversion efficiency of PV modules", *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 426–439, 2018. https://doi.org/10.1016/j.rser.2018.04.117

[9] DigiKey, "Designing a High-Efficiency Solar Power". [Online]. Available: https://www.digikey.com.au/en/articles/techzone/2011/oct/designing-a-high-efficiency-solar-power-battery-charger. [Accessed: 22-Jun-2019].

[10] M. A. Abdullah, S. F. Toha, and S. Ahmad, "Investigation on the Maximum Power Point in Solar Panel Characteristics Due to Irradiance Changes", in *IOP Conference Series: Materials Science and Engineering*, vol. 184, 2017. https://doi.org/10.1088/1757-899X/184/1/012020

[11] O. Veligorskyi et al., "A novel hysteresis power point optimizer for distributed solar power generation", *Electrical, Control and Communication Engineering*, vol. 14, no. 1, pp. 12–22, 2018. https://doi.org/10.2478/ecce-2018-0002

[12] V. Nakhodov, A. Baskys, N.-O. Skeie, C. F. Pfeiffer, and I. Dmytro, "Selection methodology of energy consumption model based on Data Envelopment Analysis", *Electrical, Control and Communication Engineering*, vol. 11, no. 1, pp. 5–12, 2016. https://doi.org/10.1515/ecce-2016-0006

[13] E. Racz, B. Horompoli, A. Varga, and E. R. Neuchel, "Experimental investigation based on analyzation of electric current-voltage characteristics on Pasan-flasher flashlight irradiated photovoltaic cells aged by various processes", *Elektroenergetika*, p. 718, 2017.

[14] BBC News, "Dutch unveil glow in the dark road", 14 April 2014. [Online]. Available: https://www.bbc.com/news/technology-27021291. [Accessed: 22-Jun-2019].

[15] PlasticRoad, "PlasticRoad - A revolution in building roads". [Online]. Available: https://www.plasticroad.eu/en/. [Accessed: 22-Jun-2019].

[16] A. Patlins, A. Hnatov, and S. Arhun, "Using of Green Energy from Sustainable Pavement Plates for Lighting Bikeways", In *Transport Means 2018, Proceedings of 22nd International Scientific Conference,* Lithuania, Trakai, 3–5 October, 2018, pp. 574–579.

[17] SolarRoadways, "Features". [Online]. Available: http://www.solarroadways.com/Product/Features. [Accessed: 22-Jun-2019].

[18] A. Gnatov, S. Argun, and O. Ulyanets, "Joint innovative double degree master program "energy-saving technologies in transport", *2017 IEEE First Ukraine Conference on Electrical and Computer Engineering* (UKRCON), pp. 1203–1207, May 29 – June 2, 2017, Kiev, Ukraine.

[19] A. Avotins, P. Apse-Apsitis, M. Kunickis, and L. Ribickis, "Development of Local Energy Consumption Monitoring System", *54th International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering: Electronic Proceedings*, Latvia, Riga, 14–16 October, RTU Press, 2013.

[20] A. Suzdaļenko and I. Galkins, "Integration of Renewable Energy Sources and LED Luminaries in DC based Street Lighting Grid", *Proceedings of the 12th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"*, Estonia, Kuressaare, 11–16 June, 2012, Elektriajam, pp. 45–47, 2012.

Antons Patlins, Dr. sc. ing., Leading Researcher, Doctor of Engineering Science, Riga Technical University (RTU), Faculty of Power and Electrical Engineering, Institute of Electrical Engineering and Electronics, Riga, Latvia. Antons Patlins is an IEEE member, the author of more than 60 scientific publications. His scientific interests are related but not limited to control algorithms and device development in the field of electrical engineering; researches are connected with the improvement of electric energy effectiveness in industrial electronics and electric transport, sustainable development of public transport system and also with sustainability and motivation in education process. More than 50 students have developed their Bachelor, Engineering and Master Theses under the supervision of Dr. Antons Patlins. The MC member of COST Action: CA16232 – "European Energy Poverty: Agenda Co-Creation and Knowledge Innovation" (ENGAGER) and MC Member Substitute of COST Action CA15127 "Resilient communication services protecting end-user applications from disaster-based failures" (RECODIS).

Address: Azenes str. 12/1, office 503, Riga, Latvia
E-mail: Antons.Patlins@rtu.lv
ORCID ID: https://orcid.org/0000-0003-1866-0835

Andrii Hnatov, Doctor of Sciences, Professor of Vehicle Electronics Department of KhNAHU. He has more than 20 years of work experience in the field of electrical engineering and energy-saving technologies, as well as in automobile transport, published over 300 scientific research papers, methodical and methodological works including 59 patents of Ukraine, 7 training manuals and tutorials and 9 monographs. 3 Doctoral Theses were defended under his guidance. Areas of expertise: teaching, training and scientific research in electric vehicles, energy-saving and energy-efficient technologies, electricity, electrical engineering; mechanical engineering; power electronics; electromagnetic compatibility; metal magnetic-pulse forming; external noncontact magnetic pulse straightening.

Address: 25, Yaroslav Mudryi street, Kharkiv, Ukraine 61002.
E-mail: kalifus76@gmail.com
ORCID iD: https://orcid.org/0000-0003-0932-8849

Shchasiana Arhun, Can. of Eng. Sc., Assoc. Prof. of Vehicle Electronics Department of KhNAHU. She has work experience in the field of electrical power engineering, energy-saving technologies and automobile transport; published over 100 scientific, methodical and research papers and works, including 24 patents of Ukraine, 3 training manuals and tutorials (1 tutorial recommended by the Ministry of Education and Science of Ukraine as a textbook for the university students) and 4 monographs. Areas of expertise: teaching and scientific research in electric vehicles, energy-saving and energy-efficient technologies, electricity; mechanical engineering; electromagnetic compatibility; metal magnetic-pulse forming; external noncontact magnetic pulse straightening; power electronics; physics.

Address: 25, Yaroslav Mudryi street, Kharkiv, Ukraine 61002.
E-mail: shasyana@gmail.com
ORCID iD: https://orcid.org/0000-0001-6098-8661

Hanna Hnatova, Student, Automobile Faculty, Vehicle Electronics Department, Kharkiv National Automobile and Highway University. Kharkiv, Ukraine. Area of specialization: 141 “Electricity, electrical engineering and electromechanics”.

Address: 25, Yaroslav Mudryi street, Kharkiv, Ukraine 61002.
E-mail: annagnatova22@gmail.com

Vasiliy Migal, Doctor of Sciences, Professor of the Department of Tractors and Cars of Kharkiv Petro Vasylenko National Technical University of Agriculture. He defended his Doctoral Thesis in 2003. He is the author of 169 scientific and pedagogical works, including 6 monographs, 44 textbooks and educational reference manuals on vibration diagnostics, technical cybernetics, technical diagnostics of cars, mechatronics and telematic and intellectual systems of automobiles and tractors, theories and methods of scientific research, design of diagnostic support of transport vehicles.

Address: 44, Alchevskyh, Kharkiv, Ukraine 61002.
E-mail: vasiliymigal9@gmail.com