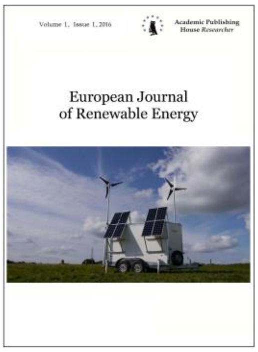

Published in the Slovak Republic
European Journal of Renewable Energy
Has been issued since 2016.
E-ISSN 2454-0870
2018, 3(1): 9-20

DOI: 10.13187/ejre.2018.1.9
www.ejournal51.com

Solar Modules for Autonomous and Mobile Energy Generation

V.A. Panchenko [a, b], V.V. Kharchenko [b]

[a] Russian University of Transport, Russian Federation
[b] Federal Scientific Agroengineering Center VIM, Russian Federation

Abstract

In the article solar modules of different design are considered. Planar and high-voltage solar modules with extended service life are presented. These modules have an increased service life of up to 40-50 years, high-voltage modules have an increased electrical efficiency up to 18 % and can be used in cogeneration plants with concentrators of solar radiation. Solar tiles presented in article can be made from recycled materials and the additionally installed concentrator reduces the number of solar cells used and makes it possible to obtain heat energy at the output. Compact folding solar modules considered in the article allow to charge electrical devices away from electrical networks. Also in the article described photovoltaic thermal solar module with paraboloid-type concentrator for solar cogeneration plants. Such an installation, along with electricity, allows to get warm water at the outlet for the power supply of autonomous consumers or in parallel with the network. Each type of solar modules is used in a stationary heat and electric power supply or mobile power generation. Under consideration were accepted modules designed and fabricated at the Federal Scientific Agroengineering Center VIM, Moscow, Russia. Surveys on the development, research and production of solar modules of various designs has been efficiently conducted over the last few decades.

Keywords: FSAC VIM, silicon solar cells, solar modules, extended service live, solar tiles, folding solar modules, high-voltage matrix solar modules, concentrators of solar radiation, photovoltaic thermal solar modules, current-voltage characteristic, cogeneration.

1. Introduction

Solar energy today is the most widely used of all existing renewable energy sources. Moreover, the photoelectric conversion of solar energy, being the most environmentally friendly way of generating electric power, has received the widest distribution both for work on the grid and for power supply of autonomous, remote consumers (Adomavicius et al., 2013). In connection with such a wide application of this method of generating electricity worldwide, searching for ways to further improve the efficiency of both solar cells and modules of existing types, as well as new designs and technological methods improve search efficiency of photoelectric conversion of the solar radiation. A large amount of work is carried out in the direction of increasing the life of elements and modules, searching for new constructive solutions and new materials. Today, the world has accumulated vast experience and formed a significant array of information on this issue.

The Federal Scientific Agroengineering Center VIM for several decades conducting research, production and testing solar modules of various designs for autonomous power supply of consumers. Each type of solar modules finds its application both in the autonomous power supply of consumers, and mobile power supply.

In the present work, we consider some of the most interesting, in the opinion of the authors, designs and technological methods aimed at increasing the efficiency and reliability of solar energy systems, as well as reducing their cost and simplifying the operation procedure.

2. Results

Main characteristics of solar cells

The solar cell, in the first place, characterizes its current-voltage characteristic. The main parameters of the solar cell include U_n – rated voltage, V; U_{oc} – open circuit voltage, V; I_{sc} – current of short circuit, A; U_{opt} – working voltage, V; I_{opt} – operating current, A; P_{max} – maximum power, W.

Improving conversion efficiency and reducing energy losses in solar cells is a very important task. And in general, the solution of this problem is reduced to a reduction in optical and electrical losses.

To reduce the optical losses associated with the incomplete use of radiation incident on the surface of the solar cell, the following methods are used: structuring the surface, leading to a decrease in the integrated reflection coefficient of the solar cell; application to the surface of the solar cell of a single or double layer antireflection coating; reducing the contact area on the face to reduce shading losses; application of the metal layer on the rear surface of the solar cell, to increase the absorption efficiency of long-wave radiation due to its multiple passage through the semiconductor volume; a decrease in the depth of the emitter junction and a decrease in the concentration of the dopant near the front surface to increase the sensitivity of the solar cell in the short-wave part of the spectrum.

Electrical losses are usually reduced by the choosing the optimal pitch and thickness of the contact bars on the front surface to reduce the solar cell series resistance, by gettering treatments to increase the lifetime of minority charge carriers, by passivation of the face to reduce the rate of surface recombination, by passivation of the rear surface and creation of isotype transitions, by minimization of the contact area and additional doping of the contact regions to reduce the recombination losses at the metal-semiconductor interface.

In polycrystalline materials, grain boundaries deteriorate the transport properties of a semiconductor; in amorphous semiconductors the situation is even more complicated. The efficiency of modern high-quality photocells on monocrystalline silicon is approximately 18 % for serially produced photocells. The efficiency of cells based on other semiconductors (for example, GaAs, InP) is even higher, and can be about 25 % in mass-produced elements. However, these cells are much more expensive and are used primarily for space purposes, where price is not a determining factor, and maximum efficiency and radiation stability are more significant.

Solar photovoltaic modules with extended service life

Solar photovoltaic modules with extended service life, produced in FSAC VIM, are intended for solar power plants and are characterized by an extended service life in comparison with standard laminated modules. The term of the rated power of modules is increased from 20–25 to 40–50 years due to the use of silicone-based polysiloxane two-component compound due to which the production of generated electricity is also increased. Solar modules are produced in four basic form factors with solar cells measuring 125 x 125 mm (156 x 156 mm optional) and polysiloxane filler. The capacities of stationary photovoltaic solar modules vary from 15 to 150 W with a working voltage of 12 or 24 V (Figure 1) (Panchenko et al., 2015).

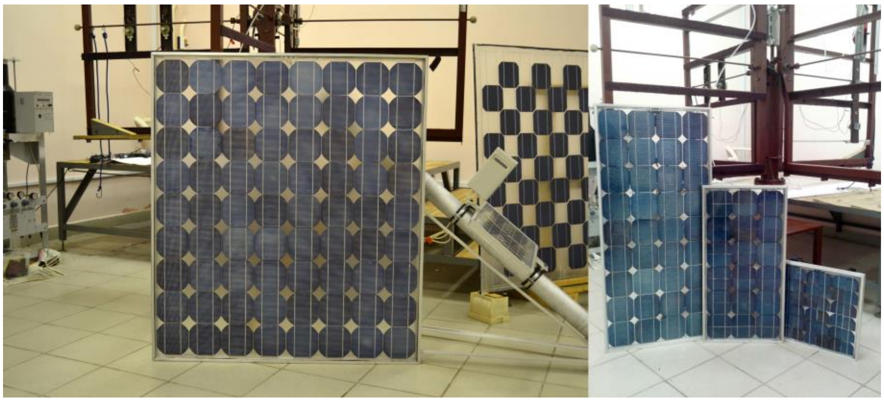

Fig. 1. Stationary solar modules with extended service life

Current-voltage characteristic of the solar module is shown in the Figure 2 and parameters of the solar module are shown in the Table 1.

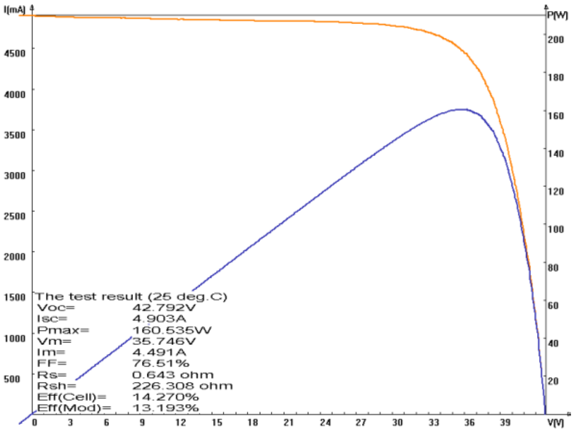

Fig. 2. Current-voltage characteristic of the solar modulewith silicone-organic two-component polysiloxane compound

Table 1. Parameters of the solar module with silicone-organic two-component polysiloxane compound

Length, mm	1180
Width, mm	1050
Thickness, mm	40
Module weight, kg	19
Warranty period, years	40
Technology	Single crystal
Number of elements, pcs.	72
The size of the elements, mm	125 x 125
Short-circuit current, A	4,8
Current at operating point, A	4,4
Open circuit voltage, V	42
Voltage at operating point, V	35
Electric power, W	158
Filling factor, %	77
Photoconversion efficiency, %	14
Frame material	Anodized Aluminum

Sealant	Silicone-organic two-component polysiloxane compound
Operating temperature, C °	- 60 ~ + 110
Junction box	IP65
Connectors	MC4
Cable length, mm	1000
Cable cross-section, mm²	6

As a result of ongoing research and testing:

- technology of manufacturing (encapsulation) of solar modules by means of pouring with a two-component compound has been worked out;
- developed and manufactured an installation for automation of the encapsulation process;
- manufactured modules have small optical losses, minimal internal mechanical stress, good vibration absorption, high resistance to temperature, ultraviolet and ozone degradation, possibility of use with concentrators, extended service life.

Roofing solar panels

One of the options for architectural solutions for the electricity supply of a residential building are solar modules built into the roofing itself, that is, the so-called roofing solar panel or "solar tile". Its use is eliminated by the known shortage of solar modules, which are now widely used – the need to install a roofing under the solar module to protect buildings from external influences, which increases the cost of finishing works. Designed module is a roofing material, comprising both the protective function of the building and power generation. When using solar tile solved architectural and construction problems and independent or parallel with the network power supply of the consumer (Figure 3) (Strebkov et al., 2015a; Strebkov et al., 2015b; Strebkov et al., 2015c; Strebkov et al., 2016).

Fig. 3. Roofing solar panels of two types with extended service life

Current-voltage characteristic of the solar tile of planar type with silicone-organic two-component polysiloxane compound is shown in the Figure 4.

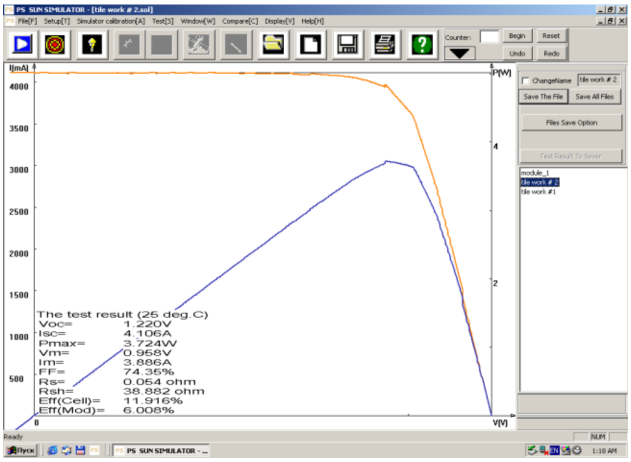

Fig. 4. Current-voltage characteristic of the solar tile with silicone-organic two-component polysiloxane compound

Current-voltage characteristic of the solar tile of planar construction and with silicone-organic two-component polysiloxane compound in full-scale conditions presented on the Figure 5 (on the left). Current-voltage characteristic of the solar tile of concentrator construction with silicone-organic two-component polysiloxane compound in full-scale conditions presented on the Figure 5 (on the right).

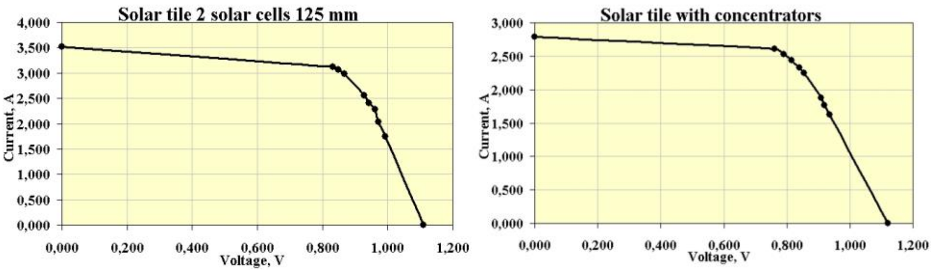

Fig. 5. Current-voltage characteristics of the solar tile of planar construction (on the left) and concentrator construction (on the right) with silicone-organic two-component polysiloxane compound in full-scale conditions

Parameters of solar tiles planar and concentrator construction are shown in the Table 2.

Table 2. Parameters of solar tiles planar and concentrator construction with silicone-organic two-component polysiloxane compound

Indicator	**The value (in the concentrator / planar (capsulation); (laminated) versions)**
Open circuit voltage, V	1,12 / 1,11; 1,08
Voltage at operating point, V	0,8 / 0,85; 0,83
Short-circuit current, A	2,8 / 3,5; 3,32
Current at operating point, A	2,53 / 3,06; 3,01
Electric power, W	2 / 2,6; 2,5
Filling factor, %	0,64 / 0,67; 0,64
Coefficient of concentration	4 (theoretical); 2 (practical) / -
Temperature of the front and back sides, °C	- / 40 and 32; 42 and 34
Dimensions of the module, mm	420 x 310 x 80 / 420 x 310 x 50

The term of the rated power, years	40–50 / 40–50; 20–25
Module weight, kg	3,5 / 2,3; 2,1

In the production of tiles using recycled materials (plastic bottles or stretch film) and binders, which reduces the cost of production and favorably affects the environment. The solar tile also includes solar cells in a polysiloxane compound that increases the term of their rated power to 40-50 years and that work together with an additional installed concentrator, which reduces the cost of the solar module due to the saving of high quality silicon. In addition to concentrator tile an optical deflection system is installed to increase the work during the day.

Foldable solar modules

Charging compact electrical devices is an actual problem when it is impossible to connect to a centralized power grid. For mobile consumers, compact portable solar modules are manufactured in the Center VIM, which are designed to power compact electric devices with charging parameters of 5 V, 0.5 A (USB standard) and more in proportion that allows power supply in stand-alone mode and direct connection without adapters and stabilizers for small electrical equipment (with the use of stabilizers and converters, the spectrum of power supplies increases) (Figure 6), (Panchenko, 2015a; Panchenko, 2015b).

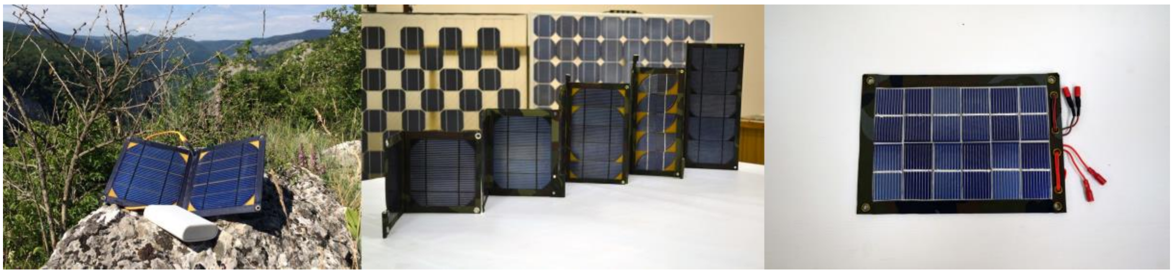

Fig. 6. Foldable solar modules

The design of the sectional solar module in the form of a tablet is unified and extends the range of potential consumers with serial-parallel witching. Current-voltage characteristics of the foldable solar modules are presented on the Figure 7.

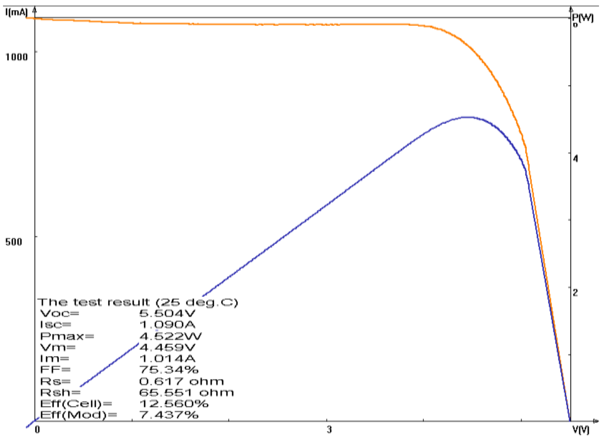

Fig. 7. Current-voltage characteristics of the foldable solar module

Parameters of foldable solar module (charging standard USB 5 V and 2 A (10 W)) are shown in the table 3.

Table 3. Parameters of foldable solar module

Indicator	Unit	Value
Electric power	W	10
Module dimensions	mm	350×165×7
Module weight	kg	0,392
Service life	years	5–15
The cost of the module	dollar	50

Foldable and sectional solar modules are manufactured with various options for exterior decoration, standard USB parameters and the possibility of switching sectional solar modules.

High-voltage matrix solar modules

In VIESH on the basis of many years of research under the supervision of Academician of the Russian Academy of Sciences, Professor D. Strebkov. Third-generation matrix solar cells based on silicon with an efficiency of up to 28 % are developed for the conversion of concentrated solar radiation with a concentration of more than 100 times (Strebkov, Tverjanovich, 2007; Strebkov 2010a; Strebkov 2010b; Strebkov 2010c). The results of these studies, which have become the logical conclusion of more than 20 years of previous studies, are reflected in the three-volume monograph.

This design of soar cells eliminates a number of disadvantages of standard solar cell. As a result of the investigations carried out, it was possible to separate the spatially illuminated surface of the solar cell on the charge carrier generation region and the p-n junction region responsible for carrier separation and collection. In this case, the area of the doped layer and the p-n junction on the surfaces of the solar cell decreases by a factor of 10, and 90 % of the surface area is reserved for generation of electron-hole pairs with direct interaction of the photons of solar radiation with the base region of the solar cell. This was done by using a silicon matrix solar cell with a Fresnel lens in the photoelectric module as a concentrator (Strebkov, Tverjanovich, 2007).

Solar cells with parameters that have no analogues in the world have been obtained. The electric power was 1 W/cm^2 (10 kW/m^2), which is 50 times higher than the power of the solar cell with an efficiency of 20 % at a standard illumination of 1 kW/m^2 and a temperature of 25 °C.

In order to create a matrix photocell, it is first necessary to fabricate a multilayer structure with a given pattern of alternating silicon layers of a given type of conductivity and resistivity. In this case, it is necessary to provide electrical ohmic contacts between adjacent p-n junctions by means of an original, non-standard reception, breakdown of the entire multilayer structure. This made it possible to substantially simplify the construction and technology of manufacturing the initial multilayer billet. The resulting multilayer system was cut into plates, but not across the axis, but along. As a result, it was possible to obtain layers with p-n junctions that emerged at their ends on the plate surface. Such a structure possessed a number of advantages over the classical planar scheme and solved a number of problems considered above.

The research work carried out in Federal Scientific Agroengineering Center has shown the promise of this direction in terms of further improvement of the technology for obtaining matrix solar cells and concentrators with the production of modules for practical use.

For autonomous supply consumers with high voltage DC (1000 V or more) and increased coefficient of solar radiation to electricity conversion Center VIM developed bilateral high-voltage matrix solar modules with a voltage more than 1000 V (Figure 8) (Strebkov et al., 2013; Panchenko et al., 2015). Such solar modules are used with transformerless inverters and connected to high-voltage direct-current lines without converter substations, they have increased specific electric power, efficiency (up to 28 %), module life (up to 40-50 years), the consumption of solar grade silicon is reduced. The design of high-voltage solar modules can be scaled, thus increasing the current or voltage. At a voltage of 1000 V and a current of 6 mA the module dimensions are 703 mm × 105 mm × 17 mm.

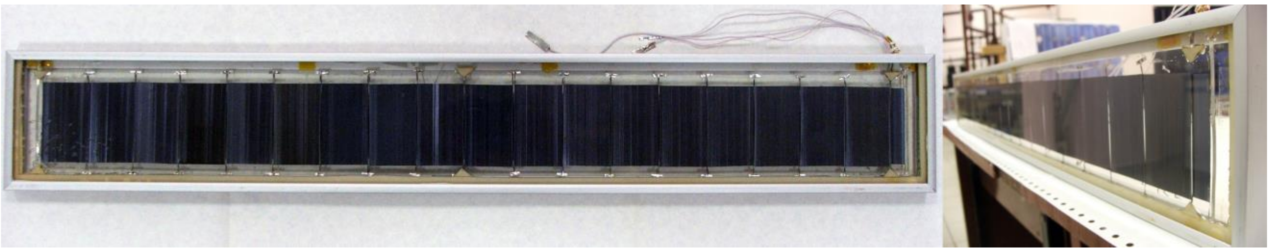

Fig. 8. High-voltage matrix solar module

Current-voltage characteristic of high-voltage matrix solar module presented on the Figure 9 and parameters of high-voltage matrix solar module are shown in the Table 4.

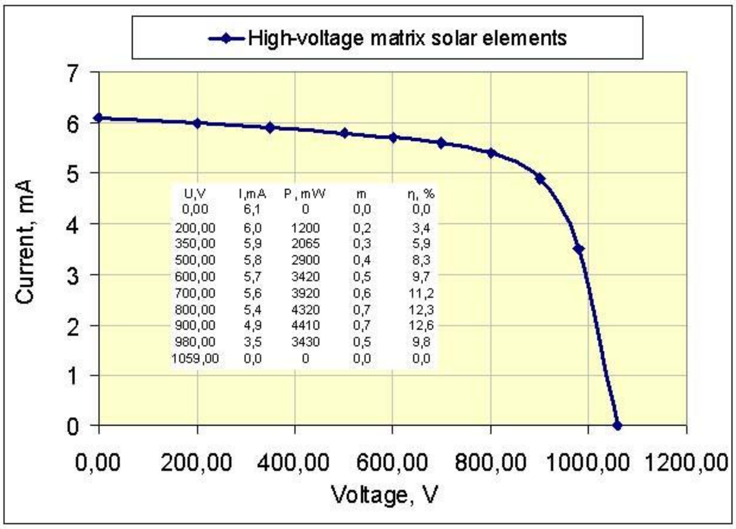

Fig. 9. Current-voltage characteristic of high-voltage matrix solar module

Table 4. Parameters of high-voltage matrix solar module

Dimensions of the module:	
Length, mm	703
Width, mm	105
Thickness, mm	17
Module weight, kg	1,8
Service life, years	40–50
Placeholder sealant	Two-component silicon organic polysiloxane compound
The possibility of using concentrator	Exist (more than 200 times, limited by concentrator)
Current growth at a concentration	Linear(Efficiency increases)
Dimensions of the one cell:	
Length, mm	35
Width, mm	60
Thickness, mm	0,3
Cell weight, kg	0,004
The number in module, pcs	18

Indicators without concentration:	
Open circuit voltage, V	1059
Short-circuit current, mA	6,1
Voltage in the operating point, V	900
Current in the operating point, mA	4,9
Electric power, W	4,4
Fill factor	0,68
Efficiency of the photoconversion, %	12,6

The high-voltage solar module with a two-sided working surface is made in the form of a matrix of commutated miniature solar cells, and is designed specifically for use with solar concentrators, with which the efficiency of the module is increased, and high efficiency is maintained even with a temperature increase of 60 °C or more, that simplifies the cooling system of the modules, the current of the module grows in proportion to the concentration, and with the use of a heat carrier, it is also possible to remove thermal energy.

Photovoltaic thermal module with concentrator of paraboloid type

For photodetectors based on high-voltage matrix solar modules, original solar concentrators of paraboloid type have been developed whose surface profile provides uniform illumination of the photodetector surface (Figure 10) (Strebkov et al., 2013a; Strebkov et al., 2013b; Mayorov et al., 2012; Kharchenko et al., 2018).

Fig. 10. Solar photovoltaic thermal module with a concentrator of paraboloid type

During the experiments, a concentrator solar photovoltaic thermal installation with paraboloid-type concentrators and various solar cells (one-sided, two-sided, thin, matrix) was investigated.

The increase in temperature and the concentration of solar radiation do not affect the efficiency of matrix solar cells as much as the efficiency of planar solar cells, the volt-ampere characteristics have a rectangular shape (Figure 11). It is possible to increase the concentration with sufficient cooling and, accordingly, to increase an efficiency and output electrical power.

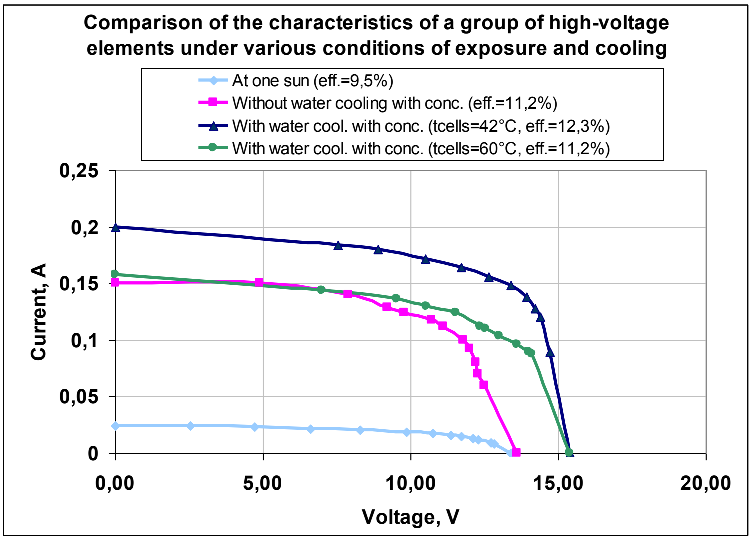

Fig. 11. Volt-ampere characteristics of a group of matrix solar cells under different lighting and cooling conditions

On the basis of the studies carried out, it has been shown that planar solar cells in different groups reduce the efficiency at the solar concentration increasing and without cooling. The efficiency of matrix solar modules when working with a concentrator without taking into account optical losses increases from 9,5 % to 12,3 %, what indicates the advisability of using matrix solar modules in a photovoltaic thermal system with concentrators of paraboloid type.

The thermal characteristics of radiator surfaces, the surface of solar cells, the water flow rate and its outlet temperature when illuminated by two concentrators with diameters of 0,6 m and 1 m with water cooling are shown at Figure 12.

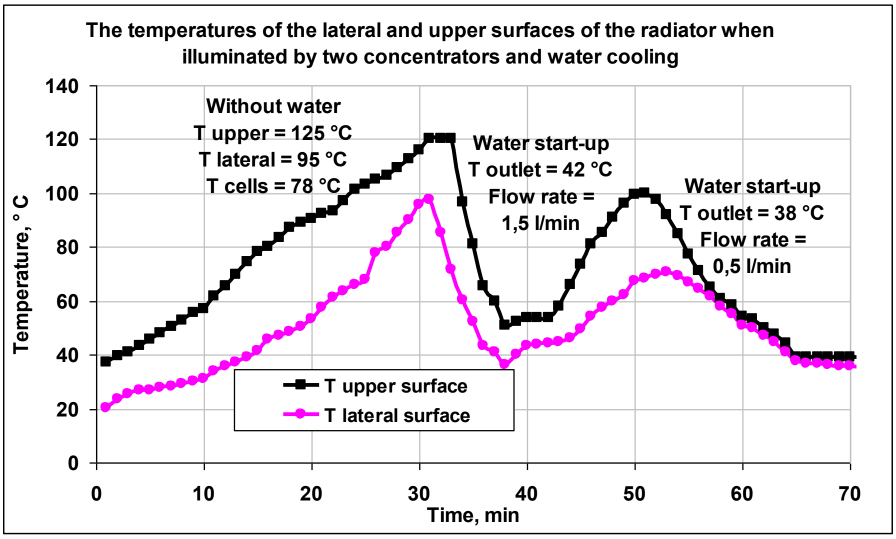

Fig. 12. The temperatures of the lateral and upper surfaces of the radiator when illuminated by two concentrators and with water cooling

The surface temperature of the solar cells at the beginning of the experiment was 78 °C without water cooling, and the temperatures of the upper and lateral parts of the radiator were 150 °C and 105 °C, respectively. At a water flow of 1,5 l/min, the outlet water temperature was 42 °C. When the flow rate was reduced to 0,5 l/min, the temperature was 38 °C. The average concentration along the lateral surface of the photoelectric receiver was about 7 times. Concentration on the upper surface of the receiver was 23 times.

Technical characteristics of the photovoltaic thermal module with a paraboloid-type concentrator with 0,785 m^2 are given in Table 5.

Table 5. Technical characteristics of the photovoltaic thermal module with a paraboloid-type concentrator

Parameter	**Value**
Concentrator type	Paraboloid
Electric power (at E = 820 W/m^2), W	18,5
The efficiency of solar cells without a concentrator, %	9,5
Open circuit voltage, V	15,4
Rated voltage, V	12
Area of photovoltaic cells, m^2	0,0224
The average concentration of solar radiation on the photovoltaic part of the receiver	7,1
The average concentration of solar radiation on the thermal part of the receiver	23
Type of solar cells	Matrix
Overall dimensions of the radiator of the solar receiver, m	0,11 x 0,11 x 0,12
Electrical efficiency	0,123
Thermal efficiency	0,5
Optical efficiency	0,65
Heat carrier	Water
Coolant flow rate, l/min	0,5
Coolant temperature at the inlet, °C	19
Coolant temperature at the outlet, °C	42
The area of the concentrator midsection for the photovoltaic part of the receiver, m^2	0,28
The area of the concentrator midsection for the thermal part of the receiver, m^2	0,5
Overall dimensions of the compound concentrator, m	0,54 x 1,05 x 1,05
Module weight, kg	2,5
The estimated cost of the module, $	60

The technology of manufacturing high-voltage matrix solar modules is adapted to the conditions of industrial production, it does not use such time-consuming operations as multi-stage diffusion, photolithography, screening, vacuum metallization, and also the use of silver for making contacts is excluded.

As a result of ongoing research and testing:

- 28 % photoconversion efficiency was achieved using concentrated solar radiation;
- a voltage of more than 1000 V was obtained from the area of the photoconverter about 0.04 m^2 and 15 to 20 V from 1 cm^2 of the photoconverter without the concentration of solar radiation;
- the term of the nominal work of the solar module has been increased from 20–25 to 40–50 years;
- cogeneration plants with concentrators and high-voltage solar modules have been designed and tested to produce electricity and warm water.

3. Conclusion

Thus, the development of the Federal Scientific Agroengineering Center VIM in the field of solar energy find its application in the areas of autonomous power supply to various consumers, both stationary and mobile. Presented developments can successfully replace foreign analogs, demonstrating the best characteristics and in some areas have no analogues abroad.

References

Adomavicius et al., 2013 – *Adomavicius, V., Kharchenko, V., Gusarov, V., Valickas J.* (2013). RES-based microgrids for environmentally friendly energy supply in agriculture. *Conference Proceeding – 5th International Conference, TAE 2013: Trends in Agricultural Engineering 2013*: 51-55.

Kharchenko et al., 2018 – *Kharchenko V., Panchenko V., Tikhonov P.V., Vasant P.* (2018). Cogenerative PV Thermal Modules of Different Design for Autonomous Heat and Electricity Supply. *Handbook of Research on Renewable Energy and Electric Resources for Sustainable Rural Development*: 86-119, DOI: 10.4018/978-1-5225-3867-7.ch004

Mayorov et al., 2012 – *Mayorov, V.A., Panchenko, V.A., Trushevsky, S.N., Trubnikov, V.Z.* (2012). Thermal photovoltaic thermo module with a parabolotor concentrator of solar radiation. Patent of the Russian Federation for Utility Model No. 132258. Application: 2012154821/06, 18.12.2012. Posted on: 10/09/2013. Bul. No. 25.

Panchenko, 2015a – *Panchenko, V.* (2015). The development and testing of folding, sectional and flexible solar modules. *Research in Agricultural Electric Engineering*. 3(3): 90-97.

Panchenko, 2015b – *Panchenko, V.A.* (2015b). Development and testing of folding, sectional and flexible solar modules. *Vestnik of VIESH*, 3(20): 50-57.

Panchenko, 2015c – *Panchenko, V.A., Strebkov, D.S., Persits, I.S.* (2015). Solar modules with extended service life at the nominal power level. *Alternative Energy and Ecology*, 19(183): 55-60.

Panchenko, 2015d – *Panchenko, V.A., Strebkov, D.S., Polyakov, V.I., Arbuzov, Yu*.D. (2015). High-voltage solar modules with a voltage of 1000 V. *Alternative energy and ecology*, 19(183):76-81.

Strebkov et al., 2013 – *Strebkov, D.S., Mayorov, V.A., Panchenko, V.A.* (2013). Solar photovoltaic thermo module with a parabolic concentrator. *Alternative energy and ecology*, 1/2: 35-39.

Strebkov et al., 2013a – *Strebkov, D.S., Polyakov, V.I., Panchenko, V.A.* (2013). Investigation of high-voltage solar silicon modules. *Alternative Energy and Ecology*, 6/2: 36-42.

Strebkov et al., 2013b – *Strebkov, D.S., Mayorov, V.A., Panchenko, V.A., Osmakov, M.I., Plokhikh S.A.* (2013). Solar installation with matrix photocells and a concentrator. *Elektro*, 2: 50-52.

Strebkov et al., 2015 – *Strebkov, D.S., Kirsanov, A.I., Irodionov, A.E., Panchenko, V.A., Mayorov, V.A.* (2015). Roof solar panel. Patent of the Russian Federation for invention No. 2557272. Application: 2014123409/20, 06/09/2014. Published: 07/20/2015. Bul. No. 20.

Strebkov et al., 2015a – *Strebkov, D., Panchenko, V., Irodionov, A., Kirsanov, A.* (2015). The development of roof solar panels. *Research in Agricultural Electric Engineering*, 3(4): 123-127.

Strebkov et al., 2015b – *Strebkov, D.S., Panchenko, V.A., Irodionov, A.E., Kirsanov, A.I.* (2015). Development of a roofing solar panel. *Vestnik VIESH*, 4(21): 107-111.

Strebkov, 2010a – *Strebkov, D.S.* (2010). *Matrix solar cells*. Volume 1, M.: GNU VIESH.

Strebkov, 2010b – *Strebkov, D.S.* (2010). *Matrix solar cells*. Volume 2, M.: GNU VIESH.

Strebkov, 2010c – *Strebkov, D.S.* (2010). *Matrix solar cells*. Volume 3, M.: GNU VIESH.

Strebkov, 2016 – *Strebkov, D.S., Bobovnikov, N.Yu., Irodionov, A.E., Kirsanov, A.I., Panchenko, V.A., Filippchenkova, N.S.* (2016). Program "One Million Solar Roofs" in Russia. *Vestnik of VIESH*, 3 (24): 80-83.

Strebkov, Tverjanovich, 2007 – Strebkov *Strebkov, D.S., Tverjanovich, E.V.* (2007). Concentrators of solar radiation. Moscow: GNU VIESH, 355 p.