Photovoltaic solar modules for autonomous heat and power supply

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Abstract. The article presents solar modules of various types and designs, in the development and study of which the author took part. Along with planar photovoltaic solar modules with an extended term of nominal power, high-voltage matrix solar modules with an extended term of nominal power and electrical efficiency up to 28% are considered. Such modules are made with the help of encapsulation technology with a polysiloxane compound, which improves the performance of solar modules and increases their service life. For autonomous power supply of mobile and compact electrical devices in the field, folding and sectional solar modules are proposed, which, when parallel-sequential switching, allow to gain the necessary power. For architectural solutions, solar roofing panels are presented, which along with electrogeneration make it possible to generate heat energy, and the base can be made of recycled plastic, which has a positive effect on the environment. To reduce the number of solar cells used, a concentrating solar roofing panel has been proposed, which allows the use of thermal energy. For the cogeneration of electric energy and thermal energy, a concentrator solar photovoltaic thermal module with a paraboloid type concentrator is also proposed. Each type of solar modules is used in a stationary heat and electric power supply and mobile power generation.

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. 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 cells as well as modules in a whole, 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 Research 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.

2. Solar photovoltaic modules with extended service life

Solar photovoltaic modules with extended service life, produced in Federal Scientific Agroengineering Center VIM (Moscow, Russia), are intended for solar power plants and 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 with solar cells measuring 125 × 125 mm (156 × 156 mm optional) and polysiloxane filler. The capacities of usually produced photovoltaic solar modules vary from 15 to 150 W with a working voltage of 12 or 24 V (Figure 1) [1].

![Figure 1. Solar modules with extended service life](image1)

Current voltage characteristic of the solar module is shown in the Figure 2.

![Figure 2. Current voltage characteristic of the solar module with silicone-organic two-component polysiloxane compound](image2)
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.

3. 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) [2, 3].

![Figure 3. Roofing solar panels of two types with extended service life](image)

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 4 (on the left). Current voltage characteristic of the solar tiles of concentrator construction with silicone-organic two-component polysiloxane compound in full-scale conditions presented on the Figure 4 (on the right).

![Figure 4. 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](image)
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.

4. 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 Federal Scientific Agroengineering 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 5) [4].

![Figure 5. Foldable and sectional solar modules](image)

The design of the sectional solar module in the form of a plane tablet is unified and extends the range of potential consumers with serial-parallelwitching. Foldable and sectional solar modules are manufactured with various options for exterior decoration, standard USB parameters and the possibility of switching sectional solar modules. Current voltage characteristic of the foldable solar module is presented on the Figure 6.

![Figure 6. Current voltage characteristic of the foldable solar module](image)
Parameters of foldable solar module (charging standard USB 5 V and 2 A (10 W)) are shown in the Table 1.

| Indicator          | Unit | Value       |
|--------------------|------|-------------|
| Electric power     | W    | 10          |
| Module dimensions  | mm   | 350 × 165 × 7 |
| Module weight      | kg   | 0.4         |
| Service life       | years | 5–15       |
| The cost of the module | dollar | 50         |

5. High-voltage matrix solar modules

In the All-Russian Institute of Electrification of Agriculture, which is continued by the Federal Scientific Agroengineering Center VIM 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 [5].

This design of solar 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 photovoltaic module as a concentrator [5].

Solar cells with parameters that have no analogues in the world have been obtained. The electric power was 1 W/cm² (10 kW/m²), which is 50 times higher than the power of the solar cell with an efficiency of 20% at a standard illumination of 1 kW/m² and a temperature of 25 °C.

For autonomous supply consumers with high voltage DC (1000 V or more) and increased coefficient of solar radiation to electricity conversion Federal Scientific Agroengineering Center VIM developed bilateral high-voltage matrix solar modules with a voltage more than 1000 V (Figure 7) [6, 7]. 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%), life time (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 the voltage of 1000 V and the current of 6 mA the module dimensions are 703 mm × 105 mm × 17 mm.

![Figure 7. High-voltage matrix solar module with voltage of 1000 V](image)

Current voltage characteristic of high-voltage matrix solar module presented on the Figure 8.
Figure 8. Current voltage characteristic of high-voltage matrix solar module with voltage of 1000 V

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, what 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.

6. Solar modules with concentrators 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 9) [8–11].

Figure 9. 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 current voltage characteristic have a rectangular shape (Figure 10). It is possible to increase the concentration with sufficient cooling and, accordingly, to increase an efficiency and output electrical power.
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%, that indicates the advisability of using matrix solar modules in a photovoltaic thermal system with concentrators of paraboloid type.

![Comparison of the characteristics of a group of high-voltage elements under various conditions of exposure and cooling](image)

**Figure 10.** Current voltage characteristics of a group of matrix solar cells under different lighting and cooling conditions

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 11. 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.

![The temperatures of the lateral and upper surfaces of the radiator when illuminated by two concentrators and water cooling](image)

**Figure 11.** The temperatures of the lateral and upper surfaces of the radiator when illuminated by two concentrators and with water cooling
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 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 for production electricity and warm water [12–14].

7. Conclusions

Thus, the development of the Federal Scientific Agroengineering Center VIM in the field of solar energy finds its application in the areas of autonomous power supply to various consumers, both stationary and mobile. Along with planar solar modules with an extended term of nominal power, high-voltage matrix solar modules with an extended term of nominal power and electrical efficiency up to 28% are proposed for solar photovoltaic stations. For architectural solutions, solar roofing panels are presented, which along with electrogeneration make it possible to generate heat energy, and the base can be made of recycled plastic, which has a positive effect on the environment. For the cogeneration of electric energy and thermal energy, a concentrator solar photovoltaic thermal module with a paraboloid type concentrator is proposed. Each type of solar modules is used in a stationary heat and electric power supply and mobile power generation.

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