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## **INTEGRATED PHOTOVOLTAIC AND THERMAL SOLAR ENERGY CONVERTER**

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The utilization of solar energy is essential to curb climate change, reduce dependence on finite fossil fuel reserves, and achieve energy independence. The leading existing technologies for the use of solar radiation are the photovoltaic (PV) conversion of light directly into electricity and the thermal conversion of solar rays into heat. The main problem with solar energy is efficiently collecting this energy and cost-effectively converting it into other useful forms. The existing solar energy systems are still expensive.

The other problem is the decreased efficiency of PV modules at high working temperatures. It is well known, that in PV solar cells, mostly made of silicon, most of the absorbed solar radiation (about 80%) is not converted into electricity but contributes to increasing the temperature of solar cells, then reducing the electrical efficiency of cells. This is the inherent drawback feature of solar cells - degradation in performance due to temperature.

Aiming to reduce the cost of solar converters and to increase solar energy transformation efficiency, a new type of Photovoltaic and Thermal (PVT) hybrid solar energy converter is developed in the research laboratory "Photovoltaic Semiconductor Devices" at National Polytechnic University of Armenia. Different innovative approaches are used in developing PVT converters. The prototype of a new type of PVT converter is prepared and tested. The new PVT converter has several advantages in comparison with general PV modules and PV module-based PVT collectors. The production of the developed new PVT collectors is cheap and can be realized using standard off-the-shelf technologies.

**Keywords:** solar, photovoltaic, thermal, efficiency, hybrid modules, dual effect.

**Introduction.** The energy sector is the source of around three-quarters of greenhouse gas emissions today. Reducing global carbon dioxide (CO<sub>2</sub>) emissions to net zero by 2050 is a critical and formidable goal. By 2050, almost 90% of electricity will come from renewable sources, with solar PV and wind accounting for nearly 70% (most of the remainder comes from nuclear). The share of solar PV in renewable sources is dominant. In accordance with the International Energy Agency report (May 2021), solar PV capacity has increased 20-fold since 2010, and wind power 11-fold [1].

Photovoltaics is a fast-growing market. The annual growth rate of PV installations was 24% between the years 2010 to 2017 since that time the PV module prices have been declining. But this declination was big in the period from 2006 to 2012. In 2006 the average price of PV modules in Germany was 3.4 €/W (for 10 kW-100 kW rooftop systems) and in 2012 it was 0.55 €/W. Starting in 2012 the manufacturing costs of PV modules are declining very slowly. From 2012 to 2018

(next 6 years) the PV module prices reduced only by 0.04 €/W and in 2018 this price was 0.51 €/W [2]. The above-mentioned PV module price stagnation during last years can be described by technological limits of the existing Si-wafer - based technology

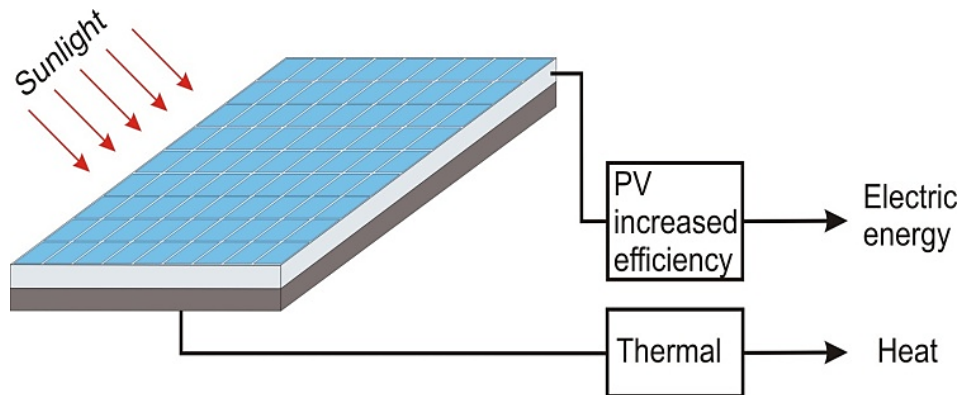
The farther reduction of PV costs and the increase in efficiency are highly important tasks for using all benefits of solar energy. At present, considerable research works are conducted to increase the efficiency of Si solar cells. The development of solar Photovoltaic (PV) and Thermal (PVT) hybrid systems is one of the promising ways for the further increase in the efficiency of solar energy transformation.

Solar PVT hybrid system is a new technology with a high potential to be an effective and viable method of producing electricity and thermal energy in the nearest future. The hybrid system proves to be much energy efficient with improved electrical efficiency due to the cooling of PV cells and gained thermal energy due to the heat absorbed by the fluid from the heated solar cells.

It is well known that in solar PV systems most of the absorbed solar radiation by a solar cell (about 80%) is not converted into electricity but contributes to the increase in the temperature of solar cells, then reducing the electrical efficiency of the cells. This is the inherent drawback feature of silicon solar cells - degradation in performance due to temperature. This feature appears also in computers or other electronic devices, when they fail due to high temperatures, since the Integrated Circuits of computers and all other devices are made of the same semiconductor material – silicon (Si).

Typical solar PV modules convert about 15 – 22% (at 25 °C - Standard Test Condition) of solar radiation into electricity; the rest heats the solar cell, and is dissipated as waste heat. On a bright sunny day, a PV module can reach temperatures in excess of 100 °C. This can reduce the efficiency as much as 37% or about 0.5% for every 1 °C temperature rise. As a result of heating the PV module, conversion efficiency reduces up to 9.5%. It means that the solar PV module with the rated power of 300 Watts at 25 °C, during the summer period, when the ambient temperature is about 40 °C, due to the heating can have an efficiency only of about 180 Watts!

This problem is solved in PVT technology by extracting the heat from the solar cells. The PVT hybrid system combines a PV solar cell, which converts solar radiation into electricity with a solar thermal collector, which captures the remaining thermal energy and removes heat from the solar cell (Fig. 1).



*Fig. 1. The operating principle of PVT solar energy converter*

Thus, the PVT module is a dual solar collector with two usable energy outputs by one collection system (two in one). In hybrid PVT systems, by cooling the solar cells, the electrical generation is increased and the waste heat is captured for utilization, thus maximizing the return from the available solar radiation.

In comparison with general separated PV and thermal collectors, the PVT systems have the following advantages:

- improved PV generation – up to 40% more electricity than an equivalent conventional PV module with the same peak output,
- less roof space required,
- increased total efficiency (about 70%) due to generating both electric (15%) and thermal (55%) energies,
- the increased lifespan of solar cells and PV modules due to the reduction of operational temperatures.

Numerous research works are conducted for the investigation of the properties of PVT hybrid systems [3 - 12]. Some companies have started the production of hybrid PVT modules. Nevertheless, the utilization of this new technology is not growing rapidly mainly due to the high cost.

To reduce the cost of PVT collectors and to increase the electrical and thermal efficiencies of transformation of solar energy, a new type of PVT solar energy collector is developed at the laboratory “Semiconductor Photovoltaic Devices” at National Polytechnic University of Armenia.

***The structure of the new type PVT solar energy collector.*** At present, the PVT hybrid collectors are made on the base of PV modules by attaching them to the rear side of the thermal collector (Fig. 2).

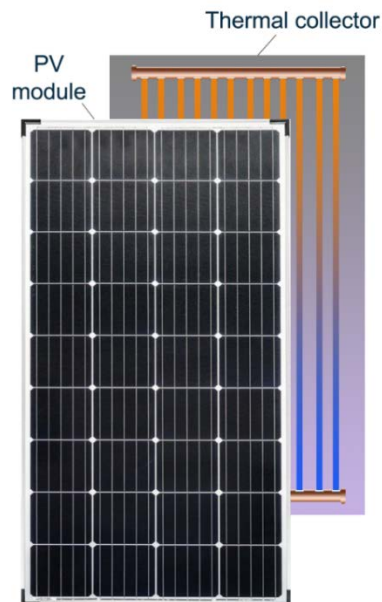


Fig. 2. The structure of a PVT hybrid collector

An additional glass cover can be applied to improve the thermal characteristics of the PVT collector [4]. These systems are expensive due to the separate fabrication of PV modules and thermal collectors and the connection of these two systems together.

In the new PVT collector, the PV module is prepared on the top of the thermal collector, i.e. two technologies are integrated and the PVT collector is fabricated during one unified technological sequence. The structure of the developed PVT solar energy converter is presented in Fig. 3. The PV component is integrated with the thermal collector, and there is a cavity between PV cells and cover glass, which increases the thermal efficiency.

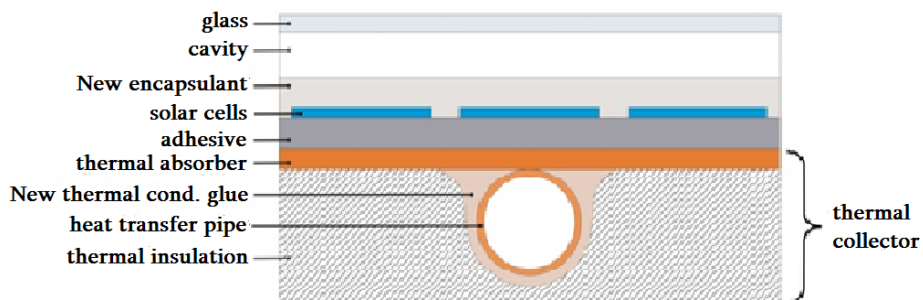


Fig.3. The structure of PVT solar energy converter

In the proposed solution, different innovative approaches are used. These innovations are:

1. Development and application of the new encapsulation technology.
2. The solar cells are integrated with the thermal collector (unified and simple production).
3. Development and application of a new thermal conductive glue.

As it is known, the traditional PV module encapsulation technology is based on the application of EVA (Ethylene - Vinyl - Acetate) film and lamination in a vacuum and heated environment. The developed new encapsulation technology is based on the application of the liquid encapsulant on the surface of solar cells. The liquid encapsulant is cured at room temperature, and an impenetrable cover around the cell is created. There is no need for a vacuum and increased temperatures. Thus, the manufacturing process is cheaper due to excluding the traditional energy and time-consuming lamination process. It is faster and can be realized with the use of simple equipment.

Besides the above-mentioned advantages, the applied encapsulation material is more transparent than EVA over the range of 280 to 400 nm (Fig. 4). This allows absorbing more solar light by solar cells and generating more electric energy, consequently increasing the cell's efficiency. As a result of the application of the new encapsulation technology and new encapsulant, the efficiency of the PV module is increased by 2.5% in comparison with traditional EVA film-based lamination technology.

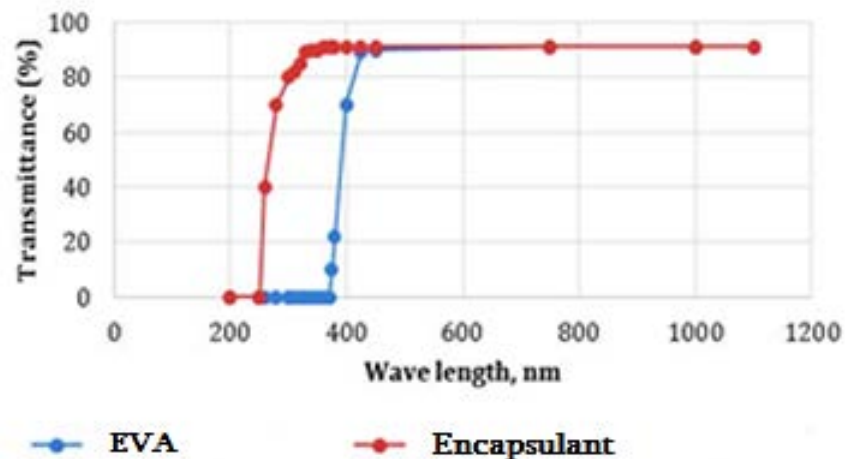


Fig. 4. The transmittance of an EVA film and a new encapsulant

With the use of the new encapsulation technology, the PV modules are produced and the stability of properties of the encapsulant are tested at "Semiconductor Photovoltaic Devices" in National Polytechnic University of Armenia (Fig. 5).



*Fig. 5. PV modules prepared with the use of a new encapsulant*

The tests are conducted both in the laboratory with the use of the solar simulator, as well as under outdoor solar radiation. The tests on the stability of parameters of PV modules are conducted during the last 10 years in the mountainous regions of Armenia, near Lake Sevan, with severe conditions (2 km elevation above sea level, high UV radiation, and cold winters). No degradation and damage or delamination of these PV modules have been detected up to now. This proves the good stability of properties of encapsulation material over a long period of operation.

The application of the new encapsulant allows preparing the PV part of the PVT collector just on the thermal absorber. Thus, the fabrication of the PV module is integrated with the preparation of the thermal collector. This allows simplifying the production sequence, reducing the fabrication costs and consequently the cost of PVT collectors.

The next innovative approach is the development and application of a new thermal conductive glue.

With the use of nano-sized graphite material, a new type of thermal conductive glue is developed. The application of this glue in the production of thermal collectors makes the fabrication process very easy and cheap. Simple equipment is needed for production.

Generally, in the existing thermal collectors made by welding of heat transferring Cu tube to Al thermal absorber sheet, cracks appear during the exploitation due to the difference of thermal expansion coefficients of Cu and Al. No similar problems arise in the case of the application of the new thermal conductive glue due to the plasticity of the glue.

***Parameters of the integrated PVT solar energy converter.*** With the use of the abovementioned innovative approaches, different PVT hybrid solar energy converters are prepared and tested. A prototype of the developed PVT collector is presented in Fig. 6 (outdoor tests during winter).

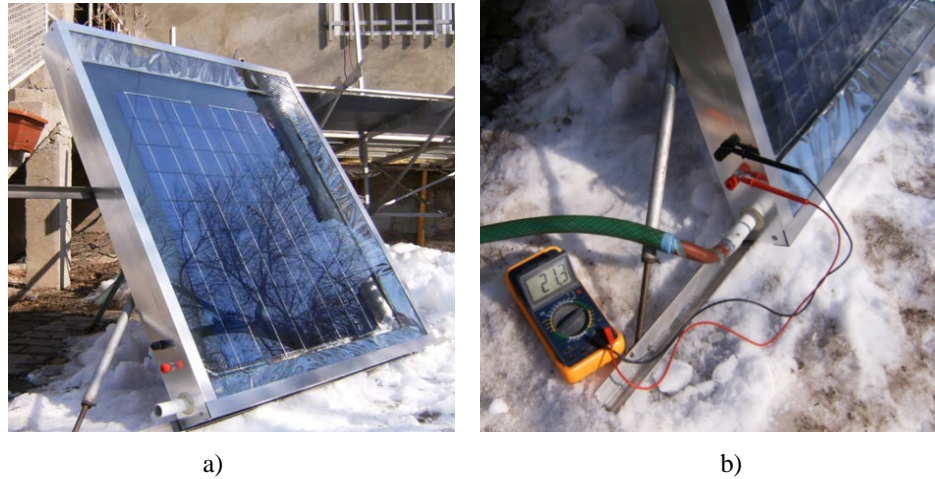


Fig. 6. A prototype of a new type PVT hybrid solar energy converter (a) and (b) testing (the open circuit voltage is 21.3 V)

The dimensions of the prototype are 1010 x 910 mm with a thickness of 90 mm with an output electric power of 64.8 W. The number of cells used is 36 with dimensions 80 x 150 mm. The PVT collector supplies about 60 liters of heated water at 50 °C during warmer climate periods.

The temperatures of the PVT prototype are tested under different environmental conditions. The temperatures of a reference general PV module are measured as well. The measured temperatures of the prototype and the general PV module at different ambient temperatures are presented in Fig. 7.

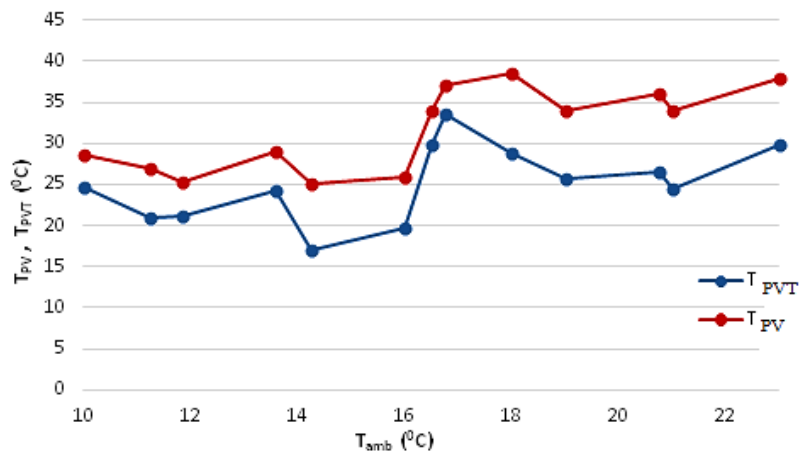


Fig. 7. The temperatures of the PVT collector and PV module at different ambient temperatures

As presented in Fig. 7, the PVT collector is cooler than the reference general PV module. It follows that the electrical efficiency of the PVT collector is higher in

comparison with a general PV module since the temperature dependence of the Si solar cells efficiency is defined as [13]:

$$\eta = \eta_0 [1 - \beta (T - T_0)],$$

where  $\eta_0$  is the reference efficiency of the solar cell, which is measured under the standard test conditions (STC),  $\beta$  is the temperature coefficient,  $T$  - the operating temperature of the solar cell,  $T_0$  - the reference temperature of the solar cell. Typically, the solar cells are rated at  $T_0 = 25 \text{ }^\circ\text{C}$  under  $1 \text{ kW/m}^2$  (STC). The quantities of  $\eta_0$  and  $\beta$  are normally given by the PV manufacturer. For the most common mono-crystalline and poly-crystalline silicon solar cells  $\beta = 0.005 \text{ }^\circ\text{C}^{-1}$  and  $\beta = 0.0045 \text{ }^\circ\text{C}^{-1}$  respectively [13].

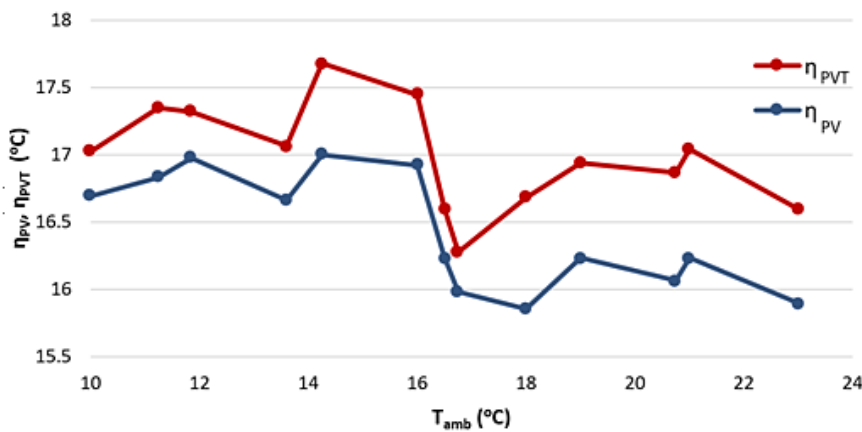


Fig. 8. Electrical efficiencies of the PVT hybrid collector and PV module at different ambient temperatures

The dependence of efficiencies of the PVT collector and general PV module, calculated by the above-mentioned formula, presented in Fig. 8. As it was expected, the mean value of electrical efficiencies decreases with increasing the temperature, and the efficiency of the PVT collector is higher than the efficiency of the general PV module.

### Conclusions

1. A new type of integrated PVT hybrid solar energy converter with cover glass and the cavity is developed.
2. The new developed PVT converters have the following advantages:
  - increased thermal efficiency due to the existence of a cavity between solar cells and cover glass;
  - increased PV efficiency (by 2.5 %) due to the use of a new encapsulant with good transparency in the short wave region of solar radiation;

- reduced production costs due to the application of a simplified (integrated) production process of PV components (PV cells are integrated with the thermal absorber);
- reduced production costs of thermal collectors due to the use of new thermal conductive glue and the new simple production sequence.

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## ԻՆՏԵԳՐՎԱԾ ՖՈՏՈՎՈԼՏԱՅԻՆ ԵՎ ՋԵՐՄԱՅԻՆ ԱՐԵՎԱՅԻՆ ԷՆԵՐԳԻԱՅԻ ԿՈՆՎԵՐՏՈՐ

Ռ.Ռ.Վարդանյան, Գ.Ս. Կարոյան

Արևային էներգիայի օգտագործումը կարևոր է կլիմայի փոփոխությունը զսպելու, հանածո վառելիքի սահմանափակ պաշարներից կախվածությունը նվազեցնելու և էներգետիկ անկախության հասնելու համար: Արեգակնային ճառագայթման օգտագործման հիմնական տեխնոլոգիաներն են լույսի ֆոտովոլտային (ՖՎ) փոխակերպումն անմիջապես էլեկտրականության և Արևի ճառագայթների ջերմային փոխակերպումը ջերմության: Արեգակնային էներգիային առնչվող հիմնական խնդիրն այդ էներգիան արդյունավետ կերպով հավաքելն ու ծախսարդյունավետ փոխակերպումն է այլ օգտակար ձևերի: Գոյություն ունեցող արևային էներգիայի համակարգերը դեռևս թանկ են:

Մյուս խնդիրը ՖՎ մոդուլների արդյունավետության նվազումն է աշխատանքային բարձր ջերմաստիճաններում: Հայտնի է, որ ՖՎ արևային մարտկոցներում, որոնք հիմնականում պատրաստված են սիլիցիումից, կլանվող արևային ճառագայթման մեծ մասը (մոտավորապես 80%) չի վերածվում էլեկտրականության, այլ նպաստում է արևային մարտկոցների ջերմաստիճանի բարձրացմանը, այնուհետև մարտկոցների էլեկտրական արդյունավետության նվազեցմանը: Սա արևային մարտկոցներին բնորոշ թերությունն է՝ ջերմաստիճանի պատճառով կատարողականի դեգրադացիան:

Նպատակ ունենալով նվազեցնելու արևային փոխարկիչների արժեքը և բարձրացնելու արևային էներգիայի փոխակերպման արդյունավետությունը՝ Հայաստանի ազգային պոլիտեխնիկական համալսարանի «Ֆոտովոլտային կիսահաղորդչային սարքեր» հետազոտական լաբորատորիայում մշակվել է ֆոտովոլտային և ջերմային (PVT) հիբրիդային արևային էներգիայի փոխարկիչ: Օգտագործվել են PVT փոխարկիչների մշակման տարբեր նորարարական մոտեցումներ: Պատրաստվել և փորձարկվել է նոր տեսակի PVT փոխարկիչի նախատիպը: Նոր PVT փոխարկիչն ունի մի քանի առավելություններ հայտնի ՖՎ մոդուլների և ՖՎ մոդուլի վրա հիմնված PVT կոլեկտորների համեմատ: Մշակված նոր PVT կոլեկտորների արտադրությունը էժան է և կարող է իրականացվել ստանդարտ տեխնոլոգիաների օգտագործմամբ:

**Առանցքային բաներ.** արևային, ֆոտովոլտային, ջերմային, արդյունավետություն, հիբրիդային մոդուլներ, երկակի էֆեկտ:

## ИНТЕГРИРОВАННЫЙ ПРЕОБРАЗОВАТЕЛЬ СОЛНЕЧНОЙ И ФОТОЭЛЕКТРИЧЕСКОЙ ЭНЕРГИИ

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Использование солнечной энергии необходимо для сдерживания изменения климата, уменьшения зависимости от ограниченных запасов ископаемого топлива и достижения энергетической независимости. Основными существующими технологиями использования солнечного излучения являются фотогальваническое преобразование света непосредственно в электричество и термическое преобразование солнечных лучей в тепло. Основная проблема, связанная с солнечной энергией, заключается в эффективном сборе этой энергии и экономичном преобразовании ее в другие полезные формы. Существующие системы солнечной энергии все еще дороги.

Другая проблема заключается в снижении эффективности фотоэлектрических модулей при высоких рабочих температурах. Известно, что в фотоэлектрических

солнечных элементах, в основном изготовленных из кремния, большая часть поглощаемой солнечной радиации (около 80%) не преобразуется в электричество, а способствует повышению температуры солнечных элементов, что приводит к снижению электрического КПД элементов. Это неотъемлемая черта солнечных батарей - ухудшение характеристик из-за температуры.

С целью снижения стоимости солнечных преобразователей и повышения эффективности преобразования солнечной энергии в научно-исследовательской лаборатории "Фотоэлектрические полупроводниковые устройства" Национального политехнического университета Армении разработан новый тип фотоэлектрического и теплового (PVT) гибридного преобразователя солнечной энергии. При разработке преобразователей PVT используются различные инновационные подходы. Изготовлен и испытан прототип преобразователя PVT нового типа. Новый преобразователь PVT имеет ряд преимуществ по сравнению с обычными фотоэлектрическими модулями и коллекторами PVT на основе фотоэлектрических модулей. Производство разработанных новых коллекторов PVT является дешевым и может осуществляться по стандартным готовым технологиям.

**Ключевые слова:** солнечный, фотоэлектрический, тепловой, эффективность, гибридные модули, двойной эффект.