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# Hybrid concentrator-planar photovoltaic module with heterostructure solar cells

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The paper presents a promising solution for photovoltaic modules that provides overcoming the main conceptual limitation for the concentrator concept in photovoltaics — the impossibility to convert diffused (scattered) solar radiation coming to the panel of sunlight concentrators. The design of a hybrid concentrator-planar photovoltaic module based on heterostructure solar cells: A3B5 triple-junction and Si-HJT is presented. The results of initial outdoor studies of the module output characteristics are discussed and estimates of its energy efficiency are given.

**Keywords:** hybrid concentrator-planar photovoltaic module, multijunction solar cell, Si-HJT planar photoconverter, diffusely scattered radiation.

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The enhancement of functionality and energy potential of photovoltaic systems for direct solar energy conversion through the use of concentrator and planar concepts is a very promising research direction.

Hybrid photovoltaic modules based on semiconductor components with III−V heterojunction structures and Si-HJT (silicon heterojunction technology) structures [1,2] provide an opportunity to convert efficiently the energy of both direct and diffuse (scattered) solar radiation by concentrator photovoltaic cells and planar solar cells, respectively. Hybrid modules have an evident advantage over classic concentrator ones in providing a significant power delivery in cloudy weather when direct radiation is attenuated or lacking, but diffuse radiation penetrates freely through a refractive concentrator (e.g., a Fresnel lens that acts as a fairly efficient diffuser for such radiation) and reaches planar solar cells. These hybrid concentrator-planar solutions hold promise for application in regions with a moderate level of direct normal irradiance (DNI) in the overall radiation flux incident on a tracking surface (global normal irradiance, GNI). If both (concentrator and planar) photovoltaic circuits are connected to the same load, the magnitude of fluctuations of power production associated with changes in the irradiance regime (transition from „mostly direct“ to „direct + diffuse (mixed)“ irradiation) and the corresponding transition from a high-efficiency III−V concentrator subsystem to a cheaper and less efficient silicon one should decrease.

The interest in hybrid (integrated) solutions stems from the need to expand the geographic range of application of high-efficiency concentrator photovoltaics and translates into a considerable number of published studies on relevant topics ranging from structural and operation specifics of hybrid modules [3–6] to the issues of estimation of their energy potential [6–9].

In the present study, we report on the development of a hybrid concentrator-planar photovoltaic module (C-PPVM) with heterojunction III−V and Si-HJT solar cells and provide data on the energy yield needed to assess its energy potential.

Two well-thought-out conceptual approaches combine to form the basis for the C-PPVM. In the concentrator circuit, this is the SMALFOC module design approach [1,10], wherein a large number of concentrator solar cells (SCs) on radiators are positioned on the front (facing inward into the module) surface of a glass plate, forming a generating panel. Triple-junction (3J) GaInP/Ga(In)As/Ge SCs mounted on small-sized ceramic radiators (DBC technology: an $Al_2O_3$ substrate with double-sided copper coating) were used as detectors and converters of concentrated solar radiation. This design provided efficient transfer of heat from 3J SCs to the glass base while minimizing the shadowing of the surface of Si-HJT SCs located below the glass

**Figure 1.** Hybrid concentrator-planar photovoltaic module.

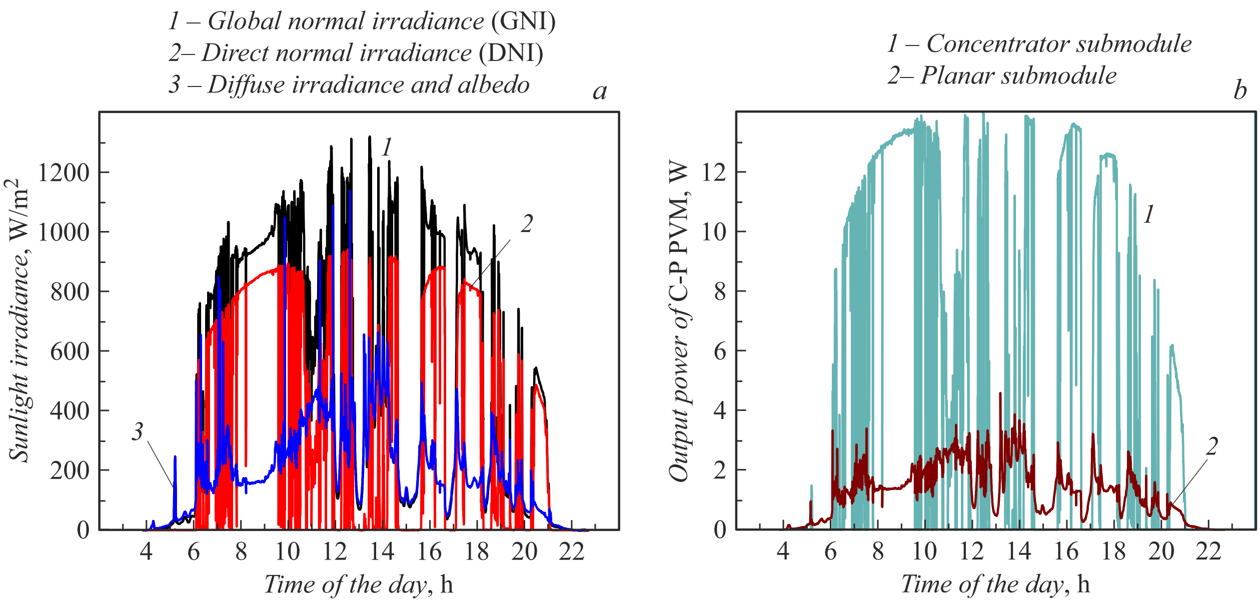


**Figure 2.** Results of C-PPVM monitoring: solar irradiance on the tracking surface (*a*) and instantaneous values of electric power generated by C-PPVM circuits (*b*) under „partly cloudy"irradiation conditions.

plate. In the planar circuit, the classical non-concentrator module layout was used: Si-HJT SCs were fixed below the glass by lamination with a film that protected their back side and electric wiring elements. A transparent film provides an opportunity to use Si-HJT SCs with bilateral sensitivity and thus enhance the energy yield of the planar photovoltaic circuit by converting radiation reflected from the surrounding infrastructure. Si-HJT SCs installed in the experimental C-PPVM model featured bilateral sensitivity with a bilaterality coefficient (i.e., the ratio of efficiencies of conversion of solar radiation by front and back surfaces) of 93%.

The experimental C-PPVM model features 32 cells with concentrators in the form of Fresnel lenses (each with a size of $40 \times 40$ mm) integrated into a single panel of $4 \times 8$ lenses. The planar photovoltaic circuit was formed based on advanced Si-HJT SCs $157.4 \times 157.4$ mm in size with bevelled corners [2,11]. A photographic image of the C-PPVM with 32 concentrator cells and two full-sized Si-HJT SCs is shown in Fig. 1. Each Si-HJT cell covered almost completely (with technological peripheral 1-mm-wide regions taken into account) a back surface area corresponding to a group of $4 \times 4$ lenses. The silicon cell surface open (with deductions for shadowing by radiators and wiring elements of the concentrator circuit) for diffuse radiation constitutes 88% of the area of the C-PPVM lens panel.

The proposed design has a major advantage in that the existing technology solutions are used to the fullest both in concentrator and in planar submodules, and all additional expenditures on processing (cutting) of commercially produced Si-HJT SCs are excluded [12]. The latter factor is the key distinctive feature of the discussed C-PPVM concept and its advantage over similar modules where silicon SCs are either produced in non-standard configurations with a specialized contact structure [9,11,13] or subjected to special processing to form apertures admitting radiation concentrated by a Fresnel lens to 3J SCs [4].

It should be noted that the most significant difference between the discussed C-PPVM and the ones proposed in [1,4] is its balanced design: planar technology complements the well-proven concentrator concept, introducing no structural or technological complications.

The production of power by both photovoltaic circuits of the proposed C-PPVM in the regime of solar irradiation with different ratios of direct and diffuse components in the overall luminous flux is of the utmost interest. Observations were performed from June 17 to September 8, 2022, in St. Petersburg (59.94°N, 30.31°E) in the mode of continuous solar tracking [13–15] with measurement of the overall, direct, diffuse, and reflected (albedo) energy components of luminous flux incident on the tracking surface. An example of daily dependences under typical partly cloudy conditions and time patterns of the output electric power of C-PPVM circuits are presented in Fig. 2.

It should be noted that the C-PPVM power output under conditions of clear sky, when the fraction of diffuse radiation in the overall luminous flux is 10–15% (at a direct flux of $\sim 800\,\mathrm{W/m^2}$ or higher), is 10–15% higher than the concentrator circuit output, and this difference is attributable to power production by the planar circuit. The percentage of power production by the planar circuit increases under partly cloudy or overcast conditions (with a greater fraction of diffuse radiation) increases, while the total C-PPVM power production decreases due to a reduction in the overall energy of the incident solar radiation

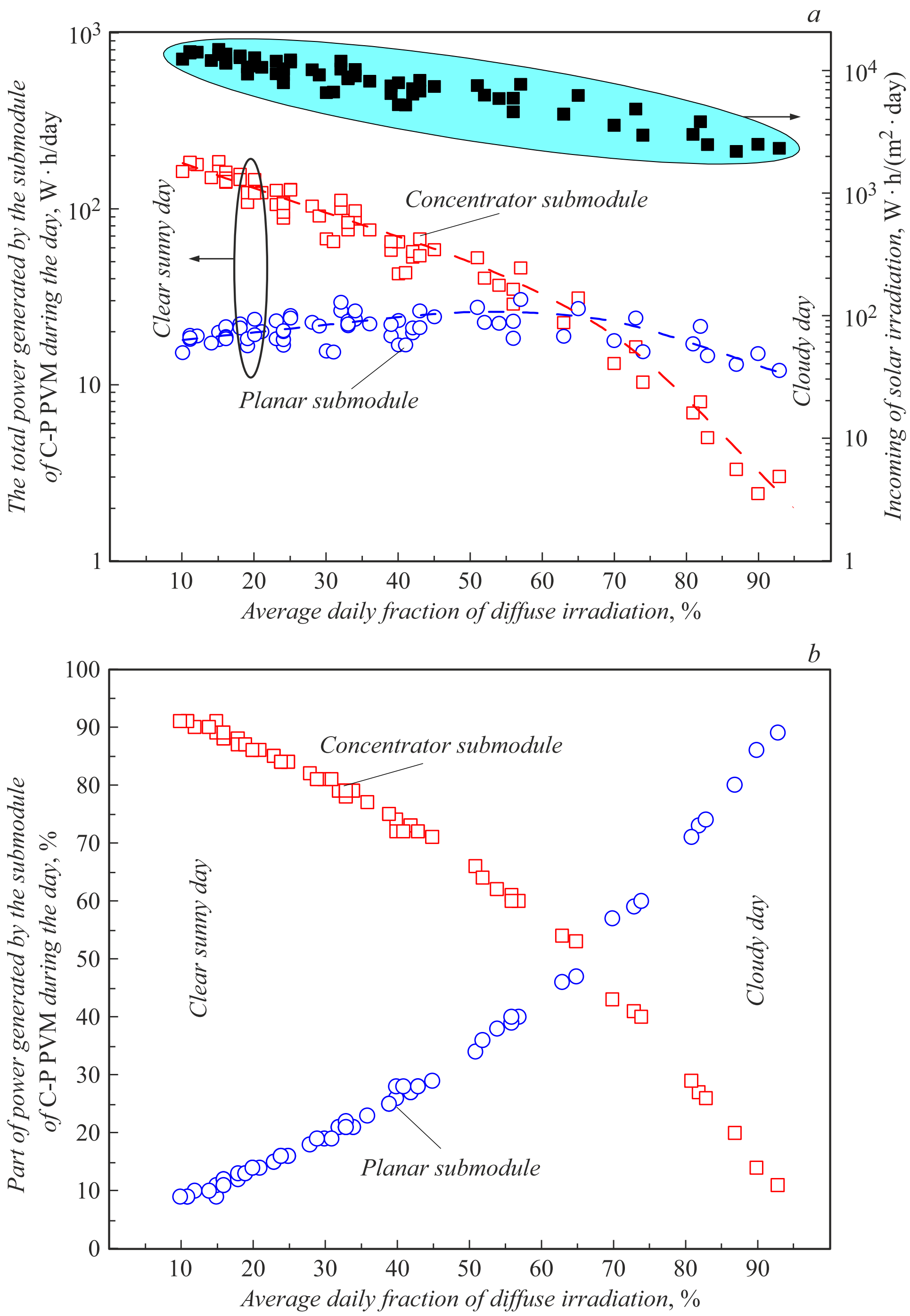


**Figure 3.** Total (*a*) and relative (*b*) (percentage fraction of the overall power delivery) power generated by concentrator and planar photovoltaic circuits of the C-PPVM during the day as function of the fraction of diffuse radiation in the overall luminous flux incident on the module surface. Observations were performed from June 17 to September 8, 2022, in St. Petersburg (59.94°N, 30.31°E) in the mode of continuous solar tracking.

flux. Under partly cloudy conditions or in the case of a considerable atmospheric opacity, when the greater part of solar energy (more than 65%) is incident in the form of diffuse radiation, the planar circuit becomes comparable to the concentrator one in terms of the daily power production or even outperforms it (Fig. 3), even though the efficiency of the concentrator circuit is almost two times higher than the efficiency of the planar one (32 and 18% at 1000 and 200 W/m$^2$ of incident radiation, respectively).

The concept of a hybrid concentrator-planar photovoltaic module based on semiconductor components with two types of materials (III–V and Si) and designed to convert the energy of solar radiation flux in full (direct radiation is converted by concentrator photovoltaic cells, while diffuse (scattered) radiation is processed by planar solar cells) was proposed. The C-PPVM has an advantage over traditional concentrator modules in that it maintains power delivery in cloudy weather when direct radiation is attenuated or lacking, but diffuse radiation penetrates freely through a concentrator (Fresnel lens) and reaches planar solar cells. Having monitored the power production of the C-PPVM, compiled large sets of experimental data, and analyzed them, we found that hybrid concentrator-planar photovoltaic modules should be advantageous for application at sites with a prevalently variable balance of direct and diffuse components of the overall solar radiation flux.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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