Photovoltaic Power Generation | Light Concentration Technology | Combined Heat and Power

Technology Reports

Design and Evaluation of Thermal-photovoltaic Hybrid Power Generation Module for More Efficient Use of Solar Energy

As environmental problems like global warming and energy depletion become increasingly severe, society is rediscovering the value of generating power using natural energy sources as in photovoltaic power generation. With the aim of reducing startup costs, improving energy-conversion efficiency, and addressing other issues hindering the widespread use of photovoltaic power generation, we propose a thermal-photovoltaic hybrid power generation module using an interface-reflection concentrator consisting of amorphous solar cells, reflective film and water. The proposed module concentrates visible light to increase the efficiency of power generation while also recovering from the water the thermal energy obtained from infrared light. We tested the operation of the module using AM1.5 artificial sunlight.

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1. Introduction

As environmental problems like global warming and energy depletion escalate, there is a renewed appreciation for power-generation equipment that uses natural energy sources as in photovoltaic power generation and wind turbines. Photovoltaic power generation has the advantage of easy installation and maintenance and features the same power-generation efficiency regardless of the scale of the system. The use of photovoltaic power generation through the installation of rooftop equipment on private residences, telecommunication buildings, and other facilities is now becoming commonplace. At the same time, photovoltaic power generation suffers from low energy density and the high cost of equipment. In other words, the high cost per unit amount of power generated is hindering the further spread of photovoltaic power generation.

Types of solar cells and their features are shown in **Figure 1**. The most widely used at present are of the silicon type, which includes crystalline-silicon type*1 and amorphous-silicon type*2 solar cells. The latter type is inferior in terms of energy-conversion efficiency, but it uses a relatively small amount of silicon and energy in its manufacture enabling costs to be reduced.

In this article, we focus on amorphous-silicon solar cells and propose a module structure that aims to improve energy-conversion efficiency while reducing costs. We also test the effectiveness of the proposed module.

*1 **Crystalline-silicon type**: Solar cells that use silicon in a crystalline state in which silicon atoms are regularly arranged.

*2 **Amorphous-silicon type**: Solar cells that use a relatively small amount of silicon in a disordered state rather than a crystalline state.

2. Concentrator-type Photovoltaic Power Generation

To lower the cost per unit amount of power in photovoltaic power generation, the amount of power generated by the same area of photovoltaic power elements must be increased. One way of accomplishing this is to raise the energy-conversion efficiency of the photovoltaic power element itself. However, the output of a photovoltaic power element also increases in proportion to the amount of sunlight irradiating it, which means that concentrating the sunlight irradiating the element can also be an effective approach.

Light concentration technology used in concentrator-type photovoltaic power generation can be broadly divided into two types: tracking type that requires solar tracking and stationary type that does not.

The tracking type of light concentration technology has the advantage of a high concentration ratio[*3], but it also requires a motor unit for tracking that adds to startup costs. It is consequently not very applicable to small-scale power generation [1][2].

The Compound Parabolic Concentrator (CPC) is typical of the stationary type of light concentration technology. The CPC features two parabolic mirrors configured so that their center axes are titled toward each other. The angle formed by these axes corresponds to the allowed angle of incidence (acceptance angle) of the CPC [3][4]. Although the value of the concentration ratio here is less than that of the tracking type, the CPC is more suitable for small-scale power-generation equipment since no motor unit is needed for solar tracking.

In concentrator-type photovoltaic power generation equipment, the rise in solar-cell temperature is higher than usual, and research on using that thermal energy to suppress this rise in temperature has been quite active [5]-[7].

In this article, we propose a thermal-photovoltaic hybrid power generation module (hereinafter referred to as "proposed module") designed to improve conversion efficiency and reduce costs. Using amorphous solar cells, the proposed module is capable of both concentrating light and recovering thermal energy in stationary equipment.

Types of solar cells			Features
Compound	Monocrystalline (GaAs, etc.)		Conversion efficiency: 20–30% Cost: very expensive
Silicon	Crystalline	Monocrystalline	Conversion efficiency: 15–20% Cost: expensive
		Polycrystalline	Conversion efficiency: 12–15% Cost: reasonable
	Amorphous		Conversion efficiency: 5–10% Cost: inexpensive
Organic	Dye-sensitized		Conversion efficiency: 3–6% Cost: very inexpensive
	Organic thin film		Conversion efficiency: 3–6% Cost: very inexpensive

Conversion efficiency and cost

Figure 1 Types and features of solar cells

3. Overview of Proposed Module

3.1 Features of Amorphous-silicon Solar Cells

The spectral sensitivity of crystalline-silicon and amorphous-silicon solar cells is shown in **Figure 2**. The main feature of crystalline-silicon solar cells is that light in both the visible region and infrared region contributes to power generation with infrared light having a particularly high ratio of contribution. Amorphous-silicon solar cells, in contrast, feature good power generation by light in the visible region but almost no contribution to power generation by light in the infrared region. Thus, in the case of outdoor use, amorphous-silicon solar cells cannot make use of the infrared light in sunlight for generating power. This is one reason why the energy-conversion efficiency of amorphous-silicon solar cells is inferior to that of crystalline-silicon solar cells.

Nevertheless, the proposed module adopts amorphous solar cells because of

*3 **Concentration ratio**: The factor by which the amount of sunlight irradiating a light-receiving surface can be increased relative to normal irradiation.

other features that help reduce module cost such as the relatively small amount of silicon and energy used in their manufacture.

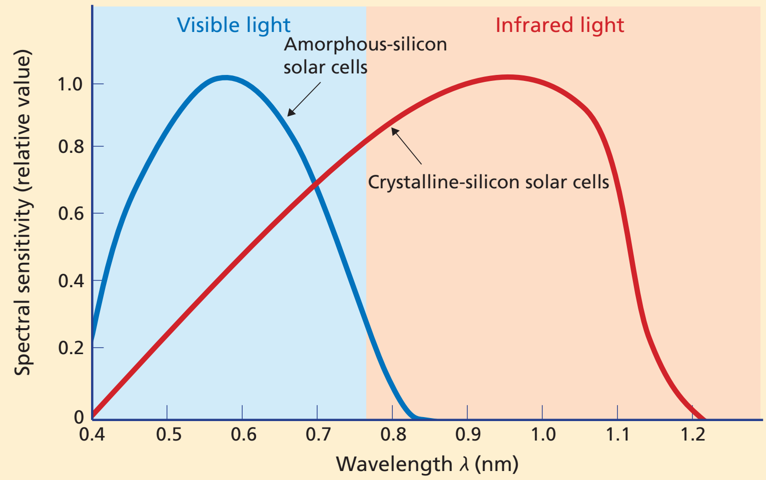

Figure 2 Spectral sensitivity of crystalline-silicon and amorphous-silicon solar cells

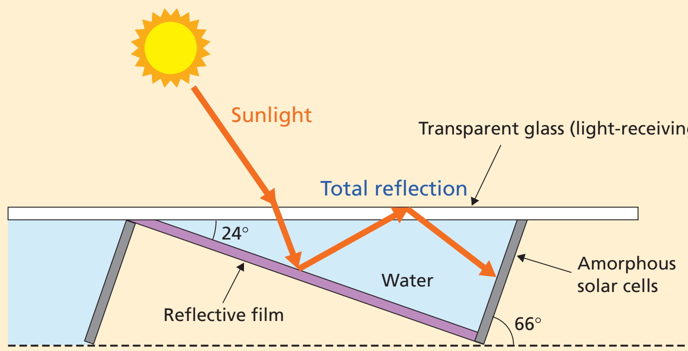

Figure 3 Cross section of proposed module and principle of light concentration

3.2 Structure of Proposed Module

The cross section of the proposed module and principle of light concentration is shown in **Figure 3**. The module consists of transparent glass (light-receiving surface), amorphous solar cells, and reflective film that form a triangle in the cross section. The inside of this module is filled with water. In actuality, the amorphous solar cells and reflective film are sealed by an acrylic sheet to prevent them from coming into direct contact with the water. The basic idea behind this structure is to have light in the visible region generate electricity via the amorphous solar cells and to have the water absorb infrared light, which does not contribute to electric power here, as thermal energy. This water, however, also has the role of concentrating light. As shown in Fig. 3, sunlight passing through the light-receiving surface first reflects off the reflective film. It then reflects totally off the interface with the outside air, and finally irradiates the amorphous solar cells. In this configuration, all sunlight irradiating the light-receiving surface will concentrate on the amorphous solar cells provided that the angle of incidence is to the left of the normal made with the light-receiving surface. In this regard, the annual maximum altitude of the sun in Tokyo is 78 degrees. Accordingly, sunlight irradiating the light-receiving surface can always be made to concentrate on the amorphous solar cells by installing the module in a tilted manner so that incident light is normal to this surface when the sun is at its maximum altitude.

3.3 Recovery of Thermal Energy

Thermal energy can be recovered by circulating the water filling the inside of the module. To this end, a water pipe is installed on either side of the module and an inlet and outlet are placed at the lower end and upper end, respectively, of either side (**Figure 4**). In this way, the thermal energy obtained from infrared light can be recovered as hot water. This hot water can be used simply as a hot-water supply or for heating purposes in homes or other buildings installing the proposed module, and in the case of telecommunication facilities, it can be used as an energy source for an absorption chiller[*4] or desiccant air conditioner[*5] to cool the facilities. In general, a solar water heater can use about 50% of incident solar energy as thermal energy, which means that its energy-conversion efficiency is dramatically higher than that of photovoltaic power generator. Thus, if the hot water produced by the proposed module can be used effectively and combined with the amount of power generated by the amorphous solar cells, it should be possible to raise the total energy-conversion efficiency of the proposed module by several times. The proposed module also features a solar-cell area that is approximately 45% the area of the light-receiving surface. In other words, the design of the proposed module makes it possible to reduce the area of solar cells thereby reducing module cost.

The proposed module in a water-filled state is shown in **Photo 1**. In actuality, solar cells are arranged crosswise in four rows, but because of the principle of reflection, it appears as if there are 12 rows of solar cells inside the module. This means that all light incident on the light-receiving surface of the module irradiates the actual solar cells.

4. Module Testing

We prepared an ordinary module and a model of the proposed module for comparing concentration ratios using Air Mass (AM) 1.5[*6] artificial sunlight (**Figure 5**). For the ordinary module, we used an amorphous-solar-cell module 2 cm×24 cm in size with an operating voltage of 2.5 V. For the proposed module, we formed a container using transparent acrylic (thickness: 3 mm) shaping it like a triangular prism. We attached a 2 cm×24 cm amorphous solar cell the same as the ordinary module to one surface of the container and reflective film to another, and filled the container with water. To compare the two modules, we irradiated both the ordinary module and proposed module with AM1.5 artificial sunlight at an angle normal to the light-receiving surface and measured generated power at an operating voltage of 2.5 V. We also measured the rise in temperature of the water inside the proposed module.

4.1 Power-generation Performance of Proposed Module

The results of testing power genera-

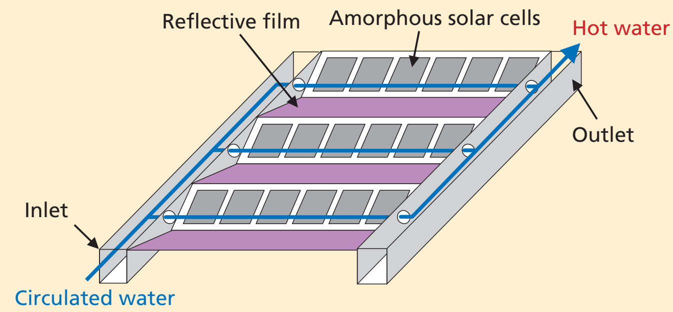

Figure 4 Structure of proposed module

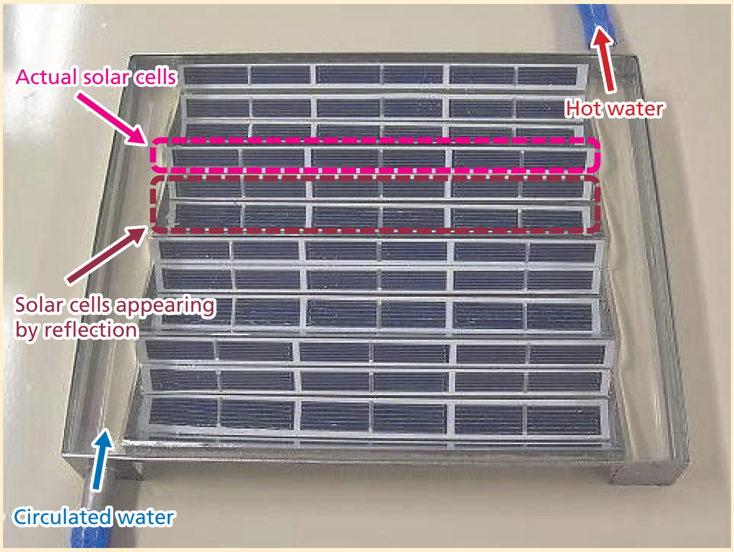

Photo 1 Proposed module in water-filled state

*4 **Absorption chiller**: A cooling machine that lowers temperature by evaporation and thermal cooling, that is, by having refrigerant evaporate at low pressure and allowing it to be absorbed by a highly absorbent liquid that requires thermal energy to be regenerated.

*5 **Desiccant air conditioner**: A type of air conditioner that performs cooling by producing dry air with desiccant material and evaporating water; the desiccant material requires thermal energy to be regenerated.

*6 **AM1.5**: Standard value of solar energy arriving at the earth's surface; approximately 1 kW/m^2.

tion are shown in **Figure 6**. We first compared power generation between the ordinary module and proposed module for the same solar cell (2 cm×24 cm). Compared to the 190 mW generated by the ordinary module, the proposed module generated 345 mW or 1.8 times as much power for the same solar cell. This result indicates that the concentration ratio of the proposed module is approximately 1.8 times that of the ordinary module.

We next compared the amount of power generated per light-receiving surface. Here, noting that the size of the light-receiving surface of the ordinary module is 2 cm×24 cm while that of the proposed module is 4.5 cm×24 cm, we multiply the power generated by the proposed module by a factor of 2/4.5 and compare power generation for the same light-receiving area of 2 cm×24 cm. In this case, the power generated by the proposed module comes out to be 155 mW or approximately 80% that of the ordinary module. This loss in power is thought to correspond to the amount of energy absorbed by the water in the module before incident light irradiates the amorphous solar cell. In short, a slight loss does occur, but these results show that 80% of generated power can be maintained by a solar-cell area approximately 45% that of the light-receiving surface.

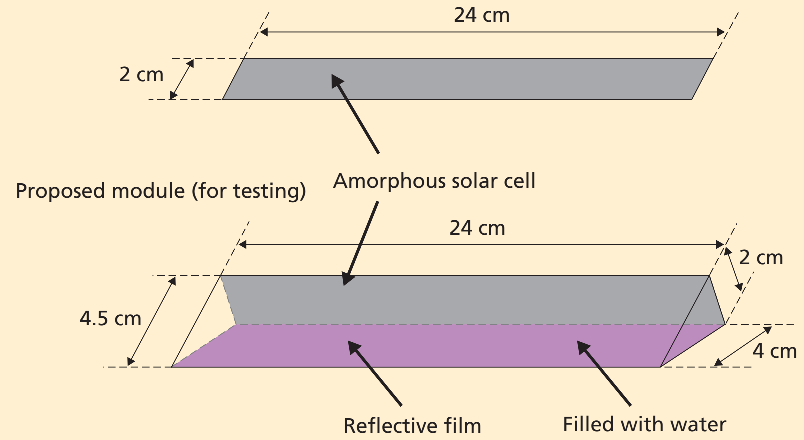

Figure 5 Ordinary module and proposed module for testing

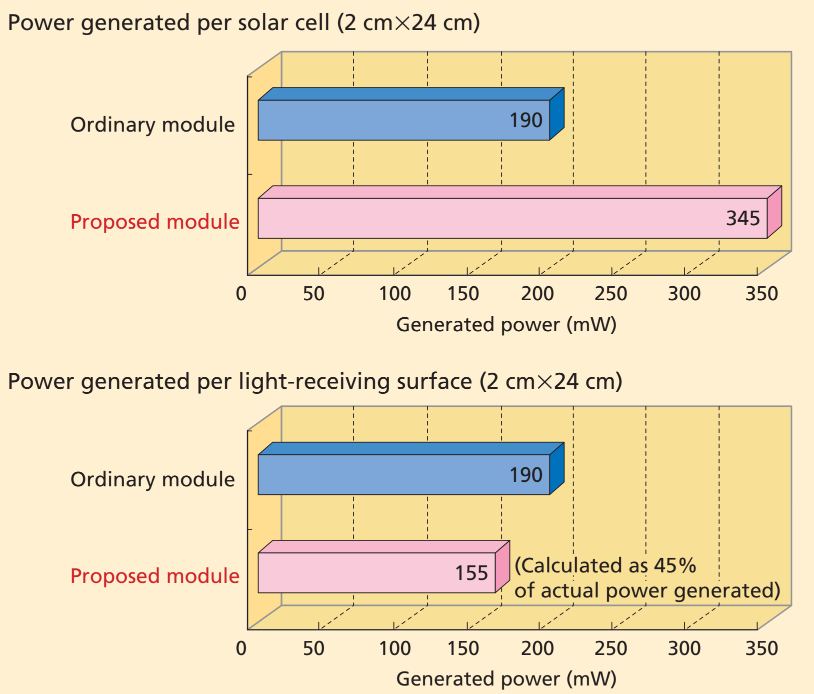

Figure 6 Results of power-generation test

4.2 Rise in Water Temperature

Rise in temperature of the water inside the proposed module versus time is shown in **Figure 7**. The temperature inside the laboratory was 24 ℃ and measurements began with the water at the same temperature. The temperature of the water rose approximately 18 ℃ in 60 minutes eventually reaching a temperature of 46 ℃. At this temperature, the water can be used as a supplementary source for household heating or simply as hot water. At temperatures below 60 ℃, however, this water could not be effectively used for an absorption chiller or desiccant air conditioner. The results shown here were obtained for a 3-mm-thick acrylic sheet as a boundary between the hot water and outside air and not for any other adiabatic structure. If the module could be given an adiabatic structure that improves thermal insulation, it should be possible to raise the temperature of the water inside the module even further.

5. Discussion

As described above, one drawback of photovoltaic power generation is low energy-conversion efficiency. Even a photovoltaic power generation module made of monocrystalline-silicon solar cells can only convert 15–20% of solar energy into electrical energy. A solar water heater, however, is one device that can make effective use of solar energy. It achieves high energy-conversion efficiency compared to photovoltaic power generation and can use 50–70% of solar energy as hot water depending on the product. At the same time, electricity is viewed as a form of energy that is easier to use than hot water, and for this reason and aesthetic considerations, more attention is currently being paid to photovoltaic power generation.

The thermal-photovoltaic hybrid power generation method proposed here generates electric power by solar cells while also recovering the solar energy that cannot be converted to electrical energy as hot water. In other words, it is a thermal-electric type of power-generation system that obtains both electric and thermal energy from solar energy. We can expect this method to raise cost performance significantly compared to ordinary photovoltaic power generation equipment provided that this thermal energy can be effectively used in an on-time manner.

The proposed module can reduce solar-cell area by virtue of its light-concentration function. And while its concentration ratio is less than that of a solar-tracking or CPC system, it can be configured as a flat-panel module enabling installations that are nearly as aesthetically pleasing as ordinary photovoltaic power generation equipment.

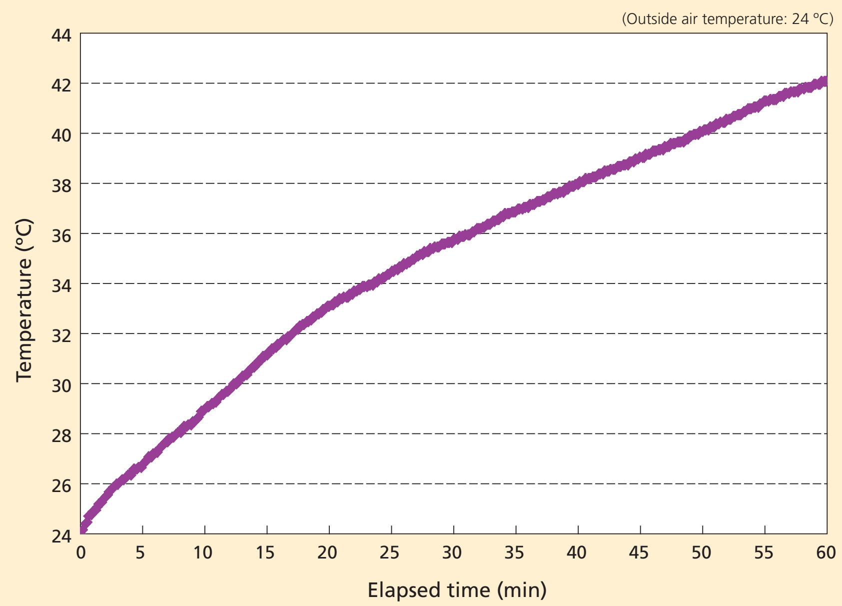

Figure 7 Rise in water temperature

6. Conclusion

Studies are being made on ways of achieving load leveling in power systems while controlling the supply and demand for energy and efficiently generating and using energy all on a local basis as in a microgrid[*7]. A cogeneration-type distributed power source[*8] that generates electric power on-site and effectively uses the accompanying heat is considered to be an important constituent element of such a system.

The thermal-photovoltaic hybrid power generation method proposed in this article can also be used as a cogen-

*7 **Microgrid**: A localized network of small and distributed energy sources (solar, wind, etc.) that can operate efficiently within a region to achieve a balance between the supply and demand of electric power and heat without having to rely on the conventional centralized power network.

*8 **Cogeneration-type distributed power source**: Equipment that supplies both electricity and heat by making effective use of the heat that accompanies the generation of electric power. Since the utility value of such equipment is high in building sites that have a demand for heat, this type of distributed power source is generally installed inside individual sites.

eration-type distributed power source that uses solar energy. This holds true even if a site where the power source is installed cannot make effective use of thermal energy since that energy can be shared with neighboring sites. In this way, the possibility of using natural energy more efficiently increases and contributions to reducing CO_2 emissions and solving the energy depletion problem can be made.

The main purpose of the testing described in this article was to assess the effectiveness of the light-concentration principle in a photovoltaic power generation module. In future research, we plan to study the efficiency of converting solar energy to thermal energy taking thermal insulation into account and means of reducing costs in mass production.

References

[1] K. Araki, H. Uozumi and M. Yamaguchi: "A simple passive cooling structure and its heat analysis for 500x concentrator PV module," Photovoltaic Specialists Conference 2002, pp.1568-1571, May 2002.

[2] A. Mohr, T. Roth, M. Epmeier and S. W. Glunz: "Silicon concentrator cells in a one-axis tracking concentrator system with a concentration ratio of 300x, " Photovoltaic Specialists Conference 2005, pp.639-642. Jan. 2005.

[3] M. Brogren, M. Ronelid and B. Karlsson: "PV-Thermal Hybrid Low Concentrating CPC Module," 16th European Photovoltaic Solar Energy Conference, pp.2121-2124, May 2000.

[4] A. Mohr, M. Steuder, A. W. Bett and S. W. Glunz: "Silicon concentrator cells designed for a direct mounting on compound parabolic concentrator," Photovoltaic Energy Conversion 2003, Vol.1, pp.841-844, 2003.

[5] J. S. Coventry: "Performance of a concentrating photovoltaic/thermal solar collector," Solar Energy, Vol.78, Issue 2, pp.211-222, 2005.

[6] A. Segal, M. Epstein and A. Yogev: "Hybrid concentrated photovoltaic and thermal power conversion at different spectral bands," Solar Energy Vol.76, No.5, pp.591-601, 2004.

[7] Y. Vorobiev, J. Gonzales-Hernandez, P. Vorobiev and L. Bulat: "Thermal-photovoltaic solar hybrid system for efficient solar energy conversion," Solar Energy Vol.80, Issue 2, pp.170-176, Feb. 2006.