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Small thermophotovoltaic prototype systems

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Abstract

In an earlier paper we reported on a small grid-connected thermophotovoltaic (TPV) system consisting of an ytterbia mantle emitter and silicon solar cells with 16% efficiency (under solar irradiance in standard test conditions, STCs). The emitter was heated up using a butane burner with a rated thermal power of 1.35 kW (referring to the lower heating value). This system produced an electrical output of 15 W, which corresponds to a thermal to electric (direct current) conversion efficiency of 1.1%. In the interim, further progress has been made, and significantly higher efficiencies have been achieved. The most important development steps are: (1) the infrared radiation-absorbing water filter between emitter and silicon cells (to protect the cells against overheating and against contact with flue gasses) has been replaced by a suitable glass tube. By doing this, it has been possible to prevent losses of convertible radiation in water. (2) Cell cooling has been significantly improved, in order to reduce cell temperature, and therefore increase conversion efficiency. (3) The shape of the emitter has been changed from spherical to a quasi-cylindrical geometry, in order to obtain a more homogeneous irradiation of the cells. (4) The metallic burner tube, on which the ytterbia emitter was fixed in the initial prototypes, has been replaced by a heat-resistant metallic rod, carrying ceramic discs as emitter holders. This has prevented the oxidation and clogging of the perforated burner tube. (5) Larger reflectors have been used to reduce losses in useful infrared radiation. (6) Smaller cells have been used, to reduce electrical series resistance losses. Applying all these improvements to the basic 1.35 kW prototype, we attained a system efficiency of 1.5%. By using preheated air for combustion (at approximately 370 °C), 1.8% was achieved. In a subsequent step, a photocell generator was constructed, consisting of high-efficiency silicon cells (21% STC efficiency). In this generator, the spaces between the cells were minimized, in order to achieve as high an active cell area as possible, while simultaneously reducing radiation losses. This new system has produced an electrical output of 48 W, corresponding to a system efficiency of 2.4%. This is the highest-ever-reported value in a silicon-cell-based TPV system using ytterbia mantle emitters. An efficiency of 2.8% was achieved by using preheated air (at approximately 500 °C). An electronic control unit (fabricated of components with low power consumption, and including a battery store) was developed, in order to make the TPV system self-powered. This unit controls the magnetic gas supply valve between gas supply cylinder and burner as well as the high-voltage ignition electrodes. Both the control unit's own power consumption and the battery-charging power are supplied directly by the TPV generator. A small commercial inverter is used to transfer excess power to the 230 V grid.

1. Introduction

Thermophotovoltaic devices convert radiant heat directly into electrical power. The integration of this principle into residential heating systems would open up a major potential for combined heat and power generation (Durisch et al., 1999; Palfinger et al., 2001; Crowley et al., 1999; Ferber et al.; Fraas, 2000). Part of the electrical power produced can be used to make heating systems self-powering. Such systems would continue to operate during grid failures (blackouts). Excess power can be fed into the household's grid to supply appliances, and/or transferred to the utility's grid for external consumers.

In Switzerland, about 1.5 million oil-burning and gas-

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fired domestic central heating systems could be equipped with thermophotovoltaic generators (Durisch et al., 1999). Assuming a fuel-to-alternating-current (AC) conversion efficiency of 5%, the potential for household TPV co-generation systems in Switzerland then amounts to 2.3 billion kWh of electricity per year. Furthermore, if the domestic space heating and hot water production that is presently based on electricity were replaced by oil-burning and gas-fired TPV co-generation systems, an additional contribution of about 0.5 billion kWh/year could be produced, resulting in an effective TPV potential of 2.8 billion kWh/year. This corresponds to 6% of the total annual electricity consumption in Switzerland, which means that decentralized TPV co-generation systems could—in the long term—provide a valuable contribution to the Swiss electricity supply. However, further research, development and demonstration work will be required to achieve a fuel-to-AC efficiency of 5%. Based on the latest economic considerations (Palfinger et al., 2001), it is concluded that competitive electricity prices should be anticipated in comparison with prices for household electricity.

2. 15 W prototype

The purpose of developing TPV prototype systems was: (1) To investigate the influence of different components and configurations on electrical output, (2) to improve system design and enhance device efficiency, (3) to provide experimental data for the modeling of larger systems, (4) to demonstrate the feasibility for continuous operation, (5) to demonstrate self-powered operation, (6) to demonstrate self-powered operation plus the simultaneous feeding of excess power to the 230 V grid.

A first prototype system was presented by Durisch et al. (1999). This consists of a conventional butane burner (rated thermal power 1.35 kW), which was equipped with a spherical mantle emitter made of ytterbia, Yb_2O_3. Gaseous butane is provided by evaporation of liquid butane contained in a steel cylinder. Eight commercial silicon solar cells, measuring 5 cm×10 cm, made by TESSAG, Heilbronn, Germany, with a standard test condition (STC) efficiency of 16%, were used to fabricate the photocell generator. In order to obtain as high a voltage as possible, the cells were connected in series. An infrared radiation-absorbing water layer between the emitter and photocell-generator protects the photocells from overheating and against direct contact of the cells with flue gasses The cell temperature was limited to about 55 °C by additional free convection cooling. Upper and lower reflectors prevent axial radiation losses. Under emitter radiation, the photocell generator produced a maximum power point (mpp) current of 4.6 A at an mpp voltage of 3.3 V, corresponding to a direct current (DC) output of 15.2 W and a thermal input to DC output conversion efficiency of 1.1%. The short circuit current was 5.0 A and the open circuit voltage 4.5 V, resulting in a fairly low fill factor of 0.67.

A high efficiency DC/DC converter (voltage multiplier), developed at the University of Lausanne, Switzerland, and an inverter specially developed by the Swiss company, LEC, Küsnacht were used to feed the generated power into the local 230 V utility grid (Durisch et al., 1999). An overall converter/inverter interface efficiency of up to 89% was achieved. Using commercially available DC/DC converters led to unsatisfactory results (very low interface efficiency due to low efficiency of a series connection of two industrial DC/DC converters).

3. 30 W prototype

A second prototype, based on the same butane burner, was developed in order to increase the electrical output and system efficiency. The same ytterbia mantle structure as in the first prototype was used as emitter. A detailed simulation model (Mayor, 2000) was used to study the effect of the geometrical form of the emitter on the illumination of the photocells. Spherical emitters in a cylindrical cell-generator lead to a non-homogeneous irradiation distribution on the photocells, and hence a reduction in their efficiency. The emitter geometry was therefore changed from spherical to ellipsoidal. Furthermore, the perforated burner tube was replaced by a metallic diffuser/rod system with ceramic mantle holders in order to eliminate oxidation and clogging of the tube. Bitnar et al. (2000) showed that the water filter also absorbs some of the convertible emitter radiation. In order to reduce these losses, a glass tube replaced the water filter. However, this requires much more efficient cell cooling. Therefore the cells were glued onto metallic support plates that were cooled by tap water flowing through boreholes. In spite of the higher heat load on the cells, this produced a reduction in the cell temperature, resulting in higher cell efficiency. A glass tube between emitter and photocell generator is necessary to avoid direct contact between the cells and flue gasses, and to prevent the condensation of water (contained in the flue gas) onto the cell surface. We installed larger lower and upper reflectors to reduce axial radiation losses. The result of all these measures is shown in Fig. 1.

In this second prototype, we again used silicon solar cells made by TESSAG, with an STC efficiency of 16%. We used smaller cells, producing lower currents, in order to minimize series resistance losses in the cell circuitry. A total of 16 cells were installed, each measuring 2.4 cm by 9.8 cm. The active cell area amounts to 376 cm^2. All the cells were connected in series to achieve as high an output voltage as possible.

An electrical output of 29 W was obtained at a thermal input of 1905 W, corresponding to a system efficiency of 1.5%. The short circuit current and open circuit voltage were measured to be 4.0 A and 10.4 V, respectively,

Fig. 1. The 30 W TPV prototype system. The incandescent mantle emitter made from ytterbia, Yb_2O_3, is positioned in the center. Upper and lower reflectors prevent axial radiation losses. The silicon photocells can be seen in the background. Cell temperature is kept at an acceptable level by efficient cell cooling, using tap water. A glass tube between the emitter and photocell generator prevents contact between the cells and exhaust gases.

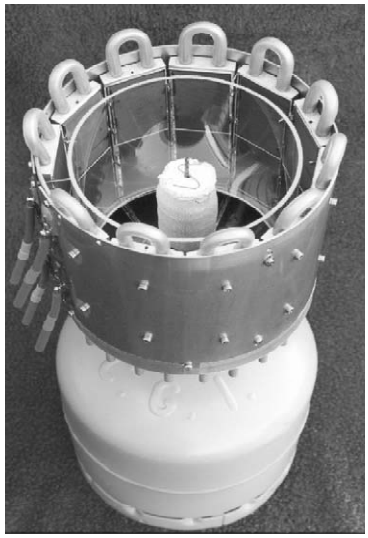

Fig. 2. The 50 W TPV prototype system. A cylindrical ceramic mantel emitter made from ytterbia, Yb_2O_3, was placed in the center of a photocell generator. Butane combustion heats up the emitter. A glass tube is positioned between the emitter and photocells to protect the photocells from the hot exhaust gases. Tap water flows through the cell support plates to provide an efficient cell cooling. Lower and upper reflectors (upper reflector not shown in this picture) reduce radiation losses in the axial direction.

leading to a fill factor of 0.7. At the maximum power point, the current and voltage were 3.7 A and 7.8 V, respectively.

The electrical data for the photocell generators was acquired using a current/voltage (I/V) test device developed by PSI (Durisch et al., 2000). This consists of a dynamic load, electronic load control, three precise digital multimeters and a notebook. Suitable precision resistors are used to measure the current. Surface temperature probes (Pt-100) are arranged on the rear side of the photocells to measure their temperatures. The signals from the multimeters are transmitted via an IEEE bus to the notebook. Specially developed software allows to evaluate the measured data on line. The results are stored, and can be printed out immediately in the form of a condensed test report, containing all the relevant electrical data and the temperature of the generator under test.

4. 50 W prototype

A third prototype was fabricated (see Fig. 2), based on the experience gained with the previous prototypes.

The main improvements are: (1) high efficiency monocrystalline silicon solar cells from the University of New South Wales, UNSW, Sydney, Australia, with an STC efficiency of 21.1%. (2) A cylindrical Yb_2O_3 emitter for more homogeneous illumination of the photocells. (3) Active cell area increased from 376 to 477 cm^2. Two strings of 11 cells each were glued onto metallic support plates and built into a stainless steel cylinder. Each string has separate electrical connection leads, so that the strings can either be connected in parallel or in series. The axial position of the emitter was chosen in such a way that the two strings deliver almost the same short circuit current. Active cell cooling was obtained by the flow of tap water through the cell support plates, and again a glass tube protected the cells from contact with the flue gases.

Infrared mirrors (glass with 1 μm gold coating) at both ends of the glass tube reflect useful emitter radiation back to the photocells and emitter. The upper reflector (not shown in Fig. 2) has a hole in its center to allow the flue gas to escape. The flow rate of butane was determined by measuring the time and butane mass before and after each experiment.

An electrical output of 47.9 W was attained at a thermal input power of 1985 W, corresponding to a system efficiency of 2.4%. The short circuit current and open circuit voltage were measured to be 4.0 A and 16.0 V, respectively (all cells in series). From I/V tests, the mpp-data were found to be: $I_{mpp}=3.76$ A and $V_{mpp}=12.73$ V, leading to a fill factor of 0.75. Using tap water at 14 °C, the cell temperature was kept at 20.6 °C in the lower string and at 23.6 °C in the upper string. By using preheated air

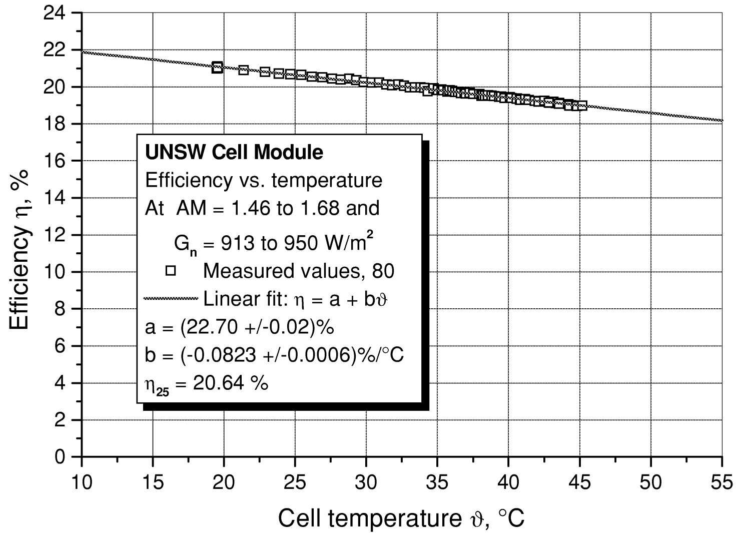

Fig. 3. Efficiency η vs. cell temperature ϑ at an air mass AM of approximately 1.5, and at an almost constant global normal irradiance G_n of 930 W/m^2. The test module consists of 22 series-connected high efficiency monocrystalline silicon solar cells from the University of New South Wales, UNSW, Sydney, Australia.

(at approximately 500 °C) for combustion, a system efficiency of 2.8% was achieved.

A series of I/V tests were carried out under solar irradiation before mounting the photocell generator into the steel cylinder. The result shown in Fig. 3 was obtained after evaluation of the tests.

According to Fig. 3, the STC efficiency of the UNSW cell module used as TPV-generator is found to be 20.64%. As expected for a series-connected string, this value is somewhat lower than the supplier's specification for the single cells, which is in the range of 21.0 to 21.2%. Using the STC efficiency, STC power is found to be 9.85 W. This means that the generator, in comparison with sun illumination, produces 5.7-times more output power under the emitter radiation in the TPV system.

In a realistic domestic CHP system the cells will be cooled by water returning from the radiators, which has a temperature of about 30 °C in modern low temperature heating systems. From Fig. 3 it can be estimated, that the cell efficiency will drop in this case by about one percentage point compared to the experiment with 14 °C tap water cooling.

5. Self-powered grid-connected system

In order to demonstrate the feasibility of self-powered operation of TPV systems, the 15 W prototype presented by Durisch et al. (1999) was supplemented by an electronic control unit developed by PSI. This operates the magnetic gas supply valve as well as the high-voltage ignition electrodes. Furthermore, a commercial DC/AC grid inverter from NKF, Delft, The Netherlands, was added in order to demonstrate simultaneous back-supply of excess power into the 230 V utility grid. The complete TPV system is schematically represented in Fig. 4.

Because the mpp voltage of the photocell generator is only 3.3 V, it was necessary to use a voltage multiplier (factor 8) to generate the 24 V input voltage required by the grid inverter. An additional multiplier (factor 4) was required to obtain enough voltage for charging the 12 V battery store, used to deliver the power to open the gas

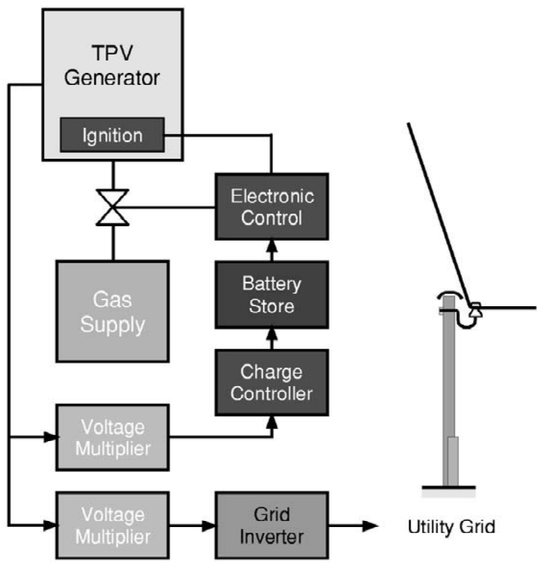

Fig. 4. Schematic representation of a self-powered thermophotovoltaic system with back-supply of excess power to the local 230 V grid.

valve, supply the ignition electrodes and power the control unit.

Measurements showed that power consumption for the gas valve during continuous operation of the burner was 0.71 W, and that for the control unit was 1.36 W. In total, 2.07 W (or 14%) of the photocell output is required for self-powered operation. The remaining part is fed into the grid.

In order to reduce investment costs, the necessity for the multipliers mentioned above can be avoided by replacing the eight large photocells with 60 smaller cells, all series-connected, and by changing the control unit's supply voltage from 12 to 24 V.

A series type of charge controller is required to charge the battery store, since shunt controllers short circuit the photocell-generator at fully charged store and therefore impede simultaneous back-supply to the utility grid.

6. Summary and outlook

Two new small thermophotovoltaic prototype systems were successfully realized and tested. System efficiencies of up to 2.8% were achieved.

Electrical characterization of the UNSW high efficiency photocell-generator under solar illumination and under selective emitter radiation (Bitnar et al., 2001) in a TPV-prototype revealed an almost sixfold electrical power density of the photocells installed in TPV systems, reducing the specific generator cost considerably as compared with solar photovoltaics.

We have successfully demonstrated the self-powered operation of a small TPV system, including simultaneous back-supply of excess power to the 230 V utility grid. For this purpose an electronic control unit was developed by PSI using components with low power consumption. The principle can easily be applied to larger TPV systems.

In future, emphasis will have to be placed on the development, investigation and practical use of appropriate emitters, taking account of thermal emission characteristics as well as the chemical, thermal and mechanical properties. However, simplified, efficient, cost-effective and reliable photocell-generators will also be important. Finally, system's development and testing will be indispensable.

In a next important step a photocell-generator and a burner/emitter system developed by PSI will be installed in a commercial boiler produced and sold by Hoval, Vaduz, Fürstentum Liechtenstein. In laboratory tests the generator produced an electrical power of 164 W, which is sufficient for self-powered operation of such boilers.

Our goal is to investigate in detail the thermophotovoltaic conversion of radiant heat into electricity, in order to provide the basic understanding of the physical processes involved. This is required to transfer this new technology successfully into industry, as an efficient, economical and sustainable new technique for combined heat and power generation.

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