The design and analysis of a prototype concentrated solar power installation with PV cells

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Abstract

The rise of energy demand and the need to decrease carbon dioxide emissions worldwide led to a rapid development of renewable energy technologies, including solar energy systems. Concentration solar technologies, such as Concentrated Solar Power (CSP) and Concentrated Photovoltaics (CPV) have also gained scientific interest. A concentrating photovoltaic thermal (CPVT) collector uses a concentrated beam of light to generate useful heat and electricity simultaneously. In frames of the thesis, a prototype parabolic trough type CSP installation with PV cells attached to the receiver (CPVT collector) has been built and its performance has been analyzed. The influence of different types of PV cells on the energy output has been investigated. Data was collected using multimeters, pyranometers, thermocouples and an infra-red camera. The results obtained in this study have been compared with literature and potential improvements of the system have been proposed. Under concentrated irradiance monocrytalline silicon and amorphous silicon cells achieved 13,54±0,24% and 7,69±0,14% electrical efficiency respectively. The thermal efficiency of the system was equal to 77,20±6,09%.

Keywords: renewable energy, solar energy, concentrating solar power, concentrating photovoltaics

1. Introduction

Solar energy is a very universal form of energy, since solar irradiance can be relatively easily converted into heat or electricity, as well as used in chemical and biological processes [1].

The most commonly used solar energy devices are solar panels (assembled by connecting a number of solar cells) and solar thermal collectors. Whilst solar panels generate electricity, solar collectors generate heat (usually in a form of hot water) [2].

Furthermore, there are also concentrated solar technologies, which use devices to focus sunlight at a specific area in order to generate energy. Amongst concentrated solar technologies there is a distinction between concentrated photovoltaics and concentrated solar power [3].

Concentrated photovoltaics, usually abbreviated as CPV, is a type of photovoltaic energy system, that uses lenses, curved mirrors and other types of optical instruments to concentrate a big amount of solar irradiance at a small area of a solar cell to generate electrical energy.

Concentrated photovoltaics technology competes also with concentrated solar thermal power plants. Photovoltaic systems convert sunlight directly to electricity, whereas solar thermal power plants first convert sunlight to heat, and only then is the heat transformed into electricity. Such technology is commonly known as Concentrated Solar Power (CSP) and is more widely used than CPV [4].

Sometimes however, concentrated solar energy systems are used to generate both heat and electricity simultaneously. An example of this technology is a Concentrating Photovoltaic Thermal (CPVT) system.

CPVT collectors usually use one or several curved mirrors to focus light onto the receiver. The receiver is equipped with solar cells, which under concentrated irradiance generate more electricity when compared to a conventional photovoltaic system of equal size. Working fluid flows through the receiver and absorbs heat from the walls and the solar cells – thus generating useful heat. Working fluid also plays a role of a coolant, decreasing the temperatures of the solar cells [5]. Figure 1 shows an exemplary prototype CPVT installation.

Figure 1. Prototype CPVT collector [6]

2. System construction

A CPVT collector was designed and assembled. Key elements of the system are as follows: parabolic trough concentrator, heat absorbing duct, hosepipes and water source, sets of PV cells, Sun tracker, electronic load. In order to perform all necessary measurements, the following elements are needed: Multimeters, electronic load, IR camera, laser pyrometer, thermocouples, flow-meters, computer-supported measuring system.

The parabolic trough concentrator was designed to be 2m long. It consisted of curved polycarbonate construction and with reflecting mirrors attached with stripes. The concentrator was profiled using TracePro software.

The heat absorbing duct was designed to be made of aluminum and in a hexagonal shape. The fluid flowing through the duct absorbs the heat and thus the temperature of the fluid rises. The hexagonal shape was chosen to make the system more flexible and allow for measurement of various parameters for a number of PV technologies at the same time.

Hosepipes were designed to fit the duct and allow for uninterrupted fluid flow. Water was directed to the installation from the plumbing system.

As for the solar cells, it was decided that high efficiency monocrytalline cells as well as amorphous silicon cells would be used.

A steel construction with a two-axis solar tracker was installed at the rooftop of a D9 building at the AGH campus in Cracow. The concentrator was placed onto the construction in a proper way in order to ensure concentration of sunlight above the center of the concentrator. Solar cells were soldered and connected to one another via copper wires. The cells were attached to the aluminum hexagonal shape duct with thermally conductive adhesive. The duct equipped with solar cells was then placed above the concentrator. After connecting the water hoses and electrical cables the CPVT collector was fully operational. Figure 2 shows a fully assembled CPVT installation.

Figure 2. Fully assembled CPVT installation

3. Experimental analysis and results

First, only electrical parameters of the solar cells were measured. Three groups of three thin-film cells connected in series were investigated first – each group was analyzed individually. Then, these three sets were connected in parallel and electrical parameters of such a connection were measured. Taking into account the relationship between voltage and current of parallel and series connections, as well as the specifications of the thin-film cells, it was decided that such a connection would deliver the most meaningful results. They are referred to as Set A (a-si).

Then, monocrystalline silicon cells were analyzed, with first focusing on four groups of three cells connected in series – each group was analyzed individually. Then, all twelve cells were connected in series and their electrical parameters were measured. Taking into account the relationship between voltage and current of series connections, as well as the specifications of the monocrystalline silicon cells, it was decided that such a connection would deliver the most meaningful results. They are referred to as Set B (m-si).

All measurements were performed under a clear sky. The irradiance ranged from around 825 W/m^2 to around 875 W/m^2 during the measurements. It was thus assumed, that the average irradiance was equal to 850±25 W/m^2, and this value was be used in further calculations. IV and power curves for solar cells were plotted under both non-concentrated and concentrated irradiance. Figure 3 shows the curves for monocrystalline silicon cells under 1-sun irradiance.

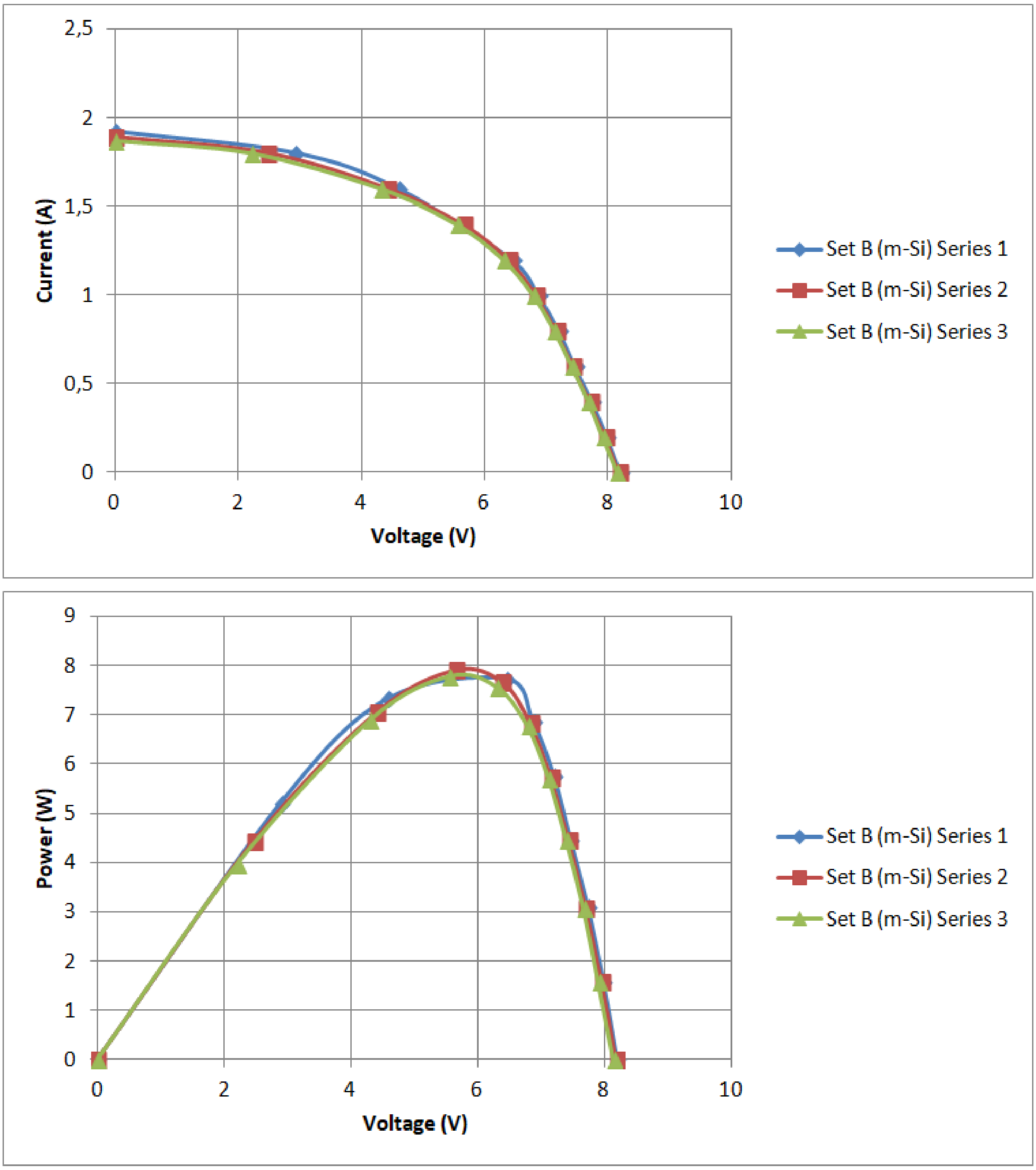

Figure 3. IV and power curves for Set B (m-si) under non-concentrated irradiance

Having gathered data for all cells, calculations were performed to determine the electrical efficiencies. The values are presented in Table 1.

Table 1. Maximum electrical efficiency values under concentrated and non-concentrated irradiance

	non-concentrated irradiance		concentrated irradiance	
	Set A (a-Si)	Set B (m-Si)	Set A (a-Si)	Set B (m-Si)
Maximum electrical efficiency [-]	6,90±0,12%	14,91±0,25%	6,77±0,11%	11,76±0,2%

Later, two key parameters were measured: cells' temperature and water temperature. In order to properly measure the cells' temperature, a laser pyranometer as well as IR camera were used. Figure 4 shows a thermal image taken by an infra-red camera.

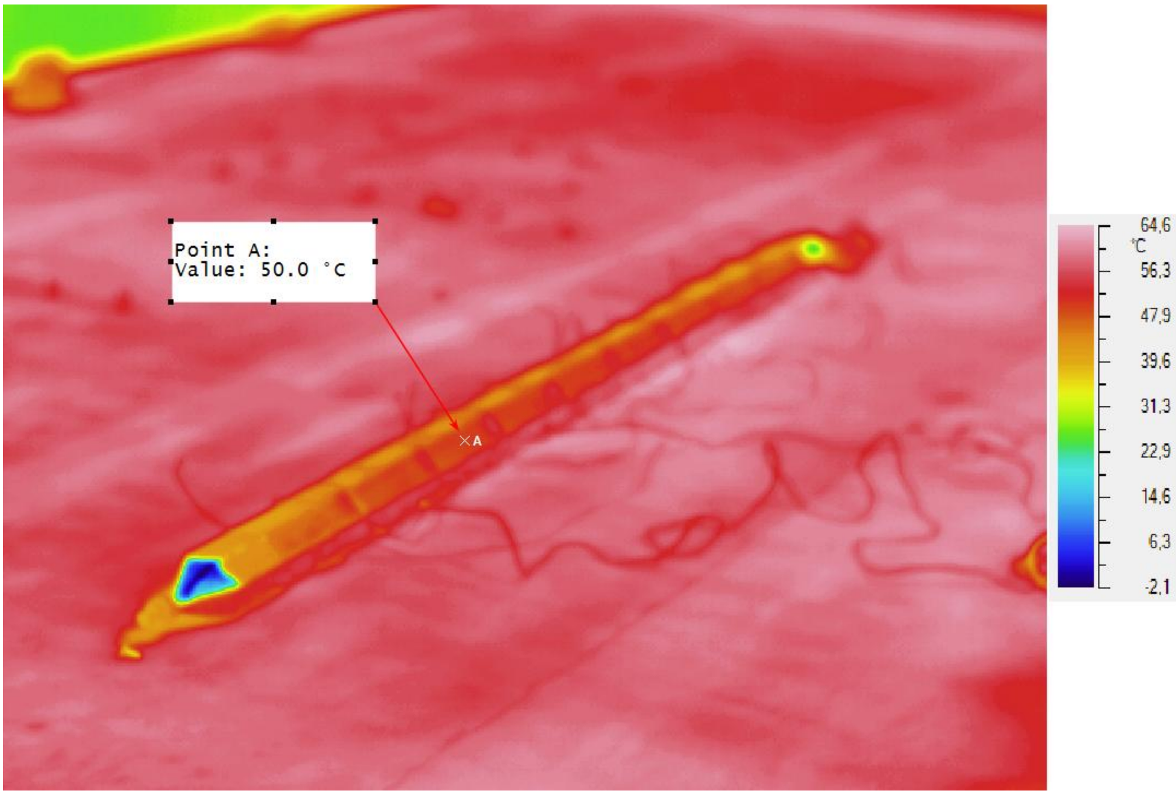

Figure 4. IR camera image – amorphous cells under 1 sun irradiance

With the help of a software, detailed temperature analysis could be performed. Figure 5 shows a temperature distribution across the amorphous silicon cells.

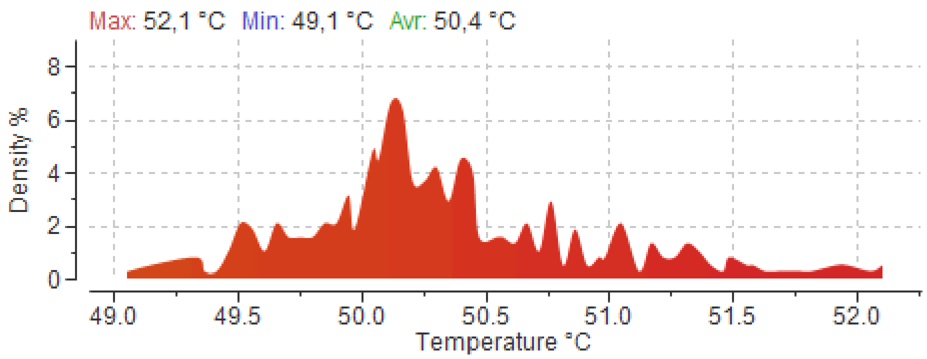

Figure 5. Temperature distribution for a-Si cells

Thermocouples were used to determine the temperature of the water. Information about the difference in water temperature on inlets and outlets allowed to calculate the amount of heat generated. These values were measured when monocrystalline and amorphous silicon cells were irradiated and two flow rates were investigated – 2l/min and 4l/min. Results have been gathered in Table 2.

Table 2. Water temperature and heat generated by the system under non-concentrated irradiance

	a-Si cells		m-Si cells	
	flow [2l/min]	flow 4[l/min]	flow [2l/min]	flow 4[l/min]
inlet temperature [°C]	29,8±0,1	27,2±0,1	29,6±0,1	28,2±0,1
outlet temperature [°C]	31,6±0,1	28,5±0,1	31,5±0,1	29,3±0,1
temperature difference [°C]	1,8±0,1	1,3±0,1	1,9±0,1	1,1±0,1
Thermal power generated [W]	252±14	364±28	266±14	308±28

In the final part of the thesis, simultaneous heat and electricity generation was investigated. Four scenarios, each under different conditions, were analyzed. The CPVT system outputs were measured under the following conditions:

S1: Without concentration, without cooling

S2: With Concentration, without cooling

S3: With concentration, with cooling

S4: Without concentration, with cooling

IV and power curves for each scenario are shown in Figure 6.

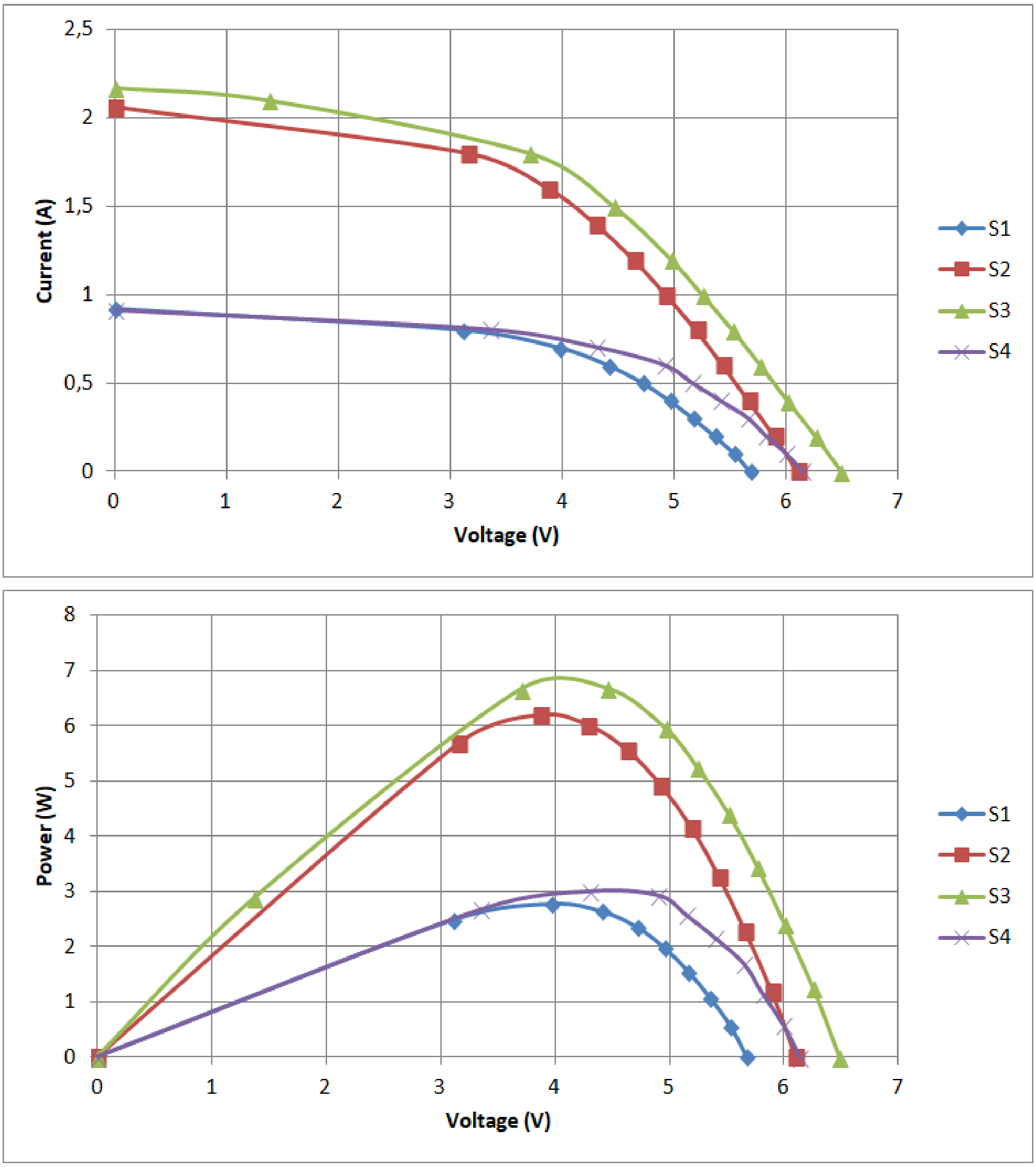

Figure 6. IV and power curves for chosen scenarios for Set A (a-si)

In order to maximize the energy output of the installation, all 6 walls of the receiver should be equipped with solar cells. With the results obtained in previous sections, total energy output and system efficiency when solar cells are attached to all walls of the receiver can be calculated.

Two cases will be investigated: (1) equipping the receiver fully with a-Si cells and (2) equipping the receiver fully with m-Si. All calculations are performed based on the equations mentioned in previous parts of the thesis. Table 3 contains information regarding the efficiency and the amount of power generated in both cases.

Table 3. Systems efficiency and energy output values

	amorphous silicon cells	monocrystalline silicon cells
Electrical power generated [W]	19.58±0,01	47,6±0,01
Thermal power generated [W]	420±28	420±28
Electrical efficiency [-]	7,69±0,14%	13,54±0,24%
Thermal efficiency [-]	77,20±6,09%	77,20±6,09%

4. Conclusions

As the result of the analysis it was possible to determine the power generated and efficiency achieved by the system. It was determined that if all walls of the receiver were equipped with solar cells, a decent efficiency can be achieved. Thermal efficiency of around 77%, is higher than most systems described in literature. Electrical efficiencies of around 7,7% and 13,54% (depending on which solar cells were used) is comparable with similar prototype devices described in literature [7][8][9].

However, the amount of useful heat and electricity generated is too low for a system of this size to compete with conventional solar panels and solar collectors. It will thus most likely not find any commercial uses, but can certainly be a valuable experimental installation for research.

Concentrating irradiance leads to the increase of a short circuit current, but keeps the open circuit voltage on almost the same level. However, the higher the irradiance, the higher the cells temperature – and it leads to the decrease of the cells' efficiency. The results showed, that monocrystalline silicon cells' efficiency is much more sensitive to sunlight than amorphous silicon cells' efficiency.

It was determined that the heat is efficiently recovered by the cooling fluid, with thermal efficiency exceeding 70%. The reason the thermal efficiency of the CPVT collector investigated in this thesis is so high, is that working fluid temperatures are low, which significantly decreases thermal losses in the system. The use of the cooling fluid also leads to a noticeable decrease of the solar cells' temperature thus improving the electrical efficiency of the cells.

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