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Formation of photovoltaic modules based on polycrystalline solar cells

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Manufacturing and processing

ABSTRACT

Purpose: The main aim of the paper is formation of photovoltaic modules and analysis of their main electric parameters.
Design/methodology/approach: Photovoltaic modules were produced from four polycrystalline silicon solar cells, that were cut and next joined in series. Soft soldering technique and copper-tin strip were used for joining cells.
Findings: In order to provide useful power for any application, the individual solar cells must be connected together to give the appropriate current and voltage levels. Taking this fact into account the analysis of photovoltaic module construction was performed.
Research limitations/implications: The main goal of the research is to show the practical application of solar cells. Two photovoltaic modules were assembled and their basic electric properties were analysed. It was shown that they may be successively applied as an alternative energy source.
Practical implications: Photovoltaic modules are irreplaceable in areas which are far away from power network. Simply photovoltaic module can supply small device without any problem.
Originality/value: The produced photovoltaic modules and photovoltaic systems confirm the utility of solar energy in every place where the sun radiation is available. Because of exhaust conventional energy sources like coal or earth gas, new renewable sources of energy (sunlight, wind) are more and more often used. It brings huge ecological benefits.
Keywords: Photovoltaic; Solar cells; Photovoltaic module; Polycrystalline silicon

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1. Introduction

To reduce greenhouse effect, environment pollution and the other problems associated with fossil fuels conventional and non-renewable energy sources are more and more often replaced by new, renewable sources like sunlight, wind and biomass [1-4]. Moreover, these traditional resources of energy are run low. The environmental protection regulations play the important role in this problem. European Parliament and European Council directive, number 2001/77/WE, on the promotion of electricity produced from renewable energy sources imposes an obligation upon members of European Union to develop technologies based on renewable energy sources [5]. Among renewable sources we distinguish [3,4]:

- solar radiation,
- wind power,
- water energy,
- geothermal energy,
- biomass energy.

The greatest part in obtained electric energy from renewable sources comes from solar radiation. Photovoltaic technology makes use of the abundant energy in the sun and it has little impact on environment. Photovoltaics can be used in a wide range of products, from small items to large commercial solar electric systems [6,7,8].

Technologies of production of solar cells are based on semiconductor materials. The greatest development is observed in technologies based on polycrystalline, monocrystalline or amorphous silicon. The best properties exhibit monocrystalline silicon solar cells. However, technology of this kind of solar cells is the most expensive. The lowest costs are generated in production of amorphous solar cells, but they have no satisfactory properties. Polycrystalline silicon solar cells are cheaper than monocrystalline solar cells and exhibit better properties than amorphous silicon solar cells. For this reason photovoltaic industry, to a large degree, takes advantage of polycrystalline solar cells [9-13].

One single polycrystalline solar cell with an area of approximately 12.5 cm^2 generates a short circuit current of 0.3 A and open circuit voltage 0.5 V when exposed to full sunshine.

In most practical cases a single crystalline solar cell 12,5 cm^2 generates not enough electric power which reaches approximately 0.12 Wp (peak Watts) at the maximum only. That is why, it is necessary to interconnect greater number of solar cells into solar module. Depending on the requirements, the individual solar cells can be connected in series or parallel only or both in series and parallel [11-14].

Series connection (series circuit) is the connection in which components are connected along a single path, so the same current flows through all of the components. In a series circuit, the current through each of the components is the same, and the voltage across the components is the sum of the partial voltages across the individual components (Fig. 1) [9,11,14].

It is important to have well matched cells in the series chain, particularly with respect to current. If one cell produces a significantly lower current than the other cells, then a whole chain will operate at that lower current level and the remaining cells will not be operating at their maximum power points [12-14].

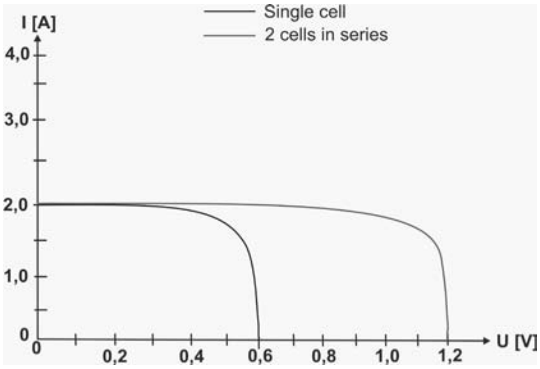

Fig. 1. Current-voltage characteristics of solar cells connected in series [11,14]

Series connection of the solar cells causes also undesired effects when an individual cell or several cells are fully or partially shaded (Fig. 2). In general, the weakest link in the chain determines the quality of the whole system. Even when only one cell is shaded, the effect is the same as if all series-connected cells were shaded. Additionally, so called local hot spots may occur in series connection when individual cells are partially shaded. In this case shaded cell represents a diode of a very high resistance compared to the load. Thus, most of the voltage drop generated by the other cells appears at shaded cell (Fig. 2). To avoid these undesired effects in ideal solution bypass diodes are connected antiparallel to each individual solar cell (Fig. 3) such that large voltage difference cannot arise in the reverse-current direction of the solar cell. In industrial practice, one bypass diode is provided for protection of more than one solar cells (approximately 15-20) (Fig. 4) [9,11,14].

Parallel connection (parallel circuit) is the connection in which components are connected so that the same voltage is applied to each component. In a parallel circuit, the voltage across each of the components is the same, and the total current is the sum of the currents through all the components (Fig. 5) [9-14].

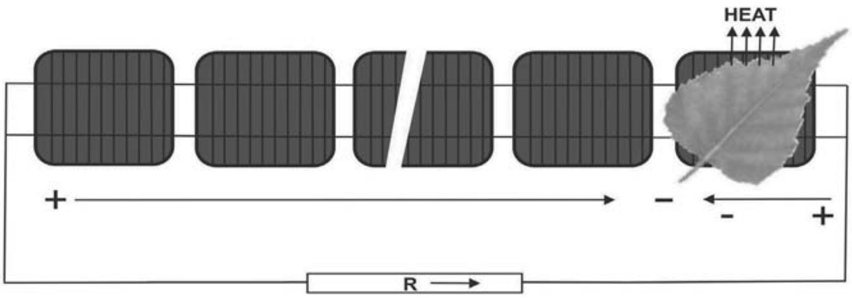

Fig. 2. Undesired change in the current flow due to shading of one cell [9,11]

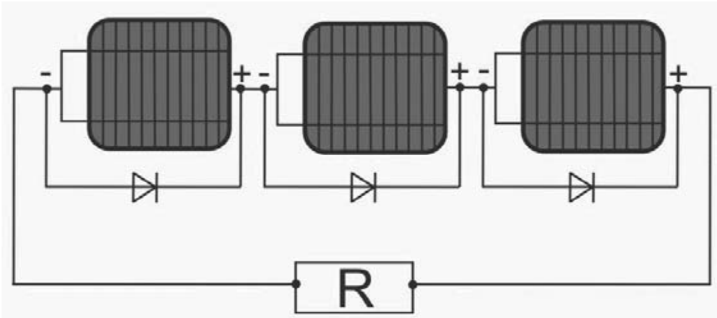

Fig. 3. The bypass diode preventing the occurrence of hot spots when one of the cells is shaded [9,11,14]

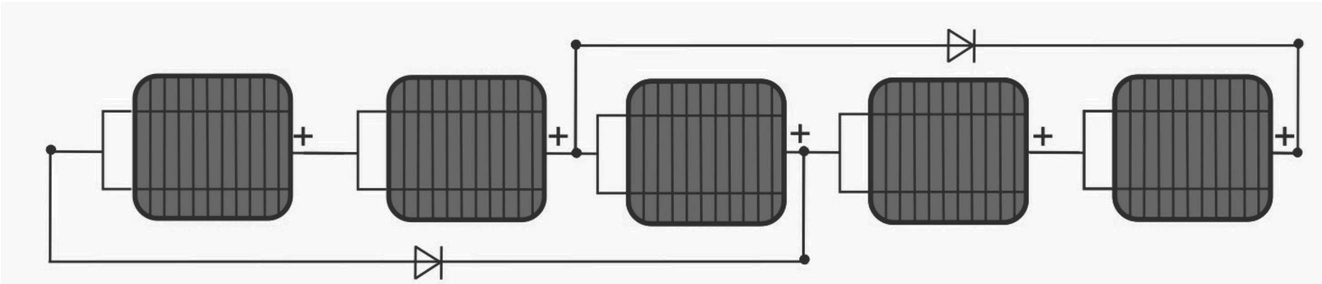

Fig. 4. The one bypass diode protection for more the one solar cells [11]

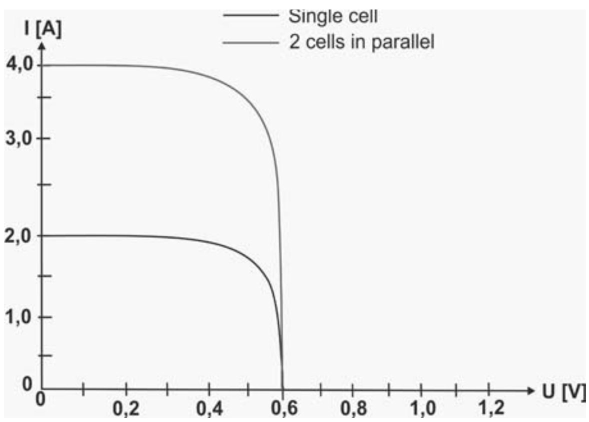

Fig. 5. Current-voltage characteristics of solar cells connected in parallel [9,11,14]

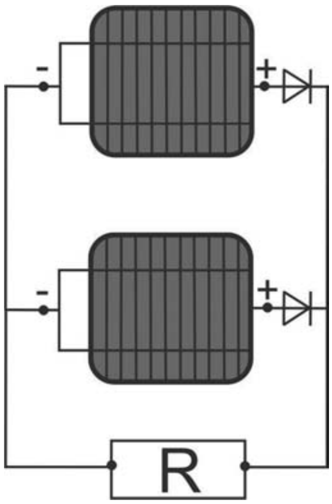

Fig. 6. Parallel connection of solar cells [9,14]

Protection diodes connected in series to solar cells in both branches prevent from current flow in incorrect direction when one of solar cells is broken down or shaded (Fig. 6) [11].

Series-parallel connection is a combination of series and parallel connection (Fig. 7). In this connection both output current and voltage of system is higher compared to individual cells (Fig. 8) [11,14].

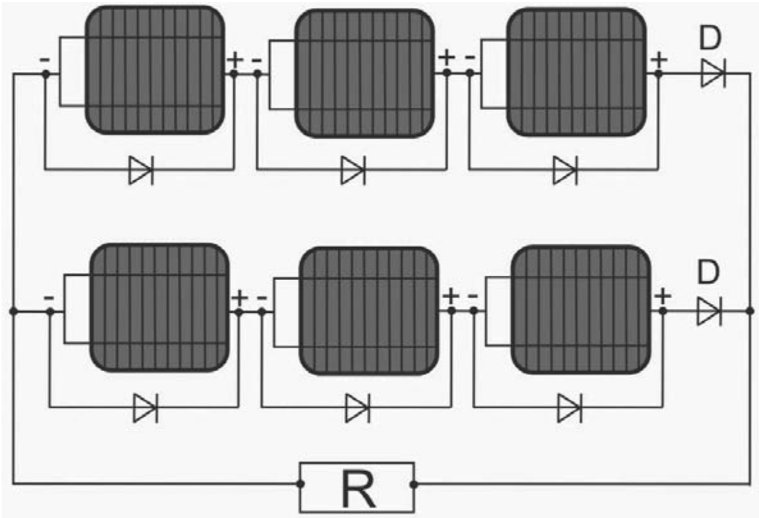

Fig. 7. Series-parallel connection of solar cells [9, 11,14]

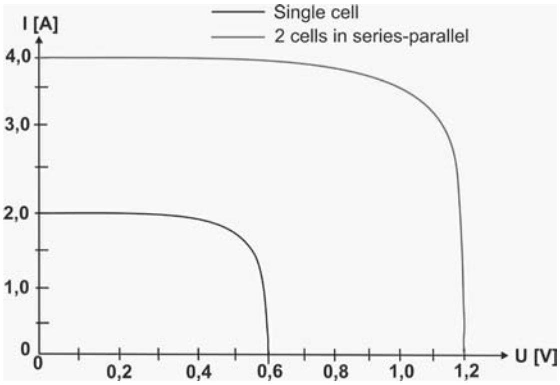

Fig. 8. Current-voltage characteristics of solar cells connected in series-parallel [9,11, 14]

Quick development of photovoltaic industry stimulates researches to wide studies concentrated on technologies of solar cells production and photovoltaic modules.

The main purpose of the research was to construct two photovoltaic modules, check their electric properties and demonstrate their practical applications.

2. Experimental

2.1. Material

To prepare photovoltaic modules four polycrystalline silicon solar cells each of dimension 10x10 cm were used (Fig. 9).

a) b)

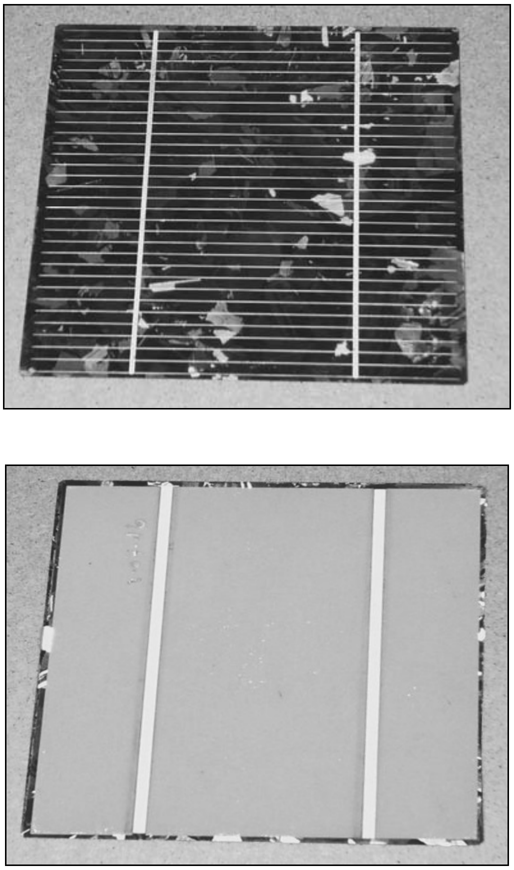

Fig. 9. Polycrystalline silicon solar cells a) front surface, b) back surface

Process of solar cells production comprises [15-29]:

- texturing of silicon wafer,
- formation of p-n junction,
- passivation of silicon surface,
- screen printing and cofiring of front and back contacts,
- antireflection layer deposition.

The main electric properties of solar cells, which were used for preparing photovoltaic modules, are presented in Table 1.

Table 1.
Basic electric properties of silicon solar cells

Electric parameters	Solar cell number			
	1	2	3	4
$I_{sc}[A]^*$	2,54	2,53	2,48	2,30
$U_{oc}[V]^*$	0,54	0,54	0,54	0,54
$I_m[A]^*$	2,28	2,31	2,27	2,11
$U_m[V]^*$	0,44	0,44	0,44	0,42
$P_m[W]^*$	1,01	1,03	1,01	0,90
FF^*	0,74	0,74	0,74	0,72
$\eta[\%]^*$	10	10	10	9

$^*I_{sc}$ – short-circuit current [A], U_{oc} – open circuit voltage [V], I_m – maximum power current [A], U_m – maximum power voltage [V], P_m – maximum power [W], FF – fill factor , η – efficiency [%].

2.2. Research methodology

In order to provide useful power for any application, the individual solar cells must be connected together to give the appropriate current and voltage levels. They must be also protected from damages derived from the environment in which they operate.

Photovoltaic modules were made in process consisting of:

- cutting of solar cells,
- joining single cells in modules,
- performing of casing.

Cutting of solar cells:

For experiment four polycrystalline silicon solar cells were used. Three of them are characterized by U_{oc} ≈0,54 V and I_{sc}≈2,5 A, the last exhibits U_{oc} ≈0,54 V and I_{sc}≈2,3 A. Each of them was cut on eight cells. As a result of cutting four 10x10 cm^2 solar cells, thirty two 5x2,5 cm^2 cells were obtained. The cutting was realized by Nd:YAG laser.

Two photovoltaic modules were produced:

- Module I consisting of 24 solar cells obtained after cutting of 3 solar cells denoted by number 1, 2, 3 (Tab. 1),
- Module II consisting of 6 solar cells obtained after cutting of solar cell denoted by number 4 (Tab. 1).

Joining single cells in modules:

In order to get photovoltaic modules with output equal to voltage as a sum of all single cells, series connection was used. The stages of joining process were presented in Fig. 10.

In order to assembly module, solar cells were interconnected by copper-tin strip. The strip was attached by soft soldering technique. For that purpose, soldering iron with power rating 40 W and common-solder with solder flux were used. In order to obtain series connection, strip was fixed on front contact of the first cell and back contact of the second one. In the same way all of the 24 solar cells was joined in module I and 6 solar cells in module II.

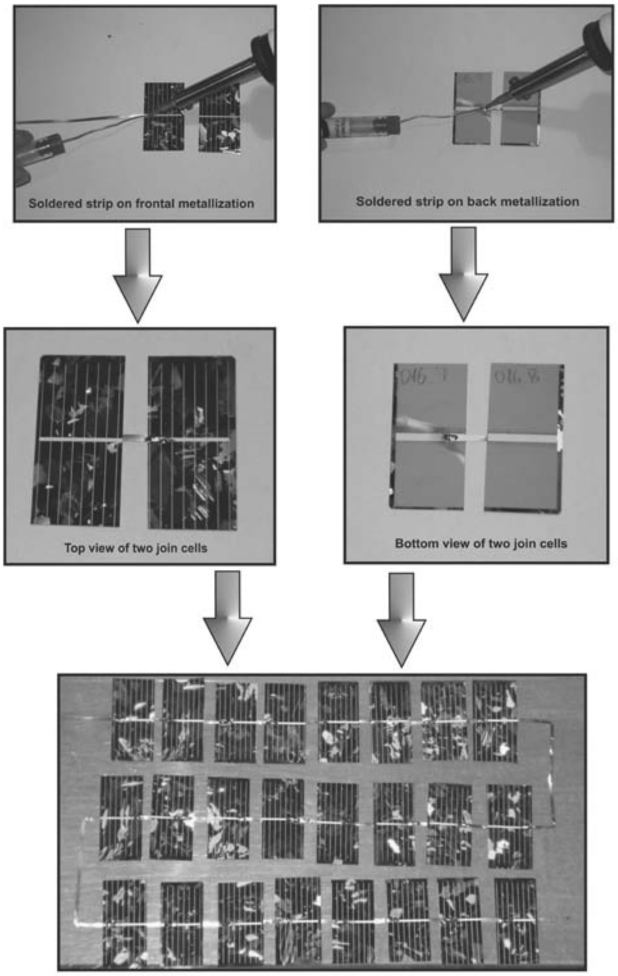

Fig. 10. Stages of joining process of solar cells to Module I

Encapsulation:

To assure longterm operation modules must be protected from damage by the environment in which they operate. In order to complete modules, plate of polymetakrylate methyl was used as a casing. Thanks to this enclosure, solar cells are protected against damages and whole module is stable. As a material of casing, PMMA was chosen. This kind of material – like glass – is characterized by high transparency. Thanks to this property PMMA do not reflect a sunlight and is weatherproof.

Joined solar cells were stuck on PMMA plate by adhesive type. Next, the other PMMA plate was stuck on plate by glue for plastics named „Allplast". Thanks to this ready photovoltaic modules – Modules I and Modules II were obtained (Fig. 11).

a)
b)

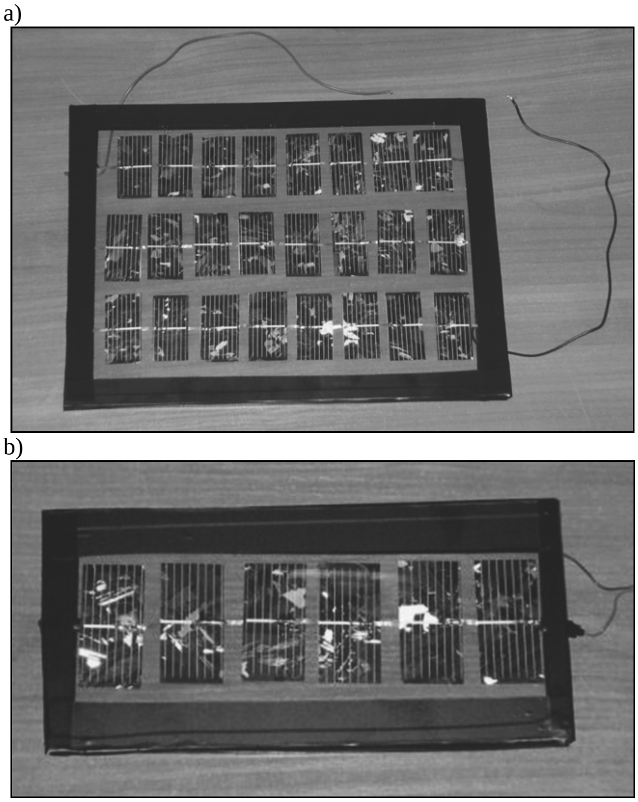

Fig. 11. Encapsulated: a) Module I, b) Module II

3. Results

Electric properties of two photovoltaic modules were studied. The main electric properties of photovoltaic modules, are presented in Table 2. Current-voltage characteristics of photovoltaic modules are presented on Figs. 12 and 13.

Table 2.
Electric properties of photovoltaic modules

Parameter	Module I	Module II
I_{sc}[A]	0.291	0.268
U_{oc}[V]	13.292	3.29
I_m[A]	0.253	0.242
U_m[V]	11.311	2.732
P_m[W]	2.861	0.662

Photovoltaic modules were used for preparing demonstrative examples of photovoltaic systems, which are supplied by solar energy.

Photovoltaic Module I was used for constructing a mini-irrigating system. The system consist of: photovoltaic Module I, buzzer, pump, accumulator, ventilator, two LED diodes and water vessel. Schema of this system is presented in Fig. 14.

The pump was connected with the vessel, from which the water is pumped outside. Additionally, accumulator was connected to the system in order to supply pump. Accumulator is charged by photovoltaic Module I. Buzzer signalising module operation is supplied directly by Module I.

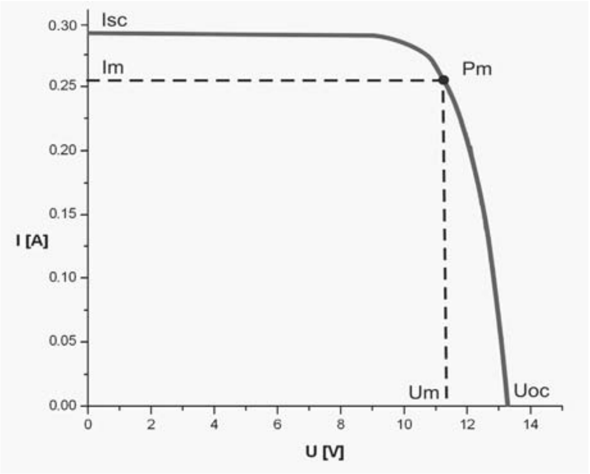

Fig. 12. Current-voltage characteristic of Module I

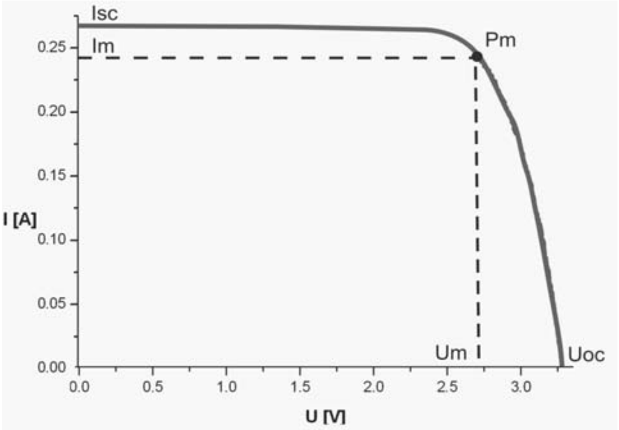

Fig. 13. Current-voltage characteristic of Module II

Capacity of accumulator was selected on the basis of the following formula:

$$C = T_w I_c \quad (1)$$

where:
C – capacity of accumulator,
T_w – pump worktime,
I_c – current consumed by pump.

Assuming that pump should operate within two hours accumulator capacity determined by means of formula (1) is equal to 3 Ah.

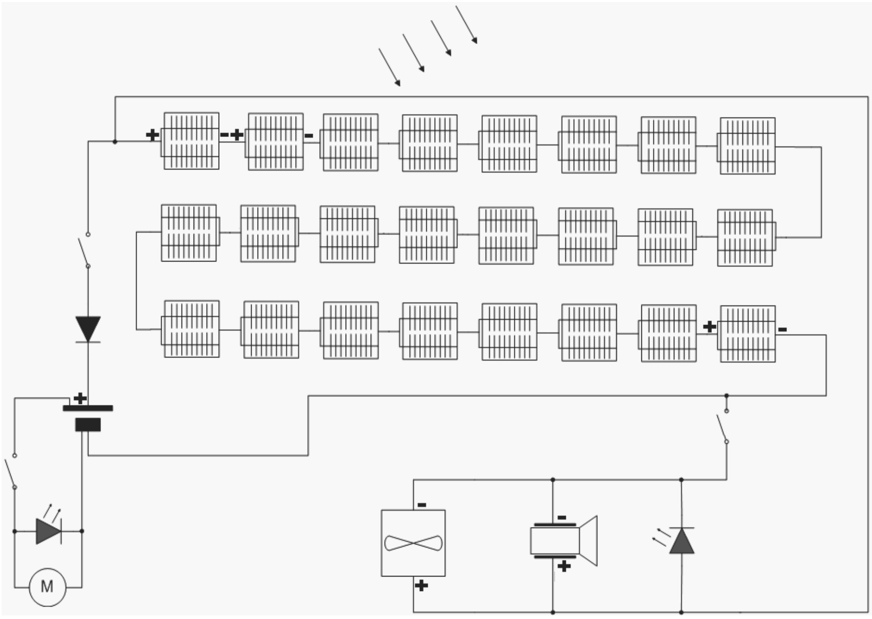

Fig. 14. Schema of mini-irrigating system

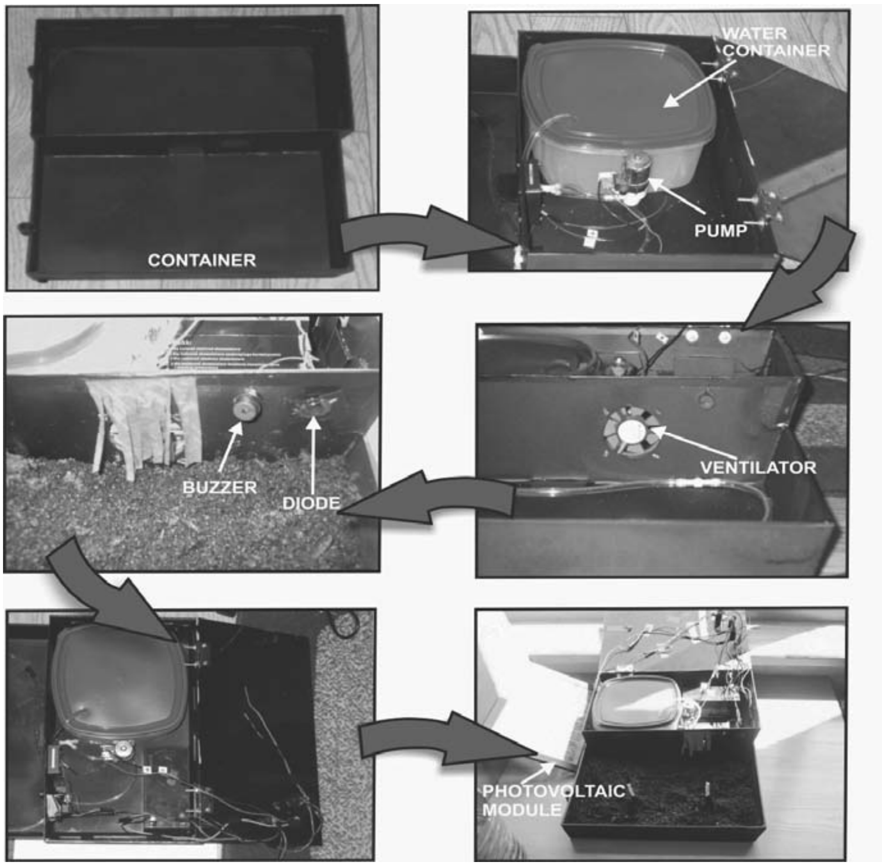

Fig. 15. Main elements of mini-irrigating system

Main elements of mini-irrigate system are presented in Fig. 15.

Second demonstrative system (luminous arrow) is supplied by photovoltaic Module II which demonstrates open circuit voltage U_{oc}=3,29 V and short circuit current I_{sc}=0,268 A. For this photovoltaic system nine LED diodes were used. The diodes were connected in parallel.

Schema of second system is presented in Fig. 16, while Fig. 17 presents luminous arrow photovoltaic system in operation.

Diodes were connected in parallel for the sake of following factors:

- in case of series connection, the more diodes, the higher supply voltage is required (e.g. nine 3 V diodes required supplying voltage is equal to 27 V, while our module exhibits 3,39 V).
- in case of series connection if one diode is broken down, the rest of diodes will be turned off.

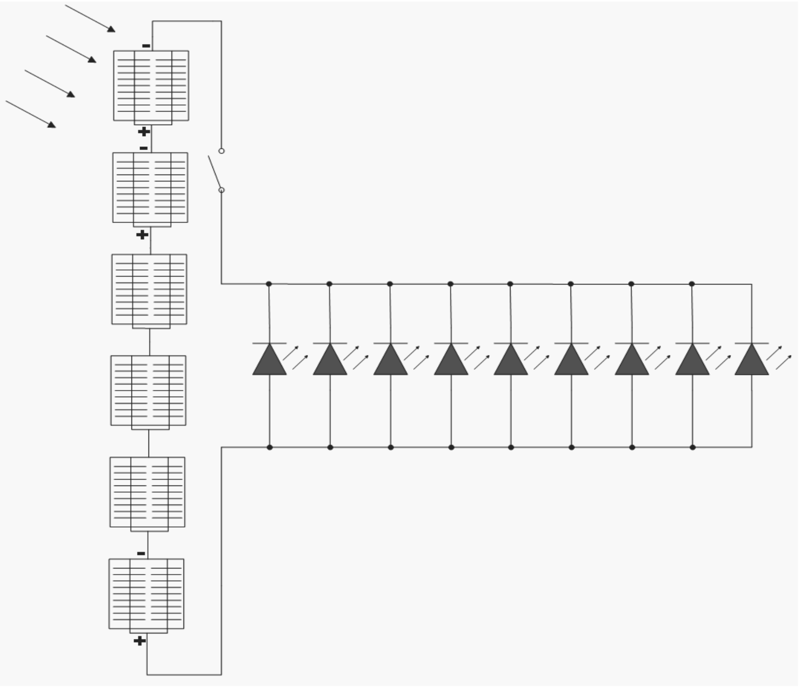

Fig.16. Schema of luminous arrow photovoltaic system

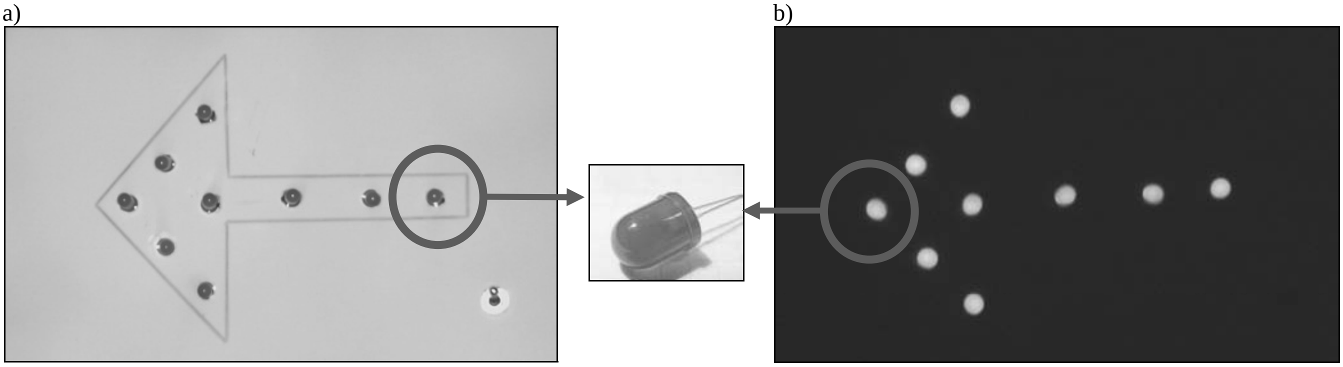

Fig. 17. Luminous arrow photovoltaic system: a) switched off, b) in operation

4. Conclusions

Performed investigations shown that photovoltaic modules under consideration can be successfully used as a renewable source of energy. Some of modules available on the market demonstrate better electric properties than modules under discussion. In the presented solution technological steps used in commercial production process of photovoltaic modules were applied.

The investigations performed on two photovoltaic modules allowed to formulate the following statements:

- It was shown that interconnecting many solar cells that can produced a limited amount of power, it is possible to assembly photovoltaic module fulfilling current-voltage requirements of supplied devices,
- Series connection of solar cells allowed to obtain two photovoltaic modules: module I that shows U_{oc}=13,292 V, I_{sc}=0.291 A and module II that demonstrates U_{oc}=3,29 V, I_{sc}=0.268 A;
- Module I and II was used to supply two constructed photovoltaic systems which represents practical application of renewable source of energy.

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