TECHNICAL AND ECONOMIC ANALYSIS OF USE OF SOLAR COLLECTORS IN GREENHOUSE PRODUCTION

Slawomir Kurpaska, Pawel Kielbasa
University of Agriculture in Krakow, Poland
rtkurpas@cyf-kr.edu.pl, pawel.kielbasa@urk.edu.pl

Abstract. The paper presents the results of the research on effectiveness of conversion of solar radiation into heat with the use of plate and vacuum solar collectors. Studies on effectiveness were carried out on a measurement stand, where the obtained results were monitored and archived with a computer measurement system. Based on the obtained results, thermal and economic effects of use of the investigated collectors on production demands of cultivated greenhouse tomatoes were analysed. After determination of the model surface area of a greenhouse and a type of cultivated plants, an annual amount of heat was calculated. With the assumed data, in the year's scale, as a result of the used collectors for the needs of plant cultivation, it was calculated that the suggested system of collectors provides almost 45 GJ of heat. As a result of the economic analysis that was carried out, it was concluded that in the present condition of prices the most advantageous solution is to use flat collectors for which, in relation to the fuel type, the payback period of the installation is within 13.5 to 16.7 years.

Keywords: plate, vacuum collectors, greenhouse, Static Payback Period.

Introduction

In the age of searching for technical solutions that aim at lowering the production costs and reduction of nuisance for the environment, the use of energy from conversion of solar radiation for production processes in facilities under covers is an interesting issue. This issue was analysed by inter alia Gavril and Gontean [1]. They presented a concept of a greenhouse on the roof, which had transparent photovoltaic panels mounted on, from which generated energy was used for controlling the climate parameters inside the facility. Taki et al. [2] determined energy effects when using energy saving technologies in greenhouse production. An emphasis was given to photovoltaic modules, solar collectors, hybrid collectors (heat and electric energy), systems and materials used in heat storage, techniques, energy-saving heat pumps, alternative elevation materials for better thermal isolation and energy production. Tadili et al. [3] presented a concept of a system along with effects, in which solar energy generated as a result of conversion in an innovative collector was used for heating a greenhouse. Villamil et al. [4] discussed the use of solar collectors (thermal, for production of electric energy) in various industrial processes along with their present local regionalization indicating areas, which are recommended for their wide use. Yadav et al. [5] presented systems of conversion of solar energy into heat and arguments in favour of storing hot water in accumulators that use a phase transition of a medium, concluding that this system is characterised by higher indexes when solar energy is used passively. Benli and Aydin [6] discussed the system of heat storage in a body that is subject to phase transition cooperating with solar collectors. The authors described a percentage participation of this energy in covering a heat demand by the heated greenhouse. Alkais et al. [7] presented the most important technologies, where solar energy converted into electric energy was used for desalination of water used for social and industrial purposes. On the other hand, Ben et al. [8] analysed irrigation technologies supplied with solar energy (PV and thermal solar technologies), which may be used by users in rural farms, concluding that the best effects are obtained in case of drip irrigation. Drip irrigation, due to a possibility of reduction of production costs through saving and precise water management and the use of mineral fertilizers (use of fertilization with hydration), is a commonly used system in facilities under covers. For example, in Poland in 2015 cultivation of vegetables under covers achieved over 8000 ha, out of which over 2800 ha of cultivated tomatoes [9]. Most often in horticultural farms water for hydration is collected from a deep water well. Due to lower water temperature, it is purposefully heated with solar collectors to the temperature close to the temperature of the surroundings. The effect of solar energy conversion in heat depends on the type and construction of a collector and parameters of the surrounding microclimate [10-12]. Thus, the paper analyses the system where water for hydration is heated in solar collectors. The discussed system consists of solar collectors, a container for storing heated water and control and measurement fittings.

Additionally, a payback period of financial expenditures was analysed with a static method of assessment of the investment.

Materials and methods

In order to determine effectiveness of solar collectors' operation, the studies were performed on the stand, the schematic representation of which is presented in Figure 1.

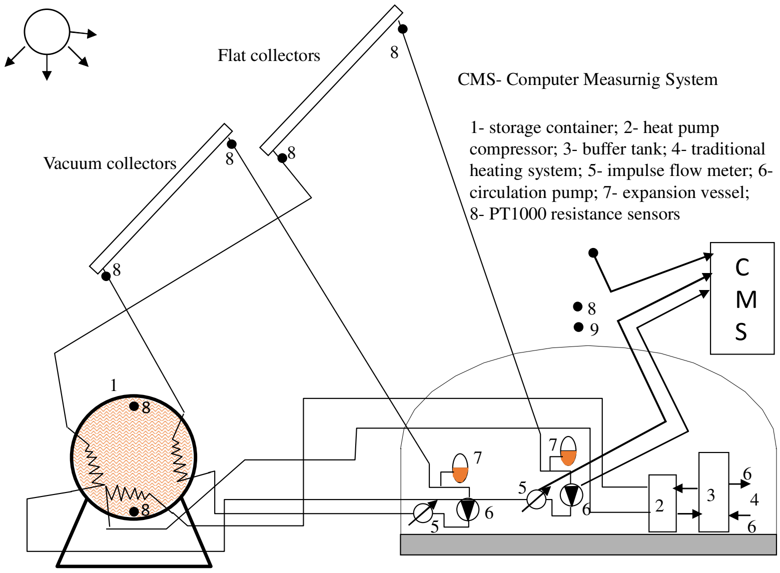

Fig. 1. **Schematic representation of measurement stand**

The measurement stand includes: plate and vacuum collectors (respectively with the surface area of 7.9 and 2.15 m^2); container (1) with the cubic capacity of 5m3 for water storage; circulation pumps (6), impulse flowmeters (5) – ALV3 type. Diaphragm exchangers were installed inside the tank (pipe coil made of a copper pipe), which were connected to both solar collectors. The following sensors were used for measuring: temperature (8) – with measures PT1000, intensity of solar radiation (9) with a pyranometer LP PYRA 02AV, flow of the transfer fluid with impulse flow-meters Type ALV3. Measured parameters were controlled and archived in the assumed sampling time by the Computer Measuring System (CSM). During the experiments a heat pump compressor (2) cooperating with a buffer tank (3) constituted an equivalent of energy for heating water collected for plant irrigation.

Theoretical analysis

Efficiency of solar radiation conversion was computed as a ratio of utility energy collected in the storage container to the amount of solar energy radiation on the collector, namely, in the differential time dτ defined as (1):

$$\eta = \frac{\int_0^\tau q_u d\tau}{F_k \cdot \int_0^\tau R_z d\tau}. \quad (1)$$

This equation after the assumed time of sampling ($\Delta\tau$) may be written as (2):

$$\eta = \frac{q_u \cdot \Delta\tau}{\sum R_z^{\Delta\tau} \cdot F_k}, \quad (2)$$

where the utility heat stream (q_u) was calculated from the following relations (3):

$$q_u = m_{cz} \cdot c_{cz} \cdot (T_{WY} - T_{WE}), \quad (3)$$

where F_k – surface area of collectors, m^2;

R_z – intensity of solar radiation, $W \cdot m^{-2}$;

τ – time, s;
m_{cz} – stream of transfer fluid, kg·s^{-1};
c_{cz} – specific heat of fluid, J·kg^{-1}·K^{-1};
T_{WE} – temperature of fluid, respectively at the input from a collector, ºC;
T_{WE} – temperature of fluid, respectively at the output from a collector, ºC.

For analysis of water consumption for irrigation purposes, it was assumed that the cultivation plants will be greenhouse tomatoes. Table 1 presents the set of the water demand assumed for analysis. Data were taken from the paper [13,14].

Table 1

Estimated water demand (mw) by tomatoes cultivated in a greenhouse

Specification	**Months**											
Water demand, m_w [kg·plant^{-1}·day^{-1}]	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	0.2	0.5	1.0	1.6	2.7	2.6	2.2	2.1	1.9	1.8	1.6	1.2

The analysis assumed that the temperature of water (T_0) collected from a deep water well is 10 ºC and the required final temperature (T_k) is 18 ºC. A daily heat demand for heating water (Q_d) was described with a relation (4):

$$Q_d = m_w \cdot c_w \cdot (T_k - T_0) \tag{4}$$

and the required surface area (F) of collectors (5):

$$F = \frac{Q_d}{\sum R_z \cdot \eta} \ . \tag{5}$$

Economic analysis was carried out according to the static method procedure (assuming invariability in time of the value of money). Therefore, surplus of investment inputs of the suggested option (costs of the system consisting of collectors: n_k, storage tank: n_{zb} and control and measurement devices: nap) were calculated from the relations (6):

$$\Delta N = K_1 - N \tag{6}$$

where

$$K_1 = N + n_k + n_{zb} + n_{ap} + \frac{n_k + n_{zb} + n_{ap}}{i}$$

heat generated as a result of radiation conversion (Q_r) in the discussed system (7):

$$Q_r = \sum_{i=1}^{12} \left(F \cdot n \cdot \sum R_{z-d} \cdot \eta \right), \tag{7}$$

on the other hand, annual reduction of the demand for fossil fuel (m_p) was expressed as (8):

$$m_p = \frac{Q_r}{W_u \ \ \eta_b}, \tag{8}$$

reduction of costs of fuel consumption (ΔC) as a result of application of the system (9):

$$\Delta C = m_p \cdot C_{j-p} - \sum E_{el} \cdot C_{j-el} \ . \tag{9}$$

And, finally, the static payback period of financial inputs (SPP) incurred on construction and functioning of the system (10):

$$SPP = \frac{n}{C}, \tag{10}$$

where m_w – daily water mass, kg;

c_w – specific heat of water, J·kg^{-1}·K^{-1};
i – number of years of use, -;
i – amortization period in years;
ΣR_z – sum of solar radiation, J;
N – number of days in a month, -;
$R_{z\text{-}d}$ – daily sum of solar radiation in the analysed months of the year, J;
W_u – calorific value of fuel, J·kg^{-1} (coal) or J·m^{-3} (for natural gas);
η_b – efficiency of the furnace; -;
$C_{j\text{-}p}$ – cost of fuel EUR·kg^{-1} or EUR·m^{-3};
ΣE_{el} – annual electric energy demand for system functioning, kWh;
$C_{j\text{-}el}$ – cost of electric energy, EUR·kWh^{-1}.

Results and discussion

Analysis was carried out for a greenhouse with the surface area of 1000 m^2 and average plant concentration in the amount of 2.5 plant·m^{-2}. It was assumed that a farm incurs net prices and the following input data were assumed for analysis: i = 20; Wu = 24 MJ·kg^{-1} (coal) or 31 MJ·m^{-3} (natural gas); η_b = 0,85; $C_{j\text{-}p}$ = 0.116 EUR·kg^{-1} (coal) and $C_{j\text{-}p}$ = 0.35 EUR·m^{-3} (natural gas); $C_{j\text{-}el}$ = 0.08 EUR·kWh^{-1}.Figure 2 presents the results of efficiency of the analysed solar collectors. It was assumed that the collectors will work through 800 h·year^{-1}.

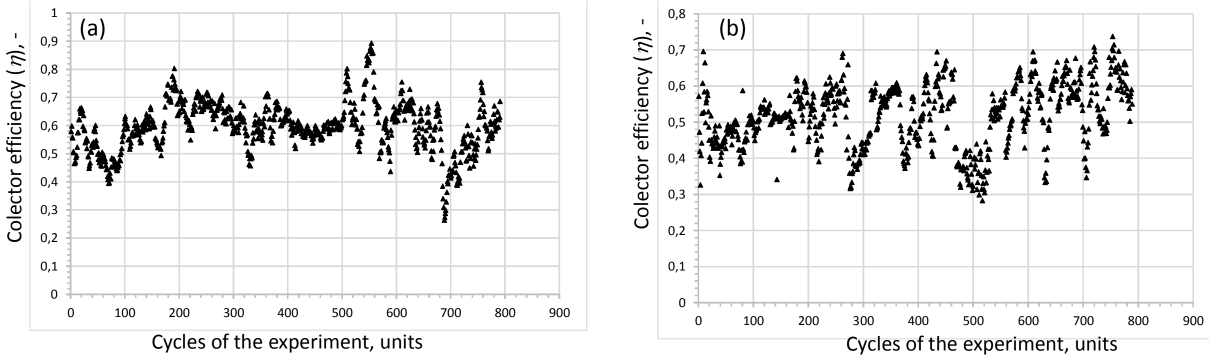

Fig. 2. **Efficiency of analysed collectors:** a – plate; b – vacuum

The presented results are related to the ranges of variables: the intensity of solar radiation from 144 to 2541 kJ·m^{-2} and the temperature of the surroundings from 4.6 to 37 ºC. The average effectiveness of conversion for the plate collectors was 0.58 and for the vacuum ones 0.53.Table 2 presents indispensable input data for calculation of the surface area of solar collectors. Analysis was carried out for Krakow and the data concerning the sun exposure were obtained from the web page: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.

Table 2

Daily values of heat demand and the sum of solar radiation energy

Specification	**Months**											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Daily heat demand (Q_d), MJ·day^{-1}	16.7	41.9	83.8	134	226	217	184	174	159	151	167	100
Daily sum of solar radiation (ΣR_z), MJ·day^{-1}	2.59	4.6	9.75	15.3	17.3	18.3	18.6	16.2	11.2	6.8	3.3	2.2

Figure 3 presents the required surface area of the solar collectors.

As presented, to ensure heating of the assumed mass of water for irrigation, from approximately 11m^2 of the surface area (January – plate collectors) to over 84m^2 (December – vacuum collectors) should be installed in the heating system. Variability of this surface area results from varied hot water demand (which depends on plant transpiration) and effectiveness of radiation conversion:

effectiveness determined in the research for plate collectors towards vacuum collectors was by almost 10 % higher. For further analysis a system of 10 plate collectors was accepted (with the surface area of 1.95m^2 each) and 10 sets of vacuum collectors (surface area of 2.15m^2 each). Figure 4 illustrates a daily and annual amount of heat generated in the discussed system.

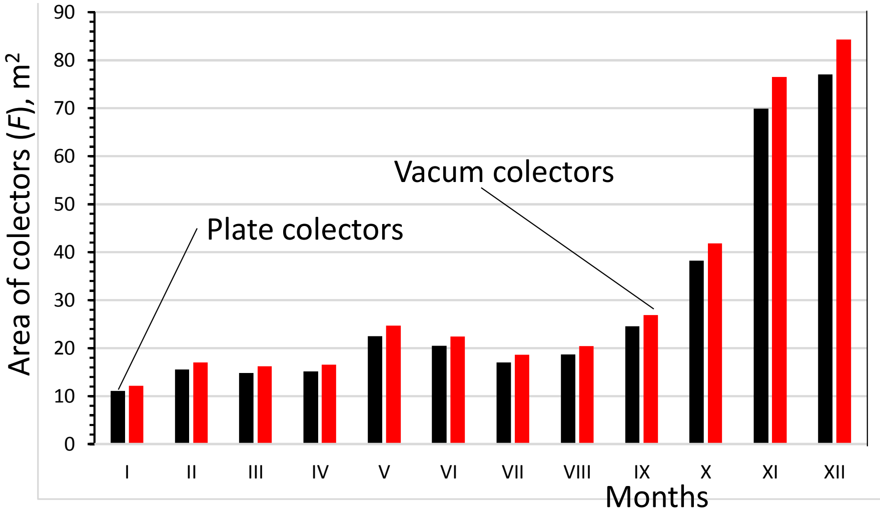

Fig. 3. **Required surface area of solar collectors for irrigation of plants**

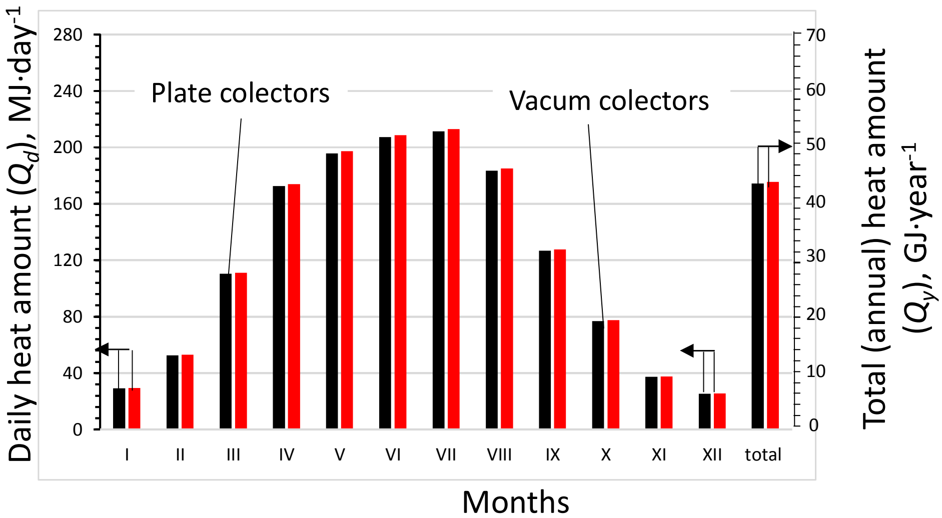

Fig. 4. **Daily and annual amount of heat in discussed system with plate and vacuum solar collectors**

As said above, the amount of heat generated as a result of solar radiation conversion, in relation to the type of collectors, changes from approx. 25 to almost 212 MJ and the annual amount is over 44 GJ of heat. This analysis shows that in some months, at the arbitrary assumed surface area of collectors, heat from conversion exceeds a demand for irrigation purposes. Table 3 presents the global daily amount of heat, which may be designed for the facility heating demand.

Table 3

Daily amount of heat for heating purposes of the discussed facility, MJ·day-1

Specification	**Months**											
Plate collectors:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Daily heat for objects heating	12.6	10.6	26.5	38.5	-30	-10	27	7.6	-33	-74	-96	-75
Vacum collectors: Daily heat for objects heating	12.7	11	27.4	39.8	-29	-9.1	28.5	9.1	-31	-73	-96	-74

The marked negative values prove that at the assumed surface area of solar collectors from 29 to 75MJ· day^{-1} should be provided from an additional source. For a detailed economic analysis at the accepted amortization period and the assumption that the total renovation costs of a fireroom and the costs of ash transport with the costs related to the costs of emission of hazardous substances to atmosphere are 200 EUR·year^{-1}(for coal) and 100 EUR·year^{-1} (for natural gas). The analysis includes the system, the cost of which was determined based on present pries, namely: plate collectors – n_k, = 3400 EUR, vacuum ones n_k, = 8100 EUR, a storage container (of cubic capacity f 1000l)- n_{zb} = 2700 EUR and controlling and measuring devices: circulating pump – power of 0.6 kW, diaphragm vessel, controlling module, assembly set, liquid in the installation – n_{ap} = 1750 EUR. Moreover, it was assumed that collectors will work through 800h·year^{-1} and that they will be installed on the surface area of a land and costs of labour will be 2000 EUR. For the provided conditions, the payback period of the analysed system is set in Table 4.

Table 4

Static payback period in years (SPP) of the discussed systems of conversion of radiation including fuel type

Specification		Collector types	
		Plate	Vacuum
Fuel	Coal	16.7	25.6
	Natural gas	13.5	20.7

As said above, with the present price relation, from the point of view of incurred financial inputs, application of plate solar collectors is the most advantageous.

Conclusions

1. In the investigated conditions, the average efficiency of conversion of the plate collectors was 0.58 and the vacuum collectors 0.53.
2. In the year's scale, at the assumed number of sets of solar collectors, the total amount of heat for hydration and heating demands ca. 44GJ.
3. The payback period calculated with the static method, for the discussed cases (collector types, fuel type), at the assumed market prices of the conversion system is within 13.5 to 25.6 years.

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