РОЗДІЛ 2 ЕНЕРГЕТИКА ТА ЕНЕРГОЗБЕРЕЖЕННЯ

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POLYMERIC MATERIALS FOR SOLAR ENERGY UTILIZATION: A COMPARATIVE EXPERIMENTAL STUDY AND ENVIRONMENTAL ASPECTS

Full-scale metal solar collectors and solar collectors fabricated from polymeric materials are studied in present research. Honeycomb multichannel plates made from polycarbonate were chosen to create a polymeric solar collector. Polymeric collector is 67.8% lighter than metal solar collector. It was experimentally shown that the efficiency of a polymeric collector is 7–14% lower than a traditional collector. An ecologically based Life Cycle Assessment showed the advantages of the application of polymeric materials in the construction of solar collectors.

Keywords: *Polymeric materials; Solar collector; Test rig; Hot water supply system; Environment.*

I. INTRODUCTION

The utilization of solar energy to produce hot water for hot water supply systems (HWSS) has long been of particular interest because such systems are easy to design and solar energy is available for practical application almost anywhere on earth.

The most expensive part of an HWSS is the solar collector (SC) – the heart of solar thermal power technology. The remaining system components comprise 20–60% of an SC's cost, depending on the complexity of the system (tubes, tank-accumulators, pumps, stop valves, automatic control system, supporting construction, etc.).

Currently, the most widely used HWSSs are those with flat plate SC, although recently, the application of vacuum SC increased considerably due to their significantly decreasing cost [1–3, 6-9].

Nevertheless, the construction of an HWSS is expensive and this is the main reason for restraint in the application of such systems. Thus, the direction of the development of solar systems is toward the design of more economical SC with high efficiency.

Researchers have been working on the development of new and more efficient and effective SC. Although a great number of studies have been devoted to this issue, almost all of them are based on the application of non-ferrous metals in the construction of SCs [1,4].

The latest trend in product selection is the application of environmentally friendly goods. Life Cycle Assessment (LCA) methodology can assess and compare similar products and recommend those with the lowest environmental effect, beginning with raw material production, right up to product disposal.

The concept of using polymeric materials (PMs) to make cheaper, lower-weight SCs is not new[5,6,9]. The production of PMs allows the manufacture of modern plastics that are stable against ultraviolet radiation (UVR). This property makes them suitable for solar energy application. Likewise, LCA shows that PMs have several environmental advantages over metals. PMs are less costly than non-ferrous metals. PMs also weight less, which decreases the material capacity of SCs and their supporting construction.

The main purpose of the present research is the creation of a flat plate polymeric SC featuring low cost with high thermo technical characteristics congruous to the corresponding characteristics in traditional SC. Comparable experimental research on various SC shows that SC made from PMs (SC-P) could be constructed and applied in HWSS. LCA analysis of all tested SC is made and environmental advantages of SC-P are shown.

II. SOLAR COLLECTORS DESIGNED FOR THE EXPERIMENTAL RESEARCH. EXPERIMENTAL RESULTS AND ANALYSIS

Analysis of polymeric materials used for solar collectors [22]. Most SCs are composed of the following elements: an absorber, a transparent cover, insulation, and a frame (Fig. 1). The main part of the SC, which determines its efficiency, is the absorber–the heat exchange device that transfers heat from the solar insolation to the working fluid. The frame and absorber are usually made from non-ferrous metals (aluminum and copper). Glass (a heavy, fragile material) is used as a transparent cover. The analysis and selection of the PM to be used for the creation of an SC-P for an HWSS is presented in this section. The problem of using PMs in the construction of SCs has been studied by several research centers and production companies [5–9]. Many PMs have the potential for use in SC construction: polypropylene (PP), polystyrene (PS), polymethyl methacrylate (PMMA) also known as acryl, polycarbonate (PC), polysulfone (PSU), polyethylsulfone (PES), polyetherimide (PEI), polyamid (PA), polyvinylchloride (PVC), and polymethylpentene (PMP), along with several others [6]. Long-lasting operation of SCs under open environment conditions necessitates several strict requirements for construction materials. When selecting a PM for solar energy technology, it is necessary to take into consideration the following conditions: the optical transmission capacity of the material should be not lower than 90%; working temperatures (thermal stability) should be in the range of –15˚C to +130˚C; and the material should be stable to UVR. An analysis of the PM properties [22] shows that only some of these materials are suitable for such applications. Polypropylene, polysulfone, polyethylsulfone and cellulose polymers are unsuitable because of poor optical properties; polysulfone and polyethersulfone are stable against UVR, but they have an undesirable yellow color and mean transparency. Amorphous polyamid can be made with high optical transparency, but it is sensitive to hydrolysis and unstable to UVR. Acryl is highly resistant to UVR, but it is fragile and can be used at temperatures under 100˚C. Polyetherimide is notch sensitive and relatively expensive. For application as a transparent cover and absorber in the polymeric SC, polycarbonate plates were chosen for the present research study. The plate of the honeycomb PC is represented by two parallel sheets with transversal diaphragms integrated into the whole structure, as shown in Fig. 1. The temperature range for the PC operation is - 40^{o}C to + 135^{o}C, which allows its application in “open” systems. The maximum thermal dilatation (at $\Delta T = 80^oC$) is 2.5 mm/m. The optical transparence of the PM is crucial to its selection as a material for the transparent covering. The plates of PC have an optical transmission of 70–90%, depending on the plate thickness. The 4mm-thick plate with the highest transmission was chosen as the transparent cover. The important property of the material is its stability against UVR. Modern PC panels are produced with a special coating to prevent the penetration of UVR into the structure of the PC, which causes degradation. UVR in the range lower than 390nm, which is the most destructive, barely penetrates PC panels. The transmission of the infrared part of the spectrum (more than 5000nm) is also minimal, causing the heat emitted by the SC absorber to stay inside the collector. Compared to other glassing of the same thickness, heat loss through the honeycomb PC panels is considerably lower and the heat insulation is much higher, ensuring higher SC efficiency. Solar panels made from PC feature high mechanical properties, such as hardness and resistance against impingement attack during long operation in ambient conditions. PC is stable against a number of chemical substances, including highly concentrated mineral acids, organic acids, neutral and acidic salt solutions, oils, paraffins, saturated aliphates, and cycloaliphates, except methyl alcohol. PC is susceptible to decay caused by water or alcoholic solution of alkalis, by ammonia and ammoniacal solutions and amines. The degree of sensitivity to the various chemical substances depends on such factors as concentration, temperature, surface contact time, pressure, and tension in the PC honeycomb panel. This makes PC a suitable material for glassing and an absorber in the construction of an SC.

Several SC were used for the experimental research presented in this study. The first one was a traditional SC mass-produced in Ukraine [9]. Aluminum ribbed, solid-drawn tubes, which were made by the extrusion method, were used as an absorber in its construction. A transparent covering was made of 4 mm-thick glass. The total area of one SC was 1.1 m^2, and the weight was 23 kg. The frame and the bottom were made from aluminum and galvanized steel, respectively. This SC is identified as SC-A for the present study.

The general view of SC-A is presented in Fig. 1. The absorber tubes and the hydraulic collector were connected by argon-arc welding. Manufacturing of the absorber using the extrusion method (uniform item “tube/rib”) results in minimal thermal resistance. Glass wool with thickness of 40mm was used as insulation in this SC. Since 1997, several solar HWSSs using SC-A have been installed in the southern part of Ukraine. These systems show satisfactory efficiency during the period from spring to autumn.

The application of nonferrous metals, and their processing and connection are the main reasons for the high cost of constructing traditional SCs. Honeycomb PC plates with thicknesses of 4 mm and 8 mm, respectively, were used as a transparent cover and an absorber for the creation of a polymeric SC. Aluminum was used only for the construction of rigid frame. In the present study, this collector is specified as SC-P due to extensive application of PM in its construction. The specific weight of SC-P was 8.0 kg/m^2. Polyfoam with thickness of 20mm was used as insulation in SC-P. The structure of SC-P is presented in Fig. 1. In several constructions of SC-P it is suggested to use a honeycomb PC plate as insulation.

The technical characteristics of all SCs studied in this research are presented in Table 1.

When using a honeycomb PC plate as an absorber, the problem of connecting it to the hydraulic collector arises. It is necessary to take into account the thermal expansion factors of the different materials. Two types of SC-Ps with similar geometries were manufactured, differing by the placement of the blackened absorber coating: in SC-P1.25↑ (Table 1), the coating was placed on the upper surface of the absorber; in SC-P1.25↓, it was placed on the inferior surface. This is not an issue for traditional SCs with metal absorbers, but for SC-P, this problem was caused by the transparency of the absorber material. In the first case, the solar energy passing through the transparent cover is absorbed by the upper surface of the absorber and transferred to the working fluid mainly by thermal conductivity and convection. In the second case, after passing through the transparent cover, the solar energy penetrates the upper side of the absorber (partially being absorbed), passes through the transparent working fluid, and is finally absorbed by the lower side of the absorber. Several researches used black-colored working fluid to prevent this problem[5,6]. (Even though this step was taken for experimental purposes, it is rarely done in actual systems.) Comparative experimental tests on SC-P1.25↑ and SC-P1.25↓ showed that the placement of the covering of the transparent absorber (upper or lower) does not affect the cumulative daily thermal performance (the difference was negligible). All the results connected with SC-P in present study are related to the one with the coating placed on the upper side of the absorber.

Table 1. Technical characteristics of the studied solar collectors SC.

Characteristic	Solar collector type			
	SC-A 1.1	SC-C 1.25	SC-P1.25↑	SC-P1.25↓
Overall dimensions, mm	1200x900	1250x996	1250x996	1250x996
Thickness, mm	108	58	58	58
Weight, kg	23	18	10	10
Transparent cover material	glass	PC	PC	PC
Placement of the absorber coating	upper	upper	*upper*	*bottom*
Absorber area, m^2	1.04	1.16	1.16	1.16
Insulation material	glass wool	polyfoam	polyfoam	polyfoam
Insulation thickness, mm	40	20	20	20
Air gap, mm	30	22/32[*)]	16	16
Transparent cover thickness, mm	4	4	4	4
Number of channels in absorber	10	10	86	86
Shape of the channels in absorber	○	⬭	▭▭▭	▭▭▭
Inner diameter of absorber channel, mm	14	9	7/11[**)]	7/11[**)]
Absorber thickness, mm	-	-	8	8

Remarks:

[*)] The first value is the distance from the transparent cover to the tube; the second value is the distance from the transparent cover to the absorber metal sheet.

[**)] The first value is the vertical size of the channel; the second value is the horizontal size of the channel.

Description of experimental setup: Testing technique [22]. Different testing standards that are used worldwide for SC performance determination including ASHRAE-93 Standard (USA) and EN-12975 (European Union) [10,11] were used to follow the main challenges in the present research, which included: comparative testing of the different SC modifications when the SCs are operated in similar systems under the same conditions; the resolution of technological and constructive problems connected with the development of SC-P; comparison of the experimental results with those from previous similar research[22]. Comparative testing of the various SCs was carried out in 2011 and 2012 for the ambient conditions experienced in Ukraine (Odessa, coordinates: 46°28′N, 30°44′E) in the period from early spring until late autumn. The test rig was constructed for full-scale experimental study of the efficiency characteristics of various SCs.

Tests were carried out under natural convection conditions (without a pump) when the motion of the working fluid was realized as a result of the density difference due to a temperature increase caused by solar energy. A special series of tests were carried out in the late autumn to analyze efficiency, peculiarities, and the mode of operation. These tests showed that the system becomes more sensitive to meteorological conditions. The maximum flow rate (at midday in summer) was about 50 l/h (per 1 m^2 of SC). There are three types of working fluid motion through SCs [12]: «Low Flow»–systems with small flow rates (10…20 l/(h m^2), the temperature difference at the exit and entrance of the SC can reach 50ºC); «Match Flow»–systems with average flow rates (20…40 l/(h m^2), the temperature difference is about 20ºC); and «High Flow»–systems with large flow rates (40…70 l/(h m^2), the temperature difference is up to 15ºC. According to this gradation, the system in the present research corresponds to the third division–systems with a high working fluid flow rate and a relatively small temperature drop.

Experimental results and analysis [22]. The comparative behavior of the average temperature in the tank-accumulators according to time is presented for SC-A and SC-P shows the comparative temperature distribution of water at different heights in the tank-accumulator for SC-A and SC-P. The average water temperature in the tank-accumulator is the integrated quantity, which determines the energy collected by the SC. Integral data about SC efficiency show that the thermal efficiency of the traditional SC-A is 7 – 14% higher compared to SC-P, according to the difference in average water temperature in the tank-accumulator at the end of the day. The experimental results show that the dynamic behavior of the exit and entrance water temperatures has several zones, which were similar for all tested SCs. The first zone is typical for the time the water temperature increases in the tank-accumulator (the first circulation); the second zone characterizes the gradual increase of the temperatures proportional to solar irradiation; the third zone appears when the temperature of the water coming from the SC drops slowly due to decreasing solar irradiation after midday; and the fourth zone corresponds to the relative tranquility of the system during the night. The durations of these zones are functions of solar irradiation intensity. In the spring and autumn, the durations of the first and second zones were longer due to lower solar irradiation. Reverse circulation, featured in thermosiphon solar HWSS, as mentioned in several studies [11,13] never occurred in the present research, mainly because the bottom of the tank-accumulator was 40 cm higher than the top of the tested SCs. Higher efficiency of the traditional SC-A can be explained by the superior transparency of the glass compared to the honeycomb PC panel and by the worse thermal conductivity of PC compared to aluminum.

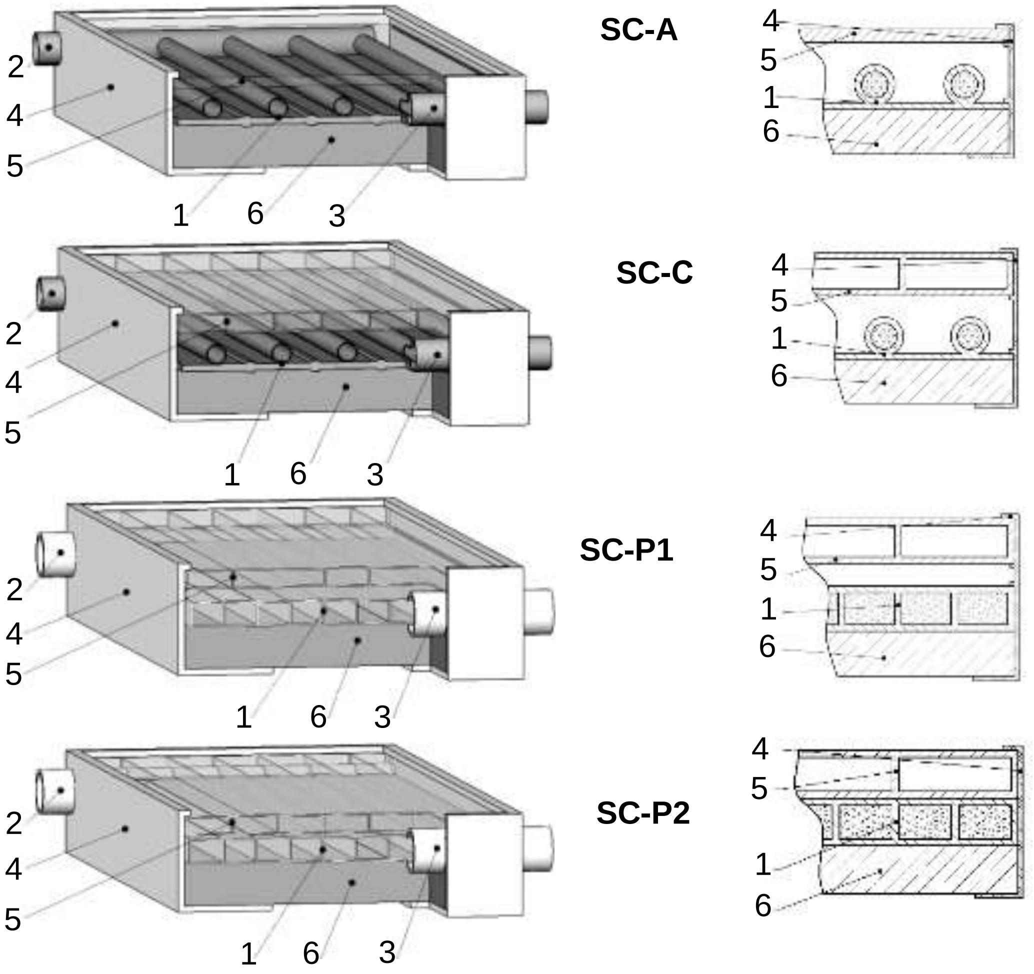

Figure 1 *– General views of the studied solar collectors:*
1 – absorber; 2, 3 – hydraulic collectors; 4 – frame, 5 – transparent cover; 6 – thermal insulation

III. COMPARATIVE ANALYSIS OF SOLAR COLLECTORS INFLUENCE ON THE ENVIRONMENT

The LCA method is employed in this section to evaluate the performance of studied SCs from environmental point of view, and to quantify environmental burdens associated with their production, usage and disposal stages. LCA is generally accepted as an application of system analysis whose prime objective is to provide a picture of the interactions of an activity with the environment. As such, LCA has two main objectives: to quantify and evaluate the environmental performance of a product or a process, so as to help decision makers to choose among alternatives and to provide a basis for assessing potential improvements in the environmental performance of the system.

There are various pollution types that may be considered for life cycle of SCs, e.g. green house gas (GHG) emission, ozone depletion, acidification, human/ecology toxicity, etc. The LCA methodology consists basically of four steps. First are goal and scope definition and set up a functional unit. Second, an inventory data of inputs and outputs is established for each stage of the product life cycle by determining the material and energy expenses, including transportation.

Third, the share of different emissions is calculated for each stage of solar collector life cycle based on chosen types of environmental impacts. Finally the environmental profiles of the products are compared in a qualitative way in order to discover, which product is more environmentally friendly one.

The materials included in the model are in many cases produced in different countries. As it difficult to get energy and emission data for the various processes in different countries, the supply system has been assumed to follow EU conditions presented in "SimaPro-5" software tool used in the study[21]. This means that the energy used to produce the SCs is included in the energy data given despite the actual origin of the energy source. However, conversion and distribution are assumed to follow EU conditions. For example, although aluminum is produced in Ukraine with a relatively large amount of hydropower, EU energy data are used. Also the model neglects small contributions associated with capital energy of the entire infrastructure of plants and any ancillary energy inputs (this can lead to an error not more than 5%). Based on the above-mentioned assumptions the total energy used and emissions related to the production, transportation and manufacturing of 1kg of material for specific substances has been calculated in the model. The stages of the life cycle include resources extraction, resources transportation, materials processing, components manufacturing, components transportation, collector assembly, collector transportation, collector operation, disassembly of collector, disposal of components. All the stages have been included in the model and assessed.

The analysis is restricted for climate conditions in Ukraine and current Ukrainian and EU industry. There are differences between two types of studied collectors in terms of years in service (15 years for SC-A and 10 years for SC-P), amount of energy produced during years in service and the temperature of hot water produced by each collector (approximately 62°C for SC-A and 58°C for SC-P for climate conditions in Ukraine). The basis of equality (functional unit) is found as 1GJ of heat supplied by collector based on modified performance criteria for cogeneration cycle[16]. Based on this assumption the amount of energy produced by collector during years in service is:

$$W = \beta\, \omega\, [\, E + \varphi\, (Q \; - E\,) \qquad (1)$$

where E – is the exergy of heat Q supplying by collector per day, W; ω – is a number of years in service, $\varphi = 0.12$ – is the constant whose value is obtained from the literature for ideal heating device [16]; β = 31/0.28 = = 110.7 – is a coefficient (where 31 – is a number of days in July and 0.28 – is the part of year's heat supplied by collector in July).

The exergy E can be presented as work done by ideal thermal cycle:

$$E = (1 - T_a / T_{hw}\,)\, Q \qquad (2)$$

where T_{hw} – is the hot water temperature, °C.

The data used for the calculation is presented in Table 2.

Table 2. Parameters of solar collectors used for calculation of environmental impact (T_a = 22 ^{O}C)

Parameter	SC-A	SC-P
Term in service ω, years	15	10
Hot water temperature T_{hw} ^{O}C	62	58
Heat supplied by collector per day, MJ	13.5	12.1
Produced energy during years in service W, GJ (Eq. 1)	5.097	2.889

Life cycle inventory data form the core of any LCA study. Collecting life cycle inventory data involves quantifying the inputs and outputs of material and energy associated with the product system considered. The product system generally consists from four stages:

1 – extraction and processing raw materials;

2 – product manufacture;

3 – use of the product;

4 – processing of the used product.

Furthermore, only the first-order (the actual processes) and second order processes (energy production from primary energy carriers) are taken into account. Third order processes (production of capital goods) and forth order processes (services) are not incorporated in the assessment. These environmental inputs (materials and energy) and outputs (waste and emissions to air, water and soil) of processes are referred to as impacts in the Eco-indicator 95 method [17,18].

In this study nine types of environmental impacts are taken into account: global warming potential (GWP); ozone layer depletion; acidification; eutrophication; heavy metals; winter smog; summer smog; energy resources and solid waste. The cumulative energy requirement is calculated by converting all energy requirements with the help of LCA aid software tool "SimaPro-5" to the use of primary energy carriers and then adding up the primary energy requirements. The contributions to the GWP, ozone depletion, acidification, eutrophication, winter and summer smog are established by calculating the equivalent emissions with the help of the software tool. Non-hazardous solid waste is calculated by adding together the contributions of the separate processes.

The environmental profiles of the two different types of solar collectors have been compared by a qualitative way in order to discover which of them is more environmentally friendly one. The calculation of the Eco-

It value (the single score of the environmental impact) as a global environmental score, scale the environmental profile with appropriate weighting factors, which express the relative importance among the effects. The environmental impact index is measured in Eco-indicator milli-points (mPt) [18].

The total amount of materials for each collector is shown in Table 3.

Table 3. Solar collectors component materials and their quantity

Component	**Material (weight)**	
	SC-A	SC-P
Frame	Al (5.5kg)	Al (1.2kg)
Bottom	Al (2.5kg)	PC (0.6kg)
Absorber	Al (8.0kg)	PC (2.9kg)
Hydraulic collector	Al (2.5kg)	PVC (1.5kg)
Transparent cover	Glass (4.0kg)	PC (1.4kg)
Insulation	Glass wool (0.5kg)	Polyfoam (0.4kg)
Total weight	23.0 (kg)	7.4 (kg)

The results of the LCA study of solar collectors using “SimaPro 5” software tool [21] with impact assessment method “Eco-indicator 95”[18] are shown in Figs. 2-3.

Presented in Fig. 2 comparison of different environmental impacts for three collectors per 1GJ of produced energy shows that for SC-P the environmental impacts for most categories is much less than for conventional collector excluding two impact categories: heavy metal and solid waste, where the environmental impact from plastic collector is slightly higher than for conventional collector.

The overall advantage of the plastic collector from environmental point of view can be clearly seen from the Fig. 3A. The environmental impact of SC-A is almost two times higher compared to SC-P due to the metals in the construction of SC-A.

In the present study the assumptions have been made for disposal and recycling stage for each collector. To evaluate significance of these assumptions the sensitivity analysis for two different scenarios of the disposal stage has been performed:

1) recycling 30% of main materials (aluminum, glass, plastics), and

2) recycling 80% of the main materials (plastics recycling means incineration for energy production).

The obtained results for total environmental score for each collector are shown in Fig. 3. Presented results show that disposal and recycling stage has a relatively small impact on environmental performance of SC-P, but it has a significant impact on environmental performance of SC-A. The difference between total score for conventional collector is 42mPt i.e. total environmental impact about 1.8 times decreases if recycling percentages increase from 30% to 80%. But for SC-P the difference between total score is only 5.3mPt i.e. only 10.6% lower. The results show that the increasing of the rate of metal and glass recycling has a significant advantage in term of reducing of environmental impact. At the same time incineration of plastics has smaller advantage, as the rate of energy production is low and it creates an additional pollution.

The data obtained from the calculations allow estimate pay back time for energy consumption for each collector, which is 55.2% (8.3 years) and 38.3% (3.8 years) for SC-A and SC-P, respectively. GHG emission in CO_2 equivalent per 1GJ of heat for East/Central Europe from electricity and natural gas is 119.2kg and 52.1kg, respectively[19]. The pay back time of GHG emission for each collector can be estimated. The calculated pay back time is 23.4% (3.5 years) and 18.7% (1.9 years) for electrical heating and 53.7% (8.1 years) and 42.8% (4.3 years) for gas heating for SC-A and SC-P, respectively.

The figures for energy consumption and GHG emission have been taken into account only from direct burning of fossil fuels with goal to compare the pay back time for each collector (adding the energy consumption and GHG emission for making electrical and gas heaters will reduce obtained figures).

IV. CONCLUSIONS

Experimental investigation showed that the efficiency of the polymeric solar collector designed in the present study decreased 7-14% compared to traditional SCs [9, 15, 22].

The application of polymeric materials in the construction of solar collectors was studied according to the methodology of Life Cycle Assessment. The environmental influence for most of the impact categories for the polymeric collector was smaller than that for traditional SC (up to about 67% for winter smog). It is shown that recycling scenario for traditional SCs is more important than for polymeric SC due to the content of the metal components, which can be easily recycled. The increase in the recycling materials percentage from 30% to 80% leads to 45% decreasing of the environmental impact for SC-A, and only 10.6% decreasing for SC-P.

According to the LCA methodology, the energy return time (payback energy) will be 55.2% (8.3 years) and 38.3% (3.8 years) for SC-A and SC-P, respectively.

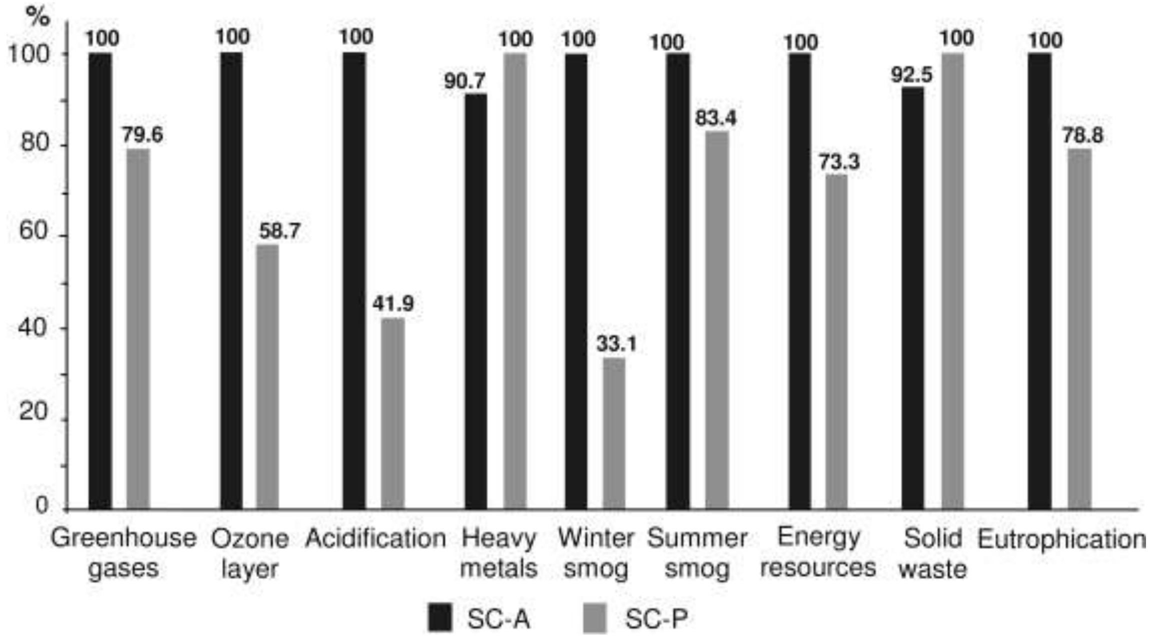

Figure 2 *− Comparison of different environmental impacts for SC-A and SC-P per 1GJ of produced heat.*

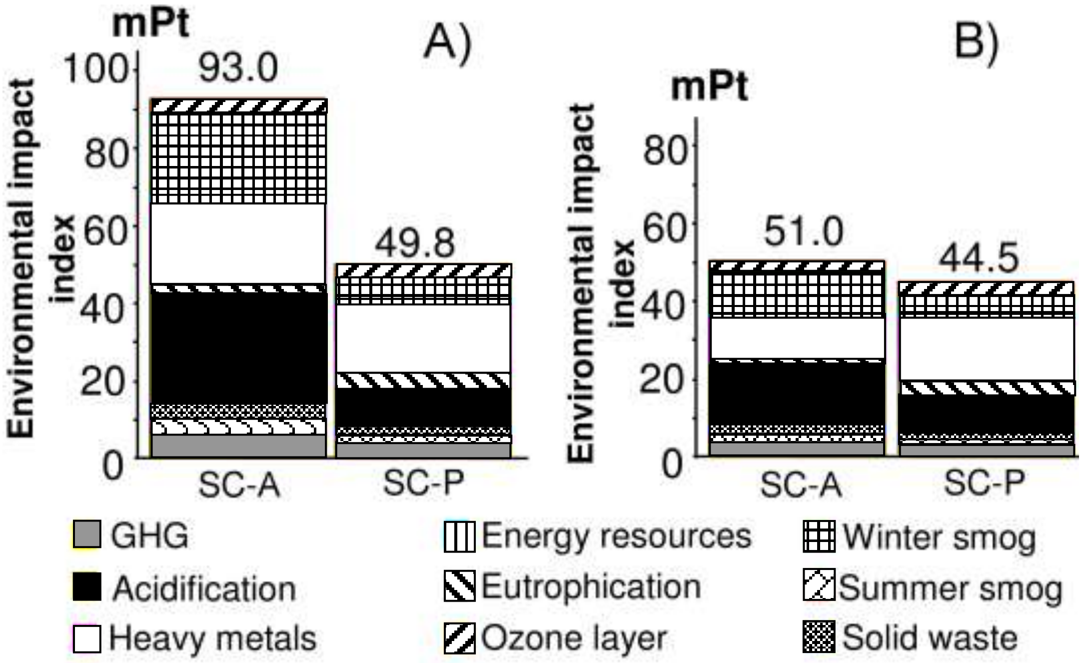

Figure 3 *− Environmental score in case of 30% recycling (A) and 80% recycling (B) of main materials.*

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ПОЛІМЕРНІ МАТЕРІАЛИ ДЛЯ УТИЛІЗАЦІЇ СОНЯЧНОЇ ЕНЕРГІЇ: ПОРІВНЯЛЬНЕ ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ТА ЕКОЛОГІЧНІ АСПЕКТИ

У роботі виконано порівняльне дослідження характеристик традиційних типів рідинних сонячних колекторів металевого типу (з теплоприймачем, виконаним з алюмінієвих і мідних трубок, СК-А) і нового типу сонячного колектора, виготовленого з полімерного матеріалу (СК-П). Полімерний сонячний колектор СК-П виконаний з багатоканальних полікарбонатних плит і являє собою багатоярусну сендвіч-структуру. Експериментальне обладнання забезпечувало проведення паралельних порівняльних випробувань двох модифікацій сонячних колекторів у відкритому середовищі при повністю ідентичних зовнішніх умовах (інтенсивність сонячного випромінювання, рівень вітронавантаження та температура навколишнього середовища). Випробування проведені при природній і вимушеній циркуляції теплоносія. Експериментальні результати свідчать, що ефективність полімерного сонячного колектора порівняно з традиційним металевим колектором знижується в середньому на 7-14%. Виконано, з використанням методології «Повний життєвий цикл» (Life Cycle Assessment), порівняльний аналіз екологічних характеристик порівнюваних модифікацій сонячних колекторів, що показав суттєві переваги полімерного колектора СК-П

Ключові слова: Полімерні матеріали; Сонячний колектор; Експериментальне обладнання; Система гарячого водопостачання.