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The Influence of Collector Type on Emission Indicators in Solar Systems Life Cycle Assessment

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1. Introduction

The growth of energy consumption, which accompanies the civilization development, results in depletion of traditional energy resources – mostly fossil fuels as coal, oil and natural gas [5, 20]. It is widely considered that the increasing use of fossils causes the pollution of environment, which in turn is the reason of many undesired phenomena, like ozone layer depletion, global warming, acid rains, health problems, etc [6, 7, 13]. Thus, renewable energy sources are becoming more and more popular in many applications.

Renewable energy means energy gained from natural and continuous processes like water movement, sun radiation, wind, geothermal heat, etc. In polish regulations, this term includes also biomass, biofuels and biogas production, which undergo [12, 19]. It is also worth to underline that there are other alternative energy sources available, for example those based on energy recovery from wastes incineration [17].

Generally, the production of primary energy in European Union insignificantly decreased in the last decade and accounted 839.9 Mtoe in 2010. At the same time, the share of renewable energy increased up to 20.1% in EU and 10.2% in Poland [22], which is connected with the EU policy towards sustainable energy sector.

Sustainable development may be simply defined as a pattern of resource use which aims in ensuring the access to the resources we can exploit for the future generations [8, 15]. The introduction of sustainable development idea in Brundtland Report in 1987 [15, 21] became a precursor of a change in natural resources exploitation pattern.

The concept of sustainable development was created as the antonym to the traditional development based on economy. Sustainability includes environmental, economic and social problems. Nowadays, moral, technical, regulation and political issues are considered [14, 15]. Sustainable development rule is nowadays a necessary element of every official document on both state and international level [16].

When it comes to the sustainable energy policy, it is commonly understood as the increase of the renewables share in energy market [4]. Renewable energy sources are considered to be environmentally – friendly as their use is not connected with direct emissions from fossil fuels burning. However, to ensure the appropriate assessment of the given technology, it is necessary to take into account all the stages of life cycle. The holistic perspective of Life Cycle Assessment makes this method an useful tool for environmental analysis of renewable energies' systems. In this paper, the LCA method was applied to compare resource use and other environmental burdens related to entire life cycle of hot water system with different types of solar thermal collectors.

2. Solar energy conversion in Poland

The primary source of energy for the Earth is the Sun. Solar energy used in the process of photosynthesis stands at the base of every food chain, it is also the driving force for the movement of the water and the wind used to produce energy, and before millions of years it has been trapped in coal and oil resources [18].

Solar energy is used in many applications. The typical examples include the commonly used systems of passive heating by radiation throughout glass surfaces of windows or electricity savings connected with daylight. The tunnels and greenhouses used in agriculture are also popular form of sun radiation use.

In Poland, solar systems as thermal collectors and panels appeared in the market relatively recently. Statistical data included in the Central Statistical Office reports show that energy gained in the processes of thermal conversion of solar radiation increased during the last six years more than ten times (Figure 1).

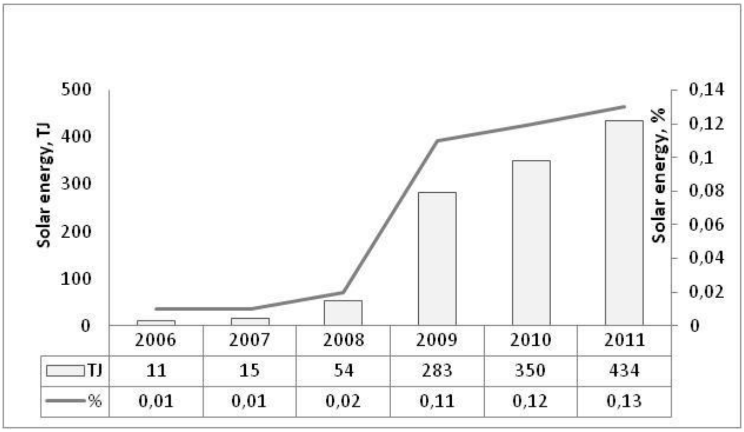

Fig. 1. Solar energy in Poland from 2006 to 2011, TJ, and its share in energy production, % (www.sat.gov.pl)
Rys. 1. Produkcja energii na bazie promieniowania słonecznego w Polsce od 2006 do 2011, TJ, oraz jej udział w całkowitej produkcji energii, % (www.stat.gov.pl).

The ongoing increase of renewable energy share in the market was predicted in the framework of Directive 2009/28/EC of the European Parliament and of the Council and it was one of actions according to the climate package „3x20". The planned share of renewable sources by 2020 are 20% for Europe (the countries of "old" European Union) and 15% for Poland [15]. The increasing number of devices for thermal conversion of solar energy is connected with the various measures of public support for investors.

3. Environmental LCA of solar systems in literature

Life Cycle Assessment is the environmental analysis, which treats a product as a system of interconnections and the circulation of mass and energy in the life cycle – from cradle to grave. It takes into account the full life cycle of the product, materials and energy inputs in the process of its production, as well as the effect of final use and disposal on the environment [24].

According to the ISO 14041 standard, LCA is a technique for evaluation of environmental aspects and potential impacts associated with a certain product and expressed for the functional unit. It is realized through the data collection of relevant inputs and outputs for a given system, an assessment of the potential environmental impacts associated with the data, interpretation of the results and life cycle impact assessment as a final stage of analysis [21].

In the scientific literature of the last decade the new articles concerning Life Cycle Assessment of renewable energy sources appeared, including these covering solar hot water systems. Ardente [1] applied Life Cycle Assessment for the evaluation of carbon footprint of solar thermal collector (surface 2.13 m^2) production phase. Author recognized the primary energy use during the collector manufacture as 11.5 GJ, and emission of carbon dioxide equivalent as 721 kg CO_{2eq}. Energy used directly for collector production in the plant accounts only 5% of total consumption, another 6% is used for transportation. Most of the primary energy is spent during the pre-production phase – raw materials extraction. The final conclusion is that direct energy consumption is less important, than indirect energy usage.

Solar thermal collector integrated with storage system was analysed by Battisi and Corrado [2]. The idea of such a device performance is connected with the increased heat exchanger capacity; however, it cannot work in polish climate conditions because of the external temperatures in the winter season. Primary energy consumption for production, distribution and final disposal of analyzed system was estimated as 3.1 GJ, and greenhouse gases emission as 219.4 kg CO_{2eq}. These indicators are generally associated with production phase (97.8%). The operation phase was neglected in the inventory analysis because of specific construction of a system which does not need any additional medium, what excludes the necessity of pumping.

In Kalogirou's research works [9, 10], the Life Cycle Assessment of solar flat collectors are described. For the first system, working as integrated with water storage, the primary energy use was estimated as 2.7 GJ. For traditional system with two media (polypropylene glycol for the collector's cycle and hot water in the installation) author counted the primary energy consumption as 3.5 GJ.

In both of the cases, the analysis show that solar hot water systems are characterized by low carbon dioxide emissions as compared with the conventional energy sources. Moreover, the payback time for emissions from production phase is shorter than the total period of life cycle. Nevertheless, it is necessary to emphasize that analysis were conducted for favorable solar radiation conditions in Mediterranean countries. Therefore, the aim of this paper is to perform Life Cycle Assessment for various solar hot water system operating in local climate conditions of Lublin area.

4. LCA of solar hot water system

As the method of analysis, Life cycle Assessment was used. LCA is based on the estimation of energy and materials use as well as contaminants and wastes emissions, which are connected with entire period of product's life. According to the technological scheme, LCA is consisted of four phases:

1. Goal and scope definition;
2. Inventory Analysis;
3. Impact Assessment;
4. Interpretation [11].

In this research work, LCA is used for the quantification of materials and energy flows in three various SHW systems working in detached houses (hot water consumption – 120 l per day, radiation conditions for Lublin):

S1 – System 1 consisted of 2 flat plate collectors, 2.33 m^2 each, with aluminum absorber and equipment: pipes (copper), pump, electronic regulator, expansion vessel, armature, ethylene glycol and 150l hot water tank.

S2 – System 2 consisted of 2 flat plate collectors, 2.33 m^2 each, with aluminum/copper absorber and equipment: pipes (copper), pump, electronic regulator, expansion vessel, armature, ethylene glycol and 150l hot water tank.

S3 – System 3 consisted of 2 flat plate collectors, 2.33 m^2 each, with copper absorber and equipment: pipes (copper), pump, electronic regulator, expansion vessel, armature, ethylene glycol and 150l hot water tank.

<u>Goal and scope definition</u>

The goal of analysis was to estimate the environmental effects connected with the usage of solar hot water systems supplied by different flat plate collectors. The installation is sourced both by solar thermal collectors (2 flat collectors, 2.33 m^2 each) and natural gas boiler as basic energy source. The boiler with atmospheric burning covers from 41% of hot water needs for Cu absorber collector to 45% for Al absorber, while the left percentage is covered by solar energy.

The extent of analysis includes solar system construction (flat collectors, pipes and instrumentation, pump and steering device, medium – ethylene glycol, hot water storage bin, energy and fuels used for transport and building) and the operation phase. The functional unit is 1 kWh of energy produced during the operation of system in Lublin climate conditions.

Inventory analysis

The inventory analysis was performed on the basis of materials calculation in SHW system project, as well as collector producers and local companies data. The data used for analysis cover the materials and energy consumption in the stated life cycle stages. The Ecoinvent database was used as a source of information about the pre-produced materials.

The main materials in collector's construction are: copper or/and aluminum for absorber production, steel frame, solar glass, PU foam insulation, epoxy resin, brass and PCV connection elements. As copper extraction is extremely energy consuming process, this material has a significant impact on the total indicator of collector production phase. To ensure the data relevant for polish market, the recycling of copper and Aluminum was included in inventory, based on Central Statistical Office data [22].

Impact assessment

Life Cycle Impact Assessment stage of analysis included three main assessment methods: Global Warming Potential (GWP) and EcoIndicator'99 for the whole life cycle of a solar hot water system, and Cumulative Energy Demand for production phase of collectors.

GWP method allows to calculate the greenhouse gases emissions in the mass unit – kg CO_{2eq} [3]. Carbon dioxide equivalent is a measure used to express and compare the emissions from diverse greenhouse gases based upon their global warming potential. For example, 1 kg of methane is parallel to 25 kg of carbon dioxide.

As the complementary method, EcoIndicator'99 was used. It allows to simplify environmental burden categories into one indicator expressed in points Pt, which includes three types of damage: Human health, Ecosystem Quality and Resources, with impact balance 40%, 40%, 20% respectively.

For production phase assessment, Cumulative Energy Demand (CED) method was used to estimate the total energy consumption (GJ) for production of a single collector.

Interpretation

The final results were recalculated to the functional unit (1 kWh of produced heat). To ensure the right interpretation, the final result was compared to the traditional system based on natural gas boiler. Data for characterization of conventional system were assumed on the basis of Ecoinvent database.

5. Results and discussion

Cumulative Energy Demand results for a single collector (2.33 m^2) production analysis are presented in Figure 2. Collector S1 has aluminum (Al) absorber, S2 – Al-Cu absorber, while the collector S3 was produced with the use of copper (Cu) absorber. For the sake of the nonferrous metals used for their construction, the collectors differentiate in the values of CED indicator (GJ_{eq}). The fossil energy consumption for S3 collector was the highest (1.301 GJ_{eq}) because of energy-intensive processes of materials extraction for copper absorber production. However, due to the small differences between the materials characteristic, S1 and S2 energy consumptions are at the comparable level.

The similar situation can be seen in the Figure 3, presenting the results of GWP assessment for collector production. Because the energy consumption for production is the highest for S3 collector, the emission of greenhouse gases follows this tendency.

In the case of the SHW system analysis, EcoIndicator method results expressed as total, weighted sum of indicators are presented in Figures 4 and 5. This part of results is divided into Collector (production), Equipment (other elements of SHW system – production and transportation) and Operation (energy consumption for pump and regulator, emissions from gas boiler use). As it can be noticed, operation of a system has the biggest share in total indicator characterizing S1, S2 and S3. The production of equipment is also important element, due to the materials used in installation. The only case when collectors production has higher damage indicator than other elements of system is S3, with Cu absorber.

The detailed EcoIndicator'99 results can be found in the table 1. In the case of production processes, the main impact categories are Ecotoxicity and Minerals (for systems containing copper) and Fossil fuels. Operation phase is characterized by the highest values of indicators in Fossil fuels category due to the natural gas consumption.

Table 1. EcoIndicator'99 results for SHW systems in impact categories, Pt
Tabela 1. Wyniki oceny metodą EcoIndicator'99 dla systemów słonecznych w kategoriach wpływu, Pt

	System 1			System 2			System 3		
	Collect.	Equipm.	Operation	Collect.	Equipm.	Operation	Collect.	Equipm.	Operation
Pt	11.5	69.0	225.0	32.5	69.0	237.1	83.2	69.0	207.3
Carcinogens	0.205	8.337	1.094	4.040	8.337	1.308	13.156	8.337	1.066
Respiratory organics	0.003	0.005	0.045	0.003	0.005	0.045	0.005	0.005	0.041
Respiratory inorganics	3.062	11.906	10.042	6.241	11.906	12.053	14.061	11.906	9.401
Climate change	0.660	0.823	17.458	0.652	0.823	18.372	0.710	0.823	16.085
Radiation	0.003	0.026	0.029	0.005	0.026	0.070	0.008	0.026	0.027
Ozone layer	0.000	0.000	0.011	0.000	0.000	0.012	0.000	0.000	0.010
Ecotoxicity	0.278	21.377	1.143	8.556	21.377	1.473	28.222	21.377	1.073
Acidification/ Eutrophication	0.394	0.838	1.820	0.633	0.838	2.187	1.225	0.838	1.693
Land use	0.229	1.858	1.385	0.815	1.858	1.493	2.208	1.858	1.281
Minerals	0.661	16.031	0.902	5.494	16.031	1.058	17.058	16.031	0.835
Fossil fuels	6.029	7.837	191.105	6.032	7.837	199.068	6.518	7.837	175.749

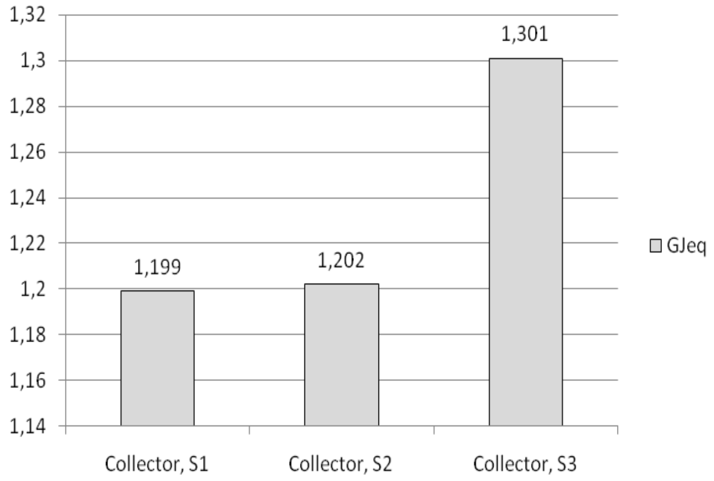

Fig. 2. CED results for production phase of collectors with Al, Al-Cu and Cu absorbers, GJ
Rys. 2. Wyniki oceny metodą CED dla fazy produkcyjnej kolektorów z absorberami Al, Al-Cu oraz Cu, GJ.

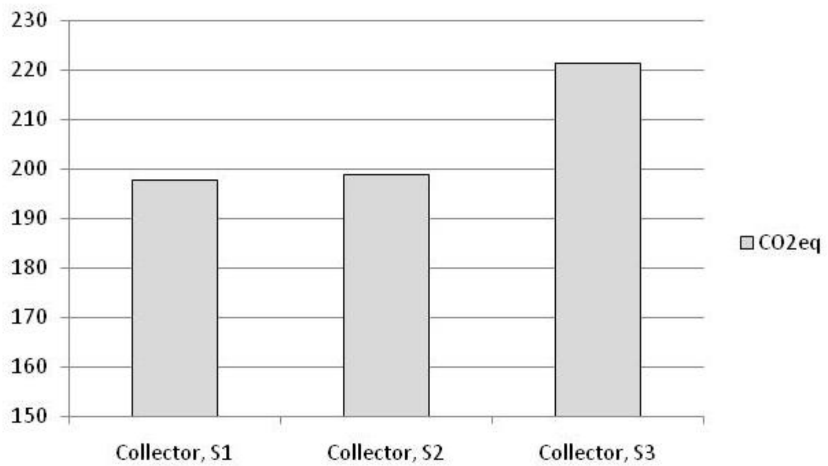

Fig. 3. GWP results for production phase of collectors with Al, Al-Cu and Cu absorbers, CO_{2eq}
Rys. 3. Wyniki oceny metodą GWP dla fazy produkcyjnej kolektorów z absorberami Al, Al-Cu oraz Cu, $CO_{2eq.}$

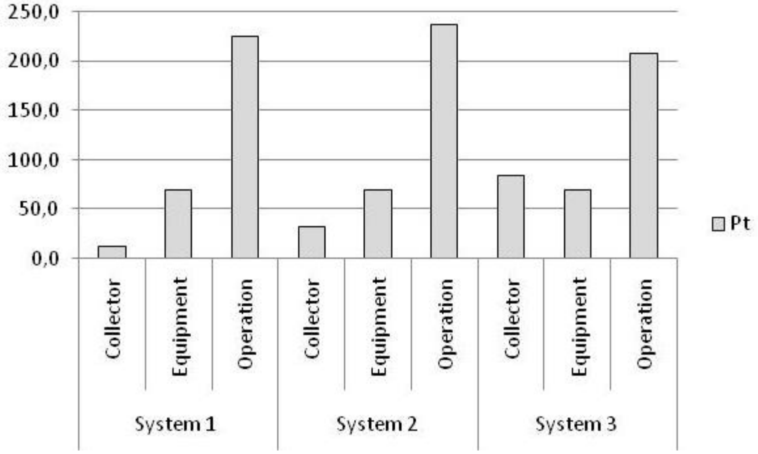

Fig. 4. EcoIndicator'99 results for solar hot water systems, Pt
Rys. 4. Wyniki oceny metodą EcoIndicator'99 dla systemów słonecznych, Pt

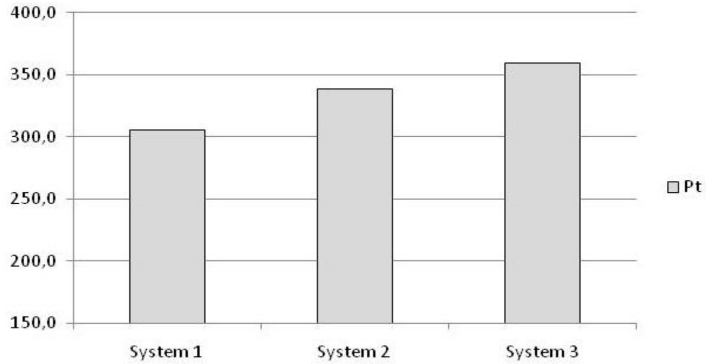

Fig. 5. EcoIndicator'99 results for solar hot water systems, single score, Pt
Rys. 5. Wyniki oceny metodą EcoIndicator'99 dla systemów słonecznych, wskaźnik scalony, Pt

The final results of analysis for the functional unit (1 kWh of produced energy) can be found in the table 2. The carbon dioxide equivalent emission indicator has the lowest value for the collector 3, with copper absorber. This fact is caused by the highest efficiency of this type of flat plate collector. However, if we compare the results of analysis for solar energy only, Al-Cu absorber seems to be better solution.Production phase and materials used have significant influence on EcoIndicator'99 method results. This is why the final results of this assessment are the most favorable in the case of system 1.

Table 2. LCA results for functional unit
Tabela 2. Wyniki LCA w przeliczeniu na jednostkę funkcjonalną

Energy generation	Unit	System 1	System 2	System 3	Gas boiler
Conventional /combined	Pt/kWh	0.0087	0.0096	0.0102	0.0153
Solar	Pt/kWh	0.0623	0.0746	0.1099	–
Conventional /combined	$kgCO_{2eq}/kWh$	0.1334	0.1397	0.1241	0.2941
Solar	$kgCO_{2eq}/kWh$	0.0185	0.0175	0.0178	–

6. Conclusions

As the member of European Union and participant of several international conventions, Poland is obliged to reduce the greenhouse gases emission by the increase of renewable sources share in the energy market. This initiative corresponds to the sustainable development requirements and leads to the decrease both in resources depletion and harmful emissions to environment. The use of solar thermal collectors is one of ways to realize this concept.

On the basis of conducted analysis, author of this work stated that solar thermal collectors of flat type distinguish for the sake of production processes, therefore they can influence the environment in different aspects. For example, flat plate collector with copper absorber has the highest impact on ecosystem quality, while the one with aluminum absorber influences mostly the damage category of resources by fossils used for production.

Global Warming Potential indicators calculated in the Life Cycle Assessment of solar hot water system show that in the case of combined system, copper absorber is the most favorable solution. However, in the case of EcoIndicator'99 method concerning all the damage categories, the system 1 with aluminum absorber seems to be less harmful during its life cycle.

When compared to the conventional energy source, all the solar hot water systems are characterized by low emissions. The decrease in GHG emission factors equals 0.161 kg CO_{2eq}, 0.154 kg CO_{2eq} and 0.170 kg CO_{2eq} for S1, S2 and S3 respectively. This allows to formulate the final conclusion that SHW systems in Lublin climate conditions can reduce greenhouse gases emissions and therefore can be treated as environmentally friendly source of energy in the life cycle perspective.

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Wpływ rodzaju kolektora na wskaźniki emisji w ocenie cyklu życia systemów słonecznych

Streszczenie

Instalacje kolektorów słonecznych są popularnym źródłem ciepłej wody użytkowej w domach prywatnych i budynkach użyteczności publicznej. Rozwój tego rodzaju rozwiązań wspierany jest przez fundusze państwowe i Europejskie, ponieważ są one traktowane jako przyjazne środowisku i nisko emisyjne źródła energii. W całościowej ocenie należy jednak wziąć pod uwagę emisje zanieczyszczeń i zubożenie zasobów naturalnych spowodowane w trakcie produkcji, transportu i użytkowania urządzeń – elementów składowych systemu słonecznego podgrzewu ciepłej wody. W tym celu wskazane jest stosowanie metody oceny cyklu życia (LCA), która jest użytecznym narzędziem do porównania wskaźników obciążenia środowiska. W fazie oceny wpływu cyklu życia (LCIA) do oszacowania obciążenia dla środowiska używane są takie techniki, jak Global Warming Potential GWP 100a do oszacowania emisji gazów cieplarnianych, Cumulative Energy Demand charakteryzująca zużycie energii z poszczególnych źródeł oraz EcoIndicator'99 odnosząca się do wpływu na zdrowie ludzkie, jakość ekosystemu i zużycie zasobów.

W niniejszej pracy przedstawiono wyniki oceny cyklu życia systemów cieplnej konwersji energii słonecznej. Wyróżniono 3 podstawowe systemy różniące się materiałami użytymi do budowy kolektora płaskiego; absorber miedziany, aluminiowy i miedziano – aluminiowy. Na podstawie danych o budowie kolektorów oraz różnych charakterystyk ich pracy w zależności od sprawności przedstawiono wyniki fazy LCIA w postaci wskaźników: GWP, CED oraz EcoIndicator'99. Rodzaj użytego kolektora wpływał istotnie na wskaźnik CED dla fazy produkcji kolektora. Różnice pomiędzy wskaźnikiem CED dla budowy kolektorów z absorberem aluminiowym i aluminiowo – miedzianym były niewielkie, natomiast CED dla kolektora z absorberem miedzianym wyniósł 1,301 GJ_{eq} i był o około 8% większy od pozostałych.

W cyklu życia obejmującym fazy produkcji, transportu oraz użytkowania systemy słoneczne są zdecydowanie źródłami niskoemisyjnymi w porównaniu ze źródłem konwencjonalnym w postaci kotła gazowego. Zmniejszenie współczynników emisji gazów cieplarnianych wynosi odpowiednio 0,161 kg CO_{2eq}, 0,154 kg CO_{2eq} i 0,170 kg CO_{2eq} dla systemów z absorberem aluminiowym, mieszanym i miedzianym. To pozwala na sformułowanie ostatecznego wniosku, że systemy podgrzewu ciepłej wody użytkowej mają potencjał zmniejszania emisji gazów cieplarnianych nawet w przypadku niezbyt sprzyjających warunków klimatycznych Lubelszczyzny i związku z tym mogą być traktowane jako przyjazne dla środowiska źródła energii.