7th International Quality Conference
May 24th 2013
Center for Quality, Faculty of Engineering, University of Kragujevac

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A REVIEW LIFE CYCLE ASSESSMENT OF A SOLAR THERMAL COLLECTOR SENSITIVITY ANALYSIS, ENERGY AND ENVIRONMENTAL BALANCES

Abstract: *All goods and services have an impact on the environment throughout its life cycle. European countries have focused their attention on this concept, given that improving eco-performance products / services focal point of the European Environment Programme. In other words, global environmental problems can only be solved if the use of energy and raw materials per unit of output decreases, or if you increase the eco-efficiency. The renewable energy sources are often presented as 'clean' sources, not considering the environmental impacts related to their manufacture. The production of the renewable plants, like every production process, entails a consumption of energy and raw materials as well as the release of pollutants. Furthermore, the impacts related to some life cycle phases (as maintenance or installation) are sometimes neglected or not adequately investigated.*

The energy and the environmental performances of one of the most common renewable technologies have been studied: the solar thermal collector for sanitary warm water.

The aim is to trace the main energy and environmental impacts related to the whole product's life cycle. The following phases have been investigated: production and delivery of energy and raw materials, production process, installation, maintenance, disposal and transports occurring during each step.

Keywords: *Life cycle assessment (LCA); Renewable energy; Solar thermal collector*

1. INTRODUCTION

All goods and services have an environmental impact along their life cycle.Onthis concept the European countries have focused their attention, considering the improvement of the eco-performances of products/services as a key point of the *European environmental programme*. In other words, global environmental problems can be met only if the use of the energy and the rawmaterials per product unitwill be reduced, i.e. eco-efficiency increased.

The need to strengthen the 'green market' has been successively confirmed in another official document named 'the green paper on Integrated Product Policy (IPP)'. Once a product is put on the market, there is relatively little that can be done to improve its environmental characteristics. The IPP approach seeks to reduce the environmental impacts occurring throughout the entire life cycle of the product since the early stages of product design and development. Furthermore, the diffusion of the ‘green public procurement’ should induce the producers to investigate the environmental impacts of their production and to disseminate the environmental information adopting scientific data format as the environmental product declaration (EPD). For IPP to be effective, life cycle thinking needs to become second nature for all those who come into contact with products. The cognitive process is at the basis of the environmental performances improving. It is necessary to have detailed and reliable data on which to base assessments regarding each life cycle step. Life cycle assessment (LCA) represents an important support tool for IPP and the ‘the best framework for assessing the potential environmental impacts of products currently available’.To obtain reliable results, data should be collected and managed following standardised procedures. The international standards of series ISO 14040 represent a widespread accepted methodology [1].

The reliability of LCAs strictly depends on complete and sharp data that unfortunately are not always available. ISO 14040 recommends to investigate all those parameters that could heavily influence the final eco-profile. [2] Because Life Cycle Inventory (LCI) results are generally used for comparative purposes, the quality of data is essential to state whether results are valid or not. Regarding data quality, LCA studies should include: time-related coverage, geographical coverage, technology coverage, precision, completeness and representativeness of data consistency and reproducibility of methods used throughout the LCA, sources of the data and their representativeness, uncertainty of the information. The international standards give little practical guidance on how to manage such information. In addition to previously listed parameters, other sources of uncertainty are:

– Data inaccuracy (due to errors and imperfection in the measurements);
– Data gaps or not representative data;
– Structure of the model (as simplified model to represent the functional relationships);
– Different choices and assumptions;
– System boundaries definition;
– Characterisation factors and weights (as those used in the calculation of potential environmental impacts);
– Mistakes (unavoidable in every step of LCA).

Furthermore, the global environmental balance of a product is strictly related to the service life (‘‘Period of time after installation during which all essential properties of an item meet or exceed the required performance’’) and durability (‘‘Capability of an item to perform its required function over a period of time’’) concepts. The durability is certainly a key element since LCA takes the life cycle of the material into account, which includes its use over a number of years: by increasing the length of the service life, the use of resources is improved as much as specific impacts are reduced. Design concepts, aiming to improve the environmental performance of a product, should include the design for durability and the design for longevity including, for example, concepts of reparability, maintainability and upgradability. However, even the durability assessment implies many problems and uncertainties as: non-reproducibility and traceability of field tracking studies, subjectivity of expert opinion, lengthof accelerated tests and natural weathering, relevance of stress test, required quality and quantity of knowledge for modelling [3].

Moreover, the study of uncertainty sources is itself affected by uncertainty. It is necessary to distinguish uncertainty, which arises due to the lack of the knowledge about the true value of a quantity, from variability that is attributable to the natural heterogeneity of values. Uncertainty could be reduced by more precise and accurate measurements while variability is entailed into processes. Details contained in the normal LCI study do not often allow distinguishing uncertainty from variability.

The present paper focuses the attention upon one of the most common renewable technologies: the solar thermal collectors for warm sanitary water demand. Renewable energy sources are often presented as 'clean' energy, not considering the environmental impacts related to their manufacture. The production of the renewable plants, like every production process, entails a consumption of energy and natural resources as well as the release of pollutants [4].

Many authors have deeply investigated the benefits related to the employment of solar systems including studies regarding LCA of solar collectors and comparative analyses of different collector's typologies [5, 6]. However, the study's assumptions or data references are often not clearly shown. In addition, results are often presented as aggregated indexes making difficult the comparison among different studies or the dominance analysis of each life cycle step are difficult. Furthermore, some life cycle steps (as, for example, installation or maintenance processes) are generally not investigated in detail or are simply neglected. Some studies, in fact, consider the full LCA of a solar collectors as too much expensive and time consuming or suppose as significant only the impacts related to materials processing and collector's assembling. On the other hand, the principles of eco-design suggest to employ disaggregated information to identify the steps with the greatest impacts and with the largest improvements potentials.

The aims of this paper are: to trace an eco-balance of equipment, referring to a thermal solar collector, to grant transparency of assumptions, system boundaries and data sources, to show the incidence of each component and life cycle step and to avoid uncertainties related to weighting processes and impacts assessment.

2. THE CHOICE OF THE FUNCTIONAL UNIT (FU)

The first phase of the LCA is the goal and scope definition. It includes an important step: the clear statement of the functional unit (FU). The FU is defined as the 'reference unit expressed as quantified performance of the product system'. The FU is important as basis for data collection and for the comparability of different studies referred to the same product category. The choice of the FU is not always immediate. In our case study FU equal to the entire equipment. The results are presented as global quantities concerning the whole collector. Probably, this is the most intuitive choice but it could cause misunderstanding. In fact, there are various typologies of collectors, which can be roughly divided in two main categories: collectors with forced circulating flow and collectors with natural circulating flow. Performing the LCA related to these two collector's types, the results could be not comparable.

2.1. The studied system

The studied FU is one solar thermal collector (dimensions: 2.005 x 1.165 x 0.91m) with a total net surface of 2.13 m^2. The FU is constituted by three main components:

– *The absorbing collector* (including the main framework, the absorbing plate and the pipes for the thermal fluid flow);

– *The water tank* (including the heat

exchanger, the coverage, the electrical resistance and the inner pipes for the sanitary water flow);

– *The external support* (employed to fasten the system on the houses roof).

The collector belongs to the category of passive solar device. The water tank and the absorbing surface are strictly connected, constituting a unique unit, and the thermal fluid circulation occurs with the natural convection. The internal fluid circuit does not need pumps and it does not cause power energy consumption. This typology of collector is particularly recommended for small domestic plants with a medium–low demand of sanitary warm water.

The water tank and the collector can be directly installed on sloping roofs. (see Figure 1)

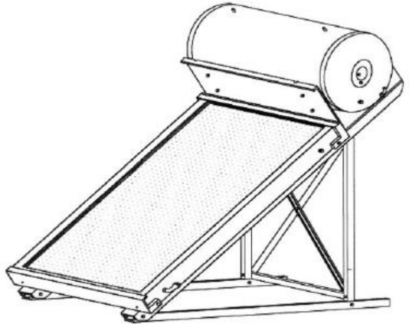

Figure 1. Solar thermal collector with water tank and support.

2.2. Technical peculiarities and mass detail

The collector framework is made of painted galvanised steel (0.003 m width). A blackpainted copper plate, welded with pipes for the thermal fluid flow, constitutes the absorbing surface. An aluminium frame with high-reflectance coefficient to increase the collector's efficiency protects the plate. The thermal insulation is granted by high-density polyurethane-PUR foam (0.03 m width).

The collector is covered by high-transparent tempered single glass with low iron-oxides percentage. The glass (0.004 m width) is shock-proof and it is hermetically fastened to the framework. To reduce heat losses, vacuum is created inside the collector. The water tank has 0.16 m3 of capacity and it mainly consists of a galvanised steel framework. It is protected by the stainless steel coverage, and it is placed on the top of the collector. The space within the water tank and the external coverage is filled with highdensity PUR foam. There are two circuits for the fluid flows: the heat carrier circuit and the sanitary water circuit. The thermal fluid is a mixture of water (50–80%) and propylene– glycol (20–50%) that avoids freezing problems during the cold season. It has been supposed to use a 50% mixture. The fluid mixture flows along a cylindrical interstice that works as heat exchanger. The water tank encloses a magnesium anode (to reduce the corrosion) and an electrical resistance. In the studied FU, this auxiliary resistance is not computed as a water tank's part but it is considered separately (in the section 'other components'). So, it is easier to state the incidence of this component on the global ecoprofile.

The section 'other components' also includes the materials for packaging (cardboardand the low density polyethylene, 'LDPE') and the external high-density polyethylene (HDPE) pipes used to connect the collector to the water tank [1,8].

3. ANALYSIS OF LIFE CYCLE PHASES

The following sections describe the study's assumptions and the related energy and environmental impacts occurring during the collector's life cycle. The following phases have been investigated: production and delivery f energy and raw materials, production process, installation, maintenance, disposal and transports occurring during each step.

3.1. Transports

As mentioned above, the FU is mainly composed of metallic and plastic components.

As it is not possible to determine the exact amount of travels for the production of the solar collector, the 'tkm' is assumed as functional unit for truck's transport. It represents 'the energy and environmental impacts referred to the transport of 1000 kg of products for 1 km route'. The impacts are then calculated by means of the masses and the distances.

Regarding all the input materials employed during the life cycle steps and considering the mean distance values, it has been estimated a global transport load of 154 tkm. Details of estimated air emissions.

3.2. The production process

Data regarding the collector's production process have been collected; thanks to a field analysis. The production process concerns mainly in metals transformation and in assembling them with other externally worked parts generally, little plastic or metal auxiliary parts). The three main components (absorbing collector, water tank and support) are produced in different periods, then packed and stored in warehouses. Successively, external companies sell the collectors, attending to transport and install them to final users.

3.2.1 Production of the absorbing collector

The absorbing collector consists mainly of three parts: the framework, the absorbing plate (including the pipes for the thermal fluid flow) and the glass. The framework is obtained using a zinc steel plate. After cutting and bending, it is glazed with epoxy powders. Both the absorber plate and pipes are copper made. The pipes are separately worked and then welded to the plate by acetylene welding. Having no available data about acetylene welding, air emissions have been not computed. However, little quantities of acetylene are used and consequently air emissions can be neglected. Absorber and pipes are then black painted to increase their absorbance. The absorbing plate, the framework and the glass are successively assembled together. Finally, PUR insulation is blown and the external framework is painted with epoxy powders. Each sub-process has been analysed to state the energy and mass flows.

3.2.2. Production of the water tank

The water tank mainly consists of three parts: the framework, the interstice and the external covering. The water tank is made using a galvanised steel sheet cylindrical shaped (diameter 0.444 m). The side parts are welded to this cylinder. A flange is annexed to one side: this flange works as support for the electrical resistance, the magnesium anode and the coil copper pipe. Successively, another cylindrical steel sheet is externally welded to the water tank. The thermal fluid flows inside this interstice and exchanges heat with water tank. The external covering is separately produced and painted. Finally, the water tank parts are assembled together and PUR is injected into empty spaces.

3.2.3 Production of the support

The support consists of various steel bars. These are cut, drilled and finally fastened together with bolts.

3.3 Air emissions in the factory

Power energy being the only energy source directly employed during the production process, there are not direct emissions from fossil fuels combustion. The production (mainly concerning with cutting and drilling processes) causes the production of scraps and metallic dusts. On the basis of data coming from the Environmental Management System, dusts have been indirectly estimated as percentage (about 1.5%) of the process scraps mass. Particular emissions are produced during the plasma cutting, the coating and the welding. No water emissions have been detected.

3.4. Installation

The installation consists of the following steps:
- Transport of the FU from the factory to storehouses for the sale by retail;
- Transport from storehouse to the user place;
- Installation of FU’s parts.

Transports from factory to storehouses employ various trucks. Also the destinations are variable (depending on the selling companies places). For these reasons, the following average conditions have been assumed:
- Functional unit: 1 tkm of 28,000 kg capacity truck;
- Covered distance (double way): 100 km.

The FU is transported from storehouse to the user place by van of 3500 kg capacity. Generally, the company makes one travel for each collector. The average covered distance (double way) is 30 km. The installation consists of:
- To fasten the support on the roof;
- To fasten the water tank and the collector to the support.

3.5. Maintenance

As suggested by the selling company we have supposed that the FU would have an average useful life of 15 years. In absence of rare external damages (as the glass break), the FU does not necessitate frequent aintenance. The ordinary cycles consist of one operation every 4–5 years (in all 2–3 operations during the FU’s useful life). Regarding the maintenance phase, main assumptions are:
- Two maintenance operations (after 5 and 10 years from the purchasing);
- Travels of maintenance technicians (overall distance 80 km by diesel car);
- Each operation includes the substitution of the following components:
- PVC gaskets;
- Sealing;
- Magnesium anode;
- Electrical resistance;
- Thermal fluid (50% water; 50% propylene–glycol)

3.6. Disposal

The FU’s manufacture causes the production of scraps and wastes (the amount is 4.4 kg, excluding the packagings that wrap raw materials). The company periodically deliver the wastes to a company that takes care about disposal.

The recycling of materials has been neglected. It is only supposed that solar collectors would be collected and disposed to the nearest landfill by truck. Suppose the transports occur by 28,000 kg truck, the release of 1.4 kg CO_2 and few quantities of other pollutants has been estimated [8, 9].

4. ENERGY ANALYSIS

The energy analysis concerns with the energy flows occurring during the life cycle of the product. The energy consumption could be split into ‘direct energy’ and ‘embodied energy’. ‘Direct’ is the energy directly used during a life cycle step. ‘Embodied’ is the energy consumed by all the processes associated with the production of the materials employed as FU’s inputs.

Besides, it is necessary to state how much of the energy consumption is related to the ‘feedstock’ rate. This is defined as ‘heat of combustion of raw material inputs, which are not used as an energy source, to a product system'. The feedstock quantifies the potential of materials (as wood or plastics) to deliver energy when they are burned with heat recovery after their useful life.

4.1. Direct energy consumption

The FU's LCA has involved two direct energy consumptions: the electricity used for the production (medium voltage) and installation (low voltage) and the diesel oil used for transports (during every life cycle phase).

Table 1. Direct energy consumption

	Direct energy consumption	
	End-energy	Primary energy
Electricity MV		
Absorbing collector	66.6 MJ	191.0 MJPrim
Water tank	113 MJ	324.0 MJPrim
Support	9.6 MJ	27.6 MJPrim
Total		542.6 MJPrim
Electricity LV		
Installation	0.56 MJ	1.8 MJPrim
Total		1.8 MJPrim
Diesel (for transports)		
Materials (process input)	6.62 kg	346.5 MJPrim
Installation	3.30 kg	172.7 MJPrim
Maintenance	2.96 kg	155.1 MJPrim
Disposal	0.45 kg	23.6 MJPrim
Total		697.9 MJPrim

However, the energy quantities described in the previous paragraphs are end-energy quantities, meaning the energy quantities consumed by final users. All these quantities have to be valued as primary, defined as the energy embodied in natural resources (e.g.coal, crude oil, sunlight, uranium) that has not undergone any anthropogenic conversion or transformation. The secondary sources can be transformed into primary quantities by means of specific conversion factors. They represent the effective MJs of energy that are necessary to deliver one MJ of energy to users, including all the energy losses occurring during the energy source life cycle. *Table 1* summarises direct energy consumption in terms of end-energy and primary-energy.

4.2. Embodied energy consumption

Analogous to the direct energy consumptions, also the embodied energy consumptions have to be computed as primary. *Table 2* summarises the primary energy demand for all the employed raw materials.

Table 2. Embodied energy consumption

	Embodied energy of materials		
	Fuel (MJprim)	Feedstok (MJprim)	Total (MJprim)
Collector	3297.1	215.3	3512.5
Water tank	3641.0	485.9	4126.9
Support	1066.4	–	1066.4
Other (HDPE pipes-resistance)	64.9	41.7	106.7
Other (packaging)	147.0	141.9	289.0
Maintenance	544.1	627.2	1171.3
Total (MJprim)	8760.6	1512.1	10272.7

4.3. Global energy consumption

The global energy consumption is obtained by adding embodied and direct contributions (*table 3*). It is possible to point out that:

– The global energy consumption is 11.5 GJPrim. The direct energy consumption is only 11%, while the indirect is 89%.

– The energy consumption for the production (542.6 MJPrim of electricity) is less than 5% of the global consumption. This value shows the low incidence of the factory process on the global energy balance. The energy consumption (direct and indirect) related to the water tank manufacture is about 4.4 GJPrim (38.6% of the global). The production of the collector has a similar energy demand (3.7 GJPrim and 32% of the global) while the support involves a lower consumption (about 1.1 GJprim).

– Installation and disposal have a low incidence. The computed impacts are mainly related to transports. About the installation, it is possible to observe that the support is used for flat-roof installation. If the support is considered as belonging to the installation, its contribution will be about 11.5% of the global consumption. The inclusion of other parts (copper resistance and HDPE-pipes) needs of a further 0.2 GJPrim (0.9% of the global). The packaging has, instead, a greater influence (0.6 GJPrim and 2.5% of global).

– Maintenance involves a significant energy consumption (about 11.5%of the global). This is caused by the use of spare parts (and, in particular, by the substitution of thermal fluid).

– The propylene–glycol is an oil-derived fluid and it involves a primary consumption of 77.4 MJprim/kg. Furthermore, this fluid is largely employed in the collector (about 19 kg all over the life cycle). Consequently, the global use of this fluid has a great incidence on the results (about 13% of the global consumption).

– Transports cause the consumption of about 700 MJprim (6.1% of the global).

– Feedstock consumption is about 13% of the global (and about 15% of the indirect contribution). This energy could be theoretically recovered when materials are burnt (with heat recovery) after their end-life. Actually, about 60% of feedstock is related to the use of propylene–glycol; this fluid is mixed to water in the thermal fluid and, generally, it is wasted without any treatment [1].

Table 3. Global energy consumption (direct and embodied contributions).

	Global energy consumption	
	Direct (GJPrim)	Embodied (GJPrim)
Transport of row mat.	0.35	
Collector	0.19	3.51
Water tank	0.32	4.13
Support	0.03	1.07
Other parts		0.11
Packaging		0.29
Installation	0.17	
Maintenance	0.16	1.17
Disposal	0.02	

5. ENVIRONMENTAL IMPACTS

The main environmental impacts can be included in the following classes:

– Resources consumption;
– Air emissions;
– Water emissions;
– Wastes and solid pollutants.

Environmental impacts have been divided into direct and indirect. Direct impacts are those directly related to the production process and to transports. Indirect are the impacts related to the production of process inputs (as raw materials and energy sources).

6. ENERGY AND CO$_2$ PAYBACK TIMES

The energy payback-time (E_{PT}) can be defined as the time necessary for a solar equipment to collect the energy valued as primary) equivalent to that used to produce it [2]

$$E_{PT} = \frac{LCA_{energy}}{E_{useful} - E_{Use}} \qquad (1)$$

where

LCA_{energy} primary energy consumed during all the life cycle phases (GJ);

E_{useful} yearly useful saved energy (GJ per year);

E_{use} energy employed during the use of the renewable system (GJ per year).

In passive collector systems the water circulation occurs naturally and, consequently, the ‘E_{use}’ is null.

The useful primary energy saving ‘E_{useful}’ is estimated 6.6 GJ per year [3]. The payback-time related to the studied equipment results lower than 2 years. This value shows the great energy convenience of such technology.

Knowing the yearly ‘E_{useful}’, we have also calculated the yearly emission saving (*EMS–i*). It represents the emissions that the auxiliary system would produce to deliver as much energy as that saved by means of the solar collector. The EMS depends on the typology of the employed auxiliary heater. The global impacts during the life cycle and the emission saving are summarised by the emission payback-time (EM_{PT}). It is defined as the time during which the avoided emissions due to the employment of the solar plant are equal to those released during the production and use of the renewable plant itself. It is possible to calculate the EM_{PT} relatively to the pollutant 'i' as [3].

$$EM_{PT-i} = \frac{EM_i}{EM_{S-i} - EM_{USE-i}} \qquad (2)$$

EM_i global emissions of generic pollutant i related to the production, assembly, transport, maintenance and disposal of the solar plant (kg$_i$);
$EMS\text{–}i$ yearly emission saving of generic pollutant 'i' (kg$_i$/year);
$EMUSE\text{–}i$ yearly emission of pollutant 'i' related to the use of the renewable plant (kg$_i$/year).

The EM_{use} could be caused by the use of the conventional energy that the plant needs to work (mainly the electricity used by pumps). In passive collectors the *EMuse* term is null. The global warming potential related to the collector life cycle is 721 kgeq.CO_2. Similarly to the energy payback-time, even the CO_2 payback-time resulted lower than 2 years [10,4].

7. CONCLUSION

The present paper shows the results of an LCA performed upon a solar thermal collector. The collected information could become an important starting point to improve the ecological performances of the product. It is important to carry out a database of FU's environmental performances as a powerful tool for the eco-oriented design. On the other hand, we would like to point out that the life cycle thinking is basic in the design for environment but the final decision regarding the product cannot be just 'environmental oriented'. Other aspects like cost, physical lifetime, and energy performances are important factors underpinning customer's preferences. To achieve a more realistic evaluation, it is important to consider a set of core criteria in addition to the main function, keeping in mind that designers generally do not give top priority to the environmental matters. In this respect, design for environment means to take environmental issues into account without compromising the other features of the product and to seek a balance among all the competing requirements.

Regarding the studied FU, it has been estimated an overall primary energy consumption of 11.5 GJ. However, the energy directly used during the production process and installation is only the 5% of the overall consumption; another 6% is consumed for transports during the various life cycle phases. The remaining percentage is employed for the production of raw materials, used as process inputs. These results show that the direct energy requirement is less important than the indirect one (in fact, the production processes consist mainly in cutting, welding, bending and assembling steps with a low energy demand). Consequently, including or neglecting some materials, the results will be sensibly modified. For example excluding the collector's support, the primary demand decreases of 1 GJ (10%of the overall consumption). Furthermore, maintenance can involve a large primary energy consumption related to the substitution of spare parts. Two maintenance cycles has been supposed with an overall primary energy demand of 1.1 GJ.

The production of the solar collector causes mainly direct emissions of metals (Fe, Mn, Mo, Cr, etc.) related to cutting and welding phases. In fact, the indirect emissions (related to production of raw materials) are about the 80–90% of the overall releases, and the results sensibly depend on the materials included in the calculations. Direct emissions related to transports have an incidence of 10–15%. Water soil releases and wastes are very low.

The last part focused on the calculation of energy and CO2 payback times. These indicators resulted very low (less than 2 years) showing the great environmental convenience of this technology.

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Acknowledgment: This investigation is a part of the project TR 33015 of Technological Development of the Republic of Serbia and the project III 42006 of Integral and Interdisciplinary investigations of the Republic of Serbia. We would like to thank to the Ministry of Education and Science of Republic of Serbia for the financial support during this investigation.