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LIFE CYCLE ANALYSES FOR SOLAR THERMAL COLLECTORS

BY

ANA-GEORGIANA LUPU[1,*], MOHAMMED SALLAH[2], CRISTINA BELECCIU[1] and ARISTOTEL POPESCU[1]

[1]“Gheorghe Asachi” Technical University of Iaşi,
Faculty of Mechanical Engineering, Iaşi, Romania
[2]Faculty of Science, Mansoura University, Mansoura, Egypt

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Abstract. The current drive towards including renewable and sustainable energy sources into energy consumption mix implies thorough studies on savings in materials, energy and waste management. Life cycle analyses are concerned with identification and quantification of each inputs and outputs of a product manufacturing process. This paper proposes complex life cycle analyses, that include assessment on inventory, analyses of energy payback time, life cycle cost and end of life applied to solar thermal collectors, as part of a solar conversion system. Results show that the categories with most impact, besides terrestrial toxicity, are human health, global warming and depletion of fossil fuels, that is, the main reasons to implement renewable energy sources.

Keywords: Life cycle analysis; thermal collectors; environmental impact; energy payback time.

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[*] Corresponding author; *e-mail*: ana-georgiana.lupu@academic.tuiasi.ro

1. Introduction

Energy is one of the fundamental concepts used in technology, and an important element in developing societies. Energy affects every aspect of everyday life as it is essential for manufacturing, providing services, developing technologies, etc.

The environmental impact of consumer products has been studied since the 1960s. These studies are the subject of long and intense debate, especially after comparative analyses ranging from original sources, manufacturing steps, properties used and recycling options to end use or disposal, (IEA, 2019).

Renewable energy is an important topic worldwide, as it relates to science and business, as well as energy policy. In this context, solar thermal technology has made a significant contribution to water heating in several countries with different solar energy resources and has the potential to be part of different scale solar thermal power generation systems, including small and distributed applications.

Solar energy is generally defined as a clean energy source and cannot ignore the environmental impacts associated with the manufacture, use and disposal of solar system components.

Solar energy is converted directly into thermal energy occurs by producing water or heating agent at high temperatures for industrial processes or solar power plants. The total operating performance of glazed (plate and evacuated tubes) and unglazed collectors (mainly used for swimming pool heating) reached. Solar thermal collectors are widely used around the world to provide low temperature for hot water, heating, and cooling. Solar thermal collector capacity has been steadily increasing, estimated to be 501 GWth by the end of the year, up 5% from 478 GWth in 2019, (REN21, 2020).

Life Cycle Analysis (LCA) is suitable for estimating energy efficiency and environmental impact of a product or service. LCA results are not accurate and precise data. The reliability of LCA relies strictly on complete and unambiguous data, but its results are influenced by subject matter, assumptions, data availability and accuracy. Thus, the method cannot be easily generalized, as LCA operators and users need to properly understand its limitations and the reliability of its conclusions.

The basic elements of LCA are standardized in ISO 14040 and ISO 14044, which define the details and principles of the procedure, (IOS, 1997).

2. LCA for Solar Thermal Collectors

The LCA analysis details the inventory of production phases for solar panel. Data extracted from literature research includes materials, energy, and processes involved in solar collector manufacture.

The solar collector has fixed components in a simple structure, with low maintenance, high reliability and good environmental protection. The system is designed to be used in isolated individual dwellings or micro-communities to provide low temperature energy for domestic hot water (DHW), heating and/or cooling applications.

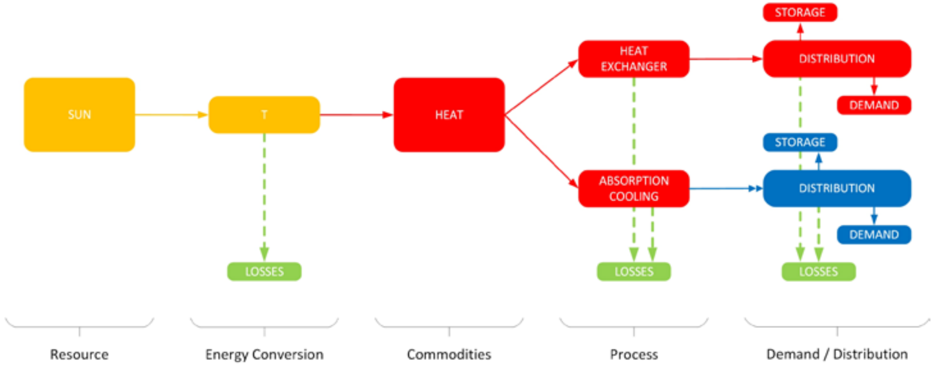

Fig. 1 – Input and outputs of the solar thermal collector, from resources to distribution.

The basic processes and main life cycle stages for the thermal system manufacturing consist in absorbing plate forming, brass connectors, welding, coating, insulation, internal framework, module assembly all processes followed by installation and manufacture of other system components and the analysis of outputs (atmospheric/waterborne/solid wastes, coproducts and other issues), (Lupu *et al.*, 2020).

An LCA study's cradle-to-grave methodology includes evaluating the environmental impact of each phase of production (from material extraction through product assembly), distribution (from production site to end user), usage, and end-of-life treatment (including recycling and disposal). The life cycle of the machinery involved in manufacturing and distribution was not considered in the study. Also, the materials used in product assembly, which accounted for less than 1% of the weight of solar panels, were left out of this analysis. The DHWSs were estimated to have a 10-year life cycle even if there are working systems that are 20 years old, (Albertí *et al.*, 2019).

System boundaries

The LCA system boundaries include extraction of raw materials, production of the collector components, collector assembling, use and disposal and all transportations, figure 2 and 3, (Battisti *et al.*, 2005).

Life cycle inventory (LCI)

This phase of the LCA includes the compilation and quantification of the relevant input and output flows for the whole life cycle of the product is called life cycle inventory (LCI).

Environmental data was collected for each process included within the system boundaries as part of the LCI analysis. Data quality may be determined by the production technique, direct measurements, estimates, allocation, or computation.

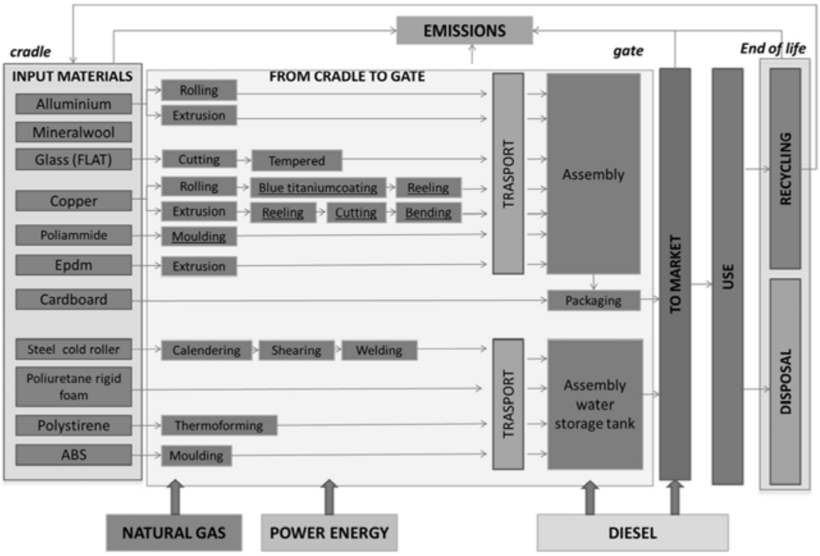

Fig. 2 − System boundaries of domestic hot water systems with glazed panel, (Comodi *et al.*, 2016).

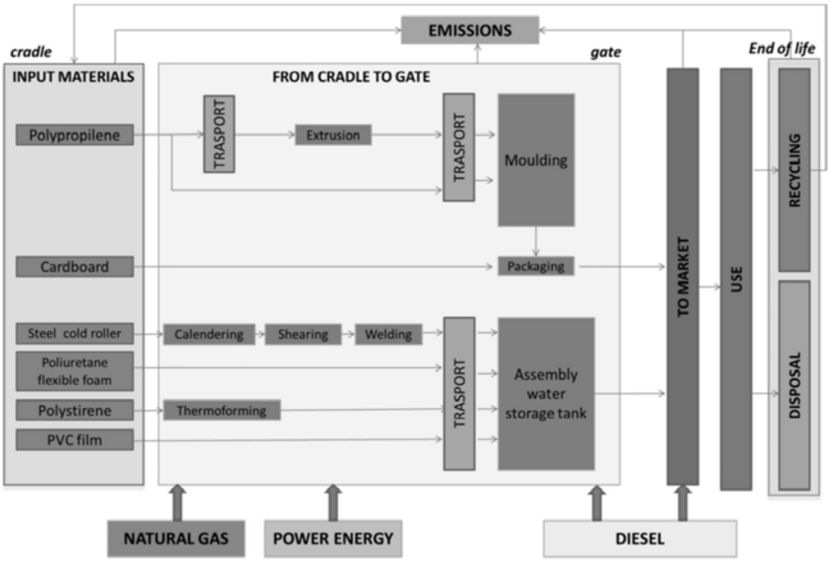

Fig. 3 − System boundaries of domestic hot water systems with unglazed panel, (Comodi *et al.*, 2016).

Table 1
Inventory of solar thermal collector, (Lupu *et al*., 2020)

Element	Material	Amount (unit)	Process
Collector	*Copper*	*8.66 kg*	*Copper, from supplier*
	Working fluid	*0.90 kg*	*Propylene glycol, liquid*
	Epoxy	*0.30 kg*	*Resin, liquid*
	HDPE	*0.87 kg*	*High density polyethylene*
	Brass connectors	*0.04 kg*	*Brass, from supplier*
	PVC	*0.01 kg*	*Polyvinylchloride, from supplier*
	Welding rod	*0.10 kg*	*Lead-free solder Sn97Cu3*
Glazing	*Glass*	*10.5 kg*	*Low-iron solar glass, from supplier*
Insulation	*Rigid*	*4.20 kg*	*Rigid foam, polyurethane*
	Flexible	*0.01 kg*	*Flexible foam, polyurethane*
Casing	*Aluminium*	*4.00 kg*	*Aluminium, formed alloy*
	Stainless steel	*6.10 kg*	*Chromium steel 18/8*
	Galvanized steel	*33.9 kg*	*Low-alloyed steel*
Support	*Stainless steel*	*27.0 kg*	*Chromium steel 18/8*
	Galvanized steel	*0.50 kg*	*Low-alloyed steel*
Energy	*Collector*	*18.5 kWh*	*Medium voltage electricity, from grid*
	Support	*2.67 kWh*	*Medium voltage electricity, from grid*

This phase is critical for determining consumption of all resources and energy, as well as the formation of waste related to the product, such as air emissions, wastewater discharges, solid waste disposal, and missing flows. The inventory (used materials, masses, and life cycle production phases) of the solar thermal collector is presented in detail in Table 1, (Lupu *et al*., 2020).

The solar panel production schedules, bills of materials, and manufacturing processes of each component were used to create the LCI. Data on production processes and assembly were acquired in the field, and data on semi-processed products was collected across the whole supply chain.

Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA) goal is to compile the data gathered throughout the inventory analysis.

The Eco-Indicator 99 technique, which is a damage-oriented approach, was used to perform the LCIA. Human health, ecological quality, and resource consumption are the three harmful categories used by the Eco-Indicator 99 approach, Table 2.

For the solar thermal system, the phases of raw material extraction, system manufacturing and usage are the life cycle stages that are the most environmentally damaging in ascending order.

In the areas of ozone depletion, element depletion, human health eco-toxicity, and marine and terrestrial ecosystems, the impact of raw material extraction and system production accounts for more than 84% of the total. (Kylili *et al.*, 2018).

The environmental indicators from the Eco-Indicator 95 technique were utilized to define the solar collector's environmental profile during its entire life cycle, (Battisti *et al.*, 2005).

Table 2

Life Cycle Impact categories for thermal module, (Lupu *et al.*, 2020)

Impact category	Unit (per m^2)	Thermal collector
Global warming	*kg CO_2-eq/kWh*	*2.38e-2*
Stratospheric ozone depletion	*kg CFC11-eq/kWh*	*1.29e-8*
Acidification	*kg SO_2-eq/kWh*	*2.07e-4*
Eutrophication	*kg P-eq/kWh*	*3.89e-5*
Photochemical Smog	*kg $PM_{2.5}$-eq/kWh*	*8.78e-5*
Terrestrial Toxicity	*kg 1.4-DCB-eq/kWh*	*8.55e-1*
Aquatic Toxicity	*kg 1.4-DCB-eq/kWh*	*6.42e-3*
Human Health	*kg 1.4-DCB-eq/kWh*	*2.24e-1*
Resource Depletion – mineral	*kg Cu-eq/kWh*	*1.02e-3*
Resource Depletion – fossil	*kg oil-eq/kWh*	*5.45e-3*
Land Use	*m^2a crop-eq/kWh*	*1.25e-3*
Water Use	*m^3/kWh*	*2.39e-4*

Table 3

Indicator values for the macro-phases in the collector life cycle, (Battisti *et al.*, 2005)

Indicator	Unit	Collector production	Distribution	Uncontrolled disposal	Total
Greenhouse effect	*kg CO_2-eq*	*215*	*4*	*0.4*	*219.4*
Ozone layer depletion	*kg CFC11*	*5.2×10^{-5}*	*4.2×10^{-6}*	*3.4×10^{-7}*	*5.65×10^{-5}*
Acidification	*kg SO_2*	*4.2*	*0.02*	*0.005*	*4.045*
Eutrophication	*kg PO_4*	*0.06*	*0.002*	*0.0007*	*0.0627*
Heavy metals	*kg Pb*	*0.01*	*4.4×10^{-6}*	*2.6×10^{-7}*	*0.01003*
Winter smog	*kg SPM*	*4*	*0.006*	*0.005*	*4.011*
Summer smog	*kg C_2H_4*	*0.4*	*0.005*	*0.001*	*0.046*
Primary energy consumption	*MJ*	*3.040*	*57*	*6*	*3103*
Solid waste production	*kg*	*67*	*0.00004*	*45*	*112*

Energy payback times (EPBT)

The idea of “energy payback time” is a significant element in the examination of renewables across their whole life cycle, allowing comparison with fossil-fuel and other renewable technologies.

The EPBT (energy payback time) is defined as the time necessary for an energy system to generate the same amount of energy that was spent to create the system itself, expressed in years; the most thorough formula is, (Carnevale *et al.*, 2014):

$$EPBT = \frac{E_{production} + E_{transports} + E_{I} + E_{EOL}}{\left(E_{produced} - E_{Q\&M}\right)_{annual}} \tag{1}$$

where, *EPBT* – energy payback time; $E_{production}$ – energy demanded for material production and processing; $E_{transports}$ – for transportations, E_I – for installing the energy system; E_{EOL} for end-of-life management; $E_{produced}$ – annual energy produced; $E_{Q\&M}$ – annual primary energy required for operating and maintenance. According to the local grid mix and efficiency, the system’s entering and exiting energy values (heat) must be converted into primary energy, (Carnevale *et al.*, 2014).

In EPBT, values calculated for end-of-life scenarios show significant energy consumption involved in the construction of solar thermal collectors, mostly due to the considerable amount of metals used. But this consumption appears to be effectively balanced by the energy output during the life period, resulting in EPBT competitive with thin film modules, (Carnevale *et al.*, 2014).

Lamnatou *et al.* (2014) demonstrate that solar water heating systems have a payback period of less than half a year in terms of both environment and energy.

Energy payback time is a critical measure to evaluate eco-performances of a renewable energy source. It is a term used in economic research to describe the amount of time it takes to recoup an initial investment (Ardente *et al.*, 2003). The EPBT is also described as the time it takes a solar equipment to gather the energy (valued as primary) that was utilized to create it.

$$EPBT = \frac{LCA_{energy}}{E_{useful} - E_{use}} \tag{2}$$

where: LCA_{energy} – primary energy consumed during all the LCA phases, [GJ]; E_{useful} – yearly useful saved energy, [GJ/year]; E_{use} – energy necessary for the use of the renewable system [GJ/year], (Ardente *et al.*, 2003).

As a result, the term E_{use} is null in passive collector systems since water circulation occurs spontaneously without the need of energy. The equipment under consideration has a payback period of 1.6 years. This number demonstrates the significant energy and environmentally benefits of using such technology, (Ardente *et al.*, 2003).

End-of-life

The end-of-life phase includes both environmental consequences from material disposal and advantages from ultimate material recycling and energy recovery. When solar thermal collectors are no longer functional, they must be removed and transferred to designated facilities for final disposal or recycling. This results in increased energy use and emissions, which must be addressed. At the same time, recycling techniques may generate benefits that outweigh the negative effects. Recycling materials as credits, which implies substituting the production of related raw materials, is a typical technique used to analyse such advantages in the context of LCA evaluation, (Carnevale *et al.*, 2014).

Recycling and waste management are critical components of a long-term economic strategy (Tomić *et al.*, 2018). Given the widespread use of steel, cooper and PUR in solar thermal applications, this analysis focuses on their recycling. There are several factors that influence the efficiency of recycling processes: primary energy demand; recycling rate; scrap and ferrochromium production; physical vs. chemical recycling (Lamnatou *et al.*, 2022).

According to waste management literature analysis, implementing steel, copper, and PUR recycling can result in significant reductions in environmental consequences. By including recycling, for example, the environmental profile of the components explored in the current work can be significantly improved. (Yang *et al.*, 2012; Lamnatou *et al.*, 2022).

Life cycle cost (LCC)

Solar water heating systems have a life cycle cost payback of 4 to 13 years (for various cities/configurations when using a typical electrical water heating system as a baseline), (Lamnatou *et al.*, 2014).

Solar thermal systems may have a longer lifespan if they are properly maintained (30 years). The solar thermal modules must be cleaned on a regular basis. Maintenance, on the other hand, analyses components such thermostatic valves, pumps, solar circuit pumps, and solar storage tanks.

This approach aims to provide professionals with knowledge when determining whether alternative strategy is superior. Here, future earnings and savings relative to current value of money are taken into account. Because capital expenses vary over time, future expenditures and earnings must be adjusted for inflation when compared to today's money. The Net Present Value (NPV) depict current investments and future profits at the comparable discount rate. From present till the end of life, this indication must be maximized. (Košičan *et al.*, 2021) express the NPV as:

$$NPV = -\sum I_i e^{-rt} + \int_0^{T^*} S_i e^{-rt} dt \tag{3}$$

where: I_i – the investment performed, and S_i – the monetary savings for the *i*-th year. The annual maintenance expenditures should be included in this analysis as a total investment, (Košičan *et al.*, 2021).

3. Conclusions

Introducing renewable and sustainable energy sources as main energy supply may involve some elements that are overlooked in estimation of overall environmental impact.

Life cycle analyses identify and quantify inputs of energy and resources and outputs of energy, pollutants and losses of a product manufacturing process. A complex life cycle analyses includes assessment on inventory, analyses of energy payback time, life cycle cost and end of life assessment. These analyses were applied to solar thermal collectors, as part of a solar conversion system.

Results show that terrestrial toxicity and human health are the highest impact categories, with values of at least one order of magnitude larger than the rest. Measured values indicate that the next group of impact categories consists of global warming, depletion of fossil fuels and depletion of mineral resources, that emphasize the main reasons of renewable energy sources implementation. These results are in very good agreement with data published in literature.

The end of life assessment of recycled parts and recovered materials influenced the overall result for greenhouse effect, carcinogens, heavy metals and solid waste categories.

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ANALIZELE CICLULUI DE VIAȚĂ PENTRU COLECTORI SOLARI TERMICI

(Rezumat)

Actualul impuls pentru includerea surselor regenerabile și durabile de energie în coşul consumului energetic implică nevoia de studii aprofundate privind economiile de materiale, energie și managementul deşeurilor. Analizele ciclului de viață se referă la identificarea și cuantificarea fiecărei intrări și ieșiri ale unui proces de fabricație a unui produs. Această lucrare propune analize complexe ale ciclului de viață, care includ evaluarea stocurilor, analize ale timpului de recuperare a energiei, costul ciclului de viață și sfârșitul duratei de viață, aplicate colectoarelor solare termice, ca parte a unui sistem de conversie solară. Rezultatele arată că, dacă se exclude toxicitatea terestră, categoriile cu cel mai mare impact sunt sănătatea umană, încălzirea globală și epuizarea combustibililor fosili, adică tocmai principalele motive pentru implementarea surselor regenerabile de energie.