Solar Energy 135 (2016) 284–290

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

# Life cycle assessment (LCA) of a solar selective surface produced by continuous process and solar flat collectors

G.A. Altun-Çiftçioğlu [a,*], O. Gökulu [a], F. Kadırgan [b,c], M.A.N. Kadırgan [a]

[a] Chemical Eng Dept, Marmara University, Istanbul 34722, Turkey
[b] Chemistry Department, Istanbul Technical University, Istanbul 34469, Turkey
[c] Selektif Teknoloji Co. Inc. Ltd., Ari Teknokent, Istanbul Technical University, Maslak, Istanbul 34469, Turkey

ARTICLE INFO

*Article history:*
Received 8 March 2016
Received in revised form 25 May 2016
Accepted 27 May 2016
Available online 13 June 2016

*Keywords:*
LCA
Solar collectors
Selective surface
Roll to roll

ABSTRACT

Roll to roll (R2R) continuous production of solar selective surface, is a cost benefit method from the energy dispenses and investment point of view, therefore it is an innovative production way. Before innovative energy systems are introduced into the market, a thorough investigation of ecological aspect is necessary. Therefore, the purpose of this study is not only to perform a life cycle assessment (LCA) and demonstrate the advantage of the life cycle thinking selective surface production process, but also as to show the effect of this production method on the manufacturing process of solar flat collectors. LCA calculations for the continuous selective surface production process and a complete solar collector were performed with using the Ecoinvent database and the build in methods in SimaPro7.3: (1) Cumulative Energy Demand (CED); (2) Greenhouse Gas Protocol (GHG); (3) the Eco-indicator 99. To reflect the total quantity of primary energy needed to produce, use, and recycle/dispose of the produced selective surface—including transportation, CED was used. CED reflects the energy demand over its entire lifecycle, and makes it possible to determine which phase consumes the most energy. In order to quantify the greenhouse gas amount, the GHG was chosen since it is the most widely used and trusted international accounting tool. At last, the environmental impact of the system in study was calculated using Eco-indicator 99 method. The CED analysis estimated a yearly demand of 7.91 TJ for 200,000 square meter net selective surface production. Further calculations also showed that the energy payback time for the innovative production is as short as 3–4 days. Cu sheet production showed the highest impact and resulted in having the highest energy demand. The coating process only requires 32% of the primary energy demand. It was found that the energy demand of the plant and the building were as low as 2%, whereas it had 20% of GHG emissions. Further the total $CO_2$ equivalent was shown to be 0.3245 kg/m$^2$. At last, the LCA for a complete solar collector having 4 m$^2$ of solar surface produced by conventional batch system and continuous roll to roll selective surface system was compared. The results also showed that using the roll to roll production technology caused reductions on the environmental burden. The results of LCA for the production of a continuous selective surface and comparison of solar flat collectors using two different selective surface production technology were presented. The energy payback time for the roll to roll selective surface production was found to be 3–4 days. The continuous process technology was shown to have a lower impact than the conventional batch selective surface production.



## 1. Introduction

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. Before innovative energy systems are introduced into the market, improvement of eco-performances of products is focused as a key point of the European environmental programme (COM, 2001a). In other words, global environmental problems can be met only if the use of the energy and the raw materials per product unit will 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

* Corresponding author at: Marmara University, Goztepe Campus, Engineering Faculty, Chemical Engineering Department, Building C, 34722, Goztepe, Istanbul, Turkey.
*E-mail address:* gciftcioglu@marmara.edu.tr (G.A. Altun-Çiftçioğlu).

http://dx.doi.org/10.1016/j.solener.2016.05.049
0038-092X/

paper on Integrated Product Policy (IPP) (COM, 2001a) So, an investigation of technical, ecological and economic aspects is necessary (COM, 2001b). It is well known that once the 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.

For IPP to be effective, life cycle assessment represents an important support tool and the best framework for assessing the potential environmental impacts of products currently available (COM, 2003). To obtain reliable results, data should be collected and managed following standardised procedures. The international standards of series ISO 14040 represent a wide spread accepted methodology (ISO 14040, 14041, 14042). Many authors have investigated the benefits related to use of solar systems (Ardente et al., 2005; Diakoulaki et al., 2001; Tsilingridis et al., 2004; Crawford and Treloar, 2004). Including studies regarding LCA of solar collectors and comparative analysis of different heating systems.

The present paper focuses on the life cycle assessment of roll to roll (R2R) continuous solar selective surface production for high efficiency solar thermal collectors. However, it should be worthy to point out the advantages of this novel method. Roll to roll continuous production of solar selective surface, is a cost benefit method from the energy dispenses and investment point of view, therefore it is an innovative production way. In this new production method, selective coating obtained via continuous chemical, electrochemical and sol–gel processes. In contrast, in a discrete R2R processing workflow each functional layer is printed or coated in a separate run; where all the design parameters fabrication method, ink, speed, drying, and etc., are needed to be optimized to speed up the production as well as decrease energy consumption (Hösel et al., 2013). If in any layers of production stage had any failure in the conventional batch system then this would result in malfunction of the end product. Thus, this disadvantage of the conventional system is taken over by the innovative R2R continuous system because full in line processing is realized in the production where it minimizes failures and reduces handling, which can lead to human errors. When considering production time of the two methods, the new method is much faster. As opposed to discrete surface production, which are bulky and rigid, the continuous system produces lightweight, flexible sheets that can be easily used on any surface (Gökulu et al., 2011). Thus such new systems will be more attractive than conventional process end products and before innovative process systems are introduced into the market, a thorough investigation of ecological aspect is necessary.

The aim was to demonstrate the advantage of the life cycle thinking selective surface production process concept is by demonstrating its practical application. Data regarding the production, the installation and maintenance phases have been directly collected with collaboration of Selektif Tecnoloji Co. Inc. Ltd. Data regarding raw materials and energy sources have been referred, when possible to Turkish mean values (Roll to roll manufacturing of solar selective sheets, 2012). When not available, data from the European Life Cycle Database (ELCD) v2.2., which is created by PE International and LBP-GaBi, University of Stuttgart, Germany as a courtesy for LCA practitioners (Ecoinvent, 2010), had been employed. At last, the net environmental effect of this innovative way of producing solar surfaces was investigated by carrying out LCA for flat solar collectors produced using solar surfaces by batch system and continuous system.

## 2. LCA methodology

The life cycle approach is a perspective which analysis a process/service/organizations starting from the used raw materials in the corresponding life stages to final disposal and reuse. It is an integrated concept addressing the environmental, economic, technological, and social aspects of products, services, and organizations (Yildiz-Geyhan et al., 2016). These integration parameters are also pillars of life cycle sustainability methodology which mainly refers to the evaluation of all negative impacts and benefits in decision-making processes towards more sustainable product and/or services throughout their life cycle (ISO, 2006a, 2006b). LCA research the essentially industrial systems from "cradle-to-grave". For a production system "Cradle-to-grave" begins with the extraction of raw materials from the earth and ends with disposal as returning back to the earth (EPA, 2006). Fig. 1 illustrates of a product's life cycle diagram.

The staged of LCA can be summarized under four main stages—goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretations. The first phase of the LCA is the goal, objective and investigation boundaries of the frame work. The inventory analysis highly affects the results of the assessment. 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 (ISO 14040)". The FU is important as basis for data collection and for the comparability of different studies referred to the same product category.

LCI stage is the most exhausting one since the key factors are developing a flow diagram of the processes, planning data collection and collecting data, and calculating LCI results. Once this stage is completed then LCIA will only depend on the selection and definition of impact categories. Last stage is the result interpretations, where identification of significant issues, evaluations, and conclusions, limitations and recommendations are presented in detail.

Different alternatives were checked in our case study:

*FU equal the entire equipment:* In our study the results are not presented as global quantities concerning the whole solar thermal collector but only selective absorber surface production was taken consideration.

*Impacts per unit of absorber area:* It is focused on how the product affects the environment using both qualitative and quantitative approach to analyse the material use, energy demand, air pollution, waste and effluent output streams.

*Impact per unit of energy output:* Although this alternative is generally chosen for energy systems, because it refers to the environmental impacts of the energy performances of the plant, this FU is applied to the LCA of the selective surface production and the calculation is made depending on the Turkish solar energy input.

## 3. LCA of the R2R selective surface

A general schematic representation for the material inputs is shown in Fig. 2 (Gökulu et al., 2011). In this study, a cradle to grave LCA was carried out on the selective surface. An area of 250,000 $m^2$ was chosen as the functional unit, which refers to a one year production. Further, assumption is made on the quality of the surface produced where the details are given below.

In the plant, selective surface with dimensions 1 m $\times$ 1 m can be produced per minute and the material and electricity consumption for 1 $m^2$ is given in Table 1 and 2, respectively. With the assumption of 4400 h of active production time 250,000 $m^2$ surface can be produced per year containing 224,000 kg Cu and 2225 kg Ni coatings. On the other hand, 80% of the produced surface is assumed to have emission and absorption specifications defined in related standards. The defective product containing 45,245 kg Cu and Ni is assumed to be recycled. The recycling process of Cu uses electro-refining method that also produces Ni