TOWARDS PROCEDURES FOR ENVIRONMENTAL PERFORMANCE ASSESSMENT OF SOLAR THERMAL PRODUCTS

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ABSTRACT

Solar energy is a "clean" energy form and it is clear that solar thermal systems will contribute to the change of the energy system towards sustainability. A change of fossil fuels with solar thermal energy will avoid considerable emissions to our environment during operation but operation energy is not the only contribution source for environmental impacts. Also contributions related to manufacturing of the system unit and its disposal must be considered. During the last years it has become important to declare the environmental impact from a product during its complete life cycle. To get credibility, relevance and comparability of the declaration it is a need for a common, independent and uniform procedure. This paper presents a literature survey of environmental impact descriptions of solar thermal systems and aims to be a base for further development of a common European procedure for environmental life cycle assessment of solar thermal systems.

1. INTRODUCTION

There is no doubt that replacement of fossil fuel energy systems by solar thermal systems (STS) will contribute to reduced environmental impact and conserve our natural resources. Their lifetime energy savings greatly exceed the "invested" energy in materials and products [1]. However, it is important to declare their environmental impact, so that they can be compared with other renewable techniques and so that their contribution to the reduction of environmental impact can be judged and evaluated in the short term as well. It is also important environmentally to label STS in order to compete with low environmental performance products on the market and to maintain continuous development of environmental improvements.

Solar thermal products provide obvious environmental advantages as a result of minimal resource depletion, air and water emissions, and waste production during operation. However, operational energy production is not the only source of environmental impact. Energy, in various forms, has also been used for production of materials and their use in solar thermal units. In addition to the energy for manufacture and delivery, large-scale introduction of solar thermal products will require considerable quantities of material resources and produce considerable quantities of waste products. Other environmental aspects, such as land use, or socio-economic aspects such as employment effects, have not been considered in this work, but have been discussed by Tsoutsos et al. [2].

1.1 The NEGST project

One part of the EU NEGST project [3] (New Generation of Solar Thermal Systems) is to coordinate, develop and agree on procedures for environmental performance assessment of STS. The final objective is to achieve a common European procedure for environmental Life Cycle Assessment (LCA). The procedure is needed, since it has become important to declare the environmental impact from a product in an independent and uniform manner. This could be the final argument for convincing decision-makers (house owners, builders etc.) to invest in solar technology. With the procedure, it will be possible to rank different systems according to "environmental performance", which is an important base for future environmental labelling of STS. The pre-normative work towards standards for environmental LCA procedures can be divided into:

- literature survey and information gathering
- exchange of experiences and know-how
- agreement on priorities for urgent needs for standards
- working towards a common European approach for standards

- validating assessment methods and procedures
- passing on requests and suggestions for new work areas to CEN Solar Thermal Work Group, TC312.

So far, the project has dealt with the first three points. This paper describes the state of the art for environmental performance assessment of STS based on a literature survey and information from the NEGST participants, as well as experience exchange.

2. ENVIRONMENTAL IMPACT DESCRIPTION

Several investigations of the environmental impacts of solar thermal products have been made during the last decade. This survey shows that they can be divided into three different methods, with different aspects of information supply and evaluation criteria:

- Energy or emission payback time
- Avoided environmental impact
- Environmental product declaration

All three methods can be used with life cycle assessment (LCA) methods, which consider the product's total environmental impact from ”cradle to grave”. An LCA can be divided into four phases:
objective and scope, *inventory analysis*, *environmental impact description* and *interpretation* [4].

These phases will have different content for each method. Life cycle assessments are used for comparisons and not for descriptions in absolute terms. The challenge is to make the LCA independent and uniform, so that it can be performed in a comparative way for two products. This means that the boundary conditions for the two products should be comparable, and a functional unit must be well defined. A common procedure for LCA realisation forms the basis for labelling and rating of environmental performance.

An environmental impact description can be expressed in different ways, depending on the objective and scope of the LCA. The literature survey shows that there are two common ways of performing the environmental impact description. The first describes the environmental impact in respect of primary energy use. In this context, primary energy considers not only the energy input in each life cycle phase, but also how this energy input is produced with the production unit’s efficiency. This means that the LCA considers the kind of energy used in each life cycle phase in order to determine the primary energy use. The second describes the environmental impact with emissions to air. Here, the kind of energy used in each life cycle phase must be considered in order to determine the primary energy use, as well as the specific energy source’s life-cycle emissions.

3. PRIMARY EMBODIED ENERGY

As pointed out by Veenstra [1], STS are mostly added as a complementary installation, without replacement of a conventional system. When considering a whole building’s energy supply system, this means that it will strongly influence the environmental balance and cause an additional effect on the environmental profile. This means that an LCA of STS must begin with declaring the environmental impact description of the STS itself during its life cycle.

The aggregated energy use for the manufacture of the STS is referred to as the embodied energy. This includes all primary energy used during manufacturing of the system, as well as energy for the extraction, production and transportation of all material used in the system. It also includes all primary energy used during the complete life cycle of the STS; transport and installation of the system in the building, maintenance and demolition. Ferrão and Lage [5] have shown that, by considering recycling of system materials, the considered embodied energy can be significantly reduced. This implication is in accordance with that described by Cellura et al. [6], which adds the “feedstock” energy to the embodied energy of materials. The feedstock energy quantifies the potential of materials (such as wood or plastic) to deliver energy when they are burned with heat recovery after their useful life. This energy can theoretically be recovered by waste burning or recycling.

4. ENERGY PAYBACK TIME

One way of assessing the environmental performance of solar thermal products is to use energy payback time. This is the period that the system has to be in operation in order to save the amount of energy that is embodied in the system (the amount of primary energy that has been used for production, operation, maintenance and demolition of the system). The energy payback time can either be “simple” or “real”, as described by Nielsen et al. [7]. A simple payback time considers the energy saved by the solar system as equal to the delivered energy for tap water or space heating, reduced by operational energy:

$$E_{SPT} = \frac{Embodied\ Energy_{system}}{E_{delivered} - E_{operation}}$$

where:
E_{SPT} = Simple energy payback time (year),
$Embodied\ Energy_{system}$ = Primary energy assembled in the STS during its complete life cycle (kWh),
$E_{delivered}$ = Energy delivered for tap water or space heating by the STS (kWh/year),

$E_{operation}$ = Operational energy needed by the STS (mainly the circulation pump) (kWh/year).

A real payback time considers the energy saved by the solar system as equal to the primary energy that should have been used for tap water or space heating by a conventional system, reduced by the amount of operational energy:

$$E_{PT} = \frac{Embodied\ Energy_{system}}{\frac{E_{delivered}}{\eta_{conventional}} - E_{operation}}$$

where:
E_{PT} = Real energy payback time (year),
$\eta_{conventional}$ = efficiency of the conventional system that the STS is replacing.

Nielsen et al. [7] have performed an LCA investigation of 15 domestic solar hot water systems (DSHWS) on the Danish market, which shows that the simple energy payback time is approximately 1.5 years, while a real payback time is between 0.7 and 1.4 years, depending on the conventional system that the DSHWS is replacing. Streicher et al. [8] have calculated the real energy payback time for two different DSHWS to below 2.3 years. Four solar combisystems were also investigated, which showed that the typical energy payback times for them are between 2.0-4.3 years. This result is similar to that from another investigation, for ten different solar combisystems, by Streicher and Peter [9], which shows that the real energy payback times are between 1.3 – 3.5 years. Ferrão and Lage [5] show that a DSHWS has a real payback time of 2.4 years when replacing an electric heater, and 1.7 years when replacing a natural gas heater. They also show that considering recycling of the system's glass and metal material may considerably reduce the payback time. This is in accordance with an investigation made by Cellura et al. [6] of a DSHWS with a real energy payback time of less than two years when replacing a conventional gas boiler. Cellura et al. [10] also performed a sensitivity analysis of the result by considering the uncertainty in eco-profiles of materials, showing that the energy payback time is less than four years even with pessimistic scenarios. Ardente et al. [11] show a payback time of less than one year for a French solar collector. Kalogirou [12] has investigated a DSHWS showing energy payback times less than 1.2 years.

5. EMISSION PAYBACK TIME

Emission payback time is another way of describing the environmental impact of an STS. In order to do so, it is necessary to define the system that is replaced by the STS. The emission payback time is defined as the time which is needed to avoid equal amount of emissions due to replacement of a conventional system as released during the life cycle of the plant itself. Each emission substance (CO_2, NO_x, SO_x etc.) will be given its specific emission payback time, such as for CO_2:

$$CO_{2\,PT} = \frac{Embodied\ CO_{2\,system}}{CO_{2\ avoided} - CO_{2\,operation}}$$

where:
CO_{2PT} = CO_2 payback time (year),
$Embodied\ CO_{2system}$ = CO_2 released during the complete life cycle of the system unit and its materials (production, transports, maintenance, installation, demolition etc.) (CO_2),
$CO_{2avoided}$ = annual emissions avoided by the STS by replacing a conventional system (CO_2/year),
$CO_{2operation}$ = annual emissions released due to use of operational energy in the STS (CO_2/year).

Kalogirou [12] has investigated the emission payback times of several emissions for a DSHWS and a solar combisystem. The embodied energy was considered as produced by average European electricity, and the emissions avoided were considered as those produced by electricity or diesel fuel. Depending on the fuel avoided and on the emission substance under investigation, the emission payback time varied from 0.06 to 9.5 years. By replacing a conventional gas boiler with a DSHWS, Cellura et al. [6] show an emission payback time for CO_2 of less than two years. Crawford et al. [13] investigated a DSHWS in comparison with electric and gas systems in two climates, showing a greenhouse emission payback time between 2.5 and 5 years, depending on the replaced fuel and location. Emissions have been calculated by multiplying a factor of 60 kg CO_2/GJ, with primary energy factors of 3.4 and 1.4 respectively for electricity and gas.

6. AVOIDED ENVIRONMENTAL IMPACT

The actual avoided emissions provide another way of describing the environmental impact, instead of using the payback time. This analysis is done by comparing the emissions caused by the STS with the emissions caused by the replaced system over a defined period of time (for example, the lifetime of the STS).

Mirasgedis et al. [14] compared three different emissions caused by the manufacture process of DSHWS when using Greek electricity. The result was expressed by showing that all installed Greek solar water systems reduce the CO_2 emissions of the entire Greek power generation by 1.4%. Tsilingiridis et al. [15] calculated the impact caused by DSHWS of different sizes with auxiliary electricity or natural gas, and compared them with the impact from corresponding electricity and natural gas systems over a period of 15 years. The environmental impact was expressed by using the ”Eco-indicator 99” assessment method, which weights material use together based on aspects of human health, ecosystem quality and resource use [16]. The “net” gain over the electrical systems varied from 696 to 2117 Eco-indicator points, and was four times higher than the “net” gain of natural gas systems.

7. ENVIRONMENTAL PRODUCT DECLARATION

The above-mentioned surveys all compare the STS with a conventional system within the same survey. This means that the LCA for each system pair uses the same system boundary, the same assumptions and the same assessment criteria in order to make the comparison possible. In order to be able to compare two systems from different LCAs, there is a need for specific rules so that the LCAs are made in the same way. Sköld and Olsson [17] have suggested rules for specific product requirements (PSR) of water and space heating systems in buildings, by studying PSR rules for electricity and district heating [18]. PSR aims to provide guidelines so that the same conditions are used for different LCA studies within the same product group. An LCA made according to the PSR can be used for an environmental product declaration, EPD. EPDs are quantitative descriptions of a product's environmental characteristics, but without assessments or specific requirements, and thus make it possible to compare different products within the same group. The EPD is basically a summary of the inventory analysis with the aims of:

- Credibility: ensuring transparent, independent and competent control of data.
- Relevance: ensuring that the main environmental aspects have been analysed.
- Comparability: allowing the user to compare different products on the basis of their environmental impacts.

LCAs for STS that could be material for an EPD have been made by Sköld and Olsson [17] and Ardante et al. [19]. Both analyses follow the international ISO 14040, 14041, 14042 and 14043 standards. Nielsen et al.[7] suggest a similar “environmental fact sheet” for presenting the result from LCA of STS.

7.1 Functional units

The two investigations have chosen different functional units for the LCA. The functional unit is the reference unit expressed as the quantified performance of the system. The functional unit is important both as a basis for data collection within the product’s LCA and for comparability with other products' LCAs. Sköld and Olsson [17] have chosen the energy output as the functional unit. The unit is 1 kWh of output heat, which is assumed to be delivered with a water temperature of 50^{o}C. Nielsen et al. [7] suggest also using energy output as the functional unit, while Ardente et al. [19] have chosen the entire equipment as the functional unit. A third option could be to use specific collector area as the criterion, i.e. the environmental impact of the equipment per m² of collector.

7.2 Presentation of results

Sköld and Olsson’s investigation [17] is based on regulations for EPD [20], which requires that the results give a quantitative description of a product's environmental characteristic, but without assessments or specific requirements. The quantities that should be given in the declaration are *resource consumption, emissions of pollutants and other information.* Resource consumption is divided into material and fuel use, broken down into renewable and non-renewable. Other information relates to hazardous waste, material and energy that will be reduced and operational electricity. Emissions of pollutants are expressed in environmental effects such as global warming, ozone depletion, acidification, eutrophication and photochemical ozone formation. Wahlström [21] suggests that emissions of fine particles should also be considered for environmental assessments of heating systems. Ardante et al. [19] also declares resource consumption in the same way as [17], while air pollutants are expressed in kg for each emission and not in environmental effects. In addition to the quantitative declaration, Ardante et al. [19] also suggest declaring the energy payback time. This is in accordance with Nielsen et al. [7], who suggests declaring information on energy payback in an environmental fact sheet together with the estimated lifetime of the system. Nielsen et al. [7] also suggests using environmental effects.

8. DISCUSSION

8.1 Functional unit

The choice of functional unit will influence the environmental assessment when LCAs of different products are compared. The environmental impact is easily referred to an STS with the *entire equipment* as the functional unit. This choice has advantages for EPD of the product and when comparing two similar STS. The disadvantage is that a comparison with other conventional systems will be complicated. To choose *collector area* as the functional unit could be misleading, since there is no correlation between two different system collector areas and their energy output. Two systems with the same total environmental impact and energy output could very well have different collector areas. Furthermore, there is no linear relationship between collector surface area and collected energy, and increasing the collector area does not necessarily imply more energy output. *Energy output* as functional unit is generally the most common alternative for energy systems [19]. This choice has benefits when comparing the LCA for an STS with another LCA for a conventional system. STS are, however, often added as complementary installations [1] and the assessment might not need a comparison with the conventional system's complete LCA, but only with the energy source's LCA. It is also difficult directly to apply this procedure to a specific STS, since the energy output depends on the solar energy input and may be completely different for the same system in a different location.

8.2 Energy and emission payback time

The advantage with expressing the environmental performance of the STS in terms of simple payback time is that it is independent of the type of conventional system that the renewable system replaces. A real payback time is more correct, but requires information on the application of the STS. Furthermore, energy output from the system is highly dependent on the solar radiation input, which means that the payback time will differ, depending on where the STS is placed. To use real energy payback time in a common LCA procedure requires a definition of a reference system and climate. An assessment of payback time ought to take lifetime into account. A short payback time will not be beneficial if the lifetime is short. The payback time is independent of the functional unit.

An emission payback time will describe the environmental impact in more detail, since differences of energy sources embodied in the STS unit and of the replaced conventional system will be considered. On the other hand, each emission has an individual payback time.

8.3 Avoided environmental impact and EPD

To compare the emissions caused by the STS with the emissions caused by the replaced system over a defined period of time will give a thorough basis for the environmental assessment. This requires, however, a lot of detailed data for both systems, and will be specific for each application. The assessment could be facilitated with PSR-rules for water and space heating products so that existing LCAs, which are declared with EPD, could be used in the assessment.

8.4 Environmental impact description

The result from the inventory analysis (presented in an EPD) will consist of quantities of several emissions and resource use, which may be very difficult to overview. This could be assisted by a characterisation where the emission's contributions to different environmental impacts are weighted together into environmental effects such as global warming, ozone depletion, acidification, eutrophication, photochemical ozone formation and fine particles. This characterisation is more or less based on science, and could be performed in an EPD while still maintaining objectivity.

The results still consist of several different parameters that may be difficult to assess. In order to facilitate the assessment of life cycle inventories in general, several assessment methods intended for different purposes have been developed during the last decade. They weigh different environmental effects and resource consumption into one or a few figures. The weighting factors could be based on society aspects, resource availability etc., and are decided with limited scientific background. An example is the Eco-indicator 99 method (mentioned above), while several other methods are presented in Bjørn et al. [22]. To make environmental performance declarations that consider different environmental effects, resource use, waste etc. into one or a few final figures requires subjective evaluations.

8.5 Databases

Making LCAs requires a lot of data in several steps, which should be specific for the production line of the particular STS. Obtaining all this data may be expensive and time-consuming. Generalised values for how material is extracted, produced and transported are therefore often used in assessments. With specific rules on procedures for performing LCAs, it would be possible to create a database with resource and energy use for material that are commonly used in STS. An example of such a database is given in Streicher and Peter [9]. Transformation of different energy uses into emissions could be performed with inventories of different energy sources' life cycles. An example of such database is described by Wahlström [21] and exemplified in EFFem [23].

8.6 Presentation of LCA results

An EPD aims quantitatively to describe a product's environmental characteristic, but without assessments or specific requirements. Environmental effects could therefore be used, since this characterisation is considered as objective. Real payback time is more or less an assessment, since the replacing system must be determined. The present literature survey shows that payback time is one important description of environmental performance since it is widely used and easy to communicate, even though it has disadvantages as described above. There is a need further to develop requirements for an environmental fact sheet, similar to Nielsen et al. [7], that will be suitable for STS products.

8.7 Possibilities for labelling

An environmental fact sheet of a STS could be a valuable tool when choosing between different water and space heating systems. The information should be sufficient to allow an environmental assessment of the choice. However, such a sheet will not be enough for labelling of the STS. A labelling system will be helpful, giving details of requirements so that the customer knows that it is a product with environmental qualifications and not simply with an environmental declaration. The requirements could, for example, be: maximum payback time, minimum lifetime, maximum metal use per energy output, maximum impact on global warming etc.

9. CONCLUSIONS

Several investigations during the last decade show that the energy payback time for different STS are between 1 and 4.3 years. One can conclude that STS are a good environmental alternative for conventional systems, even though the system is added as complementary to an existing installation. This does not imply that the impact of STS itself is negligible. Work towards systems with reduced resource use must continue, with particular emphasis on reducing the use of heavy metals such as copper, nickel or chrome [7].

The present literature survey shows that there are several ways of performing an LCA of STS. The different studies use different assumptions, boundary conditions, functional units, data bases and assessment methods, as well as reference systems (conventional system). This makes direct comparison between different assessments impossible. There is a need for common procedures for environmental LCA of STS and for all water and space heating systems.

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