Life Cycle Assessment as a tool for the selection of solar hot water system

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Abstract. During the past decades, solar hot water systems became a popular solution, enabling utilisation of renewable energy by both, single users and enterprises. Maximisation of the energy gains is one of the factors influencing the environmental burdens connected with solar systems. The second important issue is a kind of elements of system, their production, transportation, usage and disposal. Therefore, as the method for estimation of the scale of environmental indicators Life Cycle Assessment should be used. In this study, LCA was applied for the selection of the individual design on the basis of two criteria (water tank capacity and hot water demand) considered in three system scenarios. The calculated indicators included greenhouse gas emission (Global Warming Potential) and IMPACT2002+ method. The results show the importance of proper designing in the case of environmental impact reduction.

1. Introduction
Modern society with its high energy demands faces a challenge of climate changes and a threat of depletion of natural resources. Those challenges led us to a concept of sustainability, which nowadays has become a common interest of various disciplines. This common interest is expressed through the performance of the sustainable development in our economy, society and environment, which includes the introduction of sustainable energy [1].

Sustainable development in the energy branch means using systems that are environmentally responsible and resource-efficient [2]. Responsible designing of energy systems is focused on activities which aim at environmental improvement of product and improvement of system efficiency. Environmental improvement is based on application of alternative processes, selection of materials with lower environmental effect, development in logistics and final disposal, etc. [2].

The answer to the question of sustainable energy seems to be energy from renewable sources. However, the introduction of such technologies need to be accompanied by an investigation of their environmental burdens. Minimisation of such burdens can be performed within the use of several methods, including the environmental Life Cycle Assessment.

In the case of small scale solar installations, one of the most important problems resulting from the economic issues is the lack of proper, individual design. This problem can be clearly visible on the example of mass-scale installations of the same system during performance of governmental programmes. In the mentioned case, it can be observed that the slope of collectors and the dimensions of installation is not individually designed, therefore issues such as maximisation of energy gains are neglected. Another important design parameters, hot water tank capacity and water demand, are the variables in the presented study.
2. Life Cycle Assessment of solar hot water systems

The subject of studies on the environmental Life Cycle Assessment of devices and energy systems was described in many papers, where environmental assessment of renewable energy sources is one of the most important issues [3-6]. Life Cycle Assessment is a popular tool for the analyses of renewable technologies since it allows the implementation of specified life cycle model and related environmental burdens of various types, like emissions, material etc. Concerning the topic of this paper, it is necessary to note that most of the analyses concern the ecological balance of SHW systems operating in Southern Europe, or only include Life Cycle Assessment at the stage of system components production. The selected examples of LCA studies are presented below.

Life Cycle Assessment method was used by Kalogirou to determine the environmental impact of flat plate collectors. The construction phase was analysed from the point of view of embedded energy. In the first paper, a system integrated with hot water storage tank was analysed. The consumption of primary energy for the production of integrated system was estimated as 2.7 GJ [7]. In another paper, Kalogirou described LCA for a system with two media: polypropylene glycol and water and calculated the primary energy consumption as 3.5 GJ [8].

A broad approach to the LCA for solar hot water system is presented in the paper of Alberti et al [9]. The authors compared environmental performance of two scenarios: a solar thermal system for providing domestic hot water (DHW) used in conjunction with a traditional natural gas heating system, and the natural gas heating system on its own. In addition, the authors calculated the national Greenhouse Gas emission reduction potential of a wider use of domestic solar hot water systems (DSHW) in China's and Spain's built environment by the use of five displacement methods. In general, some impact categories show a markedly better performance of the solar system (-65% in the case of greenhouse gas emission). However, weak points in the solar solution have been identified as there is an increase of impacts in categories such as acidification (+6%) and eutrophication (+61%), mostly due to used metals. Reduction of national emissions by promoting DSHW depends on the actual displaced technology and, in the case when 30% of the DHW were covered with solar sources, would place between 0.38% and 0.50% in Spain and between 0.12% and 0.63% in China. A

Another example of LCA applied for the integrated solar system is the paper of Battisti and Corrado [10]. The use of primary energy in the life cycle of the tested system was calculated as 3.1 GJ, and greenhouse gas emissions equalled 219.4 kgCO2eq. The production phase of the system was responsible for 97.8% of the total value of indicator. On the other hand, its operational phase has been omitted because of the specific design of the system (a capacitive collector as a heat tank), which did not require a pump [18].

In the paper of Soulions et al. [11], the study of two advanced solar water heating systems, integrated with the facades and the roof of a social house building located in Nicosia, Cyprus and Athens, Greece, was presented. The first one comprises collector and storage tank in a single unit, called Integrated Collector Storage solar water heater; the second one combines a photovoltaic and a thermal collector called Hybrid Photovoltaic/Thermal device. The authors considered the integration of the studied solar systems on building’s envelope, focusing on the effect of these systems in terms of building's thermal load along with their capacity to cover the energy needs, especially in terms of hot water and electricity consumption.

Computer simulations of energy load of building, as well as the energy output of solar systems, were carried out for two mentioned locations within South, West and East orientation modes. The implementation of the described solar systems into the building envelope allowed to diminish the thermal energy needs up to 10% in the case of heating and cooling purposes and up to 80% in the case of hot water and electricity needs. The method used for investigation of energy contribution was Life Cycle Assessment, allowing the evaluation of environmental impacts during the entire life cycle of the considered systems.

According to the nowadays state of knowledge, most of renewable sources can be treated as a source of clean, green energy. Though, one should remember about the need to individually consider the issues
of their location. Local climate conditions are crucial for adaptation of the design solutions to the individual needs of the recipients, as well as for possible energy output of the designed systems [12].

3. Computer simulations as a tool for solar system designing

3.1. General assumptions

The presented study of system for solar hot water preparation was carried out on the basis of typical solution for a single-family house with four inhabitants. The conducted analysis included three versions of system with changing capacity of the hot water tank:

- 200 dm$^3$ in system no. 1 (S1),
- 250 dm$^3$ in system no. 2 (S2),
- 300 dm$^3$ in system no. 3 (S3).

In each system scenario hot water consumption was treated as variable between minor and higher water demand and equalled:

- 160 dm$^3$/d,
- 200 dm$^3$/d,
- 240 dm$^3$/d.

The selected location in central Poland (Łódź) is characterised by favourable insolation conditions, with yearly solar irradiance assumed in the study as 1147.93 kWh/m$^2$.

As solar thermal collector, 4.34 m$^2$ flat-plate collector with Al-Cu absorber was tested, characterised by the following data:

- optical efficiency $n_0=0.761$ [-],
- 1st order heat loss coefficient $a_1=3.438$ [W/m$^2$],
- 2nd order heat loss coefficient $a_2=0.008$ [W/m$^2$].

3.2. Materials and methods

For a widespread implementation of computer modelling into designing process, two applications (GetSolar and SimaPro) were used to incorporate the variable design conditions and environmental aspects into the analysed model. The first program was used to estimate the possible energy output with the use of mentioned variable data on water consumption and storage volume for the selected collector. The second application, SimaPro, was used for forming of the system model and its life cycle.

As first, a life cycle impact assessment method IMPACT2002+ was used. In this damage-oriented method, the calculations concerning total environmental load expressed in Points are conducted on the basis of detailed life cycle inventory. The higher the calculated indicator, the more significant the environmental impact. As the most of damage-oriented indicators, Points calculated by the use of IMPACT2002+ are used mostly for comparisons of products or systems.

The calculations are performed throughout the midpoint level, including four damage categories (Human Health, Ecosystem Quality, Climate Change and Resources) and seventeen impact categories (Human toxicity, Respiratory effects, Ionizing radiation, Ozone layer depletion, Photochemical oxidation, Aquatic ecotoxicity, Terrestrial ecotoxicity, Aquatic acidification, Aquatic eutrophication, Land occupation, Terrestrial acidification/nutrification, Water turbinable, Global Warming, Non-renewable energy, Mineral extraction, Water withdrawal, Water consumption). In the particular method, midpoint characteristics are presented in comparative way within the use of specific standard substances. The impact is considered within the time framework up to 500 years [13].

As second, a life cycle impact assessment method Global Warming Potential in 500 years perspective was used. This method is simpler than the previously described one and includes only the climate change category, based on carbon dioxide as a comparative substance. Selected emissions of substances to the air are compared with CO$_2$ on the basis of potential to cause the same effect as emission of carbon dioxide [14].

All the operations connected with environmental data modelling in this study, as well as the calculations of indicators were conducted in SimaPro v. 8.
3.3. Results of GetSolar modelling

GetSolar is the popular application enabling easy and quick modelling of solar systems power output. The necessary parameters to be implemented into the model include:

- solar collector data:
  - optical efficiency \( n_0 \) [-],
  - 1st order heat loss coefficient \( a_1 \) [W/m²],
  - 2nd order heat loss coefficient \( a_2 \) [W/m²],
  - collector area [m²].
- climate data including solar irradiance on collector plane [W/m²] and temperature.
- type of solar system (single, combined, etc.)
- type of water storage tank,
- capacity of water storage tank [dm³].
- orientation (0 – 360°)
- angle of inclination [°].

Data were assumed after the producers of collectors (technical data), and as typical design parameters. Two of the variables (water consumption and storage tank capacity) were examined to provide information about possible energy output, efficiency and the coverage of hot water demand during one year of operation.

The results of possible energy output modelling are presented in Table 1.

### Table 1. The possible energy output, efficiency and hot water demand coverage modelled for systems 1, 2 and 3 with variable water demand.

| System | Water demand, dm³/d | Capacity of water tank, dm³ | Efficiency of system, % | Coverage of hot water demand, % | Possible energy output, kWh/yr | Average gain from collector, kWh/yr/m² |
|--------|---------------------|-----------------------------|------------------------|---------------------------------|-------------------------------|-------------------------------|
| S1     | 160                 | 200                         | 33                     | 53                              | 1630                          | 376                           |
|        | 200                 |                              | 36                     | 47                              | 1814                          | 418                           |
|        | 240                 |                              | 39                     | 42                              | 1949                          | 449                           |
| S2     | 160                 | 250                         | 33                     | 53                              | 1652                          | 381                           |
|        | 200                 |                              | 37                     | 47                              | 1834                          | 423                           |
|        | 240                 |                              | 40                     | 43                              | 1978                          | 456                           |
| S3     | 160                 | 300                         | 33                     | 53                              | 1661                          | 383                           |
|        | 200                 |                              | 37                     | 48                              | 1847                          | 426                           |
|        | 240                 |                              | 40                     | 43                              | 1994                          | 459                           |

The results presented in Table 1 show potential dependence between energy output and investigated variables. The examined parameters were assumed as typical for the selected type of system, with the consideration of changing water demand and storage volume. The increase in possible energy output reaches 22% yearly between the minimum and maximum of analysed variations. However, considering only one of the variables, the change in energy output exceeds 20% for water consumption and 2% for storage tank volume.

3.4. Results of SimaPro modelling

SimaPro v8 was used to enable the calculation of Life Cycle Impact Assessment indicators, particularly IMPACT2002+ (Figure 1) and GWP100a (Figure 2). This enabled the comparison between the assumed life cycle of System 1, System 2 and System 3 in three water consumption modes, considering the related
environmental burdens. The detailed inventory, including production, operation and final disposal of System 1, System 2 and System 3, allowed the environmental impact assessment using the mentioned methods.

Figure 1. IMPACT2002+ results for System 1, System 2 and System 3 per functional unit.

Figure 2. IPCC GWP100a results for System 1, System 2 and System 3 per functional unit.

The results presented in Figure 1 and Figure 2 are calculated for the functional unit, which included the energy possibly generated by solar hot water system, according to the previously presented calculations performed in GetSolar. This allowed to select the most environmentally-friendly version of system, considering the calculated indicators with the lowest value. In the described computer simulation, this was System 3 with the highest water consumption. It should be mentioned that high values of GWP indicator result from the kind of electricity used in the SimaPro model, since the operational phase is responsible for the most of calculated indicators.

In Figure 3, total IMPACT2002+ scores for System 1, System 2 and System 3 are presented within the damage categories. In this particular case, the share of impact categories in total value of indicator are similar for analysed systems since most of the environmental impact is connected with the use of electricity (polish energy mix). Therefore, issues such as conventional fuels, carbon dioxide emission and particulate matter emission are the most meaningful aspects, together with the use of metals for production of elements of the system.
4. Conclusions

Life Cycle Assessment is an important tool that enables extending knowledge (including information about environmental burdens) of energy system designers and investors; thus, it helps in a decision-making process.

In this paper, the LCA methodology was used to assess the typical solar hot water preparation system applied to a single-family house with four inhabitants. The Global Warming Potential and IMPACT2002+ methods were used to calculate environmental indicators.

In the conducted analysis three system scenarios were considered, including different values of water tank capacity: 200 dm$^3$, 250 dm$^3$, 300 dm$^3$. Additionally, each scenario comprised three values of daily hot water consumption: 160 dm$^3$/d, 200 dm$^3$/d, 240 dm$^3$/d. The first three options influenced both the material and energy balance of examined systems, while the daily hot water consumption affected only the energy output. Therefore, three systems (System 1, System 2 and System 3) were indicated on the basis of water tank capacity, and further calculations were the options of water consumption for the mentioned systems.

The conducted analysis showed that the possible annual energy output from the different variants of examined system varies from 1630 kWh (tank capacity 200 dm$^3$, hot water demand 160 dm$^3$/d) to 1994 kWh (tank capacity 300 dm$^3$, water demand 240 dm$^3$/d). In general, in conducted analysis of systems, energy output increases with increasing tank capacity and water demand values. The difference between the highest and the lowest ones reaches 22%.

The analysis based on Life Cycle Assessment showed that System 3 (tank capacity 300 dm$^3$) with the highest water consumption of 240 dm$^3$/d is characterised by the lowest values of Global Warming Potential and IMPACT2002+ indicators. The tendency for total IMPACT2002+ score and GWP is similar for all considered scenarios since environmental impact is connected mainly with electricity consumption. For that reason, issues such as fossil fuels consumption, carbon dioxide and particulate matter emission are the biggest environmental problems.

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5. References

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