Hidden energy and environmental loads of solar thermal collectors: a case study

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The general aim of this work was to investigate a solar thermal collector and the energetic and environmental impacts related to this renewable technology. It was realised an eco-profile of an exemplary equipment, calculating the Cumulative Energy Demand (CED) and the Cumulative Emissions related to the production and use of a collector and the energy (or emissions) saved employing the renewable technology.

Keywords: Eco-profile, CED, cumulative emission, payback time, uncertainty analysis, sensitivity analysis.

I. INTRODUCTION

The renewable technologies are generally presented as clean technologies without stating the effective impacts (in terms of energy consumption or pollutant released) caused by equipment production. This paper traces an eco-profile of an exemplary solar collector and makes a balance between the production's impacts and the energetic and environmental benefit of the use of this technology.

I-A. The Energetic Analysis

The energetic consumption related to a collector is expressed by an index, the Cumulative Energy Demand (CED), which represents the energy demand that arises in connection with the production from raw materials to final product. The CED is expressed in terms of primary energy, meaning so the energy content of energy carriers that have not yet been subjected to any transformation.\(^1\) The CED was calculated with a Mass Balance Method, considering a specific energy demand factor "ced," [MJ/kg] for each employed material. They were summarised in an energetic Italian database.\(^2\)

Generally, the ced, was computed as end-energy quantities or, better, the energy consumed by the final user. These quantities were so converted in primary energy by employing some conversion factors taken from the Italian national statistics (Table 1).\(^3\) These factors represent, for each energy carrier, the energy necessary to produce 1 MJ of useable energy, including all the process steps.

| Conversion Factors [MJ\text{Prim}/MJ\text{End}] |
|-----------------|-----------------|
| Coal            | 1.06            |
| Heavy Oil       | 1.142           |
| Light Oil       | 1.105           |
| Natural Gas     | 1.06            |
| Electricity     | 3.205           |

The energetic demand for the collector production was obtained adding the share of each employed
material. The further energy expenditures for assembling and maintenance were taken into account as percentage of the overall demand.\textsuperscript{2, 7}

\section*{I-B. The Environmental Analysis}

The study was focused upon the main gaseous releases (in particular the equivalent quantity of CO\textsubscript{2}). They were calculated by employing specific emission factors [mg pollutant/MJ fuel] that represent the average quantities of pollutants produced by the utilisation of one MJ of energy carrier.\textsuperscript{3, 4} The emissions due to electricity were obtained considering the Italian electricity-mix (data are referring to 1998).\textsuperscript{3} It was performed an environmental database including the employed materials in the collector.\textsuperscript{2}

\section*{II. A CASE STUDY}

The concepts and the previous databases were applied to a case study: an exemplary water heating plant for sanitary demand of a familiar house. This plant includes the flat collectors installed on the roof, water tank, pipes, connection and heat exchangers, pump and control system. These components represent the “renewable plant” used as support to a conventional system (gas heater). The energetic analysis is summarised in the Fig. 1, the environmental loads in Table 2.

\begin{table}[h]
\centering
\caption{Environmental Loads (gaseous releases).}
\begin{tabular}{|c|c|c|}
\hline
GASEOUS RELEASES [kg] & & \\
\hline
CO\textsubscript{2} & 845 & NO\textsubscript{x} & 2.3 \\
CO\textsubscript{2}-eq & 890 & SO\textsubscript{2} & 2.4 \\
CO & 2.8 & CH\textsubscript{4} & 2 \\
Dust & 2.6 & NMVOC & 0.2 \\
\hline
\end{tabular}
\end{table}

The analyses were repeated employing a different collector type, the vacuum pipe collectors, leaving the same all the other components of the renewable plant. The new CED value was of 16.3 GJ (increment of about 3%). Likewise, the increment of gaseous releases was of the same order of magnitude. For example, the CO\textsubscript{2}-eq quantity was of 936 Kg (increment of about 5%).

\section*{III. THE ENERGY AND EMISSION SAVE}

The thermal performance of solar collectors can be evaluated by an energy balance that determines the portion of incoming radiation delivered as useful energy to the working fluid. This energy balance on the absorber plate is:

\begin{equation}
I_c \cdot A_e \cdot \tau_s \cdot \alpha_s = q_u + q_{loss} + \frac{dE_c}{dt} \quad (1)
\end{equation}

where:
- $I_c$ = solar irradiation on a collector surface [W/m\textsuperscript{2}];
- $A_e$ = collector surface [m\textsuperscript{2}];
- $\tau_s$ = solar transmittance of the collector cover;
- $\alpha_s$ = solar absorptance of the absorber plate surface;
- $q_u$ = heat transfer rate to the working fluid [W];
- $q_{loss}$ = heat losses [W];
- $dE_c / dt$ = rate of internal energy storage [W].

The energy collected by the collectors was obtained considering an averaged daily warm water demand and an Italian averaged value of solar irradiation.\textsuperscript{6}

The employment of renewable plant permits a reduction of gaseous releases, otherwise produced by the conventional heater. The saved emissions were
so calculated from the value of useful energy, supposing for a gas heater a CO$_2$-eq production of about 87 kg/GJ. The results are shown in Table 3.

Table 3. Energy and Emission Save.

<table>
<thead>
<tr>
<th>End-energy save</th>
<th>Flat Collector [GJ]</th>
<th>Vacuum Pipe [GJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-energy save</td>
<td>10.53 [GJ]</td>
<td>12.97 [GJ]</td>
</tr>
<tr>
<td>Emission save</td>
<td>918 [kg CO$_2$-eq]</td>
<td>1106 [kg CO$_2$-eq]</td>
</tr>
</tbody>
</table>

IV. ENERGY & EMISSION PAYBACK TIME.

The CED and the useful energy can be enclosed in an index: the Energy Payback Time (E$_{PT}$). It is defined as the time during which the system has to work to harvest as much as it required for its production and use (disposal and recycling phases were not included in the calculation):

$$E_{PT} = \frac{CED}{E_{useful} - E_{Use}}$$  \hspace{1cm} (2)

where:
- CED = Cumulative Energy Demand [GJ];
- E$_{useful}$ = Yearly useful energy saved with the renewable system [GJ/year];
- E$_{Use}$ = Yearly energy necessary for the use (mainly the electricity for the Pump and Control system) of the renewable system [computed as 2.17 GJ/year].

It is also possible to define an Emission Payback Time (E$_{M,PT}$) as the time during which the avoided emissions are equal to the emissions necessary for system's production and use. The index "i" is referred to the generic considered pollutant:

$$E_{M,PT,i} = \frac{EM_{i}}{EM_{CONVENTIONAL,i} - EM_{USE,i}}$$  \hspace{1cm} (3)

where:
- EM$_{i}$ = Cumulative emissions of pollutant "i" released during the production of the system [kg];
- EM$_{CONVENTIONAL,i}$ = Yearly saved emissions of pollutant "i" [kg/year];
- EM$_{USE,i}$ = Yearly emission of pollutant "i" for the use of the renewable system [for the CO$_2$-eq was computed as 476 kg/year].

The results are summarised in Table 4. It is possible to observe that the greater efficiency of vacuum collectors causes lower payback time values.

Table 4. Energy an Emission Payback time [month].

<table>
<thead>
<tr>
<th>E$_{PT}$</th>
<th>Flat Collector</th>
<th>Vacuum Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>E$_{M,PT}$ (CO$_2$-eq)</td>
<td>24</td>
<td>18</td>
</tr>
</tbody>
</table>

V. UNCERTAINTY ANALYSIS (UA)

The calculation of the cumulative energy and emission demand was performed considering for the studied materials an averaged specific "ced" value. However, there are many sources of uncertainty when trying to calculate the energy demand of a material. They influence the final system’s CED and the energetic benefit of studied plant. The energetic database was modified, supposing for each material a range of specific "ced" values, instead of a fixed one. The system’s CED was so calculated in the different scenarios considering, for each material, the lower and upper extreme of its range. Table 5 shows the range of values within that the CED can vary and the uncertainty range, which is the percent level of uncertainty calculated respect to the average value.

Table 5. CED variations and Uncertainty Range.

<table>
<thead>
<tr>
<th>Flat Collector</th>
<th>Vacuum Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Lower&quot; CED</td>
<td>14.6 [GJ]</td>
</tr>
<tr>
<td>&quot;Average&quot; CED</td>
<td>15.8 [GJ]</td>
</tr>
<tr>
<td>&quot;High&quot; CED</td>
<td>17.0 [GJ]</td>
</tr>
<tr>
<td>Uncertainty Range</td>
<td>± 7.6%</td>
</tr>
<tr>
<td>&quot;E$_{PT}$&quot; Range</td>
<td>21-24 [months]</td>
</tr>
</tbody>
</table>

The CED modify has repercussions on the payback time; the values remain, however, lower than 24 months.
It was studied the percent incidence of some materials on the overall uncertainty range, or, in other words, how much of the overall uncertainty can be related to a certain material. A comparison between all these percentages allows to obtain the “dominant” factors (Dominance Analysis).

\[
\text{Incidence}_i = 100 \cdot \frac{CED_i - CED}{CED_{\text{HIGH}} - CED}
\]  

(4)

where:
- \(CED_i\) = System’s CED obtained by supposing only one material with its upper specific “ced” value and all the others with their average value;
- CED = “Average” CED value;
- \(CED_{\text{HIGH}}\) = “High” CED value.

The incidence of a material is useful to individuate directions of possible future technological changes, as replacements or energetic improvements.

From this analysis aluminium and steel resulted as “dominant” materials. It was calculated, for example, that the energy payback time could be decreased by about 6.5% employing 20% of recycled steel and by about 8.5% employing 40% of recycled aluminium.

VI. SENSITIVITY ANALYSIS (SA)

The last part of the study focused the attention on the parameters that influence the useful energy and consequently the Energy Payback time.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>“E_P T” VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector’s Inclination</td>
<td>2 %</td>
</tr>
<tr>
<td>User’s Demand</td>
<td>5 %</td>
</tr>
<tr>
<td>Tank’s Volume</td>
<td>10 %</td>
</tr>
<tr>
<td>Water Flow</td>
<td>15 %</td>
</tr>
<tr>
<td>Collector’s Surface</td>
<td>25 %</td>
</tr>
<tr>
<td>Insulation Thickness</td>
<td>40 %</td>
</tr>
</tbody>
</table>

In Table 6 are shown the percent rate increments on the payback, calculated respect to the optimum (payback minimisation).

VII. CONCLUSION

The study has shown the great energetic convenience of thermal solar collector, especially in a country, as Italy, with a high solar radiation level also during the wintertime. In all the studied scenarios, the payback time resulted always lower than three years.

Thanks to employ of the UA and SA ones provides answer to specific question concerning the behaviour of the system under various given condition. This is an important information to optimise the eco-performances of final products (“eco-design”).

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