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ScienceDirect

Solar Energy 125 (2016) 294–306

SOLAR ENERGY

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Replacing traditional materials with polymeric materials in solar thermosiphon systems – Case study on pros and cons based on a total cost accounting approach

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Received 25 August 2015; received in revised form 24 November 2015; accepted 7 December 2015
Available online 7 January 2016

Communicated by: Associate Editor Yanjun Dai

Abstract

The pros and cons of replacing traditional materials with polymeric materials in solar thermosiphon systems were analysed by adopting a total cost accounting approach. In terms of climatic and environmental performance, polymeric materials reveal better key figures than traditional ones like metals. In terms of present value total cost of energy, taking into account functional capability, end user investment cost, O&M cost, reliability and climatic cost, the results suggest that this may also be true when comparing a polymeric based thermosiphon system with a high efficient thermosiphon system of conventional materials for DHW production in the southern Europe regions.

When present values for total energy cost are assessed for the total DHW systems including both the solar heating system and the auxiliary electric heating system, the difference in energy cost between the polymeric and the traditional systems is markedly reduced. The main reason for the difference in results can be related to the difference in thermal performance between the two systems. It can be concluded that the choice of auxiliary heating source is of utmost importance for the economical competiveness of systems and that electric heating may not be the best choice.

Keywords: Solar thermosiphon system; Polymeric solar collectors; DHW production; Total cost accounting; Economic competiveness

1. Introduction

It has been pointed out that in many cases, polymeric materials would be a better alternative to materials currently used in solar thermal energy systems; see e.g. the work recently conducted in Task 39 of the IEA Solar Heating and Cooling Programme (IEA SHC Task 39, 2010; Köhl et al., 2012) and the work of the EU funded FP7 project SCOOP (SCOOP, 2015). The introduction of new polymeric materials and technologies is today considered essential in order to meet the market requirements for heating applications in the medium and high temperature range. This requires, however, that the end user investment cost and the service-life of the new polymeric based solar thermal systems are comparable to those of conventional products.

To assess the suitability of solar collector systems in which polymeric materials are used versus those in which more traditional materials are used, a case study on solar

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http://dx.doi.org/10.1016/j.solener.2015.12.005
0038-092X/

heating combisystems was previously undertaken in the IEA task mentioned (Carlsson et al., 2014). In that case study a solar heating system with polymeric solar collectors was compared with two equivalent but more traditional solar heating systems: one with flat plate solar collectors and one with evacuated tube solar collectors. For the analysis, a typical Swedish one-family house from 1980 in Stockholm was used. The comparison was made by adopting a total cost accounting approach, which aims at taking into account all relevant factors in designing a solar heating system by simultaneously considering not only functional quality and cost effectiveness, but also reliability, long-term performance, ecological soundness, and recoverability. The difference in thermal performance between the three solar combisystems studied was compensated for by adjusting the size of the solar collector area so that the solar fraction of the three systems became the same. When considering the end-user investment cost for the three equivalent solar heating systems obtained this way, it was found that the polymeric solar collector system would be competitive with the reference flat plate solar collector system and the reference evacuated tube collector system. In this work also climatic costs per amount of solar heat collected were estimated for the three systems. It could be concluded that the climatic cost of the three kinds of collector systems were small when compared with existing energy prices. Thus, the climatic cost seemed significantly less important when compared to the end user investment cost.

In countries with a high solar irradiance and a low gross domestic product, cheaper low-tech products are preferred and the by far dominant solar thermal systems on the market are thermosiphon systems (Mauthner and Weiss, 2014). Due to low wages and low production costs, price of solar thermosiphon systems in such countries depends strongly on material costs. A reduction in price would therefore be possible by replacing traditional materials like metals with polymeric materials. In the project SCOOP previously mentioned (SCOOP, 2015), polymeric based thermosiphon systems were developed for that purpose and the systems studied in the project SCOOP were taken as the point of the departure for the present study. The aim was to assess the suitability of polymeric based solar thermosiphon systems by adopting a total cost accounting approach in the same way as was practised in the first Task 39 case study (Carlsson et al., 2014).

2. Total cost accounting approach for suitability assessment

The total cost accounting approach adopted for the present study, takes the end-user or consumer perspective and the ecological long-term perspective as a basis for compiling the contributions from all the various factors that might be important to the life cycle of a functional unit of a product or a system. In the assessment of total cost you have to take in consideration the direct costs associated with the different phases of the life cycle of a functional unit of a product or system as you do in the life cycle cost assessment (LCC). Also, indirect costs, which are associated with damage to environment and that occur in the different phases of the life cycle have to be taken into account as in life cycle analysis (LCA); see Fig. 1.

The point of departure is not a particular design alternative of the functional unit and its life cycle, but its intended function over time. When adopting the total cost accounting approach, it is, however, not the absolute value of the total cost that is of main interest, but the difference in the total cost between two design alternatives of the functional unit of the product considered (Carlsson et al., 2014; Carlsson, 2010, 2007). If one design alternative of the functional unit is chosen as reference, the model to be adopted can be described as follows: For a fixed service time, the difference in total cost (ΔC_T), between a test unit and a reference unit associated with maintaining the same specific function defined for the unit, is estimated from:

$$\Delta C_{\mathrm{T}} = \Delta C_{\mathrm{EUI}} + \Delta C_{\mathrm{NIP}} + \Delta C_{\mathrm{O\&M}} + \Delta C_{\mathrm{F}} + \Delta C_{\mathrm{EoL}} + \Delta C_{\mathrm{E}} \tag{1}$$

where ΔC_{EUI} = the difference in end user investment cost between the two systems; ΔC_{NIP} = the difference in cost associated with initial non-ideal function or performance between the two design alternatives; $\Delta C_{\mathrm{O\&M}}$ = the difference in O&M cost, operational and maintenance costs, between the two design alternatives; ΔC_{F} = the difference in cost of probable failures and damage between the two design alternatives; ΔC_{EoL} = the difference in end-of-life cost between the two design alternatives; ΔC_{E} = the difference in environmental cost associated with probable ecological damage between the two design alternatives. Detailed information on assessment of how different cost terms contribute to total cost can be found in previous work by Carlsson et al. (2014) and Carlsson (2010, 2007).

Comparing different design alternatives using the total cost accounting approach requires systematic suitability analysis. The design alternatives must therefore be clearly defined and suitability analysis be conducted, preferably in the form of a case study.

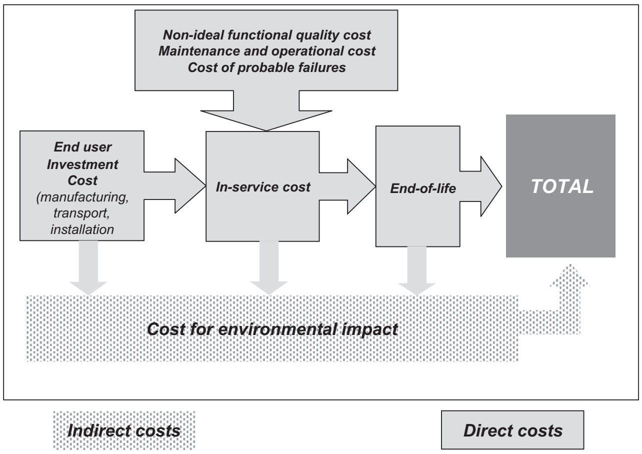


Fig. 1. Principle scheme for assessment of total cost.

3. Specification of the solar thermosiphon systems of case study

As was mentioned previously, information on polymeric based solar thermosiphon systems (TSS) developed in the framework of the SCOOP project (SCOOP, 2015) were available for this study and one such system under development by the company Aventa (Aventa, 2015) was selected as the test system for the present case study. The Aventa SCOOP solar thermosiphon system is presently available as prototype and its design based on use of commodity plastics. This TSS is named polymeric TSS in the following.

A module of this TSS uses a solar collector area of 2.0 m^2 and each module is designed for a single-family house with a DHW demand of 120 l hot water per day. Fig. 2 shows the general characteristics of the prototype system set-up and test performed at AEE INTEC's test site in Gleisdorf (Austria) during 2014. This configuration is used for the present case study. The heat storage tank of PP with a volume of 120 l uses an inner stainless steel tank as a "tank in tank" heat exchanger of a volume of 32 l. The system may be equipped with auxiliary electric heating either by using an electric heating rod or by using a continuous flow electric heater placed in the house as is shown in Fig. 2.

The reference solar thermosiphon system selected for the case study reflects a typical, high efficient, present day commercial system using mainly metallic materials. From the manufacturer of this system it was possible to get relevant design data needed for the LCA inventory, cost and thermal performance data although we were requested to keep the name of the manufacturer and the product name of the system confidential. The general characteristics of the design of this system are given in Fig. 3. The heat storage tank of steel, with a volume of 120 l, uses a double-shelled heat exchanger. The system may be equipped with auxiliary electric heating either by using an electric heating rod inserted in the double shelled heat exchanger or by using a continuous flow electric heater placed in the house as is shown in Fig. 3.

4. Thermal performance of the two solar thermosiphon systems

4.1. Application parameters and simulation models

Comparison of the two thermosiphon systems was made under the assumption that they both were placed in Athens, Greece and used for DHW production. Some characteristic data valid for Athens taken from two literature sources are shown in Table 1, i.e. reference climate EN 12976-2 (EN 12976-2, 2006) and Polysun 6.2 (Polysun 6.2, 2013).

In the analysis made, the daily domestic hot water demand was set at 110 l, which corresponds to the demand of a typical 3 person household in the region considered. The hot water set temperature was 45 °C. It was further assumed that the solar collector of the thermosiphon systems was oriented towards south and tilted 45° from the horizontal plane. Each system was also equipped with an electric auxiliary heat source (back up heating system) so that the temperature of the domestic hot water could be kept at 45 °C; see Figs. 2 and 3. With the assumptions made, the yearly total energy demand for DHW production became 1.26 MW h.

The thermal performance of the two solar thermosiphon systems was assessed by use of the software Polysun 6.2

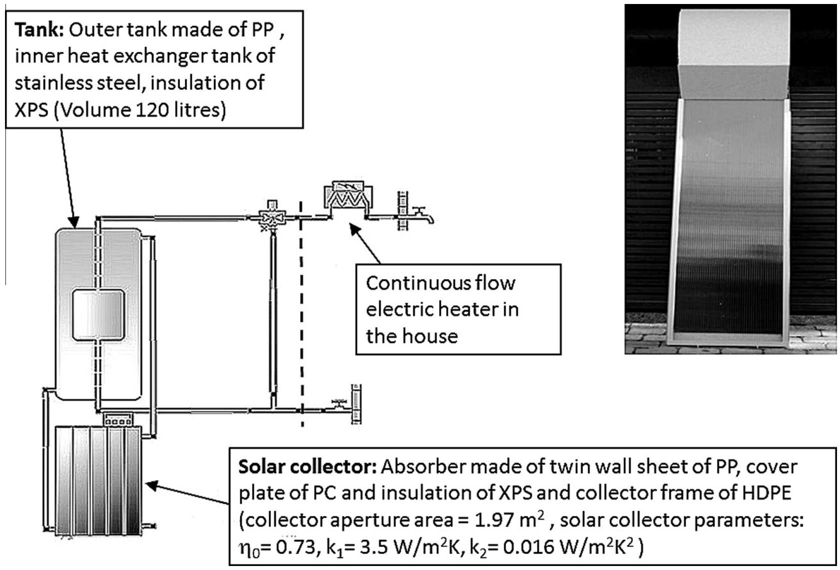


Fig. 2. General characteristics of the polymeric solar thermosiphon system of the case study. The inner heat exchanger (tank in tank) has a volume of 32 l. The total hot water tank volume is 120 l. The solar collector parameter η_0 refers to maximum solar collector efficiency if there is no heat loss, the parameters k_1 and k_2 to 1st order and 2nd order heat loss coefficients of solar collector. Values for the solar collector parameters refer to measurements made at AEE INTEC in 2010 (Hausner and Wallner, 2011).

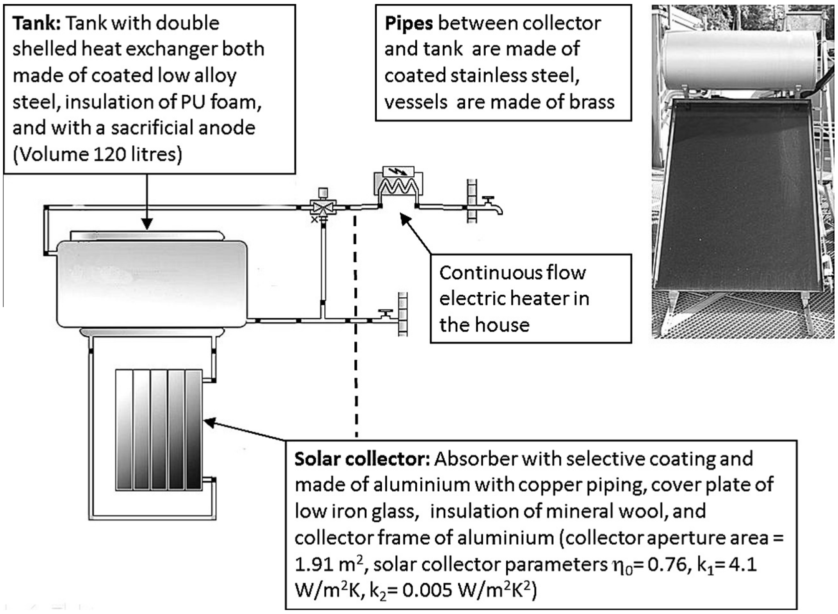


Fig. 3. General characteristics of the reference solar thermosiphon system of the case study. The solar collector parameter η_0 refers to maximum solar collector efficiency if there is no heat loss, the parameters k_1 and k_2 to 1st order and 2nd order heat loss coefficients of solar collector. Values of solar collector parameters received from test protocol of collector manufacturer.

Table 1
Some characteristic data for Athens taken from two different sources.

	Reference climate EN 12976-2	Polysun 6.2
Average annual irradiation to a surface oriented south and tilted 45°, G (kW h/m^2)	1.718	1.540
Annual mean air temperature, T_a (°C)	18.5	18.0
Annual mean cold supply (or mains) water temperature, T_c (°C)	17.8	18.0
Seasonal variation of T_c, $\pm\Delta T_c$ (°C)	7.4	3.1
Set hot water temperature to water tap (after mixing valve), T_h (°C)	45.0	45.0

(Polysun 6.2, 2013) and each system was described by the Polysun models shown in Fig. 2 and in Fig. 3, respectively. In the modelling of the heat exchange in the inner tank of the polymeric system, see Fig. 2, ideal conditions were assumed meaning that no mixing with cold water during tapping occurred. However, the choice of the tap water profile turned out to be crucial for this system. It could be concluded that 110 l hot water a day in one single taping at the end of the day as recommended in the EN standard (EN 12976-2, 2006), resulted in a too high instantaneous load. Therefore the more realistic “evening peak” tap profile given in Polysun 6.2 and shown in Fig. 4 was adopted.

For auxiliary heating, two options were considered – the first option was use of a continuous flow electric heater placed in the house and the second option was use of an electric rod heater placed in the hot water tank located outdoors. The first option is, of course, better as it gives rise to less heat losses compared to the other arrangement. However, the first alternative requires an electricity grid with high power and therefore, maybe, it will not be suitable for all locations.

The solar collecting properties of the systems calculated by use the Polysun models, were validated with results from outdoor measurements made at AEE INTEC (Preiss et al., 2014; Meir et al., 2015). The difference in thermal performance between the two solar thermosiphon systems can be seen as illustrated in Fig. 5 from their efficiency versus mean collector temperature plots valid for an ambient temperature of 30 °C.

4.2. Results from calculations

The simulation results for the reference TSS are shown in Table 2 and for the polymeric TSS in Table 3.

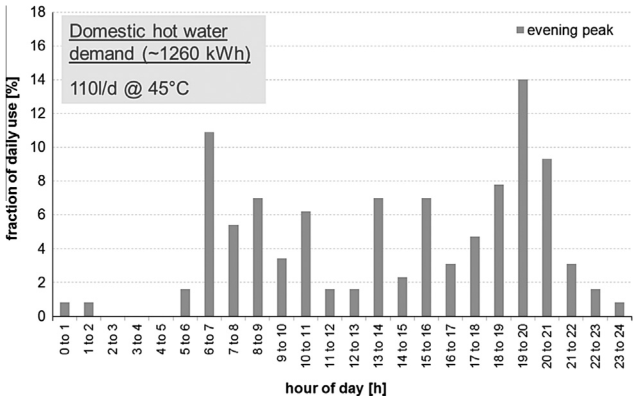


Fig. 4. Hot water tap profile used in the performance calculations of the case study.

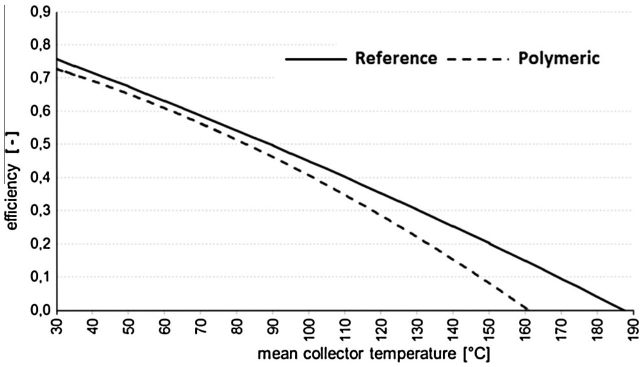


Fig. 5. Solar collector efficiencies for the two solar thermosiphon systems at an ambient temperature of 30 °C calculated by use of the solar collector thermal performance parameters given Figs. 2 and 3.

The reference TSS performs better compared to the polymeric TSS and also other TSS on the market and can from the results obtained be considered as a highly efficient system. The difference in the useful solar energy that is effectively consumed, i.e. $Q_{\text{sol,use}}$, between the polymeric TSS (Case A.1 in Table 3) and the reference TSS (Case A1 in Table 2) is in order of 8%. Increasing the solar collector area of the polymeric TSS by 38% (from Case A.1 to A.3 in Table 3) results in an increase in the parameter $Q_{\text{sol,use}}$ of only 8%. This indicates that increasing the size of the system has a rather small effect on $Q_{\text{sol,use}}$ at solar fractions in the order of 75%. However, increasing the solar collector area of the polymeric TSS by 38% in this way means that its solar fraction becomes equal to that of the reference system, Case A.1 in Table 2. As was expected the parameter $Q_{\text{sol,use}}$ is significantly lower when the continuous flow electric heater placed in the house is replaced by an electric rod heater placed in the storage tank of the TSS – by around 11% for the reference TSS and by as much as 40% in the case of the polymeric TSS.

4.3. Normalization as regards functional capability

To assess the difference in total cost between the polymeric TSS and the reference TSS their functional capabilities must most preferably be made equal, i.e. the term ΔC_{NIP} in Eq. (1) will then become equal to zero. This can be accomplished in two different ways.

The first is to adjust the size of the two systems so that their solar fractions will be the same. The second way is to adjust the energy of auxiliary heating so that the amount of heat that is effectively consumed by the users, *i.e.* Q_{use}, will be the same for the polymeric TSS and the reference TSS.

As both the polymeric TSS and the reference TSS are manufactured in modules with fixed dimensions, this means that the first way of normalization will result in a comparison between a real system and a hypothetical one and therefore the result of the comparison will become of more theoretical than of practical value. Furthermore the estimation of manufacturing cost will become very uncertain and the result therefore of minor practical interest.

The second way of normalization therefore was selected for the total cost comparison between the two TSS of the present study.

5. End user investment cost and O&M cost for the two systems

5.1. Estimation of end user cost

Assessment of end user investment cost of the two systems was complicated by the fact that none of the systems have been commercially introduced on the market yet. In case of the reference system its storage tank as well as its solar collector can separately be found on the market, but the complete TSS made of them is still in the prototype phase. The polymeric TSS is still in a development phase although prototypes of the system have been built and tested.

As guide in estimating end-user investment cost, the form shown in Table 4 was used. Not only production cost was taken into account but also reasonable surcharges for the manufacturer profit of the different parts of the system. Costs for transport to installer and to end-user were estimated and also reasonable surcharges to the distributor. Installation cost including profit to installer was then roughly estimated. Finely a VAT of 20% was added to arrive at a value for the end user investment cost.

The results obtained for the two systems are shown in Table 5. In Fig. 6 the end-user investment costs for the two systems are compared with typical ones for Southern parts of Europe. The estimated end-user investment cost of the polymeric TSS is comparable with those of the cheapest systems in the Southern of Europe, whereas the estimated end user investment cost for the reference TSS is in the same order of magnitude as the investment cost for an average TSS in the Southern part of Europe.

Table 2
Simulation results for the reference solar thermosiphon system.

Case	Aperture area (m^2)	Q_{sol} (MW h)	Q_{aux} (MW h)	Q_{use} (MW h)	SF (%)	$Q_{\text{sol,use}}$ (MW h)
A. Case with continuous flow electric heater placed in the house						
A.1	1.91	1.40	0.39	1.27	78.1	0.99
B. Case with an auxiliary electric rod heater placed in the tank						
B.1	1.91	1.34	0.57	1.25	70.2	0.88

Q_{sol} = energy transferred by the collector to the heat transfer fluid; Q_{aux} = energy from the build-in backup heater (continuous flow electric heater); Q_{use} = energy effectively consumed by the consumers; SF = solar fraction (%), *i.e.* $Q_{\text{sol}}/(Q_{\text{sol}} + Q_{\text{aux}})$; $Q_{\text{sol,use}} = 0.01$ ṡ SF ṡ Q_{use}.

Table 3
Simulation results for the polymeric solar thermosiphon system.

Case	Aperture area (m^2)	Q_{sol} (MW h)	Q_{aux} (MW h)	Q_{use} (MW h)	SF (%)	$Q_{sol,use}$ (MW h)
A. Case with continuous flow electric heater placed in the house						
A.1	1.97	1.30	0.52	1.26	71.6	0.91
A.2	2.21	1.38	0.48	1.26	74.0	0.93
A.3	2.71	1.51	0.42	1.27	78.1	0.99
B. Case with an auxiliary electric rod heater placed in the tank						
B.1	1.97	1.17	1.02	1.22	51.1	0.62
B.2	2.21	1.05	1.14	1.22	54.0	0.66

Q_{sol} = energy transferred by the collector to the heat transfer fluid; Q_{aux} = energy from the build-in backup heater (continuous flow electric heater); Q_{use} = energy effectively consumed by the consumers; SF = solar fraction (%), *i.e.* $Q_{sol}/(Q_{sol} + Q_{aux})$; $Q_{sol,use}$ = 0.01 ṡ SF ṡ Q_{use}.

Table 4
Form used as guide in estimating end user investment cost.

Actor	Process	Cost	Sell price to	Remark
Manufacturer	Collector			Cost would include 35% surcharge
	Tank			Cost would include 15% surcharge
	Mounting rack			Cost would includes 15% surcharge
	Transport			
	Packaging			
Distributor				Distributor
	Transport to installer			Cost would include 25% surcharge
Installer				Installer
	Commissioning			
	Mounting			
	Installation (piping)			
	Transport to end user			
End-user				Excluding VAT
	VAT			20%
End user				Including VAT
End user price per m^2 collector area				

5.2. Estimation of O&M costs

According to the report from the European Technology Platform on Renewable Heating and Cooling (Stryi-Hipp et al., 2012), the annual O&M cost of DHW systems in the Southern Europe is typically in the order of 1% of the end user investment cost of the system. As the TSS systems analysed in the present study were designed for the MENA region and Southern Europe markets, it seemed therefore reasonable to assume that the O&M cost would be in the same order too.

In the previous IEA SHC Task 39 total cost case study (Carlsson et al., 2014), it was assumed that the cost of maintenance corresponded to 1.5 €cent/kW h with reference to Stucki and Jungbluth (2010). If this number is recalculated and set in relation to the end user investment cost, it can be found that the number obtained is in the order of 1% of that cost too, at least for the reference TSS.

Stucki and Jungbluth assumed that the maintenance of the solar thermal system contained cleaning of the heat storage unit and the collectors, as well as controlling of the heat transfer medium every fifth year. The maintenance

Table 5
Estimated end user investment costs for the two solar thermosiphon. Value of $Q_{sol,use}$ for the reference TSS refers to Case A.1 in Table 2. Corresponding value for the polymeric TSS refers to Case A.1 in Table 3.

TSS system	Investment cost (€)	Investment cost/m^2 (€/m^2)	Investment cost/yearly $Q_{sol,use}$ (€/kW h)
Reference TSS	1366	683	1.38
Polymeric TSS	834	417	0.92

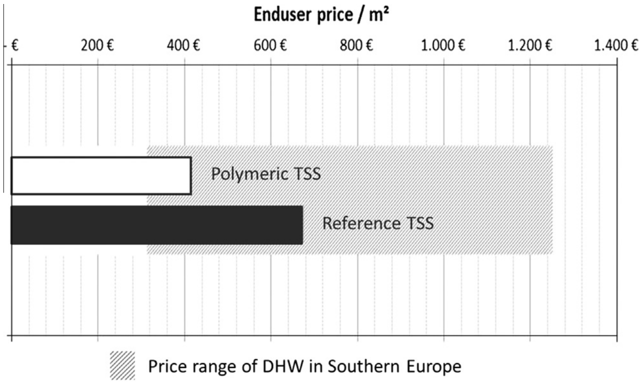


Fig. 6. The estimated end user investment costs for the polymeric TSS and for the reference TSS in relation to the range of end user prices that is reported for existing solar thermosiphon systems in Southern Europe (Stryi-Hipp et al., 2012).

required would therefore not be strongly dependent on the design of the system and the cost of maintenance would definitively not increase with the end user investment cost, we believed.

Consequently, it would be most reasonable for the purpose of the present study to consider the maintenance cost for the two TSS the same. Accordingly, the maintenance cost was set at 1.2 €cent/kW h for both systems. This value is the mean annual maintenance cost of the two TSS obtained from the data presented in Table 5 on the end user investment costs of the two systems.

6. Environmental and climatic performance of the two systems from life cycle analysis (LCA)

6.1. Models and life cycle inventory data for assessment of climatic and environmental performance and cost

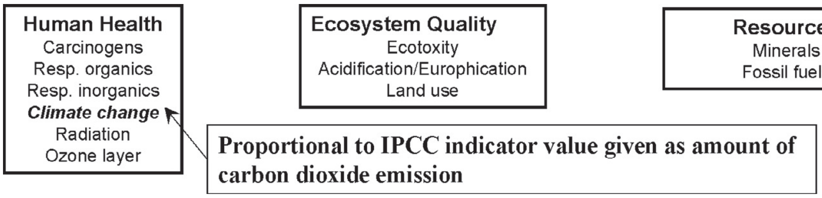
LCA was used as basis for estimating ecological risks and associated probable costs for ecological damage, *i.e.* ΔC_E in Eq. (1).

For assessment of ecological risk associated with climate change, the environmental impact indicator IPCC, 100a, see (Pachauri and Reisinger, 2007), available for a lot of standard materials and processes in most LCA softwares was used. Values for this indicator, which is expressed in terms of carbon dioxide emission, was also used to convert climatic performance into cost by making use of the EU carbon dioxide emission initial fee rate of 20 €/tonnes CO_2 from 2008 (EU TS, 2008). As a complement to this the present Swedish general tax rate for carbon dioxide emission rate of 117 €/tonnes (RIR, 2012), was also used to convert IPCC values for climatic performance into climatic cost, in accordance what was done in previous work by Carlsson et al. (2014).

In assessment of total environmental impact of technical systems by LCA many impact categories are needed to be taken into account. In the Ecoindicator 99 method (Goedkoop and Spriensma, 2010), which was adopted in the present study, the environmental impact is assessed in terms of damage to human health, ecosystem quality, and resources. As is illustrated in Fig. 7, each damage category includes a lot of subcategories so that most kinds of environmental damage are taken into account. Ecoindicator 99 values are also available for a lot of standard materials and processes in most LCA software programs.

Environmental impact according to Ecoindicator 99 is expressed in points, Pt, which can be related to the yearly environmental load or damage by one average European inhabitant in 1999 (Goedkoop and Spriensma, 2010). To convert an Ecoindicator 99 value into environmental cost, the same approach as used in the previous study by Carlsson et al. (2014) was used also in present study. The ratio between the value of the total Ecoindicator 99 in Pt and the corresponding damage to human health by climate change, also given in Pt, see Fig. 7 was first calculated. This factor was then used to convert the total Ecoindicator 99 value into environmental cost, by using the IPCC-based value for carbon dioxide emission and the associated EU carbon dioxide emission initial fee rate of 20 €/tonnes and as an alternative, the Swedish general tax rate for carbon dioxide emission rate of 117 €/tonnes (Carlsson et al., 2014).

For the LCA, the software SimaPro 7.3.0 (SimaPro, 2011) with the Ecoinvent version 2 database, see (Ecoinvent, 2008), was used so that the results would be comparable with those from the first total cost case study in IEA Task 39 (Carlsson et al., 2014). In the life cycle analysis standard inventory data for materials and processes representative for European conditions were selected if such data were available. Due to difficulties in defining



Carcinogens	Carcinogenic affects due to emissions of carcinogenic substances to air, water and soil.
Resp. organics	Respiratory effects resulting from summer smog, due to emissions of organic substances to air, causing respiratory effects.
Resp. inorganics	Respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air.
Climate change	Damage resulting from an increase of diseases and death caused by climate change.
Radiation	Damage resulting from radioactive radiation.
Ecotoxicity	Damage to ecosystem quality, as a result of emission of ecotoxic substances to air, water and soil.
Acidification/ Eutrophication	Damage to ecosystem quality, as a result of emission of acidifying substances to air, water and soil.
Land use	Damage as a result of either conversion of land or occupation of land.
Minerals	Resource depletion in minerals or ores, as a result of decreasing ore grades.
Fossil fuels	Resource depletion in fossil fuels, as a result of lower quality resources.

Fig. 7. Environmental damage categories that are taken into account by use of the environmental impact indicator Ecoindicator 99.

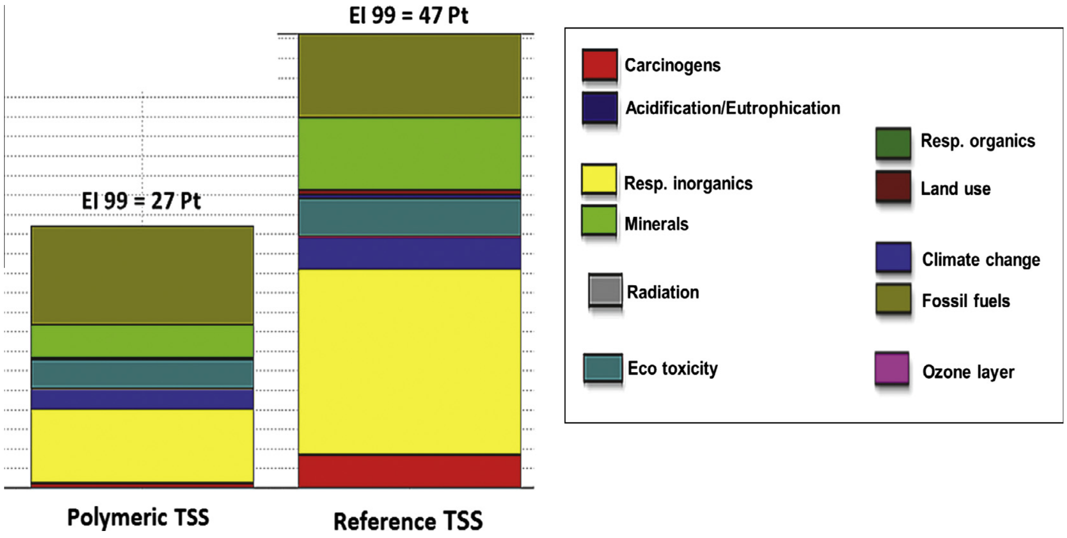


Fig. 8. Environmental impact from the assembly phase of the life cycles of two TSS illustrated in terms of the indicator Ecoindicator 99, H/A (EI99).

properly the transports needed for the manufacturing of the systems for the present study and because their total contributions to the total environmental load of the systems would be very small – less than 2% – the influence of transports on the environmental performance was not taken into account.

6.2. Results from life cycle analysis

The LCA results for the assembly phase of the life cycle of the two systems are shown in Fig. 8 and Table 6.

From the results in Fig. 8, it can be concluded that in terms of Ecoindicator 99, the polymeric TSS gives rise to an environmental impact load that is only 58% of that of the reference TSS. If the IPCC, 100a indicator and the cumulative energy demand indicator (CED), see e.g. (SimaPro 7.3.0, 2011), are used the corresponding ratios are 63% and 72%, respectively; see Table 6.

From Fig. 8 it can be understood that the dominating contribution to the Ecoindicator 99 value can be related to the negative effect on human health caused by resp. inorganics. In this respect the Polymeric TSS gives a value of only 40% compared to that of the reference TSS. It would be of interest to point out that 45% of the value for the reference TSS originates from use of low alloy steel and 12% from use of copper. The main contribution to the effect of resp. inorganic from the Polymeric TSS originates from the use of stainless steel and constitutes 62% of the total value for this damage category.

From Table 6 it can be concluded that in terms of Ecoindicator 99, the use of a stainless inner heat exchanger tank gives a contribution, which corresponds to 48% of the total Ecoindicator 99 value. The use of copper pipes in the solar collector of the reference TSS corresponds to 14% of the total Ecoindicator 99 value.

6.3. Assessment of climatic and environmental cost

In the calculation of climatic costs, CC, the indicator values of IPCC, 100a from Table 7 were used as starting point. Two different rates A and B for carbon dioxide emission were taken into account, namely:

Table 6
Environmental impact from the assembly phase of the life cycles of the two TSS expressed in terms of three different indicators.

	Solar collector	Tank	Frame	Total
EI 99 (Pt)				
Reference TSS	14 (Cu = 6.5)	28	4.5	47
Polymeric TSS	7	16 (IHET = 13)	3.5	27
IPCC, 100a (kg CO_2)				
Reference TSS	75	220	45	340
Polymeric TSS	96	96	25	217
CED (GJ)				
Reference TSS	1.3	1.6	0.9	5.5
Polymeric TSS	1.5	3.9	0.7	4.0

EI 99 = Ecoindicator 99 H/A; IPCC = CO_2 emission equivalents; CED = Cumulative Energy Demand; IHET = inner heat exchanger tank of stainless steel; Cu = contribution from copper pipes.

Table 7
Relative climatic, environmental and investment costs per useful amount of solar energy that can be taken advantage of during a service time period of 15 years.

System	CC (A) (€cent/kW h)	CC (B) (€cent/kW h)	EC (A) (€cent/kW h)	Invest C[a] (€cent/kW h)
Reference TSS	0.040	0.23	0.55	9.2
Polymeric TSS	0.020	0.12	0.34	6.1
Natural gas heating[a]		5.27[b]		

All costs are related to amount of useful solar heat during 15 years; CC (A) = Climatic cost based on the rate 2 €cent/kg CO_2; CC (B) = Climatic cost based on the rate 11.7 €cent/kg CO_2; EC (A) = Environmental cost based on the rate 2 €cent/kg CO_2 and use of Eq. (2); Invest C = End-user investment cost.

[a] Refers to end user investment cost per total amount of useful solar heat during 15 years.

[b] Data from first total cost case study of IEA SHC Task 39 based on the tax rate 11.7 €cent/kg CO_2 (Carlsson et al., 2014).

Case A: 2 €cent/kg CO_2 emitted according to EU trade rate (EU TS, 2008).
Case B: 11.7 €cent/kg CO_2 emitted according to general Swedish CO_2 emission tax rate (RIR, 2012).

As previously mentioned, the environmental cost (EC) based on Ecoindicator 99 (EI99) was estimated from data in Table 7 by using the following equation:

$$\text{EC} = (\text{Climatic cost}) \cdot (\text{EI99}_{\text{Tot}}/\text{EI99}_{\text{Climate change}}) \tag{2}$$

In Table 7 the climatic and the environmental costs obtained this way are presented per that useful amount of solar energy, i.e. $Q_{\text{sol,use}}$, that can be utilized for a service time period of 15 years. Data for $Q_{\text{sol,use}}$ have been taken from Table 2A and from Table 3A (valid for an aperture area of 1.97 m^2). Presented in Table 7 are also the corresponding end-user investment costs calculated from data presented in Tables 2, 3 and 5. As a comparison also corresponding data for natural gas heating taken from the Ecoinvent version 2 database (Ecoinvent, 2008) is also shown in the table.

In the calculations of climatic and environmental costs also the contribution from the maintenance of the systems should be taken into account. In the previous study (Carlsson et al., 2014) this was done by making use of a recommendation by Stucki and Jungbluth (2010) who assumed that the main contribution to the environmental impact from maintenance of a solar heating system originates from transport of service technicians. They assumed that the service technicians used a van every 5th year when they made their maintenance visits and at such an occasion travelled 50 km each time. In that case the contribution from maintenance to the climatic load was only 0.2% of the total climatic load per year. If the same assumption is made for the present study the contribution from maintenance will vary between 1.5% and 1.9% of the total climatic load per year, which seems relatively high in view of the fact that the cost for maintenance of a typical TSS in the southern Europe is generally considered to be around 1% of the end-user investment cost per year, as mentioned previously (Stryi-Hipp et al., 2012). As main part of the maintenance work is cleaning of the solar collector of the TSS and such work most probably would be done by some service agent company situated more near to the TSS than 250 km, we decided to exclude the contribution to the climatic load from maintenance in the present case. As we were mainly interested in the difference in climatic and environmental cost between the two systems this assumption was reasonable to make we believed.

The climatic cost and the environmental cost are very small compared to the end user investment cost as shown in Table 7. The climatic costs for the TSS systems are also very small when compared with that originating from natural gas heating.

7. Differences in reliability and long-term performance and importance of end-of-life cost

For typical DHW systems on the Southern European market, the technical service life is reported to be in the span between 15 and 20 years (Stryi-Hipp et al., 2012). In the assessment of the total cost of a system, a service time must be set according to Eq. (1). This would most preferably be as long as possible but not exceeding the technical service of the system. In the present study we therefore used two alternatives for the service time period, namely 15 and 20 years.

Regarding the Eq. (1) cost term for probable failures and damage at a service time period of 15 years, we found it reasonable to assume that this cost would be relatively small compared to other cost terms. Consequently, the difference in the cost term for probable failures and damage between the two systems would be even smaller and of insignificant importance in the comparison of the pros and cons of the two systems we believed. The same assumption had to be made also for the case of a service time of 20 years because we lacked the necessary information on the long-term performance of the systems.

The end-of-life cost of a system, which appears in Eq. (1), corresponds to the residual value of the system at the time when the service time considered just has passed. If the service time corresponds to the service life of the system its residual value can rather easily be estimated. The residual value amounts to the value of its materials minus the costs for disassembling and for waste treatment and for handling scrap for recycling, if the latter is possible to make use of. As a consequence the end-of life cost may be either positive or negative. From an end user perspective, the end-of-life cost would, we believe, be relatively small when the end-of-life time is equal to or longer than the service life. This means also that the difference in end-of-life cost between the two systems would be small and their influence on the difference in total cost can be ignored.

However, this is not true if the systems could be used for some time after the specified service time period has passed. But, in this case it is more difficult to assess their residual value as represented by the end-of-life cost term in the total cost expression.

It was, however, outside the scope of the present study to analyse in a more depth way the importance of the end-of-life cost in that respect. What we did was to assess the total cost at two different service time periods, to be able to compare the difference in total cost per energy units produced by the systems.

8. Analysis of costs and economical competiveness of systems

8.1. Model for estimation of present value total cost

Present value for capital cost and present value for O&M cost were calculated by use of Eq. (3) and of Eq. (4), respectively:

$$\text{Capital cost} = I \cdot a \cdot \left(\frac{d^{N+1}-1}{d-1}\right) \quad \text{with } d = 1/(1+z), \tag{3}$$

where I = investment cost, a = annuity factor, z = inflation rate per year, and N = number of years.

$$\text{O\&M cost} = E_0 \cdot \left(\frac{b^{N+1}-1}{b-1}\right) \quad \text{with} \quad b = \exp(x+z-z) \tag{4}$$

where E_0 = yearly O&M cost during first year, and x = net rate of increase in O&M cost.

In the analysis two cases were considered: (a) total cost of systems related to the useful solar energy produced by the TS systems, and (b) total cost of systems related to the total useful produced heat of the TS systems.

Calculations were made with two different values of the parameter N, *i.e.* $N = 15$ years and $N = 20$ years, and of the parameter x, *i.e.* $x = 0.025$ and $x = 0$. The inflation rate was assumed to be 2.5% per year. The interest rate was set at 5%, which gives annuity factors of 0.0963 ($N = 15$ years) and of 0.08038 ($N = 20$ years). Only systems with auxiliary heating by a continuous flow electric heater were considered in the calculations. Among the polymeric systems only the one with a solar collector aperture area of 1.97 m^2 was used in the calculations made.

8.2. Present value for total costs of energy from systems related to the useful solar energy produced by the TS systems

The results of the calculations are shown in Table 8 for the case when the total costs of systems are related to the useful solar energy produced by the TS systems. As seen in the table the present value for total cost of energy is significantly lower for the polymeric TSS when compared with the reference TSS, *i.e.* around 30%. It should be pointed out that the present value for cost of electric energy from Greece is 18.5 €cent/kW h, which value is obtained when Eq. (4) is applied for the case when $N = 15$ and $x = 0.025$ and the present price of electric energy in Greece of is 14.5 €cent/kW h according to the Europe's Energy Portal (2014). Consequently, in this particular case the present value total cost of solar energy compared to the present value total cost of electric energy is 28% lower when produced by the reference TSS and 49% lower when produced by the polymeric TSS.

The results in Table 8 reveal that the dominating contribution to the total cost of energy comes from the capital cost. The climatic cost contributes very little to the total

Table 8
Present values for total cost of energy when related to the useful solar energy produced by the TS systems.

A. Service time of 15 years (x = 0.025 and interest rate = 5%)				
System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
Reference TSS	11.8	1.55	0.04	13.4
Polymeric TSS	7.9	1.55	0.02	9.5
Difference	3.9	0	0.02	**3.9**
B. Service time of 20 years (x = 0.025 and interest rate = 5%)				
System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
Reference TSS	9.2	1.64	0.03	10.8
Polymeric TSS	6.1	1.64	0.02	7.8
Difference	3.1	0	0.01	**3.0**
C. Service time of 15 years (x = 0 and interest rate = 5%)				
System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
Reference TSS	11.8	1.2	0.04	13.0
Polymeric TSS	7.9	1.2	0.02	9.1
Difference	4.0	0	0.02	**3.9**

All costs are related to the amount of useful solar heat, i.e. $Q_{\text{sol,use}}$, presented in Tables 2 and 3.

[a] The maintenance cost has been calculated as described in Section 5.2 and by applying Eq. (4).

Table 9
Present value costs of energy from systems related to the total useful produced heat of the TS systems.

System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
A. Service time of 15 years (x = 0.025 and interest rate = 5%)				
Reference TSS	$9.3 + X$	6.8	$0.8 + Y$	$16.9 + X + Y$
Polymeric TSS	$5.7 + X$	8.7	$1.0 + Y$	$15.4 + X + Y$
Difference	3.6	−1.9	−0.2	**1.5**
B. Service time of 20 years (x = 0.025 and interest rate = 5%)				
System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
Reference TSS	$7.2 + X$	6.6	$0.8 + Y$	$14.6 + X + Y$
Polymeric TSS	$4.4 + X$	9.1	$1.1 + Y$	$14.6 + X + Y$
Difference	2.8	−2.5	−0.3	**0.0**
C. Service time of 15 years (x = 0 and interest rate = 5%)				
System	Capital cost (€cent/kW h)	O&M cost[a] (€cent/kW h)	Climatic cost (A) (€cent/kW h)	Total cost (€cent/kW h)
Reference TSS	$9.3 + X$	5.4	$0.6 + Y$	$15.3 + X + Y$
Polymeric TSS	$5.7 + X$	6.9	$0.8 + Y$	$13.4 + X + Y$
Difference	3.6	−1.5	−0.2	**1.9**

All costs are related to the total amount of heat demand, *i.e.* Q_{use}; X = end user investment cost of electric heater; Y = climatic cost for electric heater.

[a] The maintenance cost has been calculated as described in Section 5.2 and by applying Eq. (4). The operational cost has been calculated using the present electricity price in Greece of 14.5 €cent/kW h (Europe's Energy Portal, 2014). The present value of the electricity price is 18.4 €cent/kW h at $N = 15$ and $x = 0.025$.

cost. This would be true also when a carbon dioxide emission tax rate of 11.7 €cent/kg CO_2 is applied instead of the rate of 2 €cent/kg CO_2 used in the calculations of the results presented in Table 8.

8.3. Present value for total cost of energy from systems related to the total useful produced heat by the TS systems

When the present value for total energy cost is assessed for the total DHW systems including the solar heating system and the auxiliary electric heating system, the results are significantly changing and the difference in energy cost between the reference TSS and the polymeric TSS is becoming markedly reduced, as is illustrated in Table 9.

The main reason for the difference in results you can observe when comparing the data in Tables 8 and 9 can be related to the difference you have between the polymeric TSS and the reference TSS with respect to thermal performance. In the case considered, the solar fraction for the reference TSS is equal to 78.1% and for the polymeric TSS equal to 71.8%. This difference of about 6% in solar fraction units gives rise to a difference in the present values for total energy cost between the two systems that is about 9%; see Table 8A.

However, as can be seen for Table 9B, this difference can be even much less if the service time is extended from 15 years to 20 years. It should be pointed out that the capital cost for the polymeric solar system is only around 35–40% when related to that of the reference system. However, the operational cost and also the climatic cost become higher for the combined polymeric TSS compared to the combined reference TSS. It can be concluded that the choice of auxiliary heating source is of utmost importance for the economical competiveness of systems. Electric heating seems not the best choice in the present case.

9. Conclusions

To assess the suitability of a polymer based solar thermosiphon system (TSS), one such system (the Aventa TSS) was selected and compared with a high efficient reference thermosiphon system in which traditional materials (metals instead of polymeric materials) are used. For the comparison, a total cost accounting approach was adopted, which involved the analysis of differences in thermal performance, end-user investment costs, operation and maintenance (O&M) costs, reliability and long-term performance, of climatic and environmental performance, and the performance of the auxiliary heat source. Both thermosiphon systems were analysed on the assumption that they were installed in a one-family house in Athens, Greece.

By making use of computer simulation, the yearly solar fractions for the two systems were calculated and also calculated were the yearly amounts of energy from the auxiliary heaters that were needed to meet the heat demand for DHW in the considered application. When considering a case when the solar collector areas are the same, 2 m^2, the reference TSS performs better compared to the polymeric TSS in terms of solar fraction. The solar fraction for the reference TSS is also higher than that of most other TSS on the market and this system can therefore be considered as a high efficient system. The difference in the useful solar energy that is effectively consumed between the polymeric TSS and the reference TSS is in order of 8%. However, increasing the solar collector area of the polymeric TSS by 38% means that the solar fraction becomes equal to that of the reference system.

To assess the difference in total cost of energy between the polymeric TSS and the reference TSS their functional capabilities must be made equal and this can be accomplished in two different ways: (1) by adjusting the size of the collector areas of the two systems so that their solar fractions will be the same or (2) to compare one polymeric TSS with one reference system, that both contain electric auxiliary heating devices that gives the same amount of heat that can effectively be consumed for hot water production. As both the polymeric TSS and the reference TSS is manufactured in modules with fixed dimensions, this means that the first way of normalization will result in a comparison between a real system and a hypothetical one and therefore the result of the comparison will become of more theoretical than of practical value. The second way of normalization therefore was selected for the total cost comparison between the two TSS made in the present study.

In the estimation of the end-user investment cost not only production cost was taken into account but also reasonable surcharges for distributor and installer, for transport and installation. The estimated end-user investment cost of the polymeric TSS, at around 420 €/m^2, is comparable with those of the cheapest systems in the Southern of Europe, whereas the estimated end-user investment cost for the reference TSS, at around 680 €/m^2 is in the same order as what you have to pay for an average TSS in the Southern part of Europe.

Assessment of climatic and environmental performance and associated costs was made by life cycle analysis LCA making use of standard inventory data from the version 2 Ecoinvent database. For this assessment inventory data representative for Europe were used. The LCA results clearly indicate that a replacement of traditional materials, e.g. metals, with polymeric materials increases the climatic and environmental performance significantly, when they are expressed in terms of the IPCC,100a indicator and the Ecoindicator 99, H/A indicator. In terms of climatic and environmental costs per amount of solar heat collected, this difference, however, seems not that important compared to other cost terms. When present day carbon dioxide emission tax rates, e.g. 2 €cent/kg CO_2 or 11.7 €cent/kg CO_2, are used to convert climatic performance into climatic costs and a comparison is made with existing energy prices, the climatic cost per solar heat collected is small i.e. 0.02 €cent/kW h for the polymeric TSS and 0.04 €cent/kW h at a tax rate of 2 €cent/kg CO_2. The corresponding climatic cost for natural gas heating is around 0.9 €cent/kW h.

Present values for total energy cost for the two thermosiphon systems were estimated for service time periods of 15 years and 20 years. It was found that the present values for total cost of energy, when it is supplied in the form of solar energy only, is significantly lower, around 30%, for the polymeric TSS when compared with that provided by the reference TSS. The present value cost of solar energy is also considerably lower than that of electric energy from Greece.

When the present values for total cost are assessed for the total DWH systems including both the solar heating system and the auxiliary electric heating system, the results are significantly changing. The difference in cost between the reference TSS and the polymeric TSS is becoming markedly reduced. The main reason for the difference in results can be related to the difference you have in thermal performance between the two systems. It was found that the much lower capital cost of the polymeric solar system related to that of the reference system is not so important for the energy costs of the combined solar electric heating system in the present study. It can be concluded that the choice of auxiliary heating source is of utmost importance for the economical competiveness of systems and that electric heating seems not the best choice in the present case.

Acknowledgements

This study was financed by the Swedish Energy Agency (Project number 32462-1), by the Research Council of Norway's programme ENERGIX (Project number 208795) and by the Austrian Federal Ministry of Transport, Innovation and Technology (FFG project number 832761).

The study was part of the research of Task 39 of the IEA Solar Heating and Cooling Program and for valuable support to this study the participants of Task 39 and in particular Regine Weiß and Andreas Piekarczyk from Fhg ISE, Germany are gratefully acknowledged. Further the authors kindly acknowledge valuable inputs from the project SCOOP, which has received funding from the European Union's Seventh Program for research, technological development and demonstration under grant agreement No. 282638.

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