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A total cost perspective on use of polymeric materials in solar collectors – Importance of environmental performance on suitability

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HIGHLIGHTS

- A polymeric solar collector system was compared with two traditional ones.
- It was found the best in terms of climatic performance per solar heat collected.
- The differences in climatic cost between the systems compared however are small.
- The low climatic cost makes solar heating better compared to natural gas heating.
- Use of Ecoindicator 99 for environmental cost makes solar heating even better.

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ABSTRACT

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 was undertaken. In this 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. To make the comparison, a total cost accounting approach was adopted. The life cycle assessment (LCA) results clearly indicated that the polymeric solar collector system is the best as regards climatic and environmental performance when they are expressed in terms of the IPPC 100 a indicator and the Ecoindicator 99, H/A indicator, respectively. In terms of climatic and environmental costs per amount of solar heat collected, the differences between the three kinds of collector systems were small when compared with existing energy prices. With the present tax rates, it seems unlikely that the differences in environmental and climatic costs will have any significant influence on which system is the most favoured, from a total cost point of view. In the choice between a renewable heat source and a heat source based on the use of a fossil fuel, the conclusion was that for climatic performance to be an important economic factor, the tax or trade rate of carbon dioxide emissions must be increased significantly, given the initial EU carbon dioxide emission trade rate. The rate would need to be at least of the same order of magnitude as the general carbon dioxide emission tax rate used in Sweden. If environmental costs took into account not only the greenhouse effect but also other mechanisms for damaging the environment as, for example, the environmental impact factor Ecoindicator 99 does, the viability of solar heating versus that of a natural gas heating system would be much higher.

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. Intense research and development is being conducted on this use of polymeric materials in Task 39 of the IEA Solar Heating and Cooling Programme [1,2]. The economic viability of solar collector systems is strongly linked to thermal performance and to investment costs, and an attractive approach to cost reduction would be to replace glass and metal parts with less expensive, lighter weight polymeric components. However, the use of polymeric materials in solar technologies is still very limited because the applicability and the durability of these materials are often questioned. Because today's solar heating systems

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need to function for a long period, at least 25 years, the requirements for adequate materials durability may be hard to meet. As environmental concern is the most important incentive for installing a solar heating system today, the design concept chosen for the system must also be environmentally friendly and, in this context, polymeric materials are in general considered more suitable than other materials such as metals.

To take into account all the relevant factors for materials selection in designing a solar heating system, it would be best to take a holistic view. This would allow for simultaneously considering not only functional quality and cost effectiveness, but also reliability, long-term performance, ecological soundness, and recoverability. Consequently, a total cost accounting approach could therefore preferably be adopted. Such an analysis has not, to the knowledge of the authors, been done before [2].

A total cost accounting approach 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. 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; see, for example, [3,4].

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 (C_{RT}) associated with maintaining a specific function defined for the functional unit is estimated from

$$C_{RT} = C_{RP} + C_{RNIP} + C_{RO\&M} + C_{RF} + C_{REoL} + C_{RE} + C_{RD} \tag{1}$$

where C_{RP} = the difference in production cost between the two design alternatives; C_{RNIP} = the difference in cost associated with initial non-ideal function or performance between the two design alternatives; $C_{RO\&M}$ = the difference in operational and maintenance cost between the two design alternatives; C_{RF} = the difference in cost of probable failures and damage between the two design alternatives; C_{REoL} = the difference in end-of-life costs between the two design alternatives; C_{RE} = the difference in environmental cost associated with probable ecological damage between the two design alternatives; and C_{RD} = the difference in development cost between the two design alternatives.

Detailed information on the assessment of how the different cost terms that contribute to the total cost can be found in a previous work by Carlsson [3,4].

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

Within the framework of the IEA Solar Heating and Cooling Program Task 39 Polymeric Materials for Solar Thermal Applications, a case study therefore was undertaken to assess the suitability of solar collector systems with polymeric materials against solar collector systems using more traditional materials.

Three solar heating systems were selected for study:

- a solar heating system with polymeric flat plate solar collectors manufactured by Aventa [5] (system A);
- a solar heating system with flat plate collector with copper absorber, the New Nr. 2 system according to [6] (system B); and
- a solar heating system with evacuated tube collector, the New Nr. 8 system according to [6] (system C).

Data on the characteristics of system A were gathered mainly from the company Aventa [5], which participates in the work of Task 39. A general description of the polymeric collector and the corresponding solar heating system design is given in [2]. One of the main characteristics of the polymeric solar heating concept is that the collector loop contains pure water without additives, is not pressurised but open to atmospheric pressure. The collectors are part of a drain-back system. Favourable applications for this concept are combined solar heating systems for domestic hot water (DHW) preparation and space heating or DHW systems with large heat demand and relative low system temperature.

Systems B and C were chosen as reference systems because their characteristics are well described in the report by Stucki and Jungbluth [6].

To make a total costs comparison between the systems, it is essential first to adjust the size of the different systems so that their functional capability in the initial phase will be the same, in other words, C_{RNIP} becomes equal to zero in Eq. (1). This means that the different systems have to be compared when placed at the same location delivering the same amount of solar heat to cover the energy demand for the same kind of building. Resizing the three systems was therefore the first step in the analysis.

The next steps were (1) assessment of the difference in environmental and climatic performance of the three systems by life cycle analysis (LCA); (2) analysis of the three systems with respect to differences in investment costs, O&M costs, and end-of-life costs; and (3) analysis of the three systems with respect to differences in reliability and long-term performance.

2. Dimensioning of an equivalent set of solar combi systems with respect to functional capability

For the analysis, a typical Swedish one-family house from 1980 in Stockholm was used. The yearly heat demand for space heating was set at 30 MW h and the yearly hot water demand was set at 4.57 MW h, corresponding to 200 l of hot water a day. A wood pellet heating system was selected as an auxiliary heat source.

For assessment of thermal performance, the system simulation tool TRNSYS, developed by Klein et al. at the Solar Energy Laboratory at the University of Wisconsin, USA, was used [7]. TRNSYS contains a number of types (previously written programs that describe components) that can be connected to each other to form complete heating systems. Types representing a variety of components for modelling of heating systems are presently available from TRNSYS [8]. To fulfil the purpose of the present study, a set of suitable types and connections between them were selected to form a solar heating system.

The relatively simple type 12c was considered most suitable to describe the house based on the results of a previous study [9]. Type 12 is a simple degree-day, single-zone, single capacitance building model with internal gains. The model creates a heating need by using an effective heat capacity for the entire building together with the difference between indoor and outdoor climate.

The tank was modelled by use of Type 534; see [8]. For all solar heating systems studied, the same kind of tank was used with a volume of 1000 litre and a heat loss coefficient of 3 kJ/h,m^2,K. The tank is treated as stratified with five nodes or temperature zones interacting adiabatically with each other. To model the hot water system, Type 38-2 was used [8]. Weather data file from Meteonorm, modelled by use of Type 15, and valid for Stockholm was adopted. Within Type 15, the angle to the horizontal plane and the azimuth of the solar collector were defined as 45 degrees and 0 degrees, respectively. The model used for the solar collector was Type 136 [10]. Type 136 is a further development of the earlier Type 132 in TRNSYS 15. It takes into account the contribution of

Table 1
Performance data for the three equivalent solar heating systems A, B, and C.

Solar heating system	Solar collector parameters			Solar collector area (m^2)	Solar heat produced (MW h/year)
	a_1 (W/m^2 K)	a_2 (W/m^2 K^2)	η_0		
Polymeric collector (A)	3.0	0.035	0.78	15.0	4.89
Reference flat plate collector (B)[a]	3.8	0.013	0.815	12.8	4.88
Reference evacuated tube collector (C)[b]	1.2	0.008	0.755	8.2	4.90

[a] Soltop Cobra Evo 2.8 [13].
[b] Thermomax Mazdon 30 [14].

condensation, long-wave radiation, and wind to the thermal performance of the solar collector. The TRNSYS model is written in a way that can easily be adapted to the parameters in the EN12975 standard. A detailed description of the model's mathematics can be found in [11]. The model was originally designed for flat-plate solar collectors, but may also be applicable to evacuated tube collectors. The control strategy was defined as follows: When the outlet temperature sensor indicated that its temperature was more than 5 °C above the temperature in lowest part of the tank, the circulation pump in the solar collector loop was started. It was turned off when the mean tank temperature exceeded 90 °C. When the temperature at the top of the tank exceeded 60 °C, the wood pellets heater was turned off. The wood pellets heater was modelled by the simple Type 6 [8]. Values for the parameters, *i.e.* h_0, a_1, a_2, for the Aventa Solar collector were obtained from the manufacturer [4]; see Table 1. Corresponding parameter values for the collectors of the reference solar systems were derived from data of the collectors mentioned in a previous Ecoinvent LCA report by Jungbluth [12] and in two test reports from SPF Rapperswil, CH [13,14]; see Table 1. To assess the three equivalent solar heating systems in terms of the amount of solar heat collected, it was firstly assumed that the solar collector area of the polymeric system A was 15 m^2. Detailed information on the design, materials used, associated manufacturing processes, and transport characteristics for this system was available from the manufacturer. The yearly quantity of solar heat this system could supply to the reference building was first assessed, using TRNSYS. Next, two series of similar calculations were made for the corresponding solar heating systems equipped with the two reference collectors systems B and C to find the size of solar collector area that could produce the same quantity of solar heat to the reference building as the polymeric system A. The results are presented in Table 1.

Detailed information about materials used, manufacturing processes, and associated transport characteristics of the reference solar heating systems B and C can be found in the report by Stucki and Jungbluth [6]. However, in the case of the flat plate solar collector alternative, System B, data are given for a system with a solar collector area of 12 m^2 and in the case of the evacuated tube solar collector alternative, System C, for a system with a solar collector area of 10.5 m^2. Consequently, in the flat plate alternative, the solar collector area is very close to the one presented in Table 1. In the case of the evacuated tube collector the difference is more significant, slightly above 20%.

As can be observed from Table 1, the solar collector area required for the reference flat plate solar collector system is 85% of an equivalent solar heating system with the polymeric solar collector system. The corresponding area for the reference evacuated solar collector system is 55%. If, however, the yearly space heating demand of the house is reduced by as much as 83%, from 30 MW h to 5 MW h, the change in the required solar collector areas for the two equivalent reference systems B and C is only marginally altered. For the reference flat plate solar collector system, the required solar collector area changes from 85% to 81% relative to that of the polymeric solar collector system. In case of the evacuated tube solar collector system C, the corresponding change is from 55% to 45%. The yearly quantity of solar heat produced by the systems is reduced from 4.89 MW h to 4.30 MW h when the solar collector area for the polymeric solar collector system is 15 m^2.

If the set tank top temperature at which the pellet boiler is turned off is changed from 60 °C to 50 °C at a space heating demand of 5 MW h, the order of magnitude of the changes in the required solar collector areas is much the same as the case shown in Table 1. For the reference flat plate solar collector system and reference evacuated solar collector system, the required areas are 85% and 55%, respectively, and the yearly quantity of solar heat produced becomes 4.99 MW h. However, reducing the set tank top temperature from 60 °C to 50 °C would require a device to protect against legionella growing in the system.

3. Assessment of environmental and climatic performance by life cycle analysis (LCA)

3.1. Introduction

LCA was used to estimate the ecological risks and associated probable costs for ecological damage, C_{RE} in Eq. (1). The IPCC indicator 100a [15] is used most frequently to assess the climatic performance of energy producing systems. The result is expressed as the amount of greenhouse gases emitted into the atmosphere during production of one energy unit as, for example, kg CO_2 equivalents per 1 MJ of energy produced. We believe that translating this indicator into cost, the rate for greenhouse gas emission trading in the EU [16] would, at least in principle, be applicable, but, this has not yet been done in connection with product design, as far as we know. Using the proposed rate for greenhouse emission trading in the EU of 20 €/tonnes of carbon dioxide emission, which was representative for the first half of 2008, we converted the values for the IPCC indicator into cost. The Swedish general carbon dioxide emission tax was also used for converting the IPCC indicator into cost. This rate is 117 €/tonnes of carbon dioxide emission [17].

In the assessment of environmental impact by LCA, technical systems are generally considered in a broader sense. In the Ecoindicator 99 method [18], the environmental impact is assessed in terms of damage to human health, ecosystem quality, and resources.

The category of damage to human health comprises effects related to emissions of carcinogens, respiratory organics, and respiratory inorganics. In addition, the effects on human health related to climate change, nuclear radiation, and ozone layer depletion are included. Damage to human health is expressed as the number of life years lost and the number of years lived with a disability. These are combined as disability-adjusted life years (DALYs), an index also used by the World Bank and WHO. The category of damage to ecosystem quality comprises effects related to ecotoxicity, acidification/*eutrophication*, and land use. Damage to ecosystem quality is expressed as the loss of species over a certain area, during a certain time (PDF m^2 year). The category of damage to resources relates to depletion in natural resources in minerals and fossil

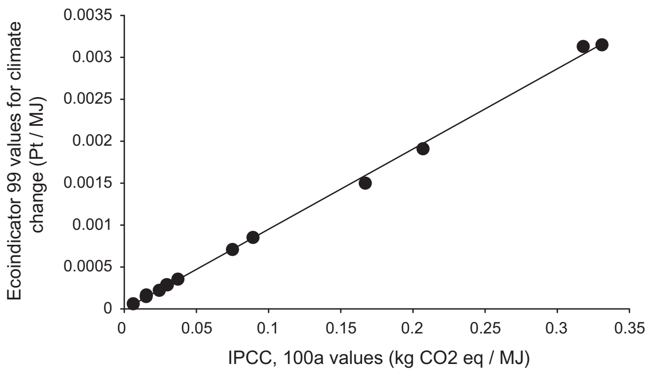

Fig. 1. Values for damage to human health by climatic change according to Ecoindicator 99 plotted versus corresponding values for IPCC, 100a, for a variety of energy systems related to production of 1 MJ of heat or electricity. The plot is based upon Ecoinvent data [18] for use of electricity in different countries of Europe, production of heat from hard coal, light oil, natural gas, wood pellets, wooden chips, and production of heat by heat pumps.

fuels. Damage to resources is expressed as the surplus energy needed for future extraction of minerals and fossil fuels (MJ surplus energy). The overall environmental impact Ecoindicator 99 then relates to the yearly environmental load or damage by one average European inhabitant and is expressed in points, Pt. To convert the Ecoindicator 99 value into cost, an approach similar to Carlsson's [3] was used. In converting the contribution from the other damage categories of Ecoindicator 99, the starting point was data representing damage to human health caused by climate change. 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, was first calculated. This factor was then used to convert the total Ecoindicator 99 value into 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; see above.

How well the values for indicator IPCC 100 a correlate with corresponding Ecoindicator 99 values for damage to human health related to climate change is illustrated in Fig. 1. Data used for the correlation plot represent various kinds of energy systems related to the production of 1 MJ of heat or electricity and were taken from the Ecoinvent data base [19]. There are data for use of electricity in different countries of Europe, production of heat from hard coal, light oil, natural gas, wood pellets, wooden chips, and the production of heat by heat pumps. As can be seen, the two sets of data correlate nicely, which would be expected. Consequently, it makes sense to express total Ecoindicator 99 values in cost terms via the IPCC 100a indicator.

A general advantage of expressing environmental impact in terms of cost is that it can be compared with other kinds of costs associated with conduct of a product life cycle. The advantage of using Ecoindicator 99 as meter for environmental impact expressed in cost terms is that it follows the price of carbon emission trading in the EU or, if more relevant, the general carbon dioxide emission tax rate used in a certain country.

3.2. Comparison in environmental performance of the solar collectors

The environmental performance differed significantly between the different solar collectors as shown in Tables 2–4 and Fig. 2, clearly indicating that the polymeric solar collector performs best. In terms of Ecoindicator 99, its environmental impact is only 31%, in comparison to the reference flat plate solar collector and 35% in comparison to the evacuated tube solar collector. However, if secondary metals, made from recycled metals, instead of primary metals are used, the environmental impact is significantly reduced. As a consequence of recycling metals, the Ecoindicator 99 values are reduced by a factor of nearly two. In this case, in terms of Ecoindicator 99, the environmental impact of the polymeric solar collector is 47% when related to the reference flat plate collector and 44% when related to the evacuated tube collector.

Metallic copper make the largest contribution to the environmental load for the reference flat plate solar collector, a contribution of 47% of the total impact from the collector. However, if secondary copper instead of primary copper is used, its contribution to the environmental load of the collector is reduced to 23%. Use of metallic copper makes a contribution to the environmental load from the evacuated tube collector that is even higher.

Metallic aluminium also gives rise to a very high environmental load, but it can be reduced significantly when secondary instead of primary metal is used; in the present case, a mixture of 90% primary and 10% secondary metal was first used and, in terms of Ecoindicator 99, this resulted in a reduction of 78%.

Stainless steel 18/8 also makes a high environmental impact, but, it can be reduced significantly if secondary steel can be used. The reduction would be by 40% in terms of Ecoindicator 99 and nearly 80% in the cumulative energy demand indicator (CED) [20].

When compared with metals, the polymeric materials used in the solar heating system A collector significantly reduce the environmental impact of the collector. In principle, they would be recyclable but this possibility was not taken into account in the present study. When compared with contributions from processing and transport, materials make the greatest contribution to the environmental load.

Table 2
Main contributions to the environmental performance, Ecoindicator 99, H/A (EI99) (>2%) of 1 m^2 of the reference flat plate solar collector with copper absorber using data from Stucki and Jungbluth [6] and the Ecoinvent database in SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED, cumulative energy demand, are also shown.

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Copper (absorber and tubing	3.0 kg	8.1 (1.8[a])		6.1 (5.7)[a]	0.11 (0.09)[a]
Aluminium (collector frame)	3.9 kg	4.0 (0.9[a])		43.5 (8.7[a])	0.69 (0.14[a])
Soft solder	0.059 kg	1.3		(<2%)	(<2%)
Solar glass	9.1 kg	1.0		6.1	0.14
Sheet rolling	2.8 kg	0.5		3.4	0.07
Transport lorry	28.4 tkm	0.4		3.5	0.06
Rock wool	2.45 kg	0.5		3.8	0.06
Propylene glycol	0.88 kg	0.3		3.7	0.09
Synthetic rubber	0.76 kg	0.3		2.0	0.07
Rest		0.8		16.9	0.29
Total		17.2 (7.8[a])	5.0 (6.6[a])	89 (54[a])	1.6 (1.0[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. Values for EI99CC have roughly been estimated from the relation shown in Fig. 1.

Table 3
Main contributions to the environmental performance Ecoindicator 99, H/A (EI99) (>1.5%) of 1 m^2 of the reference evacuated tube solar collector based on data from Stucki and Jungbluth [6] and the Ecoinvent database in SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED are also shown.

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Copper (absorber and tubing)	3.0 kg	8.1 (1.8[a])		6.1 (5.7[a])	0.11 (0.09[a])
Chromium steel (construction part)	1.1 kg	1.6 (1.0[a])[c]		6.0 (4.4[a])[d]	0.10 (0.06[a])[d]
Glass tube	14.2 kg	3.3		35.0	0.59
Sheet rolling	2.8 kg	0.5		3.4	0.07
Transport lorry	21.6 tkm	0.4		2.7	0.05
Rock wool	2.21 kg	0.4		3.4	0.05
Synthetic rubber	0.7 kg	0.3		1.9	0.05
Corrugated board	3.3 kg	0.3		3.2	0.08
Solar collector factory		0.1		0.7	0.01
Rest		0.3		12.1	0.35
Total		15.3 (8.4[a])	4.7 (8.3[a])	74.5 (72.5[a])	1.46 (1.40[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. Values for EI99 CC have roughly been estimated from the relation shown in Fig. 1.
[c] Roughly estimated values.
[d] Based upon data from [20].

Table 4
Main contributions to the environmental performance Ecoindicator 99, H/A (EI99) (>2%) of 1 m^2 of the polymeric collector evaluated by data on used materials reported by Aventa [5] and environmental impact characteristics from SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED are also shown.

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Polycarbonate (glazing)	1.9 kg	1.2		14.7	0.20
PPS (absorber)	2.7 kg	0.5		6.0	0.38
Aluminium (frame)	2.8 kg	2.2 (0.48[a])		24.1 (4.8[a])	0.38 (0.08[a])
Rock wool	0.8 kg	0.2		1.2	0.02
Extrusion plastic	4.4 kg	0.2		2.3	0.05
Solar collector factory		0.1		(<2%)	(<2%)
Transport lorry	10.6 tkm	0.2		1.3	0.02
Rest		0.8		6.5	0.03
Total		5.4 (3.7[a])	10 (10[a])	56.1 (36.8[a])	1.08 (0.78[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. Values for EI99CC have roughly been estimated from the relation shown in Fig. 1.

3.3. Comparison in environmental performance of the three equivalent solar heating system life cycles

In Tables 5–7 and Fig. 3, the environmental performance data for the three equivalent solar heating system life cycles are shown. In each system, the solar collector area has been set so all systems produce the same amount of solar heat during their service time, which was set at 25 years (Table 1).

The environmental performance also differs significantly between the different solar heating systems, in this case. Even though the solar collector area is larger for the system with the polymeric solar collector, it is still the best. In terms of Ecoindicator 99, its environmental impact is 68% when compared to the reference flat plate solar collector system and 90% when compared to the evacuated tube solar collector system. When secondary instead of primary metals are used, the environmental impact of the polymeric solar collector system is, in terms of the Ecoindicator 99 indicator 73% when compared to the reference flat plate collector solar heating system and 85% when compared to the evacuated tube collector system.

When assessing the total environmental load from the solar heating systems B and C, the following assumptions were made:

Stucki and Jungbuth [6] report environmental data for a heat storage unit with a volume of 2 m^3. We recalculated their data to a storage volume of 1 m^3 by assuming that the relative amount of a certain material in the 1 m^3 tank is $(1/\sqrt{2})$ of that in the 2 m^3 tank. In the recalculation of the data from Stucki and Jungbluth concerning piping materials, the amount of aluminium in the collector frames and the amount of propylene glycol, it was assumed that the amounts were proportional to the solar collector area. Thus, for the new reference flat plate solar collector system, the amounts were 12.8/12 relative to the corresponding amounts of those materials in the reference system specified by Stucki and Jungbluth. Accordingly, for the new reference evacuated solar collector system, the corresponding conversion factor was 8.2/10.5.

As seen, when comparing the data in Table 5 to that in Table 7, the environmental data that exclude the contribution from the solar collectors and the heat storage tanks are very much the same. There are differences concerning the contributions from the storage tanks in that the polymeric solar heating system A uses a heat storage tank of stainless steel while the heat storage tank in the reference systems B and C is made of low alloy steel and a small amount of stainless steel. Moreover, the polymeric solar heating system A does not have aluminium frames around the collector which the reference systems B and C have. In the reference systems, propylene glycol is used as heat transfer medium whereas in the polymeric solar heating system water is the heat transfer fluid. However, the contribution made by piping in the polymeric solar heating system A to the environmental impact seems underestimated, when compared with the corresponding contributions of the reference systems B and C.

From the results in Tables 5 to 7, it can further be concluded that the environmental load of the solar heating systems can be attributed mainly to the manufacturing phase of the solar heating systems and their parts. The contributions from the service phase vary between 11% and 16% for the different systems if mainly primary metals are used, and between 18% and 25% when secondary metals are used.

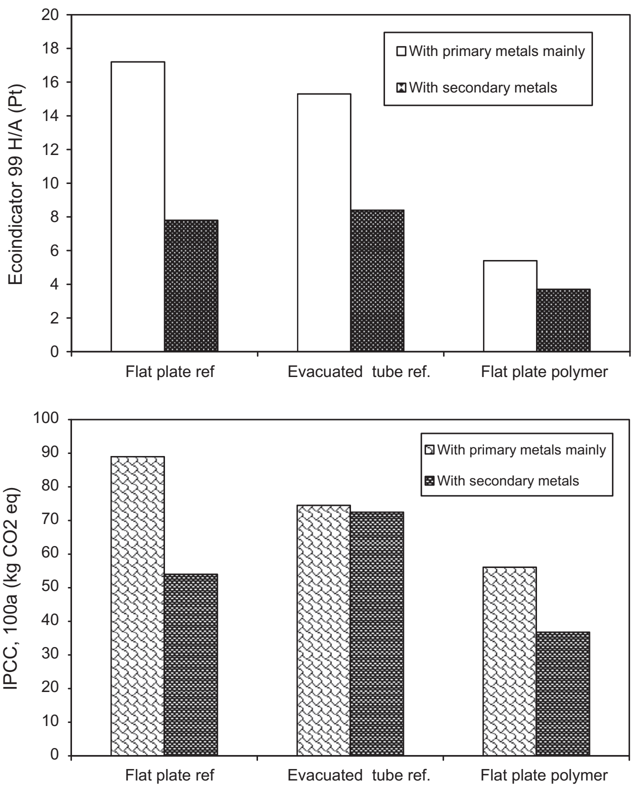

Fig. 2. Comparison of environmental impact of 1 m^2 of the three solar collectors with the use of primary metals and of secondary metals as an alternative. Upper diagram: Ecoindicator 99, H/A values; lower diagram: IPCC, 100a values.

Information from Stucki and Jungbluth [6] was used in estimating the contribution to environmental load from maintenance of the solar thermal systems. In their study, maintenance included cleaning the heat storage tank and the collectors and control of the heat transfer medium. They also assumed that maintenance involved travelling by van for 50 km every 5 years.

The need for maintenance may vary widely, but, to simplify the comparison in environmental performance between the systems, it was assumed that the contribution for maintenance was the same for all three systems.

The electricity demand for the circulation pump and the control units in the systems was set at the same level as that used by Stucki and Jungbluth. They assumed that the energy need of electricity amounts to around 2% of the solar energy collected by the systems. In our study, we assumed that the electricity used was a Swedish electricity mix that includes imported electricity. When the Ecoindicator 99 indicator is used, the contribution of electricity to the total environmental load is around 10%. If the IPCC indicator is used, the corresponding contribution is between 11% and 15%. However, if electricity mix from another country is used, for example from Germany, the contribution increases by a factor of two if Ecoindicator 99 is used, and by a factor of around 7 when the IPCC indicator is used.

The energy payback concept is sometimes used in comparing different energy systems, and for that the cumulative energy demand indicator CED is used. This indicator sums up all the energy needed to manufacture and maintain a specific system life cycle as regards functional capability. The energy payback periods obtained from this approach are shown in Table 8. As can be seen, the polymeric solar heating system A system is also the best in terms of energy payback period.

3.4. Differences in environmental life cycle cost

As mentioned, the climatic and environmental performance can be translated into cost terms. In our study firstly, the IPCC indicator reflecting climatic performance was translated into cost by using the EU carbon dioxide emission trading rate and the Swedish general carbon dioxide emission tax rate [17]. Then, those climatic costs were converted into total environmental costs by using the Ecoindicator 99 indicator. These cost data are shown in Tables 9 and 10, respectively.

In terms of climatic cost for the collectors, the differences between the three systems are small and this is particularly true in the cases when secondary instead of primary metals are used. Relative to the reference flat plate collector system B, the climatic cost of the polymeric solar heating system A is 36% lower in the first case and 25% lower in the second case. Per kW h of solar heat collected, this difference is at most equal to 0.0050 € cent if the EU trading rate is used and 0.029 € cent when the Swedish general tax rate for carbon dioxide emission is used. When the differences in the total environmental costs are considered, however, the

Table 5
Estimated main contributions to the environmental performance Ecoindicator 99, H/A (EI99) of the reference flat plate solar collector system with copper absorber based on data from Stucki and Jungbluth [6] and the Ecoinvent database in SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED are also shown. Information on service transport and electricity need are based on data from Stucki and Jungbluth [6].

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Solar collector (12.8 m^2)	(see Table 2)	220 (100[a])		1140 (692[a])	20.5 (12.8[a])
Heat storage (1 m^3)		104 (68[a,d])		587 (387[a,d])	10.9 (5.9[a,d])
Stainless steel	*24.7 kg*	*35.0*		*130*	*2.2*
Low alloy steel	*216 kg*	*60.0*		*380*	*6.2*
Circulation pump		4		15	0.2
Expansion vessel		3		25	0.4
Piping (stainless steel)		14		75	1.4
Aluminium frames		17		182	2.0
Polypropylene glycol		9		106	2.0
Transport van by service technician during 25 years	2.71 tkm/year	14		131	2.3
Electricity for circulation pump, control, etc., 25 years[e]	378 MJ/year	33		278	27.9
Total		418 (262[a])	5.8 (6.9[a])	2539 (1891[a])	67.6 (54.9[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. Values for EI99CC have roughly been estimated from the relation shown in Fig. 1.
[d] Based upon data from [20] concerning recycling of stainless steel; Data for recycled low alloy steel, and recycled materials in circulation pump, expansion vessel, piping and frame systems have been roughly estimated.
[e] Refers to Swedish country mix including import.

Table 6
Estimated main contributions to the environmental performance Ecoindicator 99, H/A (EI99) of the reference evacuated tube solar collector system based on data from Stucki and Jungbluth [6] and the Ecoinvent database in SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED are also shown. Information on service transport and electricity need are based on data from Stucki and Jungbluth [6].

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Solar collector (8.2 m^2)	(see Table 3)	125 (69[a])		611 (595[a])	12.0 (11.5[a])
Heat storage (1 m^3)		104 (68[a,c])		587 (387[a,c])	10.9 (5.9[a,c])
Stainless steel	*24.7 kg*	*35.0*		*130*	*2.2*
Low alloy steel	*216 kg*	*60.0*		*380*	*6.2*
Circulation pump		4		15	0.2
Expansion vessel		3		25	0.4
Piping (stainless steel)		13		55	0.5
Aluminium frames		13		133	1.6
Polypropylene glycol		9		77	1.2
Transport van by service technician during 25 years	2.71 tkm/year	14		131	2.3
Electricity for circulation pump, control, etc., 25 years[d]	378 MJ/year	33		278	27.9
Total		318 (226[a])	5.8 (7.2[a])	1912 (1696[a])	57.0 (51.5[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. Values for EI99 CC have roughly been estimated from the relation shown in Fig. 1.
[c] Based upon data from [19] concerning recycling of stainless steel; Data for recycled low alloy steel, and recycled materials in circulation pump, expansion vessel, piping and frame systems have been roughly estimated.
[d] Refers to Swedish country mix including import.

Table 7
Main contributions to the environmental performance Ecoindicator 99, H/A (EI99) of the polymeric flat plate solar collector system, evaluated with data on used materials and amounts reported by Aventa [5] and environmental impact characteristics from SimaPro 7.3.0 [19]. Corresponding contributions to IPCC, 100a and to CED are also shown. Information on service transport and electricity need are based on data from Stucki and Jungbluth [6].

Material/process	Amount	EI99 (Pt)	EI 99 CC[b] (% of EI99)	IPCC, 100a (kg CO_2 eq.)	CED (GJ)
Solar collectors (15 m^2)	(see Table 4)	81 (56[a])		842 (552[a])	16.2 (11.7[a])
Heat storage (1 m^3) including piping		157 (88[a,c])		590 (348[a,c])	10.4 (4.3[a,c])
Stainless steel	*98 kg*	*139*		*515*	*8.6*
Copper piping	*2.1 kg*	*5.7*		*4*	*0.1*
Pump (*Grundfoss UPS* 26–60)		*4.3*		*15*	*0.3*
Transport van by service technician during 25 years	2.71 tkm/year	14		131	2.3
Electricity for circulation pump, control etc., 25 years[d]	378 MJ/year	33		278	27.9
Total		285 (191[a])	6.2 (6.6[a])	1841 (1309[a])	56.8 (46.2[a])

[a] Use of 100% secondary metals as alternative to primary metals.
[b] CC denotes climate change. EI99 CC have roughly been estimated from the relation shown in Fig. 1.
[c] Based upon data from [19] concerning recycling of stainless steel; Data for recycled low alloy steel, and recycled materials in circulation pump, expansion vessel, piping and frame systems have been roughly estimated.
[d] Refers to Swedish country mix including import.

polymeric solar heating system A gives 170% lower value relative to that of the reference flat plate collector system when mainly primary metals are used and 41.5% when secondary metals are used. Per kW h of solar heat collected, this difference is at most equal to 0.24 € cent if the EU carbon dioxide emission trading rate is used and 1.4 € cent when the general Swedish tax rate for carbon dioxide emission is used.

If differences in the climatic costs for the complete systems with data from Table 10 are considered, the situation is essentially the same. Per kW h of solar heat collected the difference between the reference flat plate based solar heating system B and the polymeric solar heating system A is at most 0.017 € cent, when the EU carbon dioxide emission trading rate is used, and equal to 0.068 € cent, when the Swedish tax rate for carbon dioxide emission is used. In terms of total environmental cost per kW h of solar heat collected, the difference between the flat plate collector based system B and the polymeric solar heating system A is at most equal to 0.24 € cent if the EU trading rate for carbon dioxide emission is used and 1.4 € cent when the Swedish tax rate for carbon dioxide emission is used. As a comparison, it should be mentioned that the total environmental cost of the flat plate solar collector system B corresponds to 0.73 € cent when mainly primary metals are used and to 0.46 € cent when secondary metals are used. When the Swedish carbon dioxide emission tax rate is used as the base for the calculation, the corresponding numbers are 4.27 € cent and 2.69 € cent, respectively.

In order of increasing environmental cost, the polymeric solar heating system A is the best, then comes the solar heating system with evacuated tube collectors and lastly the system based on the use of flat plate solar collectors. The difference between the polymeric collector system and the evacuated tube collector system is less pronounced.

To serve as another reference, data for the climatic cost and environmental cost for natural gas heating is given in Table 10. The climatic cost per kW h is 0.55 € cent and the total environmental cost per kW h is 4.3 € cent, when the EU carbon dioxide emission rate is used. The corresponding numbers are 3.2 € cent and 25.2 € cent, respectively when the Swedish carbon dioxide emission tax rate is used.

The differences in climatic and total environmental cost between the three equivalent solar heating systems are small and it is seems unlikely that those differences would have any significant influence on the choice of which system is best, from a total cost point of view. However, in the choice between solar heating and

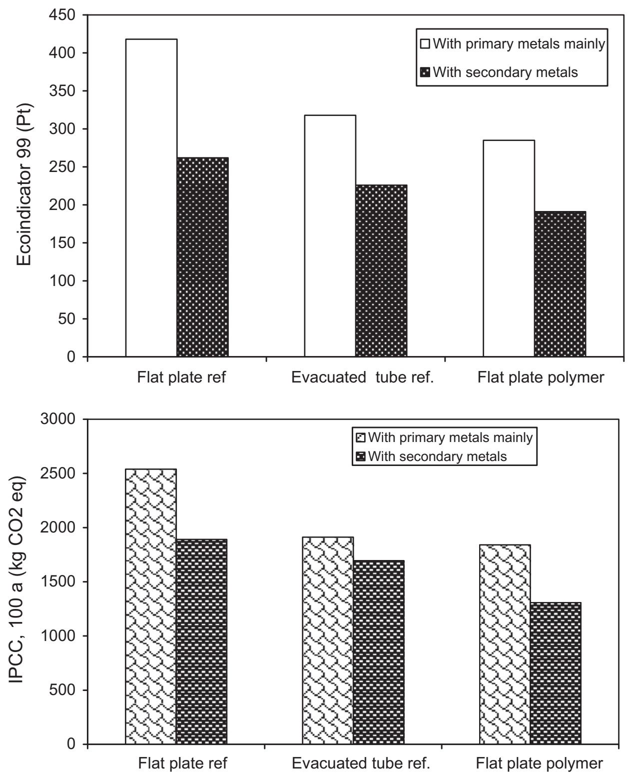

Fig. 3. Comparison in environmental impact of the three solar heating systems with use of primary metals and of secondary metals as an alternative. Lower diagram: Ecoindicator 99, H/A values; upper diagram: IPCC, 100a values.

fossil fuel based heating systems such as natural gas heating, the situation is quite different as discussed below.

4. A comparison of O&M costs and investment costs in a total cost perspective

The O&M costs considered in the present work include the cost of electricity for the circulation pump and control system. According to Stucki and Jungbluth [6], the electric energy demand corresponds to 378 MJ/year, which at a constant price of 0.179 €/kW h valid for Swedish consumers today [21], corresponds to a life cycle cost of 470 € or 0.39 € cent per kW h of solar heat collected.

The O&M costs include cost for regular maintenance of the systems also. To assess this cost, we used information from Stucki and Jungbluth [6]. Assuming regular maintenance is executed with an effort corresponding to one person day every fifth year, we were able to estimate roughly this cost at 1.5 € cent/kW h solar heat collected This number is representative for typical Swedish conditions. In the comparison between the three systems, however, it was assumed that the maintenance cost was the same for all systems.

When considering the investment costs for the three solar heating systems, two kinds of analysis were done. In the first analysis, estimates were made to find out at what collector investment cost level, the polymeric solar collector and the reference evacuated tube collector would be competitive with the reference flat plate solar collector. This analysis, which results are shown in Table 11, was based entirely on differences in the thermal performance characteristics of the three kinds of collectors. The thermal performance of the polymeric collector is lower compared to that of the flat plate collector and this means that the investment cost per collector area for the polymeric collector must be lower than that for the flat plate collector. Aventa reports that the current price of their solar collector, Solar collector in system A, would be around 190 (€/m^2) at 25% VAT [4] in Norway, which means this collector would fulfil the requirements in Table 11. Concerning the evacuated tube solar collector its price can be significantly higher compared with that of the flat plate collector (Table 11).

To analyse the viability of the complete systems, of course differences in investment costs related to the rest of the systems should also be taken into account. But for the purpose of the present study it was of main interest to find out how the relationships presented in Table 11 would change if the differences in the climatic and environmental costs between the three kinds of collectors are taken into account too.

Relative to the reference flat plate solar collector, the acceptable investment cost per m^2 for the polymeric solar collector and the evacuated tube collector are increased (Table 12). When climatic cost is taken into account by using the Swedish CO_2 emission tax rate, the acceptable investment cost per m^2 increases by only 1.8% in the polymeric solar collector case and by 0.4% in the evacuated tube solar collector case. When the environmental cost is taken into account by using the Swedish CO_2 emission tax rate, the acceptable investment cost per m^2 increases by as much as 32% in the polymeric solar collector case and by 6.4% in the evacuated tube solar collector case. Consequently, it is only when the environmental cost is taken into account the requirements on solar collector investment cost will change significantly.

To illustrate the importance of climatic and environmental costs when comparing the viability of a solar heating system with that for a more traditional heating system that uses a fossil fuel, a rough economic analysis was made. Adopting, what we see as reasonable assumptions about investment and O&M costs, use was made of Eqs. (2) and (3) to estimate viability data for the reference flat plate solar collector system and a natural gas heating system. Accordingly:

$$\text{Capital cost} = I \cdot a \cdot \frac{d^{N+1} - 1}{d - 1} \quad \text{with } d = 1/(1+z) \tag{2}$$

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

$$\text{O\&M cost} = E_0 \left(\frac{b^{N+1} - 1}{b - 1} \right) \quad \text{with } b = \exp(x + z - z) \tag{3}$$

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

In the assessment of viability, it was then assumed that the yearly rate of inflation could be set at 2.5% and that the net yearly increase in the price of electricity and natural gas could also be set at 2.5%.

As can be seen in Table 13, the viability of the solar heating system is significantly better than that of the natural gas heating system if the Swedish natural gas price is used and the assumptions made about investment costs, inflation rate, and net increase in energy are of a reasonable order of magnitude.

The consumer price of natural gas heating may vary significantly between different countries and this is of importance in the assessment of liability. The price is 11.4 € cent/kW h in Sweden and 6.14 € cent/kW h [21] in Germany. This means that when the German natural gas price is used, the sum of capital cost and O&M costs will become very close to each other for the two kinds of heating systems; see Table 13. However, if a tax were introduced based upon climate cost in keeping with the Swedish tax rate for carbon dioxide emission, solar heating would be a better alternative to natural gas heating for Germany even though Germany has a much lower natural gas price than Sweden's.

The conclusion is that that climatic performance and definitely the environmental performance would be important economic

Table 8
Energy payback periods for the solar heating systems, estimated from CED data from Tables 5–7.

Solar heating system producing 17.6 GJ heat per year located in Stockholm	Energy payback period when mainly primary metals are used (years)	Energy payback period when secondary metals are used (years)
Polymeric solar collector system (15 m^2 collector area)	1.6	1.0
Reference flat plate solar collector system (12.8 m^2 collector area)	2.3	1.5
Reference evacuated tube solar collector system (8.2 m^2 collector area)	1.7	1.3

Table 9
Climatic and environmental life cycle costs related to the different solar collectors used in the solar heating systems. Results are based on data from Tables 1 to 4.

Solar collector producing 0.12 TW h heat during a time period of 25 years in Stockholm	Climatic costs in k€ based on a CO_2 emission rate per tonnes of		Total environmental cost in k€ based on the modified Ecoindicator 99 proposed by Carlsson base on	
	20 €[eu]	117 €[sw]	EU CO_2 emission trade rate	Swedish CO_2 emission tax
Polymeric solar collector (15 m^2)	0.0168 (0.0110[a])	0.0983 (0.0644[a])	0.168 (0.110[a])	0.983 (0.644[a])
Reference flat plate collector (12.8 m^2)	0.0228 (0.0138[a])	0.133 (0.0807[a])	0.456 (0.209[a])	2.67 (1.22[a])
Reference evacuated tube collector (8.2 m^2)	0.0122 (0.0119[a])	0.0714 (0.0696[a])	0.259 (0.143[a])	1.52 (0.837[a])

[a] Use of 100% secondary metals as alternative to primary metals; [eu]EU trade rate; [sw]Swedish carbon dioxide general emission tax.

Table 10
Climatic and environmental life cycle costs related to the complete solar heating systems and a heating system with natural gas boiler.

Heating system producing 0.12 TW h solar heat during a time period of 25 years in Stockholm	Climatic costs in € cent/solar heat collected based on a CO_2 emission rate per tonnes of		Total environmental costs in € cent/solar heat collected based on the modified Ecoindicator 99 proposed by Carlsson based on	
	20 €[eu]	117 €[sw]	EU CO_2 emission trade rate	Swedish CO_2 emission tax
Solar heating system with polymeric collector (15 m^2)	0.0301 (0.0214[a])	0.175 (0.125[a])	0.486 (0.325[a])	2.85 (1.90[a])
Reference solar heating system with flat plate collector (12.8 m^2)	0.0415 (0.0309[a])	0.243 (0.181[a])	0.717 (0.448[a])	4.20 (2.62[a])
Reference solar heating system with evacuated tube collector (8.2 m^2)	0.0312 (0.0277[a])	0.182 (0.162[a])	0.539 (0.385[a])	3.15 (2.26[a])
Equivalent heating system with natural gas boiler	0.541	3.16	4.22	24.7

[a] Use of 100% secondary metals as alternative to primary metals; [eu]EU trade rate; [sw] Swedish carbon dioxide general emission tax.

Table 11
Requirements on investment cost for the polymeric and evacuated tube solar collectors to be competitive to the reference flat plate collector. Data from Table 9 and information from some Swedish solar collector manufacturers [22] were used.

Solar collector producing 0.12 TW h heat during a time period of 25 years in Stockholm	Requirement on investment cost for collectors due to differences in thermal performance (€/m^2)
Polymeric solar collector (15 m^2)	Case I*: <284 Case II*: <205
Reference flat plate solar collector (12.8 m^2)	Case I*: 333 Case II*: 240
Reference evacuated tube collector (8.2 m^2)	Case II*: <520 Case II*: <375

Case I represents a case when the collector investment cost is 333 (€/m^2) and Case II when it is 240 (€/m^2).

factors in the choice between a solar heating system and a heat source system based on the use of a fossil fuel. When comparing different solar heating systems, the climatic and environmental costs seem significantly less important.

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

All the solar heating systems analysed in this study are commercially available. The solar collectors used in the reference solar heating systems B and C have been tested regarding their long-term performance, following international practice [13,14]. The service life of those solar collectors, therefore, would most probably exceed 25 years, as Stucki and Jungbluth [5] also assumed in their LCA study. It seems reasonable to assume that the same is true for the polymeric solar collector in solar heating system A, as concluded in a recent study [23]. Using accelerated life testing involving the conduct of a series of high temperature tests, the change in mechanical properties of the PPS absorber material in the polymeric collector during ageing was investigated. By making

Table 12
Relative climatic and environmental life cycle costs per m^2 of solar collector related to the reference flat plate solar collector. Results are shown only for the case when primary metals are used.

Solar collector producing 0.12 TW h heat during a time period of 25 years in Stockholm	Climatic costs in €/m^2 solar collector area based on a CO_2 emission rate per tonnes of		Total environmental cost in €/m^2 solar collector area based on the modified Ecoindicator 99 proposed by Carlsson based on	
	20 €[eu]	117 €[sw]	EU emission trade rate	Swedish CO_2 emission tax
Polymeric solar collector (15 m^2)	−0.66	−3.8	−24.4	−66
Ref. evacuated tube solar collector (8.2 m^2)	−0.3	−1.7	−4.0	−24

[eu]EU trade rate; [sw]Swedish carbon dioxide general emission tax.

Table 13
Present value life cycle based energy costs for solar heating by a reference flat plate solar collector system and by a natural gas heating system. For the calculations the following assumptions were made: N = 25 years, a = 0.07095 (25 years, 5% interest rate), z = 2.5%, x = 2.5%; I = 7500 € (solar heating system), I = 1100 € (allocated investment cost for natural gas boiler representing 16% of the required capacity to replace solar heating, O&M costs relate to electric energy need and maintenance of the solar heating system. For the natural gas based heating system the natural gas price in Sweden of 11.4 € cent/kW h were used. For climatic costs data from Table 10 according the Swedish tax rate are used.

Heating system	Capital cost (€ cent/kW h)	O&M costs (€ cent/kW h)	Sum excluding climate cost (€ cent/kW h)	Sum including climate cost (€ cent/kW h)
Reference flat plate solar collector system	8.4	2	10.4	11.1
Natural gas heating system	1.1	15.3[a]	16.4[a]	19.6

[a] Refers to the case when the price of natural gas in Sweden is employed and the Swedish carbon dioxide emission tax rate is excluded.

use of measured absorber temperatures valid for operating conditions, the service life for the PPS absorber material was estimated slightly longer than 25 years.

Consequently, to assess the total cost for a service time as equal to 25 years seemed reasonable. We lacked the information necessary to make a distinction between the different solar heating systems regarding the cost of probable failures and damage for during their assumed service life. However, we found it reasonable to assume that during the assumed service time of 25 years, this cost would be of the same order of magnitude and relatively small compared to other cost terms that would contribute to the total cost of the three solar heating systems.

The end-of-life cost of a system corresponds to the residual value of the system after a period equal to the service time used for the total cost assessment. This means the residual values of the systems may vary significantly simply because their residual service life may differ. If the end-of-life time corresponds to the service life of a system, however, its residual value amounts to the value of its materials, minus the costs for disassembling and waste treatment and handling scrap for recycling, if that is possible. Thus, the main contributions to the residual value come from the metals used in the system. Therefore, the end-of-life cost of the reference flat plate solar collector system was estimated based upon its expected value, when taking into account its metal content and associated scrap metal prices. We believe, based upon the result of this analysis, that its end-of-life value would reduce the total cost of the system by roughly 5–10%.

However, if the systems could be used for some time after the specified service time period has passed, it is more difficult to assess their residual value as represented by the end-of-life cost term in the total cost expression. It falls, however, outside the scope of the present study to analyse in a more depth way the importance of the end-of-life cost for the total cost of the three different solar heating systems studied.

6. Summary of conclusions

By adopting a total cost accounting approach, it was possible to compare a polymeric solar collector system with two traditional systems from a holistic point of view. Not only differences in thermal performance and investment costs could be taken into account, but also in environmental and climatic costs. Differences related to durability, O&M cost, and recyclability could also be considered.

In terms of the climatic and environmental performance evaluated by LCA, the results clearly indicated that the polymeric solar collector system is the best. This is also the true after adjusting for the differences in thermal performance of the systems studied.

Climatic cost per solar heat collected, were found to be very small for all three systems and so also the differences in climatic cost between the three systems when compared to other terms contributing to the total cost. This was the result for the case when the initial EU trade rate for carbon dioxide was used to convert climatic performance into climatic cost. The same was also found true when the comparatively higher Swedish general tax rate for carbon dioxide emission was used for this conversion.

Climate costs may influence the choice between using solar heating and more traditional fossil fuel based systems such as natural gas heating. But, to become an important factor, the rate of carbon dioxide emission must be significantly higher than the initial EU carbon dioxide emission trade rate or become of the same order or even higher as the Swedish general tax rate.

If costs related to environmental impact took into account not only the greenhouse effect but also other mechanisms for damaging the environment as, for example, the environmental impact factor Ecoindicator 99 does, the viability of solar heating versus that of a natural gas heating system would be much higher.

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