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ARTICLE

Energy and Cost Analysis of Processing Flat Plate Solar Collectors

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ABSTRACT

In this work, a life cycle analysis is accomplished for flat plate solar collectors. The purpose of this investigation is to predict the energy consumption during the manufacturing processes that results in carbon dioxide emissions. Energy consumption and system efficiency enhancement will be studied and predicted. CES EduPack software is used to perform the analysis of the currently commercial system, and the suggested changes are implemented to increase the efficiency and make the comparison. Even though cost analysis is done, the priority of selection is given to the most energy conserving and environmentally friendly alternative. However, if the compared alternatives result in the same energy consumption and CO_2 emissions, the cost analysis would be a better approach. It can be stated that flat plate solar collectors are sustainable and renewable energy systems that do not produce CO_2 emissions during their active usage, but the manufacturing processes they undergo during the design contribute to the greenhouse gasses emission.

KEYWORDS

Life cycle; solar collector; renewable energy; solar thermal; CO_2 emission; economic analysis

1 Introduction

As world energy consumption is dramatically increasing and the scarcity of the existing energy sources are happening simultaneously in a problem known as supply/demand problem [1,2]. Renewable energy sources are considered as a satisfying alternative to increase the energy supply rate and compensate for the continuous decreasing of fossil fuels and different old energy generation systems with low greenhouse gas emissions [3,4]. Ellabban [5] defined renewable energy as an energy that is provided by natural sources such as sunlight, wind, rain, tides, waves, and geothermal heat. Accordingly, renewable energy systems cannot only solve the existing scarcity of energy problem but it offers a permanent solution to the problem which defines why renewable energy sources are named sustainable energy systems as well. Renewable Energy and Efficiency Partnership (REFP) defines a sustainable energy system as an energy system that serves the needs of the present without affecting the energy sources that are need for future generations. Moreover, renewable energy systems are all clean energy generation systems while they are in use, they are not accompanied with carbon dioxide or any other chlorofluorocarbon emissions and the usage of such systems may play a vital role in decreasing pollution and CO_2 generation rates and accordingly reduce global warming another issue that cannot be solved using existing sources [6,7]. Environmental Protection Agency (EPA) [8] estimated that 10% of the energy used in the U.S. were used for water heating and cooling purposes and accordingly they contributed in 10% of the overall CO_2 emissions. However, a flat plate collector that converts incident sunlight to heat can offer a more environment friendly alternative to the usage of electric or fuel heaters. It might have a lower efficiency but as long as the input energy is free it can compete with other heat exchangers.

However, the judgment that Sustainable and Renewable Energy systems (RESs) systems do not produce any pollution is not technically true. In fact the processes that RESs undergo before and after their usage and even during their lifetime contribute in pollutants emission [9]. Life cycle assessment (LCA) which is defined as a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling) [10]. The five main processes are material extraction, manufacture, transportation, maintenance and recycle or disposal shows that a RES emits CO_2 and other pollutants even though it is using a clean source usually the sun [11]. Life cycle analysis is a great procedure where you can determine which process of overall system design that consumes more energy and produces more CO_2 by knowing the details about each process designers and researchers can know where to put their effort in order to decrease energy usage and pollutants production which results in a higher system efficiency and less harm to the environment [12]. Sustainable facilities tool (SFtool) defines the scope of LCA is used to compare the full range of environmental effects assignable to products and services by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. There are two main categories of LCA which are (a) Attributional LCAs establish the burdens associated with the production and use of a product at a point in time (typically the recent past) and (b) Consequential LCAs identify the environmental consequences of a decision or a proposed change in a system under study (oriented to the future), which means that market and economic implications of a decision may have to be taken into account. LCA is widely used in industrial analysis according to a survey done by Cooper et al. [12]. LCA is generally used to support business strategy (18%) and Research and Development (18%), in addition, it is used as input in process design (15%), in education (13%) and for labeling or product declarations (11%) [11]. So far, many studies have been presented to analyze the life cycle of solar collectors. Kumar et al. [13] investigated the life cycle cost of single slope hybrid (PV/T) active solar still. This work estimated the paybackperiod of active and passive solar still-PV/T in the range of 3.3 to 23.9 years and 1.1 to 6.2 years, respectively. Araya et al. [14] analyzed the life cycle saving for a flat-plate solar water collector in Chile. The study presented the analysis of LCA flat plate solar water collector using genetic algorithms (GAs) to optimize the solar collector area and the volume of water storage tank that result in the maximum life-cycle savings. The results showed that the consumption of water and water temperature had a great influence flat plate solar water collector. Ozturk et al. [15] developed a thermodynamic and life cycle assessment of flat-plate, photovoltaic and photovoltaic thermal collector, where they proposed an energy and exergy analysis along with LCA for these collectors. The results of their study showed that the energy and CO_2 payback time for these three collectors types were 2, 12, 3.8 and 1.6, 3.6 and 1.8 years, respectively. All these mentioned studies, anaylzed the life cycle analysis when the solar collector is in use with energy storage systems, which make them different from out work.

In this work, the LCA for the current properties of solar flat plate collectors is considered to investigate and then a consequential LCA is done for a proposed change in the current system that enhances the system efficiency. The main objective of this work is to investigate which parts of the flat plate solar collector system materials consume more energy and produces more greenhouse gases during their manufacturing phase.

2 Technical Approach

2.1 Data Collection

The materials properties and environmental output/input data, which are needed in this work, can be easily accessed in the CES EduPack software database. Transportation is another important aspect in the analysis of this work. Factories that produce and manufacture each one of the materials needed in constructing the flat plate solar collector (Fig. 1) are chosen. Though, going through these factories will be done under the assumption that they produce raw materials and manufacture them in a non complicated manufacturing process. The flat plate solar collector is a static device which means only low maintenance is needed and only a yearly checkup cycle is done. The maintenance might include removal of any corrosion that might take place over time as well as the inspection of the activity of the device itself.

Figure 1: Solar flat plate collector

2.2 Data Processing

A life cycle analysis is done by using the CES EduPack software which includes all the information needed. It includes how much energy is used, the CO_2 emissions and also the cost for each process of designing the device. Each process that consumes highest amount of energy and results in toxic gasses emissions will be investigated. After that, alternatives will be suggested and will be compared with the commercial materials that are used, and based on that select the best option. The alternatives will be advised in a way that they lower the energy use and the CO_2 emissions without any alteration in the system overall efficiency or, what would be ideal, increasing it. Tab. 1 summarizes various materials that are used in the production process of different part of solar collector. In addition, the production method for each segment of the solar collector is presented in Tab. 2.

It is noteworthy to mention that the maintenance of the solar collector is considered to be 3 hours per year (only for cleaning & electroplating the frames, which include repair, inspection and planned preventive maintenance.

3 Results and Discussion

The LCA of the solar collectors was analyzed using the CES EduPack software, employing the mentioned above materials. The following assumptions are taken into account:

Table 1: Different parts of the solar collector accompanied with corresponding materials

Part of the system	Material
Riser and header (tubes)	Stainless steel/Zn alloyed
Absorber	Cast copper
Selective coating	Bronze
Transparent cover	Glass
Storage tank	Stainless steel/Zn alloyed
Collector frame	Aluminum/Zn alloyed
Collector support	Aluminum

Table 2: Production method for each part of the solar collector

Part of the system	Primary process	Secondary process
Riser and header (tubes)	Casting	Coarse machining
Absorber	Casting	Cutting and trimming
Selective coating	Casting	Cutting and trimming
Transparent cover	Fabric production	Cutting and trimming
Storage tank	Casting	Coarse machining
Collector frame	Forging	Coarse machining
Collector support	Rough rolling	Coarse machining

1. All Zn alloyed materials were considered of high corrosion resistance for this reason a high Zn percentage material have been chosen. Accordingly, no electroplating (galvanizing) is needed. Except for the collector frame which has to be both Zn alloyed and galvanized.
2. The back-insulation material (melamine foam) will be neglected from analysis since it has to be shipped from factory in china. However, this assumption is accepted in our case because the mass fraction of the foam is (1/200) kg/kg (kg of foam per kg of solar collector). Note that for commercial projects, it has to be implemented in the life cycle analysis.
3. The maintenance power rating was assumed to be 1000 W which is as low as power consumed by 10 electric bulbs because the system consists of static parts which dramatically decrease failure probabilities.

The energy consumption versus designing process bar chart below (Fig. 2) which cosnists of materials extraction, manufacturing, transporation, materials use, material disposal and end of life (EoL). The figure clearly states that raw materials production was the dominating process regarding energy consumption and accordingly CO_2 emission (Fig. 3) when it is compared to other processes of overall design. Figs. 2 and 3 show that the distributions of energy consumption and CO_2 emission have the same trend which can be explained by the fact the more energy onsumed results in more CO_2, hence they are directly proportional to each other. Fig. 2 shows that the most of energy is consumed during the preparation of the materials for PV and then followed by the manufacturing process required for the solar collector. Fig. 3 shows the distribution of CO_2 emission, which shows the highest amount of CO_2 emission also occurs the preparation of the materials for the solar collectors.

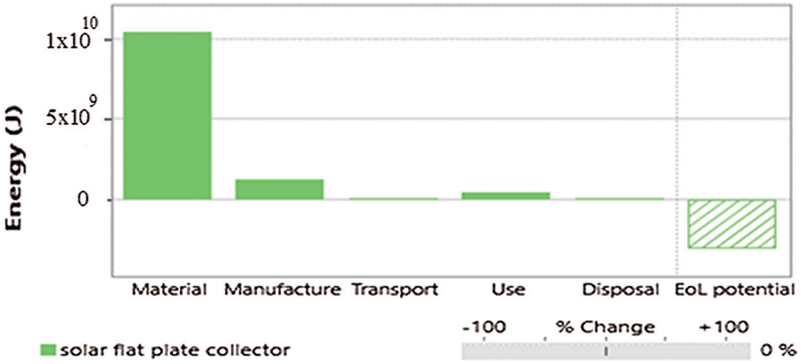

Figure 2: Energy consumption

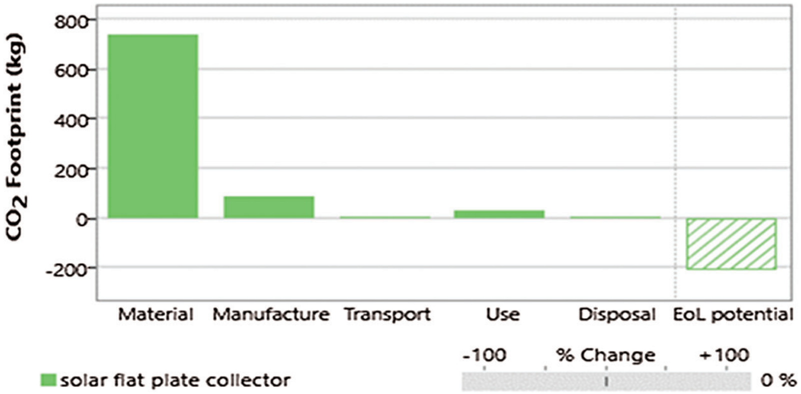

Figure 3: CO_2 emission

To investigate which parts of the flat plate solar collector during materials production, consume more energy and produces more CO_2, a detailed report from the software was extracted (Tabs. 3 and 4).

Table 3: Energy consumption details for material production process in different part of the solar collector

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (J)	%
Risers and header	Stainless steel, martensitic, ASTM CA-6NM, cast	Virgin (0%)	12	1	12	9.8×10^8	9.3
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	1.8×10^8	1.7
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	2.8×10^7	0.3
Transparent cover	Glass, S grade (10-micron monofilament, f)	Virgin (0%)	7	1	7	3.6×10^8	3.5
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	7.3×10^8	7.0
Collector frame	Aluminum, 7475, T7351	Typical %	16	1	16	2×10^9	19.0
Collector support	Aluminum, 7010, T7451	Typical %	50	1	50	6.2×10^9	59.3
Total				7	110	10^{10}	100

Table 4: CO_2 emision for the production process

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO_2 footprint (kg)	%
Risers and header	Stainless steel, martensitic, ASTM CA-6NM, cast	Virgin (0%)	12	1	12	77	10.4
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	11	1.5
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	1.8	0.2
Transparent cover	Glass, S grade (10 micron monofilament, f)	Virgin (0%)	7	1	7	21	2.8
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	59	7.9
Collector frame	Aluminum, 7475, T7351	Typical %	16	1	16	140	18.6
Collector support	Aluminum, 7010, T7451	Typical %	50	1	50	430	58.5
Total				7	110	740	100

Tabs. 3 and 4 clearly show that collector support and collector frame consume most of the energy for production of their materials and most of CO_2 emissions 59% and 19% respectively. Those values were predicted since aluminium has a relatively high embodied energy in the range 181–202 MJ per kg of materials and the collector support and frame have a high mass fractions of 0.55 and 0.38, respectively. This fraction is defined as the mass of the component devided by the total mass of the solar collector. In order to decrease the energy consumed by those parts and decrease CO_2 emission, another type of material has to be used however there are some restrictions to change those materials which are:

1. Since the two parts are used to carry functional parts weight, the new material must have a high young modulus and share close mechanical properties with aluminium.
2. The density of the new materials must be close to aluminium density in order to maintain the volume of those parts.

Zn alloyed Stainless steel was suggested as a good alternative for the two parts. Tab. 5 below compares the mechanical properties of the two materials.

Table 5: Mechanical properties comparison of aluminium and stainless steel

Property	Aluminium	Stainless steel
Young modulus	1.89×10^{11}–1.97×10^{11}	7×10^{10}–7.36×10^{10}
Yield strength	2.9×10^{8}–3.2×10^{8}	3.59×10^{8}–4.27×10^{8}
Shear modulus	7.4×10^{10}–7.8×10^{10}	2.7×10^{10}–2.34×10^{10}
Bulk modulus	1.34×10^{11}–1.46×10^{11}	6.9×10^{10}–7.25×10^{10}
Poissons's ratio	0.265–0.275	0.330–0.343

From the comparison we can see that stainless steel is a good alternative for aluminium because most of the mechanical properties of them are close.

Another suggested changes were to use copper for the risers and header (tubes) instead of stainless steel since copper has a lower embodied energy and more thermal conductivity, also laminated glass were suggested to replace fibre glass transparent cover to lower embodied energy. After these changes have been made, energy consumption by materials production was drastically decreased and also CO_2 footprint. They are dropped approximately by 40% (Figs. 4 and 5).

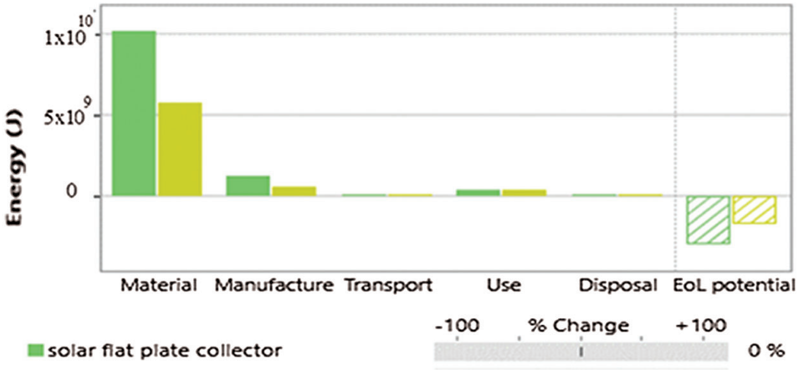

Figure 4: Comparison of energy consumption between the two scenarios

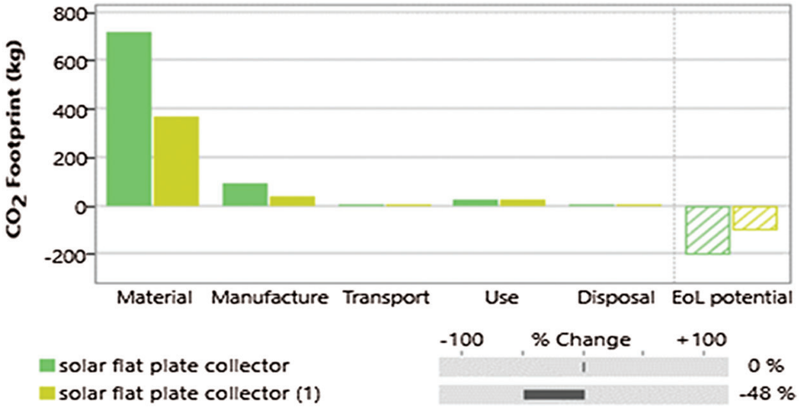

Figure 5: Comparison of CO_2 production between the two scenarios

Note that second column represents energy consumption/CO_2 footprint by materials production after materials change. Obviously, manufacturing process consumption also decreases with changing the materials. The reason of this is copper can be easily handled resulting in easier manufacturing process. However, the end of life potential (EoL) is reduced because most of the new materials recyclable content are decreased.

From Tabs. 6–9, it is possible to compare energy consumption and CO_2 emissions for materials that have been changed. After changing the collector frame and support, the energy that has been saved is about 40 MJ. Also, changing risers and header, absorber plate and transparent cover materials result in excess of 430 MJ of savings.

From the CO_2 perspective, the total savings are 375 kg which reduce the pollution in the environment. These calculations are only applied for a single mid-sized flat plate collector. Yet, for a commercial production of collectors, the savings will be multiplied by the number of units of production.

Table 6: Energy consumption details of production process after changing materials

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (J)	%
Risers and header	Copper, cast (h.c. copper)	Virgin (0%)	12	1	12	7.1×10^8	12.3
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	1.8×10^8	3.1
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	2.8×10^7	0.5
Transparent cover	Laminated glass	Virgin (0%)	7	1	7	2×10^8	3.6
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	7.3×10^8	12.8
Collector frame	Copper, cast (h.c. copper)	Virgin (0%)	16	1	16	9.4×10^8	16.4
Collector support	Copper, cast (h.c. copper)	Virgin (0%)	50	1	50	2.9×10^9	51.3
Total				7	110	5.7×10^9	100

Table 7: CO_2 footprint details for production process after changing materials

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO_2 footprint (kg)	%
Risers and header	Copper, cast (h.c. copper)	Virgin (0%)	12	1	12	43	11.9
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	11	3.1
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	1.8	0.5
Transparent cover	Laminated glass	Virgin (0%)	7	1	7	12	3.4
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	59	16.0
Collector frame	Copper, cast (h.c. copper)	Virgin (0%)	16	1	16	58	15.8
Collector support	Copper, cast (h.c. copper)	Virgin (0%)	50	1	50	180	49.4
Total				7	110	370	100

Table 8: End of life potential details for material production

Component	End of life option	% recovered	Energy (J)	%
Risers and header	Recycle	37.5	-2.9×10^8	9.2
Absorber	Recycle	43.0	-5×10^7	1.6
Selective coating	Recycle	43.0	-8×10^6	0.3
Transparent cover	Re-manufacture	0.1	-3.4×10^5	0.0
Storage tank	Recycle	37.5	-1.9×10^8	6.1
Collector frame	Recycle	42.5	-6.2×10^8	19.9
Collector support	Recycle	43.0	-2×10^9	62.9
Total			-3.1×10^9	100

From Fig. 4, we notice that EoL potential after changing the materials has been decreased and the lower recyclable content of the new materials is the reason behind this decrease. However, the actual effect of changing the materials can be better understood by calculating the end of life potential to the energy consumption ratio. The EoL potential (Tab. 8) to energy consumption ratio of the first scenario is 0.31, while the second scenario (Tab. 9) results in ($1.7 \times 10^9 / 5.7 \times 10^9$) = 0.3. Even though the energy savings after changing the materials were significant, the EoL potential to energy consumption ratio of the two scenarios are approximately equal. Hence, selecting the better alternative cannot be determined by the energy savings only, which leads to lean towards the more economical alternative. Note that EoL potential to energy consumption ratio takes into account all process (not only materials production) is 0.26 for both scenarios.

Table 9: End of life potential details after changing materials

Component	End of life option	% recovered	Energy (J)	%
Risers and header	Recycle	37.5	-2×10^8	11.8
Absorber	Recycle	43.0	-5×10^7	2.9
Selective coating	Recycle	43.0	-8×10^6	0.5
Transparent cover	Re-manufacture	0.1	-1.8×10^5	0.0
Storage tank	Recycle	37.5	-1.9×10^8	10.9
Collector frame	Recycle	42.5	-3.1×10^8	17.8
Collector support	Recycle	43.0	-9.8×10^8	56.2
Total			-1.7×10^9	100

The economic analysis which turned to be the determining factor to choose the best alternative is summarized in Fig. 6.

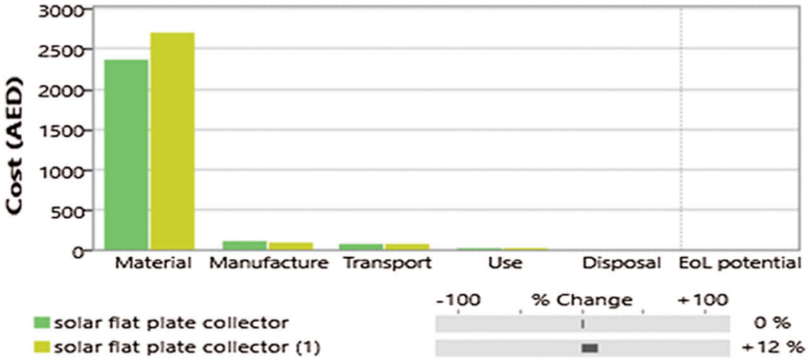

Figure 6: Comparison of total costs between the two scenarios

It is obvious that the current commercial used materials would result in less capital costs and accordingly they are preferred. The detailed cost analysis for the two situations are tabulated below, Tabs. 10 and 11.

The difference in cost of collector frame using aluminium and copper is (470–410) = 60 AED, for the collector support the difference is (1500–880) = 620 AED, for the pipes the difference is (380–120) = 260 AED, for the glazing material (190–750) = –560 AED (the negative sing here represents cost saving). The total result is 380 AED. However, manufacturing process results in 20 AED savings which reduces the result to 360 AED.

Table 10: Detailed cost analysis for materials production

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Cost (AED)	%
Risers and header	Stainless steel, martensitic, ASTM CA-6NM, cast	Virgin (0%)	12	1	12	120	4.9
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	120	5.1
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	19	0.8
Transparent cover	Glass, S grade (10 micron monofilament, f)	Virgin (0%)	7	1	7	750	31.6
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	79	3.3
Collector frame	Aluminum, 7475, T7351	Typical %	16	1	16	410	17.1
Collector support	Aluminum, 7010, T7451	Typical %	50	1	50	880	37.2
Total				7	110	2400	100

Table 11: Detailed cost analysis after changing the materials

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Cost (AED)	%
Risers and header	Copper, cast (h.c. copper)	Virgin (0%)	12	1	12	380	13.9
Absorber	Copper, cast (h.c. copper)	Typical %	4.5	1	4.5	120	4.4
Selective coating	Bronze, CuSi3.5Mn1, cast (silicon bronze)	Typical %	0.7	1	0.7	19	0.7
Transparent cover	Laminated glass	Virgin (0%)	7	1	7	190	6.9
Storage tank	Stainless steel, martensitic, ASTM CA-40, cast, tempered at 315°C	Typical %	15	1	15	79	2.9
Collector frame	Copper, cast (h.c. copper)	Virgin (0%)	16	1	16	470	17.2
Collector support	Copper, cast (h.c. copper)	Virgin (0%)	50	1	50	1500	53.9
Total				7	110	2758	100

4 Conclusions

In this work, the lifecycle of a flat plate collector for solar heating was analyzed using the CES-Edupack software to know total cost, carbon dioxide emission and total energy consumption. After completing the design for all steps materials, manufacturing, transport, use (maintenance) and end of lifecycle, it was found that the step that consumed most of the energy and had the largest CO_2 emission was the materials production process. It was also found that the parts that consumed the most energy and produced the largest amount of CO_2 in material production were the collector frame and the support. So, in order to decrease the energy production and the CO_2 emissions in the material production copper was used instead of using aluminum for the collector frame and the support, because the energy used to produce 1 kg of copper was much less than the energy consumed for producing 1 kg of aluminum, and hence resulting in less CO_2 emissions than the Aluminum production. The percentage decrease in the total energy consumption in the materials production was nearly 40%, but using copper would cause the cost to increase by almost 30%. However, the end of life potential to energy consumption ratio of using copper is approximately the same of the EOL potential to energy consumption ratio of aluminum frame and support.

To conclude, the equivalence of the two EOL potential to energy consumption ratio seems to be cost dependent and as it was found, the cost of using copper frame and support would be less than using aluminum frame and support. Hence, it is recommended to use the copper frame and support.

The major outcomes of this work are:

- Even though solar flat plate collectors are sustainable and renewable energy systems that do not produce CO_2 emissions during their active usage, the processes they undergo during the design contribute to the greenhouse gasses emission.
- Materials production are usually the phase where most of energy consumption takes place.
- By looking to the direct energy or CO_2 production rate savings, you cannot determine whether changing the materials would be beneficial to the system, EoL potential to energy consumption ratios should be the main factor of judgment.
- When changing materials of the system is desirable to achieve less energy consumption and CO_2 emissions in materials production process, new materials must share the same properties.
- Usually, environmental-friendly materials are more expensive. For this reason, commercial firms avoid such materials in designing such systems.
- Taking the cost analysis as an approach is suitable for our situation since the EoL potential to energy consumption ratios were approximately equal.

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