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# Life Cycle Assessment of the Use of Phase Change Material in an Evacuated Solar Tube Collector

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**Abstract:** This paper presents an environmental impact assessment of the entire cycle of existence of the tube-vacuum solar collector prototype. The innovativeness of the solution involved using a phase change material as a heat-storing material, which was placed inside the collector's tubes-vacuum. The PCM used in this study was paraffin. The system boundaries contained three phases: production, operation (use phase), and disposal. An ecological life cycle assessment was carried out using the SimaPro software. To compare the environmental impact of heat storage, the amount of heat generated for 15 years, starting from the beginning of a solar installation for preparing domestic hot water for a single-family residential building, was considered the functional unit. Assuming comparable production methods for individual elements of the ETC and waste management scenarios, the reduction in harmful effects on the environment by introducing a PCM that stores heat inside the ETC ranges from 17 to 24%. The performed analyses have also shown that the method itself of manufacturing the materials used for the construction of the solar collector and the choice of the scenario of the disposal of waste during decommissioning the solar collector all play an important role in its environmental assessment. With an increase in the application of the advanced technologies of materials manufacturing and an increase in the amount of waste subjected to recycling, the degree of the solar collector's environmental impact decreased by 82% compared to its standard manufacture and disposal.

**Keywords:** LCA; heat storage; evacuated solar tube collector; phase change material (PCM)

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## 1. Introduction

The building sector, with the highest demand for heat, is one of the largest energy consumers. The construction of heat production installations requires the use of environmental energy resources and generates harmful emissions, negatively affecting the natural environment. To meet basic living and economic needs in a rational and energy-saving way, it is necessary to construct installations that increasingly use renewable energy sources. One of the main renewable energy sources is solar energy, and the device used to convert solar energy to heat is a solar tube collector. Although solar energy is considered ecological, throughout the life cycle of systems using it, there are significant interactions with the environment resulting from the source, production, transportation, assembly, and use of materials. These interactions may lead to the depletion of natural resources, greenhouse gas effects, acidification, and eutrophication [1–5]. An important limitation of systems development based on the use of renewable energy sources is their specifications, which are primarily related to the availability and efficiency of conversion processes [6,7]. Therefore, there is often a discrepancy in the time between the need for energy and the possibility of its generation, over short periods (day, week) as well as seasonal periods (month, year). It is necessary to store solar energy in order to increase the efficiency of its use under conditions of randomly changing heat demand. The possibility of heat storage is a key economic aspect of increasing the share of renewable energy sources [8–20]. One way to mitigate the limited possibilities of heat storage is to use the sensible heat and latent heat of water with phase change materials (PCMs). Generally, PCMs include saturated hydrocarbons (e.g., paraffin), fatty acids, and their salts and hydrates [8,11,13,20]. Using PCMs, it is possible to store heat between 100 and 250 kJ/kg [8] and double the heat capacity of a storage tank in relation to water storage. New technologies in the field of heat storage tend to increase the efficiency of solar energy conversion and lower heat production costs, but they also affect the environment. One of the tools used to assess the environmental impact is ecological analysis of production that accounts for the entire life cycle [21–28]. The aim is not only to determine the type and size of indicators negatively affecting the surrounding nature, but also to improve the efficiency of the use of renewable and non-renewable resources to effectively manage raw materials, energy, and waste or to limit interference in the natural environment. Many studies have investigated the environmental impact of residential buildings with various energy standards using LCA [29–41] in various climatic zones (from warm (Italy) [33] to moderate (Germany) [37] to cold (Norway) [31]) and used a combination of various installations supplying buildings with electricity and heat, both from conventional and from renewable sources. In addition, the boundaries of the system for the established environmental analyses were strongly divergent. They either focused on only one phase of the life cycle (e.g., use) [42] or included all phases [33] (i.e., raw material extraction and material production, construction and operation/maintenance, or demolition and disposal of materials). Studies have also performed environmental analyses to compare the environmental impacts of different insulating materials [43–45] or construction materials [45–49]. However, there is much less information about optimization of the environmental use of solar installations, including solar tube collectors. Previous studies on solar tube collectors focused primarily on flat collectors [1–3,5,50–63]. In addition to determining the environmental impact of flat collectors, there are also indications regarding their optimization at the production stage [1–3].

A literature review shows that existing studies focus primarily on comparing, in terms of energy, vacuum collectors with flat collectors [64–74]. In the majority of instances, the evacuated tube collector exhibits better efficiency compared to the flat collector. Whereas, there are few studies that examine the ecological aspect of solar systems based on the vacuum tube technology. There are studies that investigate the life cycle of solar collectors; however, the majority of them are based on Embodied Energy (EE) and Embodied Carbon (EC) along with USEtox and Ecological Footprint (EF), or life cycle cost analysis [16,18,20,27,28,54,63,65,68,73,75–77]. Few studies consider the LCA methodology for a perspective based on actual pollutant for impact assessment individually with a single score [59,78,79]. Although the presented methods could be more attractive than LCA owing to the simplicity of approach, yet they include only one index, which might result in an excessive simplification of the analysis made. A considerable number of works related to environmental analysis include comparison of the evacuated tube collector with the flat collector [64–70,73]. The results show that, for the majority of cases examined, the vacuum collector system is more environmentally friendly than the flat collector system. This is particularly visible in the production phase, where flat solar collectors show a much greater environmental impact compared to tubular–vacuum collectors [73], with the main environmental impact factor being in the category of carcinogenicity. From the environmental protection point of view, tubular–vacuum collectors turn out to be a better option considering the least impact generated during their manufacturing phase, compared to flat collector production. Moreover, the majority of studies propose tubular–vacuum collectors for applications for integrated systems with domestic hot water preparation [27,28,63,76,80,81]. Based on the above review it can be stated that solar technologies have many areas for the implementation of innovative solutions. For this reason, this article has carried out an environmental analysis within the entire life cycle of the proposed prototype solution consisting in the integration of PCM with the tubular–vacuum collector. The purpose of comparing the two collectors was not only to obtain environmental factors, but also to help in the development of the proposed prototype.

Among the collectors, there is an interesting solution currently available commercially, which are evacuated flat plate collectors [82–86]. Works available in the literature relate primarily to improved efficiency, energy optimization, or determining their performance. The evacuated flat plate collectors offer significant efficiency advantages over both conventional flat plate and evacuated tube collectors. A simulation of such a panel connected to a heating system [82] showed that it would generate an annual heat output by 66% higher than the equivalent area of evacuated tubes and by 112% higher than that obtained from conventional flat plate collectors. Despite the high efficiency of the evacuated flat plate collectors, a problem during their operation was indicated in study [83]. This was related mainly to absorbers, enclosures, and sealing highlights.

Due to the growing importance of effective energy management and the need to reduce the consumption of conventional energy sources and harmful emissions, this article presents the results of LCA carried out for the proposed heat storage technology with and without the use of a PCM placed in an ETC. The results aimed to assess the obtained environmental indicators for the suitability of the proposed solution. The concept and results of the evacuated tube collector (ETC) solution with a PCM (ETC/S-PCM) are presented in [8,87,88]. The selection of the evacuated tube collector was guided by the opportunity to utilize the very good insulation properties of these collectors. PCM inside the vacuum tube is prone to smaller heat losses compared to flat solar collectors. Moreover, as compared to flat collectors, tubular–vacuum collectors enable higher heat carrier temperatures to be achieved and have better optical characteristics that provide a lower sensitivity to variations in solar radiation incidence angle. As shown in study [89], this makes also possible to enhance the capability of solar collectors to be used in the central heating systems of buildings.

## 2. Materials and Methods

The objective of this study was to perform an environmental evaluation of the tube-vacuum solar collector prototype during its entire cycle. The collector was developed at the Czestochowa University of Technology. Its innovativeness is the use of a phase change material (paraffin) as a heat-storing material. The effect of the analysis was not geared toward improving the heat storage technology or comparing it with others, but toward acquiring knowledge of the extent to which the collector's novel design would affect the environment compared to a tube-vacuum solar collector without a phase change material. The analysis considered the benefits of the manufacture of by-products and recycling of materials, such as steel, glass, aluminum, copper, and paraffin. Considering recycling during environmental impact analysis is important due to the varying degree of recycling achievable for different products. Products that can easily be subjected to this process are characterized by higher effectiveness, showing a beneficial impact on the environment. One of the tools for assessing and comparing the environmental impacts of different technologies or products is LCA [2,3,90,91]. To perform an environmental evaluation of the proposed ETC/S-PCM solution, an investigation was carried out using the LCA assumptions included in the EN ISO 14040 [92] and EN ISO 14044 [93] standards. In accordance with the requirements of these standards, the environmental impact assessment included the following stages: specification of the purpose and scope of tests (stage 1), data collection for analysis (LCI; stage 2), assessment of the environmental impact of technology (LCIA; stage 3), and interpretation of results (stage 4). SimaPro software was used to carry out the analyses using the Eco-indicator method'99.

### 2.1. Life Cycle Assessment Data

The heat generated by the solar collector was assumed to be intended for preparing domestic hot water (DHW) for a single-family residential building. The system will be used by 4 people who consume in total 140 $dm^3$ domestic hot water per day. The design temperature of domestic hot water will be 45 °C, while that of tap water, 10 °C. The DHW system will be supplied by ETC and ETC/S-PCM with an aperture surface of 6 and 5 $m^2$, respectively. This will enable 43.8 GJ of heat to be obtained from solar radiation energy for each solar collector variant. Therefore, the value 43.8 GJ was taken as a functional unit for the comparative analysis. By relating the amount of heat produced over the 15 years of solar installation operation to the surface area of the solar collectors, the unit heat yield will amount to 7.3 and 8.76 GJ/m$^2$, respectively, for the collector with paraffin and the collector without paraffin. This constitutes an increase in the share of solar radiation energy in the heating up of domestic hot water from 39 to 46%, when comparing the yield of heat from the solar collectors per square meter of their aperture surface area. Figure 1 represents a schematic diagram of the solar collector and installation with a domestic hot water tank. For each of the variants analyzed, tests were carried out on the identical solar collector. The difference between the variants was the mode of integration of paraffin with the collector. In Variant (a), the collector with no PCM was used. By contrast, in Variant (b), a phase-change material in the form of paraffin was introduced inside the tube where the heat pipe is situated. The basic types and quantities of materials required for the environmental analysis were derived from the technical data of the materials used for constructing solar collectors at the laboratory of the Czestochowa University of Technology. These values are presented in Table 1. The energy effects and, thus, quantities of the energy required for the analysis were obtained from laboratory tests. The results are given in [8,87,88]. The remaining data necessary for LCA, including the environmental costs of obtaining natural raw materials, transport, energy conversion, and water and sewage management, were obtained from SimaPro software using the Ecoinvent, ELCD, and USLCI databases. The values assumed were for the conditions of Middle Eastern Europe and Poland.

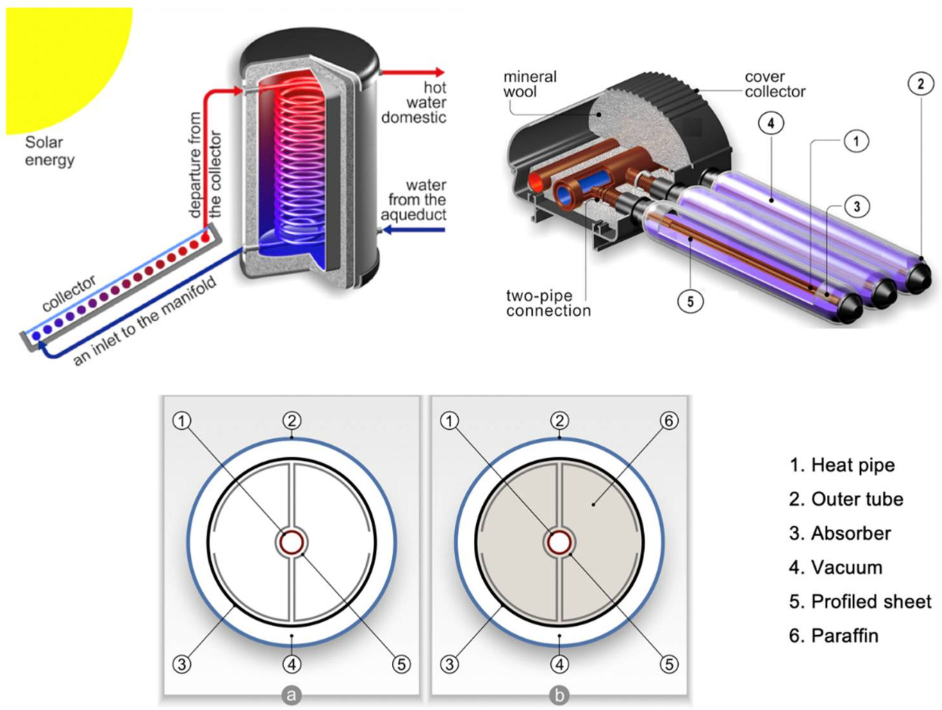


**Figure 1.** Scheme of the system: (**a**) ETC without PCM; (**b**) ETC/S integrated with PCM.

**Table 1.** The basic types and quantities of materials used in the environmental analysis.

| | Collector ETC | Collector ETC/S-PCM |
|---|---|---|
| The amount of material (kg) | | |
| Aluminum | 6.800 | 5.747 |
| Copper | 51.005 | 43.103 |
| Glass | 138.055 | 116.666 |
| Steel | 13.602 | 11.494 |
| Insulation | 20.130 | 17.011 |
| Paraffin | – | 113.821 |
| Emissions to the atmosphere (kg $GJ^{-1}$) | | |
| $CO_2$ | 3.770 | 3.1600 |
| CO | 0.0024 | 0.0020 |
| $NO_x$ | 0.0084 | 0.0071 |
| $SO_2$ | 0.0535 | 0.0449 |
| Dust | 0.0288 | 0.0241 |
| Electricity consumption $GJ_{el}/GJ_c$ | 0.06 | 0.06 |
| Solar energy (without/with paraffin) $GJ_{sol}/GJ_c$ | 0.39 | 0.46 |

The analysis was conducted in three phases: construction, operation, and disposal. The scope of the individual phases to analyze the ETC and ETC/S-PCM solutions included mineral resource extraction, fuel processing, electricity generation and distribution, the production of individual components of the solar collector, operation of the solar installation, waste treatment, and the impact of transport on the environment. The system also included benefits of the manufacture of by-products and the recycling of materials such as steel, glass, aluminum, copper, and paraffin. The detailed construction of the solar installation (hot water tank, circulation pump, expansion tank) was excluded from the system boundaries because the analyses aimed at comparing heat storage in a collector with and without paraffin. Therefore, only processes related to energy flow and heat generation were considered in the operational phase, while the system itself was established as a ready-made installation for supplying domestic hot water to a family of four. Figure 2 shows the scheme of the methods of storing heat obtained from solar radiation and the mass balance of materials used in the analyzed solutions. LCAs were carried out per functional unit and environmental burden and were expressed as eco-indicator points (Pt) throughout the life cycle of the technology. The installation's service duration of 15 years was chosen based on the expected length of life of the solar collector prototype. By continuing developmental studies, this duration can be extended in the future. The current service life of the ETC/S-PCM is shorter than that of standard tube-vacuum collectors available in the market. This made it possible to compare individual collector variants with one another, as all of them were operated under identical conditions and for the same period. Both collectors, with and without paraffin, had the same surface area and the same calorific effect of vacuum tubes. The higher amount of heat obtained from the solar collector prototype was due to the use of the phase change material. The heat capacity of the solar collector prototype was increased by placing paraffin in the interior without changing its geometry. Three groups of variants were assumed for the comparative assessment:

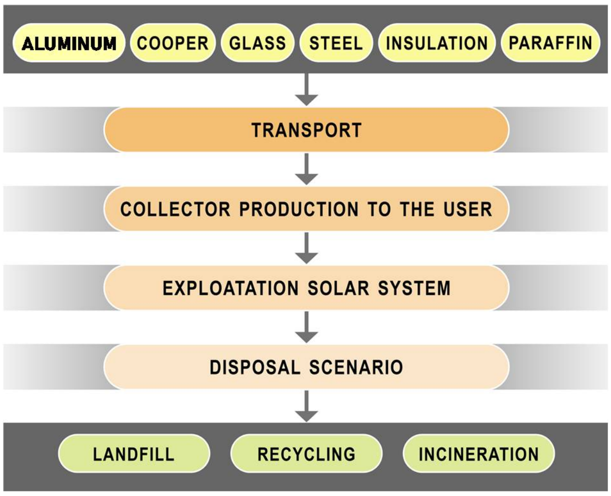


**Figure 2.** Scheme of the analysis object and material data used for LCA.

Variant 1: basic ETC

Variant 2: ETC/S-PCM that was treated as a product of oil refining and placed as one of the collector's structural elements.

Variant 3: ETC/S-PCM that was treated as waste during crude oil refining and placed as one of the collector's structural elements.

In addition, within the analyzed variants, in stage 1 of the life cycle (construction), different production methods for individual materials (including the extraction of mineral raw materials) from which the solar collector was made were compared. Three scenarios of the environmental impact of the analyzed variants were presented depending on the method of material production used to build the ETC:

P1: For each material from which the collector was built, the most burdensome environment was considered for production—currently, the most often used production method.

P2: For each material from which the collector was built, the low-burden environment was considered—the best available solution.

P3: For each material from which the collector was built, the methods of production, including the use of recycled materials already at the construction stage of the installation, were considered.

Table 2 presents the assumed values of Pt for the ETC with and without paraffin, depending on the material production method. For stage 3 of the analyzed solution, two scenarios of waste use were adopted:

**Table 2.** Values of Pt for the ETC with and without paraffin, depending on the production method; the values of Pt from SimaPro software.

| Scenario | Production Method | Value of the Ecomarker (Pt) | |
|---|---|---|---|
| | | Without Paraffin | With Paraffin |
| | Aluminum | | |
| P1 | Primary, at plant | 8.5 | 7.2 |
| P2 | Alloy $AlMg_3$, at plant | 3.1 | 2.7 |
| P3 | Secondary, from new scrap, at plant | 0.8 | 0.7 |
| | Copper | | |
| P1 | Primary, at regional storage | 444.0 | 375.2 |
| P2 | Primary, at refinery | 281.0 | 237.5 |
| P3 | Secondary, from electronic and electric scrap recycling, at refinery | 0.3 | 0.3 |

**Table 2.** *Cont.*

| Scenario | Production Method | Value of the Ecomarker (Pt) | |
|---|---|---|---|
| | | Without Paraffin | With Paraffin |
| | Glass | | |
| P1 | Solar collector glass tube, with silver mirror, at plant | 76.5 | 64.7 |
| P2 | Glass tube borosilicate, at plant | 34.2 | 28.9 |
| P3 | White glass, at plant | 14.8 | 12.5 |
| | Insulation | | |
| P1 | Tube insulation, elastomer, at plant | 11.9 | 10.0 |
| P2 | Rock wool, at plant | 4.4 | 3.7 |
| P3 | Rock wool, fleece, production mix, at plant | 1.5 | 1.2 |
| | Steel | | |
| P1 | Chromium steel, at plant | 19.2 | 16.2 |
| P2 | Stainless steel hot-rolled coil, production mix | 3.6 | 3.1 |
| P3 | Hot-rolled coil, blast furnace route, production mix, at plant | 0.7 | 0.6 |

SCENARIO A (sA) assumed the recycling of materials, such as aluminum, copper, steel, glass, and paraffin (for systems with a PCM), at a level of approximately 50% for each raw material, while 80% of the remaining waste was subjected to storage and 20%, to incineration.

SCENARIO B (sB) assumed that 90% of each of the following materials was recycled: aluminum, copper, steel, glass, and paraffin (for systems with a PCM). In addition, 100% of the remaining waste was stored.

Table 3 presents a list of variants assumed for analysis and specifies the production method of the materials and the scenario of use.

**Table 3.** Specification of the analyzed variants.

| | Without PCM | PCM as a Product | PCM as Waste | Method Producing the Most Burden | Method indirectly Burdening | Method Producing the Least Burden | 50% Recycling | 90% Recycling |
|---|---|---|---|---|---|---|---|---|
| V1-P1-sA | X | | | X | | | X | |
| V1-P2-sA | X | | | | X | | X | |
| V1-P3-sA | X | | | | | X | X | |
| V1-P1-sB | X | | | X | | | | X |
| V1-P2-sB | X | | | | X | | | X |
| V1-P3-sB | X | | | | | X | | X |
| V2-P1-sA | | X | | X | | | X | |
| V2-P2-sA | | X | | | X | | X | |
| V2-P3-sA | | X | | | | X | X | |
| V2-P1-sB | | X | | X | | | | X |
| V2-P2-sB | | X | | | X | | | X |
| V2-P3-sB | | X | | | | X | | X |
| V3-P1-sA | | | X | X | | | X | |
| V3-P2-sA | | | X | | X | | X | |
| V3-P3-sA | | | X | | | X | X | |
| V3-P1-sB | | | X | X | | | | X |
| V3-P2-sB | | | X | | X | | | X |
| V3-P3-sB | | | X | | | X | | X |

### *2.2. Data Inventory*

The main task of the LCA inventory stage was to collect input and output data for the assumed system boundaries, i.e., taken from the resource environment and released into the environment for energy, useful materials, products, etc. This stage forms the basis before the next stage of impact assessment. The data availability issue was the largest limitation in the heat storage technology analysis. The data used were made available by production plants, enterprises, and research centers and were developed based on their own reports of analyzed installations. Construction data were collected via consultations with field experts. During calculations, SimaPro also used the Ecoinvent and ELCD databases for global and regional data on material flows, fuel supplies, energy carriers, transportation, and waste treatment. These data refer mainly to Swiss and Western European settings, more extensively presented in the Swiss Center for Life Cycle Inventories report [94]. For the average share content of various recycled production materials, the USLCI database, published by the National Renewable Energy Laboratory (NREL), was used [95]. With regard to the materials produced, the cycle from raw material extraction to the finished material was investigated. The indicator referred to 1 kg of material. With regard to production processes, emissions from processes and from energy use were investigated. For extracting and processing raw energy materials, the average level of process efficiency was considered. The electricity consumed in the production stage of the analyzed systems was entirely generated in Poland. Within the limits of the system assumed for analysis, with regard to transport processes, the type and impact of emissions from fuel production and consumption during transport were investigated.

*2.3. Impact Assessment of Heat Production by the Evacuated Solar Tube Collector*

Eco-indicator 99 valuation factors are calculated in three steps:

- Damage factors for the pollutants or resource uses are calculated for different impact categories.
- Normalization of the damage factors on the level of damage categories. Normalization data is calculated on a European level, mostly based on 1993 as a base year, with updates for the most important emissions.
- Weighting for the three damage categories and calculation of weighted Eco-indicator 99 damage factors. In this method, weighting is performed at damage category level (endpoint level in ISO). A panel performed weighting of the three damage categories. For each perspective, a specific weighting set is available. The average result of the panel assessment is available as weighting set. The impact category indicators that refer to the same endpoint are all defined in such a way that the unit of the indicator result is the same. This allows addition of the indicator results by group. The Hierarchist version of Eco-indicator 99 with average weighting is chosen as default. In general, value choices made in the Hierarchist version are scientifically and politically accepted.

Figure 3 shows the normalization and weighting factors that have been used to calculate the weighted Eco-indicator 99 from the damage factors in ecoinvent. The average weighting factors are used for the Hierarchist perspective (EI'99H/A). The weights are shown as percentages, multiplied with 1000 while calculating the "weighted damage factor". The unit "points" is assigned to the results of the multiplication of the weighted damage factors with the inventory flows. In the software, the results are shown with the unit "Pt".

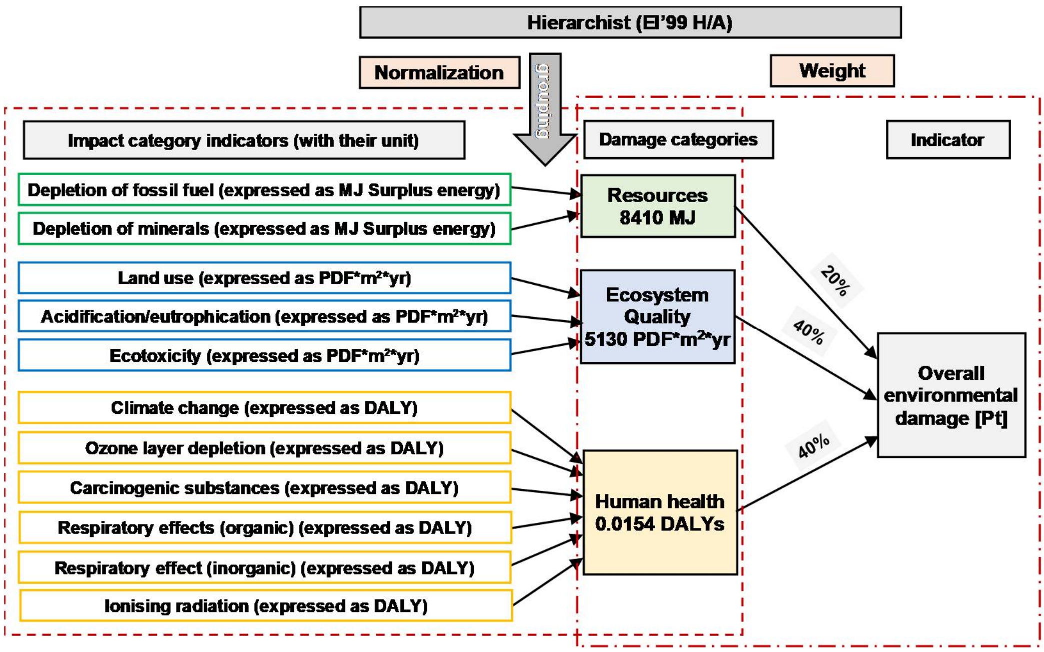


**Figure 3.** Normalization and weighting factors for the Hierachist (EI'99 H/A) perspectives on the Eco-indicator 99 method.

Damages of the impact categories result in three types of damages:

1. Damage to human health, expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World Bank and the WHO. Human health, as expressed with the Disability Adjusted Life Years unit adopted, unify the results of measuring human health impact by individual impact categories, such as climate

changes, ozone layer depletion, carcinogenicity, the effects of respiratory disorders, and ionizing radiation, per kg of emission causing a respective harm. The DALY scale was developed for the WHO. It is calculated using three quantities: the number of years lost due to a premature death or the number of years lived with a given disease, the weight of the disease, and the number of cases in a year.

2. Damage to ecosystem quality, expressed as the loss of species over an certain area, during a certain time. Ecosystem quality, defining either a depletion or disturbance in a given ecosystem, determined using the following impact categories: ecotoxicity, acidification/eutrophication, utilization and transformation of the land surface. An adopted unit that characterizes the magnitude of harm in an ecosystem is PDF (Potentially Disappeared Fraction, i.e., a fraction potentially endangered with extinction).
3. Damage to resources, expressed as the surplus energy needed for future extractions of minerals and fossil fuels. Natural resources, expressed as an excess of energy needed for the re-extraction of the unit (kg or $m^3$) of a given mineral raw material or fossil fuel.

Not all impact categories had a significant impact on the environment, so the presentation of results was limited to normalized values obtained for the selected significant impact categories. The total environmental impact of the remaining categories was approximately 1.5% of the total damage. The pre-consultation report [96] presents in detail the model and calculations of the impact assessment method. The values in all impact categories of the characterization stage were scaled to 100%, and the results were normalized by dividing the values of individual impact categories by the common reference value and weighting (the normalized values of impact categories were assigned weights). LCAs were carried out per functional unit and environmental load and expressed in the Pt value throughout the technology life cycle. This enabled a comparative analysis of the assumed heat storage options and their impact on various elements of the ecosystem and factors that most burden the environment. The impacts refer to the largest impact within a given category, so damage category standardization was carried out—determining the ratio of the amount of damage to the statistical amount of damage caused by one inhabitant of Europe during the year. Positive values indicated an adverse effect on the environment, while negative values indicated a beneficial effect on the environment, known as avoided emissions.

## 3. Results and Discussion

Figure 4 shows the results of the life cycle analysis as the final points of Pt for individual impact categories and damage categories.

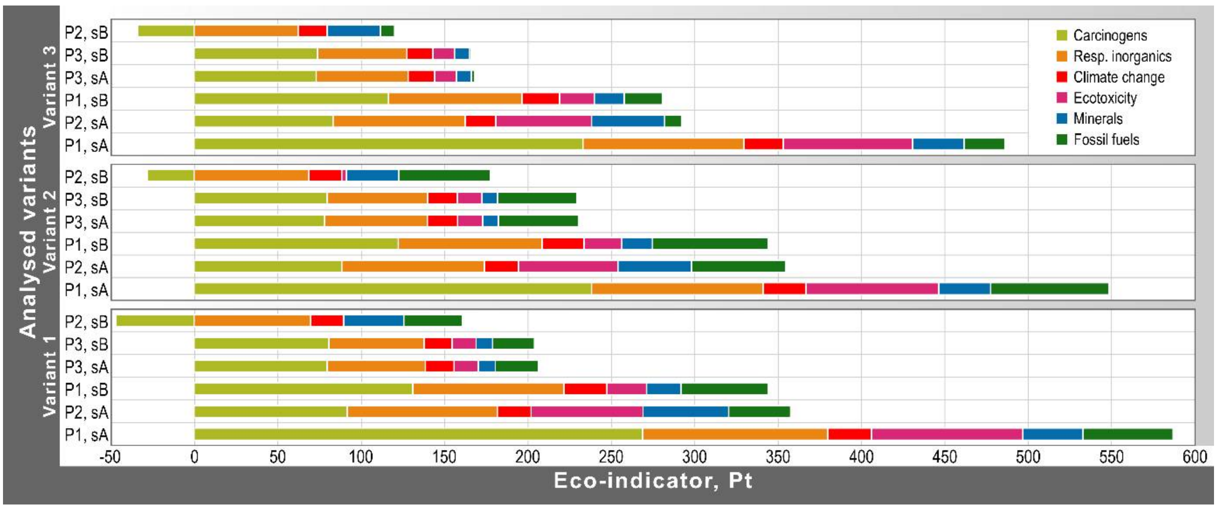


**Figure 4.** Share of individual categories of inflows in eco-indicator points.

In the analyses of 18 variants, a significant impact was observed on the technological advancement of ETC production and the disposal method. In variant 1 (collector without a PCM), the impact category that had the largest share in the overall damage from 41 to 46%, which was 47 and 269 Pt, respectively, was carcinogens. The method of producing materials as well as the increase in the share of recycling (waste use) had a significant impact on volatility. The most beneficial environmental impact was obtained for the production method P2 and the waste management scenario sB, where a positive environmental impact (avoided emissions) was found, reducing the final Pt value by 47 points. The range of the interaction of inorganic compounds with the respiratory system was 57 to 111 Pt, which was the second-largest category adversely affecting the environment. In this category, the lowest Pt was for the production of the least environment-polluting materials (P3), while the highest share was observed for variant 1 (V1-P2-sB), i.e., with the most beneficial environmental impact in variant 1. For the fossil fuels category, the highest value was obtained for variant 3 (V3-P2-sB), while the lowest was obtained for the most advantageous variant 1 (V1-P1-sA). For other impact categories, i.e., ecotoxicity, climate change, and mineral consumption, their average share accounted for 8, 9, and 11%, respectively. Carcinogenicity was also an important element in the analysis of variants with paraffin. Its share ranged from 19 to 43% in option 2 and 40 to 48% in option 3. Similar to the base variant, in this case as well, the change in the waste use scenario or the material production method significantly affected the environment, having a beneficial effect for the production method P2 and the waste management scenario sB. For the remaining categories, similar relationships were obtained for the collector without paraffin. Variant 2 was characterized by the highest share in the fossil fuel category (from 13 to 36%) among all analyzed variants. When comparing waste management scenarios sA and sB, for the production method P3, both the final values of Pt and the individual impact categories were at a similar level. The change in waste disposal from sA to sB resulted in a 41, 37, and 42% reduction in environmental rejection for the production method P1 and 81, 73, and 82% reduction in environmental rejection for the production method P2, respectively, for variants 1, 2, and 3. An equally significant reduction in the environmental impact by 65, 58, and 66% (for variants 1, 2, and 3, respectively) was obtained by changing the method of material production from P1 to P3 in the waste management scenario sA. These results show how important the chosen technology is for the production of individual materials from which the evacuated tube collector is made and how it will be managed at the end of its operational life. Although the ETC proved to be the most burdensome solution for the environment (V1-P1-sA), it showed a slightly higher value of the equator compared to the most preferred solution of the ETC/S-PCM in the production method P2 and the waste management scenario sB. In addition, it proved to be a more beneficial solution than the variant with paraffin, which was treated as a product of crude oil refining. LCAs did not show unambiguously that the use of paraffin for heat storage in a tube-vacuum manifold is significantly better for the environment compared to traditional solutions. However, the energy impact of such a solution makes it better suited for sustainable development [8,87]. Due to the continuous improvement in the efficiency of devices using renewable energy and reducing environmental impacts, the proposed ETC with a PCM seems a more favorable choice, i.e., V3-P2-sB, as characterized by the production of less environmentally burdensome materials and 90% waste recycling. Figure 5 presents the share of the individual impact categories (in ascending order for individual variants) in the final results of Pt. Detailed results are also presented in Table 4.

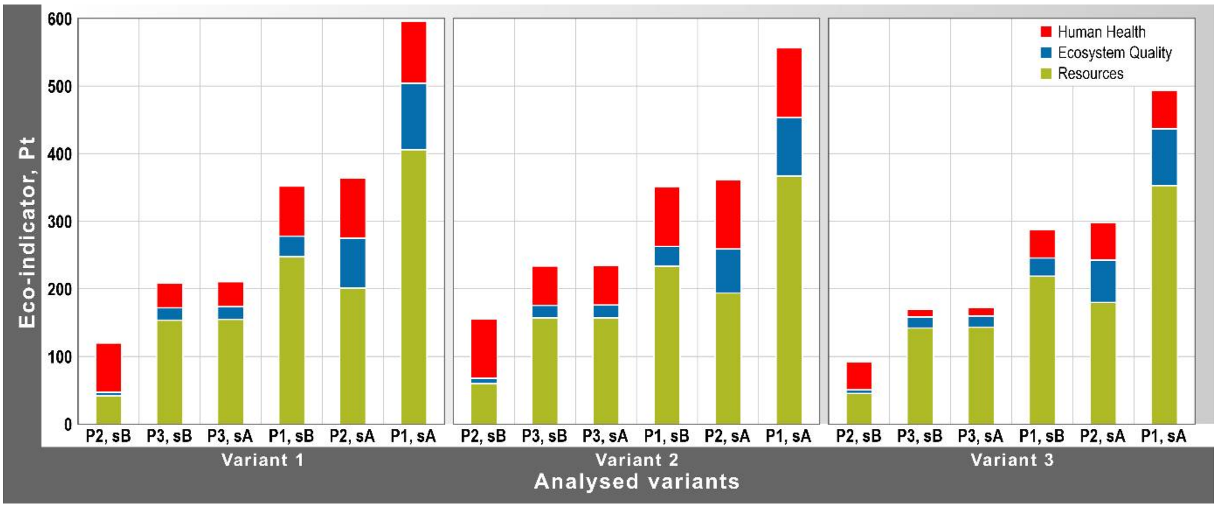


**Figure 5.** Eco-indicator results for the considered variants.

**Table 4.** Values of Pt for the analyzed damage categories and the final value of Pt for the variants studied.

| Analyzed Variant | Analyzed Options, Disposal Scenarios | Eco-Indicator (Pt) | | | |
|---|---|---|---|---|---|
| | | Resources | Ecosystem Quality | Human Health | Final Value |
| Variant1 Basic | P1, sA | 89 | 98 | 407 | 594 |
| | P2, sA | 88 | 73 | 202 | 363 |
| | P3, sA | 35 | 18 | 156 | 209 |
| | P1, sB | 72 | 31 | 248 | 351 |
| | P2, sB | 70 | 6 | 43 | 119 |
| | P3, sB | 34 | 18 | 155 | 207 |
| Variant2 PCM | P1, sA | 101 | 86 | 368 | 555 |
| | P2, sA | 100 | 65 | 195 | 360 |
| | P3, sA | 57 | 19 | 158 | 234 |
| | P1, sB | 87 | 29 | 234 | 350 |
| | P2, sB | 85 | 8 | 61 | 154 |
| | P3, sB | 56 | 19 | 158 | 233 |
| Variant3 PCM | P1, sA | 55 | 84 | 354 | 493 |
| | P2, sA | 53 | 63 | 181 | 297 |
| | P3, sA | 10 | 16 | 144 | 170 |
| | P1, sB | 40 | 27 | 220 | 287 |
| | P2, sB | 39 | 6 | 46 | 91 |
| | P3, sB | 9 | 16 | 143 | 168 |

Based on the data in Figure 5 and Table 4, the largest value of Pt was obtained for V1-P1-sA. The main areas affected by the ETC are the categories of damage related to human health (approximately 400 Pt), which is 68% of the total damage done in this variant. For most of the analyzed variants, the greatest impact on the environment was obtained in the category of human health. Only V1-P2-sB and V2-P2-sB showed more unfavorable effects in the natural resources category (59 and 55% of the total damage caused, respectively). The lowest share in the total damage for the majority of the analyzed variants was the quality of ecosystems. For variant 1, the share ranged from 5 to 20%; for variant 2, from 5 to 18%; and for variant 3, from 6 to 21%. The most preferred option was V3-P2-sB (91 Pt). If we only accept damage related to human health as the main criterion for assessing individual solutions of the heat storage, the collector without paraffin, with its proper production method (P2), shows a 15% lower negative environmental impact in this category compared to the most favorable variant (V3-P2-sB). Comparing the variants with the most and the least burden on the environment, discrepancies in the final value of Pt were obtained at a level of 85% (504 Pt). The difference between V3-P2-sA and V3-P2-sB amounted to 206 Pt (69%) and resulted only from a change in the third stage of the life cycle, i.e., waste liquidation. Such a significant decrease in the final value of Pt shows all the variants tested in the method of producing P2 materials. In the case of the production method P3, i.e., with the least burden on the environment, for each of the analyzed variants, the discrepancies reached 1%. With the use of better-quality materials, from P1 through P2 to P3 in different waste management scenarios, the demand for conventional energy decreases. In addition to introducing the product itself, which is paraffin, to the collector, we also added its manufacturing process. As paraffin is formed during the process of petroleum refining, the sole addition of this process causes an increase in value in the category of natural resources.

Considering only variants with the waste management scenario sA, the most preferred variant was V3-P3, which had a 71% smaller impact on the environment in relation to the most unfavorable variant (V1-P1-sA). Analyzing variants with the management scenario sB, the smallest impact on the environment was shown by V3-P2, which had a 74% smaller impact on the environment compared to the most unfavorable option (V1-P1-sB). In the overall balance of the environmental impact, in each variant, the method of production P2 proved to be the best solution. This comparison illustrated the impact of the assumptions made in the specific stages of the technology under study on the results of the analysis throughout the life cycle.

The introduction of paraffin requires its production, which entails an increase in the consumption of conventional energy. If generally available paraffin (P1) is used, this increase is the highest. If good-quality paraffin (P2) is used, the increase will be slightly lower; however, the difference will be small (87 to 85 Pt). A significant reduction of 56 Pt will only be achieved by introducing paraffin from waste (P3). The obtained value is even smaller than in the collector without paraffin from conventional materials (72 Pt).

The results illustrated in Figure 4 have clearly shown that the evacuated tube collector filled with paraffin, which has been regarded as waste, is the most advantageous solution to a solar collector for all scenarios analyzed. A preferred technology for the production of materials is the P2 method, that is taking into account low environmental-burdening material manufacturing methods. Moreover, the need for the 90% degree of recycling of materials, such as aluminum, copper, steel, glass, and paraffin (method B) should be assumed. The results shown in Figure 4 demonstrate that the most advantageous solar collector solution is the variants with PCM V3, P2, sB (eco index value 91 Pt). An equivalent for this solution, but without PCM, is the base variant V1, P2, sB (eco-indicator value 119 Pt). For either solution, an advantageous environmental effect was obtained in the category of carcinogenicity. In terms of carcinogenicity, the base variant ranked the best, showing a negative eco index value of −47 Pt. Nevertheless, in the case of the collector with paraffin, this environmentally beneficial effect is smaller only by 13 Pt points. A converse situation was observed for the category of fossil fuels, where the PCM variant got only 8 Pt, with 34 Pt for the variant with no PCM. This is indicative of a considerable reduction of the consumption of fossil fuels for the variant V3, P2, sB, i.e., for the new solar collector design. In the category of inorganic compound impact on the respiratory system and mineral consumption, the differences between the two solutions were small. However, in both cases, the new solar collector design variant turned out more advantageous. It can also be accepted that both solutions, i.e., V3, P2, Sb and V1, P2, sB, have a comparable effect on climate changes and ecotoxicity. To sum up the comparison of the most advantageous solar collector solutions either with PCM or with PCM, it can be stated that the fundamental difference resulting from the collector design occurs in terms of natural resources utilization. For the PCM solar collector, it is 44% lower than for the base collector with no PCM. This effect is chiefly due to the reduction of fossil fuel consumption for the new solar collector design.

## 4. Conclusions

A reduction in the harmful environmental impacts of ETC installation resulting from its production and use can be achieved by applying a higher technological level in the production process and increasing the degree of material recovery in the waste management process. In the case of the base variant (variant 1), i.e., the ETC without a PCM and the ETC, the selection of low-burner production techniques and the adoption of 90% recycled materials at the end of operation can reduce the harmful environmental impact by 80%. In the case of the evacuated tube collector with a PCM and ETC/S-PCM, this reduction was 72 and 82%, respectively, for variant 2 (paraffin formed in the production process) and variant 3 (recovered paraffin). Nevertheless, of these two variants (ETC with PCM), the second option, where paraffin was obtained as a recycled product, was the most advantageous solution in terms of the environmental impact compared to the base variant. Assuming comparable production methods for individual elements of the ETC and waste management scenarios, the reduction in harmful effects on the environment by introducing a PCM that stores heat inside the ETC ranges from 17 to 24%. Considering the increase in the use of solar energy in the domestic hot water preparation process amounting to 20.5% in the analyzed case and the environmental effect achieved, the proposed ETC with a PCM, i.e., ETC/S-PCM, achieves environmental acceptability from two points of view: an increase in the solar energy in the heating installation and the circular economy aspect, thus contributing to the principle of sustainable development. In the assessment of the life cycle of the analyzed variants, many environmental impact categories and technical aspects were considered, but the main areas of the impact of ETC damage categories were related to human health.

The lowest environmental cost necessary to apply the more energy-efficient ETC/S-PCM prototype, even lower than the environmental cost for the traditional ETC tube-vacuum solar collector, is achievable for the variant V3-P2-sB. For the construction of the ETC/S-PCM solar collector, the paraffin used is waste from petroleum refining, and for each collector material, the current low-environmental methods of production are considered, with 90% recycling of aluminum, copper, steel, glass, and paraffin.

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## Nomenclature

| | |
|---|---|
| PCM | phase change material |
| ETC | evacuated tube collector |
| LCA | life cycle assessment |
| ETC/S-PCM | phase change material with the evacuated tube collector |
| LCI | data collection for analysis |
| LCIA | assessment of the environmental impact of the technology |
| DHW | domestic hot water |
| Pt | value of eco-indicator points |
| P1, P2, P3 | methods of material production |
| sA, sB | scenarios of waste management |
| V1, V2, V3 | analyzed variants |
| NREL | National Renewable Energy Laboratory |
| ELCD | European Platform on Life Cycle Assessment |
| USLCI | US Life Cycle Inventory Database |

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