Hybrid PV-TE-T modules: life cycle analysis and end of life assessment

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Abstract. World population growth along with requirements for more energy forced scientists into research for cleaner and sustainable energy sources. The largest available energy source, solar energy requires improved technologies and processes for conversion into electrical and thermal energy. This paper continues a series of analyses of a proposed hybrid module, which combines direct photovoltaic (PV) conversion to electricity with thermal conversion (T) and thermal waste heat recovery (using thermoelectric devices, TE). An extended life cycle analysis (LCA) is performed on each of the three components of hybrid module, carefully identifying inputs, processes and outputs, as well as impact per each standard category. Also, a review on end of life assessment is presented for the hybrid PV-TE-T module.

1. Introduction

The sun is working as a nuclear fusion reactor and is transmitting more energy to the Earth than humankind could use, but technologies have not yet been fully developed to ensure its efficient conversion. The incident solar radiation sets in motion the Earth’s climate system, by ensuring the water circuit in nature, including rains that feed the hydrological network, occurrence of air movements (wind), generation of waves, respectively supports development of biomass through biological phenomena. Proper use of these energy sources and flows would replace the use of fossil fuels. The renewable energy sources (RES) that are being connected in one way or another to solar energy are solar, wind, geothermal, bio- and hydro-power. If current technologies would be able to capture and convert the entire incident solar heat flux, the annual global energy demand would represent only 0.01%.

Global energy demand increased by 0.9% in 2019, i.e. 120 million tonnes of oil equivalent (Mtoe), 40% the rate of growth observed in 2018, [1].

Nowadays, the most significant part of the global energy needed for daily consumption is still obtained from the non-renewable energy sources, by combustion of fossil fuels, even though, those sources are limited.

Recent significant progress made in conversion efficiency, in diversifying areas of applicability, in lowering maintenance costs and increasing reliability of systems using RES, generated each year more electricity from renewable energy than in the previous year. The installed renewable power capacity at end of 2018 was enough to supply around 26.2% of global electricity production. Yet, even though the interest on RES increased in the last decades, the share of solar energy in global energy and electricity production is still very low, i.e. 2.4%, figure 1.
2. Hybrid PV – TE – T modules

2.1. Solar energy - photovoltaic

There are many technologies for converting solar radiation into electricity. The easiest method is to use photovoltaic (PV) panels, which perform direct conversion by using semiconductor materials that exhibit photoelectric effect. The PV solution are at any scale, from residential applications to solar PV parks/farms. In recent years, PV panels are becoming more attractive due to the considerable decrease in electricity generation costs for civil and industrial applications. The total capacity of PV systems installed globally at the end of 2018 was 505 GW, according to REN21 2019, [2].

From a constructive perspective, a PV panel consists of several mono-crystalline or poly-crystalline solar cells disposed in a matrix and interconnected by tin strips, encapsulated in a transparent layer of plastic (ethylene vinyl acetate, ETA) or silicone rubber. For protection, the system is set between a glazing top and a laminated plastic back plate. An aluminium frame encloses the entire stack (figure 2c) for protection, handling, mounting, and stiffening, as well as for fixing the junctions and electrical protection box.

PV technologies classification takes into account the nature of absorbing material, mostly being used the mono-crystalline, poly-crystalline and thin films, figure 3. In this order, the conversion efficiency decreases, as well as the manufacturing costs.

The conversion efficiency for commercial PV panels has increased to about 20%, depending on the type of cells used, the level of solar radiation and the operating temperature of the panel, due to advancing technologies and new materials.

Numerous publications in the PV field, in terms of new materials, production methods and technologies and conversion efficiency, indicate the enhanced attention of scientific research to improve the efficiency of conversion of solar energy into electricity. National Renewable Energy Laboratory (NREL) compiles and publishes the latest available world data and findings regarding the efficiency of photovoltaic cells, [3]. The four-junction PV cells reached a conversion efficiency of 47.1% in special laboratory conditions and with a concentration of over 500 suns. The values reported for measurements performed in laboratory and certified conditions, indicated the conversion efficiency of 26.7% for mono-crystalline cells and 22.3% for multi-crystalline cells, and with technologies based on silicon disks. The maximum reported values for PV technologies with thin film deposition are 22.1% for CdTe based solar cells and 23.4% for those with CIGS (Cd-In-Ga-Se), figure 4.
Figure 2. The structure and functioning of a PV module
a) constructive details of a PV cell; b) details of operation; c) constructive details of PV panel.

Figure 3. Processing of crystalline silicon PV cells (c-Si).
The optimal operation of PV panels is at the lowest temperature possible, a fact observed since the first theoretical studies in the PV area, published in the early 1980s. Approximately 80-85% of the incident solar energy represents the residual heat, i.e. the thermal energy that must be eliminated. For this reason, research in the field of operational temperature control and optimization of photovoltaic panel performance has intensified significantly. The overall efficiency of the solar panel (electrical and thermal) is greatly improved when this residual energy is exploited, [4–9].

Finding different ways to solve the temperature problem is critical to obtaining improved conversion efficiency. Several thorough literature reviews mention various technologies to cool the photovoltaic panel surfaces, in order to obtain an increased electrical and overall efficiency of the solar conversion system, [10, 11].

The PV modules cooling systems become essential during operation and should be an integral part of PV systems, especially in the case of those operating in warm areas. In recent decades, researchers have investigated various methods that can provide sustainable thermal management for PV systems. Thus, the most important cooling methods developed are those with air, liquids, thermal tubes, phase change materials or thermoelectric modules, figure 5, [12].

The newly designed hybrid systems may reduce the disadvantages of a simple PV system, despite the complexity of manufacturing and higher prices, [11].

2.2. Thermo-electricity
Thermoelectric modules (TE) are built from materials with specific physical transport characteristics of direct conversion between thermal and electrical energy. TE consists of two different semiconductor materials connected electrically in series and thermally connected in parallel. The properties of TE modules are useful for thermal management of PV cells: they are compact, light, noiseless operation, motionless components and does not require maintenance.

The constructive scheme of a TE module is simple, figure 6. Between two ceramic plates, that will serve for uniform cooling/heat absorption and heating/heat rejection, are sandwiched the n (negative, free electrons) and p (positive, free holes) semiconductor elements, connected to each other in series electrically and in parallel thermally. The ends of the series of n and p semiconductor legs are connected with electrical conductors to either charge or battery, [13].
Figure 5. PV cooling methods and technologies, [12].

Figure 6. The components of thermoelectric module, [13].
Depending on the physical phenomenon employed in their operation, TE are divided into two groups: thermoelectric generators (TEG) and thermoelectric coolers (TEC), figure 7.

TEC are used to cool down electronic components or medical instruments, because they can provide specific temperature control, which allows operation within limited thermal intervals. The operating principle of TEC is based on a phenomenon discovered by Peltier in 1834, [15]: when the solid-state device is powered by an electricity source, one surface cools down and the other heats up, generating a temperature gradient. TEC modules may be used to cool PV cells, but given the electricity consumption, they would be justified only in some special cases, e.g. cooling concentrated PV.

TEG have a great potential for use in waste heat recovery from various industrial processes, thermal power plants, automobiles and solar energy, because they directly convert heat into electricity. TEG operating principle, based on Seebeck effect discovered in 1821, converts the thermal energy of a temperature gradient into electricity. That is, if the surfaces of TEG are in contact with heat sources of different temperatures, the device generates electricity. TEG modules have been included in PV systems to extract low temperature energy from waste heat, while ensuring the cooling of PV cells, [16].

2.3. Solar energy - thermal
The direct conversion of solar energy into thermal energy is achieved by producing hot water or heating agent at high temperatures for industrial processes or in solar power plants. Solar-thermal technologies (glazed or unglazed solar collectors) are used comprehensively all over the world to supply low-temperature heat for hot water, heating or cooling installations. The installed capacity of solar thermal collectors has grown continuously, reaching in 2018 a global total of 480 GWh, [2].

Figure 7. (a) TE Cooling (TEC – Peltier), (b) TE Generation (TEG – Seebeck) and figure of merit for various thermoelectric materials, (c) n-type and (d) p-type, [14].
Considered to be equivalent to special heat exchangers, the solar thermal collector (STC) absorbs incident solar energy and converts it into internal energy of a working fluid (frequently air, water, glycol). The energy thus integrated in the fluid is transported to the point of consumption, directly used as domestic hot water (DHW) or space heating purposes.

The technologies used for small and medium applications employ different types of collectors: flat panel collectors (FPC), evacuated tube (ETC) or heat pipes (HP-ETC).

The industrial sized systems operate at much higher temperatures and use concentrators and trackers to follow the Sun’s movement. The concentrates solar power (CSP) installations include either Fresnel Liner Reflectors (LFR) or parabolic trough collectors (PTC) for one-axis tracking, or two-axes focal point concentrators, parabolic dish reflector (PDR) and heliostat field concentrator (HFC), figure 8.

2.4. Hybrid PV-TE-T modules

In the last few years, researchers performed in-depth analyses in the field of solar cogeneration and tri-generation. They recommended various theoretical mixtures depending on specific applications and the accessibility of parts and technologies. A general CCHP structure (Combined Cooling, Heat and Power), depicted in figure 9, uses various resources, whilst term tri-generation refers to a single source.

The proposed module uses photovoltaic (PV) conversion, combined with a system for heat extraction (T) and improved with a thermoelectric (TE) generation system. The trifold energy conversion system offers stimulating opportunities, producing both electricity with a higher conversion efficiency (from PV cells combined with TE) and thermal energy for solutions of DWH or AC applications. The hybrid system can include electrical and thermal storage units for the periods with low solar radiation.

The applied manufacturing results described in the literature cover different settings of elementary installation, [18, 19].

The hybrid system contains a straightforward structure, with fixed parts, thus being reliable, low maintenance and environmentally safe. This design recommends the system for isolated individual residences or micro-communities to provide electricity, DHW and for AC applications.

The complexity of a hybrid system involves several parameters that influence the design and operation of system components. Some parameters are the material structure, heat transfer particularity, environmental specific feature, solar concentrator system, etc., [20].
Figure 9. Structure and elements of the energy system model based on user input.

Figure 10. Hybrid trifold concept, [20].
3. Life cycle analysis
With technology advancements of the recent years, there has been an intense awareness on importance of environmental protection. The analysis of manufactured and consumed products becomes necessary to intervene in understanding, reducing and estimating the environmental impact and for estimating the energy efficiency. One technique developed for this purpose is life cycle analysis or assessment (LCA). International Standards, [21], depicts the fundamentals and framework for conducting and reporting LCA studies, and contains certain minimal requirements.

LCA is an evaluation technique with a systematic approach and is carried out in several steps. The ISO standard [21] specifies four main steps that apply to either stage of a product’s life, from the perspective that one operation leads to the next, figure 10. This analysis provides quantitative data to researchers or companies for their products. LCA allows estimating the impact on the environment resulting from all stages of the product life cycle, from raw materials acquisition, material processing, part manufacturing, assembly, product use to waste management/end of life, and all transportation, [22].

The first phase of LCA, goal and scope definition, describes the product, process or activity and sets the functional unit, boundary conditions and environmental effects of the analysis.

The life cycle inventory (LCI) collects and relates data on processes and materials. The data quality can be from the production, direct measurements, estimations, allocated or calculation method. This phase is important for understanding the consumption of all materials and energy, as well as creation of waste associated with the product, e.g. air emissions, solid waste disposal, wastewater discharges, missing flows.

The life cycle impact assessment methods perform an appraisal on selected impact categories. These can value different impact such as characterization, classification, normalization, grouping or weighting profile, e.g. damage to ecosystems, acidification, or global warming.

Data interpretation contain the results of inventory analysis and impact assessment, evaluated based on the objectives of selected product, process or service with a clear understanding of the contribution, perturbation, sensitivity and uncertainty used to generate the results. This step is important to identify the environmental hot spots in the production, or to compare alternative products based on specific criteria. The result should be well-balanced conclusions and/or recommendations.

The applications step represents a product development and/or improvement, a strategic planning, public policy making, marketing, etc.

Basic life cycle stages imply the analysis of inputs (raw materials and energy), of processes within system boundaries (raw materials acquisition, manufacturing, use/reuse/maintenance and recycle/waste management) and of outputs (atmospheric/waterborne/solid wastes, coproducts and other releases).

Since the proposed hybrid unit encompasses three distinct subsystems, the following analysis details in Tables 1 – 3 the inventories of production phases for each part (photovoltaic, thermal, thermoelectric). Compiling data from an extensive literature review, [23 – 34], each inventory describes the materials, energy and processes involved in manufacturing the subsystem. Figure 12 presents the basic processes and main life cycle stages for the entire hybrid module.
Table 1. Inventory of the photovoltaic (PV) subsystem production phase.

| Element          | Material                  | Amount | Unit     | Process                                                                 |
|------------------|---------------------------|--------|----------|-------------------------------------------------------------------------|
| SG silicon       | MG-silicon                | 1.13   | kg       | Metallurgical grade silicon                                             |
|                  | Inorganic chemicals       | 2.00   | kg       | Mix of NaOH, HCl and H₂                                                 |
| Poly-Si Ingot    | SG silicon                | 1.30   | kg       | Solar grade, poly-crystalline silicon                                  |
|                  | Quartz crucible           | 0.39   | kg       | For ingot growing                                                       |
|                  | Gases (N₂, Ar, He)        | 0.35   | kg       | For ingot growing                                                       |
| Si Cell          | Glass                     | 0.01   | kg       | Attachment to wire sawing equipment                                    |
|                  | Water                     | 0.06   | kg       | Ingot sawing                                                           |
|                  | Silicon carbide (SiC)     | 2.63   | kg       | Virgin and recycled, for sawing slurry                                 |
|                  | Polyethylene glycol       | 2.71   | kg       | Virgin and recycled, for sawing slurry                                 |
|                  | Steel wire                | 1.49   | kg       | Wafer cutting                                                          |
|                  | Inorganic chemicals       | 0.30   | kg       | Wafer cleaning                                                         |
| PV Module        | Solar cells               | 61.2   | p        | +2% cell loss                                                          |
|                  | Frame                     | 4.20   | kg       | Aluminium, formed alloy                                                |
|                  | Junction box              | 0.30   | kg       | Polyphenyleneoxid, from manufacturer                                   |
|                  | Glass sheet               | 16.1   | kg       | 4-mm-thick, low iron, tempered                                         |
|                  | Ethyl Vinyl Acetate       | 1.60   | kg       | EVA, 0.96 kg/m²                                                         |
|                  | Back protection foil      | 0.83   | kg       | Polyethylene terephthalate (PET, Tedlar)                               |
|                  | Copper                    | 0.18   | kg       | Copper ribbons for cell interconnections                                |
|                  | Tin, Lead, Nickel, Solder | 0.04   | kg       | Soldering, plating, tabbing interconnect                                 |
| Energy           | SG Silicon                | 185    | MJ       | Process heat, from natural gas                                         |
| Si Cell          | 30.0                      | kWh     |          | Electricity, medium voltage, from grid                                  |
| Module assembly  | 10.7                      | kWh     |          | Electricity, medium voltage, from grid                                  |

Table 2. Inventory of the thermal (T) subsystem production phase.

| Element  | Material                  | Amount | Unit     | Process                                      |
|----------|---------------------------|--------|----------|----------------------------------------------|
| Collector| Copper                    | 8.66   | kg       | Copper, from supplier                        |
|          | Working fluid             | 0.90   | kg       | Propylene glycol, liquid                     |
|          | Epoxy                     | 0.30   | kg       | Resin, liquid                               |
|          | HDPE                      | 0.87   | kg       | High density polyethylene                    |
|          | Brass connectors           | 0.04   | kg       | Brass, from supplier                         |
|          | PVC                       | 0.01   | kg       | Polyvinylchloride, from supplier             |
|          | Welding rod               | 0.10   | kg       | Lead-free solder Sn97Cu3                     |
| Glazing  | Glass                     | 10.5   | kg       | Low-iron solar glass, from supplier          |
| Insulation| Rigid                    | 4.20   | kg       | Rigid foam, polyurethane                     |
|          | Flexible                  | 0.01   | kg       | Flexible foam, polyurethane                  |
| Casing   | Aluminium                 | 4.00   | kg       | Aluminium, formed alloy                      |
|          | Stainless steel           | 6.10   | kg       | Chromium steel 18/8                         |
|          | Galvanized steel          | 33.9   | kg       | Low-alloyed steel                            |
| Support  | Stainless steel           | 27.0   | kg       | Chromium steel 18/8                         |
|          | Galvanized steel          | 0.50   | kg       | Low-alloyed steel                            |
| Energy   | Collector                 | 18.5   | kWh      | Medium voltage electricity, from grid        |
|          | Support                   | 2.67   | kWh      | Medium voltage electricity, from grid        |
Table 3. Inventory of the thermoelectric (TE) subsystem production phase.

| Element       | Material               | Process                                                   |
|---------------|------------------------|-----------------------------------------------------------|
| Bi$_2$Te$_3$ Leg | TE material synthesis  | Ball milling powders of constituents                      |
|               | Ingot forming / consolidation | Hot pressing / Spark plasma sintering                   |
|               | Sawing blade, sawing fluids | Ingot dicing and polishing                             |
|               | Ingot metallization     | Protective coating against chipping / fractures           |
|               | Sawing blade, sawing fluids | Leg sawing                                             |
|               | Cleaning fluids         | Leg cleaning                                              |
| TE Module     | Interconnectors         | Cu-based (Mo-Cu, W-Cu) alloys interconnectors            |
|               | Diffusion barrier       | SnTe thin layer deposition                               |
|               | Braze / solder          | Au on Ni, Sputtering / electrodeless plating             |
|               | Ceramic substrates      | Thin ceramic, alumina based                              |
|               | Adhesive                | Resin                                                    |
| Energy        | Material synthesis      | Ball milling materials into powder                       |
|               | Ingot consolidation     | High temperature                                         |
|               | Module assembly         | Electricity, medium voltage, from grid                   |

Figure 12. Basic LCA stages for the proposed hybrid PV-TE-T module.
Table 4. Commonly used Life Cycle Impact categories, [24].

| Impact Category          | Scale         | Examples of LCI Data (i.e. classification)                                                                 | Common Possible Characterization Factor | Description of Characterization Factor                                                                 |
|--------------------------|---------------|-----------------------------------------------------------------------------------------------------------|----------------------------------------|---------------------------------------------------------------------------------------------------------|
| Global Warming           | Global        | Carbon Dioxide (CO₂) Nitrogen Dioxide (NO₂) Methane (CH₄) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH₃Br) | Global Warming Potential               | Converts LCI data to carbon dioxide (CO₂) equivalents Note: global warming potentials can be 50, 100, or 500-year potentials. |
| Stratospheric Ozone Depletion | Global        | Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH₃Br) | Ozone Depleting Potential             | Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.                                      |
| Acidification            | Regional      | Sulphur Oxides (SOₓ) Nitrogen Oxides (NOₓ) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH₃) | Acidification Potential                | Converts LCI data to hydrogen (H⁺) ion equivalents.                                                    |
| Eutrophication           | Local         | Phosphate (PO₄) Nitrogen Oxide (NO) Nitrogen Dioxide (NO₂) Nitrates Ammonia (NH₃)                         | Eutrophication Potential               | Converts LCI data to phosphate (PO₄) equivalents.                                                      |
| Photochemical Smog       | Local         | Non-methane hydrocarbon (NMHC)                                                                            | Photochemical Oxidant Creation Potential | Converts LCI data to ethane (C₂H₆) equivalents.                                                       |
| Terrestrial Toxicity     | Local         | Toxic chemicals with a reported lethal concentration to rodents                                            | LC₅₀                                   | Converts LC₅₀ data to equivalents; uses multimedia modelling, exposure pathways.                      |
| Aquatic Toxicity         | Local         | Toxic chemicals with a reported lethal concentration to fish                                               | LC₅₀                                   | Converts LC₅₀ data to equivalents; uses multimedia modelling, exposure pathways.                      |
| Human Health             | Global Regional | Total releases to air, water, and soil.                                                                   | LC₅₀                                   | Converts LC₅₀ data to equivalents; uses multimedia modelling, exposure pathways.                      |
| Resource Depletion       | Global Regional | Quantity of minerals usedQuantity of fossil fuels used                                                  | Resource Depletion Potential           | Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve. |
| Land Use                 | Global Regional | Quantity disposed of in a landfill or other land modifications                                            | Land Availability                     | Converts mass of solid waste into volume using an estimated density.                                   |
| Water Use                | Regional      | Water used or consumed                                                                                   | Water Shortage Potential               | Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.    |
Figure 13. Main areas of protection from impact categories, [33].

Table 5. Life Cycle Impact categories for the hybrid PV-TE-T module.

| Impact Category                      | Unit (per m²) | PV panel mc-Si | Thermal collector | TE ceramic |
|--------------------------------------|---------------|---------------|-------------------|------------|
| Global warming                       | kg CO₂-eq/kWh | 4.43e-2       | 2.38e-2           | 6.18e-2    |
| Stratospheric ozone depletion        | kg CFC11-eq/kWh | 2.06e-8       | 1.29e-8           | 1.17e-8    |
| Acidification                        | kg SO₂-eq/kWh | 2.21e-4       | 2.07e-4           | 2.44e-4    |
| Eutrophication                       | kg P-eq/kWh   | 3.78e-5       | 3.89e-5           | 6.87e-6    |
| Photochemical Smog                   | kg PM₂.₅-eq/kWh | 1.04e-4       | 8.78e-5           | 6.28e-5    |
| Terrestrial Toxicity                 | kg 1,4-DCB-eq/kWh | 1.17e-0       | 8.55e-1           | 1.30e-0    |
| Aquatic Toxicity                     | kg 1,4-DCB-eq/kWh | 1.16e-2       | 6.42e-3           | 5.25e-0    |
| Human Health                         | kg 1,4-DCB-eq/kWh | 1.63e-1       | 2.24e-1           | 1.16e-1    |
| Resource Depletion - mineral         | kg Cu-eq/kWh  | 5.54e-4       | 1.02e-3           | 4.88e-3    |
| Resource Depletion - fossil          | kg oil-eq/kWh | 1.08e-2       | 5.45e-3           | *          |
| Land Use                             | m²/a crop-eq/kWh | 1.23e-3       | 1.25e-3           | 3.89e-1    |
| Water Use                            | m³/kWh        | 1.35e-3       | 2.39e-4           | *          |

*No value calculated / found in literature

The inventories of materials, energy and processes performed in the LCI within LCA are useful to establish potential impact of various components on environment. The life cycle impact assessment (LCIA) does not quantify any specific actual impacts associated with a product, process, or activity, but seeks to establish a connection between the system and potential impacts. The literature specifies several commonly used impact categories, equally observing human health, environmental and resources aspects, [24], figure 13, [33].
Following the description of the characterization factors from table 4, the table 5 collects computed and/or literature data for the specified subsystems of proposed hybrid module. The analysis of each category shows slightly larger values for the ceramic part of the TE unit, but most of data is in the same approximate range for all three subsystems.

By eliminating the terrestrial toxicity, which is at least one order of magnitude larger than all other impact categories, the following three important categories refer to current topics of concern worldwide: human health, global warming and fossil resource depletion.

4. End of life assessment
Most of research performed and industrial applications developed currently worldwide are concerned with new materials, processes and/or technologies for conversion of energy from RES. Usually, the literature presents the benefits of RES devices, but lately questions arise on recycling RES devices and manufacturing waste, collection and recycling infrastructure, as well as current and emerging recycling technologies. For the topic of this paper, the main emphasis is on recycling the PV subsystem, but also briefly analyzes the T and TE subsystems.

The PV panels are expected to have an operational life of up to 25-30 years, depending on the quality and manufacturing technology. Given the materials used for their manufacture, some expensive, some hazardous, the environmental regulations regulate the decommissioning procedures, [35]. The first step in PV end-of-life (EoL) recycling is to dismantle the frame and junction box, both being recoverable materials. Then, after shredding the EVA and glass protection, also recoverable, the metals are recovered by either smelting and refining or hydrometallurgicall separation.

The EoL assessment is also useful as an extension of the LCA – LCIA analysis. If EoL dismantling and recycling phases are included supplemental in the LCIA characterization, the impact values and influence may show a different image. A study published such results for a PV-T system, [26], and demonstrated that EoL scenario influenced the result of the analysis, specifically for the greenhouse effect, carcinogens, heavy metals and solid waste categories.

5. Conclusions
Benefits of using PV technologies increase if the module is connected with thermal and thermoelectric units. Despite the escalation in complexity of manufacturing such a hybrid module, the energetic benefits increase even more due to added thermal conversion and improved electric conversion efficiency.

The LCA (combined with LCIA) and EoL assessments presented in this paper with respect to the proposed hybrid PV-TE-T module, demonstrate the benefits of using such a device in relation to total energy, impact on human health, environment, and cost.

The assessments demonstrated that even acting in positive directions towards developing and using green energy and technologies, there will be a quantifiable impact on human health, global warming and fossil resource depletion. Recycling is technologically feasible and economically beneficial, by lessen the burden on these categories, but may influence other factors.

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