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# LCA and LCC of Emerging and Incumbent Technologies on Energy Harvesters †

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**Abstract:** In this study, life cycle assessment and life cycle costing results about piezoelectric and thermoelectric materials for energy harvesters (EHs) are extracted from the literature and evaluated. This study serves as a basis for comparing current EHs with innovative EHs that will be developed within the Horizon 2020 FAST SMART project. FAST—SMART aims at increasing the performance of current EHs while reducing at the same time: The use of rare elements and toxic substances; resources and energy consumption; environmental impact and costs; paving the way for the adoption of new and more environmental-friendly systems for energy harvesting.

**Keywords:** life cycle assessment; life cycle costing; piezoelectric materials; thermoelectric materials; energy harvesters



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## 1. Introduction

Energy harvesters (EHs) could be the key for our future. Global demand for energy is continuously increasing despite the COVID-19 pandemic caused a drop in consumption. Projections clearly indicate that in 2021 the energy consumption will increase worldwide in an average of 4.5% [1]. Energy was and will always be the key for economic rebounding and industrial growth. Thousand billion of Euros are invested every year around the world to make the production and use of energy more efficient.

Alternative and renewables sources appear to be the most promising in terms of environmental impact, cost for investment and, with the proper technological improvements, efficiency. Harvesting energy from the environment is an attractive option. It is based on ambient energy such as solar power, thermal energy, wind energy, and kinetic energy [2]. Vibrations and temperature gradients can be used to produce electricity through two types of materials: piezoelectric (PE) and thermoelectric (TE). PE materials generate an electric charge in response to a mechanical stress. This effect was discovered in 1880 by Pierre and Marie Curie [3]. TE materials generate an electric charge in response to the application of a difference of temperature to their p-n junctions (Seebeck effect, 1821) or, in reversible way, the material generates a difference of temperature between its p-n junctions when an electric charge is applied (Peltier effect, 1834) [4]. Materials efficiency and behavior are, therefore, key parameters in the development of PE or TE-based EHs. However, despite the great potential, their use is limited by several issues: toxicity of the elements used, long-term performance, manufacturing, and assembly cost. One of the main critical factors in EHs production is that the chemical compositions present in the market strongly depend on the materials classified as critical for Europe and, moreover, they contain lead that is well-known for its poisoning effects. Since 2011 the European Commission actively worked on listing elements considered strategic for its economy and whose scarcity and/or dependence can strongly jeopardize Europe's economy [5]. At the same time the European Commission started promoting and supporting initiatives and R&D activities aimed to substitute these elements with more available ones and not politically at risk. The EU published in 2020 a list of 30 Critical Raw Materials [6], including several elements contained in materials used for EHs. This situation poses a great challenge in the further penetration of EHs as alternative source of energy especially for supporting wide implementation of Internet of Things, and hence, promoting the Digital Single Market (DSM) in Europe.

To overcome these limitations, methodologies such as the life cycle assessment (LCA) and life cycle costing (LCC) can be applied to better understand the causes for high environmental and cost impact and thus, to define strategies for its reduction. LCA allows for the quantitative analysis of the whole life cycle of a system or product mainly in relation to its environmental impacts. A central role has been given to LCA in environmental regulations in many parts of the world, demonstrated also by ISO standard certifications and the strong increase in its use over the past decades [7]. In LCC all the costs incurred during the life cycle of a product or service, from its early stage toward its end of life, are identified, accounted, and categorized to be integrated into the decision-making process. As the idea to combine LCA and LCC in a more comprehensive and integrated approach, despite several key methodological differences between the two assessments [8], has become, recently, very attractive, LCC can be constructed in such a way so as its framework is based on the four LCA phases [9]. Concurrent LCA and LCC results of a product or service can guide the decision-makers toward more sustainable scenarios. On top of that, LCC can also incorporate external costs (environmental and social impacts) that are outside the system boundaries by monetizing them [8].

Environmental and economical sustainability is one of the main drives and targets of the H2020 FAST SMART project (www.fast-smart.org, accessed on 20 August 2021), which gathered a consortium of excellence constituted by 13 partners from 7 EU countries with a worldwide recognized expertise in the field of material science, EHs manufacturing and assembly, risk and safety. In order to support EU targets on the social, economic, and environmental development, FAST SMART project has the ambitious goal to develop high-quality nano powders as basis for lead-free and rare-earth free PE and TE materials. In addition, highly efficient sintering methods and novel EH structures and systems to drastically reduce the environmental impact of commercial EHs will be developed in order to open the way to a new generation of materials and devices for energy harvesting with no health issues and with high cost/benefit ratios. A complete and exhaustive LCA and LCC of commercially EHs is therefore carried out to identify a quantitative term of comparison for the new materials and processes that will be created in FAST SMART project. This study focuses on creating a detailed cradle-to-gate plus end-of-life (EoL) LCA and LCC model based on current literature for conventional PE and TE EH devices. Results from the two methods are extracted and evaluated to identify present environmental impact and cost as well as trade-offs across the supply chain of a product, guiding the development of FAST SMART EHs.

## 2. LCA—LCC Inventories for Materials and Devices for Energy Harvesting

### *2.1. Piezoelectric Material and Device*

The PE material for vibration-based energy harvesting to analyze according to LCA-LCC principles is selected regarding the demonstrator to be used in FAST SMART: a system for structural health monitoring in railways. Three types of transducers are used to obtain electrical energy from mechanical vibration: electromagnetic, electrostatic, and piezoelectric [10]. PE generator shows higher energy conversion [11] although current PE EHs are only effective within a limited frequency bandwidth because they are linear vibration based [12]. The most common type of PE used in power harvesting is lead zirconate titanate (PZT), a PE ceramic [13], and it was selected as the main material for the EH.

Data for the LCI of PZT production are extrapolated from the literature [14] and the machining process contribution is considered negligible assuming the use of a table CNC cutting machine. The functional unit for the analyses is an amplified PE actuator. The main components other than PZT are a metallic (Stainless-steel) support and Teflon end-stops. Processes of the assembly phase are considered having a minimal impact on LCA results. According to Tseng et al. [15], maximum output power density in PE devices is generally less than 30 W/cm$^3$. This value will be considered in the comparison with FAST SMART results, because improvements will be obtained in relation to the performance as well.

The LCA does not consider the final use phase contribution because the main objective is to highlight the differences between commercial and FAST SMART EHs devices in relation to materials, manufacturing processes, and the definition of ad hoc recycling strategies. Furthermore, this choice allows for comparison also in use cases other than the railways health monitoring. For the EoL of the PE commercial device, after the disassembly (considered negligible for LCA), the considered scenario is landfill. This choice is motivated by the novelty of such devices that are not yet produced in large scale. For this reason, their disposal is not a common procedure, and they might be just returned to the manufacturer and stored. The assumptions related to the use phase and EoL scenario are applied to the TE modules presented in Section 2.2 as well.

### 2.2. Thermoelectric Materials and Devices

Nowadays, applications for TE materials are remote power supply, solar–thermal systems, implantable or wearable devices, the automotive industry, temperature sensors, and many others [16]. In FAST SMART, the developed materials and devices will be tested on two types of demonstrators, according to their operational temperature ranges. In particular, the first type of demonstrator is represented by hybrid TE-PV solar panels where the required maximum temperature difference (ΔT) that the TE module can generate across itself is about 100–150 °C. Among TE materials, bismuth telluride (BT) compounds are the most widespread because of their relatively high figure of merit (ZT) [17]. Therefore, a TE module based on these compounds will be evaluated. The second demonstrator is a hybrid powered automobile with a desired ΔT of 250–300 °C. In this case, Skutterudites (SK) are analyzed because they present different advantages: abundant and cheap material among other TE; high figure of merit; temperature range from room temperature to 625 °C; good mechanical performance [18].

The LCI of the BT and SK -based modules is based on the BT-1 and SK-1 modules described in the study of Iyer, R.K. et al. [19]. However, changes were made to consider dimensions and materials quantities comparable to modules to be developed in FAST SMART. The functional units (1 cm$^2$ of the modules surface) were selected in order to consider the performance of the new products along with their environmental and economic impact. Commercial values of the achievable performance are based on the ratio of matched load output power and heat flow through module per cm$^2$ and are equal to 0.0013 for the BT module (data from the European Thermodynamics Company, Kibworth, Leicestershire, UK) and 0.0022 for the SK module [19].

### 2.3. Inventories for LCC

The selection of the LCC model (e.g., the choice of different cost categories and life cycle stages) depends each time on the examined system and the goal and scope of the study. Here, the most important cost categories were considered such as cost of raw materials, utilities cost, cost of waste treatment, equipment cost, labor cost, cost of transportation of raw materials, and cost of EoL. The prices of the raw materials were acquired either from chemical sales companies (e.g., Merck KGaA, Darmstadt, Germany, Thermo Fisher Scientific Inc. (NYSE: TMO)) or personal communication with industrial partners. The unit prices of waste types were taken from Turton et al. [20] while the unitary costs of electricity were taken from Eurostat for 2020 [21]. Subsequently, the equipment cost was taken from LeBlanc et al. [22] where it was normalized to the annual equipment cost assuming 20 years of plant lifespan using the annuity cost [23] and to the annual plant capacity. Finally, the cost of EoL was assessed by summing up (i) the cost of transportation from the use stage to the EoL facilities, (ii) the cost of sorting, and (iii) the cost of landfill which was calculated using a EU28 average estimate [24].

## 3. Results for the Performed LCA—LCC Analyses

The LCA analyses were performed according to the CML-IA baseline method (Normalization set EU25+3) and the Ecological Scarcity method (2013) using the SimaPro software. The main results are presented in Sections 3.1 and 3.2 and completed by the LCC analysis results.

### *3.1. Piezoelectric Device*

The EoL scenario has a minimal impact on the life cycle of the device as shown in Figure 1. However, it should be noticed that recycling processes could have a positive effect by reducing the value of mineral resources impact category, where the PZT and the metallic part contribute the most. The PZT material production has a relevant impact on the global warming category as well, together with the Teflon component, which is responsible for the ozone layer depletion, in spite of the small amount of material, mostly because of the methane chlorodifluoro. Furthermore, by applying the CML-IA baseline method, another important result is reported for the marine aquatic ecotoxicity level, mainly affected by the presence of hydrogen fluoride, beryllium, nickel, and selenium (listed as hazardous substances in the Regulation EC No. 1272/2008 of the European Parliament) in the production processes of Teflon and PZT.

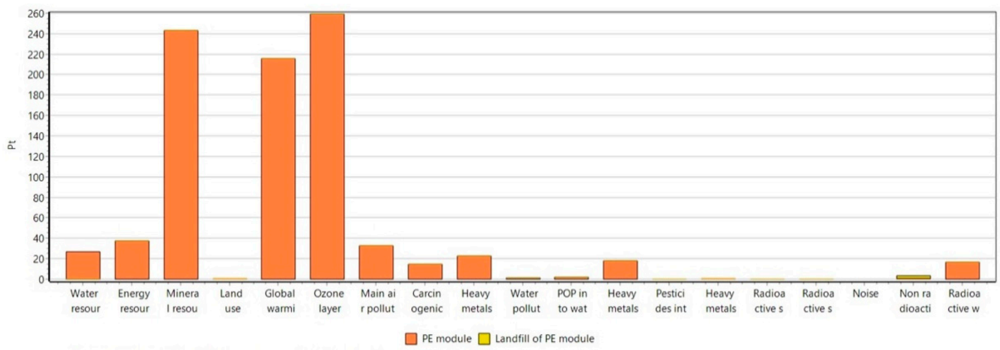


**Figure 1.** LCA Results for the PZT module according to the Ecological Scarcity 2013 Method.

The cost breakdown analysis for the PE module is shown in Figure 2. Approximately, 39.2% is attributed to the cost of raw materials while 31.3% is due to the equipment cost. Other significant cost categories were found to be the labor cost with 18.6% and the utilities cost with 10.7%. The rest of the cost categories (cost of EoL, cost of transportation, and cost of waste treatment) were rather unimportant, each one contributing less than 0.15% to the total LCC. The total LCC of the PE EH was estimated at €10.4 per module.

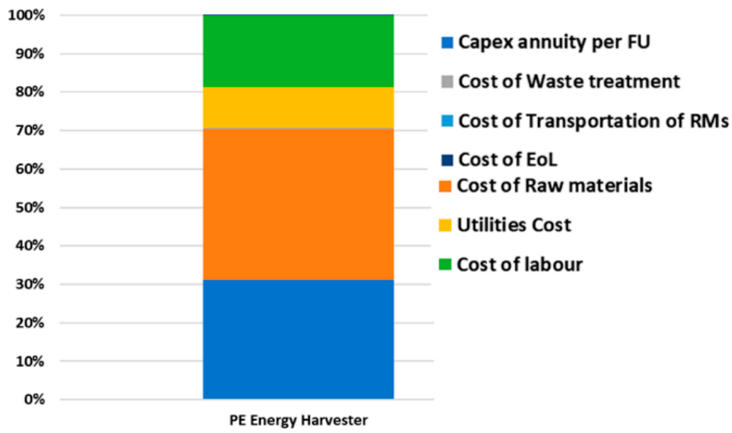


**Figure 2.** Cost breakdown of a PE module.

## 3.2. Thermoelectric Devices

The results obtained for both the BT and SK modules are represented in Figure 3. The extremely high impact on the mineral resources category for the BT module is caused by the presence of bismuth, antimony, tellurium, and selenium in large quantities in the production steps. All the mentioned raw materials are included in the EU's list of Critical Raw Materials [5]. In particular, the legs dicing step implies a huge waste of the BT material, much higher than the SK waste, as assumed in Iyer, R.K. et al. [19]. Different production processes might reduce such a massive impact on resources depletion. Aquatic ecotoxicity and human toxicity are the categories that, after the abiotic depletion one, present the major relevance for the BT module according to the CML-IA baseline method. Although wastage of the TE material is lower for the SK module production, the impact on mineral resources is serious. Even in this case, critical raw materials are used, such as antimony and cobalt. Moreover, p- and n-type legs both contain rare earths like didymium (obtained from praseodymium and neodymium), lanthanum, and ytterbium. Alumina plates and p-type legs production processes affect global warming and air pollutants and PM categories the most, more than the BT module, despite the smaller amount of material required for production. Another significative result is related to the radioactive waste, which mainly depends on the amount of electrical energy needed for the production processes. In the modelling phase, an averaged input parameter was selected for the electricity production and consumption, which refers to the European statistics and, thus, it includes electricity production from nuclear plants.

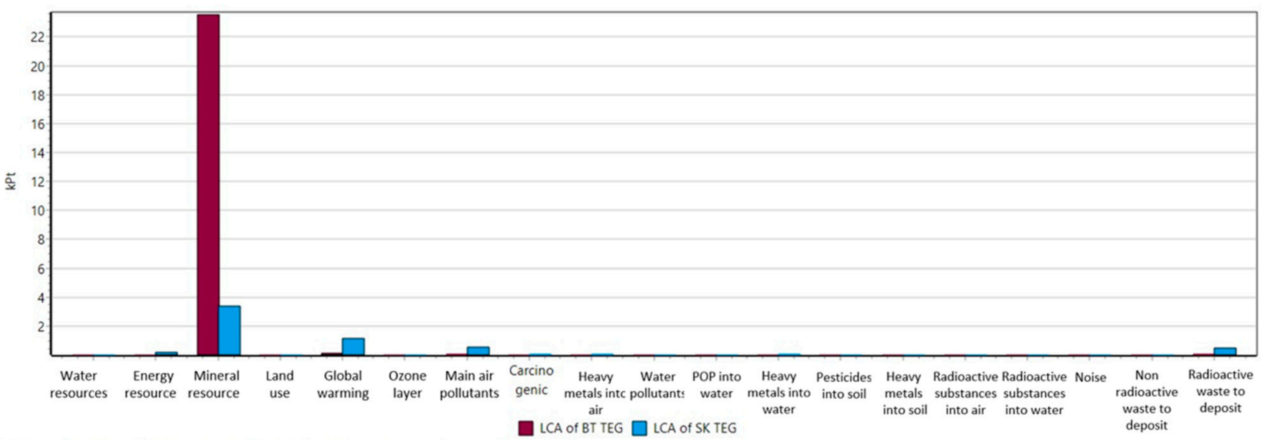


**Figure 3.** Comparison of LCA results for BT and SK modules (Ecological Scarcity 2013 Method).

LCC results on TE EHs for BT and SK are illustrated in Table 1. The total cost per functional unit was calculated at 1.606 € for BT and 0.695 € for SK. For both modules, the production cost of p-type and n-type legs contribute the most to the LCC while the cost of EoL is negligible (<0.1%).

**Table 1.** Contribution cost for the BT and SK energy harvester.

| BT | Cost | SK | Cost | Units |
|---|---|---|---|---|
| p-type leg | 1.466 | p-type leg | 0.515 | €/g |
| n-type leg | 1.467 | n-type leg | 0.464 | €/g |
| Alumina plates | 0.933 | Alumina plates | 0.162 | €/g |
| Copper tabs | 0.096 | Copper tabs | 0.088 | €/g |
| TE module | 35.526 | TE module | 23.373 | €/item |
| TE (0.0013 W/W/cm$^2$) | 1.606 | TE (0.0022 W/W/cm$^2$) | 0.695 | €/FU |

## 4. Discussion

The present analysis takes into consideration one PE material and two TE materials identified in the literature as the most representative solutions present in the market of EHs, whose chemical formulas are specified in Table 2.

**Table 2.** Materials for energy harvesting.

| MATERIAL | FORMULA |
|---|---|
| PE Lead Zirconate Titanate [14] | $Pb(Zr,Ti)O_3$ |
| TE1 Bismuth Telluride [19] | $Bi_{0,4}Sb_{1,6}Te_3$ (p type leg)<br>$Bi_2Te_{2,4}Se_{0,6}$ (n type leg) |
| TE2 Skutterudite [19] | $DD_{0,76}Fe_{3,45}Ni_{0,6}Sb_{12}$ (p type leg)<br>$Ba_{0.08}La_{0.05}Yb_{0.04}Co_4Sb_{12}$ (n type leg) |

Several of the elements in the three commercial materials are classified as critical raw materials [5], specifically antimony, baryte, bismuth, cobalt, heavy rare earth elements, light rare earth elements, and titanium. Considering the hazardous effect of using lead and the dangerous dependency from materials considered at risk for the European economy, it can be clearly understood how strategic will be in the future to change this design paradigm to make Europe competitive and independent in the new strategic market of the renewable energy. Lead-free compositions and substitution of critical raw materials are the main targets of FAST SMART that will bring into the market a new generation of EHs for the automotive, energy, and transport sector.

To tackle the rapid growth of e-waste, the Waste from Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [25] and the restriction of hazardous substances (RoHS) [26] promote separate collection systems that will allow the preparation to reuse and recycling or recovery of electronic and electrical devices to minimize municipal waste landfilling, setting targets for recovery and recycling at 85% and 80% respectively. The application of WEEE often encounters technical difficulties and may be subject to environmental concerns (e.g., heavy metals contamination, cross-linked polymers, and hazardous chemical elements). Novel PE and TE EHs to be developed in FAST-SMART aim to increase the recyclability and reduce hazardous waste by at least 50% through improving material processing and deploying high-efficient recycling technologies.

## 5. Conclusions

Available clean energy at competitive price is the key for the survival of every economy. Oil dependency and scarcity of certain elements oblige Europe to orientate its economy in the search of alternative solutions capable to make it become independent from external supplies and create environmental and health-friendly devices. This study serves as a basis for building up the new LCI models for TE and PE EHs that will be developed in the

FAST SMART project. Moreover, it attempts to enhance the state-of-the-art regarding the coupling of LCA and LCC for PE and TE EHs as little can be found in the literature on this topic. The reference cases evaluation will contribute to the definition of new strategies for the performance improvement of current EHs while reducing at the same time: The use of rare elements and toxic substances; resources and energy consumption; environmental impact and costs; paving the way for the adoption of new and more environmental-friendly systems for energy harvesting.

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